Searches for Extra Dimensions and Black Holes at Colliders

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Outline

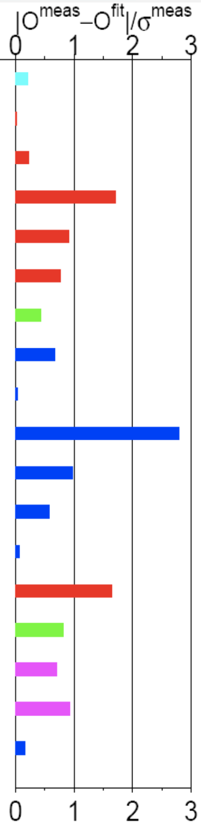
- The Hierarchy Problem
- Intro into Extra Dimensions
- Gravity Measurements at Short Distances
- Limits from Astrophysics and Cosmology
- Collider Searches for Extra Dimensions
- Black Holes at Colliders
- Conclusions

- Not in this talk (but I have slides, anyway):
  - Universal Extra Dimensions
  - Experimental Challenges
  - Randall-Sundrum Black Holes
  - Black Holes in Cosmic Rays
  - New Physics in Black Hole Decays

Standard Model: Beauty & the Beast

Beauty

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



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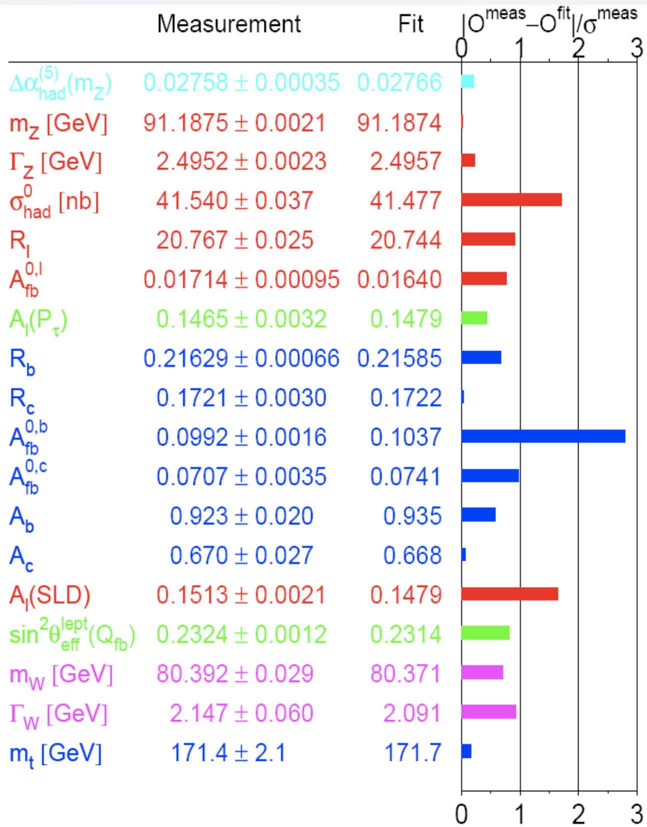

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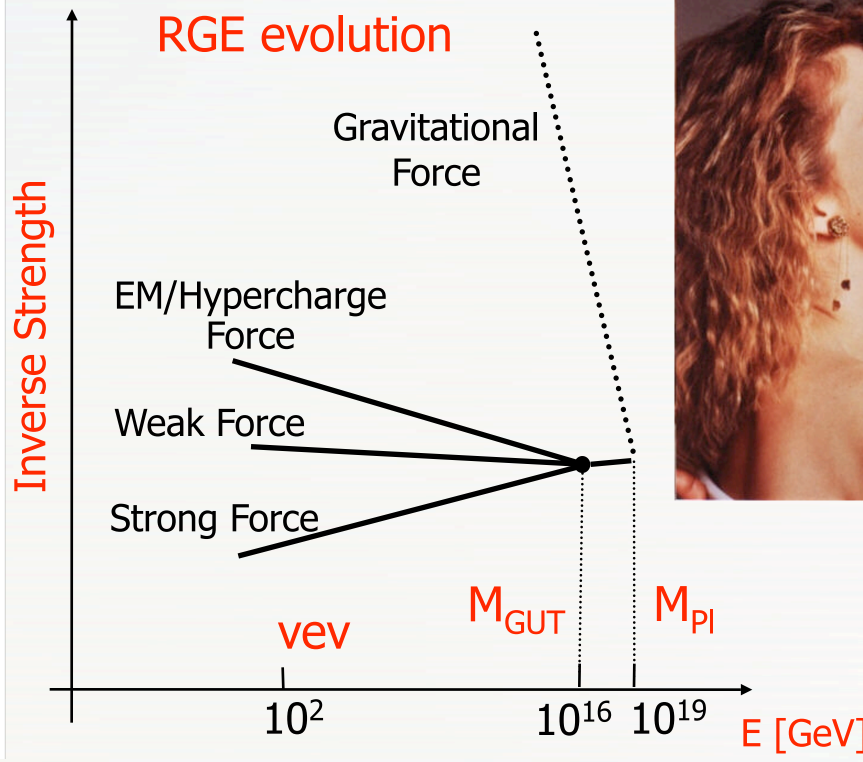

$M_{GUT}, M_{Pl} \gg vev$

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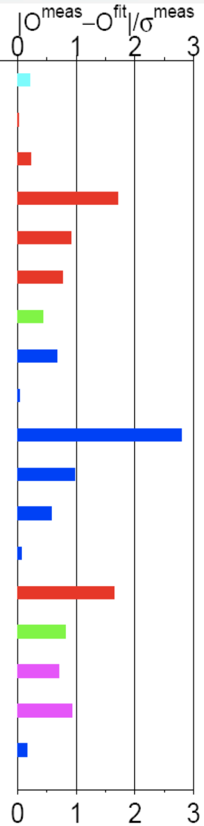
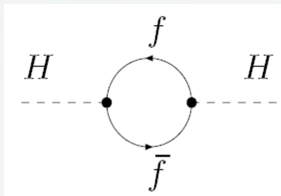


Extra spatial dimensions may get rid of the beast while preserving SM's natural beauty!

Naturalness and Triviality

- Higgs mass receives corrections from fermion loops:

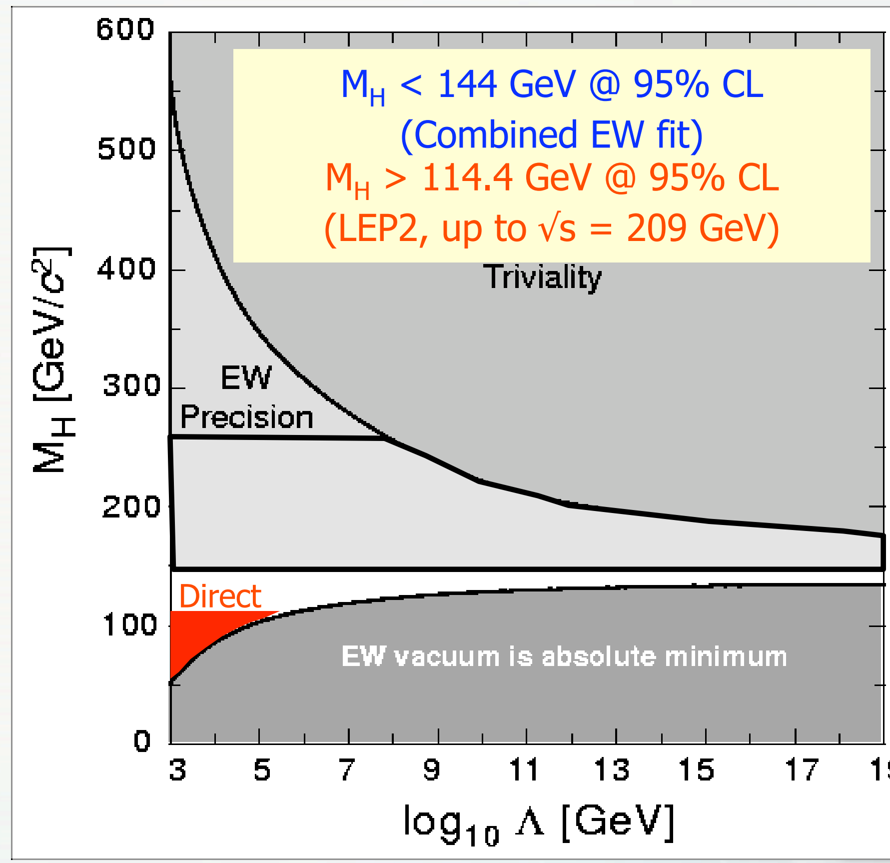


- The size of corrections is ~ to the UV cutoff (Λ) squared:

$$\Delta M_H^2 = \frac{\lambda_f^2}{4\pi^2}\left(\Lambda^2 + M_f^2\right) + \ldots$$

- In order for the Higgs mass to be finite, a fine tuning (cancellation) of various loops is required to a precision $\sim(M_H/\Lambda)^2 \sim 10^{-34}$ for $\Lambda \sim M_{Pl}$
- Higgs mass can't be too light or the potential won't have a Mexican hat shape and will turn negative at large values
- For the SM to be valid up to Planck scale, $M_H > 135$ GeV

- Triviality: if the Higgs mass is too large, the Higgs self-coupling drives the mass to infinity above certain scale
- If one wants the SM to be correct all the way up to Planck scale, $135 < M_H < 175$ GeV is required



Large Hierarchies Tend to Collapse…

Note: Some Hierarchies are …

Note: Some Hierarchies are Surprisingly Stable...

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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
  - Is it time to give up science for philosophy? – So far reductionist method worked very well!

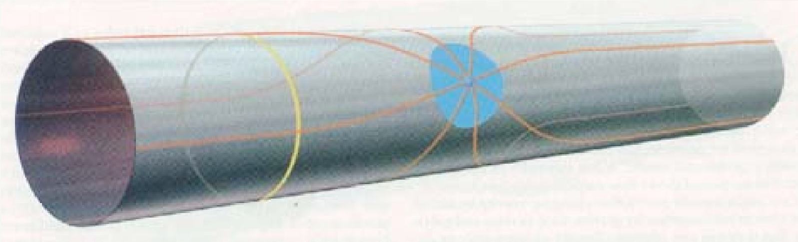
1998: Large Extra Dimensions

- 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
  - Radical 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?

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

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

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



- 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

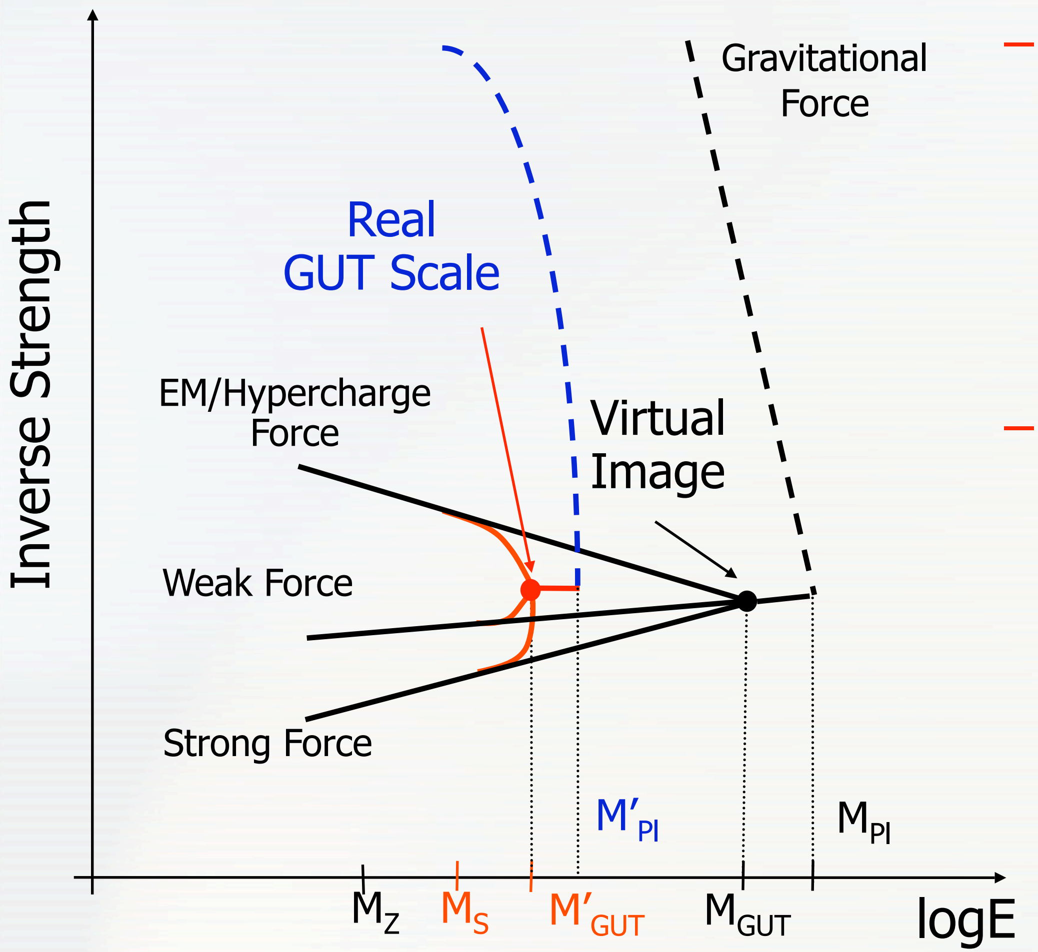
$$M_D^{n+2} \propto M_{Pl}^2/R^n$$

- More precisely, from Gauss's law:

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

- 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

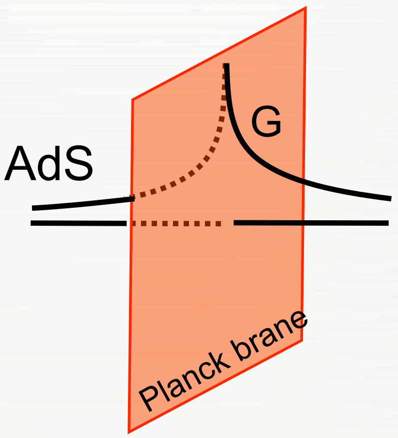
1998: TeV^{-1} Extra Dimensions

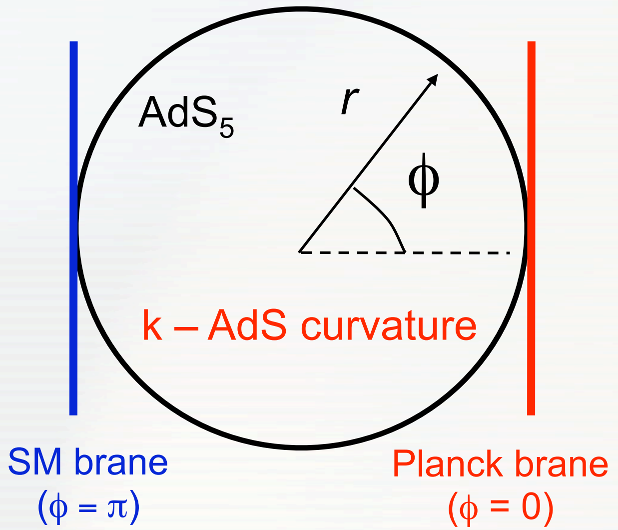


- Simultaneously, another idea has appeared:
  - Explore modification of force behavior in (3+n)-dimensions to achieve low-energy grand unification [Dienes, Dudas, Gherghetta, PL **B436**, 55 (1998)]
  - To achieve that, allow other force carriers (g, γ, W, and Z) to propagate in an extra dimension,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





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

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

Reduced Planck mass:

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

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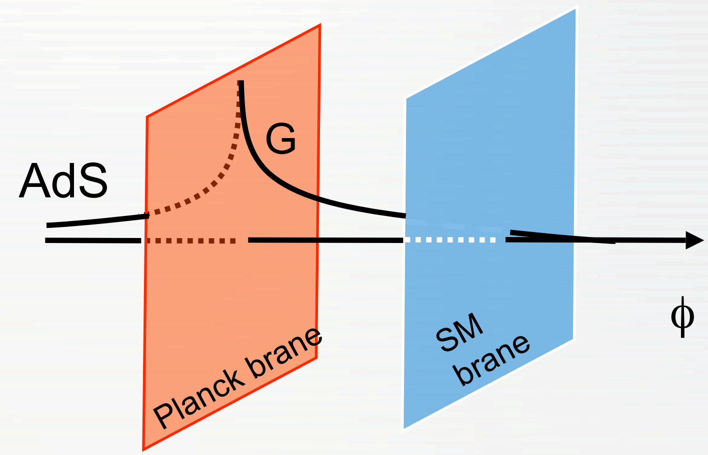

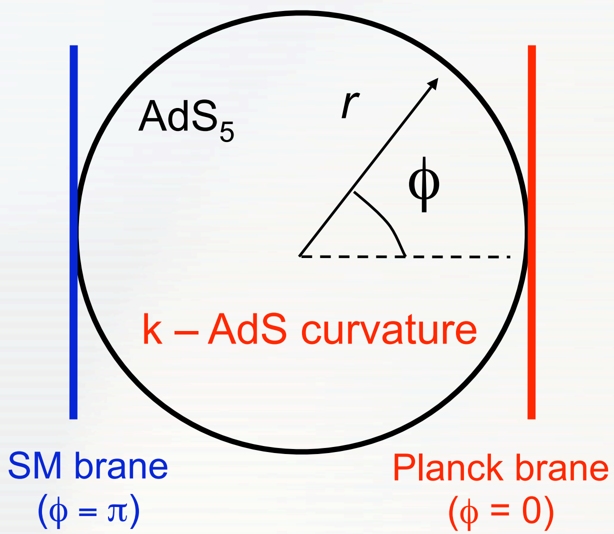

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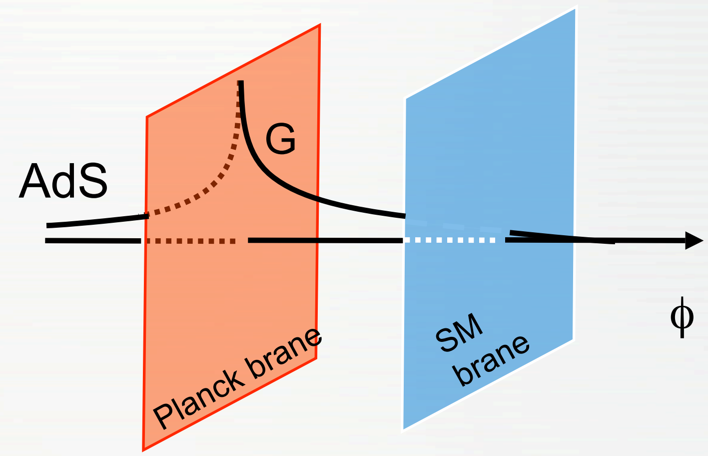

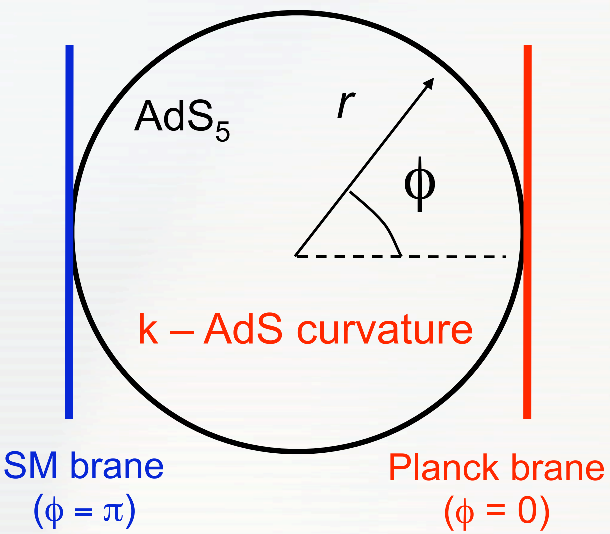

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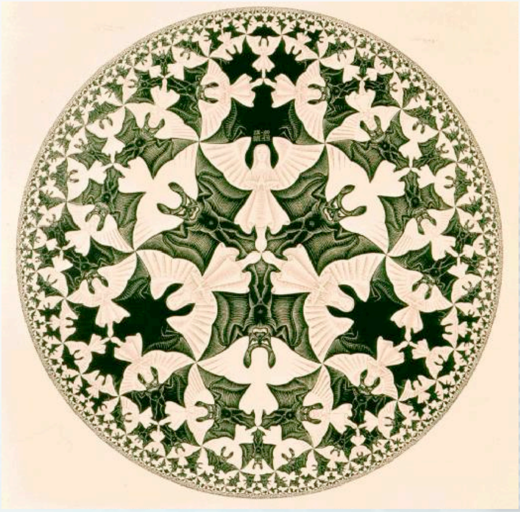
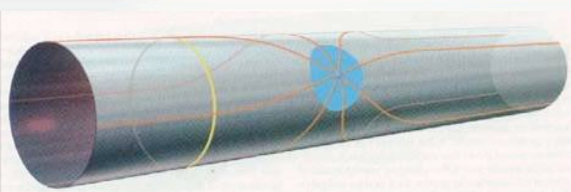


Extra Dimensions: a Brief Recap

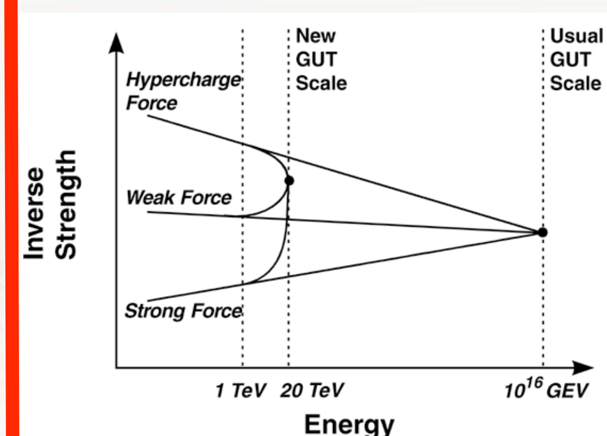
ADD Paradigm:

- 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



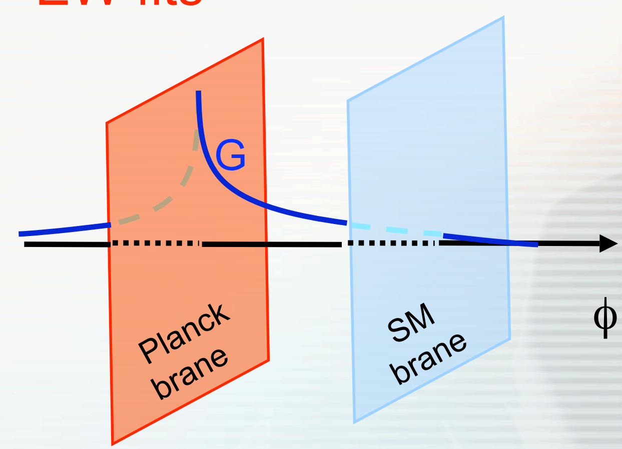
TeV^{-1} Scenario:

- 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:

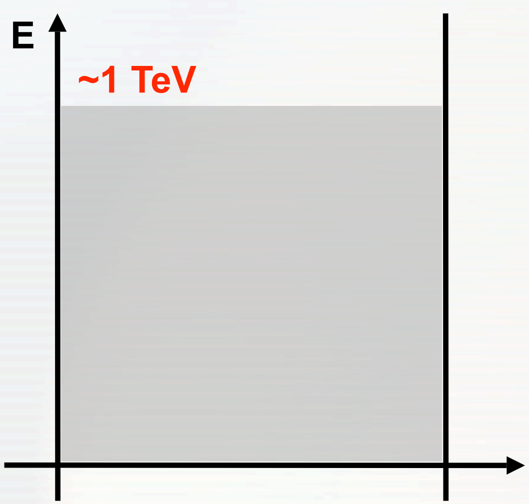
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

ADD Paradigm:

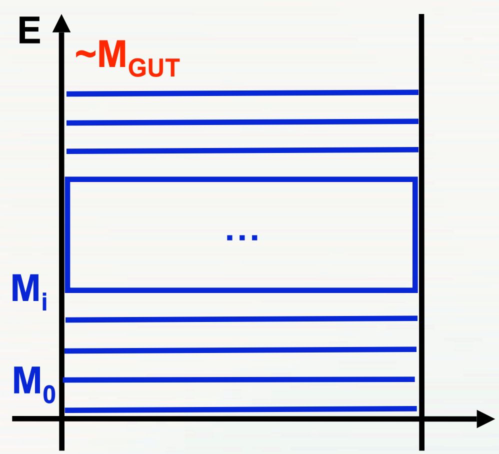
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Experimentally can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



TeV^{-1} Scenario:

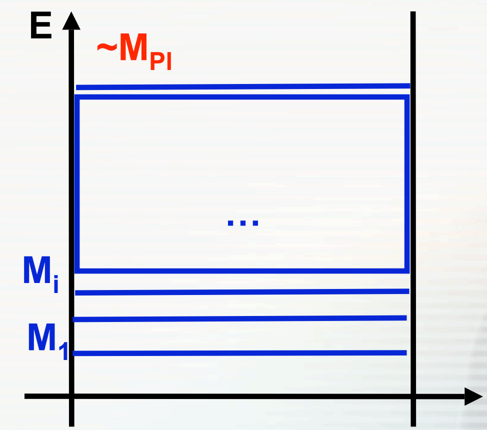
- Winding modes with nearly equal energy spacing ~1/r, i.e. ~ 1 TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: ~g_W per mode

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



RS Model:

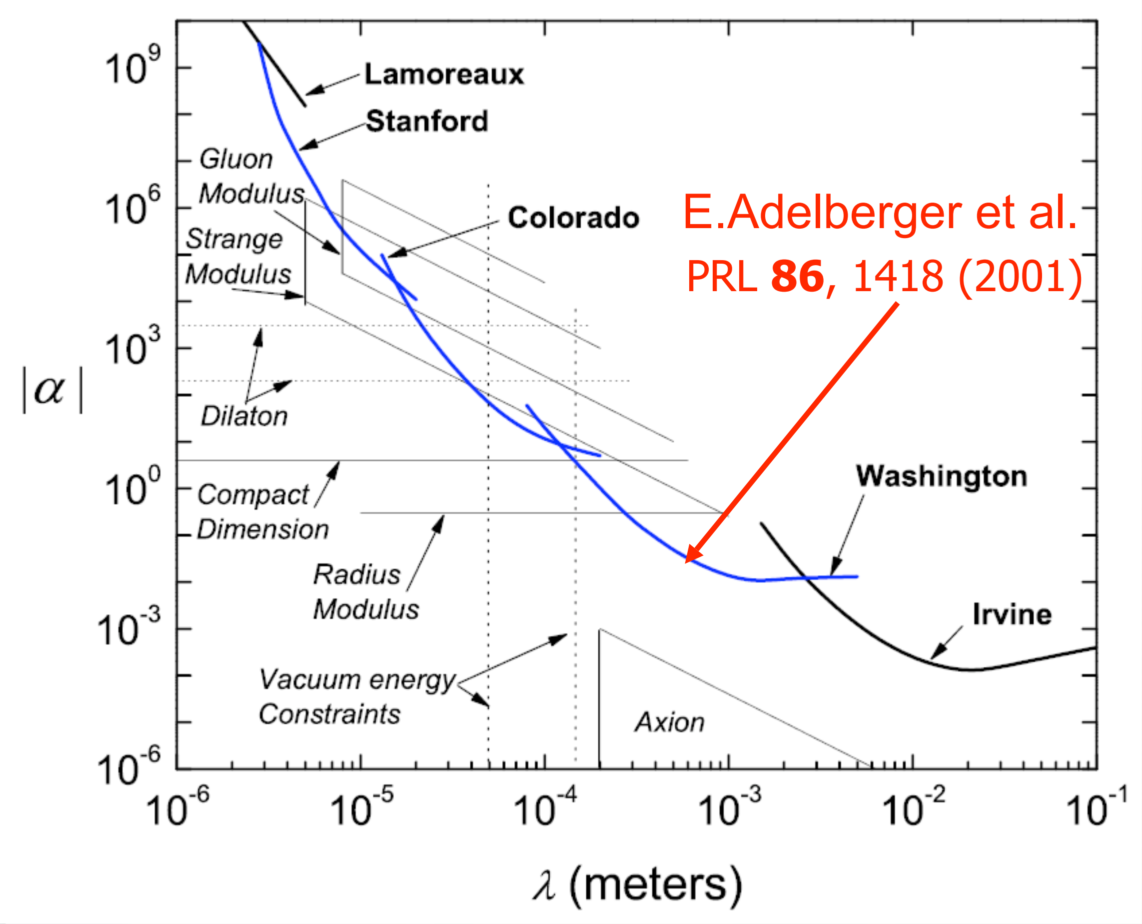
- "Particle in a box" with special AdS metric
- Energy eigenvalues are given by the zeroes of Bessel function J_1
- Light modes might be accessible at colliders
- Coupling: G_N for the zero mode; $1/\Lambda_\pi^2$ for the others



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

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

Large ED: Gravity at Short Distances

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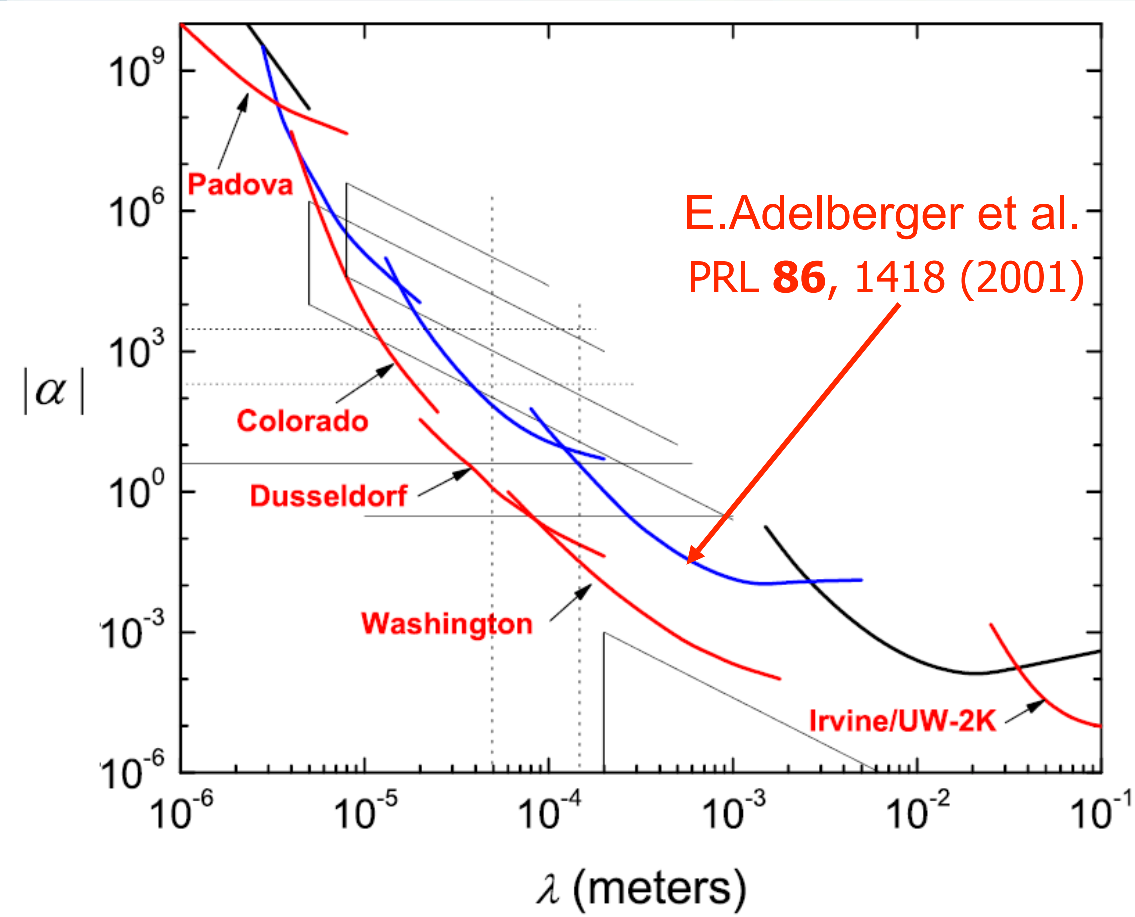

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Large ED: Astro & Cosmo Constraints

- Supernova cooling due to graviton emission – an alternative cooling mechanism that would decrease the dominant cooling via neutrino emission
  - Tightest limits on any additional cooling sources come from the measurement of the SN1987A neutrino flux by the 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)]:
  - $M_D > 25\text{-}30$ TeV (n=2)
  - $M_D > 2\text{-}4$ 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)
- 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
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Collider Signatures for Large ED

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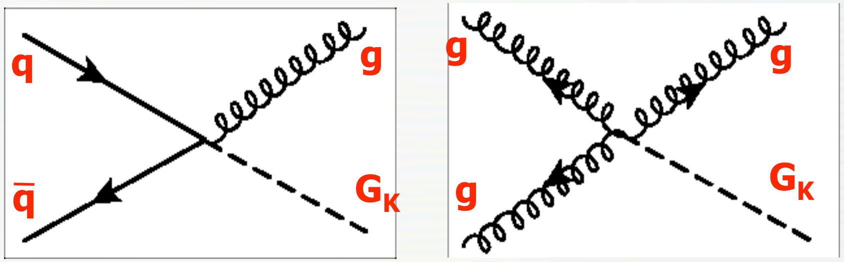
Real Graviton Emission

Monojets at hadron colliders



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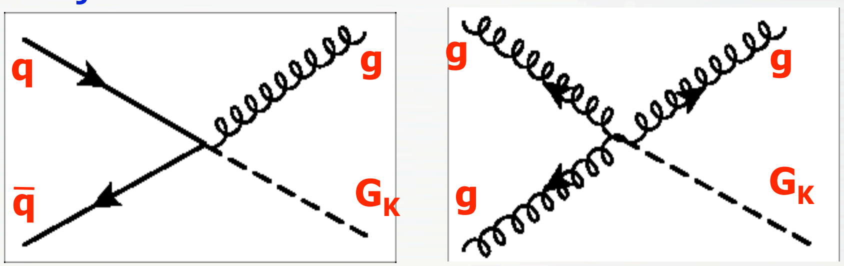
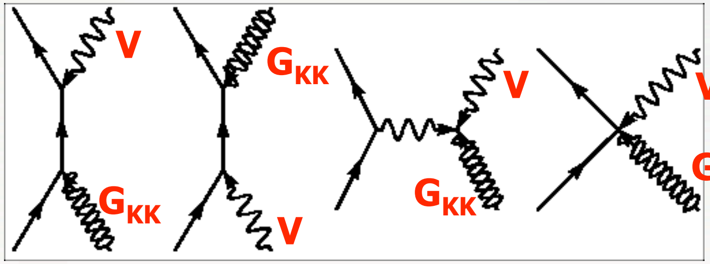


Single VB at hadron or e^+e^- colliders



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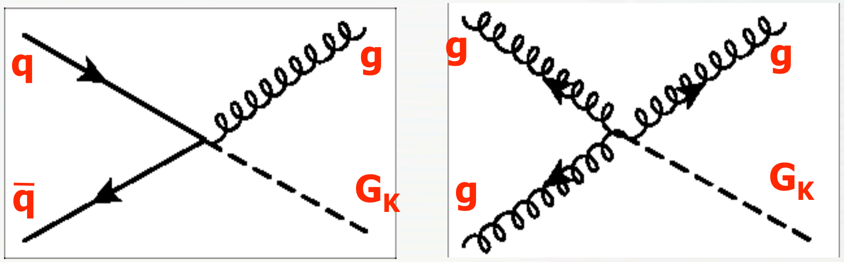

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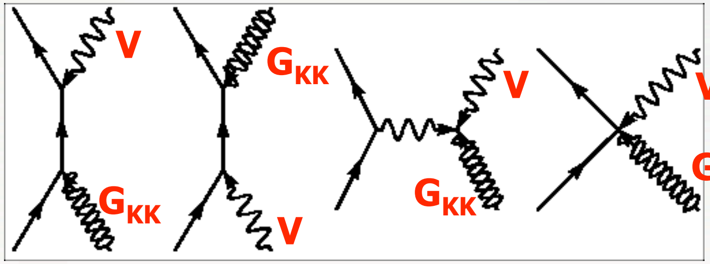
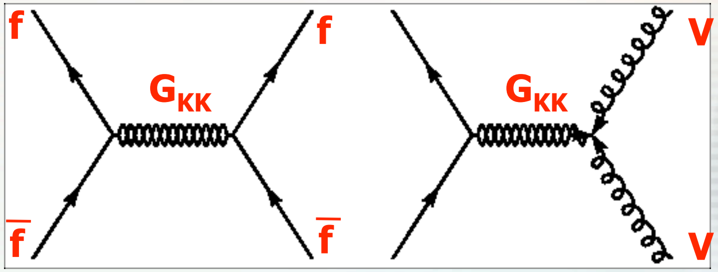


Virtual Graviton Effects

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
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 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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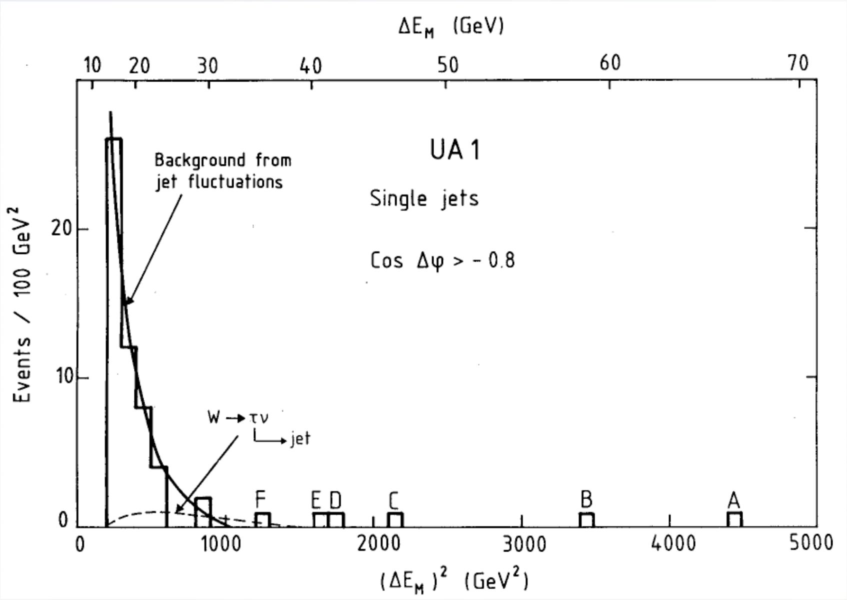
VOLUME 54, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 1985

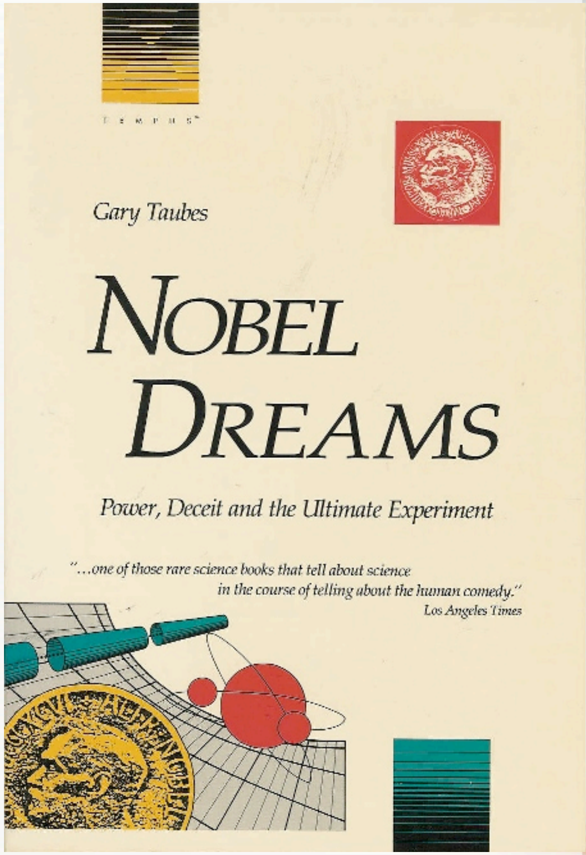
Monojets from *Z* Decay without Extra Neutrinos or Higgs Particles

Stephen F. King
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(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

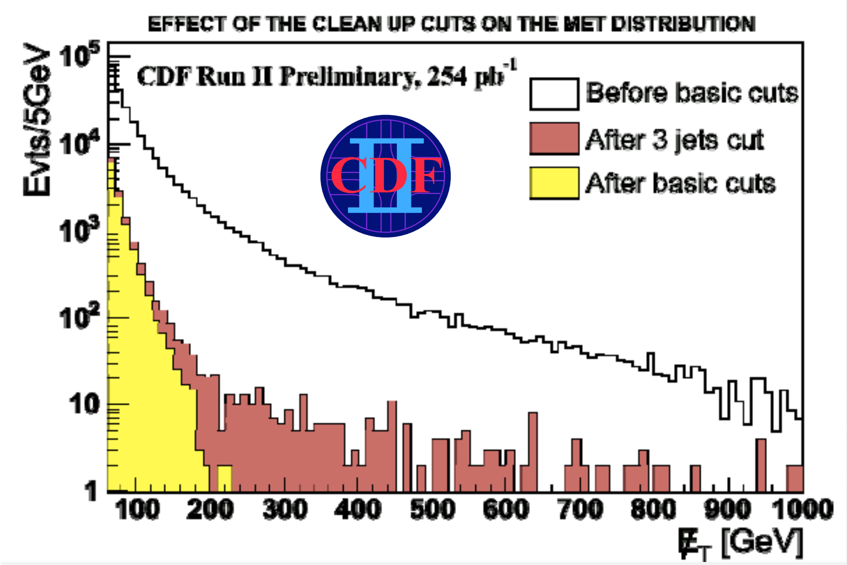


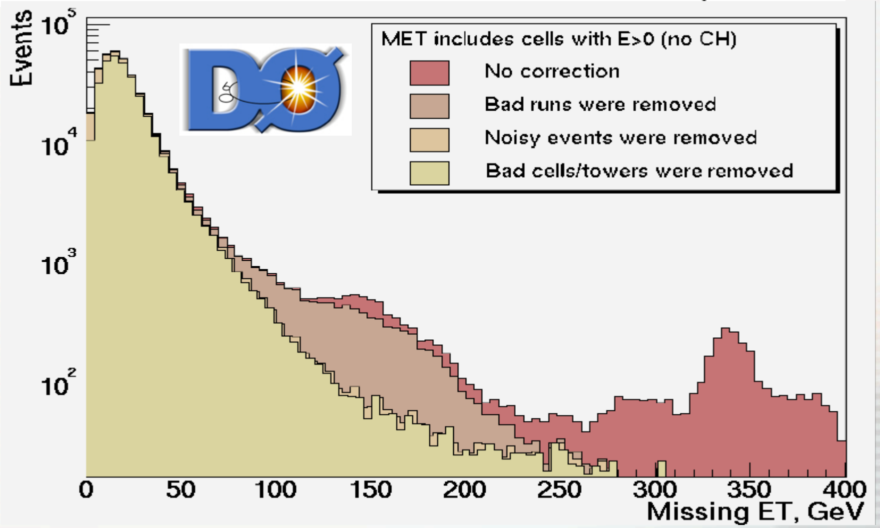


- These monojets turned out to be due to unaccounted background
- The signature was deemed doomed and nearly forgotten
- It took many years for successful monojet analyses at a hadron collider to be completed (CDF/DØ)

Why Jets+ME_T is Tough?

- Jets tend to fluctuate wildly:
  - Large shower fluctuation
  - Non-linear calorimeter response
  - Non-compensation (i.e., $e/h \neq 1$)
  - Fluctuations in the e/h energy ratio
- Instrumental effects:
  - Dead or “hot” calorimeter cells
  - Cosmic rays
  - Poorly instrumented area of the detector
- Note that in Run II DØ showed the first results in this channel only in 2005 (4 years into the run); CDF made their results public and published them in 2006
- Likely not an early LHC running measurement!

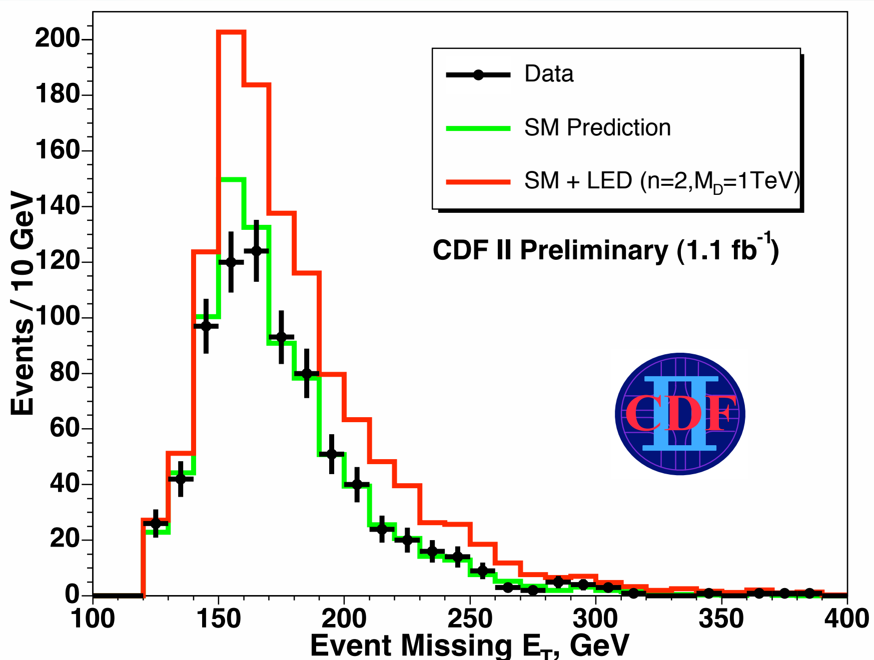


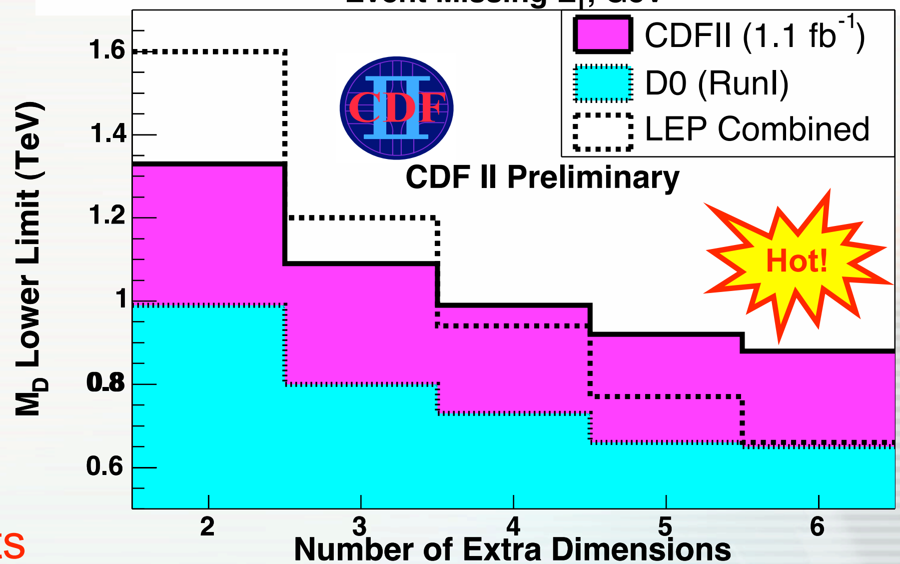


- Raw ME_T spectrum at the Tevatron and that after thorough clean-up

Tevatron: Large ED Search via Monojets

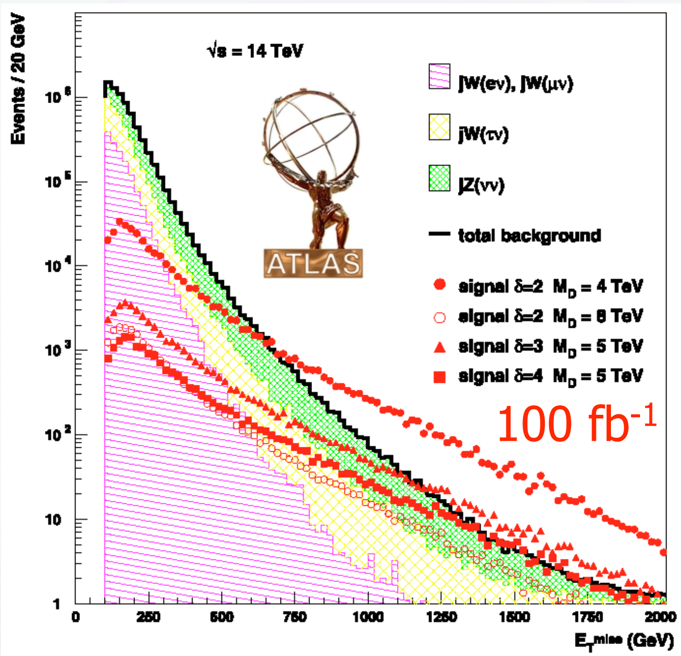
- jets + ME_T final state
- $Z(\nu\nu)$+jets is irreducible background
  - Challenging signature due to large instrumental backgrounds from jet mismeasurement, cosmics, etc.
- DØ pioneered this search and set limits [PRL, **90** 251802 (2003)] M_P > 1.0-0.6 TeV for n=2…7
- New CDF analysis w/ 1.1 fb^{-1}
  - 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 $Z(\nu\nu)$+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





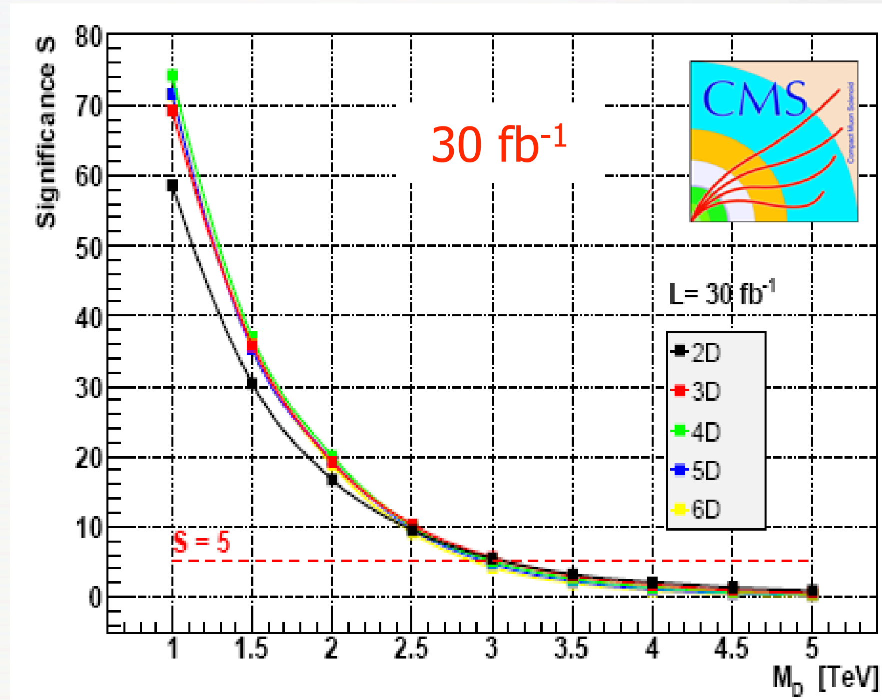
Expectations at the LHC

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



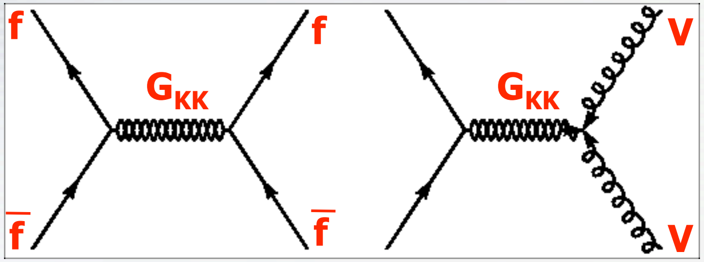
δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

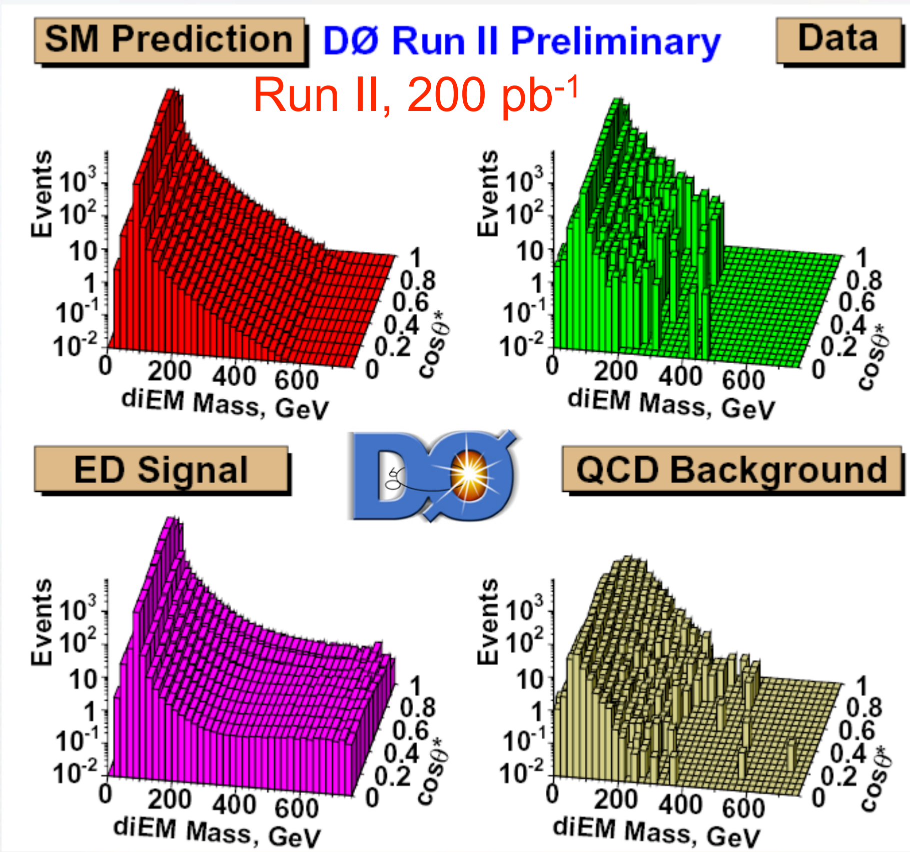
- Monophotons:
  - ATLAS and CMS simulations for 100 fb^{-1} and 30 fb^{-1}, respectively



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

Tevatron: Virtual Graviton Effects





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

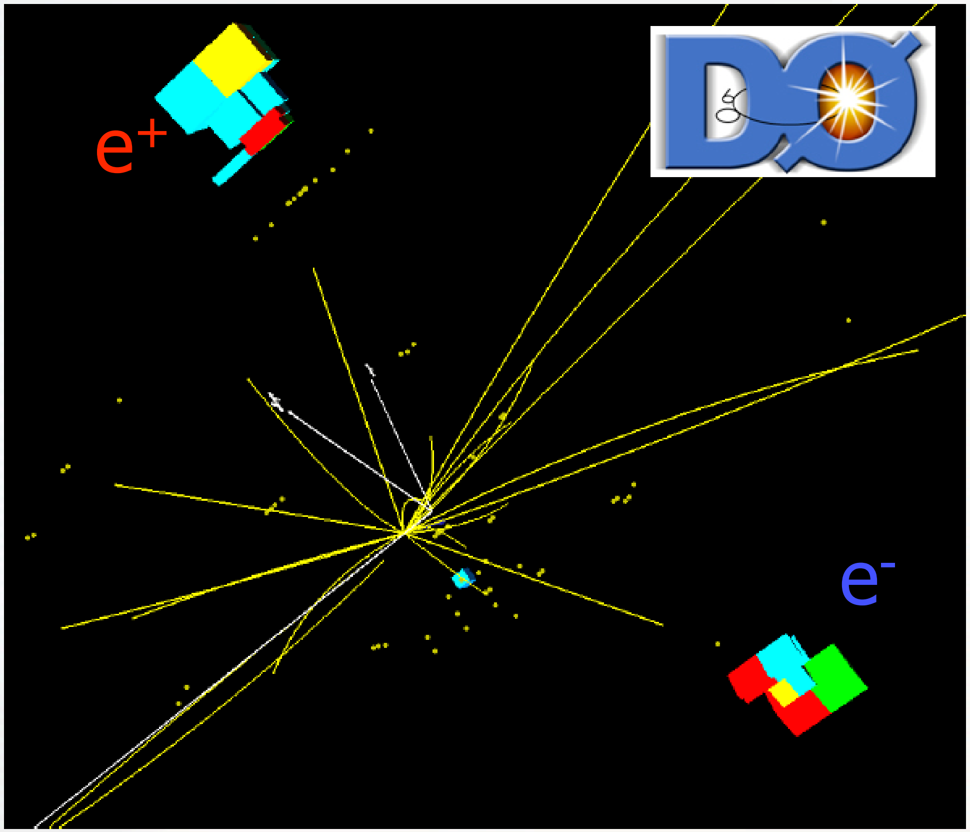
$$\frac{d^2\sigma}{d\cos\theta^* dM} = \frac{d^2\sigma_{SM}}{d\cos\theta^* dM} + \frac{a(n)}{M_S^4} f_1(\cos\theta^*, M) + \frac{b(n)}{M_S^8} f_2(\cos\theta^*, M)$$

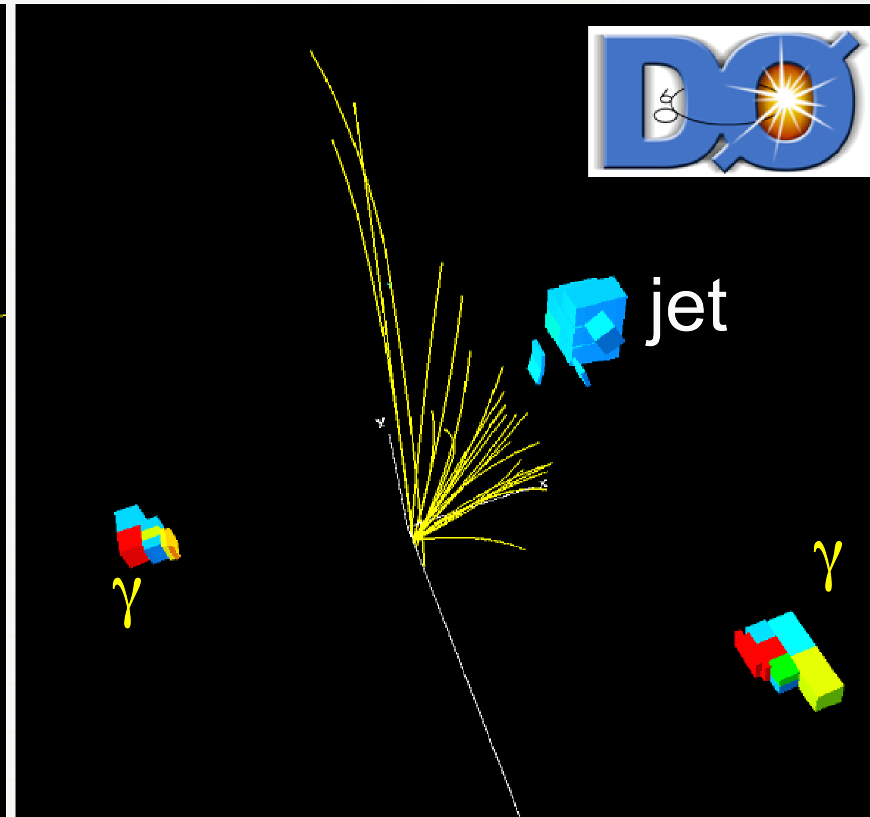
- High-mass, low $|\cos\theta^*|$ tail is a characteristic signature of LED [Cheung, GL, PRD **62** 076003 (2000)]
- Best limits on the effective Planck scale come from new DØ Run II data:
  - M_S > 1.1-1.6 TeV (n=2-7)
- Combined with the Run I DØ result:
  - M_S > 1.1-1.7 TeV – tightest to date
- Sensitivity in Run II and at the LHC:

	Run II, 2 fb^{-1}	LHC, 100 fb^{-1}
$e^+e^- + \mu^+\mu^-$	1.3-1.9 TeV	6.5-10 TeV
$\gamma\gamma$	1.5-2.4 TeV	7.5-12 TeV
$e^+e^- + \mu^+\mu^- + \gamma\gamma$	**1.5-2.5 TeV**	**7.9-13 TeV**

Interesting Candidate Events

- While the DØ data are consistent with the SM, the two highest-mass candidates have anomalously low value of cosθ* typical of ED signal:

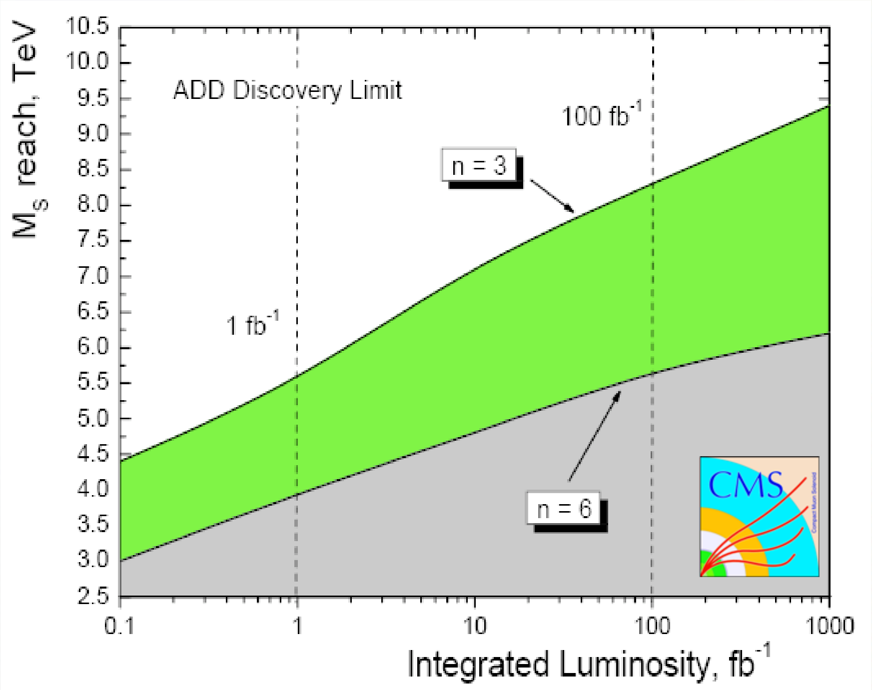




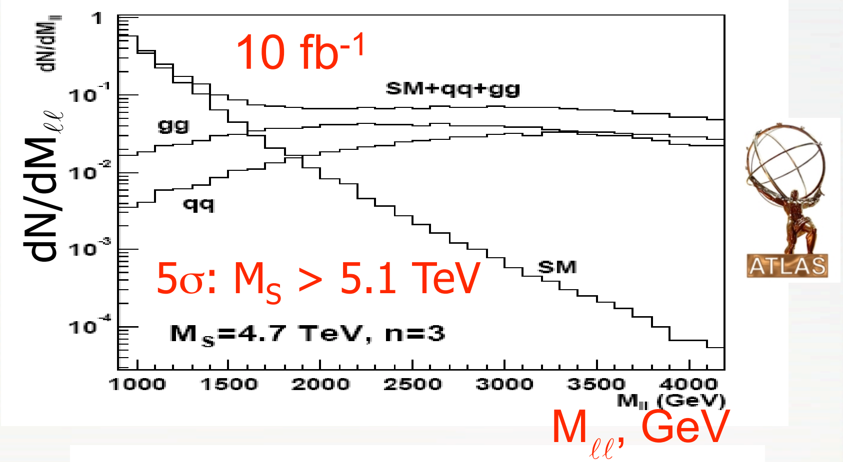
Event Callas: M_{ee} = 475 GeV, cosη* = 0.01 Event Farrar: $M_{\gamma\gamma}$ = 436 GeV, cosη* = 0.03

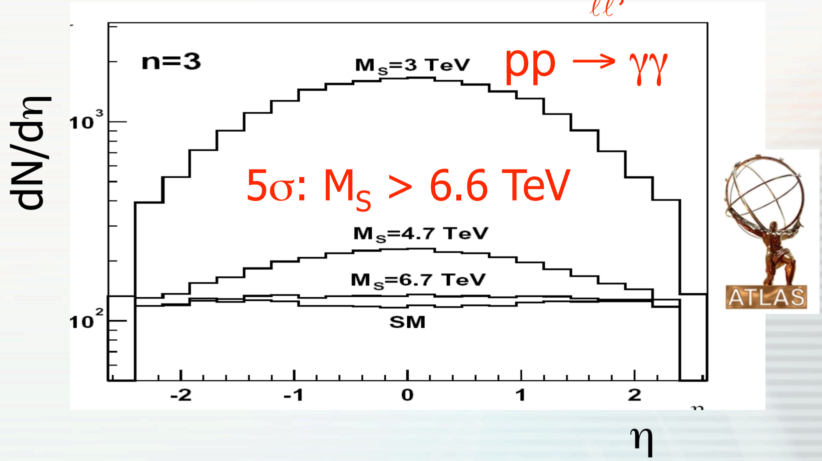
Virtual Graviton Effects at the LHC

- 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

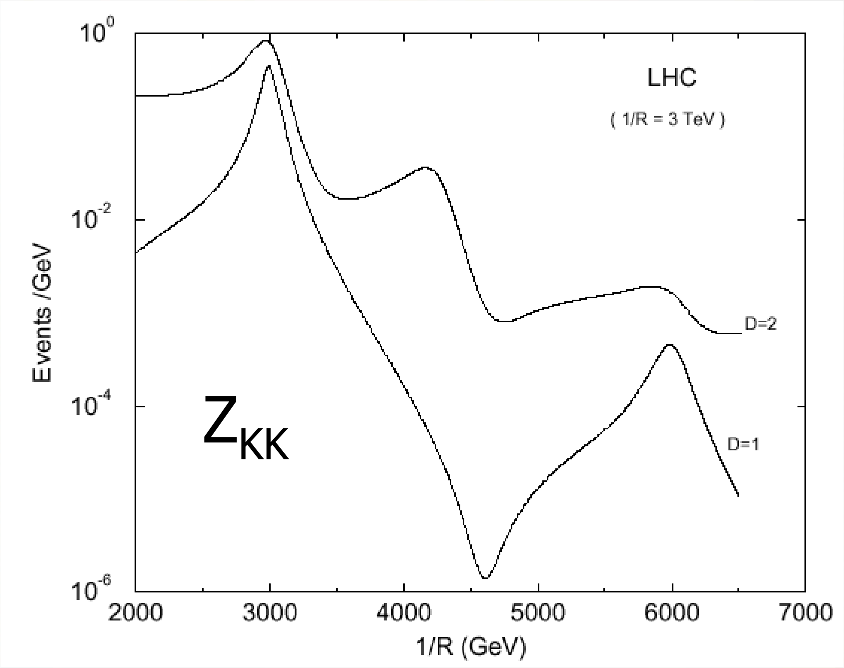




TeV^{-1} Extra Dimensions

- 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: $1/r \sim 6$ TeV

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

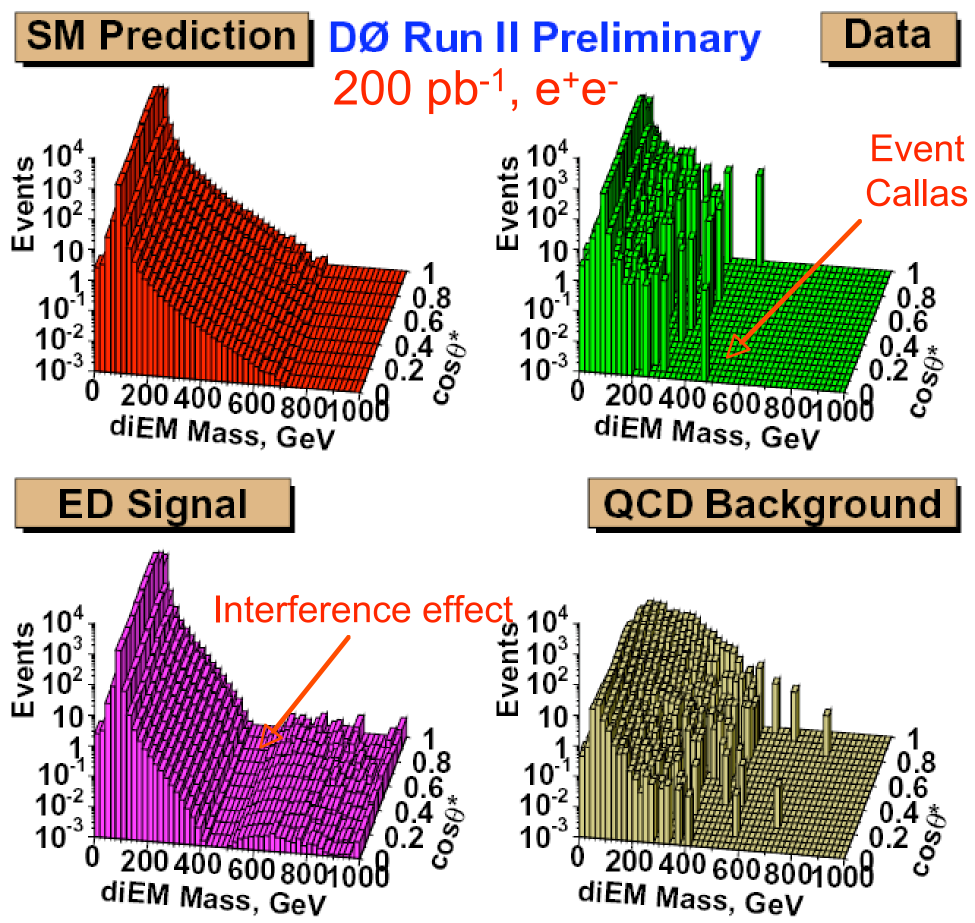


Current Limits on TeV^{-1} ED

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

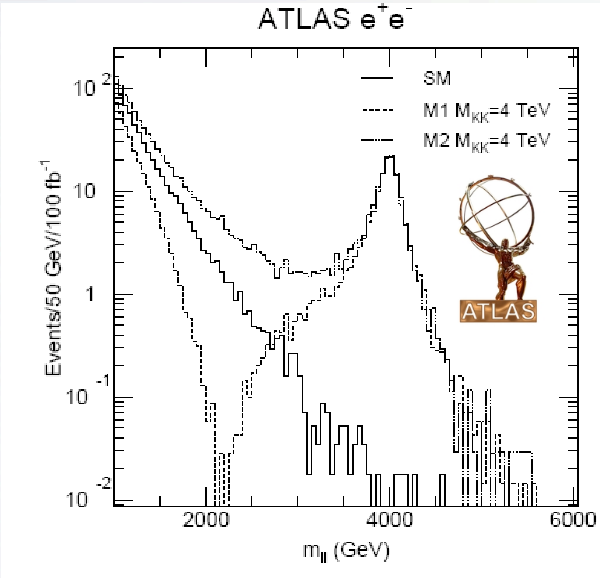
First Dedicated Search for TeV^{-1} ED

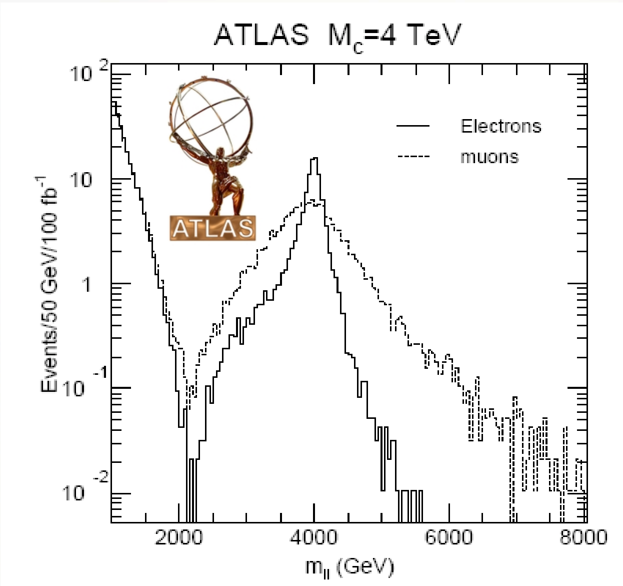


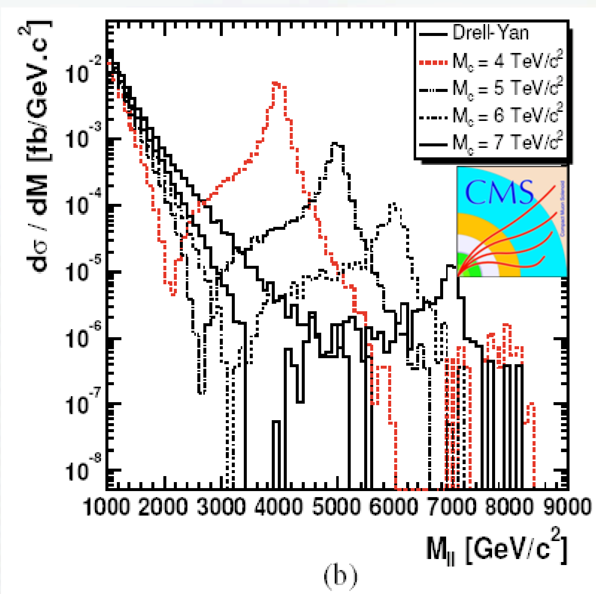
TeV^{-1} ED, 1/R = 0.8 TeV

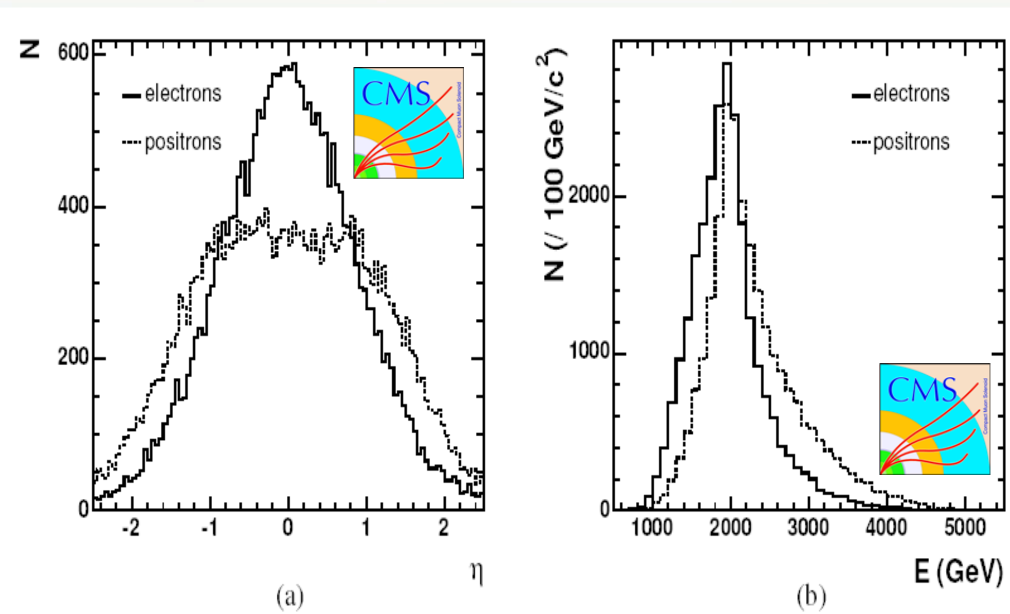
- While the Tevatron sensitivity is inferior to indirect limits, it explores the effects of virtual KK modes at higher energies, i.e. complementary to those in the EW data
- DØ has performed the first dedicated search of this kind in the dielectron channel based on 200 pb^{-1} of Run II data (Z_{KK}, $\gamma_{KK} \rightarrow e^+e^-$)
- The 2D-technique similar to the search for ADD effects in the virtual exchange yields the best sensitivity in the DY production [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 x 10^{-19} m

LHC: KK Excitations of the Z Boson



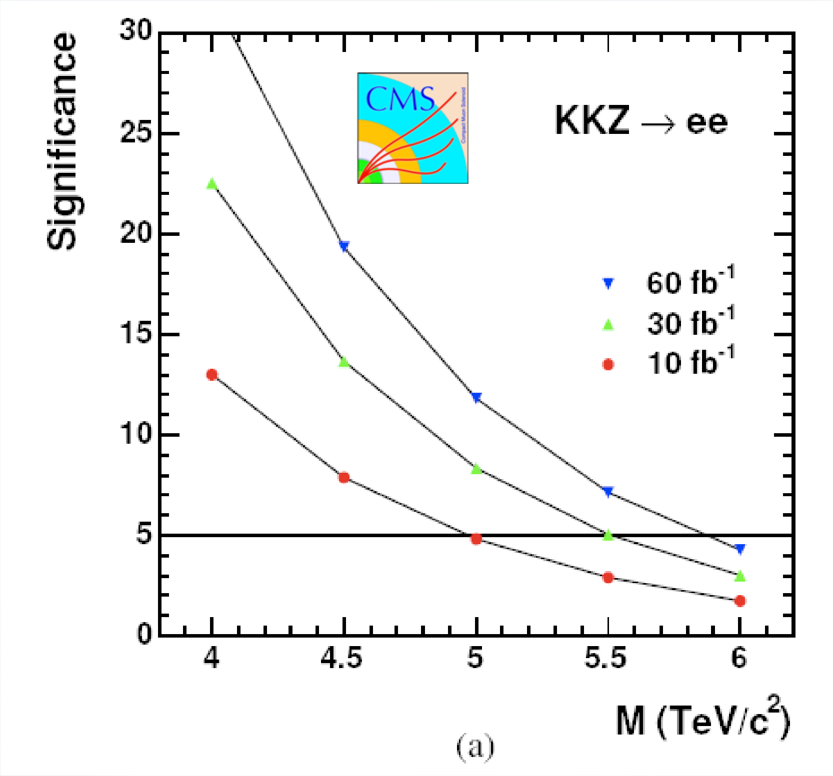


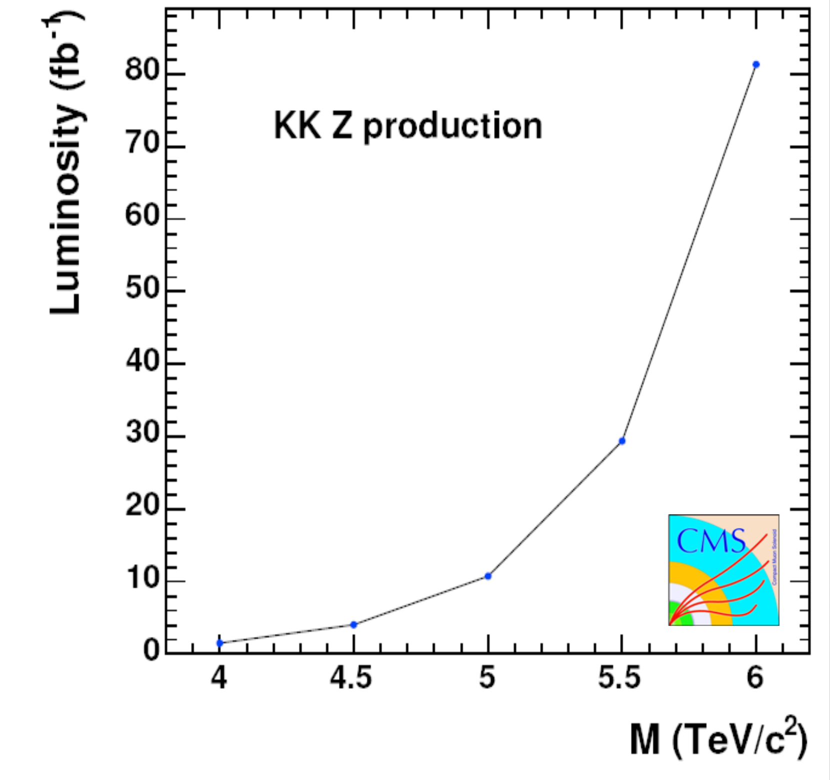




KK Resonance Reach at the LHC

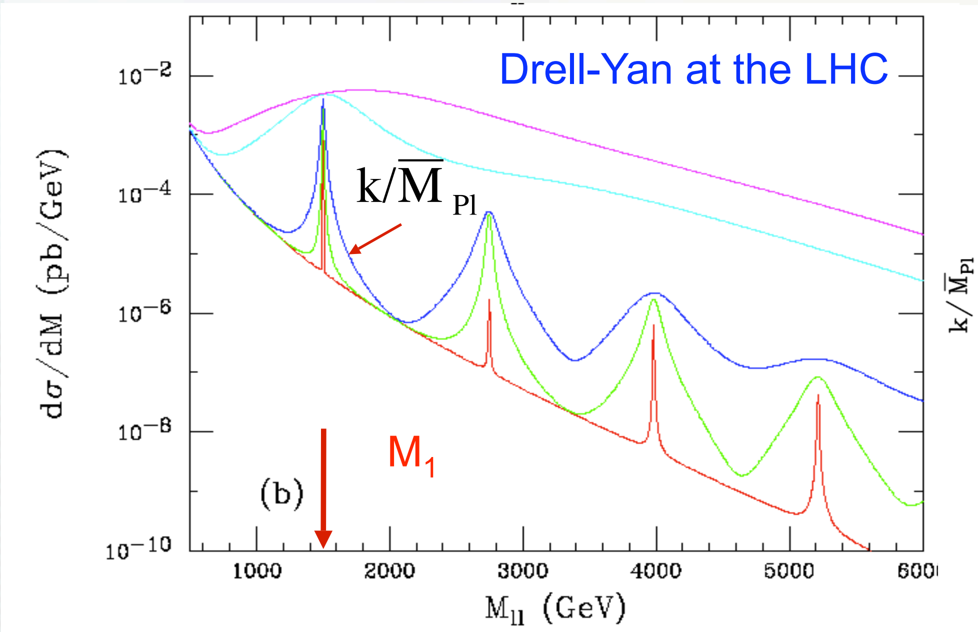
- Dramatic reach even with ~1 fb^{-1}

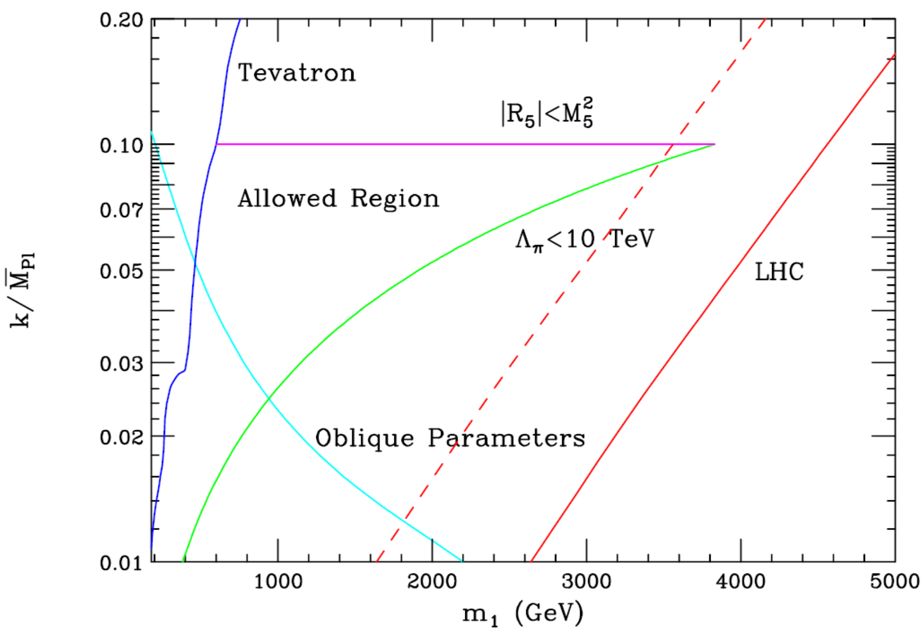




Randall-Sundrum Model Observables

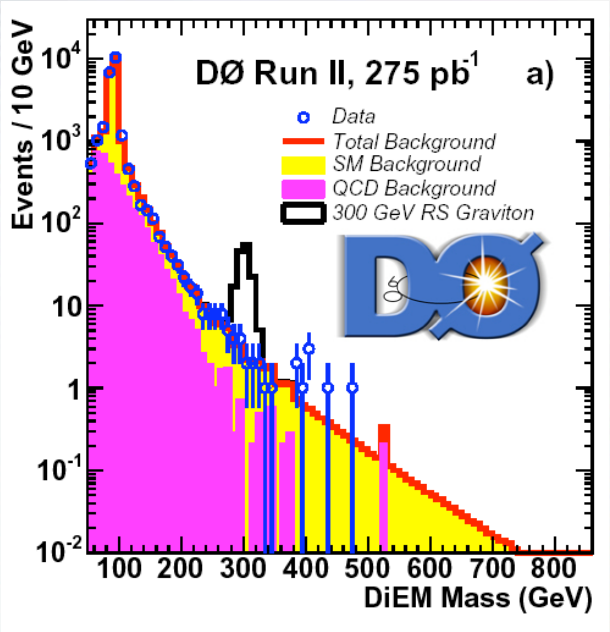
- Need only two parameters to define the model: k and r
- Equivalent set of parameters:
  - The mass of the first KK mode, M_1
  - Dimensionless coupling $k/\overline{M}_{\rm Pl}$, which determines the graviton width
- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too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

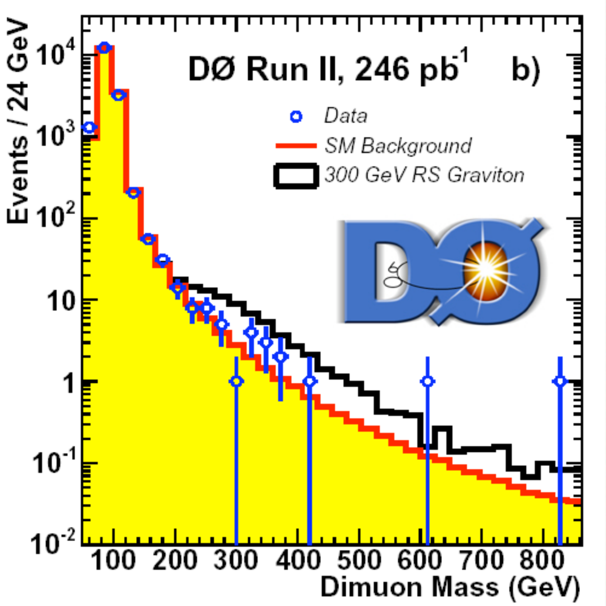


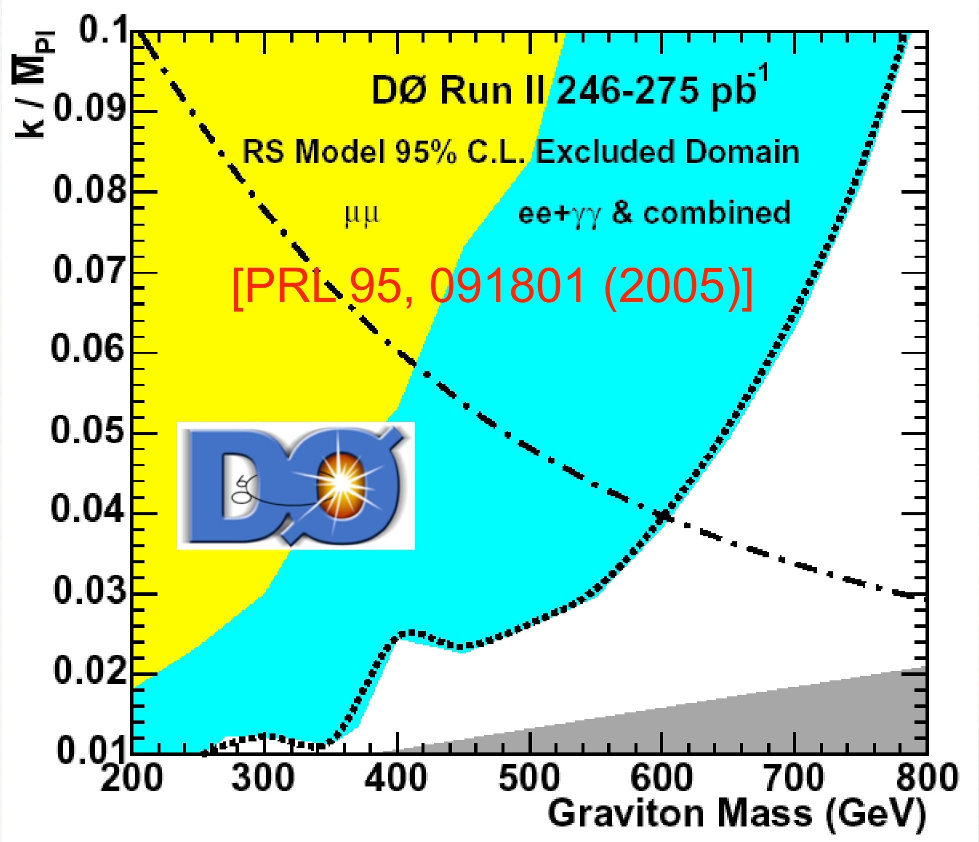


Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]

First Search for RS Gravitons



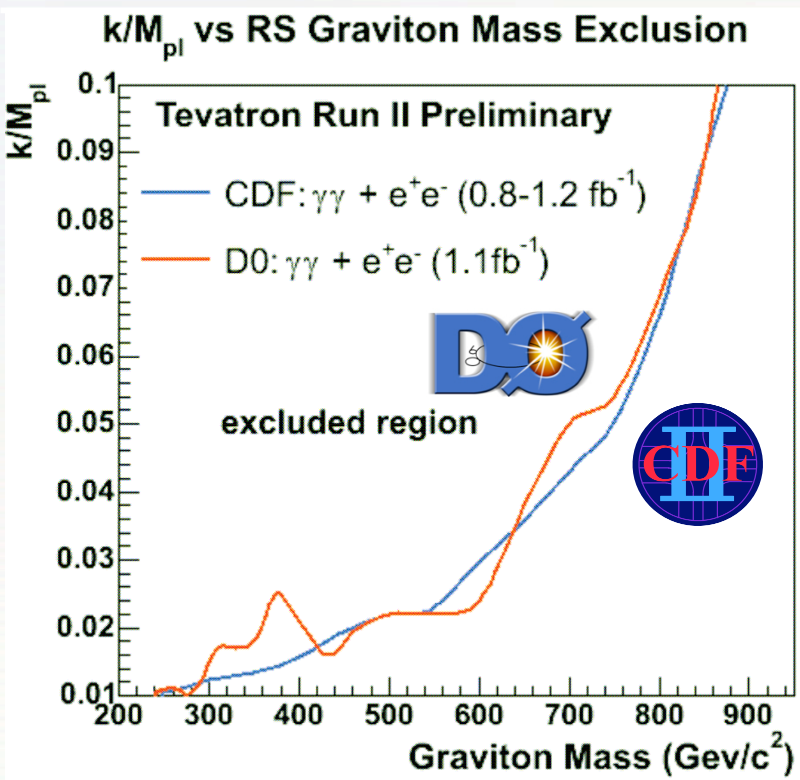


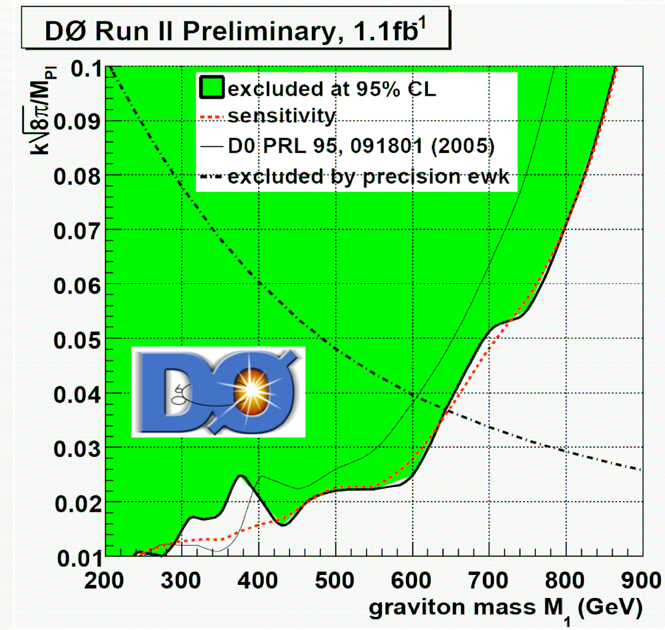


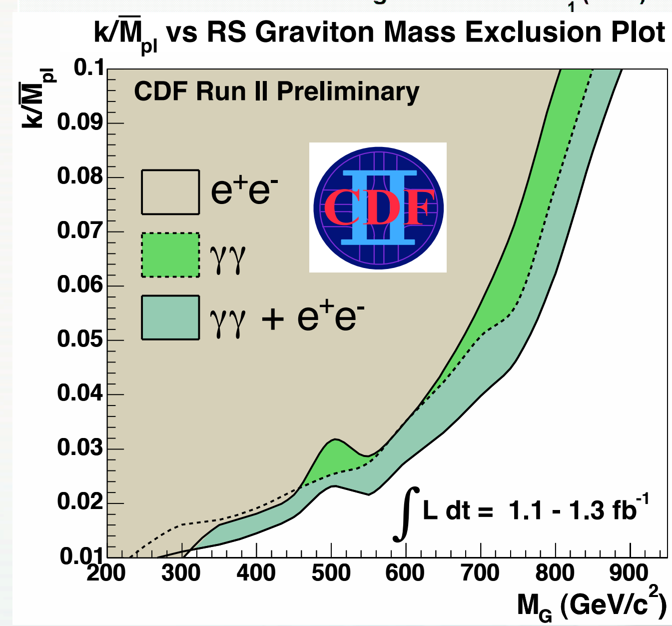
Assume fixed *K*-factor of 1.3 for the signal

Most Recent Limits

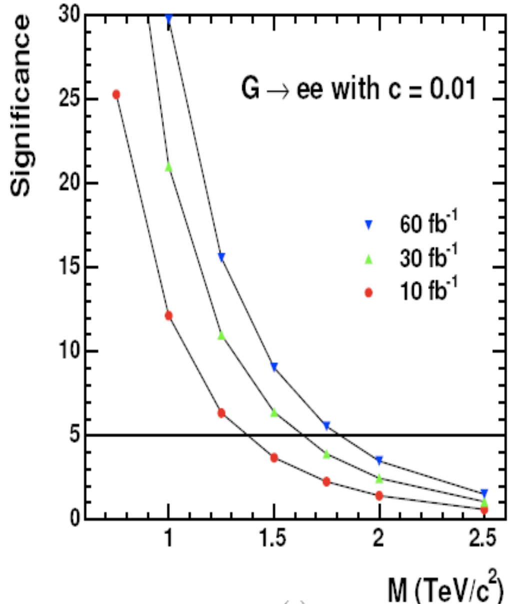
- Latest limits are 10% higher than the original ones despite 4x statistics
  - Tevatron sensitivity has really maxed out - need higher energies!



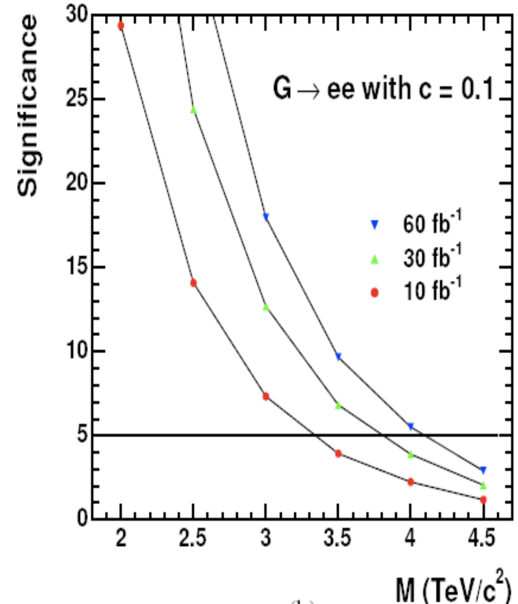




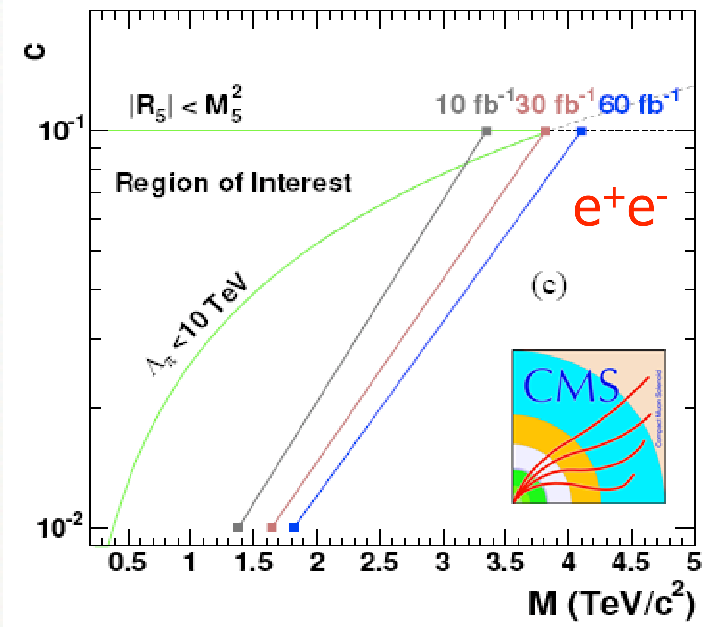
LHC: Randall-Sundrum Graviton Reach

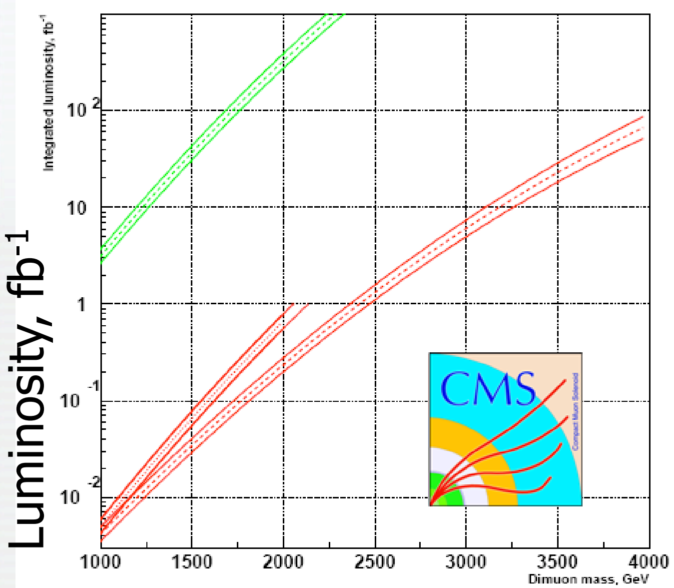


(a)

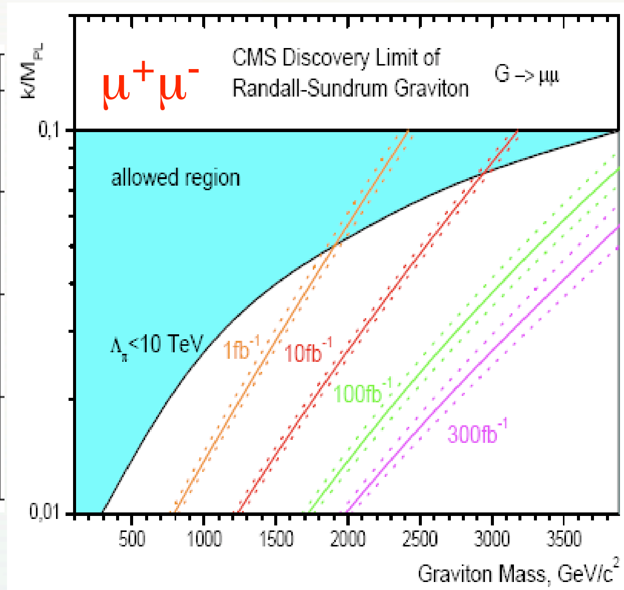


(b)



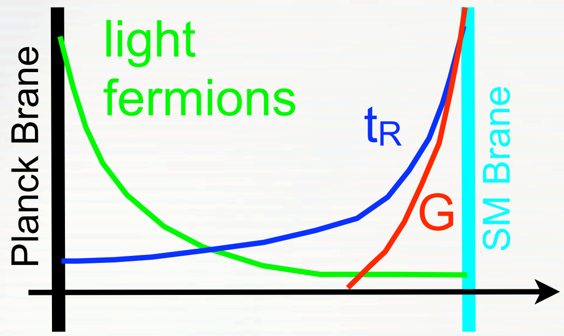


Coupling constant c	Estimator	1 fb^{-1}	10 fb^{-1}
0.01	S_{cP}	0.75	1.20
	S_{cL}	0.77	1.21
	S_L	0.78	1.23
0.02	S_{cP}	1.21	1.72
	S_{cL}	1.22	1.72
	S_L	1.22	1.74
0.05	S_{cP}	1.83	2.48
	S_{cL}	1.85	2.49
	S_L	1.85	2.51
0.1	S_{cP}	2.34	3.11
	S_{cL}	2.36	3.13
	S_L	2.36	3.16

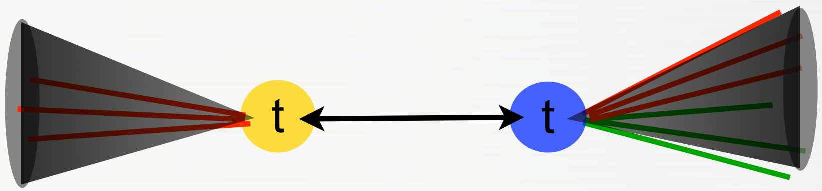


But: Life May be Much More Complicated!

- 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.

Black Holes at the LHC?

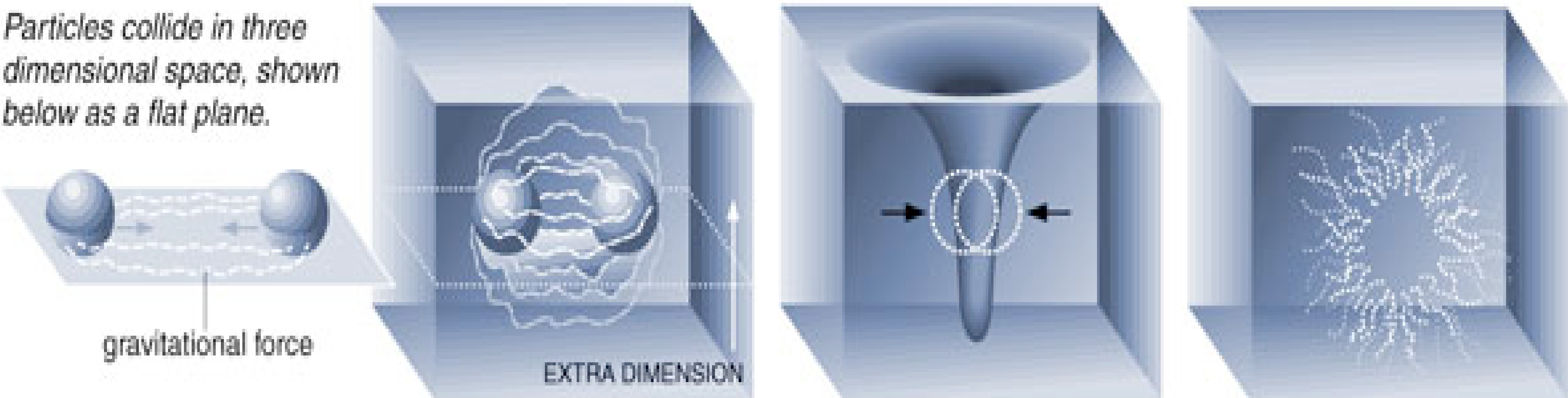
Black Holes on Demand

NYT, 9/11/01

The New York Times ON THE WEB

Black Holes on Demand

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.

Black Holes in General Relativity

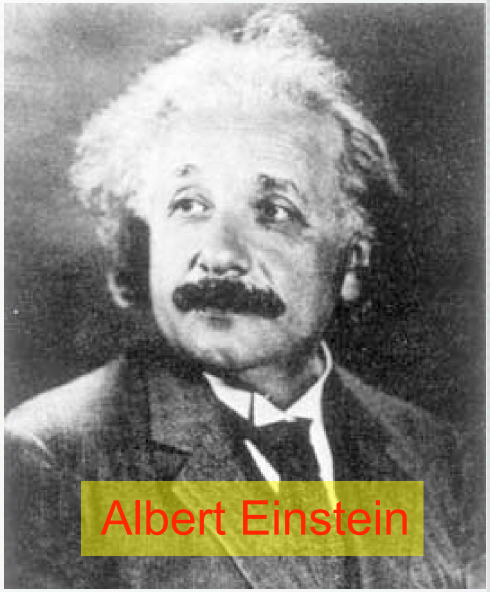
- Black Holes are direct prediction of Einstein's general relativity theory, established in 1915 (although they were never quite accepted by Einstein!)
- In 1916 Karl Schwarzschild applied GR to a static non-spinning massive object and derived famous metric with a singularity at a *Schwarzschild radius* $r = R_S \equiv 2MG_N/c^2$:

$$g_{\mu\nu} = \begin{pmatrix} 1 - \frac{2MG_N}{rc^2} & 0 & 0 & 0 \\ 0 & -(1 - \frac{2MG_N}{rc^2})^{-1} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2 \sin\theta \end{pmatrix}$$

} time

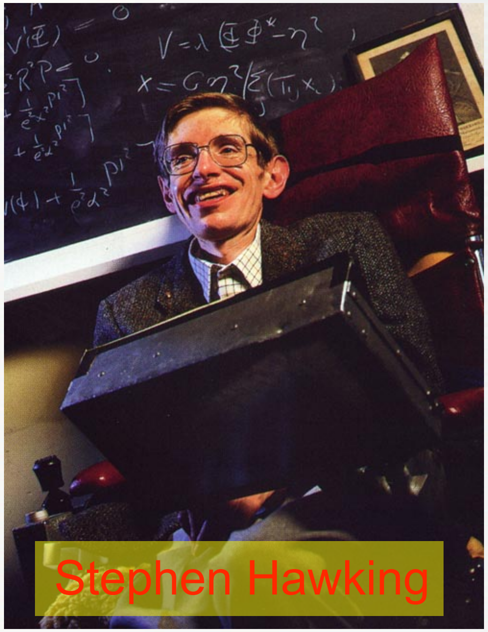
} space

- If the radius of the object is less than R_S, a black hole with the event horizon at R_S is formed
- The term "black-hole" was introduced only around 1967 by John Wheeler



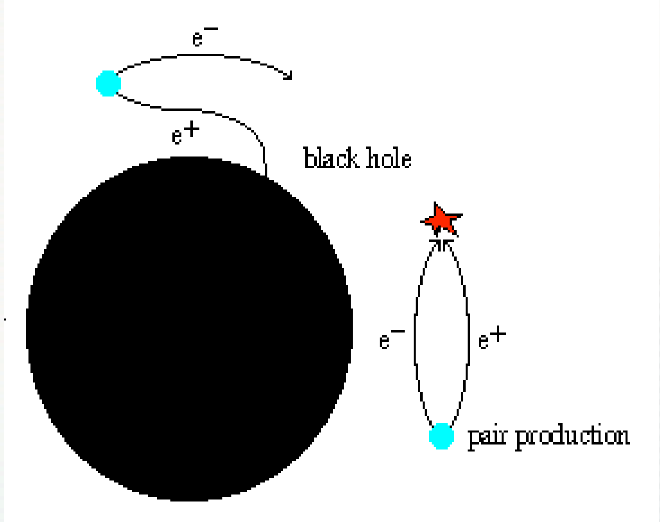
Black Hole Evolution

- Naïvely, black holes would only grow once they are formed
- In 1975 Steven Hawking showed that this is not true [Commun. Math. Phys. **43**, 199 (1975)], as the black hole can evaporate by emitting pairs of virtual photons at the event horizon, with one of the pair escaping the BH gravity
- These photons have a perfect black-body spectrum with the *Hawking temperature*:



$$T_H = \frac{\hbar c}{4\pi k R_S}$$

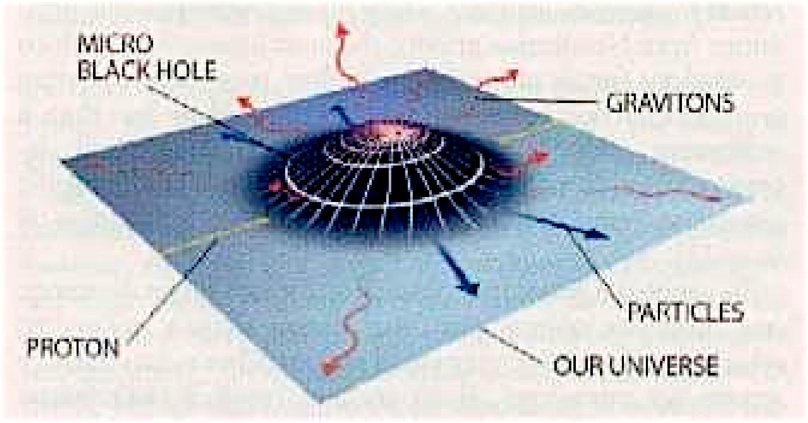
- In natural units ($\hbar = c = k_B = 1$), one has the following fundamental relationship: $R_S T_H = (4\pi)^{-1}$
- If T_H is high enough, massive particles can also be produced in evaporation
- Information paradox: if we throw an encyclopedia in a black hole, and watch it evaporating, where would the information disappear?
- This paradox is possibly solved in the only model of quantum gravity we know of: string theory



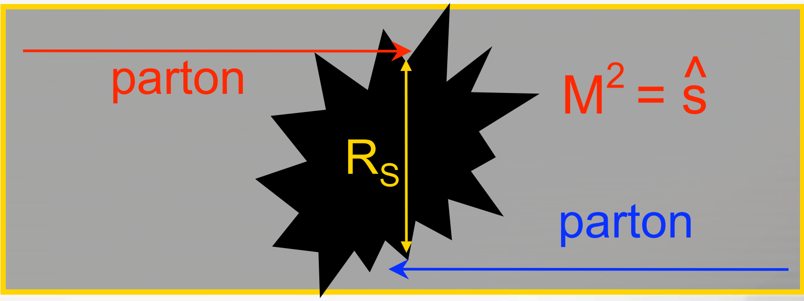
BH at LHC: Theoretical Framework

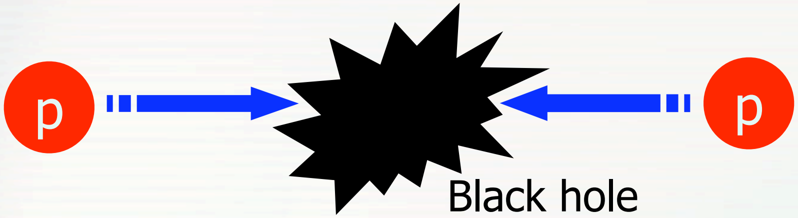
- Based on the work done with Dimopoulos a few years ago [PRL **87**, 161602 (2001)] and a related study by Giddings/Thomas [PRD **65**, 056010 (2002)]
- Extends previous, more theoretical studies by Argyres/Dimopoulos/March-Russell [PL **B441**, 96 (1998)], Banks/Fischler [JHEP, **9906**, 014 (1999)], 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:





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

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** (1986) 304]; it leads to:

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

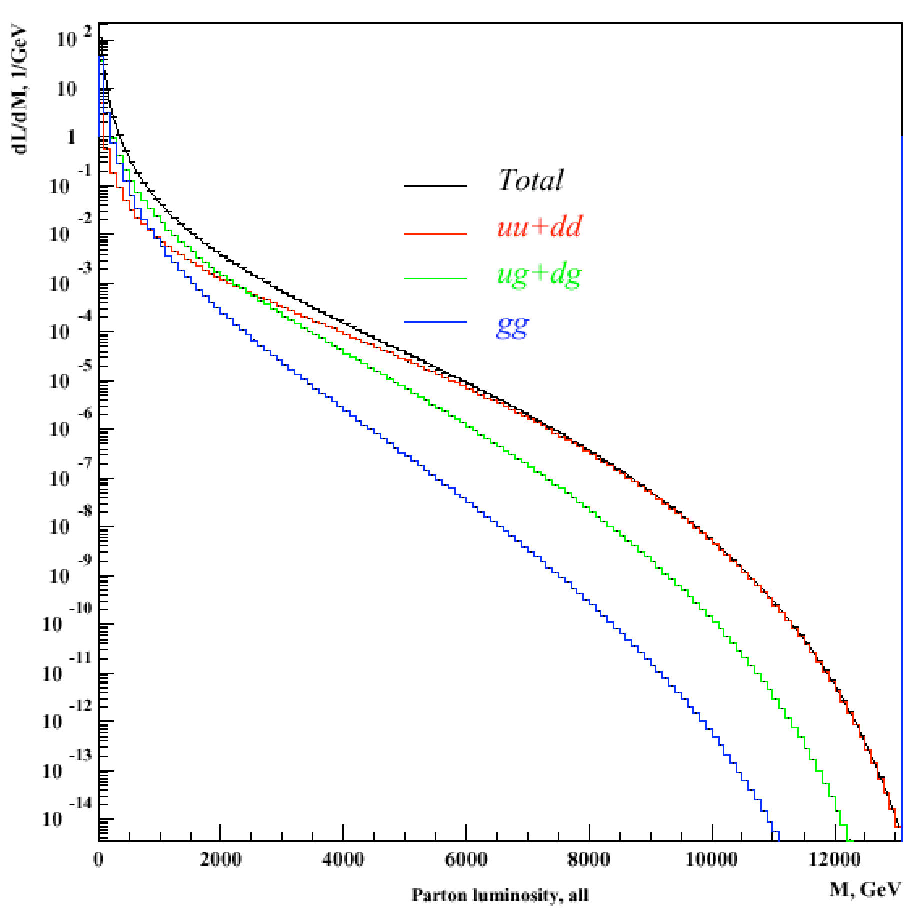
- Use parton luminosity approach with quark momentum distribution given by parton distribution functions

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

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

- 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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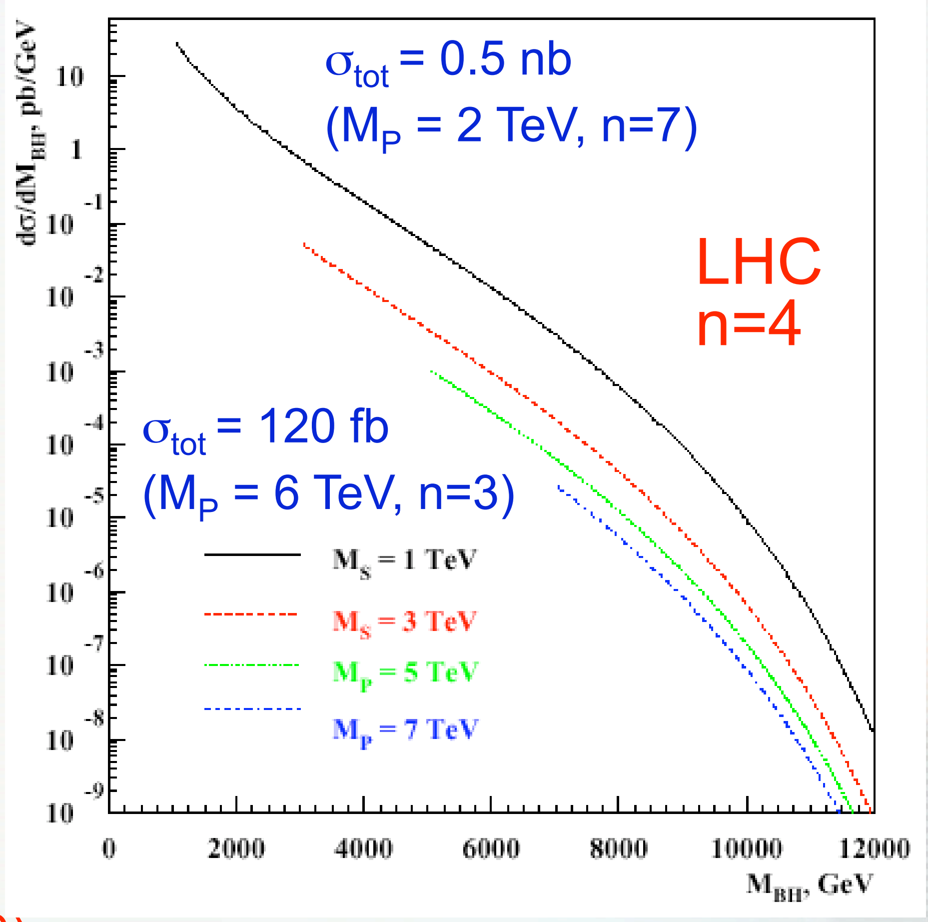
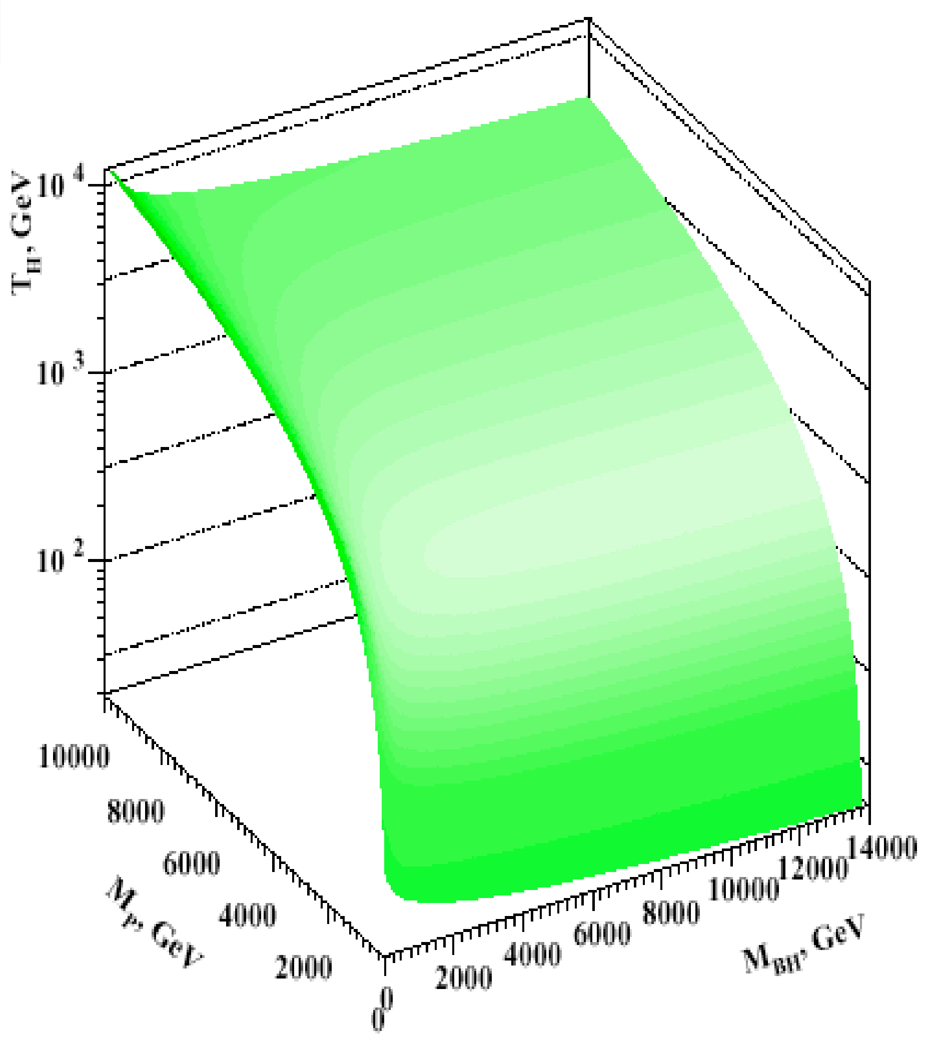


Black Hole Decay

- 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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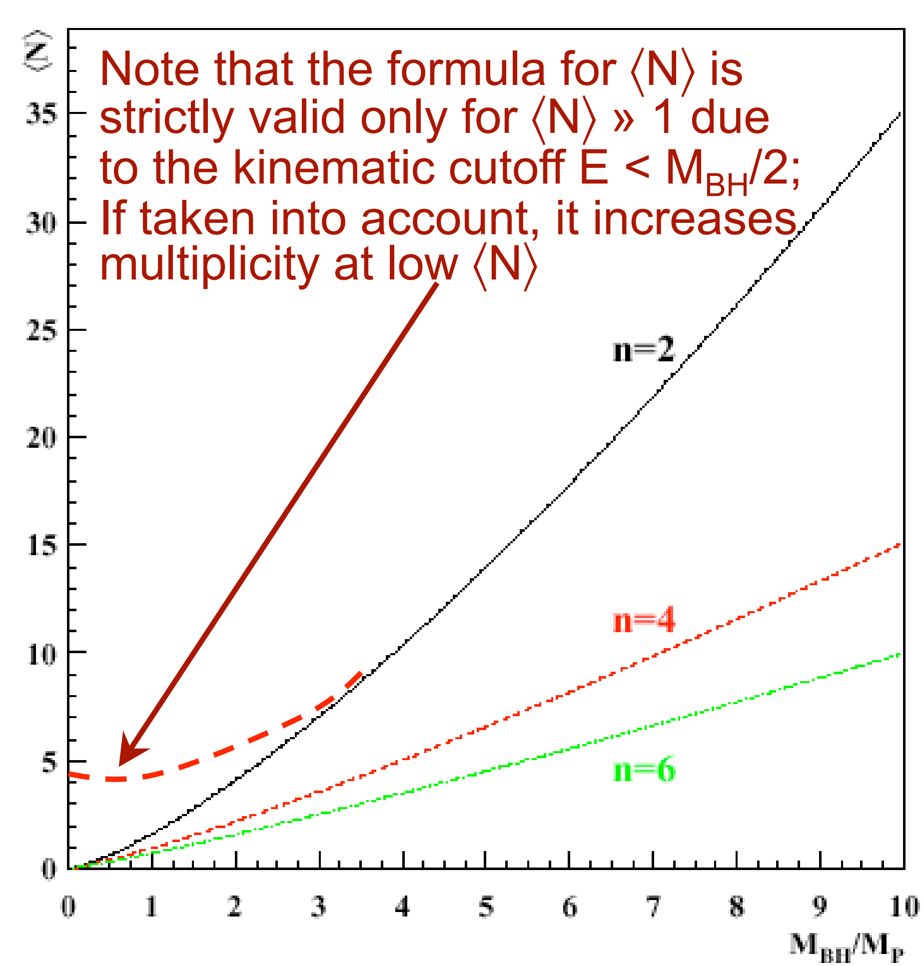
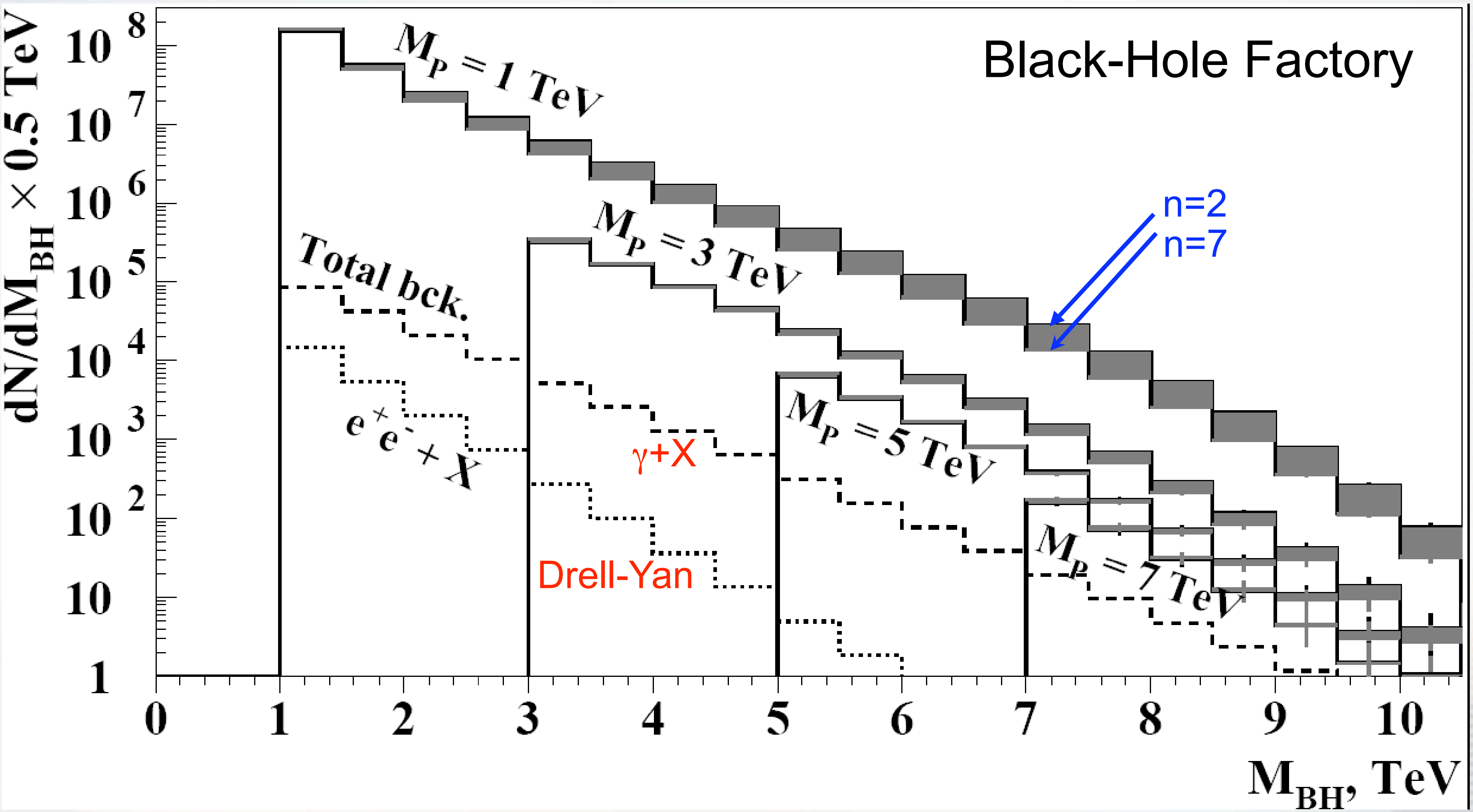


Stefan's law: $\tau \sim 10^{-26}$ s

Black Hole Factory

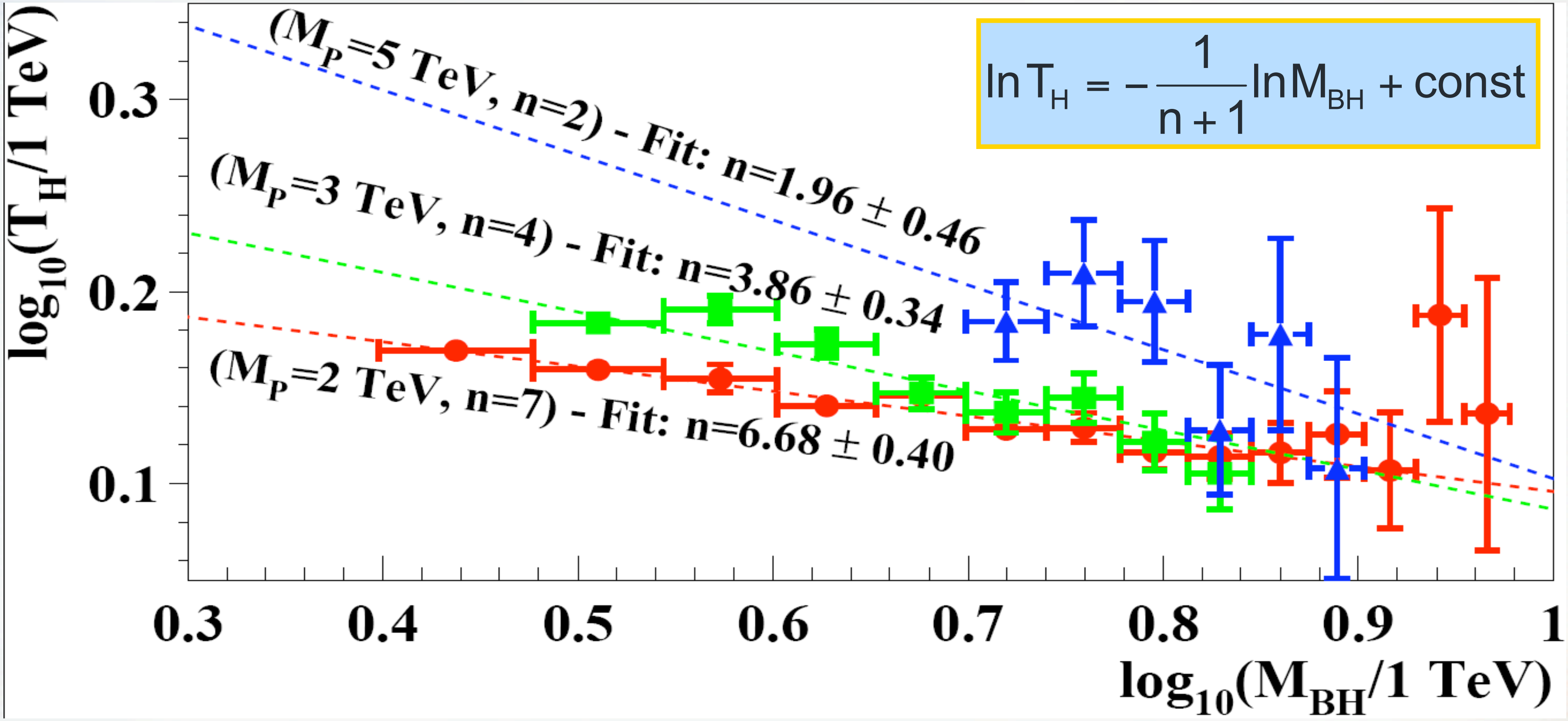
[Dimopoulos, GL, PRL **87**, 161602 (2001)]



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

Shape of Gravity at the LHC

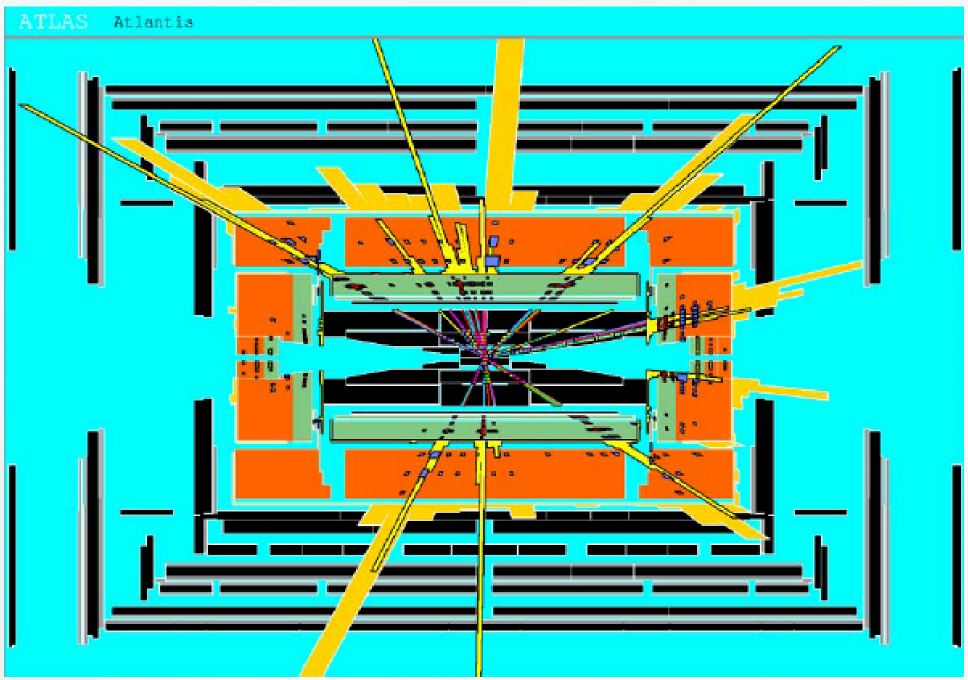
[Dimopoulos, GL, PRL **87**, 161602 (2001)]



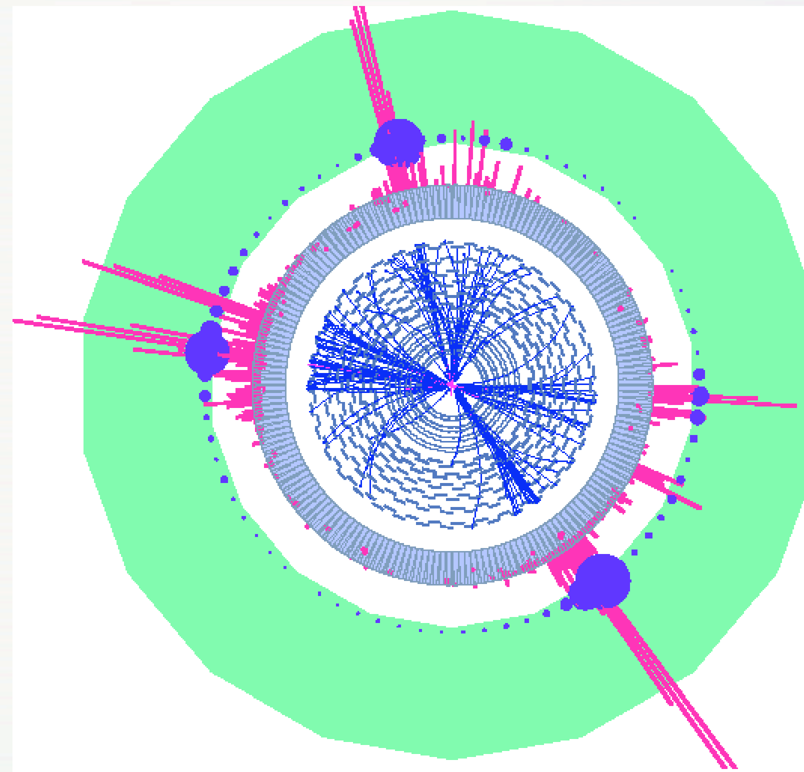
- Relationship between $\log T_H$ and $\log M_{BH}$ allows to find the number of ED
  - This result is independent of their shape!
  - This approach drastically differs from analyzing other collider signatures and would constitute a "smoking cannon" signature for a TeV Planck scale

Black Hole Events

- Detailed studies already started in ATLAS and CMS
  - ATLAS –CHARYBDIS (HERWIG-based generator witan elaborated decay model [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. de Roeck & S. Wynhoff]

Conclusions

- 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 5 years, both on the theoretical/phenomenological and on experimental sides
- Spectacular signatures, large cross sections make these models extremely attractive for full exploration at the LHC
  - Some of the signatures may nevertheless be quite challenging!
- If the scale of gravity is ~1 TeV, copious production of black holes at the LHC is likely to be an early and definitely most spectacular signature for extra dimensions
- Such a possibility would fulfill our dreams for Grand Unification of an ultimate kind: that of particle physics, astrophysics and cosmology!


MY COMPUTER DOESN'T WORK! THE HARD DRIVE CRASHED! WHAT DO I DO?!
DID YOU BACK UP?
WHY? IS IT GONNA BLOW?!
STEINFELD ©96

Fine Tuning Explained…

- Fine tuning explained:
  - Numerology: 987654321/123456789 = 8.000000073 ?
    - Numerology it is not!

$$\lim_{N \to \infty} \frac{NML\ldots987654321}{123456789\ldots LMN} = N - 2$$

  - Seeing is believing:
    - In hexadecimal system, FEDCBA987654321/123456789ABCDEF = 14.0000000000000183

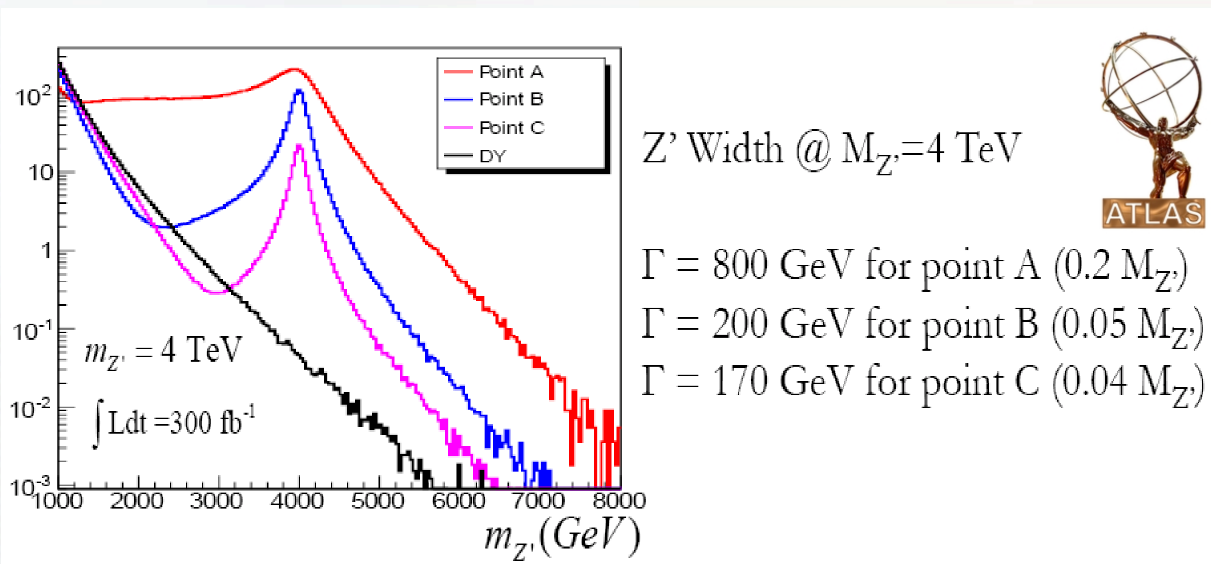
Before One Can Succeed in Searches

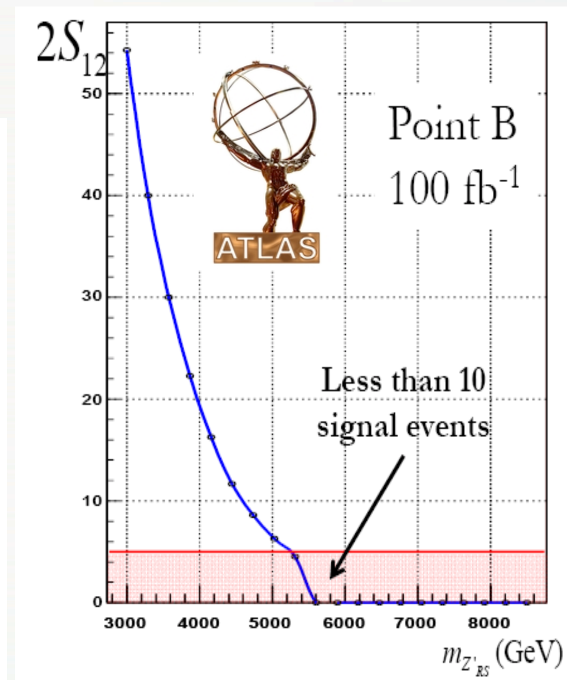
- Proper detector calibration, alignment, and detailed simulation is required
  - Taunting task, which easily takes several years
- Searches typically look for one event in a million; that means that the detector often has to be understood to the 10^{-6} level!
- Use calibration samples of well understood nature:
  - Test beams (initial calibration)
  - Cosmic runs (alignment, efficiency)
  - Minbias data (channel-by-channel calibration)
  - "Standard candles" – Z, W, top (efficiency, non-Gaussian tails in resolution, b-tagging)
  - Z(ee) and γ + jets (jet energy calibration and resolution)
  - High-p_T dijets (saturation, ME_T resolution and tails)
- Easily a subject for several dedicated lectures; not covered here in detail:
  - See 2006 Hadron Collider Physics Summer School proceedings: http://www.fnal.gov/HCPSS06 for dedicated talks
- Note: while a few spectacular discoveries may happen as early as 2008, most would require two-three years of accelerator running and operating the detectors!
  - Gear up for a long(er) ride!

Challenges: General

- Broad resonances are possible at high masses; signal starts looking like compositeness (or instrumental effect!)
- Reduces the reach; requires different optimization of the search

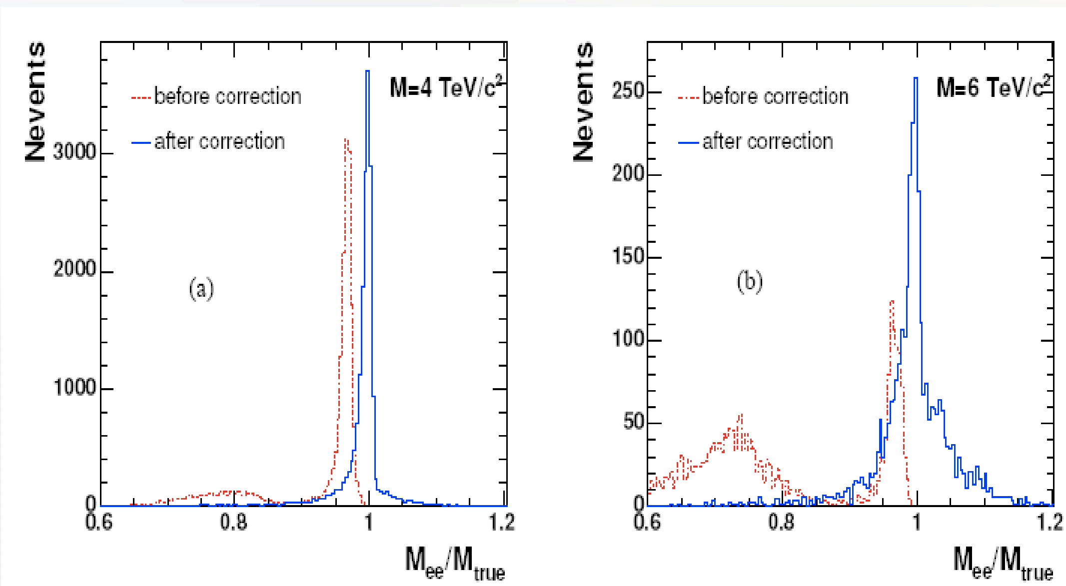
Example: bulk Z_{KK} in RS model

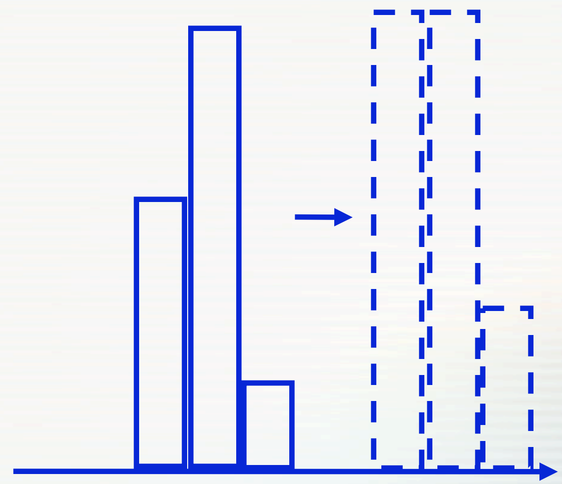




Challenges: CMS

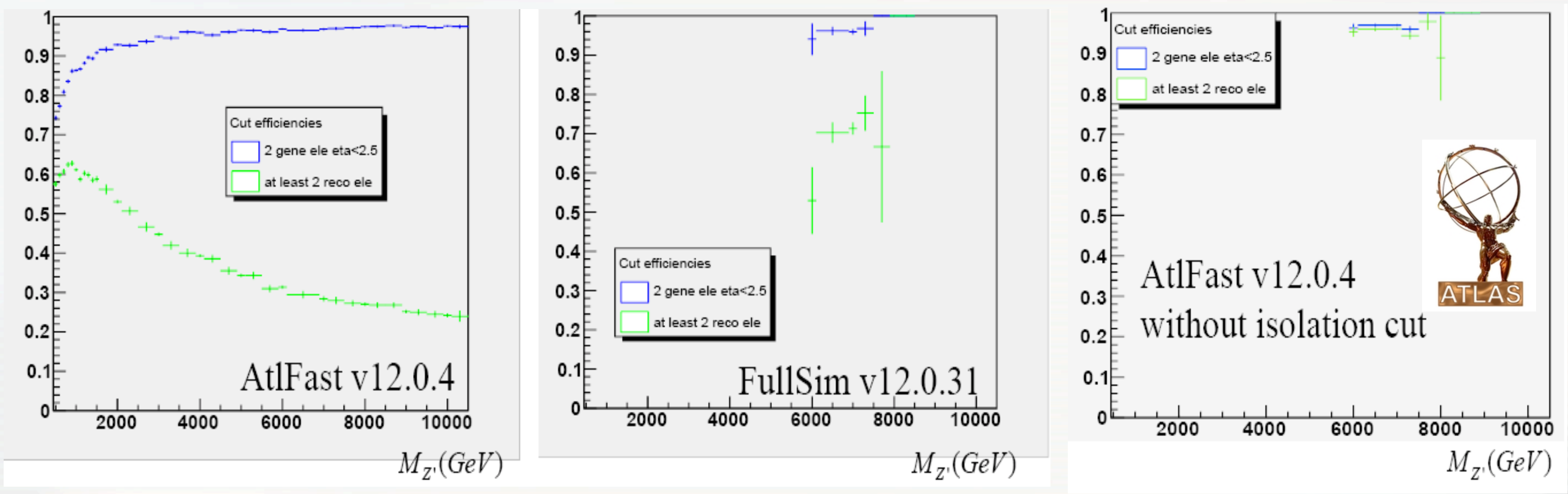
- ECAL saturation: a single crystal saturates at ~1.7 TeV; start seeing effect for >4 TeV Z'
- Correct energy at a slight resolution loss using "charge-sharing" technique
- Triggering with saturation could present another challenge!





Challenges: ATLAS

- Electron efficiency drops fast with mass when “standard” isolation cut is used
  - Loosely confirmed by full simulation
- New set of isolation cuts is being developed to recover efficiency at high masses



More Challenges: Universal ED

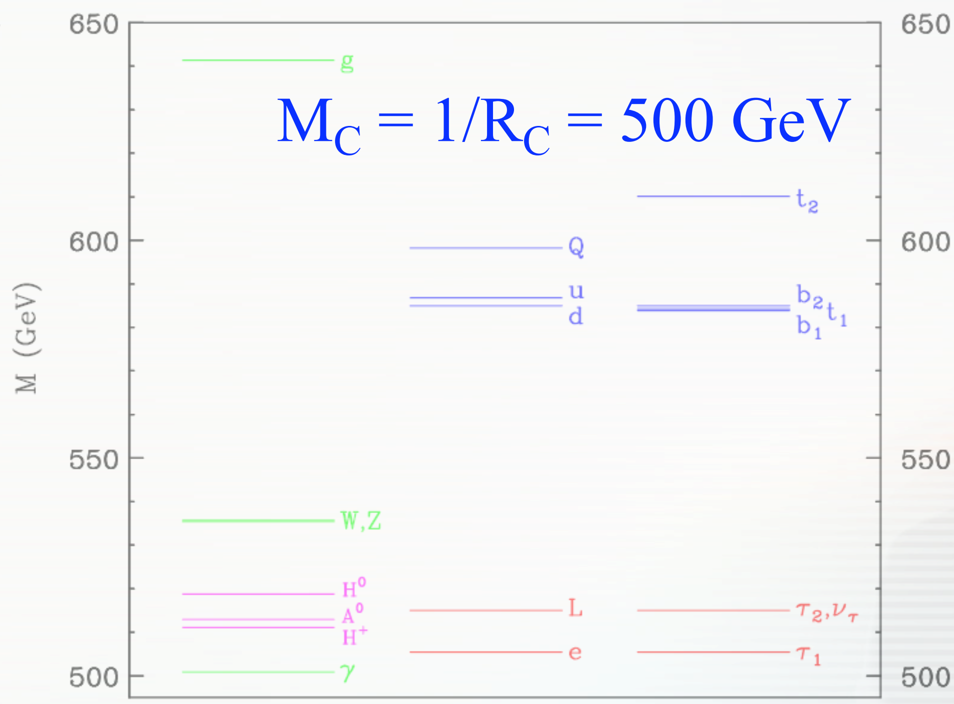
- The most "democratic" ED model: *all* the SM fields are free to propagate in extra dimension(s) with the size $R_c = 1/M_c \sim 1\ \text{TeV}^{-1}$ [Appelquist, Cheng, Dobrescu, PRD **64**, 035002 (2001)]
  - Instead of chiral doublets and singlets, model contains vector-like quarks and leptons
  - 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)

UED Phenomenology

- Naively, one would expect large clusters of nearly degenerate states with the mass around $1/R_C$, $2/R_C$, …
- 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

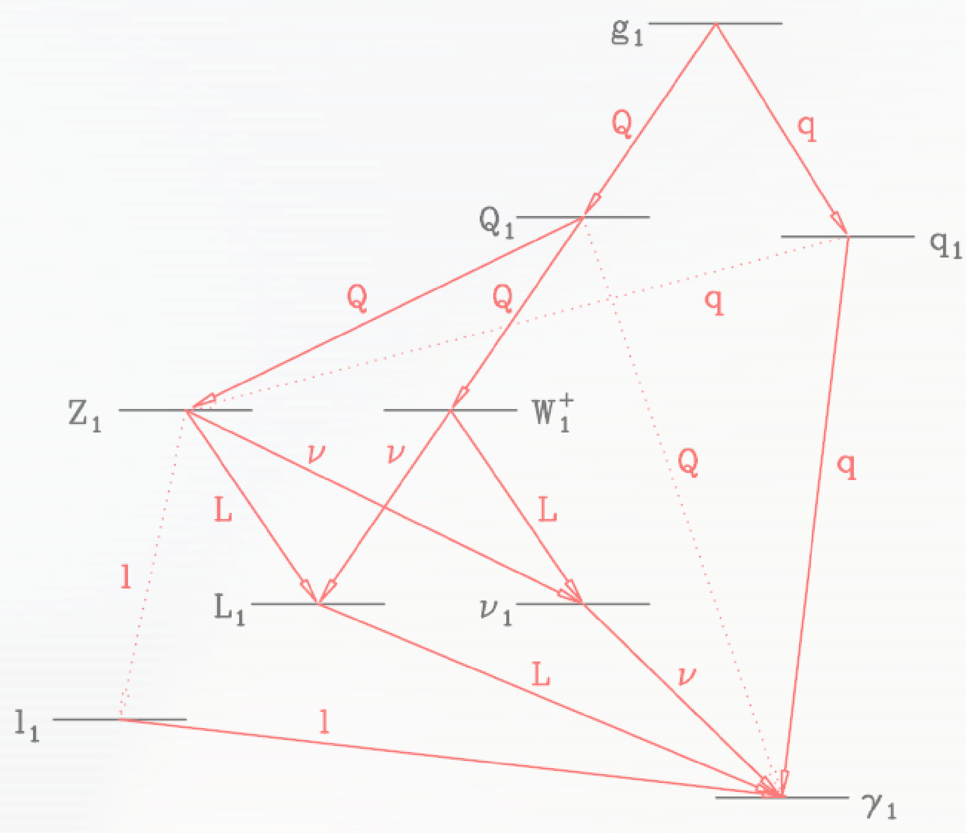
[Cheng, Matchev, Schmaltz, PRD **66**, 056006 (2002)]



UED Spectroscopy

- First level KK-states spectroscopy

[CMS, PRD **66**, 056006 (2002)]

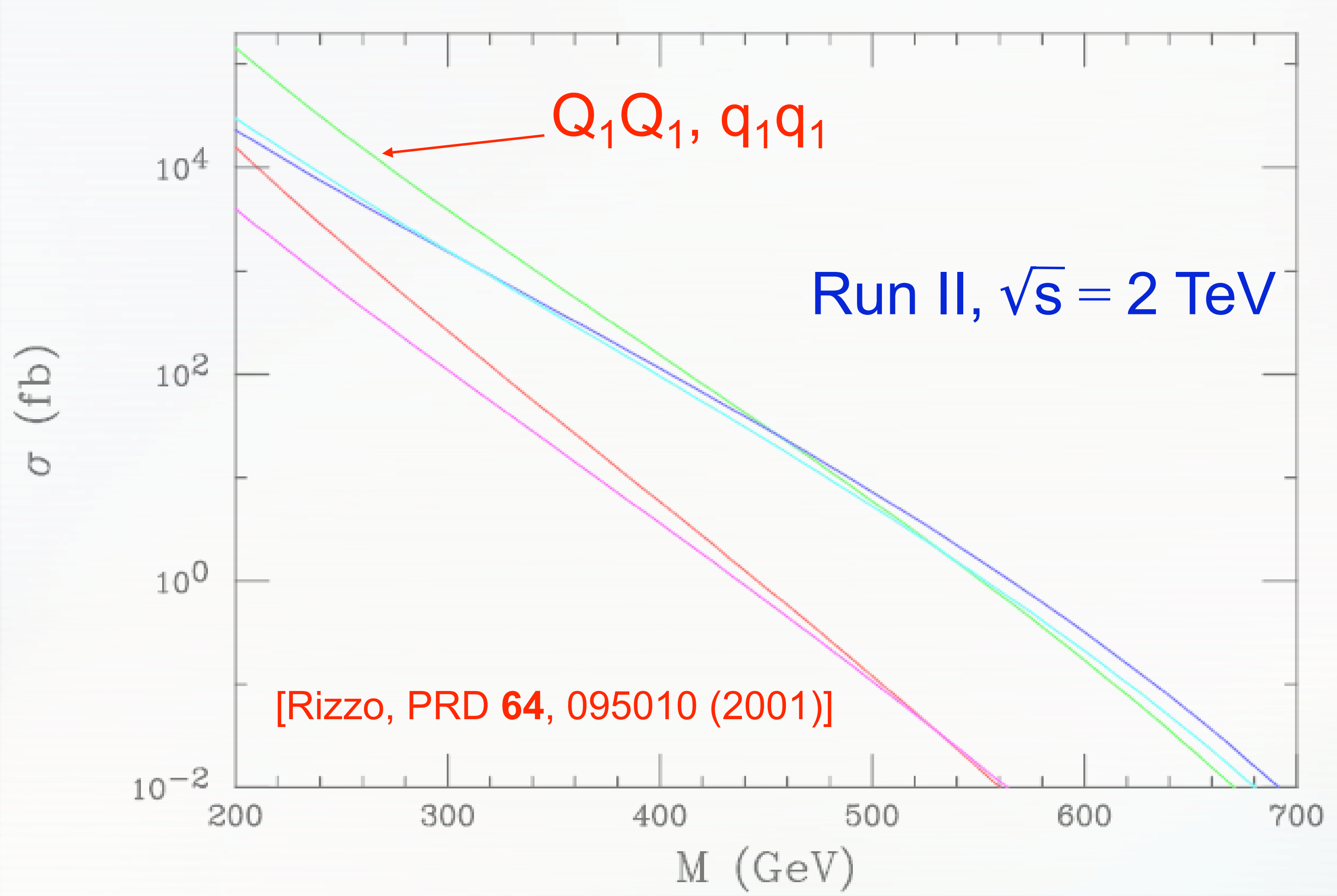


Decay:
$B(g_1 \to Q_1 Q) \sim 50\%$
$B(g_1 \to q_1 q) \sim 50\%$
$B(q_1 \to q\gamma_1) \sim 100\%$
$B(t_1 \to W_1 b, H_1^+ b) \sim 100\%$
$B(Q_1 \to QZ_1 : W_1 : \gamma_1) \sim 33\% : 65\% : 2\%$
$B(W_1 \to \nu L_1 : \nu_1 L) = 1/6 : 1/6$ (per flavor)
$B(Z_1 \to \nu\nu_1 : LL_1) \sim 1/6 : 1/6$ (per 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 $\to$ 2-4 ℓ + ME_T ($\sim\sigma_{had}/4$)

Production Cross Section

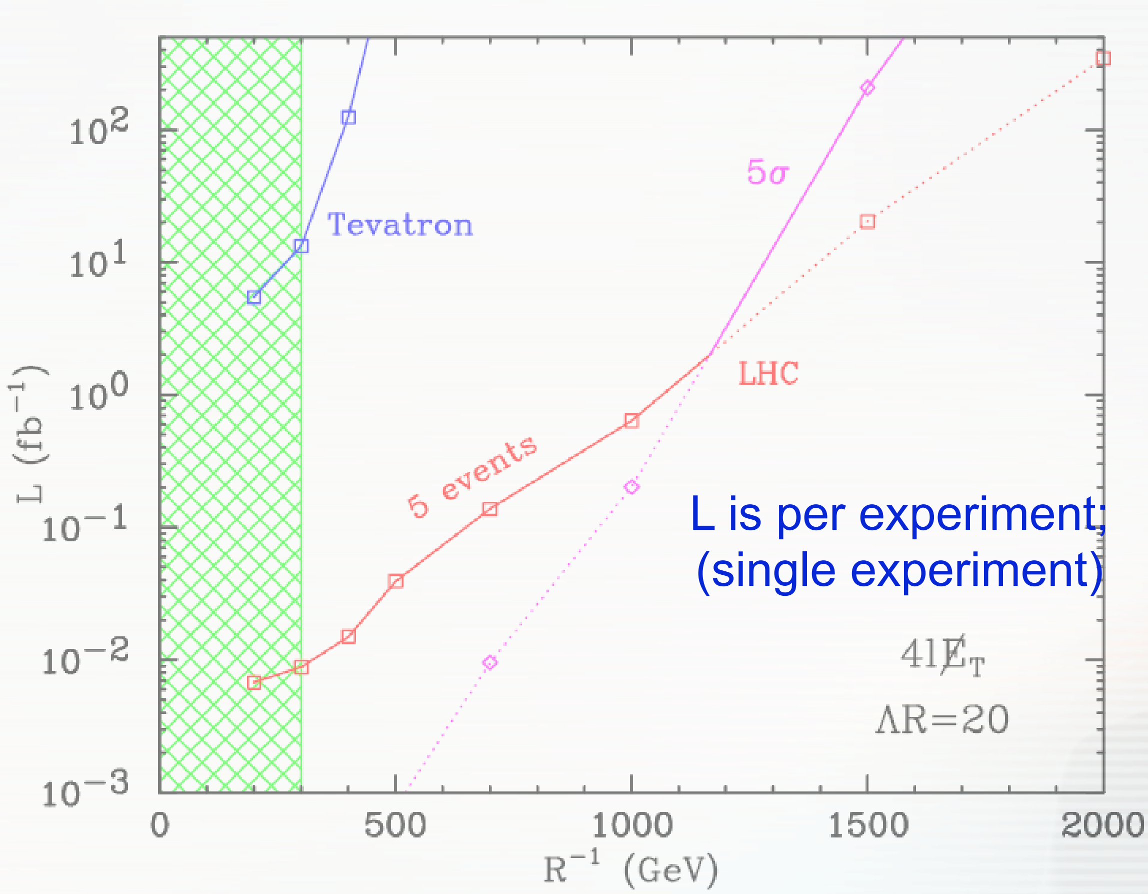
Reasonably high rate up to M ~ 500 GeV



Sensitivity in the Four-Lepton Mode

- Only the gold-plated 4-leptons + ME_T mode has been considered in the original paper
- Even at the Tevatron sensitivity can exceed current limits
- Much more promising channels:
  - dileptons + jets + ME_T + X (x9 cross section)
  - trileptons + jets + ME_T + X (x5 cross section)
- Detailed simulations is required: CompHEP and PYTHIA implementations now exist

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



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 $e^{-k\pi R_c}$)
- Nevertheless, the comparison with the ADD BH is trivial, GL, [hep-ph/0607297]
  - If $R_S e^{-k\pi R_c} << \pi R_C$ 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

RS to ADD Mapping

- Unlike the ADD, the 5D Planck scale, M, is of order of M_{Pl}:

$$M_{\rm Pl}^2 = \frac{M^3}{k}\left(1 - e^{-2\pi kr}\right) \approx \frac{M^3}{k} \sim M^2$$

- The Schwarzschild radius: $R_s = \frac{1}{\pi M e^{-\pi kr}} \sqrt{\frac{M_{\rm BH}}{3 M e^{-\pi kr}}}$

- Given $M^3 \approx k M_{Pl}^2 = \Lambda_\pi^2 k e^{2\pi kr}$, $R_s = \frac{1}{\sqrt{3}\pi\Lambda_\pi}\sqrt{\frac{M_{\rm BH}}{\tilde{k}\Lambda_\pi}} \sim \frac{1}{\Lambda_\pi}$

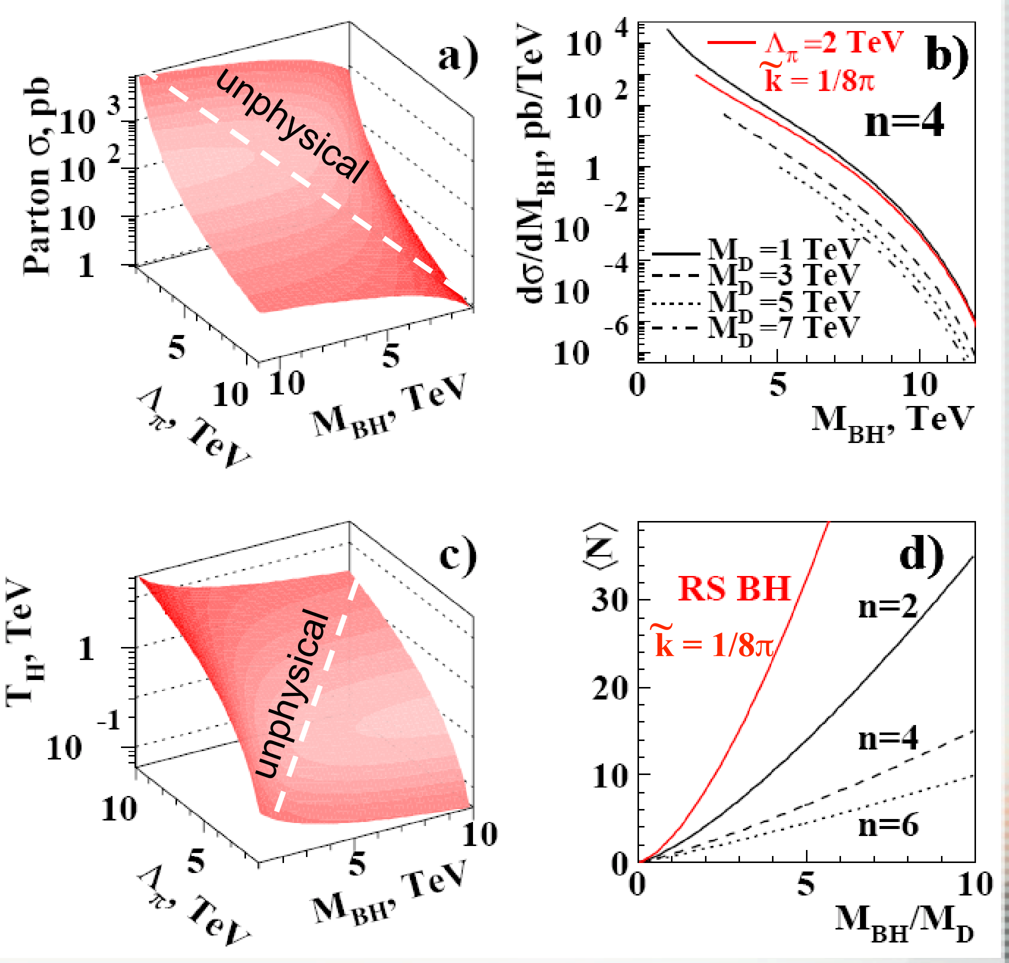
- Compare with: $R_S^{\rm ADD}(5D) = \frac{1}{\sqrt{\pi} M_D}\sqrt{\frac{8 M_{\rm BH}}{3 M_D}}$

- Then if one sets $\Lambda_\pi = M_D$ and $k = 1/8\pi \approx 0.04$, the RS formula turns into the ADD one! Thus, the two cases are equivalent within the approximations we used!

- $T_H = 1/(2\pi R_S)$ (ADD formula in 5D)

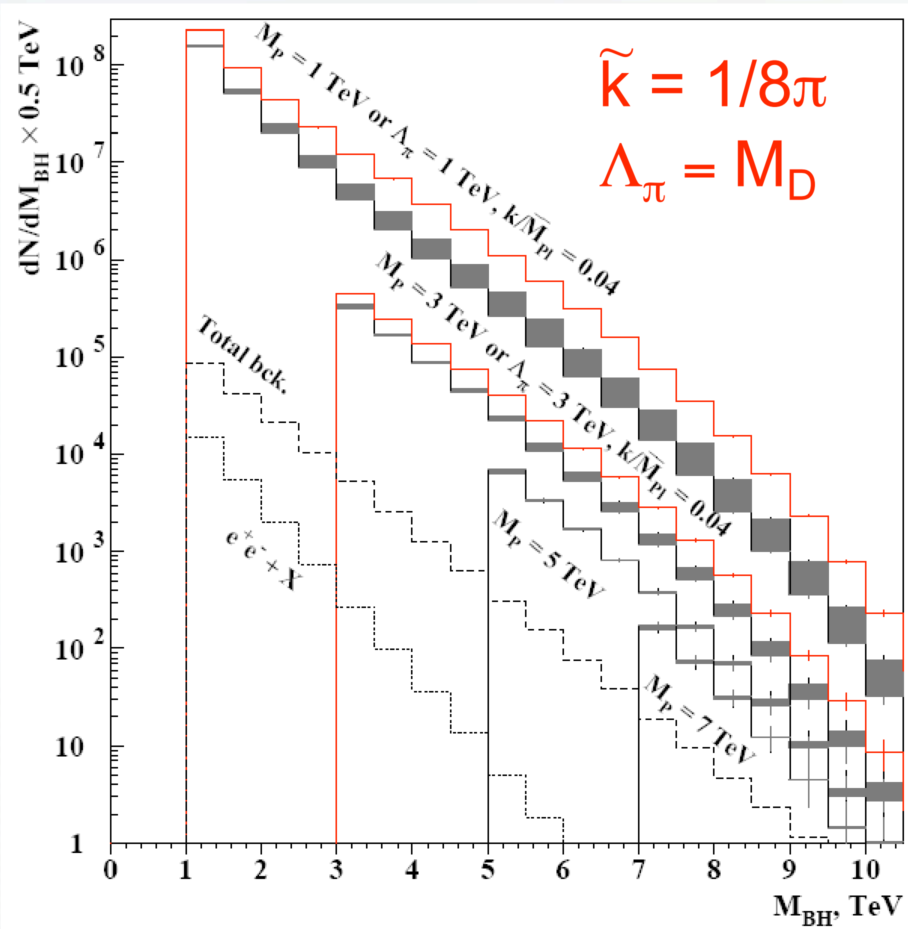
Results for RS Black Holes

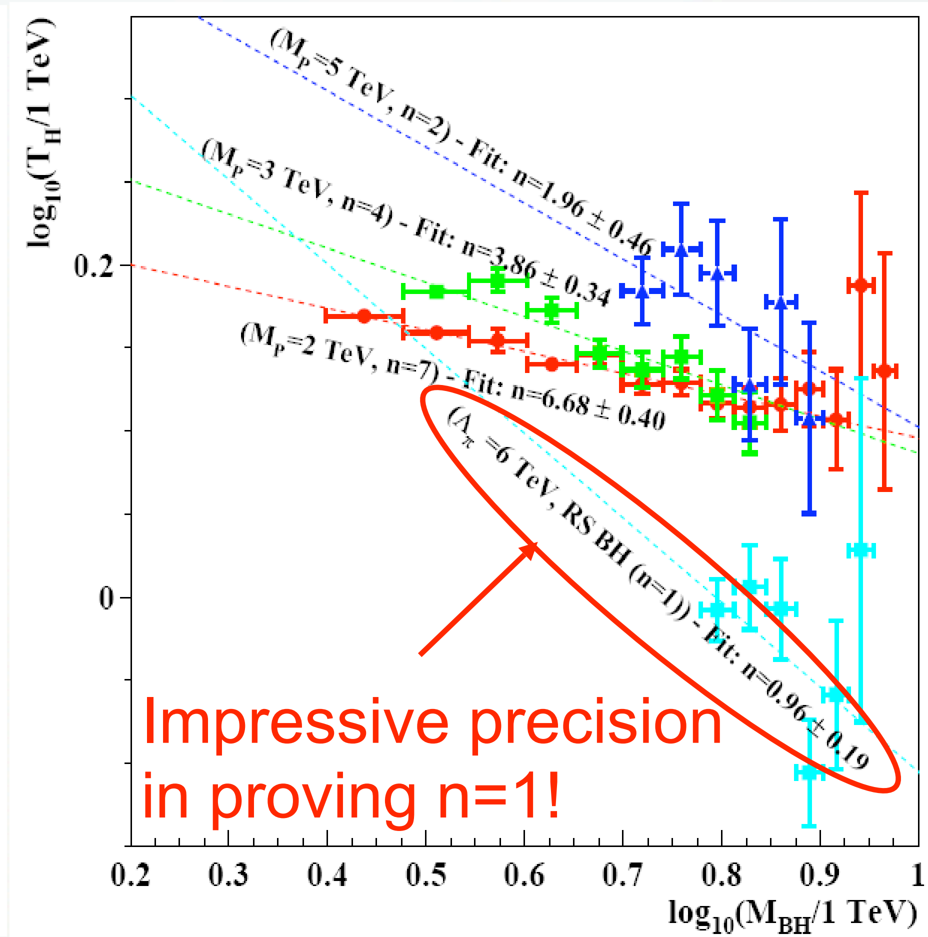
- More generally, the mapping between the ADD and RS parameters is as follows: $n = 1,\ M_D = \Lambda_\pi(8\pi\tilde{k})^{1/3}$
  - Note that generally, the BH production cutoff, if chosen equal to Λ_π, won't be equal to M_D
  - However, this parameter set is usable in the BH event generators to study arbitrary coupling values
- Cross section is somewhat higher for RS BH and they are colder than their ADD counterparts
- Consequently, the RS BH decay results in higher number of final state particles, making it easier to establish the signal



RS BH: Samples & Wien's Law

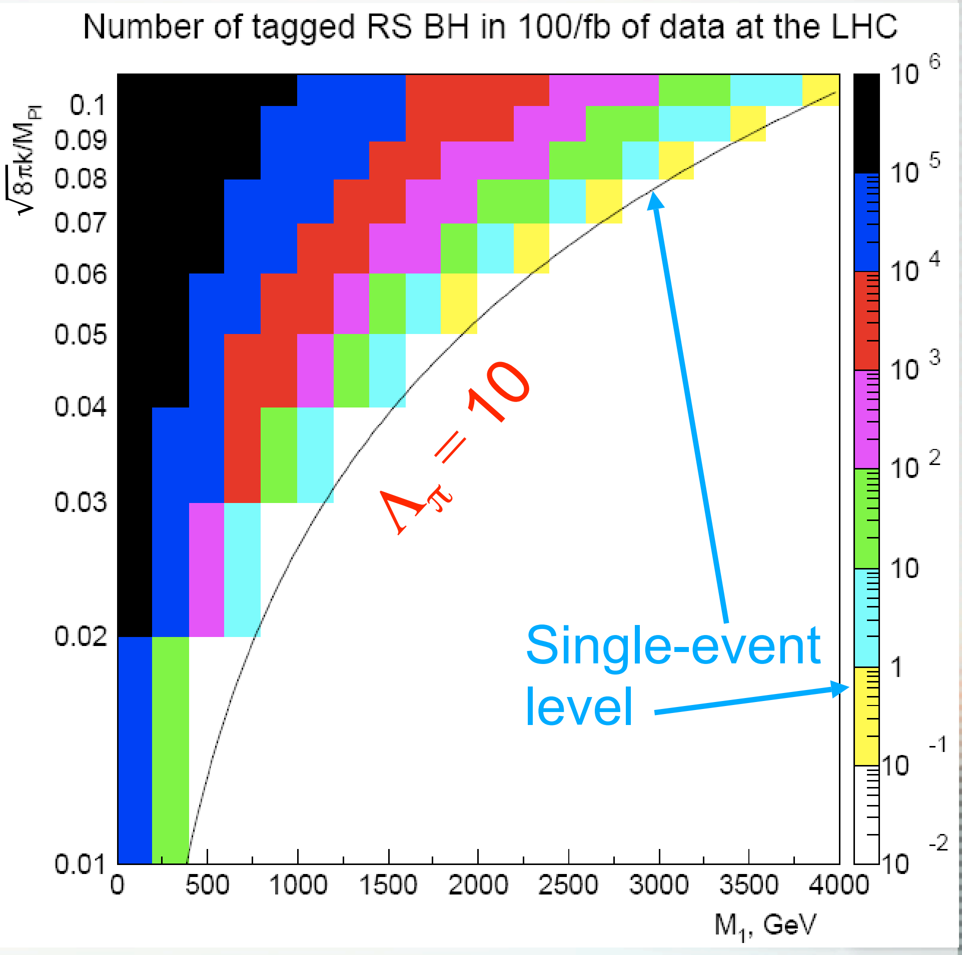
100 fb^{-1} @ the LHC

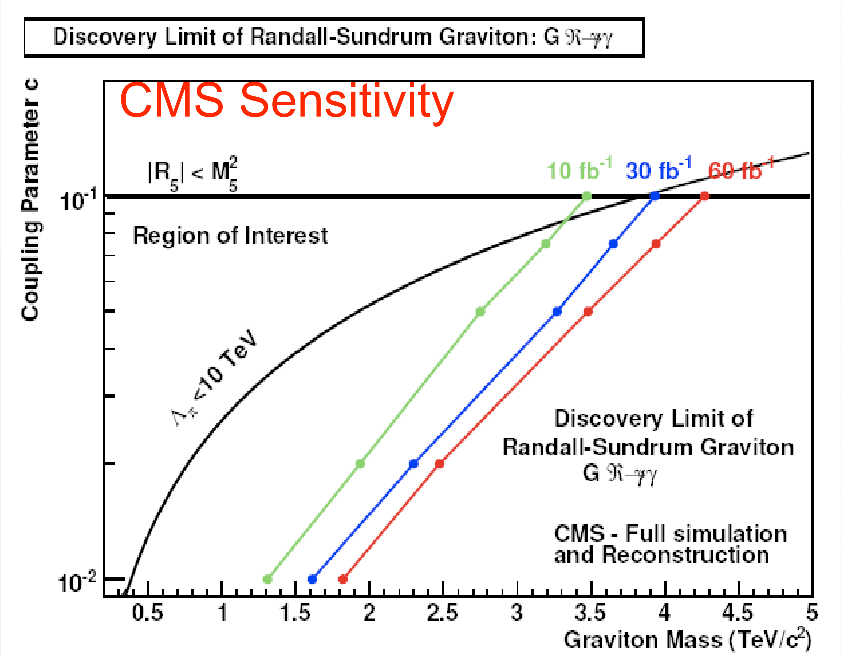




Probing Randall-Sundrum Model w/ BH

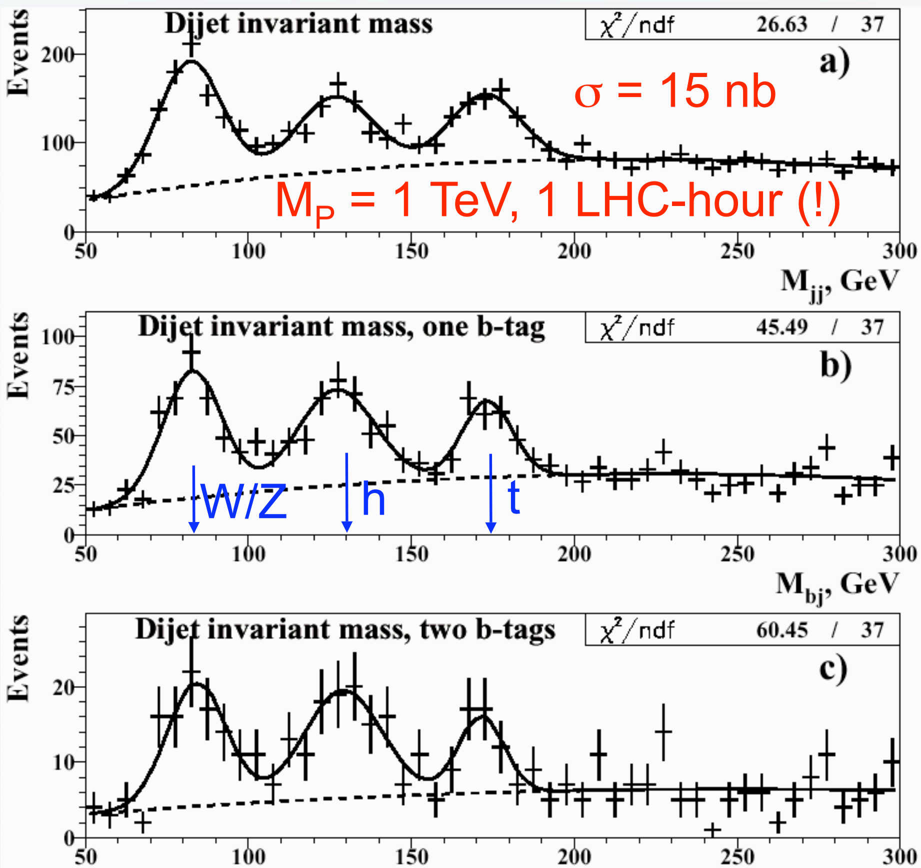
- In terms of probing $\tilde{k}$ vs. M_1, RS black holes would offer the entire allowed range to be probed with ~1 year at a nominal LHC luminosity
- Significant fraction of the allowed parameter space can be probed with just 1 fb^{-1} (up to M_1 ~ 3 TeV for $\tilde{k}$ = 0.1)
- The reach is fairly competitive with direct searches for RS gravitons in the dilepton/diphoton mode





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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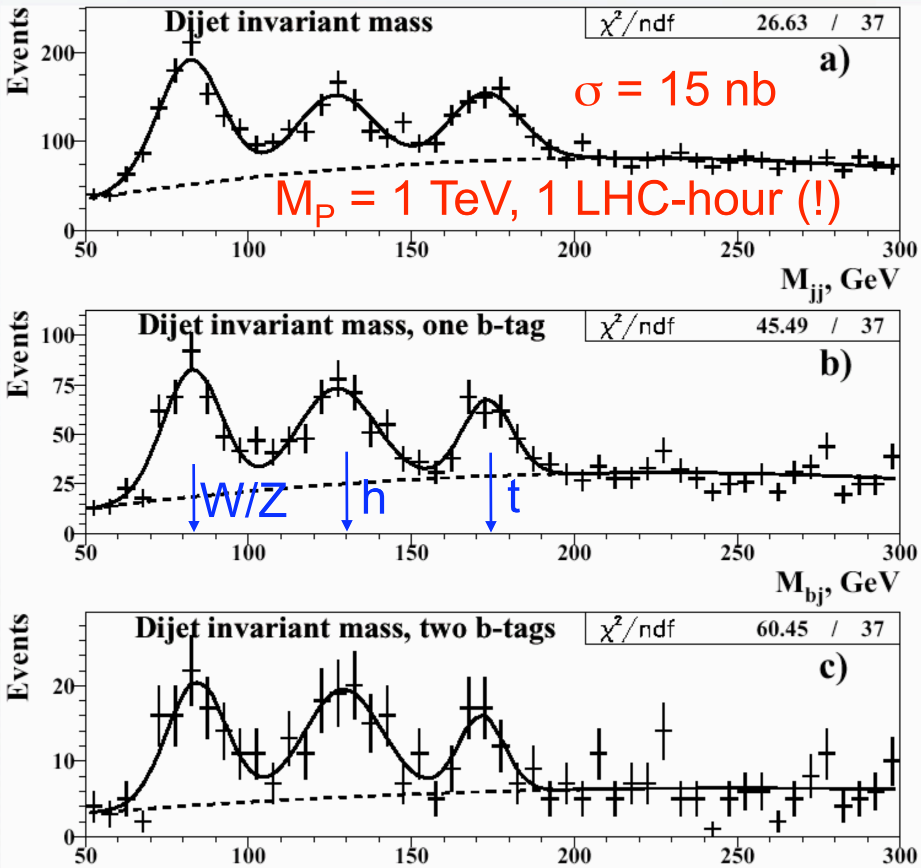

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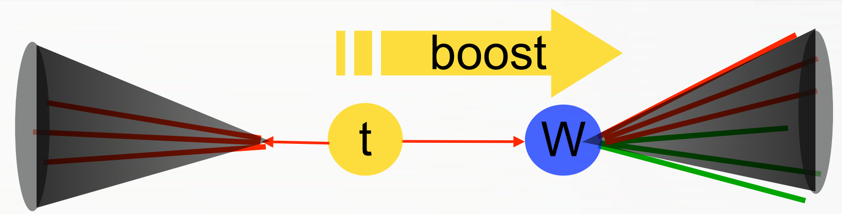

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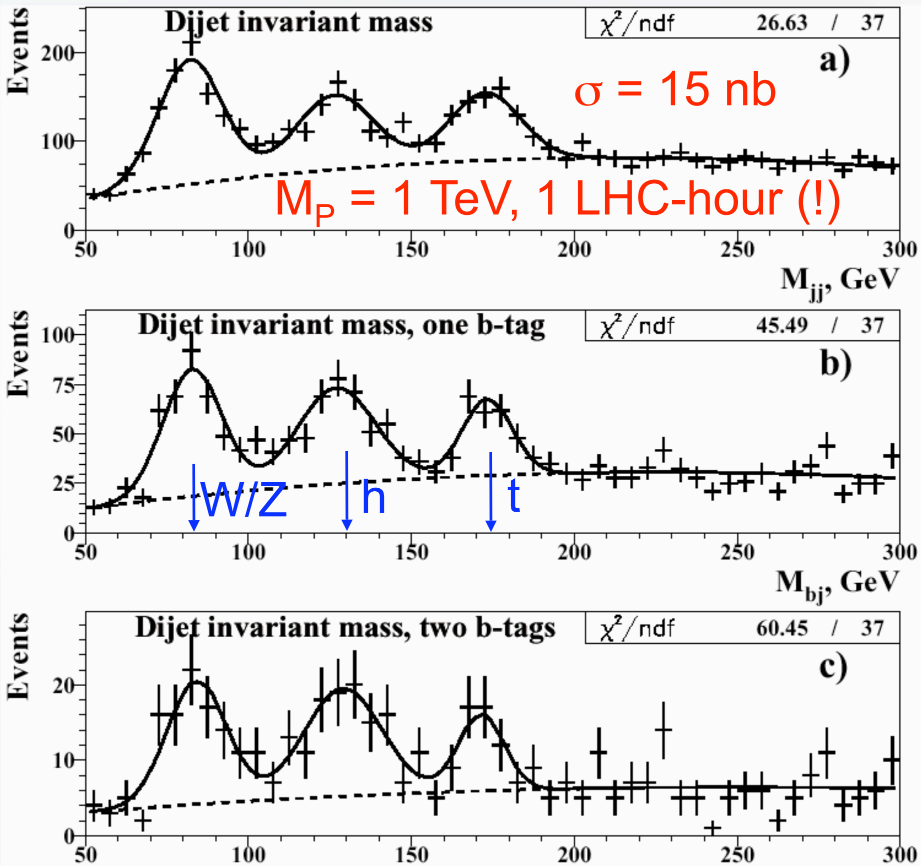

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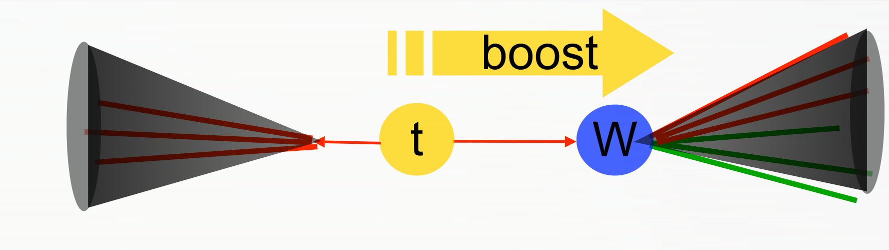
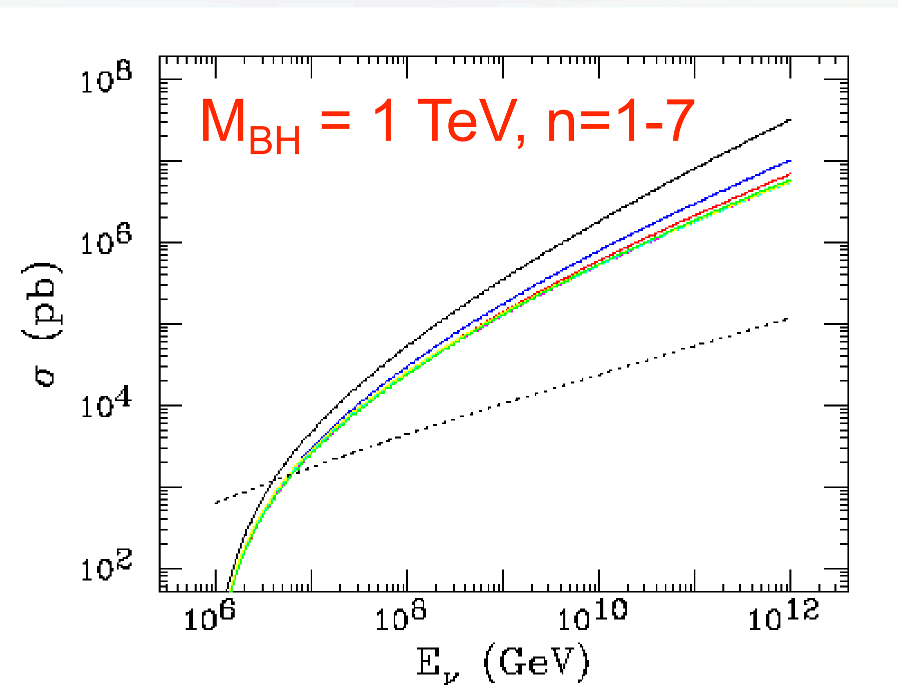


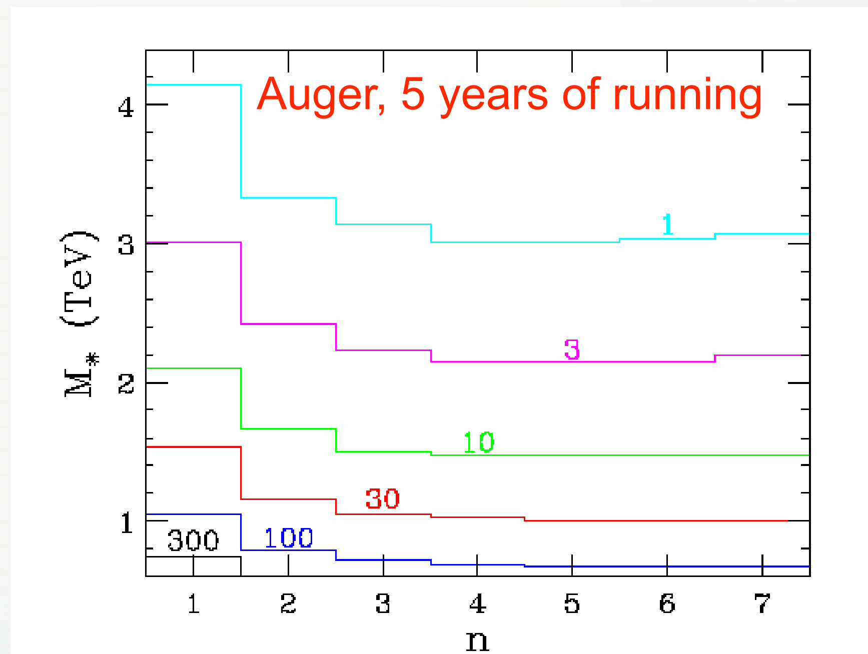
- Higgs observation in the black hole decays is possible at the LHC as early as in the first day of running even with the incomplete and poorly calibrated detectors!
- For M_P = 1, 2, 3, and 4 TeV one needs 1 day, 1 week, 1 month, or 1 year of running to find a 5σ signal
- Higgs is just an example –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

Black Holes in the Cosmic Rays

- Discussed by Feng/Shapere [PRL 88 (2002) 021303]; Anchordoqui/ Goldberg [hep-ph/0109242]; Emparan/ Massip/Rattazzi [hep-ph/0109287], …
- Proton primaries have very high SM interaction rate; consider BH production by quasi-horizontal UHE neutrinos

- Detect them, e.g. in the Pierre Auger fluorescence experiment or AGASA
- A few to a hundred BHs can be detected before the LHC turns on
- Might be possible to establish the uniqueness of the signature by comparing several neutrino-induced processes





[Feng & Shapere, PRL **88** (2002) 021303]