Looking for Extra Dimensions and Black Holes with Early LHC Data

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Brown University

LIP/CFTP Seminar

November 10, 2008

Outline

- The Hierarchy Problem
- Models with Extra Dimensions
- Gravity at Short Distances
- Astrophysical Constraints
- Collider Searches for Extra Dimensions
- Black Holes at the LHC
- Conclusions

Large Hierarchies Tend to Collapse...

More Large Hierarchies

Collapse of the Soviet Union

The nineties…

Gravitational Hierarchy Collapse

With thanks to Chris Quigg and the B44 restaurant in San Francisco

- Human Castles in Catalonia

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- Alternative: the *anthropic principle*
  - Properties of the universe are so special because we happen to exist and be able to ask these very questions
  - Not covered in this talk

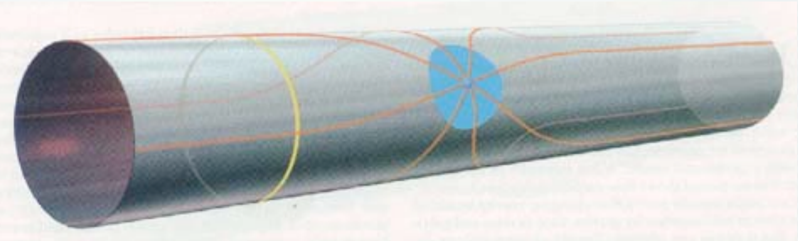
1998: Large Extra Dimensions

- But: what if there is no other scale, and SM model is correct up to M_{Pl}?
  - Give up naturalness: inevitably leads to anthropic reasoning
  - Radically new approach – Arkani-Hamed, Dimopoulos, Dvali (ADD, 1998): maybe the fundamental Planck scale is only ~ 1 TeV?!!
- Gravity is made strong at a TeV scale due to existence of *large* (r ~ 1mm – 1fm) extra spatial dimensions:
  - –SM particles are confined to a 3D "brane"
  - –Gravity is the only force that permeates "bulk" space
- What about Newton's law?

$$V(\rho) = \frac{1}{M_{\rm Pl}^2}\frac{m_1 m_2}{\rho^{n+1}} \to \frac{1}{\left(M_{\rm Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{\rho^{n+1}}$$

- Ruled out for infinite ED, but does not apply for compact ones:

$$V(\rho) \approx \frac{1}{\left(M_{\rm Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^n \rho}, \text{for} \rho \gg r$$



- Gravity is fundamentally strong force, but we do not feel that as it is diluted by the large volume of the bulk space $G'_N = 1/(M_{\rm Pl}^{[3+n]})^2$ = $1/M_D^2$; M_D ~ 1 TeV

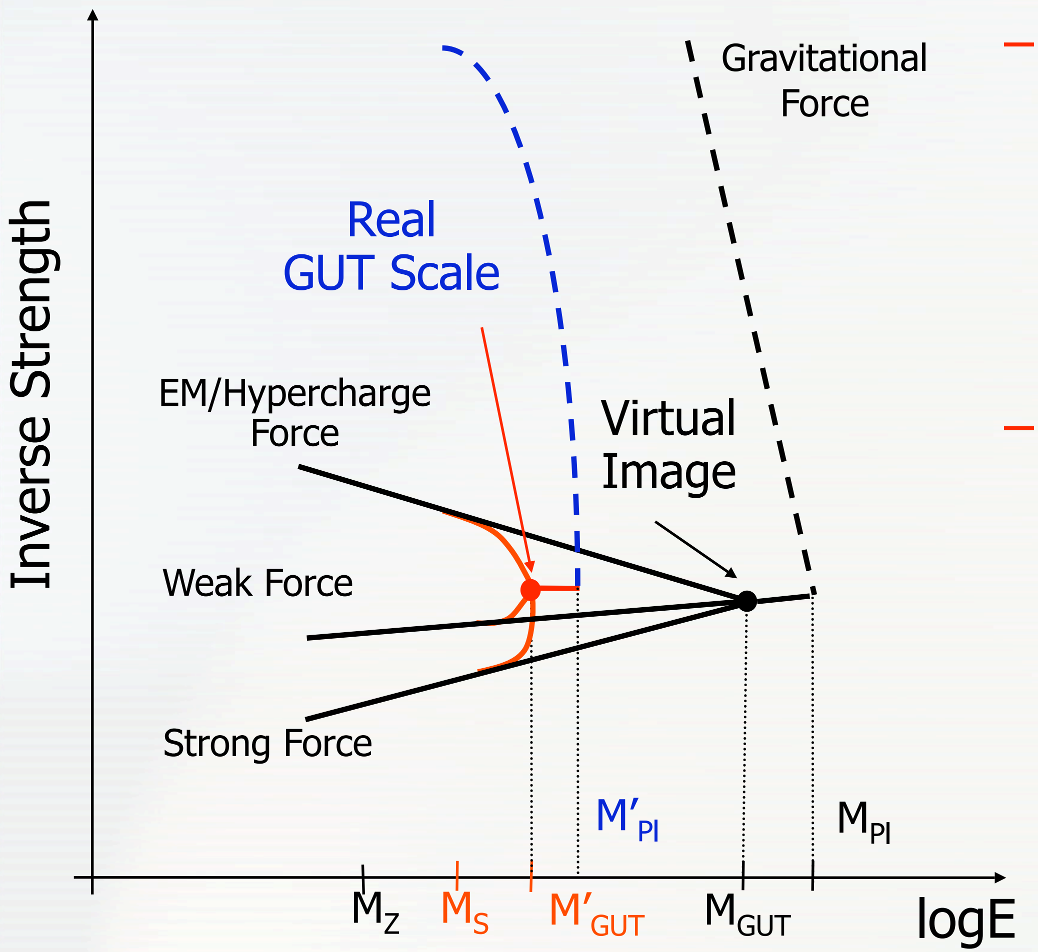
$$M_D^{n+2} \sim M_{\rm Pl}^2/r^n$$

- More precisely, from Gauss's law:

$$r = \frac{1}{\sqrt{4\pi}M_D}\left(\frac{M_{\rm Pl}}{M_D}\right)^{2/n} \sim \begin{cases} 8\times 10^{12} m, & n=1 \\ 0.7mm, & n=2 \\ 3nm, & n=3 \\ 6\times 10^{-12} m, & n=4 \end{cases}$$

- Amazing as it is, but as of 1998 no one has tested Newton's law to distances less than ~ 1mm!
- Thus, the fundamental Planck scale could be as low as 1 TeV for n > 1

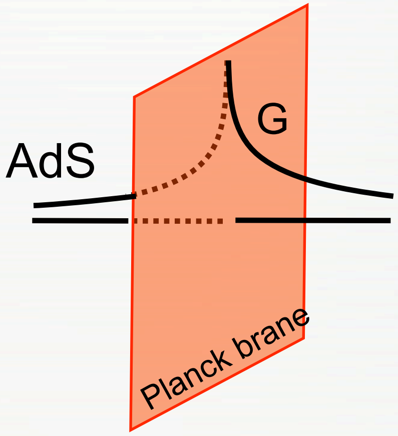
1998: TeV^{-1} Extra Dimensions



- Simultaneously, another idea has appeared:
  - Explore modification of force behavior in (3+n)-dimensions to achieve low-energy grand unification [Dienes, Dudas, Gherghetta, PL **B436**, 55 (1998)]
  - To achieve that, allow other force carriers (g, γ, W, and Z) to propagate in an extra dimension, which is "longitudinal" to the SM brane and compactified on a "natural" EW scale:
    - $R \sim 1\ TeV^{-1} \sim 10^{-19}$ m

1999: Randall-Sundrum Model

- Randall-Sundrum (RS) model [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - –One + brane – no low energy effects
  - –Two + and – branes – TeV Kaluza-Klein modes of graviton
  - –Low energy effects on SM brane are given by Λ_π; for kr ~ 10, Λ_π ~ 1 TeV and the hierarchy problem is solved naturally



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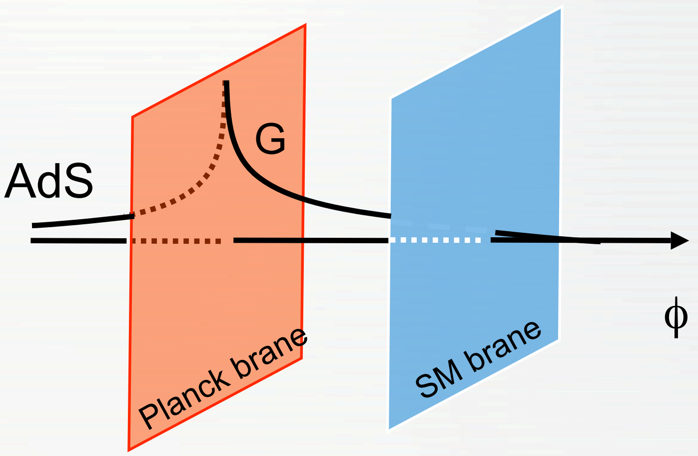

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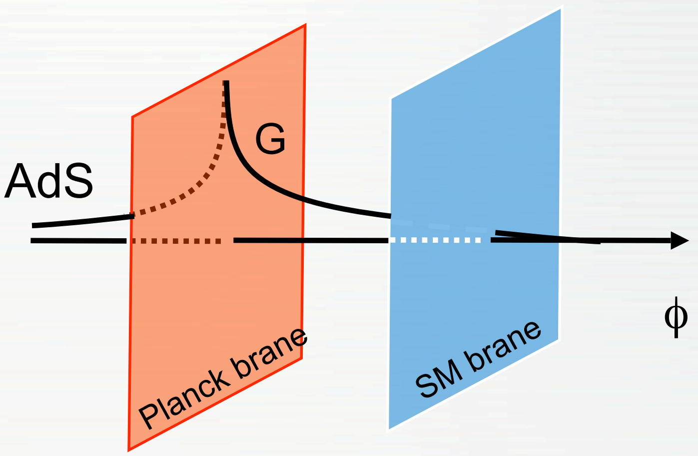
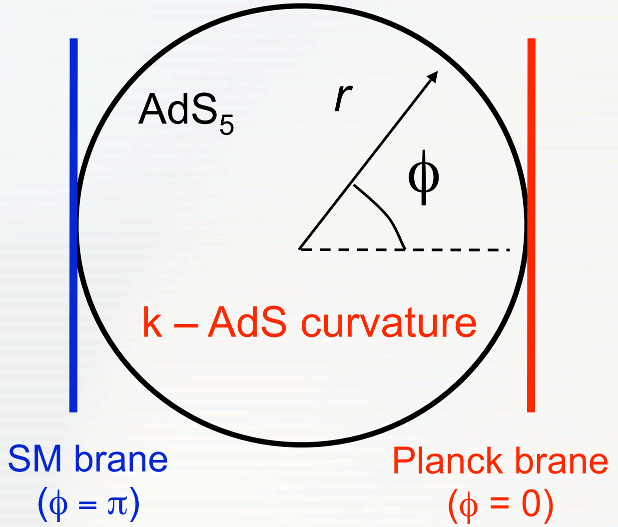




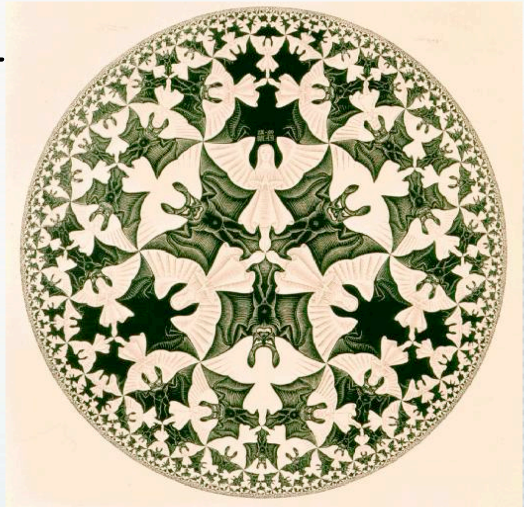
Anti-deSitter space-time metric:

$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$

$$\Lambda_\pi = \overline{M}_{\rm Pl} e^{-kr\pi}$$

Reduced Planck mass:

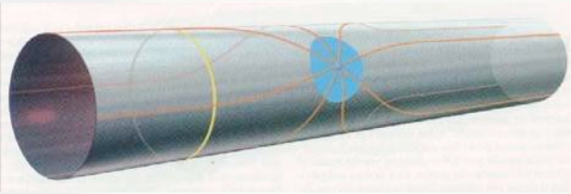
$$\overline{M}_{\rm Pl} \equiv M_{\rm Pl}/\sqrt{8\pi}$$



Extra Dimensions: a Brief Recap

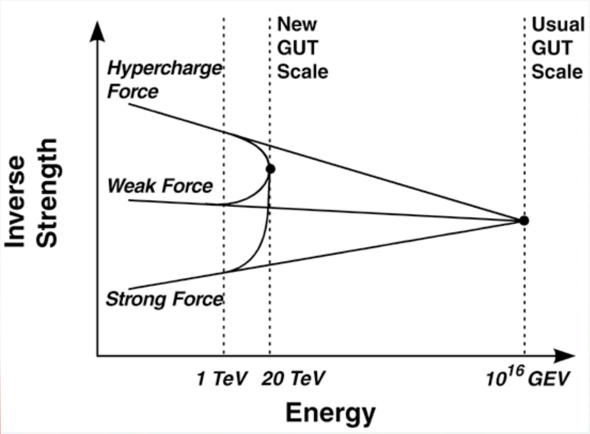
ADD Paradigm:

- 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 and in the UHE cosmic rays
- Con: Doesn't explain why ED are so large



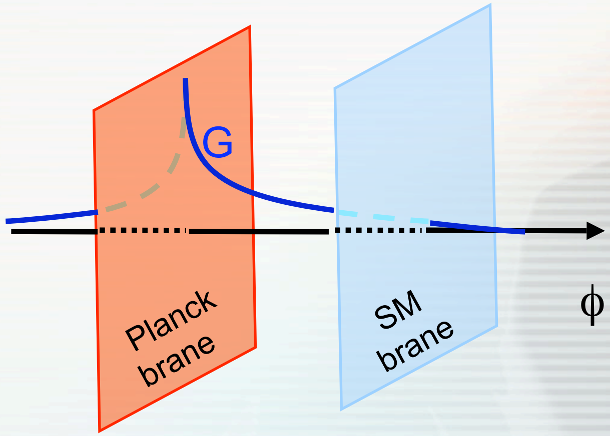
TeV^{-1} Scenario:

- Pro: Lowers GUT scale by changing the running of couplings
- Only gauge bosons (g/γ/W/Z) "live" in ED's
- Size of ED's ~1 TeV^{-1} or ~10^{-19} m – i.e., natural EWSB size
- Con: Gravity is not in the picture



RS Model:

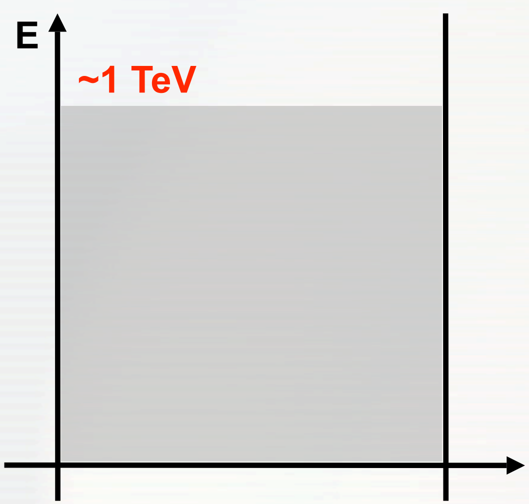
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

ADD Paradigm:

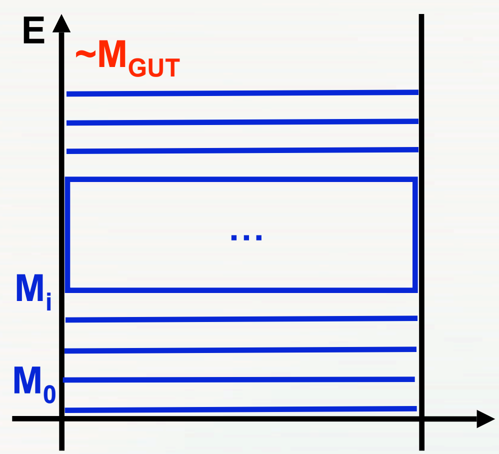
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Experimentally can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



TeV^{-1} Scenario:

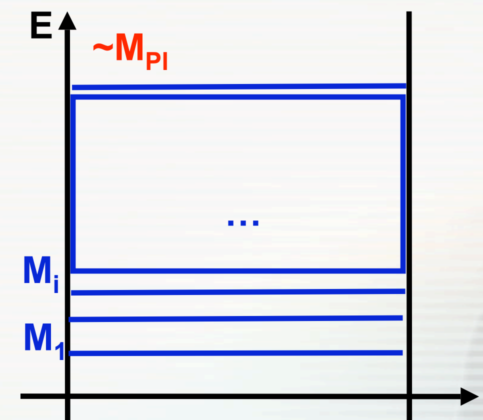
- Winding modes with nearly equal energy spacing ~1/r, i.e. ~ 1 TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: ~g_W per mode

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



RS Model:

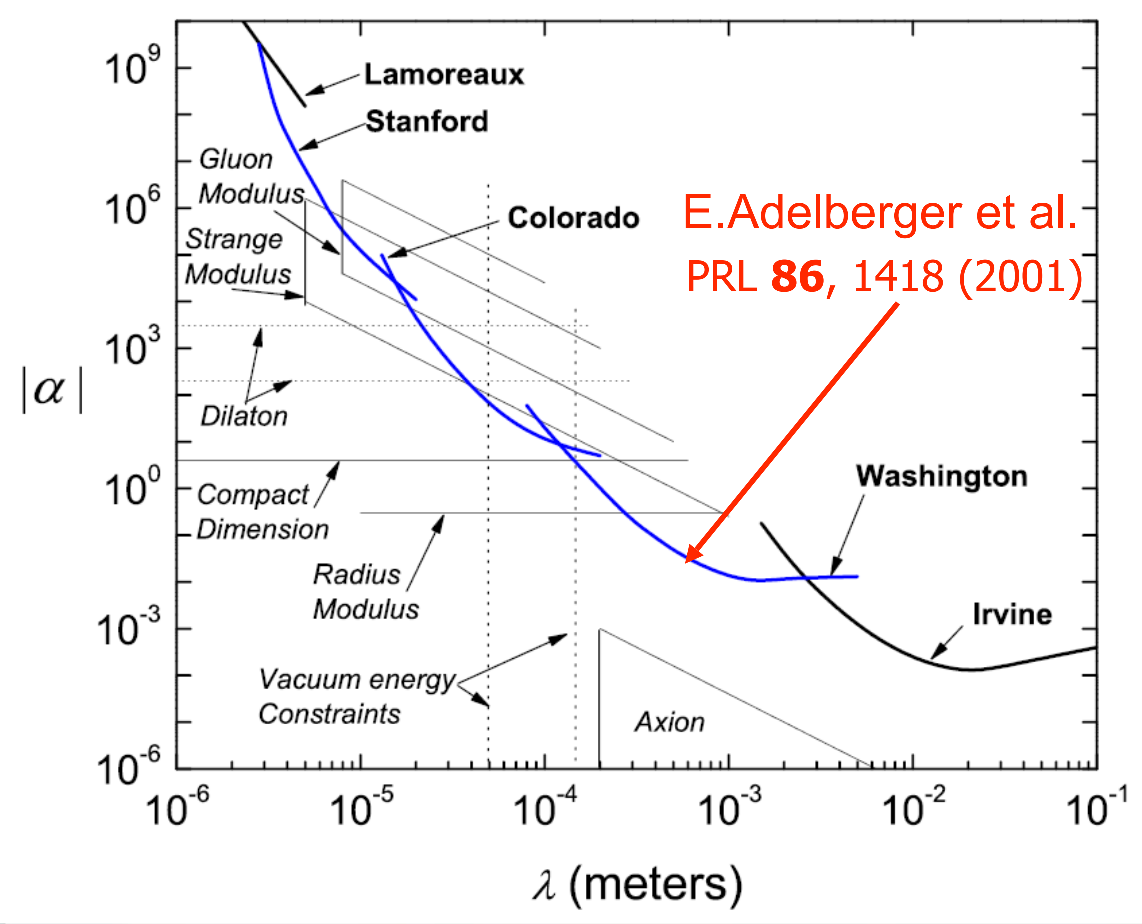
- "Particle in a box" with special AdS metric
- Energy eigenvalues are given by the zeroes of Bessel function J_1
- Light modes might be accessible at colliders
- Coupling: G_N for the zero mode; $1/\Lambda_\pi^2$ for the others



$$M_0 = 0;\ M_i = M_1 \frac{x_i}{x_1} \approx M_1,\ 1.83 M_1,\ 2.66 M_1,\ 3.48 M_1,\ \ldots$$

Large ED: Gravity at Short Distances

[J. Long, J. Price, hep-ph/0303057]



- Sub-millimeter gravity measurements could probe *only* n=2 case *only* within the ADD model
  - The best sensitivity so far have been achieved in the U of Washington torsion balance experiment – a high-tech "remake" of the 1798 Cavendish experiment
    - $R \lesssim 0.16$ mm ($M_D \gtrsim 1.7$ TeV)
- Sensitivity vanishes quickly with the distance – can't push limits further down significantly
  - Started restricting ADD with 2 extra dimensions; can't probe any higher number
  - Ultimately push the sensitivity by a factor of two in terms of the distance
- No sensitivity to the TeV^{-1} and RS models

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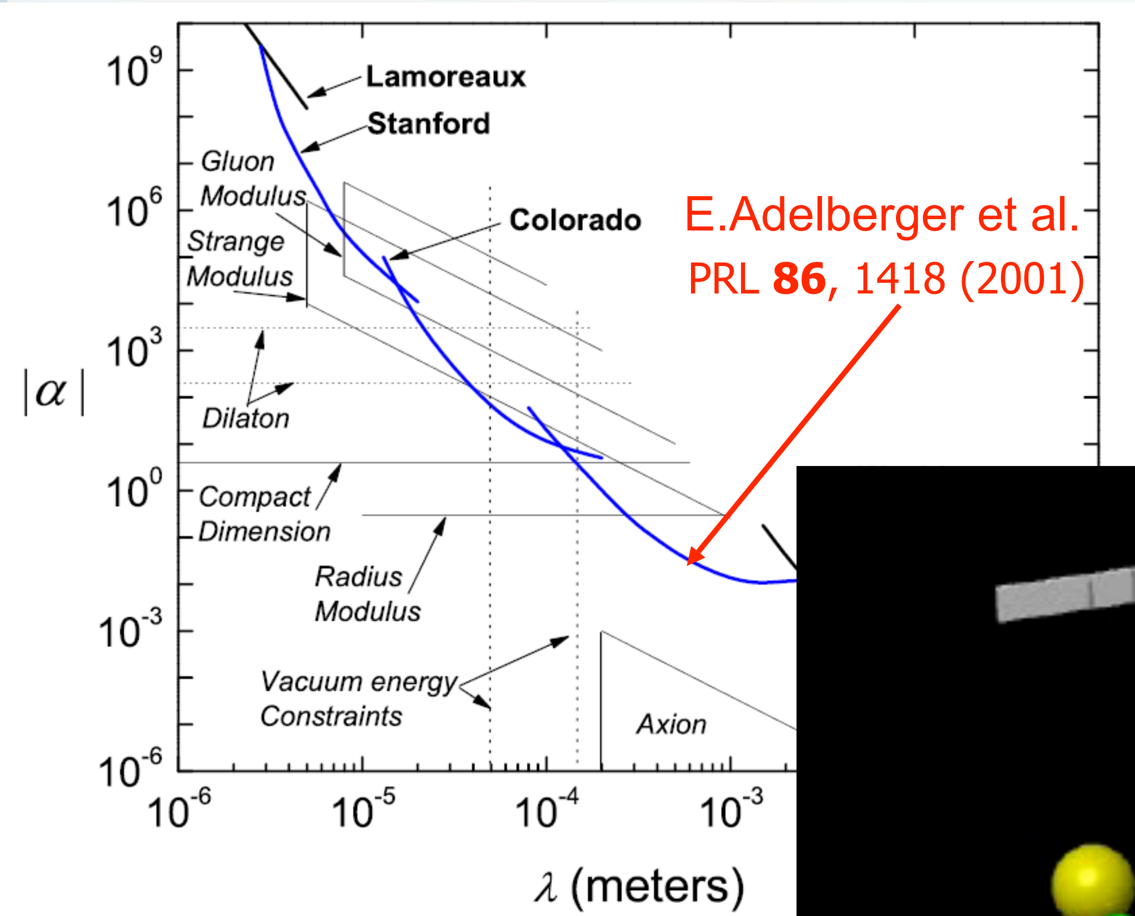

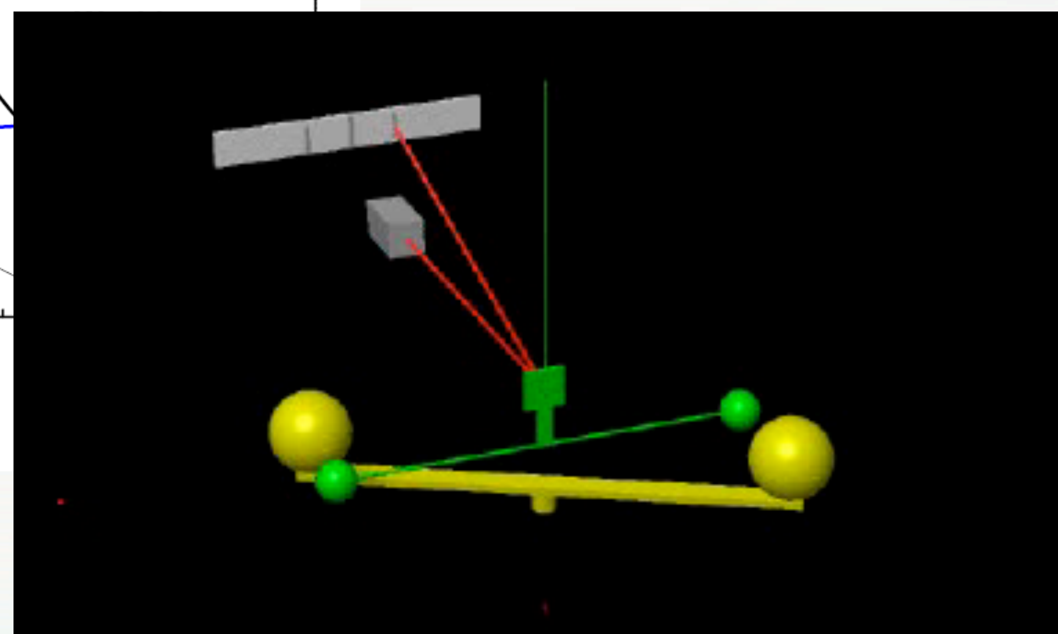

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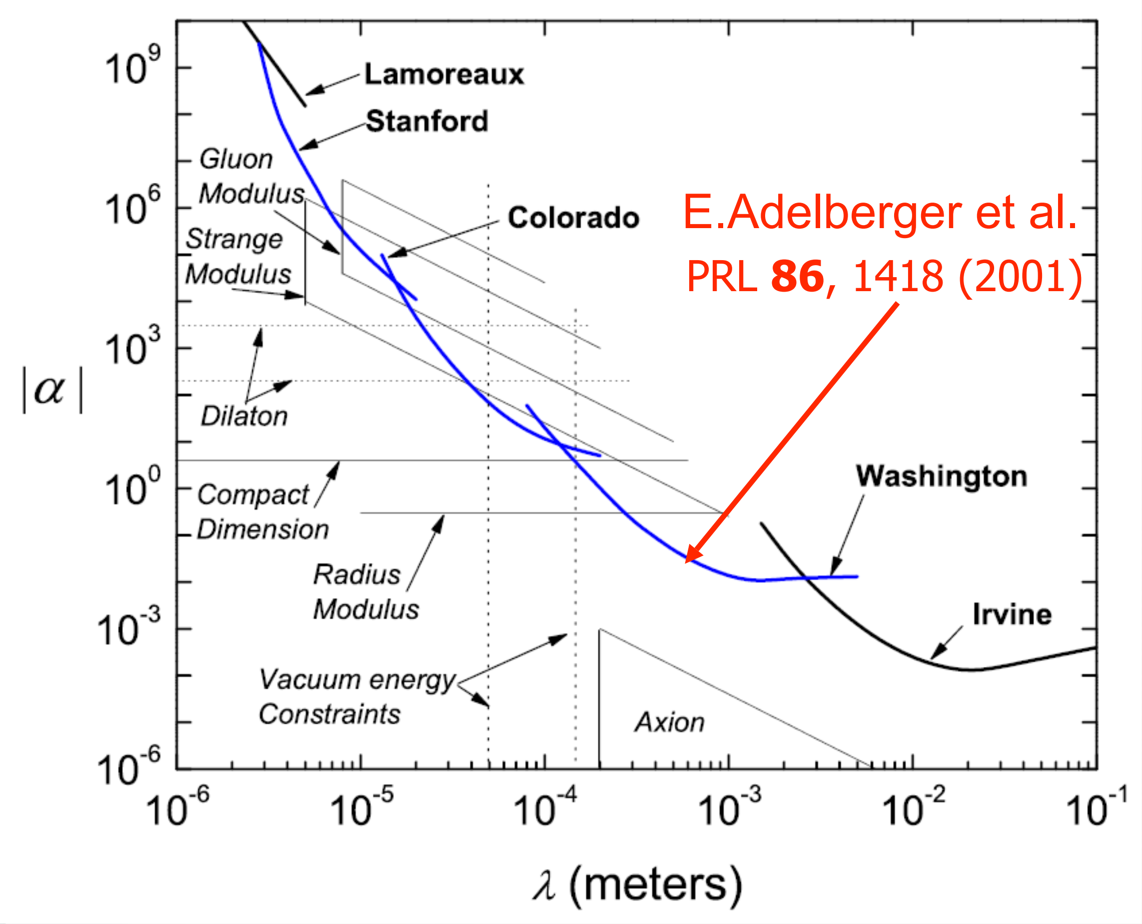

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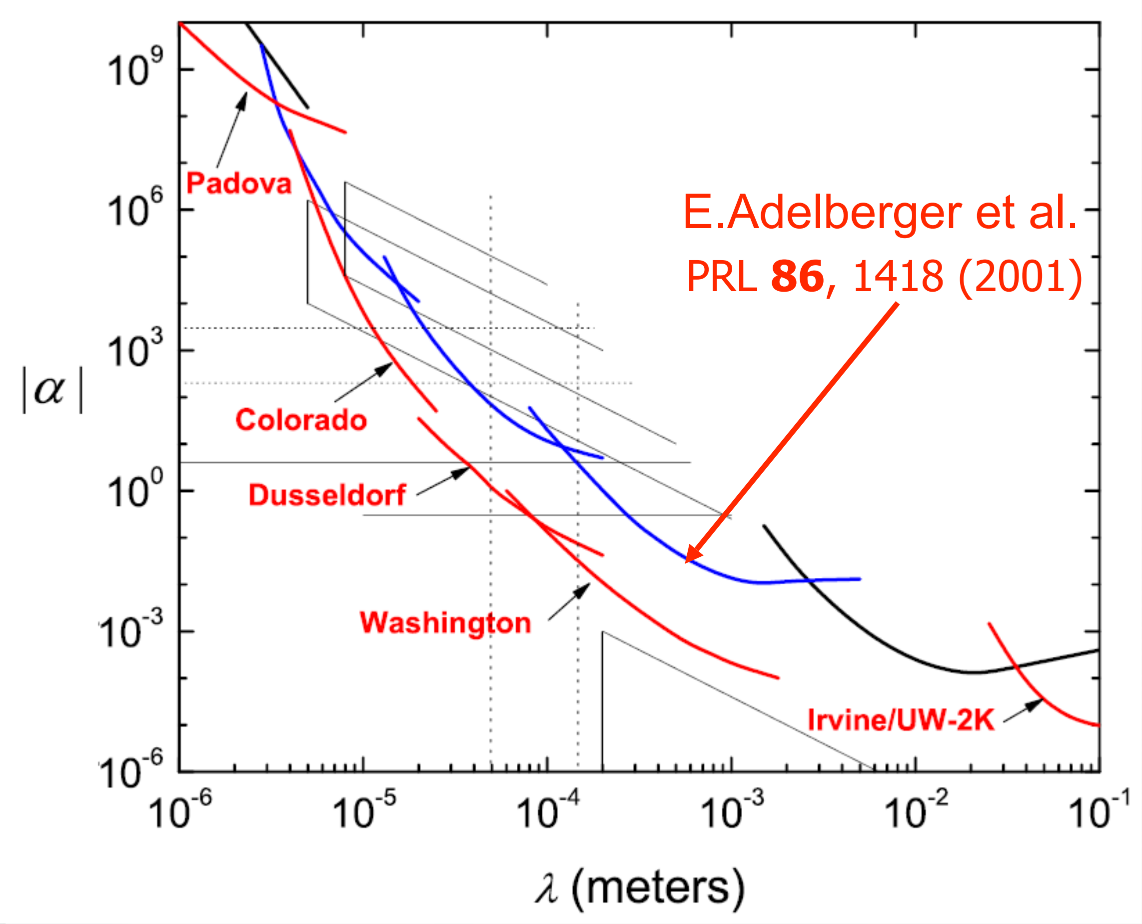

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Large ED: Astro & Cosmo Constraints

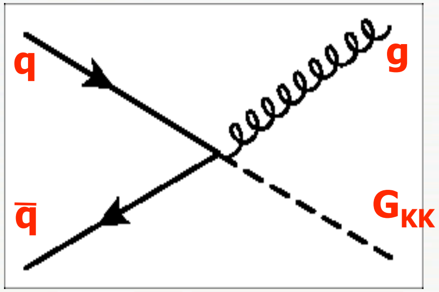
- Supernova cooling due to graviton emission – an alternative cooling mechanism that would decrease the dominant one via neutrino emission
  - Tightest limits on any additional cooling sources come from the measurement of the SN1987A neutrino flux by Kamiokande and IMB
  - Application to the ADD scenario: Cullen and Perelstein [PRL **83**, 268 (1999)]; Hanhart, Phillips, Reddy, and Savage [Nucl. Phys. **B595**, 335 (2001)]:
    - M_D > 25-30 TeV (n=2)
    - M_D > 2-4 TeV (n=3)
- Distortion of the cosmic diffuse gamma radiation (CDG) spectrum due to the $G_{KK} \to \gamma\gamma$ decays: Hall and Smith [PRD **60**, 085008 (1999)]:
  - M_D > 100 TeV (n=2)
  - M_D > 5 TeV (n=3)
- Overclosure of the universe, matter dominance in the early universe, Fairbairn [Phys. Lett. **B508**, 335 (2001)]; Fairbairn, Griffiths [JHEP 0202, **024** (2002)]
  - M_D > 86 TeV (n=2)
  - M_D > 7.4 TeV (n=3)
- Neutron star γ-emission from radiative decays of the gravitons trapped during the supernova collapse, Hannestad and Raffelt [PRL **88**, 071301 (2002)]:
  - M_D > 1700 TeV (n=2)
  - M_D > 60 TeV (n=3)
- Caveat: there are many known (and unknown!) uncertainties, so the cosmological bounds are reliable only as an order of magnitude estimate
- Still, n=2 is largely disfavored

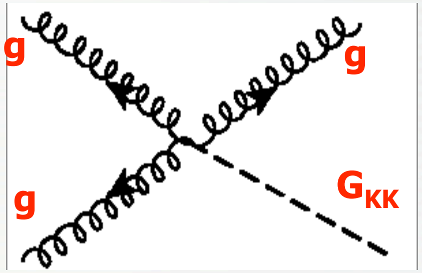
Collider Signatures for Large ED

- 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)]
- Graviton emission: direct sensitivity to the fundamental Planck scale M_D
- Virtual effects: sensitive to the ultraviolet cutoff M_S, expected to be $\sim M_D$ (and likely $< M_D$)
- The two processes are complementary

Real Graviton Emission

Monojets at hadron colliders





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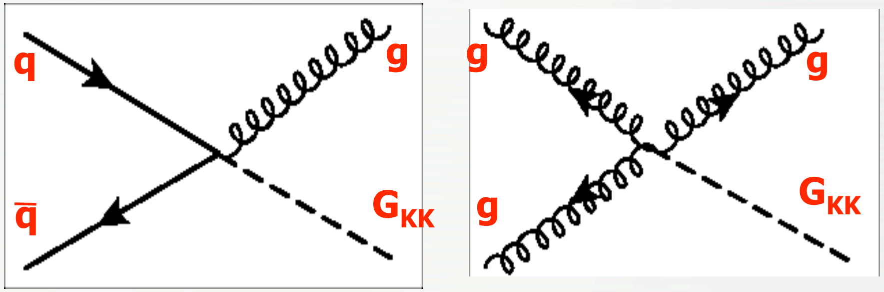
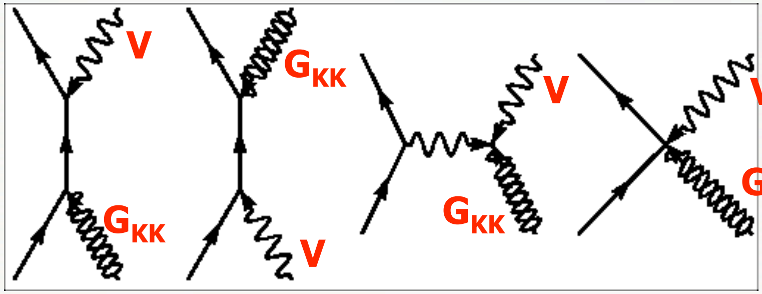


Single VB at hadron or e^+e^- colliders



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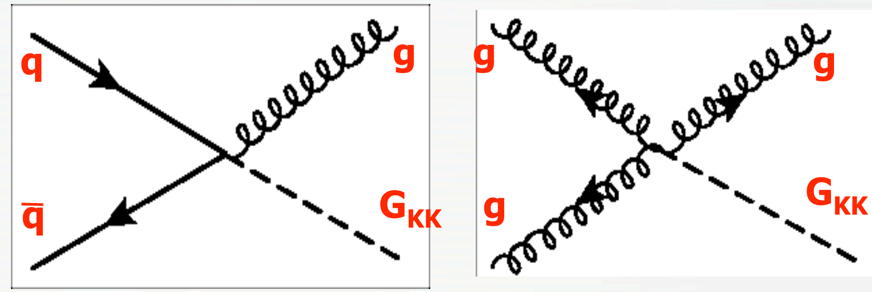

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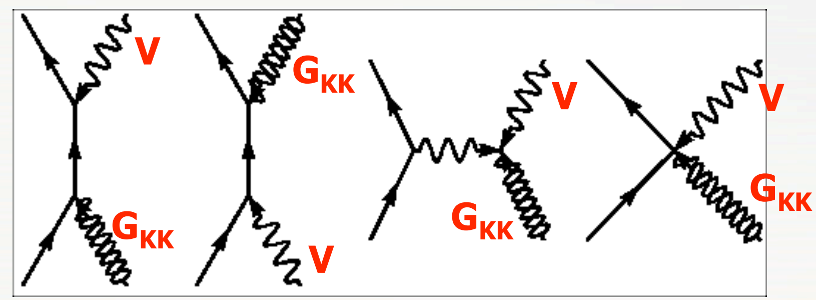
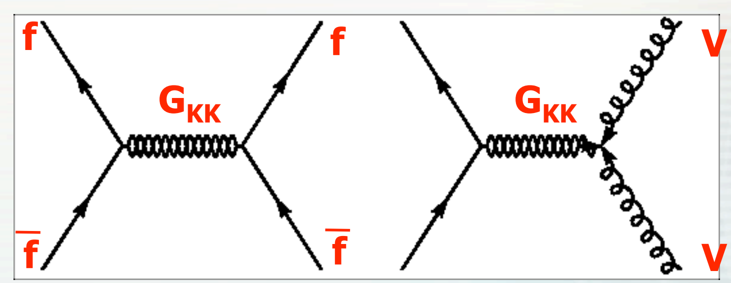


Virtual Graviton Effects

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



L'EPilogue (Large ED)

Direct Graviton Emission

Experiment	$e^+e^- \to \gamma G$ n=2	n=3	n=4	n=5	n=6	$e^+e^- \to ZG$ n=2	n=3	n=4	n=5	n=6	Color coding
ALEPH	1.28	0.97	0.78	0.66	0.57	0.35	0.22	0.17	0.14	0.12	≤184 GeV
DELPHI	1.38	**1.02**	0.84	**0.68**	0.58						≤189 GeV
L3	1.02	0.81	0.67	0.58	0.51	0.60	0.38	0.29	**0.24**	**0.21**	>200 GeV
OPAL	1.09	0.86	0.71	0.61	0.53						λ=-1 λ=+1 **GL**

All limits are in TeV

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		1.0/1.1 (<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 TeV

Monojets: Tainted History

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

[PL, **139B**, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland

Abstract

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

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UA1 Collaboration, CERN, Geneva, Switzerland

Abstract

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

Monojets: Tainted History

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

[PL, **139B**, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland

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Monojets from *Z* Decay without Extra Neutrinos or Higgs Particles

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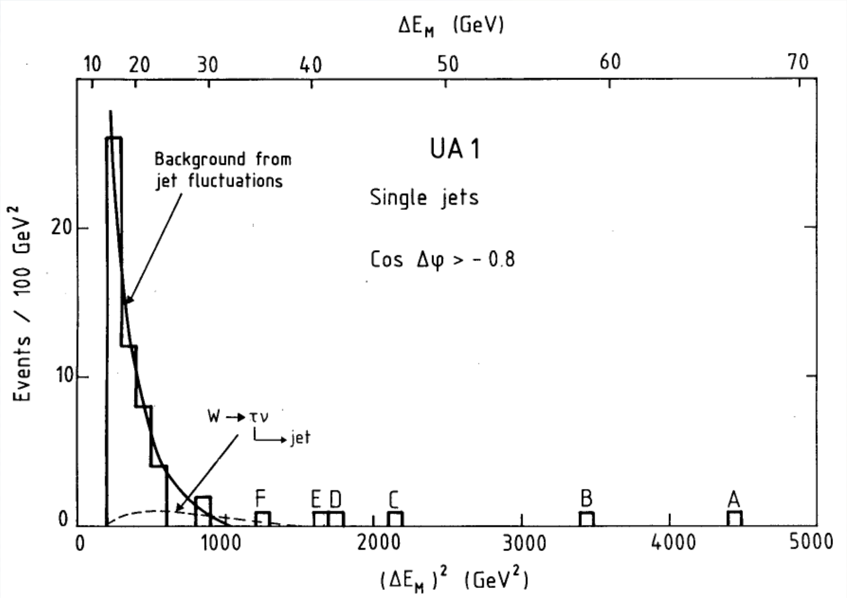
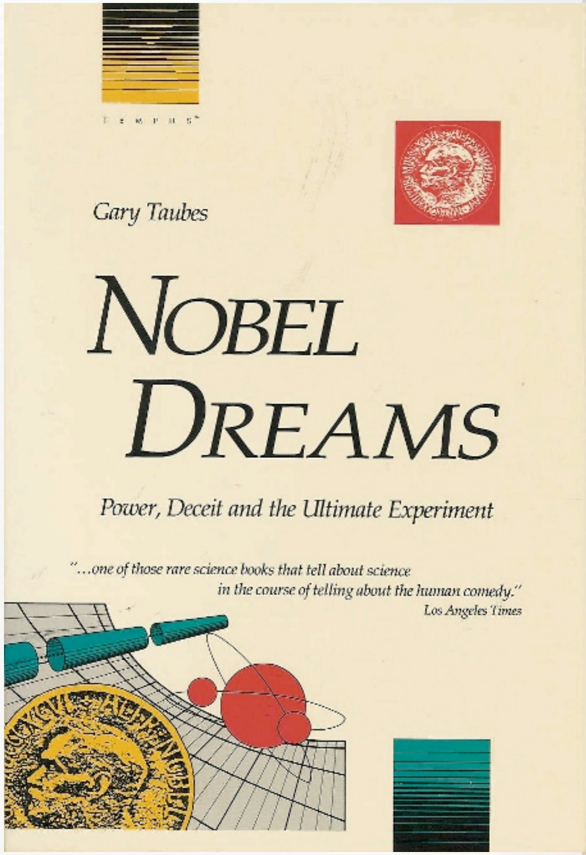
(Received 26 November 1984)

The recent discovery of monojets by Arnison *et al.*[1] at the CERN $p\bar{p}$ collider has caused ripples of excitement throughout the particle physics world, since they cannot be explained by the minimal standard model.[2]

Monojets: Tainted History

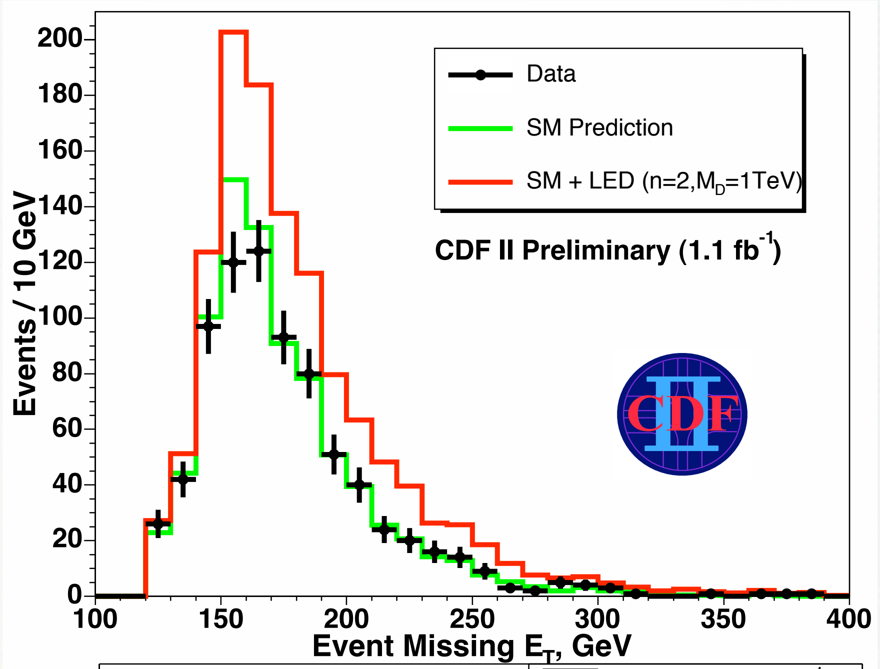


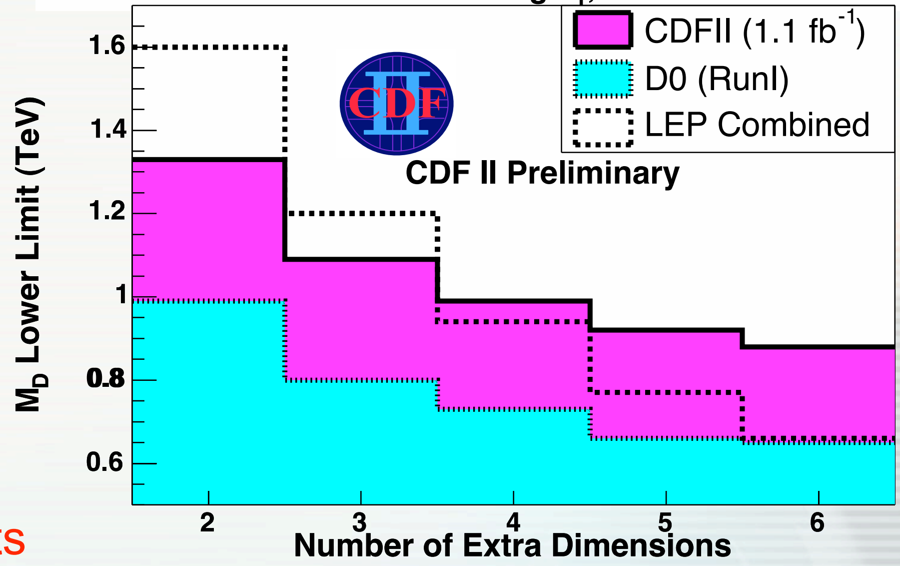


- These monojets turned out to be due to unaccounted background
- The signature was deemed doomed and nearly forgotten
- It took many years for successful monojet analyses at a hadron collider to be completed (CDF/DØ)

Tevatron: Large ED Search via Monojets

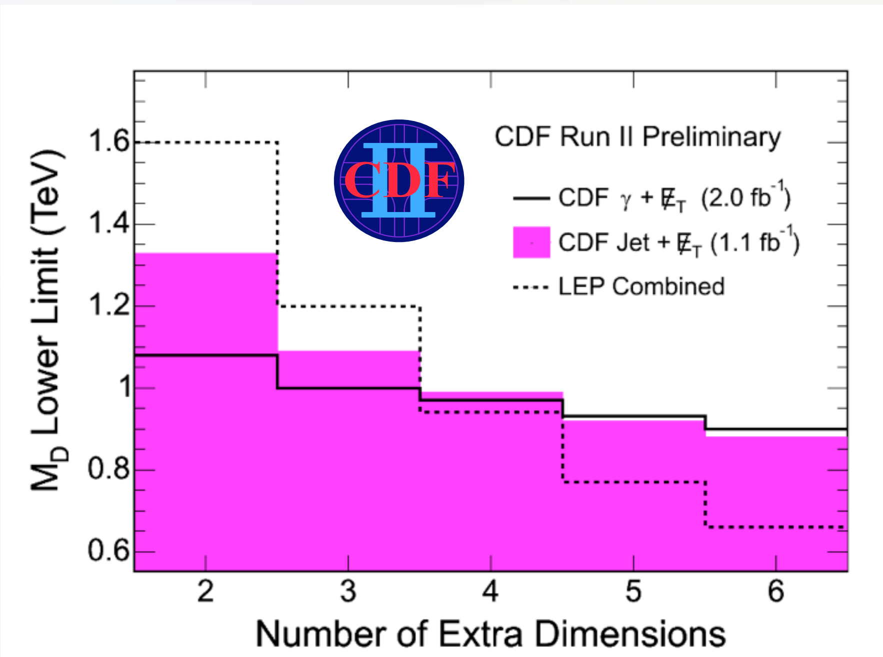
- jets + ME_T final state
- Z(νν)+jets is irreducible background
  - Challenging signature due to large instrumental backgrounds from jet mismeasurement, cosmics, etc.
- DØ pioneered this search and set limits [PRL, **90** 251802 (2003)] M_P > 1.0-0.6 TeV for n=2…7
- CDF analysis based on 1.1 fb^{-1}
  - Central jet w/ E_T > 150 GeV
  - ME_T > 120 GeV
  - No other jets w/ E_T > 60 GeV
  - 779 events observed with 819 ± 71 expected (half comes from Z(νν)+j)
  - Set limits on the fundamental Planck scale between 0.88 and 1.33 TeV
  - Similar results with looser ME_T, E_T^j cuts

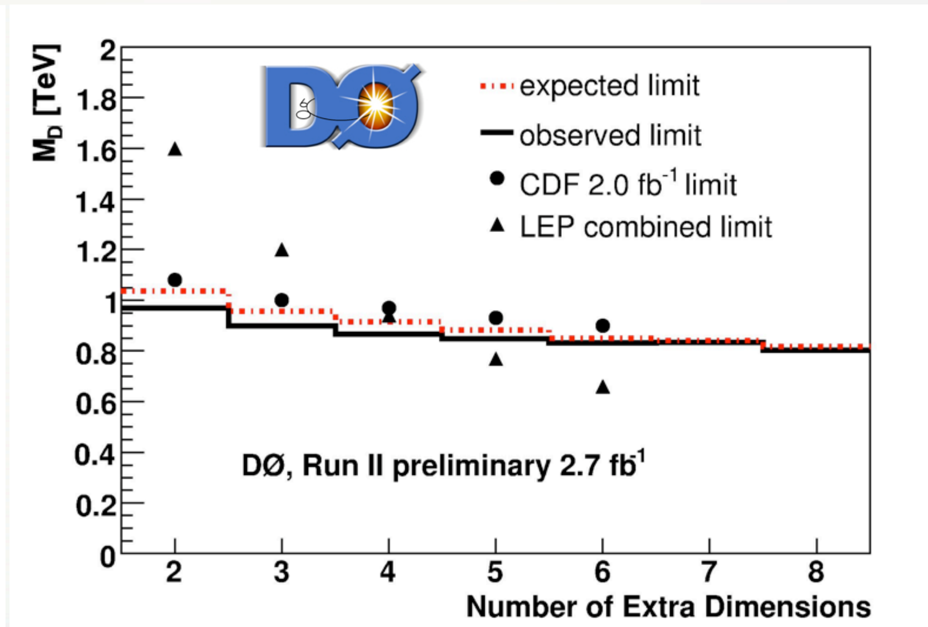




Tevatron Searches for ED in Monophotons

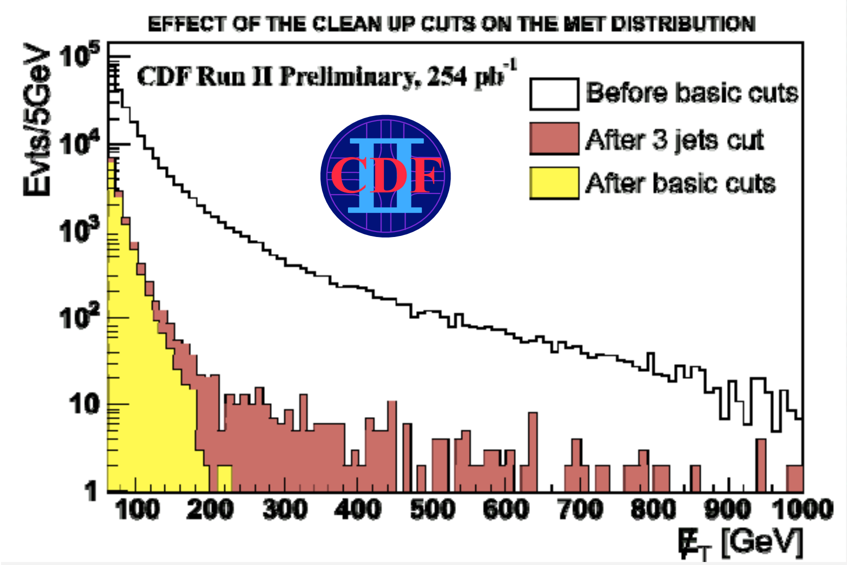
- Both CDF and DØ completed monophoton searches
- While easier than the monojet one, the sensitivity is typically not as good, especially for low number of ED
  - CDF monophoton limits approach monojet ones at large n, but require twice the luminosity

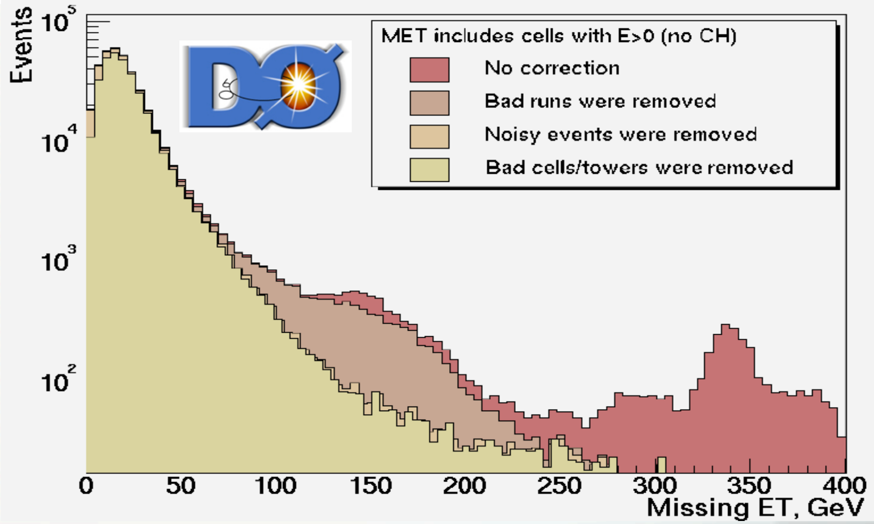




Why ME_T is Tough?

- Fake ME_T appears naturally in multijet events, which have enormous rate at the LHC
- Jets tend to fluctuate wildly:
  - Large shower fluctuation
  - Fluctuations in the e/h energy ratio
  - Non-linear calorimeter response
  - Non-compensation (i.e., $e/h \neq 1$)
- Instrumental effects:
  - Dead or "hot" calorimeter cells
  - Cosmic ray bremsstrahlung
  - Poorly instrumented area of the detector
- Consequently, it will be a challenge to use in early LHC running
- Nevertheless, ME_T is one of the most prominent signatures for new physics and thus must be pursued

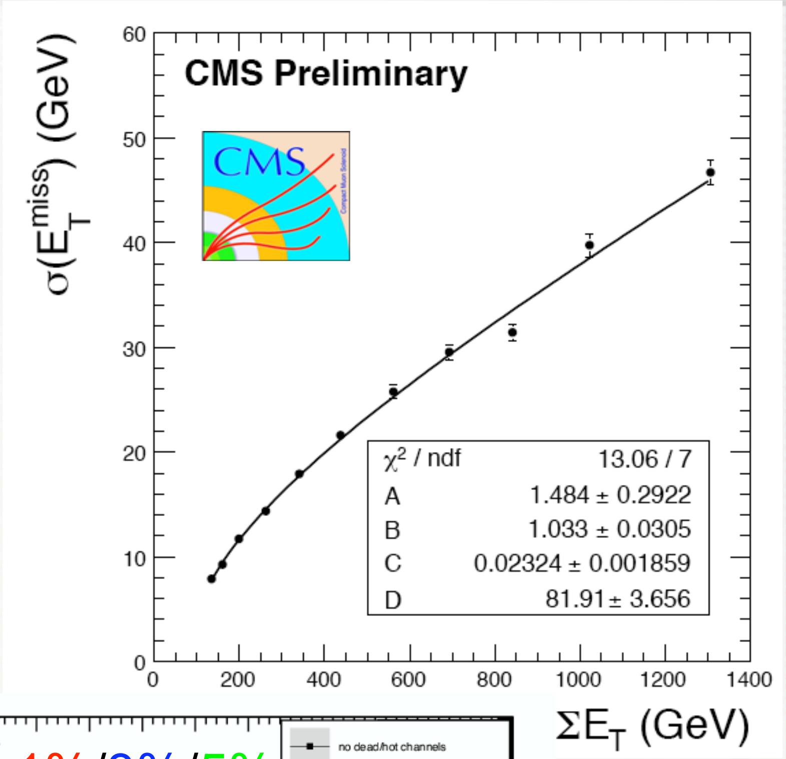


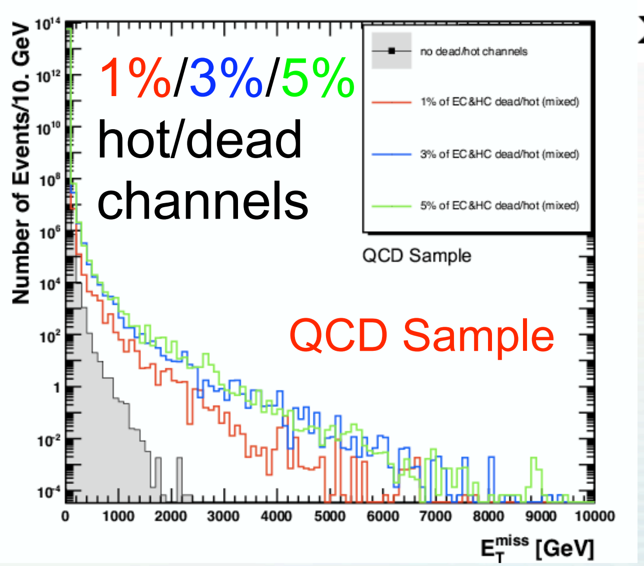


- Raw ME_T spectrum at the Tevatron and that after thorough clean-up

ME_T in CMS

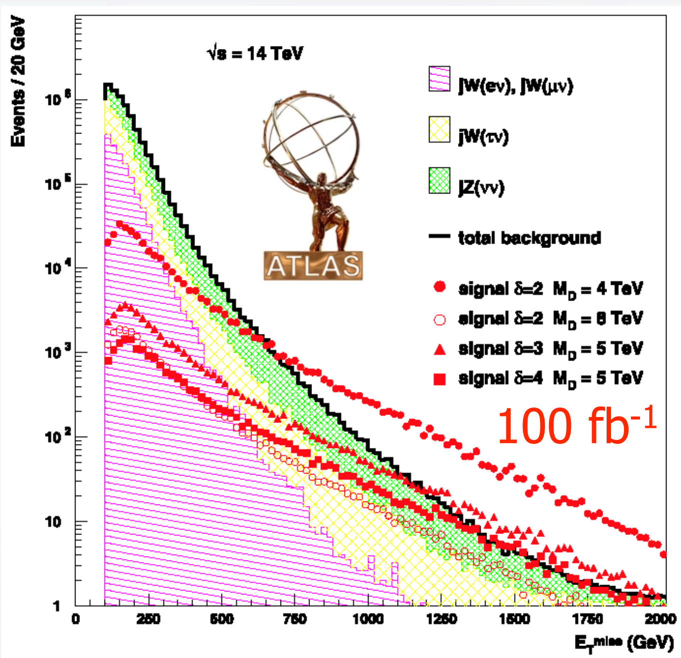
- Parameters:
  - A = 1.48 GeV (noise term)
  - B = 1.03 GeV$^{1/2}$ (sampling term)
  - C = 0.023 (constant term; dominates at large S_T)
  - D = 82 GeV (ΣE_T with no beam)
- Apart from the resolution an important characteristic is the non-Gaussian tails
- Better performance at the low end is expected from particle flow
- Very hard to simulate; will have to wait for real data to see how large the effect is
  - A few special cases have been looked at already, e.g. the effect of hot/dead channels





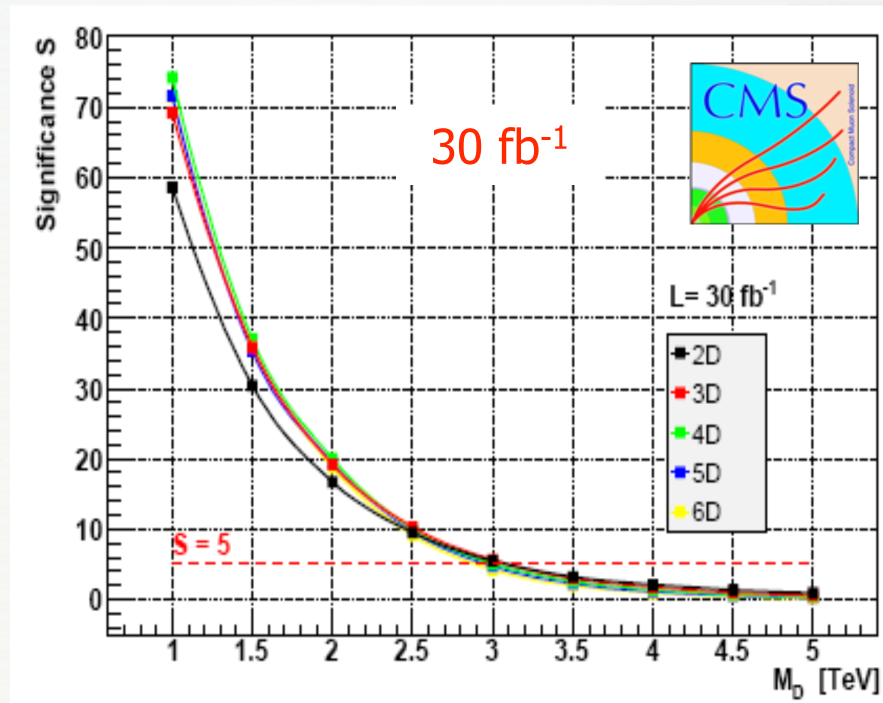
Expectations at the LHC

- Monojets:
  - ATLAS fast simulation for 30 and 100 fb^{-1} (caveat: no instrumental bckg. included)



δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

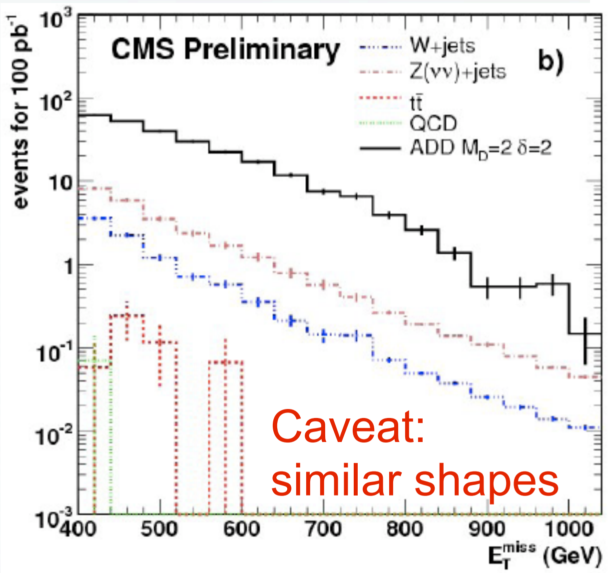
- Monophotons:
  - ATLAS and CMS simulations for 100 fb^{-1} and 30 fb^{-1}, respectively

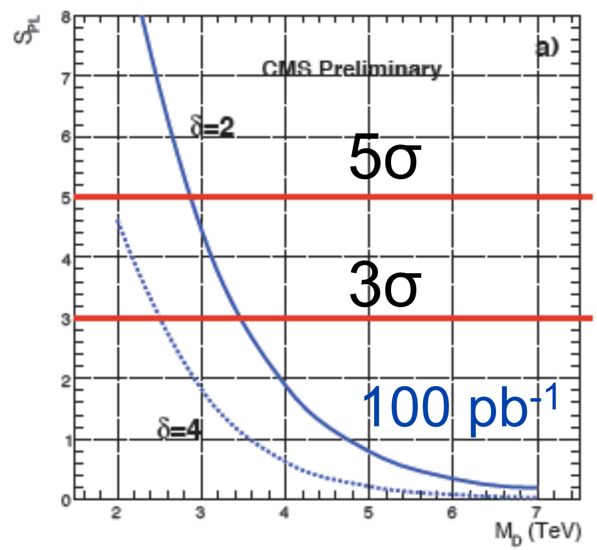


δ	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	4	~ 3.5

New CMS Monojet Analysis

- Jet E_T > 350 GeV (|η| < 1.7) and ME_T > 400 GeV
- Second jet veto (E_T < 40 GeV, |η| < 3)
- Dominated by the irreducible background (determined from W+jets)





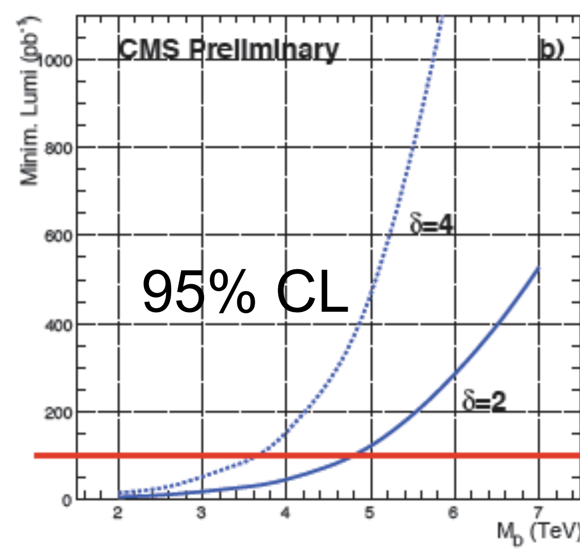
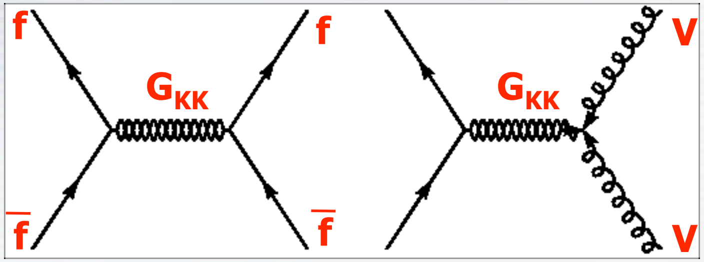


Table 1: Most recent 95% CL lower limits on the fundamental Planck scale M_D (in TeV).

Experiment and channel	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$
LEP Combined [12]	1.60	1.20	0.94	0.77	0.66
CDF monophotons, 2.0 fb^{-1} [18]	1.08	1.00	0.97	0.93	0.90
DØ monophotons, 2.7 fb^{-1} [19]	0.97	0.90	0.87	0.85	0.83
CDF monojets, 1.1 fb^{-1} [20]	1.31	1.08	0.98	0.91	0.88
CDF combined [18]	1.42	1.16	1.06	0.99	0.95

CMS reach w/ 100 pb^{-1}
95% CL exclusion:
n=2 - 4.8 TeV
n=4 - 3.6 TeV
5σ observation:
n=2 - 2.8 TeV
n=4 - 1.8 TeV

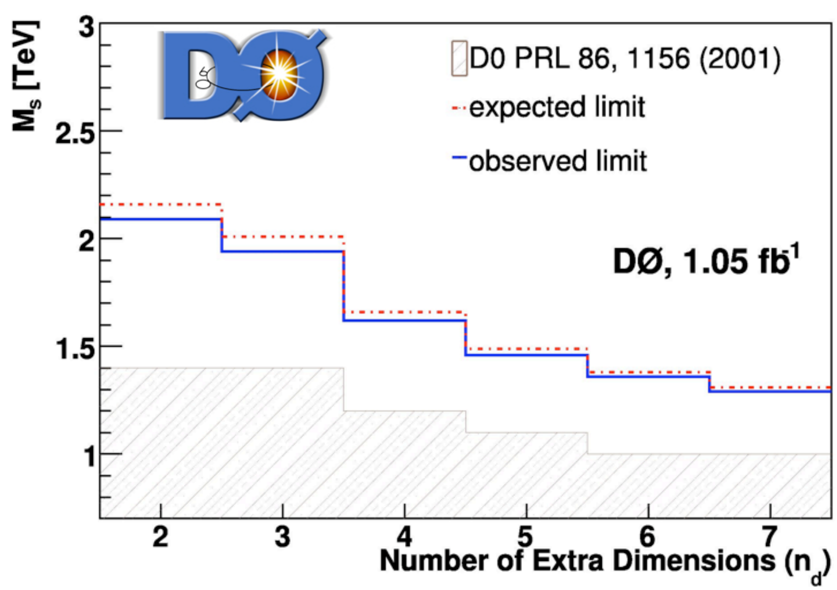
Tevatron: Virtual Graviton Effects



- Expect an interference with the SM fermion or boson pair production

$$\frac{d^2\sigma}{d\cos\theta^* dM} = \frac{d^2\sigma_{SM}}{d\cos\theta^* dM} + \frac{a(n)}{M_S^4} f_1(\cos\theta^*, M) + \frac{b(n)}{M_S^8} f_2(\cos\theta^*, M)$$

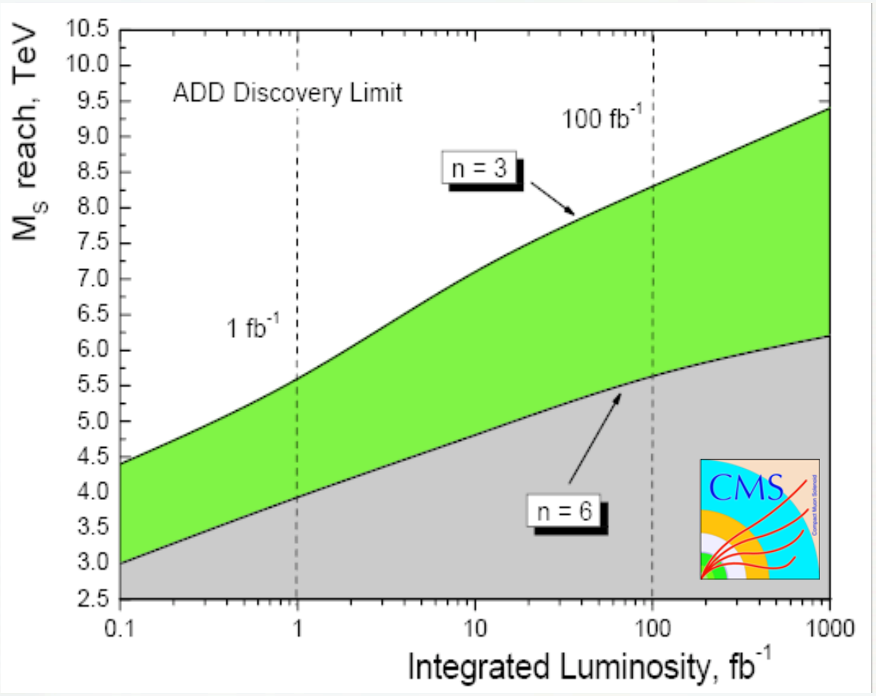
- High-mass, low $|\cos\theta^*|$ tail is a characteristic signature of LED Cheung, GL [PRD **62** 076003 (2000)]
- Best limits on the effective Planck scale come from 1 fb^{-1} DØ Run II data:
  - M_S > 1.3-2.1 TeV (n=2-7) - tightest to date
- Recent results from dijets yield similar sensitivity



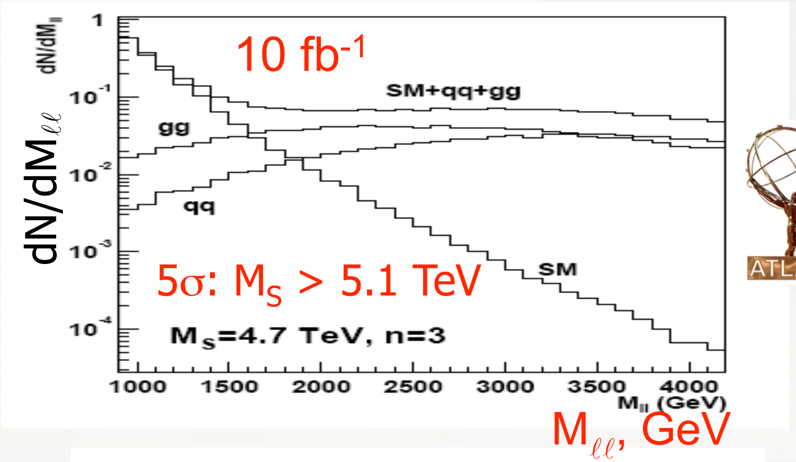
DØ Signature	GRW [2]	HLZ [11]					
		n=2	n=3	n=4	n=5	n=6	n=7
$ee+\gamma\gamma$, 1.1 fb^{-1} [21]	1.62	2.09	1.94	1.62	1.46	1.36	1.29
Dijets, 0.7 fb^{-1} [22]	1.56		1.85	1.56	1.41	1.31	1.24

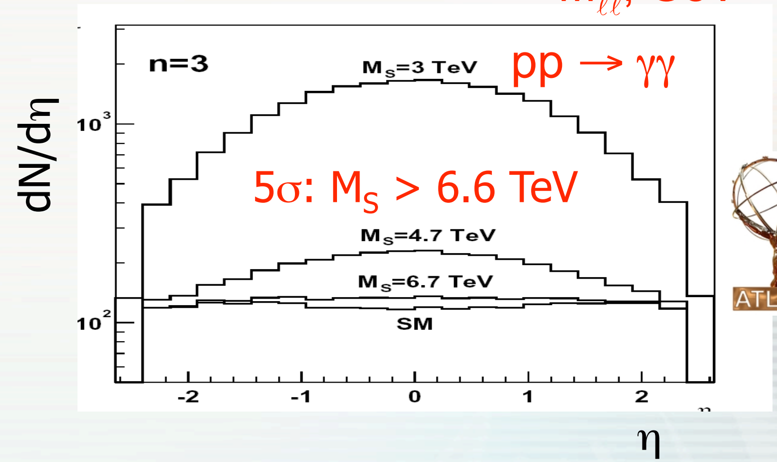
Virtual Graviton Effects at the LHC

- Clean signature, with a huge potential of a quick discovery in dimuon, dielectron, and diphoton channels:
  - Factor of ~3 gain over the Tevatron/Cosmic Ray limits in just 100 pb^{-1}
  - Will also probe generic compositeness models with similar increase in sensitivity compared to the existing limits



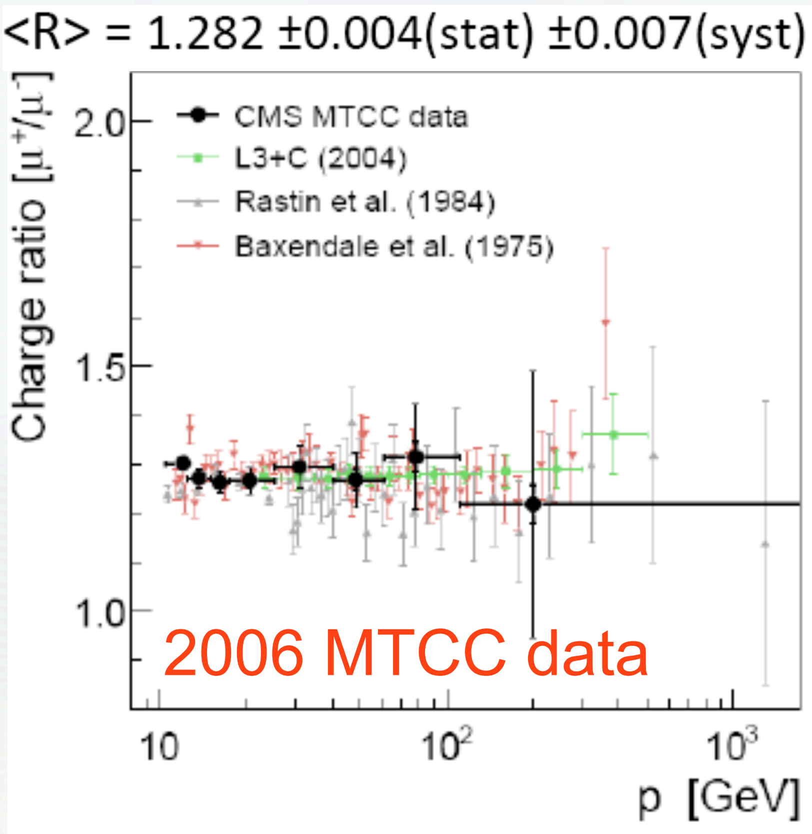
CMS reach for large ED in the dimuon channel

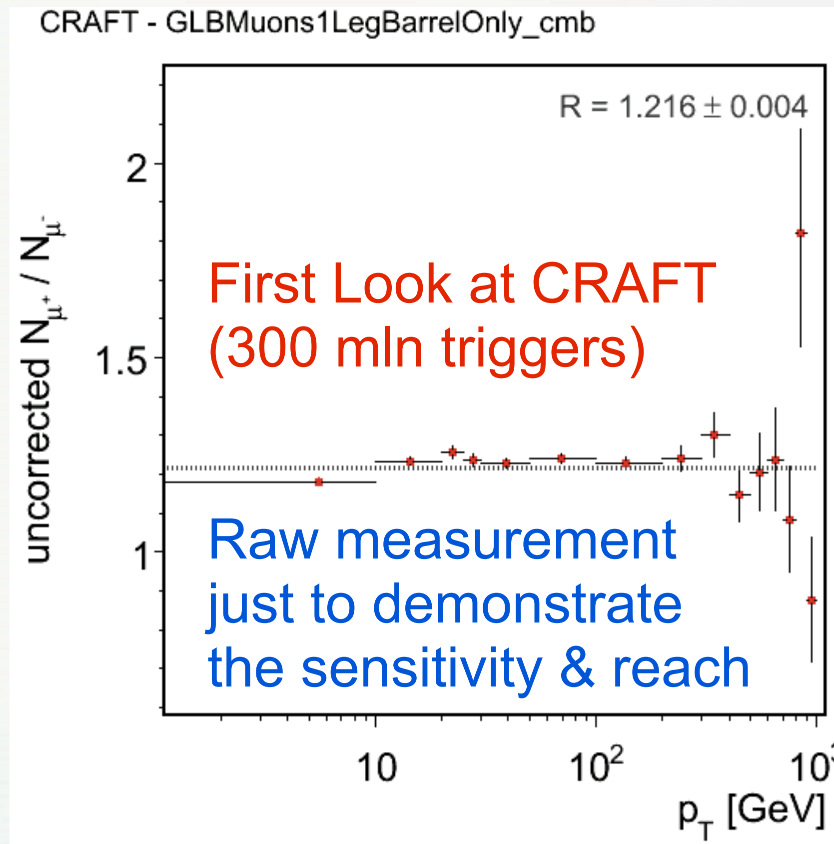




First High-p_T Muons in CMS

- While waiting for the collision data, CMS is already looking for high-p_T muons from cosmic rays
- Charge ratio for atmospheric muons agrees with other measurements and approaches their precision

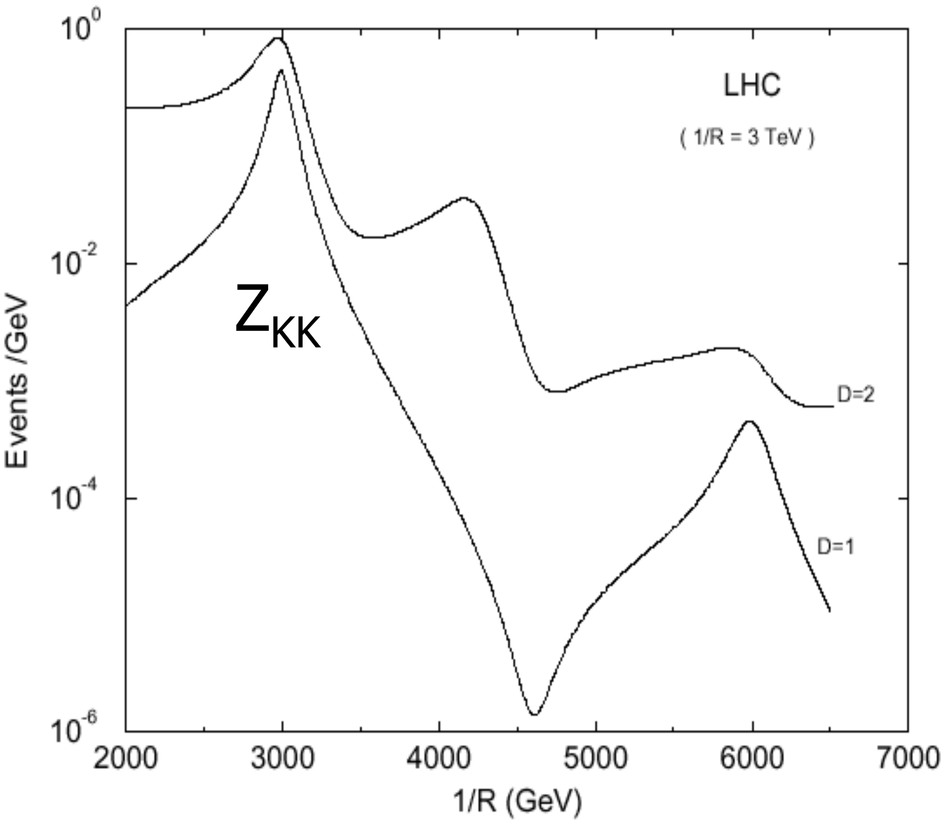




TeV^{-1} Extra Dimensions

- Intermediate-size extra dimensions with ~TeV^{-1} radius
- Introduced by Antoniadis [PL **B246**, 377 (1990)] in the string theory context
- Used by Dienes, Dudas, and Gherghetta [PL **B436**, 55 (1998)] to allow for low-energy unification
  - Expect Z_{KK}, W_{KK}, g_{KK} resonances at the LHC energies
  - At lower energies, can study effects of virtual exchange of the Kaluza-Klein modes of vector bosons
- Current indirect constraints come from precision EW measurements:
  - 1/r ~ 6 TeV

Antoniadis, Benaklis, and Quiros [PL **B460**, 176 (1999)]

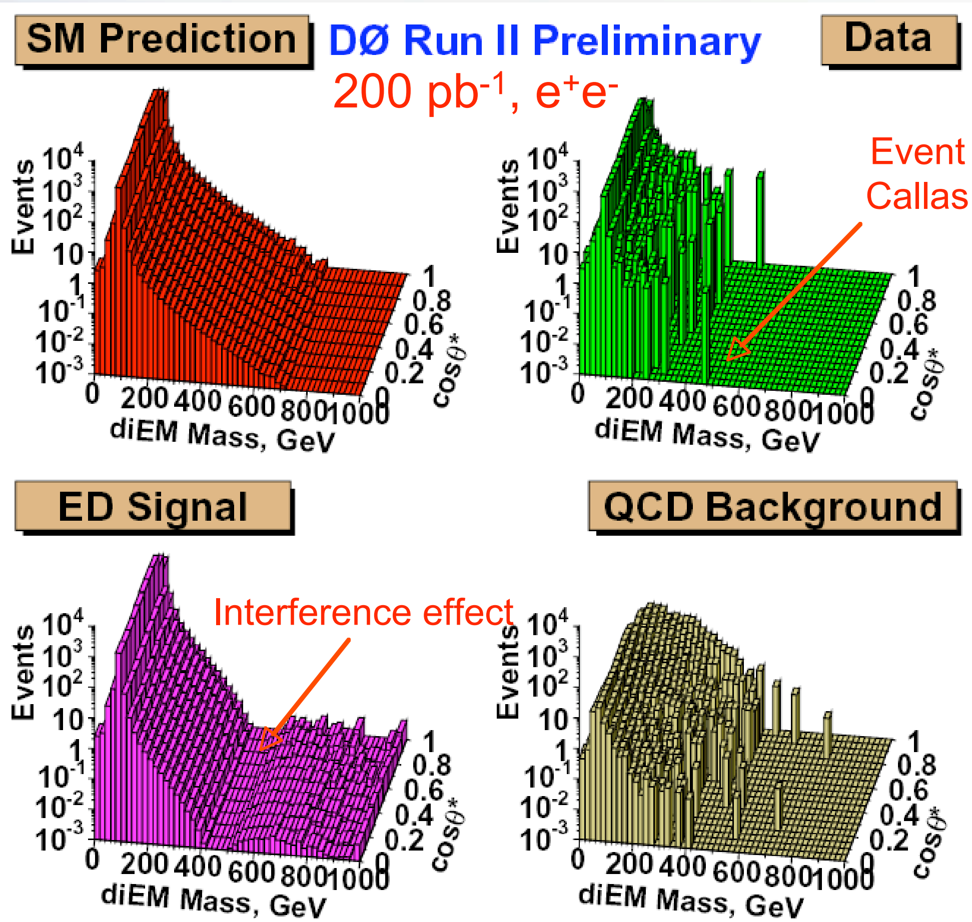


Current Limits on TeV^{-1} ED

From Cheung & GL [PRD **65**, 076003 (2002)]

	η (TeV^{-2})	η_{95} (TeV^{-2})	M_C^{95} (TeV)
LEP 2:			
hadronic cross section, ang. dist., $R_{b,c}$	$-0.33^{+0.13}_{-0.13}$	0.12	5.3
μ, τ cross section & ang. dist.	$0.09^{+0.18}_{-0.18}$	0.42	2.8
ee cross section & ang. dist.	$-0.62^{+0.20}_{-0.20}$	0.16	4.5
LEP combined	$-0.28^{+0.092}_{-0.092}$	0.076	6.6
HERA:			
NC	$-2.74^{+1.49}_{-1.51}$	1.59	1.4
CC	$-0.057^{+1.28}_{-1.31}$	2.45	1.2
HERA combined	$-1.23^{+0.98}_{-0.99}$	1.25	1.6
TEVATRON:			
Drell-yan	$-0.87^{+1.12}_{-1.03}$	1.96	1.3
Tevatron dijet	$0.46^{+0.37}_{-0.58}$	1.0	1.8
Tevatron top production	$-0.53^{+0.51}_{-0.49}$	9.2	0.60
Tevatron combined	$-0.38^{+0.52}_{-0.48}$	0.65	2.3
All combined	$-0.29^{+0.090}_{-0.090}$	0.071	6.8

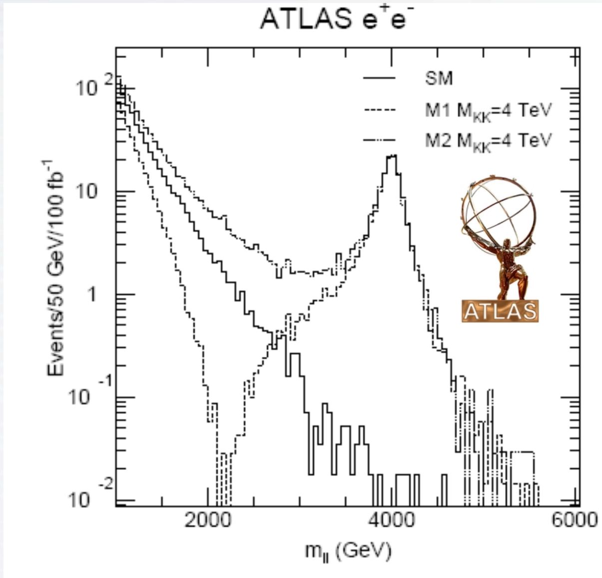
First Dedicated Search for TeV^{-1} ED

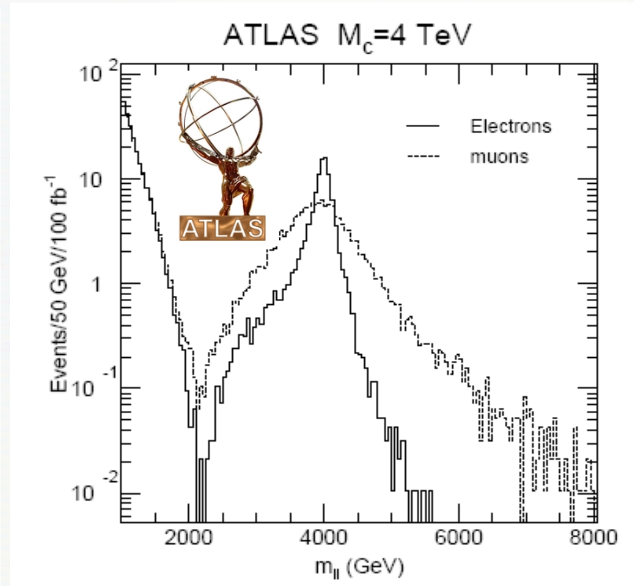


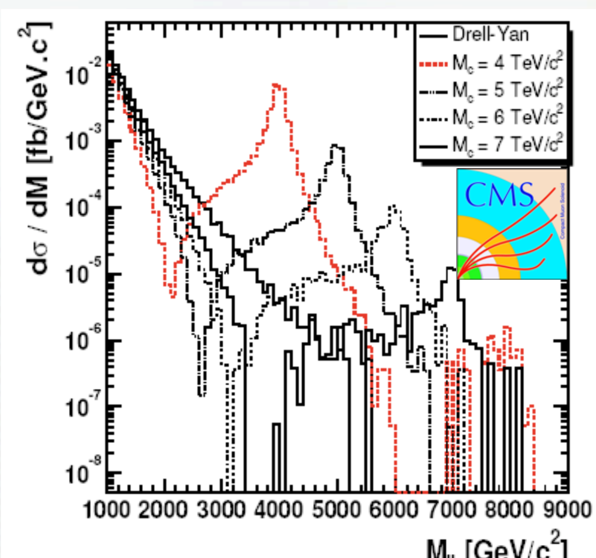
TeV^{-1} ED, 1/R = 0.8 TeV

- While the Tevatron sensitivity is inferior to indirect limits, it explores the effects of virtual KK modes at higher energies, i.e. complementary to those in the EW data
- DØ has performed the first dedicated search of this kind in the dielectron channel based on 200 pb^{-1} of Run II data (Z_{KK}, $\gamma_{KK} \rightarrow e^+e^-$)
- The 2D-technique similar to the search for ADD effects in the virtual exchange yields the best sensitivity Cheung, GL[PRD **65**, 076003 (2002)]
- Data agree with the SM predictions, which resulted in the following limit:
  - $1/r > 1.12$ TeV @ 95% CL
  - $r < 1.75 \times 10^{-19}$ m
- From dijets (700 pb^{-1}) the limit is:
  - $1/r > 1.4$ TeV @ 95% CL

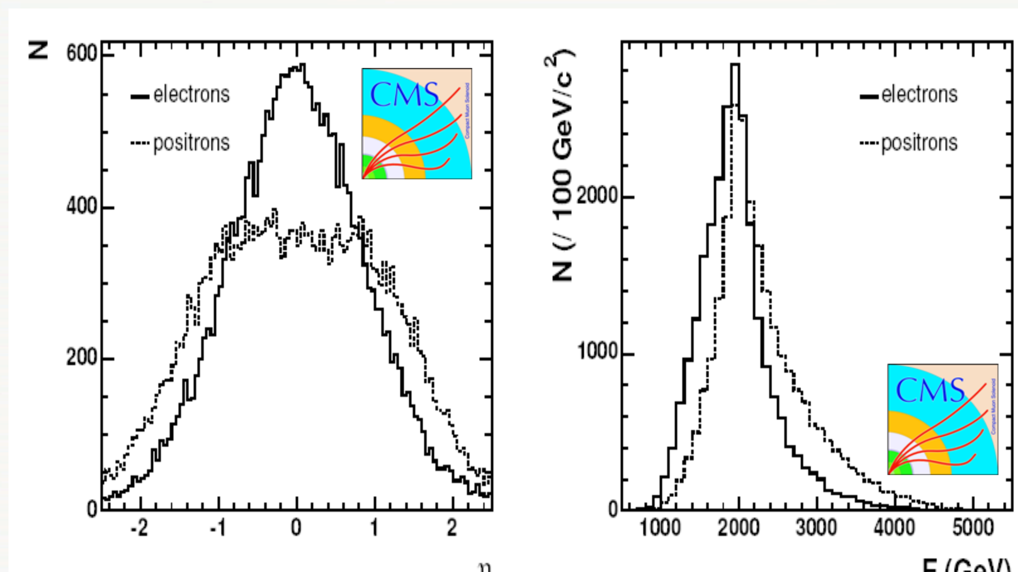
LHC: KK Excitations of the Z Boson







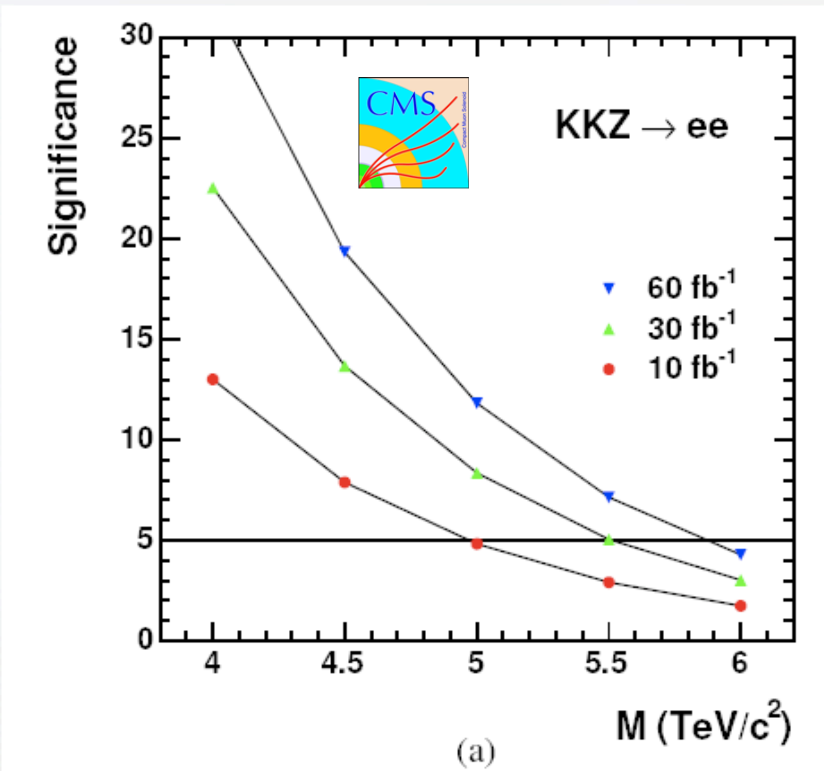
(b)

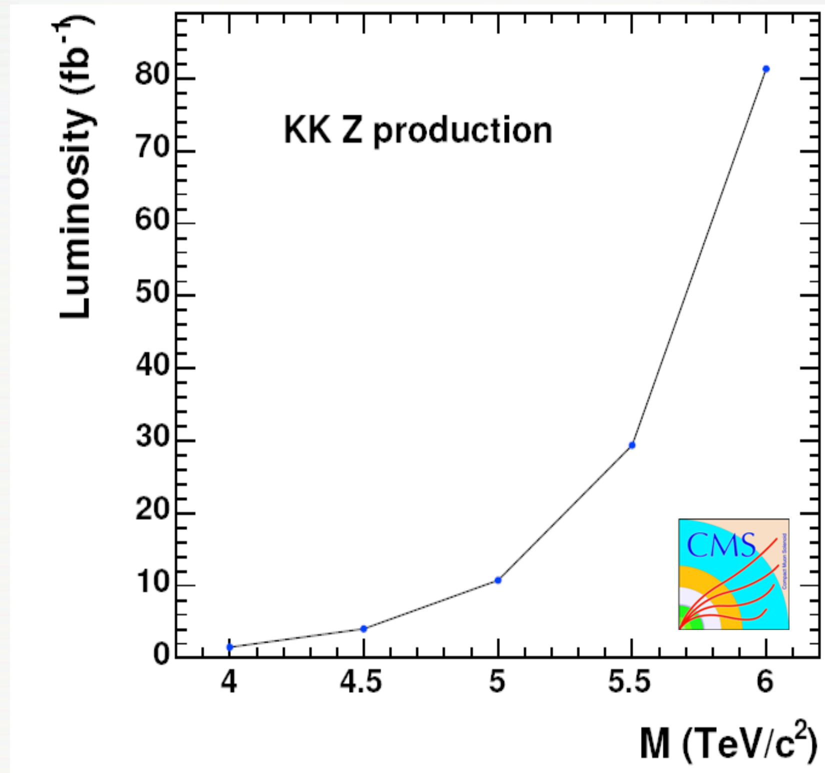


(a) (b)

KK Resonance Reach at the LHC

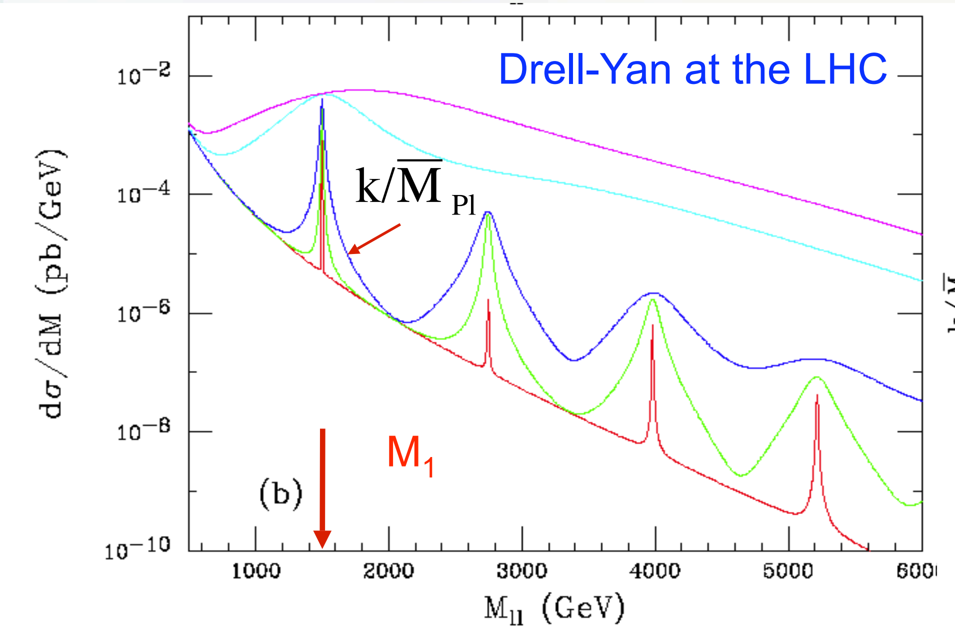
- Dramatic reach even with ~1 fb^{-1}

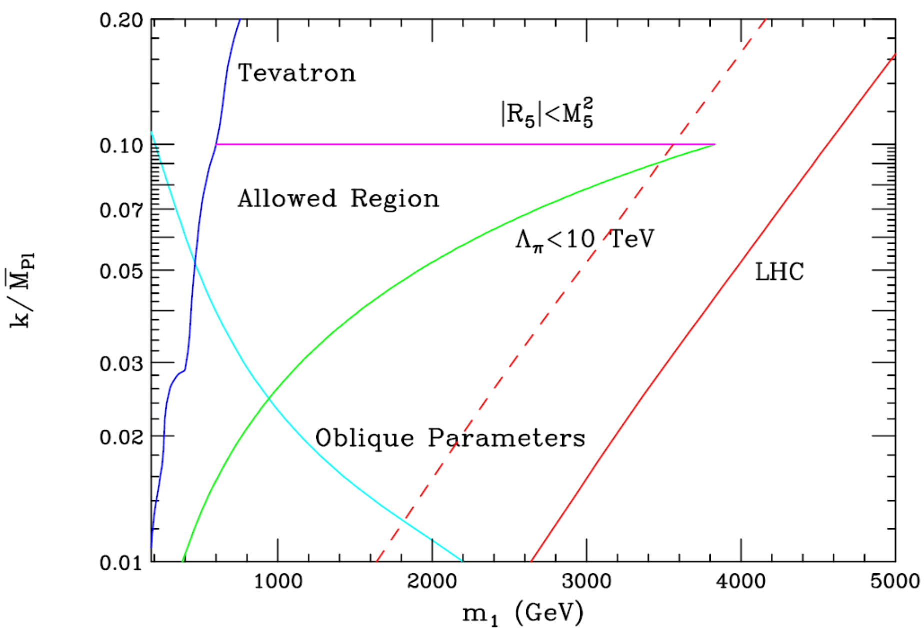




Randall-Sundrum Model Observables

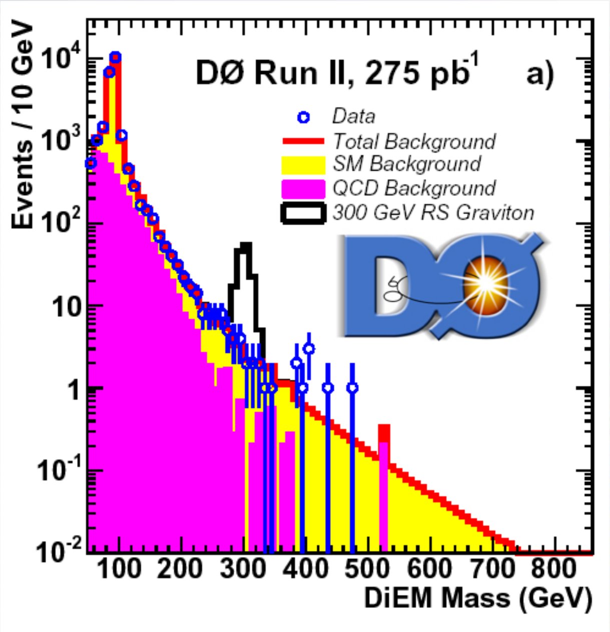
- Need only two parameters to define the model: k and r
- Equivalent set of parameters:
  - The mass of the first KK mode, M_1
  - Dimensionless coupling $k/\overline{M}_{\rm Pl}$, which determines the graviton width
- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too small
- $0.01 \leq k/\overline{M}_{\rm Pl} \leq 0.10$ is the expected range
- Gravitons are narrow
- Similar observables for Z_{KK}/g_{KK} in TeV^{-1} models

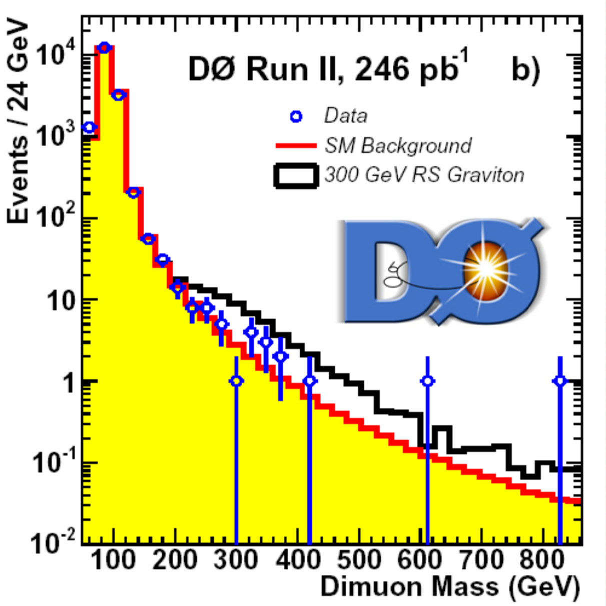


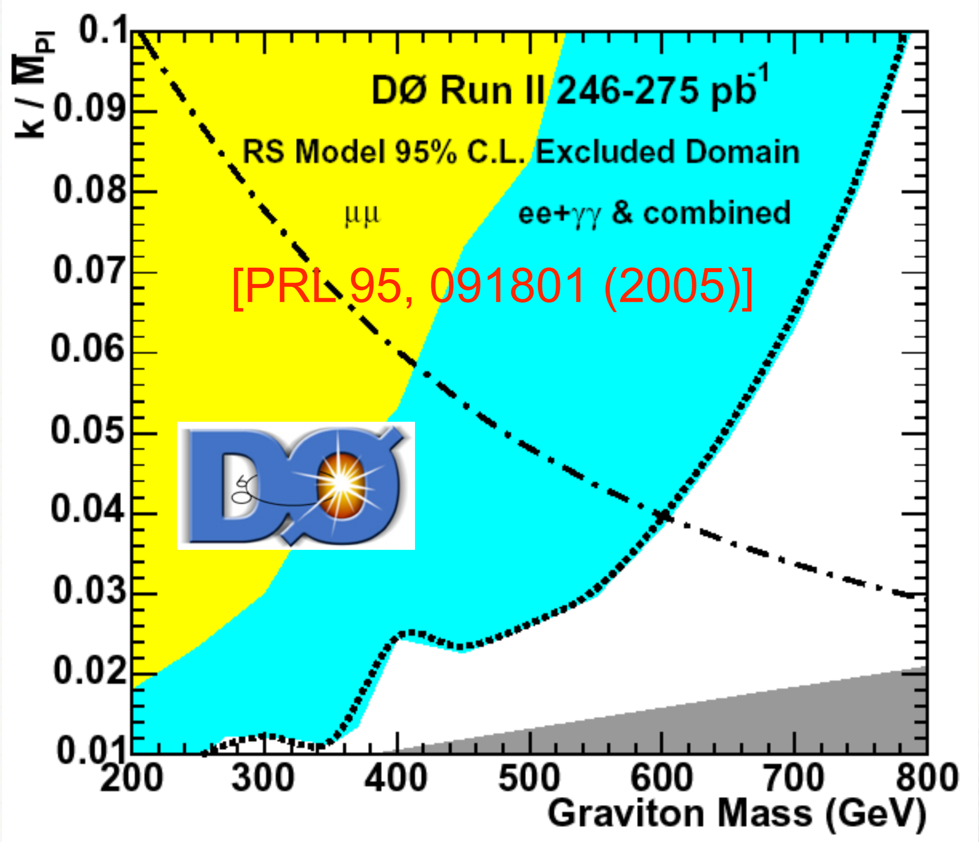


Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]

First Search for RS Gravitons



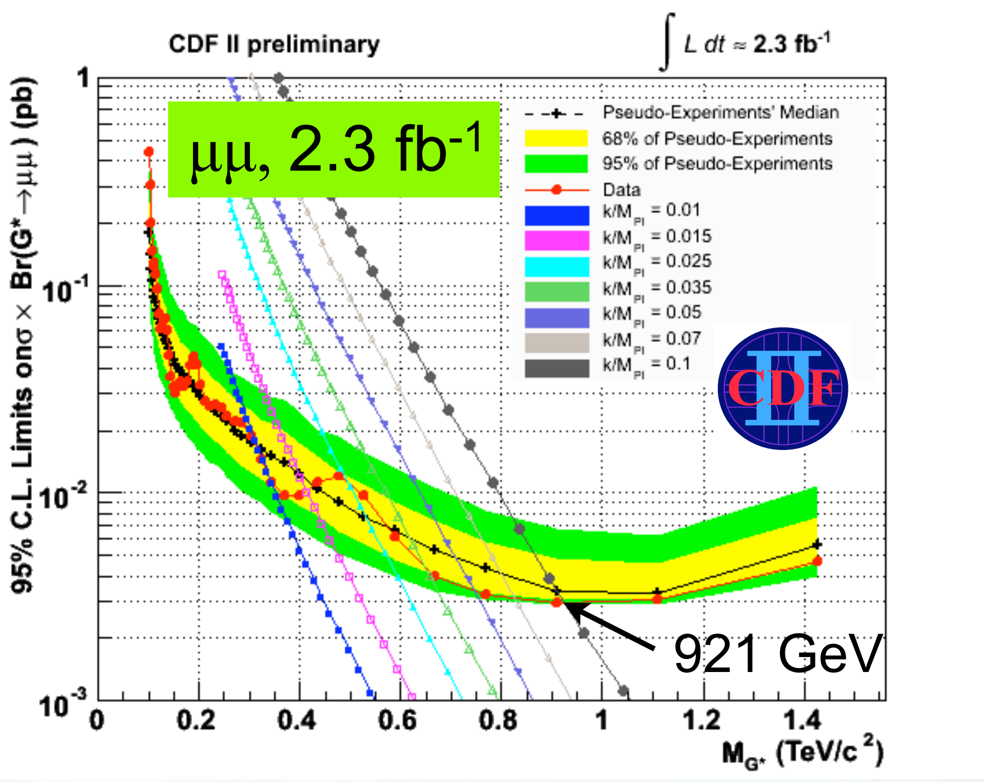


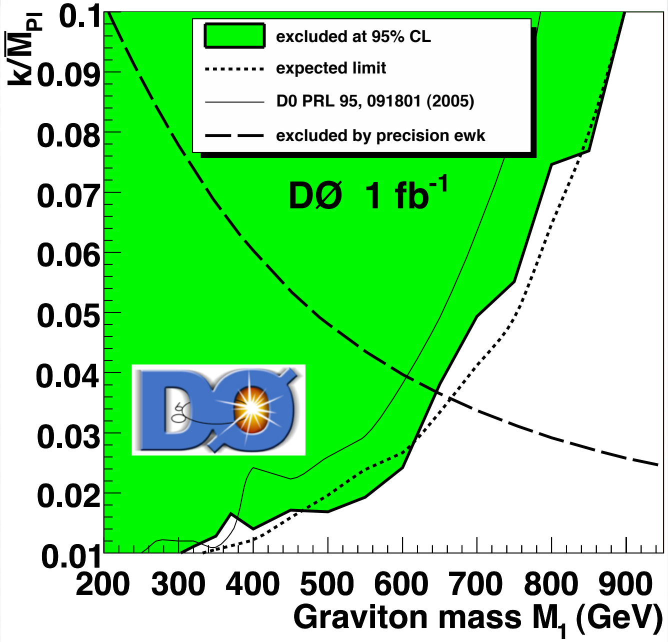


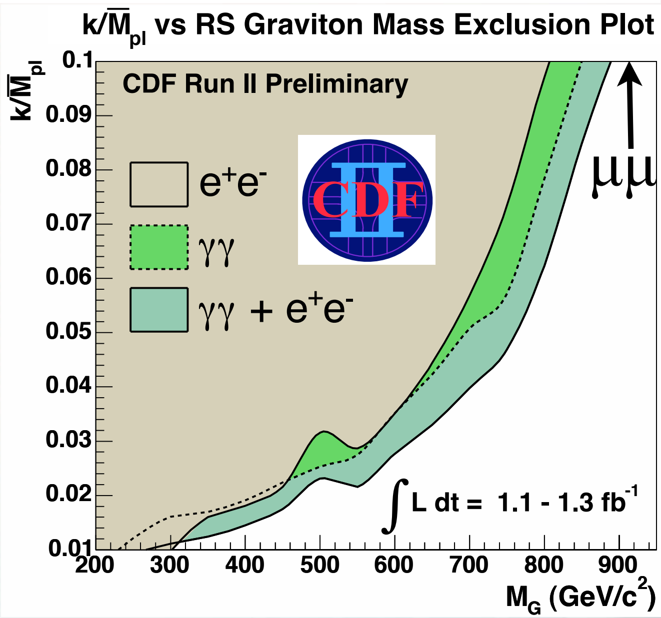
Assume a fixed K-factor of 1.3 for the signal

Most Recent Limits

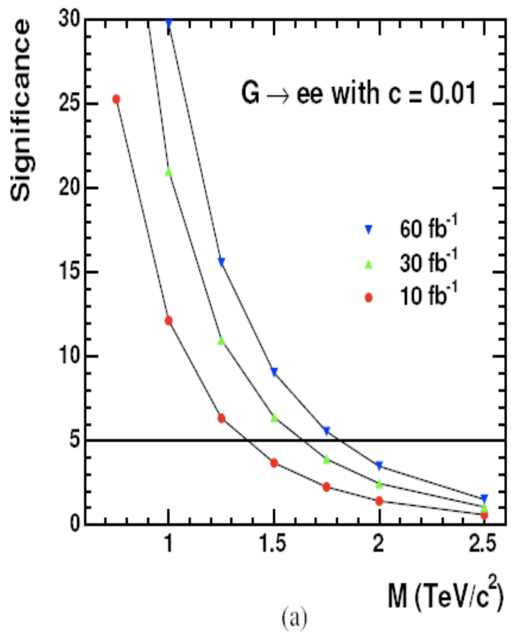
- Latest limits are 10% higher than the original ones despite 4x statistics
  - Tevatron sensitivity has really maxed out - need higher energies!

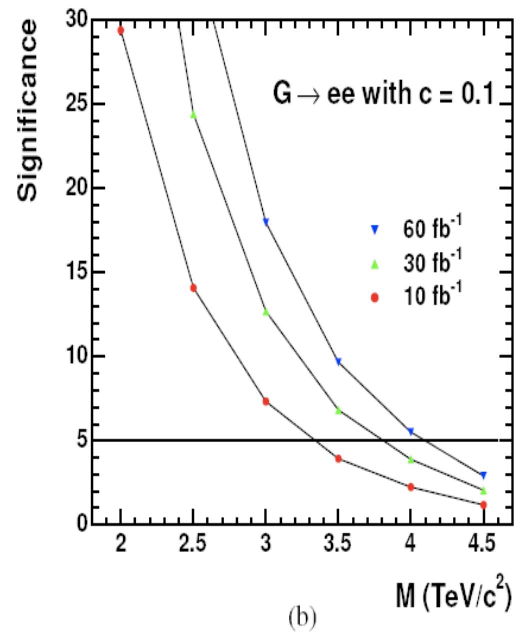


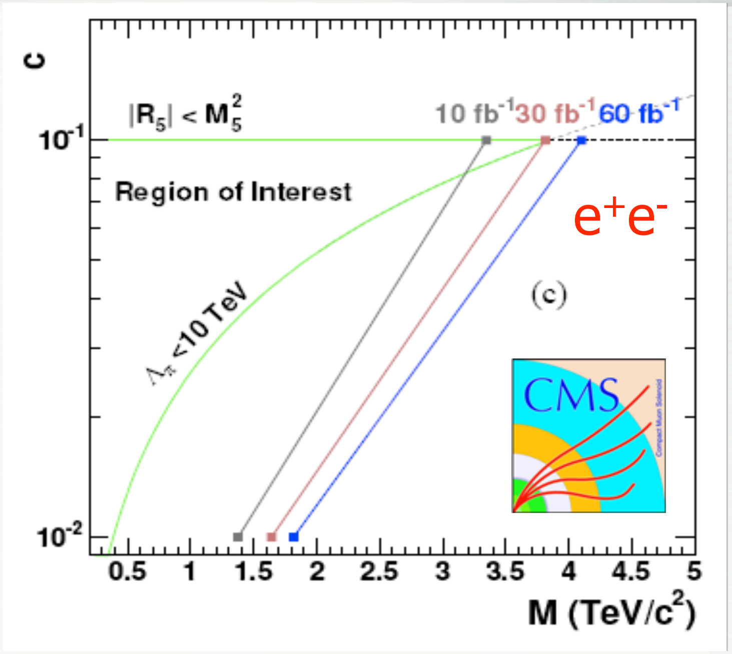


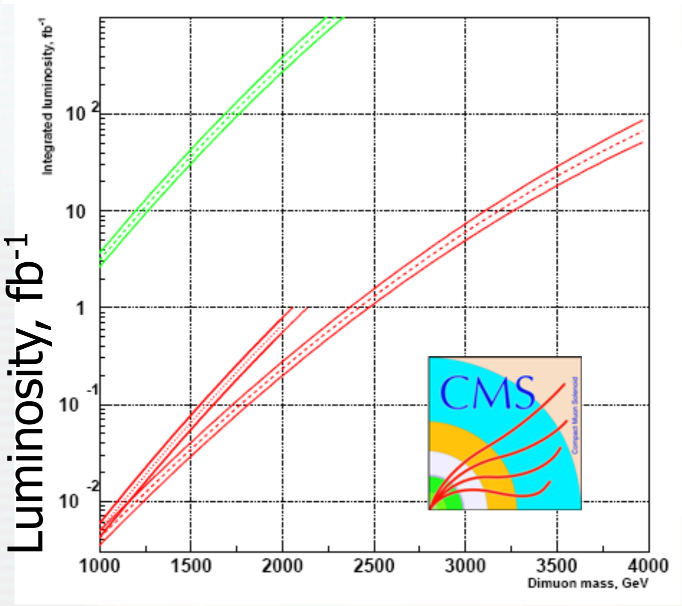


LHC: Randall-Sundrum Graviton Reach

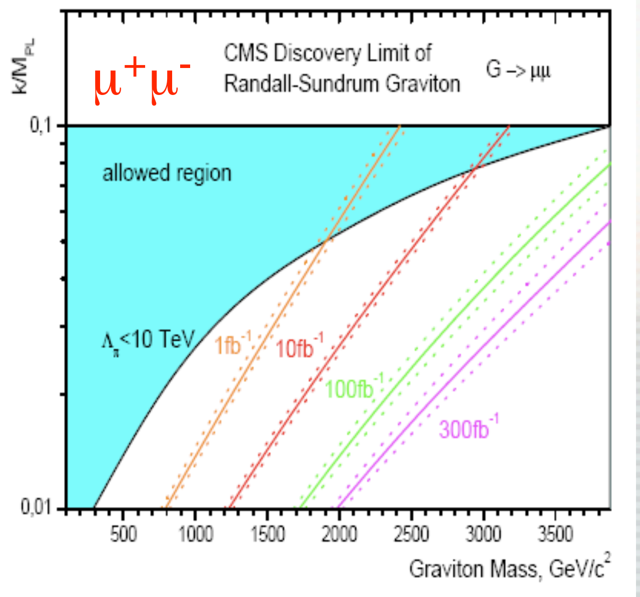






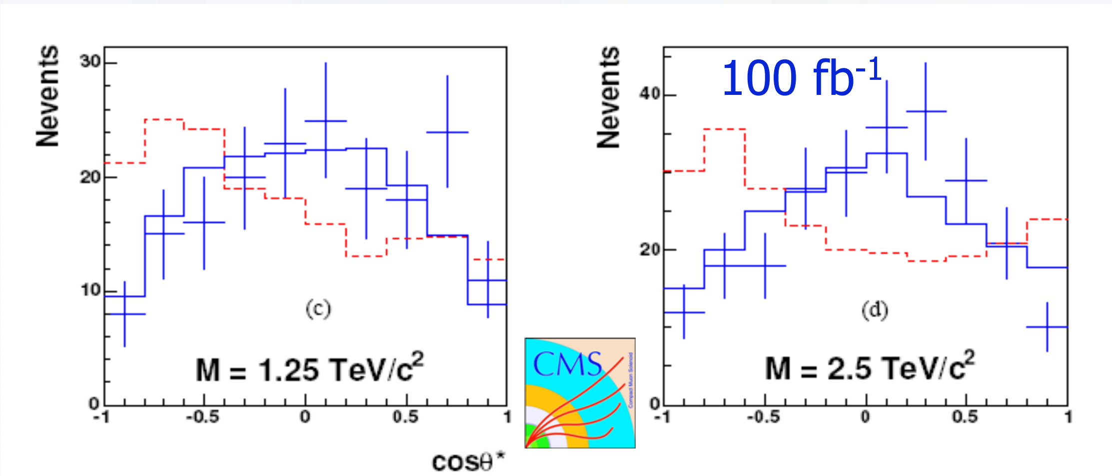


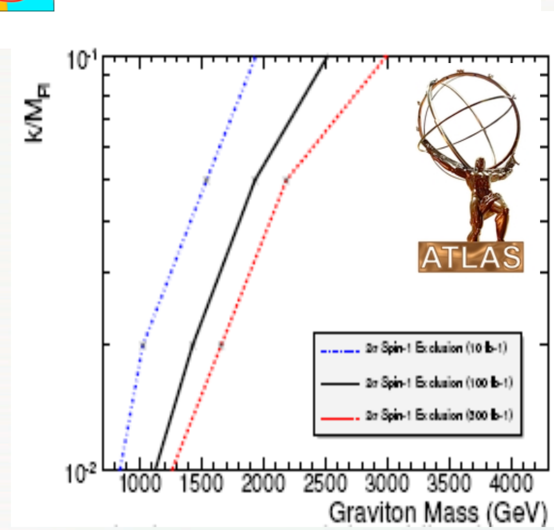
Coupling constant c	Estimator	1 fb^{-1}	10 fb^{-1}
0.01	S_{cP}	0.75	1.20
	S_{cL}	0.77	1.21
	S_L	0.78	1.23
0.02	S_{cP}	1.21	1.72
	S_{cL}	1.22	1.72
	S_L	1.22	1.74
0.05	S_{cP}	1.83	2.48
	S_{cL}	1.85	2.49
	S_L	1.85	2.51
0.1	S_{cP}	2.34	3.11
	S_{cL}	2.36	3.13
	S_L	2.36	3.16

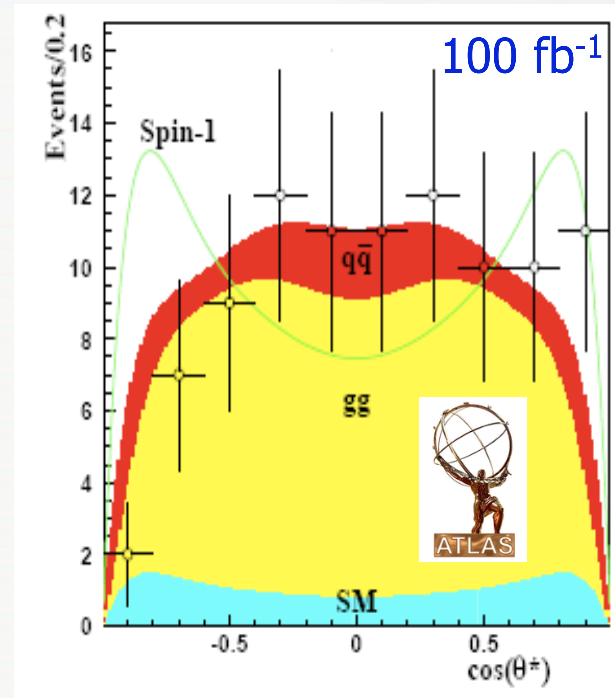


LHC: Graviton Spin?

- Not in the early running!
  - "One event – discovery; two events – cross section measurement; three events – angular distributions"

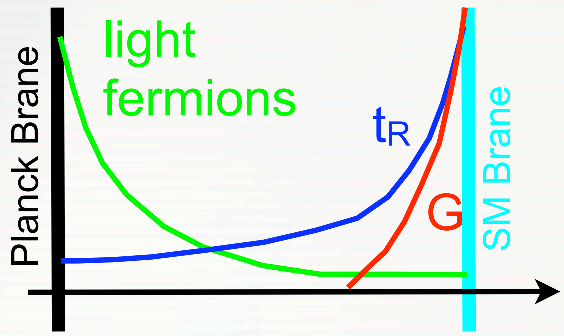




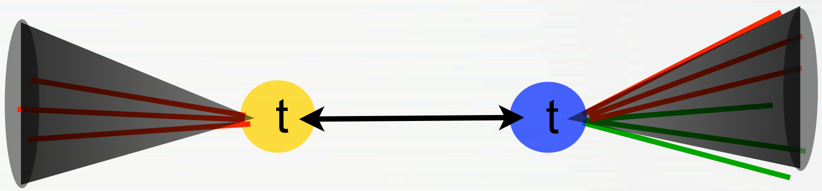


But: Life May be More Complicated!

- Simple RS model has many potential problems: FCNC, CP-violation
  - Those can be solved by putting fermions in the bulk
- Top quark is localized near the SM brane; light fermions are near the Planck brane
- Graviton mainly couples to the top quark, and thus the dominant decay mode is a pair of top quarks



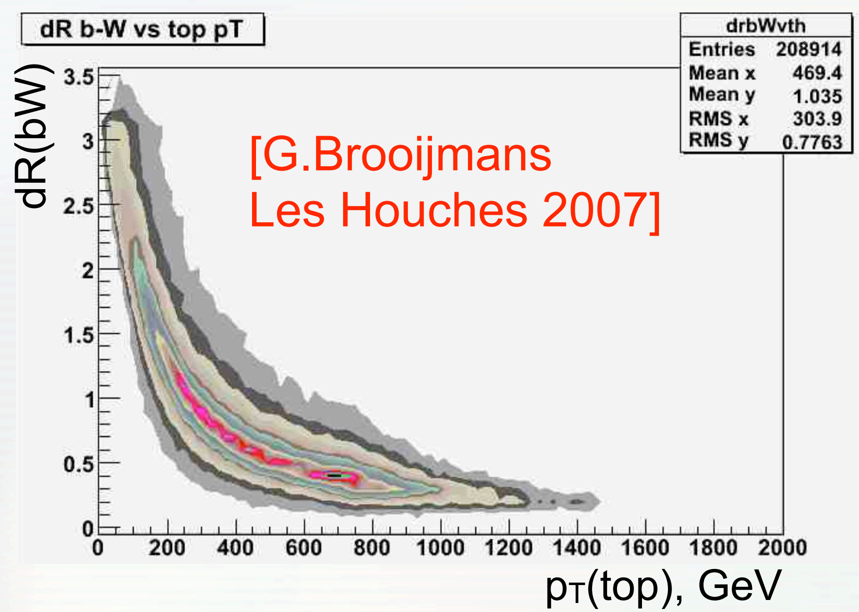
- For graviton masses ~2-3 TeV, top quarks emerge highly boosted, which makes it challenging to reconstruct them

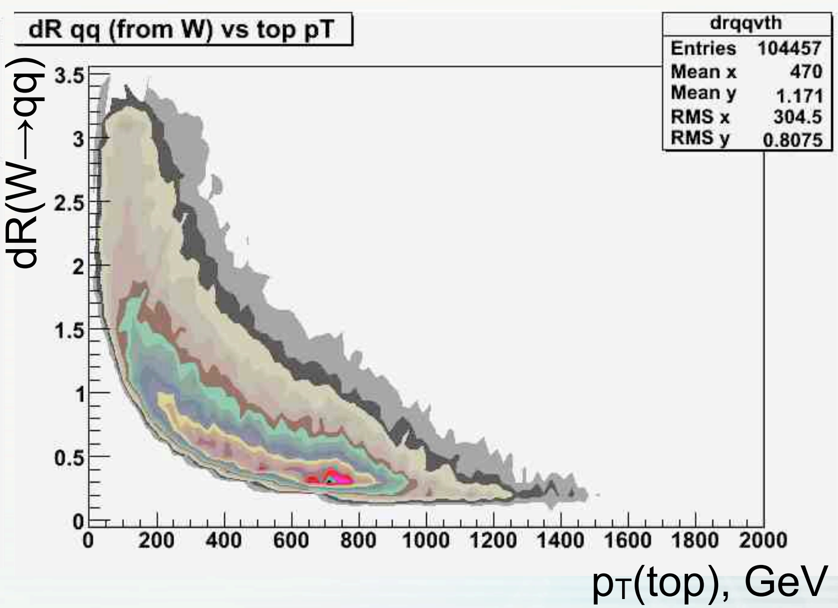


- Several challenges:
  - for 3-jet top decays jets are often merged in a single "fat" jet
  - b-tagging efficiency drops dramatically, as the opening angle between the tracks becomes small.

Possible Remedies

- Several have been suggested:
  - Use of top-jet mass: poorly defined; depends on the jet algorithm and pile-up/underlying event; depends on the calorimeter granularity
  - 3D b-tagging
  - k_T algorithm with small D ~ 0.1-0.2 within the “fat” jet
- Requires serious experimental studies with realistic detector effects
  - dedicated groups in both ATLAS and CMS are exploring this topic





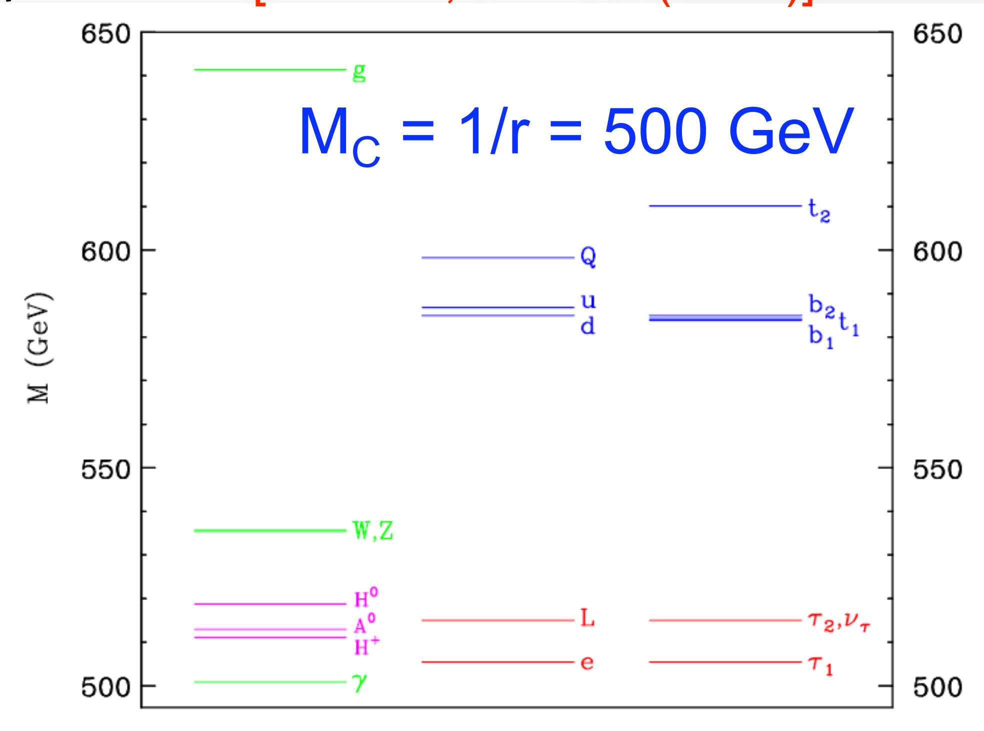
More Challenges: Universal ED

- The most "democratic" ED model: *all* the SM fields are free to propagate in extra dimension(s) with the size $r = 1/M_c \sim 1\ \text{TeV}^{-1}$ Appelquist, Cheng, Dobrescu [PRD **64**, 035002 (2001)]
  - Instead of chiral doublets and singlets, model contains vector-like quarks and leptons
  - Gravitational force 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 additional 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 tree level, i.e. $n_1 \pm n_2 \pm n_3 \pm \ldots = 0$; consequently, the lightest KK mode cold be stable (and is an excellent dark matter candidate Cheng, Feng, Matchev [PRL **89**, 211301 (2002)])
- Hence, first level 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)
- CDF unpublished Run I analysis based on 90 pb^{-1} set $M_c > 280$ GeV

UED Phenomenology

- Naively, one would expect large clusters of nearly degenerate states with masses around 1/r, 2/r, …
- Cheng, Feng, 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, so that they vanish in the SM
- Q, L (q, l) are SU(2) doublets (singlets) and contain both chiralities

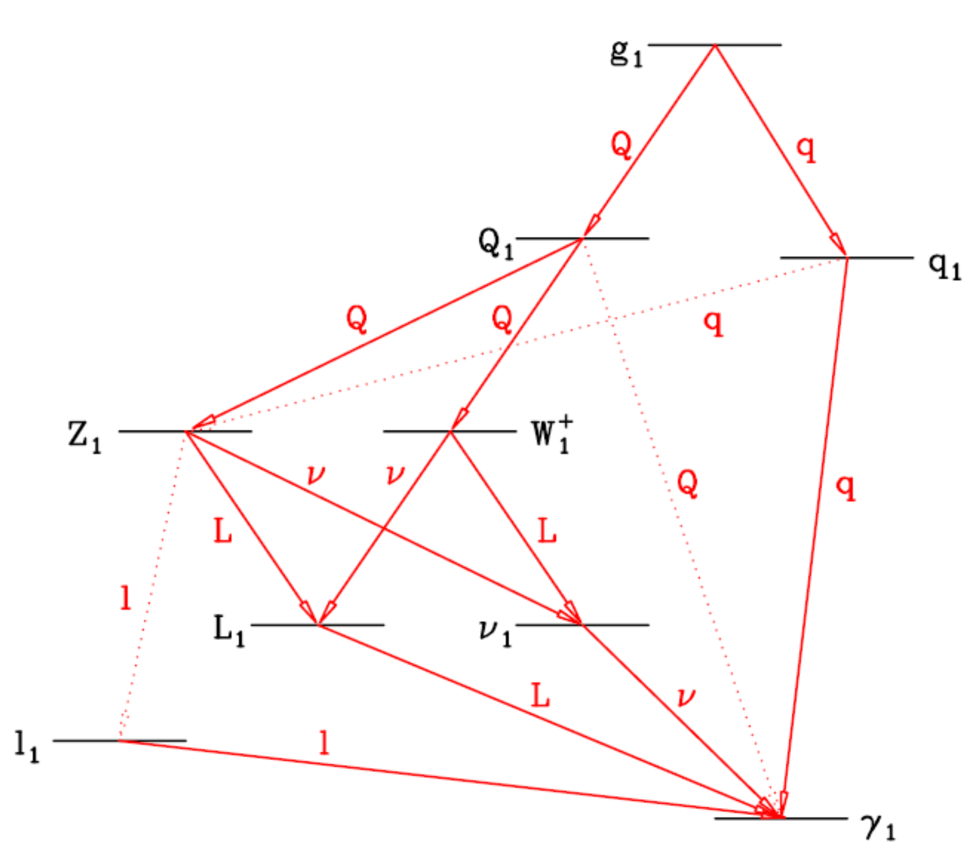
Cheng, Matchev, Schmaltz [PRD **66**, 056006 (2002)]



Mass Spectrum and Decays

- First level KK-states spectroscopy

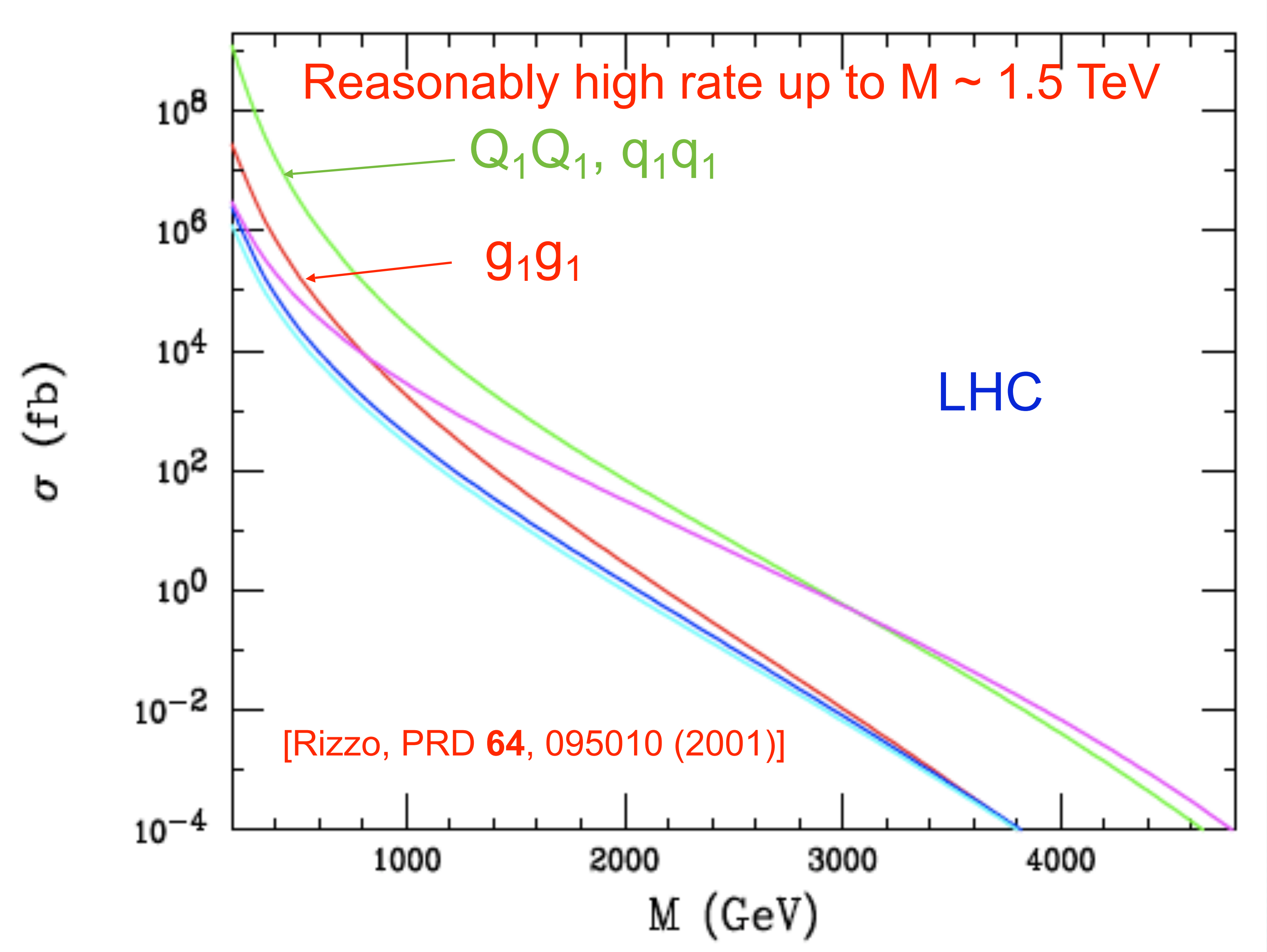
Cheng, Matchev, Schmaltz
[PRD **66**, 056006 (2002)]



Decay:
$B(g_1 \rightarrow Q_1 Q) \sim 50\%$
$B(g_1 \rightarrow q_1 q) \sim 50\%$
$B(q_1 \rightarrow q\gamma_1) \sim 100\%$
$B(t_1 \rightarrow W_1 b, H_1^+ b) \sim 100\%$
$B(Q_1 \rightarrow QZ_1 : W_1 : \gamma_1) \sim 33\% : 65\% : 2\%$
$B(W_1 \rightarrow \nu L_1 : \nu_1 L) = 1/6 : 1/6$ (per flavor)
$B(Z_1 \rightarrow \nu\nu_1 : LL_1) \sim 1/6 : 1/6$ (per flavor)
$B(L_1 \rightarrow \gamma_1 L) \sim 100\%$
$B(\nu_1 \rightarrow \gamma_1 \nu) \sim 100\%$
$B(H_1^\pm \rightarrow \gamma\gamma_1, H^\pm \gamma_1) \sim 100\%$

Production:
$q_1 q_1 + X \rightarrow ME_T$ + jets ($\sim\sigma_{had}/4$); but: low ME_T
$Q_1 Q_1 + X \rightarrow V_1 V'_1$ + jets $\rightarrow$ 2-4 ℓ + ME_T ($\sim\sigma_{had}/4$)

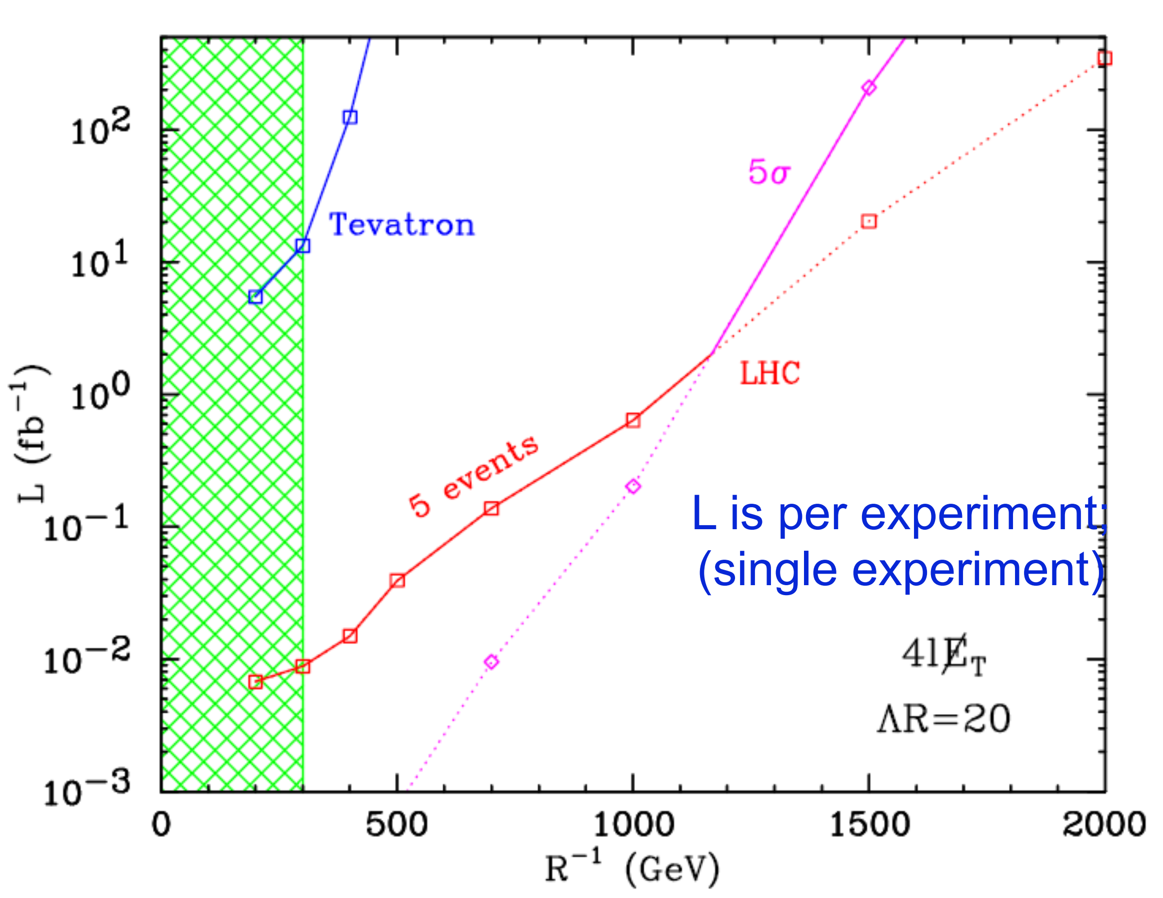
Production Cross Section



Sensitivity in the Four-Lepton Mode

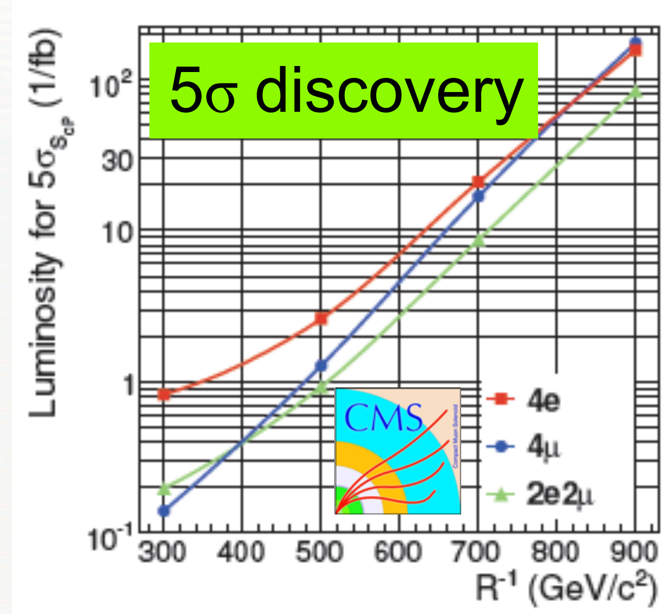
- Only the gold-plated 4-leptons + ME_T mode has been considered in the original paper and the subsequent studies
- Other promising channels:
  - dileptons + jets + ME_T + X (x9 cross section)
  - trileptons + jets + ME_T + X (x5 cross section)
  - Single production of the second KK excitation (via one loop)
- Detailed simulations are required: CompHEP and PYTHIA implementations now exist

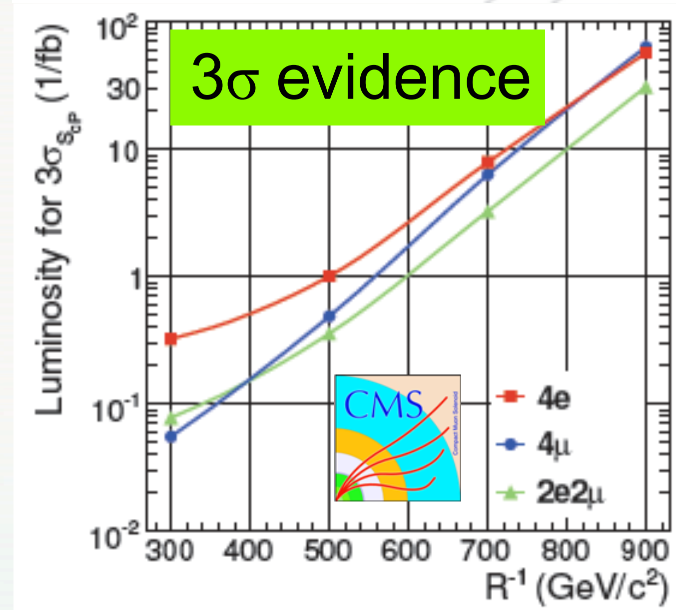
Cheng, Matchev, Schmaltz [PRD **66**, 056006 (2002)]

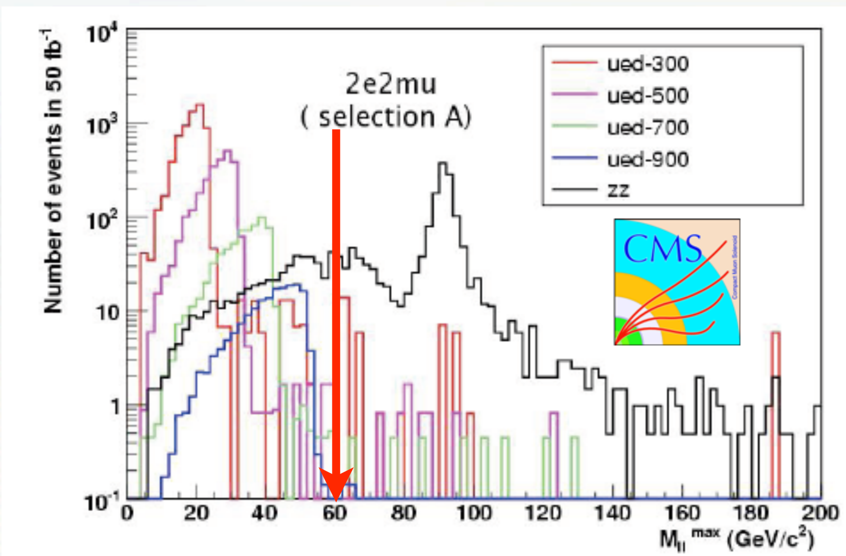


Early UED Searches in CMS

- Very recently approved analysis by the LIP group
- Consider 4e, 4μ, 2e2μ channels
- Tight selection for low 1/R and looser selection for high 1/R
- Signal is found at low dilepton invariant mass
- Background is dominated by the physics $(Z/\gamma^*)(Z/\gamma^*)$ background







Black Holes at the LHC?

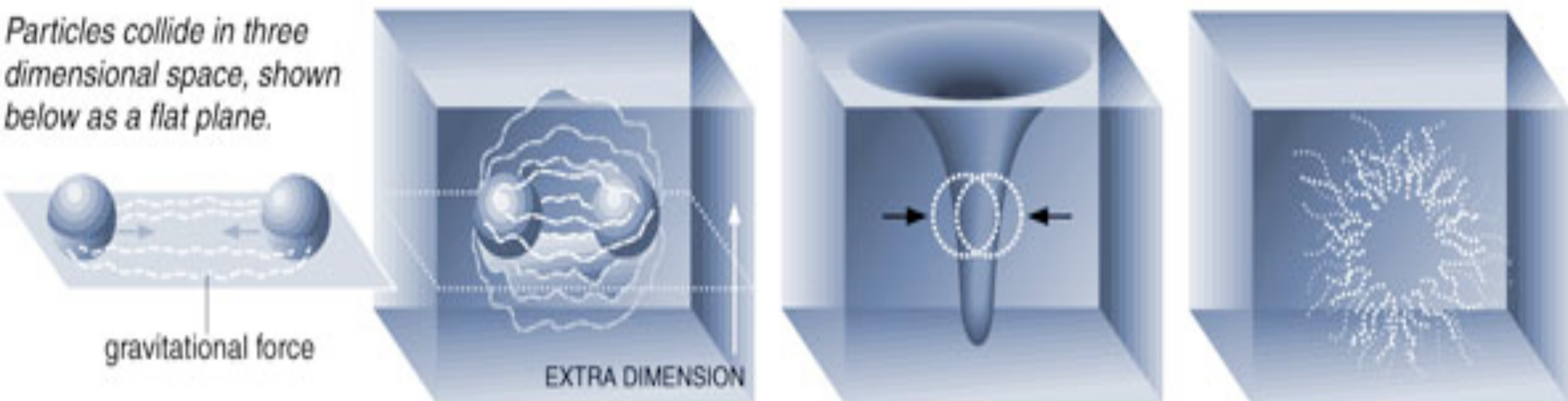
Black Holes on Demand

Black Holes on Demand

NYT, 9/11/01

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:



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

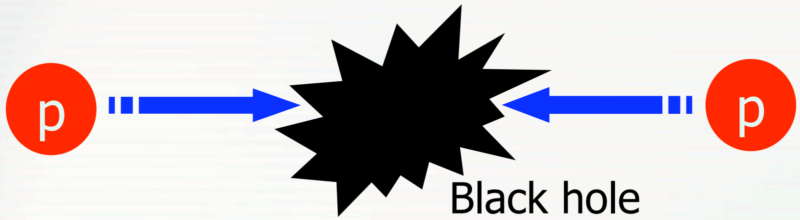
When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

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

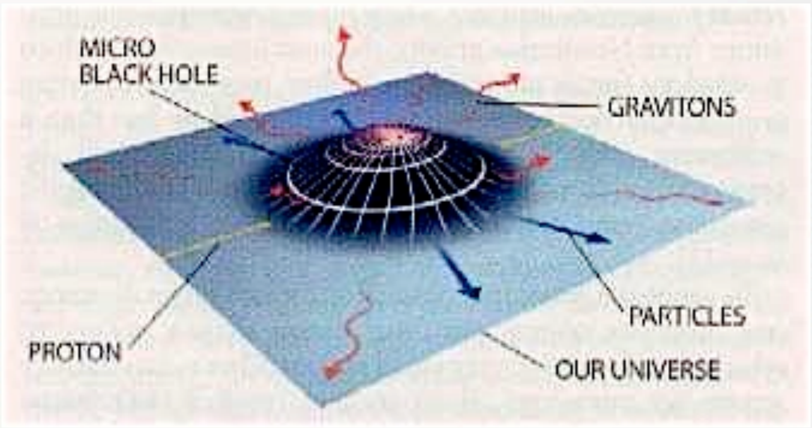
Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

BH at LHC: Theoretical Framework

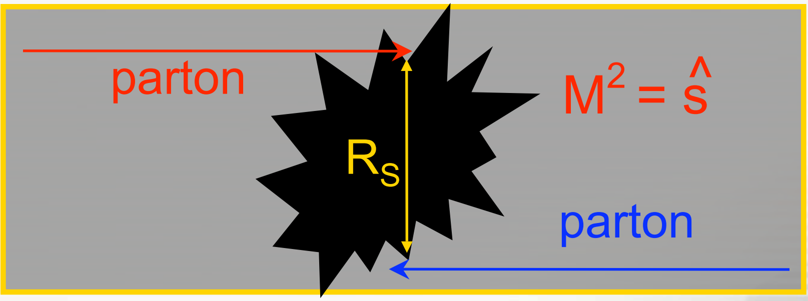
- Based on the work done with Dimopoulos a few years ago [PRL **87**, 161602 (2001)] and a related study by Giddings/Thomas [PRD **65,** 056010 (2002)]
- Extends previous, more theoretical studies by Argyres/Dimopoulos/March-Russell [PL **B441**, 96 (1998)], Banks/Fischler [JHEP, **9906**, 014 (1999)], Emparan/Horowitz/Myers [PRL **85**, 499 (2000)] to collider phenomenology
- Big surprise: BH production is not an exotic remote possibility, but the dominant effect!
- Main idea: when the c.o.m. energy reaches the fundamental Planck scale, a BH is formed!
- Also true in the RS models where Λ_π is the characteristic scale



Artist's view:



Cross section is given by a black disk approximation:



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

Comparable with that of the top-quark pair production!

Assumptions and Approximations

- Fundamental limitation: our lack of knowledge of quantum gravity effects close to the Planck scale
- Consequently, no attempts for partial improvement of the results, e.g.:
  - Grey body factors
  - BH spin, charge, color hair
  - Relativistic effects and time-dependence
- The underlying assumptions rely on two simple qualitative properties:
  - The absence of small couplings;
  - The “democratic” nature of BH decays
- We expect these features to survive for light BH
- Use semi-classical approach strictly valid only for $M_{BH} \gg M_P$; only consider $M_{BH} > M_P$
- Clearly, these are important limitations, but there is no way around them without the knowledge of QG

Black Hole Production

- Schwarzschild radius is given by Argyres et al. [hep-th/9808138], after Myers/Perry [Ann. Phys. **172**, 304(1986)]; it leads to:

$$\sigma(\hat{s} = M_{\rm BH}^2) = \pi R_S^2 = \frac{1}{M_{\rm Pl}^2}\left[\frac{M_{\rm BH}}{M_{\rm Pl}}\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{2}{n+1}}$$

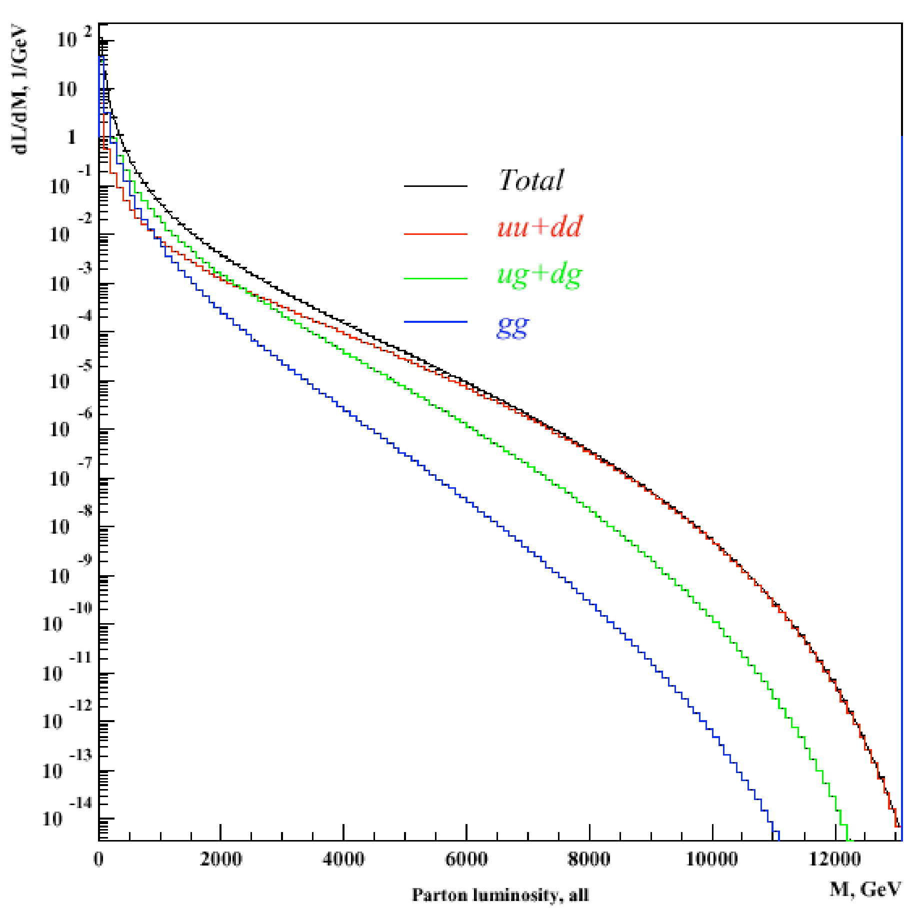
- Use parton luminosity approach with quark momentum distribution given by parton distribution functions

$$\frac{d\sigma(pp\to{\rm BH}+X)}{dM_{\rm BH}} = \frac{dL}{dM_{\rm BH}}\,\hat{\sigma}(ab\to{\rm BH})\big|_{\hat{s}=M_{\rm BH}^2}$$

$$\frac{dL}{dM_{\rm BH}} = \frac{2M_{\rm BH}}{s}\sum_{a,b}\int_{M_{\rm BH}^2/s}^{1}\frac{dx_a}{x_a}f_a(x_a)f_b\left(\frac{M_{\rm BH}^2}{sx_a}\right)$$

- Note: at c.o.m. energies ~1 TeV the dominant contribution is from quark-quark interactions (BH w/ color, B ≠ 0)

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



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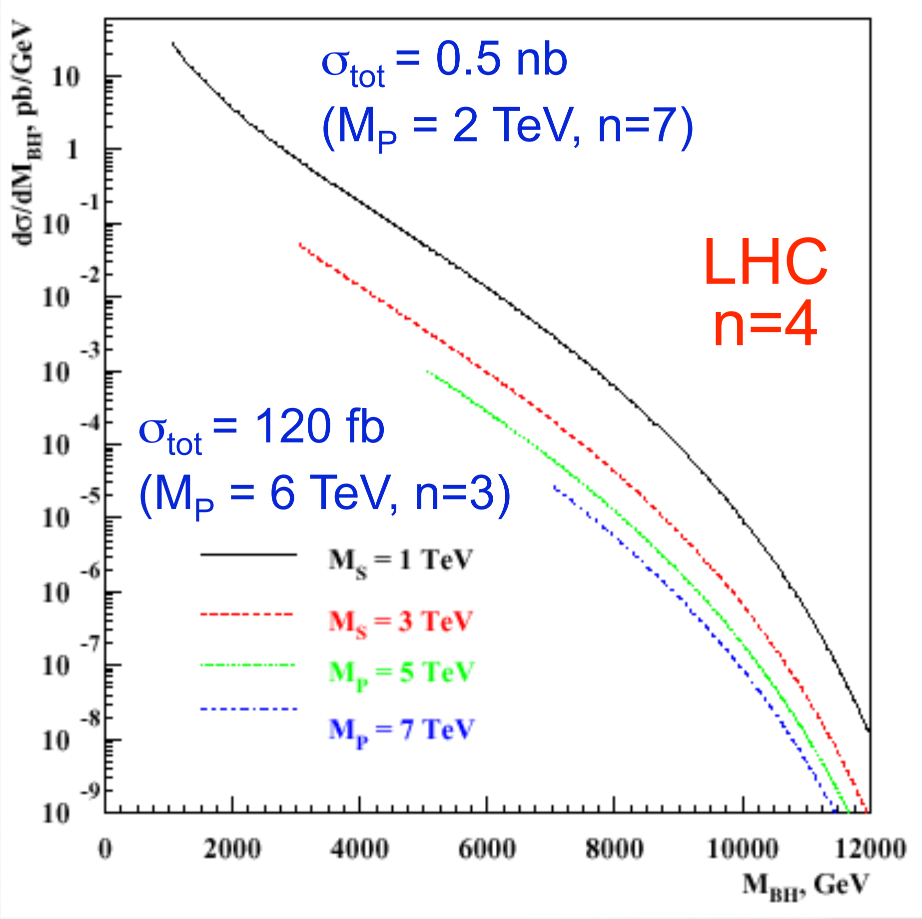
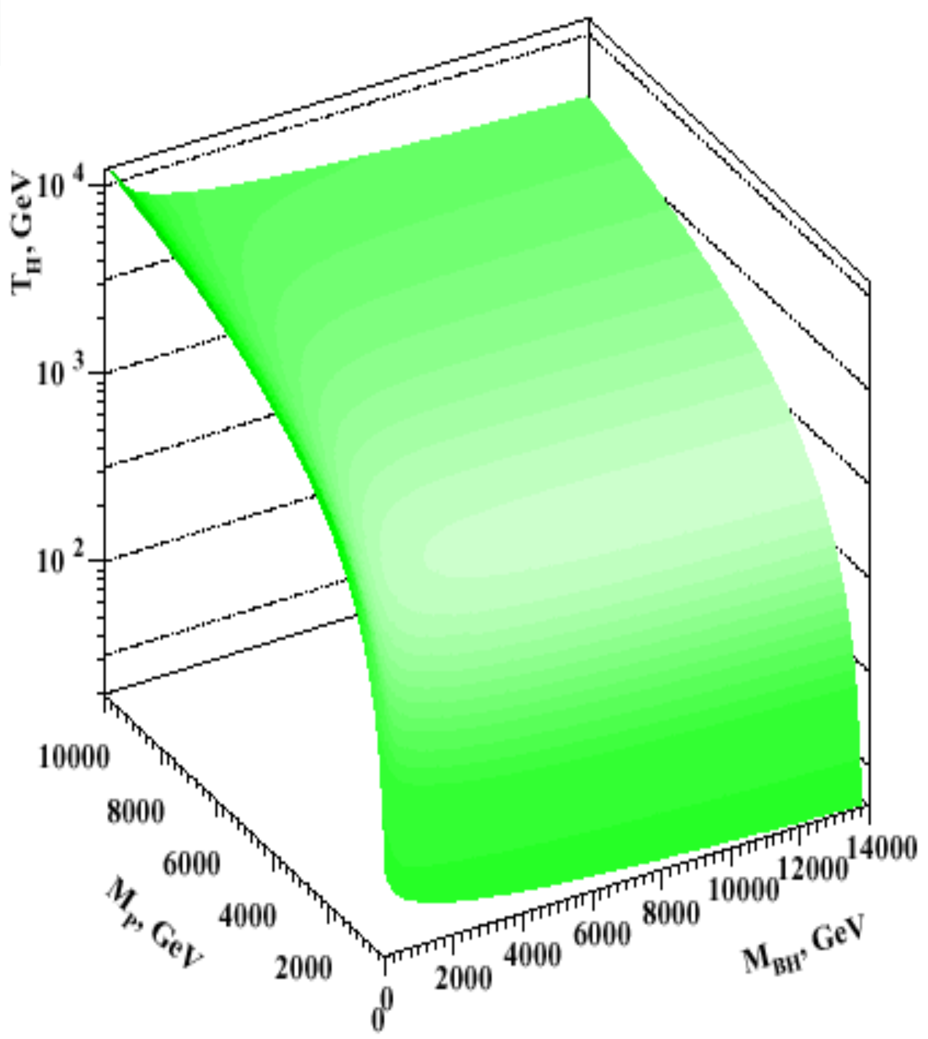


Black Hole Decay

- Hawking temperature: $R_S T_H = (n+1)/4\pi$ (in natural units $\hbar = c = k = 1$)
- BH radiates mainly in our 3D world: Emparan/Horowitz/Myers [PRL **85**, 499 (2000)]
  - $\lambda \sim 2\pi/T_H > R_S$; hence, the BH is a point radiator, producing s-waves, which depends only on the radial component
  - The decay into a particle on the brane and in the bulk is thus the same
  - Since there are much more particles on the brane, than in the bulk, decay into gravitons is largely suppressed
- Democratic couplings to ~120 SM d.o.f. yield probability of Hawking evaporation into γ, $\ell^{\pm}$, and ν ~2%, 10%, and 5% respectively
- Averaging over the BB spectrum gives average multiplicity of decay products:

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



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

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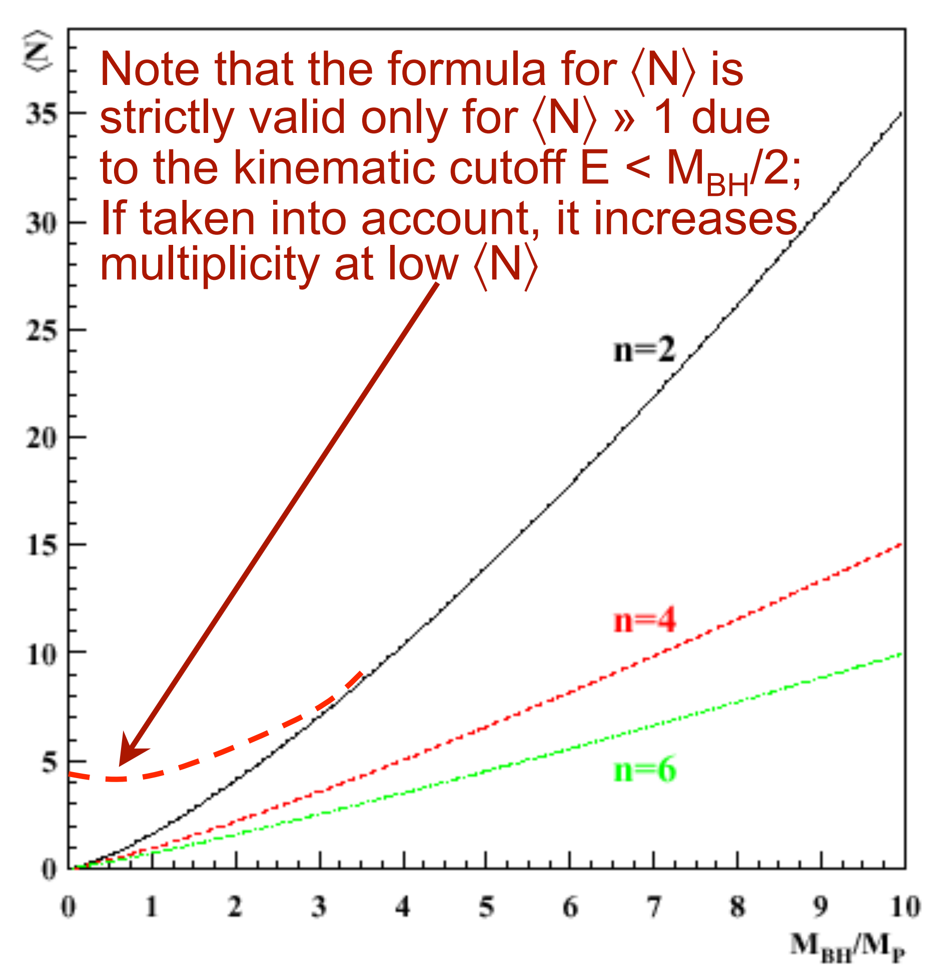

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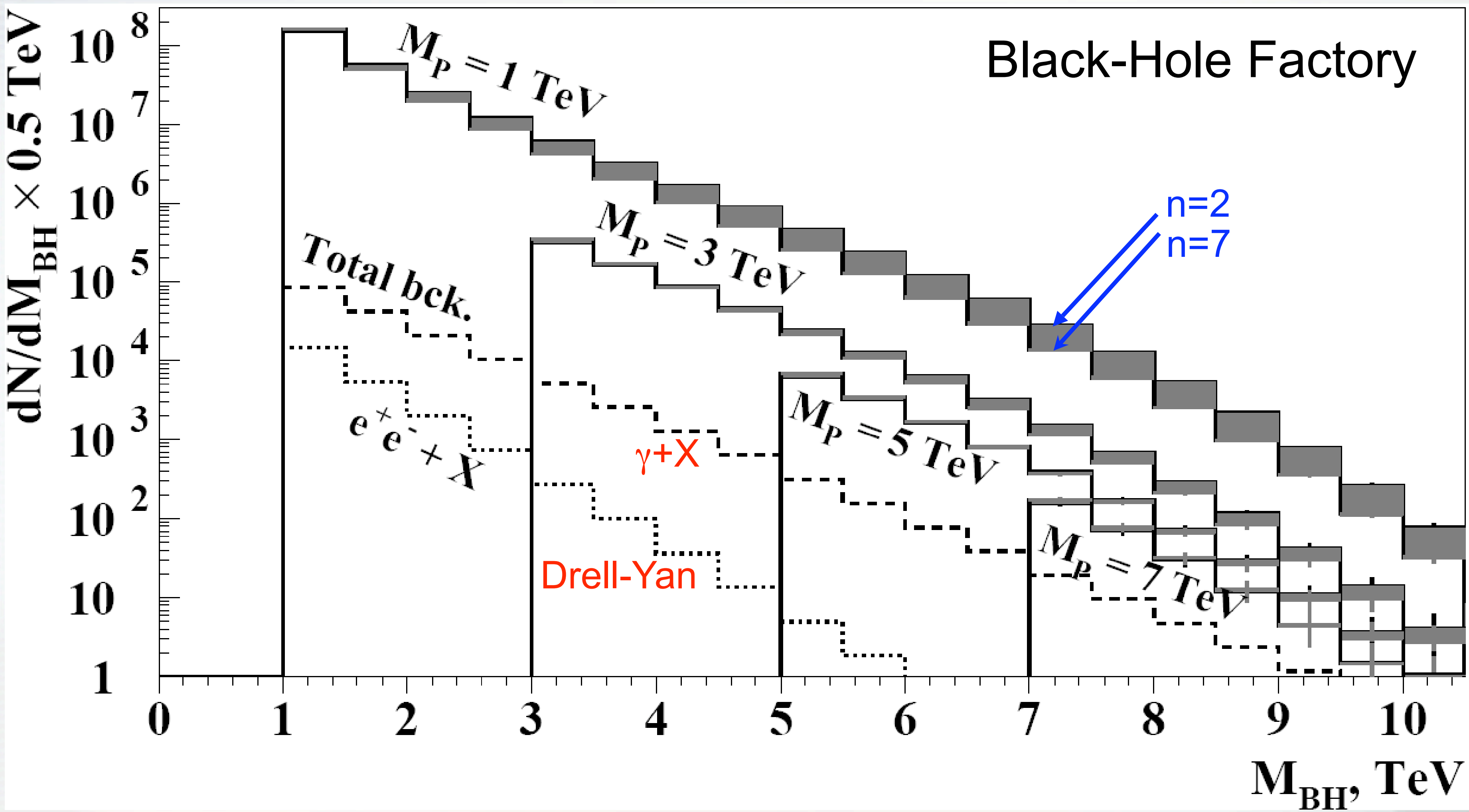
Black Hole Factory

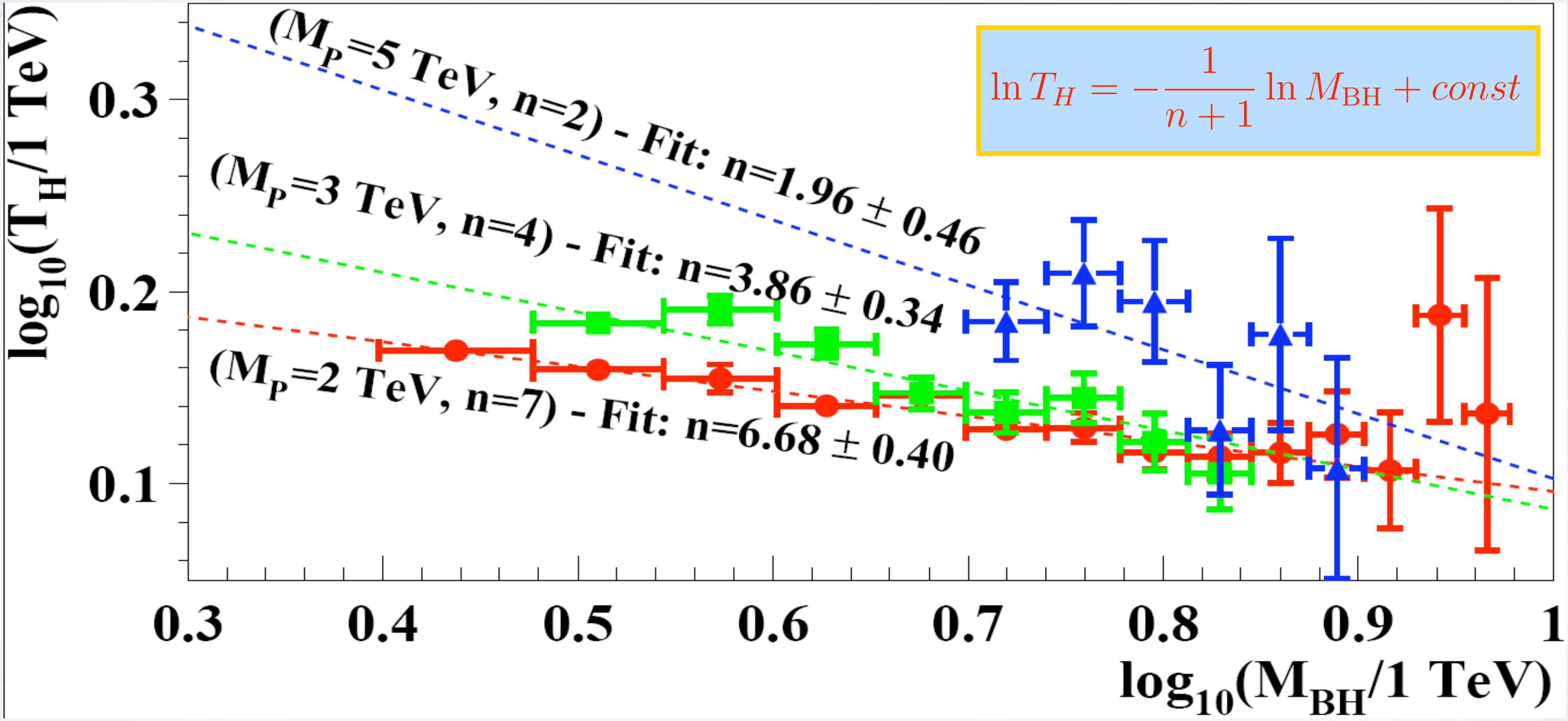
Dimopoulos, GL [PRL **87**, 161602 (2001)]



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

Shape of Gravity at the LHC

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



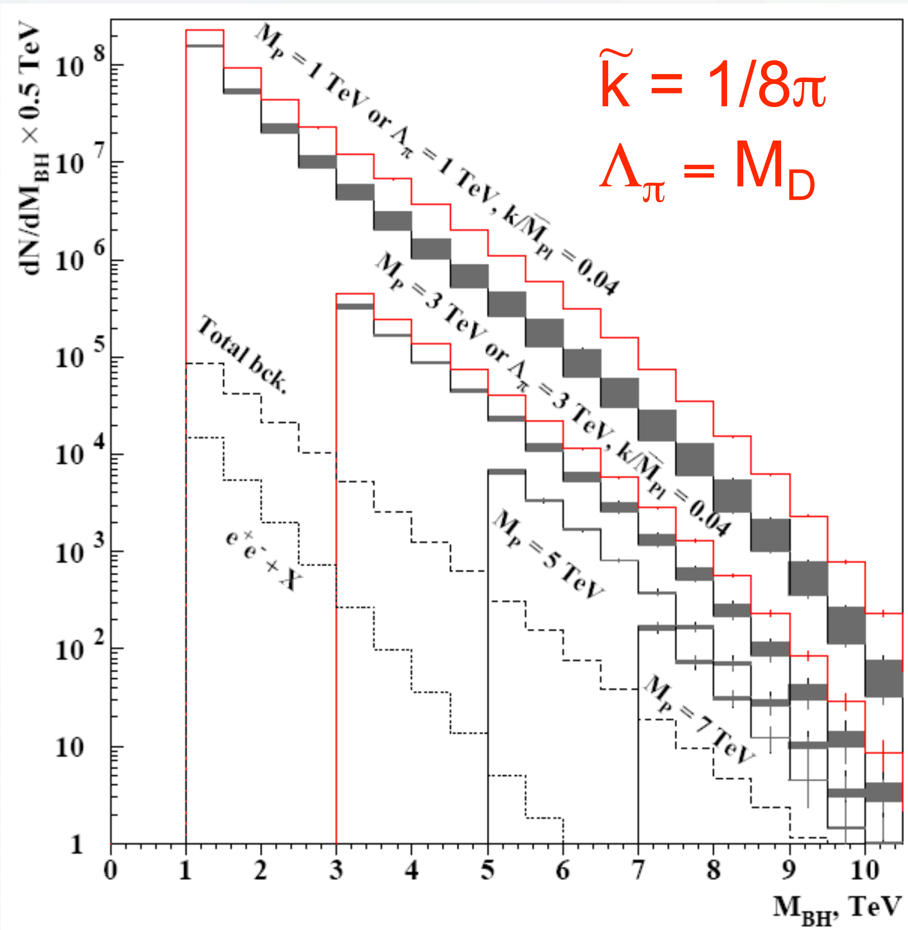
- Relationship between $\log T_H$ and $\log M_{BH}$ allows to find the number of ED
  - This result is independent of their shape!
  - This approach drastically differs from analyzing other collider signatures and would constitute a "smoking cannon" signature for a TeV Planck scale

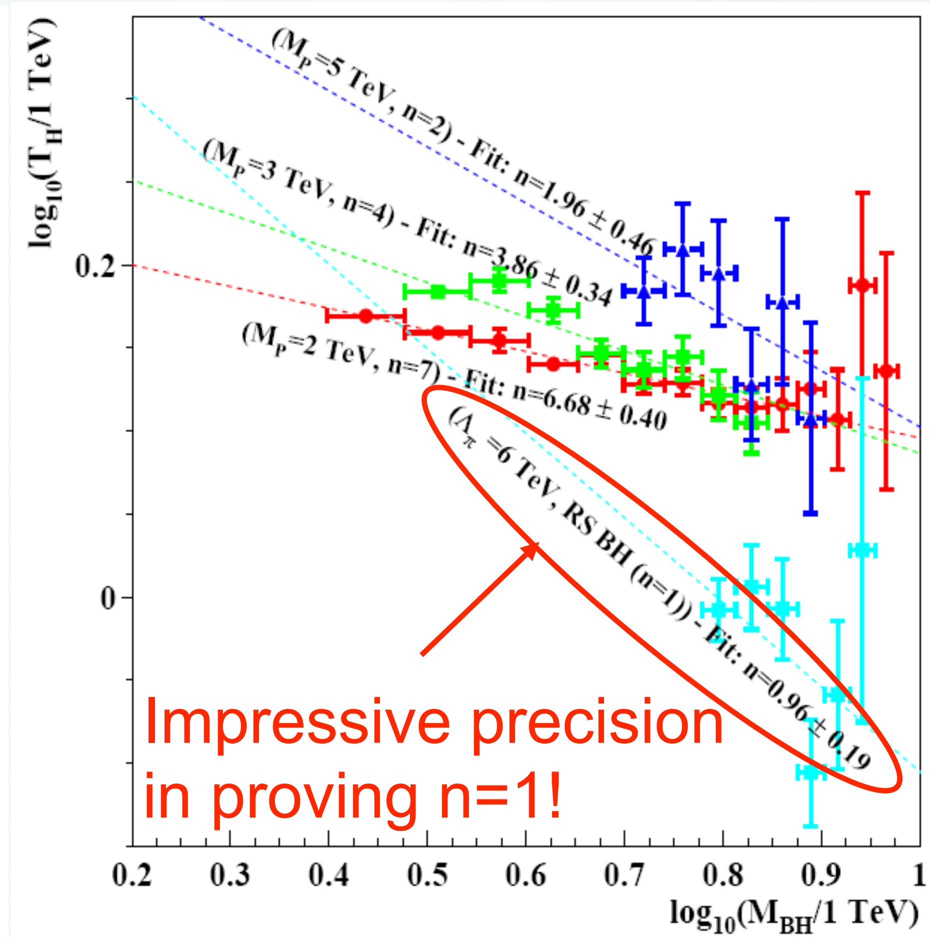
Randall-Sundrum Black Holes

- Not nearly as studied as BH in large ED
  - Originally suggested in Anchordoqui, Goldberg, Shapere [PRD **66**, 024033 (2002)]
  - A few authors extended work to various cases: Rizzo [JHEP **0501**, 28 (2005); hep-ph/0510420; hep-ph/0603242]; Stojkovic [PRL **94**, 011603 (2005)]
  - The event horizon has a pancake-like shape (squashed in the 5th dimension by $e^{-k\pi r}$)
- Nevertheless, the comparison with the ADD BH is trivial, GL [J. Phys. **G32**, R337 (2006)]
  - If $R_S e^{-k\pi r} << \pi r$ the BH is still "small" and can be treated as a 5D BH in flat space (ignoring the AdS curvature at the SM brane $\sim k^2 << 1$)
  - For BH production, Λ_π in the RS model plays the same role as the fundamental Planck scale M_D in the ADD model
  - Recent paper by Meade/Randall [arXiv:0708.3017] used a different characteristic scale: $\overline{M_{\rm Pl}} e^{-k\pi r}$, which resulted in a more conservative cross section estimate

RS BH: Samples & Wien's Law

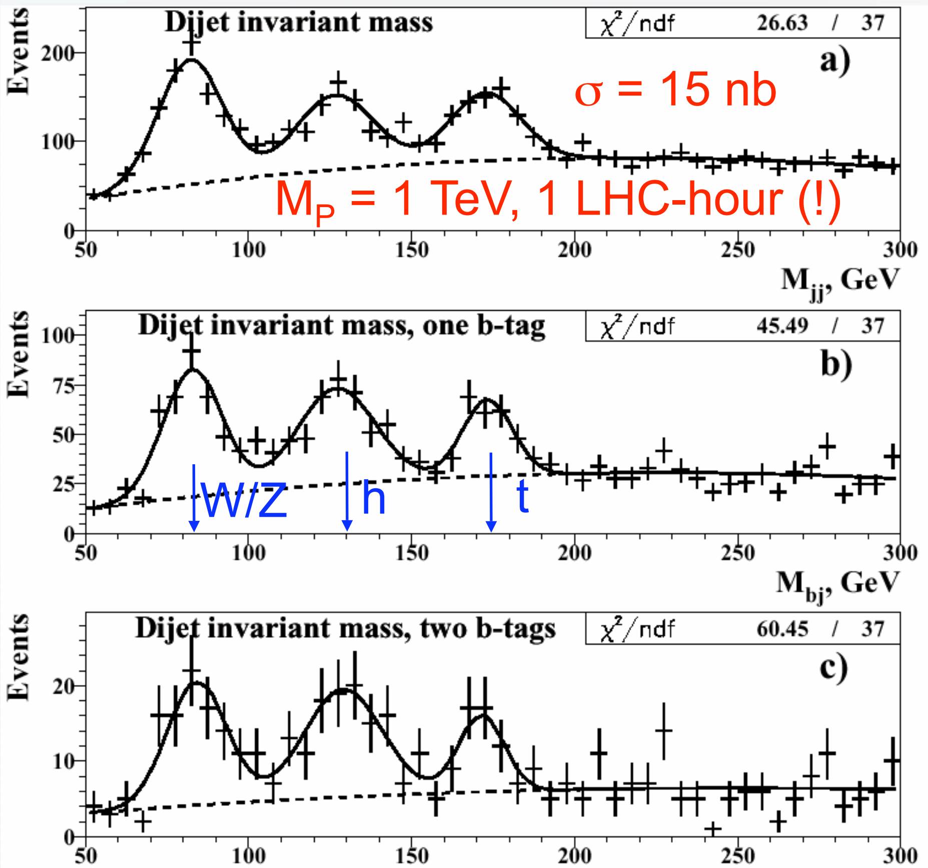
100 fb^{-1} @ the LHC





New Physics in BH Decays

- Example: Higgs with the mass of 130 GeV decays predominantly into $b\bar{b}$
  - Tag BH events with leptons or photons, and look at the dijet invariant mass; does not even require b-tagging!
- Use typical LHC detector response to obtain realistic results



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

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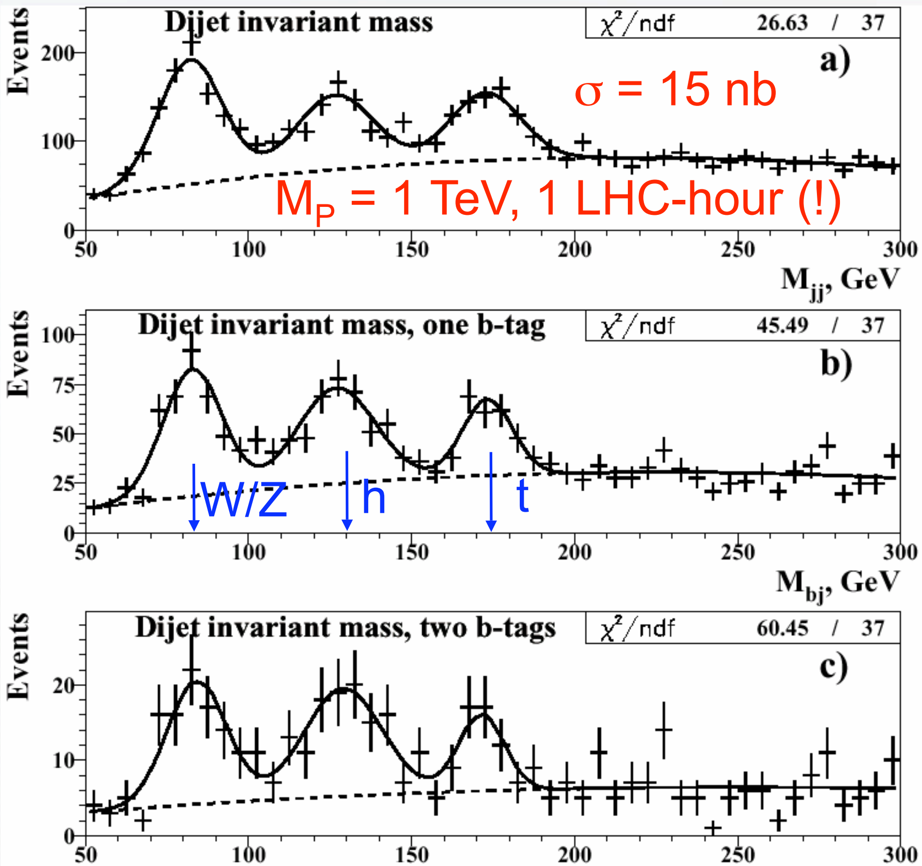

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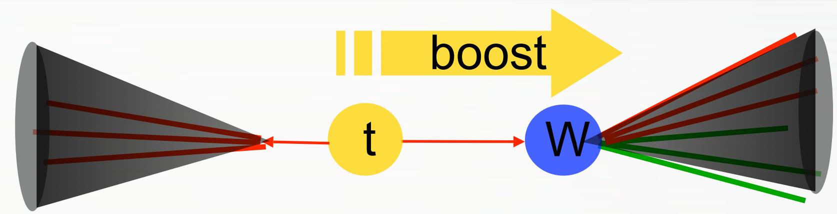

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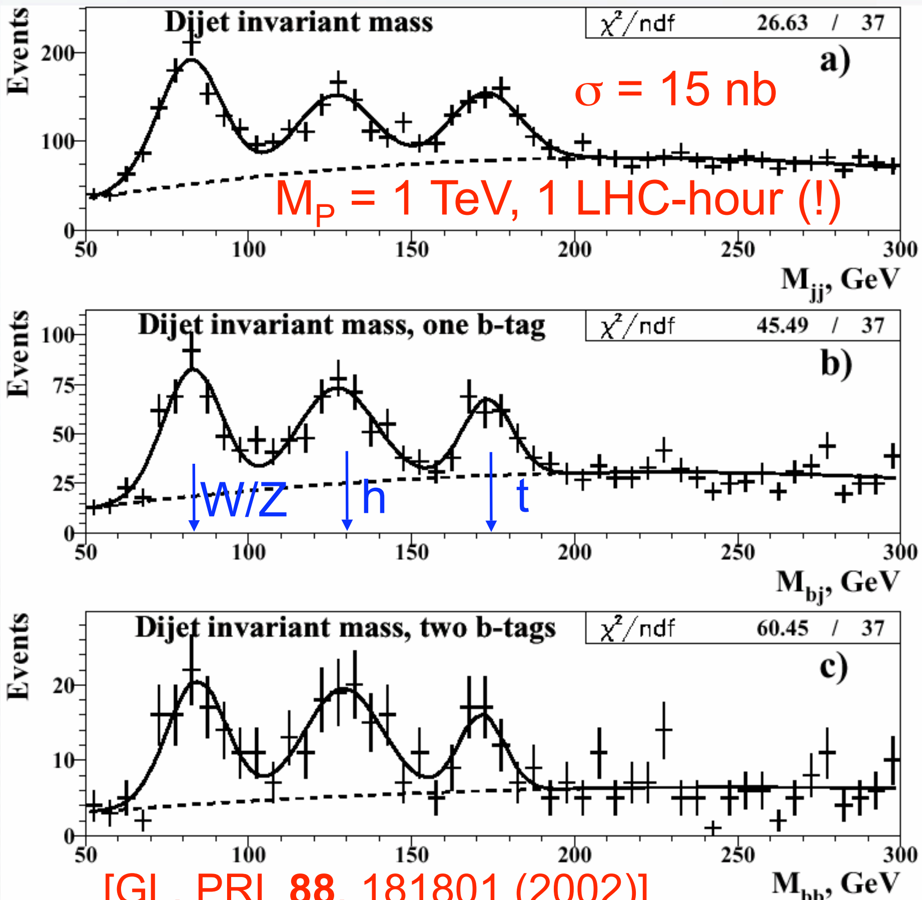

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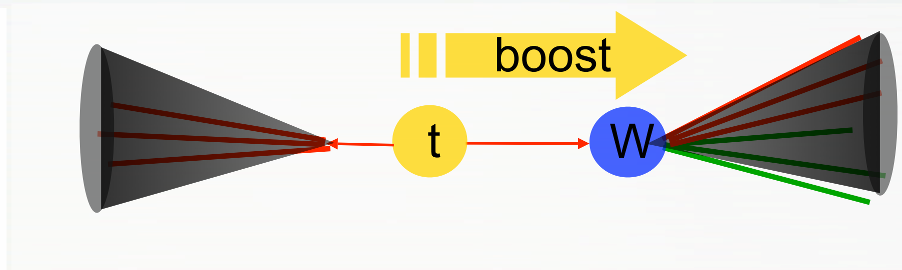
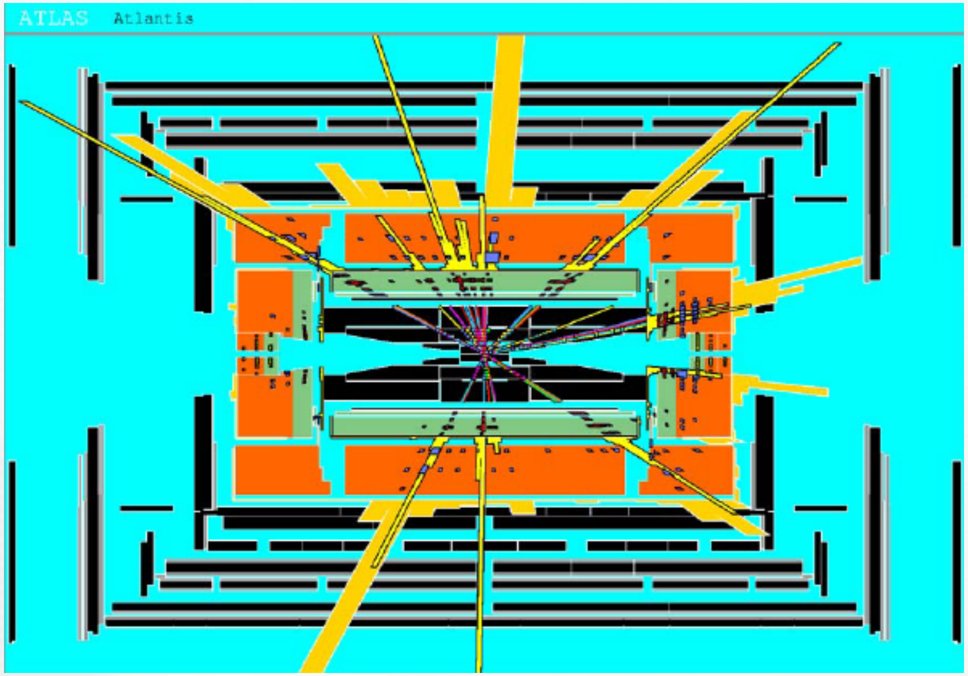


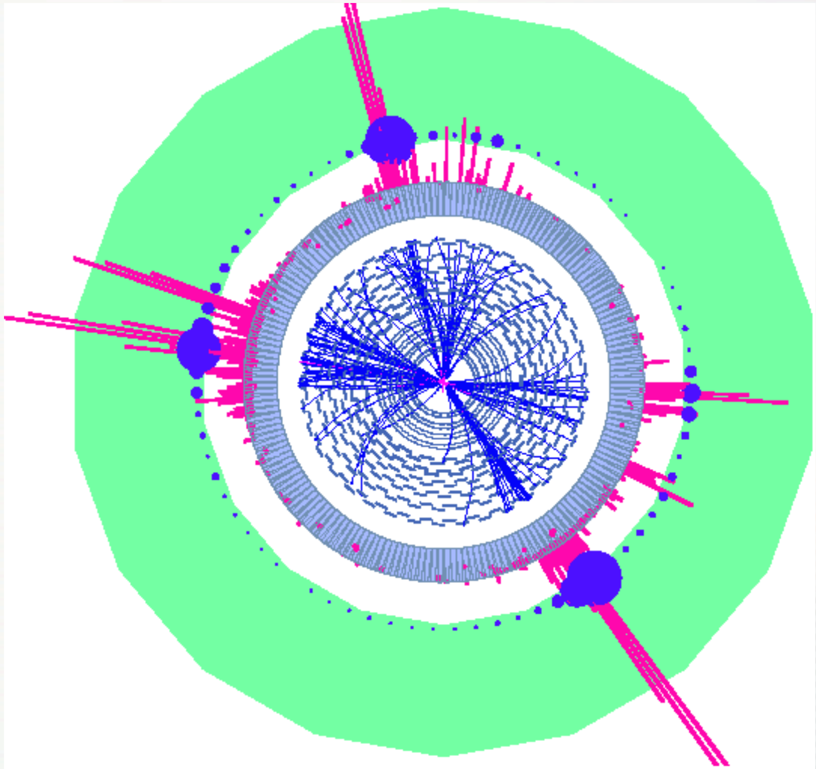
- Higgs observation in the black hole decays is possible at the LHC as early as in the first day of running even with the incomplete and poorly calibrated detectors!
- For M_P = 1, 2, 3, and 4 TeV one needs 1 day, 1 week, 1 month, or 1 year of running to find a 5σ signal
- Higgs is just an example – this applies to most of the new particles with the mass ~100 GeV

Black Hole Events

- Detailed studies already started in ATLAS and CMS
  - ATLAS –CHARYBDIS (HERWIG-based generator with an elaborated decay model by Harris/Richardson/Webber)
  - CMS – TRUENOIR, GL/CHARYBDIS
- The hunt is going on!



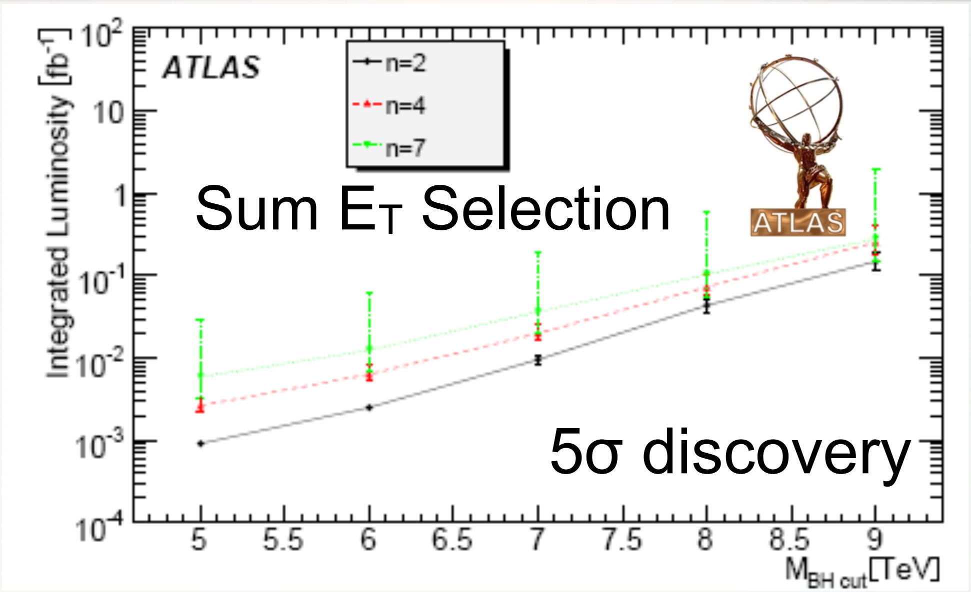
Simulated black hole event in the ATLAS detector, from ATLAS-Japan Group

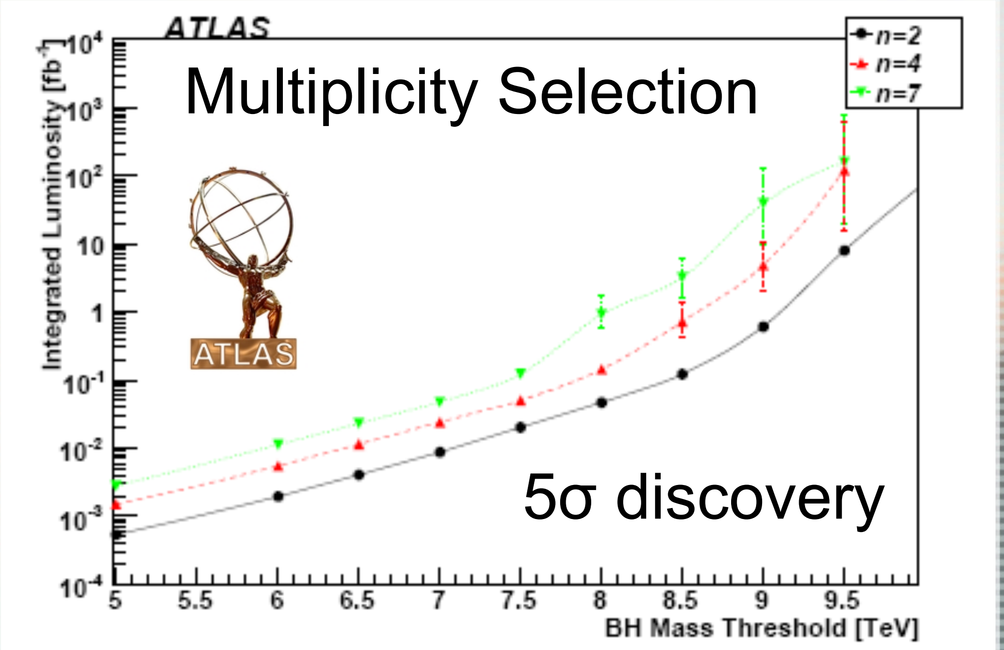


Simulated black hole event in the CMS detector, A. deRoeck & S. Wynhoff

ATLAS Early Search for Black Holes

- Considered two selections:
  - Sum E_T selection: S_T > 2.5 TeV, p_T^l > 50 GeV
  - Multiplicity selection: require at least four energetic objects (p_T > 200 GeV) in the final state; at least one is lepton
- For M_D of 1 TeV discovery of >5 TeV BH's is possible with a fraction of fb^{-1}





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  - Attempts to solve the hierarchy problem and other problems of the SM via an alternative framework

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- Possibility of Extra Dimensions in space is a bold theoretical idea, which recently has acquired a new face:
  – Attempts to solve the hierarchy problem and other problems of the SM via an alternative framework
- Enormous amount of interest in the past 10 years, both on the theoretical/phenomenological and on experimental sides

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- Such a possibility would fulfill our dreams for Grand Unification of an ultimate kind: that of particle physics, astrophysics, and cosmology!