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SCUOLA NORMALE SUPERIORE PISA

Experimental bounds on large extra dimensions from di-jet event production in hadron collisions

main reference: [**Roberto Franceschini**, P.P.G., **Gian Giudice**, P.L., **Alessandro Strumia**, arXiv:1101.4919]

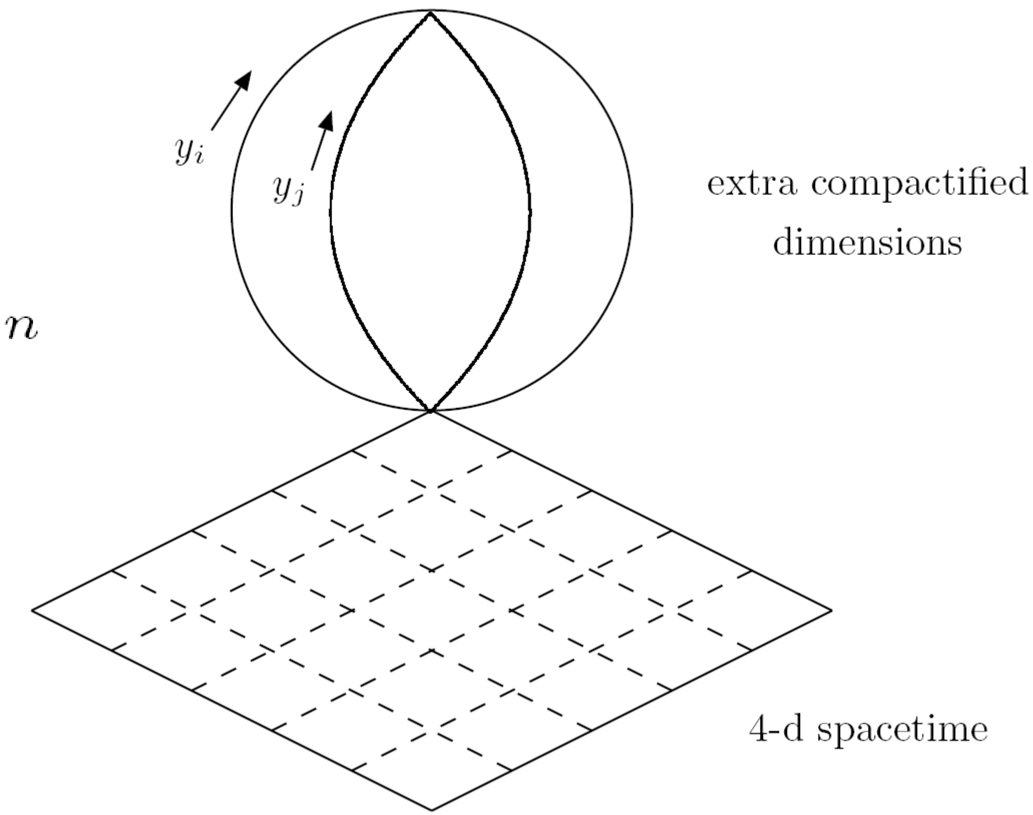
[Arkani-Hamed, Dimopoulos, Dvali, 1998]

1/10) Large Extra Dimensions (very brief introduction)

$$S_{\rm bulk} = -\frac{1}{2}\int d^{4+n}x\sqrt{-g^{(4+n)}}M_\star^{n+2}R^{(4+n)}$$

“integrating out” the extra dimensions:

$$M_{\rm Pl}^2 = M_\star^{n+2}(2\pi r)^n$$



Quantum gravity scale could be much lower than M_{Pl} !

Fundamental ASSUMPTION:
only gravity propagates in the extra dimensions

- Expected deviations from Newtonian gravity:

$$V(r') = \begin{cases} -G_N^{(4+n)} \dfrac{m_1 m_2}{r'^{1+n}} & r' < r \\ -G_N \dfrac{m_1 m_2}{r'} & r' > r \end{cases}$$

(r = "size" of the (compactified) extra dimensions)

- Experimental bounds:

1) Cavendish-type experiments → $r \leq 0.2\ \mathrm{mm}$ ($M_* \sim 10^3\ \mathrm{GeV}$ and $n \geq 2$ is ok)

2) Astrophysics → Strong bounds for $n \leq 3$ [0103201] [0110067]

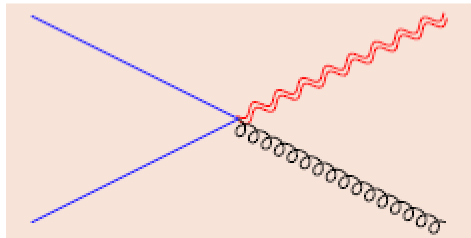
M* ≈ TeV is a serious possibility at colliders. For $n = \delta \leq 3$ one needs a bit of warping to avoid the other bounds [Giudice, Plehn, Strumia 2004]

2/10) LED phenomenology

Signal computable if $E << M_D$ or $E >> M_D$ $(D=4+\delta)$

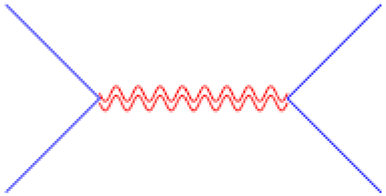
$E << M_D$: no cutoff!

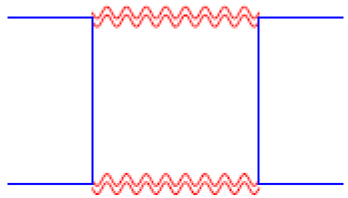
- Missing P_T from emission



need cutoff Λ

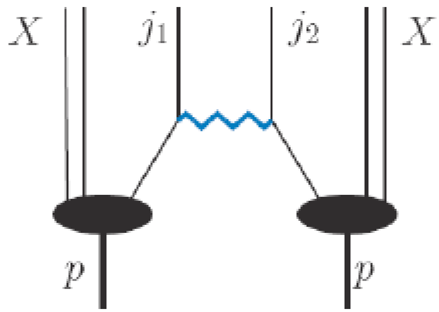
- Tree level exchange
- One loop exchange





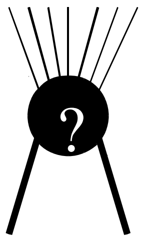
$E >> M_D$: no cutoff!

- Transplanckian scattering



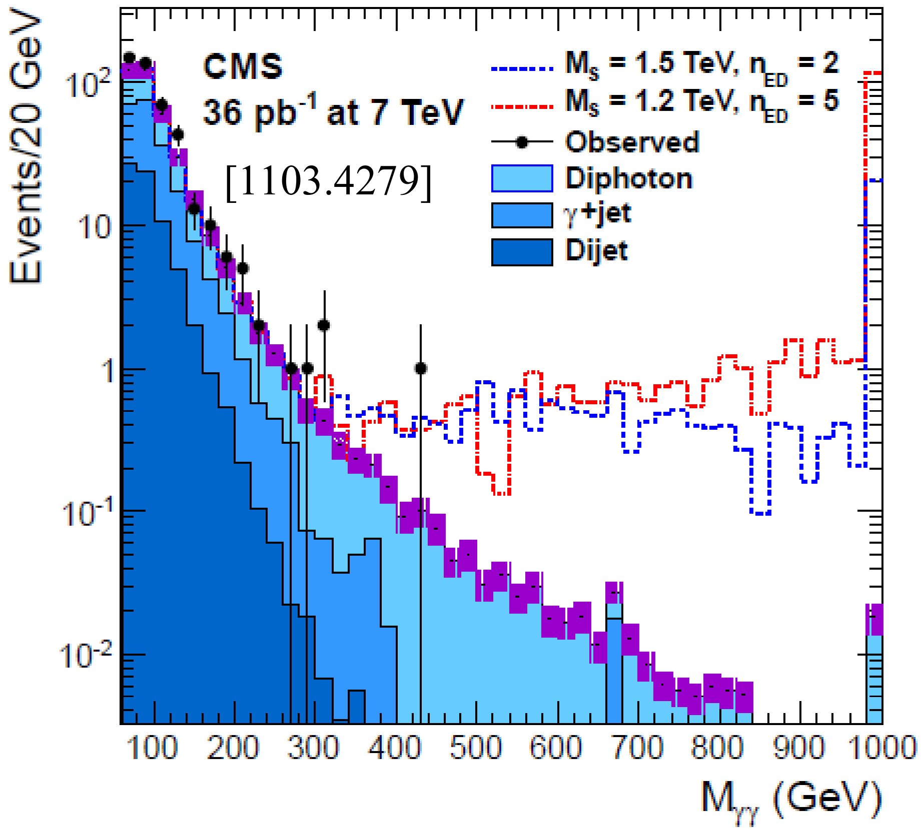
only estimate

- Black hole production



3/10) Most relevant observables

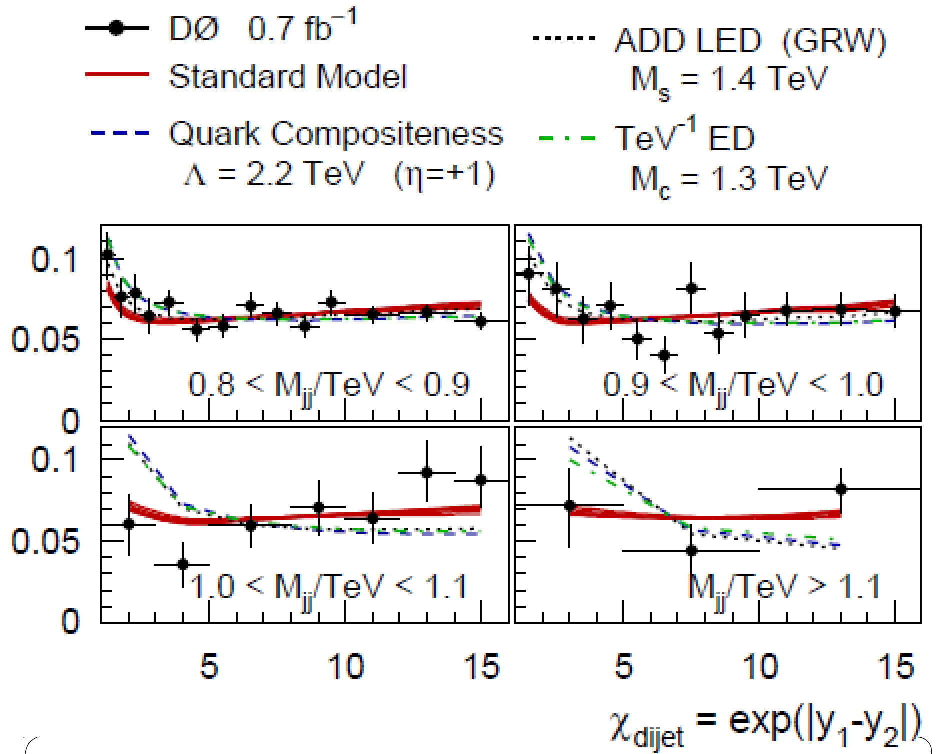
- $pp \to \gamma\gamma$



(counting experiment, E_T>30 GeV, |η|<1.44)

(analogously $pp \to \ell\ell$ [CDF, 0004035])

- $pp \to jj$



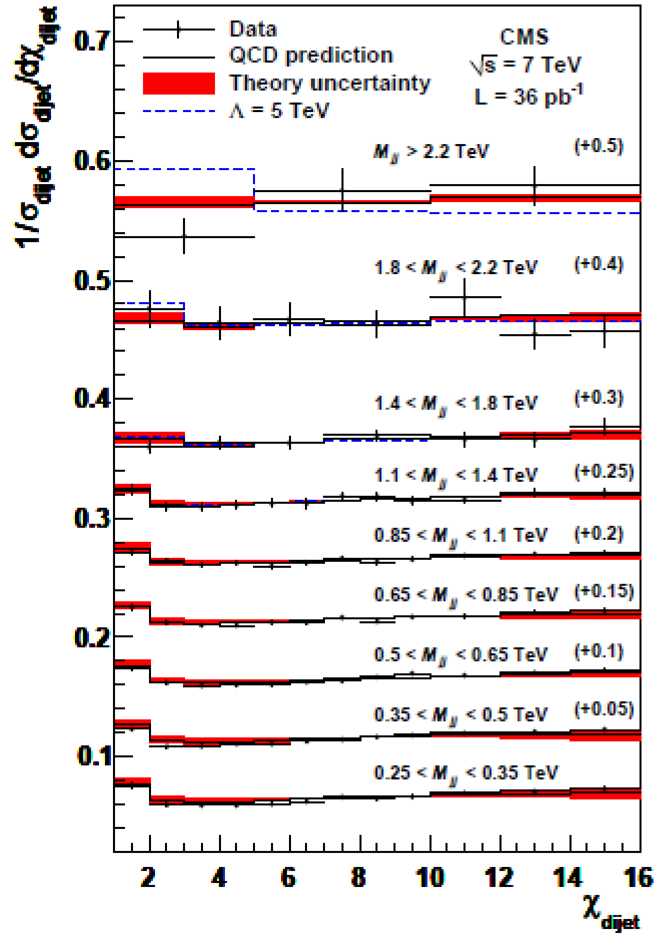
$y = 0.5 \ln[(1+\beta\cos\theta)/(1-\beta\cos\theta)]$ with $\beta = |\vec{p}|/E$

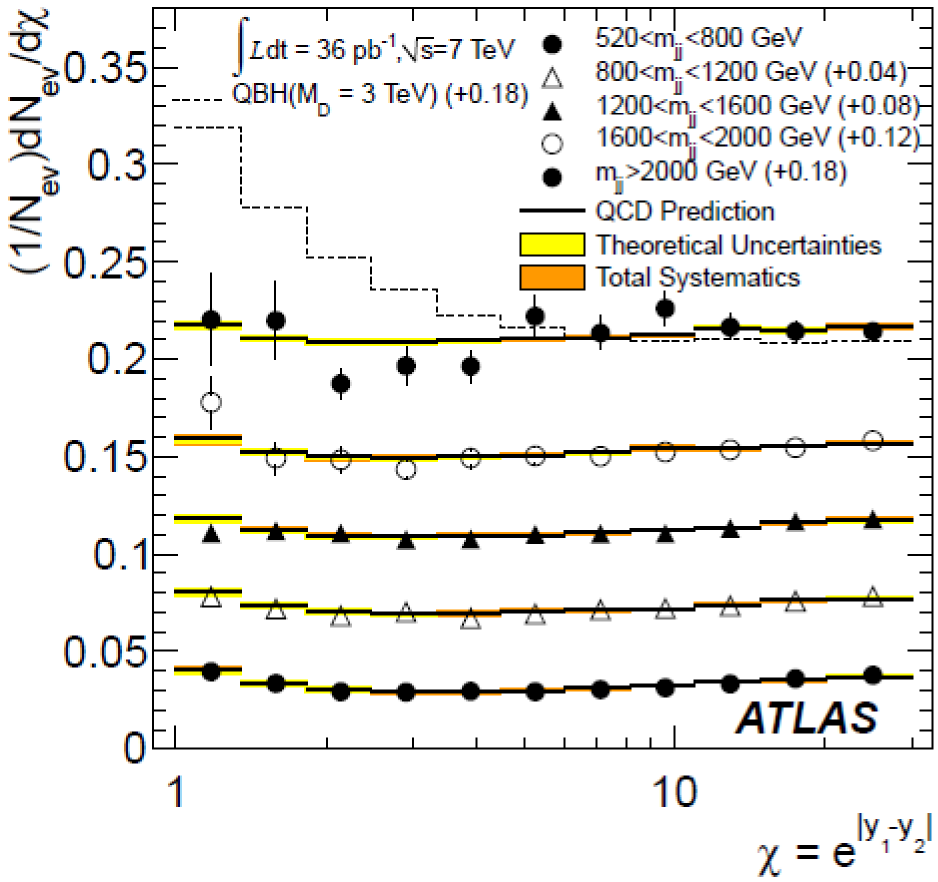
(angular distribution, χ<16, $|y_1+y_2|$<2)
[D0, 0906.4819])

3bis/10) Most recent di-jet measurments:

Also 3.1 pb^{-1} [1009.5096]

- CMS (36 pb^{-1}) [1102.2020]
- ATLAS (36 pb^{-1}) [1103.3864]





χ = angular jj distance. Coulomb-like QCD gives a quasi-flat distribution. New massive particles or effective $\mathcal{O}$ give effects at large M_{jj} and small angle χ

4/10) Tree level exchange

At low energies described by the dimension 8 effective operator:

$$\mathscr{L}_{\text{eff}} = c_{\mathcal{T}}\ \mathcal{T} \qquad c_{\mathcal{T}} = 8/M_{\mathcal{T}}^4$$ (Hewett normalization)

$$\mathcal{T} = \frac{1}{2}\Big(T_{\mu\nu}T^{\mu\nu} - \frac{\overbrace{T^\mu_\mu T^\nu_\nu}^{\text{irrelevant}}}{\delta+2}\Big)^2 \sim (\bar\Psi\partial\Psi + \bar\Psi A\Psi + F^2_{\mu\nu})^2$$

$$\sigma = \left(\frac{2\,\text{TeV}}{M_{\mathcal{T}}}\right)^8 \times \begin{cases} 12.5\,\text{pb} & \text{for } pp\to jj \\ 10.4\,\text{fb} & \text{for } pp\to \mu^+\mu^- \\ 21.3\,\text{fb} & \text{for } pp\to\gamma\gamma \end{cases}$$

$pp \to jj$ is much better at low statistics
thanks to the energetic $uu \to uu$.
(cuts: $\sqrt{s} = 7$ TeV, $M_{\text{eff}} > 1$ TeV, $\eta < 2.5$)

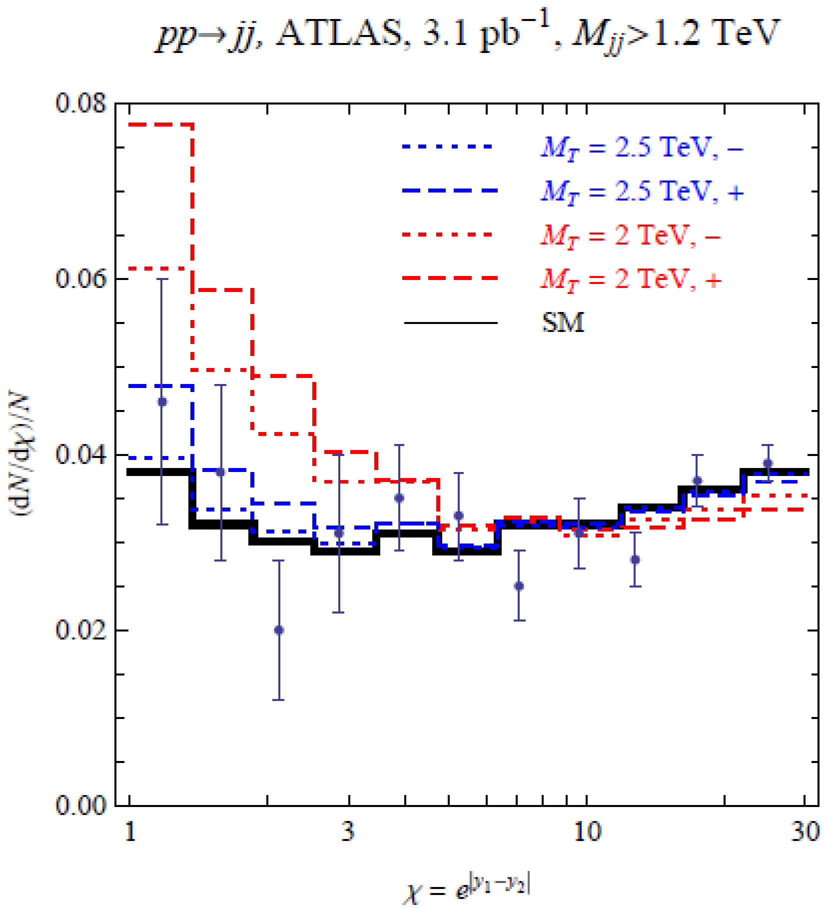
Energy is the key factor !

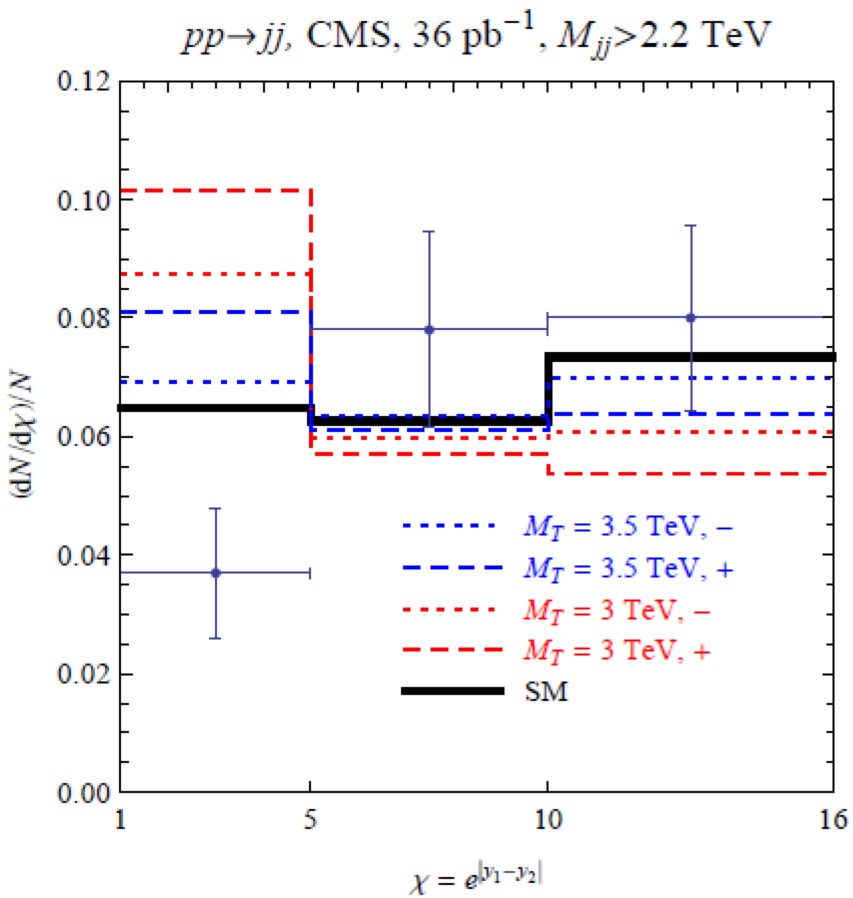
4bis/10) Bounds on tree level exchange

Experiment	Process	+	−
LEP	$e^+e^- \to \gamma\gamma$	0.93 TeV	1.01 TeV
LEP	$e^+e^- \to e^+e^-$	1.18 TeV	1.17 TeV
H1, ZEUS	e^+p and e^-p	0.74 TeV	0.73 TeV
CDF	$p\bar{p} \to e^+e^-, \gamma\gamma$	0.99 TeV	0.96 TeV
DØ	$p\bar{p} \to e^+e^-, \gamma\gamma$	1.28 TeV	1.14 TeV
DØ	$p\bar{p} \to jj$	1.48 TeV	1.48 TeV
CMS at 7 TeV with 34/pb	$pp \to \gamma\gamma$	1.72 TeV	1.70 TeV
ATLAS at 7 TeV with 3.1/pb	$pp \to jj$	2.2 TeV	2.1 TeV
CMS at 7 TeV with 36/pb	$pp \to jj$	4.2 TeV	3.4 TeV
ATLAS at 7 TeV with 36 / pb	$pp \to jj$	4.2 TeV	3.2 TeV

ATLAS at 3.1/pb (september 2010) already beated all previous bounds

5/10) Example of LHC data vs new effects





Computed implementing in MadGraph and Pythia

6/10) Loop level exchange

At low energies described by the dimension 6 effective operator:

$$\mathscr{L} = c_\Upsilon \times \Upsilon, \qquad \Upsilon = \frac{1}{2}\Big(\sum_f \bar{f}\gamma_\mu\gamma_5 f\Big)^2$$

see [Giudice, Strumia, 2003]

95% CL limits on $\lvert c_\Upsilon/4\pi\rvert^{-1/2}$ in TeV			
Experiment	Process	+	−
LEP combined	$e^+e^- \to \ell^+\ell^-$	17.2	15.1
LEP combined	$e^+e^- \to b\bar{b}$	15.3	11.5
ZEUS, H1	e^+p and e^-p	4.6	5.3
DØ	$p\bar{p} \to e^+e^-$	4.7	5.5
CDF	$p\bar{p} \to \ell^+\ell^-$	4.5	5.6
CCFR	νN scattering	3.7	5.9
DØ	$p\bar{p} \to jj$	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

Tevatron and LHC (for the moment) do not improve on LEP

7/10) Full amplitude $\mathcal{A} = \mathcal{S}(s) T^2_{\mu\nu}$

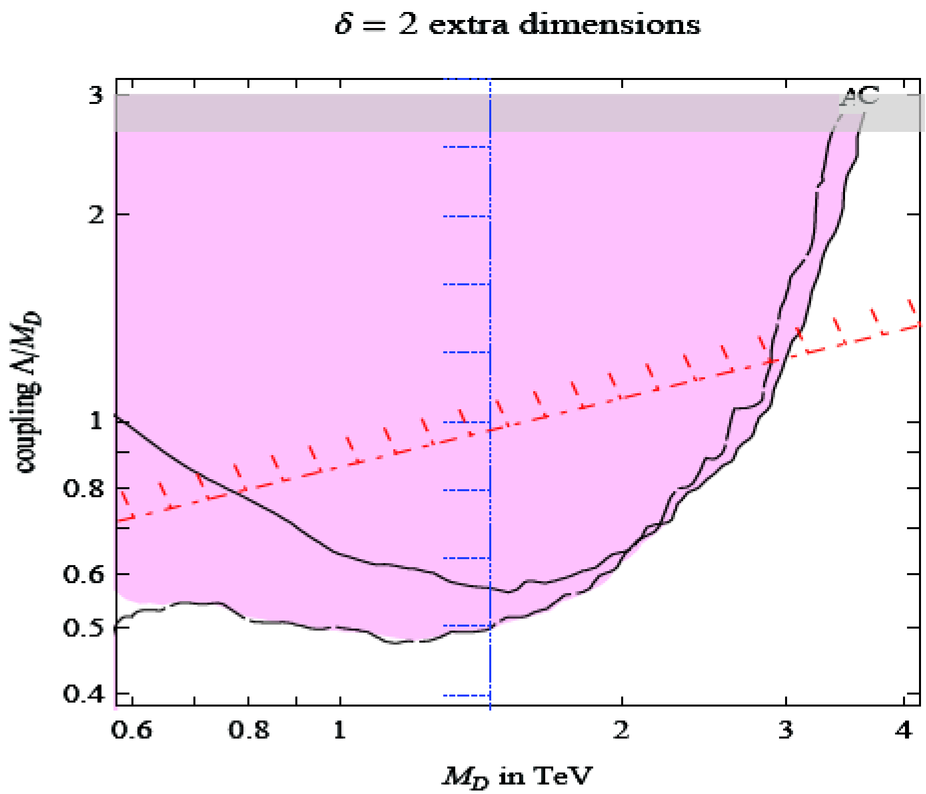
- Reconsider the theory behind $c_\mathcal{T} = 8/M_\mathcal{T}^4$.
  Truncate KK tower at $m < \Lambda$ to mimic UVC (QG):

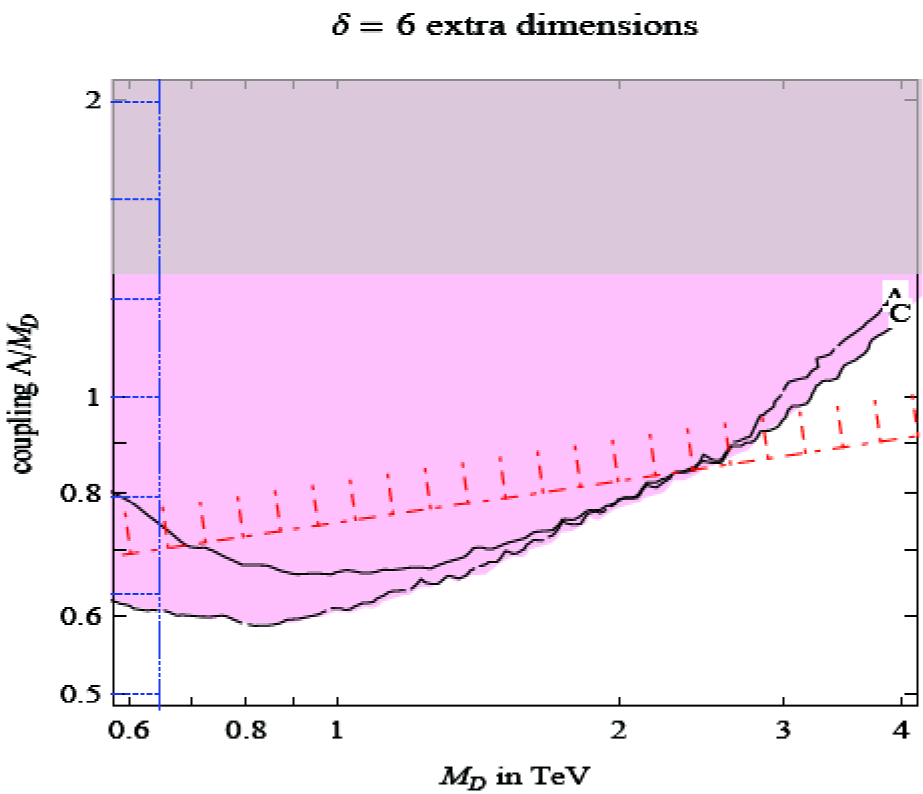
$$\mathcal{S}(s) = \frac{1}{M_{\text{Pl}}^2} \sum_i \frac{1}{s - m_i^2 + i m_i \Gamma_G(m_i)} = \frac{1}{M_D^{2+\delta}} \int_{|q|<\Lambda} \frac{d^\delta q}{s - q^2 + i\varepsilon}$$

$$c_\mathcal{T} = \mathcal{S}(s \ll \Lambda^2) = \begin{cases} \frac{\pi^{\delta/2}}{(1-\delta/2)\Gamma(\delta/2)} \frac{\Lambda^{\delta-2}}{M_D^{\delta+2}} \equiv \frac{8}{M_\mathcal{T}^4} & \text{for } \delta > 2 \\ \frac{\pi}{M_D^4} \ln \frac{s}{\Lambda^2} & \text{for } \delta = 2 \\ \frac{-i\pi}{M_D^3 \sqrt{s}} & \text{for } \delta = 1 \end{cases}$$

- Subtlety: $\mathcal{S}_\int = \langle \mathcal{S}_\sum \rangle$ only if resonances not well separated, otherwise resonant contribution...

8/10) Fit to the full amplitude





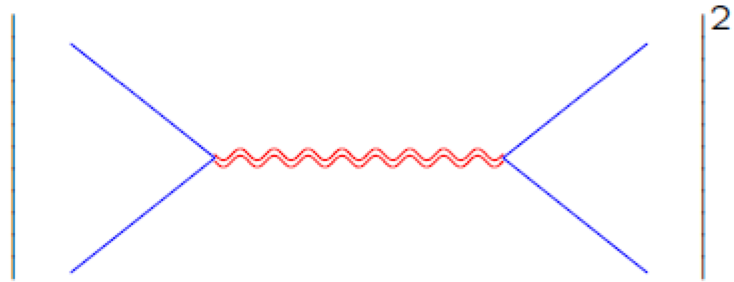
- Shaded: LHC (continuous = CMS; dashed = ALTAS)
- Blue: gravition emission, ignoring the dependence on Λ
- Red: NDA estimate of graviton loop
- Gray: non-perturbative quantum gravity

9/10) Resonant contribution (δ>1)

$\Gamma_G = 283 m^3/960\pi M_{\rm Pl}^2$ is small: gravitons decay far away. But the S-matrix keeps them: $\langle|\mathcal{S}|^2\rangle = ({\rm Re}\,\mathcal{S})^2 + ({\rm Im}\,\mathcal{S})^2/\epsilon$ with $\epsilon = \pi\Gamma_G/2\Delta m \sim (s/M_D^2)^{1+\delta/2}$.

Resonant graviton production must be subtracted

Consider just one particle with coupling g ($g \sim E/M_{\rm Pl} \ll 1$ for KK gravitons):

$\sigma =$ 

One would guess $\sigma \sim g^4$ but actually $\sigma \sim g^2$, due to $pp \to$ graviton.
Next graviton decays with 100% probability and width $\Gamma \sim mg^2$.

We find $\sigma_{\rm subtracted} \sim -g^4$, up to $\mathcal{O}(g^4)$ terms, such as NLO corrections to Γ.

We presume that $\langle|\mathcal{S}|^2\rangle_{\rm subtracted} = |\langle\mathcal{S}\rangle|^2$ is the right result

Anyhow, even the unsubtracted $1/g^2$ enhancement (present for $\delta = 1$) is numerically irrelevant for $pp \to jj$.

10/10) Conclusions

- $pp \to jj$ is a very good competitor to $pp \to \gamma\gamma$, $\ell\ell$, especially at low statistic

Experiment	Process	+	−
CMS at 7 TeV with 36/pb	$pp \to jj$	4.2 TeV	3.4 TeV
ATLAS at 7 TeV with 36 / pb	$pp \to jj$	4.2 TeV	3.2 TeV

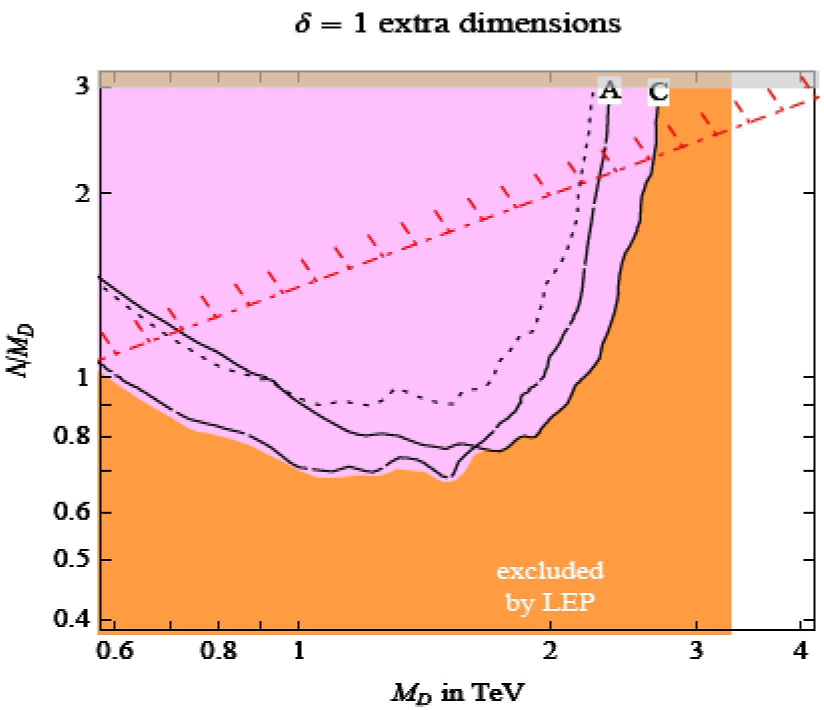
- ATLAS data at 3.1/pb already set the most stringent bound (to date)

Experiment	Process	+	−
ATLAS at 7 TeV with 3.1/pb	$pp \to jj$	2.2 TeV	2.1 TeV

- We made a fit of the full amplitude
- Precise treatment of s-channel is numerically unimportant for pp

Backup Slides

B1) Case δ=1 (special...)



See Erratum of [Giudice, Pleh, Strumia, 2004] that will appear soon

A bit of warping makes less KK gravitons with larger couplings: $\delta = 1$ is allowed.

But special: gravitons decay promptly in the detector:

- graviton production gives no $\not{E}_T$ signals.
- tree level exchange of *virtual and real* gravitons give $e^+e^- \to \ell^+\ell^-$ and $pp \to jj$.

B2) Case δ=1: resonant contribution

$$\mathcal{S}(s) = \frac{1}{\Lambda_\pi^2}\sum_n \frac{1}{s - m_n^2 + i m_n \Gamma_G(m_n)} = -\frac{\pi}{M_5^3\sqrt{s}} K$$

$$\Lambda_\pi^2 = \frac{{M_5}^3}{2\pi\mu}$$

$$\Delta m = \pi\mu$$

$$\Gamma_G(m_n) = \frac{c\, m_n^3}{\pi\Lambda_\pi^2}$$

$$K = \frac{\sin 2A + i\sinh 2\epsilon}{2(\cos^2 A + \sinh^2\epsilon)} \qquad A = \pi\left(\frac{\sqrt{s}}{\Delta m} + \frac{1}{4}\right) \qquad \epsilon = \frac{\pi\Gamma_G}{2\Delta m}\bigg|_{m=\sqrt{s}}$$

$$\Rightarrow \quad \epsilon = c\left(\frac{\sqrt{s}}{M_5}\right)^3$$

in the case in which the energy spread of the initial and final states is broader than the mass separation μ

$$\langle\mathcal{S}\rangle = -\frac{i\pi}{M_5^3\sqrt{s}} \quad \Leftrightarrow \quad \mathcal{S}(s) = \frac{1}{\Lambda_\pi^2}\int\frac{dm}{\pi\mu}\frac{1}{s - m^2 + i m\Gamma_G(m)} \overset{\Gamma_G\to 0}{\simeq} -\frac{i\pi}{M_5^3\sqrt{s}}$$

modulus square averaged over an oscillation period

$$\langle|\mathcal{S}|^2\rangle = \frac{\pi^2}{M_5^6 s}\left(1 + \frac{4}{e^{4\epsilon} - 1}\right) \overset{\epsilon\to 0}{\simeq} \frac{1}{\epsilon}\left(\frac{\pi}{M_5^3\sqrt{s}}\right)^2$$

$$\Leftrightarrow \quad |\mathcal{S}|^2 = \frac{1}{\Lambda_\pi^4}\int\frac{dm}{\pi\mu}\frac{1}{(s - m^2)^2 + m^2\Gamma_G^2} \overset{\Gamma_G\to 0}{\simeq} \frac{1}{\epsilon}\left(\frac{\pi}{M_5^3\sqrt{s}}\right)^2$$

B3) Bound from graviton emission

Experiment	$\delta = 2$	$\delta = 3$	$\delta = 4$	$\delta = 5$	$\delta = 6$
ALEPH [13]	1.26	0.95	0.77	0.65	0.57
DELPHI [14]	1.36	1.05	0.84	0.69	0.59
L3 [15]	1.02	0.81	0.67	0.58	0.51
OPAL [16]	1.09	0.86	0.71	0.61	0.53
DØ [17]	0.89	0.73	0.68	0.64	0.63
combined	1.45	1.09	0.87	0.72	0.65

Table 1: *95% CL limits on the D-dimensional Planck mass M_D (in TeV), for some values of the number of extra dimensions δ, from* graviton-emission *processes in different experiments.*

[13] A. Heister *et al.* [ALEPH Collaboration], CERN-EP/2002-033.

[14] S. Ask *et al.* [DELPHI Collaboration], DELPHI 2002-077 CONF 611.

[15] M. Acciarri *et al.* [L3 Collaboration], *Phys. Lett.* B470 (1999) 268.

[16] G. Abbiendi *et al.* [OPAL Collaboration], *Eur. Phys. J.* C18 (2001) 253.

[17] S. Hagopian [D0 Collaboration], *hep-ex/0205048*.

Taken from [Giudice, Strumia, 0301232].

For δ=1 see Erratum of [Giudice, Plehn, Strumia, 0408320] that will appear soon.

B4) Conventions for *Ms*

single variable $\eta_G = \mathcal{F} / M_S^4$

$$\mathcal{F} = 1 \quad \text{(Guidice, Rattazzi, and Wells, GRW [5])},$$

$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right) & \text{if } n_{\text{ED}} = 2 \\ \frac{2}{(n_{\text{ED}}-2)} & \text{if } n_{\text{ED}} > 2 \end{cases} \quad \text{(Han, Lykken, and Zhang, HLZ [6])},$$

$$\mathcal{F} = \pm\frac{2}{\pi} \quad \text{(Hewett [7])},$$

[5] G. Giudice, R. Rattazzi, and J. Wells, "Quantum gravity and extra dimensions at high-energy colliders", *Nucl. Phys.* **B544** (1999) 3, arXiv:hep-ph/9811291v2. doi:10.1016/S0550-3213(99)00044-9.

[6] T. Han, J. Lykken, and R.-J. Zhang, "On Kaluza-Klein states from large extra dimensions", *Phys. Rev.* **D59** (1999) 105006, arXiv:hep-ph/9811350v4. doi:10.1103/PhysRevD.59.105006.

[7] J. Hewett, "Indirect collider signals for extra dimensions", *Phys. Rev. Lett.* **82** (1999) 4765, arXiv:hep-ph/9811356v2. doi:10.1103/PhysRevLett.82.4765.

B5) Definition of 95% CL bound

We compare data with the theoretical expectation and we compute the 95% CL bound on the coefficient of the $\mathcal{T}$ operator by imposing

$$\chi^2 = \sum_i^{\text{bins}} \frac{(t_i(c_\mathcal{T}) - \mu_i)^2}{\sigma_{i\ \text{stat}}^2 + \sigma_{\text{syst}}^2} < \chi^2_{\text{min}} + 3.84\,,$$

where μ_i are the experimental central values, $\sigma_{i\ \text{stat}}$ the statistical errors, $\sigma_{\text{syst}} \approx 0.003$ estimates the systematic uncertainties (we ignore possible correlations between different bins) which are presently subdominant and $t_i(c_\mathcal{T})$ are the theoretical predictions, computed for some values of $c_\mathcal{T}$ and fitted in each bin as a quadratic function of $c_\mathcal{T} = 8/M_\mathcal{T}^4$.

B6) Simplified Fχ fit

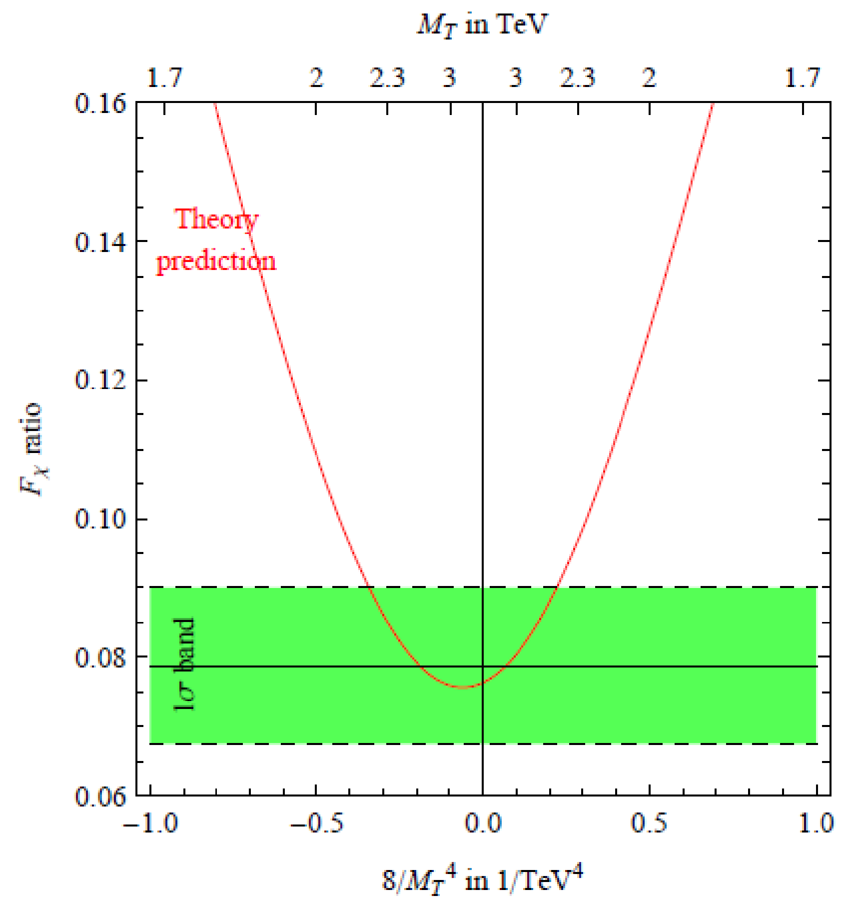
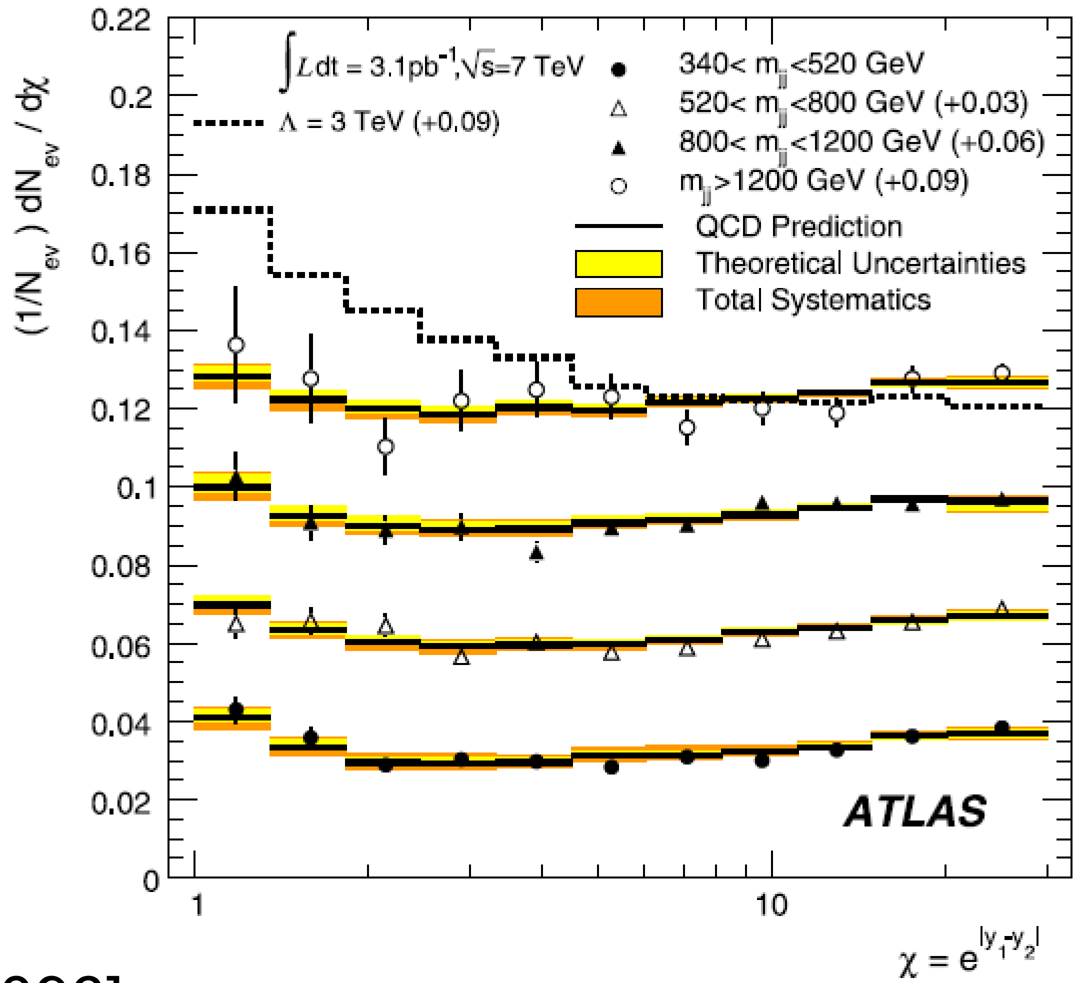


Figure 3: *Experimental values from ATLAS and theoretical values of the variable* F_χ *(fraction of* jj *events with* $M_{jj} > 1.2\,\text{TeV}$ *in the central region).*

B7) ATLAS at 3.1/pb

Fig. 1. The normalized χ distributions for $340 < m_{jj} < 520$ GeV, $520 < m_{jj} < 800$ GeV, $800 < m_{jj} < 1200$ GeV, and $m_{jj} > 1200$ GeV, with plotting offsets shown in parentheses. Shown are the QCD predictions with systematic uncertainties (bands), and data points with statistical uncertainties. The prediction for QCD with an added quark contact term with $\Lambda = 3.0$ TeV is shown for the highest mass bin $m_{jj} > 1200$ GeV.



[1009.5096]

B7bis) ATLAS data vs various signals

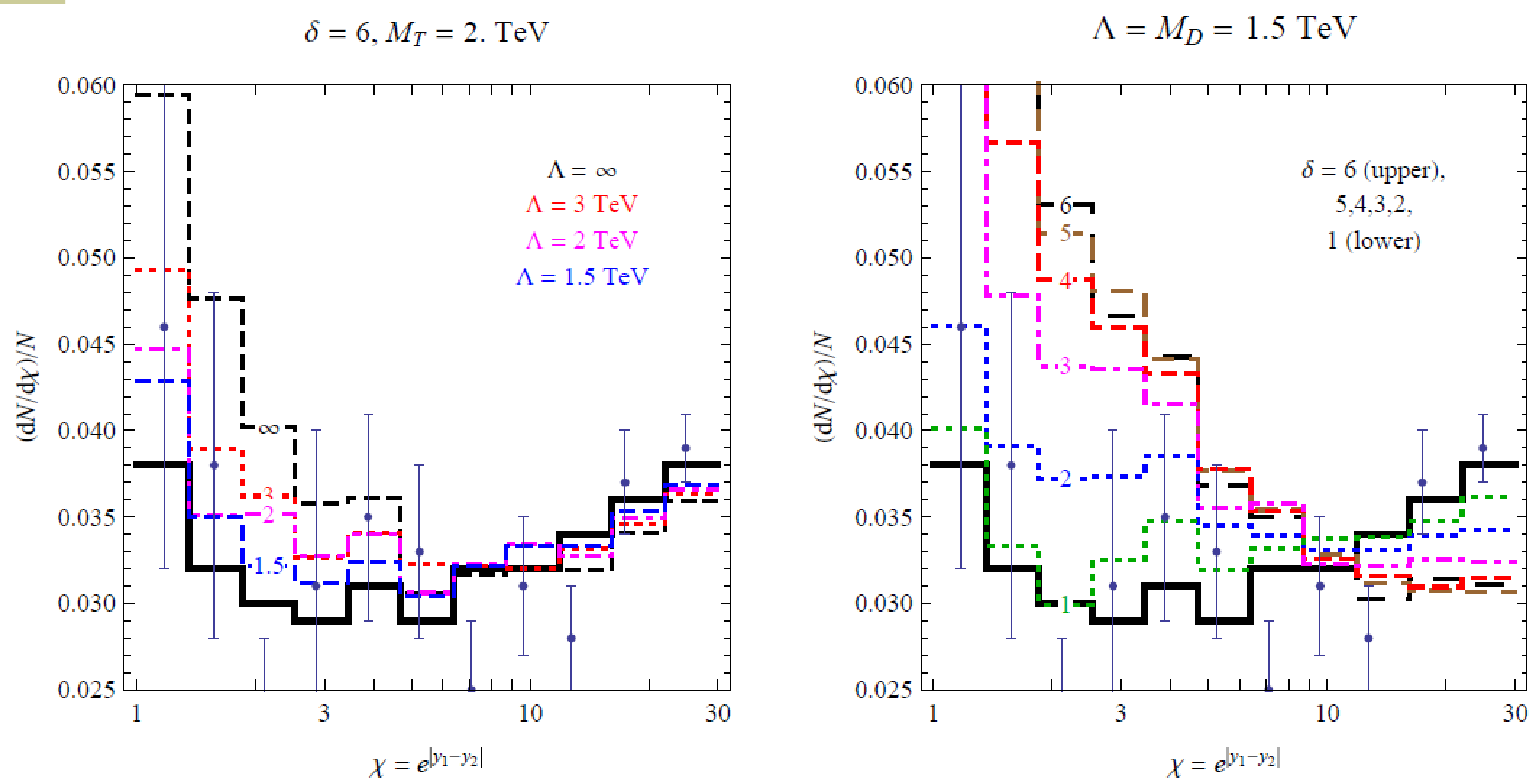


Figure 5: *Left:* $pp \to jj$ *angular distribution for fixed* $\delta = 6$, $M_T = 2\,\text{TeV}$, $M_{jj} > 1.2\,\text{TeV}$ *and different values of* Λ *(as indicated) and consequently of* M_D. *The effective-operator* $\mathcal{T}$ *is formally reproduced in the limit* $\Lambda \to \infty$. *Right: dependence on the number* δ *of extra dimensions at fixed* $M_D = \Lambda = 1.5\,\text{TeV}$. *The data are from ATLAS.*

B8) Example of cross sections

- **fermion antifermion → photon photon**

$$\frac{d\sigma}{dt}(f\bar{f} \to \gamma\gamma) = \frac{t^2+u^2}{64\pi s^2 tu N_f}|2Q_f^2 - tu\mathcal{S}(s)|^2$$

where $N_f = 1$ and $Q_f = -e$ if $f = e$; $N_f = 3$ if f is a quark.

- **quark antiquark → quark antiquark.** Including only the gluon and the graviton contributions we find

$$\begin{aligned}\frac{d\sigma}{dt}(q\bar{q} \to q\bar{q}) \quad = \quad & \frac{1}{16\pi s^2}\Bigg[\frac{8g_3^4}{27s^2t^2}(s^2 - st + t^2)(3s^2 + 5st + 3t^2) \\ & + \frac{2g_3^2}{9}u^2 \mathrm{Re}\left(\frac{4t+s}{t}\mathcal{S}(s)^* + \frac{4s+t}{s}\mathcal{S}(t)^*\right) \\ & + \frac{|\mathcal{S}(s)^2|G(s,t) + |\mathcal{S}(t)^2|G(t,s)}{8} + \frac{\mathrm{Re}\,\mathcal{S}(s)\mathcal{S}(t)^*}{48}(4s+t)(4t+s)u^2\Bigg]\end{aligned}$$

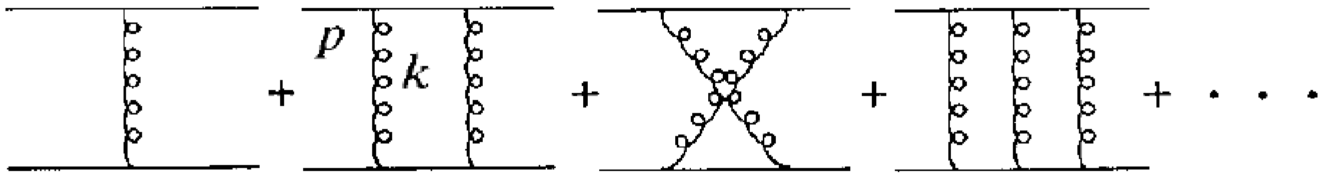
$$G(s,t) \equiv \frac{s^4 + 10s^3t + 42s^2t^2 + 64st^3 + 32t^4}{4}$$

ecc... - see appendix of
[Giudice, Strumia, Plehn 2004]

D. Kabat and M. Ortiz, Nucl. Phys. B **388**, 570 (1992)

B9) Transplanckian case: eikonal resummation

evaluate leading behaviour at high energy and small angles by summing an infinite number of diagrams



approximation:

- Take on shell vertices
- Use: $\frac{1}{(p+k)^2+m^2-i\epsilon} \approx \frac{1}{2p\cdot k - i\epsilon}$

(resummation)

$$\mathcal{A}_{\text{eik}} = -2is\int d^2b_\perp e^{iq_\perp b_\perp}\left(e^{i\chi}-1\right)$$

$t = q^2 \simeq -q_\perp^2$

$$\chi(b_\perp) = \frac{1}{2s}\int \frac{d^2q_\perp}{(2\pi)^2} e^{-iq_\perp b_\perp} \mathcal{A}_{\text{Born}}(q_\perp^2) = \left(\frac{b_c}{b}\right)^n$$

- No UV sensitivity
- Spin independent

B9bis) Transplanckian case: shock wave computation

Let us consider the plane wavefunction colliding with the classical AS shock wave. The wavefunction describes a particle of energy E' moving in the negative z direction. Thus $p' = (E', -E', 0)$ and before the collision the wavefunction is:

$$\psi(x) = \exp(+ip'x) = \exp(-iE'(z+t))$$

After the collision the wavefunction remains continuous in the x' coordinates, i.e.

$$\psi(x') = \exp(-iE'x^{+\prime}) = \exp(-iE'(x^+ - \Phi(x_\perp))) \quad , \quad x^- = \varepsilon > 0 \text{ small}$$

(i.e. immediately after collision). Thus we get eikonal amplitude:

$$\boxed{e^{i\chi} = \exp(iE'\Phi)}$$

$$\left(\Omega_k = \frac{2\pi^{(k+1)/2}}{\Gamma((k+1)/2)} \right)$$

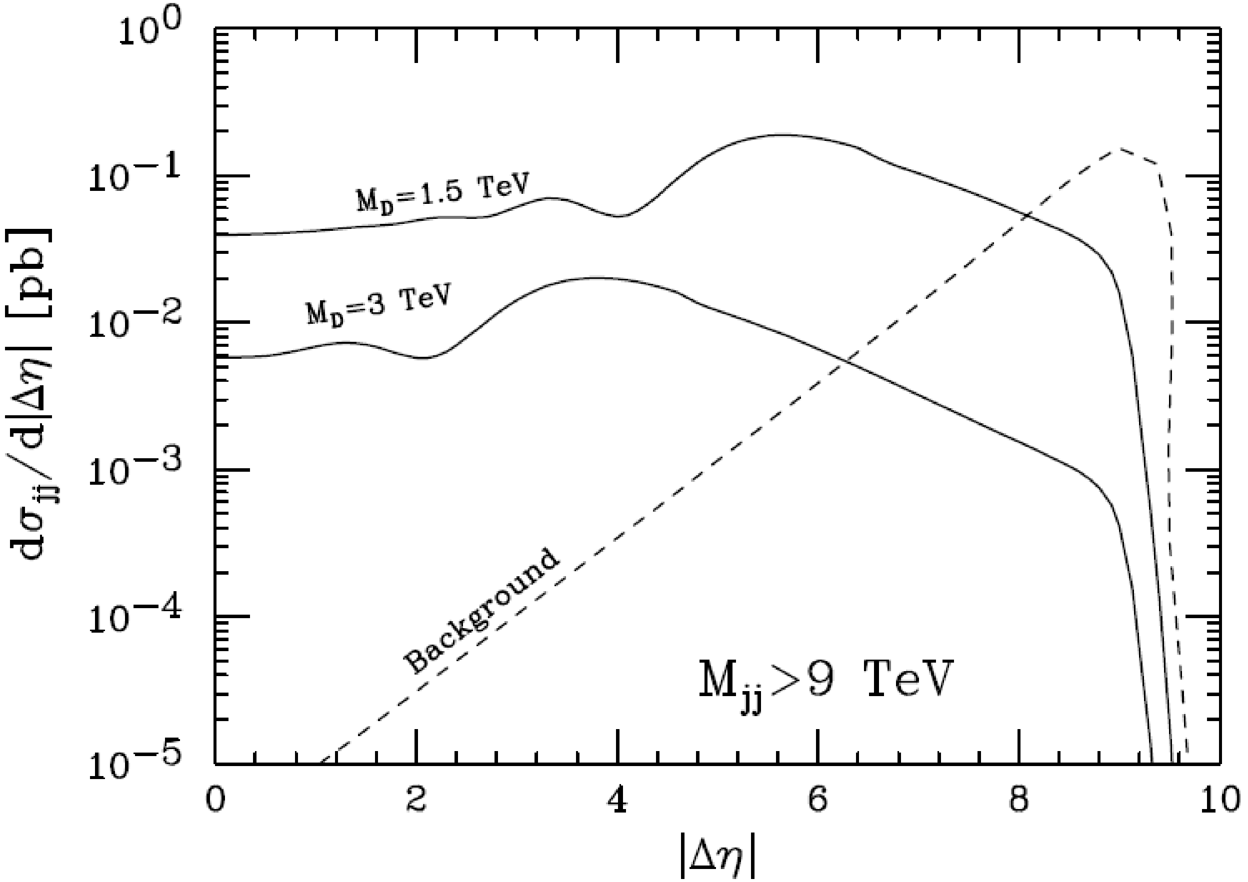
Check:

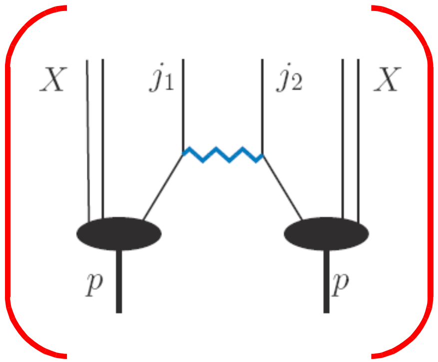
$$\chi = 8\pi G_D \frac{2}{\Omega_{D-3}(D-4)b^n} EE' = \frac{(2\pi)^n}{M_D^{2+n}} \frac{\Gamma((k+1)/2)}{2\pi^{(k+1)/2}}\Big|_{k=n+1} \frac{2}{n} \frac{s}{4b^n}$$

$$= \frac{(2\pi)^n}{M_D^{2+n}} \frac{\Gamma(\frac{n}{2}+1)}{2\pi^{\frac{n}{2}+1}} \frac{2}{n} \frac{s}{4b^n} = \frac{2^{n-2}\pi^{\frac{n}{2}-1}}{M_D^{2+n}} \frac{\Gamma(\frac{n}{2})}{2} \frac{s}{b^n} = \frac{(4\pi)^{\frac{n}{2}-1}}{M_D^{2+n}} \frac{\Gamma(\frac{n}{2})}{2} \frac{s}{b^n} = \left(\frac{b_c}{b}\right)^n$$

G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B **630**, 293 (2002) [arXiv:hep-ph/0112161]

B10) *p*-*p*: example of transplanckian di-jet signal at the LHC





($\sqrt{s}$ =14 TeV)

Figure 4: The di-jet differential cross section $d\sigma_{jj}/d|\Delta\eta|$ from eikonal gravity for $n = 6$, $M_{jj} > 9\,\text{TeV}$, when both jets have $|\eta| < 5$ and $p_T > 100\,\text{GeV}$, and for $M_D = 1.5\,\text{TeV}$ and $3\,\text{TeV}$. The dashed line is the expected rate from QCD.

G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B **630**, 293 (2002) [arXiv:hep-ph/0112161]

B11) Lengthscales in T-scattering

- Relevant scales:

$$D = 4 + n \qquad \lambda_P = \left(\frac{G_D \hbar}{c^3}\right)^{\frac{1}{n+2}} \qquad \lambda_B = \frac{4\pi\hbar c}{\sqrt{s}}$$

$$\left(G_D = \frac{(2\pi)^{n-1}\hbar^{n+1}}{4c^{n-1}M_D^{n+2}}\right) \qquad R_S = \frac{1}{\sqrt{\pi}}\left[\frac{8\Gamma\left(\frac{n+3}{2}\right)}{(n+2)}\right]^{\frac{1}{n+1}} \left(\frac{G_D\sqrt{s}}{c^4}\right)^{\frac{1}{n+1}}$$

- Peculiar feature: NEW SCALE (assume $b_c \gg R_S$)

$$b_c \propto \left(\frac{G_D s}{\hbar c^5}\right)^{\frac{1}{n}}$$

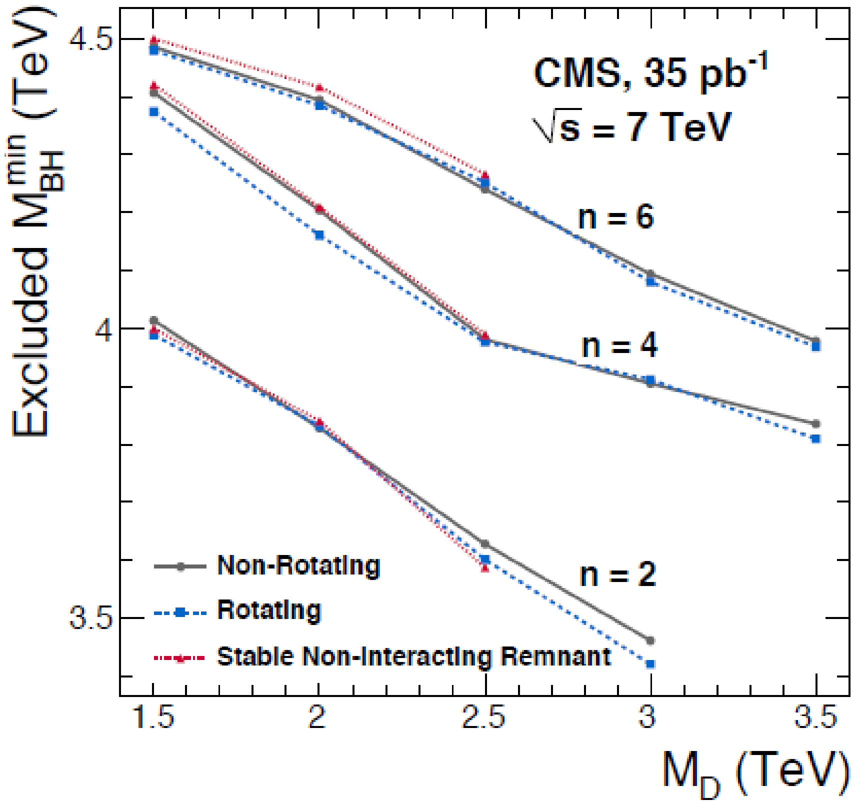
- Cannot be defined if n=0
- Goes to infinity if $\hbar \to 0$ with G_D constant

⇒ "Size of classical region" ($q\, b_c \gg 1 \rightarrow$ semicl. process)

B12) About black holes

(slide taken from A. Strumia, 'Implications of the first LHC results')

No black holes in first LHC data

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"È LA FINE DEL MONDO"

La conferma del Cern

Il buco nero creato dal Large Hadron Collider è destinato a inghiottire il nostro pianeta nelle prossime settimane. Secondo Walter Wagner anche l'universo è in pericolo. Scene di panico durante la conferenza stampa del Cern a Parigi.

IL VIDEO / LE PRIME IMMAGINI

La Svizzera inghiottita dal buco nero

Sarkozy contrario all'evacuazione

"A quoi bon? Tra qualche ora saremo comunque tutti morti". Berlusconi caustico: "risolta la questione Alitalia".

"Pregate, ma non garantisco niente"

Lo scetticismo di Papa Benedetto

"Il buco nero è il risultato ultimo di ricerca scientifica dissennata che ha voluto porre l'uomo davanti a Dio. Non resta che la preghiera, forse". Dal suo ritiro in Alto Adige, il Papa gela i pellegrini venuti ad ascoltare un messaggio di speranza.

IL VIDEO / LE IMMAGINI / "SANTITA', IL BUCO NERO E' L'INFERNO?"

Net Monitor: "Proprio adesso che andavo in ferie" di V. ZAMBARDINO

Hawking deluso: "mi sono sbagliato"

"La mia radiazione avrebbe dovuto eliminare il buco nero, ma evidentemente ho sbagliato qualcosa". Lo scienziato non esclude la possibilità che un nuovo universo possa riformarsi dal caos. "Ci vorranno milioni di anni, ma la prossima volta saremo più prudenti".

Software | Società | Curiosità

Troppa pancia per Babbo Natale è tempo di dieta

Si sono incontrati in 150 per l'annuale congresso in Danimarca. E hanno deciso di perdere qualche chilo. Messa da parte la slitta, per qualche tempo andranno in bici e faranno ginnastica

LE IMMAGINI
La dea del metrò colpisce ancora lap dance sui pali della strada
LA FOTOSEQUENZA NEL METRO'

LE IMMAGINI
Pechino indossa la sottoveste sono le olimpiadi della lingerie

LE IMMAGINI
Miracolo a Saint Tropez in acqua c'è Bar Rafaeli

LE IMMAGINI
Pamela a Central Park spunta l'amico misterioso