Extra Dimensions

For explanation of terms used and discussion of significant model dependence of following limits, see the "Extra Dimensions Review." Limits are expressed in conventions of of Giudice, Rattazzi, and Wells as explained in the Review. Footnotes describe originally quoted limit. n indicates the number of extra dimensions.

Limits not encoded here are summarized in the "Extra Dimensions Review."

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Mass Limits on M_H

This section includes limits on mass scale of coefficient of dim-8 operators from KK graviton exchange in models with large extra dimensions. Ambiguity of UV divergent summation is represented by unknown λ. Quoted limits on M_H arbitrarily assume $|\lambda|=1$. Different papers use slightly different definitions of the mass scale; two popular conventions, M_H and Λ_T, are discussed in the above Review on "Extra Dimensions."

VALUE (TeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.84	95	[1] ACHARD	02D	L3	$e^+e^- \rightarrow \gamma\gamma$ ($\lambda=+1$)
>0.99	95	[1] ACHARD	02D	L3	$e^+e^- \rightarrow \gamma\gamma$ ($\lambda=-1$)
>1.2	95	[2] ABBOTT	01	D0	$p\overline{p} \rightarrow e^+e^-, \gamma\gamma, \lambda=+1$
>1.1	95	[2] ABBOTT	01	D0	$p\overline{p} \rightarrow e^+e^-, \gamma\gamma, \lambda=-1$
>0.60	95	[3] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \mu^+\mu, \lambda=+1$
>0.63	95	[3] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \mu^+\mu, \lambda=-1$
>0.63	95	[3] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \tau^+\tau^-, \lambda=+1$
>0.50	95	[3] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \tau^+\tau^-, \lambda=-1$
>0.68	95	[3] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \mu^+\mu, \tau^+\tau^-, \lambda=+1$
>0.61	95	[3] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \mu^+\mu, \tau^+\tau^-, \lambda=-1$
		[4] ABREU	00A	DLPH	
>0.559	95	[5] ABREU	00S	DLPH	$e^+e^- \rightarrow \mu^+\mu^-, \lambda=-1$
>0.649	95	[5] ABREU	00S	DLPH	$e^+e^- \rightarrow \mu^+\mu^-, \lambda=+1$
>0.450	95	[5] ABREU	00S	DLPH	$e^+e^- \rightarrow \tau^+\tau^-, \lambda=-1$
>0.564	95	[5] ABREU	00S	DLPH	$e^+e^- \rightarrow \tau^+\tau^-, \lambda=+1$
>0.542	95	[5] ABREU	00S	DLPH	$e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-, \lambda=-1$
>0.680	95	[5] ABREU	00S	DLPH	$e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-, \lambda=+1$
>0.48	95	[6] ADLOFF	00	H1	$ep \rightarrow eX, \lambda=+1$
>0.72	95	[6] ADLOFF	00	H1	$ep \rightarrow eX, \lambda=-1$
$>$ 15–28	99.7	[7] CHANG	00B	RVUE	Electroweak
>0.98	95	[8] CHEUNG	00	RVUE	$e^+e^- \rightarrow \gamma\gamma$
$>$ 0.29–0.38	95	[9] GRAESSER	00	RVUE	$(g-2)_\mu$
$>$ 0.50–1.1	95	[10] HAN	00	RVUE	Electroweak

>2.0	95	[11] MATHEWS	00	RVUE	$\overline{p}p \rightarrow jj$ ($\lambda=\pm1$)
>1.0	95	[12] MELE	00	RVUE	$e^+e^- \rightarrow VV$, $\lambda=+1$
>1.1	95	[12] MELE	00	RVUE	$e^+e^- \rightarrow VV$, $\lambda=-1$
		[13] ABBIENDI	99P	OPAL	
		[14] ACCIARRI	99M	L3	
		[15] ACCIARRI	99S	L3	
>1.412	95	[16] BOURILKOV	99		$e^+e^- \rightarrow e^+e^-$, $\lambda=+1$
>1.077	95	[16] BOURILKOV	99		$e^+e^- \rightarrow e^+e^-$, $\lambda=-1$

[1] ACHARD 02 search for s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at $E_{\rm cm}$ = 192–209 GeV.

[2] ABBOTT 01 search for variations in differential cross sections to e^+e^- and $\gamma\gamma$ final states at the Tevatron. Bounds scale as $\lambda^{1/4}$.

[3] ABBIENDI 00R uses e^+e^- collisions at $\sqrt{s}$= 189 GeV. Bound is on M_H, where $\Lambda_T^4 = \frac{\pi}{2} M_H^4/|\lambda|$.

[4] ABREU 00A search for s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at $E_{\rm cm}$= 189–202 GeV. The limits $M_s > 713$ (691) GeV for $\lambda=+1$ (-1) are obtained, where M_s is a string mass scale.

[5] ABREU 00S uses e^+e^- collisions at $\sqrt{s}$=183 and 189 GeV. Bound is on M_H, where $\Lambda_T^4 = \frac{\pi}{2} M_H^4/|\lambda|$.

[6] ADLOFF 00 uses ep collisions at $\sqrt{s}$= 300 GeV. Bound is on M_H, where $\Lambda_T^4 = \frac{\pi}{2} M_H^4/|\lambda|$.

[7] CHANG 00B derive 3σ limit on M_H of (28,19,15) TeV for n=(2,4,6) respectively assuming the presence of a torsional coupling in the gravitational action. Highly model dependent.

[8] CHEUNG 00 obtains limits from anomalous diphoton production at OPAL due to graviton exchange. Original limit for n=4. However, unknown UV theory renders n dependence unreliable. Original paper works in HLZ convention. Limit scales as $\lambda^{1/4}$.

[9] GRAESSER 00 obtains a bound from graviton contributions to $g-2$ of the muon through loops of 0.29 TeV for n=2 and 0.38 TeV for n=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."

[10] HAN 00 calculates corrections to gauge boson self-energies from KK graviton loops and constrain them using S and T. Bounds on M_H range from 0.5 TeV (n=6) to 1.1 TeV (n=2); see text. Limits have strong dependence, λ^{n+2}, on unknown λ coefficient.

[11] MATHEWS 00 search for evidence of graviton exchange in CDF and DØ dijet production data. See their Table 2 for slightly stronger n-dependent bounds. Limits expressed in terms of $\widetilde{M}_S^4 = m_H^4/8$.

[12] MELE 00 obtains bound from KK graviton contributions to $e^+e^- \rightarrow VV$ (V=γ,W,Z) at LEP. Authors use Hewett conventions. Limits scale as $\lambda^{1/4}$.

[13] ABBIENDI 99P search for s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at $E_{\rm cm}$=189 GeV. The limits $G_+ > 660$ GeV and $G_- > 634$ GeV are obtained from combined $E_{\rm cm}$=183 and 189 GeV data, where $G_\pm$ is a scale related to the fundamental gravity scale.

[14] 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^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\overline{q}$ at $E_{\rm cm}$=183 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.

[15] 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^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\overline{q}$ at $E_{\rm cm}$=189 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.

[16] BOURILKOV 99 performs global analysis of LEP data on e^+e^- collisions at $\sqrt{s}$=183 and 189 GeV. Bound is on Λ_T.

Limits on *R* from On-Shell Production of Gravitons

This section include limits on on-shell (OS) production of gravitons, usually in astrophysical systems. Bounds quoted are on *R* the assumed common radius of the flat extra dimensions. *n* is the number of extra dimensions. Strong model dependence on light KK spectrum as explained in the "Extra Dimensions Review."

VALUE (nm)		CL%	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 9.6	(n=2)		[17] HANNESTAD	02	Astrophysics
< 0.04	(n=3)		[17] HANNESTAD	02	Astrophysics
< 0.07	(n=2)		[18] HANNESTAD	02	Astrophysics
< 0.001	(n=3)		[18] HANNESTAD	02	Astrophysics
< 660	(n=2)	95	[19] HANHART	01	Supernova
< 0.8	(n=3)	95	[19] HANHART	01	Supernova
< 90	(n=2)	95	[20] HANNESTAD	01	Astrophysics
< 0.19	(n=3)	95	[20] HANNESTAD	01	Astrophysics

[17] HANNESTAD 02 obtain a limit on *R* from emission of KK gravitons in supernovae which subsequently decay to $\gamma\gamma$, e^+e^-, and $\nu\overline{\nu}$, contaminating the diffuse γ-ray background.

[18] HANNESTAD 02 obtain a limit on *R* from bounds on the heating of neutron stars by the decay of the halo of KK gravitons produced in SN explosions and which surround neutron stars.

[19] HANHART 01 obtain bounds on *R* from limits on graviton cooling of supernova SN 1987a using numerical simulations of proto-neutron star neutrino emission.

[20] HANNESTAD 01 obtain a limit on *R* from emission of KK gravitons in supernovae which subsequently decay to $\gamma\gamma$, e^+e^-, and $\nu\overline{\nu}$, contaminating the diffuse γ-ray background.

Limits on M_D from On-Shell Production of Gravitons

This section include limits on on-shell (OS) production of gravitons, usually in astrophysical systems. Bounds quoted are on M_D, which is related to the fundamental scale $\overline{M}_D$, introduced in Eq. (3) of the above note on "Extra Dimensions" by $M_D = (2\pi)^{n/(2+n)}\overline{M}_D$. Strong model dependence on light KK spectrum as explained in the "Extra Dimensions Review."

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$\gtrsim 1$–2		[21] ANCHORDOQ...	02B	RVUE	Cosmic Rays
$\gtrsim 1000$		[22] FAIRBAIRN	01		Cosmology
>1.10	95	[23] ABREU	00Z	DLPH	$e^+e^- \rightarrow \gamma G$
$\gtrsim 3$–4		[24] CASSISI	00		Red giants
		[25] ACCIARRI	99M	L3	
		[26] ACCIARRI	99R	L3	
		[27] ACCIARRI	99S	L3	

[21] ANCHORDOQUI 02B derive bound on M_D from non-observation of black hole production in high-energy cosmic rays. Bound is stronger for larger *n*, but depends sensitively on threshold for black hole production.

[22] FAIRBAIRN 01 obtains bound on the fundamental scale M_f, defined by $4\pi G = (1/(RM_f))^n/M_f^2$, from overproduction of KK modes in the early universe.

[23] ABREU 00Z uses e^+e^- collisions at $\sqrt{s}$= 189 GeV. Bound is n=2, and is equivalent to bound on common radius of $R<$ 0.4 mm. For n=4 and 6, they obtain $>$ 0.68 and 0.51 TeV, respectively. Systematic errors reduce limits by 9%, 3%, and 3% respectively.

[24] CASSISI 00 obtains bound from red-giant cooling, assuming n=2. Bound is on the scale M_s defined by $R^n = M^2_{P\ell}/(M_s^{n+2}\Omega_n)$ where Ω_n is the volume of the n-dimensional sphere with unit radius.
[25] 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^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\overline{q}$ at $E_{\rm cm}$=183 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.
[26] ACCIARRI 99R search for the reaction $e^+e^- \rightarrow \gamma G$ at $E_{\rm cm}$=189 GeV. Limits on the gravity scale are listed in their Table 4.
[27] 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^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\overline{q}$ at $E_{\rm cm}$=189 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.

Limits on Mass of Radion

This section includes limits on mass of radion, usually in context of Randall-Sundrum models. See the "Extra Dimension Review" for discussion of model dependence.

VALUE (GeV)	*DOCUMENT ID*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$\gtrsim$ 35	[28] MAHANTA	00	$Z \rightarrow$ radion $\ell\overline{\ell}$
>120	[29] MAHANTA	00B	$p\overline{p} \rightarrow$ radion $\rightarrow \gamma\gamma$

[28] MAHANTA 00 obtain bound on radion mass in the RS model. Bound is from Higgs boson search at LEP I.
[29] MAHANTA 00B uses $p\overline{p}$ collisions at $\sqrt{s}$= 1.8 TeV; production via gluon-gluon fusion. Authors assume a radion vacuum expectation value of 1 TeV.

Limits on $1/R = M_c$

This section includes limits on $1/R = M_c$, the compactification scale in models with TeV extra dimensions, due to exchange of Standard Model KK excitations. See the "Extra Dimension Review" for discussion of model dependence.

VALUE (TeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>3.3	95	[30] CORNET	00	RVUE	Electroweak
> 3.3–3.8	95	[31] RIZZO	00	RVUE	Electroweak

[30] CORNET 00 translates a bound on the coefficient of the 4-fermion operator $(\overline{\ell}\gamma_\mu\tau^a\ell)(\overline{\ell}\gamma^\mu\tau^a\ell)$ derived by Hagiwara and Matsumoto into a limit on the mass scale of KK W bosons.
[31] 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 M_s

This section includes limits on the cutoff scale or string scale as indicated (TeV).

VALUE (TeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>0.49	[32] ACCIARRI	00P	L3	$e^+e^- \rightarrow e^+e^-$

[32] ACCIARRI 00P uses e^+e^- collisions at $\sqrt{s}$= 183 and 189 GeV. Bound on string scale M_s from massive string modes. M_s is defined in hep-ph/0001166 by $M_s(1/\pi)^{1/8}\alpha^{-1/4} = M$ where $(4\pi G)^{-1} = M^{n+2}R^n$.

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