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See the related review(s):  
[Mass and Width of the  \$W\$  Boson](#)

### W MASS

The  $W$ -mass listed here corresponds to the mass parameter in a Breit-Wigner distribution with mass-dependent width. To obtain the world average, common systematic uncertainties between experiments are properly taken into account. The LEP-2 average  $W$  mass based on published results from ALEPH, DELPHI, L3, and OPAL is  $80.376 \pm 0.033$  GeV [SCHAEL 13A]. The combined Tevatron data from CDF and D0 yields an average  $W$  mass of  $80.387 \pm 0.016$  GeV [AALTONEN 13N]. Assuming a common systematic error of 9 MeV due to PDF uncertainty, the combined LHC data from ATLAS [AABOUD 18J] and LHCb [AAIJ 22c] yields an average  $W$  mass of  $80.366 \pm 0.017$  GeV [J. Erler and A. Freitas, "Electroweak Model and Constraints on New Physics" review, PDG 22]. Assuming 7 MeV as the common systematic uncertainty between the LHC and Tevatron results, the average  $W$  mass from the two hadron colliders is estimated to be  $80.377 \pm 0.013$  GeV. Combining this result with the LEP-2 value assuming no correlations, the world average  $W$  mass of  $80.377 \pm 0.012$  GeV is obtained [Ibid].

PDG 2022 pre AALTONEN 22 CDF quotes this value for the  $W$  mass.

More information is given in M. Grunewald and A. Gurtu, "Mass and Width of the  $W$  Boson" review [PDG 22].

In April 2022 the CDF collaboration published a determination of the  $W$  mass based on their full Run-2 dataset of  $8.8 \text{ fb}^{-1}$  [AALTONEN 22], with much reduced uncertainty:  $80433.5 \pm 9.4$  MeV. This new CDF result, which includes the data of their previous result [AALTONEN 12E] and thus supersedes it, is of higher precision than our world average quoted above. However, the two determinations disagree significantly.

The Tevatron-LHC  $W$ -boson mass combination working group, consisting of experts from the hadron collider experiments, ATLAS, CDF, CMS, D0, and LHCb, is examining in detail all aspects of the measurements, paying attention to corrections and correlated uncertainties in order to treat all results on an equal footing and properly account for correlations in various averages. The report from the combination group is awaited.

VALUE (GeV)	EVTS	DOCUMENT ID	TECN	COMMENT
<b><math>80.377 \pm 0.012</math></b>	<b>OUR FIT</b>	(PDG 2022 pre AALTONEN 22 CDF)		
<b><math>80.4335 \pm 0.0094</math></b>		(AALTONEN 22 CDF)		
$80.354 \pm 0.023 \pm 0.022$	2.4M	1 AAIJ	22c LHCb	$E_{\text{cm}}^{pp} = 13 \text{ TeV}$
$80.4335 \pm 0.0064 \pm 0.0069$	4.2M	2 AALTONEN	22 CDF	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
$80.370 \pm 0.007 \pm 0.017$	13.7M	3 AABOUD	18J ATLS	$E_{\text{cm}}^{pp} = 7 \text{ TeV}$
$80.387 \pm 0.012 \pm 0.015$	1095k	4 AALTONEN	12E CDF	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$

80.375 ± 0.011 ± 0.020	2177k	5	ABAZOV	12F	D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
80.336 ± 0.055 ± 0.039	10.3k	6	ABDALLAH	08A	DLPH	$E_{\text{cm}}^{ee} = 161\text{--}209 \text{ GeV}$
80.415 ± 0.042 ± 0.031	11830	7	ABBIENDI	06	OPAL	$E_{\text{cm}}^{ee} = 170\text{--}209 \text{ GeV}$
80.270 ± 0.046 ± 0.031	9909	8	ACHARD	06	L3	$E_{\text{cm}}^{ee} = 161\text{--}209 \text{ GeV}$
80.440 ± 0.043 ± 0.027	8692	9	SCHAELE	06	ALEP	$E_{\text{cm}}^{ee} = 161\text{--}209 \text{ GeV}$
80.483 ± 0.084	49247	10	ABAZOV	02D	D0	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
80.433 ± 0.079	53841	11	AFFOLDER	01E	CDF	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●						
80.520 ± 0.070 ± 0.092		12	ANDREEV	18A	H1	$e^{\pm} p$
80.367 ± 0.013 ± 0.022	1677k	13	ABAZOV	12F	D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
80.401 ± 0.021 ± 0.038	500k	14	ABAZOV	09AB	D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
80.413 ± 0.034 ± 0.034	115k	15	AALTONEN	07F	CDF	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
82.87 ± 1.82 $^{+0.30}_{-0.16}$	1500	16	AKTAS	06	H1	$e^{\pm} p \rightarrow \bar{\nu}_e(\nu_e)X, \sqrt{s} \approx 300 \text{ GeV}$
80.3 ± 2.1 ± 1.2 ± 1.0	645	17	CHEKANOV	02C	ZEUS	$e^{-} p \rightarrow \nu_e X, \sqrt{s} = 318 \text{ GeV}$
81.4 $^{+2.7}_{-2.6}$ ± 2.0 $^{+3.3}_{-3.0}$	1086	18	BREITWEG	00D	ZEUS	$e^{+} p \rightarrow \bar{\nu}_e X, \sqrt{s} \approx 300 \text{ GeV}$
80.84 ± 0.22 ± 0.83	2065	19	ALITTI	92B	UA2	See $W/Z$ ratio below
80.79 ± 0.31 ± 0.84		20	ALITTI	90B	UA2	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$
80.0 ± 3.3 ± 2.4	22	21	ABE	89I	CDF	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
82.7 ± 1.0 ± 2.7	149	22	ALBAJAR	89	UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$
81.8 $^{+6.0}_{-5.3}$ ± 2.6	46	23	ALBAJAR	89	UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$
89 ± 3 ± 6	32	24	ALBAJAR	89	UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$
81. ± 5.	6		ARNISON	83	UA1	$E_{\text{cm}}^{ee} = 546 \text{ GeV}$
80. $^{+10.}_{-6.}$	4		BANNER	83B	UA2	Repl. by ALITTI 90B

<sup>1</sup> AAIJ 22C analyse  $W$  production in the muon decay channel, with the transverse momentum of the muon required to be between 28 and 52 GeV. Analysing the distribution of the muon charge divided by the muon transverse momentum of approximately 2.4 million selected  $W$  candidates, a value of  $M_W = 80354 \pm 23(\text{stat.}) \pm 10(\text{exp.}) \pm 17(\text{theo.}) \pm 9(\text{PDF}) \text{ MeV}$  is obtained; we combine the three systematic uncertainties in quadrature.

<sup>2</sup> AALTONEN 22 select a data sample of about 4 million  $W$  boson candidates in  $8.8 \text{ fb}^{-1}$  of Run-II data. The mass is determined using the transverse mass, transverse lepton momentum and transverse missing momentum distributions of  $W$  decays into electrons or muons, accounting for correlations. This measurement supersedes AALTONEN 12E, but it is not used in the evaluation of OUR FIT (PDG 2022 pre AALTONEN 22 CDF) value.

<sup>3</sup> AABOUD 18J select 4.61M  $W^+ \rightarrow \mu^+ \nu_{\mu}$ , 3.40M  $W^+ \rightarrow e^+ \nu_e$ , 3.23M  $W^- \rightarrow \mu^- \bar{\nu}_{\mu}$  and 2.49M  $W^- \rightarrow e^- \bar{\nu}_e$  events in  $4.6 \text{ fb}^{-1} pp$  data at 7 TeV. The  $W$  mass is determined using the transverse mass and transverse lepton momentum distributions, accounting for correlations. The systematic error includes 0.011 GeV experimental and 0.014 GeV modelling uncertainties.

- 4 AALTONEN 12E select 470k  $W \rightarrow e\nu$  decays and 625k  $W \rightarrow \mu\nu$  decays in 2.2 fb<sup>-1</sup> of Run-II data. The mass is determined using the transverse mass, transverse lepton momentum and transverse missing energy distributions, accounting for correlations. This result supersedes AALTONEN 07F. AALTONEN 14D gives more details on the procedures followed by the authors. This measurement is superseded by AALTONEN 22, but it is used in the evaluation of OUR FIT (PDG 2022 pre AALTONEN 22 CDF) value.
- 5 Combination of results from ABAZOV 12F and ABAZOV 09AB as quoted in ABAZOV 12F.
- 6 ABDALLAH 08A use direct reconstruction of the kinematics of  $W^+W^- \rightarrow q\bar{q}\ell\nu$  and  $W^+W^- \rightarrow q\bar{q}q\bar{q}$  events for energies 172 GeV and above. The  $W$  mass was also extracted from the dependence of the  $WW$  cross section close to the production threshold and combined appropriately to obtain the final result. The systematic error includes  $\pm 0.025$  GeV due to final state interactions and  $\pm 0.009$  GeV due to LEP energy uncertainty.
- 7 ABBIENDI 06 use direct reconstruction of the kinematics of  $W^+W^- \rightarrow q\bar{q}\ell\nu_\ell$  and  $W^+W^- \rightarrow q\bar{q}q\bar{q}$  events. The result quoted here is obtained combining this mass value with the results using  $W^+W^- \rightarrow \ell\nu_\ell\ell'\nu_{\ell'}$  events in the energy range 183–207 GeV (ABBIENDI 03C) and the dependence of the  $WW$  production cross-section on  $m_{WW}$  at threshold. The systematic error includes  $\pm 0.009$  GeV due to the uncertainty on the LEP beam energy.
- 8 ACHARD 06 use direct reconstruction of the kinematics of  $W^+W^- \rightarrow q\bar{q}\ell\nu_\ell$  and  $W^+W^- \rightarrow q\bar{q}q\bar{q}$  events in the C.M. energy range 189–209 GeV. The result quoted here is obtained combining this mass value with the results obtained from a direct  $W$  mass reconstruction at 172 and 183 GeV and with those from the dependence of the  $WW$  production cross-section on  $m_{WW}$  at 161 and 172 GeV (ACCIARRI 99).
- 9 SCHAEEL 06 use direct reconstruction of the kinematics of  $W^+W^- \rightarrow q\bar{q}\ell\nu_\ell$  and  $W^+W^- \rightarrow q\bar{q}q\bar{q}$  events in the C.M. energy range 183–209 GeV. The result quoted here is obtained combining this mass value with those obtained from the dependence of the  $W$  pair production cross-section on  $m_{WW}$  at 161 and 172 GeV (BARATE 97 and BARATE 97S respectively). The systematic error includes  $\pm 0.009$  GeV due to possible effects of final state interactions in the  $q\bar{q}q\bar{q}$  channel and  $\pm 0.009$  GeV due to the uncertainty on the LEP beam energy.
- 10 ABAZOV 02D improve the measurement of the  $W$ -boson mass including  $W \rightarrow e\nu_e$  events in which the electron is close to a boundary of a central electromagnetic calorimeter module. Properly combining the results obtained by fitting  $m_T(W)$ ,  $p_T(e)$ , and  $p_T(\nu)$ , this sample provides a mass value of  $80.574 \pm 0.405$  GeV. The value reported here is a combination of this measurement with all previous  $D\bar{D}$   $W$ -boson mass measurements.
- 11 AFFOLDER 01E fit the transverse mass spectrum of 30115  $W \rightarrow e\nu_e$  events ( $M_{WW} = 80.473 \pm 0.065 \pm 0.092$  GeV) and of 14740  $W \rightarrow \mu\nu_\mu$  events ( $M_{WW} = 80.465 \pm 0.100 \pm 0.103$  GeV) obtained in the run IB (1994-95). Combining the electron and muon results, accounting for correlated uncertainties, yields  $M_{WW} = 80.470 \pm 0.089$  GeV. They combine this value with their measurement of ABE 95P reported in run IA (1992-93) to obtain the quoted value.
- 12 ANDREEV 18A obtain this result in a combined electroweak and QCD analysis using all deep-inelastic  $e^+p$  and  $e^-p$  neutral current and charged current scattering cross sections published by the H1 Collaboration, including data with longitudinally polarized lepton beams.
- 13 ABAZOV 12F select 1677k  $W \rightarrow e\nu$  decays in 4.3 fb<sup>-1</sup> of Run-II data. The mass is determined using the transverse mass and transverse lepton momentum distributions, accounting for correlations.
- 14 ABAZOV 09AB study the transverse mass, transverse electron momentum, and transverse missing energy in a sample of 0.5 million  $W \rightarrow e\nu$  decays selected in Run-II data. The quoted result combines all three methods, accounting for correlations.
- 15 AALTONEN 07F obtain high purity  $W \rightarrow e\nu_e$  and  $W \rightarrow \mu\nu_\mu$  candidate samples totaling 63,964 and 51,128 events respectively. The  $W$  mass value quoted above is

- derived by simultaneously fitting the transverse mass and the lepton, and neutrino  $p_T$  distributions.
- 16 AKTAS 06 fit the  $Q^2$  dependence ( $300 < Q^2 < 30,000 \text{ GeV}^2$ ) of the charged-current differential cross section with a propagator mass. The first error is experimental and the second corresponds to uncertainties due to input parameters and model assumptions.
  - 17 CHEKANOV 02C fit the  $Q^2$  dependence ( $200 < Q^2 < 60000 \text{ GeV}^2$ ) of the charged-current differential cross sections with a propagator mass fit. The last error is due to the uncertainty on the probability density functions.
  - 18 BREITWEG 00D fit the  $Q^2$  dependence ( $200 < Q^2 < 22500 \text{ GeV}^2$ ) of the charged-current differential cross sections with a propagator mass fit. The last error is due to the uncertainty on the probability density functions.
  - 19 ALITTI 92B result has two contributions to the systematic error ( $\pm 0.83$ ); one ( $\pm 0.81$ ) cancels in  $m_W/m_Z$  and one ( $\pm 0.17$ ) is noncancelling. These were added in quadrature. We choose the ALITTI 92B value without using the LEP  $m_Z$  value, because we perform our own combined fit.
  - 20 There are two contributions to the systematic error ( $\pm 0.84$ ): one ( $\pm 0.81$ ) which cancels in  $m_W/m_Z$  and one ( $\pm 0.21$ ) which is non-cancelling. These were added in quadrature.
  - 21 ABE 89I systematic error dominated by the uncertainty in the absolute energy scale.
  - 22 ALBAJAR 89 result is from a total sample of 299  $W \rightarrow e\nu$  events.
  - 23 ALBAJAR 89 result is from a total sample of 67  $W \rightarrow \mu\nu$  events.
  - 24 ALBAJAR 89 result is from  $W \rightarrow \tau\nu$  events.

### W/Z MASS RATIO

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<b>0.88145 ± 0.00013</b>		<sup>1</sup> PDG	22	
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
0.8821 ± 0.0011 ± 0.0008	28323	<sup>2</sup> ABBOTT	98N D0	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
0.88114 ± 0.00154 ± 0.00252	5982	<sup>3</sup> ABBOTT	98P D0	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
0.8813 ± 0.0036 ± 0.0019	156	<sup>4</sup> ALITTI	92B UA2	$E_{\text{cm}}^{p\bar{p}} = 630 \text{ GeV}$

- <sup>1</sup> This value was obtained using the world average values of  $m_Z$  and  $m_W$  as listed in these listings.
- <sup>2</sup> ABBOTT 98N obtain this from a study of 28323  $W \rightarrow e\nu_e$  and 3294  $Z \rightarrow e^+e^-$  decays. Of this latter sample, 2179 events are used to calibrate the electron energy scale.
- <sup>3</sup> ABBOTT 98P obtain this from a study of 5982  $W \rightarrow e\nu_e$  events. The systematic error includes an uncertainty of  $\pm 0.00175$  due to the electron energy scale.
- <sup>4</sup> Scale error cancels in this ratio.

### $m_Z - m_W$

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
<b>10.811 ± 0.012</b>	<sup>1</sup> PDG	22	
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
10.4 ± 1.4 ± 0.8	ALBAJAR	89 UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$
11.3 ± 1.3 ± 0.9	ANSARI	87 UA2	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$

- <sup>1</sup> This value was obtained using the world average values of  $m_Z$  and  $m_W$  as listed in these listings.

$$m_{W^+} - m_{W^-}$$

Test of *CPT* invariance.

<u>VALUE (GeV)</u>	<u>EVTs</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>-0.029±0.028 OUR AVERAGE</b>				
-0.029±0.013±0.025	13.7M	<sup>1</sup> AABOUD	18J ATLS	$E_{cm}^{pp} = 7 \text{ TeV}$
-0.19 ±0.58	1722	ABE	90G CDF	$E_{cm}^{pp} = 1.8 \text{ TeV}$
<sup>1</sup> AABOUD 18J select 4.61M $W^+ \rightarrow \mu^+ \nu_\mu$ , 3.40M $W^+ \rightarrow e^+ \nu_e$ , 3.23M $W^- \rightarrow \mu^- \bar{\nu}_\mu$ and 2.49M $W^- \rightarrow e^- \bar{\nu}_e$ events in $4.6 \text{ fb}^{-1}$ $pp$ data at 7 TeV. The $W$ mass is determined using the transverse mass and transverse lepton momentum distributions, accounting for correlations. The systematic error includes 0.007 GeV experimental and 0.024 GeV modelling uncertainties.				

## W WIDTH

The  $W$  width listed here corresponds to the width parameter in a Breit-Wigner distribution with mass-dependent width. To obtain the world average, common systematic uncertainties between experiments are properly taken into account. The LEP-2 average  $W$  width based on published results is  $2.195 \pm 0.083 \text{ GeV}$  [SCHAEL 13A]. The combined Tevatron data yields an average  $W$  width of  $2.046 \pm 0.049 \text{ GeV}$  [FERMILAB-TM-2460-E].

OUR FIT uses these average LEP and Tevatron width values and combines them assuming no correlations.

<u>VALUE (GeV)</u>	<u>EVTs</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>2.085±0.042 OUR FIT</b>				
2.028±0.072	5272	<sup>1</sup> ABAZOV	09AK D0	$E_{cm}^{pp} = 1.96 \text{ GeV}$
2.032±0.045±0.057	6055	<sup>2</sup> AALTONEN	08B CDF	$E_{cm}^{pp} = 1.96 \text{ TeV}$
2.404±0.140±0.101	10.3k	<sup>3</sup> ABDALLAH	08A DLPH	$E_{cm}^{ee} = 183\text{--}209 \text{ GeV}$
1.996±0.096±0.102	10729	<sup>4</sup> ABBIENDI	06 OPAL	$E_{cm}^{ee} = 170\text{--}209 \text{ GeV}$
2.18 ±0.11 ±0.09	9795	<sup>5</sup> ACHARD	06 L3	$E_{cm}^{ee} = 172\text{--}209 \text{ GeV}$
2.14 ±0.09 ±0.06	8717	<sup>6</sup> SCHAEL	06 ALEP	$E_{cm}^{ee} = 183\text{--}209 \text{ GeV}$
2.23 <sup>+0.15</sup> / <sub>-0.14</sub> ±0.10	294	<sup>7</sup> ABAZOV	02E D0	$E_{cm}^{pp} = 1.8 \text{ TeV}$
2.05 ±0.10 ±0.08	662	<sup>8</sup> AFFOLDER	00M CDF	$E_{cm}^{pp} = 1.8 \text{ TeV}$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
2.152±0.066	79176	<sup>9</sup> ABBOTT	00B D0	Extracted value
2.064±0.060±0.059		<sup>10</sup> ABE	95W CDF	Extracted value
2.10 <sup>+0.14</sup> / <sub>-0.13</sub> ±0.09	3559	<sup>11</sup> ALITTI	92 UA2	Extracted value
2.18 <sup>+0.26</sup> / <sub>-0.24</sub> ±0.04		<sup>12</sup> ALBAJAR	91 UA1	Extracted value

<sup>1</sup> ABAZOV 09AK obtain this result fitting the high-end tail (100-200 GeV) of the transverse mass spectrum in  $W \rightarrow e\nu$  decays.

<sup>2</sup> AALTONEN 08B obtain this result fitting the high-end tail (90-200 GeV) of the transverse mass spectrum in semileptonic  $W \rightarrow e\nu_e$  and  $W \rightarrow \mu\nu_\mu$  decays.

- <sup>3</sup> ABDALLAH 08A use direct reconstruction of the kinematics of  $W^+ W^- \rightarrow q\bar{q}\ell\nu$  and  $W^+ W^- \rightarrow q\bar{q}q\bar{q}$  events. The systematic error includes  $\pm 0.065$  GeV due to final state interactions.
- <sup>4</sup> ABBIENDI 06 use direct reconstruction of the kinematics of  $W^+ W^- \rightarrow q\bar{q}\ell\nu_\ell$  and  $W^+ W^- \rightarrow q\bar{q}q\bar{q}$  events. The systematic error includes  $\pm 0.003$  GeV due to the uncertainty on the LEP beam energy.
- <sup>5</sup> ACHARD 06 use direct reconstruction of the kinematics of  $W^+ W^- \rightarrow q\bar{q}\ell\nu_\ell$  and  $W^+ W^- \rightarrow q\bar{q}q\bar{q}$  events in the C.M. energy range 189–209 GeV. The result quoted here is obtained combining this value of the width with the result obtained from a direct  $W$  mass reconstruction at 172 and 183 GeV (ACCIARRI 99).
- <sup>6</sup> SCHAEEL 06 use direct reconstruction of the kinematics of  $W^+ W^- \rightarrow q\bar{q}\ell\nu_\ell$  and  $W^+ W^- \rightarrow q\bar{q}q\bar{q}$  events. The systematic error includes  $\pm 0.05$  GeV due to possible effects of final state interactions in the  $q\bar{q}q\bar{q}$  channel and  $\pm 0.01$  GeV due to the uncertainty on the LEP beam energy.
- <sup>7</sup> ABAZOV 02E obtain this result fitting the high-end tail (90–200 GeV) of the transverse-mass spectrum in semileptonic  $W \rightarrow e\nu_e$  decays.
- <sup>8</sup> AFFOLDER 00M fit the high transverse mass (100–200 GeV)  $W \rightarrow e\nu_e$  and  $W \rightarrow \mu\nu_\mu$  events to obtain  $\Gamma(W) = 2.04 \pm 0.11(\text{stat}) \pm 0.09(\text{syst})$  GeV. This is combined with the earlier CDF measurement (ABE 95C) to obtain the quoted result.
- <sup>9</sup> ABBOTT 00B measure  $R = 10.43 \pm 0.27$  for the  $W \rightarrow e\nu_e$  decay channel. They use the SM theoretical predictions for  $\sigma(W)/\sigma(Z)$  and  $\Gamma(W \rightarrow e\nu_e)$  and the world average for  $B(Z \rightarrow ee)$ . The value quoted here is obtained combining this result ( $2.169 \pm 0.070$  GeV) with that of ABBOTT 99H.
- <sup>10</sup> ABE 95W measured  $R = 10.90 \pm 0.32 \pm 0.29$ . They use  $m_W = 80.23 \pm 0.18$  GeV,  $\sigma(W)/\sigma(Z) = 3.35 \pm 0.03$ ,  $\Gamma(W \rightarrow e\nu) = 225.9 \pm 0.9$  MeV,  $\Gamma(Z \rightarrow e^+e^-) = 83.98 \pm 0.18$  MeV, and  $\Gamma(Z) = 2.4969 \pm 0.0038$  GeV.
- <sup>11</sup> ALITTI 92 measured  $R = 10.4^{+0.7}_{-0.6} \pm 0.3$ . The values of  $\sigma(Z)$  and  $\sigma(W)$  come from  $O(\alpha_s^2)$  calculations using  $m_W = 80.14 \pm 0.27$  GeV, and  $m_Z = 91.175 \pm 0.021$  GeV along with the corresponding value of  $\sin^2\theta_W = 0.2274$ . They use  $\sigma(W)/\sigma(Z) = 3.26 \pm 0.07 \pm 0.05$  and  $\Gamma(Z) = 2.487 \pm 0.010$  GeV.
- <sup>12</sup> ALBAJAR 91 measured  $R = 9.5^{+1.1}_{-1.0}$  (stat. + syst.).  $\sigma(W)/\sigma(Z)$  is calculated in QCD at the parton level using  $m_W = 80.18 \pm 0.28$  GeV and  $m_Z = 91.172 \pm 0.031$  GeV along with  $\sin^2\theta_W = 0.2322 \pm 0.0014$ . They use  $\sigma(W)/\sigma(Z) = 3.23 \pm 0.05$  and  $\Gamma(Z) = 2.498 \pm 0.020$  GeV. This measurement is obtained combining both the electron and muon channels.

## W<sup>+</sup> DECAY MODES

$W^-$  modes are charge conjugates of the modes below.

Mode	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level
$\Gamma_1$ $\ell^+\nu$	[a] $(10.86 \pm 0.09)$ %	
$\Gamma_2$ $e^+\nu$	$(10.71 \pm 0.16)$ %	
$\Gamma_3$ $\mu^+\nu$	$(10.63 \pm 0.15)$ %	
$\Gamma_4$ $\tau^+\nu$	$(11.38 \pm 0.21)$ %	
$\Gamma_5$ hadrons	$(67.41 \pm 0.27)$ %	
$\Gamma_6$ $\pi^+\gamma$	$< 7$	$\times 10^{-6}$ 95%
$\Gamma_7$ $D_s^+\gamma$	$< 1.3$	$\times 10^{-3}$ 95%
$\Gamma_8$ $cX$	$(33.3 \pm 2.6)$ %	

$\Gamma_9$	$c\bar{s}$	(31	$\begin{matrix} +13 \\ -11 \end{matrix}$	) %
$\Gamma_{10}$	invisible	[b]	( 1.4 $\pm$ 2.9 )	%
$\Gamma_{11}$	$\pi^+ \pi^+ \pi^-$	< 1.01	$\times 10^{-6}$	95%

[a]  $\ell$  indicates each type of lepton ( $e$ ,  $\mu$ , and  $\tau$ ), not sum over them.

[b] This represents the width for the decay of the  $W$  boson into a charged particle with momentum below detectability,  $p < 200$  MeV.

## W PARTIAL WIDTHS

**$\Gamma(\text{invisible})$**   **$\Gamma_{10}$**

This represents the width for the decay of the  $W$  boson into a charged particle with momentum below detectability,  $p < 200$  MeV.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
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<b><math>30^{+52}_{-48} \pm 33</math></b>	<sup>1</sup> BARATE	99I	ALEP $E_{\text{cm}}^{ee} = 161+172+183$ GeV
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• • • We do not use the following data for averages, fits, limits, etc. • • •

	<sup>2</sup> BARATE	99L	ALEP $E_{\text{cm}}^{ee} = 161+172+183$ GeV
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<sup>1</sup> BARATE 99I measure this quantity using the dependence of the total cross section  $\sigma_{WW}$  upon a change in the total width. The fit is performed to the  $WW$  measured cross sections at 161, 172, and 183 GeV. This partial width is  $< 139$  MeV at 95%CL.

<sup>2</sup> BARATE 99L use  $W$ -pair production to search for effectively invisible  $W$  decays, tagging with the decay of the other  $W$  boson to Standard Model particles. The partial width for effectively invisible decay is  $< 27$  MeV at 95%CL.

## W BRANCHING RATIOS

Overall fits are performed to determine the branching ratios of the  $W$  boson. Averages on  $W \rightarrow e\nu$ ,  $W \rightarrow \mu\nu$ , and  $W \rightarrow \tau\nu$ , and their correlations are obtained by combining results from the four LEP experiments properly taking into account the common systematic uncertainties and their correlations [SCHAEEL 13A]. A first fit determines the three individual leptonic branching ratios  $B(W \rightarrow e\nu)$ ,  $B(W \rightarrow \mu\nu)$ , and  $B(W \rightarrow \tau\nu)$ . This fit has a  $\chi^2 = 6.3$  for 9 degrees of freedom. The correlation coefficients between the branching fractions are 0.14 ( $e - \mu$ ),  $-0.20$  ( $e - \tau$ ),  $-0.12$  ( $\mu - \tau$ ). A second fit assumes lepton universality and determines the leptonic branching ratio  $B(W \rightarrow \ell\nu)$  and the hadronic branching ratio is derived as  $B(W \rightarrow \text{hadrons}) = 1 - 3 B(W \rightarrow \ell\nu)$ . This fit has a  $\chi^2 = 15.4$  for 11 degrees of freedom.

**$\Gamma(\ell^+ \nu) / \Gamma_{\text{total}}$**   **$\Gamma_1 / \Gamma$**

$\ell$  indicates average over  $e$ ,  $\mu$ , and  $\tau$  modes, not sum over modes.

VALUE (units $10^{-2}$ )	EVTS	DOCUMENT ID	TECN	COMMENT
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**10.86  $\pm$  0.09 OUR FIT**

10.89 $\pm$ 0.01 $\pm$ 0.08		TUMASYAN	22F	CMS $E_{\text{cm}}^{pp} = 13$ TeV
10.86 $\pm$ 0.12 $\pm$ 0.08	16438	ABBIENDI	07A	OPAL $E_{\text{cm}}^{ee} = 161-209$ GeV
10.85 $\pm$ 0.14 $\pm$ 0.08	13600	ABDALLAH	04G	DLPH $E_{\text{cm}}^{ee} = 161-209$ GeV
10.83 $\pm$ 0.14 $\pm$ 0.10	11246	ACHARD	04J	L3 $E_{\text{cm}}^{ee} = 161-209$ GeV
10.96 $\pm$ 0.12 $\pm$ 0.05	16116	SCHAEEL	04A	ALEP $E_{\text{cm}}^{ee} = 183-209$ GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

$11.02 \pm 0.52$	11858	<sup>1</sup> ABBOTT	99H	D0	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
$10.4 \pm 0.8$	3642	<sup>2</sup> ABE	92I	CDF	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$

<sup>1</sup> ABBOTT 99H measure  $R \equiv [\sigma_W B(W \rightarrow \ell\nu_\ell)] / [\sigma_Z B(Z \rightarrow \ell\ell)] = 10.90 \pm 0.52$  combining electron and muon channels. They use  $M_W = 80.39 \pm 0.06 \text{ GeV}$  and the SM theoretical predictions for  $\sigma(W)/\sigma(Z)$  and  $B(Z \rightarrow \ell\ell)$ .

<sup>2</sup>  $1216 \pm 38_{-31}^{+27} W \rightarrow \mu\nu$  events from ABE 92I and  $2426 W \rightarrow e\nu$  events of ABE 91C. ABE 92I give the inverse quantity as  $9.6 \pm 0.7$  and we have inverted.

### $\Gamma(e^+\nu)/\Gamma_{\text{total}}$ $\Gamma_2/\Gamma$

VALUE (units $10^{-2}$ )	EVTS	DOCUMENT ID	TECN	COMMENT
<b>10.71 ± 0.16 OUR FIT</b>				
$10.83 \pm 0.01 \pm 0.10$		TUMASYAN	22F CMS	$E_{\text{cm}}^{p\bar{p}} = 13 \text{ TeV}$
$10.71 \pm 0.25 \pm 0.11$	2374	ABBIENDI	07A OPAL	$E_{\text{cm}}^{e\bar{e}} = 161\text{--}209 \text{ GeV}$
$10.55 \pm 0.31 \pm 0.14$	1804	ABDALLAH	04G DLPH	$E_{\text{cm}}^{e\bar{e}} = 161\text{--}209 \text{ GeV}$
$10.78 \pm 0.29 \pm 0.13$	1576	ACHARD	04J L3	$E_{\text{cm}}^{e\bar{e}} = 161\text{--}209 \text{ GeV}$
$10.78 \pm 0.27 \pm 0.10$	2142	SCHAEL	04A ALEP	$E_{\text{cm}}^{e\bar{e}} = 183\text{--}209 \text{ GeV}$

• • • We do not use the following data for averages, fits, limits, etc. • • •

$10.61 \pm 0.28$		<sup>1</sup> ABAZOV	04D	TEVA	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
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<sup>1</sup> ABAZOV 04D take into account all correlations to properly combine the CDF (ABE 95W) and  $D\bar{D}$  (ABBOTT 00B) measurements of the ratio R in the electron channel. The ratio R is defined as  $[\sigma_W \cdot B(W \rightarrow e\nu_e)] / [\sigma_Z \cdot B(Z \rightarrow ee)]$ . The combination gives  $R^{\text{TeVatron}} = 10.59 \pm 0.23$ .  $\sigma_W / \sigma_Z$  is calculated at next-to-next-to-leading order ( $3.360 \pm 0.051$ ). The branching fraction  $B(Z \rightarrow ee)$  is taken from this Review as  $(3.363 \pm 0.004)\%$ .

### $\Gamma(\mu^+\nu)/\Gamma_{\text{total}}$ $\Gamma_3/\Gamma$

VALUE (units $10^{-2}$ )	EVTS	DOCUMENT ID	TECN	COMMENT
<b>10.63 ± 0.15 OUR FIT</b>				
$10.94 \pm 0.01 \pm 0.08$		TUMASYAN	22F CMS	$E_{\text{cm}}^{p\bar{p}} = 13 \text{ TeV}$
$10.78 \pm 0.24 \pm 0.10$	2397	ABBIENDI	07A OPAL	$E_{\text{cm}}^{e\bar{e}} = 161\text{--}209 \text{ GeV}$
$10.65 \pm 0.26 \pm 0.08$	1998	ABDALLAH	04G DLPH	$E_{\text{cm}}^{e\bar{e}} = 161\text{--}209 \text{ GeV}$
$10.03 \pm 0.29 \pm 0.12$	1423	ACHARD	04J L3	$E_{\text{cm}}^{e\bar{e}} = 161\text{--}209 \text{ GeV}$
$10.87 \pm 0.25 \pm 0.08$	2216	SCHAEL	04A ALEP	$E_{\text{cm}}^{e\bar{e}} = 183\text{--}209 \text{ GeV}$

### $\Gamma(\mu^+\nu)/\Gamma(e^+\nu)$ $\Gamma_3/\Gamma_2$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<b>1.002 ± 0.006 OUR AVERAGE</b>				
$1.009 \pm 0.009$		TUMASYAN	22F CMS	$E_{\text{cm}}^{p\bar{p}} = 13 \text{ TeV}$
$1.003 \pm 0.010$		<sup>1</sup> AABOUD	17Q ATLS	$E_{\text{cm}}^{p\bar{p}} = 7 \text{ TeV}$
$0.980 \pm 0.018$		<sup>2</sup> AAIJ	16AJ LHCB	$E_{\text{cm}}^{p\bar{p}} = 8 \text{ TeV}$
$0.993 \pm 0.019$		SCHAEL	13A LEP	$E_{\text{cm}}^{e\bar{e}} = 130\text{--}209 \text{ GeV}$
$0.89 \pm 0.10$	13k	<sup>3</sup> ABACHI	95D D0	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
$1.02 \pm 0.08$	1216	<sup>4</sup> ABE	92I CDF	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$
$1.00 \pm 0.14 \pm 0.08$	67	ALBAJAR	89 UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630 \text{ GeV}$



• • • We do not use the following data for averages, fits, limits, etc. • • •

1.24  $\begin{matrix} +0.6 \\ -0.4 \end{matrix}$  14 ARNISON 84D UA1 Repl. by ALBAJAR 89

<sup>1</sup> AABOUD 17Q make a precise determination of  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  production in the following fiducial phase space: lepton pseudo-rapidity range  $|\eta| < 2.5$ , lepton and neutrino transverse momenta larger than 25 GeV each, and  $W$  transverse mass larger than 25 GeV. They determine the ratio of the  $W$  branching fractions  $B(W \rightarrow e\nu)/B(W \rightarrow \mu\nu) = 0.9967 \pm 0.0004 \pm 0.0101 = 0.997 \pm 0.010$ .

<sup>2</sup> AAIJ 16AJ make precise measurements of forward  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  production in proton-proton collisions at 8 TeV and determine the ratio of the  $W$  branching fractions  $B(W \rightarrow e\nu)/B(W \rightarrow \mu\nu) = 1.020 \pm 0.002 \pm 0.019$ .

<sup>3</sup> ABACHI 95D obtain this result from the measured  $\sigma_W B(W \rightarrow \mu\nu) = 2.09 \pm 0.23 \pm 0.11$  nb and  $\sigma_W B(W \rightarrow e\nu) = 2.36 \pm 0.07 \pm 0.13$  nb in which the first error is the combined statistical and systematic uncertainty, the second reflects the uncertainty in the luminosity.

<sup>4</sup> ABE 92I obtain  $\sigma_W B(W \rightarrow \mu\nu) = 2.21 \pm 0.07 \pm 0.21$  and combine with ABE 91C  $\sigma_W B(W \rightarrow e\nu)$  to give a ratio of the couplings from which we derive this measurement.

$\Gamma(\tau^+ \nu) / \Gamma_{\text{total}}$   $\Gamma_4 / \Gamma$

VALUE (units $10^{-2}$ )	EVTS	DOCUMENT ID	TECN	COMMENT
<b>11.38 ± 0.21 OUR FIT</b>				
10.77 ± 0.05 ± 0.21		TUMASYAN	22F CMS	$E_{\text{cm}}^{pp} = 13$ TeV
11.14 ± 0.31 ± 0.17	2177	ABBIENDI	07A OPAL	$E_{\text{cm}}^{ee} = 161\text{--}209$ GeV
11.46 ± 0.39 ± 0.19	2034	ABDALLAH	04G DLPH	$E_{\text{cm}}^{ee} = 161\text{--}209$ GeV
11.89 ± 0.40 ± 0.20	1375	ACHARD	04J L3	$E_{\text{cm}}^{ee} = 161\text{--}209$ GeV
11.25 ± 0.32 ± 0.20	2070	SCHAEL	04A ALEP	$E_{\text{cm}}^{ee} = 183\text{--}209$ GeV

$\Gamma(\tau^+ \nu) / \Gamma(e^+ \nu)$   $\Gamma_4 / \Gamma_2$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<b>1.015 ± 0.020 OUR AVERAGE</b> Error includes scale factor of 1.3. See the ideogram below.				
0.994 ± 0.021		TUMASYAN	22F CMS	$E_{\text{cm}}^{pp} = 13$ TeV
1.063 ± 0.027		SCHAEL	13A LEP	$E_{\text{cm}}^{ee} = 130\text{--}209$ GeV
0.961 ± 0.061	980	<sup>1</sup> ABBOTT	00D D0	$E_{\text{cm}}^{p\bar{p}} = 1.8$ TeV
0.94 ± 0.14	179	<sup>2</sup> ABE	92E CDF	$E_{\text{cm}}^{p\bar{p}} = 1.8$ TeV
1.04 ± 0.08 ± 0.08	754	<sup>3</sup> ALITTI	92F UA2	$E_{\text{cm}}^{p\bar{p}} = 630$ GeV
1.02 ± 0.20 ± 0.12	32	ALBAJAR	89 UA1	$E_{\text{cm}}^{p\bar{p}} = 546,630$ GeV

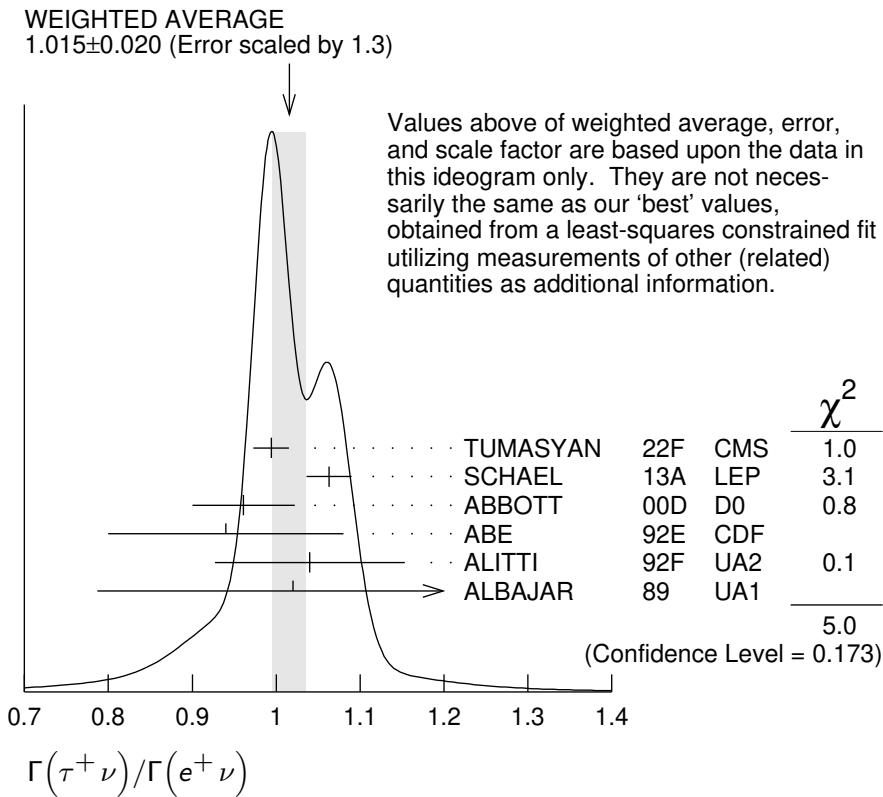
• • • We do not use the following data for averages, fits, limits, etc. • • •

0.995 ± 0.112 ± 0.083 198 ALITTI 91C UA2 Repl. by ALITTI 92F  
 1.02 ± 0.20 ± 0.10 32 ALBAJAR 87 UA1 Repl. by ALBAJAR 89

<sup>1</sup> ABBOTT 00D measure  $\sigma_W \times B(W \rightarrow \tau\nu_\tau) = 2.22 \pm 0.09 \pm 0.10 \pm 0.10$  nb. Using the ABBOTT 00B result  $\sigma_W \times B(W \rightarrow e\nu_e) = 2.31 \pm 0.01 \pm 0.05 \pm 0.10$  nb, they quote the ratio of the couplings from which we derive this measurement.

<sup>2</sup> ABE 92E use two procedures for selecting  $W \rightarrow \tau\nu_\tau$  events. The missing  $E_\tau$  trigger leads to  $132 \pm 14 \pm 8$  events and the  $\tau$  trigger to  $47 \pm 9 \pm 4$  events. Proper statistical and systematic correlations are taken into account to arrive at  $\sigma B(W \rightarrow \tau\nu) = 2.05 \pm 0.27$  nb. Combined with ABE 91C result on  $\sigma B(W \rightarrow e\nu)$ , ABE 92E quote a ratio of the couplings from which we derive this measurement.

<sup>3</sup> This measurement is derived by us from the ratio of the couplings of ALITTI 92F.

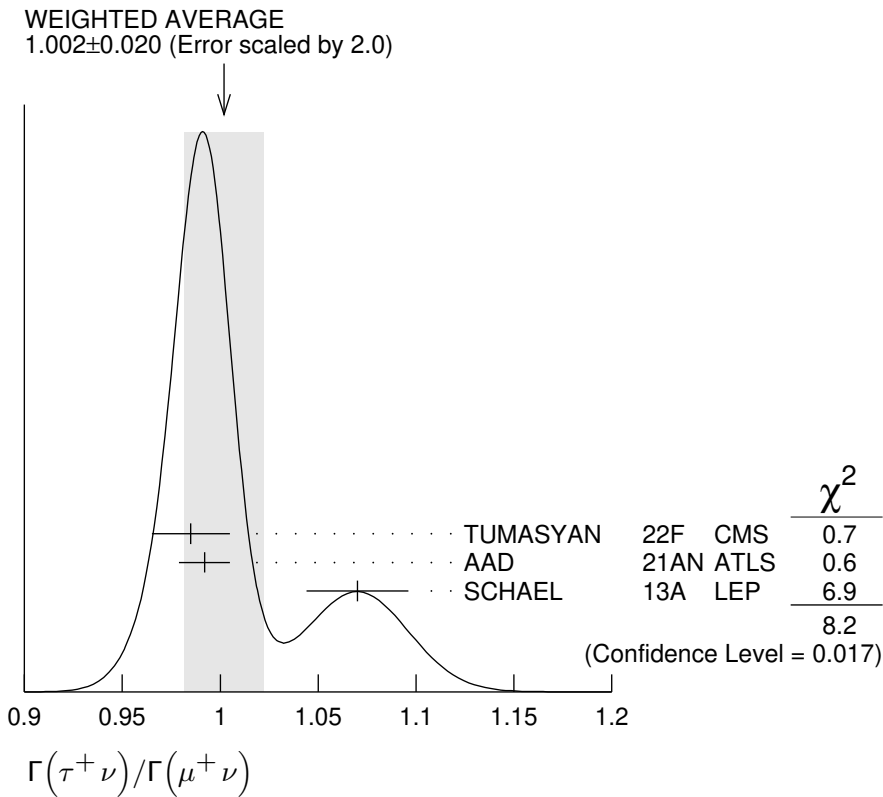


$\Gamma(\tau^+ \nu) / \Gamma(\mu^+ \nu)$

$\Gamma_4 / \Gamma_3$

VALUE	DOCUMENT ID	TECN	COMMENT
<b><math>1.002 \pm 0.020</math> OUR AVERAGE</b>	Error includes scale factor of 2.0. See the ideogram below.		
$0.985 \pm 0.020$	TUMASYAN	22F CMS	$E_{cm}^{pp} = 13$ TeV
$0.992 \pm 0.007 \pm 0.011$	<sup>1</sup> AAD	21AN ATLS	$E_{cm}^{pp} = 13$ TeV
$1.070 \pm 0.026$	SCHAEL	13A LEP	$E_{cm}^{ee} = 130-209$ GeV

<sup>1</sup>AAD 21AN study  $t\bar{t}$  production, with the  $W$  bosons in top-quark decay decaying to electrons or taus, with the tau decaying further into a muon. Analyzing the muon impact parameter and its transverse momentum, the contributions from prompt muons (arising from  $W$  decay) and non-prompt muons (arising from tau decay) are separated, allowing a measurement of the ratio of the  $W$  branching fractions into taus and muons,  $R(\tau/\mu) = 0.992 \pm 0.007 \pm 0.011$  where the first error is statistical and the second systematic.



### $\Gamma(\text{hadrons}) / \Gamma_{\text{total}}$

### $\Gamma_5 / \Gamma$

OUR FIT value is obtained by a fit to the lepton branching ratio data assuming lepton universality.

VALUE (units $10^{-2}$ )	EVTS	DOCUMENT ID	TECN	COMMENT
<b><math>67.41 \pm 0.27</math> OUR FIT</b>				
$67.32 \pm 0.02 \pm 0.23$		TUMASYAN 22F CMS		$E_{\text{cm}}^{pp} = 13 \text{ TeV}$
$67.41 \pm 0.37 \pm 0.23$	16438	ABBIENDI 07A OPAL		$E_{\text{cm}}^{ee} = 161\text{--}209 \text{ GeV}$
$67.45 \pm 0.41 \pm 0.24$	13600	ABDALLAH 04G DLPH		$E_{\text{cm}}^{ee} = 161\text{--}209 \text{ GeV}$
$67.50 \pm 0.42 \pm 0.30$	11246	ACHARD 04J L3		$E_{\text{cm}}^{ee} = 161\text{--}209 \text{ GeV}$
$67.13 \pm 0.37 \pm 0.15$	16116	SCHAEEL 04A ALEP		$E_{\text{cm}}^{ee} = 183\text{--}209 \text{ GeV}$

### $\Gamma(\pi^+ \gamma) / \Gamma_{\text{total}}$

### $\Gamma_6 / \Gamma$

VALUE	CL%	DOCUMENT ID	COMMENT
$< 1.50 \times 10^{-5}$	95	<sup>1</sup> SIRUNYAN 21i	$E_{\text{cm}}^{pp} = 13 \text{ TeV}$

<sup>1</sup>SIRUNYAN 21i search for the rare decay of a  $W$  boson into a charged pion accompanied by a photon. A signal is not observed, and an upper limit on the branching fraction  $B(W \rightarrow \pi \gamma) < 1.50 \times 10^{-5}$  is obtained at 95% C.L.

### $\Gamma(\pi^+ \gamma) / \Gamma(e^+ \nu)$

### $\Gamma_6 / \Gamma_2$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$< 6.4 \times 10^{-5}$	95	AALTONEN 12W CDF		$E_{\text{cm}}^{pp} = 1.96 \text{ TeV}$
$< 7 \times 10^{-4}$	95	ABE 98H CDF		$E_{\text{cm}}^{pp} = 1.8 \text{ TeV}$

$< 4.9 \times 10^{-3}$	95	<sup>1</sup> ALITTI	92D	UA2	$E_{\text{cm}}^{p\bar{p}} = 630 \text{ GeV}$
$< 58 \times 10^{-3}$	95	<sup>2</sup> ALBAJAR	90	UA1	$E_{\text{cm}}^{p\bar{p}} = 546, 630 \text{ GeV}$
<sup>1</sup> ALITTI 92D limit is $3.8 \times 10^{-3}$ at 90%CL.					
<sup>2</sup> ALBAJAR 90 obtain $< 0.048$ at 90%CL.					

$\Gamma(D_s^+ \gamma)/\Gamma(e^+ \nu)$   $\Gamma_7/\Gamma_2$

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
$< 1.2 \times 10^{-2}$	95	ABE	98P	CDF $E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$

$\Gamma(cX)/\Gamma(\text{hadrons})$   $\Gamma_8/\Gamma_5$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<b>0.49 ± 0.04 OUR AVERAGE</b>				
0.481 ± 0.042 ± 0.032	3005	<sup>1</sup> ABBIENDI	00V	OPAL $E_{\text{cm}}^{ee} = 183 + 189 \text{ GeV}$
0.51 ± 0.05 ± 0.03	746	<sup>2</sup> BARATE	99M	ALEP $E_{\text{cm}}^{ee} = 172 + 183 \text{ GeV}$

<sup>1</sup> ABBIENDI 00V tag  $W \rightarrow cX$  decays using measured jet properties, lifetime information, and leptons produced in charm decays. From this result, and using the additional measurements of  $\Gamma(W)$  and  $B(W \rightarrow \text{hadrons})$ ,  $|V_{cs}|$  is determined to be  $0.969 \pm 0.045 \pm 0.036$ .

<sup>2</sup> BARATE 99M tag  $c$  jets using a neural network algorithm. From this measurement  $|V_{cs}|$  is determined to be  $1.00 \pm 0.11 \pm 0.07$ .

$\Gamma(\pi^+ \pi^+ \pi^-)/\Gamma_{\text{total}}$   $\Gamma_{11}/\Gamma$

VALUE (units $10^{-6}$ )	CL%	DOCUMENT ID	TECN	COMMENT
<b>&lt; 1.01</b>	95	<sup>1</sup> SIRUNYAN	19BG	CMS $E_{\text{cm}}^{pp} = 13 \text{ TeV}$

<sup>1</sup> SIRUNYAN 19BG search for the rare decay of a  $W$  boson into three charged pions. Three pion candidates are required in each event, with transverse momentum larger than 35 GeV, 35 GeV, 18 GeV, respectively, while the transverse momentum of the three-pion system is required to be larger than 40 GeV. Analyzing the three-pion invariant mass, no excess is observed in the  $W$  mass region, leading to the 95% C.L. upper limit on the branching fraction.

$R_{cs} = \Gamma(c\bar{s})/\Gamma(\text{hadrons})$   $\Gamma_9/\Gamma_5$

VALUE	DOCUMENT ID	TECN	COMMENT
<b>0.46<sup>+0.18</sup><sub>-0.14</sub> ± 0.07</b>	<sup>1</sup> ABREU	98N	DLPH $E_{\text{cm}}^{ee} = 161+172 \text{ GeV}$

<sup>1</sup> ABREU 98N tag  $c$  and  $s$  jets by identifying a charged kaon as the highest momentum particle in a hadronic jet. They also use a lifetime tag to independently identify a  $c$  jet, based on the impact parameter distribution of charged particles in a jet. From this measurement  $|V_{cs}|$  is determined to be  $0.94_{-0.26}^{+0.32} \pm 0.13$ .

**AVERAGE PARTICLE MULTIPLICITIES IN HADRONIC  $W$  DECAY**

Summed over particle and antiparticle, when appropriate.

$\langle N_{\pi^\pm} \rangle$

VALUE	DOCUMENT ID	TECN	COMMENT
<b>15.70 ± 0.35</b>	<sup>1</sup> ABREU,P	00F	DLPH $E_{\text{cm}}^{ee} = 189 \text{ GeV}$

<sup>1</sup> ABREU,P 00F measure  $\langle N_{\pi^\pm} \rangle = 31.65 \pm 0.48 \pm 0.76$  and  $15.51 \pm 0.38 \pm 0.40$  in the fully hadronic and semileptonic final states respectively. The value quoted is a weighted average without assuming any correlations.

### $\langle N_{K^\pm} \rangle$

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>2.20±0.19</b>	<sup>1</sup> ABREU,P	00F	DLPH $E_{cm}^{ee} = 189$ GeV

<sup>1</sup> ABREU,P 00F measure  $\langle N_{K^\pm} \rangle = 4.38 \pm 0.42 \pm 0.12$  and  $2.23 \pm 0.32 \pm 0.17$  in the fully hadronic and semileptonic final states respectively. The value quoted is a weighted average without assuming any correlations.

### $\langle N_p \rangle$

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>0.92±0.14</b>	<sup>1</sup> ABREU,P	00F	DLPH $E_{cm}^{ee} = 189$ GeV

<sup>1</sup> ABREU,P 00F measure  $\langle N_p \rangle = 1.82 \pm 0.29 \pm 0.16$  and  $0.94 \pm 0.23 \pm 0.06$  in the fully hadronic and semileptonic final states respectively. The value quoted is a weighted average without assuming any correlations.

### $\langle N_{\text{charged}} \rangle$

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>19.39±0.08 OUR AVERAGE</b>			
19.38±0.05±0.08	<sup>1</sup> ABBIENDI	06A	OPAL $E_{cm}^{ee} = 189\text{--}209$ GeV
19.44±0.17	<sup>2</sup> ABREU,P	00F	DLPH $E_{cm}^{ee} = 183\text{+}189$ GeV
19.3 ±0.3 ±0.3	<sup>3</sup> ABBIENDI	99N	OPAL $E_{cm}^{ee} = 183$ GeV
19.23±0.74	<sup>4</sup> ABREU	98C	DLPH $E_{cm}^{ee} = 172$ GeV

<sup>1</sup> ABBIENDI 06A measure  $\langle N_{\text{charged}} \rangle = 38.74 \pm 0.12 \pm 0.26$  when both  $W$  bosons decay hadronically and  $\langle N_{\text{charged}} \rangle = 19.39 \pm 0.11 \pm 0.09$  when one  $W$  boson decays semileptonically. The value quoted here is obtained under the assumption that there is no color reconnection between  $W$  bosons; the value is a weighted average taking into account correlations in the systematic uncertainties.

<sup>2</sup> ABREU,P 00F measure  $\langle N_{\text{charged}} \rangle = 39.12 \pm 0.33 \pm 0.36$  and  $38.11 \pm 0.57 \pm 0.44$  in the fully hadronic final states at 189 and 183 GeV respectively, and  $\langle N_{\text{charged}} \rangle = 19.49 \pm 0.31 \pm 0.27$  and  $19.78 \pm 0.49 \pm 0.43$  in the semileptonic final states. The value quoted is a weighted average without assuming any correlations.

<sup>3</sup> ABBIENDI 99N use the final states  $W^+ W^- \rightarrow q\bar{q}\ell\bar{\nu}_\ell$  to derive this value.

<sup>4</sup> ABREU 98C combine results from both the fully hadronic as well semileptonic  $W W$  final states after demonstrating that the  $W$  decay charged multiplicity is independent of the topology within errors.

## TRIPLE GAUGE COUPLINGS (TGC'S)

Revised April 2017 by M.W. Grünewald (U. College Dublin) and A. Gurtu (Formerly Tata Inst.).

Fourteen independent couplings, seven each for  $ZWW$  and  $\gamma WW$ , completely describe the  $VWW$  vertices within the most general framework of the electroweak Standard Model (SM) consistent with Lorentz invariance and U(1) gauge invariance. Of each of the seven TGCs, three conserve  $C$  and  $P$  individually, three violate  $CP$ , and one violates  $C$  and  $P$  individually

while conserving  $CP$ . Assumption of  $C$  and  $P$  conservation and electromagnetic gauge invariance reduces the number of independent  $VWW$  couplings to five: one common set [1,2] is  $(\kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z, g_1^Z)$ , where  $\kappa_\gamma = \kappa_Z = g_1^Z = 1$  and  $\lambda_\gamma = \lambda_Z = 0$  in the Standard Model at tree level. The parameters  $\kappa_Z$  and  $\lambda_Z$  are related to the other three due to constraints of gauge invariance as follows:  $\kappa_Z = g_1^Z - (\kappa_\gamma - 1) \tan^2 \theta_W$  and  $\lambda_Z = \lambda_\gamma$ , where  $\theta_W$  is the weak mixing angle. The  $W$  magnetic dipole moment,  $\mu_W$ , and the  $W$  electric quadrupole moment,  $q_W$ , are expressed as  $\mu_W = e(1 + \kappa_\gamma + \lambda_\gamma)/2M_W$  and  $q_W = -e(\kappa_\gamma - \lambda_\gamma)/M_W^2$ .

Precision measurements of suitable observables at LEP1 has already led to an exploration of much of the TGC parameter space. At LEP2, the  $VWW$  coupling arises in  $W$ -pair production via  $s$ -channel exchange, or in single  $W$  production via the radiation of a virtual photon off the incident  $e^+$  or  $e^-$ . At the Tevatron and the LHC, hard-photon bremsstrahlung off a produced  $W$  or  $Z$  signals the presence of a triple-gauge vertex. In order to extract the value of one TGC, the others are generally kept fixed to their SM values. While most analyses use the above gauge constraints in the extraction of TGCs, one analysis of  $W$ -pair events also determines the real and imaginary parts of all 14 couplings using unconstrained single-parameter fits [3]. The results are consistent. Some experiments have determined limits on the couplings under various non-LEP scenarios and assuming different values of the form factor  $\Lambda$ , where the coupling parameters are scaled by  $1/(1 + s/\Lambda^2)^2$ . For practical reasons it is not possible to quote all such determinations in the listings. For that the individual papers may be consulted. Recently, EFT-inspired sets of couplings [4,5], such as  $c_{WWW}/\Lambda^2, c_W/\Lambda^2, c_B/\Lambda^2$  which are linearly related to the

couplings discussed above, are also determined by the LHC experiments.

## References

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2. G. Gounaris *et al.*, CERN 96-01 p. 525.
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5. C. Degrande *et al.*, Annals Phys. 335 (2013) 21-32.

**$g_1^Z$**

OUR FIT below is taken from [SCHAEL 13A].

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>0.984<sup>+0.018</sup><sub>-0.020</sub> OUR FIT</b>				
0.975 <sup>+0.033</sup> <sub>-0.030</sub>	7872	1 ABDALLAH	10 DLPH	$E_{cm}^{ee} = 189-209$ GeV
1.001 $\pm$ 0.027 $\pm$ 0.013	9310	2 SCHAEL	05A ALEP	$E_{cm}^{ee} = 183-209$ GeV
0.987 <sup>+0.034</sup> <sub>-0.033</sub>	9800	3 ABBIENDI	04D OPAL	$E_{cm}^{ee} = 183-209$ GeV
0.966 <sup>+0.034</sup> <sub>-0.032</sub> $\pm$ 0.015	8325	4 ACHARD	04D L3	$E_{cm}^{ee} = 161-209$ GeV
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		5 SIRUNYAN	20BA CMS	$E_{cm}^{pp} = 13$ TeV
		6 SIRUNYAN	19CL CMS	$E_{cm}^{pp} = 13$ TeV
		7 SIRUNYAN	18BZ CMS	$E_{cm}^{pp} = 13$ TeV
		8 AABOUD	17S ATLS	$E_{cm}^{pp} = 7+8$ TeV
		9 AABOUD	17U ATLS	$E_{cm}^{pp} = 8$ TeV
		10 KHACHATRY...	17O CMS	$E_{cm}^{pp} = 8$ TeV
		11 SIRUNYAN	17X CMS	$E_{cm}^{pp} = 8$ TeV
		12 AAD	16AR ATLS	$E_{cm}^{pp} = 8$ TeV
		13 AAD	16P ATLS	$E_{cm}^{pp} = 8$ TeV
		14 AAD	14Y ATLS	$E_{cm}^{pp} = 8$ TeV
		15 AAD	13AL ATLS	$E_{cm}^{pp} = 7$ TeV
		16 CHATRCHYAN	13BF CMS	$E_{cm}^{pp} = 7$ TeV
		17 AAD	12CD ATLS	$E_{cm}^{pp} = 7$ TeV
		18 AALTONEN	12AC CDF	$E_{cm}^{p\bar{p}} = 1.96$ TeV
		19 ABAZOV	12AG D0	$E_{cm}^{p\bar{p}} = 1.96$ TeV
	34	20 ABAZOV	11 D0	$E_{cm}^{p\bar{p}} = 1.96$ TeV

	334	21	AALTONEN	10K	CDF	$E_{\text{cm}}^{p\bar{p}} = 1.96$ TeV
1.04 ± 0.09		22	ABAZOV	09AD	D0	$E_{\text{cm}}^{p\bar{p}} = 1.96$ TeV
		23	ABAZOV	09AJ	D0	$E_{\text{cm}}^{p\bar{p}} = 1.96$ TeV
1.07 <sup>+0.08</sup> <sub>-0.12</sub>	1880	24	ABDALLAH	08C	DLPH	Superseded by ABDALLAH 10
	13	25	ABAZOV	07Z	D0	$E_{\text{cm}}^{p\bar{p}} = 1.96$ TeV
	2.3	26	ABAZOV	05S	D0	$E_{\text{cm}}^{p\bar{p}} = 1.96$ TeV
0.98 ± 0.07 ± 0.01	2114	27	ABREU	01I	DLPH	$E_{\text{cm}}^{ee} = 183+189$ GeV
	331	28	ABBOTT	99I	D0	$E_{\text{cm}}^{p\bar{p}} = 1.8$ TeV

<sup>1</sup> ABDALLAH 10 use data on the final states  $e^+ e^- \rightarrow jj\ell\nu, jjjj, jjX, \ell X$ , at center-of-mass energies between 189–209 GeV at LEP2, where  $j = \text{jet}$ ,  $\ell = \text{lepton}$ , and  $X$  represents missing momentum. The fit is carried out keeping all other parameters fixed at their SM values.

<sup>2</sup> SCHAEEL 05A study single-photon, single- $W$ , and  $WW$ -pair production from 183 to 209 GeV. The result quoted here is derived from the  $WW$ -pair production sample. Each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values.

<sup>3</sup> ABBIENDI 04D combine results from  $W^+ W^-$  in all decay channels. Only  $CP$ -conserving couplings are considered and each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values. The 95% confidence interval is  $0.923 < g_1^Z < 1.054$ .

<sup>4</sup> ACHARD 04D study  $WW$ -pair production, single- $W$  production and single-photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained from the  $WW$ -pair production sample including data from 161 to 183 GeV, ACCIARRI 99Q. Each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values.

<sup>5</sup> SIRUNYAN 20BA study electroweak production of a  $W$  boson in association with two jets, using  $W$  decays in the electron or muon channel. The isolated muons (electrons) are required to have a transverse momentum larger than 25 (30) GeV, while the transverse momentum of the two jets has to be larger than 50 and 30 GeV. A total of 2.382 (1.051) million events are selected in the muon (electron) channel, with a Standard Model expectation of  $2.39 \pm 0.17$  ( $1.054 \pm 0.058$ ) million events. Analyzing the transverse momentum distribution of the charged leptons from  $W$  decay, the following 95% C.L. limit is obtained:  $0.971 < g_1^Z < 1.044$ . Combining this result with that from the closely-related electroweak  $Z$ -jet-jet production SIRUNYAN 18BZ, the limit becomes:  $0.979 < g_1^Z < 1.034$ .

<sup>6</sup> SIRUNYAN 19CL study  $WW$  and  $WZ$  production in lepton + jet events, with one  $W$  boson decaying leptonically (electron or muon), and another  $W$  or  $Z$  boson decaying hadronically, reconstructed as a single massive large-radius jet. In the electron channel 2,456 (2,235) events are selected in the  $WW(WZ)$  category, while in the muon channel 3,996 (3572) events are selected in the  $WW(WZ)$  category. Analysing the di-boson invariant mass distribution, the following 95% C.L. limit is obtained:  $0.9939 < g_1^Z < 1.0074$ .

<sup>7</sup> SIRUNYAN 18BZ study  $pp \rightarrow Z \text{ jet jet}$  events at 13 TeV where  $Z \rightarrow e^+ e^- / \mu^+ \mu^-$ . Isolated electrons and muons are selected with  $p_T$  of the leading/sub-leading lepton  $> 30/20$  GeV and  $|\eta| < 2.4$ , with the di-lepton invariant mass within 15 GeV of the  $Z$  mass. The two highest  $p_T$  jets are selected with  $p_T$  of the leading/sub-leading jet  $> 50/30$  GeV respectively and dijet invariant mass  $> 200$  GeV. Templates in the transverse momentum of the  $Z$  are utilized to set limits on the triple gauge couplings in the EFT and the LEP parametrizations. The following 95% C.L. limit is obtained:  $0.965 < g_1^Z < 1.042$ .

<sup>8</sup> AABOUD 17S analyze electroweak production of a  $W$  boson in association with two jets at high dijet invariant mass, with the  $W$  boson decaying to electron or muon plus



neutrino. In the signal region of dijet mass larger than 1 TeV and leading-jet transverse momentum larger than 600 GeV, 30 events are observed in the data with  $39 \pm 4$  events expected in the Standard Model, yielding the following limit at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $0.87 < g_1^Z < 1.12$ .

- <sup>9</sup> AABOUD 17U analyze production of  $WW$  or  $WZ$  boson pairs with one  $W$  boson decaying to electron or muon plus neutrino, and the other  $W$  or  $Z$  boson decaying hadronically. The hadronic decay system is reconstructed as either a resolved two-jet system or as a single large jet. Analysing the transverse momentum distribution of the hadronic system above 100 GeV yields the following limit at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $0.979 < g_1^Z < 1.024$ .
- <sup>10</sup> KHACHATRYAN 17O analyse  $WZ$  production where each boson decays into electrons or muons. Events are required to have a tri-lepton invariant mass larger than 100 GeV, with one of the lepton pairs having an invariant mass within 20 GeV of the  $Z$  boson mass. The  $Z$  transverse momentum spectrum is analyzed to set a 95% C.L. limit of:  $0.982 < g_1^Z < 1.035$ .
- <sup>11</sup> SIRUNYAN 17X study  $pp \rightarrow WW/WZ \rightarrow \ell\nu q\bar{q}$  production at 8 TeV where  $\ell$  is an electron or muon with  $p_T > 30$  or 25 GeV respectively. Suitable cuts are put on the  $p_T$  of the dijet system and the missing  $E_T$  of the event yielding a total of 285 and 204  $WV$  events observed in the electron and muon channels. The following 95% C.L. limit is obtained:  $0.9913 < g_1^Z < 1.024$ .
- <sup>12</sup> AAD 16AR study  $WW$  production in  $pp$  collisions and select 6636  $WW$  candidates in decay modes with electrons or muons with an expected background of  $1546 \pm 157$  events. Assuming the LEP formulation and setting the form-factor  $\Lambda$  to infinity, a fit to the transverse momentum distribution of the leading charged lepton, leads to a 95% C.L. range of  $0.984 < g_1^Z < 1.027$ .
- <sup>13</sup> AAD 16P study  $WZ$  production in  $pp$  collisions and select 2091  $WZ$  candidates in 4 decay modes with electrons and muons, with an expected background of  $1825 \pm 7$  events. Analyzing the  $WZ$  transverse momentum distribution, the resulting 95% C.L. limit is:  $0.981 < g_1^Z < 1.029$ .
- <sup>14</sup> AAD 14Y determine the electroweak  $Z$ -dijet cross section in 8 TeV  $pp$  collisions.  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  decays are selected with the di-lepton  $p_T > 20$  GeV and mass in the 81–101 GeV range. Minimum two jets are required with  $p_T > 55$  and 45 GeV and no additional jets with  $p_T > 25$  GeV in the rapidity interval between them. The normalized  $p_T$  balance between the  $Z$  and the two jets is required to be  $< 0.15$ . This leads to a selection of 900 events with dijet mass  $> 1$  TeV. The number of signal and background events expected is 261 and 592 respectively. A Poisson likelihood method is used on an event by event basis to obtain the 95% CL limit  $0.5 < g_1^Z < 1.26$  for a form factor value  $\Lambda = \infty$ .
- <sup>15</sup> AAD 13AL study  $WW$  production in  $pp$  collisions and select 1325  $WW$  candidates in decay modes with electrons or muons with an expected background of  $369 \pm 61$  events. Assuming the LEP formulation and setting the form-factor  $\Lambda = \infty$ , a fit to the transverse momentum distribution of the leading charged lepton, leads to a 95% C.L. range of  $0.961 < g_1^Z < 1.052$ . Supersedes AAD 12AC.
- <sup>16</sup> CHATRCHYAN 13BF determine the  $W^+W^-$  production cross section using unlike sign di-lepton ( $e$  or  $\mu$ ) events with high  $p_T$ . The leptons have  $p_T > 20$  GeV/c and are isolated. 1134 candidate events are observed with an expected SM background of  $247 \pm 34$ . The  $p_T$  distribution of the leading lepton is fitted to obtain 95% C.L. limits of  $0.905 \leq g_1^Z \leq 1.095$ .
- <sup>17</sup> AAD 12CD study  $WZ$  production in  $pp$  collisions and select 317  $WZ$  candidates in three  $\ell\nu$  decay modes with an expected background of  $68.0 \pm 10.0$  events. The resulting 95% C.L. range is:  $0.943 < g_1^Z < 1.093$ . Supersedes AAD 12V.
- <sup>18</sup> AALTONEN 12AC study  $WZ$  production in  $p\bar{p}$  collisions and select 63  $WZ$  candidates in three  $\ell\nu$  decay modes with an expected background of  $7.9 \pm 1.0$  events. Based on

the cross section and shape of the  $Z$  transverse momentum spectrum, the following 95% C.L. range is reported:  $0.92 < g_1^Z < 1.20$  for a form factor of  $\Lambda = 2$  TeV.

- 19 ABAZOV 12AG combine new results with already published results on  $W\gamma$ ,  $WW$  and  $WZ$  production in order to determine the couplings with increased precision, superseding ABAZOV 08R, ABAZOV 11AC, ABAZOV 09AJ, ABAZOV 09AD. The 68% C.L. result for a formfactor cutoff of  $\Lambda = 2$  TeV is  $g_1^Z = 1.022_{-0.030}^{+0.032}$ .
- 20 ABAZOV 11 study the  $p\bar{p} \rightarrow 3\ell\nu$  process arising in  $WZ$  production. They observe 34  $WZ$  candidates with an estimated background of 6 events. An analysis of the  $p_T$  spectrum of the  $Z$  boson leads to a 95% C.L. limit of  $0.944 < g_1^Z < 1.154$ , for a form factor  $\Lambda = 2$  TeV.
- 21 AALTONEN 10K study  $p\bar{p} \rightarrow W^+W^-$  with  $W \rightarrow e/\mu\nu$ . The  $p_T$  of the leading (second) lepton is required to be  $> 20$  (10) GeV. The final number of events selected is  $654$  of which  $320 \pm 47$  are estimated to be background. The 95% C.L. interval is  $0.76 < g_1^Z < 1.34$  for  $\Lambda = 1.5$  TeV and  $0.78 < g_1^Z < 1.30$  for  $\Lambda = 2$  TeV.
- 22 ABAZOV 09AD study the  $p\bar{p} \rightarrow \ell\nu 2\text{jet}$  process arising in  $WW$  and  $WZ$  production. They select 12,473 (14,392) events in the electron (muon) channel with an expected di-boson signal of 436 (527) events. The results on the anomalous couplings are derived from an analysis of the  $p_T$  spectrum of the 2-jet system and quoted at 68% C.L. and for a form factor of 2 TeV. This measurement is not used for obtaining the mean as it is for a specific form factor. The 95% confidence interval is  $0.88 < g_1^Z < 1.20$ .
- 23 ABAZOV 09AJ study the  $p\bar{p} \rightarrow 2\ell 2\nu$  process arising in  $WW$  production. They select 100 events with an expected  $WW$  signal of 65 events. An analysis of the  $p_T$  spectrum of the two charged leptons leads to 95% C.L. limits of  $0.86 < g_1^Z < 1.3$ , for a form factor  $\Lambda = 2$  TeV.
- 24 ABDALLAH 08C determine this triple gauge coupling from the measurement of the spin density matrix elements in  $e^+e^- \rightarrow W^+W^- \rightarrow (qq)(\ell\nu)$ , where  $\ell = e$  or  $\mu$ . Values of all other couplings are fixed to their standard model values.
- 25 ABAZOV 07Z set limits on anomalous TGCs using the measured cross section and  $p_T(Z)$  distribution in  $WZ$  production with both the  $W$  and the  $Z$  decaying leptonically into electrons and muons. Setting the other couplings to their standard model values, the 95% C.L. limit for a form factor scale  $\Lambda = 2$  TeV is  $0.86 < g_1^Z < 1.35$ .
- 26 ABAZOV 05S study  $p\bar{p} \rightarrow WZ$  production with a subsequent trilepton decay to  $\ell\nu\ell'\bar{\ell}'$  ( $\ell$  and  $\ell' = e$  or  $\mu$ ). Three events (estimated background  $0.71 \pm 0.08$  events) with  $WZ$  decay characteristics are observed from which they derive limits on the anomalous  $WWZ$  couplings. The 95% CL limit for a form factor scale  $\Lambda = 1.5$  TeV is  $0.51 < g_1^Z < 1.66$ , fixing  $\lambda_Z$  and  $\kappa_Z$  to their Standard Model values.
- 27 ABREU 01i combine results from  $e^+e^-$  interactions at 189 GeV leading to  $W^+W^-$  and  $W e\nu_e$  final states with results from ABREU 99L at 183 GeV. The 95% confidence interval is  $0.84 < g_1^Z < 1.13$ .
- 28 ABBOTT 99i perform a simultaneous fit to the  $W\gamma$ ,  $WW \rightarrow$  dilepton,  $WW/WZ \rightarrow e\nu jj$ ,  $WW/WZ \rightarrow \mu\nu jj$ , and  $WZ \rightarrow$  trilepton data samples. For  $\Lambda = 2.0$  TeV, the 95%CL limits are  $0.63 < g_1^Z < 1.57$ , fixing  $\lambda_Z$  and  $\kappa_Z$  to their Standard Model values, and assuming Standard Model values for the  $WW\gamma$  couplings.

$\kappa_\gamma$

OUR FIT below is taken from [SCHAEEL 13A].

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>0.982±0.042 OUR FIT</b>				
1.024 <sup>+0.077</sup> <sub>-0.081</sub>	7872	1 ABDALLAH	10 DLPH	$E_{cm}^{ee} = 189\text{--}209$ GeV
0.971±0.055±0.030	10689	2 SCHAEEL	05A ALEP	$E_{cm}^{ee} = 183\text{--}209$ GeV
0.88 <sup>+0.09</sup> <sub>-0.08</sub>	9800	3 ABBIENDI	04D OPAL	$E_{cm}^{ee} = 183\text{--}209$ GeV
1.013 <sup>+0.067</sup> <sub>-0.064</sub> ±0.026	10575	4 ACHARD	04D L3	$E_{cm}^{ee} = 161\text{--}209$ GeV
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		5 AABOUD	17U ATLS	$E_{cm}^{pp} = 8$ TeV
		6 SIRUNYAN	17X CMS	$E_{cm}^{pp} = 8$ TeV
		7 CHATRCHYAN	14AB CMS	$E_{cm}^{pp} = 7$ TeV
		8 AAD	13AN ATLS	$E_{cm}^{pp} = 7$ TeV
		9 CHATRCHYAN	13BF CMS	$E_{cm}^{pp} = 7$ TeV
		10 ABAZOV	12AG D0	$E_{cm}^{pp} = 1.96$ TeV
		11 ABAZOV	11AC D0	$E_{cm}^{pp} = 1.96$ TeV
		12 CHATRCHYAN	11M CMS	$E_{cm}^{pp} = 7$ TeV
	334	13 AALTONEN	10K CDF	$E_{cm}^{pp} = 1.96$ TeV
	53	14 AARON	09B H1	$E_{cm}^{ep} = 0.3$ TeV
1.07 <sup>+0.26</sup> <sub>-0.29</sub>		15 ABAZOV	09AD D0	$E_{cm}^{pp} = 1.96$ TeV
		16 ABAZOV	09AJ D0	$E_{cm}^{pp} = 1.96$ TeV
		17 ABAZOV	08R D0	$E_{cm}^{pp} = 1.96$ TeV
0.68 <sup>+0.17</sup> <sub>-0.15</sub>	1880	18 ABDALLAH	08C DLPH	Superseded by ABDALLAH 10
	1617	19 AALTONEN	07L CDF	$E_{cm}^{pp} = 1.96$ GeV
	17	20 ABAZOV	06H D0	$E_{cm}^{pp} = 1.96$ TeV
	141	21 ABAZOV	05J D0	$E_{cm}^{pp} = 1.96$ TeV
1.25 <sup>+0.21</sup> <sub>-0.20</sub> ±0.06	2298	22 ABREU	01I DLPH	$E_{cm}^{ee} = 183\text{--}189$ GeV
		23 BREITWEG	00 ZEUS	$e^+ p \rightarrow e^+ W^\pm X$ , $\sqrt{s} \approx 300$ GeV
0.92 ±0.34	331	24 ABBOTT	99I D0	$E_{cm}^{pp} = 1.8$ TeV

<sup>1</sup> ABDALLAH 10 use data on the final states  $e^+ e^- \rightarrow jj\ell\nu, jjjj, jjX, \ell X$ , at center-of-mass energies between 189–209 GeV at LEP2, where  $j = \text{jet}$ ,  $\ell = \text{lepton}$ , and  $X$  represents missing momentum. The fit is carried out keeping all other parameters fixed at their SM values.

<sup>2</sup> SCHAEEL 05A study single-photon, single- $W$ , and  $WW$ -pair production from 183 to 209 GeV. Each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values.

<sup>3</sup> ABBIENDI 04D combine results from  $W^+ W^-$  in all decay channels. Only  $CP$ -conserving couplings are considered and each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values. The 95% confidence interval is  $0.73 < \kappa_\gamma < 1.07$ .

<sup>4</sup> ACHARD 04D study  $WW$ -pair production, single- $W$  production and single-photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained including data from 161 to 183 GeV, ACCIARRI 99Q. Each parameter is determined

- from a single-parameter fit in which the other parameters assume their Standard Model values.
- 5 AABOUD 17U analyze production of  $WW$  or  $WZ$  boson pairs with one  $W$  boson decaying to electron or muon plus neutrino, and the other  $W$  or  $Z$  boson decaying hadronically. The hadronic decay system is reconstructed as either a resolved two-jet system or as a single large jet. Analysing the transverse momentum distribution of the hadronic system above 100 GeV yields the following limit at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $0.939 < \kappa_\gamma < 1.064$ .
  - 6 SIRUNYAN 17X study  $pp \rightarrow WW/WZ \rightarrow \ell\nu q\bar{q}$  production at 8 TeV where  $\ell$  is an electron or muon with  $p_T > 30$  or 25 GeV respectively. Suitable cuts are put on the  $p_T$  of the dijet system and the missing  $E_T$  of the event yielding a total of 285 and 204  $WV$  events observed in the electron and muon channels. The following 95% C.L. limit is obtained:  $0.956 < \kappa_\gamma < 1.063$ .
  - 7 CHATRCHYAN 14AB measure  $W\gamma$  production cross section for  $p_T^\gamma > 15$  GeV and  $R(\ell\gamma) > 0.7$ , which is the separation between the  $\gamma$  and the final state charged lepton ( $e$  or  $\mu$ ) in the azimuthal angle-pseudorapidity ( $\phi - \eta$ ) plane. After background subtraction the number of  $e\nu\gamma$  and  $\mu\nu\gamma$  events is determined to be  $3200 \pm 325$  and  $4970 \pm 543$  respectively, compatible with expectations from the SM. This leads to a 95% CL limit of  $0.62 < \kappa_\gamma < 1.29$ , assuming other parameters have SM values.
  - 8 AAD 13AN study  $W\gamma$  production in  $pp$  collisions. In events with no additional jet, 4449 (6578)  $W$  decays to electron (muon) are selected, with an expected background of  $1662 \pm 262$  ( $2538 \pm 362$ ) events. Analysing the photon  $p_T$  spectrum above 100 GeV yields a 95% C.L. limit of  $0.59 < \kappa_\gamma < 1.46$ . Supersedes AAD 12BX.
  - 9 CHATRCHYAN 13BF determine the  $W^+W^-$  production cross section using unlike sign di-lepton ( $e$  or  $\mu$ ) events with high  $p_T$ . The leptons have  $p_T > 20$  GeV/c and are isolated. 1134 candidate events are observed with an expected SM background of  $247 \pm 34$ . The  $p_T$  distribution of the leading lepton is fitted to obtain 95% C.L. limits of  $0.79 \leq \kappa_\gamma \leq 1.22$ .
  - 10 ABAZOV 12AG combine new results with already published results on  $W\gamma$ ,  $WW$  and  $WZ$  production in order to determine the couplings with increased precision, superseding ABAZOV 08R, ABAZOV 11AC, ABAZOV 09AJ, ABAZOV 09AD. The 68% C.L. result for a formfactor cutoff of  $\Lambda = 2$  TeV is  $\kappa_\gamma = 1.048^{+0.106}_{-0.105}$ .
  - 11 ABAZOV 11AC study  $W\gamma$  production in  $p\bar{p}$  collisions at 1.96 TeV, with the  $W$  decay products containing an electron or a muon. They select 196 (363) events in the electron (muon) mode, with a SM expectation of 190 (372) events. A likelihood fit to the photon  $E_T$  spectrum above 15 GeV yields at 95% C.L. the result:  $0.6 < \kappa_\gamma < 1.4$  for a formfactor  $\Lambda = 2$  TeV.
  - 12 CHATRCHYAN 11M study  $W\gamma$  production in  $pp$  collisions at  $\sqrt{s} = 7$  TeV using  $36 \text{ pb}^{-1}$   $pp$  data with the  $W$  decaying to electron and muon. The total cross section is measured for photon transverse energy  $E_T^\gamma > 10$  GeV and spatial separation from charged leptons in the plane of pseudo rapidity and azimuthal angle  $\Delta R(\ell, \gamma) > 0.7$ . The number of candidate (background) events is 452 ( $228 \pm 21$ ) for the electron channel and 520 ( $277 \pm 25$ ) for the muon channel. Setting other couplings to their standard model value, they derive a 95% CL limit of  $-0.11 < \kappa_\gamma < 2.04$ .
  - 13 AALTONEN 10K study  $p\bar{p} \rightarrow W^+W^-$  with  $W \rightarrow e/\mu\nu$ . The  $p_T$  of the leading (second) lepton is required to be  $> 20$  (10) GeV. The final number of events selected is 654 of which  $320 \pm 47$  are estimated to be background. The 95% C.L. interval is  $0.37 < \kappa_\gamma < 1.72$  for  $\Lambda = 1.5$  TeV and  $0.43 < \kappa_\gamma < 1.65$  for  $\Lambda = 2$  TeV.
  - 14 AARON 09B study single- $W$  production in  $ep$  collisions at 0.3 TeV C.M. energy. They select 53  $W \rightarrow e/\mu$  events with a standard model expectation of  $54.1 \pm 7.4$  events. Fitting the transverse momentum spectrum of the hadronic recoil system they obtain a 95% C.L. limit of  $-3.7 < \kappa_\gamma < -1.5$  or  $0.3 < \kappa_\gamma < 1.5$ , where the ambiguity is due to the quadratic dependence of the cross section to the coupling parameter.

- 15 ABAZOV 09AD study the  $p\bar{p} \rightarrow \ell\nu 2\text{jet}$  process arising in  $WW$  and  $WZ$  production. They select 12,473 (14,392) events in the electron (muon) channel with an expected di-boson signal of 436 (527) events. The results on the anomalous couplings are derived from an analysis of the  $p_T$  spectrum of the 2-jet system and quoted at 68% C.L. and for a form factor of 2 TeV. This measurement is not used for obtaining the mean as it is for a specific form factor. The 95% confidence interval is  $0.56 < \kappa_\gamma < 1.55$ .
- 16 ABAZOV 09AJ study the  $p\bar{p} \rightarrow 2\ell 2\nu$  process arising in  $WW$  production. They select 100 events with an expected  $WW$  signal of 65 events. An analysis of the  $p_T$  spectrum of the two charged leptons leads to 95% C.L. limits of  $0.46 < \kappa_\gamma < 1.83$ , for a form factor  $\Lambda = 2$  TeV.
- 17 ABAZOV 08R use  $0.7 \text{ fb}^{-1}$   $p\bar{p}$  data at  $\sqrt{s} = 1.96$  TeV to select 263  $W\gamma + X$  events, of which 187 constitute signal, with the  $W$  decaying into an electron or a muon, which is required to be well separated from a photon with  $E_T > 9$  GeV. A likelihood fit to the photon  $E_T$  spectrum yields a 95% CL limit  $0.49 < \kappa_\gamma < 1.51$  with other couplings fixed to their Standard Model values.
- 18 ABDALLAH 08C determine this triple gauge coupling from the measurement of the spin density matrix elements in  $e^+e^- \rightarrow W^+W^- \rightarrow (qq)(\ell\nu)$ , where  $\ell = e$  or  $\mu$ . Values of all other couplings are fixed to their standard model values.
- 19 AALTONEN 07L set limits on anomalous TGCs using the  $p_T(W)$  distribution in  $WW$  and  $WZ$  production with the  $W$  decaying to an electron or muon and the  $Z$  to 2 jets. Setting other couplings to their standard model value, the 95% C.L. limits are  $0.54 < \kappa_\gamma < 1.39$  for a form factor scale  $\Lambda = 1.5$  TeV.
- 20 ABAZOV 06H study  $p\bar{p} \rightarrow WW$  production with a subsequent decay  $WW \rightarrow e^+\nu_e e^-\bar{\nu}_e$ ,  $WW \rightarrow e^\pm\nu_e e^\mp\nu_\mu$  or  $WW \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$ . The 95% C.L. limit for a form factor scale  $\Lambda = 1$  TeV is  $-0.05 < \kappa_\gamma < 2.29$ , fixing  $\lambda_\gamma=0$ . With the assumption that the  $WW\gamma$  and  $WWZ$  couplings are equal the 95% C.L. one-dimensional limit ( $\Lambda = 2$  TeV) is  $0.68 < \kappa < 1.45$ .
- 21 ABAZOV 05J perform a likelihood fit to the photon  $E_T$  spectrum of  $W\gamma + X$  events, where the  $W$  decays to an electron or muon which is required to be well separated from the photon. For  $\Lambda = 2.0$  TeV the 95% CL limits are  $0.12 < \kappa_\gamma < 1.96$ . In the fit  $\lambda_\gamma$  is kept fixed to its Standard Model value.
- 22 ABREU 01i combine results from  $e^+e^-$  interactions at 189 GeV leading to  $W^+W^-$ ,  $W e\nu_e$ , and  $\nu\bar{\nu}\gamma$  final states with results from ABREU 99L at 183 GeV. The 95% confidence interval is  $0.87 < \kappa_\gamma < 1.68$ .
- 23 BREITWEG 00 search for  $W$  production in events with large hadronic  $p_T$ . For  $p_T > 20$  GeV, the upper limit on the cross section gives the 95%CL limit  $-3.7 < \kappa_\gamma < 2.5$  (for  $\lambda_\gamma=0$ ).
- 24 ABBOTT 99i perform a simultaneous fit to the  $W\gamma$ ,  $WW \rightarrow$  dilepton,  $WW/WZ \rightarrow e\nu jj$ ,  $WW/WZ \rightarrow \mu\nu jj$ , and  $WZ \rightarrow$  trilepton data samples. For  $\Lambda = 2.0$  TeV, the 95%CL limits are  $0.75 < \kappa_\gamma < 1.39$ .

### $\lambda_\gamma$

OUR FIT below is taken from [SCHAEL 13A].

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>-0.022±0.019 OUR FIT</b>				
0.002±0.035	7872	1 ABDALLAH	10 DLPH	$E_{\text{cm}}^{ee} = 189\text{--}209$ GeV
-0.012±0.027±0.011	10689	2 SCHAEL	05A ALEP	$E_{\text{cm}}^{ee} = 183\text{--}209$ GeV
-0.060 <sup>+0.034</sup> <sub>-0.033</sub>	9800	3 ABBIENDI	04D OPAL	$E_{\text{cm}}^{ee} = 183\text{--}209$ GeV
-0.021 <sup>+0.035</sup> <sub>-0.034</sub> ±0.017	10575	4 ACHARD	04D L3	$E_{\text{cm}}^{ee} = 161\text{--}209$ GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

		5	CHATRCHYAN 14AB	CMS	$E_{\text{cm}}^{pp} = 7 \text{ TeV}$
		6	AAD	13AN ATLS	$E_{\text{cm}}^{pp} = 7 \text{ TeV}$
		7	ABAZOV	12AG D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
		8	ABAZOV	11AC D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
		9	CHATRCHYAN 11M	CMS	$E_{\text{cm}}^{pp} = 7 \text{ TeV}$
	53	10	AARON	09B H1	$E_{\text{cm}}^{ep} = 0.3 \text{ TeV}$
0.00 ± 0.06		11	ABAZOV	09AD D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
		12	ABAZOV	09AJ D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
		13	ABAZOV	08R D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
0.16 $\begin{smallmatrix} +0.12 \\ -0.13 \end{smallmatrix}$	1880	14	ABDALLAH	08C DLPH	Superseded by ABDAL- LAH 10
	1617	15	AALTONEN	07L CDF	$E_{\text{cm}}^{pp} = 1.96 \text{ GeV}$
	17	16	ABAZOV	06H D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
	141	17	ABAZOV	05J D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
0.05 ± 0.09 ± 0.01	2298	18	ABREU	01I DLPH	$E_{\text{cm}}^{ee} = 183+189 \text{ GeV}$
		19	BREITWEG	00 ZEUS	$e^+ p \rightarrow e^+ W^\pm X,$ $\sqrt{s} \approx 300 \text{ GeV}$
0.00 $\begin{smallmatrix} +0.10 \\ -0.09 \end{smallmatrix}$	331	20	ABBOTT	99I D0	$E_{\text{cm}}^{p\bar{p}} = 1.8 \text{ TeV}$

<sup>1</sup> ABDALLAH 10 use data on the final states  $e^+ e^- \rightarrow jj\ell\nu, jjjj, jjX, \ell X$ , at center-of-mass energies between 189–209 GeV at LEP2, where  $j = \text{jet}$ ,  $\ell = \text{lepton}$ , and  $X$  represents missing momentum. The fit is carried out keeping all other parameters fixed at their SM values.

<sup>2</sup> SCHAEEL 05A study single-photon, single- $W$ , and  $WW$ -pair production from 183 to 209 GeV. Each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values.

<sup>3</sup> ABBIENDI 04D combine results from  $W^+ W^-$  in all decay channels. Only  $CP$ -conserving couplings are considered and each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values. The 95% confidence interval is  $-0.13 < \lambda_\gamma < 0.01$ .

<sup>4</sup> ACHARD 04D study  $WW$ -pair production, single- $W$  production and single-photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained including data from 161 to 183 GeV, ACCIARRI 99Q. Each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values.

<sup>5</sup> CHATRCHYAN 14AB measure  $W\gamma$  production cross section for  $p_T^\gamma > 15 \text{ GeV}$  and  $R(\ell\gamma) > 0.7$ , which is the separation between the  $\gamma$  and the final state charged lepton ( $e$  or  $\mu$ ) in the azimuthal angle-pseudorapidity ( $\phi - \eta$ ) plane. After background subtraction the number of  $e\nu\gamma$  and  $\mu\nu\gamma$  events is determined to be  $3200 \pm 325$  and  $4970 \pm 543$  respectively, compatible with expectations from the SM. This leads to a 95% CL limit of  $-0.050 < \lambda_\gamma < 0.037$ , assuming all other parameters have SM values.

<sup>6</sup> AAD 13AN study  $W\gamma$  production in  $pp$  collisions. In events with no additional jet, 4449 (6578)  $W$  decays to electron (muon) are selected, with an expected background of  $1662 \pm 262$  ( $2538 \pm 362$ ) events. Analysing the photon  $p_T$  spectrum above 100 GeV yields a 95% C.L. limit of  $-0.065 < \lambda_\gamma < 0.061$ . Supersedes AAD 12BX.

<sup>7</sup> ABAZOV 12AG combine new results with already published results on  $W\gamma$ ,  $WW$  and  $WZ$  production in order to determine the couplings with increased precision, superseding ABAZOV 08R, ABAZOV 11AC, ABAZOV 09AJ, ABAZOV 09AD. The 68% C.L. result for a formfactor cutoff of  $\Lambda = 2 \text{ TeV}$  is  $\lambda_\gamma = 0.007 \begin{smallmatrix} +0.021 \\ -0.022 \end{smallmatrix}$ .

- <sup>8</sup> ABAZOV 11AC study  $W\gamma$  production in  $p\bar{p}$  collisions at 1.96 TeV, with the  $W$  decay products containing an electron or a muon. They select 196 (363) events in the electron (muon) mode, with a SM expectation of 190 (372) events. A likelihood fit to the photon  $E_T$  spectrum above 15 GeV yields at 95% C.L. the result:  $-0.08 < \lambda_\gamma < 0.07$  for a formfactor  $\Lambda = 2$  TeV.
- <sup>9</sup> CHATRCHYAN 11M study  $W\gamma$  production in  $pp$  collisions at  $\sqrt{s} = 7$  TeV using  $36 \text{ pb}^{-1}$   $pp$  data with the  $W$  decaying to electron and muon. The total cross section is measured for photon transverse energy  $E_T^\gamma > 10$  GeV and spatial separation from charged leptons in the plane of pseudo rapidity and azimuthal angle  $\Delta R(\ell, \gamma) > 0.7$ . The number of candidate (background) events is 452 ( $228 \pm 21$ ) for the electron channel and 520 ( $277 \pm 25$ ) for the muon channel. Setting other couplings to their standard model value, they derive a 95% CL limit of  $-0.18 < \lambda_\gamma < 0.17$ .
- <sup>10</sup> AARON 09B study single- $W$  production in  $ep$  collisions at 0.3 TeV C.M. energy. They select 53  $W \rightarrow e/\mu$  events with a standard model expectation of  $54.1 \pm 7.4$  events. Fitting the transverse momentum spectrum of the hadronic recoil system they obtain a 95% C.L. limit of  $-2.5 < \lambda_\gamma < 2.5$ .
- <sup>11</sup> ABAZOV 09AD study the  $p\bar{p} \rightarrow \ell\nu 2\text{jet}$  process arising in  $WW$  and  $WZ$  production. They select 12,473 (14,392) events in the electron (muon) channel with an expected di-boson signal of 436 (527) events. The results on the anomalous couplings are derived from an analysis of the  $p_T$  spectrum of the 2-jet system and quoted at 68% C.L. and for a form factor of 2 TeV. This measurement is not used for obtaining the mean as it is for a specific form factor. The 95% confidence interval is  $-0.10 < \lambda_\gamma < 0.11$ .
- <sup>12</sup> ABAZOV 09AJ study the  $p\bar{p} \rightarrow 2\ell 2\nu$  process arising in  $WW$  production. They select 100 events with an expected  $WW$  signal of 65 events. An analysis of the  $p_T$  spectrum of the two charged leptons leads to 95% C.L. limits of  $-0.14 < \lambda_\gamma < 0.18$ , for a form factor  $\Lambda = 2$  TeV.
- <sup>13</sup> ABAZOV 08R use  $0.7 \text{ fb}^{-1}$   $p\bar{p}$  data at  $\sqrt{s} = 1.96$  TeV to select 263  $W\gamma + X$  events, of which 187 constitute signal, with the  $W$  decaying into an electron or a muon, which is required to be well separated from a photon with  $E_T > 9$  GeV. A likelihood fit to the photon  $E_T$  spectrum yields a 95% CL limit  $-0.12 < \lambda_\gamma < 0.13$  with other couplings fixed to their Standard Model values.
- <sup>14</sup> ABDALLAH 08C determine this triple gauge coupling from the measurement of the spin density matrix elements in  $e^+e^- \rightarrow W^+W^- \rightarrow (qq)(\ell\nu)$ , where  $\ell = e$  or  $\mu$ . Values of all other couplings are fixed to their standard model values.
- <sup>15</sup> AALTONEN 07L set limits on anomalous TGCs using the  $p_T(W)$  distribution in  $WW$  and  $WZ$  production with the  $W$  decaying to an electron or muon and the  $Z$  to 2 jets. Setting other couplings to their standard model value, the 95% C.L. limits are  $-0.18 < \lambda_\gamma < 0.17$  for a form factor scale  $\Lambda = 1.5$  TeV.
- <sup>16</sup> ABAZOV 06H study  $\bar{p}p \rightarrow WW$  production with a subsequent decay  $WW \rightarrow e^+\nu_e e^-\bar{\nu}_e$ ,  $WW \rightarrow e^\pm\nu_e e^\mp\nu_\mu$  or  $WW \rightarrow \mu^+\nu_\mu \mu^-\bar{\nu}_\mu$ . The 95% C.L. limit for a form factor scale  $\Lambda = 1$  TeV is  $-0.97 < \lambda_\gamma < 1.04$ , fixing  $\kappa_\gamma = 1$ . With the assumption that the  $WW\gamma$  and  $WWZ$  couplings are equal the 95% C.L. one-dimensional limit ( $\Lambda = 2$  TeV) is  $-0.29 < \lambda < 0.30$ .
- <sup>17</sup> ABAZOV 05J perform a likelihood fit to the photon  $E_T$  spectrum of  $W\gamma + X$  events, where the  $W$  decays to an electron or muon which is required to be well separated from the photon. For  $\Lambda = 2.0$  TeV the 95% CL limits are  $-0.20 < \lambda_\gamma < 0.20$ . In the fit  $\kappa_\gamma$  is kept fixed to its Standard Model value.
- <sup>18</sup> ABREU 01I combine results from  $e^+e^-$  interactions at 189 GeV leading to  $W^+W^-$ ,  $W e\nu_e$ , and  $\nu\bar{\nu}\gamma$  final states with results from ABREU 99L at 183 GeV. The 95% confidence interval is  $-0.11 < \lambda_\gamma < 0.23$ .
- <sup>19</sup> BREITWEG 00 search for  $W$  production in events with large hadronic  $p_T$ . For  $p_T > 20$  GeV, the upper limit on the cross section gives the 95%CL limit  $-3.2 < \lambda_\gamma < 3.2$  for  $\kappa_\gamma$  fixed to its Standard Model value.

<sup>20</sup> ABBOTT 99I perform a simultaneous fit to the  $W\gamma$ ,  $WW \rightarrow$  dilepton,  $WW/WZ \rightarrow e\nu jj$ ,  $WW/WZ \rightarrow \mu\nu jj$ , and  $WZ \rightarrow$  trilepton data samples. For  $\Lambda = 2.0$  TeV, the 95%CL limits are  $-0.18 < \lambda_\gamma < 0.19$ .

**$\kappa_Z$**

This coupling is  $CP$ -conserving ( $C$ - and  $P$ - separately conserving).

<u>VALUE</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b><math>0.924^{+0.059}_{-0.056} \pm 0.024</math></b>	7171	<sup>1</sup> ACHARD	04D L3	$E_{cm}^{ee} = 189\text{--}209$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		<sup>2</sup> SIRUNYAN	20BA CMS	$E_{cm}^{pp} = 13$ TeV
		<sup>3</sup> SIRUNYAN	19CL CMS	$E_{cm}^{pp} = 13$ TeV
		<sup>4</sup> AABOUD	17S ATLS	$E_{cm}^{pp} = 7+8$ TeV
		<sup>5</sup> KHACHATRYAN	17O CMS	$E_{cm}^{pp} = 8$ TeV
		<sup>6</sup> AAD	16AR ATLS	$E_{cm}^{pp} = 8$ TeV
		<sup>7</sup> AAD	16P ATLS	$E_{cm}^{pp} = 8$ TeV
		<sup>8</sup> AAD	13AL ATLS	$E_{cm}^{pp} = 7$ TeV
		<sup>9</sup> AAD	12CD ATLS	$E_{cm}^{pp} = 7$ TeV
		<sup>10</sup> AALTONEN	12AC CDF	$E_{cm}^{p\bar{p}} = 1.96$ TeV
	34	<sup>11</sup> ABAZOV	11 D0	$E_{cm}^{p\bar{p}} = 1.96$ TeV
	17	<sup>12</sup> ABAZOV	06H D0	$E_{cm}^{p\bar{p}} = 1.96$ TeV
	2.3	<sup>13</sup> ABAZOV	05S D0	$E_{cm}^{p\bar{p}} = 1.96$ TeV

<sup>1</sup> ACHARD 04D study  $WW$ -pair production, single- $W$  production and single-photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained using the  $WW$ -pair production sample. Each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values.

<sup>2</sup> SIRUNYAN 20BA study electroweak production of a  $W$  boson in association with two jets, using  $W$  decays in the electron or muon channel. The isolated muons (electrons) are required to have a transverse momentum larger than 25 (30) GeV, while the transverse momentum of the two jets has to be larger than 50 and 30 GeV. A total of 2.382 (1.051) million events are selected in the muon (electron) channel, with a Standard Model expectation of  $2.39 \pm 0.17$  ( $1.054 \pm 0.058$ ) million events. Analysing the transverse momentum distribution of the charged leptons from  $W$  decay, the following 95% C.L. limit is obtained:  $0.956 < \kappa_Z < 1.044$ . Combining this result with that from the closely-related electroweak  $Z$ -jet-jet production SIRUNYAN 18BZ, the limit becomes:  $0.957 < \kappa_Z < 1.042$ .

<sup>3</sup> SIRUNYAN 19CL study  $WW$  and  $WZ$  production in lepton + jet events, with one  $W$  boson decaying leptonically (electron or muon), and another  $W$  or  $Z$  boson decaying hadronically, reconstructed as a single massive large-radius jet. In the electron channel 2,456 (2,235) events are selected in the  $WW(WZ)$  category, while in the muon channel 3,996 (3572) events are selected in the  $WW(WZ)$  category. Analysing the di-boson invariant mass distribution, the following 95% C.L. limit is obtained:  $0.9921 < \kappa_Z < 1.0082$ .

<sup>4</sup> AABOUD 17S analyze electroweak production of a  $W$  boson in association with two jets at high dijet invariant mass, with the  $W$  boson decaying to electron or muon plus neutrino. In the signal region of dijet mass larger than 1 TeV and leading-jet transverse momentum larger than 600 GeV, 30 events are observed in the data with  $39 \pm 4$  events expected in the Standard Model, yielding the following limit at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $0.85 < \kappa_Z < 1.16$ .

<sup>5</sup> KHACHATRYAN 17O analyse  $WZ$  production where each boson decays into electrons or muons. Events are required to have a tri-lepton invariant mass larger than 100 GeV,



with one of the lepton pairs having an invariant mass within 20 GeV of the Z boson mass. The Z transverse momentum spectrum is analyzed to set a 95% C.L. limit of:  $0.79 < \kappa_Z < 1.25$ .

- <sup>6</sup> AAD 16AR study  $WW$  production in  $pp$  collisions and select 6636  $WW$  candidates in decay modes with electrons or muons with an expected background of  $1546 \pm 157$  events. Assuming the LEP formulation and setting the form-factor  $\Lambda$  to infinity, a fit to the transverse momentum distribution of the leading charged lepton, leads to a 95% C.L. range of  $0.975 < \kappa_Z < 1.020$ .
- <sup>7</sup> AAD 16P study  $WZ$  production in  $pp$  collisions and select 2091  $WZ$  candidates in 4 decay modes with electrons and muons, with an expected background of  $1825 \pm 7$  events. Analyzing the  $WZ$  transverse momentum distribution, the resulting 95% C.L. limit is:  $0.81 < \kappa_Z < 1.30$ .
- <sup>8</sup> AAD 13AL study  $WW$  production in  $pp$  collisions and select 1325  $WW$  candidates in decay modes with electrons or muons with an expected background of  $369 \pm 61$  events. Assuming the LEP formulation and setting the form-factor  $\Lambda = \text{infinity}$ , a fit to the transverse momentum distribution of the leading charged lepton, leads to a 95% C.L. range of  $0.957 < \kappa_Z < 1.043$ . Supersedes AAD 12AC.
- <sup>9</sup> AAD 12CD study  $WZ$  production in  $pp$  collisions and select 317  $WZ$  candidates in three  $\ell\nu$  decay modes with an expected background of  $68.0 \pm 10.0$  events. The resulting 95% C.L. range is:  $0.63 < \kappa_Z < 1.57$ . Supersedes AAD 12V.
- <sup>10</sup> AALTONEN 12AC study  $WZ$  production in  $p\bar{p}$  collisions and select 63  $WZ$  candidates in three  $\ell\nu$  decay modes with an expected background of  $7.9 \pm 1.0$  events. Based on the cross section and shape of the Z transverse momentum spectrum, the following 95% C.L. range is reported:  $0.61 < \kappa_Z < 1.90$  for a form factor of  $\Lambda = 2$  TeV.
- <sup>11</sup> ABAZOV 11 study the  $p\bar{p} \rightarrow 3\ell\nu$  process arising in  $WZ$  production. They observe 34  $WZ$  candidates with an estimated background of 6 events. An analysis of the  $p_T$  spectrum of the Z boson leads to a 95% C.L. limit of  $0.600 < \kappa_Z < 1.675$ , for a form factor  $\Lambda = 2$  TeV.
- <sup>12</sup> ABAZOV 06H study  $p\bar{p} \rightarrow WW$  production with a subsequent decay  $WW \rightarrow e^+\nu_e e^-\bar{\nu}_e$ ,  $WW \rightarrow e^\pm\nu_e\mu^\mp\nu_\mu$  or  $WW \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$ . The 95% C.L. limit for a form factor scale  $\Lambda = 2$  TeV is  $0.55 < \kappa_Z < 1.55$ , fixing  $\lambda_Z=0$ . With the assumption that the  $WW\gamma$  and  $WWZ$  couplings are equal the 95% C.L. one-dimensional limit ( $\Lambda = 2$  TeV) is  $0.68 < \kappa < 1.45$ .
- <sup>13</sup> ABAZOV 05S study  $p\bar{p} \rightarrow WZ$  production with a subsequent trilepton decay to  $\ell\nu\ell'\bar{\ell}'$  ( $\ell$  and  $\ell' = e$  or  $\mu$ ). Three events (estimated background  $0.71 \pm 0.08$  events) with  $WZ$  decay characteristics are observed from which they derive limits on the anomalous  $WWZ$  couplings. The 95% CL limit for a form factor scale  $\Lambda = 1$  TeV is  $-1.0 < \kappa_Z < 3.4$ , fixing  $\lambda_Z$  and  $g_1^Z$  to their Standard Model values.

## $\lambda_Z$

This coupling is CP-conserving (C- and P- separately conserving).

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
$-0.088^{+0.060}_{-0.057} \pm 0.023$	7171	<sup>1</sup> ACHARD	04D L3	$E_{cm}^{ee} = 189-209$ GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

<sup>2</sup> SIRUNYAN	20BA CMS	$E_{cm}^{pp} = 13$ TeV
<sup>3</sup> SIRUNYAN	19CL CMS	$E_{cm}^{pp} = 13$ TeV
<sup>4</sup> SIRUNYAN	18BZ CMS	$E_{cm}^{pp} = 13$ TeV
<sup>5</sup> AABOUD	17S ATLS	$E_{cm}^{pp} = 7+8$ TeV
<sup>6</sup> AABOUD	17U ATLS	$E_{cm}^{pp} = 8$ TeV
<sup>7</sup> KHACHATRY..17O	CMS	$E_{cm}^{pp} = 8$ TeV
<sup>8</sup> SIRUNYAN	17X CMS	$E_{cm}^{pp} = 8$ TeV

	9	AAD	16AR	ATLS	$E_{\text{cm}}^{pp} = 8 \text{ TeV}$
	10	AAD	16P	ATLS	$E_{\text{cm}}^{pp} = 8 \text{ TeV}$
	11	AAD	14Y	ATLS	$E_{\text{cm}}^{pp} = 8 \text{ TeV}$
	12	AAD	13AL	ATLS	$E_{\text{cm}}^{pp} = 7 \text{ TeV}$
	13	CHATRCHYAN	13BF	CMS	$E_{\text{cm}}^{pp} = 7 \text{ TeV}$
	14	AAD	12CD	ATLS	$E_{\text{cm}}^{pp} = 7 \text{ TeV}$
	15	AALTONEN	12AC	CDF	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
	34	16	ABAZOV	11 D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
	334	17	AALTONEN	10K CDF	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
	13	18	ABAZOV	07Z D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
	17	19	ABAZOV	06H D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$
	2.3	20	ABAZOV	05S D0	$E_{\text{cm}}^{p\bar{p}} = 1.96 \text{ TeV}$

- <sup>1</sup> ACHARD 04D study  $WW$ -pair production, single- $W$  production and single-photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained using the  $WW$ -pair production sample. Each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values.
- <sup>2</sup> SIRUNYAN 20BA study electroweak production of a  $W$  boson in association with two jets, using  $W$  decays in the electron or muon channel. The isolated muons (electrons) are required to have a transverse momentum larger than 25 (30) GeV, while the transverse momentum of the two jets has to be larger than 50 and 30 GeV. A total of 2.382 (1.051) million events are selected in the muon (electron) channel, with a Standard Model expectation of  $2.39 \pm 0.17$  ( $1.054 \pm 0.058$ ) million events. Analysing the transverse momentum distribution of the charged leptons from  $W$  decay, the following 95% C.L. limit is obtained:  $-0.0088 < \lambda_Z < 0.0095$ . Combining this result with that from the closely-related electroweak  $Z$ -jet-jet production SIRUNYAN 18BZ, the limit becomes:  $-0.0071 < \lambda_Z < 0.0076$ .
- <sup>3</sup> SIRUNYAN 19CL study  $WW$  and  $WZ$  production in lepton + jet events, with one  $W$  boson decaying leptonically (electron or muon), and another  $W$  or  $Z$  boson decaying hadronically, reconstructed as a single massive large-radius jet. In the electron channel 2,456 (2,235) events are selected in the  $WW(WZ)$  category, while in the muon channel 3,996 (3572) events are selected in the  $WW(WZ)$  category. Analysing the di-boson invariant mass distribution, the following 95% C.L. limit is obtained:  $-0.0065 < \lambda_Z < 0.0066$ .
- <sup>4</sup> SIRUNYAN 18BZ study  $pp \rightarrow Z \text{ jet jet}$  events at 13 TeV where  $Z \rightarrow e^+e^-/\mu^+\mu^-$ . Isolated electrons and muons are selected with  $p_T$  of the leading/sub-leading lepton  $> 30/20$  GeV and  $|\eta| < 2.4$ , with the di-lepton invariant mass within 15 GeV of the  $Z$  mass. The two highest  $p_T$  jets are selected with  $p_T$  of the leading/sub-leading jet  $> 50/30$  GeV respectively and dijet invariant mass  $> 200$  GeV. Templates in the transverse momentum of the  $Z$  are utilized to set limits on the triple gauge couplings in the EFT and the LEP parametrizations. The following 95% C.L. limit is obtained  $-0.010 < \lambda_Z < 0.010$ .
- <sup>5</sup> AABOUD 17S analyze electroweak production of a  $W$  boson in association with two jets at high dijet invariant mass, with the  $W$  boson decaying to electron or muon plus neutrino. In the signal region of dijet mass larger than 1 TeV and leading-jet transverse momentum larger than 600 GeV, 30 events are observed in the data with  $39 \pm 4$  events expected in the Standard Model, yielding the following limit at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $-0.053 < \lambda_Z < 0.042$ .
- <sup>6</sup> AABOUD 17U analyze production of  $WW$  or  $WZ$  boson pairs with one  $W$  boson decaying to electron or muon plus neutrino, and the other  $W$  or  $Z$  boson decaying hadronically. The hadronic decay system is reconstructed as either a resolved two-jet system or as a single large jet. Analysing the transverse momentum distribution of the hadronic system above 100 GeV yields the following limit at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $-0.013 < \lambda_Z < 0.013$ .

- <sup>7</sup> KHACHATRYAN 17O analyse  $WZ$  production where each boson decays into electrons or muons. Events are required to have a tri-lepton invariant mass larger than 100 GeV, with one of the lepton pairs having an invariant mass within 20 GeV of the  $Z$  boson mass. The  $Z$  transverse momentum spectrum is analyzed to set a 95% C.L. limit of:  $-0.018 < \lambda_Z < 0.016$ .
- <sup>8</sup> SIRUNYAN 17X study  $pp \rightarrow WW/WZ \rightarrow \ell\nu q\bar{q}$  production at 8 TeV where  $\ell$  is an electron or muon with  $p_T > 30$  or 25 GeV respectively. Suitable cuts are put on the  $p_T$  of the dijet system and the missing  $E_T$  of the event yielding a total of 285 and 204  $WV$  events observed in the electron and muon channels. The following 95% C.L. limit is obtained:  $-0.011 < \lambda_Z < 0.011$ .
- <sup>9</sup> AAD 16AR study  $WW$  production in  $pp$  collisions and select 6636  $WW$  candidates in decay modes with electrons or muons with an expected background of  $1546 \pm 157$  events. Assuming the LEP formulation and setting the form-factor  $\Lambda$  to infinity, a fit to the transverse momentum distribution of the leading charged lepton, leads to a 95% C.L. range of  $-0.019 < \lambda_Z < 0.019$ .
- <sup>10</sup> AAD 16P study  $WZ$  production in  $pp$  collisions and select 2091  $WZ$  candidates in 4 decay modes with electrons and muons, with an expected background of  $1825 \pm 7$  events. Analyzing the  $WZ$  transverse momentum distribution, the resulting 95% C.L. limit is:  $-0.016 < \lambda_Z < 0.016$ .
- <sup>11</sup> AAD 14Y determine the electroweak  $Z$ -dijet cross section in 8 TeV  $pp$  collisions.  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  decays are selected with the di-lepton  $p_T > 20$  GeV and mass in the 81–101 GeV range. Minimum two jets are required with  $p_T > 55$  and 45 GeV and no additional jets with  $p_T > 25$  GeV in the rapidity interval between them. The normalized  $p_T$  balance between the  $Z$  and the two jets is required to be  $< 0.15$ . This leads to a selection of 900 events with dijet mass  $> 1$  TeV. The number of signal and background events expected is 261 and 592 respectively. A Poisson likelihood method is used on an event by event basis to obtain the 95% CL limit  $-0.15 < \lambda_Z < 0.13$  for a form factor value  $\Lambda = \infty$ .
- <sup>12</sup> AAD 13AL study  $WW$  production in  $pp$  collisions and select 1325  $WW$  candidates in decay modes with electrons or muons with an expected background of  $369 \pm 61$  events. Assuming the LEP formulation and setting the form-factor  $\Lambda = \infty$ , a fit to the transverse momentum distribution of the leading charged lepton, leads to a 95% C.L. range of  $-0.062 < \lambda_Z < 0.059$ . Supersedes AAD 12AC.
- <sup>13</sup> CHATRCHYAN 13BF determine the  $W^+W^-$  production cross section using unlike sign di-lepton ( $e$  or  $\mu$ ) events with high  $p_T$ . The leptons have  $p_T > 20$  GeV/ $c$  and are isolated. 1134 candidate events are observed with an expected SM background of  $247 \pm 34$ . The  $p_T$  distribution of the leading lepton is fitted to obtain 95% C.L. limits of  $-0.048 \leq \lambda_Z \leq 0.048$ .
- <sup>14</sup> AAD 12CD study  $WZ$  production in  $pp$  collisions and select 317  $WZ$  candidates in three  $\ell\nu$  decay modes with an expected background of  $68.0 \pm 10.0$  events. The resulting 95% C.L. range is:  $-0.046 < \lambda_Z < 0.047$ . Supersedes AAD 12V.
- <sup>15</sup> AALTONEN 12AC study  $WZ$  production in  $p\bar{p}$  collisions and select 63  $WZ$  candidates in three  $\ell\nu$  decay modes with an expected background of  $7.9 \pm 1.0$  events. Based on the cross section and shape of the  $Z$  transverse momentum spectrum, the following 95% C.L. range is reported:  $-0.08 < \lambda_Z < 0.10$  for a form factor of  $\Lambda = 2$  TeV.
- <sup>16</sup> ABAZOV 11 study the  $p\bar{p} \rightarrow 3\ell\nu$  process arising in  $WZ$  production. They observe 34  $WZ$  candidates with an estimated background of 6 events. An analysis of the  $p_T$  spectrum of the  $Z$  boson leads to a 95% C.L. limit of  $-0.077 < \lambda_Z < 0.093$ , for a form factor  $\Lambda = 2$  TeV.
- <sup>17</sup> AALTONEN 10K study  $p\bar{p} \rightarrow W^+W^-$  with  $W \rightarrow e/\mu\nu$ . The  $p_T$  of the leading (second) lepton is required to be  $> 20$  (10) GeV. The final number of events selected is 654 of which  $320 \pm 47$  are estimated to be background. The 95% C.L. interval is  $-0.16 < \lambda_Z < 0.16$  for  $\Lambda = 1.5$  TeV and  $-0.14 < \lambda_Z < 0.15$  for  $\Lambda = 2$  TeV.
- <sup>18</sup> ABAZOV 07Z set limits on anomalous TGCs using the measured cross section and  $p_T(Z)$  distribution in  $WZ$  production with both the  $W$  and the  $Z$  decaying leptonically into electrons and muons. Setting the other couplings to their standard model values, the 95% C.L. limit for a form factor scale  $\Lambda = 2$  TeV is  $-0.17 < \lambda_Z < 0.21$ .

- <sup>19</sup> ABAZOV 06H study  $\bar{p}p \rightarrow WW$  production with a subsequent decay  $WW \rightarrow e^+\nu_e e^-\bar{\nu}_e$ ,  $WW \rightarrow e^\pm\nu_e\mu^\mp\nu_\mu$  or  $WW \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$ . The 95% C.L. limit for a form factor scale  $\Lambda = 2$  TeV is  $-0.39 < \lambda_Z < 0.39$ , fixing  $\kappa_Z=1$ . With the assumption that the  $WW\gamma$  and  $WWZ$  couplings are equal the 95% C.L. one-dimensional limit ( $\Lambda = 2$  TeV) is  $-0.29 < \lambda < 0.30$ .
- <sup>20</sup> ABAZOV 05S study  $\bar{p}p \rightarrow WZ$  production with a subsequent tripleton decay to  $\ell\nu\ell'\bar{\ell}'$  ( $\ell$  and  $\ell' = e$  or  $\mu$ ). Three events (estimated background  $0.71 \pm 0.08$  events) with  $WZ$  decay characteristics are observed from which they derive limits on the anomalous  $WWZ$  couplings. The 95% CL limit for a form factor scale  $\Lambda = 1.5$  TeV is  $-0.48 < \lambda_Z < 0.48$ , fixing  $g_1^Z$  and  $\kappa_Z$  to their Standard Model values.

### $g_5^Z$

This coupling is  $CP$ -conserving but  $C$ - and  $P$ -violating.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<b><math>-0.07 \pm 0.09</math> OUR AVERAGE</b>		Error includes scale factor of 1.1.		
$-0.04^{+0.13}_{-0.12}$	9800	<sup>1</sup> ABBIENDI	04D OPAL	$E_{cm}^{ee} = 183\text{--}209$ GeV
$0.00 \pm 0.13 \pm 0.05$	7171	<sup>2</sup> ACHARD	04D L3	$E_{cm}^{ee} = 189\text{--}209$ GeV
$-0.44^{+0.23}_{-0.22} \pm 0.12$	1154	<sup>3</sup> ACCIARRI	99Q L3	$E_{cm}^{ee} = 161+172+ 183$ GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

$-0.31 \pm 0.23$  <sup>4</sup> EBOLI 00 THEO LEP1, SLC+ Tevatron

<sup>1</sup> ABBIENDI 04D combine results from  $W^+W^-$  in all decay channels. Only  $CP$ -conserving couplings are considered and each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values. The 95% confidence interval is  $-0.28 < g_5^Z < +0.21$ .

<sup>2</sup> ACHARD 04D study  $WW$ -pair production, single- $W$  production and single-photon production with missing energy from 189 to 209 GeV. The result quoted here is obtained using the  $WW$ -pair production sample. Each parameter is determined from a single-parameter fit in which the other parameters assume their Standard Model values.

<sup>3</sup> ACCIARRI 99Q study  $W$ -pair, single- $W$ , and single photon events.

<sup>4</sup> EBOLI 00 extract this indirect value of the coupling studying the non-universal one-loop contributions to the experimental value of the  $Z \rightarrow b\bar{b}$  width ( $\Lambda=1$  TeV is assumed).

### $g_4^Z$

This coupling is  $CP$ -violating ( $C$ -violating and  $P$ -conserving).

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
<b><math>-0.30 \pm 0.17</math> OUR AVERAGE</b>				
$-0.39^{+0.19}_{-0.20}$	1880	<sup>1</sup> ABDALLAH	08C DLPH	$E_{cm}^{ee} = 189\text{--}209$ GeV
$-0.02^{+0.32}_{-0.33}$	1065	<sup>2</sup> ABBIENDI	01H OPAL	$E_{cm}^{ee} = 189$ GeV

<sup>1</sup> ABDALLAH 08C determine this triple gauge coupling from the measurement of the spin density matrix elements in  $e^+e^- \rightarrow W^+W^- \rightarrow (qq)(\ell\nu)$ , where  $\ell = e$  or  $\mu$ . Values of all other couplings are fixed to their standard model values.

<sup>2</sup> ABBIENDI 01H study  $W$ -pair events, with one leptonically and one hadronically decaying  $W$ . The coupling is extracted using information from the  $W$  production angle together with decay angles from the leptonically decaying  $W$ .

### $\tilde{\kappa}_Z$

This coupling is *CP*-violating (*C*-conserving and *P*-violating).

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
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**$-0.12^{+0.06}_{-0.04}$  OUR AVERAGE**

$-0.09^{+0.08}_{-0.05}$  1880 1 ABDALLAH 08C DLPH  $E_{\text{cm}}^{ee} = 189\text{--}209$  GeV

$-0.20^{+0.10}_{-0.07}$  1065 2 ABBIENDI 01H OPAL  $E_{\text{cm}}^{ee} = 189$  GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

3 AABOUD 17S ATLS  $E_{\text{cm}}^{pp} = 7\text{+}8$  TeV

4 BLINOV 11 LEP  $E_{\text{cm}}^{ee} = 183\text{--}207$  GeV

<sup>1</sup> ABDALLAH 08C determine this triple gauge coupling from the measurement of the spin density matrix elements in  $e^+e^- \rightarrow W^+W^- \rightarrow (qq)(\ell\nu)$ , where  $\ell = e$  or  $\mu$ . Values of all other couplings are fixed to their standard model values.

<sup>2</sup> ABBIENDI 01H study *W*-pair events, with one leptonically and one hadronically decaying *W*. The coupling is extracted using information from the *W* production angle together with decay angles from the leptonically decaying *W*.

<sup>3</sup> AABOUD 17S analyze electroweak production of a *W* boson in association with two jets at high dijet invariant mass, with the *W* boson decaying to electron or muon plus neutrino. In the signal region of dijet mass larger than 1 TeV and leading-jet transverse momentum larger than 600 GeV, 30 events are observed in the data with  $39 \pm 4$  events expected in the Standard Model, yielding the following limit at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $-0.56 < \tilde{\kappa}_Z < 0.56$ .

<sup>4</sup> BLINOV 11 use the LEP-average  $e^+e^- \rightarrow W^+W^-$  cross section data for  $\sqrt{s} = 183\text{--}207$  GeV to determine an upper limit on the TGC  $\tilde{\kappa}_Z$ . The average values of the cross sections as well as their correlation matrix, and standard model expectations of the cross sections are taken from the LEPEWWG note hep-ex/0612034. At 95% confidence level  $|\tilde{\kappa}_Z| < 0.13$ .

### $\tilde{\lambda}_Z$

This coupling is *CP*-violating (*C*-conserving and *P*-violating).

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
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**$-0.09 \pm 0.07$  OUR AVERAGE**

$-0.08 \pm 0.07$  1880 1 ABDALLAH 08C DLPH  $E_{\text{cm}}^{ee} = 189\text{--}209$  GeV

$-0.18^{+0.24}_{-0.16}$  1065 2 ABBIENDI 01H OPAL  $E_{\text{cm}}^{ee} = 189$  GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

3 AABOUD 17S ATLS  $E_{\text{cm}}^{pp} = 7\text{+}8$  TeV

4 BLINOV 11 LEP  $E_{\text{cm}}^{ee} = 183\text{--}207$  GeV

<sup>1</sup> ABDALLAH 08C determine this triple gauge coupling from the measurement of the spin density matrix elements in  $e^+e^- \rightarrow W^+W^- \rightarrow (qq)(\ell\nu)$ , where  $\ell = e$  or  $\mu$ . Values of all other couplings are fixed to their standard model values.

<sup>2</sup> ABBIENDI 01H study *W*-pair events, with one leptonically and one hadronically decaying *W*. The coupling is extracted using information from the *W* production angle together with decay angles from the leptonically decaying *W*.

<sup>3</sup> AABOUD 17S analyze electroweak production of a *W* boson in association with two jets at high dijet invariant mass, with the *W* boson decaying to electron or muon plus neutrino. In the signal region of dijet mass larger than 1 TeV and leading-jet transverse momentum larger than 600 GeV, 30 events are observed in the data with  $39 \pm 4$  events expected in the Standard Model, yielding the following limit at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $-0.047 < \tilde{\lambda}_Z < 0.046$ .

<sup>4</sup>BLINOV 11 use the LEP-average  $e^+e^- \rightarrow W^+W^-$  cross section data for  $\sqrt{s} = 183\text{--}207$  GeV to determine an upper limit on the TGC  $\tilde{\lambda}_Z$ . The average values of the cross sections as well as their correlation matrix, and standard model expectations of the cross sections are taken from the LEPEWWG note hep-ex/0612034. At 95% confidence level  $|\tilde{\lambda}_Z| < 0.31$ .

## W ANOMALOUS MAGNETIC MOMENT

The full magnetic moment is given by  $\mu_W = e(1+\kappa + \lambda)/2m_W$ . In the Standard Model, at tree level,  $\kappa = 1$  and  $\lambda = 0$ . Some papers have defined  $\Delta\kappa = 1-\kappa$  and assume that  $\lambda = 0$ . Note that the electric quadrupole moment is given by  $-e(\kappa-\lambda)/m_W^2$ . A description of the parameterization of these moments and additional references can be found in HAGIWARA 87 and BAUR 88. The parameter  $\Lambda$  appearing in the theoretical limits below is a regularization cutoff which roughly corresponds to the energy scale where the structure of the  $W$  boson becomes manifest.

VALUE ( $e/2m_W$ )	EVTS	DOCUMENT ID	TECN	COMMENT
<b>2.22<sup>+0.20</sup><sub>-0.19</sub></b>	2298	1 ABREU	01i	DLPH $E_{\text{cm}}^{ee} = 183+189$ GeV
• • •		2 ABE	95G	CDF
		3 ALITTI	92C	UA2
		4 SAMUEL	92	THEO
		5 SAMUEL	91	THEO
		6 GRIFOLS	88	THEO
		7 GROTCCH	87	THEO
		8 VANDERBIJ	87	THEO
		9 GRAU	85	THEO
		10 SUZUKI	85	THEO
		11 HERZOG	84	THEO

<sup>1</sup>ABREU 01i combine results from  $e^+e^-$  interactions at 189 GeV leading to  $W^+W^-$ ,  $W e \nu_e$ , and  $\nu\bar{\nu}\gamma$  final states with results from ABREU 99L at 183 GeV to determine  $\Delta g_1^Z$ ,  $\Delta\kappa_\gamma$ , and  $\lambda_\gamma$ .  $\Delta\kappa_\gamma$  and  $\lambda_\gamma$  are simultaneously floated in the fit to determine  $\mu_W$ .

<sup>2</sup>ABE 95G report  $-1.3 < \kappa < 3.2$  for  $\lambda=0$  and  $-0.7 < \lambda < 0.7$  for  $\kappa=1$  in  $p\bar{p} \rightarrow e\nu_e\gamma X$  and  $\mu\nu_\mu\gamma X$  at  $\sqrt{s} = 1.8$  TeV.

<sup>3</sup>ALITTI 92C measure  $\kappa = 1_{-2.2}^{+2.6}$  and  $\lambda = 0_{-1.8}^{+1.7}$  in  $p\bar{p} \rightarrow e\nu\gamma + X$  at  $\sqrt{s} = 630$  GeV. At 95%CL they report  $-3.5 < \kappa < 5.9$  and  $-3.6 < \lambda < 3.5$ .

<sup>4</sup>SAMUEL 92 use preliminary CDF and UA2 data and find  $-2.4 < \kappa < 3.7$  at 96%CL and  $-3.1 < \kappa < 4.2$  at 95%CL respectively. They use data for  $W\gamma$  production and radiative  $W$  decay.

<sup>5</sup>SAMUEL 91 use preliminary CDF data for  $p\bar{p} \rightarrow W\gamma X$  to obtain  $-11.3 \leq \Delta\kappa \leq 10.9$ . Note that their  $\kappa = 1-\Delta\kappa$ .

<sup>6</sup>GRIFOLS 88 uses deviation from  $\rho$  parameter to set limit  $\Delta\kappa \lesssim 65 (M_W^2/\Lambda^2)$ .

<sup>7</sup>GROTCCH 87 finds the limit  $-37 < \Delta\kappa < 73.5$  (90% CL) from the experimental limits on  $e^+e^- \rightarrow \nu\bar{\nu}\gamma$  assuming three neutrino generations and  $-19.5 < \Delta\kappa < 56$  for four generations. Note their  $\Delta\kappa$  has the opposite sign as our definition.

<sup>8</sup>VANDERBIJ 87 uses existing limits to the photon structure to obtain  $|\Delta\kappa| < 33 (m_W/\Lambda)$ . In addition VANDERBIJ 87 discusses problems with using the  $\rho$  parameter of the Standard Model to determine  $\Delta\kappa$ .

- <sup>9</sup> GRAU 85 uses the muon anomaly to derive a coupled limit on the anomalous magnetic dipole and electric quadrupole ( $\lambda$ ) moments  $1.05 > \Delta\kappa \ln(\Lambda/m_W) + \lambda/2 > -2.77$ . In the Standard Model  $\lambda = 0$ .
- <sup>10</sup> SUZUKI 85 uses partial-wave unitarity at high energies to obtain  $|\Delta\kappa| \lesssim 190 (m_W/\Lambda)^2$ . From the anomalous magnetic moment of the muon, SUZUKI 85 obtains  $|\Delta\kappa| \lesssim 2.2/\ln(\Lambda/m_W)$ . Finally SUZUKI 85 uses deviations from the  $\rho$  parameter and obtains a very qualitative, order-of-magnitude limit  $|\Delta\kappa| \lesssim 150 (m_W/\Lambda)^4$  if  $|\Delta\kappa| \ll 1$ .
- <sup>11</sup> HERZOG 84 consider the contribution of  $W$ -boson to muon magnetic moment including anomalous coupling of  $W W \gamma$ . Obtain a limit  $-1 < \Delta\kappa < 3$  for  $\Lambda \gtrsim 1$  TeV.

### $c_{WWW}/\Lambda^2, c_W/\Lambda^2, c_B/\Lambda^2$

These couplings are used in EFT-based approaches to anomalous couplings. They are linearly related to the couplings discussed above.

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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• • • We do not use the following data for averages, fits, limits, etc. • • •

1	TUMASYAN	22AB CMS	$E_{cm}^{pp} = 13$ TeV
2	TUMASYAN	22E CMS	$E_{cm}^{pp} = 13$ TeV
3	AAD	21AC ATLS	$E_{cm}^{pp} = 13$ TeV
4	AAD	21W ATLS	$E_{cm}^{pp} = 13$ TeV
5	SIRUNYAN	21G CMS	$E_{cm}^{pp} = 13$ TeV
6	SIRUNYAN	20BA CMS	$E_{cm}^{pp} = 13$ TeV
7	SIRUNYAN	20BF CMS	$E_{cm}^{pp} = 13$ TeV
8	AABOUD	19BA ATLS	$E_{cm}^{pp} = 13$ TeV
9	SIRUNYAN	19AD CMS	$E_{cm}^{pp} = 13$ TeV
10	SIRUNYAN	19CL CMS	$E_{cm}^{pp} = 13$ TeV
11	AABOUD	18Q ATLS	$E_{cm}^{pp} = 13$ TeV
12	SIRUNYAN	18BZ CMS	$E_{cm}^{pp} = 13$ TeV
13	AABOUD	17s ATLS	$E_{cm}^{pp} = 7+8$ TeV
14	AABOUD	17U ATLS	$E_{cm}^{pp} = 8$ TeV
15	KHACHATRY...17O	CMS	$E_{cm}^{pp} = 8$ TeV
16	SIRUNYAN	17X CMS	$E_{cm}^{pp} = 8$ TeV
17	AAD	16AR ATLS	$E_{cm}^{pp} = 8$ TeV
18	AAD	16P ATLS	$E_{cm}^{pp} = 8$ TeV
19	KHACHATRY...16BI	CMS	$E_{cm}^{pp} = 8$ TeV

<sup>1</sup> TUMASYAN 22AB study  $WZ$  production, measuring cross sections and various distributions. Analysing the  $WZ$  invariant mass distribution, the following 95% C.L. limits are derived in units of  $\text{TeV}^{-2}$ :  $-2.5 < c_W/\Lambda^2 < 0.3$ ,  $-1.0 < c_{WWW}/\Lambda^2 < 1.2$ ,  $-43 < c_b/\Lambda^2 < 113$ ,  $-0.62 < \tilde{c}_{WWW}/\Lambda^2 < 0.53$ ,  $-32 < \tilde{c}_W/\Lambda^2 < 32$ .

<sup>2</sup> TUMASYAN 22E measure  $W\gamma$  production where the  $W$  boson decays to electrons or muons. Analysing the photon transverse momentum distribution in bins of lepton azimuth, the following 95% C.L. limit is derived in units of  $\text{TeV}^{-2}$ :  $-0.062 < c_{3W}/\Lambda^2 < 0.052$ . This limit is derived including the non-SM, SM and their interference effects.

<sup>3</sup> AAD 21AC study the differential cross-section for the electroweak production of dijets in association with a  $Z$  boson, where the  $Z$  boson decays to electrons or muons. The

number of events selected in the data is 10,870 (12,125) in the electron (muon) channel. Analyzing the distribution of the azimuthal separation of the two jets, the following 95% C.L. limits are derived in units of  $\text{TeV}^{-2}$ :  $-2.7 < c_{WWW}/\Lambda^2 < 5.8$ ,  $-1.6 < \tilde{c}_{WWW}/\Lambda^2 < 2.0$ ,  $-0.19 < c_W/\Lambda^2 < 0.41$ ,  $-0.11 < \tilde{c}_W/\Lambda^2 < 0.14$ ,  $-6.31 < c_{HWB}/\Lambda^2 < 1.01$ ,  $0.23 < \tilde{c}_{HWB}/\Lambda^2 < 2.35$ .

<sup>4</sup> AAD 21W analyze  $W^+ W^-$  production in association with at least one jet. Events with exactly one oppositely-charged electron-muon pair and at least one hadronic jet of transverse momentum larger than 30 GeV (120 GeV) are selected. In the data, 89,239 (5,825) events are found, with a total Standard-Model expectation of  $91600 \pm 2500$  ( $5980 \pm 150$ ). Analyzing the electron-muon invariant mass distribution, the following limit at 95% C.L. is obtained:  $-0.33 < c_W/\Lambda^2 < 0.33$  ( $-0.60 < c_W/\Lambda^2 < 0.58$ ), for a fixed choice of  $\Lambda = 1$  TeV.

<sup>5</sup> SIRUNYAN 21G measure  $W\gamma$  production where the  $W$  decays into electrons or muons. In the data, 385,224 (395,818) events are selected in the electron (muon) channel, with a total Standard-Model expectation of  $396913 \pm 54686$  ( $396257 \pm 22837$ ) events. Analysing the photon transverse momentum distribution, the following 95% C.L. limits are derived in units of  $\text{TeV}^{-2}$ :  $-0.90 < c_{WWW}/\Lambda^2 < 0.91$ ,  $-40 < c_B/\Lambda^2 < 41$ ,  $-0.45 < c_{\overline{WWW}}/\Lambda^2 < 0.45$ ,  $-20 < c_{\overline{W}}/\Lambda^2 < 20$ .

<sup>6</sup> SIRUNYAN 20BA study electroweak production of a  $W$  boson in association with two jets, using  $W$  decays in the electron or muon channel. The isolated muons (electrons) are required to have a transverse momentum larger than 25 (30) GeV, while the transverse momentum of the two jets has to be larger than 50 and 30 GeV. A total of 2.382 (1.051) million events are selected in the muon (electron) channel, with a Standard Model expectation of  $2.39 \pm 0.17$  ( $1.054 \pm 0.058$ ) million events. Analysing the transverse momentum distribution of the charged leptons from  $W$  decay, the following 95% C.L. limits are obtained in units of  $\text{TeV}^{-2}$ :  $-2.3 < c_{WWW}/\Lambda^2 < 2.5$ ,  $-8.8 < c_W/\Lambda^2 < 16$ ,  $-45 < c_B/\Lambda^2 < 46$ . Combining these results with those from the closely-related electroweak  $Z$ -jet-jet production SIRUNYAN 18BZ, the limits become:  $-1.8 < c_{WWW}/\Lambda^2 < 2.0$ ,  $-5.8 < c_W/\Lambda^2 < 10$ ,  $-43 < c_B/\Lambda^2 < 45$ .

<sup>7</sup> SIRUNYAN 20BF study  $W^+ W^-$  production with the  $W$  bosons decaying to electrons or muons. The leading (subleading) lepton is required to have a transverse momentum larger than 25 (20) GeV. Events with a same-flavor di-lepton invariant mass within 15 GeV of the  $Z$  mass are rejected, as are event with a third lepton of transverse momentum larger than 10 GeV. In the same- (different-) flavor category a total of 9,604 (20,270) events are selected while the number of expected events is  $9640 \pm 490$  ( $20280 \pm 430$ ). Analyzing the different-flavor di-lepton invariant mass distribution, the following 95% C.L. limits are obtained in units of  $\text{TeV}^{-2}$ :  $-1.8 < c_{WWW}/\Lambda^2 < 1.8$ ,  $-3.6 < c_W/\Lambda^2 < 2.8$ ,  $-9.4 < c_B/\Lambda^2 < 8.5$ .

<sup>8</sup> AABOUD 19BA study  $W W$  production in decay modes with an electron and a muon. The charged leptons are each required to have a transverse momentum larger than 27 GeV and rapidity less than 2.5. The electron-muon system is required to have a mass larger than 55 GeV and a transverse momentum larger than 30 GeV. The missing transverse energy must be larger than 20 GeV. Events containing a jet with transverse momentum exceeding 35 GeV and rapidity smaller than 4.5 are rejected. A total of 12,659 events are selected in the data, with an expected background of  $4240 \pm 477$  events. Analysing the transverse momentum spectrum of the leading charged lepton, the following 95% C.L. limits are derived in units of  $\text{TeV}^{-2}$ :  $-3.4 < c_{WWW}/\Lambda^2 < 3.3$ ,  $-7.4 < c_W/\Lambda^2 < 4.1$ ,  $-21 < c_B/\Lambda^2 < 18$ ,  $-1.6 < c_{\overline{WWW}}/\Lambda^2 < 1.6$ ,  $-76 < c_{\overline{W}}/\Lambda^2 < 76$ .

<sup>9</sup> SIRUNYAN 19AD study inclusive  $WZ$  production, with  $W$  and  $Z$  decaying to electrons or muons. The leading (subleading) charged lepton candidate from the  $Z$  boson decay is required to have a transverse momentum larger than 25 GeV (10 GeV). The charged lepton candidate from the  $W$  boson decay is required to have a transverse momentum larger than 25 GeV. The invariant mass of the two leptons from  $Z$  decay is required to be within 15 GeV of the  $Z$  mass, while the invariant mass of the tri-lepton system



- is required to exceed 100 GeV. A total of 3,831 tri-lepton events are observed, with a fitted SM  $WZ$  signal of  $3166 \pm 62$  events and a fitted background of  $666 \pm 45$  events. The approximated  $WZ$  invariant mass distribution is analyzed to set 95% C.L. limits as follows:  $-4.1 < c_W/\Lambda^2 < 1.1$ ,  $-2.0 < c_{WWW}/\Lambda^2 < 2.1$ ,  $-100 < c_B/\Lambda^2 < 160$ , in units of  $\text{TeV}^{-2}$ .
- <sup>10</sup> SIRUNYAN 19CL study  $WW$  and  $WZ$  production in lepton + jet events, with one  $W$  boson decaying leptonically (electron or muon), and another  $W$  or  $Z$  boson decaying hadronically, reconstructed as a single massive large-radius jet. In the electron channel 2,456 (2,235) events are selected in the  $WW(WZ)$  category, while in the muon channel 3,996 (3572) events are selected in the  $WW(WZ)$  category. Analysing the di-boson invariant mass distribution, the following 95% C.L. limits are obtained in units of  $\text{TeV}^{-2}$ :  $-1.58 < c_{WWW}/\Lambda^2 < 1.59$ ,  $-2.00 < c_W/\Lambda^2 < 2.65$ ,  $-8.78 < c_B/\Lambda^2 < 8.54$ .
- <sup>11</sup> AABOUD 18Q study  $pp \rightarrow ZZ$  events at  $\sqrt{s} = 13$  TeV with  $Z \rightarrow e^+e^-$  or  $Z \rightarrow \mu^+\mu^-$ . The number of events observed in the  $4e$ ,  $2e2\mu$ , and  $4\mu$  channels is 249, 465, and 303 respectively. Analysing the  $p_T$  spectrum of the leading  $Z$  boson, the following the following 95% C.L. limits are derived in units of  $\text{TeV}^{-4}$ :  $-5.9 < c_{\tilde{B}W}/\Lambda^4 < 5.9$ ,  $-3.0 < c_{WW}/\Lambda^4 < 3.0$ ,  $-3.3 < c_{BW}/\Lambda^4 < 3.3$ ,  $-2.7 < c_{BB}/\Lambda^4 < 2.8$ .
- <sup>12</sup> SIRUNYAN 18BZ study  $pp \rightarrow Z \text{ jet jet}$  events at 13 TeV where  $Z \rightarrow e^+e^-/\mu^+\mu^-$ . Isolated electrons and muons are selected with  $p_T$  of the leading/sub-leading lepton  $> 30/20$  GeV and  $|\eta| < 2.4$ , with the di-lepton invariant mass within 15 GeV of the  $Z$  mass. The two highest  $p_T$  jets are selected with  $p_T$  of the leading/sub-leading jet  $> 50/30$  GeV respectively and dijet invariant mass  $> 200$  GeV. Templates in the transverse momentum of the  $Z$  are utilized to set limits on the triple gauge couplings in the EFT and the LEP parametrizations. The following 95% C.L. limits are obtained in units of  $\text{TeV}^{-2}$ :  $-2.6 < c_{WWW}/\Lambda^2 < 2.6$  and  $-8.4 < c_W/\Lambda^2 < 10.1$ .
- <sup>13</sup> AABOUD 17S analyze electroweak production of a  $W$  boson in association with two jets at high dijet invariant mass, with the  $W$  boson decaying to electron or muon plus neutrino. In the signal region of dijet mass larger than 1 TeV and leading-jet transverse momentum larger than 600 GeV, 30 events are observed in the data with  $39 \pm 4$  events expected in the Standard Model, yielding the following limits at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $-33 < c_W/\Lambda^2 < 30$ ,  $-170 < c_B/\Lambda^2 < 160$ ,  $-13 < c_{WWW}/\Lambda^2 < 9$ ,  $-580 < c_{\tilde{W}}/\Lambda^2 < 580$ ,  $-11 < c_{\tilde{WWW}}/\Lambda^2 < 11$ , in units of  $\text{TeV}^{-2}$ .
- <sup>14</sup> AABOUD 17U analyze production of  $WW$  or  $WZ$  boson pairs with one  $W$  boson decaying to electron or muon plus neutrino, and the other  $W$  or  $Z$  boson decaying hadronically. The hadronic decay system is reconstructed as either a resolved two-jet system or as a single large jet. Analysing the transverse momentum distribution of the hadronic system above 100 GeV yields the following limits at 95% CL for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $-3.1 < c_{WWW}/\Lambda^2 < 3.1$ ,  $-19 < c_B/\Lambda^2 < 20$ ,  $-5.1 < c_W/\Lambda^2 < 5.8$ , in units of  $\text{TeV}^{-2}$ .
- <sup>15</sup> KHACHATRYAN 17O analyse  $WZ$  production where each boson decays into electrons or muons. Events are required to have a tri-lepton invariant mass larger than 100 GeV, with one of the lepton pairs having an invariant mass within 20 GeV of the  $Z$  boson mass. The  $Z$  transverse momentum spectrum is analyzed to set 95% C.L. limits of:  $-260 < c_B/\Lambda^2 < 210$ ,  $-4.2 < c_W/\Lambda^2 < 8.0$ ,  $-4.6 < c_{WWW}/\Lambda^2 < 4.2$ , in units of  $\text{TeV}^{-2}$ .
- <sup>16</sup> SIRUNYAN 17X study  $pp \rightarrow WW/WZ \rightarrow \ell\nu q\bar{q}$  production at 8 TeV where  $\ell$  is an electron or muon with  $p_T > 30$  or 25 GeV respectively. Suitable cuts are put on the  $p_T$  of the dijet system and the missing  $E_T$  of the event yielding a total of 285 and 204  $WV$  events observed in the electron and muon channels. The following 95% C.L. limits in units of  $\text{TeV}^{-2}$  are obtained:  $-2.7 < c_{WWW}/\Lambda^2 < 2.7$ ,  $-14 < c_B/\Lambda^2 < 17$ ,  $-2.0 < c_W/\Lambda^2 < 5.7$ .

- <sup>17</sup> AAD 16AR study  $WW$  production in  $pp$  collisions and select 6636  $WW$  candidates in decay modes with electrons or muons with an expected background of  $1546 \pm 157$  events. Assuming an EFT formulation, a fit to the transverse momentum distribution of the leading charged lepton, leads to 95% C.L. ranges of:  $-4.61 < c_{WWW}/\Lambda^2 < 4.60$ ,  $-5.87 < c_W/\Lambda^2 < 10.54$  and  $-20.9 < c_B/\Lambda^2 < 26.3$ , in units of  $\text{TeV}^{-2}$ .
- <sup>18</sup> AAD 16P study  $WZ$  production in  $pp$  collisions and select 2091  $WZ$  candidates in 4 decay modes with electrons and muons, with an expected background of  $1825 \pm 7$  events. Analyzing the  $WZ$  transverse momentum distribution, the resulting 95% C.L. limits are:  $-3.9 < c_{WWW}/\Lambda^2 < 4.0$ ,  $-4.3 < c_W/\Lambda^2 < 6.8$ , and  $-320 < c_B/\Lambda^2 < 210$ , in units of  $\text{TeV}^{-2}$ .
- <sup>19</sup> KHACHATRYAN 16BI determine the  $W^+W^-$  production cross section using unlike sign di-lepton ( $e$  or  $\mu$ ) events with high  $p_T$ . The leptons have  $p_T > 20$  GeV/ $c$  and are isolated. Events are required to have no jets above  $p_T$  of 30 GeV/ $c$ . 4847 (2233) events are selected with different (same) flavor leptons, with an expected total background of  $1179 \pm 123$  ( $643 \pm 73$ ) events. Analysing the di-lepton invariant mass spectrum, the following values are obtained:  $c_{WWW}/\Lambda^2 = 0.1 \pm 3.2$ ,  $c_W/\Lambda^2 = -3.6^{+5.0}_{-4.5}$  and  $c_B/\Lambda^2 = -3.2^{+15.0}_{-14.5}$ , in units of  $\text{TeV}^{-2}$ . The limits at 95% C.L. are:  $-5.7 < c_{WWW}/\Lambda^2 < 5.9$ ,  $-11.4 < c_W/\Lambda^2 < 5.4$  and  $-29.2 < c_B/\Lambda^2 < 23.9$ , in units of  $\text{TeV}^{-2}$ .

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### ANOMALOUS W/Z QUARTIC COUPLINGS

Revised November 2015 by M.W. Grünewald (U. College Dublin) and A. Gurtu (Formerly Tata Inst.).

Quartic couplings,  $WWZZ$ ,  $WWZ\gamma$ ,  $WW\gamma\gamma$ , and  $ZZ\gamma\gamma$ , were studied at LEP and Tevatron at energies at which the Standard Model predicts negligible contributions to multiboson production. Thus, to parametrize limits on these couplings, an effective theory approach is adopted which supplements the Standard Model Lagrangian with higher dimensional operators which include quartic couplings. The LEP collaborations chose the lowest dimensional representation of operators (dimension 6) which presumes the  $SU(2) \times U(1)$  gauge symmetry is broken by means other than the conventional Higgs scalar doublet [1–3]. In this representation possible quartic couplings,  $a_0, a_c, a_n$ , are expressed in terms of the following dimension-6 operators [1,2];

$$L_6^0 = -\frac{e^2}{16\Lambda^2} a_0 F^{\mu\nu} F_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha$$

$$L_6^c = -\frac{e^2}{16\Lambda^2} a_c F^{\mu\alpha} F_{\mu\beta} \vec{W}^\beta \cdot \vec{W}_\alpha$$

$$L_6^n = -i\frac{e^2}{16\Lambda^2} a_n \epsilon_{ijk} W_{\mu\alpha}^{(i)} W_\nu^{(j)} W^{(k)\alpha} F^{\mu\nu}$$

$$\begin{aligned}\tilde{L}_6^0 &= -\frac{e^2}{16\Lambda^2} \tilde{a}_0 F^{\mu\nu} \tilde{F}_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha \\ \tilde{L}_6^n &= -i\frac{e^2}{16\Lambda^2} \tilde{a}_n \epsilon_{ijk} W_{\mu\alpha}^{(i)} W_\nu^{(j)} W^{(k)\alpha} \tilde{F}^{\mu\nu}\end{aligned}$$

where  $F, W$  are photon and  $W$  fields,  $L_6^0$  and  $L_6^c$  conserve  $C, P$  separately ( $\tilde{L}_6^0$  conserves only  $C$ ) and generate anomalous  $W^+W^-\gamma\gamma$  and  $ZZ\gamma\gamma$  couplings,  $L_6^n$  violates  $CP$  ( $\tilde{L}_6^n$  violates both  $C$  and  $P$ ) and generates an anomalous  $W^+W^-Z\gamma$  coupling, and  $\Lambda$  is an energy scale for new physics. For the  $ZZ\gamma\gamma$  coupling the  $CP$ -violating term represented by  $L_6^n$  does not contribute. These couplings are assumed to be real and to vanish at tree level in the Standard Model.

Within the same framework as above, a more recent description of the quartic couplings [3] treats the anomalous parts of the  $WW\gamma\gamma$  and  $ZZ\gamma\gamma$  couplings separately, leading to two sets parametrized as  $a_0^V/\Lambda^2$  and  $a_c^V/\Lambda^2$ , where  $V = W$  or  $Z$ .

With the discovery of a Higgs at the LHC in 2012, it is then useful to go to the next higher dimensional representation (dimension 8 operators) in which the gauge symmetry is broken by the conventional Higgs scalar doublet [3,4]. There are 14 operators which can contribute to the anomalous quartic coupling signal. Some of the operators have analogues in the dimension 6 scheme. The CMS collaboration, [5], have used this parametrization, in which the connections between the two schemes are also summarized:

$$\begin{aligned}\mathcal{L}_{AQGC} &= -\frac{e^2 a_0^W}{8 \Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+a} W_a^- \\ &\quad -\frac{e^2 a_c^W}{16 \Lambda^2} F_{\mu\nu} F^{\mu a} (W^{+\nu} W_a^- + W^{-\nu} W_a^+) \\ &\quad -e^2 g^2 \frac{\kappa_0^W}{\Lambda^2} F_{\mu\nu} Z^{\mu\nu} W^{+a} W_a^- \\ &\quad -\frac{e^2 g^2 \kappa_c^W}{2 \Lambda^2} F_{\mu\nu} Z^{\mu a} (W^{+\nu} W_a^- + W^{-\nu} W_a^+) \\ &\quad + \frac{f_{T,0}}{\Lambda^4} Tr[\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu}] \times Tr[\widehat{W}_{\alpha\beta} \widehat{W}^{\alpha\beta}]\end{aligned}$$

The energy scale of possible new physics is  $\Lambda$ , and  $g = e/\sin(\theta_W)$ ,  $e$  being the unit electric charge and  $\theta_W$  the Weinberg angle. The field tensors are described in [3,4].

The two dimension 6 operators  $a_0^W/\Lambda^2$  and  $a_c^W/\Lambda^2$  are associated with the  $WW\gamma\gamma$  vertex. Among dimension 8 operators,  $\kappa_0^W/\Lambda^2$  and  $\kappa_c^W/\Lambda^2$  are associated with the  $WWZ\gamma$  vertex, whereas the parameter  $f_{T,0}/\Lambda^4$  contributes to both vertices. There is a relationship between these two dimension 6 parameters and the dimension 8 parameters  $f_{M,i}/\Lambda^4$  as follows [3]:

$$\frac{a_0^W}{\Lambda^2} = -\frac{4M_W^2}{g^2} \frac{f_{M,0}}{\Lambda^4} - \frac{8M_W^2}{g'^2} \frac{f_{M,2}}{\Lambda^4}$$

$$\frac{a_c^W}{\Lambda^2} = -\frac{4M_W^2}{g^2} \frac{f_{M,1}}{\Lambda^4} - \frac{8M_W^2}{g'^2} \frac{f_{M,3}}{\Lambda^4}$$

where  $g' = e/\cos(\theta_W)$  and  $M_W$  is the invariant mass of the  $W$  boson. This relation provides a translation between limits on dimension 6 operators  $a_{0,c}^W$  and  $f_{M,j}/\Lambda^4$ . It is further required [4] that  $f_{M,0} = 2f_{M,2}$  and  $f_{M,1} = 2f_{M,3}$  which suppresses contributions to the  $WWZ\gamma$  vertex. The complete set of Lagrangian contributions as presented in [4] corresponds to 19 anomalous couplings in total –  $f_{S,i}$ ,  $i = 1, 2$ ,  $f_{M,i}$ ,  $i = 0, \dots, 8$  and  $f_{T,i}$ ,  $i = 0, \dots, 9$  – each scaled by  $1/\Lambda^4$ .

The ATLAS collaboration [6], on the other hand, follows a K-matrix driven approach of Ref. 7 in which the anomalous couplings can be expressed in terms of two parameters  $\alpha_4$  and  $\alpha_5$ , which account for all BSM effects.

It is the early stages in the determination of quartic couplings by the LHC experiments. It is hoped that the two collaborations, ATLAS and CMS, will agree to use at least one common set of parameters to express these limits to enable the

reader to make a comparison and allow for a possible LHC combination.

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$a_0/\Lambda^2, a_c/\Lambda^2, a_n/\Lambda^2, \kappa_0^W/\Lambda^2, \kappa_c^W/\Lambda^2, f_{T,0}/\Lambda^4, f_{M,i}/\Lambda^4, \alpha_4, \alpha_5,$   
 $F_{S,i}/\Lambda^4, F_{M,i}/\Lambda^4, F_{T,i}/\Lambda^4$

Anomalous  $W$  quartic couplings are measured by the experiments at LEP, the Tevatron, and the LHC. Some of the recent results from the Tevatron and LHC experiments individually surpass the combined LEP-2 results in precision (see below). As discussed in the review on the "Anomalous  $W/Z$  quartic couplings (QGCS)," the measurements are typically done using different operator expansions which then do not allow the results to be compared and averaged. At least one common framework should be agreed upon for the use in the future publications by the experiments.

Some publications from LHC experiments derive limits for various assumed values of the form-factor cutoff  $\Lambda_{FF}$ . The values quoted below are for  $\Lambda_{FF} \rightarrow \infty$ .

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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• • • We do not use the following data for averages, fits, limits, etc. • • •

1	SIRUNYAN	21	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
2	TUMASYAN	21A	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
3	TUMASYAN	21B	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
4	SIRUNAYN	20	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
5	SIRUNYAN	20AL	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
6	SIRUNYAN	20BD	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
7	SIRUNYAN	19BM	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
8	SIRUNYAN	19BP	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
9	SIRUNYAN	19CQ	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
10	SIRUNYAN	18CC	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
11	AABOUD	17AA	ATLS	$E_{\text{cm}}^{pp} = 8$ TeV
12	AABOUD	17AG	ATLS	$E_{\text{cm}}^{pp} = 8$ TeV
13	AABOUD	17D	ATLS	$E_{\text{cm}}^{pp} = 8$ TeV
14	AABOUD	17J	ATLS	$E_{\text{cm}}^{pp} = 8$ TeV
15	AABOUD	17M	ATLS	$E_{\text{cm}}^{pp} = 8$ TeV
16	KHACHATRY...	17AA	CMS	$E_{\text{cm}}^{pp} = 8$ TeV
17	KHACHATRY...	17M	CMS	$E_{\text{cm}}^{pp} = 8$ TeV
18	SIRUNYAN	17AD	CMS	$E_{\text{cm}}^{pp} = 13$ TeV
19	SIRUNYAN	17AR	CMS	$E_{\text{cm}}^{pp} = 8$ TeV
20	AABOUD	16E	ATLS	$E_{\text{cm}}^{pp} = 8$ TeV
21	AAD	16Q	ATLS	$E_{\text{cm}}^{pp} = 8$ TeV
22	KHACHATRY...	16AX	CMS	$E_{\text{cm}}^{pp} = 8$ TeV
23	AAD	15N	ATLS	$E_{\text{cm}}^{pp} = 8$ TeV
24	KHACHATRY...	15D	CMS	$E_{\text{cm}}^{pp} = 8$ TeV
25	AAD	14AM	ATLS	
26	CHATRCHYAN	14Q	CMS	
27	ABAZOV	13D	D0	
28	CHATRCHYAN	13AA	CMS	
29	ABBIENDI	04B	OPAL	
30	ABBIENDI	04L	OPAL	
31	HEISTER	04A	ALEP	
32	ABDALLAH	03I	DLPH	
33	ACHARD	02F	L3	

<sup>1</sup>SIRUNYAN 21 study electroweak  $Z$ -pair production in association with two jets, with the  $Z$  bosons decaying to oppositely-charged electron or muon pairs. Leptons with high transverse momentum are selected, with the di-lepton invariant mass of the two  $Z$  boson candidates between 60 GeV and 120 GeV, and the four-lepton invariant mass larger than 180 GeV. A total of 365 events are selected in the data, while the number of expected events is  $370 \pm 48$ . Analyzing the four-lepton invariant mass distribution, the following 95% C.L. limits are derived:  $-0.24 < f_{T,0}/\Lambda^4 < 0.22$ ,  $-0.31 < f_{T,1}/\Lambda^4 < 0.31$ ,  $-0.63 < f_{T,2}/\Lambda^4 < 0.59$ ,  $-0.43 < f_{T,8}/\Lambda^4 < 0.43$ ,  $-0.92 < f_{T,9}/\Lambda^4 < 0.92$ , in units of  $\text{TeV}^{-4}$ .

<sup>2</sup>TUMASYAN 21A study electroweak  $Z\gamma$  production in association with two jets, where the  $Z$  boson decays to electron or muon pairs and the pair of two jets has high invariant

mass, superseding SIRUNYAN 20AL. The number of observed (expected) electron events in the barrel and endcap regions are 375 ( $349 \pm 9$ ) and 174 ( $166 \pm 6$ ) events, respectively, while for muon events the respective numbers are 584 ( $612 \pm 13$ ) and 320 ( $303 \pm 8$ ). Analysing the  $Z\gamma$  invariant mass distribution, the following 95% C.L. limits are derived:  
 $-15.8 < f_{M,0}/\Lambda^4 < 16.0$ ,  $-35.0 < f_{M,1}/\Lambda^4 < 34.7$ ,  $-6.55 < f_{M,2}/\Lambda^4 < 6.49$ ,  
 $-13.0 < f_{M,3}/\Lambda^4 < 13.0$ ,  $-13.0 < f_{M,4}/\Lambda^4 < 12.7$ ,  $-22.2 < f_{M,5}/\Lambda^4 < 21.3$ ,  
 $-56.6 < f_{M,7}/\Lambda^4 < 55.9$ ,  $-0.64 < f_{T,0}/\Lambda^4 < 0.57$ ,  $-0.81 < f_{T,1}/\Lambda^4 < 0.90$ ,  
 $-1.68 < f_{T,2}/\Lambda^4 < 1.54$ ,  $-0.58 < f_{T,5}/\Lambda^4 < 0.64$ ,  $-1.30 < f_{T,6}/\Lambda^4 < 1.33$ ,  
 $-2.15 < f_{T,7}/\Lambda^4 < 2.43$ ,  $-0.47 < f_{T,8}/\Lambda^4 < 0.47$ ,  $-0.91 < f_{T,9}/\Lambda^4 < 0.91$ , in units of  $\text{TeV}^{-4}$ .

<sup>3</sup> TUMASYAN 21B measure  $W$  or  $Z$  boson production in association with two photons, using the leptonic decays modes of  $W$  and  $Z$  with electrons or muons. The number of selected  $W \rightarrow e(\mu)\nu$  events is 1987 (2384) and the number of selected  $Z \rightarrow ee(\mu\mu)$  events is 110 (272) respectively. Analyzing the transverse momentum of the di-photon system, the following 95 % C.L. limits are derived in units of  $\text{TeV}^{-4}$ : In the  $W$  production channel, the observed limits are:  $-39.9 < f_{M,2}/\Lambda^4 < 39.5$ ,  $-63.8 < f_{M,3}/\Lambda^4 < 65.0$ ,  $-1.30 < f_{T,0}/\Lambda^4 < 1.30$ ,  $-1.70 < f_{T,1}/\Lambda^4 < 1.66$ ,  $-3.64 < f_{T,2}/\Lambda^4 < 3.64$ ,  $-0.52 < f_{T,5}/\Lambda^4 < 0.60$ ,  $-0.60 < f_{T,6}/\Lambda^4 < 0.68$ ,  $-1.16 < f_{T,7}/\Lambda^4 < 1.16$ . In the  $Z$  production channel, the observed limits are:  $-5.70 < f_{T,0}/\Lambda^4 < 5.46$ ,  $-5.70 < f_{T,1}/\Lambda^4 < 5.46$ ,  $-11.4 < f_{T,2}/\Lambda^4 < 10.9$ ,  $-2.92 < f_{T,5}/\Lambda^4 < 2.92$ ,  $-3.80 < f_{T,6}/\Lambda^4 < 3.88$ ,  $-7.88 < f_{T,7}/\Lambda^4 < 7.72$ ,  $-1.06 < f_{T,8}/\Lambda^4 < 1.10$ ,  $-1.82 < f_{T,9}/\Lambda^4 < 1.82$ , in units of  $\text{TeV}^{-4}$ .

<sup>4</sup> SIRUNAYN 20 study  $WZ$  and same-sign  $WW$  production in association with two jets, using the leptonic decays modes of the  $W$  and  $Z$  bosons with electrons or muons. Overall, 524  $WW$  events and 229  $WZ$  events are selected, with a Standard Model expectation of  $535 \pm 52$  and  $216 \pm 21$  events, respectively. Analyzing the transverse mass spectrum of the di-boson system and the di-jet invariant mass, the following 95% C.L. limits are derived, not using any unitarization procedure:  $-0.25 < f_{T,0}/\Lambda^4 < 0.28$ ,  $-0.12 < f_{T,1}/\Lambda^4 < 0.14$ ,  $-0.35 < f_{T,2}/\Lambda^4 < 0.48$ ,  $-2.7 < f_{M,0}/\Lambda^4 < 2.9$ ,  $-4.1 < f_{M,1}/\Lambda^4 < 4.2$ ,  $-5.4 < f_{M,6}/\Lambda^4 < 5.8$ ,  $-5.7 < f_{M,7}/\Lambda^4 < 6.0$ ,  $-5.7 < f_{S,0}/\Lambda^4 < 6.1$ ,  $-16 < f_{S,1}/\Lambda^4 < 17$ , in units of  $\text{TeV}^{-4}$ . The article also reports limits on these couplings by cutting the EFT expansion at the unitarity limit.

<sup>5</sup> SIRUNYAN 20AL study electroweak production of a  $Z$  boson and a photon in association with two jets in the electron and muon decay modes of the  $Z$ . A signal with a significance of 3.9 standard deviations is observed, compared to a Standard Model expectation of 5.2 standard deviations. Combining with KHACHATRYAN 17AA data at 8 TeV the final observed and expected signal significance is 4.7 and 5.5 standard deviations. Analyzing the  $Z$ -photon invariant mass distribution, the following 95% C.L. limits are derived:  
 $-19.5 < f_{M,0}/\Lambda^4 < 20.3$ ,  $-40.5 < f_{M,1}/\Lambda^4 < 39.5$ ,  $-8.22 < f_{M,2}/\Lambda^4 < 8.10$ ,  
 $-17.7 < f_{M,3}/\Lambda^4 < 17.9$ ,  $-15.3 < f_{M,4}/\Lambda^4 < 15.8$ ,  $-25.1 < f_{M,5}/\Lambda^4 < 24.5$ ,  
 $-38.9 < f_{M,6}/\Lambda^4 < 40.6$ ,  $-60.3 < f_{M,7}/\Lambda^4 < 62.5$ ,  $-0.74 < f_{T,0}/\Lambda^4 < 0.69$ ,  
 $-0.98 < f_{T,1}/\Lambda^4 < 0.96$ ,  $-1.97 < f_{T,2}/\Lambda^4 < 1.86$ ,  $-0.70 < f_{T,5}/\Lambda^4 < 0.75$ ,  
 $-1.64 < f_{T,6}/\Lambda^4 < 1.68$ ,  $-2.59 < f_{T,7}/\Lambda^4 < 2.82$ ,  $-0.47 < f_{T,8}/\Lambda^4 < 0.47$ ,  
 $-1.27 < f_{T,9}/\Lambda^4 < 1.27$ , in units of  $\text{TeV}^{-4}$ .

<sup>6</sup> SIRUNYAN 20BD study electroweak  $W\gamma$  production in association with two jets, where the  $W$  boson decays to electron or muon and the two jets have high invariant mass. The number of observed (expected) electron events with the photon in the barrel and

endcap regions are  $393 (397.1 \pm 18.5)$  and  $159 (145.2 \pm 10.0)$  respectively, while for muon events the respective numbers are  $565 (537.9 \pm 21.4)$  and  $201 (188.2 \pm 10.5)$ . Analyzing the  $W\gamma$  invariant mass distribution, the following 95% C.L. limits are derived:  $-8.1 < f_{M,0}/\Lambda^4 < 8.0$ ,  $-12 < f_{M,1}/\Lambda^4 < 12$ ,  $-2.8 < f_{M,2}/\Lambda^4 < 2.8$ ,  $-4.4 < f_{M,3}/\Lambda^4 < 4.4$ ,  $-5.0 < f_{M,4}/\Lambda^4 < 5.0$ ,  $-8.3 < f_{M,5}/\Lambda^4 < 8.3$ ,  $-16 < f_{M,6}/\Lambda^4 < 16$ ,  $-21 < f_{M,7}/\Lambda^4 < 20$ ,  $-0.6 < f_{T,0}/\Lambda^4 < 0.6$ ,  $-0.4 < f_{T,1}/\Lambda^4 < 0.4$ ,  $-1.0 < f_{T,2}/\Lambda^4 < 1.2$ ,  $-0.5 < f_{T,5}/\Lambda^4 < 0.5$ ,  $-0.4 < f_{T,6}/\Lambda^4 < 0.4$ ,  $-0.9 < f_{T,7}/\Lambda^4 < 0.9$ , in units of  $\text{TeV}^{-4}$ .

<sup>7</sup> SIRUNYAN 19BM search for the final state  $W^+ W^- W^\pm$  using  $W$  decays to electrons or muons. Two event samples are considered, events with three leptons, or events with two oppositely charged leptons accompanied by two jets. In a kinematic region selected to enhance the effect of anomalous couplings, no events are selected in the data, and 95% C.L. upper limits are obtained as follows:  $-1.2 < f_{T,0}/\Lambda^4 < 1.2$ ,  $-3.3 < f_{T,1}/\Lambda^4 < 3.3$ ,  $-2.7 < f_{T,2}/\Lambda^4 < 2.6$ , in units of  $\text{TeV}^{-4}$  and without application of a form factor.

<sup>8</sup> SIRUNYAN 19BP study  $WZ$  plus 2 jets production, using  $W$  and  $Z$  decay channels with electrons or muons. In the data, 75 events are selected, with a fitted SM signal of  $15.1 \pm 1.6$  events and a fitted background of  $62.4 \pm 2.8$  events. The transverse mass distribution of the  $WZ$  system is analyzed to set the following limits at 95% C.L., in units of  $\text{TeV}^{-4}$ :  $-9.15 < f_{M,0}/\Lambda^4 < 9.15$ ,  $-9.15 < f_{M,1}/\Lambda^4 < 9.45$ ,  $-26.5 < f_{S,0}/\Lambda^4 < 27.5$ ,  $-41.2 < f_{S,1}/\Lambda^4 < 42.8$ ,  $-0.75 < f_{T,0}/\Lambda^4 < 0.81$ ,  $-0.49 < f_{T,1}/\Lambda^4 < 0.55$ ,  $-1.49 < f_{T,2}/\Lambda^4 < 1.85$ .

<sup>9</sup> SIRUNYAN 19CQ search for anomalous electroweak production of vector boson pairs in association with two jets. Events are selected by requiring two jets with a large invariant mass and rapidity separation, one or two leptons (electrons or muons), and a  $W$  or  $Z$  boson decaying hadronically. In the  $WV$  ( $ZV$ ) channel, 347 (47) events are selected in the data, with a total expected background of  $352 \pm 19$  ( $50.3 \pm 5.8$ ) events. Analysing the mass distribution of the  $WV$  or  $ZV$  system, the following 95% C.L. limits are obtained:  $-2.7 < f_{S,0}/\Lambda^4 < 2.7$ ,  $-3.4 < f_{S,1}/\Lambda^4 < 3.4$ ,  $-0.69 < f_{M,0}/\Lambda^4 < 0.70$ ,  $-2.0 < f_{M,1}/\Lambda^4 < 2.1$ ,  $-1.3 < f_{M,6}/\Lambda^4 < 1.3$ ,  $-3.4 < f_{M,7}/\Lambda^4 < 3.4$ ,  $-0.12 < f_{T,0}/\Lambda^4 < 0.11$ ,  $-0.12 < f_{T,1}/\Lambda^4 < 0.13$ ,  $-0.28 < f_{T,2}/\Lambda^4 < 0.28$ , in units of  $\text{TeV}^{-4}$ .

<sup>10</sup> SIRUNYAN 18CC study  $pp$  collisions at  $\sqrt{s} = 13$  TeV leading to a pair of same-sign  $W$  pairs decaying leptonically ( $e$  or  $\mu$ ) associated with a pair of jets. Isolated leptons with  $p_T > 25$  (20) GeV for the leading (trailing) lepton, with  $|\eta| < 2.5$  (2.4) for  $e$  ( $\mu$ ) and jets with  $p_T > 30$  GeV,  $|\eta| < 5.0$ ,  $|\Delta\eta_{jj}| > 2.5$  and  $m_{jj} > 500$  GeV is required. Further cuts are applied to minimize  $Z \rightarrow ee$  events, non-prompt leptons and hadronically decaying taus. The number of selected events is 201, with an expected SM signal of  $66.9 \pm 2.4$  and background of  $138 \pm 13$  events. Analysing the dilepton invariant mass spectrum the following 95% C.L. limits are derived:  $-7.7 < f_{S,0}/\Lambda^4 < 7.7$ ,  $-21.6 < f_{S,1}/\Lambda^4 < 21.8$ ,  $-6.0 < f_{M,0}/\Lambda^4 < 5.9$ ,  $-8.7 < f_{M,1}/\Lambda^4 < 9.1$ ,  $-11.9 < f_{M,6}/\Lambda^4 < 11.8$ ,  $-13.3 < f_{M,7}/\Lambda^4 < 12.9$ ,  $-0.62 < f_{T,0}/\Lambda^4 < 0.65$ ,  $-0.28 < f_{T,1}/\Lambda^4 < 0.31$ ,  $-0.89 < f_{T,2}/\Lambda^4 < 1.02$ .

<sup>11</sup> AABOUD 17AA analyze  $W^\pm W^\pm$  production in association with two jets and  $W$  decay modes with electrons or muons. In the kinematic region of VBS the effect of anomalous QGCs is enhanced by requiring the transverse mass of the  $WW$  system to be larger than 400 GeV. In the data, 8 events are selected with a total background expected from SM processes of  $3.8 \pm 0.6$  events. Assuming the other QGC coupling to have the SM



- value of zero, the observed event yield is used to determine 95% CL limits on the QGCs:  $-0.14 < \alpha_4 < 0.15$  and  $-0.22 < \alpha_5 < 0.22$ . Supersedes AAD 14AM.
- 12 AABOUD 17AG determine the  $W W \gamma$  and  $W Z \gamma$  cross sections in 8 TeV  $pp$  interactions by studying the final states  $e\nu\mu\nu\gamma$  and  $e\nu jj\gamma$  or  $\mu\nu jj\gamma$ . Upper limits on the production cross sections are derived in a fiducial region optimized for BSM physics. These are used to derive the following 95% C.L. upper limits for quartic couplings assuming the form scale factor,  $\Lambda_{FF} = \infty$  (all in units of  $10^3 \text{ TeV}^{-4}$ ):  $-0.3 < f_{M,0}/\Lambda^4 < 0.3$ ,  $-0.5 < f_{M,1}/\Lambda^4 < 0.5$ ,  $-1.8 < f_{M,2}/\Lambda^4 < 1.8$ ,  $-1.1 < f_{M,4}/\Lambda^4 < 1.1$ ,  $-1.7 < f_{M,5}/\Lambda^4 < 1.7$ ,  $-0.6 < f_{M,6}/\Lambda^4 < 0.6$ ,  $-1.1 < f_{M,7}/\Lambda^4 < 1.1$ ,  $-0.1 < f_{T,0}/\Lambda^4 < 0.1$ ,  $-0.2 < f_{T,1}/\Lambda^4 < 0.2$ ,  $-0.4 < f_{T,4}/\Lambda^4 < 0.4$ ,  $-1.5 < f_{T,5}/\Lambda^4 < 1.6$ ,  $-1.9 < f_{T,6}/\Lambda^4 < 1.9$ ,  $-4.3 < f_{T,7}/\Lambda^4 < 4.3$ .
- 13 AABOUD 17D analyze electroweak diboson ( $W V$ ,  $V = W, Z$ ) production in association with a high-mass dijet system. In the data, 32 events are selected with an expected total background of  $32 \pm 12$  events. Analysing the transverse mass distribution of the  $W V$  system, the following limits are set at 95% C.L.:  $-0.024 < \alpha_4 < 0.030$  and  $-0.028 < \alpha_5 < 0.033$ .
- 14 AABOUD 17J analyze the  $Z \gamma$  production in association with a high-mass dijet system, with the  $Z$  boson decaying into a pair of electrons, muons, or neutrinos. In the charged lepton (neutrino) channel, events are selected with a dijet mass larger than 500 (600) GeV and a transverse photon energy larger than 250 (150) GeV, with 2 (4) events selected in the data and  $0.30 \pm 0.08$  ( $1.6 \pm 0.5$ ) expected background events. The observed event yield is used to determine 95% CL limits as follows:  $-4.1 \times 10^3 < f_{T,9}/\Lambda^4 < 4.2 \times 10^3$ ,  $-1.9 \times 10^3 < f_{T,8}/\Lambda^4 < 2.1 \times 10^3$ ,  $-1.9 \times 10^1 < f_{T,0}/\Lambda^4 < 1.6 \times 10^1$ ,  $-1.6 \times 10^2 < f_{M,0}/\Lambda^4 < 1.8 \times 10^2$ ,  $-3.5 \times 10^2 < f_{M,1}/\Lambda^4 < 3.4 \times 10^2$ ,  $-8.9 \times 10^2 < f_{M,2}/\Lambda^4 < 8.9 \times 10^2$ ,  $-1.7 \times 10^3 < f_{M,3}/\Lambda^4 < 1.7 \times 10^3$ , in units of  $\text{TeV}^{-4}$  and without application of a form factor.
- 15 AABOUD 17M analyze tri-boson  $W^\pm W^\pm W^\mp$  production in decay channels with three charged leptons or two like-sign charged leptons with two jets, where the lepton can be an electron or muon. In the data, 24 tri-lepton events and 21 di-lepton plus jets events are selected, compared to a total event yield expected in the SM of  $30.8 \pm 3.0$  and  $21.9 \pm 2.0$ , respectively. Analysing the tri-lepton transverse mass or the transverse momentum sum of the two leptons, two jets and the missing transverse energy, the following limits at 95% CL are derived for the form factor cut-off scale  $\Lambda_{FF} \rightarrow \infty$ :  $-0.13 < f_{S,0}/\Lambda^4 < 0.18$ ,  $-0.21 < f_{S,1}/\Lambda^4 < 0.27$ , in units of  $10^4 \text{ TeV}^{-4}$ , which are converted into the following limits:  $-0.49 < \alpha_4 < 0.75$  and  $-0.48 < \alpha_5 < 0.62$ .
- 16 KHACHATRYAN 17AA analyse electroweak production of  $Z \gamma$  in association with two hadronic jets, with the  $Z$  boson decaying to electron or muon pairs. Events with photon transverse momentum larger than 60 GeV and di-jet invariant mass larger than 400 GeV are selected. The  $Z \gamma$  invariant mass spectrum is analysed to set 95% C.L. limits as follows:  $-71 < f_{M,0}/\Lambda^4 < 75$ ,  $-190 < f_{M,1}/\Lambda^4 < 182$ ,  $-32 < f_{M,2}/\Lambda^4 < 31$ ,  $-58 < f_{M,3}/\Lambda^4 < 59$ ,  $-3.8 < f_{T,0}/\Lambda^4 < 3.4$ ,  $-4.4 < f_{T,1}/\Lambda^4 < 4.4$ ,  $-9.9 < f_{T,2}/\Lambda^4 < 9.0$ ,  $-1.8 < f_{T,8}/\Lambda^4 < 1.8$ ,  $-4.0 < f_{T,9}/\Lambda^4 < 4.0$ , in units of  $\text{TeV}^{-4}$  and without application of a form factor.
- 17 KHACHATRYAN 17M analyse electroweak production of  $W \gamma$  in association with two hadronic jets, with the  $W$  boson decaying to electrons or muons. Events with photon transverse momentum larger than 200 GeV and di-jet invariant mass larger than 200 GeV are selected. The  $W$  transverse momentum spectrum is analysed to set 95% C.L. limits as follows:  $-77 < f_{M,0}/\Lambda^4 < 74$ ,  $-125 < f_{M,1}/\Lambda^4 < 129$ ,  $-26 < f_{M,2}/\Lambda^4 < 26$ ,  $-43 < f_{M,3}/\Lambda^4 < 44$ ,  $-40 < f_{M,4}/\Lambda^4 < 40$ ,  $-65 < f_{M,5}/\Lambda^4 < 65$ ,  $-129 <$

- $f_{M,6}/\Lambda^4 < 129$ ,  $-164 < f_{M,7}/\Lambda^4 < 162$ ,  $-5.4 < f_{T,0}/\Lambda^4 < 5.6$ ,  $-3.7 < f_{T,1}/\Lambda^4 < 4.0$ ,  $-11 < f_{T,2}/\Lambda^4 < 12$ ,  $-3.8 < f_{T,5}/\Lambda^4 < 3.8$ ,  $-2.8 < f_{T,6}/\Lambda^4 < 3.0$ ,  $-7.3 < f_{T,7}/\Lambda^4 < 7.7$ , in units of  $\text{TeV}^{-4}$  and without application of a form factor.
- <sup>18</sup> SIRUNYAN 17AD study  $pp$  collisions at  $\sqrt{s} = 13$  TeV to determine the cross section of  $Z Z j j$  with the  $Z$  decaying to  $e e$  or  $\mu \mu$ . The  $Z Z$  mass distribution is used to set upper limits on the anomalous quartic couplings. The 95% upper limits for the relevant quartic couplings in units of  $\text{TeV}^{-4}$  are:  $-0.46 < f_{T,0}/\Lambda^4 < 0.44$ ,  $-0.61 < f_{T,1}/\Lambda^4 < 0.61$ ,  $-1.2 < f_{T,2}/\Lambda^4 < 1.2$ ,  $-0.84 < f_{T,8}/\Lambda^4 < 0.84$ ,  $-1.8 < f_{T,9}/\Lambda^4 < 1.8$ .
- <sup>19</sup> SIRUNYAN 17AR study  $pp$  collisions at  $\sqrt{s} = 8$  TeV to determine the cross section of  $pp \rightarrow W \gamma \gamma$  and  $pp \rightarrow Z \gamma \gamma$  where  $W \rightarrow \ell \nu$  and  $Z \rightarrow \ell^+ \ell^-$ ,  $\ell$  being an electron or a muon. The number of  $W$  events in the  $e$  and  $\mu$  channels is 63 and 108 respectively, and the number of  $Z$  events in the  $e$  and  $\mu$  channels is 117 and 141. To increase sensitivity, the transverse momentum of the leading photon is required to be larger than 70 GeV. The 95% C.L. upper limits in units of  $\text{TeV}^{-4}$  are  $-701 < f_{M,2}/\Lambda^4 < 683$ ,  $-1170 < f_{M,3}/\Lambda^4 < 1220$ ,  $-33.5 < f_{T,0}/\Lambda^4 < 34.0$ ,  $-44.3 < f_{T,1}/\Lambda^4 < 44.8$ ,  $-93.8 < f_{T,2}/\Lambda^4 < 93.2$ .
- <sup>20</sup> AABOUD 16E study  $W W$  production in two-photon mediated  $pp$  collisions at 8 TeV where the  $W$  boson decays into an electron or muon, probing the  $\gamma \gamma W W$  vertex for anomalous quartic gauge couplings. The lepton  $p_T$  is required to be larger than 30 GeV. Limits on anomalous couplings are determined from events with  $p_T$  larger than 120 GeV where the aQGC effect is enhanced and the SM background reduced; in the data corresponding to an integrated luminosity of  $20.2 \text{ fb}^{-1}$ , 1 event is selected with an expected SM background of  $0.37 \pm 0.13$  events. The 95% C.L. limits without a form-factor cutoff ( $\Lambda_{\text{cutoff}} \rightarrow \infty$ ) are as follows:  $-1.7 < a_0^W/\Lambda^2 < 1.7$  and  $-6.4 < a_C^W/\Lambda^2 < 6.3$  in units of  $10^{-6} \text{ GeV}^{-2}$ . In terms of another set of variables:  $-6.6 < f_{M,0}/\Lambda^4 < 6.6$  and  $-24 < f_{M,1}/\Lambda^4 < 25$  in units of  $10^{-11} \text{ GeV}^{-4}$ .
- <sup>21</sup> AAD 16Q study  $Z \gamma \gamma$  production in  $pp$  collisions. In events with no additional jets, 29 (22)  $Z$  decays to electron (muon) pairs are selected, with an expected background of  $3.3 \pm 1.1$  ( $6.5 \pm 2.0$ ) events, as well as 19  $Z$  decays to neutrino pairs with an expected background of  $8.3 \pm 4.4$  events. Analysing the photon transverse momentum distribution for  $m_{\gamma \gamma}$  above 200 GeV (300 GeV) for lepton (neutrino) events, yields the 95% C.L. limits:  $-1.6 \times 10^4 < f_{M,2}/\Lambda^4 < 1.6 \times 10^4$ ,  $-2.9 \times 10^4 < f_{M,3}/\Lambda^4 < 2.7 \times 10^4$ ,  $-0.86 \times 10^2 < f_{T,0}/\Lambda^4 < 1.03 \times 10^2$ ,  $-0.69 \times 10^3 < f_{T,5}/\Lambda^4 < 0.68 \times 10^3$ ,  $-0.74 \times 10^4 < f_{T,9}/\Lambda^4 < 0.74 \times 10^4$  in units of  $\text{TeV}^{-4}$  and without application of a form factor  $\Lambda_{\text{FF}}$ .
- <sup>22</sup> KHACHATRYAN 16AX searches for anomalous  $W W \gamma \gamma$  quartic gauge couplings in the two-photon-mediated process  $pp \rightarrow pp W W$ , assuming the  $W W \gamma$  triple gauge boson couplings to be at their Standard Model values. 13 events containing an  $e^\pm \mu^\mp$  pair with  $p_T(e, \mu) > 30$  GeV are selected in a total luminosity of  $19.7 \text{ fb}^{-1}$ , with an expected  $\gamma \gamma \rightarrow W W$  signal of  $5.3 \pm 0.1$  events and an expected background of  $3.9 \pm 0.5$  events. When combining with the data collected at 7 TeV (CHATRCHYAN 13AA), and not assuming a form factor, the following 1-parameter limits at 95% C.L. are obtained from the  $p_T(e, \mu)$  spectrum:  $|a_0^W/\Lambda^2| < 1.1 \times 10^{-6} \text{ GeV}^{-2}$  ( $a_C^W = 0$ ), and  $|a_C^W/\Lambda^2| < 4.1 \times 10^{-6} \text{ GeV}^{-2}$  ( $a_0^W = 0$ ). In terms of another set of variables:  $|f_{M,0}/\Lambda^4| < 4.2 \times 10^{-12} \text{ GeV}^{-4}$ ,  $|f_{M,1}/\Lambda^4| < 16 \times 10^{-12} \text{ GeV}^{-4}$ ,  $|f_{M,2}/\Lambda^4| < 2.1 \times 10^{-12} \text{ GeV}^{-4}$ ,  $|f_{M,3}/\Lambda^4| < 7.8 \times 10^{-12} \text{ GeV}^{-4}$ .
- <sup>23</sup> AAD 15N study  $W \gamma \gamma$  events in 8 TeV  $pp$  interactions, where the  $W$  decays into an electron or a muon. The events are characterized by an isolated lepton, a missing

transverse energy due to the decay neutrino, and two isolated photons, with the  $p_T$  of the lepton and the photons being  $> 20$  GeV. The number of candidate events observed in the electron channel for  $N(\text{jet}) \geq 0$  and  $N(\text{jet}) = 0$  is 47 and 15, the corresponding numbers for the muon channel being 110 and 53. The backgrounds expected are  $30.2 \pm 7.4$ ,  $8.7 \pm 3.0$ ,  $52.1 \pm 12.2$ , and  $24.4 \pm 8.3$  respectively. The 95% C.L. limits on the values of the parameters  $f_{T,0}/\Lambda^4$ ,  $f_{M,2}/\Lambda^4$  and  $f_{M,3}/\Lambda^4$  are  $-0.9-0.9 \times 10^2$ ,  $-0.8-0.8 \times 10^4$ , and  $-1.5-1.4 \times 10^4$  respectively, without application of a form factor  $\Lambda_{\text{FF}}$ .

- 24 KHACHATRYAN 15D study vector-boson-scattering tagged by two jets, requiring two same-sign charged leptons arising from  $W^\pm W^\pm$  production and decay. The two jets must have a transverse momentum larger than 30 GeV, while the leptons, electrons or muons, must have a transverse momentum  $> 20$  GeV. The dijet mass is required to be  $> 500$  GeV, the dilepton mass  $> 50$  GeV, with additional requirement of differing from the  $Z$  mass by  $> 15$  GeV. In the two categories  $W^+ W^+$  and  $W^- W^-$ , 10 and 2 data events are observed in a data sample corresponding to an integrated luminosity of  $19.4 \text{ fb}^{-1}$ , with an expected background of  $3.1 \pm 0.6$  and  $2.6 \pm 0.5$  events. Analysing the distribution of the dilepton invariant mass, the following limits at 95% C.L. are obtained, in units of  $\text{TeV}^{-4}$ :  $-38 < F_{S,0}/\Lambda^4 < 40$ ,  $-118 < F_{S,1}/\Lambda^4 < 120$ ,  $-33 < F_{M,0}/\Lambda^4 < 32$ ,  $-44 < F_{M,1}/\Lambda^4 < 47$ ,  $-65 < F_{M,6}/\Lambda^4 < 63$ ,  $-70 < F_{M,7}/\Lambda^4 < 66$ ,  $-4.2 < F_{T,0}/\Lambda^4 < 4.6$ ,  $-1.9 < F_{T,1}/\Lambda^4 < 2.2$ ,  $-5.2 < F_{T,2}/\Lambda^4 < 6.4$ .
- 25 AAD 14AM analyze electroweak production of  $W W$  jet jet same-charge diboson plus two jets production, with the  $W$  bosons decaying to electron or muon, to study the quartic  $W W W W$  coupling. In a kinematic region enhancing the electroweak production over the strong production, 34 events are observed in the data while  $29.8 \pm 2.4$  events are expected with a background of  $15.9 \pm 1.9$  events. Assuming the other QGC coupling to have the SM value of zero, the observed event yield is used to determine 95% CL limits on the quartic gauge couplings:  $-0.14 < \alpha_4 < 0.16$  and  $-0.23 < \alpha_5 < 0.24$ .
- 26 CHATRCHYAN 14Q study  $W V \gamma$  production in 8 TeV  $pp$  collisions, in the single lepton final state, with  $W \rightarrow \ell \nu$ ,  $Z \rightarrow \text{dijet}$  or  $W \rightarrow \ell \nu$ ,  $W \rightarrow \text{dijet}$ , the dijet mass resolution precluding differentiation between the  $W$  and  $Z$ .  $p_T$  and pseudo-rapidity cuts are put on the lepton, the photon and the two jets to minimize backgrounds. The dijet mass is required to be between 70–100 GeV and  $|\Delta\eta_{jj}| < 1.4$ . The selected number of muon (electron) events are 183 (139), with SM expectation being  $194.2 \pm 11.5$  ( $147.9 \pm 10.7$ ) including signal and background. The photon  $E_T$  distribution is used to set limits on the anomalous quartic couplings. The following 95% CL limits are deduced (all in units of  $\text{TeV}^{-2}$  or  $\text{TeV}^{-4}$ ):  $-21 < a_0^W/\Lambda^2 < 20$ ,  $-34 < a_c^W/\Lambda^2 < 32$ ,  $-12 < \kappa_0^W/\Lambda^2 < 10$  and  $-18 < \kappa_c^W/\Lambda^2 < 17$ ; and  $-25 < f_{T,0}/\Lambda^4 < 24 \text{ TeV}^{-4}$ .
- 27 ABAZOV 13D searches for anomalous  $W W \gamma \gamma$  quartic gauge couplings in the two-photon-mediated process  $pp \rightarrow pp W W$ , assuming the  $W W \gamma$  triple gauge boson couplings to be at their Standard Model values. 946 events containing an  $e^+ e^-$  pair with missing energy are selected in a total luminosity of  $9.7 \text{ fb}^{-1}$ , with an expectation of  $983 \pm 108$  events from Standard-Model processes. The following 1-parameter limits at 95% CL are obtained:  $|a_0^W/\Lambda^2| < 4.3 \times 10^{-4} \text{ GeV}^{-2}$  ( $a_c^W = 0$ ),  $|a_c^W/\Lambda^2| < 1.5 \times 10^{-3} \text{ GeV}^{-2}$  ( $a_0^W = 0$ ).
- 28 CHATRCHYAN 13AA searches for anomalous  $W W \gamma \gamma$  quartic gauge couplings in the two-photon-mediated process  $pp \rightarrow pp W W$ , assuming the  $W W \gamma$  triple gauge boson couplings to be at their Standard Model values. 2 events containing an  $e^\pm \mu^\mp$  pair with  $p_T(e, \mu) > 30$  GeV are selected in a total luminosity of  $5.05 \text{ fb}^{-1}$ , with an expected  $pp W W$  signal of  $2.2 \pm 0.4$  events and an expected background of  $0.84 \pm 0.15$  events. The following 1-parameter limits at 95% CL are obtained from the  $p_T(e, \mu)$  spectrum:  $|a_0^W/\Lambda^2| < 4.0 \times 10^{-6} \text{ GeV}^{-2}$  ( $a_c^W = 0$ ),  $|a_c^W/\Lambda^2| < 1.5 \times 10^{-5} \text{ GeV}^{-2}$  ( $a_0^W = 0$ ).

- <sup>29</sup> ABBIENDI 04B select 187  $e^+e^- \rightarrow W^+W^-\gamma$  events in the C.M. energy range 180–209 GeV, where  $E_\gamma > 2.5$  GeV, the photon has a polar angle  $|\cos\theta_\gamma| < 0.975$  and is well isolated from the nearest jet and charged lepton, and the effective masses of both fermion-antifermion systems agree with the  $W$  mass within  $3\Gamma_W$ . The measured differential cross section as a function of the photon energy and photon polar angle is used to extract the 95% CL limits:  $-0.020 \text{ GeV}^{-2} < a_0/\Lambda^2 < 0.020 \text{ GeV}^{-2}$ ,  $-0.053 \text{ GeV}^{-2} < a_c/\Lambda^2 < 0.037 \text{ GeV}^{-2}$  and  $-0.16 \text{ GeV}^{-2} < a_n/\Lambda^2 < 0.15 \text{ GeV}^{-2}$ .
- <sup>30</sup> ABBIENDI 04L select 20  $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$  acoplanar events in the energy range 180–209 GeV and 176  $e^+e^- \rightarrow q\bar{q}\gamma\gamma$  events in the energy range 130–209 GeV. These samples are used to constrain possible anomalous  $W^+W^-\gamma\gamma$  and  $ZZ\gamma\gamma$  quartic couplings. Further combining with the  $W^+W^-\gamma$  sample of ABBIENDI 04B the following one-parameter 95% CL limits are obtained:  $-0.007 < a_0^Z/\Lambda^2 < 0.023 \text{ GeV}^{-2}$ ,  $-0.029 < a_c^Z/\Lambda^2 < 0.029 \text{ GeV}^{-2}$ ,  $-0.020 < a_0^W/\Lambda^2 < 0.020 \text{ GeV}^{-2}$ ,  $-0.052 < a_c^W/\Lambda^2 < 0.037 \text{ GeV}^{-2}$ .
- <sup>31</sup> In the CM energy range 183 to 209 GeV HEISTER 04A select 30  $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$  events with two acoplanar, high energy and high transverse momentum photons. The photon-photon acoplanarity is required to be  $> 5^\circ$ ,  $E_\gamma/\sqrt{s} > 0.025$  (the more energetic photon having energy  $> 0.2\sqrt{s}$ ),  $p_{T,\gamma}/E_{\text{beam}} > 0.05$  and  $|\cos\theta_\gamma| < 0.94$ . A likelihood fit to the photon energy and recoil missing mass yields the following one-parameter 95% CL limits:  $-0.012 < a_0^Z/\Lambda^2 < 0.019 \text{ GeV}^{-2}$ ,  $-0.041 < a_c^Z/\Lambda^2 < 0.044 \text{ GeV}^{-2}$ ,  $-0.060 < a_0^W/\Lambda^2 < 0.055 \text{ GeV}^{-2}$ ,  $-0.099 < a_c^W/\Lambda^2 < 0.093 \text{ GeV}^{-2}$ .
- <sup>32</sup> ABDALLAH 03I select 122  $e^+e^- \rightarrow W^+W^-\gamma$  events in the C.M. energy range 189–209 GeV, where  $E_\gamma > 5$  GeV, the photon has a polar angle  $|\cos\theta_\gamma| < 0.95$  and is well isolated from the nearest charged fermion. A fit to the photon energy spectra yields  $a_c/\Lambda^2 = 0.000_{-0.040}^{+0.019} \text{ GeV}^{-2}$ ,  $a_0/\Lambda^2 = -0.004_{-0.010}^{+0.018} \text{ GeV}^{-2}$ ,  $\tilde{a}_0/\Lambda^2 = -0.007_{-0.008}^{+0.019} \text{ GeV}^{-2}$ ,  $a_n/\Lambda^2 = -0.09_{-0.05}^{+0.16} \text{ GeV}^{-2}$ , and  $\tilde{a}_n/\Lambda^2 = +0.05_{-0.15}^{+0.07} \text{ GeV}^{-2}$ , keeping the other parameters fixed to their Standard Model values (0). The 95% CL limits are:  $-0.063 \text{ GeV}^{-2} < a_c/\Lambda^2 < +0.032 \text{ GeV}^{-2}$ ,  $-0.020 \text{ GeV}^{-2} < a_0/\Lambda^2 < +0.020 \text{ GeV}^{-2}$ ,  $-0.020 \text{ GeV}^{-2} < \tilde{a}_0/\Lambda^2 < +0.020 \text{ GeV}^{-2}$ ,  $-0.18 \text{ GeV}^{-2} < a_n/\Lambda^2 < +0.14 \text{ GeV}^{-2}$ ,  $-0.16 \text{ GeV}^{-2} < \tilde{a}_n/\Lambda^2 < +0.17 \text{ GeV}^{-2}$ .
- <sup>33</sup> ACHARD 02F select 86  $e^+e^- \rightarrow W^+W^-\gamma$  events at 192–207 GeV, where  $E_\gamma > 5$  GeV and the photon is well isolated. They also select 43 acoplanar  $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$  events in this energy range, where the photon energies are  $> 5$  GeV and  $> 1$  GeV and the photon polar angles are between  $14^\circ$  and  $166^\circ$ . All these 43 events are in the recoil mass region corresponding to the  $Z$  (75–110 GeV). Using the shape and normalization of the photon spectra in the  $W^+W^-\gamma$  events, and combining with the 42 event sample from 189 GeV data (ACCIARRI 00T), they obtain:  $a_0/\Lambda^2 = 0.000 \pm 0.010 \text{ GeV}^{-2}$ ,  $a_c/\Lambda^2 = -0.013 \pm 0.023 \text{ GeV}^{-2}$ , and  $a_n/\Lambda^2 = -0.002 \pm 0.076 \text{ GeV}^{-2}$ . Further combining the analyses of  $W^+W^-\gamma$  events with the low recoil mass region of  $\nu\bar{\nu}\gamma\gamma$  events (including samples collected at 183 + 189 GeV), they obtain the following one-parameter 95% CL limits:  $-0.015 \text{ GeV}^{-2} < a_0/\Lambda^2 < 0.015 \text{ GeV}^{-2}$ ,  $-0.048 \text{ GeV}^{-2} < a_c/\Lambda^2 < 0.026 \text{ GeV}^{-2}$ , and  $-0.14 \text{ GeV}^{-2} < a_n/\Lambda^2 < 0.13 \text{ GeV}^{-2}$ .

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ABBIENDI	00V	PL B490 71	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBOTT	00B	PR D61 072001	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	00D	PRL 84 5710	B. Abbott <i>et al.</i>	(D0 Collab.)
ABREU,P	00F	EPJ C18 203	P. Abreu <i>et al.</i>	(DELPHI Collab.)
Also		EPJ C25 493 (errat.)	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACCIARRI	00T	PL B490 187	M. Acciarri <i>et al.</i>	(L3 Collab.)
AFFOLDER	00M	PRL 85 3347	T. Affolder <i>et al.</i>	(CDF Collab.)
BREITWEG	00	PL B471 411	J. Breitweg <i>et al.</i>	(ZEUS Collab.)
BREITWEG	00D	EPJ C12 411	J. Breitweg <i>et al.</i>	(ZEUS Collab.)
EBOLI	00	MPL A15 1	O. Eboli, M. Gonzalez-Garcia, S. Novaes	
ABBIENDI	99N	PL B453 153	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBOTT	99H	PR D60 052003	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	99I	PR D60 072002	B. Abbott <i>et al.</i>	(D0 Collab.)
ABREU	99L	PL B459 382	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACCIARRI	99	PL B454 386	M. Acciarri <i>et al.</i>	(L3 Collab.)
ACCIARRI	99Q	PL B467 171	M. Acciarri <i>et al.</i>	(L3 Collab.)
BARATE	99I	PL B453 107	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARATE	99L	PL B462 389	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARATE	99M	PL B465 349	R. Barate <i>et al.</i>	(ALEPH Collab.)

ABBOTT	98N	PR D58 092003	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	98P	PR D58 012002	B. Abbott <i>et al.</i>	(D0 Collab.)
ABE	98H	PR D58 031101	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	98P	PR D58 091101	F. Abe <i>et al.</i>	(CDF Collab.)
ABREU	98C	PL B416 233	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABREU	98N	PL B439 209	P. Abreu <i>et al.</i>	(DELPHI Collab.)
BARATE	97	PL B401 347	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARATE	97S	PL B415 435	R. Barate <i>et al.</i>	(ALEPH Collab.)
ABACHI	95D	PRL 75 1456	S. Abachi <i>et al.</i>	(D0 Collab.)
ABE	95C	PRL 74 341	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	95G	PRL 74 1936	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	95P	PRL 75 11	F. Abe <i>et al.</i>	(CDF Collab.)
Also		PR D52 4784	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	95W	PR D52 2624	F. Abe <i>et al.</i>	(CDF Collab.)
Also		PRL 73 220	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	92E	PRL 68 3398	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	92I	PRL 69 28	F. Abe <i>et al.</i>	(CDF Collab.)
ALITTI	92	PL B276 365	J. Alitti <i>et al.</i>	(UA2 Collab.)
ALITTI	92B	PL B276 354	J. Alitti <i>et al.</i>	(UA2 Collab.)
ALITTI	92C	PL B277 194	J. Alitti <i>et al.</i>	(UA2 Collab.)
ALITTI	92D	PL B277 203	J. Alitti <i>et al.</i>	(UA2 Collab.)
ALITTI	92F	PL B280 137	J. Alitti <i>et al.</i>	(UA2 Collab.)
SAMUEL	92	PL B280 124	M.A. Samuel <i>et al.</i>	(OKSU, CARL)
ABE	91C	PR D44 29	F. Abe <i>et al.</i>	(CDF Collab.)
ALBAJAR	91	PL B253 503	C. Albajar <i>et al.</i>	(UA1 Collab.)
ALITTI	91C	ZPHY C52 209	J. Alitti <i>et al.</i>	(UA2 Collab.)
SAMUEL	91	PRL 67 9	M.A. Samuel <i>et al.</i>	(OKSU, CARL)
Also		PRL 67 2920 (erratum)	M.A. Samuel <i>et al.</i>	
ABE	90G	PRL 65 2243	F. Abe <i>et al.</i>	(CDF Collab.)
Also		PR D43 2070	F. Abe <i>et al.</i>	(CDF Collab.)
ALBAJAR	90	PL B241 283	C. Albajar <i>et al.</i>	(UA1 Collab.)
ALITTI	90B	PL B241 150	J. Alitti <i>et al.</i>	(UA2 Collab.)
ABE	89I	PRL 62 1005	F. Abe <i>et al.</i>	(CDF Collab.)
ALBAJAR	89	ZPHY C44 15	C. Albajar <i>et al.</i>	(UA1 Collab.)
BAUR	88	NP B308 127	U. Baur, D. Zeppenfeld	(FSU, WISC)
GRIFOLS	88	IJMP A3 225	J.A. Grifols, S. Peris, J. Sola	(BARC, DESY)
Also		PL B197 437	J.A. Grifols, S. Peris, J. Sola	(BARC, DESY)
ALBAJAR	87	PL B185 233	C. Albajar <i>et al.</i>	(UA1 Collab.)
ANSARI	87	PL B186 440	R. Ansari <i>et al.</i>	(UA2 Collab.)
GROTCH	87	PR D36 2153	H. Grotch, R.W. Robinett	(PSU)
HAGIWARA	87	NP B282 253	K. Hagiwara <i>et al.</i>	(KEK, UCLA, FSU)
VANDERBIJ	87	PR D35 1088	J.J. van der Bij	(FNAL)
GRAU	85	PL 154B 283	A. Grau, J.A. Grifols	(BARC)
SUZUKI	85	PL 153B 289	M. Suzuki	(LBL)
ARNISON	84D	PL 134B 469	G.T.J. Arnison <i>et al.</i>	(UA1 Collab.)
HERZOG	84	PL 148B 355	F. Herzog	(WISC)
Also		PL 155B 468 (erratum)	F. Herzog	(WISC)
ARNISON	83	PL 122B 103	G.T.J. Arnison <i>et al.</i>	(UA1 Collab.)
BANNER	83B	PL 122B 476	M. Banner <i>et al.</i>	(UA2 Collab.)