Bounds on large extra-dimensions from the LHC

arXiv:1101.4919
with
P.P. Giardino, G.F. Giudice, P. Lodone, A. Strumia

Roberto Franceschini

EPFL Lausanne

September 1st 2011

Outline

- Motivation
- Phenomenology
- Bounds on tree-level graviton exchange
- Real graviton emission
- Conclusions

Motivation and set-up

after all the hierarchy might be between two not so separated scales ...

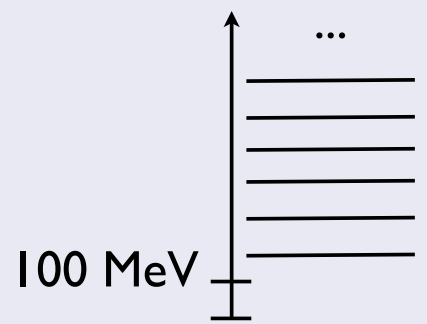
This is what happens when gravity feels $D = 4 + \delta$ dimensions:

- $\bar{M}_{pl}^2 = \bar{M}_D^{2+\delta} \cdot V_{(\delta)}$ where $V \sim R^\delta$, $\bar{M} \equiv M/\sqrt{8\pi}$

$R = 10^{12}, 10^{-3}, 10^{-12}, 10^{-15}\,\mathrm{m}$ for $\delta = 1, 2, 4, 6$
$\frac{1}{R} = 10^{-21}\,\mathrm{eV}, 10^{-4}\,\mathrm{eV}, 20\,\mathrm{KeV}, 7\,\mathrm{MeV}$ for $\delta = 1, 2, 4, 6$

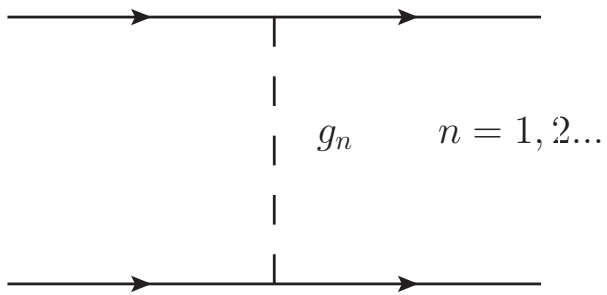
- KK expansions naively gives $m_{g_n} \sim \frac{n}{R}$
- astrophysics limits for gravitons below $O(100)\,\mathrm{MeV}$ (arXiv:hep-ph/0304029)
- can be avoided lifting the KK tower above $O(100)\,\mathrm{MeV}$ with a modification of the metric of the ED (arXiv:hep-ph/0002001,hep-ph/0108115,hep-ph/0408320)

such modifications are irrelevant for a collider



Gravitons exchange

- KK states of the graviton tower can mediate $2 \to 2$ scattering



- Each graviton is weakly coupled, $\sim 1/M_{pl}$, but there are many KK (due to the large ED phase-space as $m_{KK} = p_{ED}$)
- The effect might be dominated by UV physics ($\delta > 2$)
- At the very least you can model the effect of tree-level exchange of gravitons with a dimension-8 operator

$$\mathcal{L} \supset c_T \mathcal{T} \equiv \frac{8}{M_T^4} \cdot \frac{1}{2} \left(T_{\mu\nu} T^{\mu\nu} + \frac{1}{\delta + 2} T^{\mu}_{\mu} T^{\nu}_{\nu} \right)$$

$pp \to \gamma\gamma, \ell\bar{\ell}$, ... and do not forget jj

Energy pays off to probe the dim-8: LHC7@2010 $\gg$ TeVatron

$$\sigma = \left(\frac{2\ \text{TeV}}{M_T}\right)^8 \times \begin{cases} 12.5\,\text{pb} & \text{for } pp \to jj \quad \text{no search so far ...} \\ 10.4\,\text{fb} & \text{for } pp \to \mu^+\mu^- \quad \text{EXO-11-039} \\ 21.3\,\text{fb} & \text{for } pp \to \gamma\gamma \quad \text{EXO-11-038} \end{cases}$$

- $\ell\bar{\ell}$ and $\gamma\gamma$ roughly a cut-and-count in the high mass region
- jj has a larger rate, but cut-and-count is risky due to QCD uncertainties

$pp \to \gamma\gamma, \ell\bar{\ell}$, ... and do not forget jj

Energy pays off to probe the dim-8: LHC7@2010 $\gg$ TeVatron

$$\sigma = \left(\frac{2\ \text{TeV}}{M_T}\right)^8 \times \begin{cases} 12.5\,\text{pb} & \text{for } pp \to jj \quad \text{no search so far ...} \\ 10.4\,\text{fb} & \text{for } pp \to \mu^+\mu^- \quad \text{EXO-11-039} \\ 21.3\,\text{fb} & \text{for } pp \to \gamma\gamma \quad \text{EXO-11-038} \end{cases}$$

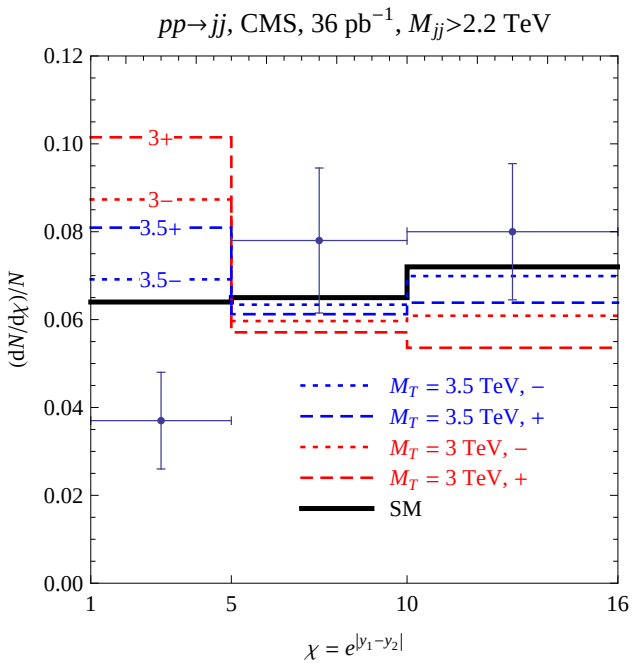
- $\ell\bar{\ell}$ and $\gamma\gamma$ roughly a cut-and-count in the high mass region
- jj has a larger rate, but cut-and-count is risky due to QCD uncertainties

- Bounds can be extracted from the angular distribution arXiv:0906.4819 (D0)
- $uu \to uu$ dominates at LHC $\Rightarrow$ jj is even better than at TeVatron

$\frac{d\sigma}{d\chi}$ angular distribution, $\chi \equiv \exp|y_1 - y_2|$

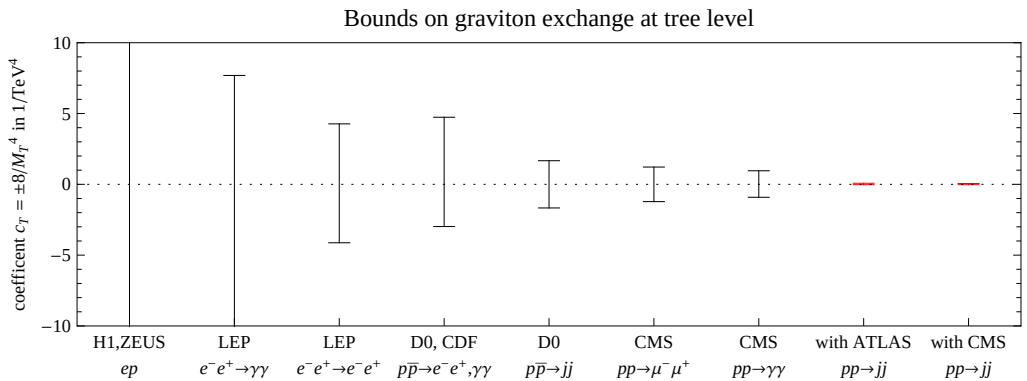
Being the mediator a spin-2 each vertex has a p_T^2 dependence as opposed to the p_T dependence of a spin-1.

- Signal gives more central events (small χ)



M_T >3.4 TeV with 36/pb, waiting for the update

- higher mass m_{jj} as $\mathcal{L}$ increases
- smaller region in χ (if the detector allows)



arXiv:1103.3864,1102.2020

Virtual Gravitons in $\gamma\gamma$ and $\mu\bar{\mu}$ searches

$pp \to \mu\bar{\mu}$ with $\mathcal{L} \sim 1$/fb: $M_T > 2.3$ TeV

Table 3: Observed 95% upper limits in TeV with respect to GRW and HLZ conventions for full model validity in $\sqrt{\hat{s}}$ and truncation at $M_{\mu\mu} = M_s$ (HLZ) or $M_{\mu\mu} = \Lambda_T$ (GRW).

	Λ_T [TeV] (GRW)	M_s [TeV] (HLZ)					
		$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
ADD k-factor: 1.0							
Full	2.62	2.58	3.12	2.62	2.36	2.20	2.08
Truncated	2.56	2.58	3.10	2.56	2.27	2.09	1.95
ADD k-factor: 1.3							
Full	2.70	2.72	3.22	2.70	2.44	2.28	2.16
Truncated	2.66	2.72	3.20	2.66	2.37	2.17	2.02

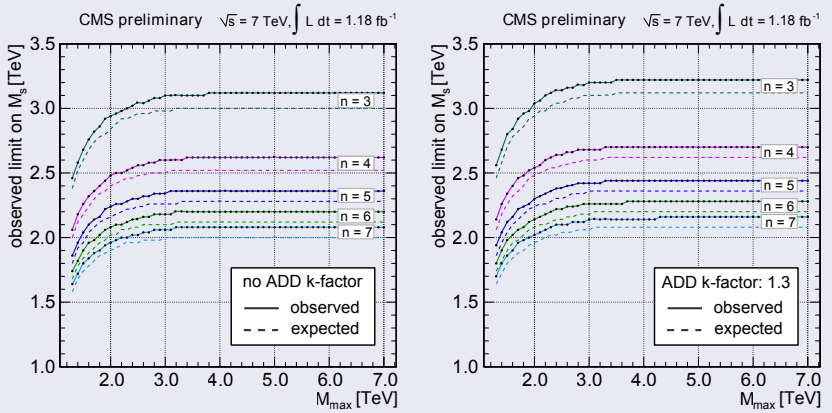


Figure 3: Observed 95% upper limits on M_s for different numbers of extra dimensions n with (Left) and without (Right) ADD k-factor.

EXO-11-039

$pp \to \gamma\gamma$ with $\mathcal{L} \sim 1$/fb: $M_T > 2.7$ TeV

Table 2: Table of 95% CL lower limits on M_S (in TeV), as a function of the number of EDs in the HLZ convention for two different values of the ADD signal K factor. All limits are computed with a signal cross section truncated to zero when $\sqrt{\hat{s}} > M_S$.

K factor	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
1.0	3.2	3.4	2.8	2.6	2.4	2.2
1.6	3.5	3.7	3.1	2.8	2.6	2.4

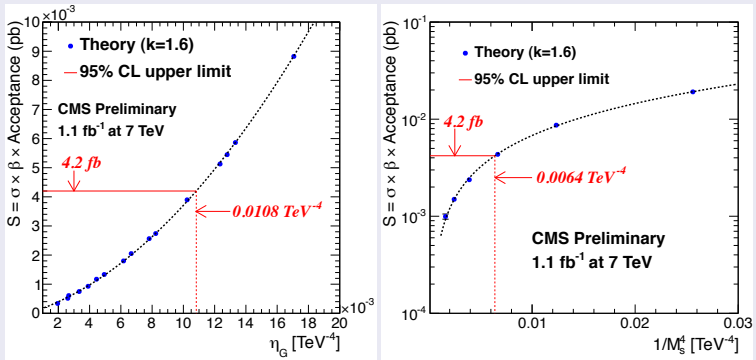


Figure 4: Signal cross section parameterization as a function of the strength of the ED effects, η_G (left) and as a function of $1/M_s^4$ for the $n_{ED} = 2$ case (right).

EXO-11-038

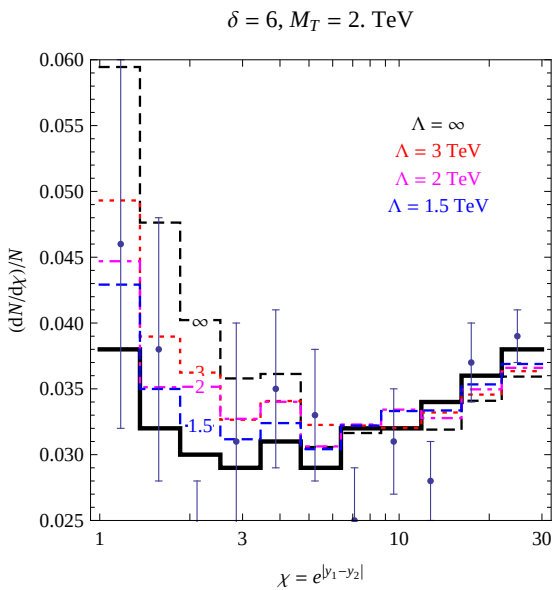
$\frac{d\sigma}{d\chi}$ angular distribution, $\chi \equiv \exp|y_1 - y_2|$

Being the mediator a spin-2 each vertex has a p_T^2 dependence as opposed to the p_T dependence of a spin-1.

- Signal gives more central events (small χ)

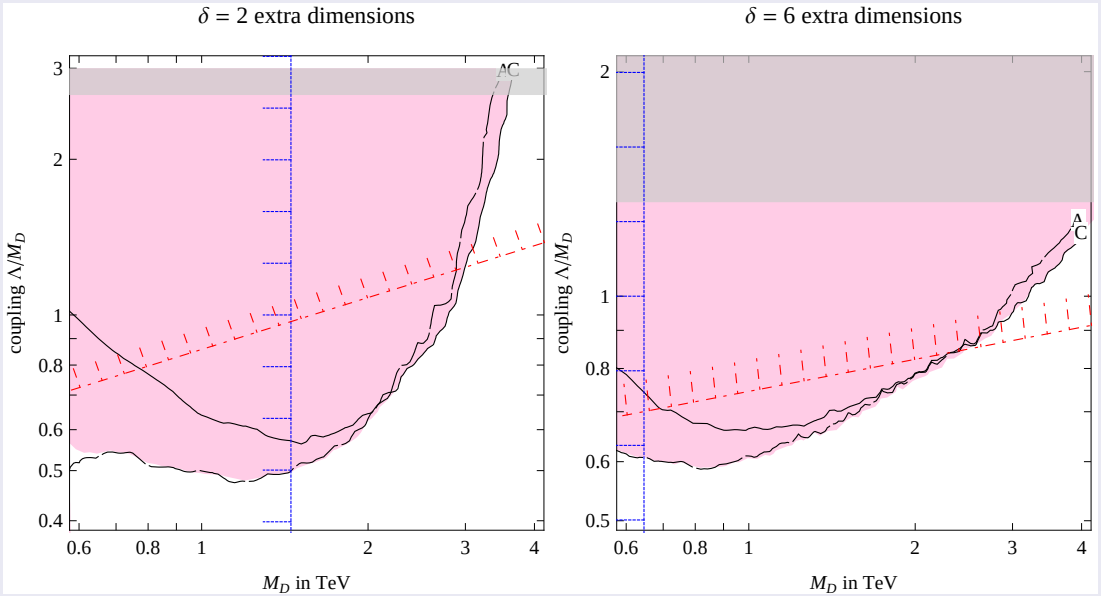
$$\mathcal{A} = \mathcal{S}_{\delta,\Lambda}(s)\left(T_{\mu\nu}T^{\mu\nu} - \frac{T^{\mu}_{\mu}T^{\nu}_{\nu}}{\delta+2}\right)$$

$$\mathcal{S}_{\delta,\Lambda}(s) = \frac{1}{M_D^{\delta+2}}\int_{|q|<\Lambda}\frac{d^{\delta}q}{s-q^2+i\epsilon}$$



$\frac{d\sigma}{d\chi}$ angular distribution, $\chi \equiv \exp|y_1 - y_2|$

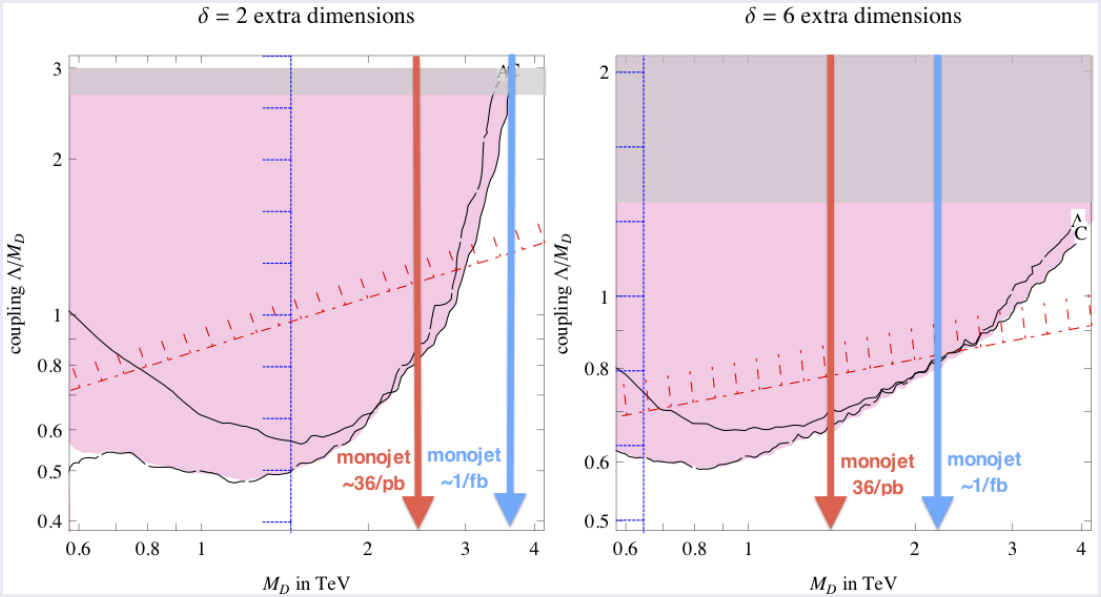
ATLAS and CMS with 36/pb



$\frac{d\sigma}{d\chi}$ angular distribution, $\chi \equiv \exp|y_1 - y_2|$

ATLAS and CMS with 36/pb plus monojet searches

EXO-11-058, EXO-11-059, ATLAS-CONF-2011-096, arXiv:1103.3864,1102.2020



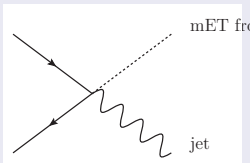
- ED pushed in the multi-TeV region

Extending the reach of ED searches

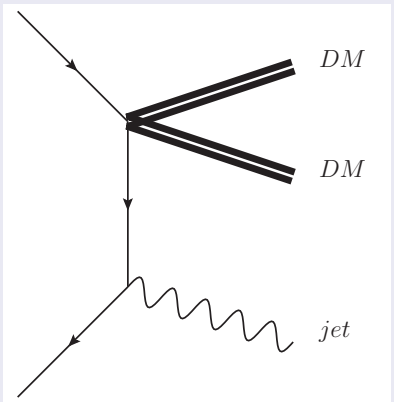
limits from j+mET and γ+mET

- Extra-dimensions searches

  EXO-11-058, EXO-11-059, ATLAS-CONF-2011-096



- dark matter production (see T. Tait)



Sparse thoughts:
(personal set of open questions)

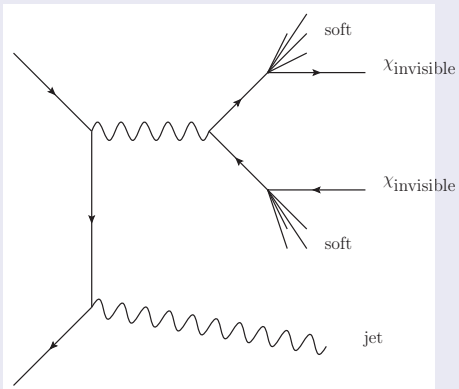
- one or many invisible body final states?

  see R. Mahbubani and B. Gripaios on arXiv:1108.1800

- continuos spectrum of invisibles or just a single/multi body final state?

- any chance to catch difficult scenarios as degenerate (N)LSP in jet+mET+soft ℓs?

  (Giudice, Han, Wang, Wang arXiv:1004:4901, Buckley, Randall, Shuve arXiv:0909.4549)



Conclusions

- No signal of large extra-dimensions so far (M_D constrained in the multi-TeV region)
- Best bounds on tree-level gravitons from the angular distribution in $pp \to jj$
- Monojet searches can be recycled for DM searches and more (discussion?)

$$\mathcal{S}(s) = \frac{1}{M_D^{2+\delta}} \int_{|q|<\Lambda} \frac{d^\delta q}{s - q^2 + i\varepsilon} = \frac{\pi^{\delta/2}\,\Lambda^{\delta-2}}{\Gamma(\delta/2)\,M_D^{2+\delta}} F_\delta(\frac{s}{\Lambda^2})$$

$$F_{\delta+2}(x) = xF_\delta(x) - \frac{2}{\delta}$$

$$F_1(x) = \frac{2}{\sqrt{x}}\,\mathrm{arctanh}\frac{1}{\sqrt{x}}, \qquad F_2(x) = -\log\left(1 - \frac{1}{x}\right).$$

$$M_S(\mathrm{Hewett})\,|_{\lambda=+1} = \sqrt[4]{\frac{2}{\pi}}\,M_S(\mathrm{HLZ})\,|_{n=4}$$
$$\Lambda_T = M_S(\mathrm{HLZ})\,|_{n=4}\ .$$

Table 1. Lower limits at the 95% CL on the effective Planck scale, M_S(Hewett), in TeV, from searches for direct graviton production at LEP. Limits from $\sqrt{s} > 200$ GeV data are shown in normal font; limits from 189 GeV data are in *italics*; limits from 184 GeV data are in **bold** script.

Experiment	$e^+e^- \to \gamma G_{\rm KK}$					$e^+e^- \to Z G_{\rm KK}$				
	n=2	n=3	n=4	n=5	n=6	n=2	n=3	n=4	n=5	n=6
ALEPH	1.10	0.86	0.70	0.60	0.52	**0.35**	**0.22**	**0.17**	**0.14**	**0.12**
DELPHI	1.25	0.97	0.79	0.68	0.59	N/A	N/A	N/A	N/A	N/A
L3	*1.02*	*0.81*	*0.67*	*0.58*	*0.51*	*0.60*	*0.38*	*0.29*	*0.24*	*0.21*
OPAL	*1.09*	*0.86*	*0.71*	*0.61*	*0.53*	N/A	N/A	N/A	N/A	N/A

Experiment	Process	+	−
LEP [7]	$e^+e^- \to \gamma\gamma$	0.93 TeV	1.01 TeV
LEP [8]	$e^+e^- \to e^+e^-$	1.18 TeV	1.17 TeV
H1 [9]	e^+p and e^-p	0.74 TeV	0.71 TeV
ZEUS [10]	e^+p and e^-p	0.72 TeV	0.73 TeV
CDF [11]	$p\bar{p} \to e^+e^-, \gamma\gamma$	0.99 TeV	0.96 TeV
DØ [11]	$p\bar{p} \to e^+e^-, \gamma\gamma$	1.28 TeV	1.14 TeV
DØ [12]	$p\bar{p} \to jj$	1.48 TeV	1.48 TeV
CMS at 7 TeV with 40/pb [13]	$pp \to \mu^-\mu^+$	1.6 TeV	1.6 TeV
CMS at 7 TeV with 36/pb [23]	$pp \to \gamma\gamma$	1.74 TeV	1.71 TeV
ATLAS at 7 TeV with 3.1/pb	$pp \to jj$	2.2 TeV	2.1 TeV
ATLAS at 7 TeV with 36/pb	$pp \to jj$	4.2 TeV	3.2 TeV
CMS at 7 TeV with 36/pb	$pp \to jj$	4.2 TeV	3.4 TeV

Experiment	Process	+	−
LEP combined [15]	$e^+e^- \to e^+e^-$	11.3	11.5
LEP combined [15]	$e^+e^- \to \mu^+\mu^-$	16.4	12.7
LEP combined [15]	$e^+e^- \to \ell^+\ell^-$	17.2	15.1
LEP combined [15]	$e^+e^- \to b\bar{b}$	15.3	11.5
H1 [9]	e^+p and e^-p	2.5	3.9
ZEUS [10]	e^+p and e^-p	4.6	5.3
DØ [16]	$p\bar{p} \to e^+e^-$	4.7	5.5
CDF [16]	$p\bar{p} \to \ell^+\ell^-$	4.5	5.6
CCFR [17]	νN scattering	3.7	5.9
DØ [16]	$p\bar{p} \to jj$	3.2	3.1
ATLAS at 7 TeV with 3.1/pb	$pp \to jj$	5.3	4.2
CMS at 7 TeV with 36/pb	$pp \to jj$	11	8.1
combined		22.4	15.7

Table 2: **Loop-level graviton exchange**: *95% CL limits on the coefficient* $|c_\Upsilon/4\pi|^{-1/2}$ *(in* TeV*) of the dimension-6 operator* Υ *of eq. (3) for positive and negative values of* c_Υ.