

Extra Dimensions

For explanation of terms used and discussion of significant model dependence of following limits, see the “Extra Dimensions” review. Footnotes describe originally quoted limit. δ indicates the number of extra dimensions.

Limits not encoded here are summarized in the “Extra Dimensions” review, where the latest unpublished results are also described.

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Limits on R from Deviations in Gravitational Force Law

This section includes limits on the size of extra dimensions from deviations in the Newtonian ($1/r^2$) gravitational force law at short distances. Deviations are parametrized by a gravitational potential of the form $V = -(G m m'/r) [1 + \alpha \exp(-r/R)]$. For δ toroidal extra dimensions of equal size, $\alpha = 8\delta/3$. Quoted bounds are for $\delta = 2$ unless otherwise noted.

<u>VALUE (μm)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>COMMENT</u>
< 30	95	1 KAPNER 07	Torsion pendulum
• • • We do not use the following data for averages, fits, limits, etc. • • •			
		2 BEZERRA 11	Torsion oscillator
		3 SUSHKOV 11	Torsion pendulum
		4 BEZERRA 10	Microcantilever
		5 MASUDA 09	Torsion pendulum
		6 GERACI 08	Microcantilever
		7 TRENKEL 08	Newton's constant
		8 DECCA 07A	Torsion oscillator
< 47	95	9 TU 07	Torsion pendulum
		10 SMULLIN 05	Microcantilever
<130	95	11 HOYLE 04	Torsion pendulum
		12 CHIAVERINI 03	Microcantilever
$\lesssim 200$	95	13 LONG 03	Microcantilever
<190	95	14 HOYLE 01	Torsion pendulum
		15 HOSKINS 85	Torsion pendulum

- ¹ KAPNER 07 search for new forces, probing a range of $\alpha \simeq 10^{-3}$ – 10^5 and length scales $R \simeq 10$ – $1000 \mu\text{m}$. For $\delta = 1$ the bound on R is $44 \mu\text{m}$. For $\delta = 2$, the bound is expressed in terms of M_* , here translated to a bound on the radius. See their Fig. 6 for details on the bound.
 - ² BEZERRA 11 obtain constraints on non-Newtonian forces with strengths $10^{11} \lesssim |\alpha| \lesssim 10^{18}$ and length scales $R = 30$ – 1260 nm . See their Fig. 2 for more details. These constraints do not place limits on the size of extra flat dimensions.
 - ³ SUSHKOV 11 obtain improved limits on non-Newtonian forces with strengths $10^7 \lesssim |\alpha| \lesssim 10^{11}$ and length scales $0.4 \mu\text{m} < R < 4 \mu\text{m}$ (95% CL). See their Fig. 2. These bounds do not place limits on the size of extra flat dimensions. However, a model dependent bound of $M_* > 70 \text{ TeV}$ is obtained assuming gauge bosons that couple to baryon number also propagate in $(4 + \delta)$ dimensions.
 - ⁴ BEZERRA 10 obtain improved constraints on non-Newtonian forces with strengths $10^{19} \lesssim |\alpha| \lesssim 10^{29}$ and length scales $R = 1.6$ – 14 nm (95% CL). See their Fig. 1. This bound does not place limits on the size of extra flat dimensions.
 - ⁵ MASUDA 09 obtain improved constraints on non-Newtonian forces with strengths $10^9 \lesssim |\alpha| \lesssim 10^{11}$ and length scales $R = 1.0$ – $2.9 \mu\text{m}$ (95% CL). See their Fig. 3. This bound does not place limits on the size of extra flat dimensions.
 - ⁶ GERACI 08 obtain improved constraints on non-Newtonian forces with strengths $|\alpha| > 14,000$ and length scales $R = 5$ – $15 \mu\text{m}$. See their Fig. 9. This bound does not place limits on the size of extra flat dimensions.
 - ⁷ TRENKEL 08 uses two independent measurements of Newton's constant G to constrain new forces with strength $|\alpha| \simeq 10^{-4}$ and length scales $R = 0.02$ – 1 m . See their Fig. 1. This bound does not place limits on the size of extra flat dimensions.
 - ⁸ DECCA 07A search for new forces and obtain bounds in the region with strengths $|\alpha| \simeq 10^{13}$ – 10^{18} and length scales $R = 20$ – 86 nm . See their Fig. 6. This bound does not place limits on the size of extra flat dimensions.
 - ⁹ TU 07 search for new forces probing a range of $|\alpha| \simeq 10^{-1}$ – 10^5 and length scales $R \simeq 20$ – $1000 \mu\text{m}$. For $\delta = 1$ the bound on R is $53 \mu\text{m}$. See their Fig. 3 for details on the bound.
 - ¹⁰ SMULLIN 05 search for new forces, and obtain bounds in the region with strengths $\alpha \simeq 10^3$ – 10^8 and length scales $R = 6$ – $20 \mu\text{m}$. See their Figs. 1 and 16 for details on the bound. This work does not place limits on the size of extra flat dimensions.
 - ¹¹ HOYLE 04 search for new forces, probing α down to 10^{-2} and distances down to $10 \mu\text{m}$. Quoted bound on R is for $\delta = 2$. For $\delta = 1$, bound goes to $160 \mu\text{m}$. See their Fig. 34 for details on the bound.
 - ¹² CHIAVERINI 03 search for new forces, probing α above 10^4 and λ down to $3 \mu\text{m}$, finding no signal. See their Fig. 4 for details on the bound. This bound does not place limits on the size of extra flat dimensions.
 - ¹³ LONG 03 search for new forces, probing α down to 3, and distances down to about $10 \mu\text{m}$. See their Fig. 4 for details on the bound.
 - ¹⁴ HOYLE 01 search for new forces, probing α down to 10^{-2} and distances down to $20 \mu\text{m}$. See their Fig. 4 for details on the bound. The quoted bound is for $\alpha \geq 3$.
 - ¹⁵ HOSKINS 85 search for new forces, probing distances down to 4 mm . See their Fig. 13 for details on the bound. This bound does not place limits on the size of extra flat dimensions.
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Limits on R from On-Shell Production of Gravitons: $\delta = 2$

This section includes limits on on-shell production of gravitons in collider and astrophysical processes. Bounds quoted are on R , the assumed common radius of the flat extra dimensions, for $\delta = 2$ extra dimensions. Studies often quote bounds in terms of derived parameter; experiments are actually sensitive to the masses of the KK gravitons: $m_{\vec{n}} = |\vec{n}|/R$. See the Review on “Extra Dimensions” for details. Bounds are given in μm for $\delta = 2$.

<u>VALUE (μm)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
< 23	95	¹ CHATRCHYAN 12AP	CMS	$pp \rightarrow jG$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
< 127	95	² AAD	13C ATLS	$pp \rightarrow \gamma G$
< 34.4	95	³ AAD	13D ATLS	$pp \rightarrow jj$
< 0.0087	95	⁴ AJELLO	12 FRMI	Neutron star γ sources
< 92	95	⁵ AAD	11S ATLS	$pp \rightarrow jG$
< 72	95	⁶ CHATRCHYAN 11U	CMS	$pp \rightarrow jG$
< 245	95	⁷ AALTONEN	08AC CDF	$p\bar{p} \rightarrow \gamma G, jG$
< 615	95	⁸ ABAZOV	08S D0	$p\bar{p} \rightarrow \gamma G$
< 0.916	95	⁹ DAS	08	Supernova cooling
< 350	95	¹⁰ ABULENCIA,A	06 CDF	$p\bar{p} \rightarrow jG$
< 270	95	¹¹ ABDALLAH	05B DLPH	$e^+e^- \rightarrow \gamma G$
< 210	95	¹² ACHARD	04E L3	$e^+e^- \rightarrow \gamma G$
< 480	95	¹³ ACOSTA	04C CDF	$p\bar{p} \rightarrow jG$
< 0.00038	95	¹⁴ CASSE	04	Neutron star γ sources
< 610	95	¹⁵ ABAZOV	03 D0	$p\bar{p} \rightarrow jG$
< 0.96	95	¹⁶ HANNESTAD	03	Supernova cooling
< 0.096	95	¹⁷ HANNESTAD	03	Diffuse γ background
< 0.051	95	¹⁸ HANNESTAD	03	Neutron star γ sources
< 0.00016	95	¹⁹ HANNESTAD	03	Neutron star heating
< 300	95	²⁰ HEISTER	03C ALEP	$e^+e^- \rightarrow \gamma G$
		²¹ FAIRBAIRN	01	Cosmology
< 0.66	95	²² HANHART	01	Supernova cooling
		²³ CASSISI	00	Red giants
<1300	95	²⁴ ACCIARRI	99S L3	$e^+e^- \rightarrow ZG$

¹ CHATRCHYAN 12AP search for $pp \rightarrow jG$, using 5.0 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ to place bounds on M_D for two to six extra dimensions, from which this bound on R is derived. See their Table 7 for bounds on all $\delta \leq 6$.

² AAD 13C search for $pp \rightarrow \gamma G$, using 4.6 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ to place bounds on M_D for two to six extra dimensions, from which this bound on R is derived.

³ AAD 13D search for the dijet decay of quantum black holes in 4.8 fb^{-1} of data produced in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to place bounds on M_D for two to seven extra dimensions, from which these bounds on R are derived. Limits on M_D for all $\delta \leq 7$ are given in their Table 3.

⁴ AJELLO 12 obtain a limit on R from the gamma-ray emission of point γ sources that arise from the photon decay of KK gravitons which are gravitationally bound around neutron stars. Limits for all $\delta \leq 7$ are given in their Table 7.

⁵ AAD 11S search for $pp \rightarrow jG$, using 33 pb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$, to place bounds on M_D for two to four extra dimensions, from which these bounds on R are derived. See their Table 3 for bounds on all $\delta \leq 4$.

⁶ CHATRCHYAN 11U search for $pp \rightarrow jG$, using 36 pb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$, to place bounds on M_D for two to six extra dimensions, from which these bounds on R are derived. See their Table 3 for bounds on all $\delta \leq 6$.

- 7 AALTONEN 08AC search for $p\bar{p} \rightarrow \gamma G$ and $p\bar{p} \rightarrow jG$ at $\sqrt{s} = 1.96$ TeV with 2.0 fb^{-1} and 1.1 fb^{-1} respectively, in order to place bounds on the fundamental scale and size of the extra dimensions. See their Table III for limits on all $\delta \leq 6$.
- 8 ABAZOV 08S search for $p\bar{p} \rightarrow \gamma G$, using 1 fb^{-1} of data at $\sqrt{s} = 1.96$ TeV to place bounds on M_D for two to eight extra dimensions, from which these bounds on R are derived. See their paper for intermediate values of δ .
- 9 DAS 08 obtain a limit on R from Kaluza-Klein graviton cooling of SN1987A due to plasmon-plasmon annihilation.
- 10 ABULENCIA,A 06 search for $p\bar{p} \rightarrow jG$ using 368 pb^{-1} of data at $\sqrt{s} = 1.96$ TeV. See their Table II for bounds for all $\delta \leq 6$.
- 11 ABDALLAH 05B search for $e^+e^- \rightarrow \gamma G$ at $\sqrt{s} = 180\text{--}209$ GeV to place bounds on the size of extra dimensions and the fundamental scale. Limits for all $\delta \leq 6$ are given in their Table 6. These limits supersede those in ABREU 00Z.
- 12 ACHARD 04E search for $e^+e^- \rightarrow \gamma G$ at $\sqrt{s} = 189\text{--}209$ GeV to place bounds on the size of extra dimensions and the fundamental scale. See their Table 8 for limits with $\delta \leq 8$. These limits supersede those in ACCIARRI 99R.
- 13 ACOSTA 04C search for $p\bar{p} \rightarrow jG$ at $\sqrt{s} = 1.8$ TeV to place bounds on the size of extra dimensions and the fundamental scale. See their paper for bounds on $\delta = 4, 6$.
- 14 CASSE 04 obtain a limit on R from the gamma-ray emission of point γ sources that arises from the photon decay of gravitons around newly born neutron stars, applying the technique of HANNESTAD 03 to neutron stars in the galactic bulge. Limits for all $\delta \leq 7$ are given in their Table I.
- 15 ABAZOV 03 search for $p\bar{p} \rightarrow jG$ at $\sqrt{s}=1.8$ TeV to place bounds on M_D for 2 to 7 extra dimensions, from which these bounds on R are derived. See their paper for bounds on intermediate values of δ . We quote results without the approximate NLO scaling introduced in the paper.
- 16 HANNESTAD 03 obtain a limit on R from graviton cooling of supernova SN1987a. Limits for all $\delta \leq 7$ are given in their Tables V and VI.
- 17 HANNESTAD 03 obtain a limit on R from gravitons emitted in supernovae and which subsequently decay, contaminating the diffuse cosmic γ background. Limits for all $\delta \leq 7$ are given in their Tables V and VI. These limits supersede those in HANNESTAD 02.
- 18 HANNESTAD 03 obtain a limit on R from gravitons emitted in two recent supernovae and which subsequently decay, creating point γ sources. Limits for all $\delta \leq 7$ are given in their Tables V and VI. These limits are corrected in the published erratum.
- 19 HANNESTAD 03 obtain a limit on R from the heating of old neutron stars by the surrounding cloud of trapped KK gravitons. Limits for all $\delta \leq 7$ are given in their Tables V and VI. These limits supersede those in HANNESTAD 02.
- 20 HEISTER 03C use the process $e^+e^- \rightarrow \gamma G$ at $\sqrt{s} = 189\text{--}209$ GeV to place bounds on the size of extra dimensions and the scale of gravity. See their Table 4 for limits with $\delta \leq 6$ for derived limits on M_D .
- 21 FAIRBAIRN 01 obtains bounds on R from over production of KK gravitons in the early universe. Bounds are quoted in paper in terms of fundamental scale of gravity. Bounds depend strongly on temperature of QCD phase transition and range from $R < 0.13 \mu\text{m}$ to $0.001 \mu\text{m}$ for $\delta=2$; bounds for $\delta=3,4$ can be derived from Table 1 in the paper.
- 22 HANHART 01 obtain bounds on R from limits on graviton cooling of supernova SN 1987a using numerical simulations of proto-neutron star neutrino emission.
- 23 CASSISI 00 obtain rough bounds on M_D (and thus R) from red giant cooling for $\delta=2,3$. See their paper for details.
- 24 ACCIARRI 99S search for $e^+e^- \rightarrow ZG$ at $\sqrt{s}=189$ GeV. Limits on the gravity scale are found in their Table 2, for $\delta \leq 4$.

Mass Limits on $M_{\mathcal{T}\mathcal{T}}$

This section includes limits on the cut-off mass scale, $M_{\mathcal{T}\mathcal{T}}$, of dimension-8 operators from KK graviton exchange in models of large extra dimensions. Ambiguities in the UV-divergent summation are absorbed into the parameter λ , which is taken to be $\lambda =$

± 1 in the following analyses. Bounds for $\lambda = -1$ are shown in parenthesis after the bound for $\lambda = +1$, if appropriate. Different papers use slightly different definitions of the mass scale. The definition used here is related to another popular convention by $M_{TT}^4 = (2/\pi) \Lambda_T^4$, as discussed in the above Review on "Extra Dimensions."

VALUE (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 3.2	95	¹ AAD	13E ATLS	$pp \rightarrow e^+ e^-, \mu^+ \mu^-, \gamma\gamma$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 2.66	(>2.27) 95	² AAD	12Y ATLS	$pp \rightarrow \gamma\gamma$
		³ BAAK	12 RVUE	Electroweak
> 2.86	95	⁴ CHATRCHYAN	12J CMS	$pp \rightarrow e^+ e^-, \mu^+ \mu^-$
> 2.84	(>2.41) 95	⁵ CHATRCHYAN	12R CMS	$pp \rightarrow \gamma\gamma$
> 0.90	(>0.92) 95	⁶ AARON	11C H1	$e^\pm p \rightarrow e^\pm X$
> 1.74	(>1.71) 95	⁷ CHATRCHYAN	11A CMS	$pp \rightarrow \gamma\gamma$
> 1.48	95	⁸ ABAZOV	09AE D0	$p\bar{p} \rightarrow$ dijet, ang. distrib.
> 1.45	95	⁹ ABAZOV	09D D0	$p\bar{p} \rightarrow e^+ e^-, \gamma\gamma$
> 1.1	(> 1.0) 95	¹⁰ SCHAELE	07A ALEP	$e^+ e^- \rightarrow e^+ e^-$
> 0.898	(> 0.998) 95	¹¹ ABDALLAH	06C DLPH	$e^+ e^- \rightarrow \ell^+ \ell^-$
> 0.853	(> 0.939) 95	¹² GERDES	06	$p\bar{p} \rightarrow e^+ e^-, \gamma\gamma$
> 0.96	(> 0.93) 95	¹³ ABAZOV	05V D0	$p\bar{p} \rightarrow \mu^+ \mu^-$
> 0.78	(> 0.79) 95	¹⁴ CHEKANOV	04B ZEUS	$e^\pm p \rightarrow e^\pm X$
> 0.805	(> 0.956) 95	¹⁵ ABBIENDI	03D OPAL	$e^+ e^- \rightarrow \gamma\gamma$
> 0.7	(> 0.7) 95	¹⁶ ACHARD	03D L3	$e^+ e^- \rightarrow ZZ$
> 0.82	(> 0.78) 95	¹⁷ ADLOFF	03 H1	$e^\pm p \rightarrow e^\pm X$
> 1.28	(> 1.25) 95	¹⁸ GIUDICE	03 RVUE	
>20.6	(> 15.7) 95	¹⁹ GIUDICE	03 RVUE	Dim-6 operators
> 0.80	(> 0.85) 95	²⁰ HEISTER	03C ALEP	$e^+ e^- \rightarrow \gamma\gamma$
> 0.84	(> 0.99) 95	²¹ ACHARD	02D L3	$e^+ e^- \rightarrow \gamma\gamma$
> 1.2	(> 1.1) 95	²² ABBOTT	01 D0	$p\bar{p} \rightarrow e^+ e^-, \gamma\gamma$
> 0.60	(> 0.63) 95	²³ ABBIENDI	00R OPAL	$e^+ e^- \rightarrow \mu^+ \mu^-$
> 0.63	(> 0.50) 95	²³ ABBIENDI	00R OPAL	$e^+ e^- \rightarrow \tau^+ \tau^-$
> 0.68	(> 0.61) 95	²³ ABBIENDI	00R OPAL	$e^+ e^- \rightarrow \mu^+ \mu^-, \tau^+ \tau^-$
		²⁴ ABREU	00A DLPH	$e^+ e^- \rightarrow \gamma\gamma$
> 0.680	(> 0.542) 95	²⁵ ABREU	00S DLPH	$e^+ e^- \rightarrow \mu^+ \mu^-, \tau^+ \tau^-$
> 15–28	99.7	²⁶ CHANG	00B RVUE	Electroweak
> 0.98	95	²⁷ CHEUNG	00 RVUE	$e^+ e^- \rightarrow \gamma\gamma$
> 0.29–0.38	95	²⁸ GRAESSER	00 RVUE	$(g-2)_\mu$
> 0.50–1.1	95	²⁹ HAN	00 RVUE	Electroweak
> 2.0	(> 2.0) 95	³⁰ MATHEWS	00 RVUE	$p\bar{p} \rightarrow jj$
> 1.0	(> 1.1) 95	³¹ MELE	00 RVUE	$e^+ e^- \rightarrow VV$
		³² ABBIENDI	99P OPAL	
		³³ ACCIARRI	99M L3	
		³⁴ ACCIARRI	99S L3	
> 1.412	(> 1.077) 95	³⁵ BOURILKOV	99	$e^+ e^- \rightarrow e^+ e^-$

¹ AAD 13E use 4.9 and 5.0 fb⁻¹ of data from pp collisions at $\sqrt{s} = 7$ TeV in the dielectron and dimuon channels, respectively, to place lower limits on M_{TT} (equivalent to their M_S). The dielectron and dimuon channels are combined with previous results in the diphoton channel to set the best limit. Bounds on individual channels and different priors can be found in their Table VIII.

- 2 AAD 12Y use 2.12 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to place lower limits on M_{TT} .
- 3 BAAK 12 use electroweak precision observables to place bounds on the ratio Λ_T/M_D as a function of M_D . See their Fig. 22 for constraints with a Higgs mass of 120 GeV.
- 4 CHATRCHYAN 12J use approximately 2 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ in the dielectron and dimuon channels to place lower limits on Λ_T , here converted to M_{TT} .
- 5 CHATRCHYAN 12R use 2.2 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to place lower limits on M_{TT} (equivalent to their M_S).
- 6 AARON 11C search for deviations in the differential cross section of $e^\pm p \rightarrow e^\pm X$ in 446 pb^{-1} of data taken at $\sqrt{s} = 301$ and 319 GeV to place a bound on M_{TT} .
- 7 CHATRCHYAN 11A use 36 pb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to place lower limits on Λ_T , here converted to M_{TT} .
- 8 ABAZOV 09AE use dijet angular distributions in 0.7 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to place lower bounds on Λ_T (equivalent to their M_S), here converted to M_{TT} .
- 9 ABAZOV 09D use 1.05 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to place lower bounds on Λ_T (equivalent to their M_S), here converted to M_{TT} .
- 10 SCHAEEL 07A use e^+e^- collisions at $\sqrt{s} = 189\text{--}209 \text{ GeV}$ to place lower limits on Λ_T , here converted to limits on M_{TT} .
- 11 ABDALLAH 06C use e^+e^- collisions at $\sqrt{s} \sim 130\text{--}207 \text{ GeV}$ to place lower limits on M_{TT} , which is equivalent to their definition of M_S . Bound shown includes all possible final state leptons, $\ell = e, \mu, \tau$. Bounds on individual leptonic final states can be found in their Table 31.
- 12 GERDES 06 use 100 to 110 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.8 \text{ TeV}$, as recorded by the CDF Collaboration during Run I of the Tevatron. Bound shown includes a K -factor of 1.3. Bounds on individual e^+e^- and $\gamma\gamma$ final states are found in their Table I.
- 13 ABAZOV 05V use 246 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to search for deviations in the differential cross section to $\mu^+\mu^-$ from graviton exchange.
- 14 CHEKANOV 04B search for deviations in the differential cross section of $e^\pm p \rightarrow e^\pm X$ with 130 pb^{-1} of combined data and Q^2 values up to $40,000 \text{ GeV}^2$ to place a bound on M_{TT} .
- 15 ABBIENDI 03D use e^+e^- collisions at $\sqrt{s}=181\text{--}209 \text{ GeV}$ to place bounds on the ultra-violet scale M_{TT} , which is equivalent to their definition of M_S .
- 16 ACHARD 03D look for deviations in the cross section for $e^+e^- \rightarrow ZZ$ from $\sqrt{s} = 200\text{--}209 \text{ GeV}$ to place a bound on M_{TT} .
- 17 ADLOFF 03 search for deviations in the differential cross section of $e^\pm p \rightarrow e^\pm X$ at $\sqrt{s}=301$ and 319 GeV to place bounds on M_{TT} .
- 18 GIUDICE 03 review existing experimental bounds on M_{TT} and derive a combined limit.
- 19 GIUDICE 03 place bounds on Λ_6 , the coefficient of the gravitationally-induced dimension-6 operator $(2\pi\lambda/\Lambda_6^2)(\sum \bar{f}\gamma_\mu\gamma^5 f)(\sum \bar{f}\gamma^\mu\gamma^5 f)$, using data from a variety of experiments. Results are quoted for $\lambda=\pm 1$ and are independent of δ .
- 20 HEISTER 03C use e^+e^- collisions at $\sqrt{s}= 189\text{--}209 \text{ GeV}$ to place bounds on the scale of dim-8 gravitational interactions. Their M_S^\pm is equivalent to our M_{TT} with $\lambda=\pm 1$.
- 21 ACHARD 02 search for s -channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at $E_{\text{cm}} = 192\text{--}209 \text{ GeV}$.
- 22 ABBOTT 01 search for variations in differential cross sections to e^+e^- and $\gamma\gamma$ final states at the Tevatron.
- 23 ABBIENDI 00R uses e^+e^- collisions at $\sqrt{s}= 189 \text{ GeV}$.
- 24 ABREU 00A search for s -channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at $E_{\text{cm}} = 189\text{--}202 \text{ GeV}$.

- 25 ABREU 00S uses e^+e^- collisions at $\sqrt{s}=183$ and 189 GeV. Bounds on μ and τ individual final states given in paper.
- 26 CHANG 00B derive 3σ limit on M_{TT} of (28,19,15) TeV for $\delta=(2,4,6)$ respectively assuming the presence of a torsional coupling in the gravitational action. Highly model dependent.
- 27 CHEUNG 00 obtains limits from anomalous diphoton production at OPAL due to graviton exchange. Original limit for $\delta=4$. However, unknown UV theory renders δ dependence unreliable. Original paper works in HLZ convention.
- 28 GRAESSER 00 obtains a bound from graviton contributions to $g-2$ of the muon through loops of 0.29 TeV for $\delta=2$ and 0.38 TeV for $\delta=4,6$. Limits scale as $\lambda^{1/2}$. However calculational scheme not well-defined without specification of high-scale theory. See the "Extra Dimensions Review."
- 29 HAN 00 calculates corrections to gauge boson self-energies from KK graviton loops and constrain them using S and T . Bounds on M_{TT} range from 0.5 TeV ($\delta=6$) to 1.1 TeV ($\delta=2$); see text. Limits have strong dependence, $\lambda^{\delta+2}$, on unknown λ coefficient.
- 30 MATHEWS 00 search for evidence of graviton exchange in CDF and DØ dijet production data. See their Table 2 for slightly stronger δ -dependent bounds. Limits expressed in terms of $\tilde{M}_S^4 = M_{TT}^4/8$.
- 31 MELE 00 obtains bound from KK graviton contributions to $e^+e^- \rightarrow VV$ ($V=\gamma, W, Z$) at LEP. Authors use Hewett conventions.
- 32 ABBIENDI 99P search for s -channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at $E_{cm}=189$ GeV. The limits $G_+ > 660$ GeV and $G_- > 634$ GeV are obtained from combined $E_{cm}=183$ and 189 GeV data, where G_{\pm} is a scale related to the fundamental gravity scale.
- 33 ACCIARRI 99M search for the reaction $e^+e^- \rightarrow \gamma G$ and s -channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma, W^+W^-, ZZ, e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}$ at $E_{cm}=183$ GeV. Limits on the gravity scale are listed in their Tables 1 and 2.
- 34 ACCIARRI 99S search for the reaction $e^+e^- \rightarrow ZG$ and s -channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma, W^+W^-, ZZ, e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}$ at $E_{cm}=189$ GeV. Limits on the gravity scale are listed in their Tables 1 and 2.
- 35 BOURILKOV 99 performs global analysis of LEP data on e^+e^- collisions at $\sqrt{s}=183$ and 189 GeV. Bound is on Λ_T .

Limits on $1/R = M_c$

This section includes limits on $1/R = M_c$, the compactification scale in models with TeV extra dimensions, due to exchange of Standard Model KK excitations. Bounds assume fermions are not in the bulk, unless stated otherwise. See the "Extra Dimensions" review for discussion of model dependence.

VALUE (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
>4.16	95	1 AAD	12CC ATLS	$pp \rightarrow \ell\bar{\ell}$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>1.40	95	2 AAD	12CP ATLS	$pp \rightarrow \gamma\gamma, \delta=6, M_D=5$ TeV
>1.23	95	3 AAD	12X ATLS	$pp \rightarrow \gamma\gamma, \delta=6, M_D=5$ TeV
>0.26	95	4 ABAZOV	12M D0	$p\bar{p} \rightarrow \mu\mu$
>0.75	95	5 BAAK	12 RVUE	Electroweak
		6 FLACKE	12 RVUE	Electroweak
>0.43	95	7 NISHIWAKI	12 RVUE	$H \rightarrow WW, \gamma\gamma$
>0.729	95	8 AAD	11F ATLS	$pp \rightarrow \gamma\gamma, \delta=6, M_D=5$ TeV

>0.961	95	⁹ AAD	11X	ATLS	$pp \rightarrow \gamma\gamma, \delta=6, M_D=5 \text{ TeV}$
>0.477	95	¹⁰ ABAZOV	10P	D0	$p\bar{p} \rightarrow \gamma\gamma, \delta=6, M_D=5 \text{ TeV}$
>1.59	95	¹¹ ABAZOV	09AE	D0	$p\bar{p} \rightarrow \text{dijet, angular dist.}$
>0.6	95	¹² HAISCH	07	RVUE	$\bar{B} \rightarrow X_s \gamma$
>0.6	90	¹³ GOGOLADZE	06	RVUE	Electroweak
>3.3	95	¹⁴ CORNET	00	RVUE	Electroweak
> 3.3–3.8	95	¹⁵ RIZZO	00	RVUE	Electroweak

¹ AAD 12CC use 4.9 and 5.0 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ in the dielectron and dimuon channels, respectively, to place a lower bound on the mass of the lightest KK Z/γ boson (equivalent to $1/R = M_C$). The limit quoted here assumes a flat prior corresponding to when the pure Z/γ KK cross section term dominates. See their Section 15 for more details.

² AAD 12CP use diphoton events with large missing transverse momentum in 4.8 fb^{-1} of data produced from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to place a lower bound on the compactification scale in a universal extra dimension model with gravitational decays. The bound assumes that the cutoff scale Λ , for the radiative corrections to the Kaluza-Klein masses, satisfies $\Lambda/M_C = 20$. The model parameters are chosen such that the decay $\gamma^* \rightarrow G\gamma$ occurs with an appreciable branching fraction.

³ AAD 12X use diphoton events with large missing transverse momentum in 1.07 fb^{-1} of data produced from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to place a lower bound on the compactification scale in a universal extra dimension model with gravitational decays. The bound assumes that the cutoff scale Λ , for the radiative corrections to the Kaluza-Klein masses, satisfies $\Lambda/M_C = 20$. The model parameters are chosen such that the decay $\gamma^* \rightarrow G\gamma$ occurs with an appreciable branching fraction.

⁴ ABAZOV 12M use same-sign dimuon events in 7.3 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to place a lower bound on the compactification scale $1/R$, in models with universal extra dimensions where all Standard Model fields propagate in the bulk.

⁵ BAAK 12 use electroweak precision observables to place a lower bound on the compactification scale $1/R$, in models with universal extra dimensions and Standard Model fields propagating in the bulk. Bound assumes a 125 GeV Higgs mass. See their Fig. 25 for the bound as a function of the Higgs mass.

⁶ FLACKE 12 use electroweak precision observables to place a lower bound on the compactification scale $1/R$, in models with universal extra dimensions and Standard Model fields propagating in the bulk. See their Fig. 1 for the bound as a function of the universal bulk fermion mass parameter μ .

⁷ NISHIWAKI 12 use up to 2 fb^{-1} of data from the ATLAS and CMS experiments that constrains the production cross section of a Higgs-like particle to place a lower bound on the compactification scale $1/R$ in universal extra dimension models. The quoted bound assumes Standard Model fields propagating in the bulk and a 125 GeV Higgs mass. See their Fig. 1 for the bound as a function of the Higgs mass.

⁸ AAD 11F use diphoton events with large missing transverse energy in 3.1 pb^{-1} of data produced from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to place a lower bound on the compactification scale in a universal extra dimension model with gravitational decays. The bound assumes that the cutoff scale Λ , for the radiative corrections to the Kaluza-Klein masses, satisfies $\Lambda/M_C = 20$. The model parameters are chosen such that the decay $\gamma^* \rightarrow G\gamma$ occurs with an appreciable branching fraction.

⁹ AAD 11X use diphoton events with large missing transverse energy in 36 pb^{-1} of data produced from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to place a lower bound on the compactification scale in a universal extra dimension model with gravitational decays. The bound assumes that the cutoff scale Λ , for the radiative corrections to the Kaluza-Klein masses, satisfies $\Lambda/M_C = 20$. The model parameters are chosen such that the decay $\gamma^* \rightarrow G\gamma$ occurs with an appreciable branching fraction.

¹⁰ ABAZOV 10P use diphoton events with large missing transverse energy in 6.3 fb^{-1} of data produced from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to place a lower bound on the compactification scale in a universal extra dimension model with gravitational decays.

The bound assumes that the cutoff scale Λ , for the radiative corrections to the Kaluza-Klein masses, satisfies $\Lambda/M_c=20$. The model parameters are chosen such that the decay $\gamma^* \rightarrow G\gamma$ occurs with an appreciable branching fraction.

- 11 ABAZOV 09AE use dijet angular distributions in 0.7 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to place a lower bound on the compactification scale.
- 12 HAISCH 07 use inclusive \bar{B} -meson decays to place a Higgs mass independent bound on the compactification scale $1/R$ in the minimal universal extra dimension model.
- 13 GOGOLADZE 06 use electroweak precision observables to place a lower bound on the compactification scale in models with universal extra dimensions. Bound assumes a 115 GeV Higgs mass. See their Fig. 3 for the bound as a function of the Higgs mass.
- 14 CORNET 00 translates a bound on the coefficient of the 4-fermion operator $(\bar{\ell}\gamma_\mu\tau^a\ell)(\bar{\ell}\gamma^\mu\tau^a\ell)$ derived by Hagiwara and Matsumoto into a limit on the mass scale of KK W bosons.
- 15 RIZZO 00 obtains limits from global electroweak fits in models with a Higgs in the bulk (3.8 TeV) or on the standard brane (3.3 TeV).

Limits on Kaluza-Klein Gravitons in Warped Extra Dimensions

This sections places limits on the mass of the first Kaluza-Klein (KK) excitation of the graviton in the warped extra dimension model of Randall and Sundrum. Bounds in parenthesis assume Standard Model fields propagate in the bulk. Experimental bounds depend strongly on the warp parameter, k . See the "Extra Dimensions" review for a full discussion.

Here we list limits for the value of the warp parameter $k/\overline{M}_P = 0.1$.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>2160	95	1 AAD	12CC ATLS	$p\bar{p} \rightarrow G \rightarrow \ell\bar{\ell}$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>1230	(>840)	2 AAD	13A ATLS	$p\bar{p} \rightarrow G \rightarrow WW$
> 845	95	3 AAD	12AD ATLS	$p\bar{p} \rightarrow G \rightarrow ZZ$
>1950	95	4 AAD	12Y ATLS	$p\bar{p} \rightarrow \gamma\gamma, e^+e^-, \mu^+\mu^-$
		5 AALTONEN	12V CDF	$p\bar{p} \rightarrow G \rightarrow ZZ$
		6 BAAK	12 RVUE	Electroweak
>1840	95	7 CHATRCHYAN	12R CMS	$p\bar{p} \rightarrow G \rightarrow \gamma\gamma$
>1630	95	8 AAD	11AD ATLS	$p\bar{p} \rightarrow G \rightarrow \ell\bar{\ell}$
		9 AALTONEN	11G CDF	$p\bar{p} \rightarrow G \rightarrow ZZ$
>1058	95	10 AALTONEN	11R CDF	$p\bar{p} \rightarrow G \rightarrow e^+e^-, \gamma\gamma$
> 754	95	11 ABAZOV	11H D0	$p\bar{p} \rightarrow G \rightarrow WW$
>1079	95	12 CHATRCHYAN	11 CMS	$p\bar{p} \rightarrow G \rightarrow \ell\bar{\ell}$
> 607		13 AALTONEN	10N CDF	$p\bar{p} \rightarrow G \rightarrow WW$
>1050		14 ABAZOV	10F D0	$p\bar{p} \rightarrow G \rightarrow e^+e^-, \gamma\gamma$
		15 AALTONEN	08S CDF	$p\bar{p} \rightarrow G \rightarrow ZZ$
> 900		16 ABAZOV	08J D0	$p\bar{p} \rightarrow G \rightarrow e^+e^-, \gamma\gamma$
		17 AALTONEN	07G CDF	$p\bar{p} \rightarrow G \rightarrow \gamma\gamma$
> 889		18 AALTONEN	07H CDF	$p\bar{p} \rightarrow G \rightarrow e\bar{e}$
> 785		19 ABAZOV	05N D0	$p\bar{p} \rightarrow G \rightarrow \ell\ell, \gamma\gamma$
> 710		20 ABULENCIA	05A CDF	$p\bar{p} \rightarrow G \rightarrow \ell\bar{\ell}$

- ¹ AAD 12CC use 4.9 and 5.0 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ in the dielectron and dimuon channels, respectively, to place a lower bound on the mass of the lightest KK graviton. See their Figure 5 for limits on the lightest KK graviton mass as a function of k/\overline{M}_P .
- ² AAD 13A use 4.7 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to place a lower bound on the mass of the lightest KK graviton.
- ³ AAD 12AD use 1.02 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ to search for KK gravitons in a warped extra dimension decaying to ZZ dibosons in the $lljj$ and $llll$ channels ($\ell=e, \mu$). The limit is quoted for the combined $lljj + llll$ channels. See their Figure 5 for limits on the cross section $\sigma(G \rightarrow ZZ)$ as a function of the graviton mass.
- ⁴ AAD 12Y use 2.12 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ in the diphoton channel to place lower limits on the mass of the lightest KK graviton. The diphoton channel is combined with previous results in the dielectric and dimuon channels to set the best limit. See their Table 3 for warp parameter values k/\overline{M}_P between 0.01 and 0.1.
- ⁵ AALTONEN 12V use 6 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to search for KK gravitons in a warped extra dimension decaying to ZZ dibosons in the $lljj$ and $llll$ channels ($\ell=e, \mu$). It provides improved limits over the previous analysis in AALTONEN 11G. See their Figure 16 for limits from all channels combined on the cross section times branching ratio $\sigma(p\bar{p} \rightarrow G^* \rightarrow ZZ)$ as a function of the graviton mass.
- ⁶ BAAK 12 use electroweak precision observables to place a lower bound on the compactification scale $k e^{-\pi k R}$, assuming Standard Model fields propagate in the bulk and the Higgs is confined to the IR brane. See their Fig. 27 for more details.
- ⁷ CHATRCHYAN 12R use 2.2 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ in the diphoton channel to place lower limits on the mass of the lightest KK graviton. See their Table III for warp parameter values k/\overline{M}_P between 0.01 and 0.1.
- ⁸ AAD 11AD use 1.08 and 1.21 fb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ in the dielectron and dimuon channels, respectively, to place a lower bound on the mass of the lightest graviton. For warp parameter values k/\overline{M}_P between 0.01 to 0.1 the lower limit on the mass of the lightest graviton is between 0.71 and 1.63 TeV. See their Table IV for more details.
- ⁹ AALTONEN 11G use $2.5\text{--}2.9 \text{ fb}^{-1}$ of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to search for KK gravitons in a warped extra dimension decaying to ZZ dibosons via the $eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$, $eejj$, and $\mu\mu jj$ channels. See their Fig. 20 for limits on the cross section $\sigma(G \rightarrow ZZ)$ as a function of the graviton mass.
- ¹⁰ AALTONEN 11R uses 5.7 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ in the dielectron channel to place a lower bound on the mass of the lightest graviton. It provides combined limits with the diphoton channel analysis of AALTONEN 11U. For warp parameter values k/\overline{M}_P between 0.01 to 0.1 the lower limit on the mass of the lightest graviton is between 612 and 1058 GeV. See their Table I for more details.
- ¹¹ ABAZOV 11H use 5.4 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to place a lower bound on the mass of the lightest graviton. Their 95% C.L. exclusion limit does not include masses less than 300 GeV.
- ¹² CHATRCHYAN 11 use 35 and 40 pb^{-1} of data from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ in the dielectron and dimuon channels, respectively, to place a lower bound on the mass of the lightest graviton. For a warp parameter value $k/\overline{M}_P = 0.05$, the lower limit on the mass of the lightest graviton is 0.855 TeV.
- ¹³ AALTONEN 10N use 2.9 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to place a lower bound on the mass of the lightest graviton.
- ¹⁴ ABAZOV 10F use 5.4 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to place a lower bound on the mass of the lightest graviton. For warp parameter values of k/\overline{M}_P between 0.01 and 0.1 the lower limit on the mass of the lightest graviton is between 560 and 1050 GeV. See their Fig. 3 for more details.
- ¹⁵ AALTONEN 08S use $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to four electrons via two Z bosons using 1.1 fb^{-1} of data. See their Fig. 8 for limits on $\sigma \cdot \text{B}(G \rightarrow ZZ)$ versus the graviton mass.

- ¹⁶ ABAZOV 08J use $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to electrons and photons using 1 fb^{-1} of data. For warp parameter values of k/\overline{M}_P between 0.01 and 0.1 the lower limit on the mass of the lightest excitation is between 300 and 900 GeV. See their Fig. 4 for more details.
- ¹⁷ AALTONEN 07G use $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to photons using 1.2 fb^{-1} of data. For warp parameter values of $k/\overline{M}_P = 0.1, 0.05,$ and 0.01 the bounds on the graviton mass are 850, 694, and 230 GeV, respectively. See their Fig. 3 for more details. See also AALTONEN 07H.
- ¹⁸ AALTONEN 07H use $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to electrons using 1.3 fb^{-1} of data. For a warp parameter value of $k/\overline{M}_P = 0.1$ the bound on the graviton mass is 807 GeV. See their Fig. 4 for more details. A combined analysis with the diphoton data of AALTONEN 07G yields for $k/\overline{M}_P = 0.1$ a graviton mass lower bound of 889 GeV.
- ¹⁹ ABAZOV 05N use $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to muons, electrons or photons, using 260 pb^{-1} of data. For warp parameter values of $k/\overline{M}_P = 0.1, 0.05,$ and $0.01,$ the bounds on the graviton mass are 785, 650 and 250 GeV respectively. See their Fig. 3 for more details.
- ²⁰ ABULENCIA 05A use $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to muons or electrons, using 200 pb^{-1} of data. For warp parameter values of $k/\overline{M}_P = 0.1, 0.05,$ and $0.01,$ the bounds on the graviton mass are 710, 510 and 170 GeV respectively.

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