Identifying Graviton Signals at the LHC : a discussion

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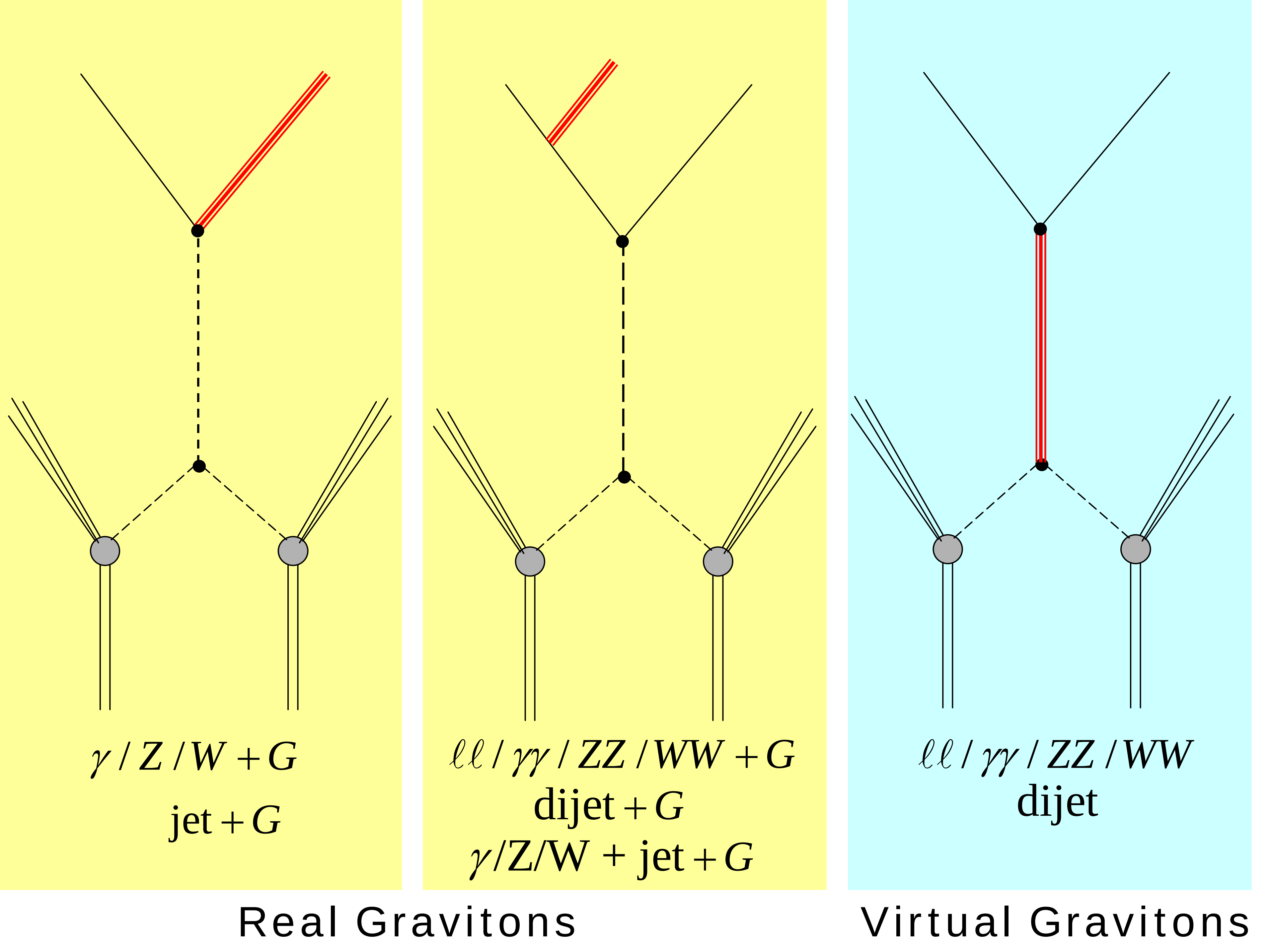
Workshop on the Physics of Warped Extra Dimensions

IIT-KGP, Feb 2008


$\gamma / Z / W + G$
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dijet
Real Gravitons
Virtual Gravitons

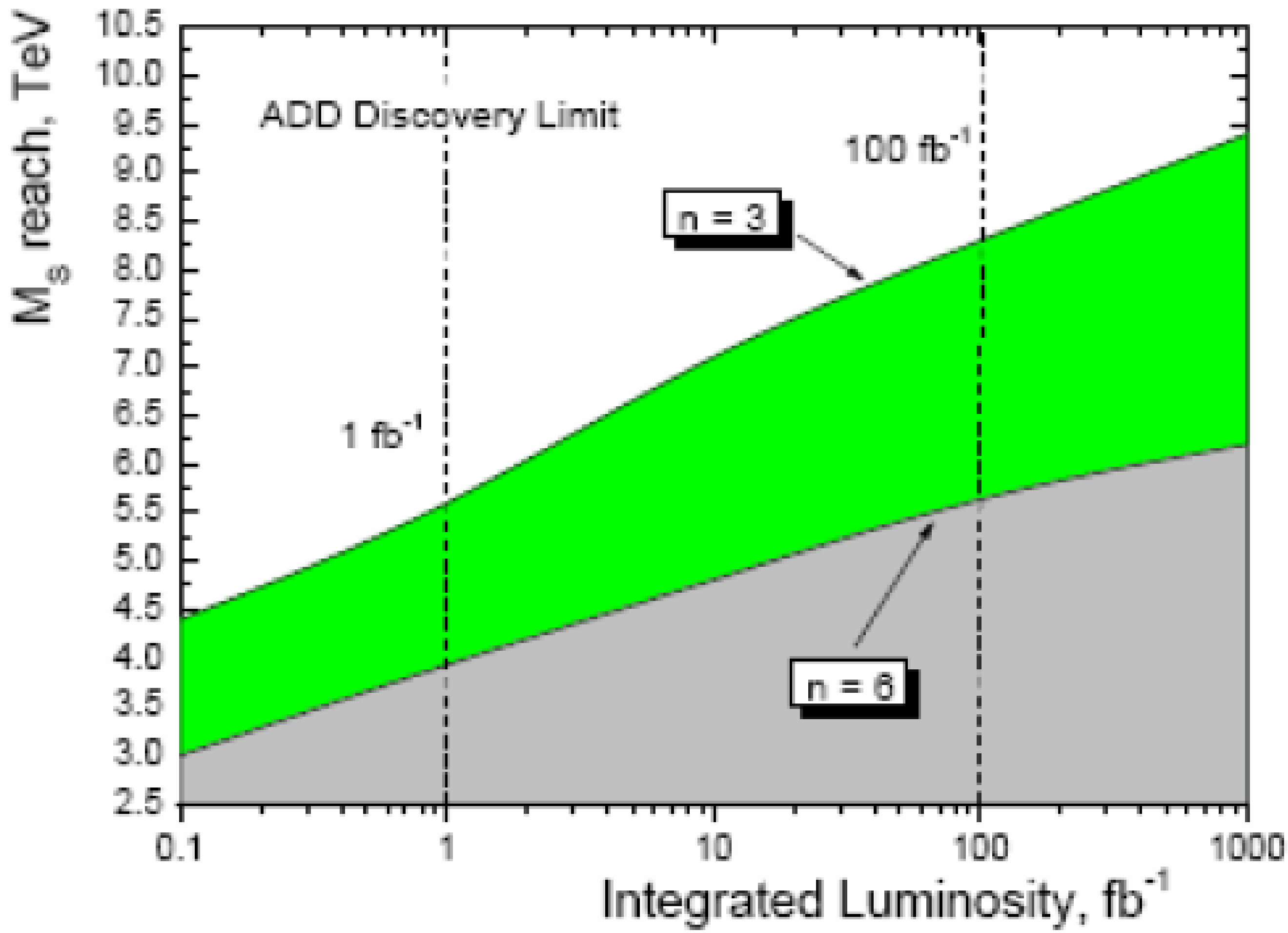

Fig. 2. 5σ limit on M_D for the number of extra dimensions $n = 3, 4, 5, 6$. Muon pair production is considered [7].

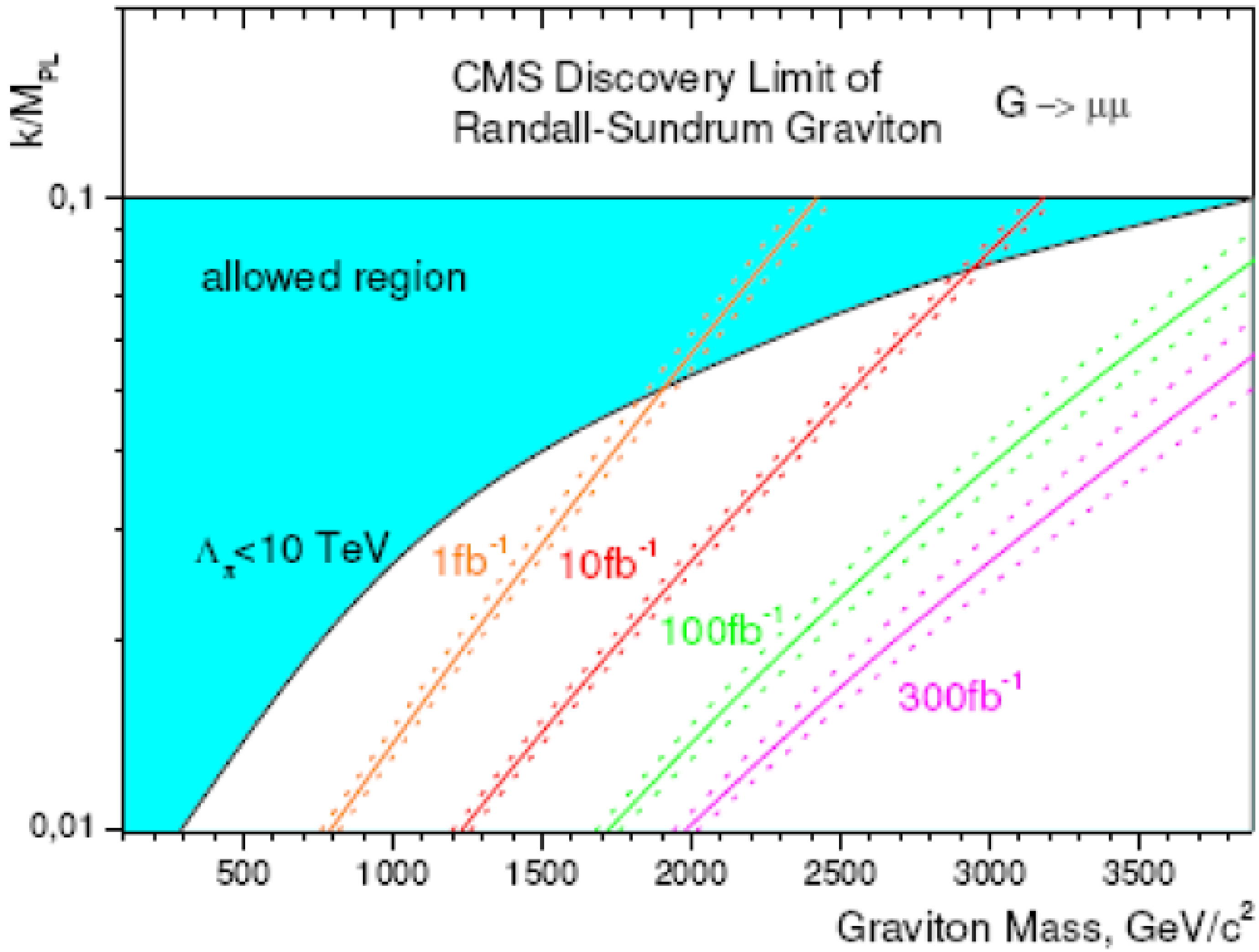

Fig. 3. Theoretical and LHC constraints on the RS1 scenario parameter in the $k{=}M_{Pl}$ and $m_1 = m_G$ plane for

What are the parameters we can constrain?

What are the uncertainties in calculation?

Which signals are unmistakably gravitons?

How to disentangle ADD and RS?

How to disentangle radion and Higgs?

What are the parameters we can constrain?

Real Gravitons (ADD):

$$\hat{s} = x_1 x_2 s$$

$$\sigma_d = \int dx_1 dx_2\, f_{\pi_1/p}(x_1)\, f_{\pi_2/p}(x_2) \int_0^{\hat{s}} dM^2 \rho_d\left(M^2, \frac{M_P^2}{\hat{M}_P^2}\right) \frac{1}{M_P^2} \hat{\sigma}(\hat{s}, M^2)$$

$$= \sigma_d\left(\frac{s}{\hat{M}_P^2}\right)$$

$$\frac{1}{\hat{M}_P^{2+\frac{d}{2}}} = 16\pi \hat{G}_{4+d}$$

- Machine energy naturally cuts off KK sum
- 4-D Planck Mass M_P cancels out of the calculation

$\Rightarrow$ Bounds from real graviton emission directly constrain the d-dimensional gravitational *coupling constant*

Virtual Gravitons (ADD):

$$\sigma = \int dx_1 dx_2\, f_{\pi_1/p}(x_1)\, f_{\pi_2/p}(x_2) \int d\Phi \left| \mathcal{A}_{SM}(\hat{s}) + \int_0^{\Lambda^2} dM^2 \rho_d \left(M^2, \frac{M_P^2}{\hat{M}_P^2} \right) \frac{1}{M_P^2} \mathcal{A}\left(\hat{s}, M^2\right) \right|^2$$

$$= \int dx_1 dx_2\, f_{\pi_1/p}(x_1)\, f_{\pi_2/p}(x_2) \int d\Phi \left| \mathcal{A}_{SM}(\hat{s}) + \frac{\lambda(s,d)}{\hat{M}_P^{2+d/2} \Lambda^{2-d/2}} \mathcal{A}\left(\hat{s}, M^2\right) \right|^2$$

$$= \int dx_1 dx_2\, f_{\pi_1/p}(x_1)\, f_{\pi_2/p}(x_2) \int d\Phi \left| \mathcal{A}_{SM}(\hat{s}) + \frac{1}{\hat{M}_S^4} \mathcal{A}\left(\hat{s}, M^2\right) \right|^2$$

sum over propagators

$$= \sigma_{SM} + \frac{1}{\hat{M}_S^8} \sigma_G + \frac{1}{\hat{M}_S^4} \sigma_{\text{int}}$$

$\Rightarrow$ Bounds from virtual graviton emission constrain the so-called *string scale*

$$M_S = \left[\frac{\hat{M}_P^{2+d/2} \Lambda^{2-d/2}}{\lambda(s,d)} \right]^{1/4} \sim \hat{M}_P$$

RS Parameters :

warp factor: $e^{-\pi KR}$

$K \Rightarrow$ curvature of 5th dim.

$R \Rightarrow$ radius of 5th dim.

$$m_0 = Ke^{-\pi KR}$$

> 220 GeV

$$c_0 = \frac{K}{M_P}$$

$0.1 - 0.01$

$$M_1 = 1.22\pi\, m_0$$

> 850 GeV

$$c = \frac{K}{\bar{M}_P} = \sqrt{8\pi}\, c_0$$

$0.5 - 0.05$

Since each graviton behaves as a weakly-coupled particle with electroweak order mass, we can only constrain the (m_0, c_0) plane

For radions, we can only constrain the (M_Φ, Λ_Φ) plane

What are the uncertainties in calculation?

Three kinds of uncertainties:

- model uncertainties
- PDF uncertainties
- experimental uncertainties

Model uncertainties:

1. We do not have a unique model!
2. ADD model calculations have a strong cutoff dependence – truncation issue
3. RS-GW model calculations neglect back-reaction effects

Truncation issue:

Cutoff in the ADD model is around a TeV

LHC experiments will actually achieve this energy

Low-energy effective theory breaks down at the cutoff!

For ease in calculation, we generally cut off such events

Most interesting new physics effects may lie just there!

To predict something, we require a (toy) string theory?

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TeV Strings and Collider Probes of Large Extra Dimensions

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PDF uncertainties:

We do not really know the PDFs at LHC energies – will require "educated" extrapolation from Tevatron data

Tevatron had initially found an excess in high-pT events

It was soon explained away as a PDF effect

$\because$ it appeared in all processes

Same phenomenon may well repeat at LHC!

Graviton effects also appear in all processes!

Need to ensure that graviton effects are not misinterpreted as PDF effects…

PROTON STRUCTURE IMPACT ON SENSITIVITY TO EXTRA-DIMENIONS AT LHC

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Laboratoire de Physique Nucléaire et des hautes Energies, Paris, France

The LHC data will provide sensitivity to an unification of the couplings at low energies in the range ∼10-100 TeV. It is demonstrated in this note that the lack of knowledge on the proton structure, specifically its gluon distribution, can lower dramatically the sensitivity of bare cross section measurements to this physics. However, some more elaborated strategies could probably be developped to recover an important part of the sensitivity.

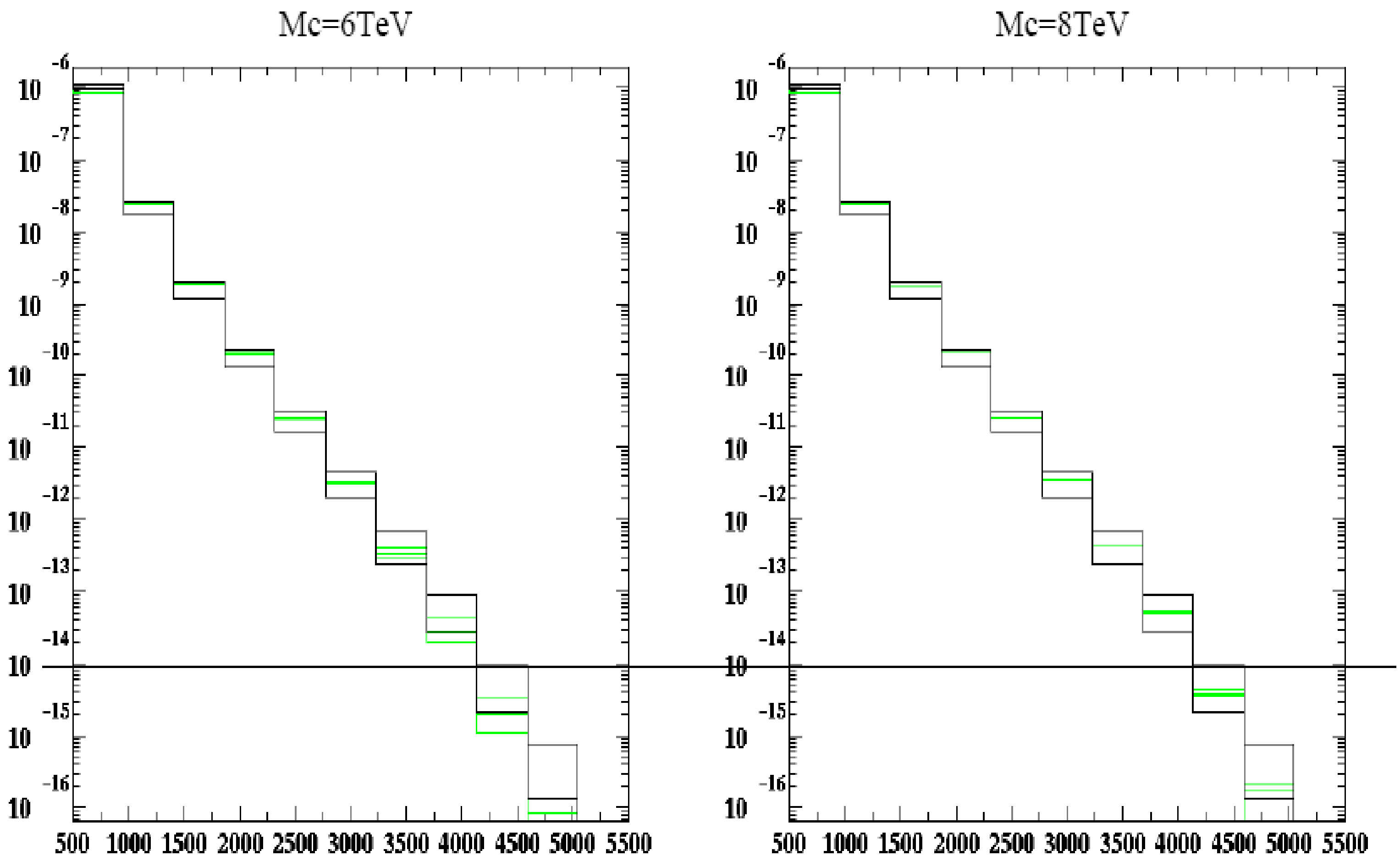


Figure 8: *Standard Model and extra-dimensions predictions comparison: The extra-dimension predictions are well separated from the Standard Model uncertainties zone for $M_c = 2$ TeV (up left). By increasing the compactification scale, some of those predictions falls into the Standard Model band and may be considered as Standard Model prediction with a new PDF fit.*

It is interesting to notice that every measured di-jet cross section in this zone is explained within the Standard Model by a simple new PDF fit. This interpretation means also that *in this zone, every power of discovering new physics is killed and absorbed by a PDF fit.* One expects a reduction of the sensitivity to extra-dimensions because of these uncertainties.

Table 1: *Upper limit in compactification scale reached by the sensitivity to extra-dimensions including and without including the proton structure uncertainties. The discovery potential is fixed for a value of the significance $S > 5\sigma$.*

	2 extra-dimensions	4 extra-dimensions	6 extra-dimensions
Theoretically	5 TeV	5 TeV	5 TeV
including PDF uncertainties	< 2 TeV	< 3 TeV	< 4 TeV

Can we combine this with some sort of spin measurements etc to increase the sensitivity?

Multi-particle interactions:

Spectator model is no longer very accurate at LHC energies – we will have multi-parton interactions (minimum bias events)

Experimental excess CS = New physics excess
+ PDF excess
+ Minimum bias events

In a naive analysis, excess cross-section could be interpreted as PDF/MB effect or a new physics effect

Even if we assume no new physics, PDF effect may get mixed up with minimum bias effects

Require to filter out the minimum bias effects

– heavily model-dependent

Models for hadron-hadron collisions

- Need to connect hard scattering processes (perturbative QCD) to the soft processes (non-perturbative models).

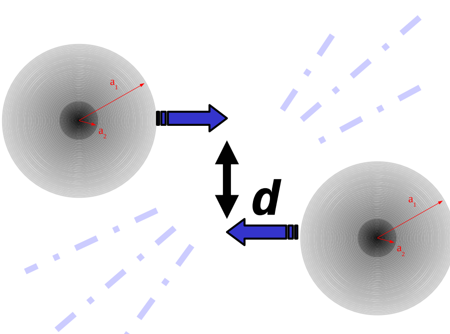
PYTHIA

- Attempts to extend perturbative high-pt picture down to the low-p_T region.
  - Parton-parton cross section become larger than proton-proton - interpreted as multiple parton interactions

$$\sigma_{\text{int}} = \int_{p_{(T\min)}}^{s/4} \frac{d\sigma}{dp_t^2} \, dp_t^2$$

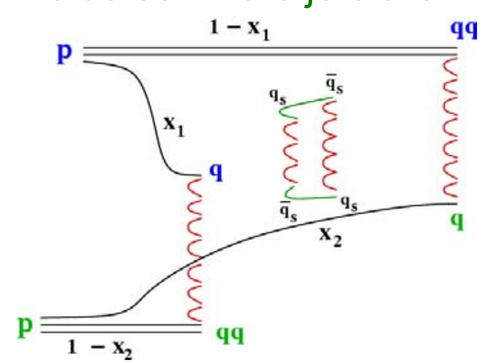
- Decreasing $p_{T\min}$ increases number of parton-parton interactions, and vice-versa.

- Multiple interaction model needed to describe data.
  - Correlations introduced via a **varying impact parameter**.



PHOJET

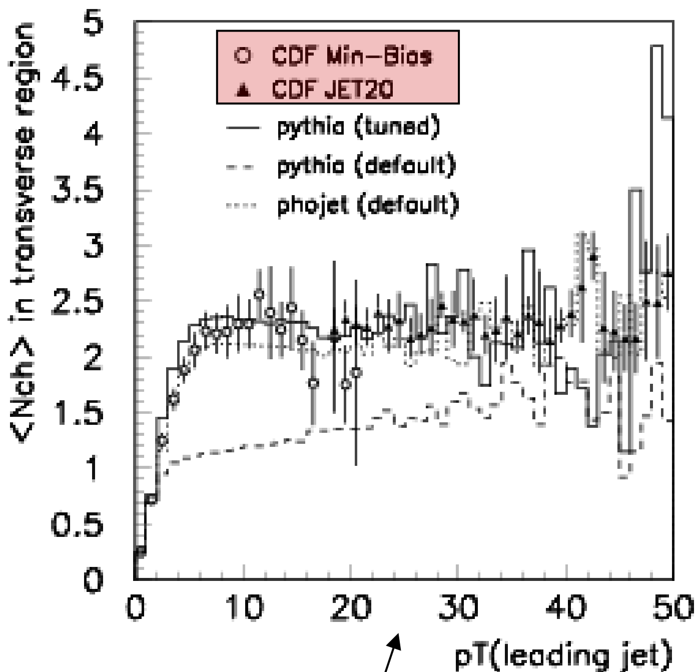
- Developed mainly for soft and semi-hard particle production.
  - Implements ideas of **Dual Parton Model** for low-p_T processes.
  - Multiple **Pomeron** exchanges give rise to sea-quark multi-chains
- Unlike PYTHIA, HERWIG etc., PHOJET not developed for Standard Model (and beyond) physics analyses.
  - Limited to production mechanisms of strong interactions.
  - However, useful tool for **MB** and **UE** studies where jets are involved.

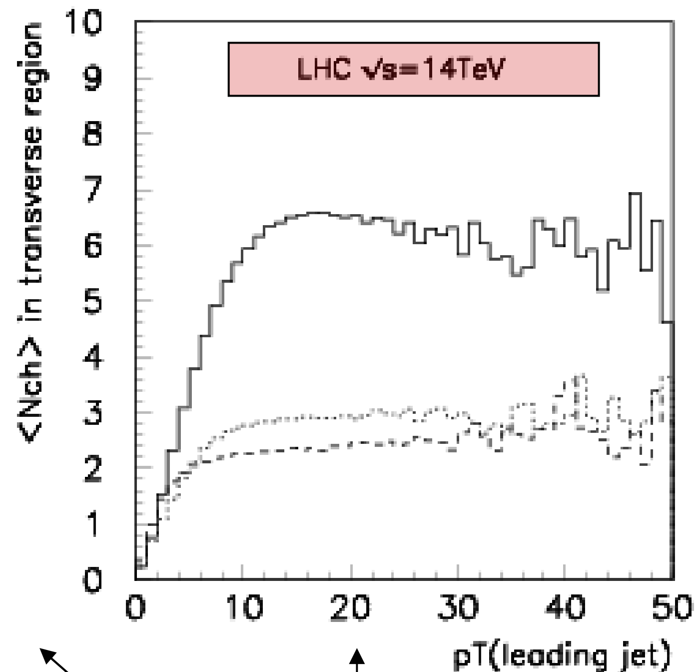


Dawson, Butter & Moraes 2003

Underlying event in charged jet evolution

- How does particle density in “transverse region” vary with leading jet p_T ?





Again, default PYTHIA does not give enough “activity” in “transverse region”. (Need to increase correlations in multiple interactions.) Tuned-PYTHIA and PHOJET agree well with data.

PYTHIA predicts significant increase in event activity in the UE at the LHC. While tuned-PYTHIA and PHOJET both agree well with CDF data, their predictions at LHC energies differ by more than a factor of 2.

Which signals are unmistakably gravitons?

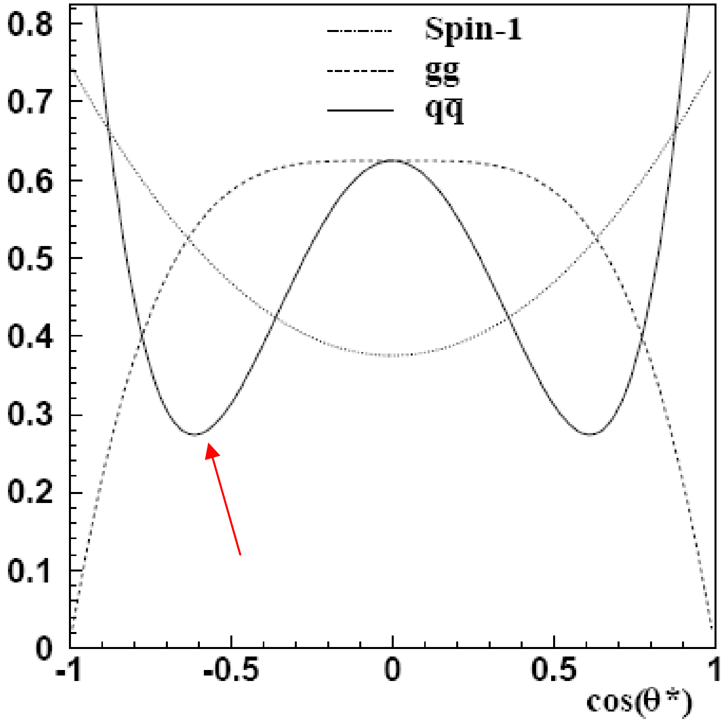
Hallmarks of KK graviton interactions:

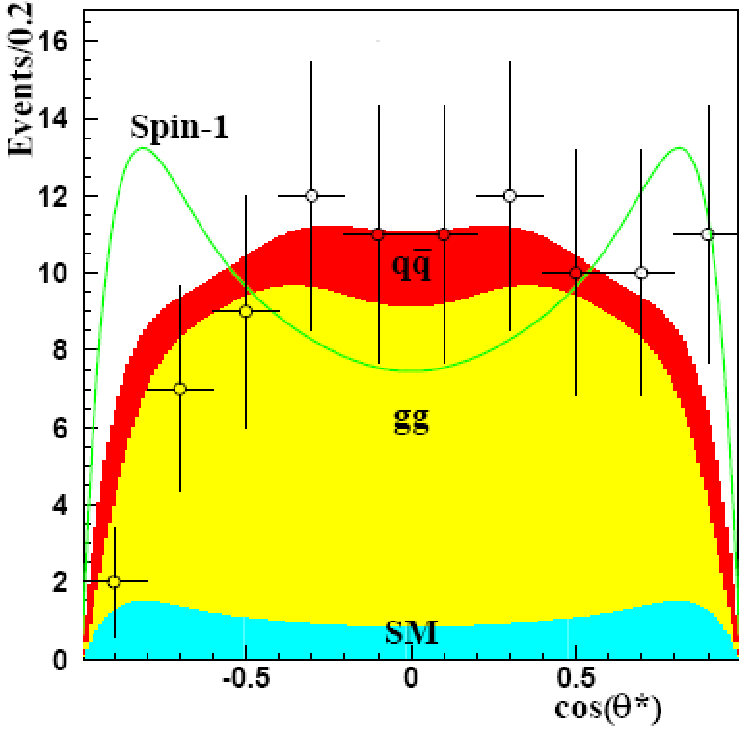
- universality of coupling
- growth with higher energy (non-unitarity)
- spin-2 characteristics
- missing energy (in ADD-type models)
- pattern of masses (in RS-type models)

Generic problems in checking these:

1. Similar signals arise from other new physics, e.g. unparticles
2. May not be able to kinematically access multiple resonances
3. LHC experiments may not have necessary sensitivity

Spin-2 would be the most clinching argument





B.C. Allanach*, K. Odagiri†, M.A. Parker‡ and B.R. Webber‡,$

Study of narrow RS graviton resonances at the LHC (ATLAS detector)

Exploring Small Extra Dimensions at the Large Hadron Collider

B.C. Allanach[$], K. Odagiri[†], M.J. Palmer[‡], M.A. Parker[‡], A. Sabetfakhri[‡] and B.R. Webber[‡]

Process	Distribution	Plot
$gg \to G \to f\bar{f}$	$\sin^2\theta^*(2-\beta^2\sin^2\theta^*)$	a
$q\bar{q} \to G \to f\bar{f}$	$1+\cos^2\theta^* - 4\beta^2\sin^2\theta^*\cos^2\theta^*$	b
$gg \to G \to \gamma\gamma, gg$	$1+6\cos^2\theta^* + \cos^4\theta^*$	c
$q\bar{q} \to G \to \gamma\gamma, gg$	$1-\cos^4\theta^*$	a
$gg \to G \to WW, ZZ$	$1-\beta^2\sin^2\theta^* + \frac{3}{16}\beta^4\sin^4\theta^*$	d
$q\bar{q} \to G \to WW, ZZ$	$2-\beta^2(1+\cos^2\theta^*) + \frac{3}{2}\beta^4\sin^2\theta^*\cos^2\theta^*$	e
$gg \to G \to HH$	$\sin^4\theta^*$	f
$q\bar{q} \to G \to HH$	$\sin^2\theta^*\cos^2\theta^*$	g

Table 1: Angular distributions in graviton production and decay. θ^* is the polar angle of the outgoing fermion in the graviton rest frame. The letters in the "plot" column refer to the curves in Figure 4.

Center–edge asymmetry $A_{\rm CE}$

The center–edge and total cross sections can at the parton level be defined like for initial-state electrons and positrons:[6]

$$\hat{\sigma}_{\rm CE} \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1}\right)\right] \frac{d\hat{\sigma}}{dz}\, dz, \quad \hat{\sigma} \equiv \int_{-1}^{1} \frac{d\hat{\sigma}}{dz}\, dz, \tag{7}$$

where $z = \cos\theta_{\rm cm}$, with $\theta_{\rm cm}$ the angle, in the c.m. frame of the two leptons, between the lepton and the proton. Here, $0 < z^* < 1$ is a parameter which defines the border between the "center" and the "edge" regions. This asymmetry has been demonstrated very selective to the ADD effects in the electron-positron case,[6] and we want to test its use in the more complicated (but experimentally forthcoming) subprocesses (5) and (6).

The center–edge asymmetry can then for a given dilepton invariant mass M be defined as

$$A_{\rm CE}(M) = \frac{d\sigma_{\rm CE}/dM}{d\sigma/dM}, \tag{8}$$

where a convolution over parton momenta is performed, and we obtain $d\sigma_{\rm CE}/dM$ and $d\sigma/dM$ from the inclusive differential cross sections $d\sigma_{\rm CE}/dM\,dy\,dz$ and $d\sigma/dM\,dy\,dz$, respectively, by integrating over z according to Eq. (7) and over rapidity y between $-Y$ and Y, with $Y = \log(\sqrt{s}/M)$.[7]

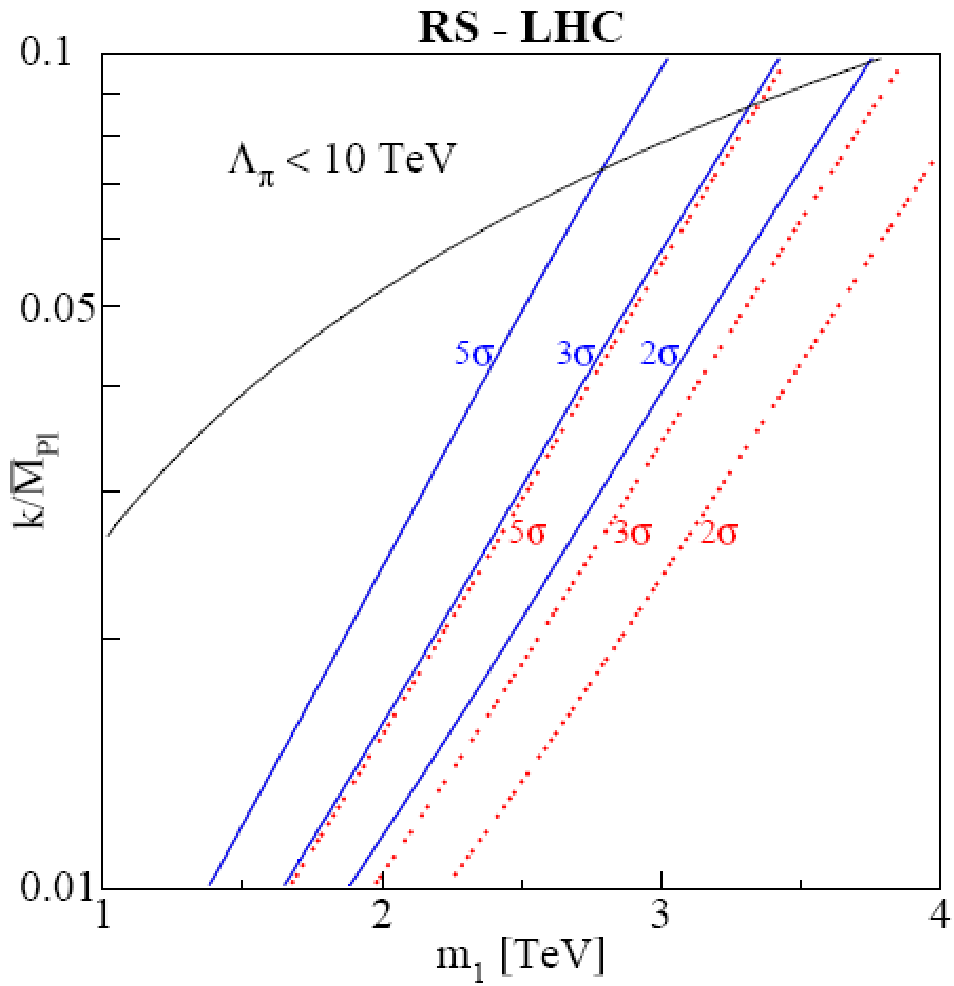
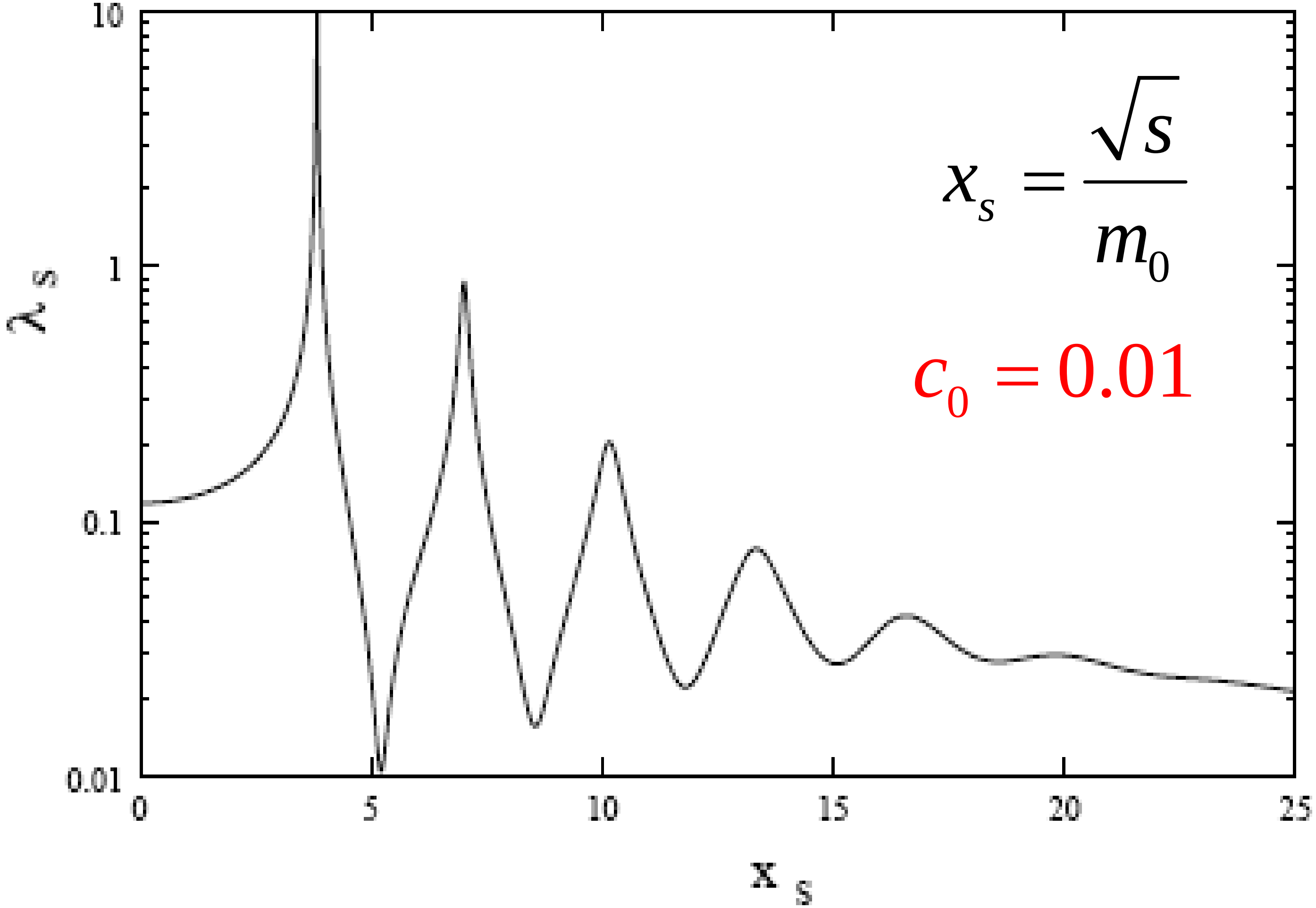


Figure 1: Spin-2 identification of an RS resonance, using the center–edge asymmetry, integrated over bins of 200 GeV around the peak. Solid (dotted) 2σ, 3σ, 5σ contours: $\mathcal{L}_{\rm int} = 100\ \mathrm{fb}^{-1}$ ($300\ \mathrm{fb}^{-1}$). The theoretically favored region, $\Lambda_\pi < 10$ TeV, is indicated.

How to disentangle ADD and RS?

$$D(s)=\sum_{n=0}^{\infty}\frac{\kappa e^{-kR_C\pi}}{s-M_n^2+iM_n\Gamma_n}=\frac{\lambda(x_s)}{m_0^4}$$



Graviton width grows rapidly!

$$\Gamma_n \propto c_0^2 x_n^3 m_0$$

For large widths RS signal begins to look like ADD signal

- both would have spin-2 character: angular distributions with $P_2(\cos\theta)$.
- both would give similar excess in all the SM channels, for correct choice of parameters
- invariant mass excess would be smeared-out, with broad overlapping resonances in RS, "quasi-continuum" in ADD

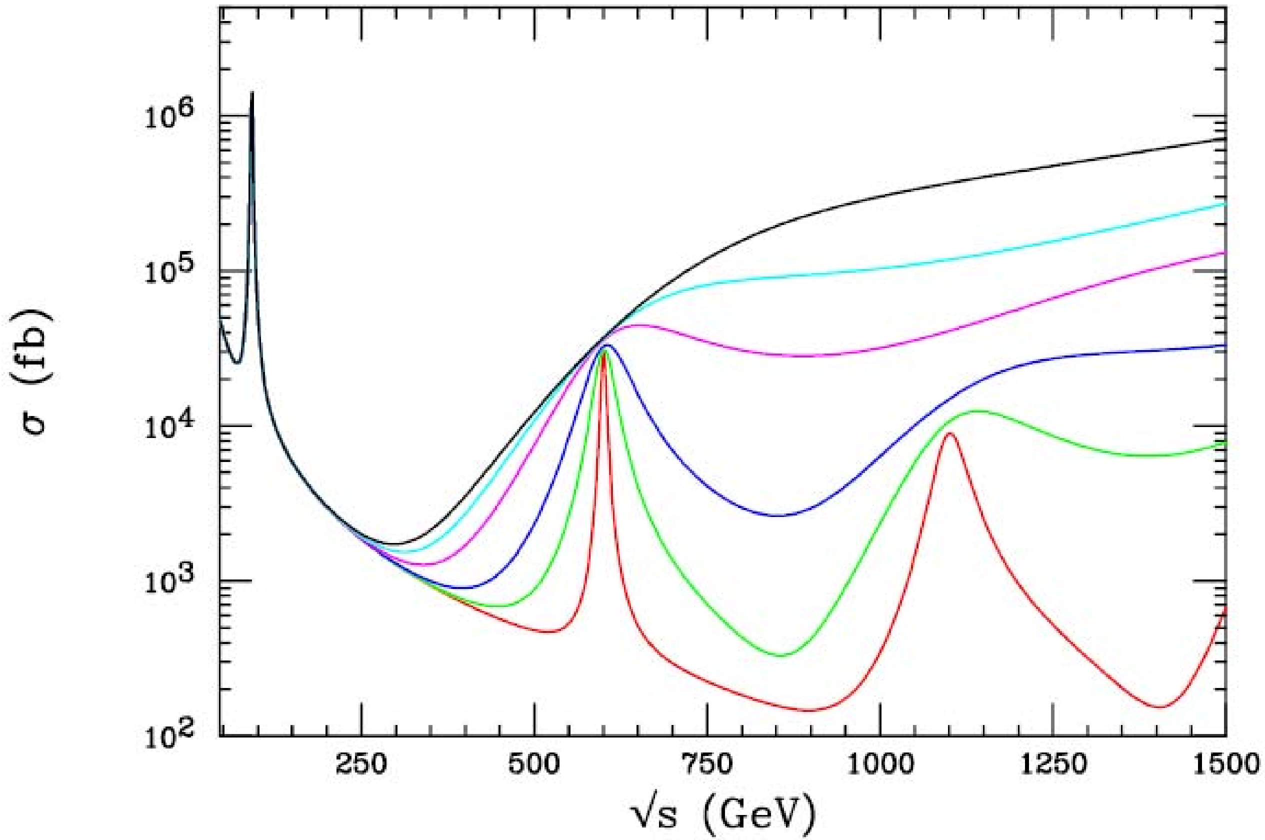


Figure 2: The cross section for $e^+e^- \to \mu^+\mu^-$ including the exchange of a tower of KK gravitons, taking the mass of the first mode to be 600 GeV, as a function of $\sqrt{s}$. From top to bottom the curves correspond to $k/\overline{M}_{Pl} = 1.0,\ 0.7,\ 0.5,\ 0.3,\ 0.2,\ 0.1$.

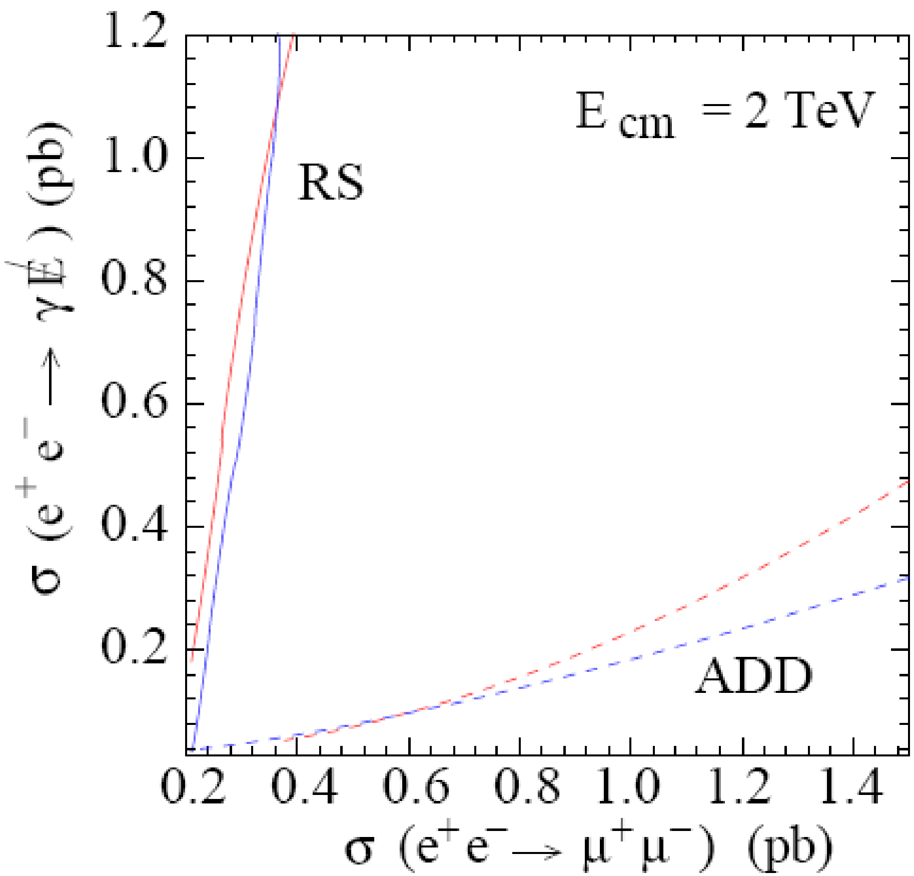


Figure 8. *Correlation plot showing the cross-section for the single photon signal vis-á-vis the cross-section for muon pair-production. Broken lines correspond to the ADD model for two values of* $d = 3$ *(red) and 6 (blue), while solid lines correspond to the RS model for two values of* $m_0 = 200$ *GeV (red), 400 GeV (blue).*

Rai & SR 2003

Trying to repeat similar study at LHC : Dixit & SR

COMMENTS

- LHC will start running a few months from now
- If there are TeV-scale extra dimensions, we hope to see them at LHC
- We must be careful not to

  (a) miss the XD effects by being too conservative

  (b) misinterpret SM effects as XD effects
- If we have new physics, we need to pin it down.
- Time has come to make detailed analyses and address the more difficult questions…

THANK YOU