Discovering Extra Dimensions and Black Holes at the LHC

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DESY HEP Seminar

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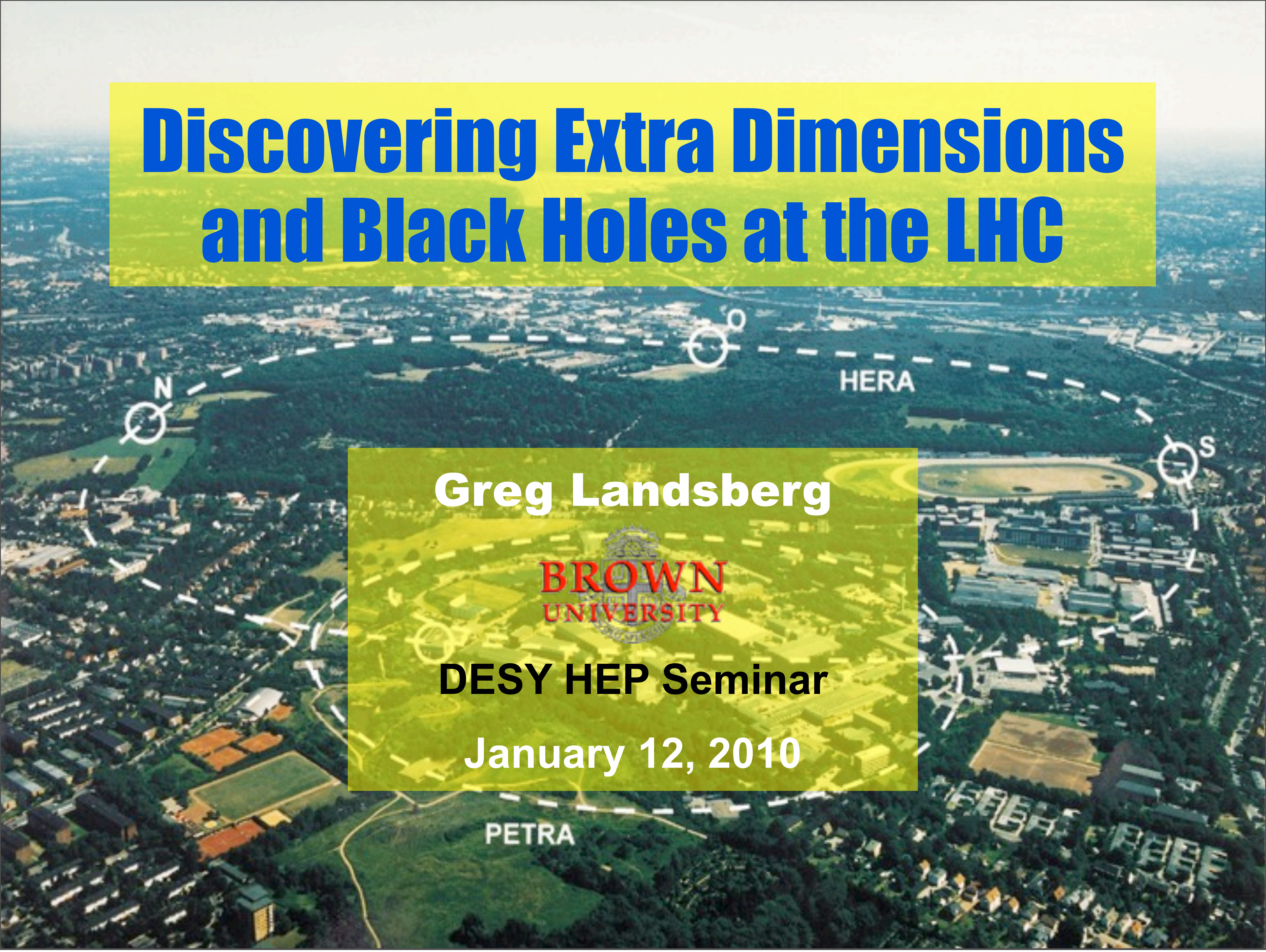
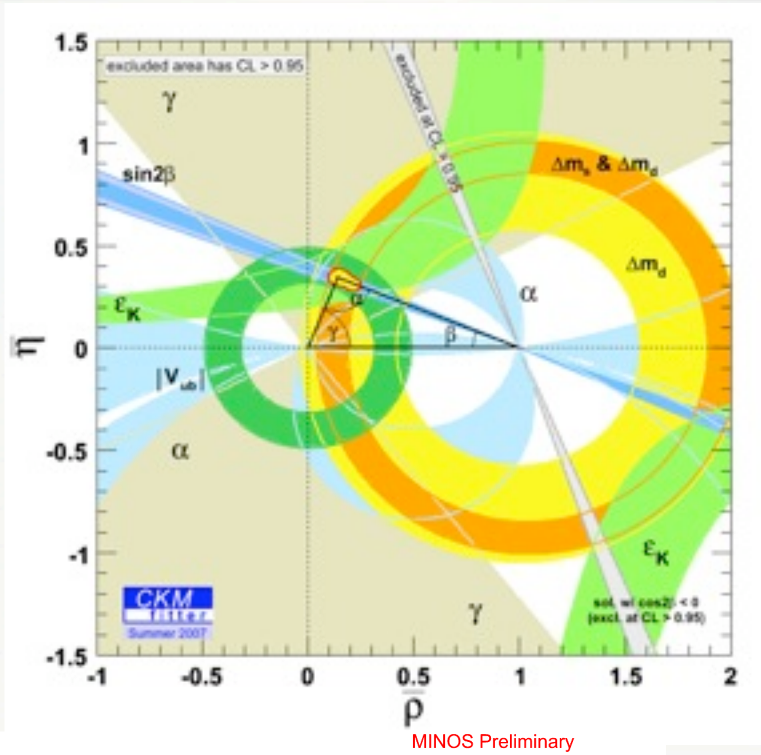
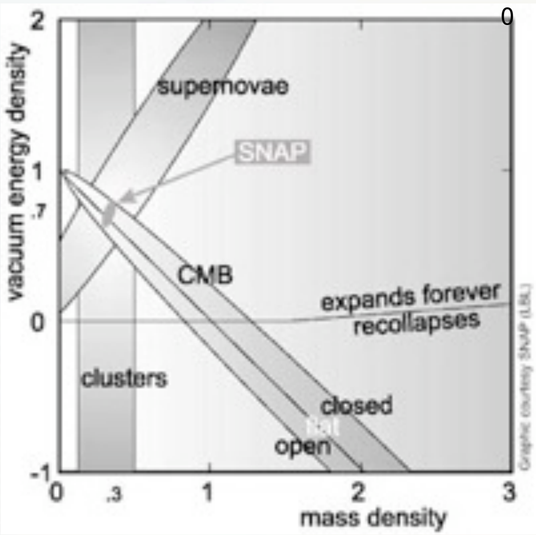


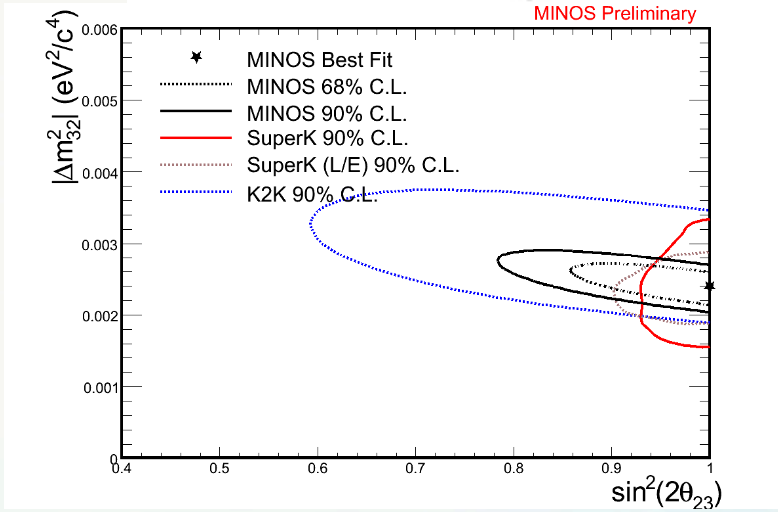
Outline

- *The Hierarchy Problem*
- *Setting the scene: Extra Dimensional Paradigms*
  - *Omit Universal Extra Dimensions*
- *Collider Phenomenology*
- *Current Limits*
- *The LHC Discovery Reach*
- *Black Holes at the LHC*
  - *Only basics; omit RS Black Holes and String Balls*
- *Conclusions*

We Live in Precision Times...







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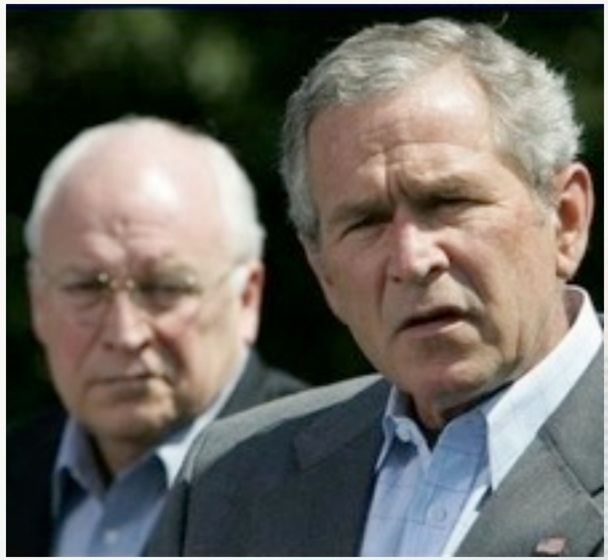
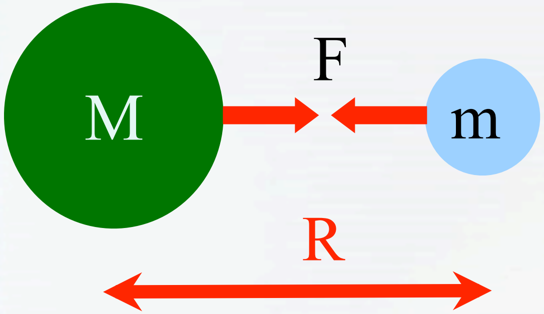


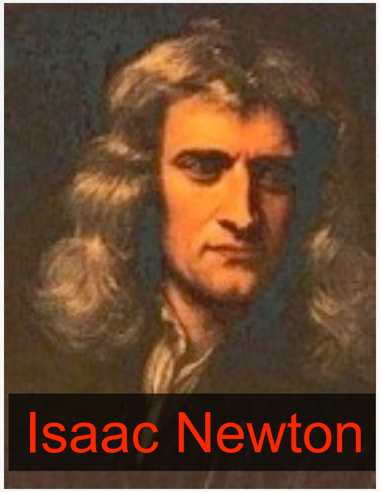
A lot of dark energy...

Puzzle: Mass and Gravity

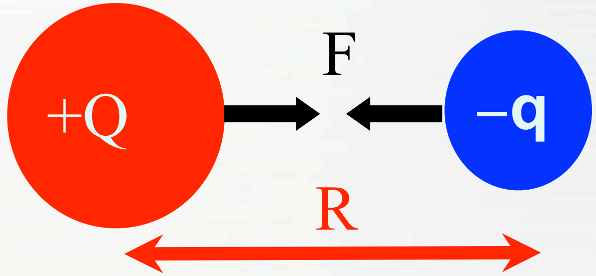
- Isaac Newton: the force that makes the apple fall is the same force that keeps the moon going around the Earth!
- Charles Coulomb: opposite electric charges attract!



$$F = G_N \frac{Mm}{R^2}$$



Isaac Newton



$$F = G_C \frac{Qq}{R^2}$$

Charles Coulomb

- Mass is analogous to electric charge?!
- But gravity is 10^{38}=100,000,000,000,000,000,000,000,000,000,000,000,000 (hundred trillion trillion trillions!) times WEAKER than electricity!
- The hierarchy problem: $M_{Pl} = G_N^{-1/2} \approx 10^{16}$ TeV » $M_{EW} \sim 1$ TeV ~ 1000 M_p

Large Hierarchies Tend to Collapse...

The eighties…

More Large Hierarchies

Collapse of the Soviet Union

The nineties…

Even More Large Hierarchies

This decade...

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  (Food for thought: is it really numerology?)

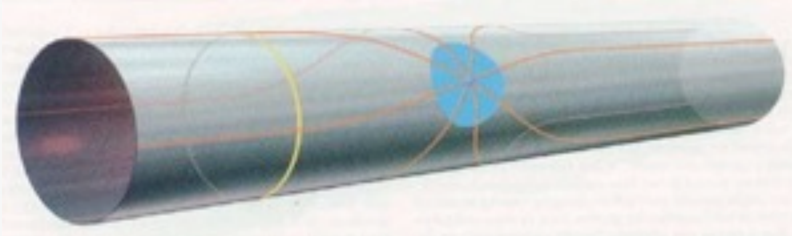
1998: Large Extra Dimensions

- 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 $G'_N = 1/(M_{\rm Pl}^{[3+n]})^2 = 1/M_D^2$; $M_D \sim 1$ TeV

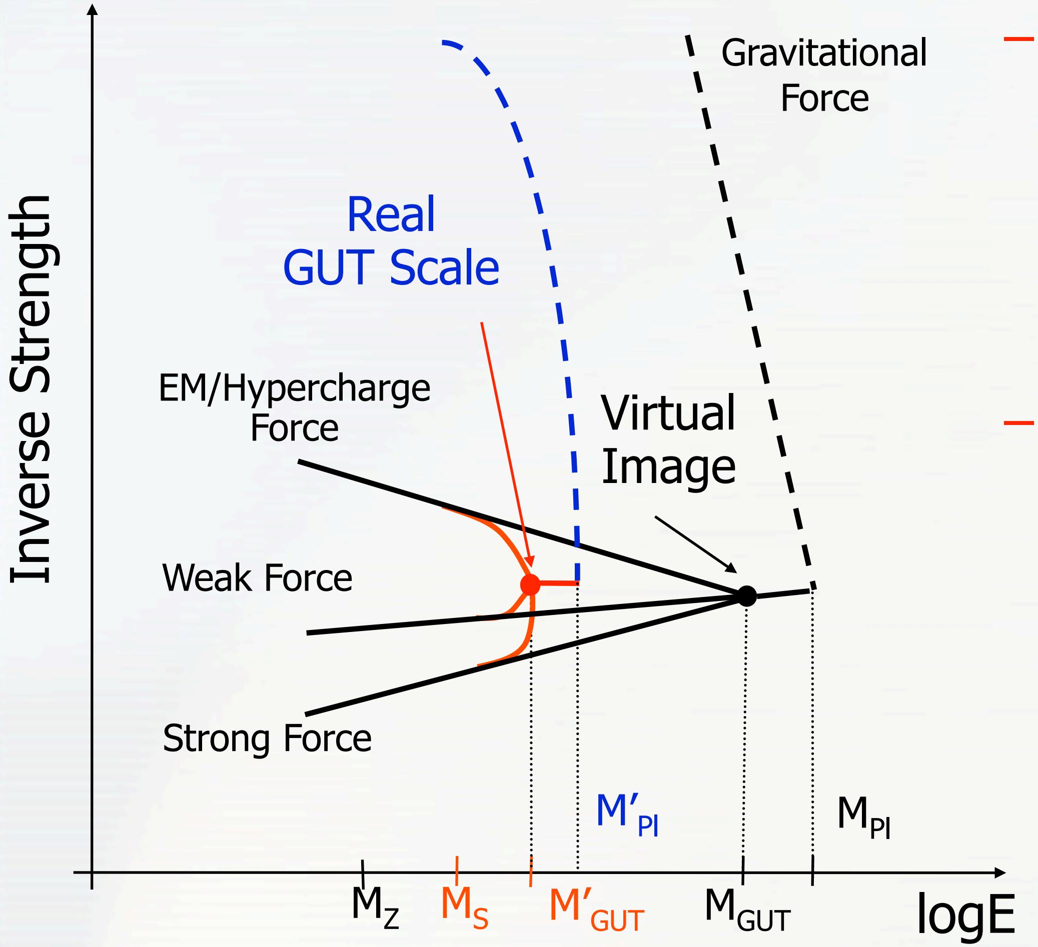
$$M_D^{n+2} \sim M_{\rm Pl}^2/r^n$$

- More precisely, from Gauss's law:

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

- Amazing as it is, but as of 1998 no one has tested Newton's law to distances less than ~ 1mm! (Even now it's been tested to only 0.16mm!)
- Thus, the fundamental Planck scale could be as low as 1 TeV for n > 1

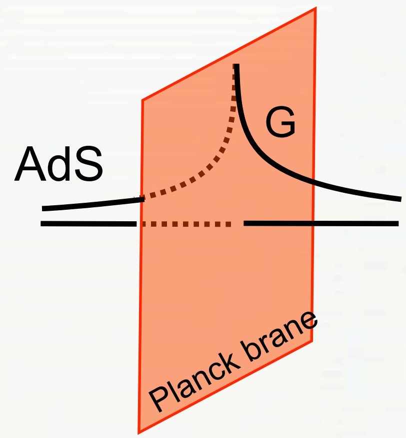
TeV^{-1} Extra Dimensions



- 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

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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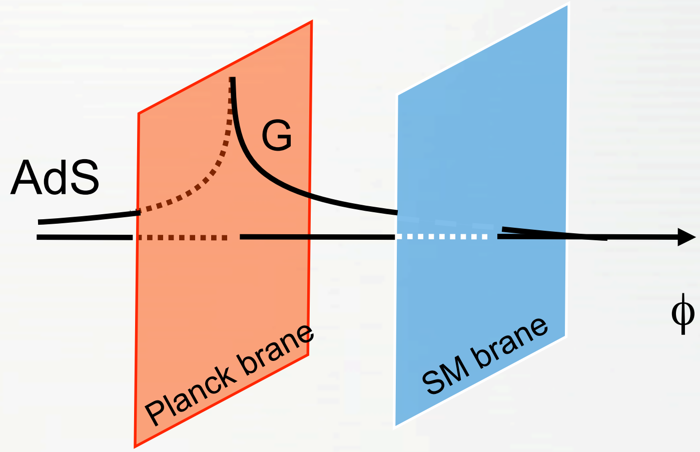

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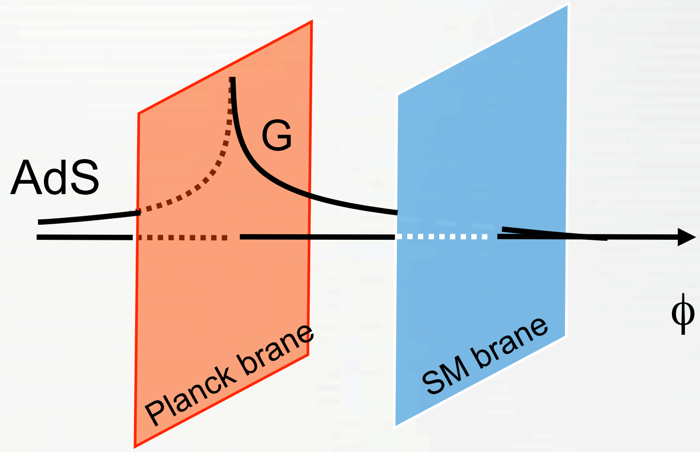
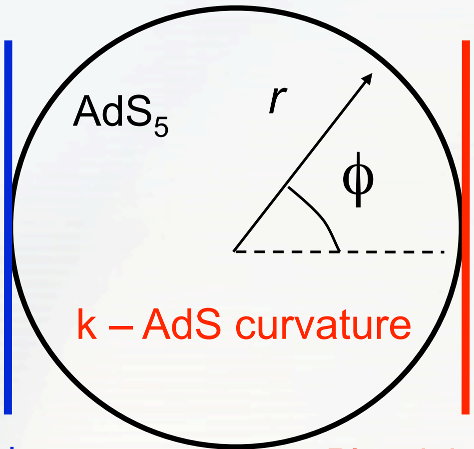




Anti-deSitter space-time metric:

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

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

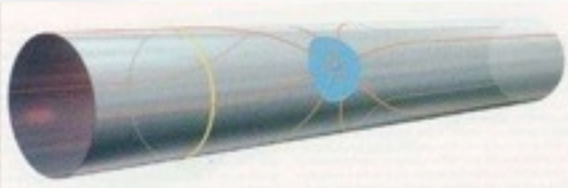
Reduced Planck mass:

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

Extra Dimensions: a Brief Summary

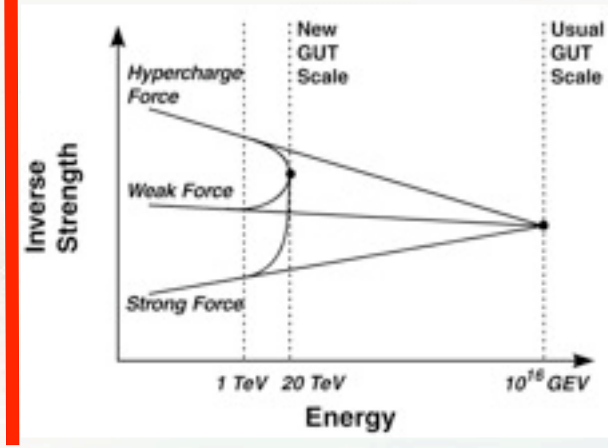
ADD Paradigm:

- 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



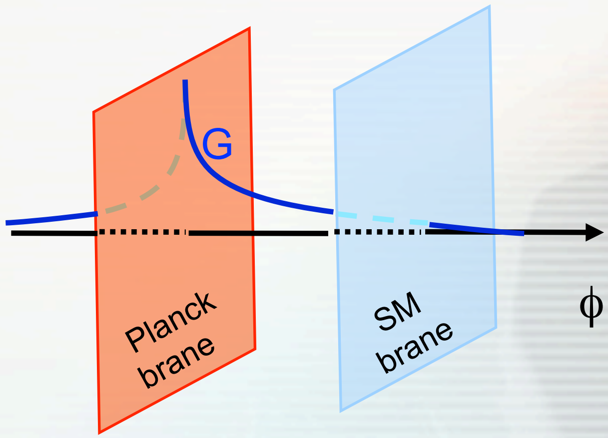
TeV^{-1} Scenario:

- 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:

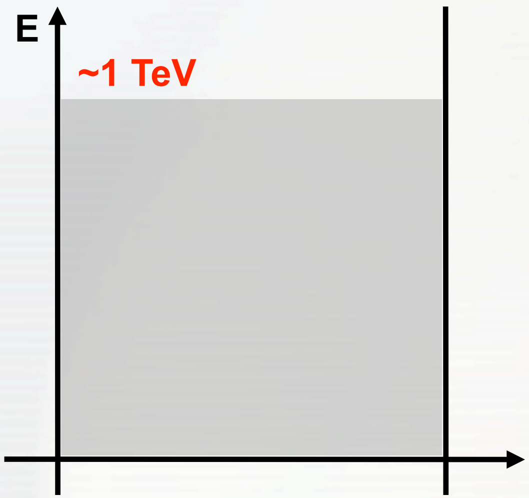
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

ADD Paradigm:

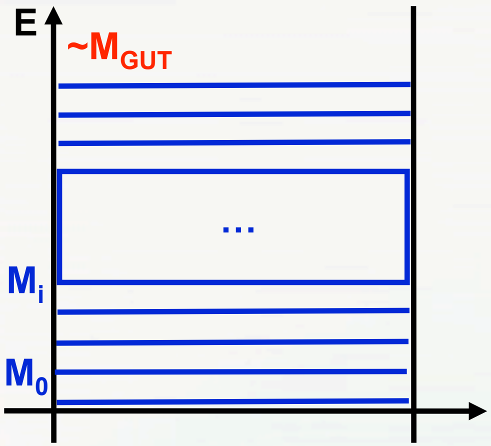
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Experimentally can't resolve these modes – they appear as continuous spectrum
- Coupling: G_N per mode; compensated by large number of modes



TeV^{-1} Scenario:

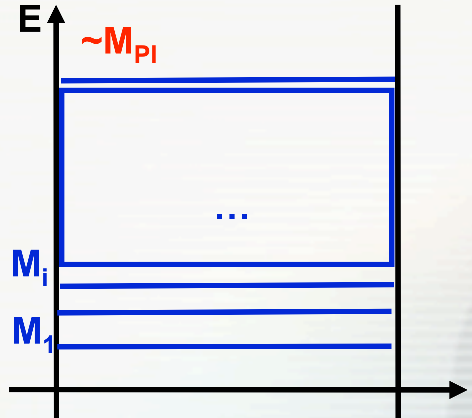
- Winding modes with nearly equal energy spacing ~1/r, i.e. ~ 1 TeV
- Can excite individual modes at colliders or look for indirect effects
- Coupling: ~g_w per mode

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



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



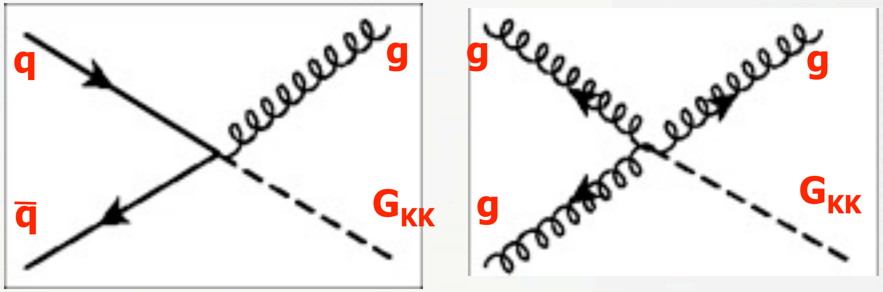
$$M_0 = 0;\ M_i = M_1 \frac{x_i}{x_1} \approx$$
$$M_1,\ 1.83M_1,\ 2.66M_1,\ 3.48M_1,\ \ldots$$

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 ~M_D (and likely < M_D)
- The two processes are complementary

Real Graviton Emission

Monojets at hadron colliders



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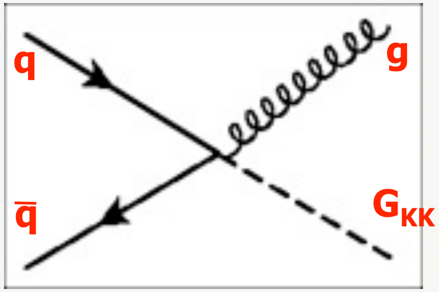
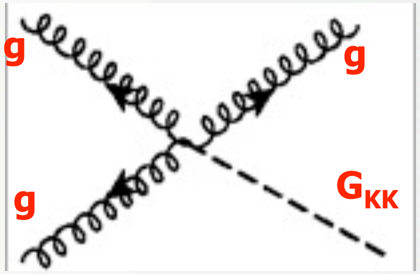
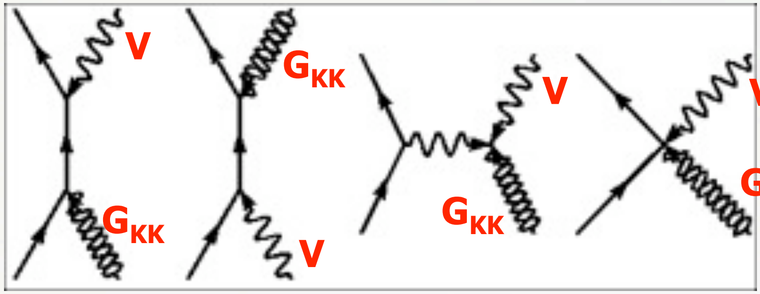




Single VB at hadron or e^+e^- colliders



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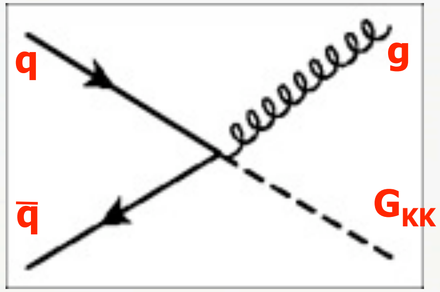

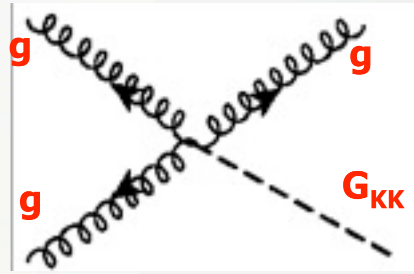

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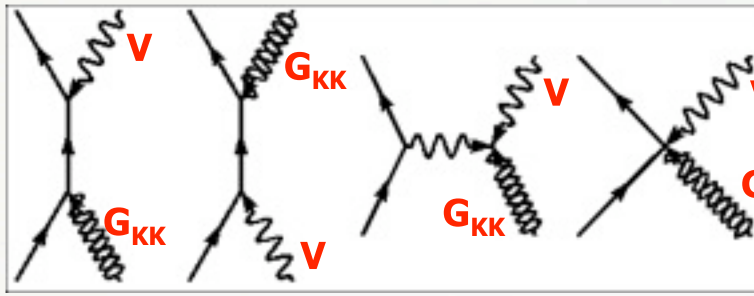
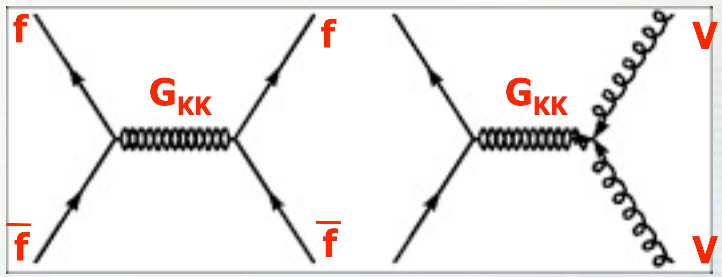


Virtual Graviton Effects

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



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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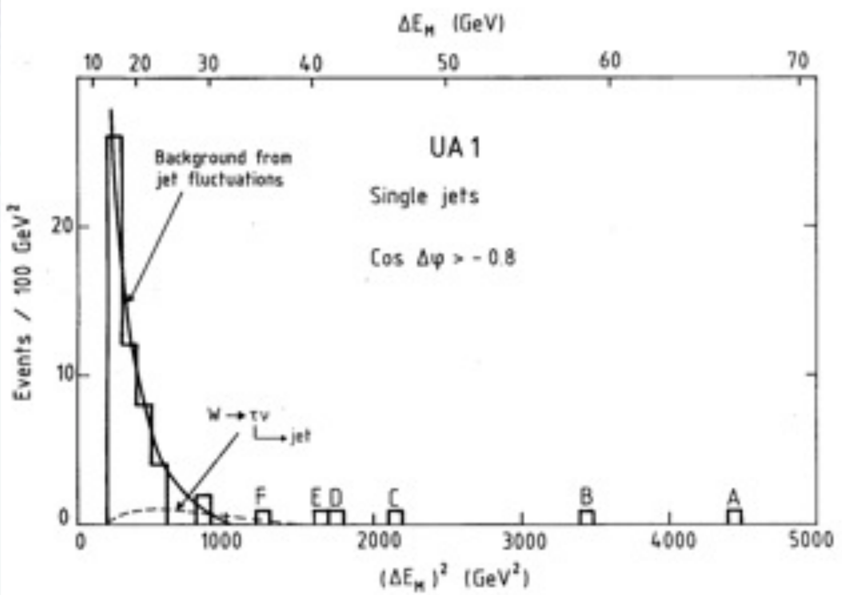
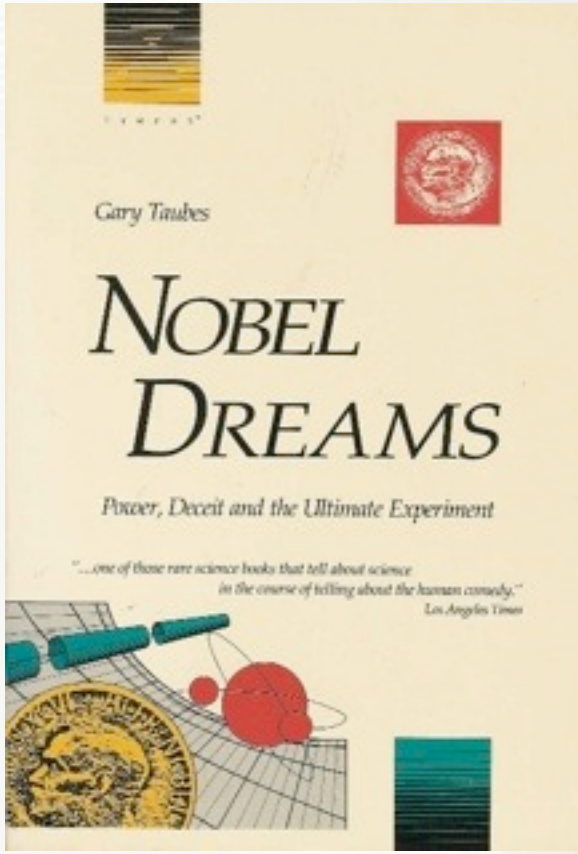




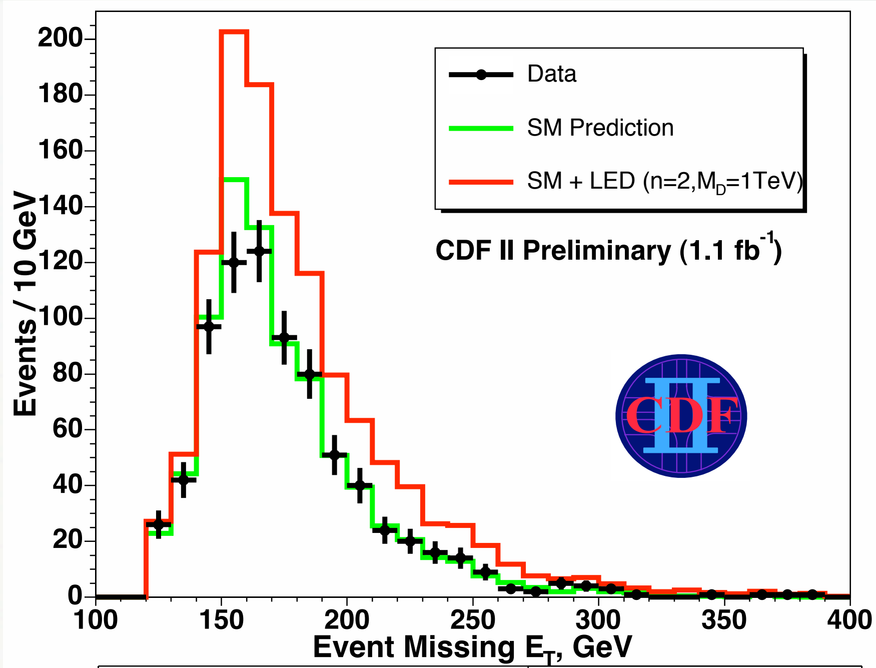
- These monojets turned out to be due to unaccounted background

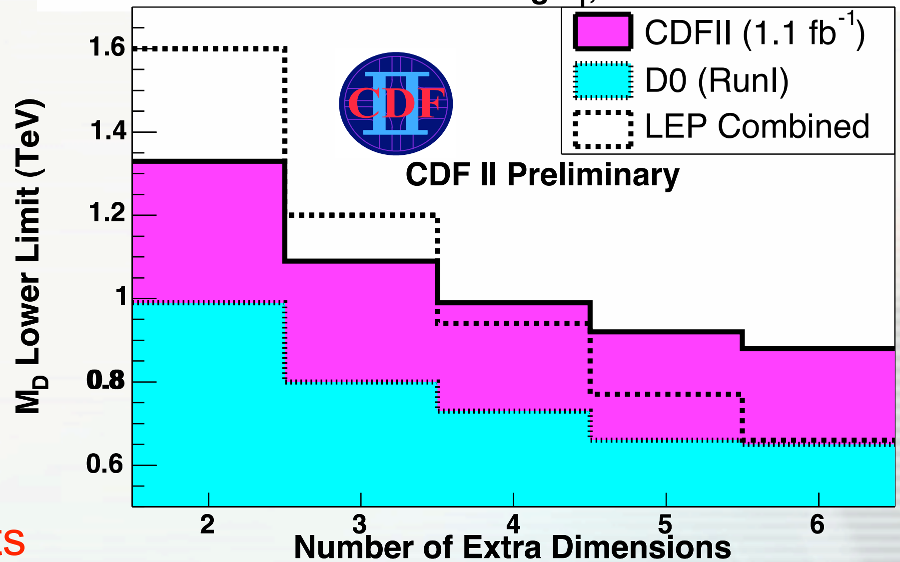
- The signature was deemed doomed and nearly forgotten

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

Tevatron: Large ED Search via Monojets

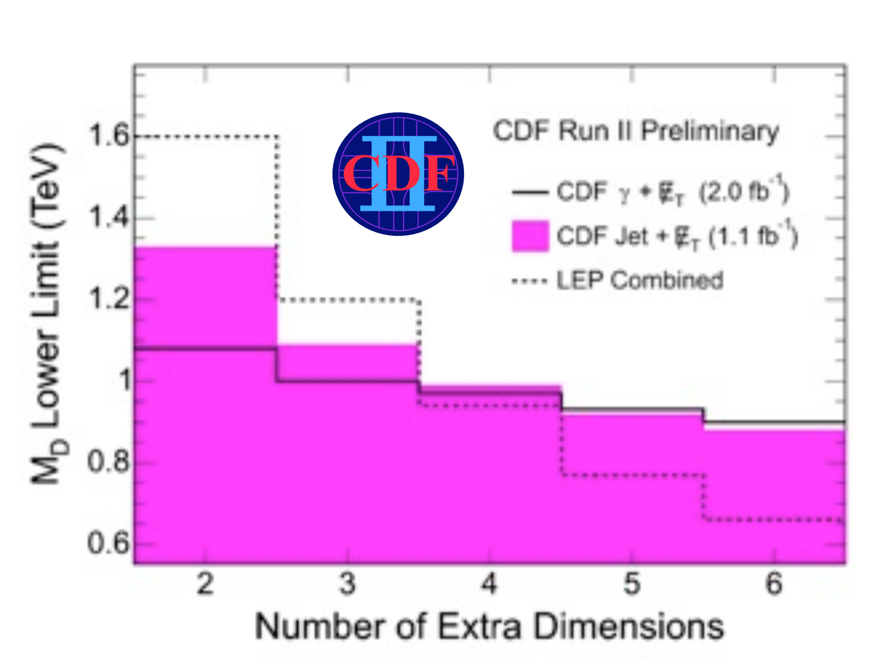
- jets + ME_T final state
- $Z(\nu\nu)$+jets is irreducible background
  - Challenging signature due to large instrumental backgrounds from jet mismeasurement, cosmics, etc.
- DØ pioneered this search and set limits [PRL, **90** 251802 (2003)] M_P > 1.0-0.6 TeV for n=2…7
- CDF analysis based on 1.1 fb^{-1}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

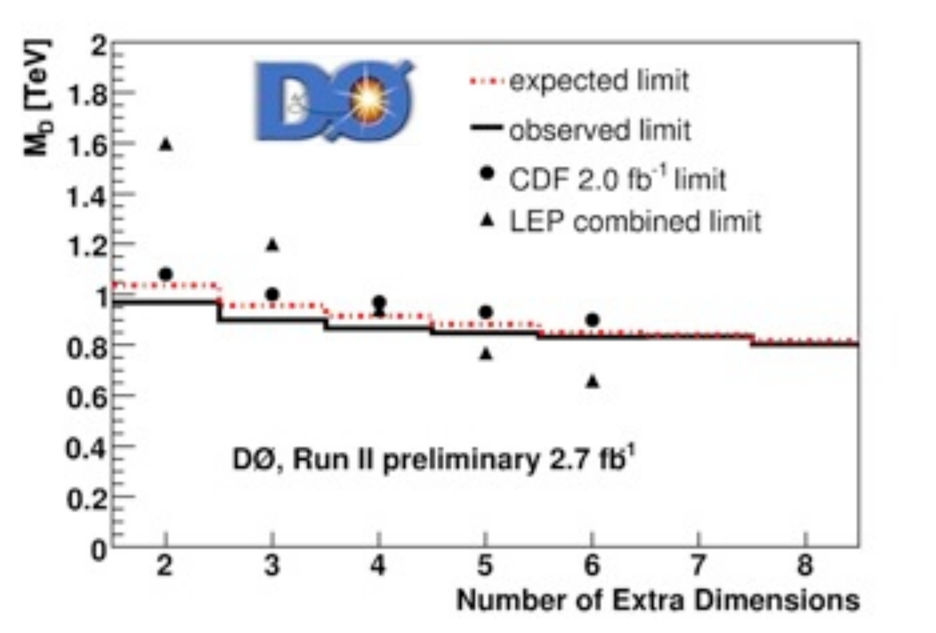




Tevatron Searches for ED in Monophotons

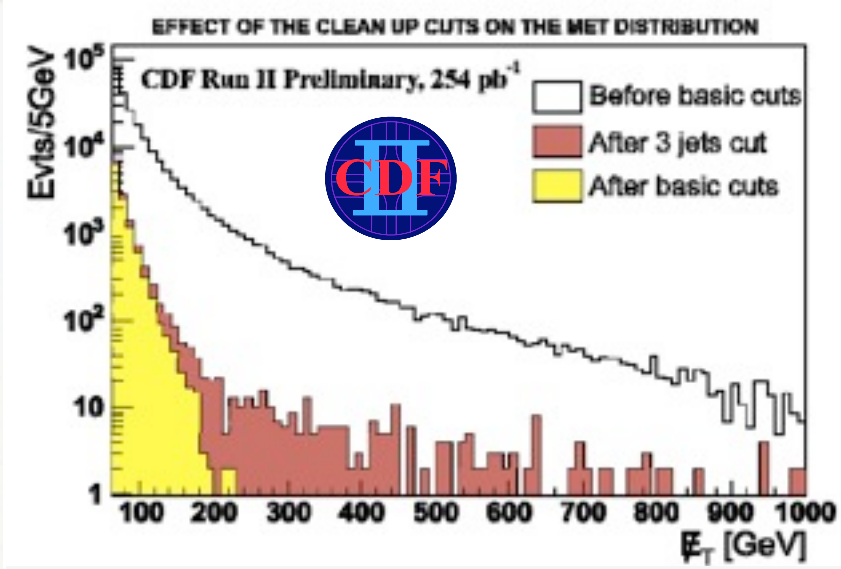
- Both CDF and DØ completed monophoton searches
- While easier than the monojet one, the sensitivity is typically not as good, especially for low number of ED
  - CDF monophoton limits approach monojet ones at large n, but require twice the luminosity

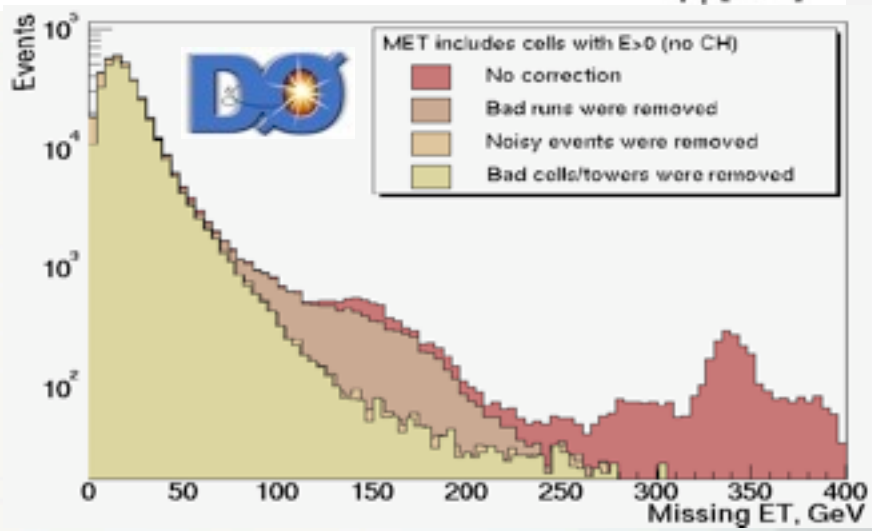




Why ME_T is Tough?

- 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 ≠ 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

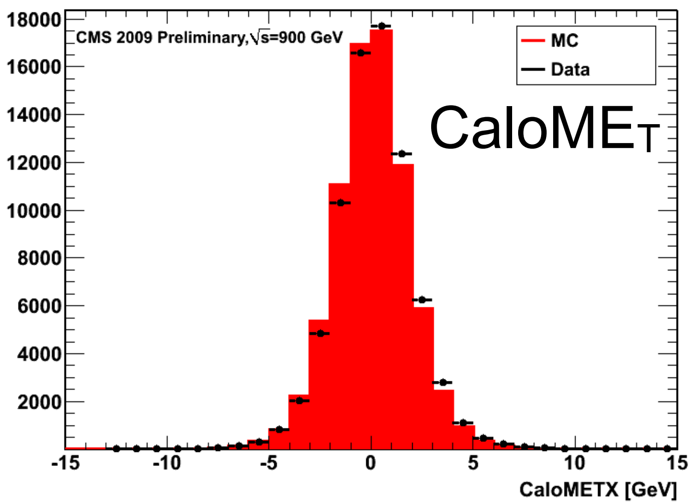


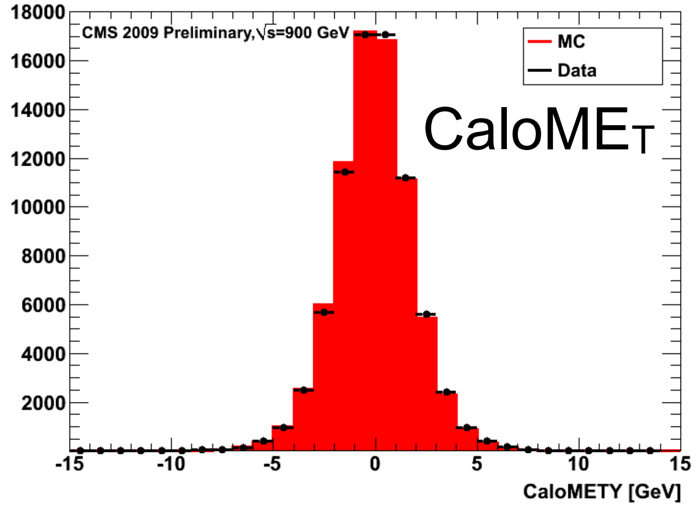


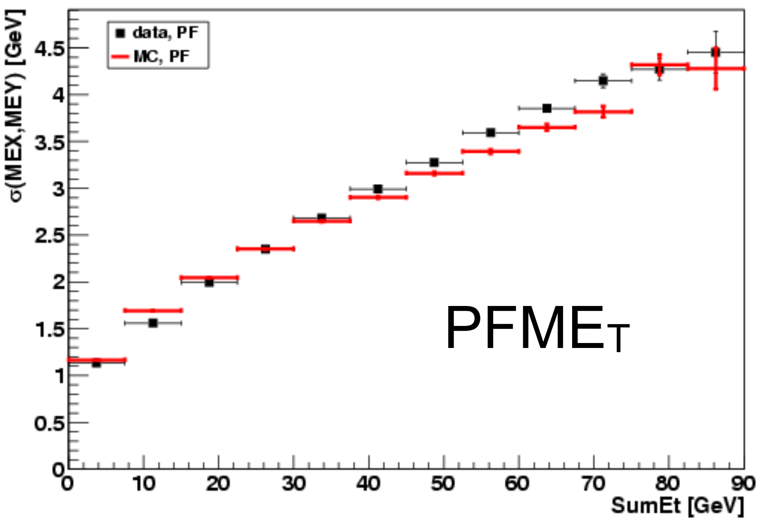
- Raw ME_T spectrum at the Tevatron and that after thorough clean-up

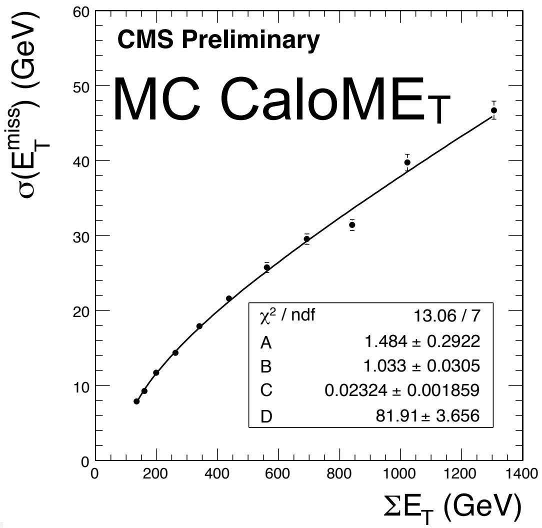
ME_T in CMS in Collision Data

- Very encouraging performance seen in first LHC collision data: both PF and Calorimeter based ME_T



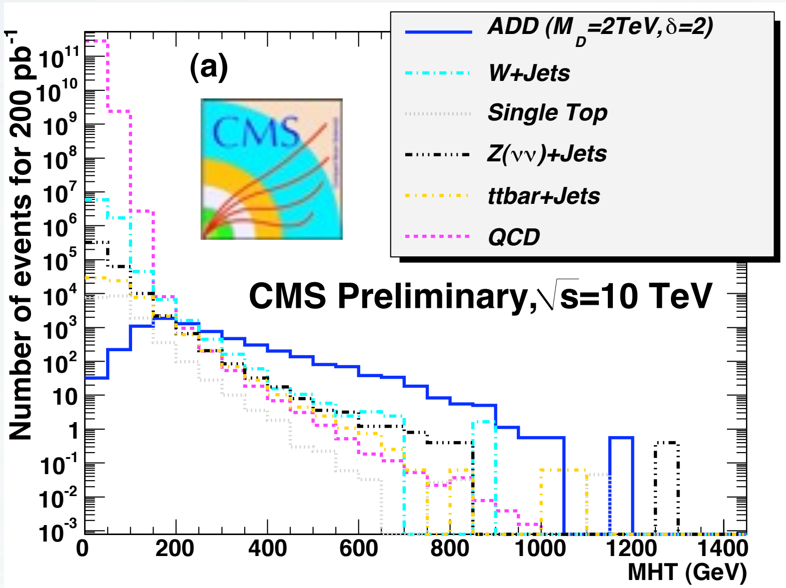


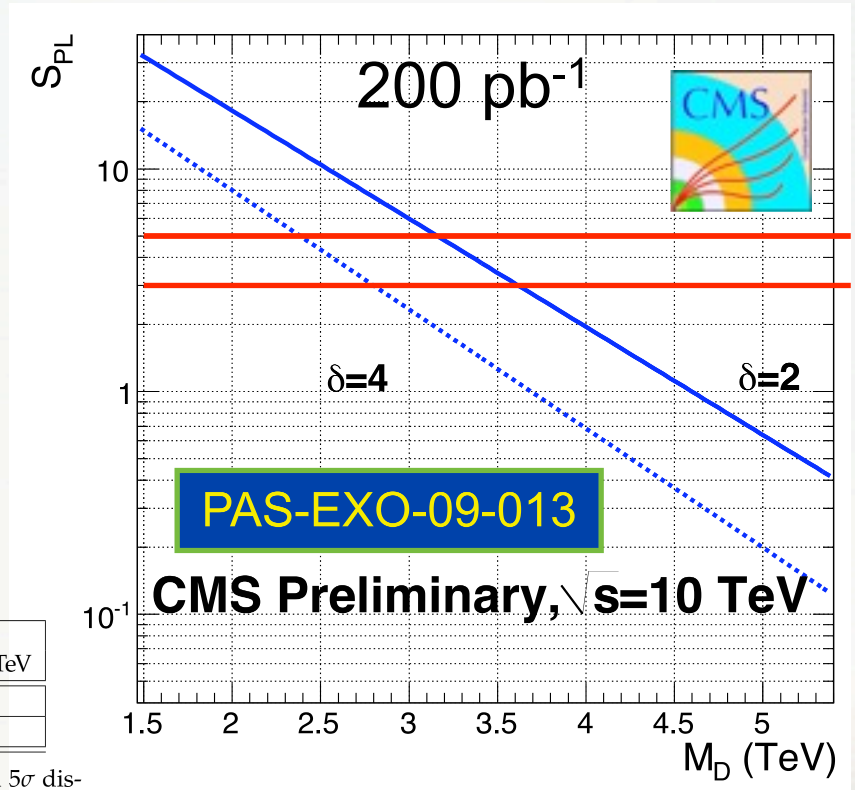




CMS Monojet Analysis

- Look for deviations from the SM in the negative vector sum of jet transverse energies (MH_T > 250 GeV) - more robust than ME_T





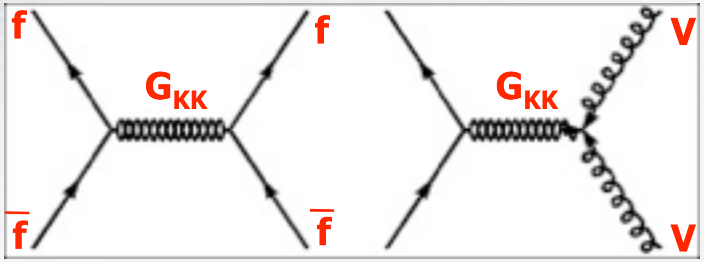
	δ = 2			δ = 4	
	M_D = 1 TeV	M_D = 2 TeV	M_D = 3 TeV	M_D = 1 TeV	M_D = 2 TeV
95% C.L.	0.2	1.1	10	0.5	4.9
5σ	1.7	14	160	6.0	68

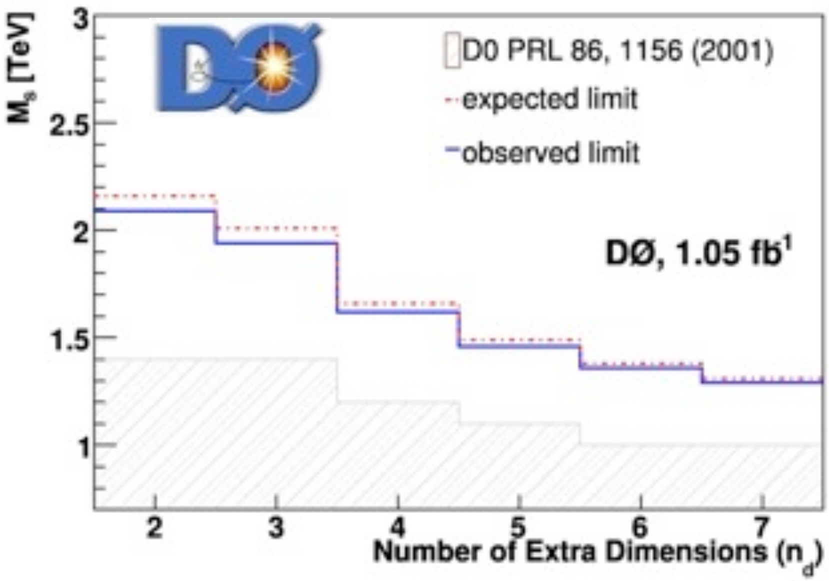
Table 3: Minimum integrated luminosity (pb^{-1}) needed for a 95% C.L. exclusion or a 5σ discovery, for different ADD points.

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

Tevatron: Virtual Graviton Effects





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

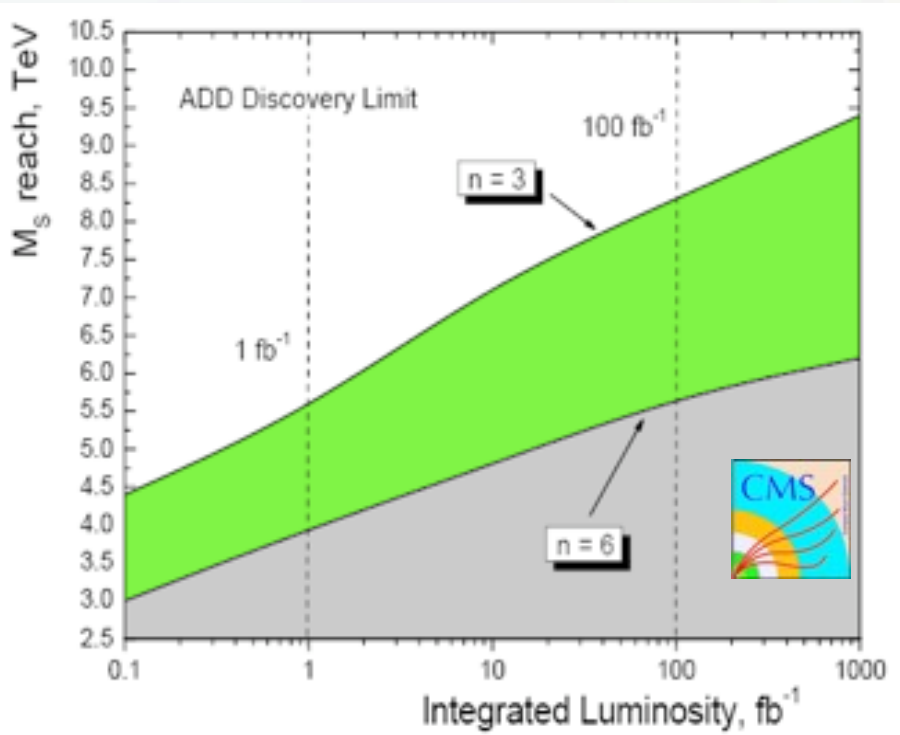
$$\frac{d^2\sigma}{d\cos\theta^* dM} = \frac{d^2\sigma_{SM}}{d\cos\theta^* dM} + \frac{a(n)}{M_S^4} f_1(\cos\theta^*, M) + \frac{b(n)}{M_S^8} f_2(\cos\theta^*, M)$$

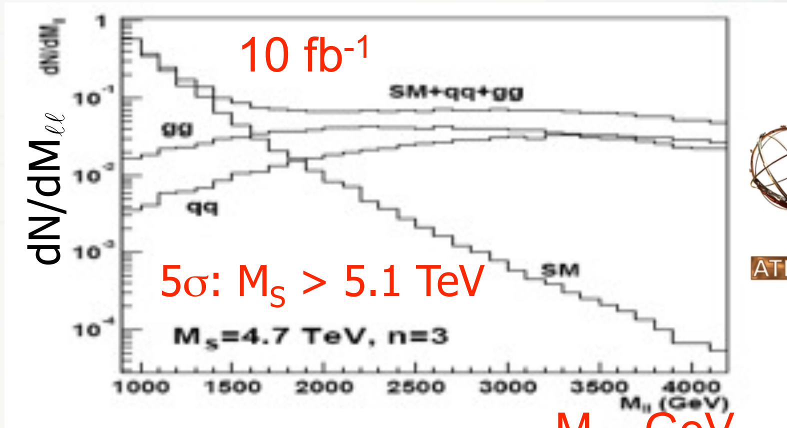
- High-mass, low $|\cos\theta^*|$ tail is a characteristic signature of LED Cheung, GL [PRD **62** 076003 (2000)]
- Best limits on the effective Planck scale come from 1 fb^{-1} DØ Run II data:
  - M_S > 1.3-2.1 TeV (n=2-7) - tightest to date
- Recent results from dijets yield similar sensitivity

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

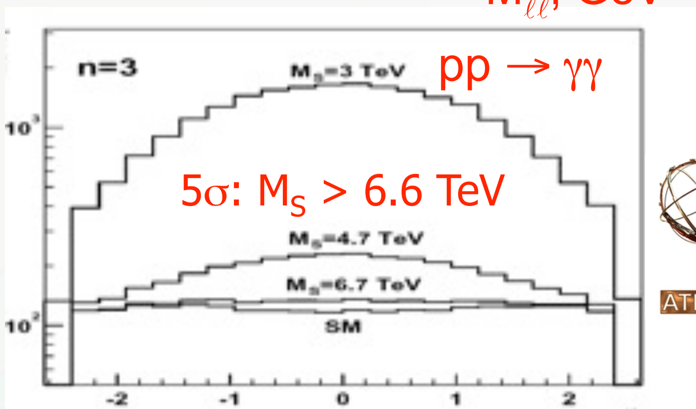
Virtual Graviton Effects at the LHC

- 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 1 fb^{-1}
  - Will also probe generic compositeness models with similar increase in sensitivity compared to the existing limits





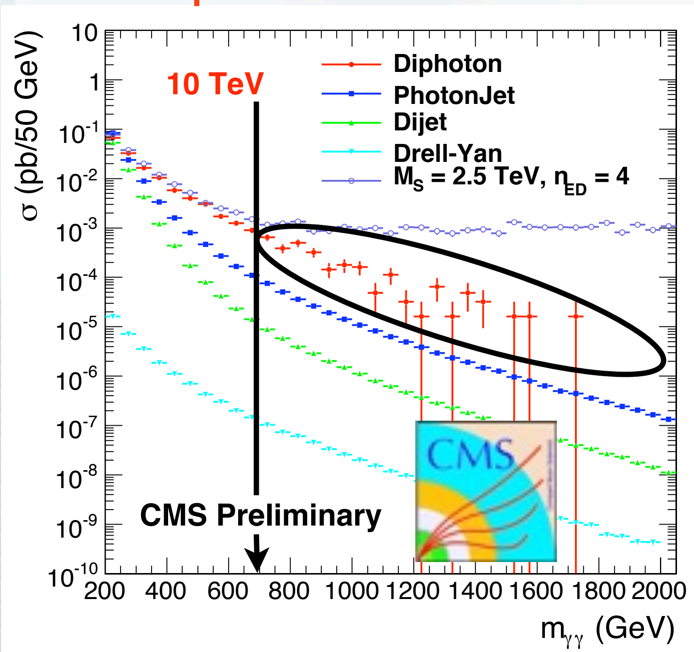
M_ll, GeV

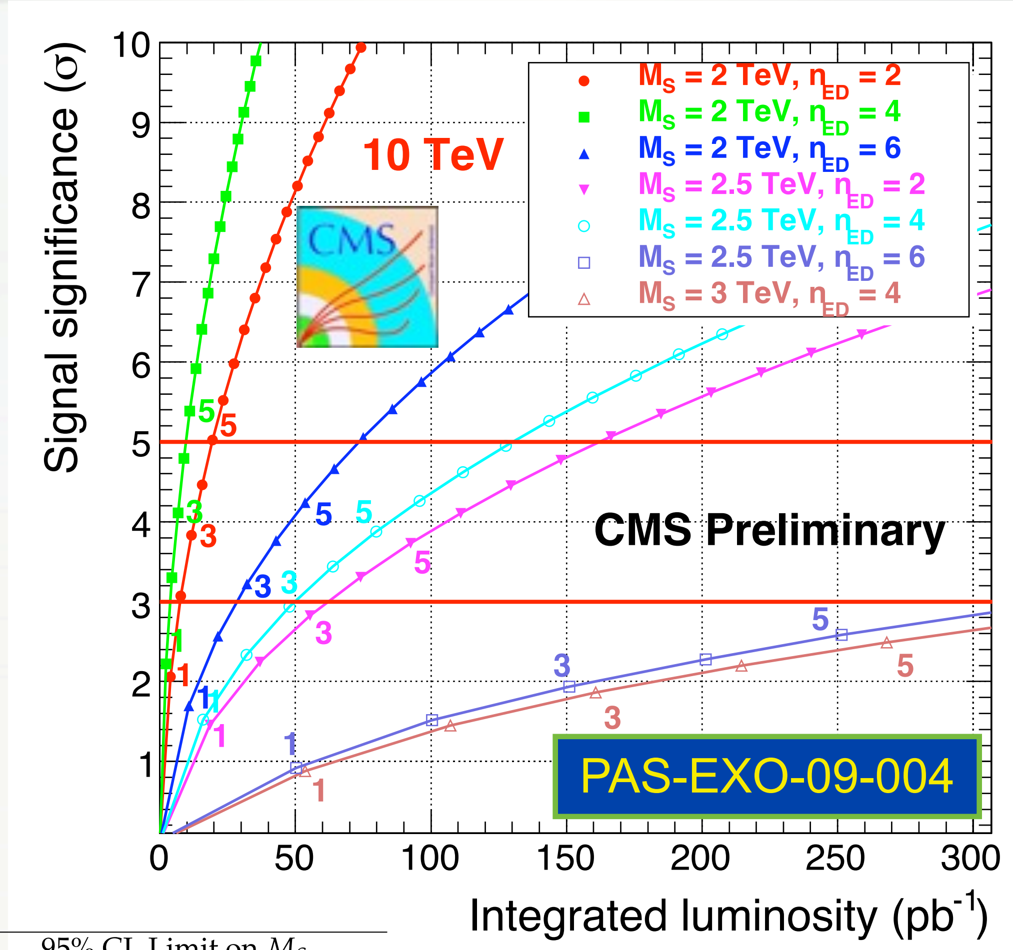


η

Early CMS Search: $\gamma\gamma$

- Virtual graviton effects in the diphoton channel
- Higher sensitivity than ee or $\mu\mu$
- Use $M_{\gamma\gamma}$ > 700 GeV cut and central photons
  - B = 0.40 events for 100 pb^{-1}





n_{ED}	95% CL Limit on M_S		
	50 pb^{-1}	100 pb^{-1}	200 pb^{-1}
2	2.5 TeV	2.7 TeV	2.9 TeV
3	3.0 TeV	3.3 TeV	3.5 TeV
4	2.6 TeV	2.8 TeV	3.0 TeV
5	2.3 TeV	2.5 TeV	2.7 TeV
6	2.1 TeV	2.3 TeV	2.5 TeV
7	2.0 TeV	2.2 TeV	2.4 TeV

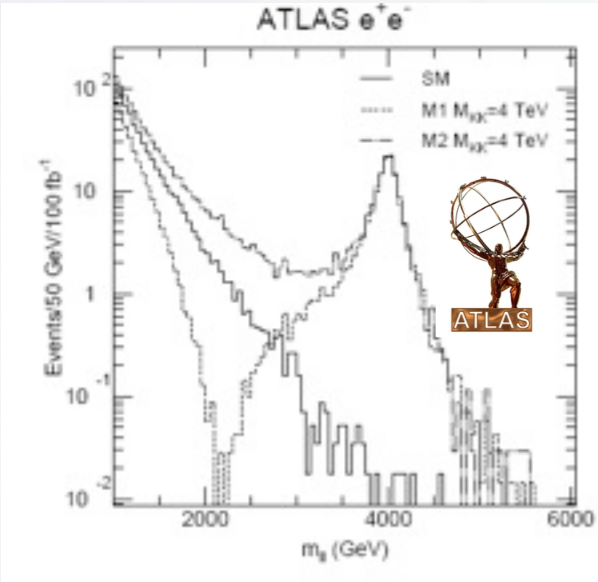
Factor of two higher sensitivity with 100 pb^{-1} compared to the Tevatron

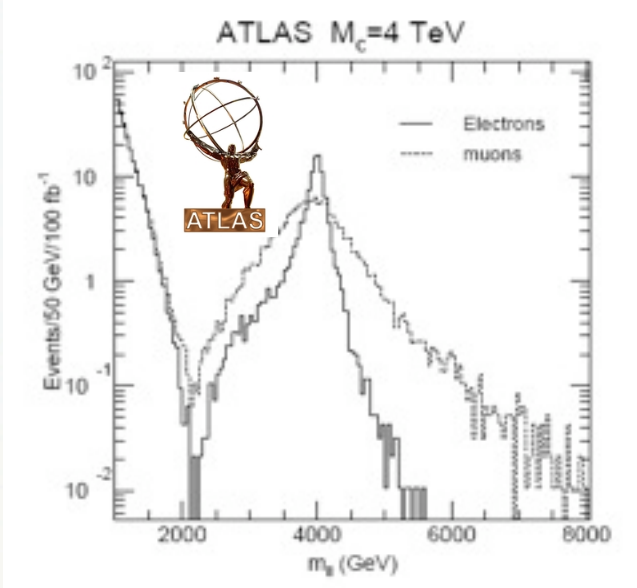
Current Limits on TeV^{-1} ED

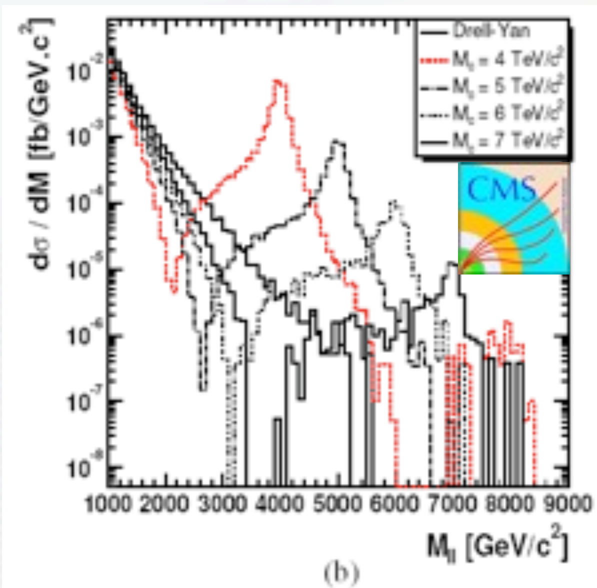
From Cheung & GL [PRD **65**, 076003 (2002)]

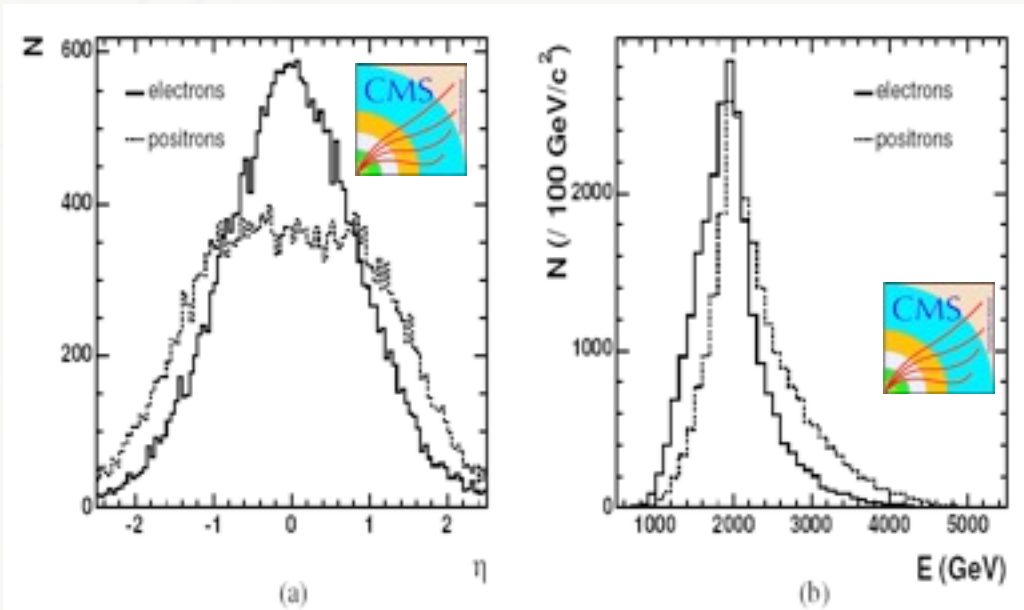
	η (TeV^{-2})	η_{95} (TeV^{-2})	M_C^{95} (TeV)
LEP 2:			
hadronic cross section, ang. dist., $R_{b,c}$	$-0.33\,^{+0.13}_{-0.13}$	0.12	5.3
μ, τ cross section & ang. dist.	$0.09\,^{+0.18}_{-0.18}$	0.42	2.8
ee cross section & ang. dist.	$-0.62\,^{+0.20}_{-0.20}$	0.16	4.5
LEP combined	$-0.28\,^{+0.092}_{-0.092}$	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

Z_{KK} Excitations at the LHC



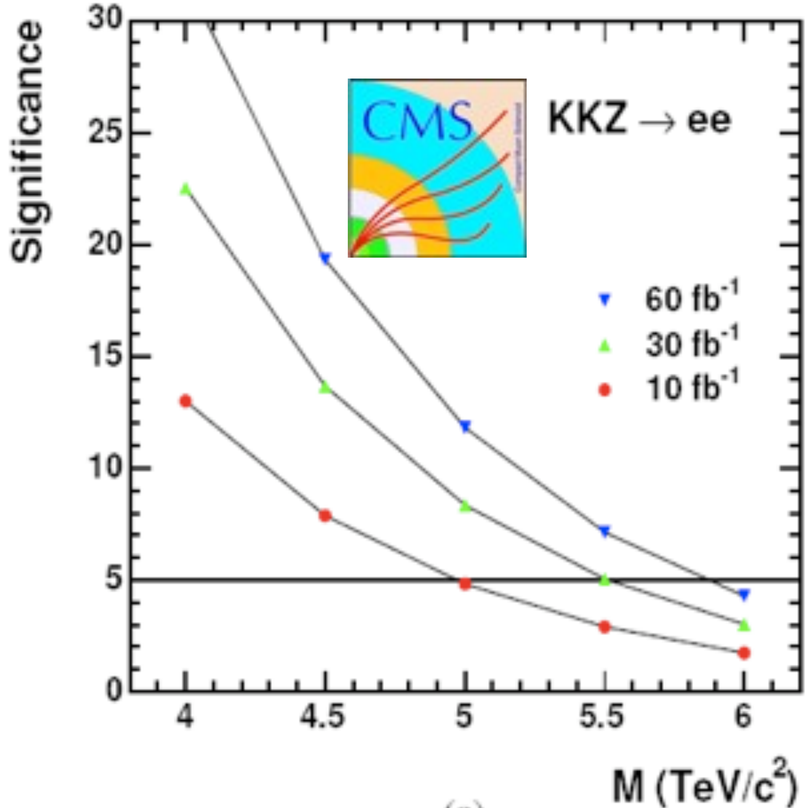




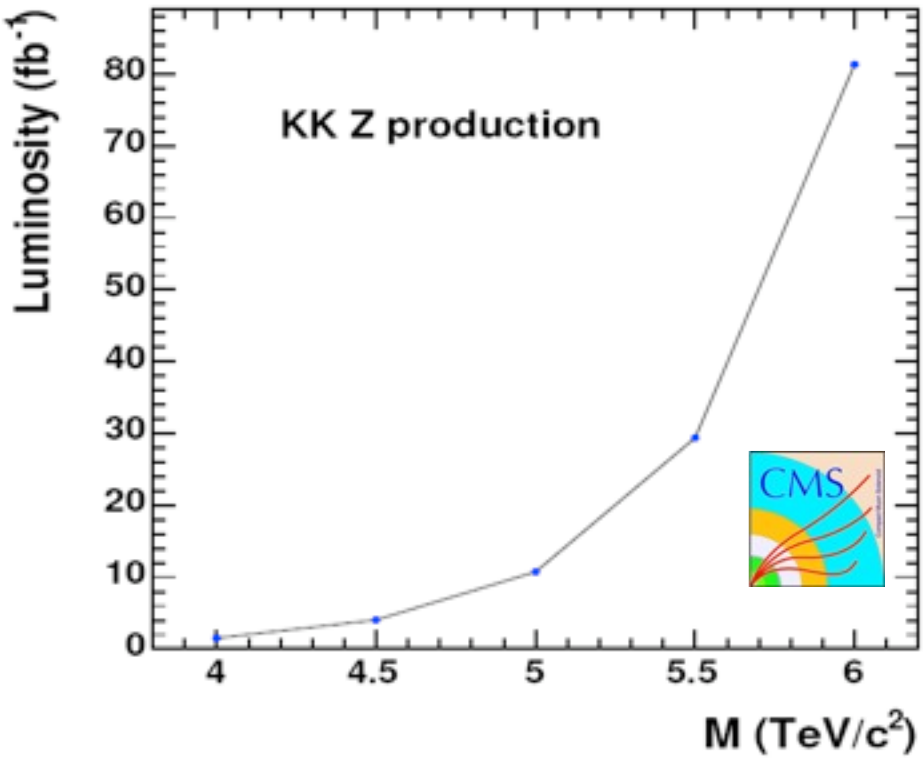


KK Reach

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



(a)



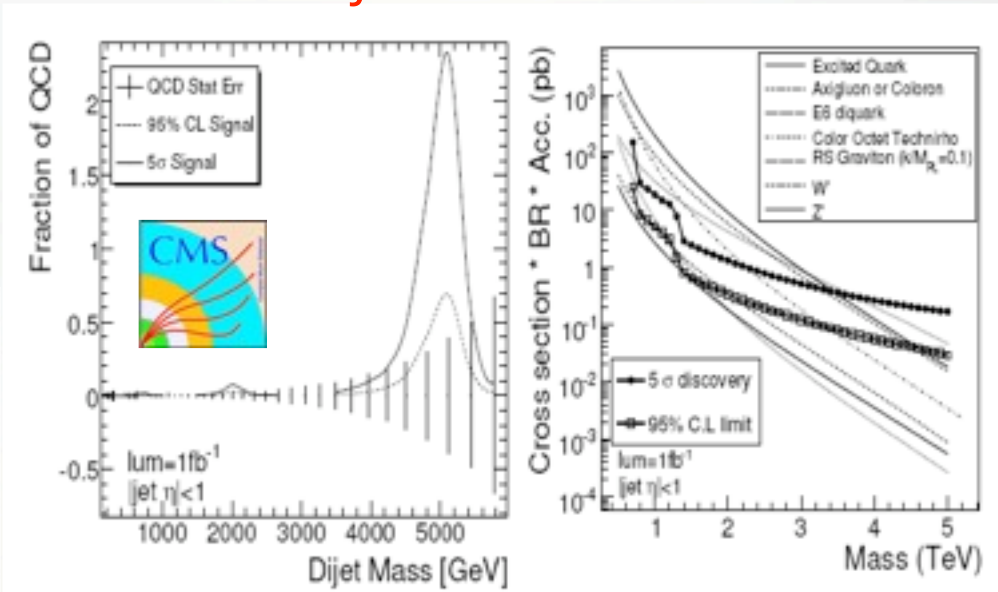
What about Dijets/Ditaus?

- If jet energy scale is fixed with early data, dijets channel is also sensitive to KK modes
  - CMS 0.1-10 fb^{-1} simulations
  - Caveat: PDF uncertainties are large: poor reach in the ADD scenario

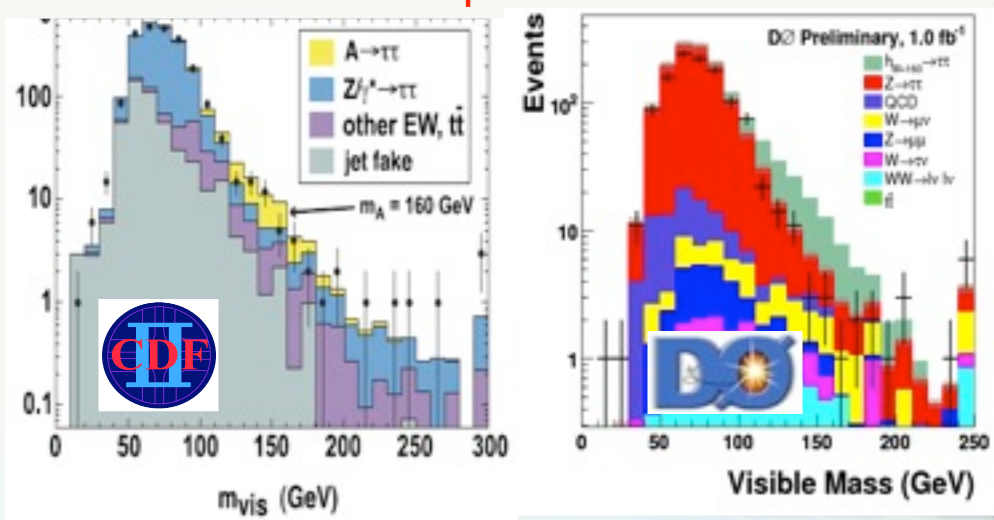
Resonance Model	95% CL Excluded Mass (TeV/c^2)			5σ Discovered Mass (TeV/c^2)		
	100 pb^{-1}	1 fb^{-1}	10 fb^{-1}	100 pb^{-1}	1 fb^{-1}	10 fb^{-1}
Excited Quark	0.7 - 3.6	0.7 - 4.6	0.7 - 5.4	0.7 - 2.5	0.7 - 3.4	0.7 - 4.4
Axigluon or Colouron	0.7 - 3.5	0.7 - 4.5	0.7 - 5.3	0.7 - 2.2	0.7 - 3.3	0.7 - 4.3
E_6 diquarks	0.7 - 4.0	0.7 - 5.4	0.7 - 6.1	0.8 - 2.0	0.8 - 3.7	0.8 - 5.1
Colour Octet Technirho	0.7 - 2.4	0.7 - 3.3	0.7 - 4.3	0.7 - 1.5	0.7 - 2.2	0.7 - 3.1
Randall-Sundrum Graviton	0.7 - 1.1	0.7 - 1.1 1.3 - 1.6	0.7 - 1.1 1.3 - 1.6 2.1 - 2.3	N/A	N/A	N/A
W'	0.8 - 0.9	0.8 - 0.9 1.3 - 2.0	0.8 - 1.0 1.3 - 3.2	N/A	N/A	N/A
Z'	N/A	N/A	2.1 - 2.5	N/A	N/A	N/A

- Ditau channel is less studied for BSM discovery reach by the LHC collaborations, but still can be accessible for early physics
  - N.B. The first Tevatron Run II precision measurement paper was DØ Z(ττ) cross section determination
- Very interesting reach for MSSM Higgs and other resonances; could also be tricky?

Dijets at the LHC

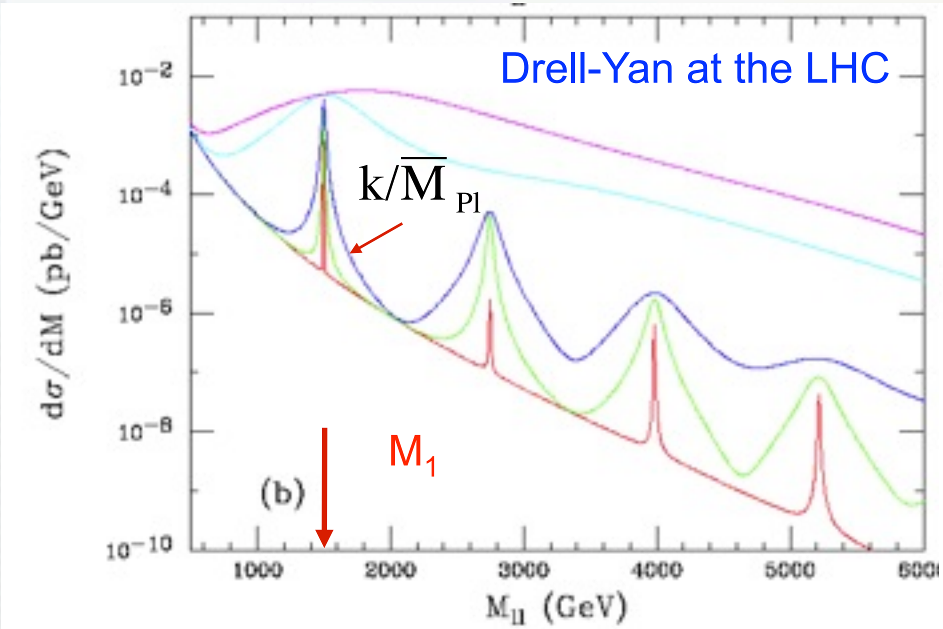


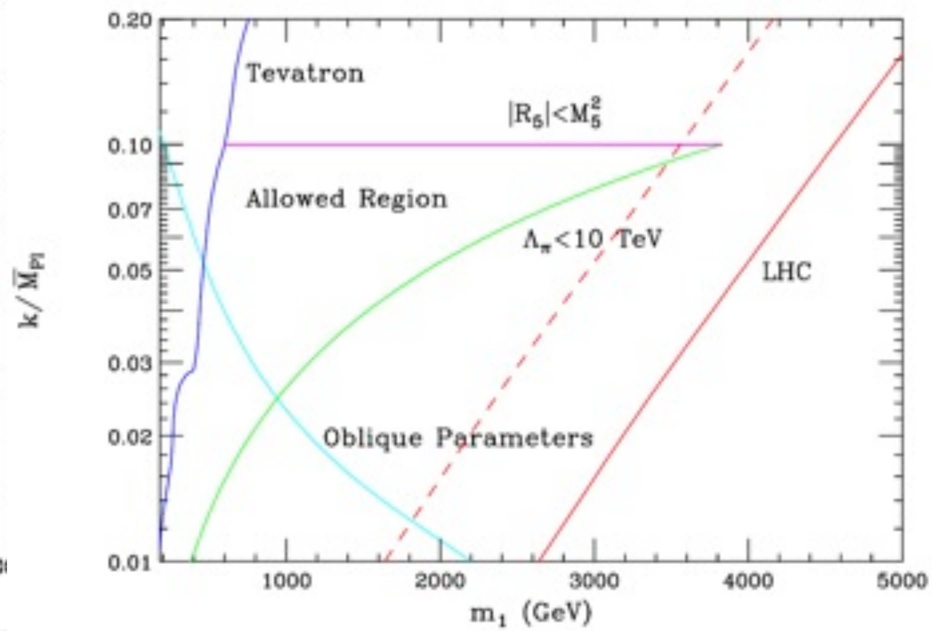
1 fb^{-1} ditau surprise at the Tevatron



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

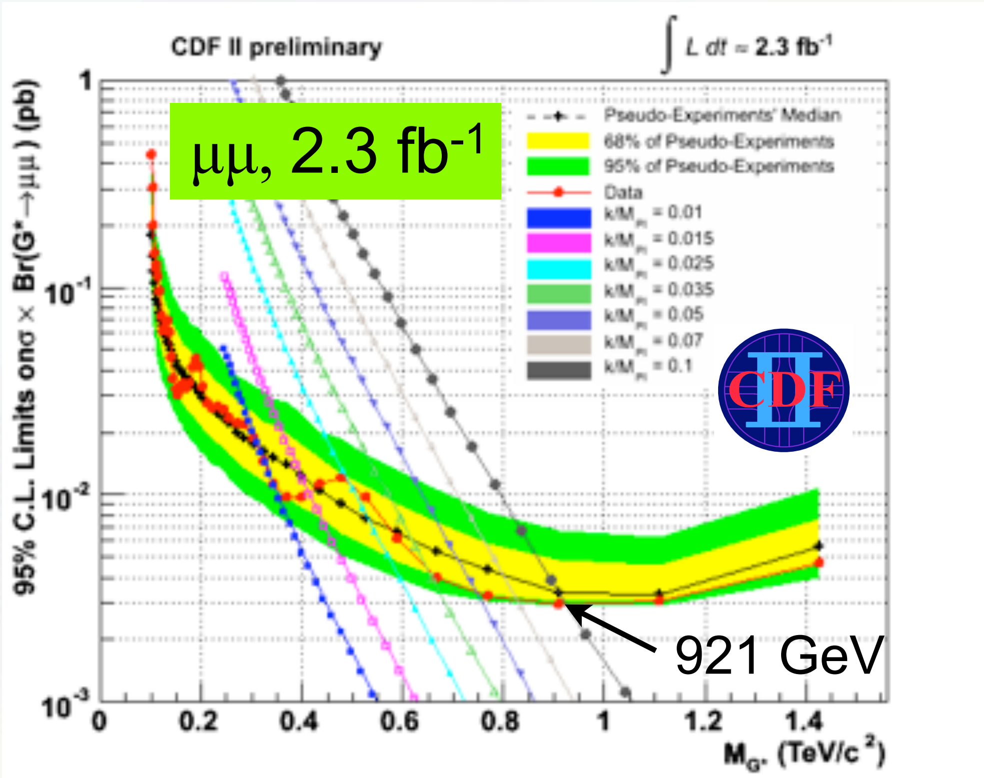


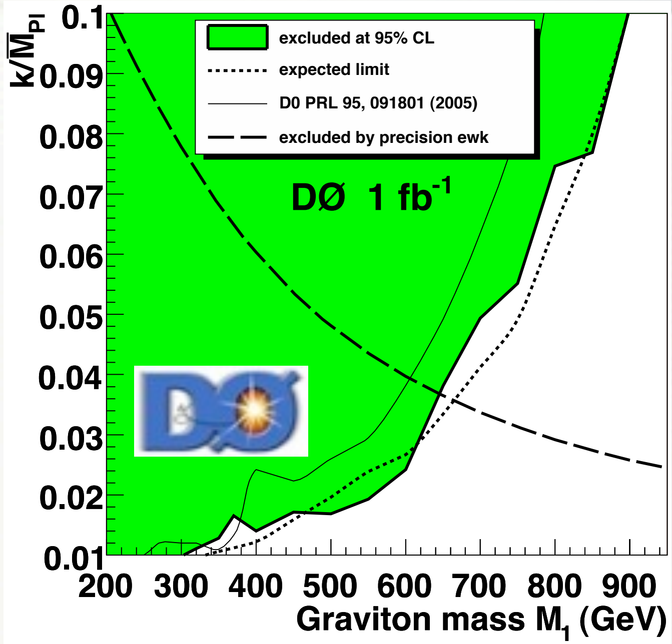


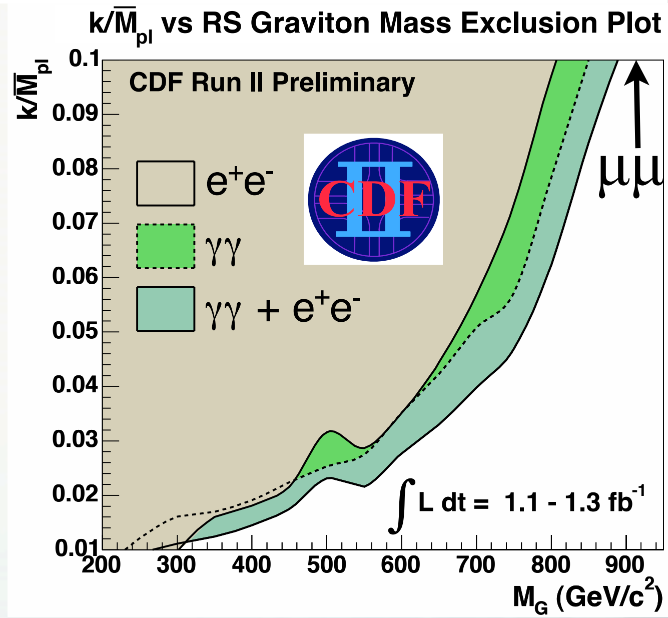
Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]

Most Recent Limits on G_{KK}

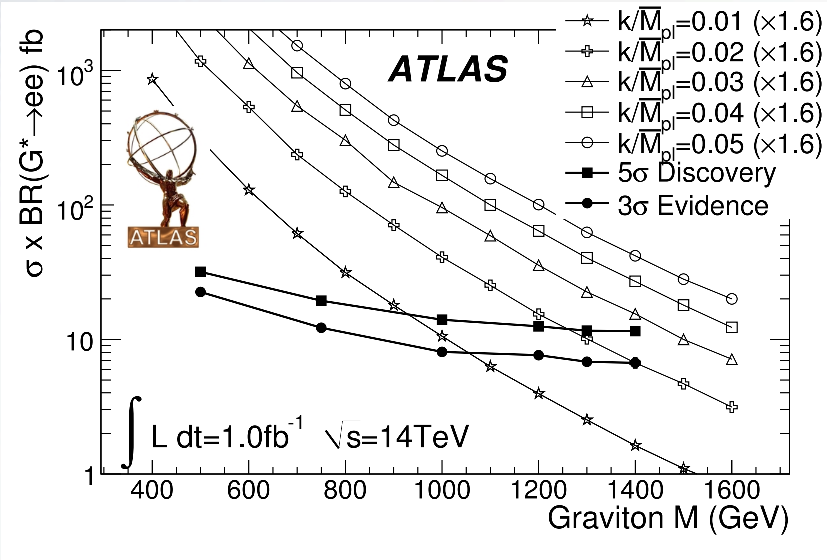
- Latest limits are 10% higher than the original ones despite 4x statistics
  - Tevatron sensitivity has really maxed out - need higher energies!

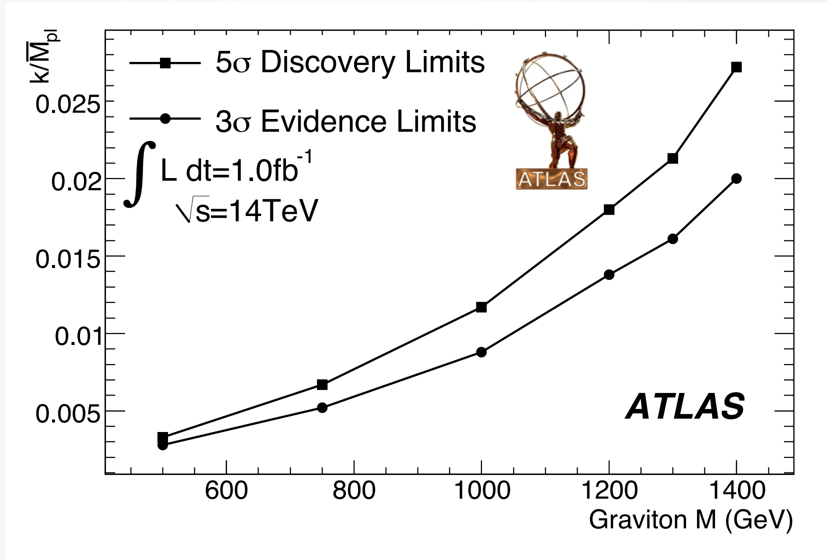


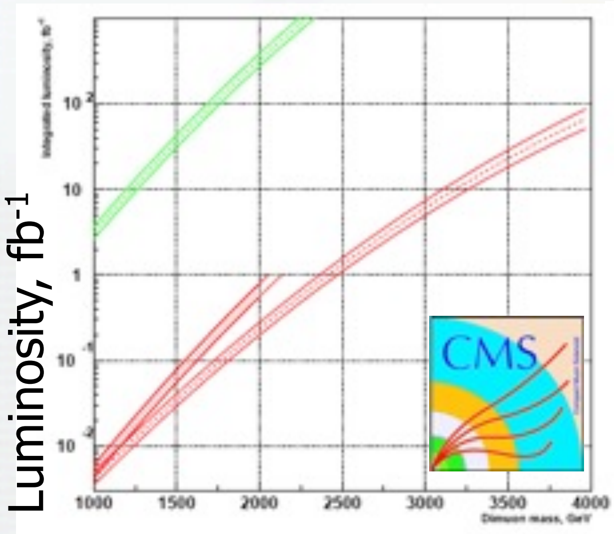


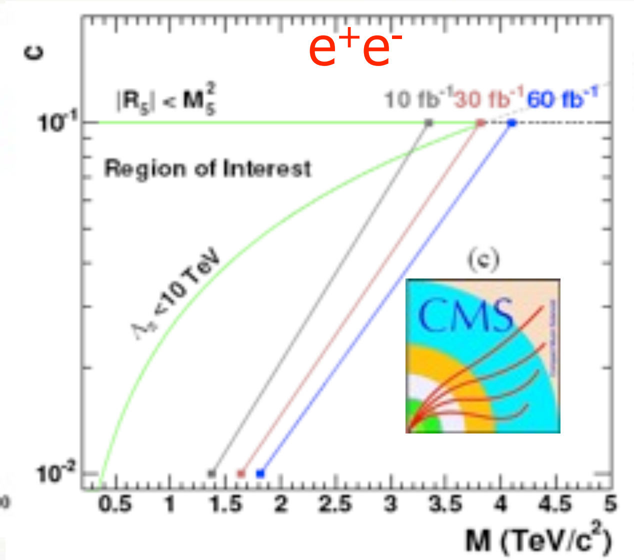


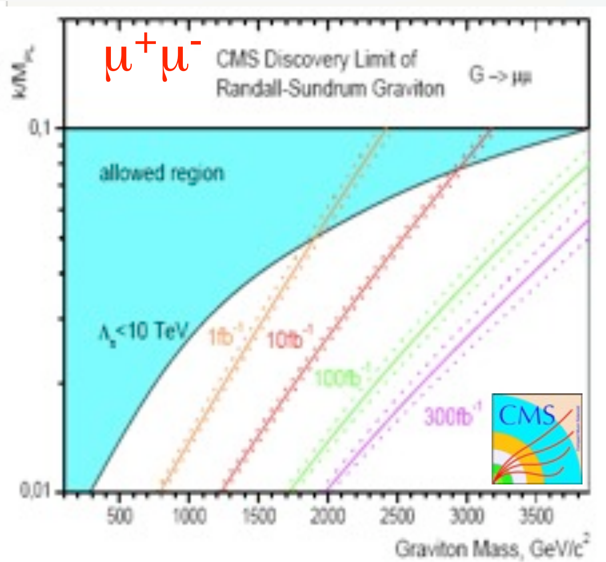
Randall-Sundrum Graviton Reach







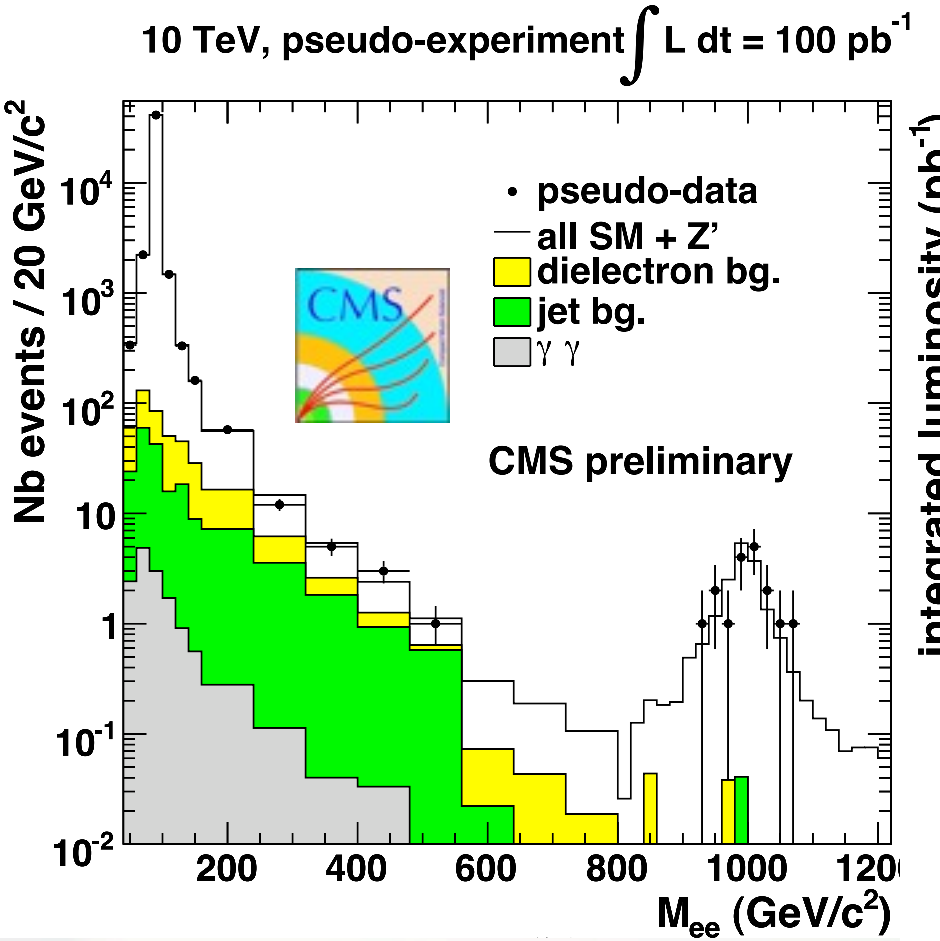


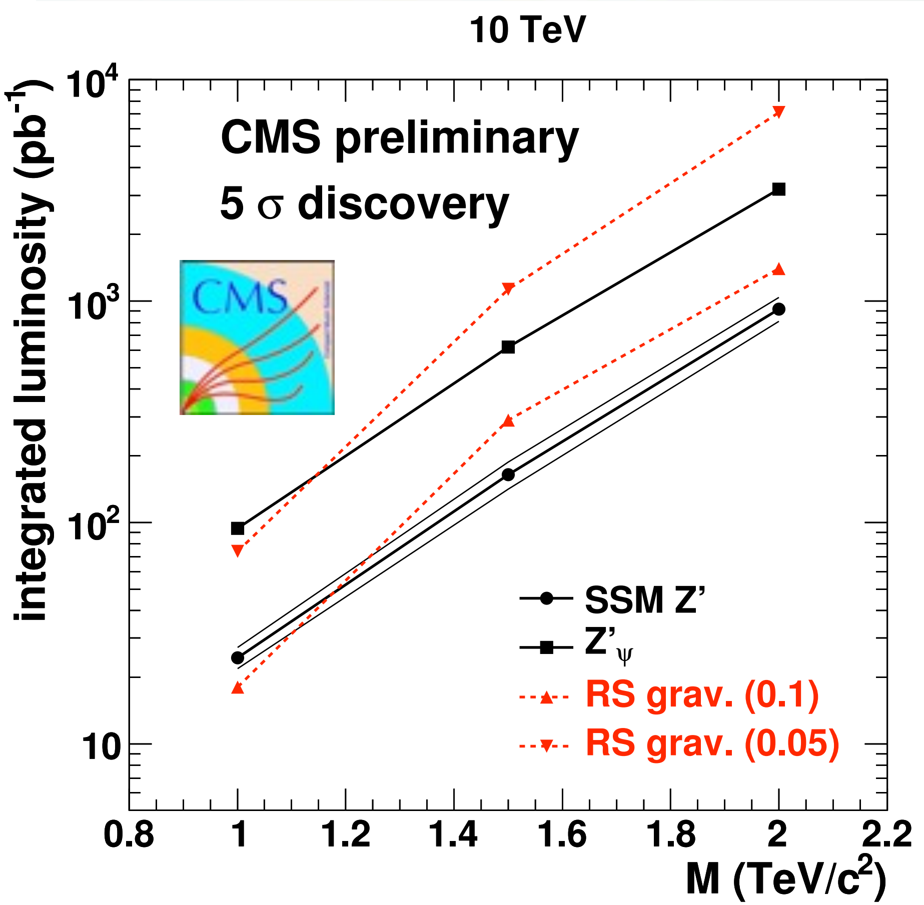


Early CMS Analysis: Dielectrons

- $Z'/G_{KK}(ee)$

Discovery reach up to 1.2-1.3 TeV for SM-like Z'

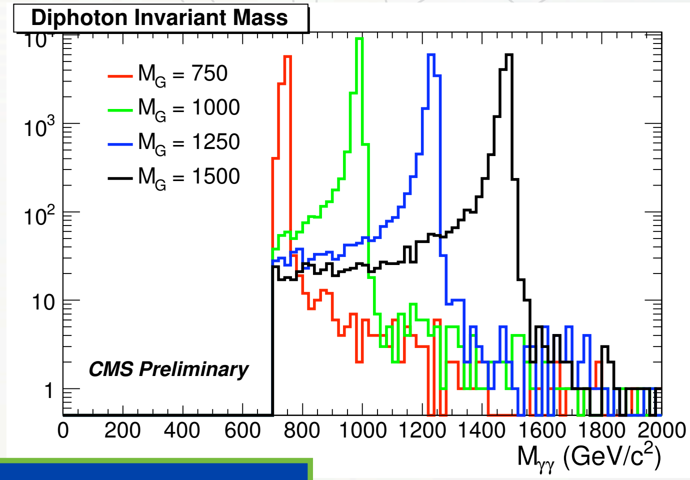




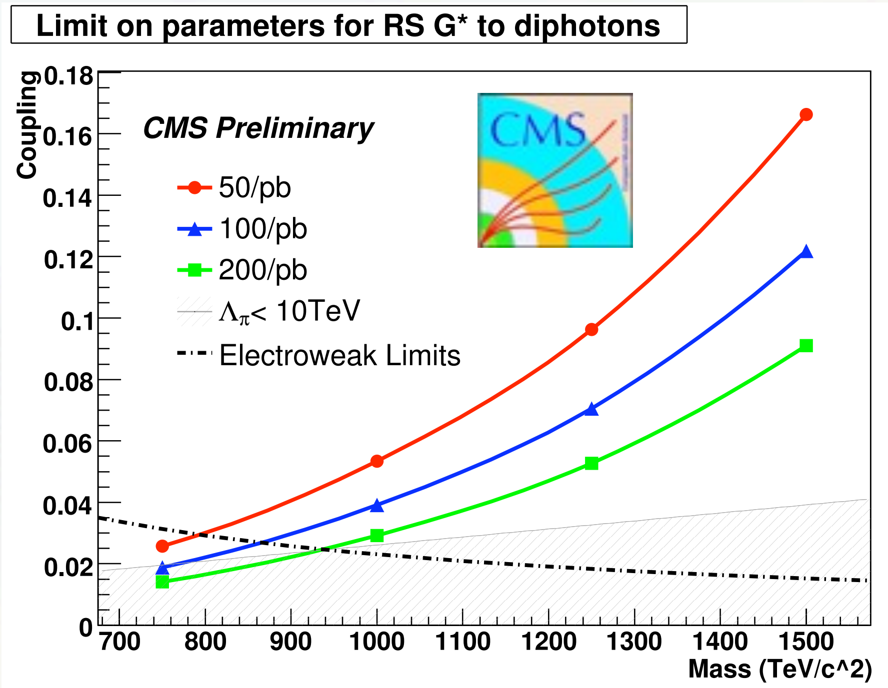
PAS-EXO-09-006

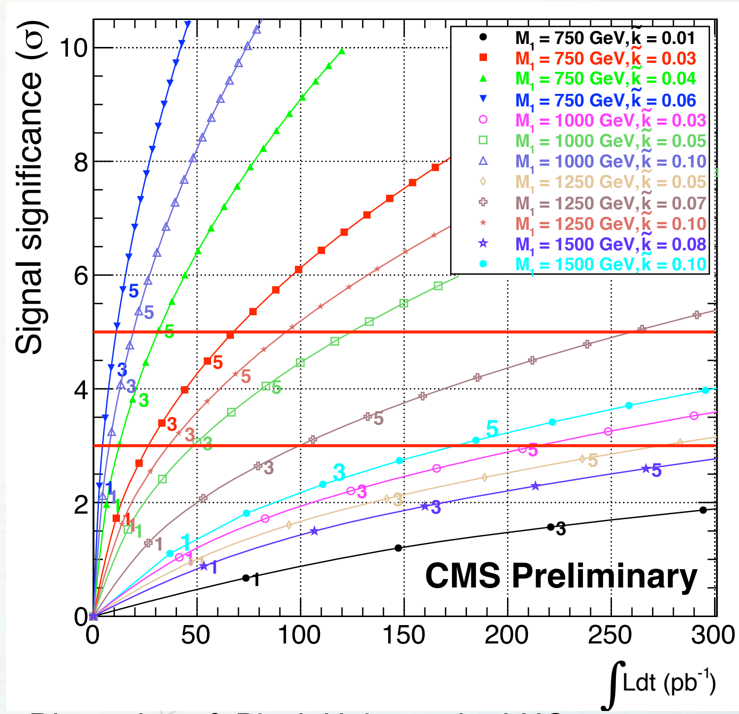
Early CMS Analysis: Diphotons

- Large ED diphoton analysis can be reused in inventive ways:
  - Low background above certain mass
  - Search for $\gamma\gamma$ resonances (e.g. RS gravitons)
  - Search for other diphoton spectrum enhancements (e.g. due to unparticles)



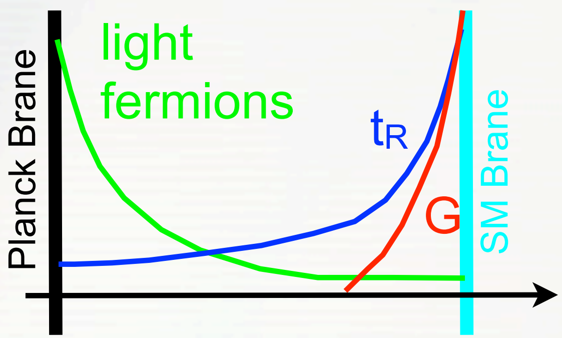
PAS-EXO-09-009



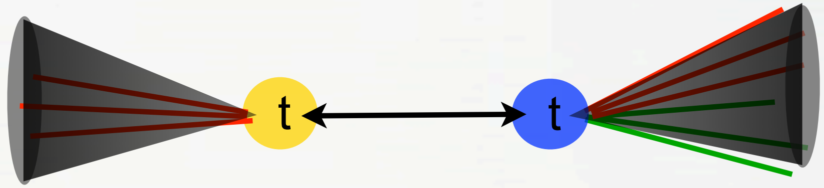


But: Life May be More Complicated!

- 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



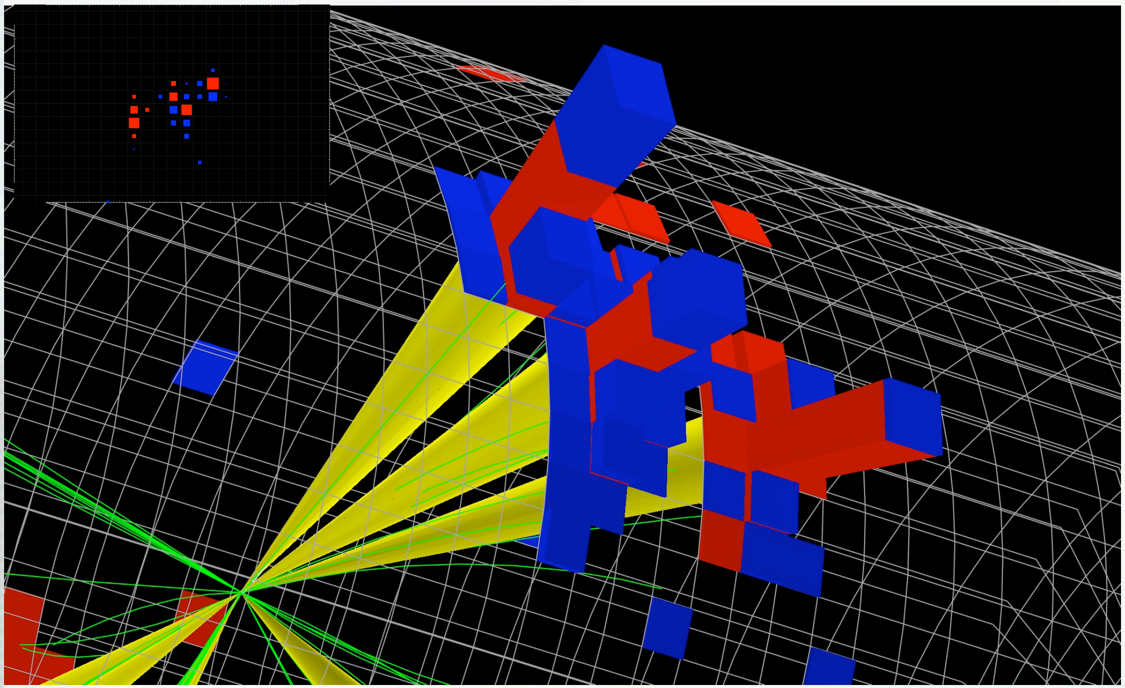
- For graviton masses ~2-3 TeV, top quarks emerge highly boosted, which makes it challenging to reconstruct them

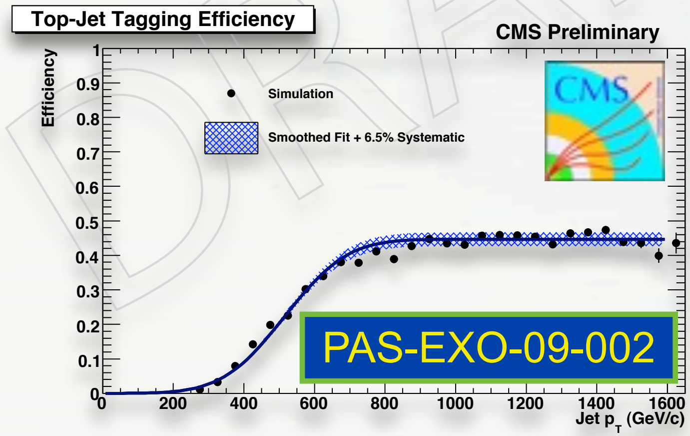


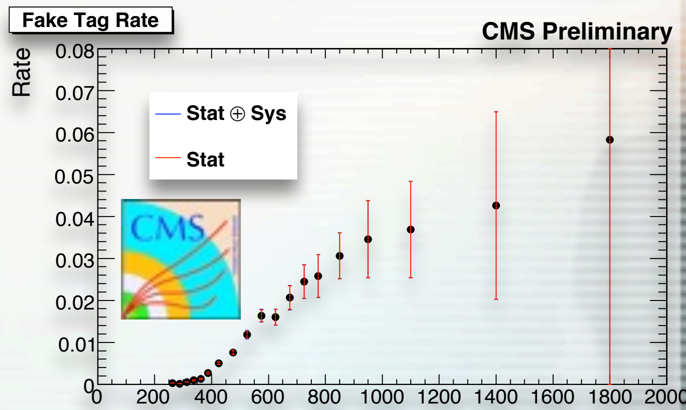
- Several challenges:
  - for 3-jet top decays jets are often merged in a single “fat” jet
  - b-tagging efficiency drops dramatically, as the opening angle between the tracks becomes small.

Remedies

- New techniques in jet reconstruction and b-tagging
- Work in progress at both ATLAS and CMS
- Preliminary CMS studies show that boosted top tagging efficiency can reach ~40% with a few per cent mistag rate - similar to b-tagging performance!

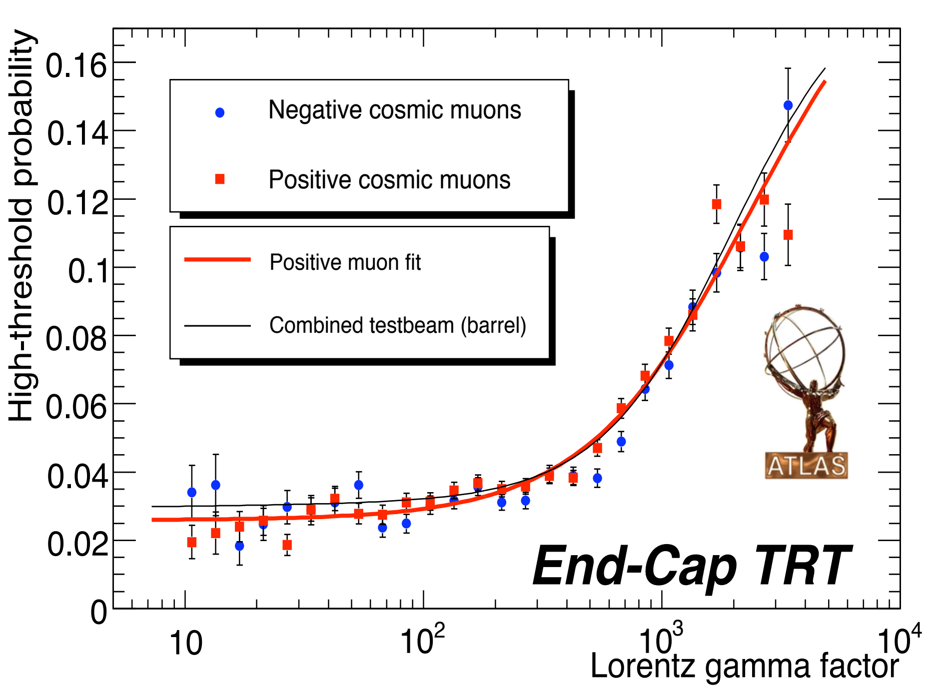


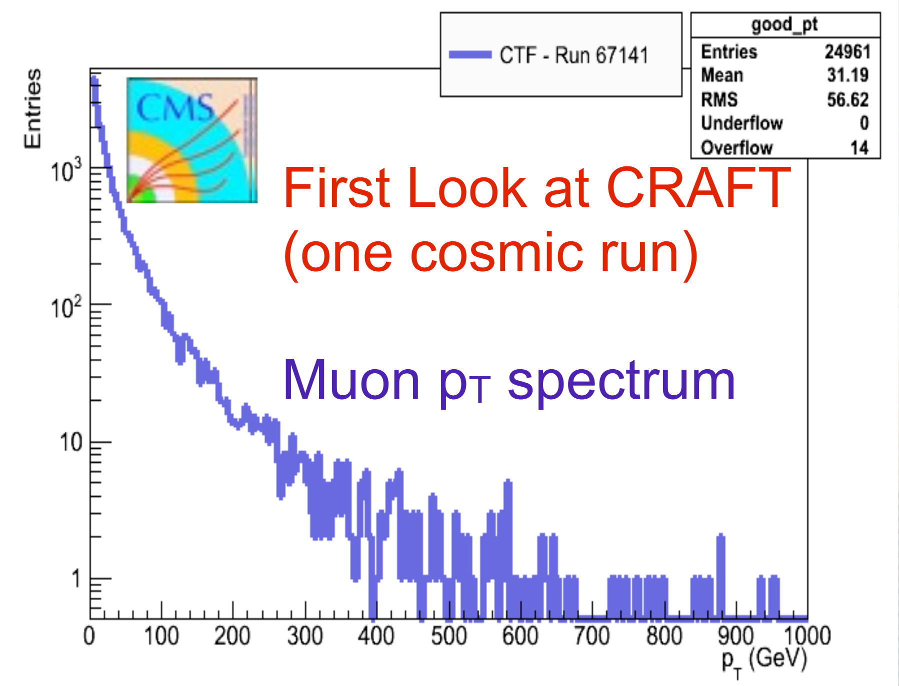




High-p_T Muons in ATLAS & CMS

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





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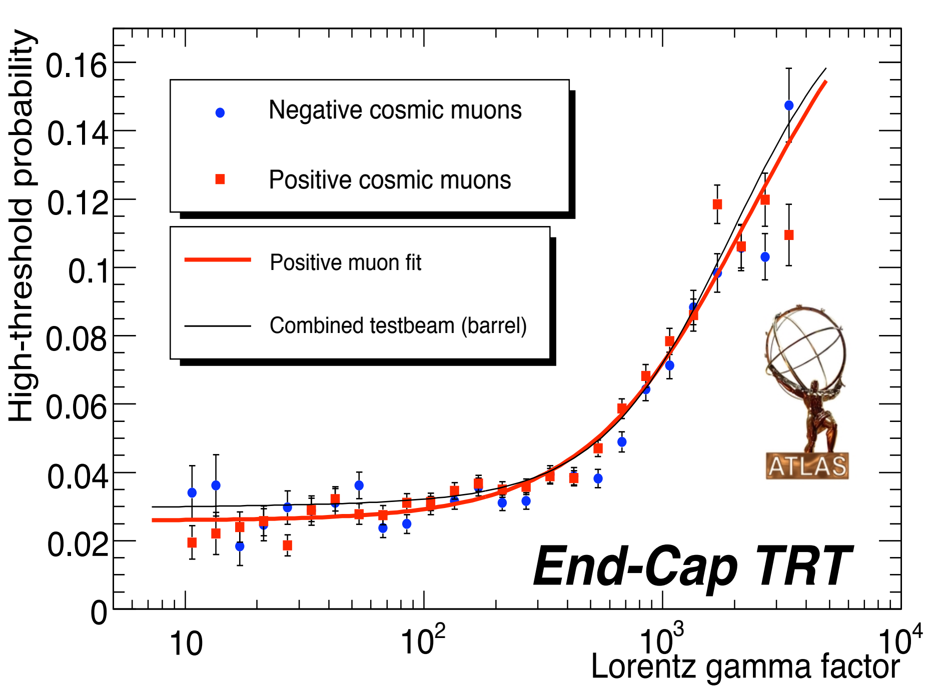
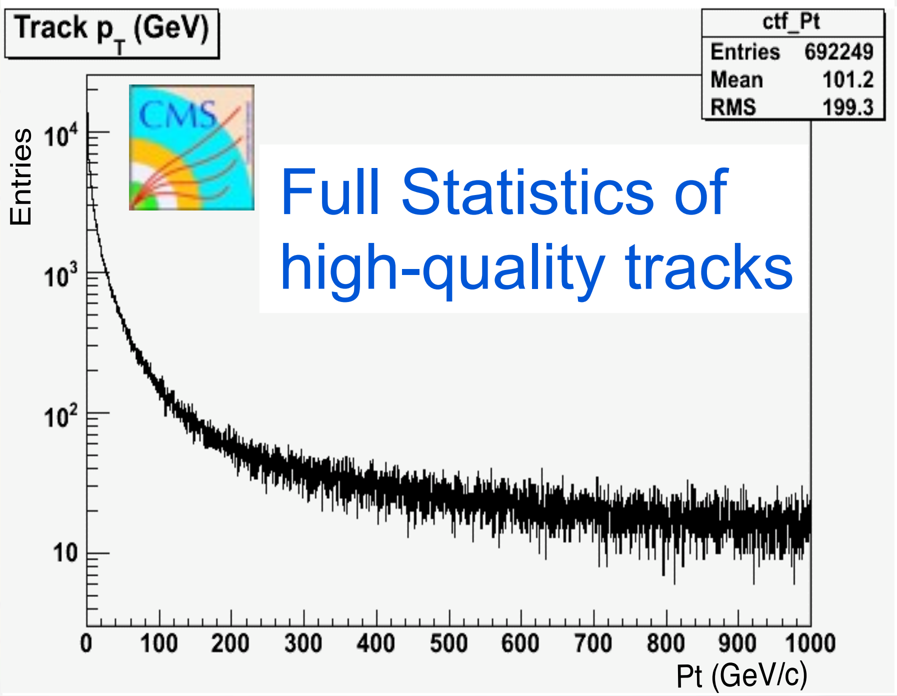
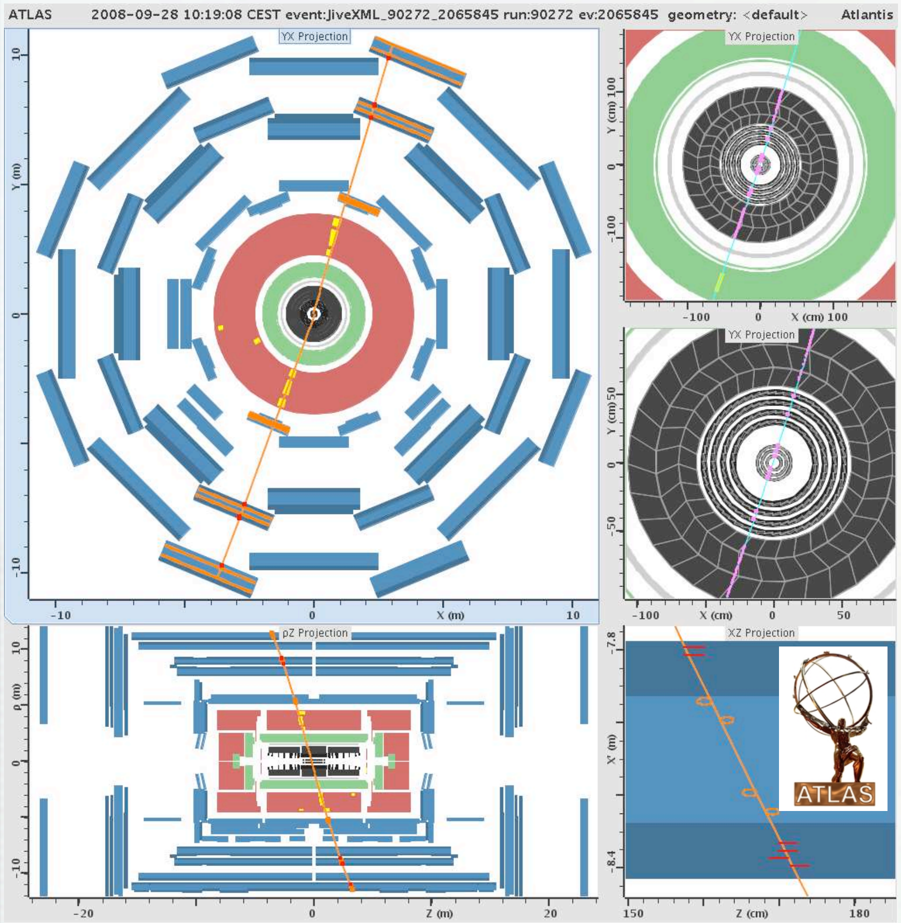
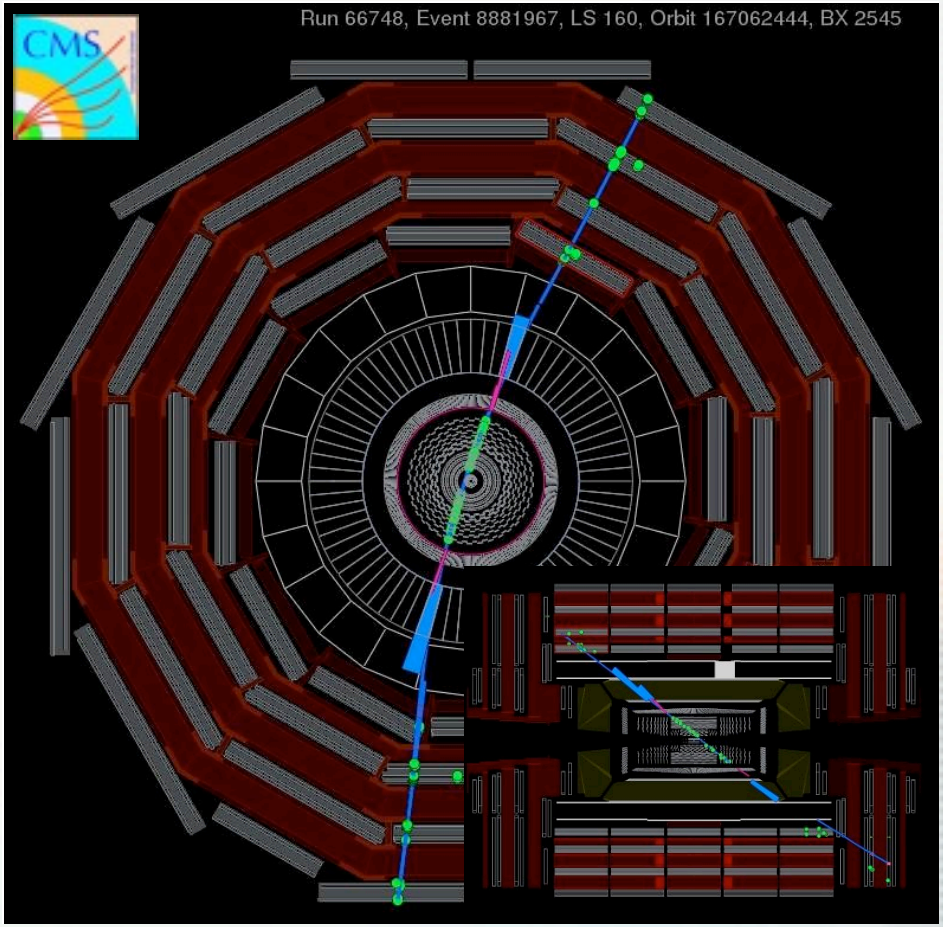




Cosmic Muons in ATLAS and CMS

- Very clean and spectacular events
- Plethora of important information (alignment, bremsstrahlung, magnetic field mapping)





Black Holes at the LHC?

Black Holes on Demand

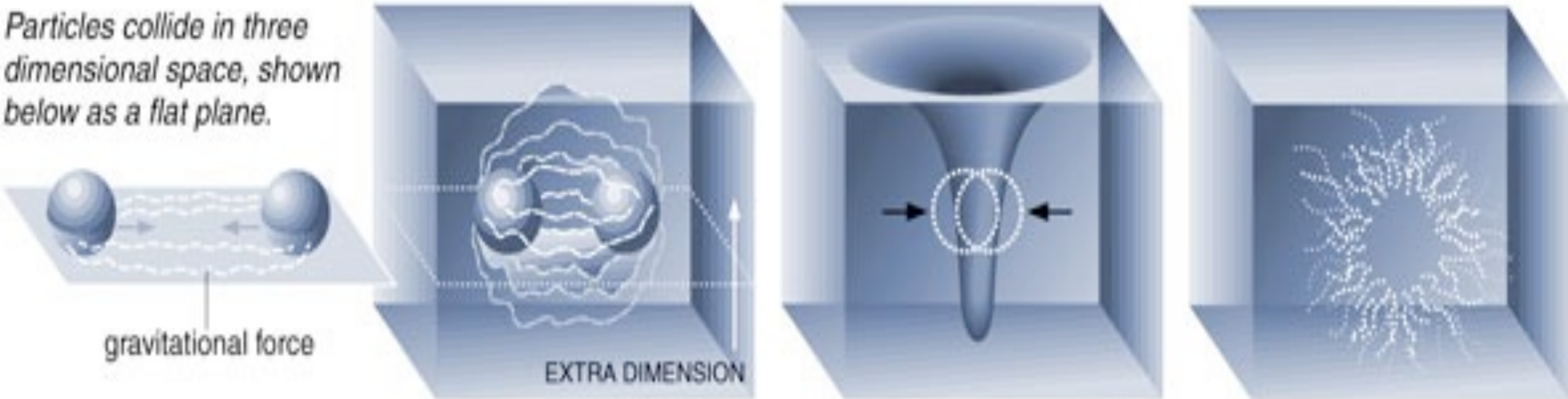
NYT, 9/11/01

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:

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



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

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

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

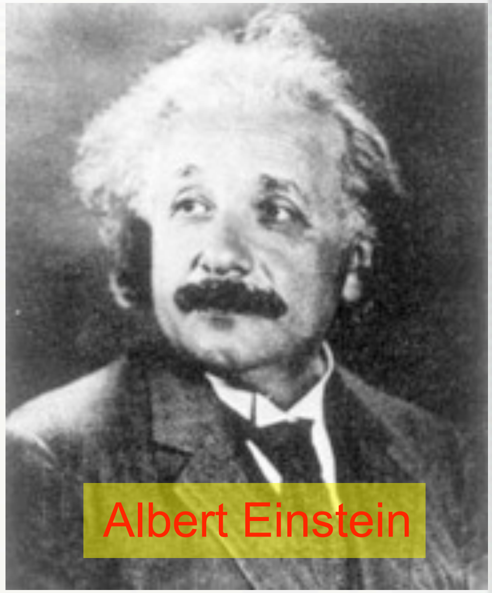
Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

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* $r = R_S \equiv 2MG_N/c^2$:

$$g_{\mu\nu} = \begin{pmatrix} 1 - \frac{2MG_N}{rc^2} & 0 & 0 & 0 \\ 0 & -(1 - \frac{2MG_N}{rc^2})^{-1} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2 \sin\theta \end{pmatrix} \begin{array}{l} \}\ \text{time} \\ \left.\begin{array}{l} \\ \\ \\ \end{array}\right\}\ \text{space} \end{array}$$

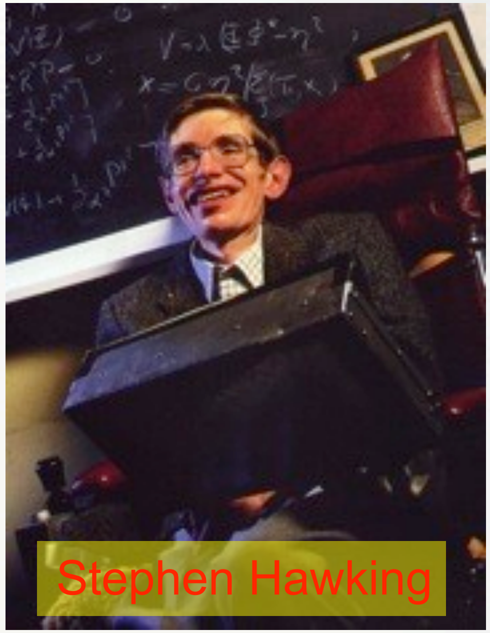
- If the radius of the object is less than R_S, a black hole with the event horizon at R_S is formed
- The term "black-hole" was introduced only around 1967 by John Wheeler



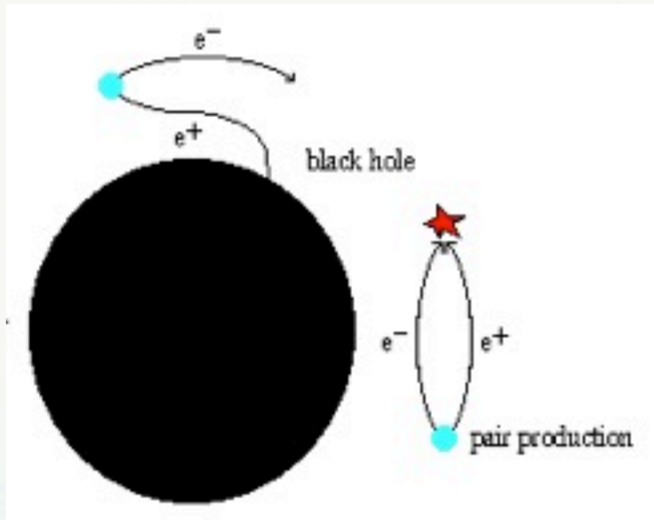
Black Hole Evolution

- 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*:

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

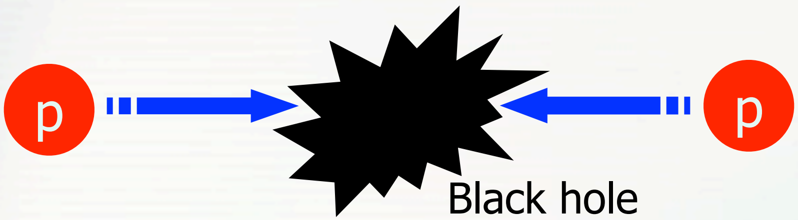


- In natural units ($\hbar = c = k_B = 1$), one has the following fundamental relationship: $R_S T_H = (4\pi)^{-1}$
- If T_H is high enough, massive particles can also be produced in evaporation
- Information paradox: if we throw an encyclopedia in a black hole, and watch it evaporating, where would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

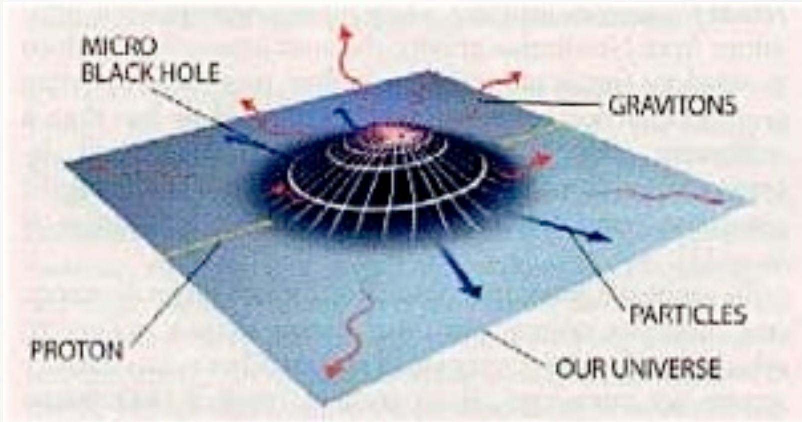


BH at LHC: Theoretical Framework

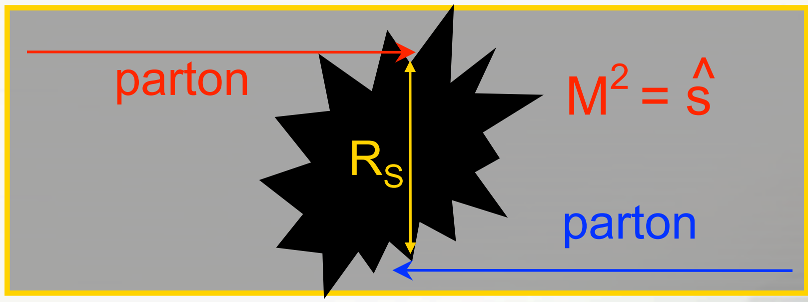
- Based on the work done with Dimopoulos a few years ago [PRL **87**, 161602 (2001)] and a related study by Giddings/Thomas [PRD **65**, 056010 (2002)]
- Extends previous, more theoretical studies by Argyres/Dimopoulos/March-Russell [PL **B441**, 96 (1998)], Banks/Fischler [JHEP, **9906**, 014 (1999)],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



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

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
- Many subsequent publications tried to study those, but it's not strict science
- 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:

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

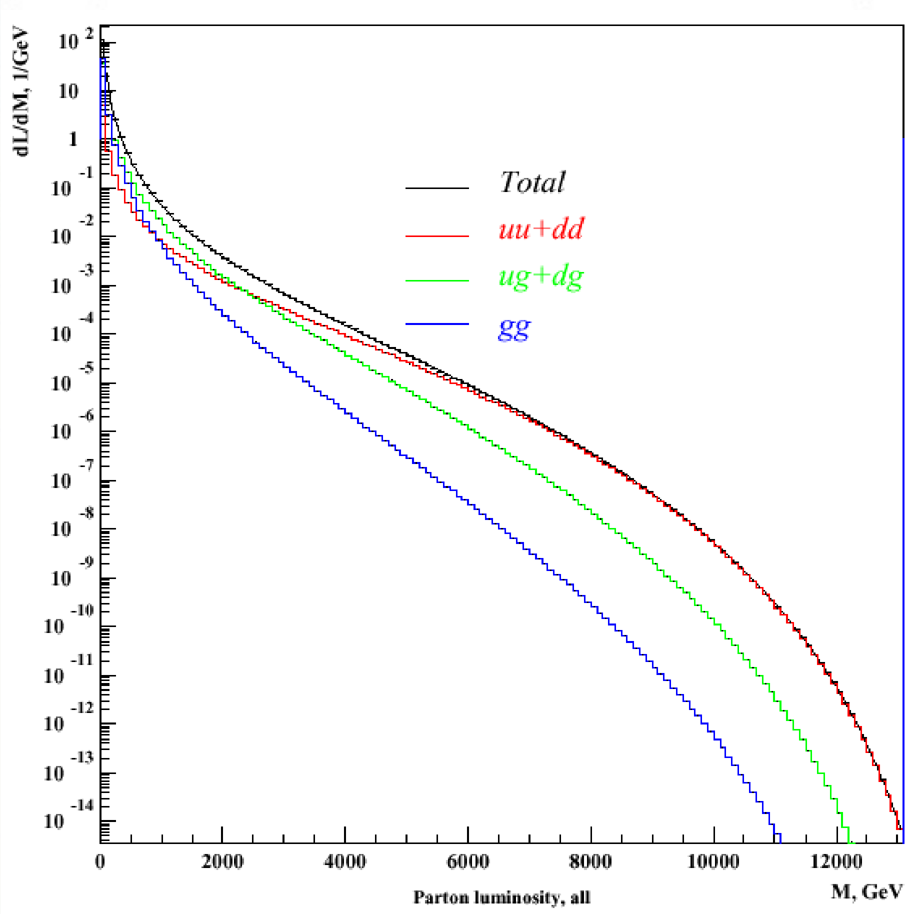
- Use parton luminosity approach with quark momentum distribution given by parton distribution functions

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

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

- 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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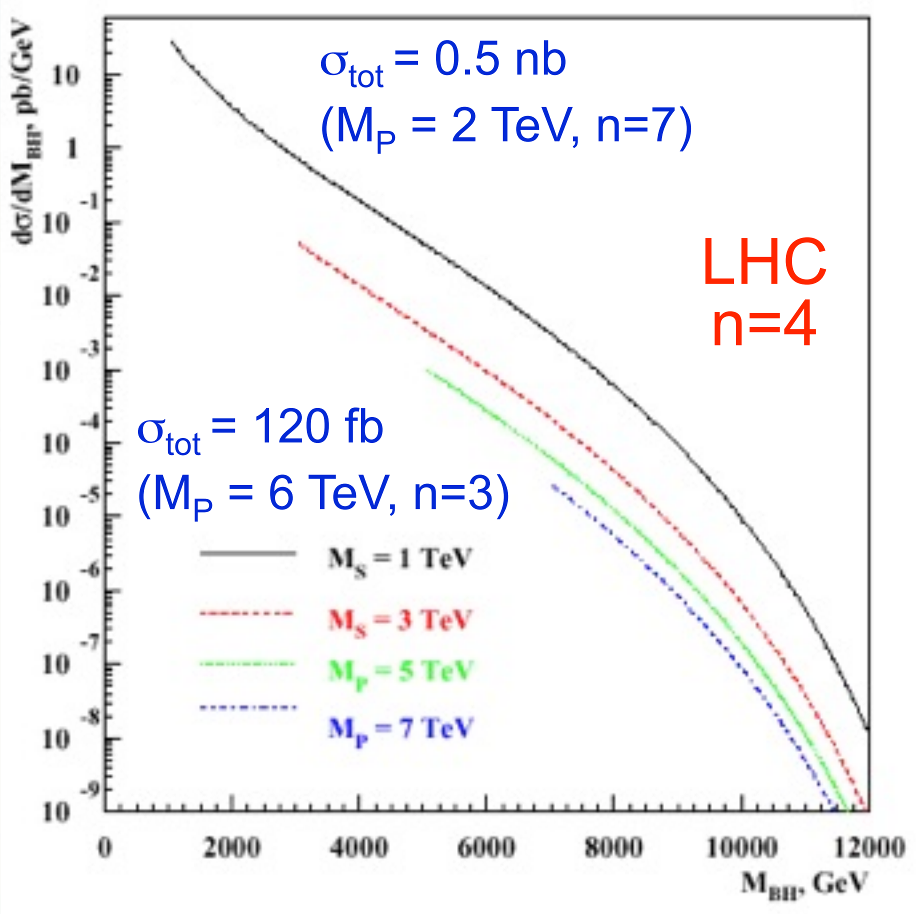
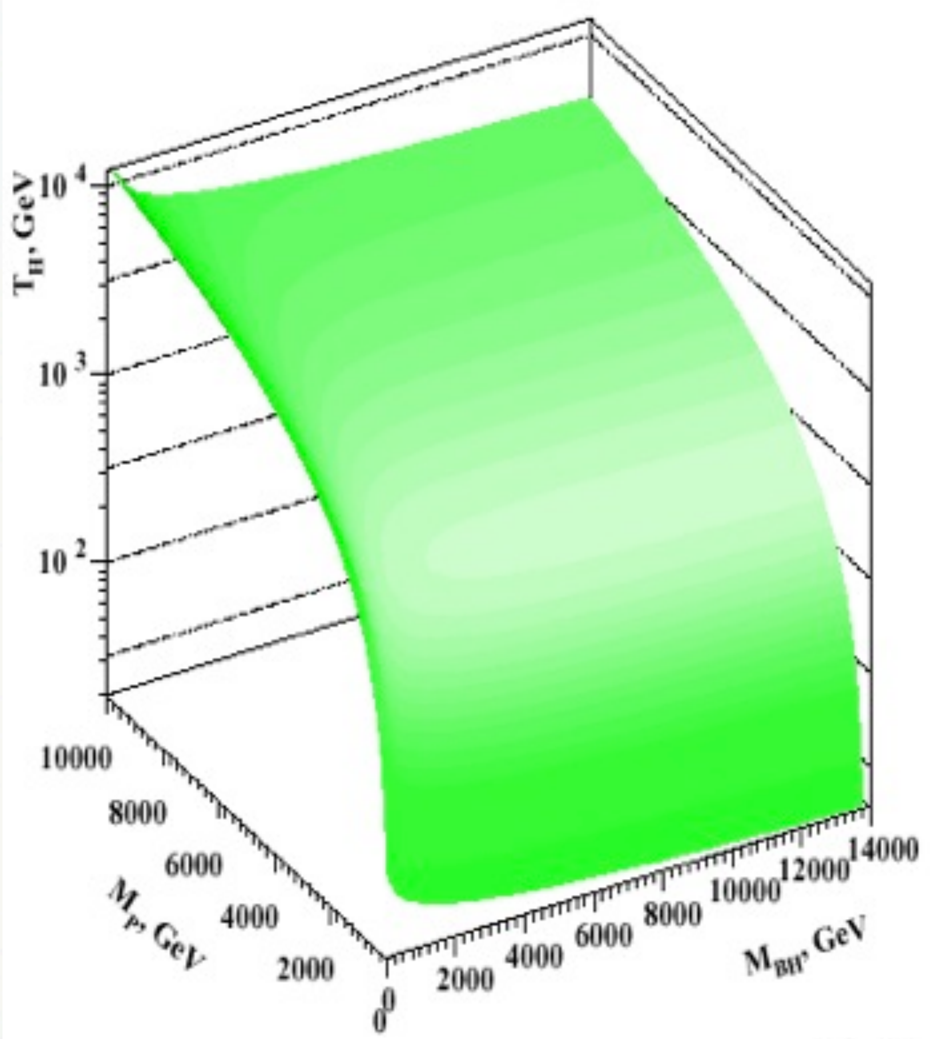


Black Hole Decay

- 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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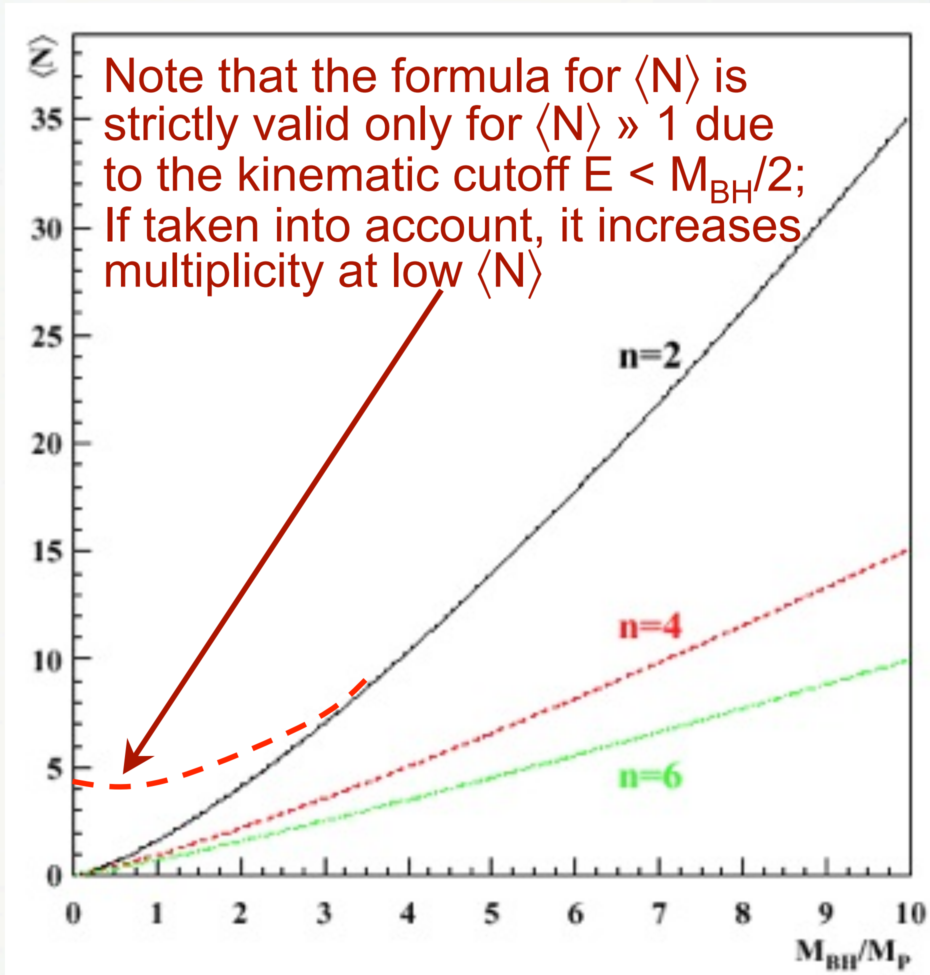

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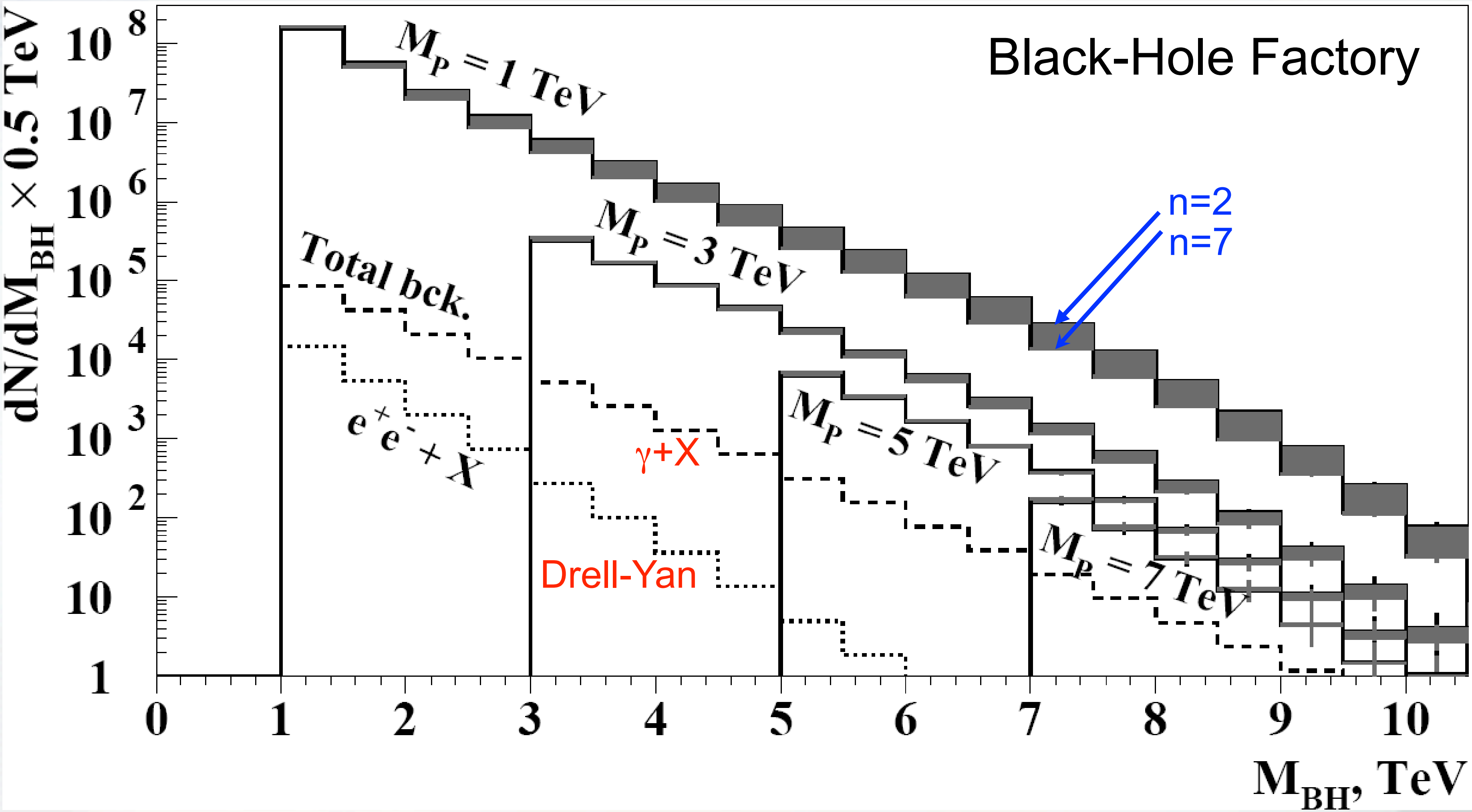
Black Hole Factory

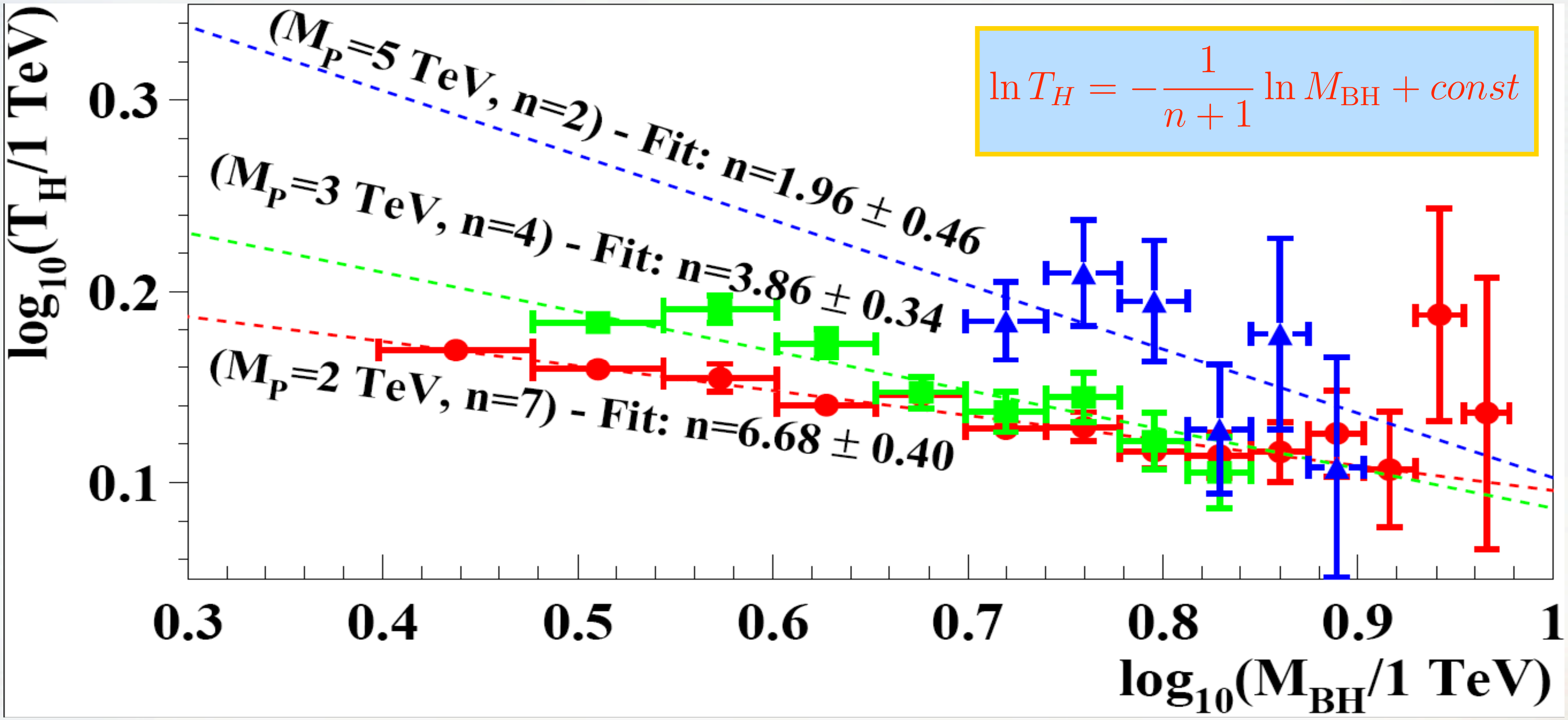
Dimopoulos, GL [PRL **87**, 161602 (2001)]



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)]



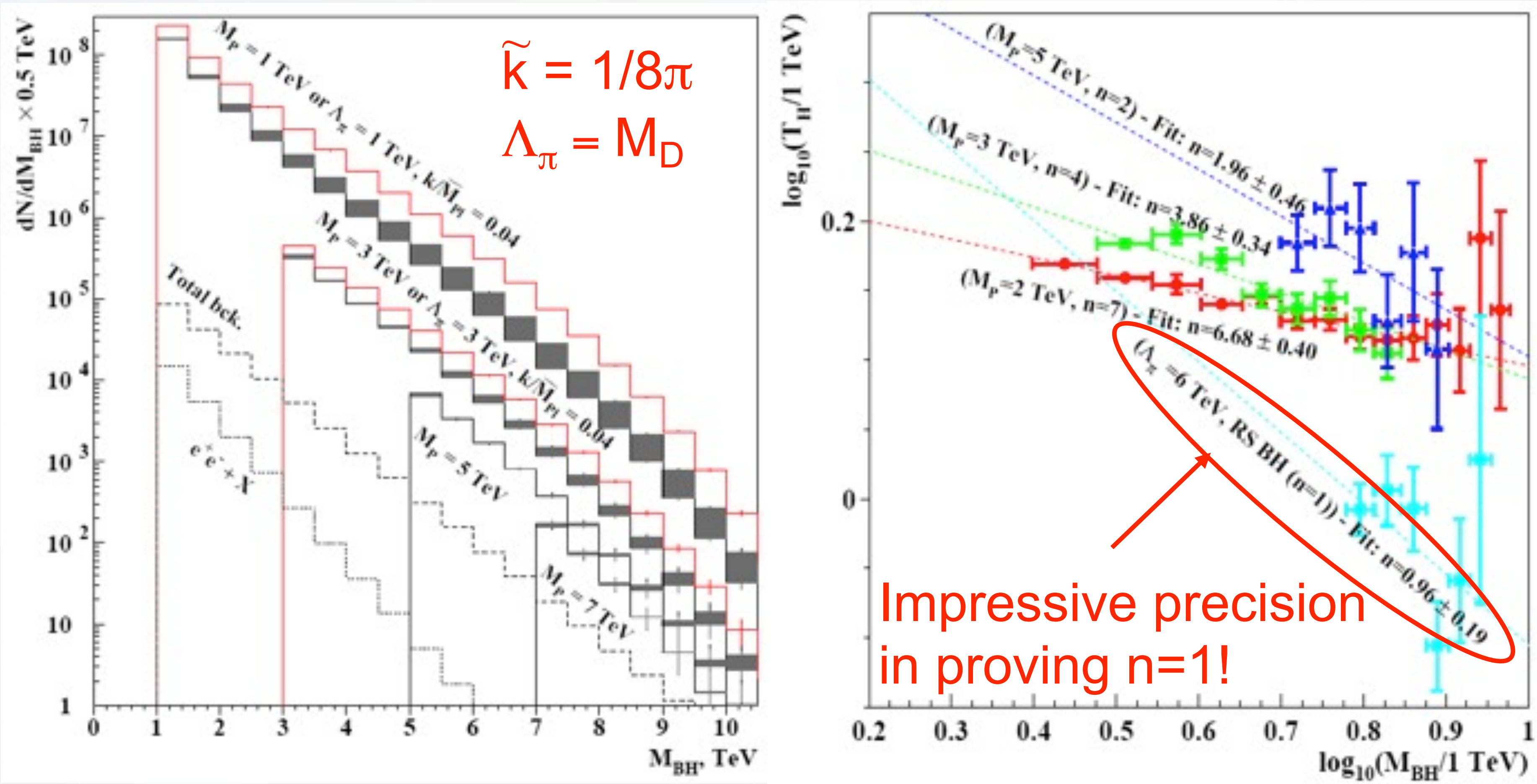
- Relationship between $\log T_H$ and $\log M_{BH}$ allows to find the number of ED
  - This result is independent of their shape!
  - This approach drastically differs from analyzing other collider signatures and would constitute a "smoking cannon" signature for a TeV Planck scale

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 ~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

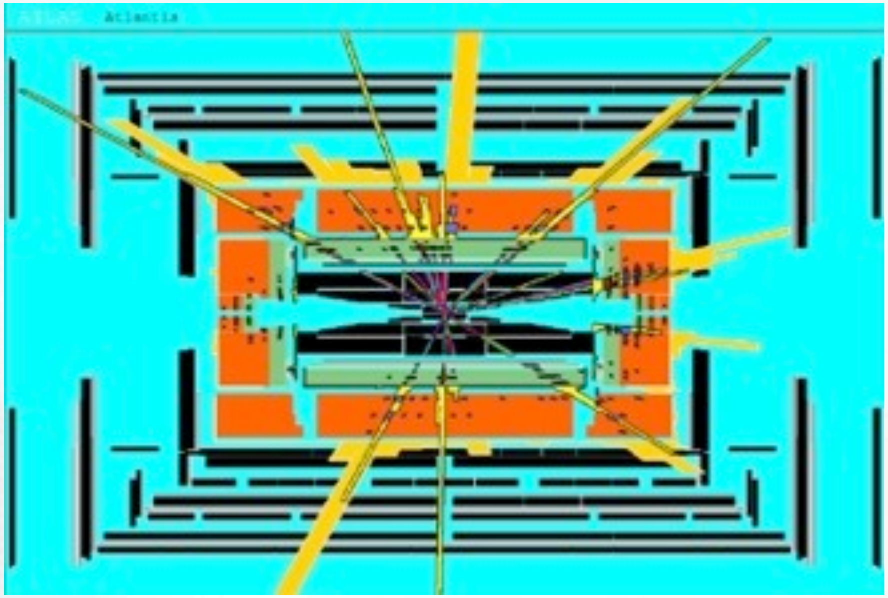
RS BH: Samples & Wien's Law

100 fb^{-1} @ the LHC

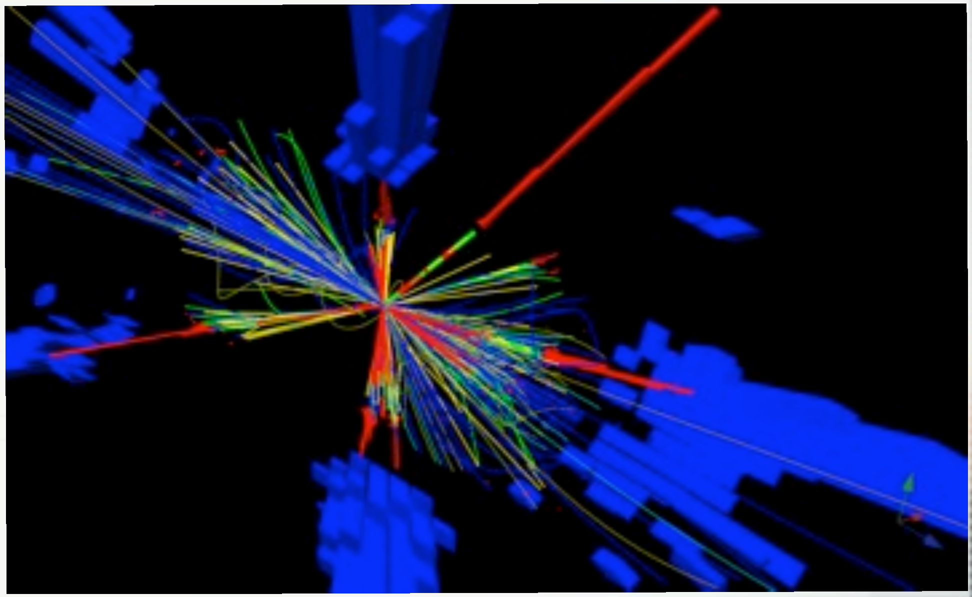


Black Hole Events

- Detailed studies ongoing in ATLAS and CMS
  - ATLAS –CHARYBDIS (HERWIG-based generator with an elaborated decay model by Harris/Richardson/Webber)
  - CMS – TRUENOIR (GL)/CHARYBDIS/CATFISH (Cavaglia) /BLACKMAX (Dai et al.)
  - The hunt is going on!



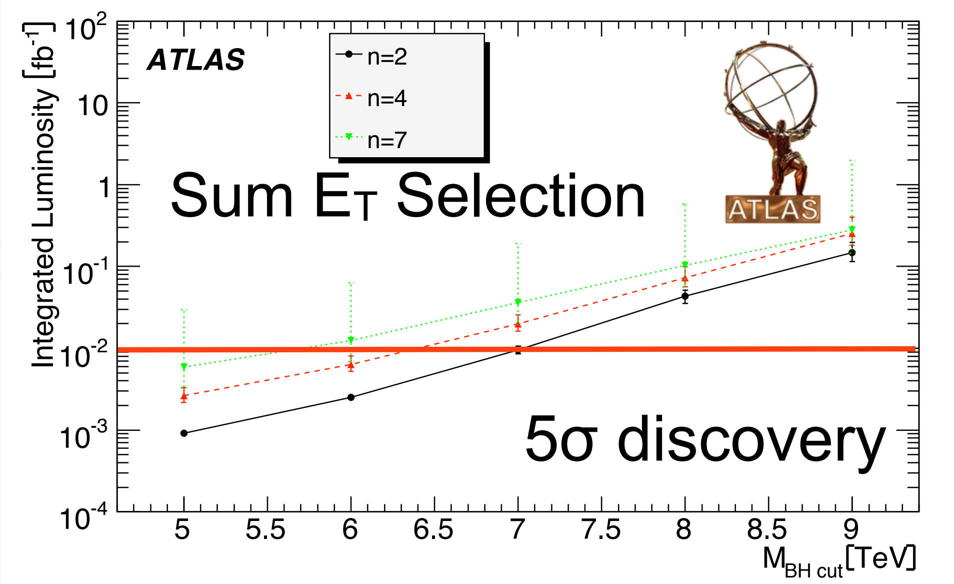
Simulated black hole event in the ATLAS detector

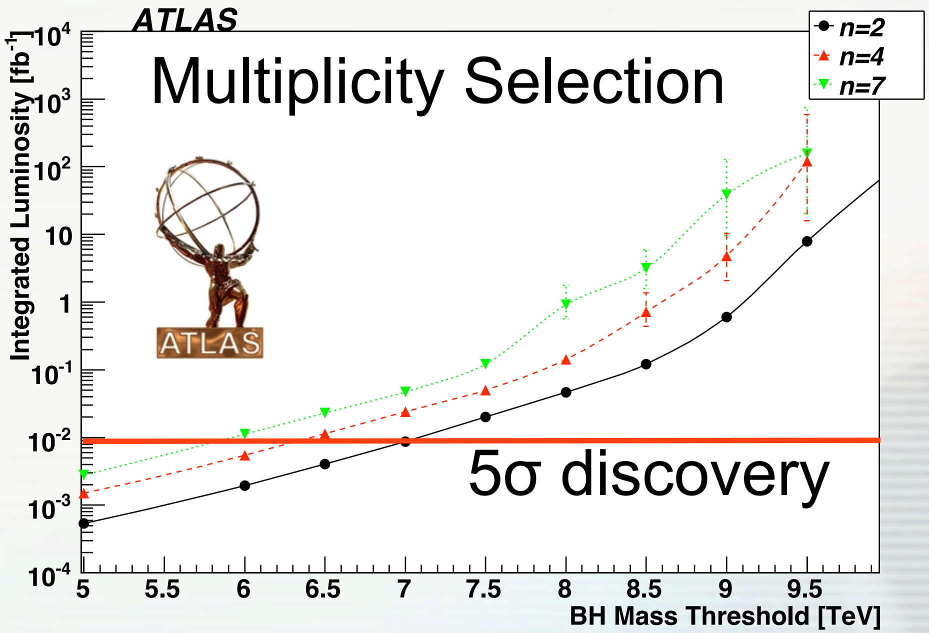


Simulated black hole event in the CMS detector

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 6-7 TeV BH's is possible with a fraction of fb^{-1}
- Analogous analysis ongoing in CMS
  - Good opportunity to join





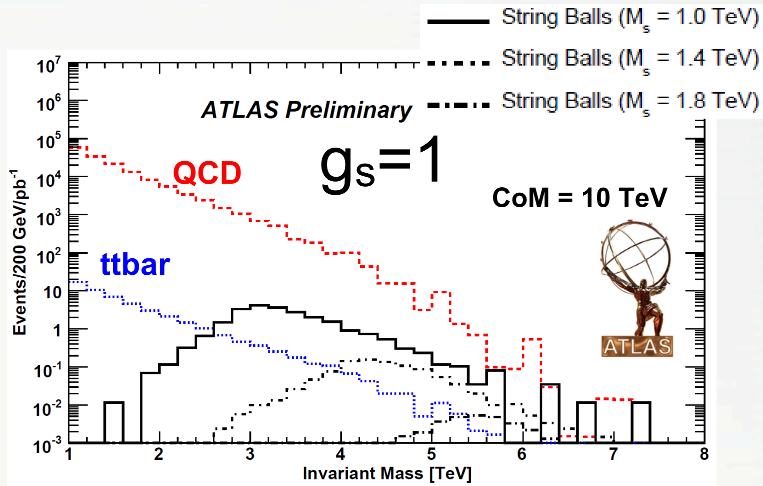
String Balls at the LHC

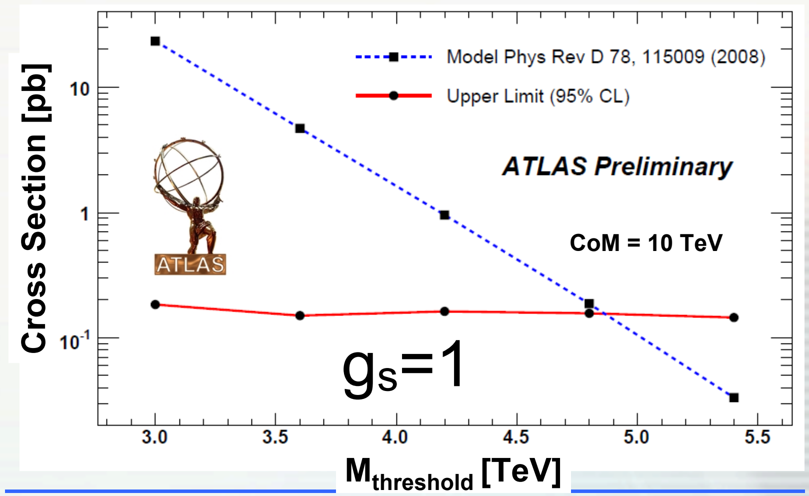
- Dimopoulos/Emparan, [PL B**526**, 393 (2002)] – an attempt to account for stringy behavior for $M_{BH} \sim M_S$
- GR is applicable only for $M_{BH} > M_{min} \sim M_S/g_S^2$, where g_S is the string coupling; M_P is typically less than M_{min}
- They show that for $M_S < M < M_{min}$, a *string ball*, which is a long jagged string, is formed
- Properties of a string-ball are similar to that of a BH: it evaporates at a Hagedorn temperature:

$$T_H = \frac{M_S}{2\sqrt{2}\pi}$$

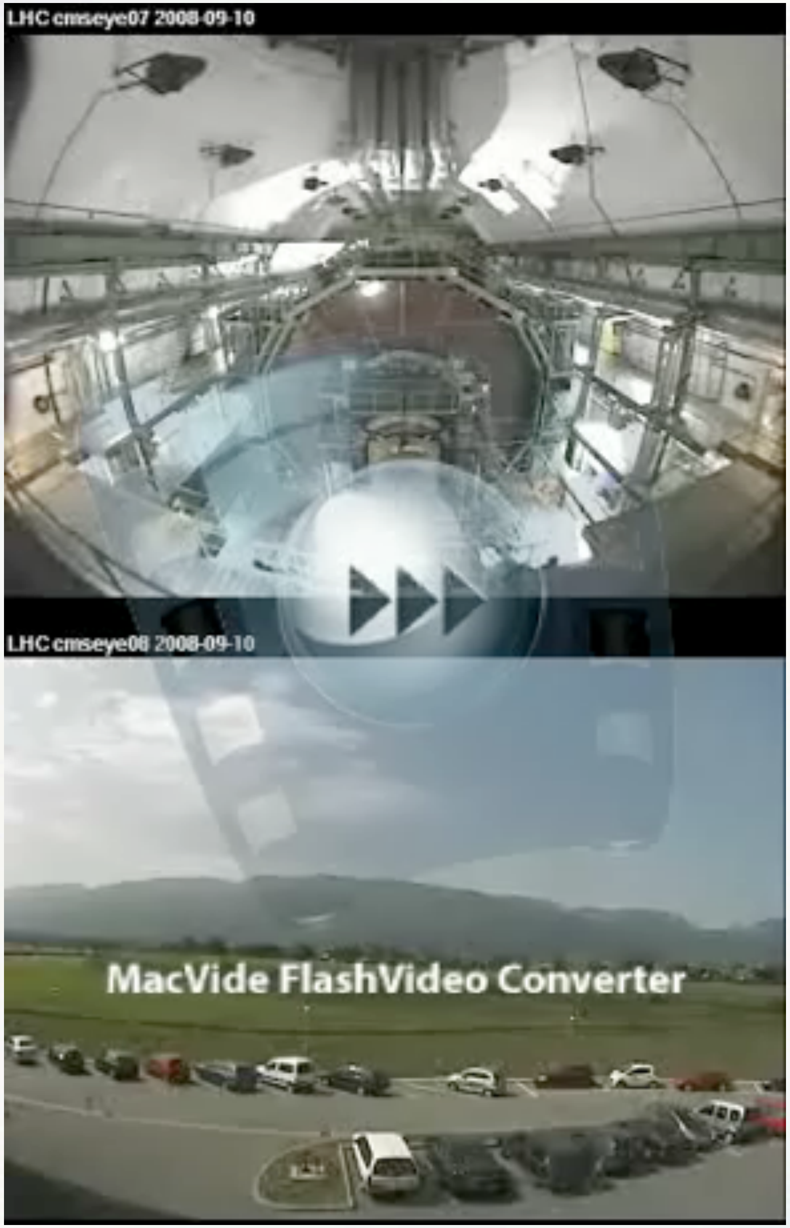
  in a similar mix of particles, with perhaps a larger bulk component
- Cross section is numerically similar to that for a black hole

$$\sigma \sim \begin{cases} \dfrac{g_s^2 M_{SB}^2}{M_s^4} & M_s \ll M_{SB} \le M_s/g_s\,, \\ \dfrac{1}{M_s^2} & M_s/g_s < M_{SB} \le M_s/g_s^2\,, \\ \dfrac{1}{M_P^2}\left(\dfrac{M_{BH}}{M_P}\right)^{\frac{2}{n+1}} & M_s/g_s^2 < M_{BH}\,. \end{cases}$$





Black Holes in CMS



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- 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!

Thank You!