Probing Quantum Gravity at Colliders

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TeV4 LHC Workshop

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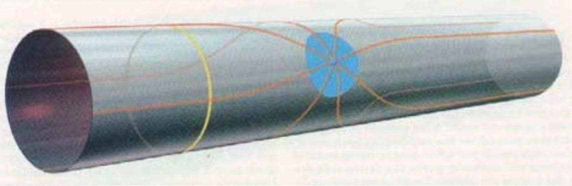
Outline

- Realms of Quantum Gravity
- Some Lessons of the Tevatron
- Beyond the Tevatron
- Conclusions

Models of Extra Dimensions

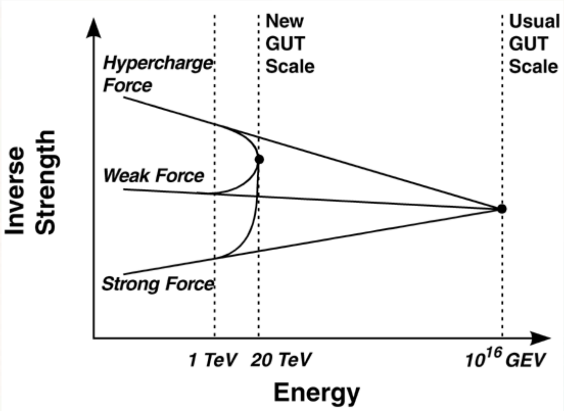
ADD Scenario:

- Pro: "Eliminates" the hierarchy problem by stating that physics ends at a TeV scale
- Only gravity lives in the "bulk" space
- Size of ED's (n=2-7) between ~100 μm and ~1 fm
- Black holes at the LHC
- Con: Doesn't explain how to make ED large



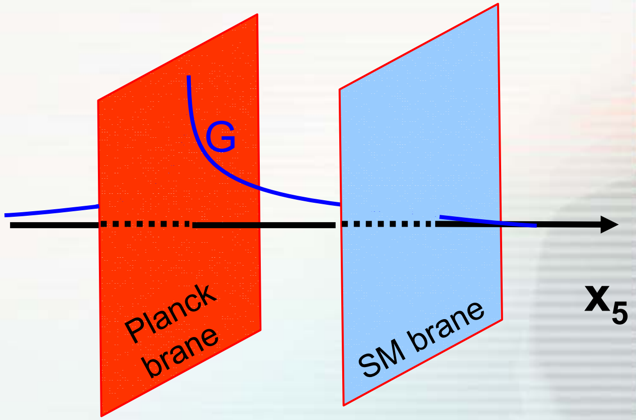
Small ED:

- Pro: Could lower GUT scale by changing the running of couplings
- At least gauge bosons (g/γ/W/Z) "live" in ED's
- Size of ED's ~1 TeV^{-1} or ~10^{-19} m
- Con: Gravity is not in the picture



RS Model:

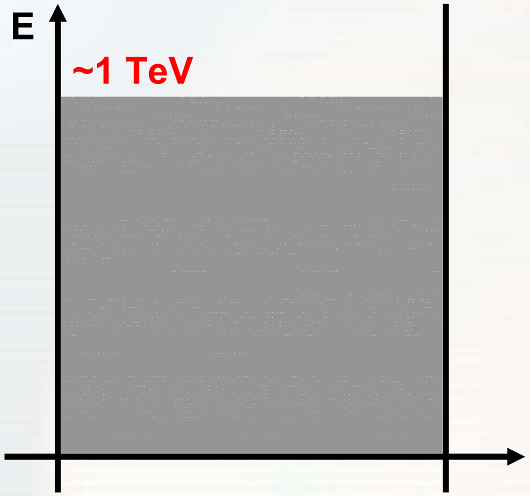
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, w/ special metric
- Higgs-like particle: radion
- Con: Size of ED as small as ~$1/M_{Pl}$ or ~10^{-35} m



Kaluza-Klein Spectrum

ADD Model:

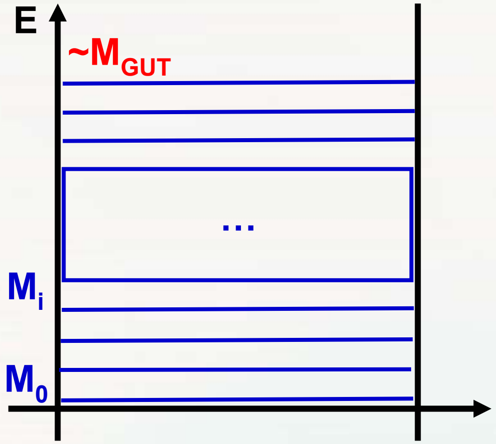
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



Small ED:

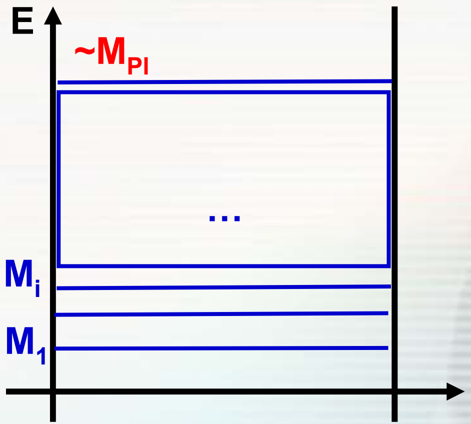
- Winding modes with nearly equal energy spacing ~1/r, i.e. ~TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: ~g_w per mode

$$M_i = \sqrt{M_0^2 + i^2/r^2}$$



RS Model:

- "Particle in a box" with special AdS metric
- Energy eigenvalues are given by zeroes of Bessel function J_1
- Light modes might be accessible at colliders
- Coupling: G_N for zero mode; $1/\Lambda_\pi^2$ for the others



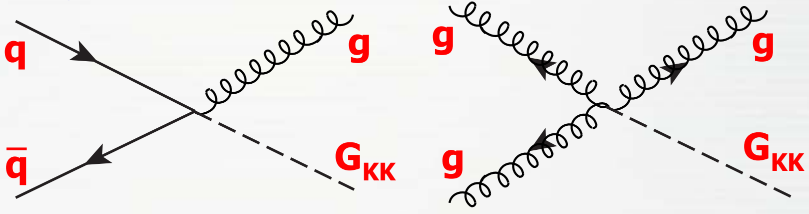
$$M_0 = 0; M_i = M_1 x_i/x_1 \approx M_1, 1.83M_1, 2.66M_1, 3.48M_1, 4.30M_1, \ldots$$

Collider Signatures for ED

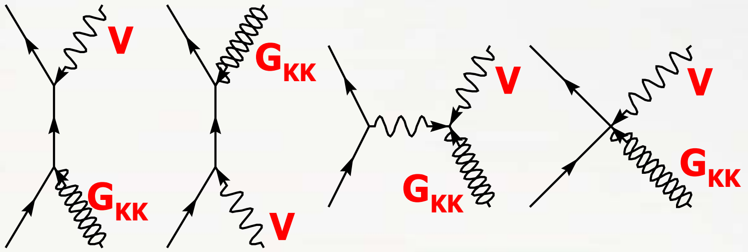
- Kaluza-Klein gravitons couple to the energy-momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - [Han, Lykken, Zhang, PRD **59**, 105006 (1999)]
  - [Giudice, Rattazzi, Wells, NP **B544**, 3 (1999)]
- Since graviton can propagate in the bulk, energy and momentum are not conserved in the G_{KK} emission from the point of view of our 3+1 space-time
- Depending on whether the G_{KK} leaves our world or remains virtual, the collider signatures include single photons/Z/jets with missing E_T or fermion/vector boson pair production
- Graviton emission: direct sensitivity to the fundamental Planck scale M_D
- Virtual effects: sensitive to the ultraviolet cutoff M_S, expected to be ~M_D (and likely < M_D)
- The two processes are complementary

Real Graviton Emission (Large ED)

Monojets at hadron colliders

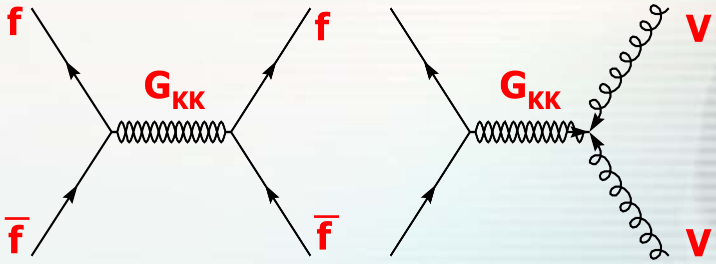


Single VB at hadron or e^+e^- colliders



Virtual Effects (all ED)

Fermion or VB pairs at hadron or e^+e^- colliders



L’EPilogue (Large ED)

	$e^+e^- \to \gamma G$					$e^+e^- \to ZG$				
Experiment	n=2	n=3	n=4	n=5	n=6	n=2	n=3	n=4	n=5	n=6
ALEPH	1.28	0.97	0.78	0.66	0.57	0.35	0.22	0.17	0.14	0.12
DELPHI	1.38	**1.02**	0.84	**0.68**	0.58					
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					

Color coding
≤184 GeV
≤189 GeV
>200 GeV
λ=-1 **λ=+1**

Virtual Graviton Exchange

Experiment	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	qq	ff	$\gamma\gamma$	WW	ZZ	**Combined**
ALEPH	1.04 0.81	0.65 0.67	0.60 0.62	0.53/0.57 0.46/0.46 (bb)	1.05 0.84	0.81 0.82			0.75/1.00 (<189)
DELPHI		0.59 0.73	0.56 0.65		0.60 0.76	0.83 0.91			0.60/0.76 (ff) (<202)
L3	0.98 1.06	0.56 0.69	0.58 0.54	0.49 0.49	0.84 1.00	0.99 0.84	0.68 0.79		1.1/1.0 (<202)
OPAL	1.15 1.00	0.62 0.66			0.62 0.66	0.89 0.83		0.63 0.74	1.17/1.03 (<209)

LEP Combined: 1.2/1.1

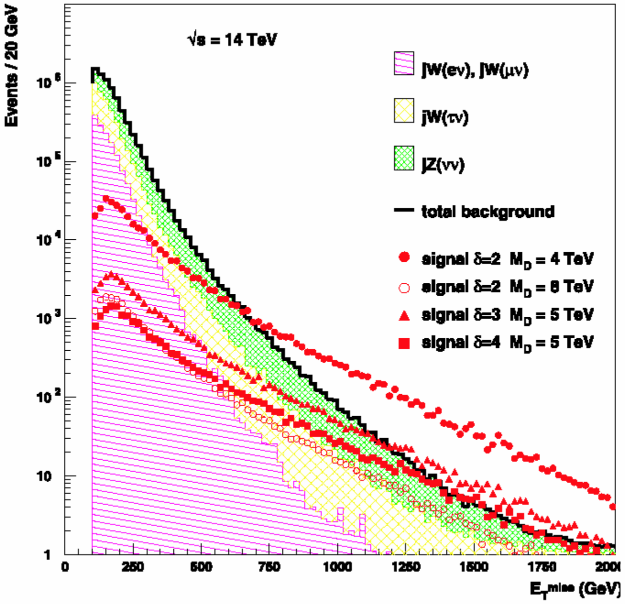
Tevatron Lessons

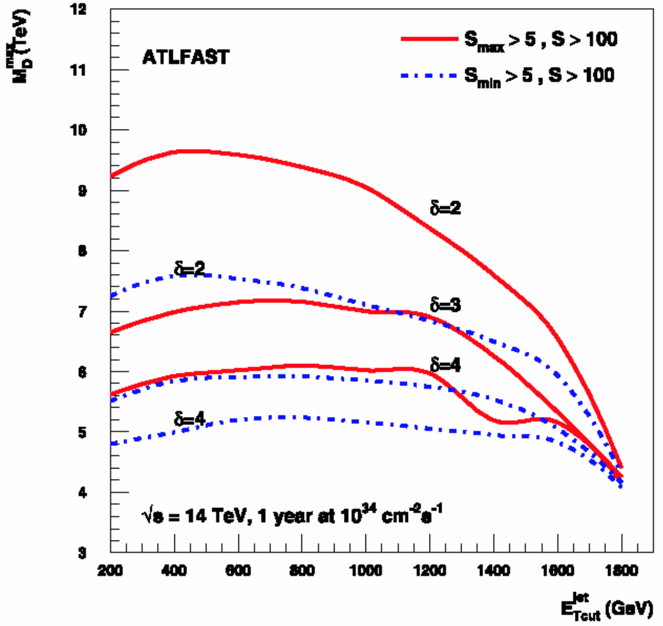
- Sensitivity achieved in Run II has superseded combined sensitivity of LEP and continues to increase
- Planck scale up to ≈ 2 TeV will be probed in the next couple years before the start of the LHC
- What are some of the lessons that we have learned?

Lesson 1: Monojets are Tough!

- Production of single jets is a classical signature for large ED, and one of the first studied phenomenologically [Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999)]; ATLAS studies [Vacavant/Hinchliffe, J. Phys. G: Nucl. Part. Phys. **27**, 1839 (2001)]
- Nevertheless, it was one of the last signatures actually probed experimentally by DØ [PRL **90**, 251802 (2003)] and CDF [PRL **92**, 121802 (2004)]
- Challenges are understanding and suppression of instrumental backgrounds and non-Gaussian tails in ME_T
  - These challenges are not unique to the Tevatron and I expect them to be quite important at the LHC as well (or so history taught us!)

n	M_D reach Run I	M_D reach Run II	M_D reach LHC 100 fb^{-1}
2	1100 GeV	1400 GeV	8.5 TeV
3	950 GeV	1150 GeV	6.8 TeV
4	850 GeV	1000 GeV	5.8 TeV
5	700 GeV	900 GeV	5.0 TeV





Monojets: Tainted History

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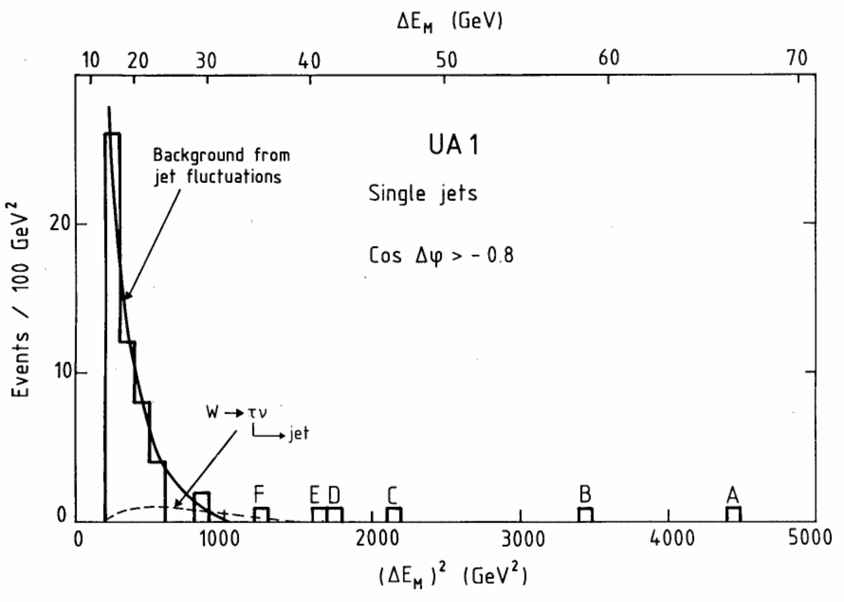
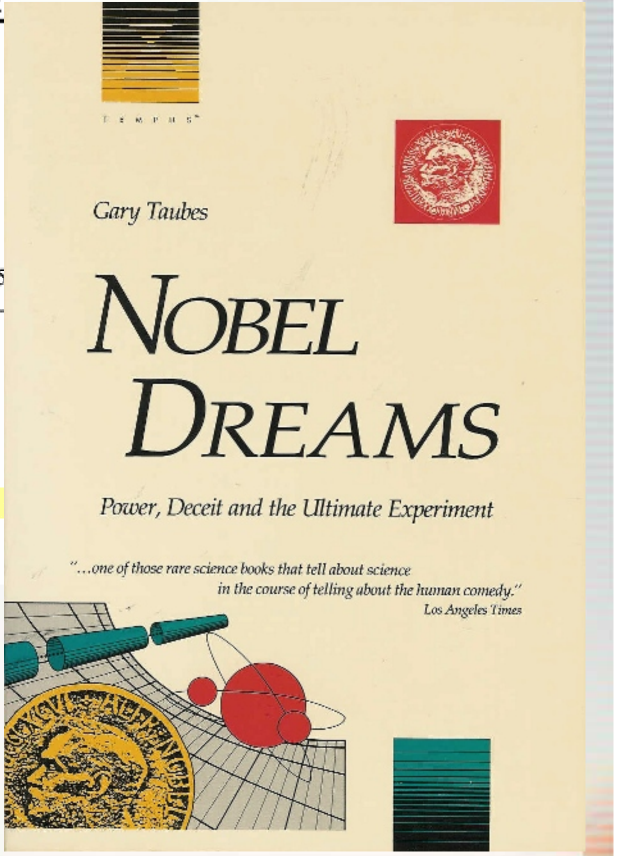


The [illegible] at the CERN $p\bar{p}$ collider has caused ripples of excitement throughout the particle physics world, since they [illegible]

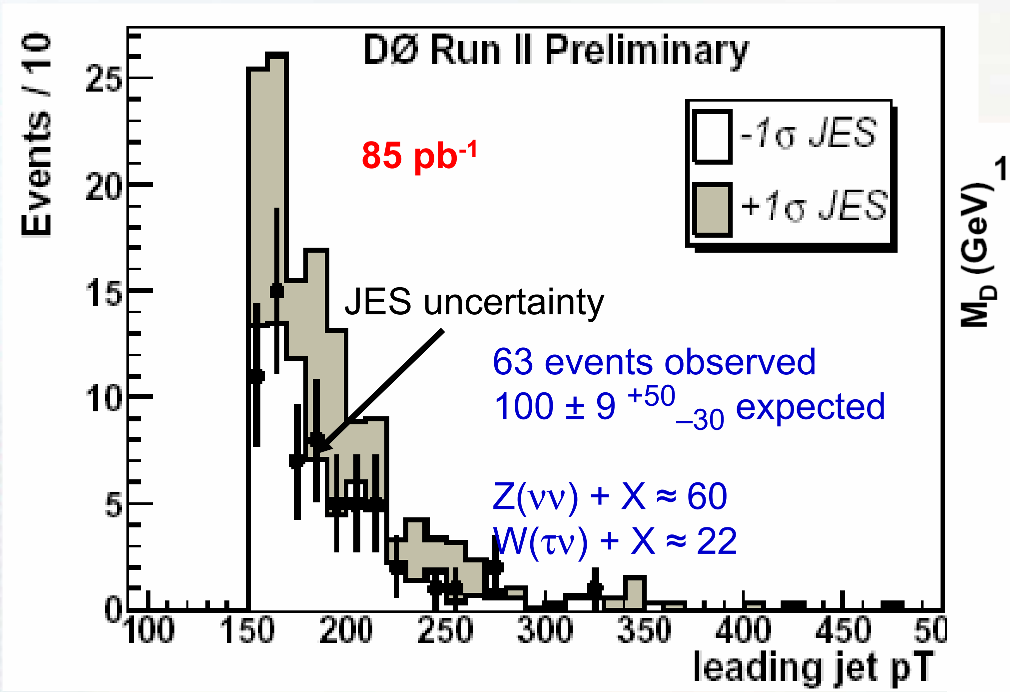


- The signature was deemed doomed and nearly forgotten

- It took many years for successful monojet analyses at a hadron collider to be completed (CDF/DØ)

Monojets and Jet Energy Scale

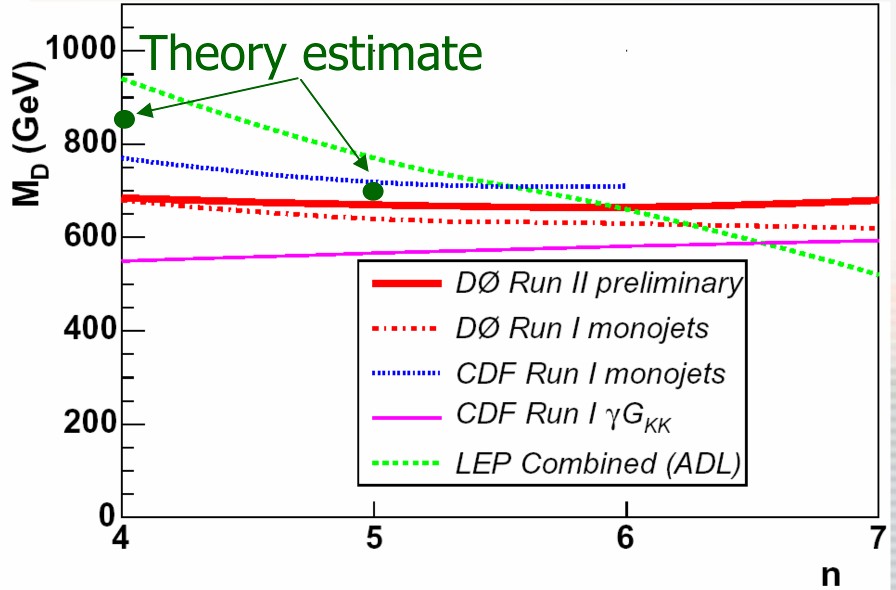
- Tevatron Run II: major systematics comes from the jet energy scale
- For the DØ Run II case it will be reduced soon by a factor of 2-3, but will still be important, if not dominant!
- Expect this uncertainty to be a major source of systematics at the LHC
- Getting JES uncertainty down to a few per cent level at the LHC would take time



63 events observed
100 ± 9 $^{+50}_{-30}$ expected

Z(νν) + X ≈ 60
W(τν) + X ≈ 22

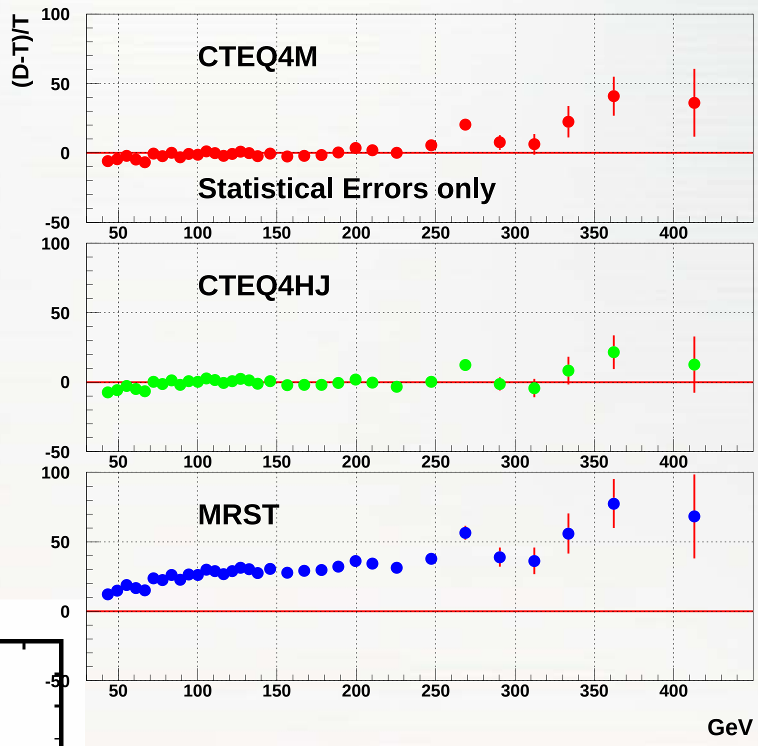
K-factor = 1
n=4, M_D > 0.68 TeV, n=5, M_D > 0.67 TeV
n=6, M_D > 0.66 TeV, n=7, M_D > 0.68 TeV

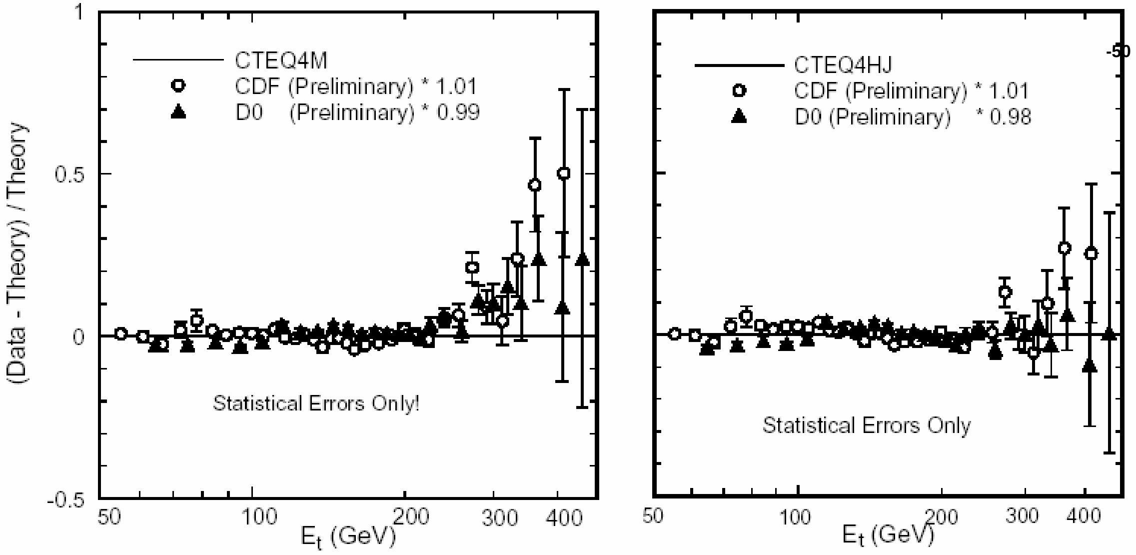


Lesson 2: Tricks of the PDF's

- PDF effects could play nasty tricks in searches for new physics
  - Cf. apparent excess of high-p_T jets observed by CDF in Run I
  - Later explained by modification of gluon part of PDF (still poorly constrained!)
  - Will have impact on ED searches at the LHC

Inclusive Jet Cross Section (CDF Preliminary)

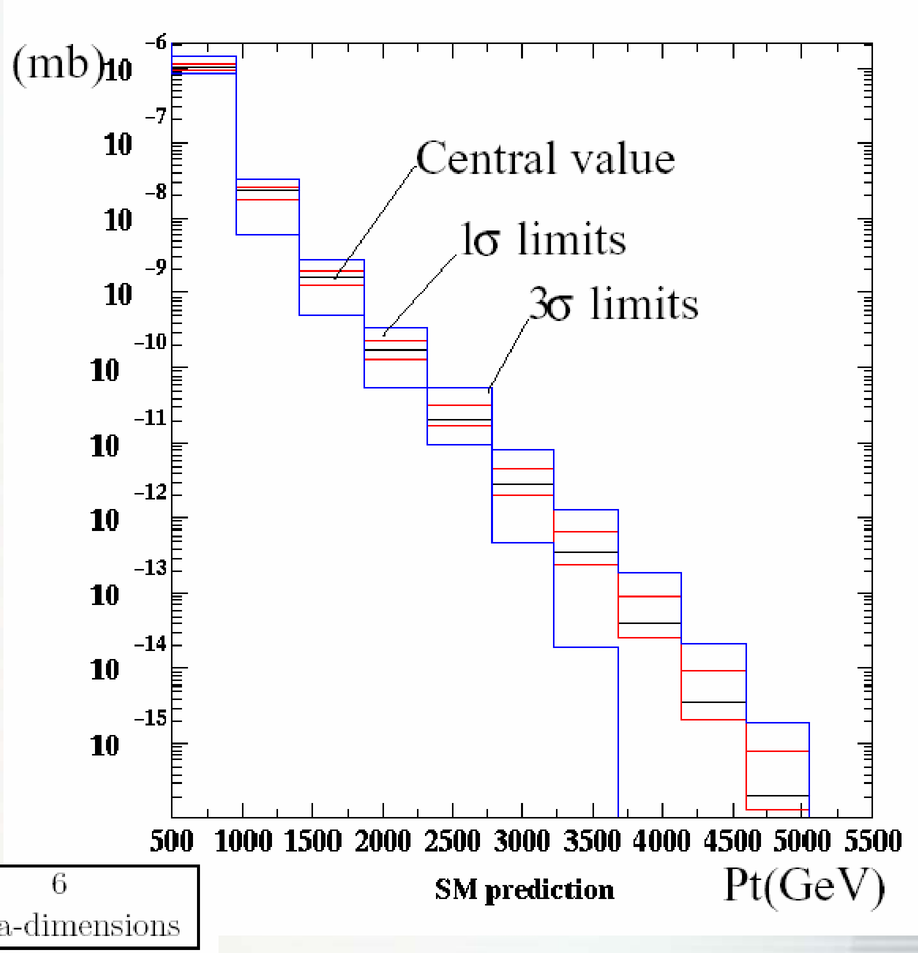




PDF Effects at the LHC

- CTEQ6M error set provides a great tool for studies of the PDF uncertainty effects
- Example: PDF effects in dijet production
  - Offers direct sensitivity to ED models via virtual exchange
  - Accounting for the PDF uncertainty results in significantly reduced sensitivity to ED effects
  - Expect comparable effect for monojet production

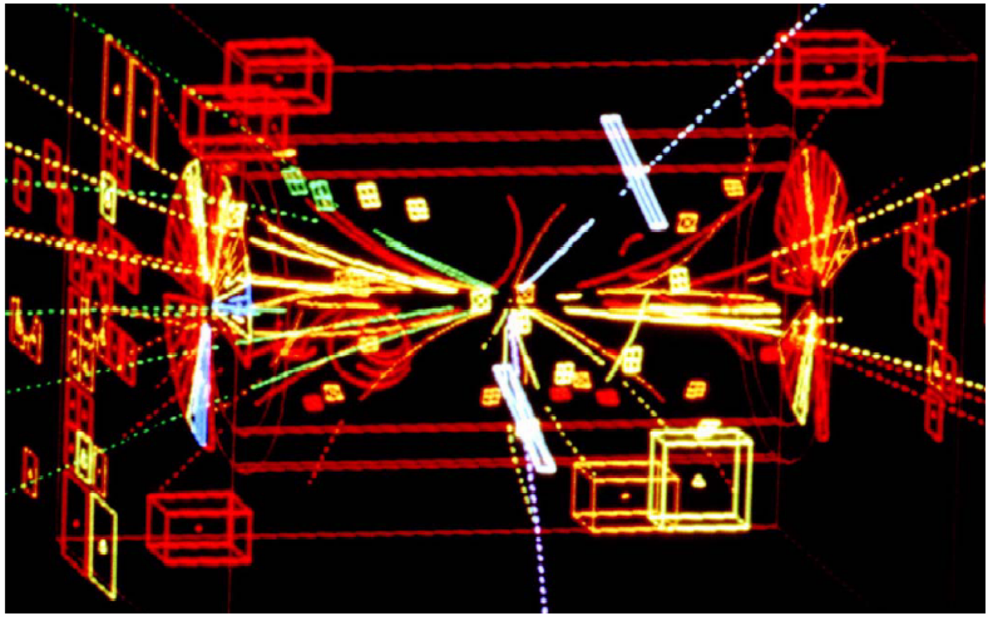
[S. Ferrag, hep-ph/0407303]



	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

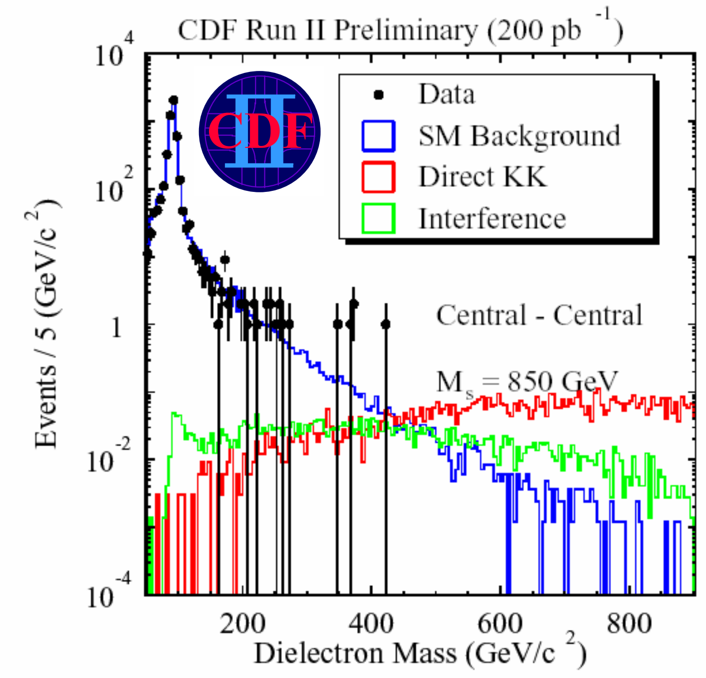
Lesson 3: Drell-Yan and Diphotons

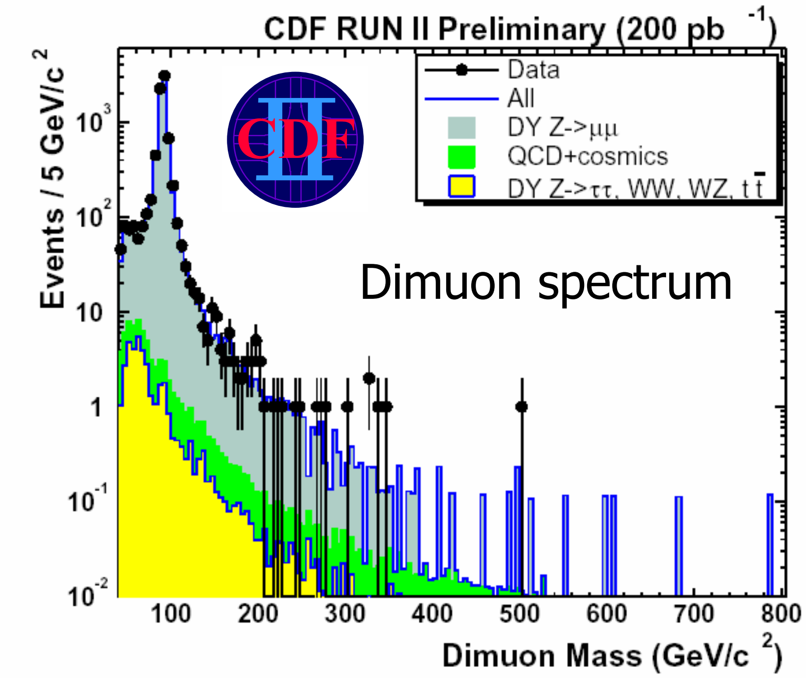
- Not all the Tevatron lessons are “negative”!
- Drell-Yan and diphoton production remain one of the best channels for “quick” discovery of ED effects at the LHC
  - Offer sensitivity to all three types of extra dimensions as well as other types of new physics (TC, Z′, …)
- Drell-Yan historically has been a fruitful channel for discoveries (J/Ψ, Υ, Z)
  - So maybe diphotons for the Higgs!

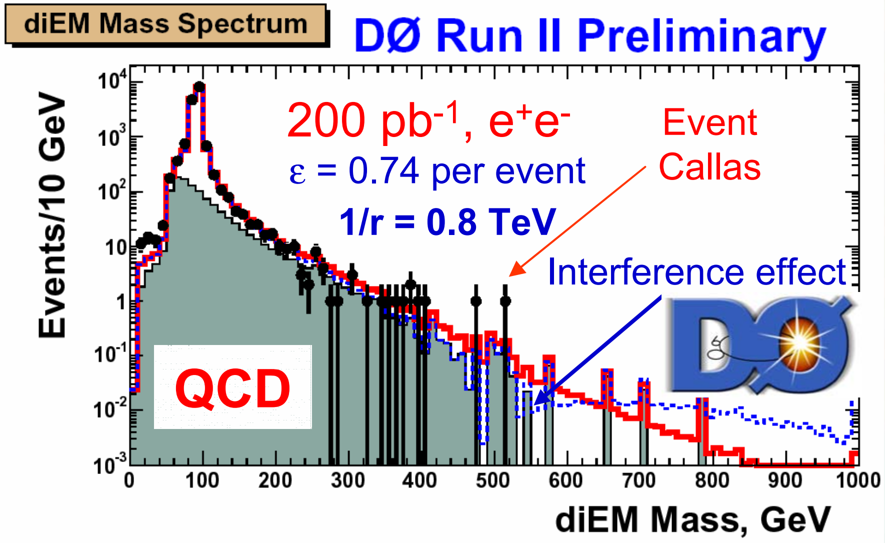


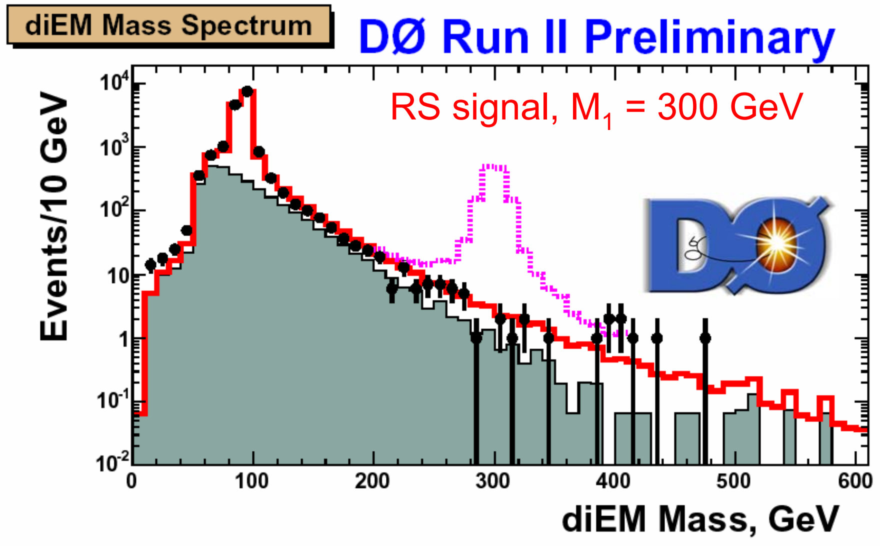
- Well-unders NNLO (DY) and NLO (d
  - Small depe
- Tevatron ex s can be performed f etector:
  - Have a “st for in situ measurem
  - Have been evatron collaborati vity to date

Invariant Mass Spectra



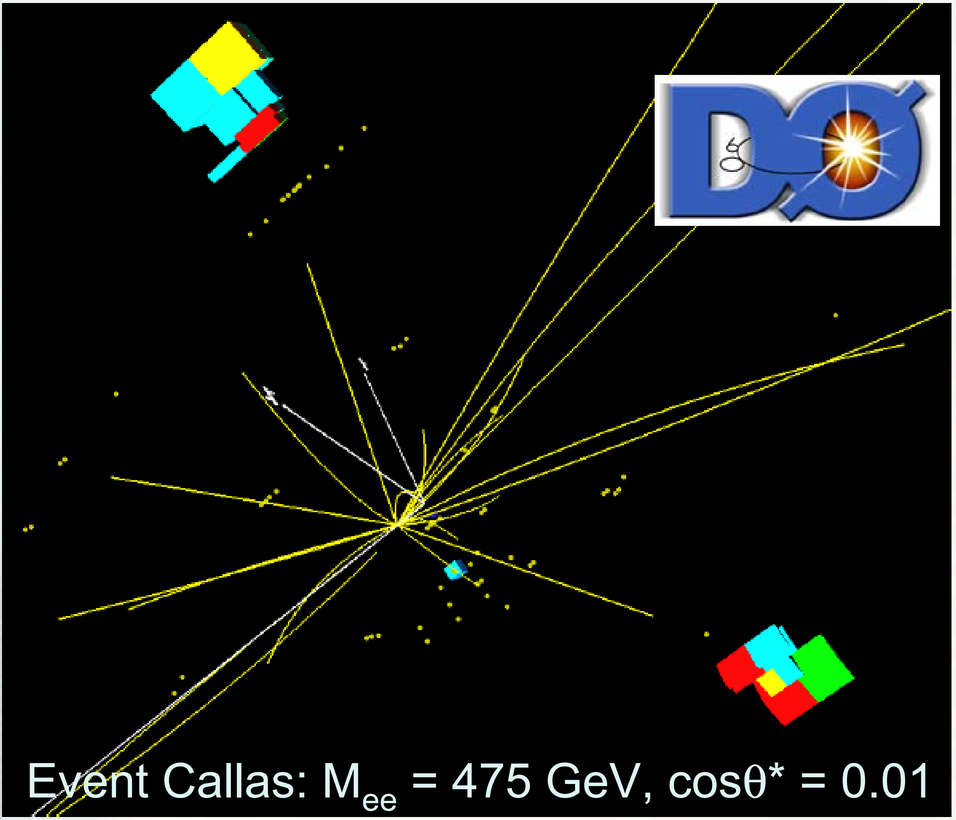


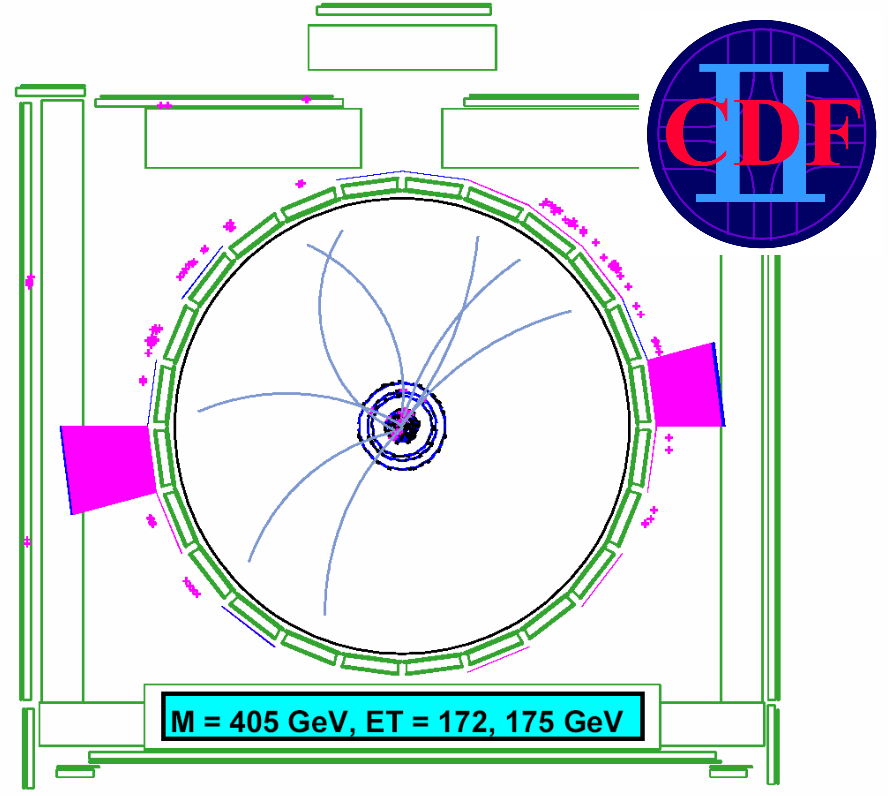




Spectacular Candidate Events

- Two highest-mass candidate events seen by DØ (e^+e^-) and CDF ($\gamma\gamma$)


Event Callas: M_{ee} = 475 GeV, $\cos\theta^*$ = 0.01



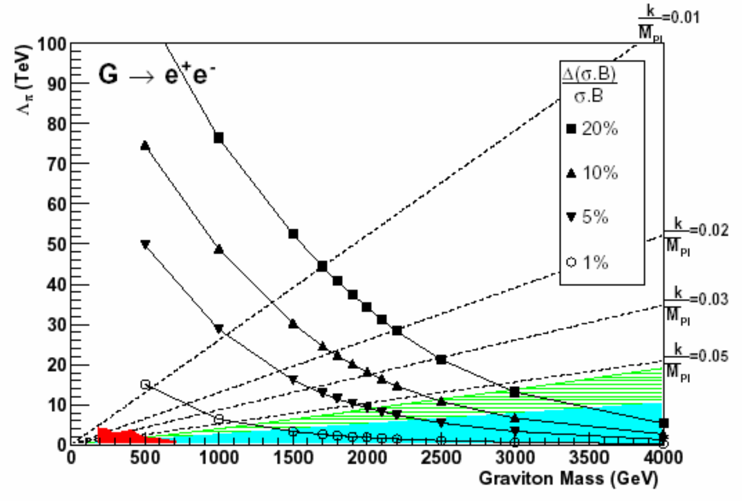
Beyond the Tevatron

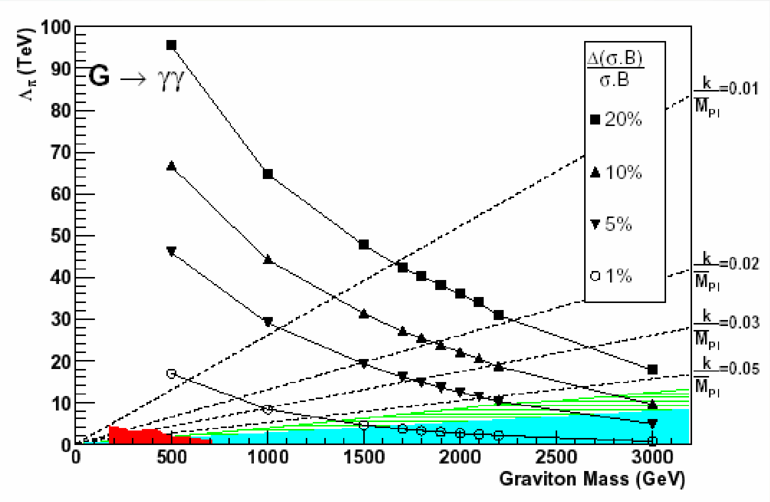
- Independent of whether the first hints of quantum gravity are seen at the Tevatron or not, LHC is the machine to study this physics
  - Sensitivity to M_{Pl} is about factor of five higher
  - Some measurements are completely unique to LHC
  - Qualitatively new physics may open up (e.g. black holes)
  - Signals for quantum gravity (if found) can be established firmly by measuring couplings, energy dependence, spin of the graviton, etc.
  - Most of the allowed model space in various scenarios can be ruled out if no indications for the signal is seen
  - Detailed studies of quantum properties of gravity may be possible

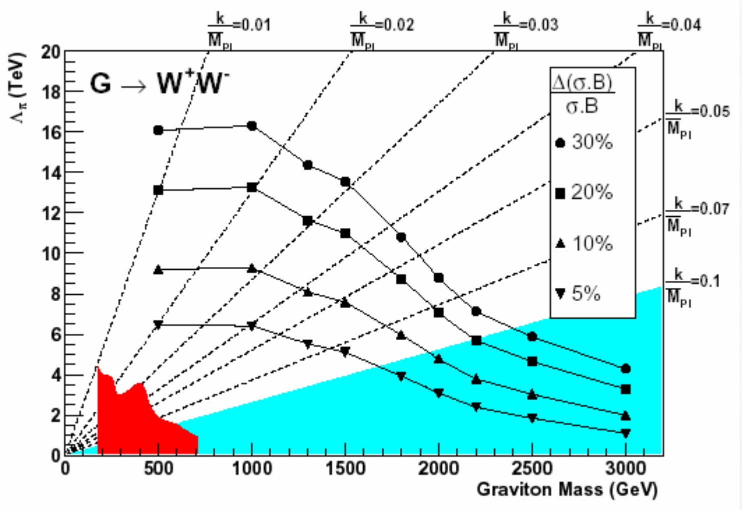
Example: Graviton Couplings

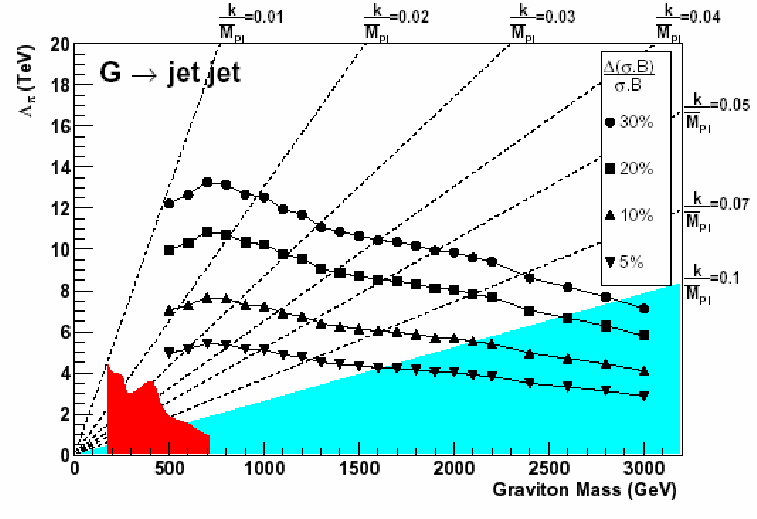
- Universality of couplings is one of the fundamental property of gravity
- Here is what LHC can do in the RS scenario:

[Allanach et al, JHEP 0212, 039 (2002)]



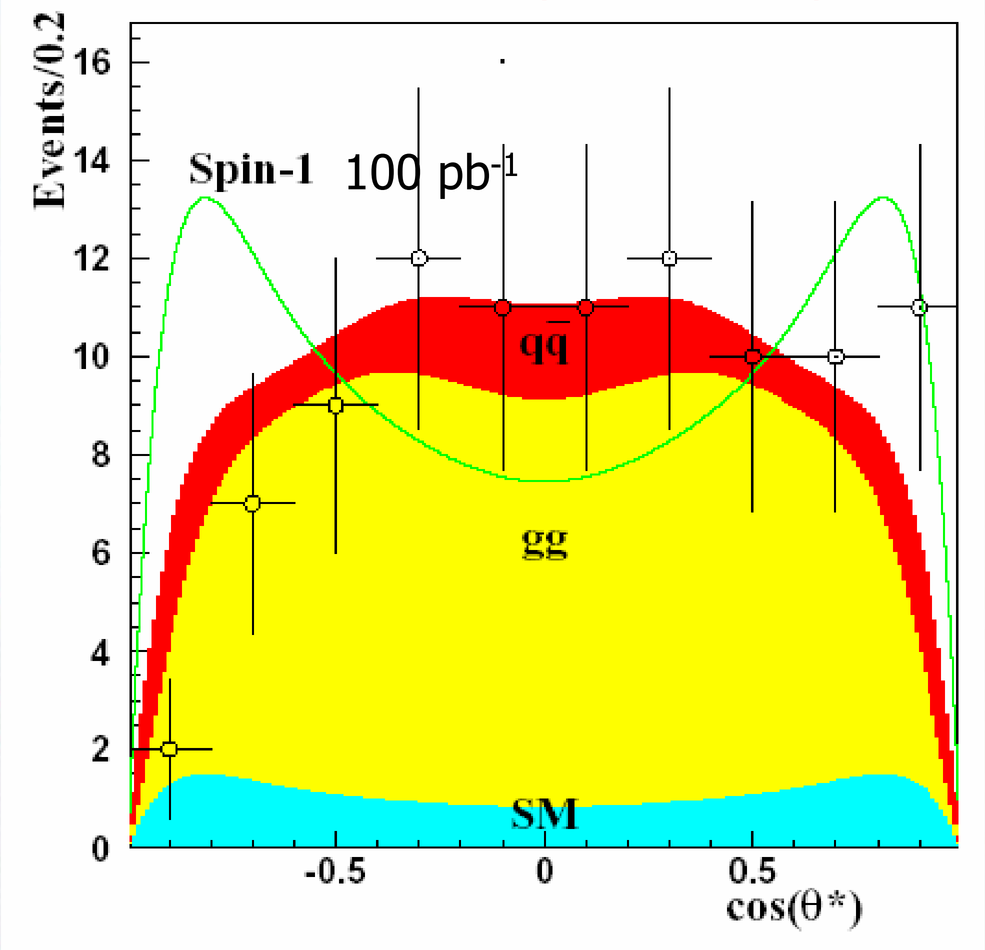






Example: Graviton Spin

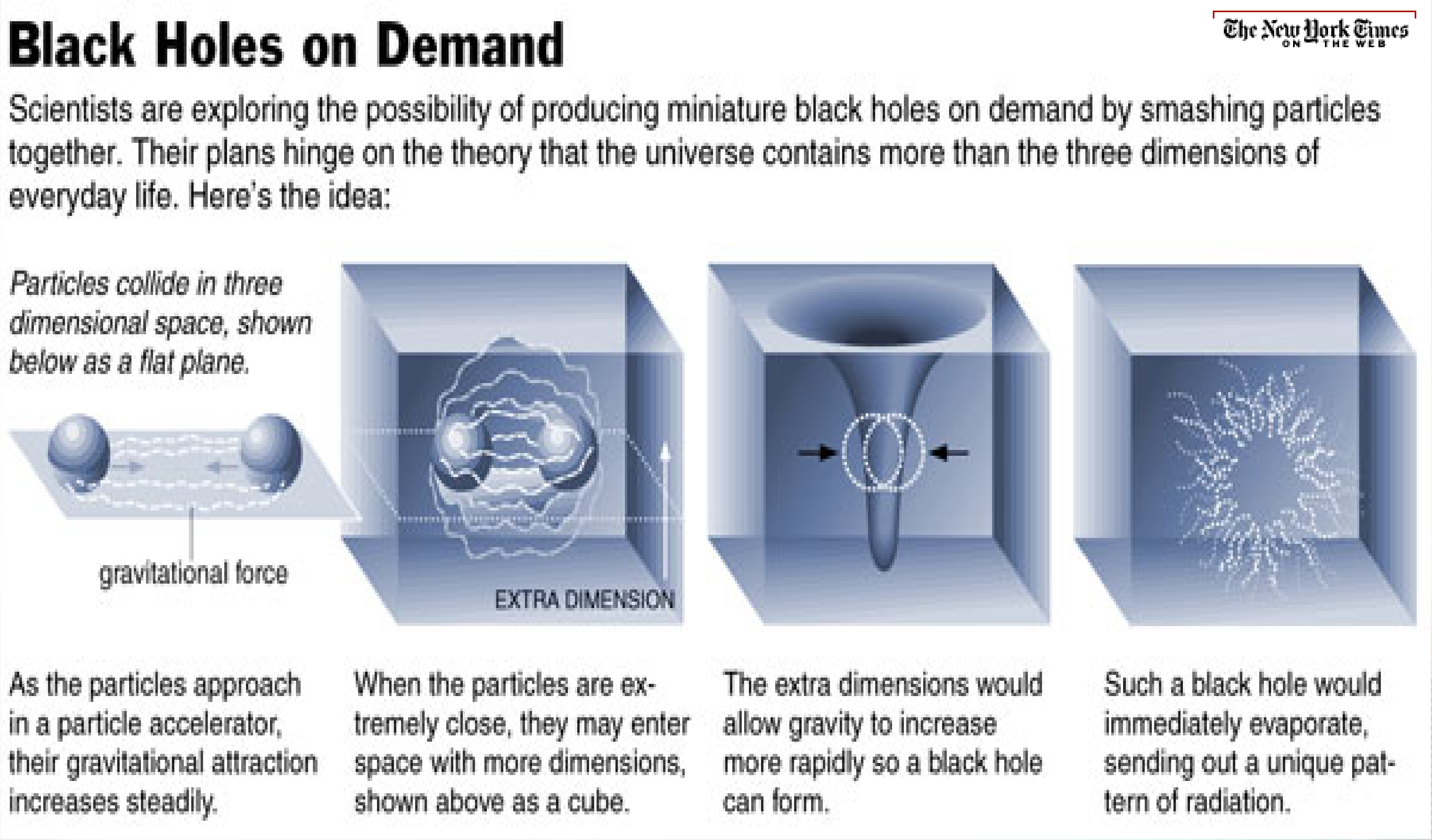
Shown: Randall-Sundrum scenario with M_G = 1.5 TeV
Error bars correspond to 100 pb^{-1}



[Allanach et al., JHEP **0009**, 019 (2000)]

- Establishing the spin-2 nature of the graviton propagator is a unique measurement possible at the LHC
  - Applies both to the Randall-Sundrum and large ED effects

Mother of All Signatures…



Black Holes on Demand

The New York Times ON THE WEB

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.

As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

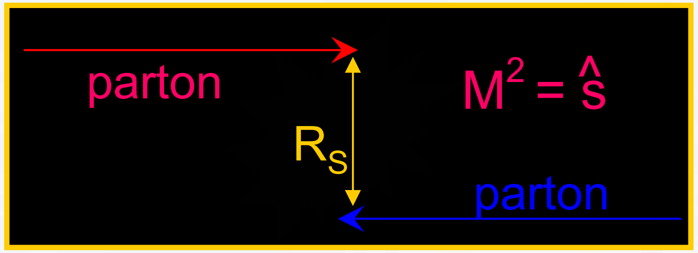
Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

NYT, 9/11/01

Black Hole Production…

- Main idea: when the c.o.m. energy reaches the fundamental Planck scale, a BH is formed; cross section is given by the black disk approximation:

$$\sigma \sim \pi R_S^2 \sim 1\ \text{TeV}^{-2} \sim 10^{-38}\ \text{m}^2 \sim 100\ \text{pb}$$



parton

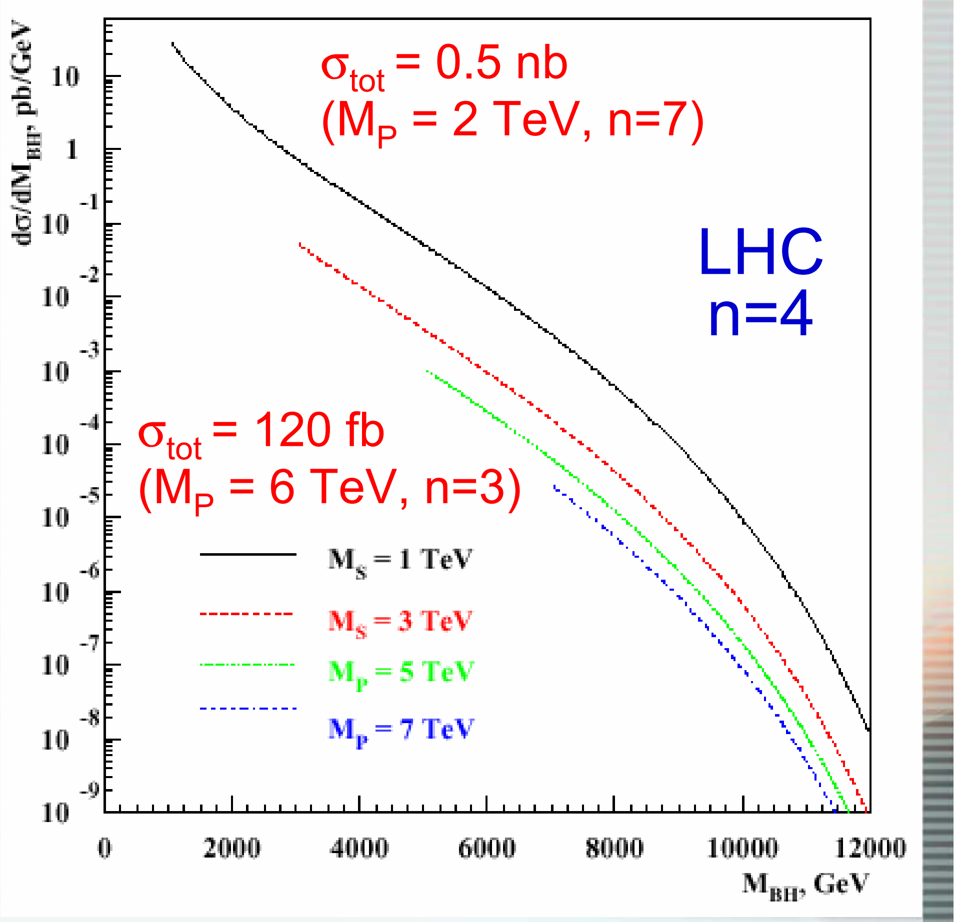
R_S

$M^2 = \hat{s}$

parton

- While we do not have quantum picture of gravity for $M_{BH} \sim M_{Pl}$, certain expectations can be used to predict behavior of near-critical BH (e.g., “democratic” couplings)
- Quantum corrections can be minimized by looking at the proper regime (cf. Planck vs. Raleigh-Jeans behavior in the infrared)

[Dimopoulos, GL, PRL **87**, 161602 (2001)]



$\sigma_{tot} = 0.5$ nb ($M_P = 2$ TeV, n=7)

LHC n=4

$\sigma_{tot} = 120$ fb ($M_P = 6$ TeV, n=3)

… and Decay

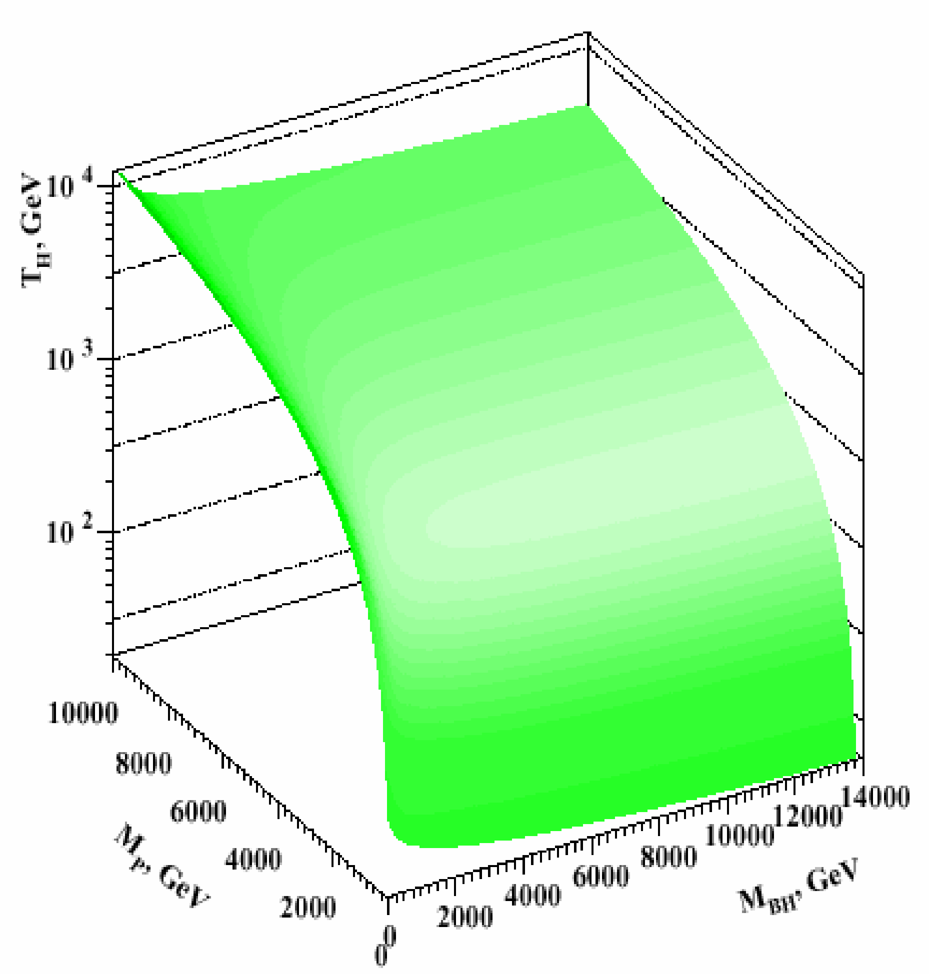
- Once produced, BH evaporates via black-body Hawking radiation
- Hawking temperature:

$$\boxed{R_S T_H = \frac{n+1}{4\pi}}$$

(in natural units $\hbar = c = k = 1$)

- BH radiates mainly on the brane [Emparan/Horowitz/Myers, hep-th/0003118]
- Democratic couplings to ~120 SM d.o.f. yield probability of Hawking evaporation into jets, γ, $l^{\pm}$, and ν ~75%, 2%, 10%, and 5% respectively
- Averaging over the BB spectrum gives average multiplicity of decay products:

$$\boxed{\langle N \rangle \approx \frac{M_{BH}}{2T_H}}$$

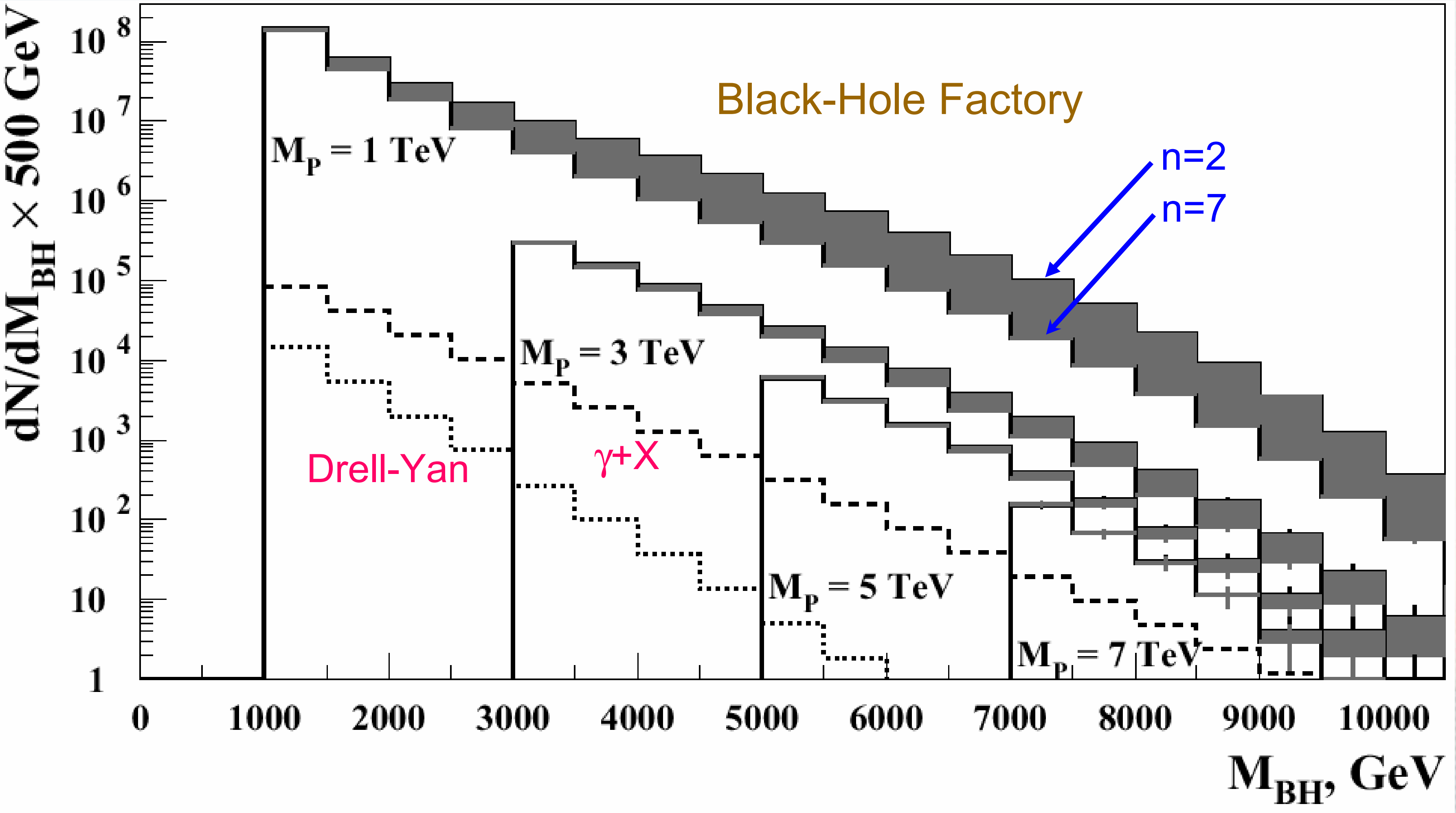


[Dimopoulos, GL, PRL **87**, 161602 (2001)]

- Stefan's law: lifetime $\tau \sim 10^{-26}$ s

Black Hole Factory

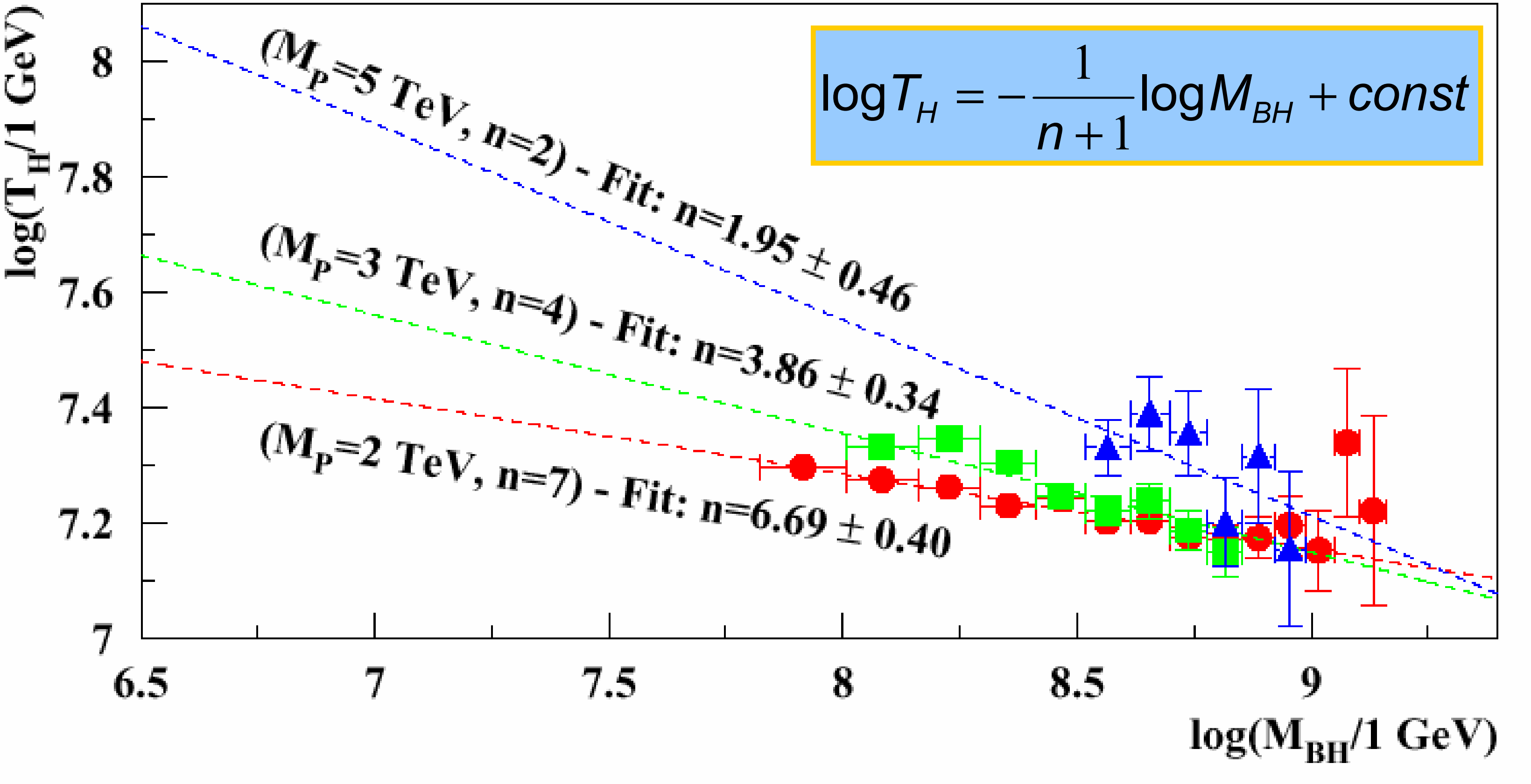
[Dimopoulos, GL, PRL 87, 161602 (2001)]



Spectrum of BH produced at the LHC with subsequent decay into final states tagged with an electron or a photon

Space Texture at the LHC

[Dimopoulos, GL, PRL **87**, 161602 (2001)]

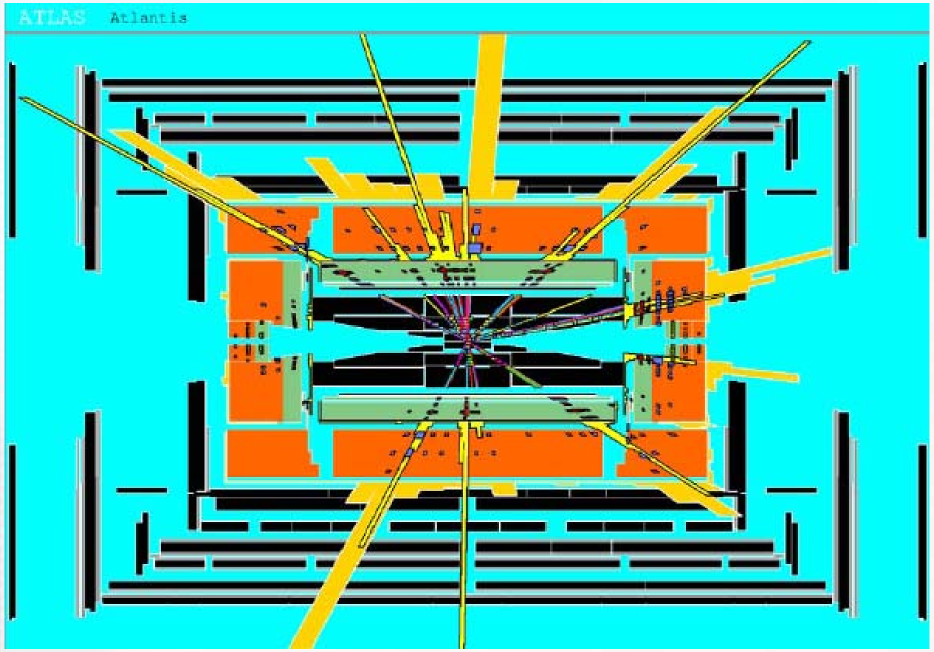


$$\log T_H = -\frac{1}{n+1}\log M_{BH} + const$$

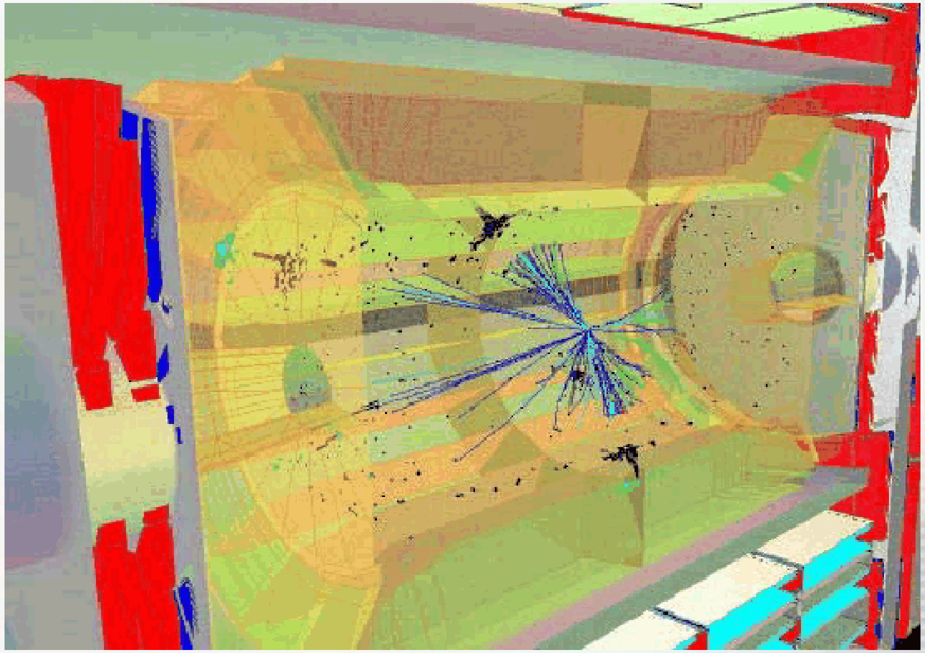
- Relationship between $\log T_H$ and $\log M_{BH}$ allows to find the number of ED
- This result is independent of their sizes and shape!
- This approach differs drastically from other collider signatures and would constitute a “smoking cannon” signature for low-scale (quantum) gravity

Black Hole Events

- First studies have been already initiated by ATLAS and CMS
  - ATLAS – CHARYBDIS HERWIG-based generator with more elaborated decay model [Harris/Richardson/Webber, JHEP **08**, 033 (2003)]
  - CMS – TRUENOIR [Dimopoulos/GL, Snowmass-2001-P321]
- While realistic simulations will be needed, the BH's are really hard to miss, so I'd wait until anything like that is seen first!



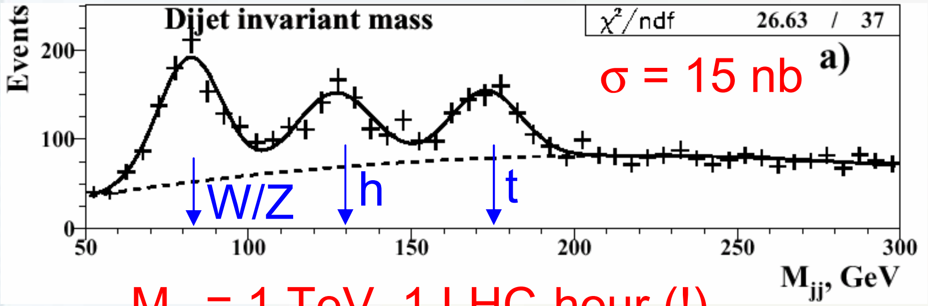
Simulated black hole event in the ATLAS detector [from ATLAS-Japan Group]



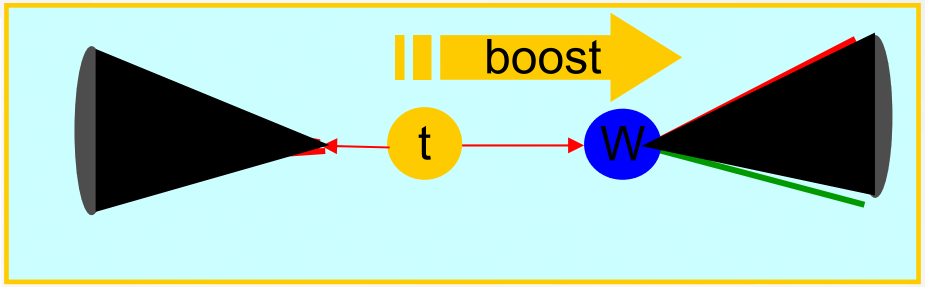
Simulated black hole event in the CMS detector [A. de Roeck & S. Wynhoff]

More Fun with Black Holes

- While we might not know about existence of new particles with masses ~100 GeV, gravity certainly does
- Opens up an alternative way of searching for new particles: in BH decay rather than in prompt production
- Example: Higgs with the mass of 130 GeV decays predominantly into a $b\bar{b}$-pair
- Approach: tag BH events with leptons or photons, and look at the dijet invariant mass; does not even require b-tagging!
- Use a typical LHC detector response to obtain realistic results



M_P = 1 TeV, 1 LHC-hour (!)



[GL, PRL **88**, 181801 (2002)]

- Higgs observation in the black hole decays is possible at the LHC as early as in the first day of running even with the incomplete and poorly calibrated detectors!
- For M_P = 1, 2, 3, and 4 TeV one needs 1 day, 1 week, 1 month, or 1 year of running to find a 5σ signal
- Main conclusion is confirmed by the CMS-specific analysis [Akchurin et al. Fermilab-FN-0752 (2004)]
- Same applies to most of new particles with the mass ~100 GeV

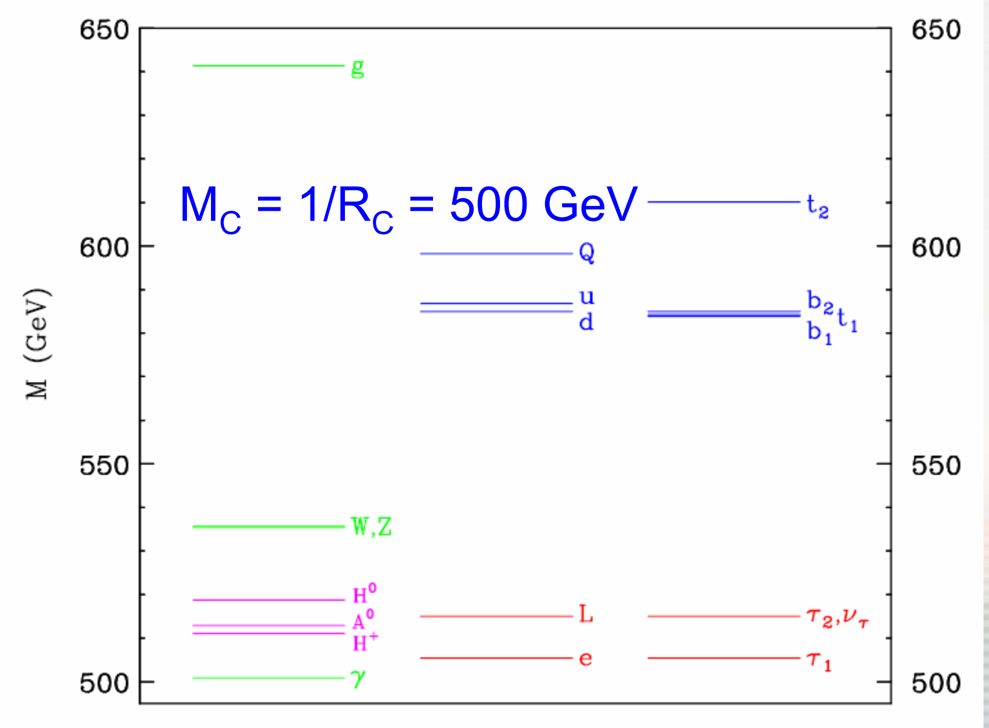
Universal Extra Dimensions

- The most "democratic" ED model: *all* the SM fields are free to propagate in extra dimension(s) with the size $R_c = 1/M_c \sim 1$ TeV^{-1} [Appelquist, Cheng, Dobrescu, PRD **64**, 035002 (2001)]
  - Instead of chiral doublets and singlets, model contains vector-like quarks and leptons
  - Gravity is not included in this model
- The number of universal extra dimensions is not fixed:
  - it's feasible that there is just one (MUED)
  - the case of two extra dimensions is theoretically attractive, as it breaks down to the chiral Standard Model and has nice features, such as guaranteed proton stability, etc.
- Every particle acquires KK modes with the masses $M_n^2 = M_0^2 + M_c^2$, n = 0, 1, 2, …
- Kaluza-Klein number (n) is conserved at the tree level, i.e. $n_1 \pm n_2 \pm n_3 \pm \ldots = 0$; consequently, the lightest KK mode is stable (and serves an excellent dark matter candidate [Cheng, Feng, Matchev, PRL **89**, 211301 (2002)])
- Hence, KK-excitations are produced in pairs, similar to SUSY particles
- Consequently, current limits (dominated by precision electroweak measurements, particularly T-parameter) are sufficiently low ($M_c \sim 300$ GeV for one ED and of the same order, albeit more model-dependent for >1 ED)

UED Phenomenology

- Naively, one would expect large clusters of nearly degenerate states with the mass around $1/R_C$, $2/R_C$, …
- Cheng, Matchev, Schmaltz: not true, as radiative corrections tend to be large (up to 30%); thus the KK excitation mass spectrum resembles that of SUSY!
- Minimal UED model with a single extra dimension, compactified on an S_1/Z_2 orbifold
  - Odd fields do not have 0 modes, so we identify them w/ “wrong” chiralities that vanish in the SM

- Q, L (q, l) are SU(2) doublets (singlets) and contain both chiralities

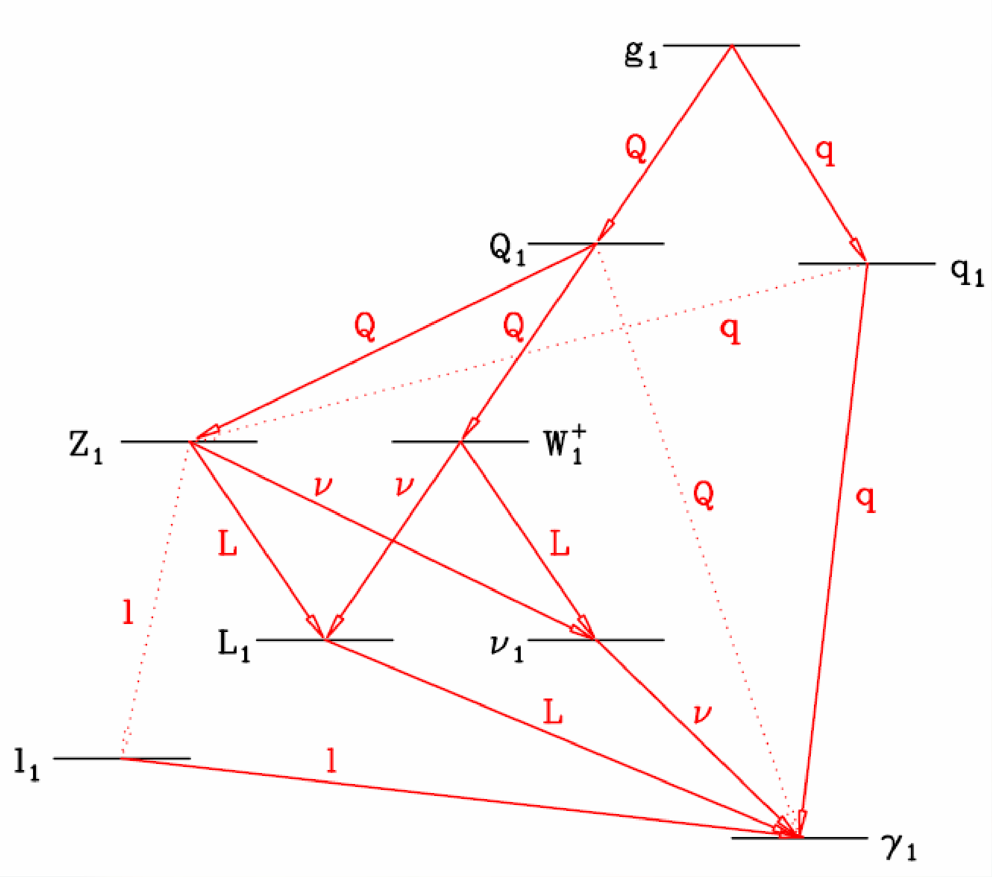


[Cheng, Matchev, Schmaltz, PRD **66**, 056006 (2002)]

SUSY Without SUSY!

- First level KK-states spectroscopy

[Cheng, Matchev, Schmaltz, PRD **66**, 056006 (2002)]



Decay:

$B(g_1 \to Q_1 Q) \sim 50\%$

$B(g_1 \to q_1 q) \sim 50\%$

$B(q_1 \to q\gamma_1) \sim 100\%$

$B(t_1 \to W_1 b,\ H_1^+ b) \sim$

$B(Q_1 \to QZ_1 : W_1 : \gamma_1) \sim 33\%:65\%:2\%$

$B(W_1 \to \nu L_1 : \nu_1 L) = 1/6:1/6$ (per flavor)

$B(Z_1 \to \nu\nu_1 : LL_1) \sim 1/6:1/6$ (per flavor)

$B(L_1 \to \gamma_1 L) \sim 100\%$

$B(\nu_1 \to \gamma_1 \nu) \sim 100\%$

$B(H_1^\pm \to \gamma\gamma_1,\ H^{\pm *}\gamma_1) \sim 100\%$

Production:

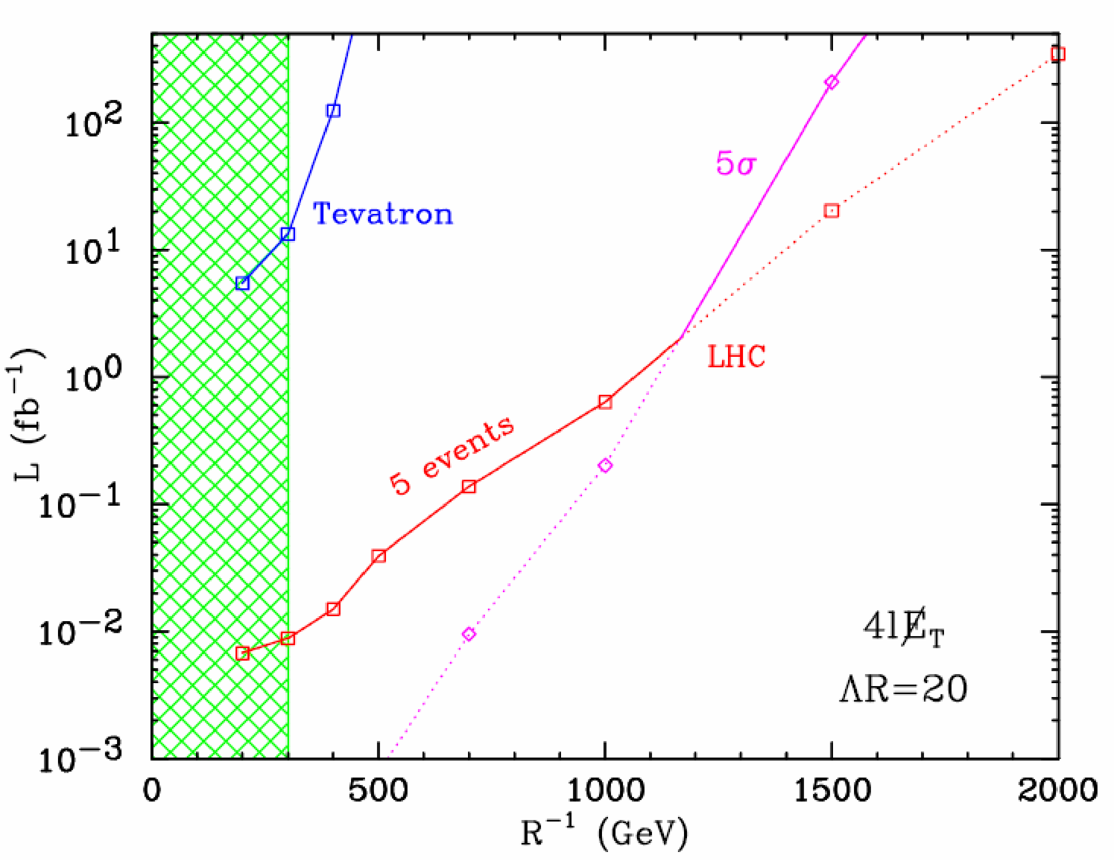
$q_1 q_1 + X \to ME_T$ + jets ($\sim\sigma_{had}/4$); but: low ME_T

$Q_1 Q_1 + X \to V_1 V'_1$ + jets → 2-4 $\ell + ME_T$ ($\sim\sigma_{had}/4$)

Sensitivity in the Four-Lepton Mode

- Only the gold-plated 4-leptons + ME_T mode has been considered in the original paper
- Much more promising channels:
  - dileptons + jets + ME_T + X (x9 cross section)
  - trileptons + jets + ME_T + X (x5 cross section)
- Detailed simulations is required: would love to see this in a MC
- Has not been studied in details neither at the Tevatron, nor at the LHC!

[Cheng, Matchev, Schmaltz, PRD **66**, 056006 (2002)]



L is per experiment (single experiment)

Conclusions

- The Tevatron provides an important input and insight for future searches for quantum gravity effects at the LHC
  - Early understanding of instrumental backgrounds
  - Jet energy scale determination
  - Optimization of ME_T resolution
- However, some inputs could only come from the LHC itself:
  - Real detector performance
  - Accelerator background conditions
  - Constraining gluon PDF's
- Discoveries are unlikely to happen "on day one" – be prepared for a long, possibly bumpy ride, but a thrilling one!
- Nevertheless, an order of magnitude higher energy at the LHC may open doors for qualitatively new physics (e.g. BH!) and lead to surprises very early on
- So, let's build the damn thing and have fun!