# Other Particle Searches

OMITTED FROM SUMMARY TABLE

## OTHER PARTICLE SEARCHES

Revised February 2018 by K. Hikasa (Tohoku University).

We collect here those searches which do not appear in any other search categories. These are listed in the following order:

- Concentration of stable particles in matter
- General new physics searches
- Limits on jet-jet resonance in hadron collisions
- Limits on neutral particle production at accelerators
- Limits on charged particles in $e^+e^-$ collisions
- Limits on charged particles in hadron reactions
- Limits on charged particles in cosmic rays
- Searches for quantum black hole production

Note that searches appear in separate sections elsewhere for Higgs bosons (and technipions), other heavy bosons (including $W_R$, $W'$, $Z'$, leptoquarks, axigluons), axions (including pseudo-Goldstone bosons, Majorons, familons), WIMPs, heavy leptons, heavy neutrinos, free quarks, monopoles, supersymmetric particles, and compositeness.

We no longer list for limits on tachyons and centauros. See our 1994 edition for these limits.

## CONCENTRATION OF STABLE PARTICLES IN MATTER

### Concentration of Heavy (Charge +1) Stable Particles in Matter

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<4 \times 10^{-17}$ | 95 | [1] YAMAGATA | 93 | SPEC | Deep sea water, $M$=5–1600$m_p$ |
| $<6 \times 10^{-15}$ | 95 | [2] VERKERK | 92 | SPEC | Water, $M = 10^5$ to $3 \times 10^7$ GeV |
| $<7 \times 10^{-15}$ | 95 | [2] VERKERK | 92 | SPEC | Water, $M = 10^4$, $6 \times 10^7$ GeV |
| $<9 \times 10^{-15}$ | 95 | [2] VERKERK | 92 | SPEC | Water, $M = 10^8$ GeV |
| $<3 \times 10^{-23}$ | 90 | [3] HEMMICK | 90 | SPEC | Water, $M = 1000 m_p$ |

| | | | | | |
|---|---|---|---|---|---|
| $<2 \times 10^{-21}$ | 90 | [3] HEMMICK | 90 | SPEC | Water, $M = 5000 m_p$ |
| $<3 \times 10^{-20}$ | 90 | [3] HEMMICK | 90 | SPEC | Water, $M = 10000 m_p$ |
| $<1. \times 10^{-29}$ | | SMITH | 82B | SPEC | Water, $M$=30–400$m_p$ |
| $<2. \times 10^{-28}$ | | SMITH | 82B | SPEC | Water, $M$=12–1000$m_p$ |
| $<1. \times 10^{-14}$ | | SMITH | 82B | SPEC | Water, $M$ >1000 $m_p$ |
| $<(0.2–1.) \times 10^{-21}$ | | SMITH | 79 | SPEC | Water, $M$=6–350 $m_p$ |

[1] YAMAGATA 93 used deep sea water at 4000 m since the concentration is enhanced in deep sea due to gravity.

[2] VERKERK 92 looked for heavy isotopes in sea water and put a bound on concentration of stable charged massive particle in sea water. The above bound can be translated into into a bound on charged dark matter particle ($5 \times 10^6$ GeV), assuming the local density, $\rho$=0.3 GeV/cm$^3$, and the mean velocity $\langle v \rangle$=300 km/s.

[3] See HEMMICK 90 Fig. 7 for other masses 100–10000 $m_p$.

## Concentration of Heavy Stable Particles Bound to Nuclei

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $< 2 \times 10^{-17}$/nucleon | 95 | [1] AFEK | 21 | | millicharged particle search |
| $<1.2 \times 10^{-11}$ | 95 | [2] JAVORSEK | 01 | SPEC | Au, $M$= 3 GeV |
| $<6.9 \times 10^{-10}$ | 95 | [2] JAVORSEK | 01 | SPEC | Au, $M$= 144 GeV |
| $<1 \times 10^{-11}$ | 95 | [3] JAVORSEK | 01B | SPEC | Au, $M$= 188 GeV |
| $<1 \times 10^{-8}$ | 95 | [3] JAVORSEK | 01B | SPEC | Au, $M$= 1669 GeV |
| $<6 \times 10^{-9}$ | 95 | [3] JAVORSEK | 01B | SPEC | Fe, $M$= 188 GeV |
| $<1 \times 10^{-8}$ | 95 | [3] JAVORSEK | 01B | SPEC | Fe, $M$= 647 GeV |
| $<4 \times 10^{-20}$ | 90 | [4] HEMMICK | 90 | SPEC | C, $M = 100 m_p$ |
| $<8 \times 10^{-20}$ | 90 | [4] HEMMICK | 90 | SPEC | C, $M = 1000 m_p$ |
| $<2 \times 10^{-16}$ | 90 | [4] HEMMICK | 90 | SPEC | C, $M = 10000 m_p$ |
| $<6 \times 10^{-13}$ | 90 | [4] HEMMICK | 90 | SPEC | Li, $M = 1000 m_p$ |
| $<1 \times 10^{-11}$ | 90 | [4] HEMMICK | 90 | SPEC | Be, $M = 1000 m_p$ |
| $<6 \times 10^{-14}$ | 90 | [4] HEMMICK | 90 | SPEC | B, $M = 1000 m_p$ |
| $<4 \times 10^{-17}$ | 90 | [4] HEMMICK | 90 | SPEC | O, $M = 1000 m_p$ |
| $<4 \times 10^{-15}$ | 90 | [4] HEMMICK | 90 | SPEC | F, $M = 1000 m_p$ |
| $< 1.5 \times 10^{-13}$/nucleon | 68 | [5] NORMAN | 89 | SPEC | $^{206}$Pb$X^-$ |
| $< 1.2 \times 10^{-12}$/nucleon | 68 | [5] NORMAN | 87 | SPEC | $^{56,58}$Fe$X^-$ |

[1] AFEK 21 search for millicharged particles bound to matter using an optomechanical device. No signal was observed. Limits placed in the abundance vs. charge plane (Fig. 3). This is translated to the mass versus charge plane by requiring bound states to be stable.

[2] JAVORSEK 01 search for (neutral) SIMPs (strongly interacting massive particles) bound to Au nuclei. Here $M$ is the effective SIMP mass.

[3] JAVORSEK 01B search for (neutral) SIMPs (strongly interacting massive particles) bound to Au and Fe nuclei from various origins with exposures on the earth's surface, in a satellite, heavy ion collisions, etc. Here $M$ is the mass of the anomalous nucleus. See also JAVORSEK 02.

[4] See HEMMICK 90 Fig. 7 for other masses 100–10000 $m_p$.

[5] Bound valid up to $m_{X^-} \sim$ 100 TeV.

# GENERAL NEW PHYSICS SEARCHES

This subsection lists some of the search experiments which look for general signatures characteristic of new physics, independent of the framework of a specific model.

The observed events are compatible with Standard Model expectation, unless noted otherwise.

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [1] ALKHATIB | 21A | SCDM | CDMSlite search for fractionally charged relics |
| | [2] AGUILAR-AR... | 20B | CONN | $\nu$ elastic scatter on nuclei |
| | [3] FEDDERKE | 20 | | CHAMPs from white dwarfs |
| | [4] SIRUNYAN | 20A | CMS | SUSY/LQ search with mT2 or long-lived charged particles |
| | [5] ALCANTARA | 19 | | Auger, superheavy DM |
| | [6] PORAYKO | 18 | PPTA | pulsar timing fuzzy DM search |
| | [7] AAD | 15AT | ATLS | $t + \not{E}_T$ |
| | [8] KHACHATRY... | 15F | CMS | $t + \not{E}_T$ |
| | [9] AALTONEN | 14J | CDF | $W$ + 2 jets |
| | [10] AAD | 13A | ATLS | $W W \rightarrow \ell \nu \ell' \nu$ |
| | [11] AAD | 13C | ATLS | $\gamma + \not{E}_T$ |
| | [12] AALTONEN | 13I | CDF | Delayed $\gamma + \not{E}_T$ |
| | [13] CHATRCHYAN | 13 | CMS | $\ell^+ \ell^-$ + jets + $\not{E}_T$ |
| | [14] AAD | 12C | ATLS | $t \overline{t} + \not{E}_T$ |
| | [15] AALTONEN | 12M | CDF | jet + $\not{E}_T$ |
| | [16] CHATRCHYAN | 12AP | CMS | jet + $\not{E}_T$ |
| | [17] CHATRCHYAN | 12Q | CMS | $Z$ + jets + $\not{E}_T$ |
| | [18] CHATRCHYAN | 12T | CMS | $\gamma + \not{E}_T$ |
| | [19] AAD | 11S | ATLS | jet + $\not{E}_T$ |
| | [20] AALTONEN | 11AF | CDF | $\ell^\pm \ell^\pm$ |
| | [21] CHATRCHYAN | 11C | CMS | $\ell^+ \ell^-$ + jets + $\not{E}_T$ |
| | [22] CHATRCHYAN | 11U | CMS | jet + $\not{E}_T$ |
| | [23] AALTONEN | 10AF | CDF | $\gamma \gamma + \ell, \not{E}_T$ |
| | [24] AALTONEN | 09AF | CDF | $\ell \gamma b \not{E}_T$ |
| | [25] AALTONEN | 09G | CDF | $\ell \ell \ell \not{E}_T$ |

[1] ALKHATIB 21A search for lightly ionizing fractionally charged relics scattering from Ge. No signal observed. Limits plotted in fractional charge f vs. vertical intensity plane for m $\sim$ 5 MeV to 100 TeV.

[2] AGUILAR-AREVALO 20B search for light BSM mediator effect on $\nu$ elastic scatter on nuclei; no signal; limits placed in m(mediator) vs. coupling plane for two models of MeV-scale mediators.

[3] FEDDERKE 20 place limits on cosmic relic charged massive particles (CHAMPs) due to their capture and subsequent disruption of old white dwarf stars; limits placed in the m(CHAMP) vs. relic density parameter plane.

[4] SIRUNYAN 20A search for SUSY and LQ production using mT2 or presence of long-lived charged particle; no signal, limits placed in various mass planes for different BSM scenarios and various assumed lifetimes.

[5] ALCANTARA 19 place limits on m(WIMPzilla=$X$) vs lifetime from upper bound on ultra high energy cosmic rays at Auger experiment: e.g. $\tau(X) < 4 \times 10^{22}$ yr for m($X$) = $10^{16}$ GeV.

[6] PORAYKO 18 search for deviations in the residuals of pulsar timing data using PPTA. No signal observed. Limits set on fuzzy DM with $3 \times 10^{-24} < $ m(DM) $< 2 \times 10^{-22}$ eV.

[7] AAD 15AT search for events with a top quark and mssing $E_T$ in $pp$ collisions at $E_{cm} = 8$ TeV with $L = 20.3$ fb$^{-1}$.

[8] KHACHATRYAN 15F search for events with a top quark and mssing $E_T$ in $pp$ collisions at $E_{cm} = 8$ TeV with $L = 19.7$ fb$^{-1}$.

[9] AALTONEN 14J examine events with a $W$ and two jets in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $L = 8.9$ fb$^{-1}$. Invariant mass distributions of the two jets are consistent with the Standard Model expectation.

[10] AAD 13A search for resonant $WW$ production in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 4.7$ fb$^{-1}$.

[11] AAD 13C search for events with a photon and missing $\not{E}_T$ in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 4.6$ fb$^{-1}$.

[12] AALTONEN 13I search for events with a photon and missing $E_T$, where the photon is detected after the expected timing, in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $L = 6.3$ fb$^{-1}$. The data are consistent with the Standard Model expectation.

[13] CHATRCHYAN 13 search for events with an opposite-sign lepton pair, jets, and missing $E_T$ in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 4.98$ fb$^{-1}$.

[14] AAD 12C search for events with a $t\overline{t}$ pair and missing $\not{E}_T$ in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 1.04$ fb$^{-1}$.

[15] AALTONEN 12M search for events with a jet and missing $E_T$ in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $L = 6.7$ fb$^{-1}$.

[16] CHATRCHYAN 12AP search for events with a jet and missing $E_T$ in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 5.0$ fb$^{-1}$.

[17] CHATRCHYAN 12Q search for events with a $Z$, jets, and missing $\not{E}_T$ in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 4.98$ fb$^{-1}$.

[18] CHATRCHYAN 12T search for events with a photon and missing $\not{E}_T$ in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 5.0$ fb$^{-1}$.

[19] AAD 11S search for events with one jet and missing $E_T$ in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 33$ pb$^{-1}$.

[20] AALTONEN 11AF search for high-$p_T$ like-sign dileptons in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $L = 6.1$ fb$^{-1}$.

[21] CHATRCHYAN 11C search for events with an opposite-sign lepton pair, jets, and missing $E_T$ in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 34$ pb$^{-1}$.

[22] CHATRCHYAN 11U search for events with one jet and missing $E_T$ in $pp$ collisions at $E_{cm} = 7$ TeV with $L = 36$ pb$^{-1}$.

[23] AALTONEN 10AF search for $\gamma\gamma$ events with $e$, $\mu$, $\tau$, or missing $E_T$ in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $L = 1.1$–$2.0$ fb$^{-1}$.

[24] AALTONEN 09AF search for $\ell\gamma b$ events with missing $E_T$ in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $L = 1.9$ fb$^{-1}$. The observed events are compatible with Standard Model expectation including $t\overline{t}\gamma$ production.

[25] AALTONEN 09G search for $\mu\mu\mu$ and $\mu\mu e$ events with missing $E_T$ in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $L = 976$ pb$^{-1}$.

# LIMITS ON JET-JET RESONANCES

## Heavy Particle Production Cross Section

Limits are for a particle decaying to two hadronic jets.

| Units(pb) | CL% | Mass(GeV) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| | | | [1] TUMASYAN | 23L | CMS | dijet resonance in 4-jet events |
| | | | [2] AAD | 20AD | ATLS | $pp$ at 13 TeV, dijet resonance |
| | | | [3] AAD | 20T | ATLS | dijet resonance search |
| | | | [4] AAD | 20W | ATLS | dijet resonance plus lepton |
| | | | [5] SIRUNYAN | 20AI | CMS | dijet resonance search |
| | | | [6] AABOUD | 19AJ | ATLS | $pp \to \gamma X$, $X \to jj$ |
| | | | [7] SIRUNYAN | 19B | CMS | $pp \to jA$, $A \to b\overline{b}$ |
| | | | [8] SIRUNYAN | 19CD | CMS | $pp \to Z'\gamma$, $Z' \to jj$ |
| | | | [9] AABOUD | 18AD | ATLS | $pp \to Y \to HX \to (bb) + (qq)$ |
| | | | [10] AABOUD | 18CK | ATLS | $pp \to bbb + \not{E}_T$ |
| | | | [11] AABOUD | 18CL | ATLS | $pp \to$ vector-like quarks |
| | | | [12] AABOUD | 18N | ATLS | $pp \to jj$ resonance |
| | | | [13] SIRUNYAN | 18DJ | CMS | $pp \to ZZ$ or $WZ \to \ell\overline{\ell}jj$ |
| | | | [14] SIRUNYAN | 18DY | CMS | $pp \to RR$; $R \to jj$ |
| | | | [15] KHACHATRY... | 17W | CMS | $pp \to jj$ resonance |
| | | | [16] KHACHATRY... | 17Y | CMS | $pp \to$ (8–10) $j+\not{E}_T$ |
| | | | [17] SIRUNYAN | 17F | CMS | $pp \to jj$ angular distribution |
| | | | [18] AABOUD | 16 | ATLS | $pp \to b +$ jet |
| | | | [19] AAD | 16N | ATLS | $pp \to$ 3 high $E_T$ jets |
| | | | [20] AAD | 16S | ATLS | $pp \to jj$ resonance |
| | | | [21] KHACHATRY... | 16K | CMS | $pp \to jj$ resonance |
| | | | [22] KHACHATRY... | 16L | CMS | $pp \to jj$ resonance |
| | | | [23] AAD | 13D | ATLS | 7 TeV $pp \to$ 2 jets |
| | | | [24] AALTONEN | 13R | CDF | 1.96 TeV $p\overline{p} \to$ 4 jets |
| | | | [25] CHATRCHYAN | 13A | CMS | 7 TeV $pp \to$ 2 jets |
| | | | [26] CHATRCHYAN | 13A | CMS | 7 TeV $pp \to b\overline{b}X$ |
| | | | [27] AAD | 12S | ATLS | 7 TeV $pp \to$ 2 jets |
| | | | [28] CHATRCHYAN | 12BL | CMS | 7 TeV $pp \to t\overline{t}X$ |
| | | | [29] AAD | 11AG | ATLS | 7 TeV $pp \to$ 2 jets |
| | | | [30] AALTONEN | 11M | CDF | 1.96 TeV $p\overline{p} \to W+$ 2 jets |
| | | | [31] ABAZOV | 11I | D0 | 1.96 TeV $p\overline{p} \to W+$ 2 jets |
| | | | [32] AAD | 10 | ATLS | 7 TeV $pp \to$ 2 jets |
| | | | [33] KHACHATRY... | 10 | CMS | 7 TeV $pp \to$ 2 jets |
| | | | [34] ABE | 99F | CDF | 1.8 TeV $p\overline{p} \to b\overline{b}+$ anything |
| | | | [35] ABE | 97G | CDF | 1.8 TeV $p\overline{p} \to$ 2 jets |
| $<2603$ | 95 | 200 | [36] ABE | 93G | CDF | 1.8 TeV $p\overline{p} \to$ 2 jets |
| $<44$ | 95 | 400 | [36] ABE | 93G | CDF | 1.8 TeV $p\overline{p} \to$ 2 jets |
| $<7$ | 95 | 600 | [36] ABE | 93G | CDF | 1.8 TeV $p\overline{p} \to$ 2 jets |

[1] TUMASYAN 23L search for dijet resonance in 4-jet events with 138 fb$^{-1}$ fb of data. There are two events in the tails of the distributions, each with a four-jet mass of 8 TeV and an average dijet mass of 2 TeV, resulting in local and global significances of 3.9 and 1.6 standard deviations, respectively, if interpreted as a signal. Limits set for simplified diquark model.

[2] AAD 20AD search for weakly supervised dijet resonance in ATLAS with 139 fb$^{-1}$ at 13 TeV; no signal; various limits placed depending on kinematics and production cross section.
[3] AAD 20T search for dijet resonance with or without $b$-jets at 13 TeV and 139 fb$^{-1}$; no signal; limits placed in $\sigma \cdot$ BF vs mass plane for various BSM models.
[4] AAD 20W search for dijet resonance plus lepton with ATLAS at 13 TeV and 139 fb$^{-1}$; no signal; limits placed in $\sigma \cdot$ BF vs. mass plane for various BSM models.
[5] SIRUNYAN 20AI search for dijet resonance in CMS at 13 TeV with 137 fb$^{-1}$; no signal; limits set in $\sigma$ vs. mass plane for various BSM models .
[6] AABOUD 19AJ search for low mass dijet resonance in $p p \rightarrow \gamma X$, $X \rightarrow j j$ at 13 TeV with 79.8 fb$^{-1}$ of data; no signal found; limits placed on $Z'$ model in coupling vs. m($Z'$) plane.
[7] SIRUNYAN 19B search for low mass resonance $p p \rightarrow j A$, $A \rightarrow b \overline{b}$ at 13 TeV using 35.9 fb$^{-1}$; no signal; exclude resonances 50–350 GeV depending on production and decay.
[8] SIRUNYAN 19CD search for $p p \rightarrow Z' \gamma$, $Z' \rightarrow j j$ with fat jet ($j j$); no signal, limits placed in m($Z'$) vs. coupling plane for $Z'$ masses from 10 to 125 GeV.
[9] AABOUD 18AD search for new heavy particle $Y \rightarrow H X \rightarrow (b b) + (q q)$. No signal observed. Limits set on m(Y) vs. m(X) in the ranges of m(Y) in 1–4 TeV and m(X) in 50–1000 GeV.
[10] AABOUD 18CK search for SUSY Higgsinos in gauge-mediation via $p p \rightarrow b b b + \not{E}_T$ at 13 TeV using two complementary analyses with 24.3/36.1 fb$^{-1}$; no signal is found and Higgsinos with masses between 130 and 230 GeV and between 290 and 880 GeV are excluded at the 95% confidence level.
[11] AABOUD 18CL search for $p p \rightarrow$ vector-like quarks $\rightarrow$ jets at 13 TeV with 36 fb$^{-1}$; no signal seen; limits set on various VLQ scenarios. For pure $B \rightarrow H b$ or $T \rightarrow H t$, set the mass limit m $>$ 1010 GeV.
[12] AABOUD 18N search for dijet resonance at Atlas with 13 TeV and 29.3 fb$^{-1}$; limits set on m($Z'$) in the mass range of 450–1800 GeV.
[13] SIRUNYAN 18DJ search for $p p \rightarrow Z Z$ or $W Z \rightarrow \ell \overline{\ell} j j$ resonance at 13 TeV, 35.9 fb$^{-1}$; no signal; limits set in the 400–4500 GeV mass range, exclusion of $W'$ up to 2270 GeV in the HVT model A, and up to 2330 GeV for HVT model B. WED bulk graviton exclusion up to 925 GeV.
[14] SIRUNYAN 18DY search for $p p \rightarrow R R$; $R \rightarrow j j$ two dijet resonances at 13 TeV 35.9 fb$^{-1}$; no signal; limits placed on RPV top-squark pair production.
[15] KHACHATRYAN 17W search for dijet resonance in 12.9 fb$^{-1}$ data at 13 TeV; see Fig. 2 for limits on axigluons, diquarks, dark matter mediators etc.
[16] KHACHATRYAN 17Y search for $p p \rightarrow$ (8–10) $j$ in 19.7 fb$^{-1}$ at 8 TeV. No signal seen. Limits set on colorons, axigluons, RPV, and SUSY.
[17] SIRUNYAN 17F measure $p p \rightarrow j j$ angular distribution in 2.6 fb$^{-1}$ at 13 TeV; limits set on LEDs and quantum black holes.
[18] AABOUD 16 search for resonant dijets including one or two $b$-jets with 3.2 fb$^{-1}$ at 13 TeV; exclude excited $b^*$ quark from 1.1–2.1 TeV; exclude leptophilic $Z'$ with SM couplings from 1.1–1.5 TeV.
[19] AAD 16N search for $\geq 3$ jets with 3.6 fb$^{-1}$ at 13 TeV; limits placed on micro black holes (Fig. 10) and string balls (Fig. 11).
[20] AAD 16S search for high mass jet-jet resonance with 3.6 fb$^{-1}$ at 13 TeV; exclude portions of excited quarks, $W'$, $Z'$ and contact interaction parameter space.
[21] KHACHATRYAN 16K search for dijet resonance in 2.4 fb$^{-1}$ data at 13 TeV; see Fig. 3 for limits on axigluons, diquarks etc.
[22] KHACHATRYAN 16L use data scouting technique to search for $j j$ resonance on 18.8 fb$^{-1}$ of data at 8 TeV. Limits on the coupling of a leptophobic $Z'$ to quarks are set, improving on the results by other experiments in the mass range between 500–800 GeV.

[23] AAD 13D search for dijet resonances in $pp$ collisions at $E_{cm}$ = 7 TeV with $L$ = 4.8 fb$^{-1}$. The observed events are compatible with Standard Model expectation. See their Fig. 6 and Table 2 for limits on resonance cross section in the range $m$ = 1.0–4.0 TeV.

[24] AALTONEN 13R search for production of a pair of jet-jet resonances in $p\overline{p}$ collisions at $E_{cm}$ = 1.96 TeV with $L$ = 6.6 fb$^{-1}$. See their Fig. 5 and Tables I, II for cross section limits.

[25] CHATRCHYAN 13A search for $qq$, $qg$, and $gg$ resonances in $pp$ collisions at $E_{cm}$ = 7 TeV with $L$ = 4.8 fb$^{-1}$. See their Fig. 3 and Table 1 for limits on resonance cross section in the range $m$ = 1.0–4.3 TeV.

[26] CHATRCHYAN 13A search for $b\overline{b}$ resonances in $pp$ collisions at $E_{cm}$ = 7 TeV with $L$ = 4.8 fb$^{-1}$. See their Fig. 8 and Table 4 for limits on resonance cross section in the range $m$ = 1.0–4.0 TeV.

[27] AAD 12S search for dijet resonances in $pp$ collisions at $E_{cm}$ = 7 TeV with $L$ = 1.0 fb$^{-1}$. See their Fig. 3 and Table 2 for limits on resonance cross section in the range $m$ = 0.9–4.0 TeV.

[28] CHATRCHYAN 12BL search for $t\overline{t}$ resonances in $pp$ collisions at $E_{cm}$ = 7 TeV with $L$ = 4.4 fb$^{-1}$. See their Fig. 4 for limits on resonance cross section in the range $m$ = 0.5–3.0 TeV.

[29] AAD 11AG search for dijet resonances in $pp$ collisions at $E_{cm}$ = 7 TeV with L = 36 pb$^{-1}$. Limits on number of events for $m$ = 0.6–4 TeV are given in their Table 3.

[30] AALTONEN 11M find a peak in two jet invariant mass distribution around 140 GeV in $W$ + 2 jet events in $p\overline{p}$ collisions at $E_{cm}$ = 1.96 TeV with L = 4.3 fb$^{-1}$.

[31] ABAZOV 11I search for two-jet resonances in $W$ + 2 jet events in $p\overline{p}$ collisions at $E_{cm}$ = 1.96 TeV with L = 4.3 fb$^{-1}$ and give limits $\sigma <$ (2.6–1.3) pb (95% CL) for $m$ = 110–170 GeV. The result is incompatible with AALTONEN 11M.

[32] AAD 10 search for narrow dijet resonances in $pp$ collisions at $E_{cm}$ = 7 TeV with L = 315 nb$^{-1}$. Limits on the cross section in the range 10–10$^3$ pb is given for $m$ = 0.3–1.7 TeV.

[33] KHACHATRYAN 10 search for narrow dijet resonances in $pp$ collisions at $E_{cm}$ = 7 TeV with L = 2.9 pb$^{-1}$. Limits on the cross section in the range 1–300 pb is given for $m$ = 0.5–2.6 TeV separately in the final states $qq$, $qg$, and $gg$.

[34] ABE 99F search for narrow $b\overline{b}$ resonances in $p\overline{p}$ collisions at $E_{cm}$=1.8 TeV. Limits on $\sigma(p\overline{p} \rightarrow X+$ anything$)\times$B$(X \rightarrow b\overline{b})$ in the range 3–10$^3$ pb (95%CL) are given for $m_X$=200–750 GeV. See their Table I.

[35] ABE 97G search for narrow dijet resonances in $p\overline{p}$ collisions with 106 pb$^{-1}$ of data at $E_{cm}$ = 1.8 TeV. Limits on $\sigma(p\overline{p} \rightarrow X+$ anything$)\cdot$B$(X \rightarrow jj)$ in the range 10$^4$–10$^{-1}$ pb (95%CL) are given for dijet mass $m$=200–1150 GeV with both jets having $|\eta| <$ 2.0 and the dijet system having $|\cos\theta^*| <$ 0.67. See their Table I for the list of limits. Supersedes ABE 93G.

[36] ABE 93G give cross section times branching ratio into light ($d$, $u$, $s$, $c$, $b$) quarks for $\Gamma$ = 0.02 $M$. Their Table II gives limits for $M$ = 200–900 GeV and $\Gamma$ = (0.02–0.2) $M$.

# LIMITS ON NEUTRAL PARTICLE PRODUCTION

## Production Cross Section of Radiatively-Decaying Neutral Particle

| VALUE (pb) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [1] ALBERT | 18C | HAWC | $\gamma$ from Sun |
| | | [2] KHACHATRY... | 17D | CMS | $Z\gamma$ resonance |
| <0.0008 | 95 | [3] AAD | 16AI | ATLS | $pp \rightarrow \gamma +$ jet |
| | | [4] KHACHATRY... | 16M | CMS | $pp \rightarrow \gamma\gamma$ resonance |

| | | | | | |
|---|---|---|---|---|---|
| <(0.043–0.17) | 95 | [5] ABBIENDI | 00D | OPAL | $e^+e^- \to X^0 Y^0$, $X^0 \to Y^0 \gamma$ |
| <(0.05–0.8) | 95 | [6] ABBIENDI | 00D | OPAL | $e^+e^- \to X^0 X^0$, $X^0 \to Y^0 \gamma$ |
| <(2.5–0.5) | 95 | [7] ACKERSTAFF | 97B | OPAL | $e^+e^- \to X^0 Y^0$, $X^0 \to Y^0 \gamma$ |
| <(1.6–0.9) | 95 | [8] ACKERSTAFF | 97B | OPAL | $e^+e^- \to X^0 X^0$, $X^0 \to Y^0 \gamma$ |

[1] ALBERT 18C search for WIMP annihilation in Sun to long-lived, radiatively decaying mediator; no signal; limits set on $\sigma^{SD}(\chi p)$ assuming long-lived mediator.

[2] KHACHATRYAN 17D search for new scalar resonance decaying to $Z\gamma$ with $Z \to e^+e^-$, $\mu^+\mu^-$ in $pp$ collisions at 8 and 13 TeV; no signal seen.

[3] AAD 16AI search for excited quarks (EQ) and quantum black holes (QBH) in 3.2 fb$^{-1}$ at 13 TeV of data; exclude EQ below 4.4 TeV and QBH below 3.8 (6.2) TeV for RS1 (ADD) models. The visible cross section limit was obtained for 5 TeV resonance with $\sigma_G/M_G = 2\%$.

[4] KHACHATRYAN 16M search for $\gamma\gamma$ resonance using 19.7 fb$^{-1}$ at 8 TeV and 3.3 fb$^{-1}$ at 13 Tev; slight excess at 750 GeV noted; limit set on RS graviton.

[5] ABBIENDI 00D associated production limit is for $m_{X^0}$= 90–188 GeV, $m_{Y^0}$=0 at $E_{\rm cm}$=189 GeV. See also their Fig. 9.

[6] ABBIENDI 00D pair production limit is for $m_{X^0}$ = 45–94 GeV, $m_{Y^0}$=0 at $E_{\rm cm}$=189 GeV. See also their Fig. 12.

[7] ACKERSTAFF 97B associated production limit is for $m_{X^0}$ = 80–160 GeV, $m_{Y^0}$=0 from 10.0 pb$^{-1}$ at $E_{\rm cm}$ = 161 GeV. See their Fig. 3(a).

[8] ACKERSTAFF 97B pair production limit is for $m_{X^0}$ = 40–80 GeV, $m_{Y^0}$=0 from 10.0 pb$^{-1}$ at $E_{\rm cm}$ = 161 GeV. See their Fig. 3(b).

## Heavy Particle Production Cross Section

| VALUE (cm$^2$/N) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [1] AAD | 23P | ATLS | exotica search in association with $h \to \gamma\gamma$ |
| | | [2] TUMASYAN | 23BC | CMS | $\gamma$-jet resonance search |
| | | [3] TUMASYAN | 23BF | CMS | $pp + \gamma/Z + X$ search |
| | | [4] TUMASYAN | 22AG | CMS | SIMP search |
| | | [5] AAD | 21F | ATLS | monojet search |
| | | [6] AAIJ | 20AL | LHCB | $pp$ at 13 TeV, dimuon resonance |
| | | [7] SIRUNYAN | 20AY | CMS | $\Upsilon(1S)\mu^+\mu^-$ decay states |
| | | [8] SIRUNYAN | 20Z | CMS | multilepton BSM search, 13 TeV |
| | | [9] AABOUD | 19H | ATLS | di-photon-jet resonance |
| | | [10] AABOUD | 19V | ATLS | review, mediator-based DM |
| | | [11] SIRUNYAN | 19O | CMS | $pp \to \gamma \not{E}_T$ |
| | | [12] AABOUD | 18CJ | ATLS | $pp \to VV/\ell\ell/\ell\nu$, $V = W,Z,h$ |
| | | [13] AABOUD | 18CM | ATLS | $pp \to e\mu/e\tau/\mu\tau$ |
| | | [14] AAIJ | 18AJ | LHCB | $pp \to A' \to \mu^+\mu^-$; dark photon |
| | | [15] BANERJEE | 18 | NA64 | $eZ \to eZX(A')$ |
| | | [16] BANERJEE | 18A | NA64 | $eZ \to eZA'$, $A' \to \chi\chi$ |

| | | | | | |
|---|---|---|---|---|---|
| | | [17] MARSICANO | 18 | E137 | $e^+ e^- \rightarrow A'(\gamma)$ visible decay |
| | | [18] SIRUNYAN | 18BB | CMS | $pp \rightarrow Z' \rightarrow \ell^+ \ell^-$ at 13 TeV |
| | | [19] SIRUNYAN | 18DA | CMS | $pp \rightarrow$ Black Hole, string ball, sphaleron |
| | | [20] SIRUNYAN | 18DD | CMS | $pp \rightarrow jj$ |
| | | [21] SIRUNYAN | 18DR | CMS | $pp \rightarrow b\mu\overline{\mu}$ |
| | | [22] SIRUNYAN | 18DU | CMS | $pp \rightarrow \gamma\gamma$ |
| | | [23] SIRUNYAN | 18ED | CMS | $pp \rightarrow V \rightarrow Wh$; $h \rightarrow b\overline{b}$; $W \rightarrow \ell\nu$ |
| | | [24] AABOUD | 17B | ATLS | $WH$, $ZH$ resonance |
| | | [25] AAIJ | 17BR | LHCB | $pp \rightarrow \pi_V \pi_V$, $\pi_V \rightarrow jj$ |
| | | [26] AAD | 16O | ATLS | $\ell$ + ($\ell$s or jets) |
| | | [27] AAD | 16R | ATLS | $WW$ ,$WZ$ ,$ZZ$ resonance |
| | | [28] KRASZNAHO... | 16 | | $p^7$Li $\rightarrow$ $^8$Be $\rightarrow X(17)N$, $X(17) \rightarrow e^+ e^-$ |
| | | [29] LEES | 15E | BABR | $e^+ e^-$ collisions |
| | | [30] ADAMS | 97B | KTEV | $m$= 1.2–5 GeV |
| $< 10^{-36}$–$10^{-33}$ | 90 | [31] GALLAS | 95 | TOF | $m$= 0.5–20 GeV |
| $<$(4–0.3) $\times 10^{-31}$ | 95 | [32] AKESSON | 91 | CNTR | $m$ = 0–5 GeV |
| $<2 \times 10^{-36}$ | 90 | [33] BADIER | 86 | BDMP | $\tau$ = (0.05–1.) $\times 10^{-8}$s |
| $<2.5 \times 10^{-35}$ | | [34] GUSTAFSON | 76 | CNTR | $\tau > 10^{-7}$ s |

[1] AAD 23P search in 22 channels for exotica produced in association with $h \rightarrow \gamma\gamma$ in 139 fb$^{-1}$ of data. No signal observed. Limits placed on production cross section in various channels.

[2] TUMASYAN 23BC search for $\gamma$-jet resonance at CMS with 138 fb$^{-1}$ of data. No signal observed. Limits placed on quantum black hole and excited quark models.

[3] TUMASYAN 23BF search for $pp \rightarrow pp + \gamma/Z + X$ search where $X$ is missing particle using CMS-TOTEM with 37.2 fb$^{-1}$ of data. No signal observed. Limits placed on $\sigma$ vs. m plane.

[4] TUMASYAN 22AG search for strongly interacting neutral massive particles via trackless jets with 16.1 fb$^{-1}$ at 13 TeV; no signal detected; limits placed in mass vs. cross section plane for various simplified models.

[5] AAD 21F search for hard monojet production at ATLAS with 139 $^{-1}$ of 13 TeV data. No signal observed. Limits placed on invisible production cross-section recoiling against ISR and interpreted in variety of BSM models.

[6] AAIJ 20AL search for dimuon resonance from promptly decaying $X$ particle; no signal; limits placed on m($X$) up to 60 GeV depending on mixing in 2HDM .

[7] SIRUNYAN 20AY measured $\Upsilon$(1S) pair production cross section and searched for new states decaying into $\Upsilon(1S)\mu^+\mu^-$ at CMS with 13 TeV with 35.9 fb$^{-1}$. No signal is found and limits are set in $\sigma \cdot$ BF vs. mass plane for tetra-$b$-quarks with masses between 17.5 and 19 GeV and for generic search for narrow resonances with mass between 16.5 and 27 GeV.

[8] SIRUNYAN 20Z search for BSM physics via multilepton production with CMS at 13 TeV with 137 fb$^{-1}$; no signal is found and limits are set on type-III seesaw and other BSM models.

[9] AABOUD 19H searches for di-photon-jet resonance at 13 TeV and 36.7 fb$^{-1}$ of data; no signal found and limits placed on $\sigma \cdot$ BR vs. mass plane for various simplified models.

[10] AABOUD 19V review ATLAS searches for mediator-based DM at 7, 8, and 13 TeV with up to 37 fb$^{-1}$ of data; no signal found and limits set for wide variety of simplified models of dark matter.

[11] SIRUNYAN 19O search for $pp \rightarrow \gamma \not{E}_T$ at 13 TeV with 36.1 fb$^{-1}$; no signal found and limits set for various simplified models.

[12] AABOUD 18CJ make multichannel search for $pp \rightarrow VV/\ell\ell/\ell\nu$, $V = W,Z,h$ at 13 TeV, 36.1 fb$^{-1}$; no signal found; limits placed for several BSM models.
[13] AABOUD 18CM search for lepton-flavor violating resonance in $pp \rightarrow e\mu/e\tau/\mu\tau$ at 13 TeV, 36.1 fb$^{-1}$; no signal is found and limits placed for various BSM models.
[14] AAIJ 18AJ search for prompt and delayed dark photon decay $A' \rightarrow \mu^+\mu^-$ at LHCb detector using 1.6 fb$^{-1}$ of $pp$ collisions at 13 TeV; limits on m($A'$) vs. kinetic mixing are set.
[15] BANERJEE 18 search for dark photon $A'$/16.7 MeV boson $X$ at NA64 via $eZ \rightarrow eZX(A')$; no signal found and limits set on the $X$-$e^-$ coupling $\epsilon_e$ in the range $1.3 \times 10^{-4} \leq \epsilon_e \leq 4.2 \times 10^{-4}$ excluding part of the allowed parameter space.
[16] BANERJEE 18A search for invisibly decaying dark photons in $eZ \rightarrow eZA'$, $A' \rightarrow$ invisible; no signal found and limits set on mixing for m($A'$) $<$ 1 GeV.
[17] MARSICANO 18 search for dark photon $e^+e^- \rightarrow A'(\gamma)$ visible decay in SLAC E137 $e$ beam dump data. No signal observed and limits set in $\epsilon$ coupling vs m($A'$) plane, see their figure 7.
[18] SIRUNYAN 18BB search for high mass dilepton resonance; no signal found and exclude portions of p-space of $Z'$, KK graviton models.
[19] SIRUNYAN 18DA search for $pp \rightarrow$ Black Hole, string ball, sphaleron via high multiplicity events at 13 TeV, 35.9 fb$^{-1}$; no signal, require e.g. m(BH) $>$ 10.1 TeV.
[20] SIRUNYAN 18DD search for $pp \rightarrow jj$ deviations in dijet angular distribution. No signal observed. Set limits on large extra dimensions, black holes and DM mediators e.g. m(BH) $>$ 5.9–8.2 TeV.
[21] SIRUNYAN 18DR search for dimuon resonance in $pp \rightarrow b\mu\overline{\mu}$ at 8 and 13 TeV. Slight excess seen at m($\mu\overline{\mu}$) $\sim$ 28 GeV in some channels.
[22] SIRUNYAN 18DU search for high mass diphoton resonance in $pp \rightarrow \gamma\gamma$ at 13 TeV using 35.9 fb$^{-1}$; no signal; limits placed on RS Graviton, LED, and clockwork.
[23] SIRUNYAN 18ED search for $pp \rightarrow V \rightarrow Wh$; $h \rightarrow b\overline{b}$; $W \rightarrow \ell\nu$ at 13 TeV with 35.9 fb$^{-1}$; no signal; limits set on m($W'$) $>$ 2.9 TeV.
[24] AABOUD 17B exclude m($W'$, $Z'$) $<$ 1.49–2.31 TeV depending on the couplings and $W'/Z'$ degeneracy assumptions via $WH$, $ZH$ search in $pp$ collisions at 13 TeV with 3.2 fb$^{-1}$ of data.
[25] AAIJ 17BR search for long-lived hidden valley pions from Higgs decay. Limits are set on the signal strength as a function of the mass and lifetime of the long-lived particle in their Fig. 4 and Tab. 4.
[26] AAD 16O search for high $E_T$ $\ell$ + ($\ell$s or jets) with 3.2 fb$^{-1}$ at 13 TeV; exclude micro black holes mass $<$ 8 TeV (Fig. 3) for models with two extra dimensions.
[27] AAD 16R search for $WW$, $WZ$, $ZZ$ resonance in 20.3 fb$^{-1}$ at 8 TeV data; limits placed on massive RS graviton (Fig. 4).
[28] KRASZNAHORKAY 16 report $p$Li $\rightarrow$ Be $\rightarrow e\overline{e}N$ 5$\sigma$ resonance at 16.7 MeV– possible evidence for nuclear interference or new light boson . However, such nuclear interference was ruled out already by ZANG 17.
[29] LEES 15E search for long-lived neutral particles produced in $e^+e^-$ collisions in the Upsilon region, which decays into $e^+e^-$, $\mu^+\mu^-$, $e^\pm\mu^\mp$, $\pi^+\pi^-$, $K^+K^-$, or $\pi^\pm K^\mp$. See their Fig. 2 for cross section limits.
[30] ADAMS 97B search for a hadron-like neutral particle produced in $pN$ interactions, which decays into a $\rho^0$ and a weakly interacting massive particle. Upper limits are given for the ratio to $K_L$ production for the mass range 1.2–5 GeV and lifetime $10^{-9}$–$10^{-4}$ s. See also our Light Gluino Section.
[31] GALLAS 95 limit is for a weakly interacting neutral particle produced in 800 GeV/$c$ $pN$ interactions decaying with a lifetime of $10^{-4}$–$10^{-8}$ s. See their Figs. 8 and 9. Similar limits are obtained for a stable particle with interaction cross section $10^{-29}$–$10^{-33}$ cm$^2$. See Fig. 10.

[32] AKESSON 91 limit is from weakly interacting neutral long-lived particles produced in $pN$ reaction at 450 GeV/$c$ performed at CERN SPS. Bourquin-Gaillard formula is used as the production model. The above limit is for $\tau > 10^{-7}$ s. For $\tau > 10^{-9}$ s, $\sigma < 10^{-30}$ cm$^{-2}$/nucleon is obtained.

[33] BADIER 86 looked for long-lived particles at 300 GeV $\pi^-$ beam dump. The limit applies for nonstrongly interacting neutral or charged particles with mass >2 GeV. The limit applies for particle modes, $\mu^+\pi^-$, $\mu^+\mu^-$, $\pi^+\pi^-$X, $\pi^+\pi^-\pi^\pm$ etc. See their figure 5 for the contours of limits in the mass-$\tau$ plane for each mode.

[34] GUSTAFSON 76 is a 300 GeV FNAL experiment looking for heavy ($m$ >2 GeV) long-lived neutral hadrons in the M4 neutral beam. The above typical value is for $m = 3$ GeV and assumes an interaction cross section of 1 mb. Values as a function of mass and interaction cross section are given in figure 2.

## Production of New Penetrating Non-$\nu$ Like States in Beam Dump

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [1] ABRATENKO | 22A | MCBN | search for LLPs |
| | [2] ANDREEV | 22A | NA64 | search for new boson $X$ in $eZ \to eZX$ |
| | [3] ANDREEV | 21 | NA64 | search for new boson $X$ in $eZ \to eZX$ |
| | [4] LOSECCO | 81 | CALO | 28 GeV protons |

[1] ABRATENKO 22A search for LLPs from kaon decay in MicroBooNE absorber; no signal observed; limits placed for heavy neutral leptons (HNLs) and Higgs portal scalars (HPSs) in the MeV mass range.

[2] ANDREEV 22A search for new light B-L gauge boson $Z' \to \nu\overline{\nu}$ in electron beam dump at NA64; no signal observed; limits set in m($Z'$) vs coupling plane for m($Z'$) $\sim 10^{-6}$–1 GeV.

[3] ANDREEV 21 search for new invisibly decaying boson $X$ in $eZ \to eZX$ at NA64. No signal observed. Limits set in coupling vs. m(X) plane for m(X) $\sim 10^{-3}$ to 1 GeV.

[4] No excess neutral-current events leads to $\sigma$(production) $\times$ $\sigma$(interaction)$\times$acceptance $< 2.26 \times 10^{-71}$ cm$^4$/nucleon$^2$ (CL = 90%) for light neutrals. Acceptance depends on models (0.1 to 4. $\times 10^{-4}$).

# LIMITS ON CHARGED PARTICLES IN $e^+e^-$

## Heavy Particle Production Cross Section in $e^+e^-$

Ratio to $\sigma(e^+e^- \to \mu^+\mu^-)$ unless noted. See also entries in Free Quark Search and Magnetic Monopole Searches.

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [1] ADACHI | 23K | BELL | search for LLP in $B$ decays |
| | | [2] KILE | 18 | ALEP | $e^+e^- \to$ 4 jets |
| $<1 \times 10^{-3}$ | 90 | [3] ABLIKIM | 17AA | BES3 | $e^+e^- \to \ell\overline{\ell}\gamma$ |
| | | [4] ACKERSTAFF | 98P | OPAL | $Q$=1,2/3, $m$=45–89.5 GeV |
| | | [5] ABREU | 97D | DLPH | $Q$=1,2/3, $m$=45–84 GeV |
| | | [6] BARATE | 97K | ALEP | $Q$=1, $m$=45–85 GeV |
| $<2 \times 10^{-5}$ | 95 | [7] AKERS | 95R | OPAL | $Q$=1, $m$= 5–45 GeV |
| $<1 \times 10^{-5}$ | 95 | [7] AKERS | 95R | OPAL | $Q$=2, $m$= 5–45 GeV |
| $<2 \times 10^{-3}$ | 90 | [8] BUSKULIC | 93C | ALEP | $Q$=1, $m$=32–72 GeV |
| $<(10^{-2}$–1) | 95 | [9] ADACHI | 90C | TOPZ | $Q$=1, $m$=1–16, 18–27 GeV |
| $<7 \times 10^{-2}$ | 90 | [10] ADACHI | 90E | TOPZ | $Q = 1$, $m$ = 5–25 GeV |

| | | | | | |
|---|---|---|---|---|---|
| $<1.6 \times 10^{-2}$ | 95 | [11] KINOSHITA | 82 | PLAS | $Q$=3–180, $m$ <14.5 GeV |
| $<5.0 \times 10^{-2}$ | 90 | [12] BARTEL | 80 | JADE | $Q$=(3,4,5)/3 2–12 GeV |

[1] ADACHI 23K search for spin-0 LLP called $S$ in $B$ decays. No signal observed. Limits placed in branching fraction vs. m(S) plane.

[2] KILE 18 investigate archived ALEPH $e^+ e^- \rightarrow$ 4 jets data and see 4–5 $\sigma$ excess at 110 GeV.

[3] ABLIKIM 17AA search for dark photon $A \rightarrow \ell\overline{\ell}$ at 3.773 GeV with 2.93 fb$^{-1}$. Limits are set in $\epsilon$ vs m($A$) plane.

[4] ACKERSTAFF 98P search for pair production of long-lived charged particles at $E_{cm}$ between 130 and 183 GeV and give limits $\sigma <$(0.05–0.2) pb (95%CL) for spin-0 and spin-1/2 particles with $m$=45–89.5 GeV, charge 1 and 2/3. The limit is translated to the cross section at $E_{cm}$=183 GeV with the $s$ dependence described in the paper. See their Figs. 2–4.

[5] ABREU 97D search for pair production of long-lived particles and give limits $\sigma <$(0.4–2.3) pb (95%CL) for various center-of-mass energies $E_{cm}$=130–136, 161, and 172 GeV, assuming an almost flat production distribution in cos$\theta$.

[6] BARATE 97K search for pair production of long-lived charged particles at $E_{cm}$ = 130, 136, 161, and 172 GeV and give limits $\sigma <$(0.2–0.4) pb (95%CL) for spin-0 and spin-1/2 particles with $m$=45–85 GeV. The limit is translated to the cross section at $E_{cm}$=172 GeV with the $E_{cm}$ dependence described in the paper. See their Figs. 2 and 3 for limits on $J = 1/2$ and $J = 0$ cases.

[7] AKERS 95R is a CERN-LEP experiment with W$_{cm}$ $\sim$ $m_Z$. The limit is for the production of a stable particle in multihadron events normalized to $\sigma(e^+ e^- \rightarrow$ hadrons). Constant phase space distribution is assumed. See their Fig. 3 for bounds for $Q = \pm 2/3$, $\pm 4/3$.

[8] BUSKULIC 93C is a CERN-LEP experiment with W$_{cm}$ = $m_Z$. The limit is for a pair or single production of heavy particles with unusual ionization loss in TPC. See their Fig. 5 and Table 1.

[9] ADACHI 90C is a KEK-TRISTAN experiment with W$_{cm}$ = 52–60 GeV. The limit is for pair production of a scalar or spin-1/2 particle. See Figs. 3 and 4.

[10] ADACHI 90E is KEK-TRISTAN experiment with W$_{cm}$ = 52–61.4 GeV. The above limit is for inclusive production cross section normalized to $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-) \cdot \beta(3 - \beta^2)/2$, where $\beta = (1 - 4m^2/\mathrm{W}^2_{cm})^{1/2}$. See the paper for the assumption about the production mechanism.

[11] KINOSHITA 82 is SLAC PEP experiment at W$_{cm}$ = 29 GeV using lexan and $^{39}$Cr plastic sheets sensitive to highly ionizing particles.

[12] BARTEL 80 is DESY-PETRA experiment with W$_{cm}$ = 27–35 GeV. Above limit is for inclusive pair production and ranges between 1. $\times 10^{-1}$ and 1. $\times 10^{-2}$ depending on mass and production momentum distributions. (See their figures 9, 10, 11).

## Branching Fraction of $Z^0$ to a Pair of Stable Charged Heavy Fermions

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<5 \times 10^{-6}$ | 95 | [1] AKERS | 95R | OPAL | $m$= 40.4–45.6 GeV |
| $<1 \times 10^{-3}$ | 95 | AKRAWY | 90O | OPAL | $m$ = 29–40 GeV |

[1] AKERS 95R give the 95% CL limit $\sigma(X\overline{X})/\sigma(\mu\mu) < 1.8\times10^{-4}$ for the pair production of singly- or doubly-charged stable particles. The limit applies for the mass range 40.4–45.6 GeV for $X^{\pm}$ and < 45.6 GeV for $X^{\pm\pm}$. See the paper for bounds for $Q = \pm 2/3$, $\pm 4/3$.

# LIMITS ON CHARGED PARTICLES IN HADRONIC REACTIONS

## MASS LIMITS for Long-Lived Charged Heavy Fermions

Limits are for spin 1/2 particles with no color and $SU(2)_L$ charge. The electric charge $Q$ of the particle (in the unit of $e$) is therefore equal to its weak hypercharge. Pair production by Drell-Yan like $\gamma$ and $Z$ exchange is assumed to derive the limits.

| VALUE (GeV) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [1] AAD | 23BT | ATLS | multi-charged LLP |
| | | [2] SIRUNYAN | 20N | CMS | disappearing track LLP |
| >660 | 95 | [3] AAD | 15BJ | ATLS | $\lvert Q\rvert = 2$ |
| >200 | 95 | [4] CHATRCHYAN | 13AB | CMS | $\lvert Q\rvert = 1/3$ |
| >480 | 95 | [4] CHATRCHYAN | 13AB | CMS | $\lvert Q\rvert = 2/3$ |
| >574 | 95 | [4] CHATRCHYAN | 13AB | CMS | $\lvert Q\rvert = 1$ |
| >685 | 95 | [4] CHATRCHYAN | 13AB | CMS | $\lvert Q\rvert = 2$ |
| >140 | 95 | [5] CHATRCHYAN | 13AR | CMS | $\lvert Q\rvert = 1/3$ |
| >310 | 95 | [5] CHATRCHYAN | 13AR | CMS | $\lvert Q\rvert = 2/3$ |

[1] AAD 23BT search for multi-charged long-lived particles with ATLAS detector using 139 $fb^{-1}$. No signal observed. Limits placed on LLP mass vs. charge plane.

[2] SIRUNYAN 20N search for LLPs using disappearing track signature at CMS at 13 TeV with 101 $fb^{-1}$; no signal; limits placed on long-lived winos and higgsinos from SUSY depending on mass and lifetime: e.g. at 95% CL, for a purely higgsino neurtalino, m(chargino) > 750 (175) GeV for $\tau = 3$ (0.05) ns, and for a purely wino neutralino, m(chargino) > 884 (474) GeV for $\tau = 3$ (0.2) ns.

[3] AAD 15BJ use 20.3 $fb^{-1}$ of $pp$ collisions at $E_{cm} = 8$ TeV. See paper for limits for $\lvert Q\rvert$ = 3, 4, 5, 6.

[4] CHATRCHYAN 13AB use 5.0 $fb^{-1}$ of $pp$ collisions at $E_{cm} = 7$ TeV and 18.8 $fb^{-1}$ at $E_{cm} = 8$ TeV. See paper for limits for $\lvert Q\rvert$ = 3, 4,..., 8.

[5] CHATRCHYAN 13AR use 5.0 $fb^{-1}$ of $pp$ collisions at $E_{cm} = 7$ TeV.

## Heavy Particle Production Cross Section

| VALUE (nb) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [1] AAD | 24B | ATLS | non-resonant jet search |
| | | [2] AAD | 22G | ATLS | vector-like matter search |
| | | [3] TUMASYAN | 22H | CMS | search for new matter via multileptons |
| | | [4] SIRUNYAN | 21T | CMS | model independent search |
| | | [5] SIRUNYAN | 20C | CMS | $4t$ search via multileptons |
| | | [6] AABOUD | 19AA | ATLS | BSM search |
| | | [7] AABOUD | 19Q | ATLS | single top +MET |
| | | [8] AABOUD | 17D | ATLS | anomalous $WWjj$, $WZjj$ |
| | | [9] AABOUD | 17L | ATLS | $m$>870 GeV, $Z(\rightarrow \nu\nu)tX$ |
| | | [10] SIRUNYAN | 17B | CMS | $tH$ |
| | | [11] SIRUNYAN | 17C | CMS | $Z + (t$ or $b)$ |
| | | [12] SIRUNYAN | 17J | CMS | $X_{5/3} \rightarrow tW$ |
| | | [13] AAIJ | 15BD | LHCB | $m$=124–309 GeV |
| | | [14] AAD | 13AH | ATLS | $\lvert q\rvert$=(2–6)$e$, $m$=50–600 GeV |
| $<1.2 \times 10^{-3}$ | 95 | [15] AAD | 11I | ATLS | $\lvert q\rvert$=10$e$, $m$=0.2–1 TeV |
| $<1.0 \times 10^{-5}$ | 95 | [16,17] AALTONEN | 09Z | CDF | $m$>100 GeV, noncolored |
| $<4.8 \times 10^{-5}$ | 95 | [16,18] AALTONEN | 09Z | CDF | $m$>100 GeV, colored |
| $< 0.31–0.04 \times 10^{-3}$ | 95 | [19] ABAZOV | 09M | D0 | pair production |

| | | | | | |
|---|---|---|---|---|---|
| <0.19 | 95 | [20] AKTAS | 04C | H1 | $m$=3–10 GeV |
| <0.05 | 95 | [21] ABE | 92J | CDF | $m$=50–200 GeV |
| <30–130 | | [22] CARROLL | 78 | SPEC | $m$=2–2.5 GeV |
| <100 | | [23] LEIPUNER | 73 | CNTR | $m$=3–11 GeV |

[1] AAD 24B search for non-resonant jets +MET at $\sqrt{s} = 13$ TeV with 139 fb$^{-1}$. No excess observed. Limits placed on dark sector model mediator mass and coupling.

[2] AAD 22G search for single vector-like quark $T$ with $T \to t h$ in all hadronic mode with 139 fb$^{-1}$ at 13 TeV; no signal observed; limits placed in mass vs. coupling plane.

[3] TUMASYAN 22H search for new states of matter via non-resonant mutilepton production based on a luminosity of 138 fb$^{-1}$; no signal observed; limits placed on vector-like leptons, leptoquarks, and new fermions from type-III seesaw model.

[4] SIRUNYAN 21T perform model unspecific search for deviations from SM with CMS at 13 TeV with 35.9$^{-1}$ fb data in numerous signature channels. No deviations from SM found.

[5] SIRUNYAN 20C search for four top-quark production with decay to multileptons at CMS at 13 TeV with 137 fb$^{-1}$; no signal is found and limits are placed on the Higgs boson oblique parameter in the effective field theory framework (EFT) and the model parameters (tan$\beta$).

[6] AABOUD 19AA search for BSM physics at 13 TeV with 3.2 fb$^{-1}$ in $> 10^5$ regions of $>$ 700 event classes; no significant signal found.

[7] AABOUD 19Q search for single top+MET events at 13 TeV with 36.1 fb$^{-1}$ of data; no signal found and limits set in $\sigma$ or coupling vs. mass plane for variety of simplified models including DM and vector-like top quark $T$.

[8] AABOUD 17D search for $WWjj$, $WZjj$ in $pp$ collisions at 8 TeV with 3.2 fb$^{-1}$; set limits on anomalous couplings.

[9] AABOUD 17L search for the pair production of heavy vector-like $T$ quarks in the $Z(\to \nu\nu)tX$ final state.

[10] SIRUNYAN 17B search for vector-like quark $pp \to TX \to tHX$ in 2.3 fb$^{-1}$ at 13 TeV; no signal seen; limits placed.

[11] SIRUNYAN 17C search for vector-like quark $pp \to TX \to Z + (t \text{ or } b)$ in 2.3 fb$^{-1}$ at 13 TeV; no signal seen; limits placed.

[12] SIRUNYAN 17J search for $pp \to X_{5/3} X_{5/3} \to tWtW$ with 2.3 fb$^{-1}$ at 13 TeV. No signal seen: m($X$) $>$ 1020 (990) GeV for RH (LH) new charge 5/3 quark.

[13] AAIJ 15BD search for production of long-lived particles in $pp$ collisions at $E_{cm} = 7$ and 8 TeV. See their Table 6 for cross section limits.

[14] AAD 13AH search for production of long-lived particles with $|q|$=(2–6)$e$ in $pp$ collisions at $E_{cm} = 7$ TeV with 4.4 fb$^{-1}$. See their Fig. 8 for cross section limits.

[15] AAD 11I search for production of highly ionizing massive particles in $pp$ collisions at $E_{cm} = 7$ TeV with L = 3.1 pb$^{-1}$. See their Table 5 for similar limits for $|q| = 6e$ and 17$e$, Table 6 for limits on pair production cross section.

[16] AALTONEN 09Z search for long-lived charged particles in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $L = 1.0$ fb$^{-1}$. The limits are on production cross section for a particle of mass above 100 GeV in the region $|\eta| \lesssim 0.7$, $p_T > 40$ GeV, and $0.4 < \beta < 1.0$.

[17] Limit for weakly interacting charge-1 particle.

[18] Limit for up-quark like particle.

[19] ABAZOV 09M search for pair production of long-lived charged particles in $p\overline{p}$ collisions at $E_{cm} = 1.96$ TeV with $L = 1.1$ fb$^{-1}$. Limit on the cross section of (0.31–0.04) pb (95% CL) is given for the mass range of 60–300 GeV, assuming the kinematics of stau pair production.

[20] AKTAS 04C look for charged particle photoproduction at HERA with mean c.m. energy of 200 GeV.

[21] ABE 92J look for pair production of unit-charged particles which leave detector before decaying. Limit shown here is for $m$=50 GeV. See their Fig. 5 for different charges and stronger limits for higher mass.

[22] CARROLL 78 look for neutral, $S = -2$ dihyperon resonance in $p p \to 2K^+ X$. Cross section varies within above limits over mass range and $p_{lab}$ = 5.1–5.9 GeV/$c$.

[23] LEIPUNER 73 is an NAL 300 GeV $p$ experiment. Would have detected particles with lifetime greater than 200 ns.

## Heavy Particle Production Differential Cross Section

| VALUE ($cm^2 sr^{-1} GeV^{-1}$) | CL% | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| | | [1] HAYRAPETY... | 23F | CMS | | top $\to$ $\ell$s via EFT ops. |
| $<2.6 \times 10^{-36}$ | 90 | [2] BALDIN | 76 | CNTR | − | $Q$= 1, $m$=2.1–9.4 GeV |
| $<2.2 \times 10^{-33}$ | 90 | [3] ALBROW | 75 | SPEC | ± | $Q$= ±1, $m$=4–15 GeV |
| $<1.1 \times 10^{-33}$ | 90 | [3] ALBROW | 75 | SPEC | ± | $Q$= ±2, $m$=6–27 GeV |
| $<8. \times 10^{-35}$ | 90 | [4] JOVANOV... | 75 | CNTR | ± | $m$=15–26 GeV |
| $<1.5 \times 10^{-34}$ | 90 | [4] JOVANOV... | 75 | CNTR | ± | $Q$= ±2, $m$=3–10 GeV |
| $<6. \times 10^{-35}$ | 90 | [4] JOVANOV... | 75 | CNTR | ± | $Q$= ±2, $m$=10–26 GeV |
| $<1. \times 10^{-31}$ | 90 | [5] APPEL | 74 | CNTR | ± | $m$=3.2–7.2 GeV |
| $<5.8 \times 10^{-34}$ | 90 | [6] ALPER | 73 | SPEC | ± | $m$=1.5–24 GeV |
| $<1.2 \times 10^{-35}$ | 90 | [7] ANTIPOV | 71B | CNTR | − | $Q$=−, $m$=2.2–2.8 |
| $<2.4 \times 10^{-35}$ | 90 | [8] ANTIPOV | 71C | CNTR | − | $Q$=−, $m$=1.2–1.7, 2.1–4 |
| $<2.4 \times 10^{-35}$ | 90 | BINON | 69 | CNTR | − | $Q$=−, $m$=1–1.8 GeV |
| $<1.5 \times 10^{-36}$ | | [9] DORFAN | 65 | CNTR | | Be target $m$=3–7 GeV |
| $<3.0 \times 10^{-36}$ | | [9] DORFAN | 65 | CNTR | | Fe target $m$=3–7 GeV |

[1] HAYRAPETYAN 23F search for anomalous top $\to$ leptons decay via effective operators. No signal observed. Limits placed on EFT operators.

[2] BALDIN 76 is a 70 GeV Serpukhov experiment. Value is per Al nucleus at $\theta = 0$. For other charges in range −0.5 to −3.0, CL = 90% limit is $(2.6 \times 10^{-36})/|(\text{charge})|$ for mass range (2.1–9.4 GeV) $\times |(\text{charge})|$. Assumes stable particle interacting with matter as do antiprotons.

[3] ALBROW 75 is a CERN ISR experiment with $E_{cm}$ = 53 GeV. $\theta$ = 40 mr. See figure 5 for mass ranges up to 35 GeV.

[4] JOVANOVICH 75 is a CERN ISR 26+26 and 15+15 GeV $p p$ experiment. Figure 4 covers ranges $Q$ = 1/3 to 2 and $m$ = 3 to 26 GeV. Value is per GeV momentum.

[5] APPEL 74 is NAL 300 GeV $p$W experiment. Studies forward production of heavy (up to 24 GeV) charged particles with momenta 24–200 GeV (−charge) and 40–150 GeV (+charge). Above typical value is for 75 GeV and is per GeV momentum per nucleon.

[6] ALPER 73 is CERN ISR 26+26 GeV $p p$ experiment. $p$ >0.9 GeV, $0.2 < \beta < 0.65$.

[7] ANTIPOV 71B is from same 70 GeV $p$ experiment as ANTIPOV 71C and BINON 69.

[8] ANTIPOV 71C limit inferred from flux ratio. 70 GeV $p$ experiment.

[9] DORFAN 65 is a 30 GeV/$c$ $p$ experiment at BNL. Units are per GeV momentum per nucleus.

## Long-Lived Heavy Particle Invariant Cross Section

| VALUE ($cm^2/GeV^2/N$) | CL% | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| $< 5–700 \times 10^{-35}$ | 90 | [1] BERNSTEIN | 88 | CNTR | | |
| $< 5–700 \times 10^{-37}$ | 90 | [1] BERNSTEIN | 88 | CNTR | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| $<2.5 \times 10^{-36}$ | 90 | [2] THRON | 85 | CNTR | $-$ | $Q$= 1, $m$=4–12 GeV |
| $<1. \times 10^{-35}$ | 90 | [2] THRON | 85 | CNTR | $+$ | $Q$= 1, $m$=4–12 GeV |
| $<6. \times 10^{-33}$ | 90 | [3] ARMITAGE | 79 | SPEC | | $m$=1.87 GeV |
| $<1.5 \times 10^{-33}$ | 90 | [3] ARMITAGE | 79 | SPEC | | $m$=1.5–3.0 GeV |
| | | [4] BOZZOLI | 79 | CNTR | $\pm$ | $Q = (2/3, 1, 4/3, 2)$ |
| $<1.1 \times 10^{-37}$ | 90 | [5] CUTTS | 78 | CNTR | | $m$=4–10 GeV |
| $<3.0 \times 10^{-37}$ | 90 | [6] VIDAL | 78 | CNTR | | $m$=4.5–6 GeV |

[1] BERNSTEIN 88 limits apply at $x = 0.2$ and $p_T = 0$. Mass and lifetime dependence of limits are shown in the regions: $m = 1.5$–$7.5$ GeV and $\tau = 10^{-8}$–$2 \times 10^{-6}$ s. First number is for hadrons; second is for weakly interacting particles.

[2] THRON 85 is FNAL 400 GeV proton experiment. Mass determined from measured velocity and momentum. Limits are for $\tau > 3 \times 10^{-9}$ s.

[3] ARMITAGE 79 is CERN-ISR experiment at $E_{cm} = 53$ GeV. Value is for $x = 0.1$ and $p_T = 0.15$. Observed particles at $m = 1.87$ GeV are found all consistent with being antideuterons.

[4] BOZZOLI 79 is CERN-SPS 200 GeV $pN$ experiment. Looks for particle with $\tau$ larger than $10^{-8}$ s. See their figure 11–18 for production cross-section upper limits vs mass.

[5] CUTTS 78 is $p$Be experiment at FNAL sensitive to particles of $\tau > 5 \times 10^{-8}$ s. Value is for $-0.3 < x < 0$ and $p_T = 0.175$.

[6] VIDAL 78 is FNAL 400 GeV proton experiment. Value is for $x = 0$ and $p_T = 0$. Puts lifetime limit of $< 5 \times 10^{-8}$ s on particle in this mass range.

## Long-Lived Heavy Particle Production ($\sigma$(Heavy Particle) / $\sigma(\pi)$)

| VALUE | EVTS | DOCUMENT ID | | TECN | CHG | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| $<10^{-8}$ | | [1] NAKAMURA | 89 | SPEC | $\pm$ | $Q$= $(-5/3,\pm2)$ |
| | 0 | [2] BUSSIERE | 80 | CNTR | $\pm$ | $Q$= (2/3,1,4/3,2) |

[1] NAKAMURA 89 is KEK experiment with 12 GeV protons on Pt target. The limit applies for mass $\lesssim$ 1.6 GeV and lifetime $\gtrsim 10^{-7}$ s.

[2] BUSSIERE 80 is CERN-SPS experiment with 200–240 GeV protons on Be and Al target. See their figures 6 and 7 for cross-section ratio vs mass.

## Production and Capture of Long-Lived Massive Particles

| VALUE ($10^{-36}$ cm$^2$) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [1] AAD | 21X | ATLS | search for captured LLPs |
| | [2] ACHARYA | 21 | INDU | dyons production, capture |
| <20 to 800 | [3] ALEKSEEV | 76 | ELEC | $\tau$=5 ms to 1 day |
| <200 to 2000 | [3] ALEKSEEV | 76B | ELEC | $\tau$=100 ms to 1 day |
| <1.4 to 9 | [4] FRANKEL | 75 | CNTR | $\tau$=50 ms to 10 hours |
| <0.1 to 9 | [5] FRANKEL | 74 | CNTR | $\tau$=1 to 1000 hours |

[1] AAD 21X search for LLPs which come to rest in ATLAS detector to deposit energy between collisions. No signal observed in 111 fb$^{-1}$ of data. Limits placed in lifetime vs. mass place assuming model with gluino hadrons: e.g. m > 1.4 TeV for $\tau \sim 10^{-5}$ to $10^3$ sec.

[2] ACHARYA 21 search for dyons (carrying electric and magnetic charge) and monopoles via production and capture in 6.46 fb$^{-1}$ of 13 TeV LHC data. No signal observed. Limits placed in mass vs. magnetic charge plane.

[3] ALEKSEEV 76 and ALEKSEEV 76B are 61–70 GeV $p$ Serpukhov experiment. Cross section is per Pb nucleus.

[4] FRANKEL 75 is extension of FRANKEL 74.

[5] FRANKEL 74 looks for particles produced in thick Al targets by 300–400 GeV/$c$ protons.

## Long-Lived Particle (LLP) Search at Hadron Collisions

Limits are for cross section times branching ratio.

| VALUE (fb) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [1] AAD | 23AM | ATLS | LLP higgsino search |
| | | [2] AAD | 23AR | ATLS | LLP search via displaced $\gamma$ |
| | | [3] AAD | 23BQ | ATLS | displaced dimuon search |
| | | [4] AAD | 23CO | ATLS | highly ionizing LLP/monopole |
| | | [5] AAD | 23G | ATLS | heavy highly ionizing LLP search |
| | | [6] AAD | 23I | ATLS | light LLP via collimated decays |
| | | [7] TUMASYAN | 23AO | CMS | LLP search via trackless jets |
| | | [8] TUMASYAN | 23G | CMS | LLP search via displaced dimuons |
| | | [9] AAD | 22H | ATLS | LLP search with $\mu$ spectrometer |
| | | [10] AAD | 22K | ATLS | LLP search via displaced jets in the calorimeter |
| | | [11] AAD | 22U | ATLS | LLP/chargino search via tracklet |
| | | [12] AAIJ | 22U | LHCB | LLP semileptonic decay to muon |
| | | [13] ACHARYA | 22A | MOED | monopoles/HECOs at LHC |
| | | [14] TUMASYAN | 22AD | CMS | heavy neutral lepton LLP search |
| | | [15] TUMASYAN | 22AF | CMS | LLP search via displaced lepton tracks |
| | | [16] TUMASYAN | 22M | CMS | LLP search via $ZH$ production |
| | | [17] TUMASYAN | 22N | CMS | LLP search via dimuons |
| | | [18] AAD | 21AL | ATLS | charged LLPs search |
| | | [19] AAD | 21BA | ATLS | LLP from higgs decay search |
| | | [20] AAIJ | 21V | LHCB | LLP $\rightarrow e\mu\nu$ search |
| | | [21] SIRUNYAN | 21AF | CMS | LLP search via displaced jets |
| $<$ 0.07 | 95 | [22] SIRUNYAN | 21U | CMS | LLP search via displaced jets |
| | | [23] TUMASYAN | 21 | CMS | LLP endcap muon detector searches |
| | | [24] AAD | 20D | ATLS | $pp \rightarrow$ LLPs at 13 TeV |
| | | [25] AAD | 20J | ATLS | scalar boson decay to LLPs |
| | | [26] AAD | 20M | ATLS | LLP top squark decay to $\mu$ |
| | | [27] AAD | 20P | ATLS | LLP dark photon search |
| | | [28] AAIJ | 20AL | LHCB | $pp$ dimuon resonance |
| | | [29] BALL | 20 | | LLP milli-charged particles at LHC |
| | | [30] AABOUD | 19AE | ATLS | $pp$ at 13 TeV |
| | | [31] AABOUD | 19AK | ATLS | $pp \rightarrow \Phi \rightarrow ZZ_d$ |
| | | [32] AABOUD | 19AM | ATLS | DY multi-charged LLP production |
| | | [33] AABOUD | 19AO | ATLS | LLP via displaced jets |
| | | [34] AABOUD | 19AT | ATLS | heavy, charged LLPs |
| | | [35] AABOUD | 19G | ATLS | LLP decay to $\mu^+\mu^-$ |
| | | [36] SIRUNYAN | 19BH | CMS | LLP via displaced jets |
| | | [37] SIRUNYAN | 19BT | CMS | LLP via displaced jets+MET |
| | | [38] SIRUNYAN | 19CA | CMS | LLP $\rightarrow \gamma$ search |
| | | [39] SIRUNYAN | 19Q | CMS | $pp \rightarrow j$ + displaced dark quark jet |
| | | [40] SIRUNYAN | 18AW | CMS | Long-lived particle search |
| | | [41] AAIJ | 16AR | LHCB | $H \rightarrow XX$ LLPs |
| | | [42] KHACHATRY... | 16BW | CMS | direct production: HSCPs |
| $<$2000 | 90 | [43] BADIER | 86 | BDMP | $\tau = (0.05\text{–}1.) \times 10^{-8}$s |

[1] AAD 23AM search for long-lived higgsinos from gauge-mediation which decay to $Z$ or $H$. No signal observed. Limits placed in $c\tau$ vs m($\chi$) plane for various simplified models.

[2] AAD 23AR search for long-lived particles via decay to displaced $\gamma$ with 139 fb$^{-1}$ of data. No signal observed. Limits placed in m vs. $\tau$ and BF vs. $\tau$ planes for gauge-mediated SUSY model.

[3] AAD 23BQ search for displaced dimuon events in ATLAS detector. No signal observed. Limits placed in smuon lifetime vs. mass plane for long-lived smuon model.

[4] AAD 23CO search for monopoles and high-electric-charge LLPs in ATLAS with 139 fb$^{-1}$ of data. No signal observed. Limits placed in mass vs. charge plane.

[5] AAD 23G search for heavy highly ionizing long-lived particles with 139 fb$^{-1}$ of data. No signal observed. Limits placed in m vs. $\tau$ plane for several SUSY models.

[6] AAD 23I search for light long-lived particles decaying to collimated decay products (e.g. dileptons). No signal observed. Limits placed in BF vs. $\tau$ plane.

[7] TUMASYAN 23AO search for trackless jets from LLP production at CMS. No signal observed. Limits placed for SUSY model with long-lived neutralino in m($\chi$) vs. $c\tau$ plane.

[8] TUMASYAN 23G search for LLP decaying to displaced dimuons at CM with 97.6 fb$^{-1}$ fb of data. No signal observed. Limits placed in $c\tau$ vs. m plane for hidden Abelian Higgs simplified model.

[9] AAD 22H search for scalar mediator decay to two LLPs which decay in muon chambers with 139 fb$^{-1}$ at 13 TeV; no signal detected; limits placed on various simplified models.

[10] AAD 22K search for LLP pair production via scalar mediator with LLP decay in hadron calorimeter; no signal detected; limits placed for various simplified models.

[11] AAD 22U search for chargino LLP via disappearing tracks; no signal observed; limits placed in m(chargino) vs lifetime plane for cases of higgsino- or wino-like chargino .

[12] AAIJ 22U reports search for LLP production at LHCB with 5.4 fb$^{-1}$ at 13 TeV followed by semileptonic decay to muon; no signal detected; limits placed in mass or lifetime vs. cross section plane for several simplified models.

[13] ACHARYA 22A report search for monople and HECO production via DY at 8 TeV LHC with 2.2 fb$^{-1}$ with MoEDAL detector; no signal detected; limits placed in mass vs. cross section plane for various electric/magnetic charge scenarios.

[14] TUMASYAN 22AD search for heavy neutral lepton which decays as LLP to trilepton state with 138 fb$^{-1}$ at 13 TeV; no signal detected; limits placed in mass vs. coupling plane.

[15] TUMASYAN 22AF search for LLPs via displaced lepton vertices. The analysis is performed with an integrated luminosity of 118 (113) fb$^{-1}$ when analyzing the $ee$ ($e\mu$, $\mu\mu$) channel; no signal detected; limits placed for a variety of simplified models.

[16] TUMASYAN 22M search in 117 fb$^{-1}$ of 13 TeV data for $ZH$ production with $H \rightarrow SS$ where $S$ is a LLP; no signal observed; limits placed in decay length vs. branching fraction plane.

[17] TUMASYAN 22N search in 101 fb$^{-1}$ of 13 TeV data for LLP production via decay to dimuons; no signal observed; limits placed on mass vs. coupling or lifetime for a variety of simplified models.

[18] AAD 21AL reports on ATLAS search for long-lived charged particles with 139 fb$^{-1}$ at 13 TeV. No signal observed. Limits placed in lifetime vs. mass plane: e.g. for $\tau$(LLP) $\sim$ 0.1 ns, m(selectron) > 720 GeV.

[19] AAD 21BA search for long-lived particles from $ZH$ production ($H \rightarrow b\overline{b}$) with 2 displaced vertices in 139 fb$^{-1}$ of data at 13 TeV. No signal detected. Limits placed in branching fraction vs. lifetime plane.

[20] AAIJ 21V search for $pp \rightarrow$ LLP + LLP with LLP$\rightarrow e\mu\nu$ in the lifetime range between 2 and 50 ps at LHCb with 5.4 fb$^{-1}$ at 13 TeV. No signal observed. Limits placed in LLP cross section vs. mass or lifetime plane for m(LLP) $\sim$ 7 to 50 GeV.

[21] SIRUNYAN 21AF search for LLPs at CMS via jets with 2 displaced vertices in 140 fb$^{-1}$ of data at 13 TeV. No signal observed. Limits placed for RPV SUSY models in which a long-lived neutralino or gluino decays into a multijet final state with top, bottom, and strange quarks.

[22] SIRUNYAN 21U search for long-lived particles (LLPs) via displaced jets at CMS with LHC13 and 132 fb$^{-1}$. No signal detected. Limits placed on simplified model production of LLP $X \rightarrow q\overline{q}$ with $\sigma < 0.07$ fb for m(X) > 500 GeV and $c\tau \sim$ 2 to 250 mm.

[23] TUMASYAN 21 search for long-lived particles in CMS muon endcap detector in 137 fb$^{-1}$ of data at 13 TeV. No signal detected. Limits are placed depending on the branching fraction of Higgs boson to LLP decaying to $dd$, $bb$, and $\tau^+\tau^-$, depending on proper decay length, and LLP masses.

[24] AAD 20D search for opposite-sign dileptons originating from long-lived particles in $pp$ collisions at 13 Tev with 32.8 fb$^{-1}$; limits placed in squark cross section vs. $c\tau$ plane for RPV SUSY.

[25] AAD 20J search for scalar boson decay to two long-lived particles; no signal; limits placed in BF vs $c\tau$ plane for various mass hypotheses. This search is also combined with other ATLAS displaced-jet searches.

[26] AAD 20M search for long-lived top-squarks decay to $\mu$ and hadrons; no signal; limits placed in cross section vs. mass and mass vs. lifetime planes .

[27] AAD 20P search for long-lived dark photons produced from the decay of a scalar boson, with each dark photon decaying into displaced collimated leptons or light hadrons at 13 TeV with 36 fb$^{-1}$; no signal; limits placed in $\sigma \cdot$ BF vs. $c\tau$ and other planes.

[28] AAIJ 20AL search for long-lived $X \rightarrow \mu^+\mu^-$ decays in 5.1 fb$^{-1}$ of LHCb data at 13 TeV; no signal; limits placed on m($X$) up to 3 GeV depending on kinetic mixing.

[29] BALL 20 search for long-lived milli-charged particles produced at LHC; limits placed in charge vs. mass plane (Fig. 8).

[30] AABOUD 19AE search for long-lived particles via displaced jets using 10.8 fb$^{-1}$ or 33.0 fb$^{-1}$ data (depending on a trigger) at 13 TeV; no signal found and limits set in branching ratio vs. decay length plane.

[31] AABOUD 19AK searches for long-lived particle $Z_d$ via $pp \rightarrow \Phi \rightarrow Z Z_d$ at 13 TeV with 36.1 fb$^{-1}$; no signal found and limits set in $\sigma\times$BR vs. lifetime plane for simplified model.

[32] AABOUD 19AM search for Drell-Yan (DY) production of long-lived multi-charge particles at 13 TeV with 36.1 fb$^{-1}$ of data; no signal found and exclude 50 GeV < m(LLMCP) < 980–1220 GeV for electric charge $|q|$ = (2–7)e.

[33] AABOUD 19AO search for neutral long-lived particles producing displaced jets at 13 TeV with 36.1 fb$^{-1}$ of data; no signal found and exclude regions of $\sigma \cdot$ BR vs. lifetime plane for various models.

[34] AABOUD 19AT search for heavy, charged long-lived particles at 13 TeV with 36.1 fb$^{-1}$; no signal found and upper limits set on masses of various hypothetical particles.

[35] AABOUD 19G search for long-lived particle with decay to $\mu^+\mu^-$ at 13 TeV with 32.9 fb$^{-1}$; no signal found and limits set in combinations of lifetime, mass and coupling planes for various simplified models.

[36] SIRUNYAN 19BH search for long-lived SUSY particles via displaced jets at 13 TeV with 35.9 fb$^{-1}$; no signal found and limits placed in mass vs lifetime plane for various hypothetical models.

[37] SIRUNYAN 19BT search for displaced jet(s)+$\not{E}_T$ at 13 TeV with 137 fb$^{-1}$; no signal found and limits placed in mass vs lifetime plane for gauge mediated SUSY breaking models.

[38] SIRUNYAN 19CA search for gluino/squark decay to long-lived neutralino, decay to $\gamma$ in GMSB; no signal, limits placed in m($\chi$) vs. lifetime plane for SPS8 GMSB benchmark point .

[39] SIRUNYAN 19Q search for $pp \rightarrow j +$ displaced jet via dark quark with 13 TeV at 16.1 fb$^{-1}$; no signal found and limits set in mass vs lifetime plane for dark quark/dark pion model.

[40] SIRUNYAN 18AW search for very long lived particles (LLPs) decaying hadronically or to $\mu\overline{\mu}$ in CMS detector; none seen/limits set on lifetime vs. cross section.

[41] AAIJ 16AR search for long lived particles from $H \rightarrow XX$ with displaced $X$ decay vertex using 0.62 fb$^{-1}$ at 7 TeV; limits set in Fig. 7.

[42] KHACHATRYAN 16BW search for heavy stable charged particles via ToF with 2.5 $\mathrm{fb}^{-1}$ at 13 TeV; require stable m(gluinoball) > 1610 GeV.

[43] BADIER 86 looked for long-lived particles at 300 GeV $\pi^-$ beam dump. The limit applies for nonstrongly interacting neutral or charged particles with mass >2 GeV. The limit applies for particle modes, $\mu^+\pi^-$, $\mu^+\mu^-$, $\pi^+\pi^-$X, $\pi^+\pi^-\pi^\pm$ etc. See their figure 5 for the contours of limits in the mass-$\tau$ plane for each mode.

## Long-Lived Heavy Particle Cross Section

| VALUE (pb/sr) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <34 | 95 | [1] RAM | 94 | SPEC | $1015 < m_{X^{++}} < 1085$ MeV |
| <75 | 95 | [1] RAM | 94 | SPEC | $920 < m_{X^{++}} < 1025$ MeV |

[1] RAM 94 search for a long-lived doubly-charged fermion $X^{++}$ with mass between $m_N$ and $m_N+m_\pi$ and baryon number +1 in the reaction $pp \to X^{++} n$. No candidate is found. The limit is for the cross section at 15° scattering angle at 460 MeV incident energy and applies for $\tau(X^{++}) \gg 0.1\,\mu$s.

# LIMITS ON CHARGED PARTICLES IN COSMIC RAYS

## Heavy Particle Flux in Cosmic Rays

| VALUE ($\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$) | CL% | EVTS | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| $< 6.2 \times 10^{-10}$ | 90 | 0 | [1] ALEMANNO | 22 | DAMP | fractionally charged particles in space |
| | | | [2] CAO | 22 | | superheavy DM → $\gamma$ rays |
| | | | [3] ALVIS | 18 | MAJD | Fractionally charged |
| $< 1 \times 10^{-8}$ | 90 | | [4] AGNESE | 15 | CDM2 | $Q = 1/6$ |
| $\sim 6 \times 10^{-9}$ | | 2 | [5] SAITO | 90 | | $Q \simeq 14$, $m \simeq 370 m_p$ |
| $< 1.4 \times 10^{-12}$ | 90 | 0 | [6] MINCER | 85 | CALO | $m \geq 1$ TeV |
| | | | [7] SAKUYAMA | 83B | PLAS | $m \sim 1$ TeV |
| $< 1.7 \times 10^{-11}$ | 99 | 0 | [8] BHAT | 82 | CC | |
| $< 1. \times 10^{-9}$ | 90 | 0 | [9] MARINI | 82 | CNTR | $Q = 1$, $m \sim 4.5 m_p$ |
| $2. \times 10^{-9}$ | | 3 | [10] YOCK | 81 | SPRK | $Q = 1$, $m \sim 4.5 m_p$ |
| | | 3 | [10] YOCK | 81 | SPRK | Fractionally charged |
| $3.0 \times 10^{-9}$ | | 3 | [11] YOCK | 80 | SPRK | $m \sim 4.5\ m_p$ |
| $(4 \pm 1) \times 10^{-11}$ | | 3 | GOODMAN | 79 | ELEC | $m \geq 5$ GeV |
| $< 1.3 \times 10^{-9}$ | 90 | | [12] BHAT | 78 | CNTR | $m$ >1 GeV |
| $< 1.0 \times 10^{-9}$ | | 0 | BRIATORE | 76 | ELEC | |
| $< 7. \times 10^{-10}$ | 90 | 0 | YOCK | 75 | ELEC | $Q > 7e$ or $< -7e$ |
| $> 6. \times 10^{-9}$ | | 5 | [13] YOCK | 74 | CNTR | $m$ >6 GeV |
| $< 3.0 \times 10^{-8}$ | | 0 | DARDO | 72 | CNTR | |
| $< 1.5 \times 10^{-9}$ | | 0 | TONWAR | 72 | CNTR | $m$ >10 GeV |
| $< 3.0 \times 10^{-10}$ | | 0 | BJORNBOE | 68 | CNTR | $m$ >5 GeV |
| $< 5.0 \times 10^{-11}$ | 90 | 0 | JONES | 67 | ELEC | $m$=5–15 GeV |

[1] ALEMANNO 22 search for flux of fractionally charged particles (FCPs) in space; no signal observed; limits set in flux vs charge plane for mass as low as GeV.

[2] CAO 22 search for superheavy DM decaying to gamma rays; no signal observed; limits placed in mass vs. lifetime plane for m $\sim$ $10^5$–$10^9$ GeV for DM decays to $b\overline{b}$ or $\tau\overline{\tau}$.

[3] ALVIS 18 search for fractional charged flux of cosmic matter at Majorana demonstrator; no signal observed and limits are set on the flux of lightly ionizing particles for charge as low as e/1000.

[4] See AGNESE 15 Fig. 6 for limits extending down to Q = 1/200.

[5] SAITO 90 candidates carry about 450 MeV/nucleon. Cannot be accounted for by conventional backgrounds. Consistent with strange quark matter hypothesis.

[6] MINCER 85 is high statistics study of calorimeter signals delayed by 20–200 ns. Calibration with AGS beam shows they can be accounted for by rare fluctuations in signals from low-energy hadrons in the shower. Claim that previous delayed signals including BJORNBOE 68, DARDO 72, BHAT 82, SAKUYAMA 83B below may be due to this fake effect.

[7] SAKUYAMA 83B analyzed 6000 extended air shower events. Increase of delayed particles and change of lateral distribution above $10^{17}$ eV may indicate production of very heavy parent at top of atmosphere.

[8] BHAT 82 observed 12 events with delay $> 2. \times 10^{-8}$ s and with more than 40 particles. 1 eV has good hadron shower. However all events are delayed in only one of two detectors in cloud chamber, and could not be due to strongly interacting massive particle.

[9] MARINI 82 applied PEP-counter for TOF. Above limit is for velocity = 0.54 of light. Limit is inconsistent with YOCK 80 YOCK 81 events if isotropic dependence on zenith angle is assumed.

[10] YOCK 81 saw another 3 events with $Q = \pm1$ and $m$ about $4.5 m_p$ as well as 2 events with $m > 5.3 m_p$, $Q = \pm0.75 \pm 0.05$ and $m > 2.8 m_p$, $Q = \pm0.70 \pm 0.05$ and 1 event with $m = (9.3 \pm 3.) m_p$, $Q = \pm0.89 \pm 0.06$ as possible heavy candidates.

[11] YOCK 80 events are with charge exactly or approximately equal to unity.

[12] BHAT 78 is at Kolar gold fields. Limit is for $\tau > 10^{-6}$ s.

[13] YOCK 74 events could be tritons.

## Superheavy Particle (Quark Matter) Flux in Cosmic Rays

| VALUE ($cm^{-2}sr^{-1}s^{-1}$) | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| | | [1] ADRIANI | 15 | PMLA | $4 < m < 1.2 \times 10^5\ m_p$ |
| $<5 \times 10^{-16}$ | 90 | [2] AMBROSIO | 00B | MCRO | $m > 5 \times 10^{14}$ GeV |
| $<1.8 \times 10^{-12}$ | 90 | [3] ASTONE | 93 | CNTR | $m \geq 1.5 \times 10^{-13}$gram |
| $<1.1 \times 10^{-14}$ | 90 | [4] AHLEN | 92 | MCRO | $10^{-10} < m < 0.1$ gram |
| $<2.2 \times 10^{-14}$ | 90 | [5] NAKAMURA | 91 | PLAS | $m > 10^{11}$ GeV |
| $<6.4 \times 10^{-16}$ | 90 | [6] ORITO | 91 | PLAS | $m > 10^{12}$ GeV |
| $<2.0 \times 10^{-11}$ | 90 | [7] LIU | 88 | BOLO | $m > 1.5 \times 10^{-13}$ gram |
| $<4.7 \times 10^{-12}$ | 90 | [8] BARISH | 87 | CNTR | $1.4 \times 10^8 < m < 10^{12}$ GeV |
| $<3.2 \times 10^{-11}$ | 90 | [9] NAKAMURA | 85 | CNTR | $m > 1.5 \times 10^{-13}$gram |
| $<3.5 \times 10^{-11}$ | 90 | [10] ULLMAN | 81 | CNTR | Planck-mass $10^{19}$GeV |
| $<7. \times 10^{-11}$ | 90 | [10] ULLMAN | 81 | CNTR | $m \leq 10^{16}$ GeV |

[1] ADRIANI 15 search for relatively light quark matter with charge $Z =$ 1–8. See their Figs. 2 and 3 for flux upper limits.

[2] AMBROSIO 00B searched for quark matter ("nuclearites") in the velocity range ($10^{-5}$–1) $c$. The listed limit is for $2 \times 10^{-3}$ $c$.

[3] ASTONE 93 searched for quark matter ("nuclearites") in the velocity range ($10^{-3}$–1) $c$. Their Table 1 gives a compilation of searches for nuclearites.

[4] AHLEN 92 searched for quark matter ("nuclearites"). The bound applies to velocity $< 2.5 \times 10^{-3}$ $c$. See their Fig. 3 for other velocity/$c$ and heavier mass range.

[5] NAKAMURA 91 searched for quark matter in the velocity range $(4 \times 10^{-5}$–$1)$ $c$.
[6] ORITO 91 searched for quark matter. The limit is for the velocity range $(10^{-4}$–$10^{-3})$ $c$.
[7] LIU 88 searched for quark matter ("nuclearites") in the velocity range $(2.5 \times 10^{-3}$–$1)c$. A less stringent limit of $5.8 \times 10^{-11}$ applies for $(1$–$2.5) \times 10^{-3}c$.
[8] BARISH 87 searched for quark matter ("nuclearites") in the velocity range $(2.7 \times 10^{-4}$–$5 \times 10^{-3})c$.
[9] NAKAMURA 85 at KEK searched for quark-matter. These might be lumps of strange quark matter with roughly equal numbers of $u$, $d$, $s$ quarks. These lumps or nuclearites were assumed to have velocity of $(10^{-4}$–$10^{-3})$ $c$.
[10] ULLMAN 81 is sensitive for heavy slow singly charge particle reaching earth with vertical velocity 100–350 km/s.

## Highly Ionizing Particle Flux

| VALUE ($m^{-2}yr^{-1}$) | CL% | EVTS | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| <0.4 | 95 | 0 | KINOSHITA 81B | PLAS | $Z/\beta$ 30–100 |

## SEARCHES FOR BLACK HOLE PRODUCTION

| VALUE | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| not seen | [1] AABOUD 16P | ATLS | 13 TeV $pp \to e\mu$, $e\tau$, $\mu\tau$ |
| | [2] AAD 15AN | ATLS | 8 TeV $pp \to$ multijets |
| | [3] AAD 14A | ATLS | 8 TeV $pp \to \gamma +$ jet |
| | [4] AAD 14AL | ATLS | 8 TeV $pp \to \ell +$ jet |
| | [5] AAD 14C | ATLS | 8 TeV $pp \to \ell + (\ell$ or jets) |
| | [6] AAD 13D | ATLS | 7 TeV $pp \to$ 2 jets |
| | [7] CHATRCHYAN 13A | CMS | 7 TeV $pp \to$ 2 jets |
| | [8] CHATRCHYAN 13AD | CMS | 8 TeV $pp \to$ multijets |
| | [9] AAD 12AK | ATLS | 7 TeV $pp \to \ell + (\ell$ or jets) |
| | [10] CHATRCHYAN 12W | CMS | 7 TeV $pp \to$ multijets |
| | [11] AAD 11AG | ATLS | 7 TeV $pp \to$ 2 jets |

[1] AABOUD 16P set limits on quantum BH production in n = 6 ADD or n = 1 RS models.
[2] AAD 15AN search for black hole or string ball formation followed by its decay to multijet final states, in $pp$ collisions at $E_{cm}$ = 8 TeV with $L = 20.3$ fb$^{-1}$. See their Figs. 6–8 for limits.
[3] AAD 14A search for quantum black hole formation followed by its decay to a $\gamma$ and a jet, in $pp$ collisions at $E_{cm}$ = 8 TeV with $L = 20$ fb$^{-1}$. See their Fig. 3 for limits.
[4] AAD 14AL search for quantum black hole formation followed by its decay to a lepton and a jet, in $pp$ collisions at $E_{cm}$ = 8 TeV with $L = 20.3$ fb$^{-1}$. See their Fig. 2 for limits.
[5] AAD 14C search for microscopic (semiclassical) black hole formation followed by its decay to final states with a lepton and $\geq$ 2 (leptons or jets), in $pp$ collisions at $E_{cm}$ = 8 TeV with $L = 20.3$ fb$^{-1}$. See their Figures 8–11, Tables 7, 8 for limits.
[6] AAD 13D search for quantum black hole formation followed by its decay to two jets, in $pp$ collisions at $E_{cm}$ = 7 TeV with $L = 4.8$ fb$^{-1}$. See their Fig. 8 and Table 3 for limits.
[7] CHATRCHYAN 13A search for quantum black hole formation followed by its decay to two jets, in $pp$ collisions at $E_{cm}$ = 7 TeV with $L = 5$ fb$^{-1}$. See their Figs. 5 and 6 for limits.

[8] CHATRCHYAN 13AD search for microscopic (semiclassical) black hole formation followed by its evapolation to multiparticle final states, in multijet (including $\gamma$, $\ell$) events in $pp$ collisions at $E_{cm}$ = 8 TeV with $L$ = 12 fb$^{-1}$. See their Figs. 5–7 for limits.

[9] AAD 12AK search for microscopic (semiclassical) black hole formation followed by its decay to final states with a lepton and $\geq$ 2 (leptons or jets), in $pp$ collisions at $E_{cm}$ = 7 TeV with $L$ = 1.04 fb$^{-1}$. See their Fig. 4 and 5 for limits.

[10] CHATRCHYAN 12W search for microscopic (semiclassical) black hole formation followed by its evapolation to multiparticle final states, in multijet (including $\gamma$, $\ell$) events in $pp$ collisions at $E_{cm}$ = 7 TeV with $L$ = 4.7 fb$^{-1}$. See their Figs. 5–8 for limits.

[11] AAD 11AG search for quantum black hole formation followed by its decay to two jets, in $pp$ collisions at $E_{cm}$ = 7 TeV with L = 36 pb$^{-1}$. See their Fig. 11 and Table 4 for limits.

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| ADRIANI | 15 | PRL 115 111101 | O. Adriani *et al.* | (PAMELA Collab.) |
| AGNESE | 15 | PRL 114 111302 | R. Agnese *et al.* | (CDMS Collab.) |
| KHACHATRY... | 15F | PRL 114 101801 | V. Khachatryan *et al.* | (CMS Collab.) |
| LEES | 15E | PRL 114 171801 | J.P. Lees *et al.* | (BABAR Collab.) |
| AAD | 14A | PL B728 562 | G. Aad *et al.* | (ATLAS Collab.) |
| AAD | 14AL | PRL 112 091804 | G. Aad *et al.* | (ATLAS Collab.) |
| AAD | 14C | JHEP 1408 103 | G. Aad *et al.* | (ATLAS Collab.) |
| AALTONEN | 14J | PR D89 092001 | T. Aaltonen *et al.* | (CDF Collab.) |
| AAD | 13A | PL B718 860 | G. Aad *et al.* | (ATLAS Collab.) |
| AAD | 13AH | PL B722 305 | G. Aad *et al.* | (ATLAS Collab.) |
| AAD | 13C | PRL 110 011802 | G. Aad *et al.* | (ATLAS Collab.) |
| AAD | 13D | JHEP 1301 029 | G. Aad *et al.* | (ATLAS Collab.) |
| AALTONEN | 13I | PR D88 031103 | T. Aaltonen *et al.* | (CDF Collab.) |
| AALTONEN | 13R | PRL 111 031802 | T. Aaltonen *et al.* | (CDF Collab.) |
| CHATRCHYAN | 13 | PL B718 815 | S. Chatrchyan *et al.* | (CMS Collab.) |
| CHATRCHYAN | 13A | JHEP 1301 013 | S. Chatrchyan *et al.* | (CMS Collab.) |
| CHATRCHYAN | 13AB | JHEP 1307 122 | S. Chatrchyan *et al.* | (CMS Collab.) |
| Also | | JHEP 2211 149 (errat.) | S. Chatrchyan *et al.* | (CMS Collab.) |
| CHATRCHYAN | 13AD | JHEP 1307 178 | S. Chatrchyan *et al.* | (CMS Collab.) |
| CHATRCHYAN | 13AR | PR D87 092008 | S. Chatrchyan *et al.* | (CMS Collab.) |
| Also | | PR D106 099903 (errat.) | S. Chatrchyan *et al.* | (CMS Collab.) |
| AAD | 12AK | PL B716 122 | G. Aad *et al.* | (ATLAS Collab.) |
| AAD | 12C | PRL 108 041805 | G. Aad *et al.* | (ATLAS Collab.) |
| AAD | 12S | PL B708 37 | G. Aad *et al.* | (ATLAS Collab.) |
| AALTONEN | 12M | PRL 108 211804 | T. Aaltonen *et al.* | (CDF Collab.) |
| CHATRCHYAN | 12AP | JHEP 1209 094 | S. Chatrchyan *et al.* | (CMS Collab.) |
| CHATRCHYAN | 12BL | JHEP 1212 015 | S. Chatrchyan *et al.* | (CMS Collab.) |
| CHATRCHYAN | 12Q | PL B716 260 | S. Chatrchyan *et al.* | (CMS Collab.) |
| CHATRCHYAN | 12T | PRL 108 261803 | S. Chatrchyan *et al.* | (CMS Collab.) |
| CHATRCHYAN | 12W | JHEP 1204 061 | S. Chatrchyan *et al.* | (CMS Collab.) |
| AAD | 11AG | NJP 13 053044 | G. Aad *et al.* | (ATLAS Collab.) |
| AAD | 11I | PL B698 353 | G. Aad *et al.* | (ATLAS Collab.) |
| AAD | 11S | PL B705 294 | G. Aad *et al.* | (ATLAS Collab.) |
| AALTONEN | 11AF | PRL 107 181801 | T. Aaltonen *et al.* | (CDF Collab.) |
| AALTONEN | 11M | PRL 106 171801 | T. Aaltonen *et al.* | (CDF Collab.) |
| ABAZOV | 11I | PRL 107 011804 | V.M. Abazov *et al.* | (D0 Collab.) |
| CHATRCHYAN | 11C | JHEP 1106 026 | S. Chatychyan *et al.* | (CMS Collab.) |
| CHATRCHYAN | 11U | PRL 107 201804 | S. Chatychyan *et al.* | (CMS Collab.) |
| AAD | 10 | PRL 105 161801 | G. Aad *et al.* | (ATLAS Collab.) |
| AALTONEN | 10AF | PR D82 052005 | T. Aaltonen *et al.* | (CDF Collab.) |
| KHACHATRY... | 10 | PRL 105 211801 | V. Khachatryan *et al.* | (CMS Collab.) |
| Also | | PRL 106 029902 | V. Khachatryan *et al.* | (CMS Collab.) |
| AALTONEN | 09AF | PR D80 011102 | T. Aaltonen *et al.* | (CDF Collab.) |
| AALTONEN | 09G | PR D79 052004 | T. Aaltonen *et al.* | (CDF Collab.) |
| AALTONEN | 09Z | PRL 103 021802 | T. Aaltonen *et al.* | (CDF Collab.) |
| ABAZOV | 09M | PRL 102 161802 | V.M. Abazov *et al.* | (D0 Collab.) |
| AKTAS | 04C | EPJ C36 413 | A. Atkas *et al.* | (H1 Collab.) |
| JAVORSEK | 02 | PR D65 072003 | D. Javorsek II *et al.* | |
| JAVORSEK | 01 | PR D64 012005 | D. Javorsek II *et al.* | |
| JAVORSEK | 01B | PRL 87 231804 | D. Javorsek II *et al.* | |
| ABBIENDI | 00D | EPJ C13 197 | G. Abbiendi *et al.* | (OPAL Collab.) |
| AMBROSIO | 00B | EPJ C13 453 | M. Ambrosio *et al.* | (MACRO Collab.) |
| ABE | 99F | PRL 82 2038 | F. Abe *et al.* | (CDF Collab.) |
| ACKERSTAFF | 98P | PL B433 195 | K. Ackerstaff *et al.* | (OPAL Collab.) |
| ABE | 97G | PR D55 5263 | F. Abe *et al.* | (CDF Collab.) |
| ABREU | 97D | PL B396 315 | P. Abreu *et al.* | (DELPHI Collab.) |
| ACKERSTAFF | 97B | PL B391 210 | K. Ackerstaff *et al.* | (OPAL Collab.) |
| ADAMS | 97B | PRL 79 4083 | J. Adams *et al.* | (FNAL KTeV Collab.) |
| BARATE | 97K | PL B405 379 | R. Barate *et al.* | (ALEPH Collab.) |

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|---|---|---|---|---|
| AKERS | 95R | ZPHY C67 203 | R. Akers *et al.* | (OPAL Collab.) |
| GALLAS | 95 | PR D52 6 | E. Gallas *et al.* | (MSU, FNAL, MIT, FLOR) |
| RAM | 94 | PR D49 3120 | S. Ram *et al.* | (TELA, TRIU) |
| ABE | 93G | PRL 71 2542 | F. Abe *et al.* | (CDF Collab.) |
| ASTONE | 93 | PR D47 4770 | P. Astone *et al.* | (ROMA, ROMAI, CATA, FRAS) |
| BUSKULIC | 93C | PL B303 198 | D. Buskulic *et al.* | (ALEPH Collab.) |
| YAMAGATA | 93 | PR D47 1231 | T. Yamagata, Y. Takamori, H. Utsunomiya | (KONAN) |
| ABE | 92J | PR D46 1889 | F. Abe *et al.* | (CDF Collab.) |
| AHLEN | 92 | PRL 69 1860 | S.P. Ahlen *et al.* | (MACRO Collab.) |
| VERKERK | 92 | PRL 68 1116 | P. Verkerk *et al.* | (ENSP, SACL, PAST) |
| AKESSON | 91 | ZPHY C52 219 | T. Akesson *et al.* | (HELIOS Collab.) |
| NAKAMURA | 91 | PL B263 529 | S. Nakamura *et al.* | |
| ORITO | 91 | PRL 66 1951 | S. Orito *et al.* | (ICEPP, WASCR, NIHO, ICRR) |
| ADACHI | 90C | PL B244 352 | I. Adachi *et al.* | (TOPAZ Collab.) |
| ADACHI | 90E | PL B249 336 | I. Adachi *et al.* | (TOPAZ Collab.) |
| AKRAWY | 90O | PL B252 290 | M.Z. Akrawy *et al.* | (OPAL Collab.) |
| HEMMICK | 90 | PR D41 2074 | T.K. Hemmick *et al.* | (ROCH, MICH, OHIO+) |
| SAITO | 90 | PRL 65 2094 | T. Saito *et al.* | (ICRR, KOBE) |
| NAKAMURA | 89 | PR D39 1261 | T.T. Nakamura *et al.* | (KYOT, TMTC) |
| NORMAN | 89 | PR D39 2499 | E.B. Norman *et al.* | (LBL) |
| BERNSTEIN | 88 | PR D37 3103 | R.M. Bernstein *et al.* | (STAN, WISC) |
| LIU | 88 | PRL 61 271 | G. Liu, B. Barish | |
| BARISH | 87 | PR D36 2641 | B.C. Barish, G. Liu, C. Lane | (CIT) |
| NORMAN | 87 | PRL 58 1403 | E.B. Norman, S.B. Gazes, D.A. Bennett | (LBL) |
| BADIER | 86 | ZPHY C31 21 | J. Badier *et al.* | (NA3 Collab.) |
| MINCER | 85 | PR D32 541 | A. Mincer *et al.* | (UMD, GMAS, NSF) |
| NAKAMURA | 85 | PL 161B 417 | K. Nakamura *et al.* | (KEK, INUS) |
| THRON | 85 | PR D31 451 | J.L. Thron *et al.* | (YALE, FNAL, IOWA) |
| SAKUYAMA | 83B | LNC 37 17 | H. Sakuyama, N. Suzuki | (MEIS) |
| Also | | LNC 36 389 | H. Sakuyama, K. Watanabe | (MEIS) |
| Also | | NC 78A 147 | H. Sakuyama, K. Watanabe | (MEIS) |
| Also | | NC 6C 371 | H. Sakuyama, K. Watanabe | (MEIS) |
| BHAT | 82 | PR D25 2820 | P.N. Bhat *et al.* | (TATA) |
| KINOSHITA | 82 | PRL 48 77 | K. Kinoshita, P.B. Price, D. Fryberger | (UCB+) |
| MARINI | 82 | PR D26 1777 | A. Marini *et al.* | (FRAS, LBL, NWES, STAN+) |
| SMITH | 82B | NP B206 333 | P.F. Smith *et al.* | (RAL) |
| KINOSHITA | 81B | PR D24 1707 | K. Kinoshita, P.B. Price | (UCB) |
| LOSECCO | 81 | PL 102B 209 | J.M. LoSecco *et al.* | (MICH, PENN, BNL) |
| ULLMAN | 81 | PRL 47 289 | J.D. Ullman | (LEHM, BNL) |
| YOCK | 81 | PR D23 1207 | P.C.M. Yock | (AUCK) |
| BARTEL | 80 | ZPHY C6 295 | W. Bartel *et al.* | (JADE Collab.) |
| BUSSIERE | 80 | NP B174 1 | A. Bussiere *et al.* | (BGNA, SACL, LAPP) |
| YOCK | 80 | PR D22 61 | P.C.M. Yock | (AUCK) |
| ARMITAGE | 79 | NP B150 87 | J.C.M. Armitage *et al.* | (CERN, DARE, FOM+) |
| BOZZOLI | 79 | NP B159 363 | W. Bozzoli *et al.* | (BGNA, LAPP, SACL+) |
| GOODMAN | 79 | PR D19 2572 | J.A. Goodman *et al.* | (UMD) |
| SMITH | 79 | NP B149 525 | P.F. Smith, J.R.J. Bennett | (RHEL) |
| BHAT | 78 | PRAM 10 115 | P.N. Bhat, P.V. Ramana Murthy | (TATA) |
| CARROLL | 78 | PRL 41 777 | A.S. Carroll *et al.* | (BNL, PRIN) |
| CUTTS | 78 | PRL 41 363 | D. Cutts *et al.* | (BROW, FNAL, ILL, BARI+) |
| VIDAL | 78 | PL 77B 344 | R.A. Vidal *et al.* | (COLU, FNAL, STON+) |
| ALEKSEEV | 76 | SJNP 22 531 | G.D. Alekseev *et al.* | (JINR) |
| | | Translated from YAF 22 1021. | | |
| ALEKSEEV | 76B | SJNP 23 633 | G.D. Alekseev *et al.* | (JINR) |
| | | Translated from YAF 23 1190. | | |
| BALDIN | 76 | SJNP 22 264 | B.Y. Baldin *et al.* | (JINR) |
| | | Translated from YAF 22 512. | | |
| BRIATORE | 76 | NC 31A 553 | L. Briatore *et al.* | (LCGT, FRAS, FREIB) |
| GUSTAFSON | 76 | PRL 37 474 | H.R. Gustafson *et al.* | (MICH) |
| ALBROW | 75 | NP B97 189 | M.G. Albrow *et al.* | (CERN, DARE, FOM+) |
| FRANKEL | 75 | PR D12 2561 | S. Frankel *et al.* | (PENN, FNAL) |
| JOVANOV... | 75 | PL 56B 105 | J.V. Jovanovich *et al.* | (MANI, AACH, CERN+) |
| YOCK | 75 | NP B86 216 | P.C.M. Yock | (AUCK, SLAC) |
| APPEL | 74 | PRL 32 428 | J.A. Appel *et al.* | (COLU, FNAL) |
| FRANKEL | 74 | PR D9 1932 | S. Frankel *et al.* | (PENN, FNAL) |
| YOCK | 74 | NP B76 175 | P.C.M. Yock | (AUCK) |
| ALPER | 73 | PL 46B 265 | B. Alper *et al.* | (CERN, LIVP, LUND, BOHR+) |
| LEIPUNER | 73 | PRL 31 1226 | L.B. Leipuner *et al.* | (BNL, YALE) |
| DARDO | 72 | NC 9A 319 | M. Dardo *et al.* | (TORI) |
| TONWAR | 72 | JP A5 569 | S.C. Tonwar, S. Naranan, B.V. Sreekantan | (TATA) |
| ANTIPOV | 71B | NP B31 235 | Y.M. Antipov *et al.* | (SERP) |
| ANTIPOV | 71C | PL 34B 164 | Y.M. Antipov *et al.* | (SERP) |

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| BINON | 69 | PL 30B 510 | F.G. Binon *et al.* | (SERP) |
| BJORNBOE | 68 | NC B53 241 | J. Bjornboe *et al.* | (BOHR, TATA, BERN+) |
| JONES | 67 | PR 164 1584 | L.W. Jones | (MICH, WISC, LBL, UCLA, MINN+) |
| DORFAN | 65 | PRL 14 999 | D.E. Dorfan *et al.* | (COLU) |