

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Limits not encoded here are summarized in the “Extra Dimensions” review, where the latest unpublished results are also described.

See the related review(s):  
[Extra Dimensions Searches](#)

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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  $\delta$  toroidal extra dimensions of equal size,  $\alpha = 8\delta/3$ . Quoted bounds are for  $\delta = 2$  unless otherwise noted.

VALUE ( $\mu\text{m}$ )	CL%	DOCUMENT ID	TECN	COMMENT
<b>&lt; 30</b>	95	1 KAPNER	07	Torsion pendulum
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		2 BERGE	18	MICR Space accelerometer
		3 FAYET	18	Space accelerometer
		4 HADDOCK	18	Neutron scattering
		5 KLIMCHITSK...17A		Torsion oscillator
		6 XU	13	Nuclei properties
		7 BEZERRA	11	Torsion oscillator
		8 SUSHKOV	11	Torsion pendulum
		9 BEZERRA	10	Microcantilever
		10 MASUDA	09	Torsion pendulum
		11 GERACI	08	Microcantilever
		12 TRENKEL	08	Newton's constant
		13 DECCA	07A	Torsion oscillator
< 47	95	14 TU	07	Torsion pendulum
		15 SMULLIN	05	Microcantilever
<130	95	16 HOYLE	04	Torsion pendulum
		17 CHIAVERINI	03	Microcantilever
$\lesssim 200$	95	18 LONG	03	Microcantilever
<190	95	19 HOYLE	01	Torsion pendulum
		20 HOSKINS	85	Torsion pendulum

- <sup>1</sup> 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.
- <sup>2</sup> BERGE 18 uses results from the MICROSCOPE experiment to obtain constraints on non-Newtonian forces with strengths  $10^{-11} \lesssim |\alpha| \lesssim 10^{-7}$  and length scales  $R \gtrsim 10^5 \text{ m}$ . See their Figure 1 for more details. These constraints do not place limits on the size of extra flat dimensions.
- <sup>3</sup> FAYET 18 uses results from the MICROSCOPE experiment to obtain constraints on an EP-violating force possibly arising from a new U(1) gauge boson. For  $R \gtrsim 10^7 \text{ m}$  the limits are  $-\alpha \lesssim$  a few  $10^{-13}$  to a few  $10^{-11}$  depending on the coupling (cf. also FAYET 18A), corresponding to  $|\epsilon| \lesssim 10^{-24}$  for the coupling of the new spin-1 or spin-0 mediator. These constraints do not place limits on the size of extra flat dimensions.
- <sup>4</sup> HADDOCK 18 obtain constraints on non-Newtonian forces with strengths  $10^{22} \lesssim |\alpha| \lesssim 10^{24}$  and length scales  $R \simeq 0.01$ – $10 \text{ nm}$ . See their Figure 8 for more details. These constraints do not place limits on the size of extra flat dimensions.
- <sup>5</sup> KLIMCHITSKAYA 17A uses an experiment that measures the difference of Casimir forces to obtain bounds on non-Newtonian forces with strengths  $|\alpha| \simeq 10^5$ – $10^{17}$  and length scales  $R = 0.03$ – $10 \mu\text{m}$ . See their Fig. 3. These constraints do not place limits on the size of extra flat dimensions.
- <sup>6</sup> XU 13 obtain constraints on non-Newtonian forces with strengths  $|\alpha| \simeq 10^{34}$ – $10^{36}$  and length scales  $R \simeq 1$ – $10 \text{ fm}$ . See their Fig. 4 for more details. These constraints do not place limits on the size of extra flat dimensions.
- <sup>7</sup> BEZERRA 11 obtain constraints on non-Newtonian forces with strengths  $10^{11} \lesssim |\alpha| \lesssim 10^{18}$  and length scales  $R = 30$ – $1260 \text{ nm}$ . See their Fig. 2 for more details. These constraints do not place limits on the size of extra flat dimensions.
- <sup>8</sup> 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.
- <sup>9</sup> BEZERRA 10 obtain improved constraints on non-Newtonian forces with strengths  $10^{19} \lesssim |\alpha| \lesssim 10^{29}$  and length scales  $R = 1.6$ – $14 \text{ nm}$  (95% CL). See their Fig. 1. This bound does not place limits on the size of extra flat dimensions.
- <sup>10</sup> 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.
- <sup>11</sup> 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.
- <sup>12</sup> TRENKEL 08 uses two independent measurements of Newton's constant  $G$  to constrain new forces with strength  $|\alpha| \simeq 10^{-4}$  and length scales  $R = 0.02$ – $1 \text{ m}$ . See their Fig. 1. This bound does not place limits on the size of extra flat dimensions.
- <sup>13</sup> DECCA 07A search for new forces and obtain bounds in the region with strengths  $|\alpha| \simeq 10^{13}$ – $10^{18}$  and length scales  $R = 20$ – $86 \text{ nm}$ . See their Fig. 6. This bound does not place limits on the size of extra flat dimensions.
- <sup>14</sup> 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.
- <sup>15</sup> 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.

- 16 HOYLE 04 search for new forces, probing  $\alpha$  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.
- 17 CHIAVERINI 03 search for new forces, probing  $\alpha$  above  $10^4$  and  $\lambda$  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.
- 18 LONG 03 search for new forces, probing  $\alpha$  down to 3, and distances down to about  $10\mu\text{m}$ . See their Fig. 4 for details on the bound.
- 19 HOYLE 01 search for new forces, probing  $\alpha$  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  $\alpha \geq 3$ .
- 20 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.

### 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  $\mu\text{m}$  for  $\delta = 2$ .

VALUE ( $\mu\text{m}$ )	CL%	DOCUMENT ID	TECN	COMMENT
< 4.8	95	1 SIRUNYAN 18S	CMS	$pp \rightarrow jG$
< 0.00016	95	2 HANNESTAD 03		Neutron star heating
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
< 8.0	95	3 AABOUD 18I	ATLS	$pp \rightarrow jG$
< 89	95	4 SIRUNYAN 18BV	CMS	$pp \rightarrow ZG$
		5 SIRUNYAN 17AQ	CMS	$pp \rightarrow \gamma G$
< 90	95	6 AABOUD 16F	ATLS	$pp \rightarrow \gamma G$
		7 KHACHATRY...16N	CMS	$pp \rightarrow \gamma G$
		8 AAD 15CS	ATLS	$pp \rightarrow \gamma G$
< 127	95	9 AAD 13C	ATLS	$pp \rightarrow \gamma G$
< 34.4	95	10 AAD 13D	ATLS	$pp \rightarrow jj$
< 0.0087	95	11 AJELLO 12	FLAT	Neutron star $\gamma$ sources
< 245	95	12 AALTONEN 08AC	CDF	$p\bar{p} \rightarrow \gamma G, jG$
< 615	95	13 ABAZOV 08S	D0	$p\bar{p} \rightarrow \gamma G$
< 0.916	95	14 DAS 08		Supernova cooling
< 350	95	15 ABULENCIA,A 06	CDF	$p\bar{p} \rightarrow jG$
< 270	95	16 ABDALLAH 05B	DLPH	$e^+e^- \rightarrow \gamma G$
< 210	95	17 ACHARD 04E	L3	$e^+e^- \rightarrow \gamma G$
< 480	95	18 ACOSTA 04C	CDF	$\bar{p}p \rightarrow jG$
< 0.00038	95	19 CASSE 04		Neutron star $\gamma$ sources
< 610	95	20 ABAZOV 03	D0	$\bar{p}p \rightarrow jG$
< 0.96	95	21 HANNESTAD 03		Supernova cooling
< 0.096	95	22 HANNESTAD 03		Diffuse $\gamma$ background
< 0.051	95	23 HANNESTAD 03		Neutron star $\gamma$ sources
< 300	95	24 HEISTER 03C	ALEP	$e^+e^- \rightarrow \gamma G$
		25 FAIRBAIRN 01		Cosmology
< 0.66	95	26 HANHART 01		Supernova cooling
		27 CASSISI 00		Red giants
<1300	95	28 ACCIARRI 99S	L3	$e^+e^- \rightarrow ZG$

- <sup>1</sup> SIRUNYAN 18S search for  $pp \rightarrow jG$ , using  $35.9 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 13 \text{ TeV}$  to place lower limits on  $M_D$  for two to six extra dimensions (see their Table VII), from which this bound on  $R$  is derived. This limit supersedes that in KHACHATRYAN 15AL.
- <sup>2</sup> 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.
- <sup>3</sup> AABOUD 18I search for  $pp \rightarrow jG$ , using  $36.1 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 13 \text{ TeV}$  to place lower limits on  $M_D$  for two to six extra dimensions (see their Table 7), from which this bound on  $R$  is derived. This limit supersedes that in AABOUD 16D.
- <sup>4</sup> SIRUNYAN 18BV search for  $pp \rightarrow ZG$ , using  $35.9 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 13 \text{ TeV}$  to place lower limits on  $M_D$  for two to seven extra dimensions (see their Figure 11), from which this bound on  $R$  is derived.
- <sup>5</sup> SIRUNYAN 17AQ search for  $pp \rightarrow \gamma G$ , using  $12.9 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 13 \text{ TeV}$  to place limits on  $M_D$  for three to six extra dimensions (see their Table 3).
- <sup>6</sup> AABOUD 16F search for  $pp \rightarrow \gamma G$ , using  $3.2 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 13 \text{ TeV}$  to place limits on  $M_D$  for two to six extra dimensions (see their Figure 9), from which this bound on  $R$  is derived.
- <sup>7</sup> KHACHATRYAN 16N search for  $pp \rightarrow \gamma G$ , using  $19.6 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 8 \text{ TeV}$  to place limits on  $M_D$  for three to six extra dimensions (see their Table 5).
- <sup>8</sup> AAD 15CS search for  $pp \rightarrow \gamma G$ , using  $20.3 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 8 \text{ TeV}$  to place lower limits on  $M_D$  for two to six extra dimensions (see their Fig. 18).
- <sup>9</sup> AAD 13C search for  $pp \rightarrow \gamma G$ , using  $4.6 \text{ fb}^{-1}$  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.
- <sup>10</sup> AAD 13D search for the dijet decay of quantum black holes in  $4.8 \text{ fb}^{-1}$  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.
- <sup>11</sup> AJELLO 12 obtain a limit on  $R$  from the gamma-ray emission of point  $\gamma$  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.
- <sup>12</sup> AALTONEN 08AC search for  $p\bar{p} \rightarrow \gamma G$  and  $p\bar{p} \rightarrow jG$  at  $\sqrt{s} = 1.96 \text{ TeV}$  with  $2.0 \text{ fb}^{-1}$  and  $1.1 \text{ fb}^{-1}$  respectively, in order to place bounds on the fundamental scale and size of the extra dimensions. See their Table III for limits on all  $\delta \leq 6$ .
- <sup>13</sup> ABAZOV 08S search for  $p\bar{p} \rightarrow \gamma G$ , using  $1 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 1.96 \text{ TeV}$  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  $\delta$ .
- <sup>14</sup> DAS 08 obtain a limit on  $R$  from Kaluza-Klein graviton cooling of SN1987A due to plasmon-plasmon annihilation.
- <sup>15</sup> ABULENCIA,A 06 search for  $p\bar{p} \rightarrow jG$  using  $368 \text{ pb}^{-1}$  of data at  $\sqrt{s} = 1.96 \text{ TeV}$ . See their Table II for bounds for all  $\delta \leq 6$ .
- <sup>16</sup> ABDALLAH 05B search for  $e^+e^- \rightarrow \gamma G$  at  $\sqrt{s} = 180\text{--}209 \text{ GeV}$  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.
- <sup>17</sup> ACHARD 04E search for  $e^+e^- \rightarrow \gamma G$  at  $\sqrt{s} = 189\text{--}209 \text{ GeV}$  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.
- <sup>18</sup> ACOSTA 04C search for  $p\bar{p} \rightarrow jG$  at  $\sqrt{s} = 1.8 \text{ TeV}$  to place bounds on the size of extra dimensions and the fundamental scale. See their paper for bounds on  $\delta = 4, 6$ .
- <sup>19</sup> CASSE 04 obtain a limit on  $R$  from the gamma-ray emission of point  $\gamma$  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.
- <sup>20</sup> ABAZOV 03 search for  $p\bar{p} \rightarrow jG$  at  $\sqrt{s}=1.8 \text{ TeV}$  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  $\delta$ . We quote results without the approximate NLO scaling introduced in the paper.

- <sup>21</sup> 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.
- <sup>22</sup> HANNESTAD 03 obtain a limit on  $R$  from gravitons emitted in supernovae and which subsequently decay, contaminating the diffuse cosmic  $\gamma$  background. Limits for all  $\delta \leq 7$  are given in their Tables V and VI. These limits supersede those in HANNESTAD 02.
- <sup>23</sup> HANNESTAD 03 obtain a limit on  $R$  from gravitons emitted in two recent supernovae and which subsequently decay, creating point  $\gamma$  sources. Limits for all  $\delta \leq 7$  are given in their Tables V and VI. These limits are corrected in the published erratum.
- <sup>24</sup> 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  $M_D$ .
- <sup>25</sup> 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.
- <sup>26</sup> HANHART 01 obtain bounds on  $R$  from limits on graviton cooling of supernova SN 1987a using numerical simulations of proto-neutron star neutrino emission.
- <sup>27</sup> CASSISI 00 obtain rough bounds on  $M_D$  (and thus  $R$ ) from red giant cooling for  $\delta=2,3$ . See their paper for details.
- <sup>28</sup> ACCIARRI 99S search for  $e^+ e^- \rightarrow Z G$  at  $\sqrt{s}=189$  GeV. Limits on the gravity scale are found in their Table 2, for  $\delta \leq 4$ .

### Mass Limits on $M_{TT}$

This section includes limits on the cut-off mass scale,  $M_{TT}$ , 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  $\lambda$ , which is taken to be  $\lambda = \pm 1$  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
<b>&gt; 9.02</b>	95	<sup>1</sup> SIRUNYAN	18DD CMS	$pp \rightarrow$ dijet, ang. distrib.
<b>&gt;20.6</b> ( <b>&gt; 15.7</b> )	95	<sup>2</sup> GIUDICE	03 RVUE	Dim-6 operators
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 7.0	(>5.6)	95 <sup>3</sup> SIRUNYAN	18DU CMS	$pp \rightarrow \gamma\gamma$
> 6.5	95	<sup>4</sup> AABOUD	17AP ATLS	$pp \rightarrow \gamma\gamma$
> 3.7	95	<sup>5</sup> KHACHATRY...	15AE CMS	$pp \rightarrow e^+ e^-, \mu^+ \mu^-$
> 3.8	95	<sup>6</sup> AAD	14BE ATLS	$pp \rightarrow e^+ e^-, \mu^+ \mu^-$
> 3.2	95	<sup>7</sup> AAD	13E ATLS	$pp \rightarrow e^+ e^-, \mu^+ \mu^-, \gamma\gamma$
		<sup>8</sup> BAAK	12 RVUE	Electroweak
> 2.86	95	<sup>9</sup> CHATRCHYAN	12J CMS	$pp \rightarrow e^+ e^-, \mu^+ \mu^-$
> 0.90	(>0.92)	95 <sup>10</sup> AARON	11C H1	$e^\pm p \rightarrow e^\pm X$
> 1.48	95	<sup>11</sup> ABAZOV	09AE D0	$p\bar{p} \rightarrow$ dijet, ang. distrib.
> 1.45	95	<sup>12</sup> ABAZOV	09D D0	$p\bar{p} \rightarrow e^+ e^-, \gamma\gamma$
> 1.1	(> 1.0)	95 <sup>13</sup> SCHAEEL	07A ALEP	$e^+ e^- \rightarrow e^+ e^-$
> 0.898	(> 0.998)	95 <sup>14</sup> ABDALLAH	06C DLPH	$e^+ e^- \rightarrow \ell^+ \ell^-$
> 0.853	(> 0.939)	95 <sup>15</sup> GERDES	06	$p\bar{p} \rightarrow e^+ e^-, \gamma\gamma$
> 0.96	(> 0.93)	95 <sup>16</sup> ABAZOV	05V D0	$p\bar{p} \rightarrow \mu^+ \mu^-$
> 0.78	(> 0.79)	95 <sup>17</sup> CHEKANOV	04B ZEUS	$e^\pm p \rightarrow e^\pm X$
> 0.805	(> 0.956)	95 <sup>18</sup> ABBIENDI	03D OPAL	$e^+ e^- \rightarrow \gamma\gamma$
> 0.7	(> 0.7)	95 <sup>19</sup> ACHARD	03D L3	$e^+ e^- \rightarrow ZZ$

> 0.82	(> 0.78)	95	20	ADLOFF	03	H1	$e^\pm p \rightarrow e^\pm X$
> 1.28	(> 1.25)	95	21	GIUDICE	03	RVUE	
> 0.80	(> 0.85)	95	22	HEISTER	03C	ALEP	$e^+ e^- \rightarrow \gamma\gamma$
> 0.84	(> 0.99)	95	23	ACHARD	02D	L3	$e^+ e^- \rightarrow \gamma\gamma$
> 1.2	(> 1.1)	95	24	ABBOTT	01	D0	$p\bar{p} \rightarrow e^+ e^-, \gamma\gamma$
> 0.60	(> 0.63)	95	25	ABBIENDI	00R	OPAL	$e^+ e^- \rightarrow \mu^+ \mu^-$
> 0.63	(> 0.50)	95	25	ABBIENDI	00R	OPAL	$e^+ e^- \rightarrow \tau^+ \tau^-$
> 0.68	(> 0.61)	95	25	ABBIENDI	00R	OPAL	$e^+ e^- \rightarrow \mu^+ \mu^-, \tau^+ \tau^-$
			26	ABREU	00A	DLPH	$e^+ e^- \rightarrow \gamma\gamma$
> 0.680	(> 0.542)	95	27	ABREU	00S	DLPH	$e^+ e^- \rightarrow \mu^+ \mu^-, \tau^+ \tau^-$
> 15–28		99.7	28	CHANG	00B	RVUE	Electroweak
> 0.98		95	29	CHEUNG	00	RVUE	$e^+ e^- \rightarrow \gamma\gamma$
> 0.29–0.38		95	30	GRAESSER	00	RVUE	$(g-2)_\mu$
> 0.50–1.1		95	31	HAN	00	RVUE	Electroweak
> 2.0	(> 2.0)	95	32	MATHEWS	00	RVUE	$\bar{p}p \rightarrow jj$
> 1.0	(> 1.1)	95	33	MELE	00	RVUE	$e^+ e^- \rightarrow VV$
			34	ABBIENDI	99P	OPAL	
			35	ACCIARRI	99M	L3	
			36	ACCIARRI	99S	L3	
> 1.412	(> 1.077)	95	37	BOURILKOV	99		$e^+ e^- \rightarrow e^+ e^-$

<sup>1</sup> SIRUNYAN 18DD use dijet angular distributions in  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to place a lower bound on  $\Lambda_{\mathcal{T}}$ , here converted to  $M_{\mathcal{T}\mathcal{T}}$ . This updates the results of SIRUNYAN 17F.

<sup>2</sup> GIUDICE 03 place bounds on  $\Lambda_6$ , 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  $\delta$ .

<sup>3</sup> SIRUNYAN 18DU use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to place lower limits on  $M_{\mathcal{T}\mathcal{T}}$  (equivalent to their  $M_S$ ). This updates the results of CHATRCHYAN 12R.

<sup>4</sup> AABOUD 17AP use  $36.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to place lower limits on  $M_{\mathcal{T}\mathcal{T}}$  (equivalent to their  $M_S$ ). This updates the results of AAD 13AS.

<sup>5</sup> KHACHATRYAN 15AE use  $20.6 (19.7) \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  in the dimuon (dielectron) channel to place a lower limit on  $\Lambda_{\mathcal{T}}$ , here converted to  $M_{\mathcal{T}\mathcal{T}}$ .

<sup>6</sup> AAD 14BE use  $20 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  in the dilepton channel to place lower limits on  $M_{\mathcal{T}\mathcal{T}}$  (equivalent to their  $M_S$ ).

<sup>7</sup> AAD 13E use  $4.9$  and  $5.0 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$  in the dielectron and dimuon channels, respectively, to place lower limits on  $M_{\mathcal{T}\mathcal{T}}$  (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.

<sup>8</sup> BAAK 12 use electroweak precision observables to place bounds on the ratio  $\Lambda_{\mathcal{T}}/M_D$  as a function of  $M_D$ . See their Fig. 22 for constraints with a Higgs mass of  $120 \text{ GeV}$ .

<sup>9</sup> CHATRCHYAN 12J use approximately  $2 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$  in the dielectron and dimuon channels to place lower limits on  $\Lambda_{\mathcal{T}}$ , here converted to  $M_{\mathcal{T}\mathcal{T}}$ .

<sup>10</sup> AARON 11C search for deviations in the differential cross section of  $e^\pm p \rightarrow e^\pm X$  in  $446 \text{ pb}^{-1}$  of data taken at  $\sqrt{s} = 301$  and  $319 \text{ GeV}$  to place a bound on  $M_{\mathcal{T}\mathcal{T}}$ .

<sup>11</sup> ABAZOV 09AE use dijet angular distributions in  $0.7 \text{ fb}^{-1}$  of data from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  to place lower bounds on  $\Lambda_{\mathcal{T}}$  (equivalent to their  $M_S$ ), here converted to  $M_{\mathcal{T}\mathcal{T}}$ .

<sup>12</sup> ABAZOV 09D use  $1.05 \text{ fb}^{-1}$  of data from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  to place lower bounds on  $\Lambda_{\mathcal{T}}$  (equivalent to their  $M_S$ ), here converted to  $M_{\mathcal{T}\mathcal{T}}$ .

- 13 SCHAEEL 07A use  $e^+e^-$  collisions at  $\sqrt{s} = 189\text{--}209$  GeV to place lower limits on  $\Lambda_{\mathcal{T}}$ , here converted to limits on  $M_{\mathcal{T}\mathcal{T}}$ .
- 14 ABDALLAH 06C use  $e^+e^-$  collisions at  $\sqrt{s} \sim 130\text{--}207$  GeV to place lower limits on  $M_{\mathcal{T}\mathcal{T}}$ , 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.
- 15 GERDES 06 use 100 to 110  $\text{pb}^{-1}$  of data from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  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.
- 16 ABAZOV 05V use 246  $\text{pb}^{-1}$  of data from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV to search for deviations in the differential cross section to  $\mu^+\mu^-$  from graviton exchange.
- 17 CHEKANOV 04B search for deviations in the differential cross section of  $e^\pm p \rightarrow e^\pm X$  with 130  $\text{pb}^{-1}$  of combined data and  $Q^2$  values up to 40,000  $\text{GeV}^2$  to place a bound on  $M_{\mathcal{T}\mathcal{T}}$ .
- 18 ABBIENDI 03D use  $e^+e^-$  collisions at  $\sqrt{s}=181\text{--}209$  GeV to place bounds on the ultra-violet scale  $M_{\mathcal{T}\mathcal{T}}$ , which is equivalent to their definition of  $M_S$ .
- 19 ACHARD 03D look for deviations in the cross section for  $e^+e^- \rightarrow ZZ$  from  $\sqrt{s} = 200\text{--}209$  GeV to place a bound on  $M_{\mathcal{T}\mathcal{T}}$ .
- 20 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  $M_{\mathcal{T}\mathcal{T}}$ .
- 21 GIUDICE 03 review existing experimental bounds on  $M_{\mathcal{T}\mathcal{T}}$  and derive a combined limit.
- 22 HEISTER 03C use  $e^+e^-$  collisions at  $\sqrt{s}=189\text{--}209$  GeV to place bounds on the scale of dim-8 gravitational interactions. Their  $M_S^\pm$  is equivalent to our  $M_{\mathcal{T}\mathcal{T}}$  with  $\lambda=\pm 1$ .
- 23 ACHARD 02 search for  $s$ -channel graviton exchange effects in  $e^+e^- \rightarrow \gamma\gamma$  at  $E_{\text{cm}} = 192\text{--}209$  GeV.
- 24 ABBOTT 01 search for variations in differential cross sections to  $e^+e^-$  and  $\gamma\gamma$  final states at the Tevatron.
- 25 ABBIENDI 00R uses  $e^+e^-$  collisions at  $\sqrt{s}=189$  GeV.
- 26 ABREU 00A search for  $s$ -channel graviton exchange effects in  $e^+e^- \rightarrow \gamma\gamma$  at  $E_{\text{cm}} = 189\text{--}202$  GeV.
- 27 ABREU 00S uses  $e^+e^-$  collisions at  $\sqrt{s}=183$  and 189 GeV. Bounds on  $\mu$  and  $\tau$  individual final states given in paper.
- 28 CHANG 00B derive  $3\sigma$  limit on  $M_{\mathcal{T}\mathcal{T}}$  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.
- 29 CHEUNG 00 obtains limits from anomalous diphoton production at OPAL due to graviton exchange. Original limit for  $\delta=4$ . However, unknown  $UV$  theory renders  $\delta$  dependence unreliable. Original paper works in HLZ convention.
- 30 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."
- 31 HAN 00 calculates corrections to gauge boson self-energies from KK graviton loops and constrain them using  $S$  and  $T$ . Bounds on  $M_{\mathcal{T}\mathcal{T}}$  range from 0.5 TeV ( $\delta=6$ ) to 1.1 TeV ( $\delta=2$ ); see text. Limits have strong dependence,  $\lambda^{\delta+2}$ , on unknown  $\lambda$  coefficient.
- 32 MATHEWS 00 search for evidence of graviton exchange in CDF and DØ dijet production data. See their Table 2 for slightly stronger  $\delta$ -dependent bounds. Limits expressed in terms of  $\widetilde{M}_S^4 = M_{\mathcal{T}\mathcal{T}}^4/8$ .
- 33 MELE 00 obtains bound from KK graviton contributions to  $e^+e^- \rightarrow VV$  ( $V=\gamma, W, Z$ ) at LEP. Authors use Hewett conventions.
- 34 ABBIENDI 99P search for  $s$ -channel graviton exchange effects in  $e^+e^- \rightarrow \gamma\gamma$  at  $E_{\text{cm}}=189$  GeV. The limits  $G_+ > 660$  GeV and  $G_- > 634$  GeV are obtained from

combined  $E_{\text{cm}}=183$  and 189 GeV data, where  $G_{\pm}$  is a scale related to the fundamental gravity scale.

- <sup>35</sup> 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  $E_{\text{cm}}=183$  GeV. Limits on the gravity scale are listed in their Tables 1 and 2.
- <sup>36</sup> 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  $E_{\text{cm}}=189$  GeV. Limits on the gravity scale are listed in their Tables 1 and 2.
- <sup>37</sup> BOURILKOV 99 performs global analysis of LEP data on  $e^+e^-$  collisions at  $\sqrt{s}=183$  and 189 GeV. Bound is on  $\Lambda_T$ .

## Limits on $1/R = M_c$

This section includes limits on  $1/R = M_c$ , the compactification scale in models with one TeV-sized extra dimension, 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
<b>&gt;4.16</b>	95	<sup>1</sup> AAD	12CC ATLS	$pp \rightarrow \ell\bar{\ell}$
<b>&gt;6.1</b>		<sup>2</sup> BARBIERI	04 RVUE	Electroweak
		<sup>3</sup> AABOUD	18AV ATLS	$pp \rightarrow t\bar{t}t\bar{t}$
		<sup>4</sup> AABOUD	18CE ATLS	$pp \rightarrow t\bar{t}t\bar{t}$
>3.8	95	<sup>5</sup> ACCOMANDO 15	RVUE	Electroweak
>3.40	95	<sup>6</sup> KHACHATRY...15T	CMS	$pp \rightarrow \ell X$
		<sup>7</sup> CHATRCHYAN 13AQ	CMS	$pp \rightarrow \ell X$
>1.38	95	<sup>8</sup> CHATRCHYAN 13W	CMS	$pp \rightarrow \gamma\gamma, \delta=6, M_D=5$ TeV
>0.715	95	<sup>9</sup> EDELHAUSER 13	RVUE	$pp \rightarrow \ell\bar{\ell} + X$
>1.40	95	<sup>10</sup> AAD	12CP ATLS	$pp \rightarrow \gamma\gamma, \delta=6, M_D=5$ TeV
>1.23	95	<sup>11</sup> AAD	12X ATLS	$pp \rightarrow \gamma\gamma, \delta=6, M_D=5$ TeV
>0.26	95	<sup>12</sup> ABAZOV	12M D0	$p\bar{p} \rightarrow \mu\mu$
>0.75	95	<sup>13</sup> BAAK	12 RVUE	Electroweak
		<sup>14</sup> FLACKE	12 RVUE	Electroweak
>0.43	95	<sup>15</sup> NISHIWAKI	12 RVUE	$H \rightarrow WW, \gamma\gamma$
>0.729	95	<sup>16</sup> AAD	11F ATLS	$pp \rightarrow \gamma\gamma, \delta=6, M_D=5$ TeV
>0.961	95	<sup>17</sup> AAD	11X ATLS	$pp \rightarrow \gamma\gamma, \delta=6, M_D=5$ TeV
>0.477	95	<sup>18</sup> ABAZOV	10P D0	$p\bar{p} \rightarrow \gamma\gamma, \delta=6, M_D=5$ TeV
>1.59	95	<sup>19</sup> ABAZOV	09AE D0	$p\bar{p} \rightarrow$ dijet, angular dist.
>0.6	95	<sup>20</sup> HAISCH	07 RVUE	$\bar{B} \rightarrow X_s \gamma$
>0.6	90	<sup>21</sup> GOGOLADZE	06 RVUE	Electroweak
>3.3	95	<sup>22</sup> CORNET	00 RVUE	Electroweak
> 3.3–3.8	95	<sup>23</sup> RIZZO	00 RVUE	Electroweak

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

<sup>2</sup> BARBIERI 04 use electroweak precision observables to place a lower bound on the compactification scale  $1/R$ . Both the gauge bosons and the Higgs boson are assumed to propagate in the bulk.



- <sup>3</sup> AABOUD 18AV use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  in final states with multiple b-jets, to place a lower bound on the compactification scale in a model with two universal extra dimensions. Assuming the radii of the two extra dimensions are equal, a lower limit of 1.8 TeV for the Kaluza-Klein mass is obtained.
- <sup>4</sup> AABOUD 18CE use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  in final states with same-charge leptons and b-jets, to place a lower bound on the compactification scale in a model with two universal extra dimensions. Assuming the radii of the two extra dimensions are equal, a lower limit of 1.45 TeV for the Kaluza-Klein mass is obtained.
- <sup>5</sup> ACCOMANDO 15 use electroweak precision observables to place a lower bound on the compactification scale  $1/R$ . See their Fig. 2 for the bound as a function of  $\sin\beta$ , which parametrizes the VEV contribution from brane and bulk Higgs fields. The quoted value is for the minimum bound which occurs at  $\sin\beta = 0.45$ .
- <sup>6</sup> KHACHATRYAN 15T use  $19.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to place a lower bound on the compactification scale  $1/R$ .
- <sup>7</sup> CHATRCHYAN 13AQ use  $5.0 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$  and a further  $3.7 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 8 \text{ TeV}$  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. 5 for the bound as a function of the universal bulk fermion mass parameter  $\mu$ .
- <sup>8</sup> CHATRCHYAN 13W use diphoton events with large missing transverse momentum in  $4.93 \text{ fb}^{-1}$  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  $\Lambda$ , 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.
- <sup>9</sup> EDELHAUSER 13 use 19.6 and  $20.6 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  analyzed by the CMS Collaboration in the dielectron and dimuon channels, respectively, to place a lower bound on the mass of the second lightest Kaluza-Klein  $Z/\gamma$  boson (converted to a limit on  $1/R = M_C$ ). The bound assumes Standard Model fields propagating in the bulk and that the cutoff scale  $\Lambda$ , for the radiative corrections to the Kaluza-Klein masses, satisfies  $\Lambda/M_C = 20$ .
- <sup>10</sup> AAD 12CP use diphoton events with large missing transverse momentum in  $4.8 \text{ fb}^{-1}$  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  $\Lambda$ , 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.
- <sup>11</sup> AAD 12X use diphoton events with large missing transverse momentum in  $1.07 \text{ fb}^{-1}$  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  $\Lambda$ , 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.
- <sup>12</sup> ABAZOV 12M use same-sign dimuon events in  $7.3 \text{ fb}^{-1}$  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.
- <sup>13</sup> 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.
- <sup>14</sup> 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  $\mu$ .
- <sup>15</sup> NISHIWAKI 12 use up to  $2 \text{ fb}^{-1}$  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.

- <sup>16</sup> AAD 11F use diphoton events with large missing transverse energy in  $3.1 \text{ pb}^{-1}$  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  $\Lambda$ , 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.
- <sup>17</sup> AAD 11X use diphoton events with large missing transverse energy in  $36 \text{ pb}^{-1}$  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  $\Lambda$ , 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.
- <sup>18</sup> ABAZOV 10P use diphoton events with large missing transverse energy in  $6.3 \text{ fb}^{-1}$  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  $\Lambda$ , 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.
- <sup>19</sup> ABAZOV 09AE use dijet angular distributions in  $0.7 \text{ fb}^{-1}$  of data from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  to place a lower bound on the compactification scale.
- <sup>20</sup> 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.
- <sup>21</sup> 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.
- <sup>22</sup> 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.
- <sup>23</sup> 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 section 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  $k/\bar{M}_P = 0.1$ .

VALUE (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;4.25</b>	95	<sup>1</sup> SIRUNYAN	18BB CMS	$pp \rightarrow G \rightarrow e^+e^-, \mu^+\mu^-$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		<sup>2</sup> AABOUD	19A ATLS	$pp \rightarrow G \rightarrow HH$
		<sup>3</sup> SIRUNYAN	19 CMS	$pp \rightarrow G \rightarrow HH$
		<sup>4</sup> AABOUD	18AK ATLS	$pp \rightarrow G \rightarrow WW$
		<sup>5</sup> AABOUD	18AL ATLS	$pp \rightarrow G \rightarrow ZZ$
		<sup>6</sup> AABOUD	18BF ATLS	$pp \rightarrow G \rightarrow ZZ$
		<sup>7</sup> AABOUD	18BI ATLS	$pp \rightarrow G \rightarrow t\bar{t}$
		<sup>8</sup> AABOUD	18CJ ATLS	$pp \rightarrow G \rightarrow VV, VH, \ell\bar{\ell}$

		9	AABOUD	18CQ ATLS	$pp \rightarrow G \rightarrow HH$
		10	AABOUD	18CWATLS	$pp \rightarrow G \rightarrow HH$
		11	AABOUD	18F ATLS	$pp \rightarrow G \rightarrow WW, ZZ$
		12	SIRUNYAN	18AF CMS	$pp \rightarrow G \rightarrow HH$
		13	SIRUNYAN	18AS CMS	$pp \rightarrow G \rightarrow ZZ$
		14	SIRUNYAN	18AX CMS	$pp \rightarrow G \rightarrow WW$
		15	SIRUNYAN	18BK CMS	$pp \rightarrow G \rightarrow ZZ$
>1.8	95	16	SIRUNYAN	18BO CMS	$pp \rightarrow G \rightarrow jj$
		17	SIRUNYAN	18CWCMS	$pp \rightarrow G \rightarrow HH$
		18	SIRUNYAN	18DJ CMS	$pp \rightarrow G \rightarrow ZZ$
>4.1	95	19	SIRUNYAN	18DU CMS	$pp \rightarrow G \rightarrow \gamma\gamma$
		20	SIRUNYAN	18F CMS	$pp \rightarrow G \rightarrow HH$
		21	SIRUNYAN	18I CMS	$pp \rightarrow G \rightarrow b\bar{b}$
		22	SIRUNYAN	18P CMS	$pp \rightarrow G \rightarrow WW, ZZ$
>4.1	95	23	AABOUD	17AP ATLS	$pp \rightarrow G \rightarrow \gamma\gamma$
		24	AAD	16R ATLS	$pp \rightarrow G \rightarrow WW, ZZ$
		25	AAD	15AU ATLS	$pp \rightarrow G \rightarrow ZZ$
		26	AAD	15AZ ATLS	$pp \rightarrow G \rightarrow WW$
		27	AAD	15CT ATLS	$pp \rightarrow G \rightarrow WW, ZZ$
>2.68	95	28	AAD	14V ATLS	$pp \rightarrow G \rightarrow e^+e^-, \mu^+\mu^-$
>1.23 (>0.84)	95	29	AAD	13A ATLS	$pp \rightarrow G \rightarrow WW$
>0.94 (>0.71)	95	30	AAD	13AO ATLS	$pp \rightarrow G \rightarrow WW$
>2.23	95	31	AAD	13AS ATLS	$pp \rightarrow \gamma\gamma, e^+e^-, \mu^+\mu^-$
>0.845	95	32	AAD	12AD ATLS	$pp \rightarrow G \rightarrow ZZ$
		33	AALTONEN	12V CDF	$p\bar{p} \rightarrow G \rightarrow ZZ$
		34	BAAK	12 RVUE	Electroweak
		35	AALTONEN	11G CDF	$p\bar{p} \rightarrow G \rightarrow ZZ$
>1.058	95	36	AALTONEN	11R CDF	$p\bar{p} \rightarrow G \rightarrow e^+e^-, \gamma\gamma$
>0.754	95	37	ABAZOV	11H D0	$p\bar{p} \rightarrow G \rightarrow WW$
>0.607		38	AALTONEN	10N CDF	$p\bar{p} \rightarrow G \rightarrow WW$
>1.05		39	ABAZOV	10F D0	$p\bar{p} \rightarrow G \rightarrow e^+e^-, \gamma\gamma$
		40	AALTONEN	08S CDF	$p\bar{p} \rightarrow G \rightarrow ZZ$
>0.90		41	ABAZOV	08J D0	$p\bar{p} \rightarrow G \rightarrow e^+e^-, \gamma\gamma$
		42	AALTONEN	07G CDF	$p\bar{p} \rightarrow G \rightarrow \gamma\gamma$
>0.889		43	AALTONEN	07H CDF	$p\bar{p} \rightarrow G \rightarrow e\bar{e}$
>0.785		44	ABAZOV	05N D0	$p\bar{p} \rightarrow G \rightarrow \ell\ell, \gamma\gamma$
>0.71		45	ABULENCIA	05A CDF	$p\bar{p} \rightarrow G \rightarrow \ell\bar{\ell}$

<sup>1</sup> SIRUNYAN 18BB use  $35.9$  ( $36.3$ )  $\text{fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13$  TeV to search for dilepton resonances in the dielectron (dimuon) channel. See their paper for other limits with warp parameter values  $k/\overline{M}_P = 0.01$  and  $0.05$ . This updates the results of KHACHATRYAN 17T.

<sup>2</sup> AABOUD 19A use  $36.1$   $\text{fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13$  TeV to search for Higgs boson pair production in the  $b\bar{b}b\bar{b}$  final state. See their Figure 9 for limits on the cross section times branching fraction as a function of the KK graviton mass. Assuming  $k/\overline{M}_P = 1$ , gravitons in the mass range 313–1362 GeV are excluded. This updates the results of AABOUD 16I.

<sup>3</sup> SIRUNYAN 19 use  $35.9$   $\text{fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13$  TeV to search for Higgs boson pair production in the  $\gamma\gamma b\bar{b}$  final state. See their Figure 9 for limits on the cross section times branching fraction as a function of the KK graviton mass. Assuming  $k/\overline{M}_P = 1$ , gravitons in the mass range 290–810 GeV are excluded. This updates the result of KHACHATRYAN 16BQ.

- 4 AABOUD 18AK use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for  $WW$  resonances in  $\ell\nu q\bar{q}$  final states ( $\ell=e, \mu$ ). See their Figure 7(d) for the limit on the cross section times branching fraction as a function of the KK graviton mass, including theoretical values for  $k/\overline{M}_P = 1$ . This updates the results of AABOUD 16AE.
- 5 AABOUD 18AL use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for diboson resonances in the  $\ell\ell q\bar{q}$  and  $\nu\bar{\nu}q\bar{q}$  final states. See their Figure 14 for the limit on cross section times branching fraction as a function of the the KK graviton mass, including theoretical values for  $k/\overline{M}_P = 0.5$  and 1. This updates the results of AABOUD 16AE.
- 6 AABOUD 18BF use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for  $ZZ$  resonances in the  $\ell\ell\ell\ell$  and  $\ell\ell\nu\bar{\nu}$  final states ( $\ell=e, \mu$ ). See their Figure 10 for the limit on the cross section times branching fraction as a function of the KK graviton mass, including theoretical values for  $k/\overline{M}_P = 1$ .
- 7 AABOUD 18BI use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for top-quark pairs decaying into the lepton-plus jets topology. See their Figure 16 for the limit on the KK graviton mass as a function of the cross section times branching fraction, including theoretical values for  $k/\overline{M}_P = 1$ .
- 8 AABOUD 18CJ combine the searches for heavy resonances decaying into bosonic and leptonic final states from  $36.1 \text{ fb}^{-1}$  of  $pp$  collision data at  $\sqrt{s} = 13 \text{ TeV}$ . The lower limit on the KK graviton mass, with  $k/\overline{M}_P = 1$ , is 2.3 TeV.
- 9 AABOUD 18CQ use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for Higgs boson pair production in the  $b\bar{b}\tau^+\tau^-$  final state. See their Figure 2 for limits on the cross section times branching fraction as a function of the KK graviton mass. Assuming  $k/\overline{M}_P = 1$ , gravitons in the mass range 325–885 GeV are excluded.
- 10 AABOUD 18CW use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for Higgs boson pair production in the  $\gamma\gamma b\bar{b}$  final state. See their Figure 7 for limits on the cross section times branching fraction as a function of the KK graviton mass.
- 11 AABOUD 18F use  $36.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for diboson resonances in the all-hadronic final state. See their Figure 5 for the limit on the cross section times branching fraction as a function of the KK graviton mass, including theoretical values for  $k/\overline{M}_P = 1$ . This updates the results of AABOUD 16AE.
- 12 SIRUNYAN 18AF use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for Higgs boson pair production in the  $b\bar{b}b\bar{b}$  final state. See their Figure 9 for limits on the cross section times branching fraction as a function of the KK graviton mass, including theoretical values for  $k/\overline{M}_P = 0.5$ . This updates the results of KHACHATRYAN 15R.
- 13 SIRUNYAN 18AS use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for  $ZZ$  resonances in the  $\ell\ell\nu\bar{\nu}$  final state ( $\ell=e, \mu$ ). See their Figure 5 for the limit on the KK graviton mass as a function of the cross section times branching fraction, including theoretical values for  $k/\overline{M}_P = 0.1, 0.5, \text{ and } 1.0$ .
- 14 SIRUNYAN 18AX use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for  $WW$  resonances in  $\ell\nu q\bar{q}$  final states ( $\ell=e, \mu$ ). See their Figure 6 for the limit on the KK graviton mass as a function of the cross section times branching fraction, including theoretical values for  $k/\overline{M}_P = 0.5$ . This updates the results of KHACHATRYAN 14A.
- 15 SIRUNYAN 18BK use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for  $ZZ$  resonances in the  $\nu\bar{\nu}q\bar{q}$  final state. See their Figure 4 for the limit on the KK graviton mass as a function of the cross section times branching fraction, including theoretical values for  $k/\overline{M}_P = 0.5$ .
- 16 SIRUNYAN 18BO use up to  $36 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for dijet resonances. Besides the quoted bound, KK graviton masses between 1.9 TeV and 2.5 TeV are also excluded. See their Figure 11 for the limit on the product of the cross section, branching fraction and acceptance as a function of the KK graviton mass. This updates the results of KHACHATRYAN 17W.

- 17 SIRUNYAN 18CW use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for Higgs boson pair production in the  $b\bar{b}b\bar{b}$  final state. See their Figure 8 for limits on the cross section times branching fraction as a function of the KK graviton mass, including theoretical values for  $k/\overline{M}_P = 0.5$ .
- 18 SIRUNYAN 18DJ use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for  $ZZ$  resonances in  $2\ell 2q$  final states ( $\ell = e, \mu$ ). See their Figure 6 for the limit on the KK graviton mass as a function of the cross section times branching fraction. Assuming  $k/\overline{M}_P = 0.5$ , a graviton mass is excluded below 925 GeV.
- 19 SIRUNYAN 18DU use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$ , in the diphoton channel to place a lower limit on the mass of the lightest KK graviton. See their paper for limits with other warp parameter values  $k/\overline{M}_P = 0.01$  and 0.2. This updates the results of KHACHATRYAN 16M.
- 20 SIRUNYAN 18F use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for Higgs boson pair production in the  $b\bar{b}\ell\nu\ell\nu$  final state. See their Figure 7 for limits on the cross section times branching fraction as a function of the KK graviton mass, including theoretical values for  $k/\overline{M}_P = 0.1$ .
- 21 SIRUNYAN 18I use  $19.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to search for narrow resonances decaying to bottom quark pairs. See their Figure 3 for the limit on the KK graviton mass as a function of the cross section times branching fraction in the mass range of 325–1200 GeV.
- 22 SIRUNYAN 18P use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for diboson resonances with dijet final states. See their Figure 6 for the limit on the KK graviton mass as a function of the cross section times branching fraction, including theoretical values for  $k/\overline{M}_P = 0.5$ . This updates the results of SIRUNYAN 17AK.
- 23 AABOUD 17AP use  $36.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  in the diphoton channel to place a lower limit on the mass of the lightest KK graviton. This updates the results of AABOUD 16H.
- 24 AAD 16R use  $20.3 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to place a lower bound on the mass of the lightest KK graviton. See their Figure 4 for the limit on the KK graviton mass as a function of the cross section times branching fraction.
- 25 AAD 15AU use  $20 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to search for KK gravitons in a warped extra dimension decaying to  $ZZ$  dibosons. See their Figure 2 for limits on the KK graviton mass as a function of the cross section times branching fraction.
- 26 AAD 15AZ use  $20.3 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to place a lower bound on the mass of the lightest KK graviton. See their Figure 2 for limits on the KK graviton mass as a function of the cross section times branching ratio.
- 27 AAD 15CT use  $20.3 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to place a lower bound on the mass of the lightest KK graviton. See their Figures 6b and 6c for the limit on the KK graviton mass as a function of the cross section times branching fraction.
- 28 AAD 14V use  $20.3$  ( $20.5$ )  $\text{fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  in the dielectron (dimuon) channels to place a lower bound on the mass of the lightest KK graviton. This updates the results of AAD 12CC .
- 29 AAD 13A use  $4.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$  in the  $\ell\nu\ell\nu$  channel, to place a lower bound on the mass of the lightest KK graviton.
- 30 AAD 13AO use  $4.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$  in the  $\ell\nu jj$  channel, to place a lower bound on the mass of the lightest KK graviton.
- 31 AAD 13AS use  $4.9 \text{ fb}^{-1}$  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 dielectron and dimuon channels to set the best limit. See their Table 2 for warp parameter values  $k/\overline{M}_P$  between 0.01 and 0.1. This updates the results of AAD 12Y .
- 32 AAD 12AD use  $1.02 \text{ fb}^{-1}$  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.

- 33 AALTONEN 12V use  $6 \text{ fb}^{-1}$  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 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.
- 34 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.
- 35 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.
- 36 AALTONEN 11R uses  $5.7 \text{ fb}^{-1}$  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.
- 37 ABAZOV 11H use  $5.4 \text{ fb}^{-1}$  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.
- 38 AALTONEN 10N use  $2.9 \text{ fb}^{-1}$  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.
- 39 ABAZOV 10F use  $5.4 \text{ fb}^{-1}$  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.
- 40 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  $1.1 \text{ fb}^{-1}$  of data. See their Fig. 8 for limits on  $\sigma \cdot \text{B}(G \rightarrow ZZ)$  versus the graviton mass.
- 41 ABAZOV 08J 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 electrons and photons using  $1 \text{ fb}^{-1}$  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.
- 42 AALTONEN 07G 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 photons using  $1.2 \text{ fb}^{-1}$  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.
- 43 AALTONEN 07H 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 electrons using  $1.3 \text{ fb}^{-1}$  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.
- 44 ABAZOV 05N 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 muons, electrons or photons, using  $260 \text{ pb}^{-1}$  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.
- 45 ABULENCIA 05A 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 muons or electrons, using  $200 \text{ pb}^{-1}$  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.

## Limits on Kaluza-Klein Gluons in Warped Extra Dimensions

This section places limits on the mass of the first Kaluza-Klein (KK) excitation of the gluon in warped extra dimension models with Standard Model fields propagating in the bulk. Bounds are given for a specific benchmark model with  $\Gamma/m = 15.3\%$  where  $\Gamma$  is the width and  $m$  the mass of the KK gluon. See the “Extra Dimensions” review for more discussion.

VALUE (TeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;3.8</b>	95	<sup>1</sup> AABOUD	18BI ATLS	$g_{KK} \rightarrow t\bar{t} \rightarrow \ell j$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>2.5	95	<sup>2</sup> CHATRCHYAN	13BM CMS	$g_{KK} \rightarrow t\bar{t}$
		<sup>3</sup> CHEN	13A	$\bar{B} \rightarrow X_S \gamma$
>1.5	95	<sup>4</sup> AAD	12BV ATLS	$g_{KK} \rightarrow t\bar{t} \rightarrow \ell j$

<sup>1</sup> AABOUD 18BI use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$ . This result updates AAD 13AQ.

<sup>2</sup> CHATRCHYAN 13BM use  $19.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$ . Bound is for a width of approximately 15–20% of the KK gluon mass.

<sup>3</sup> CHEN 13A place limits on the KK mass scale for a specific warped model with custodial symmetry and bulk fermions. See their Figures 4 and 5.

<sup>4</sup> AAD 12BV use  $2.05 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$ .

## Black Hole Production Limits

### Semiclassical Black Holes

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
	<sup>1</sup> SIRUNYAN	18DA CMS	$pp \rightarrow \text{multijet}$
	<sup>2</sup> AAD	16N ATLS	$pp \rightarrow \text{multijet}$
	<sup>3</sup> AAD	160 ATLS	$pp \rightarrow \ell + (\ell\ell/\ell j/jj)$
	<sup>4</sup> AAD	13AW ATLS	$pp \rightarrow \mu\mu$

<sup>1</sup> SIRUNYAN 18DA use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for semiclassical black holes decaying to multijet final states. No excess of events above the expected level of standard model background was observed. Exclusions at 95% CL are set on the mass threshold for black hole production as a function of the higher-dimensional Planck scale for rotating and nonrotating black holes under several model assumptions (ADD, 2, 4, 6 extra dimensions model) in the 7.1–10.3 TeV range. These limits supersede those in SIRUNYAN 17CP.

<sup>2</sup> AAD 16N use  $3.6 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for semiclassical black hole decays to multijet final states. No excess of events above the expected level of Standard Model background was observed. Exclusion contours at 95% C.L. are set on the mass threshold for black hole production versus higher-dimensional Planck scale for rotating black holes (ADD, 6 extra dimensions model).

<sup>3</sup> AAD 160 use  $3.2 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for semiclassical black hole decays to high-mass final states with leptons and jets. No excess of events above the expected level of Standard Model background was observed. Exclusion contours at 95% C.L. are set on the mass threshold for black hole production versus higher-dimensional Planck scale for rotating black holes (ADD, 2 to 6 extra dimensions).

<sup>4</sup> AAD 13AW use  $20.3 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to search for semiclassical black hole decays to like-sign dimuon final states using large track multiplicity. No excess of events above the expected level of Standard Model background was observed. Exclusion contours at 95% C.L. are set on the mass threshold for black hole production versus higher-dimensional Planck scale in various extra dimensions, rotating and non-rotating models.

**Quantum Black Holes**

<u>VALUE (GeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
• • •	We do not use the following data for averages, fits, limits, etc. • • •		
<sup>1</sup>	AABOUD 18BA	ATLS	$pp \rightarrow \gamma j$
<sup>2</sup>	AABOUD 18CM	ATLS	$pp \rightarrow e\mu, e\tau, \mu\tau$
<sup>3</sup>	SIRUNYAN 18AT	CMS	$pp \rightarrow e\mu$
<sup>4</sup>	SIRUNYAN 18DD	CMS	$pp \rightarrow$ dijet, ang. distrib.
<sup>5</sup>	AABOUD 17AK	ATLS	$pp \rightarrow jj$
<sup>6</sup>	SIRUNYAN 17CP	CMS	$pp \rightarrow jj$
<sup>7</sup>	KHACHATRY...16BE	CMS	$pp \rightarrow e\mu$
<sup>8</sup>	KHACHATRY...15V	CMS	$pp \rightarrow jj$
<sup>9</sup>	AAD 14AL	ATLS	$pp \rightarrow \ell j$
<sup>10</sup>	AAD 14V	ATLS	$pp \rightarrow ee, \mu\mu$
<sup>11</sup>	CHATRCHYAN 13A	CMS	$pp \rightarrow jj$

<sup>1</sup> AABOUD 18BA use  $36.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for quantum black hole decays to final states with a photon and a jet. No excess of events above the expected level of Standard Model background was observed. Exclusion limits at 95% C.L. are set on mass thresholds for black hole production in ADD (6 extra dimensions) and RS1 models. Assuming the black hole mass threshold is equal to the Planck scale, mass thresholds below 7.1 TeV and 4.4 TeV are excluded for the ADD and RS1 models, respectively. These limits supersede those in AAD 16Al.

<sup>2</sup> AABOUD 18CM use  $36.1 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for quantum black hole decays with different-flavor high-mass dilepton final states. No excess of events above the expected level of Standard Model background was observed. Exclusion limits at 95% C.L. are set on mass thresholds for black hole production in ADD (6 extra dimensions) and RS1 models. Assuming the black hole mass threshold is equal to the higher-dimensional Planck scale, mass thresholds below 5.6 (3.4), 4.9 (2.9), and 4.5 (2.6) TeV are excluded in the  $e\mu$ ,  $e\tau$  and  $\mu\tau$  channels for the ADD (RS1) models, respectively. These limits supersede those in AABOUD 16P.

<sup>3</sup> SIRUNYAN 18AT use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for quantum black hole decays to  $e\mu$  final states. In Figure 4, lower mass limits of 5.3, 5.5 and 5.6 TeV are placed in a model with 4, 5 and 6 extra dimensions, respectively, and a lower mass limit of 3.6 TeV is found for a single warped dimension.

<sup>4</sup> SIRUNYAN 18DD use  $35.9 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for quantum black hole decays in dijet angular distributions. A lower mass limit of 5.9 (8.2) TeV is placed in the RS (ADD) model with one (six) extra dimension(s).

<sup>5</sup> AABOUD 17AK use  $37 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for quantum black hole decays to final states with dijets. No excess of events above the expected level of Standard Model background was observed. Exclusion limits at 95% C.L. are set on mass thresholds for black hole production in an ADD (6 extra dimensions) model. Assuming the black hole mass threshold is equal to the higher-dimensional Planck scale, mass thresholds below 8.9 TeV are excluded.

<sup>6</sup> SIRUNYAN 17CP use  $2.3 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  to search for quantum black holes decaying to dijet final states. No excess of events above the expected level of standard model background was observed. Limits on the quantum black hole mass threshold are set as a function of the higher-dimensional Planck scale, under the assumption that the mass threshold must exceed the above Planck scale. Depending on the model, mass thresholds in the range up to 5.1–9.0 TeV are excluded.



- <sup>7</sup> KHACHATRYAN 16BE use  $19.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to search for quantum black holes undergoing lepton flavor violating decay to the  $e\mu$  final state. No excess of events above the expected level of standard model background was observed. Exclusion limits at 95% CL are set on mass thresholds for black hole production in the ADD (2–6 flat extra dimensions), RS1 (1 warped extra dimension), and a model with a Planck scale at the TeV scale from a renormalization of the gravitational constant (no extra dimensions). Limits on the black hole mass threshold are set assuming that it is equal to the higher-dimensional Planck scale. Mass thresholds for quantum black holes in the range up to 3.15–3.63 TeV are excluded in the ADD model. In the RS1 model, mass thresholds below 2.81 TeV are excluded in the PDG convention for the Schwarzschild radius. In the model with no extra dimensions, mass thresholds below 1.99 TeV are excluded.
- <sup>8</sup> KHACHATRYAN 15V use  $19.7 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to search for quantum black holes decaying to dijet final states. No excess of events above the expected level of standard model background was observed. Exclusion limits at 95% CL are set on mass thresholds for black hole production in the ADD (2–6 flat extra dimensions) and RS1 (1 warped extra dimension) model. Limits on the black hole mass threshold are set as a function of the higher-dimensional Planck scale, under the assumption that the mass threshold must exceed the above Planck scale. Depending on the model, mass thresholds in the range up to 5.0–6.3 TeV are excluded. This paper supersedes CHATRCHYAN 13AD.
- <sup>9</sup> AAD 14AL use  $20.3 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to search for quantum black hole decays to final states with high-invariant-mass lepton + jet. No excess of events above the expected level of Standard Model background was observed. Exclusion limits at 95% C.L. are set on mass thresholds for black hole production in an ADD (6 extra dimensions) model. Assuming the black hole mass threshold is equal to the higher-dimensional Planck scale, mass thresholds below 5.3 TeV are excluded.
- <sup>10</sup> AAD 14V use  $20.3 (20.5) \text{ fb}^{-1}$  of data in the dielectron (dimuon) channels from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  to search for quantum black hole decays involving high-mass dilepton resonances. No excess of events above the expected level of Standard Model background was observed. Exclusion limits at 95% C.L. are set on mass thresholds for black hole production in ADD (6 extra dimensions) and RS1 models. Assuming the black hole mass threshold is equal to the higher-dimensional Planck scale, mass thresholds below 3.65 TeV and 2.24 TeV are excluded for the ADD and RS1 models, respectively.
- <sup>11</sup> CHATRCHYAN 13A use  $5 \text{ fb}^{-1}$  of data from  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$  to search for quantum black holes decaying to dijet final states. No excess of events above the expected level of standard model background was observed. Exclusion limits at 95% CL are set on mass thresholds for black hole production in the ADD (2–6 flat extra dimensions) and RS (1 warped extra dimension) model. Limits on the black hole mass threshold are set as a function of the higher-dimensional Planck scale, under assumption that the mass threshold must exceed the above Planck scale. Depending on the model, mass thresholds in the range up to 4.0–5.3 TeV are excluded.

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