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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Limits on R from Deviations in Gravitational Force Law

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

VALUE (μm)	CL%	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[1] CHIAVERINI	03	Microcantilever
$\lesssim 200$	95	[2] LONG	03	Microcantilever
<190	95	[3] HOYLE	01	Torsion pendulum
		[4] HOSKINS	85	Torsion pendulum

[1] CHIAVERINI 03 search for new forces, probing α above 10^4 and λ down to 3μm, 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.

[2] LONG 03 search for new forces, probing α down to 3, and distances down to about 10μm. See their Fig. 4 for details on the bound.

[3] HOYLE 01 search for new forces, probing α down to 10^{-2} and distances down to 20μm. See their Fig. 4 for details on the bound.

[4] 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 μm for δ=2.

VALUE (μm)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 270	95	[5] ABDALLAH	05B	DLPH	$e^+ e^- \rightarrow \gamma G$
$<$ 210	95	[6] ACHARD	04E	L3	$e^+ e^- \rightarrow \gamma G$
$<$ 480	95	[7] ACOSTA	04C	CDF	$\overline{p} p \rightarrow j G$

$<$ 0.00038	95	[8] CASSE	04		Neutron star γ sources
$<$ 610	95	[9] ABAZOV	03	D0	$\overline{p}p \rightarrow jG$
$<$ 0.96	95	[10] HANNESTAD	03		Supernova cooling
$<$ 0.096	95	[11] HANNESTAD	03		Diffuse γ background
$<$ 0.051	95	[12] HANNESTAD	03		Neutron star γ sources
$<$ 0.00016	95	[13] HANNESTAD	03		Neutron star heating
$<$ 300	95	[14] HEISTER	03C	ALEP	$e^+e^- \rightarrow \gamma G$
		[15] FAIRBAIRN	01		Cosmology
$<$ 0.66	95	[16] HANHART	01		Supernova cooling
		[17] CASSISI	00		Red giants
$<$1300	95	[18] ACCIARRI	99S	L3	$e^+e^- \rightarrow ZG$

Limits on R from On-Shell Production of Gravitons: $\delta \geq 3$

This section includes limits similar to those in the previous section, but for $\delta = 3$ extra dimensions. Bounds are given in nm for $\delta = 3$. Entries are also shown for papers examining models with $\delta > 3$.

VALUE (nm)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 3.5	95	[5] ABDALLAH	05B	DLPH	$e^+e^- \rightarrow \gamma G$
$<$ 2.9	95	[6] ACHARD	04E	L3	$e^+e^- \rightarrow \gamma G$
	95	[7] ACOSTA	04C	CDF	$\overline{p}p \rightarrow jG$
$<$ 0.0042	95	[8] CASSE	04		Neutron star γ sources
$<$ 6.1	95	[9] ABAZOV	03	D0	$\overline{p}p \rightarrow jG$
$<$ 1.14	95	[10] HANNESTAD	03		Supernova cooling
$<$ 0.025	95	[11] HANNESTAD	03		Diffuse γ background
$<$ 0.11	95	[12] HANNESTAD	03		Neutron star γ sources
$<$ 0.0026	95	[13] HANNESTAD	03		Neutron star heating
$<$ 3.9	95	[14] HEISTER	03C	ALEP	$e^+e^- \rightarrow \gamma G$
		[19] ACOSTA	02H	CDF	$p\overline{p} \rightarrow \gamma G$
		[15] FAIRBAIRN	01		Cosmology
$<$ 0.8	95	[16] HANHART	01		Supernova cooling
		[17] CASSISI	00		Red giants
$<$18	95	[18] ACCIARRI	99S	L3	$e^+e^- \rightarrow ZG$

[5] ABDALLAH 05B search for $e^+e^- \rightarrow \gamma G$ at $\sqrt{s}$ = 180–209 GeV to place bounds on the size of extra dimensions and the fundamental scale. Limits for all $\delta \leq 6$ are given in their Table 6. These limits supersede those in ABREU 00Z.

[6] ACHARD 04E search for $e^+e^- \rightarrow \gamma G$ at $\sqrt{s}$ = 189–209 GeV to place bounds on the size of extra dimensions and the fundamental scale. See their Table 8 for limits with $\delta \leq 8$. These limits supersede those in ACCIARRI 99R.

[7] ACOSTA 04C search for $\overline{p}p \rightarrow jG$ at $\sqrt{s}$ = 1.8 TeV to place bounds on the size of extra dimensions and the fundamental scale. See their paper for bounds on δ = 4, 6.

[8] CASSE 04 obtain a limit on R from the gamma-ray emission of point γ sources that arises from the photon decay of gravitons around newly born neutron stars, applying the technique of HANNESTAD 03 to neutron stars in the galactic bulge. Limits for all $\delta \leq$ 7 are given in their Table I.

[9] ABAZOV 03 search for $p\overline{p} \rightarrow jG$ at $\sqrt{s}$=1.8 TeV to place bounds on M_D for 2 to 7 extra dimensions, from which these bounds on R are derived. See their paper for bounds on intermediate values of δ. We quote results without the approximate NLO scaling introduced in the paper.

[10] 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.

[11] HANNESTAD 03 obtain a limit on R from gravitons emitted in supernovae and which subsequently decay, contaminating the diffuse cosmic γ background. Limits for all $\delta \leq 7$ are given in their Tables V and VI. These limits supersede those in HANNESTAD 02.

[12] HANNESTAD 03 obtain a limit on R from gravitons emitted in two recent supernovae and which subsequently decay, creating point γ sources. Limits for all $\delta \leq 7$ are given in their Tables V and VI. These limits are corrected in the published erratum.

[13] 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.

[14] HEISTER 03C use the process $e^+e^- \rightarrow \gamma G$ at $\sqrt{s}$ = 189–209 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.

[15] 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 $R< 0.13\,\mu$m to 0.001 μm for δ=2; bounds for δ=3,4 can be derived from Table 1 in the paper.

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

[17] CASSISI 00 obtain rough bounds on M_D (and thus R) from red giant cooling for δ=2,3. See their paper for details.

[18] ACCIARRI 99S search for $e^+e^- \rightarrow ZG$ at $\sqrt{s}$=189 GeV. Limits on the gravity scale are found in their Table 2, for $\delta \leq 4$.

[19] ACOSTA 02H uses the process $p\overline{p} \rightarrow \gamma G$ at $\sqrt{s}$ = 1.8 TeV to place bounds on R for δ=4,6, and 8: R<24 nm, 55 fm, and 2.6 fm respectively. However the kinematics relevant to these bounds are probably outside the validity range of the effective theory.

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 λ, which is taken to be $\lambda = \pm1$ 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; some popular conventions, M_H and Λ_{TT}, are discussed in the above Review on "Extra Dimensions." All bounds scale as $\lambda^{1/4}$, unless otherwise stated.

VALUE (TeV)		*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
> 0.78	(> 0.79)	95	[20] CHEKANOV	04B	ZEUS	$e^{\pm}p \rightarrow e^{\pm}X$
> 0.805	(> 0.956)	95	[21] ABBIENDI	03D	OPAL	$e^+e^- \rightarrow \gamma\gamma$
> 0.7	(> 0.7)	95	[22] ACHARD	03D	L3	$e^+e^- \rightarrow ZZ$
> 0.82	(> 0.78)	95	[23] ADLOFF	03	H1	$e^{\pm}p \rightarrow e^{\pm}X$
> 1.28	(> 1.25)	95	[24] GIUDICE	03	RVUE	
>20.6	(> 15.7)	95	[25] GIUDICE	03	RVUE	Dim-6 operators
> 0.80	(> 0.85)	95	[26] HEISTER	03C	ALEP	$e^+e^- \rightarrow \gamma\gamma$
> 0.84	(> 0.99)	95	[27] ACHARD	02D	L3	$e^+e^- \rightarrow \gamma\gamma$
> 1.2	(> 1.1)	95	[28] ABBOTT	01	D0	$p\overline{p} \rightarrow e^+e^-, \gamma\gamma$
> 0.60	(> 0.63)	95	[29] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \mu^+\mu^-$
> 0.63	(> 0.50)	95	[29] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \tau^+\tau^-$
> 0.68	(> 0.61)	95	[29] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-$
			[30] ABREU	00A	DLPH	

$>$ 0.649	($>$ 0.559)	95	[31] ABREU	00S	DLPH	$e^+e^- \rightarrow \mu^+\mu^-$
$>$ 0.564	($>$ 0.450)	95	[31] ABREU	00S	DLPH	$e^+e^- \rightarrow \tau^+\tau^-$
$>$ 0.680	($>$ 0.542)	95	[31] ABREU	00S	DLPH	$e^+e^- \rightarrow \mu^+\mu^-,\tau^+\tau^-$
$>$ 15–28		99.7	[32] CHANG	00B	RVUE	Electroweak
$>$ 0.98		95	[33] CHEUNG	00	RVUE	$e^+e^- \rightarrow \gamma\gamma$
$>$ 0.29–0.38		95	[34] GRAESSER	00	RVUE	$(g-2)_\mu$
$>$ 0.50–1.1		95	[35] HAN	00	RVUE	Electroweak
$>$ 2.0	($>$ 2.0)	95	[36] MATHEWS	00	RVUE	$\overline{p}p \rightarrow jj$
$>$ 1.0	($>$ 1.1)	95	[37] MELE	00	RVUE	$e^+e^- \rightarrow VV$
			[38] ABBIENDI	99P	OPAL	
			[39] ACCIARRI	99M	L3	
			[40] ACCIARRI	99S	L3	
$>$ 1.412	($>$ 1.077)	95	[41] BOURILKOV	99		$e^+e^- \rightarrow e^+e^-$

[20] CHEKANOV 04B search for deviations in the differential cross section of $e^\pm p \rightarrow e^\pm X$ with 130 pb^{-1} of combined data and Q^2 values up to 40,000 GeV^2 to place a bound on M_{TT}.

[21] ABBIENDI 03D use e^+e^- collisions at $\sqrt{s}$=181–209 to place bounds on the ultraviolate scale M_{TT}, which is equivalent to their definition of M_s.

[22] ACHARD 03D look for deviations in the cross section for $e^+e^- \rightarrow ZZ$ from $\sqrt{s}$ = 200–209 GeV to place a bound on M_{TT}.

[23] ADLOFF 03 search for deviations in the differential cross section of $e^\pm p \rightarrow e^\pm X$ at $\sqrt{s}$=301 and 319 GeV to place bounds on M_{TT}.

[24] GIUDICE 03 review existing experimental bounds on M_{TT} and derive a combined limit.

[25] GIUDICE 03 place bounds on Λ_6, the coefficient of the gravitationally-induced dimension-6 operator $(2\pi\lambda/\Lambda_6^2)(\sum \overline{f}\gamma_\mu\gamma^5 f)(\sum \overline{f}\gamma^\mu\gamma^5 f)$, using data from a variety of experiments. Results are quoted for $\lambda=\pm1$ and are independent of δ.

[26] HEISTER 03C use e^+e^- collisions at $\sqrt{s}$= 189–209 GeV to place bounds on the scale of dim-8 gravitational interactions. Their $M_s^\pm$ is equivalent to our M_{TT} with $\lambda=\pm1$.

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

[28] ABBOTT 01 search for variations in differential cross sections to e^+e^- and $\gamma\gamma$ final states at the Tevatron.

[29] ABBIENDI 00R uses e^+e^- collisions at $\sqrt{s}$= 189 GeV.

[30] ABREU 00A search for s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at $E_{\rm cm}$= 189–202 GeV.

[31] ABREU 00S uses e^+e^- collisions at $\sqrt{s}$=183 and 189 GeV.

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

[33] CHEUNG 00 obtains limits from anomalous diphoton production at OPAL due to graviton exchange. Original limit for δ=4. However, unknown UV theory renders δ dependence unreliable. Original paper works in HLZ convention.

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

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

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

[37] MELE 00 obtains bound from KK graviton contributions to $e^+ e^- \to VV$ ($V=\gamma,W,Z$) at LEP. Authors use Hewett conventions.
[38] ABBIENDI 99P search for s-channel graviton exchange effects in $e^+ e^- \to \gamma\gamma$ at E_{cm}=189 GeV. The limits $G_+ > 660$ GeV and $G_- > 634$ GeV are obtained from combined E_{cm}=183 and 189 GeV data, where $G_\pm$ is a scale related to the fundamental gravity scale.
[39] ACCIARRI 99M search for the reaction $e^+ e^- \to \gamma G$ and s-channel graviton exchange effects in $e^+ e^- \to \gamma\gamma$, $W^+ W^-$, ZZ, $e^+ e^-$, $\mu^+ \mu^-$, $\tau^+ \tau^-$, $q\overline{q}$ at E_{cm}=183 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.
[40] ACCIARRI 99S search for the reaction $e^+ e^- \to ZG$ and s-channel graviton exchange effects in $e^+ e^- \to \gamma\gamma$, $W^+ W^-$, ZZ, $e^+ e^-$, $\mu^+ \mu^-$, $\tau^+ \tau^-$, $q\overline{q}$ at E_{cm}=189 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.
[41] BOURILKOV 99 performs global analysis of LEP data on $e^+ e^-$ collisions at $\sqrt{s}$=183 and 189 GeV. Bound is on Λ_T.

Direct Limits on Gravitational or String Mass Scale

This section includes limits on the fundamental gravitational scale and/or the string scale from processes which depend directly on one or the other of these scales.

VALUE (TeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$\gtrsim$ 1–2	[42] ANCHORDOQ...	02B	RVUE	Cosmic Rays
>0.49	[43] ACCIARRI	00P	L3	$e^+ e^- \to e^+ e^-$

[42] ANCHORDOQUI 02B derive bound on M_D from non-observation of black hole production in high-energy cosmic rays. Bound is stronger for larger δ, but depends sensitively on threshold for black hole production.
[43] 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 $(4\pi G)^{-1} = M^{n+2}R^n$.

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	[44] CORNET	00	RVUE	Electroweak
> 3.3–3.8	95	[45] RIZZO	00	RVUE	Electroweak

[44] 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.
[45] 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 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. • • •			
$\gtrsim 35$	[46] MAHANTA	00	$Z \rightarrow$ radion $\ell\overline{\ell}$
>120	[47] MAHANTA	00B	$p\overline{p} \rightarrow$ radion $\rightarrow \gamma\gamma$

[46] MAHANTA 00 obtain bound on radion mass in the RS model. Bound is from Higgs boson search at LEP I.

[47] 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.

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