Modern Constraints on TeV-Scale Gravity

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Outline

- *The Hierarchy Problem*
- *The LHC & Detectors*
- *Setting the scene: Extra Dimensional Paradigms*
- *Tabletop Experiment Limits*
- *Constraints from Astrophysics and Cosmology*
- *Collider Phenomenology and Limits*
- *Limits from (the lack of) Black Holes at the LHC*
- *Conclusions*

Large Hierarchies Tend to Collapse...

SM: 10^{-38}
fine-tuning

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    (Food for thought: is it really numerology?)

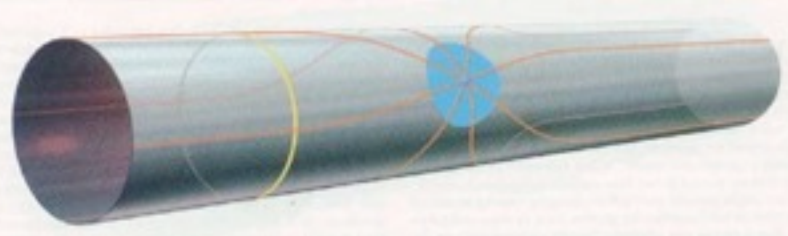
1998: Large Extra Dimensions

- 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 ~ 1 TeV

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

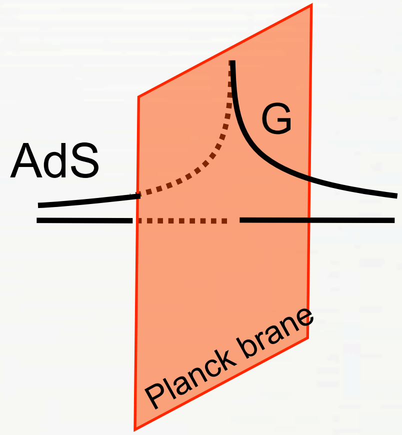
- More precisely, from Gauss's law:

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

- 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

Randall-Sundrum Model

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



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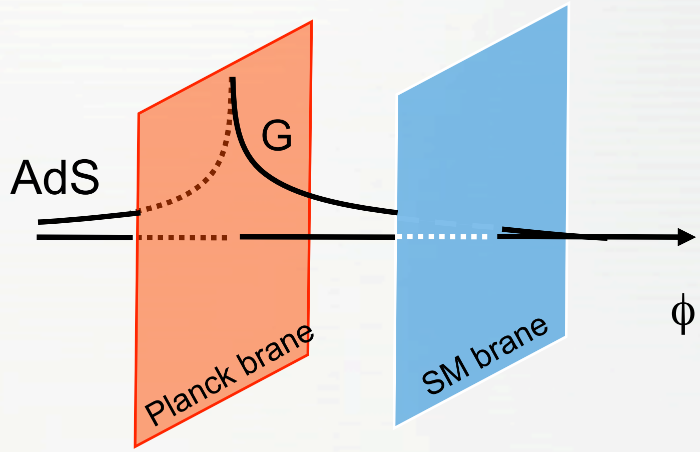

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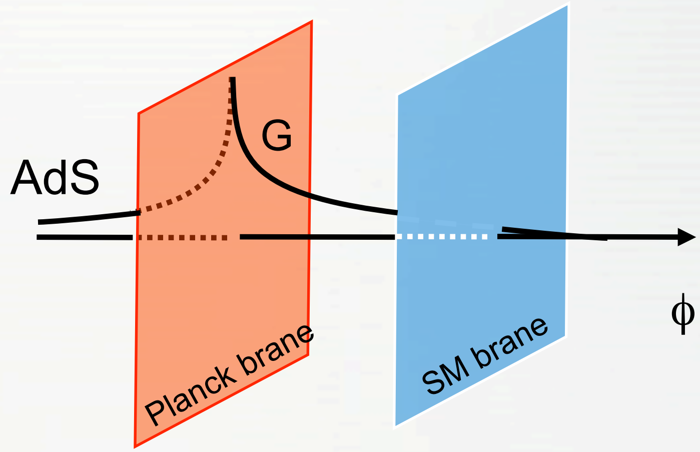
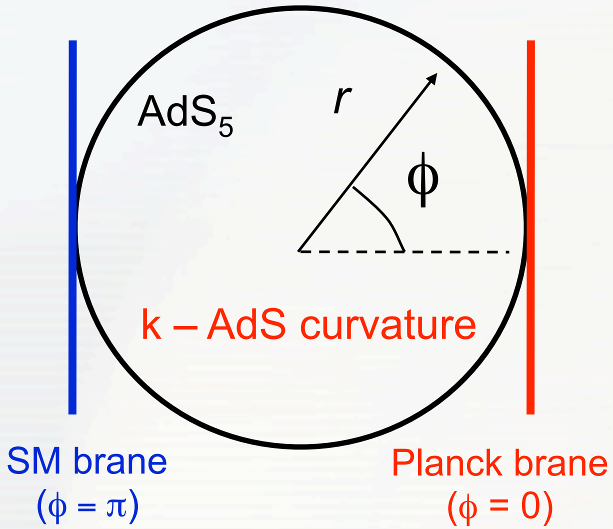




Anti-deSitter space-time metric:

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

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

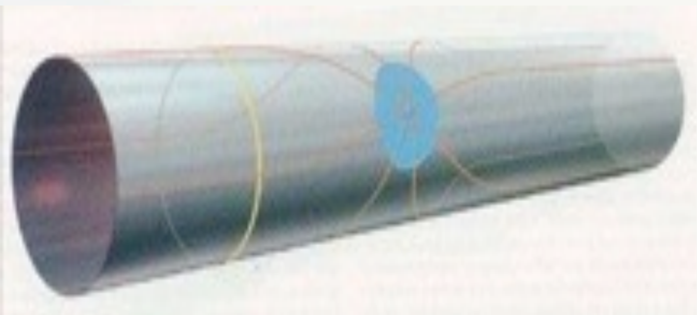
Reduced Planck mass:

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

Extra Dimensions: a Brief Summary

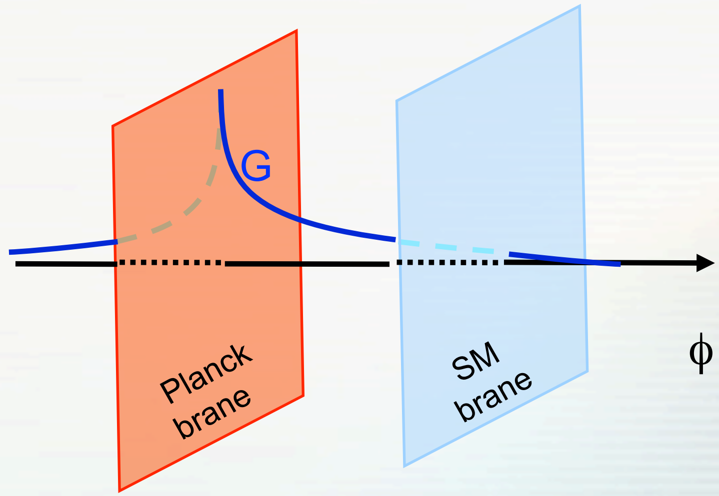
ADD Paradigm:

- 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



RS Model:

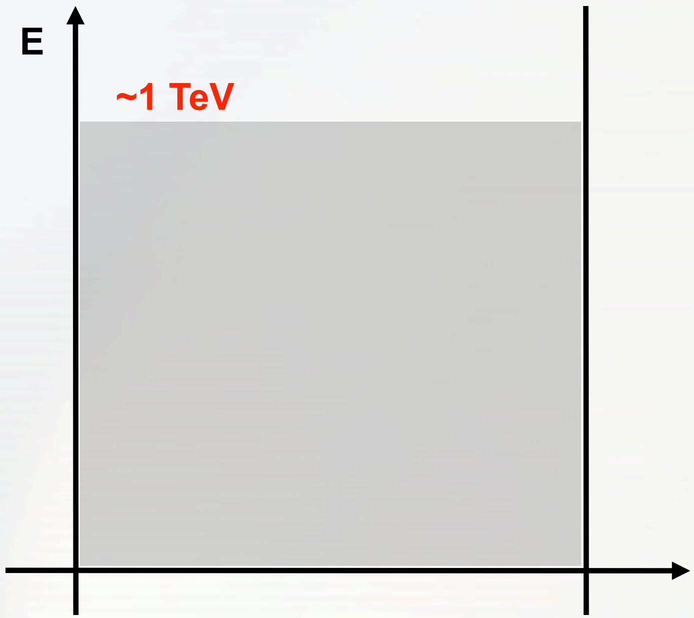
- Pro: A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, with special metric
- Black holes at the LHC and in UHE cosmic rays
- Con: Somewhat disfavored by precision EW fits



ED: Kaluza-Klein Spectrum

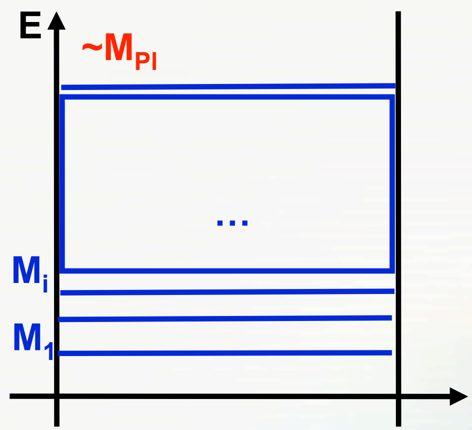
ADD Paradigm:

- 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



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



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

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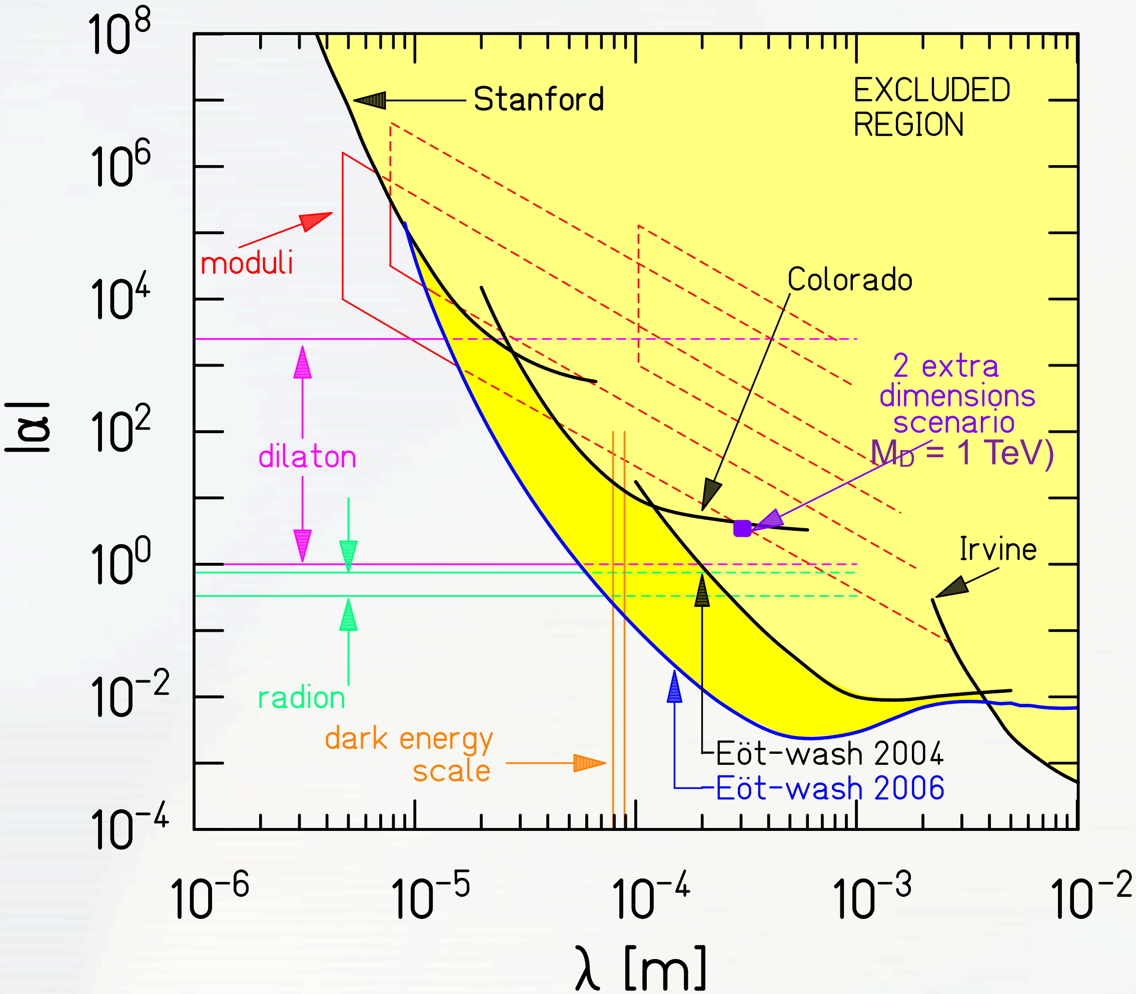
Large ED: Gravity at Short Distances

[D. Kapner et al., PRL **98** (2007) 0211001]



- 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
    - $R \lesssim 37$ mm ($M_D \gtrsim 2$ 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
- No sensitivity to the RS models

Large ED: Astro & Cosmo Constraints

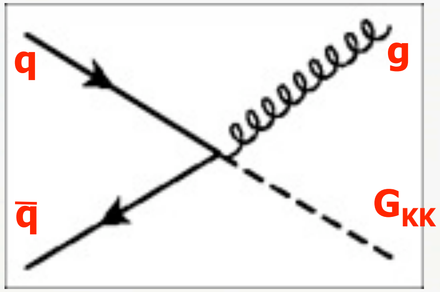
- Supernova cooling due to graviton emission – an alternative cooling mechanism that would decrease the dominant one via neutrino emission
  - Tightest limits on any additional cooling sources come from the measurement of the SN1987A neutrino flux by Kamiokande and IMB
  - Application to the ADD scenario: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

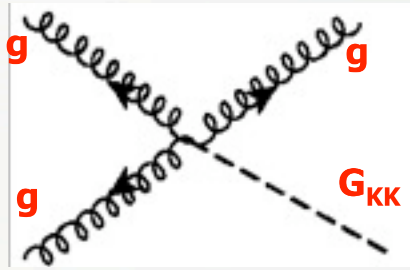
Collider Signatures for Large ED

- Kaluza-Klein gravitons couple to the energy-momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang [PRD **59**, 105006 (1999)]
  - Giudice, Rattazzi, Wells [NP **B544**, 3 (1999)]
- Graviton emission: direct sensitivity to the fundamental Planck scale M_D
- Virtual effects: sensitive to the ultraviolet cutoff M_S, expected to be $\sim M_D$ (and likely $< M_D$)
- The two processes are complementary

Real Graviton Emission

Monojets at hadron colliders





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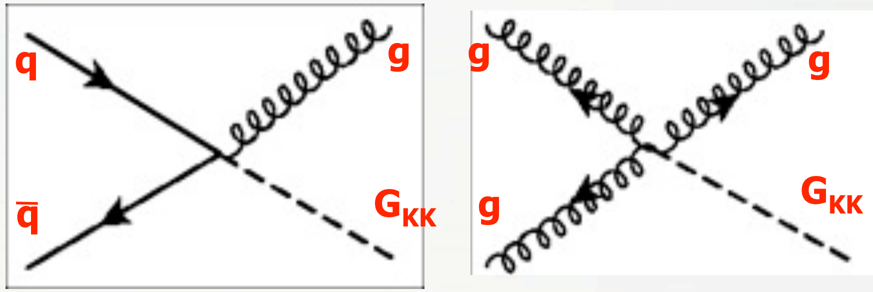
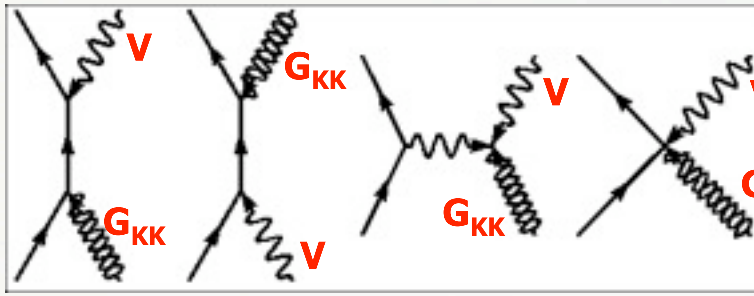


Single VB at hadron or e^+e^- colliders



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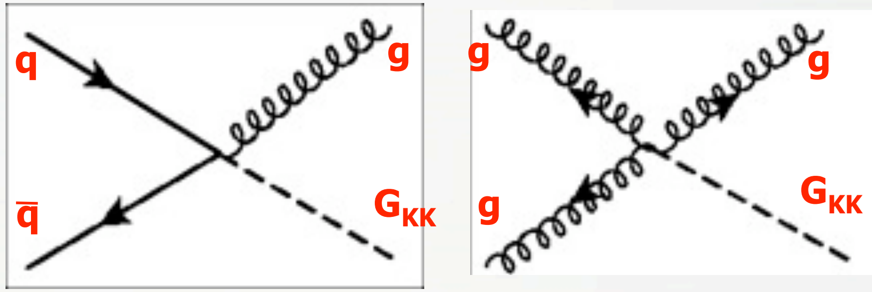

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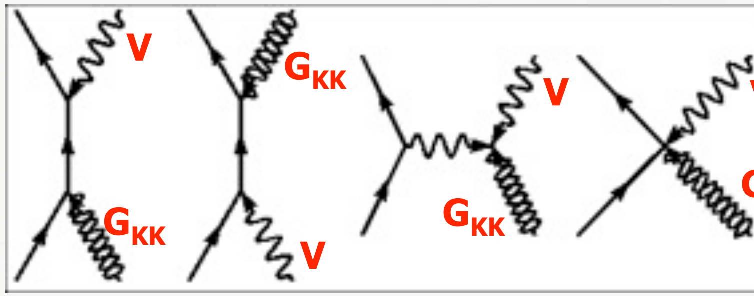
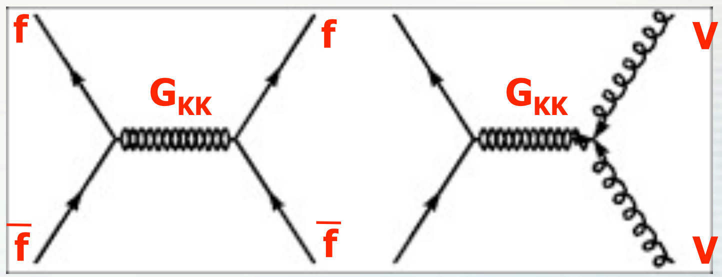


Virtual Graviton Effects

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

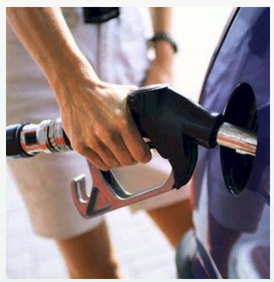


The LHC - Aerial View

LHC: facts

- Energy: 7 x 7 TeV (started at 3.5 x 3.5 TeV), i.e. 7 (3.5) times more powerful than the previous big machine, the Tevatron
- Circumference: 26.7 km
- Number of proton bunches: 2808 x 2808; 1.15×10^{11} protons/bunch
- Magnetic field: 8.3 T
- Luminosity: 10^{34} cm^{-2}s^{-1} = 10^{-2} pb^{-1}s^{-1} = 7 top pairs/s = 100 W(eν)/s
- Energy stored in magnets: 10 GJ = A380 at cruise speed of 700 km/h. Can heat and melt 12 tons of copper!

- Energy stored in a single beam: 360MJ = 90 kg of TNT = 8 liters of gas = 15 kg of chocolate

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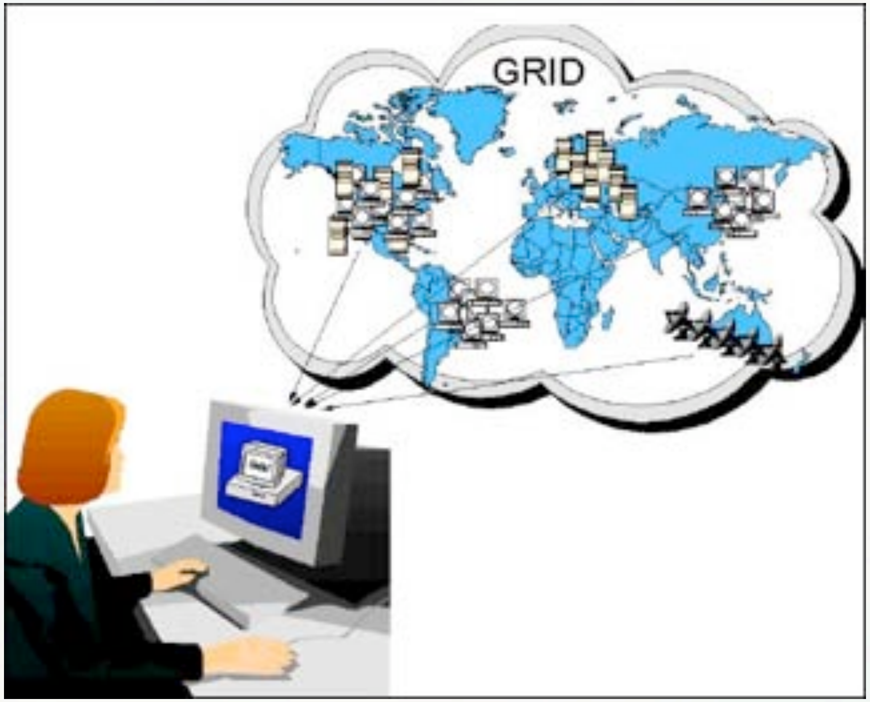
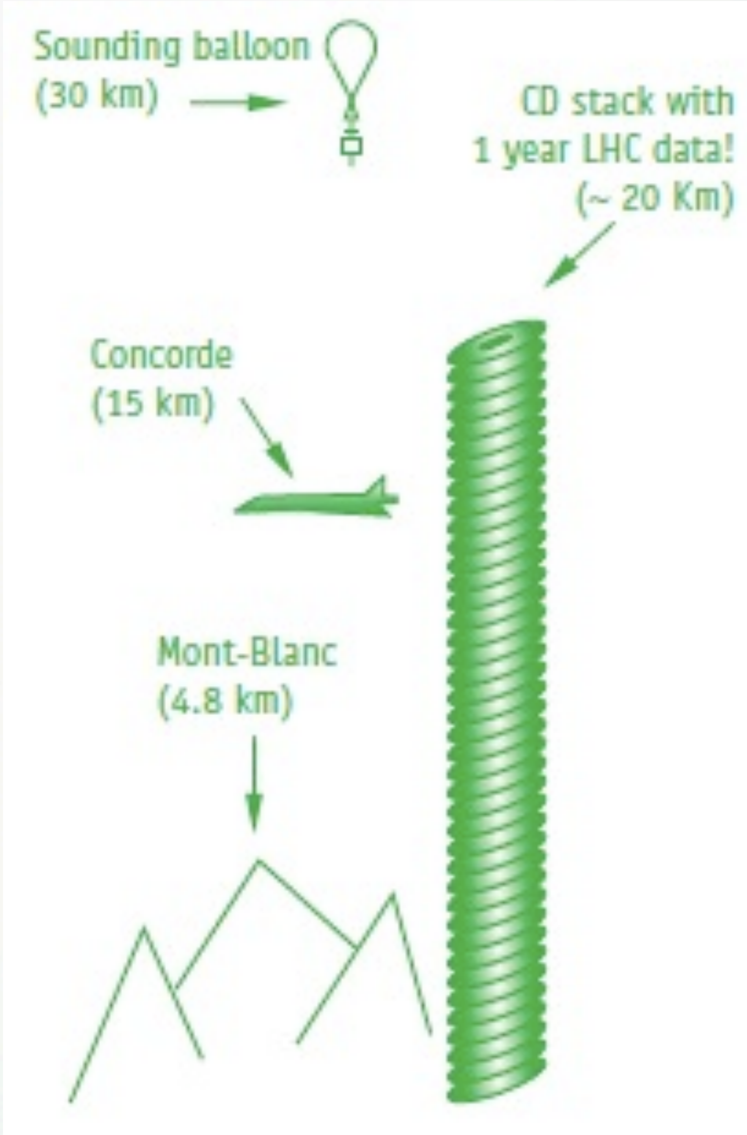
- The cost of the machine and detectors is $10B CHF or $11.5B
- Everything about LHC is at least 10 times bigger than ever attempted before!

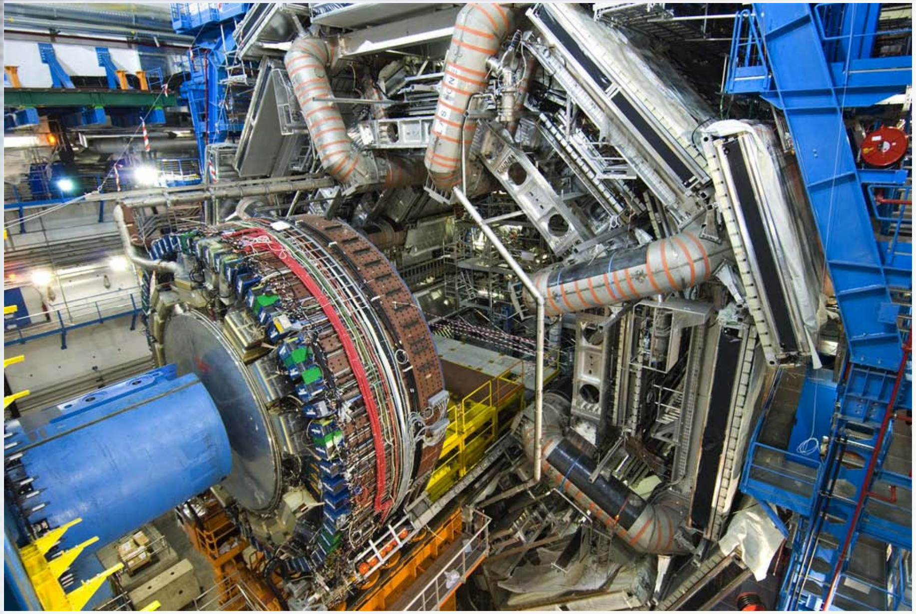
How Much Data Does it Produce?

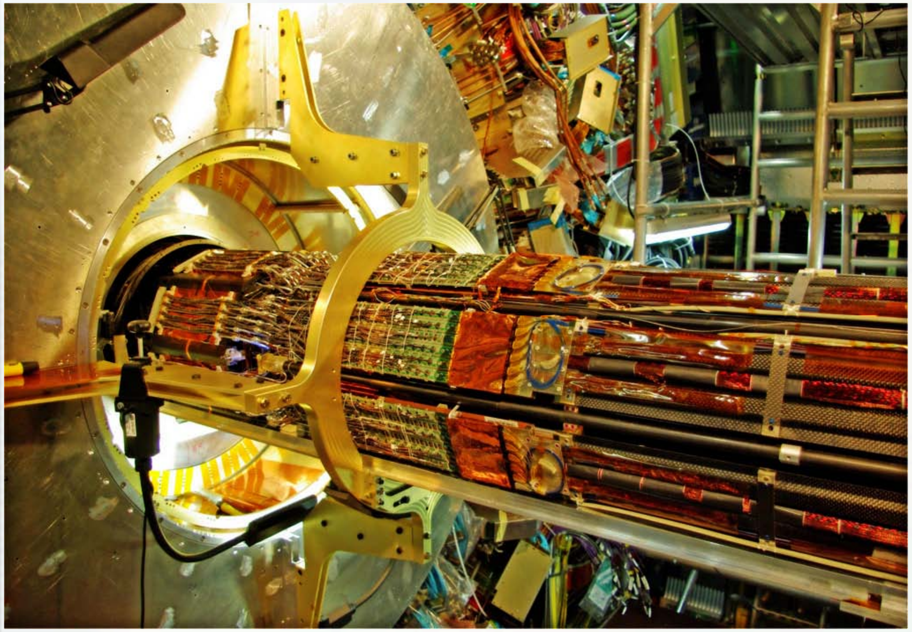
- Nearly 1 GB of data is recorded every second
  - 15,000 TB/year = 15 PB/year
  - It's like recording a DVD every 4 sec
  - Enough to fill your hard drive in 2 min
- Processed all around the world via LHC Computing Grid



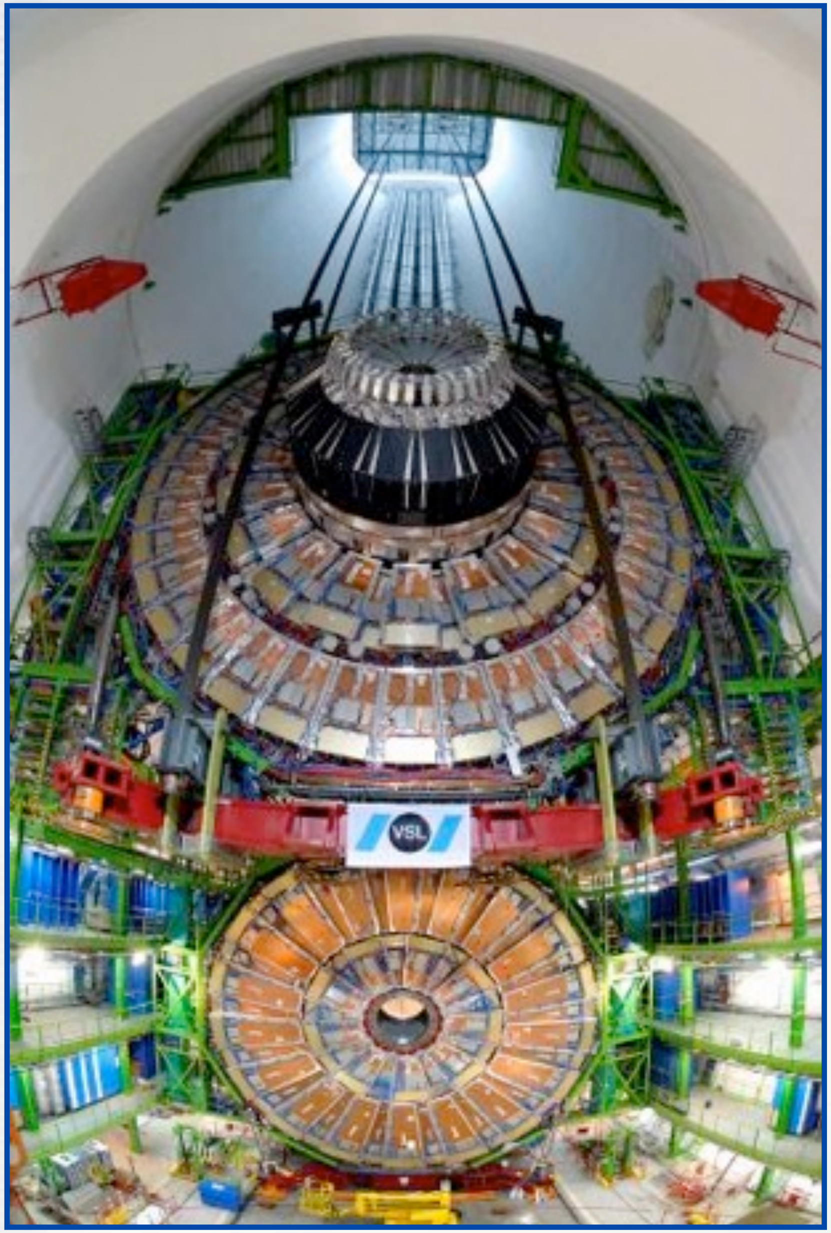


ATLAS in 2008

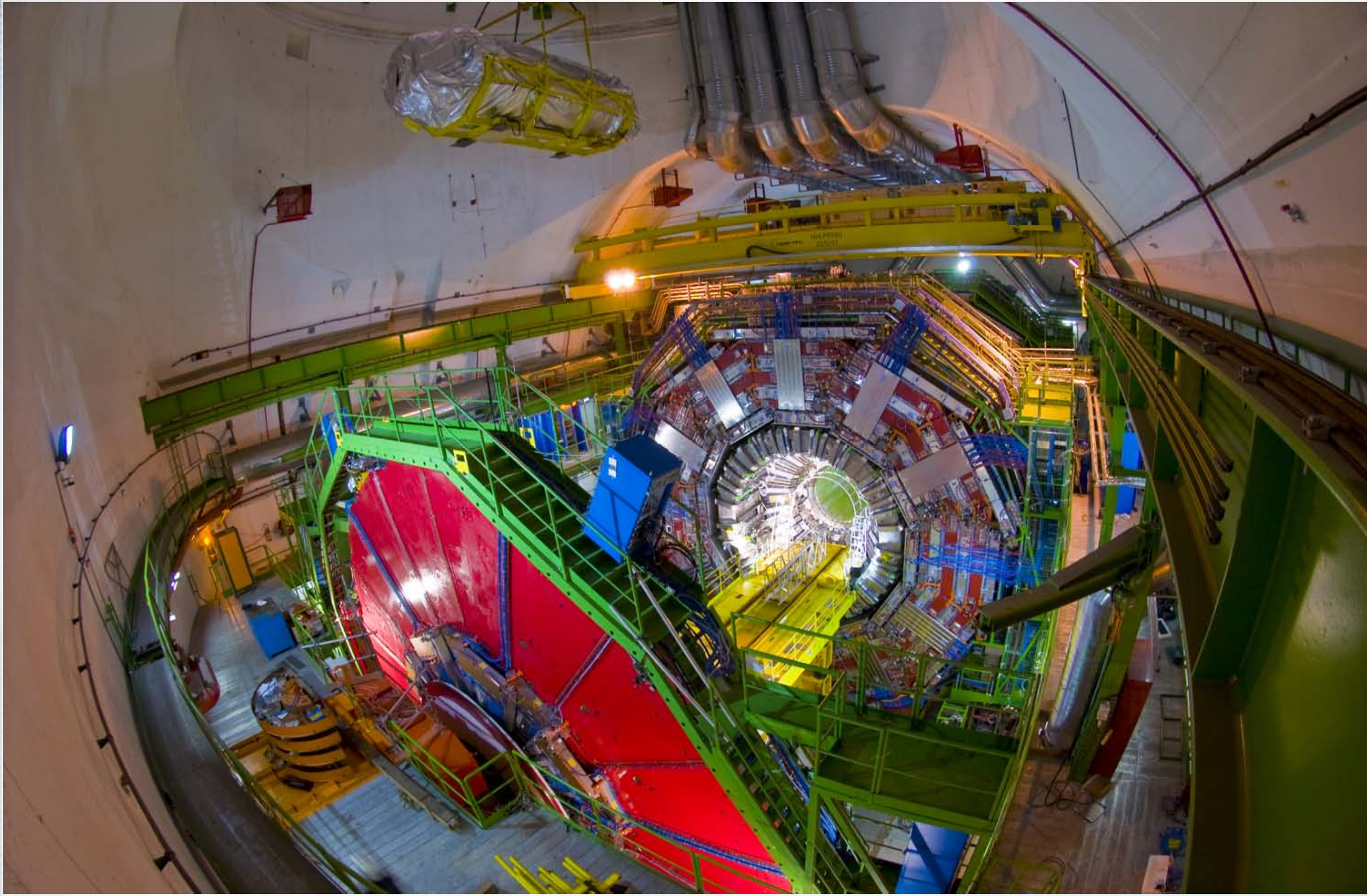




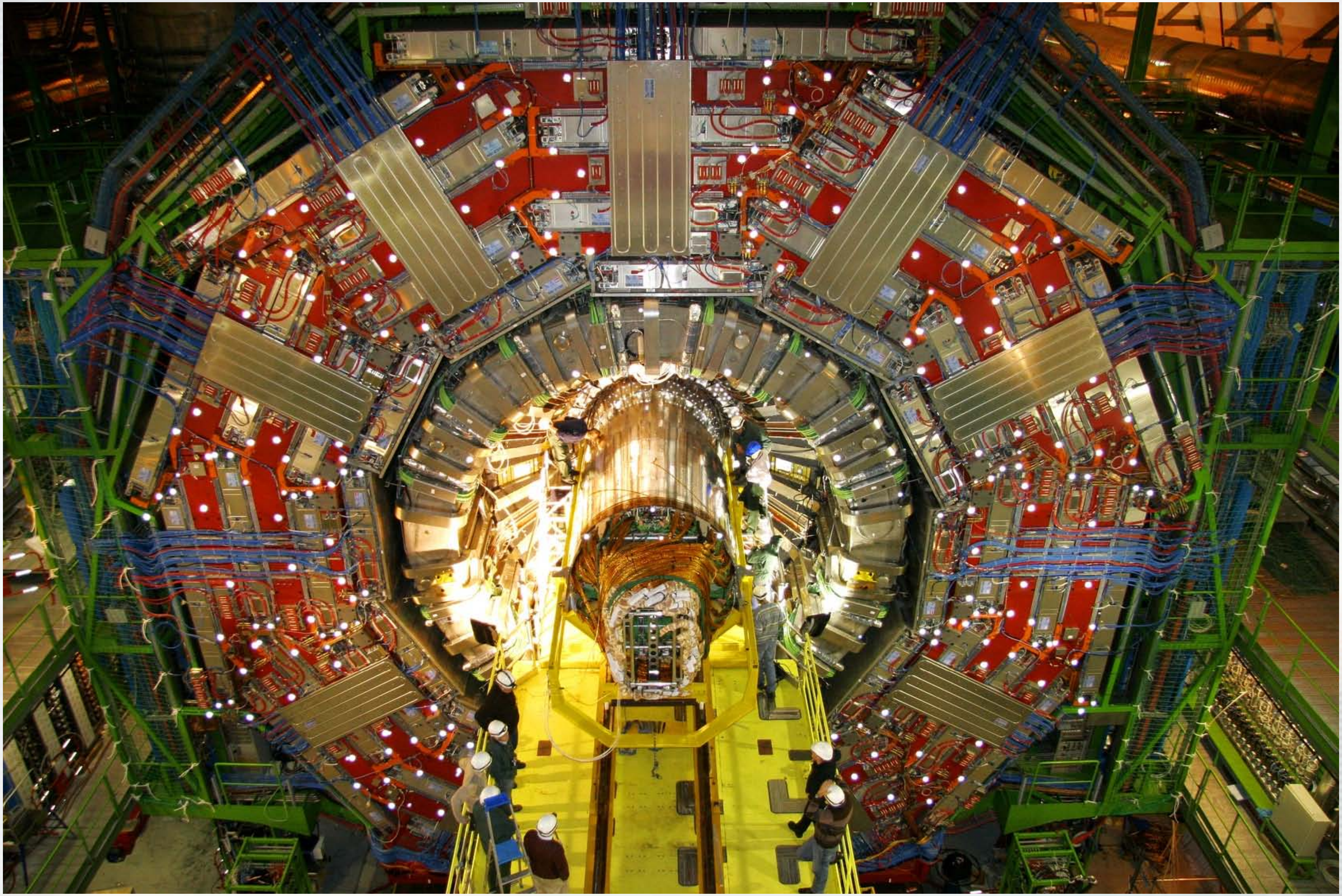
Assembling the CMS



CMS in December, 2007



CMS in January 2008



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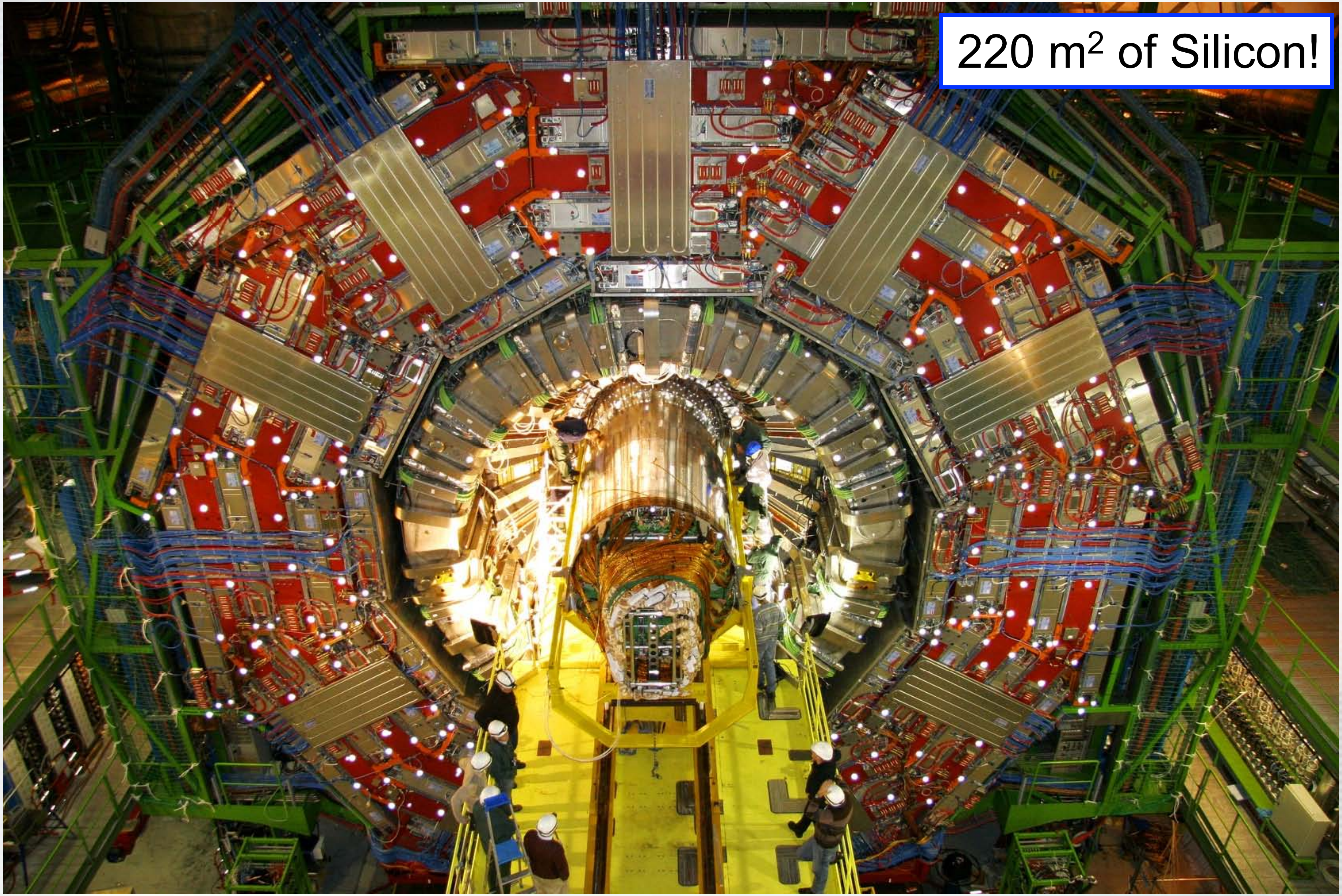


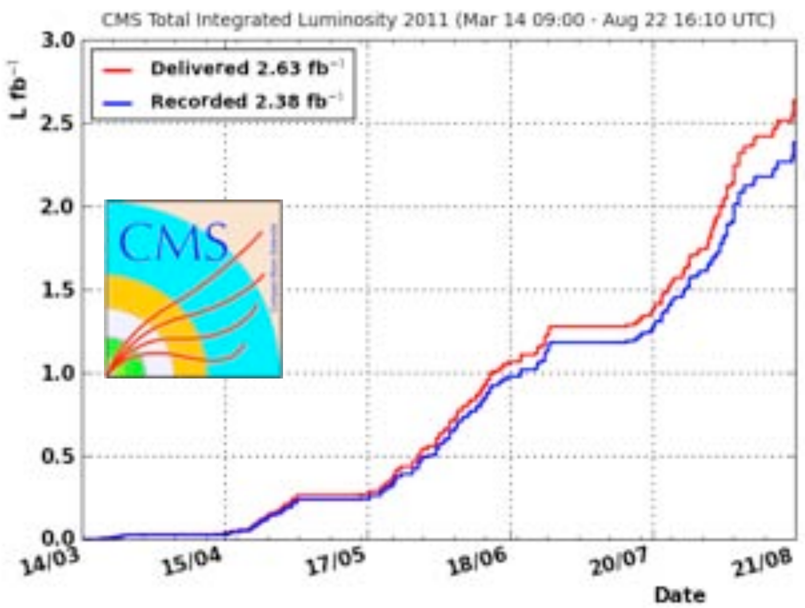
First 7 TeV Collisions - 30/3/10

Accelerator Control Room

The LHC Luminosity Plan

- Delivered 50 pb^{-1} in 2010
- Expect ~5 fb^{-1} in 2011 and ~20-30 fb^{-1} by the end of 2012
- Possibly run at 8.0-8.5 TeV next year
- Shut down for ~1.5 years either at the end of 2012 or at the beginning of 2013 and then go to ~14 TeV

>90% data taking efficiency



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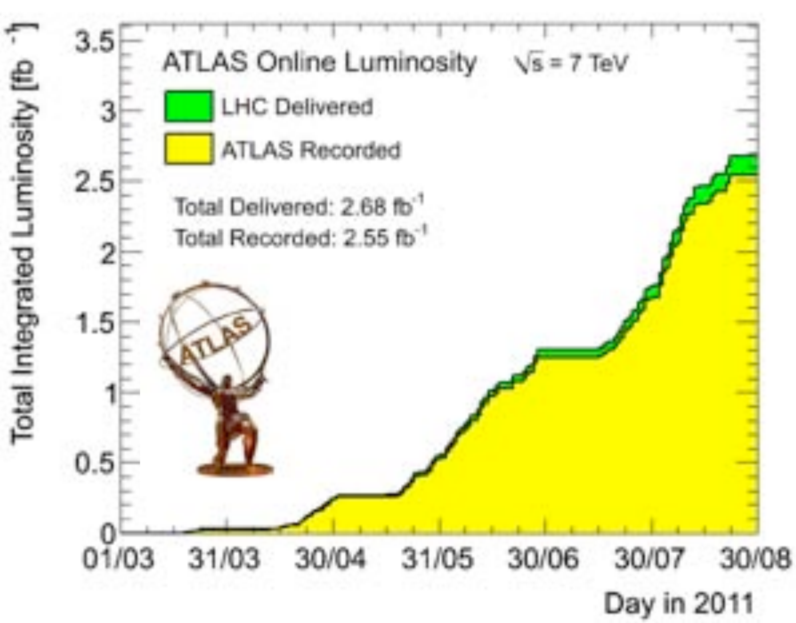
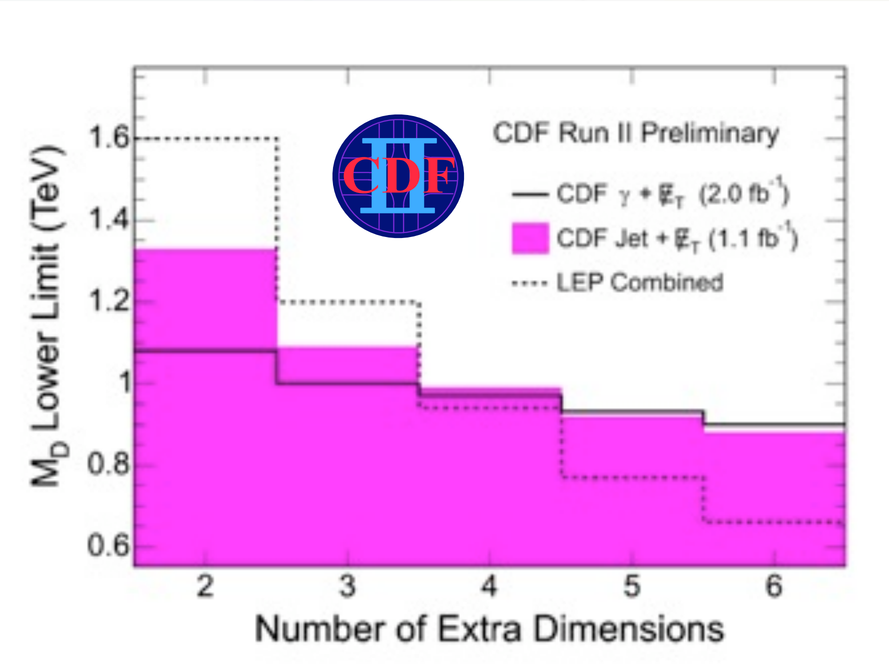
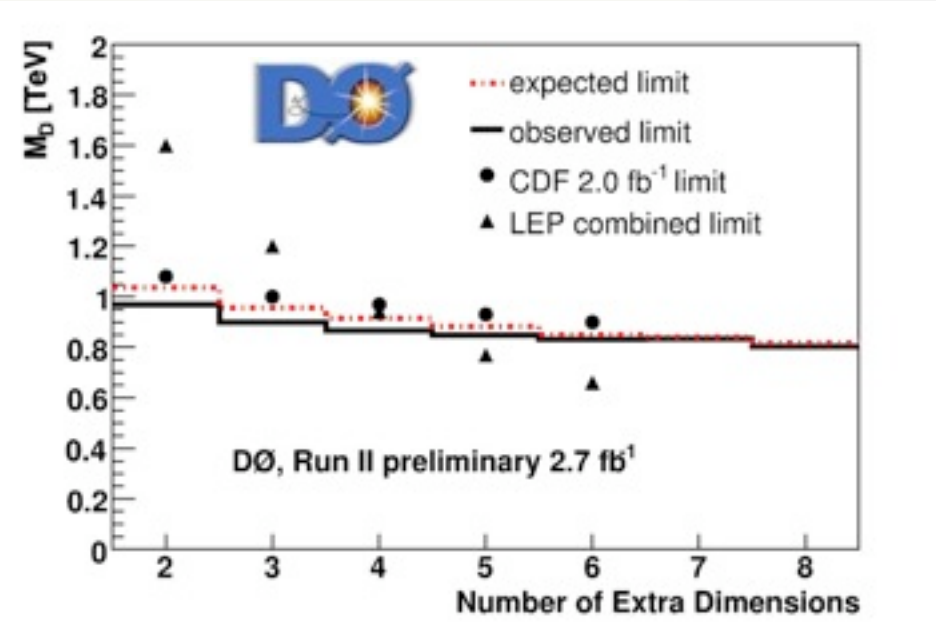


Tevatron Searches in Monojets and Monophotons

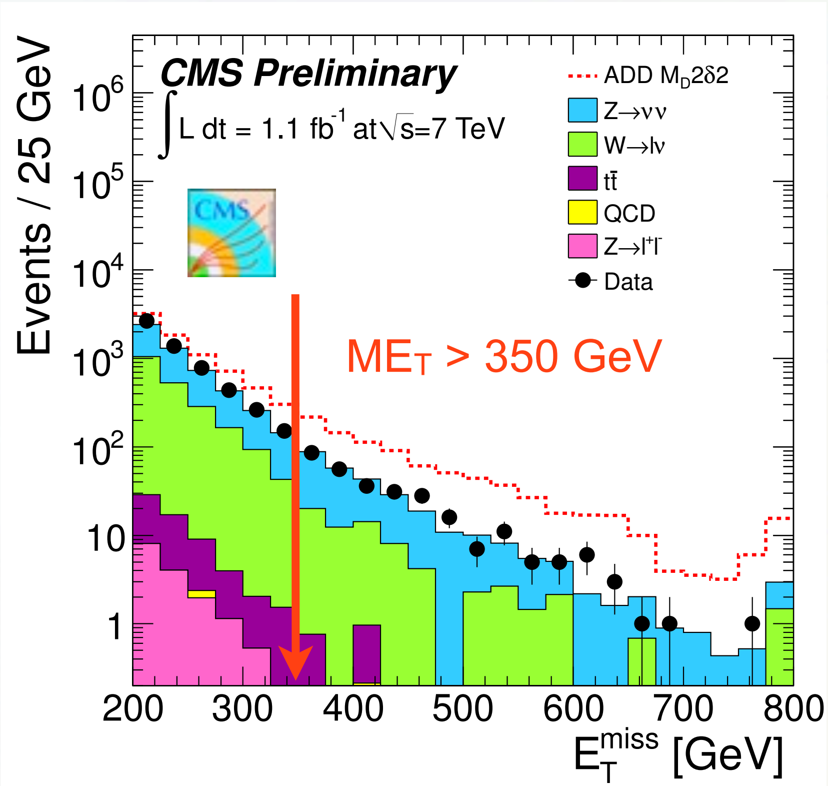
- CDF has published a 1/fb monojet search
- Both CDF and DØ completed 2/fb monophoton searches
- While easier than the monojet one, the sensitivity is typically not as good, especially for low number of ED
  - CDF monophoton limits approach monojet ones at large n, but require twice the luminosity

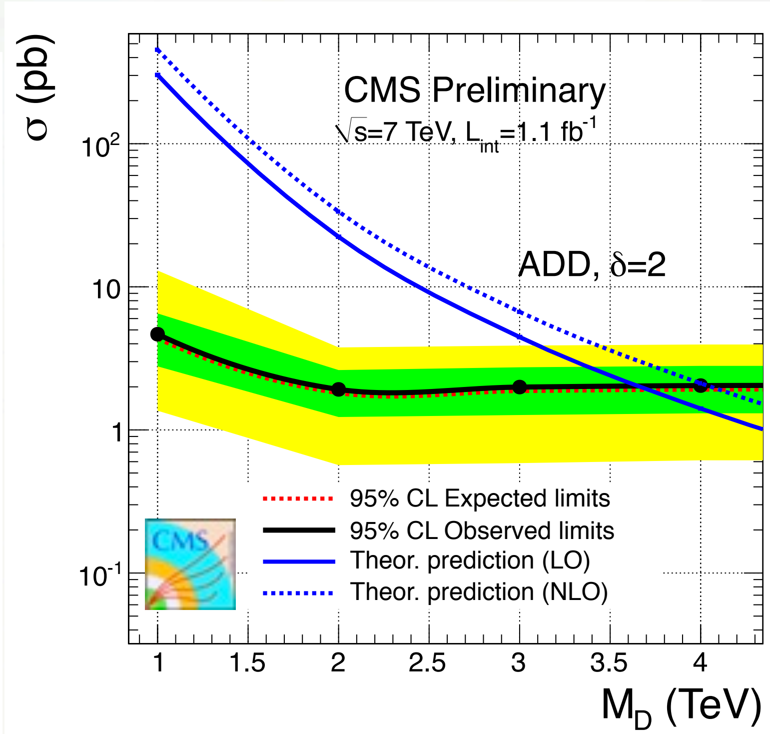




Search for Monojets at the LHC

- Both ATLAS and CMS published 2010 data search (36/pb)
- They also presented preliminary results with 2011 data (1.1/fb)
- Dominated by irreducible Z(νν)+jets background (determined from W(eν/μν)+jets)





CMS limits w/ 1.1 fb^{-1} @ 95% CL
n=2: M_D > 3.7 TeV
n=6: M_D > 2.3 TeV

ATLAS limits w/ 1.0 fb^{-1} @ 95% CL
n=2: M_D > 3.4 TeV
n=6: M_D > 2.1 TeV

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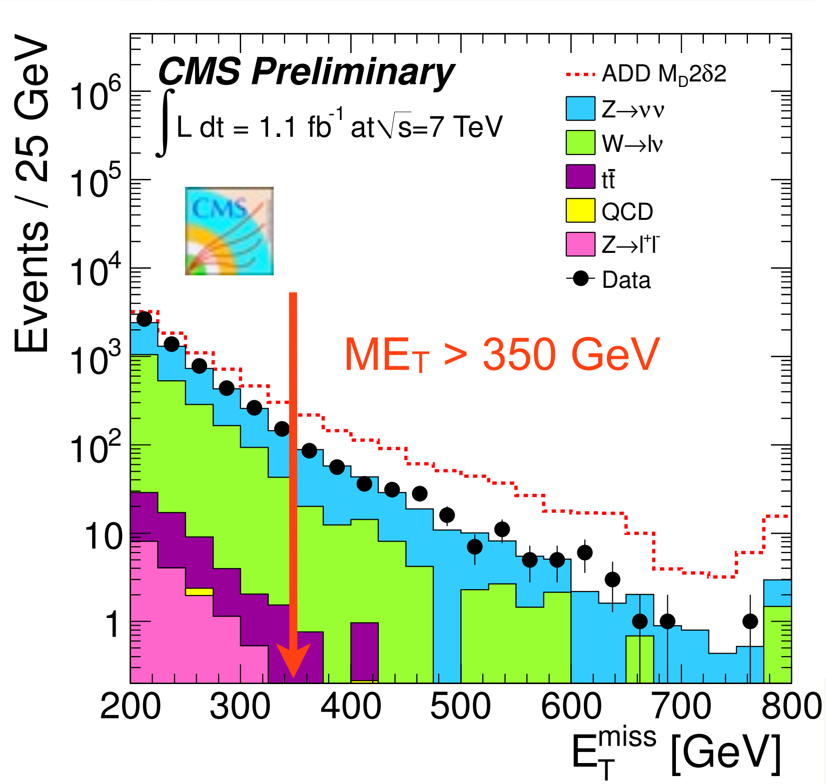
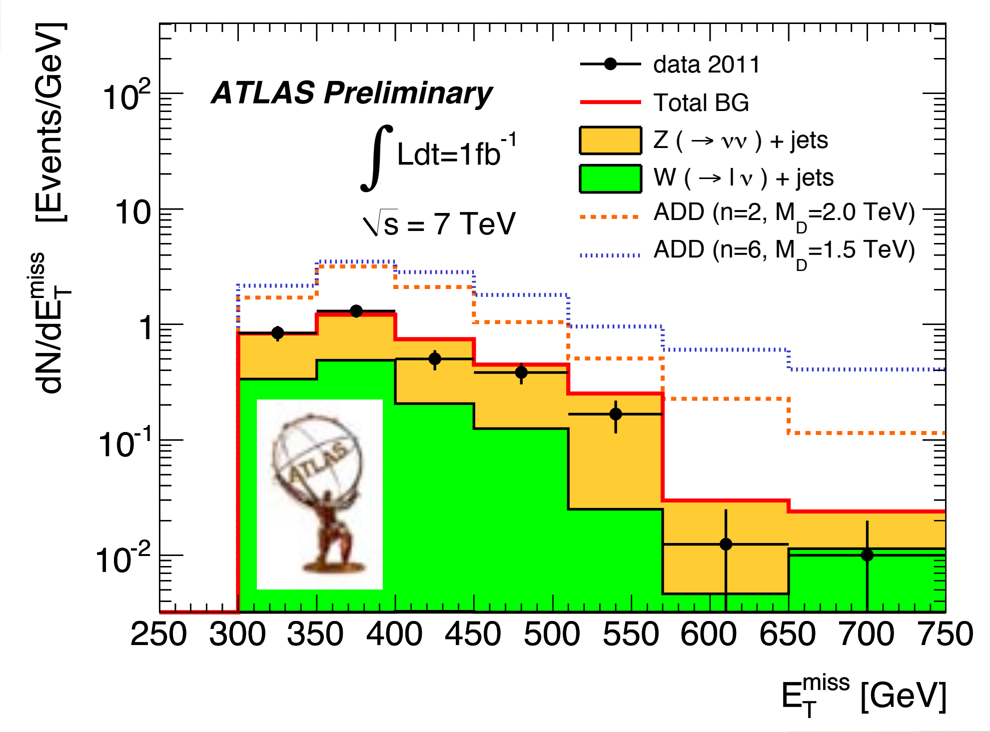
- Dominated by irreducible Z(νν)+jets background (determined from W(eν/μν)+jets)



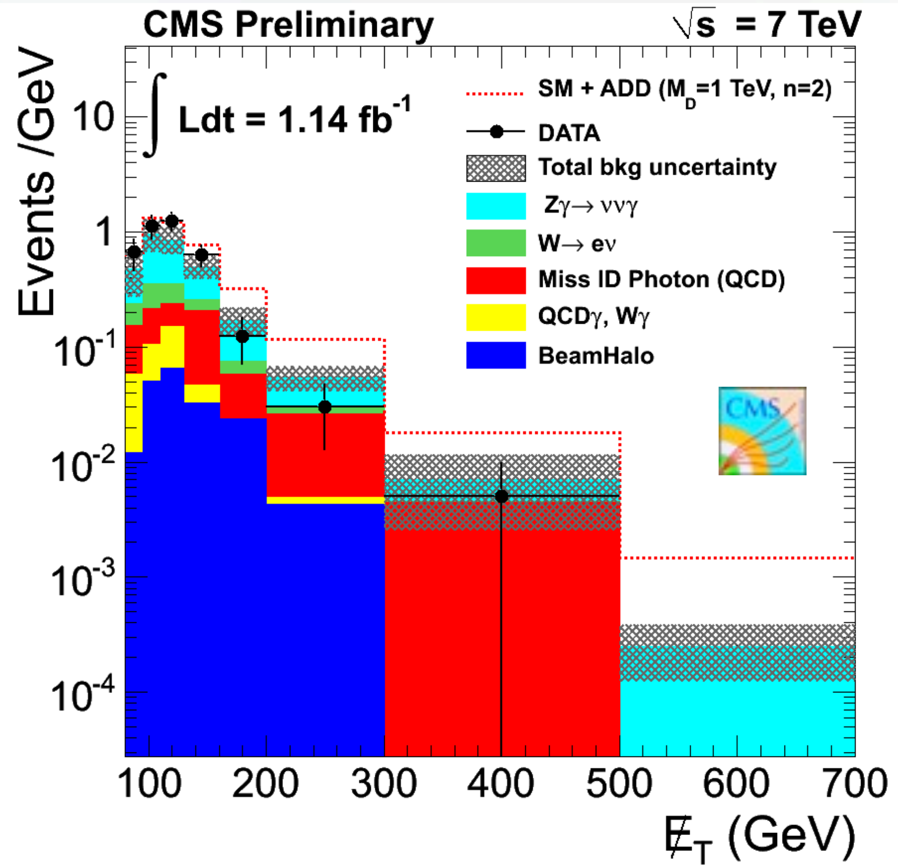


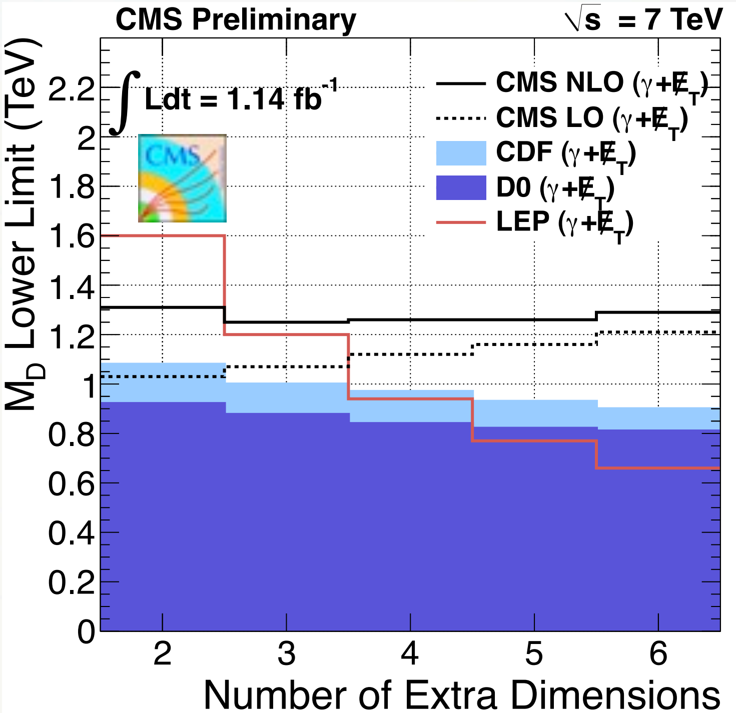
CMS limits w/ 1.1 fb^{-1} @ 95% CL
n=2: M_D > 3.7 TeV
n=6: M_D > 2.3 TeV

ATLAS limits w/ 1.0 fb^{-1} @ 95% CL
n=2: M_D > 3.4 TeV
n=6: M_D > 2.1 TeV

Search for Monophotons at CMS

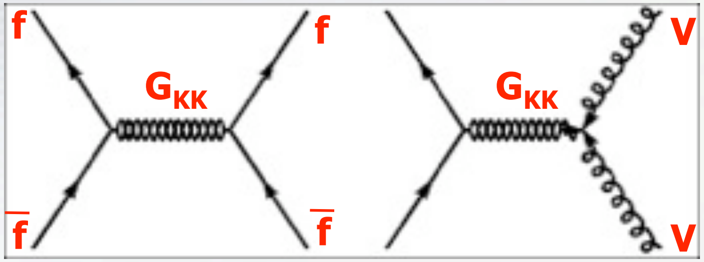
- First analysis of a kind at the LHC
- Similar techniques to the monojet analysis
- Irreducible background from Z(νν)+jets





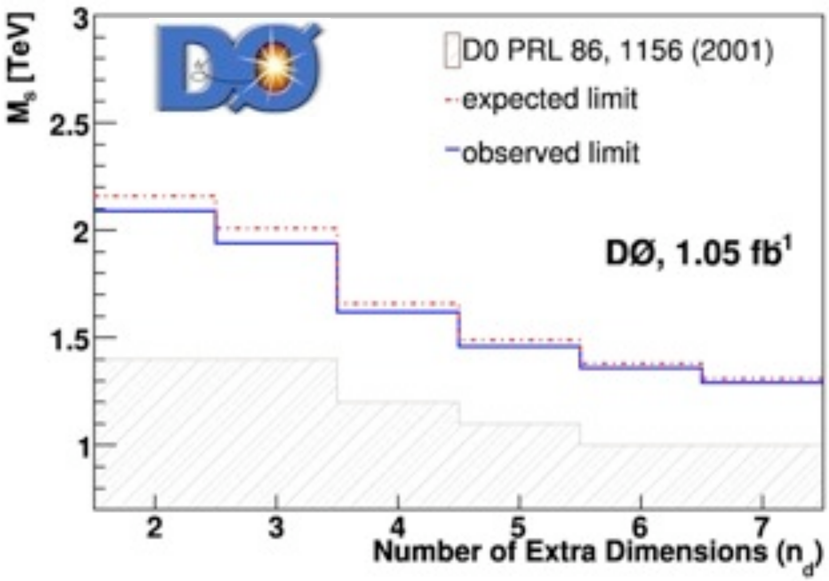
CMS limits w/ 1.14 fb^{-1}
95% CL
n=2: M_D > 1.0 TeV
n=6: M_D > 1.2 TeV

Tevatron: Virtual Graviton Effects



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

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

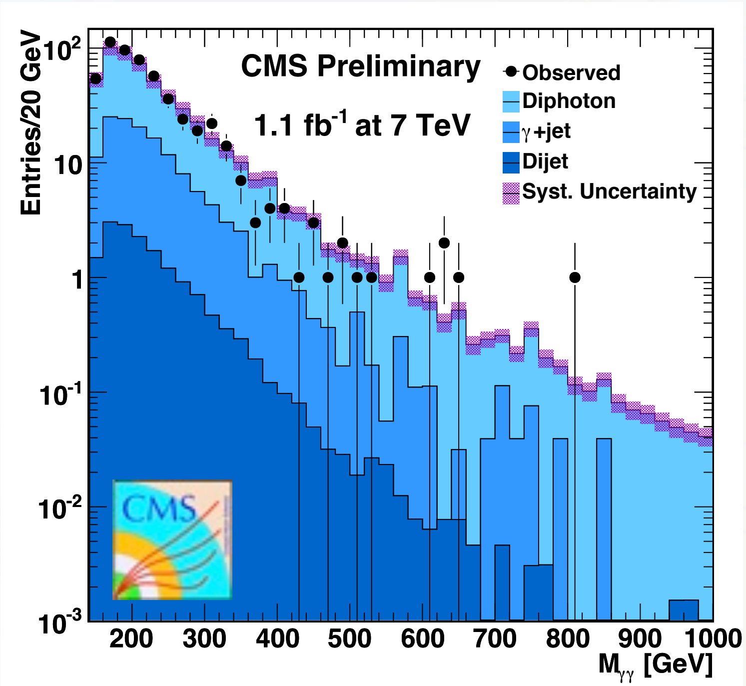


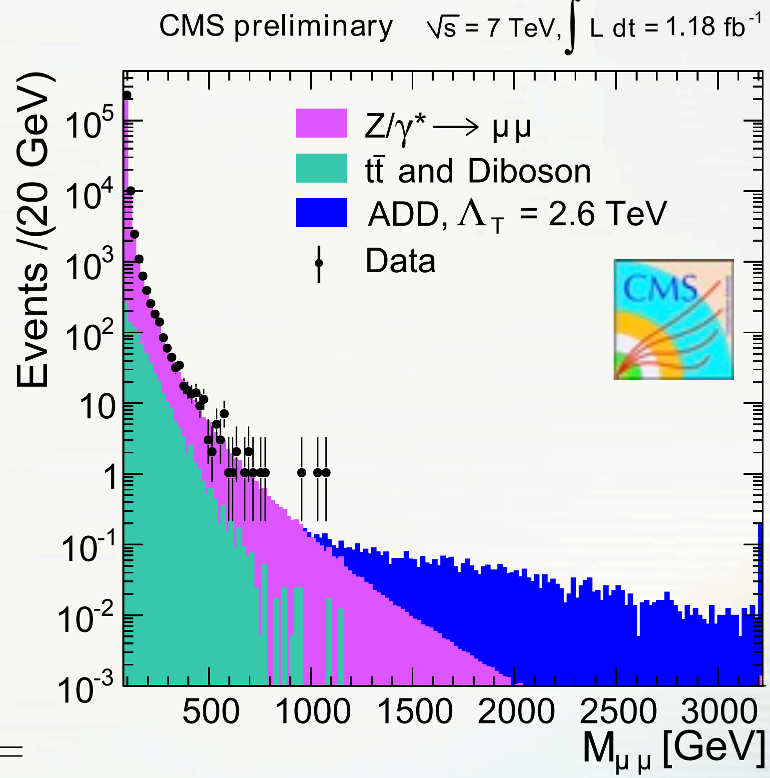
- High-mass, low |cosθ*| tail is a characteristic signature of ED Cheung, GL [PRD **62** 076003 (2000)]
- Best limits on the effective Planck scale come from ~1 fb^{-1} DØ data:
  - M_S > 1.3-2.1 TeV (n=2-7) diphotons
  - M_S > 1.3-2.0 (n=2-7) dijets

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
- CMS published $\gamma\gamma$ with 2010 data (36/pb), M_S > 1.6-2.3 TeV
- ATLAS has preliminary 36/pb $\gamma\gamma$ result
- CMS preliminary 2011 $\gamma\gamma$ and $\mu\mu$ results with 1.1-1.2/fb

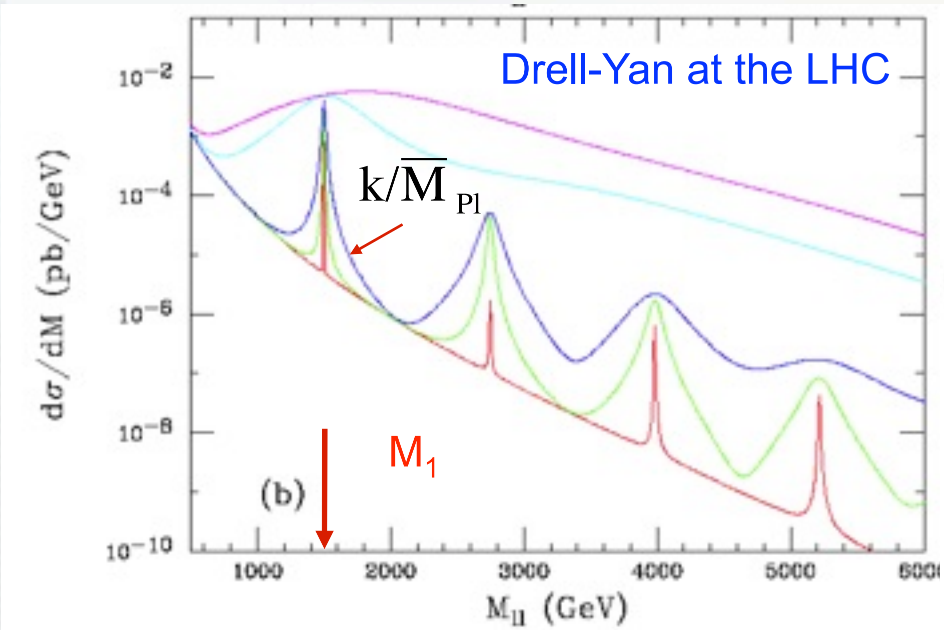


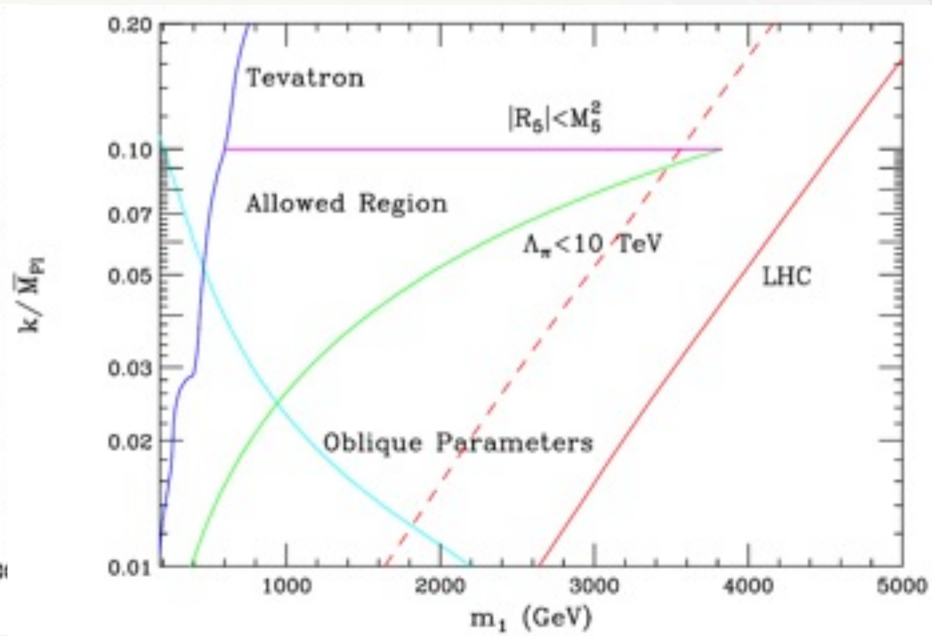


$n_{ED} = 2$	$n_{ED} = 3$	$n_{ED} = 4$	$n_{ED} = 5$	$n_{ED} = 6$	
3.2	3.4	2.8	2.6	2.4	Limits in the diphoton channel
2.58	3.12	2.62	2.36	2.20	Limits in the dimuon channel

Randall-Sundrum Model Observables

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

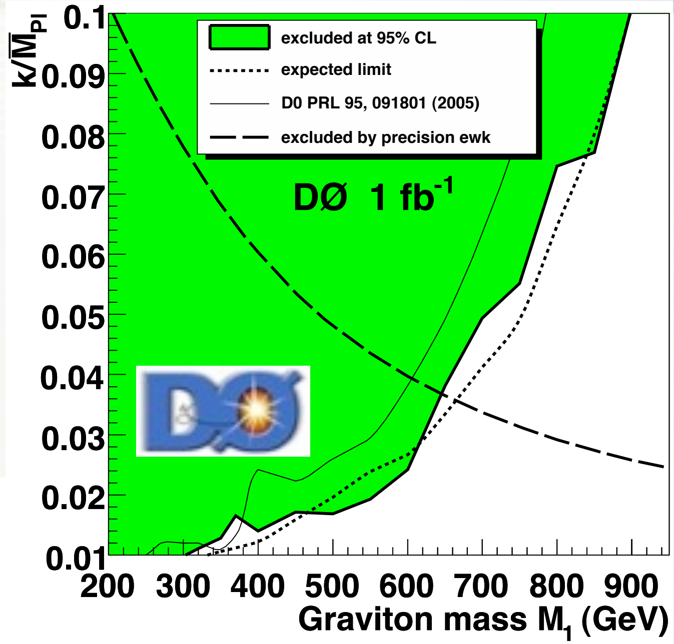


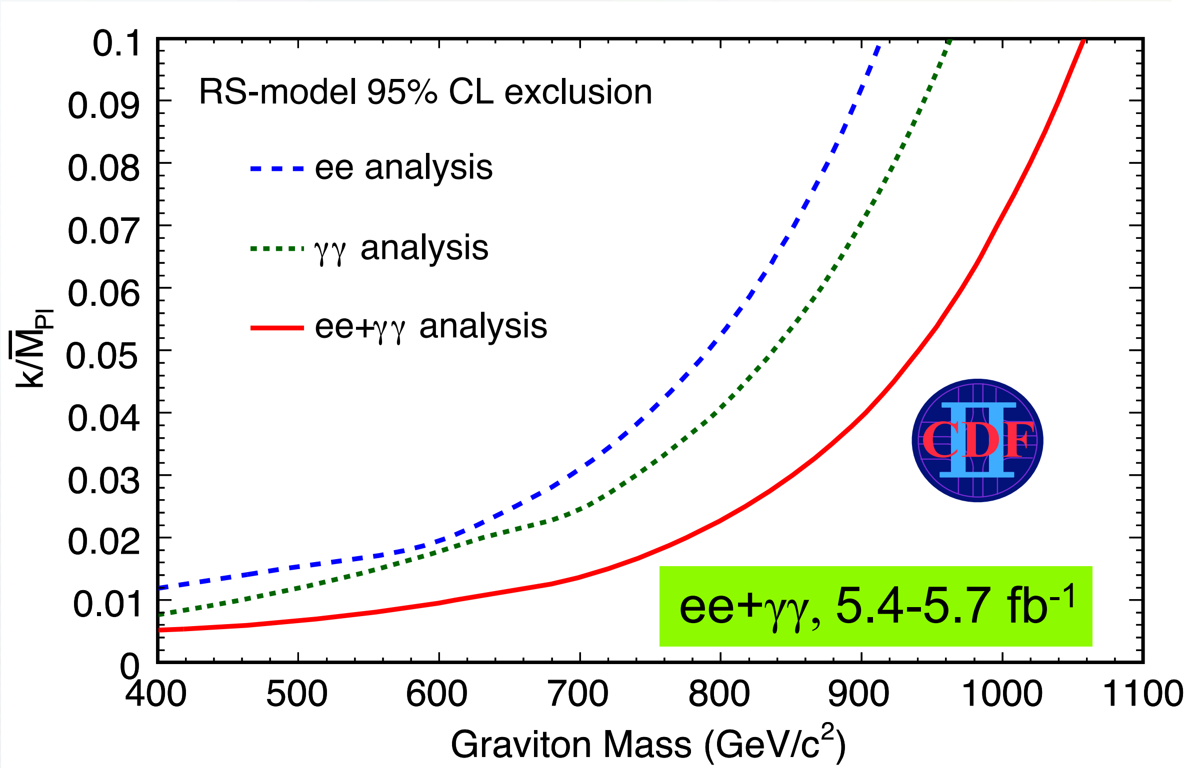


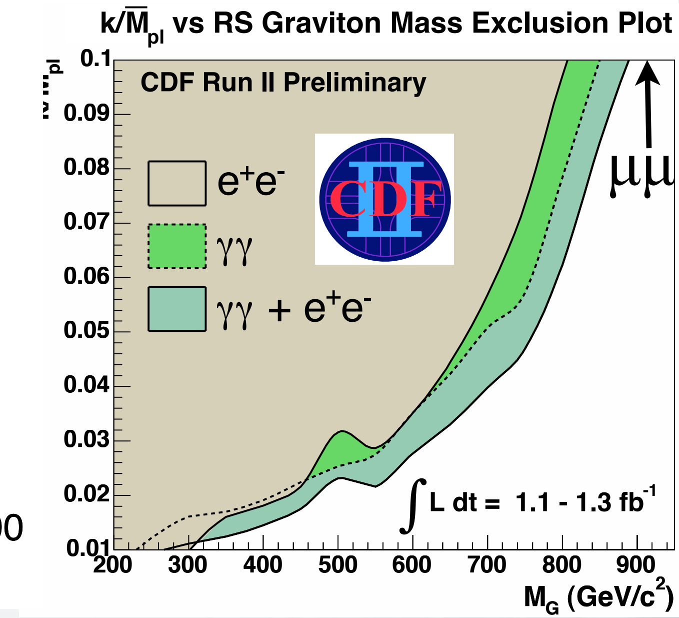
Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]

Most Recent Tevatron Limits on G_{KK}

- Latest limits are just ~10% higher than the original ones despite 5x statistics
  - Tevatron sensitivity has really maxed out - need higher energies!







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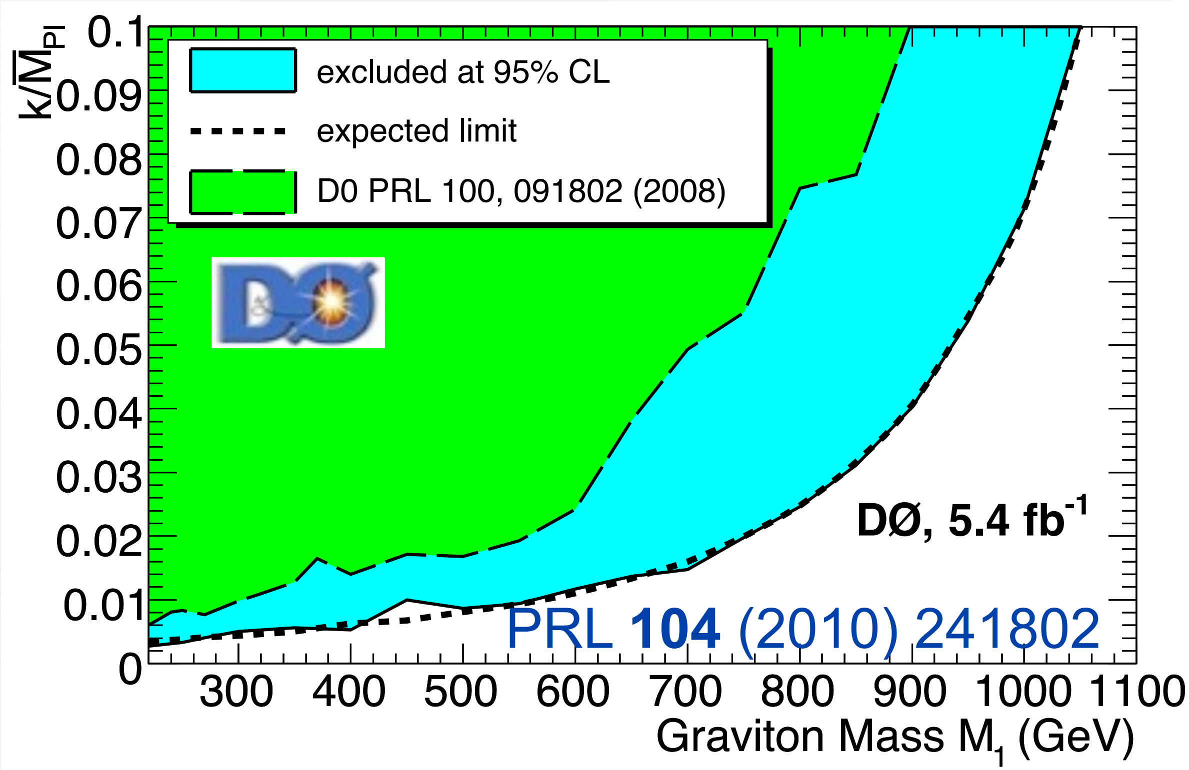
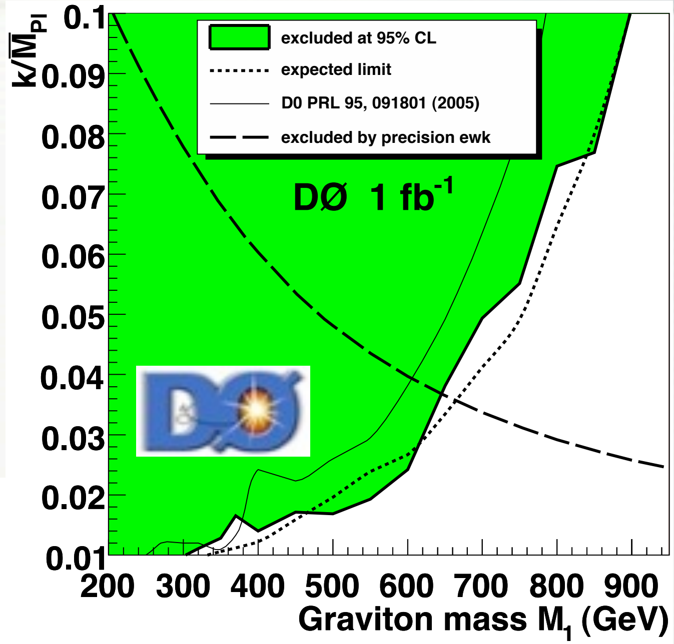
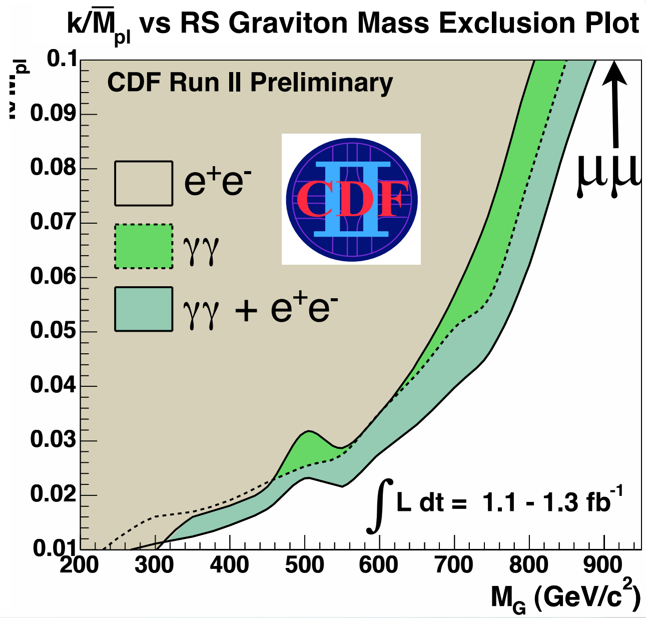
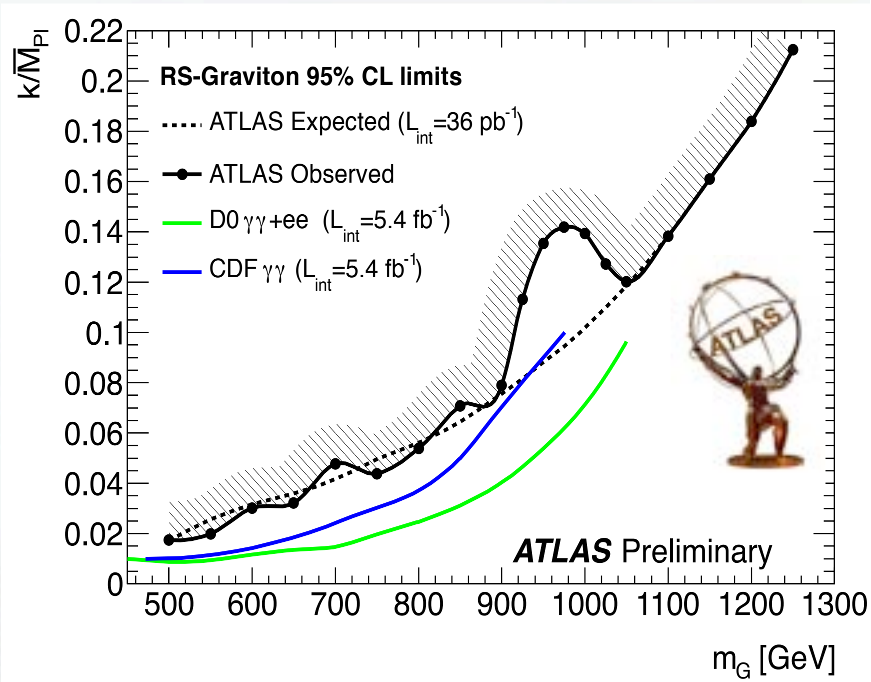


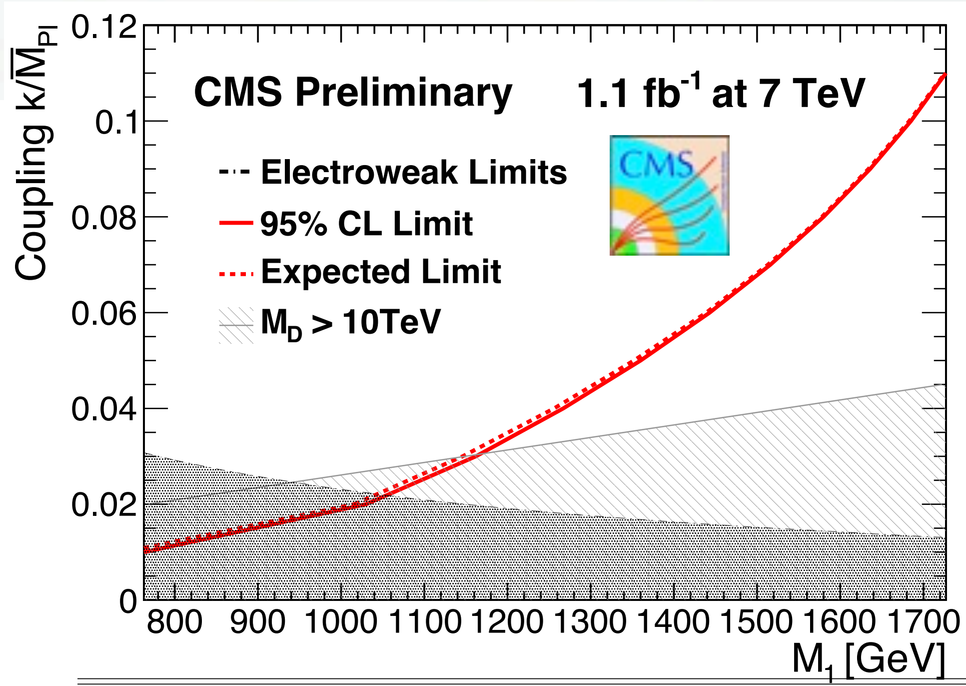




RS Gravitons at the LHC

- Same analyses can be reinterpreted as search for resonances decaying into pair of photons or letons (e.g., G_{KK})
- Significantly exceeds the Tevatron limits with ~1/fb





$\tilde{k}$	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
M_1 [TeV]	0.77	1.05	1.20	1.31	1.41	1.49	1.57	1.63	1.69	1.74	1.78

CMS: ee+μμ @1.1/fb

M > 1450-1780 GeV

for k/M_{Pl} = 0.05-0.10

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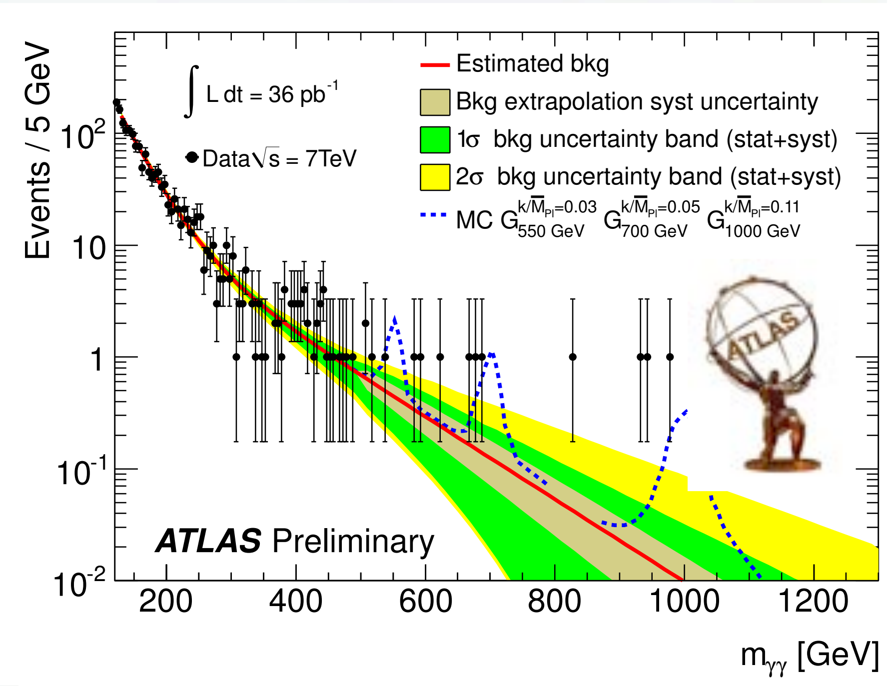

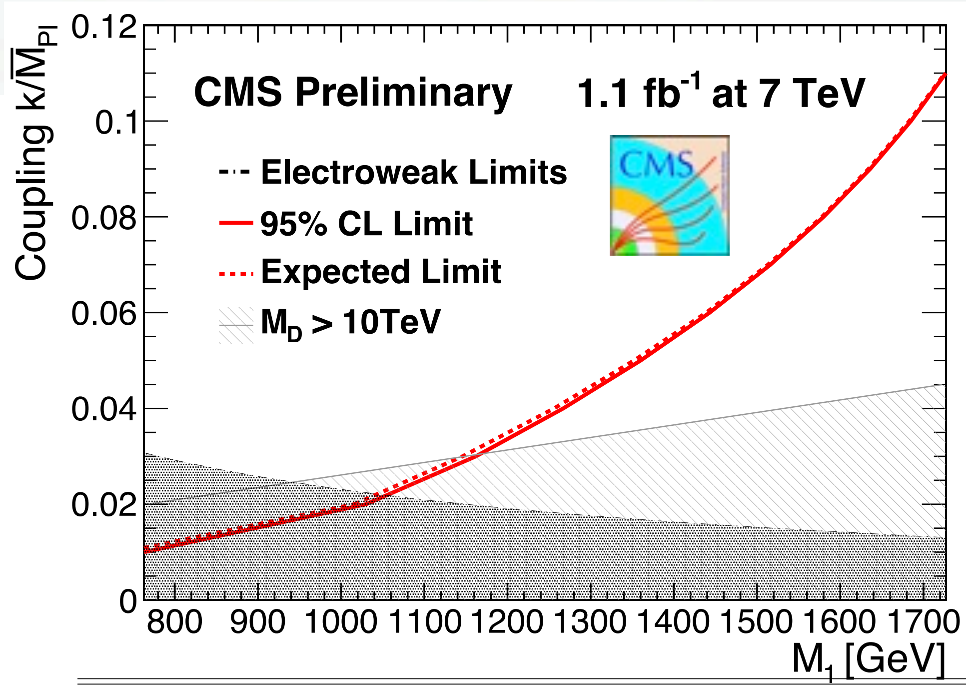

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M_1 [TeV]	0.77	1.05	1.20	1.31	1.41	1.49	1.57	1.63	1.69	1.74	1.78

ATLAS: ee+μμ @1/fb:
M > 1630 GeV for k/M_{Pl} = 0.1

CMS: ee+μμ @1.1/fb
M > 1450-1780 GeV
for k/M_{Pl} = 0.05-0.10

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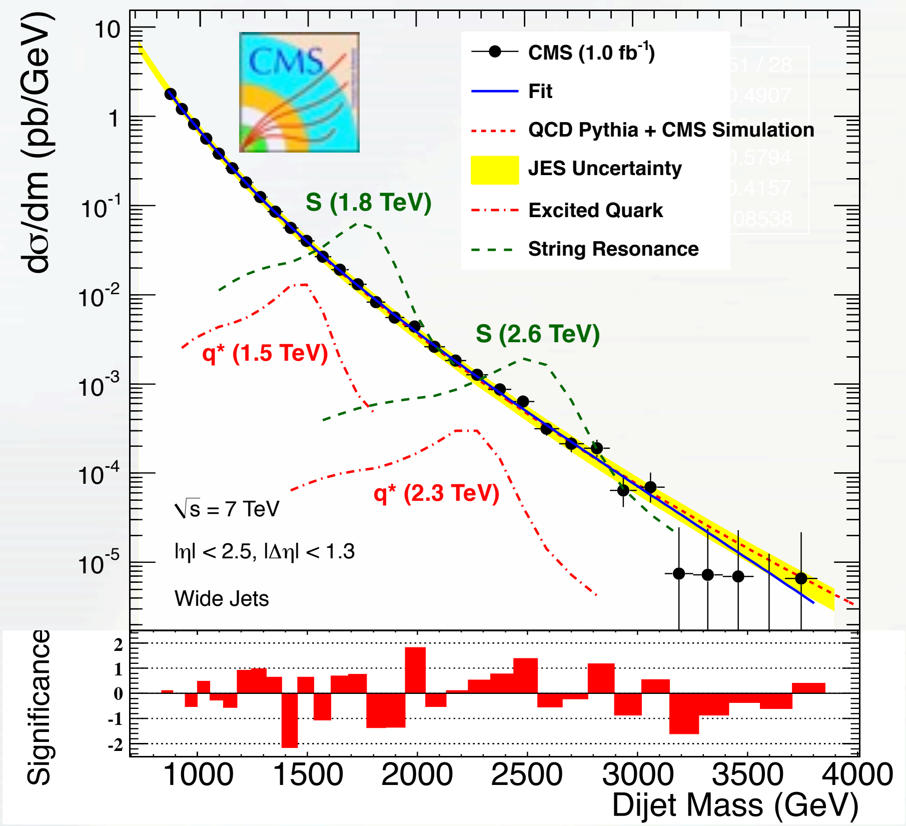
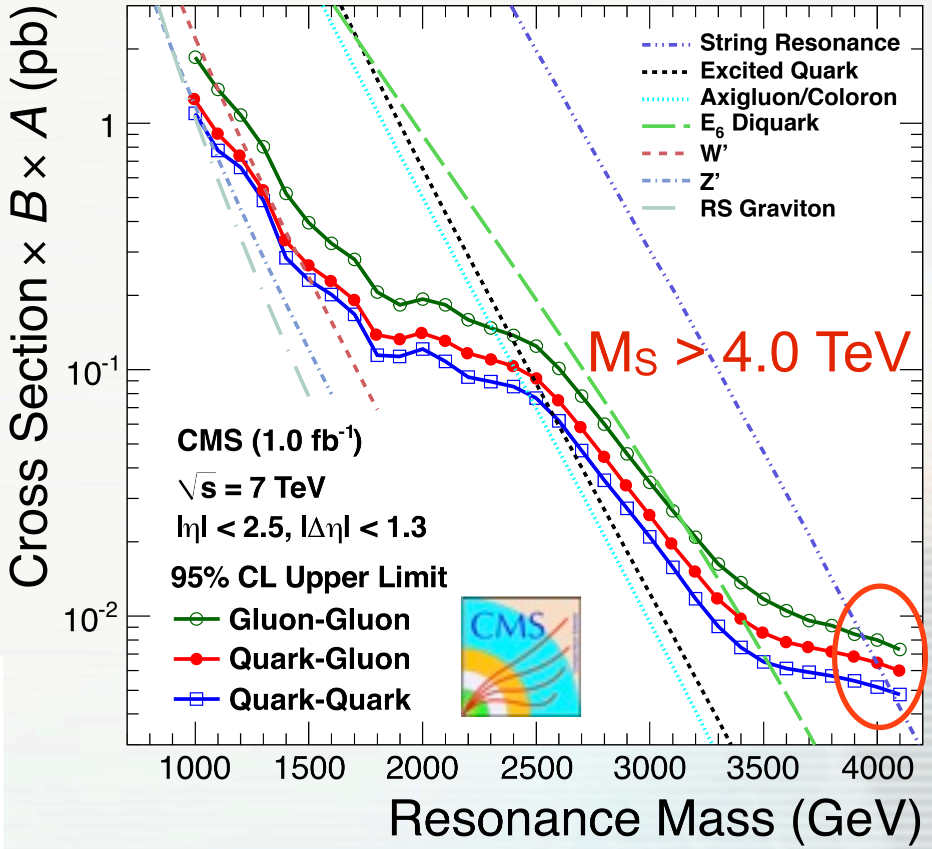
String Resonances at the LHC

- Highly-degenerate excitations of quarks & gluons, decaying into qq, gg, qg
- Look for "bumps" on top of steeply falling QCD spectrum
- Similar limits apply to quantum BH's, decaying into pair of initial partons (see Andy's talk for ATLAS results on that)





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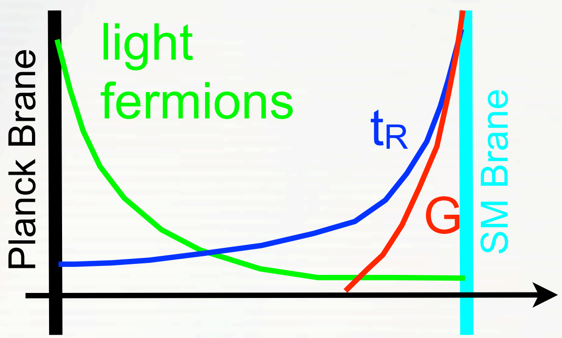
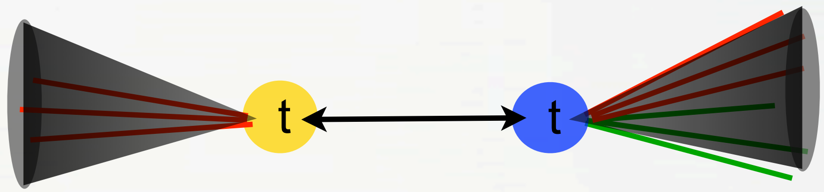
But: Life May be More Complicated!

- 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



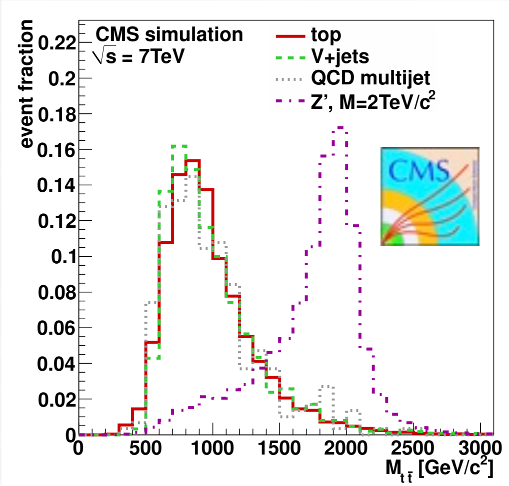
- For graviton masses ~2-3 TeV, top quarks emerge highly boosted, which makes it challenging to reconstruct them

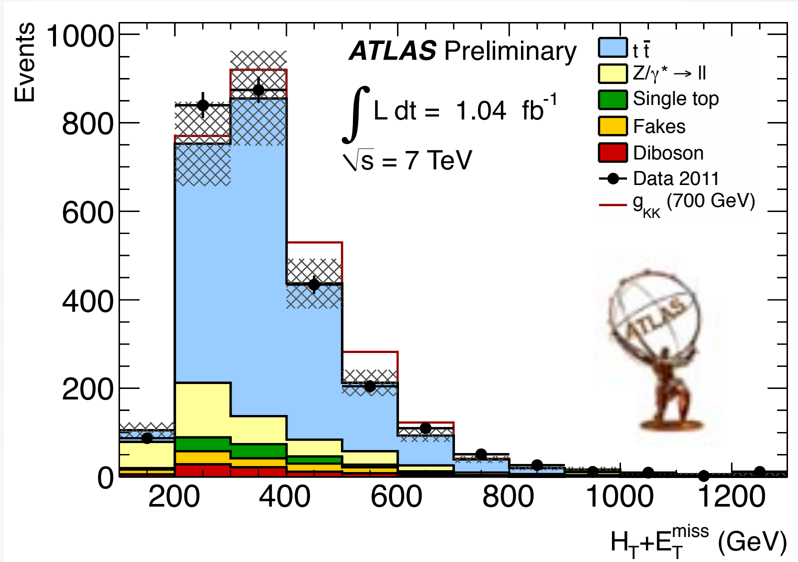


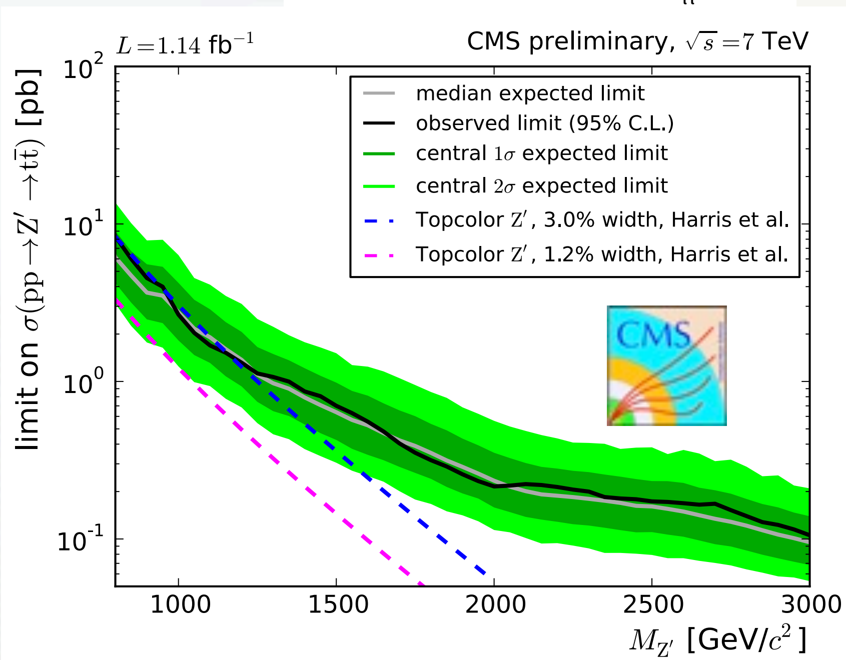
- Several challenges:
  - for 3-jet top decays jets are often merged in a single “fat” jet
  - b-tagging efficiency drops dramatically, as the opening angle between the tracks becomes small.

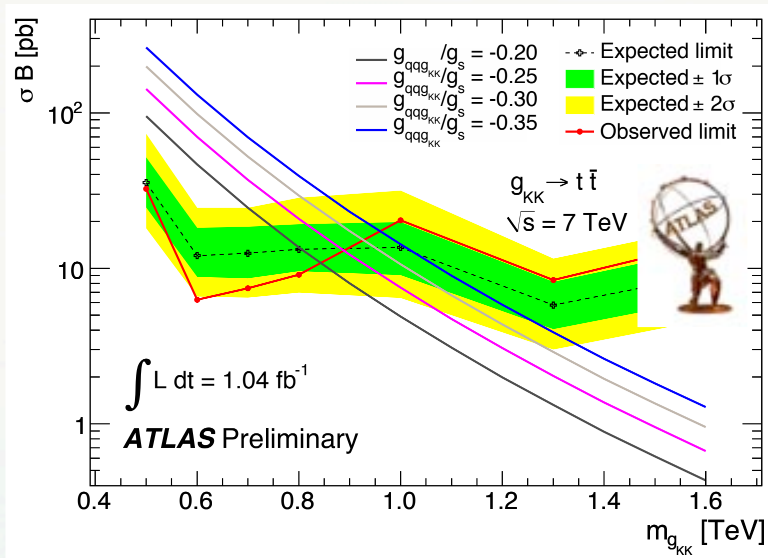
Searches for tt Resonances in l+jets

- Can also look for tt → l+jets; sensitive at the intermediate masses









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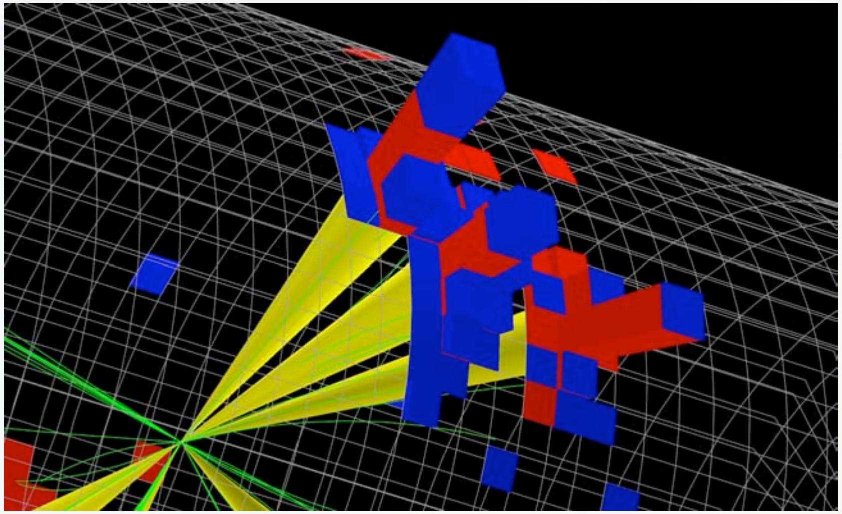
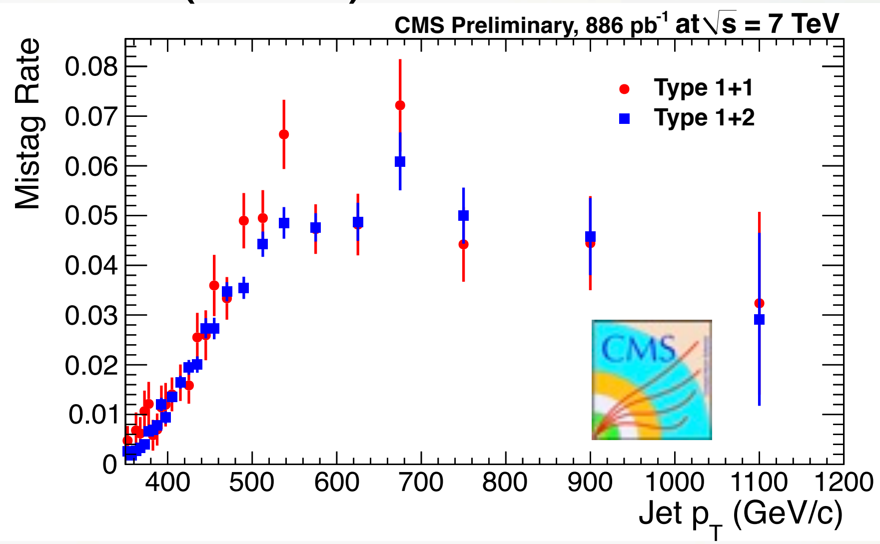
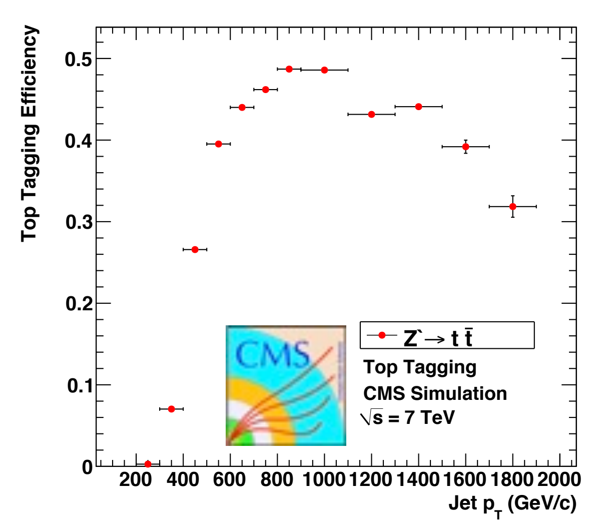
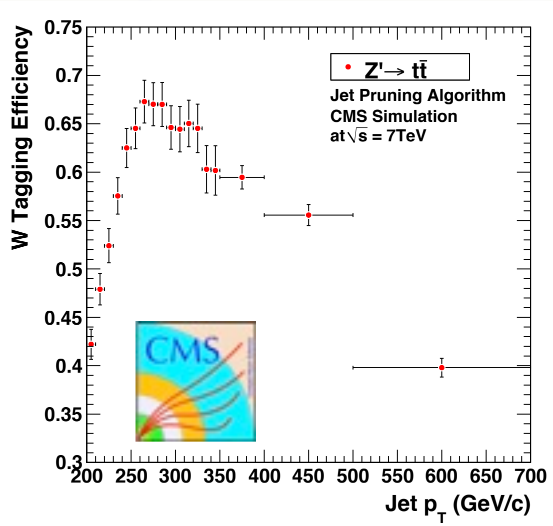
Boooooooooosted Top Searches

- New techniques in jet reconstruction and b-tagging
- E.g., Cambridge-Aachen Algorithm (CMS)









CMS PAS-EXO-11-006

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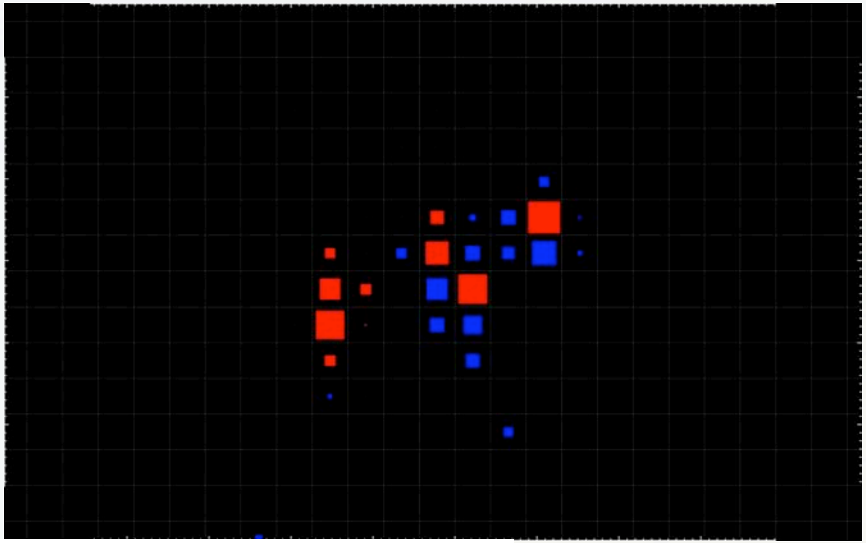

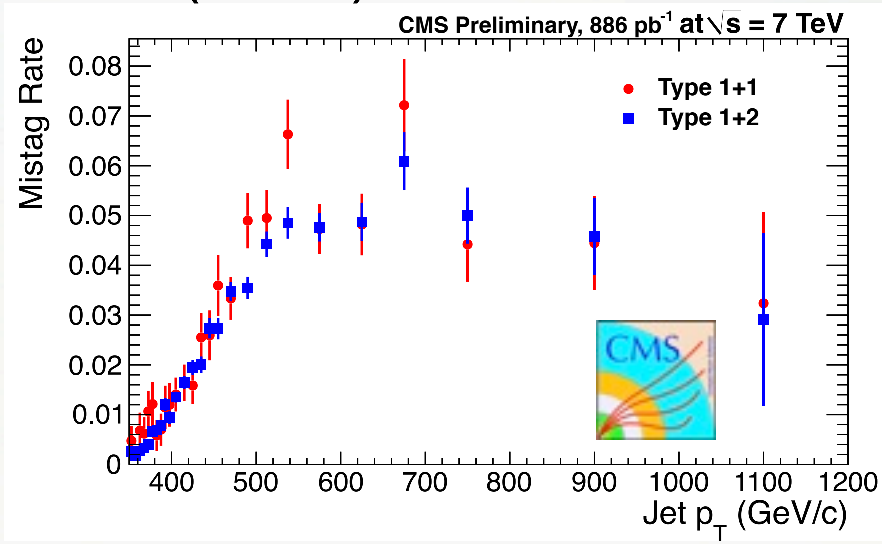

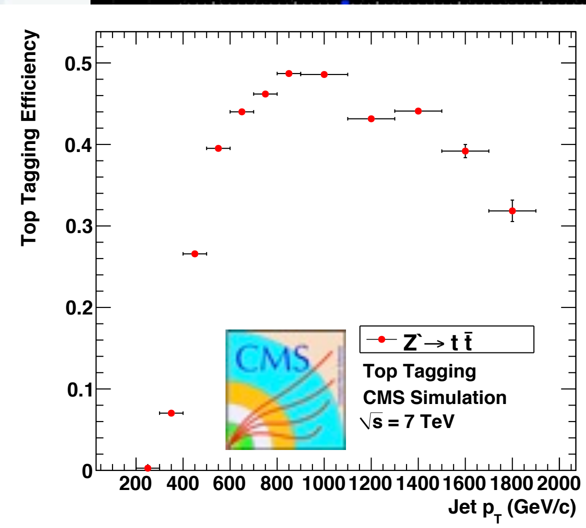

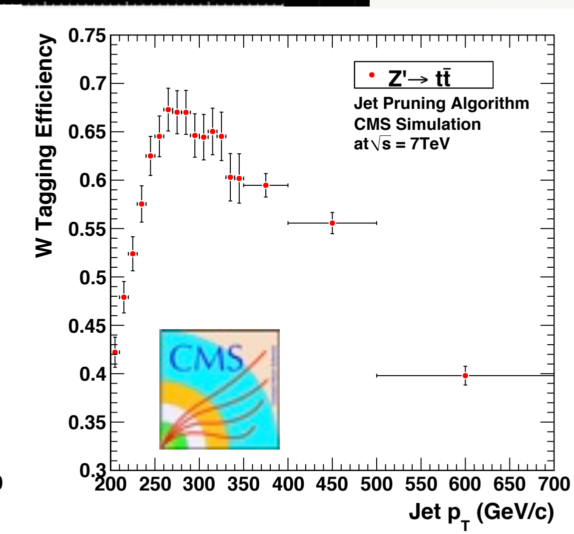

CMS PAS-EXO-11-006

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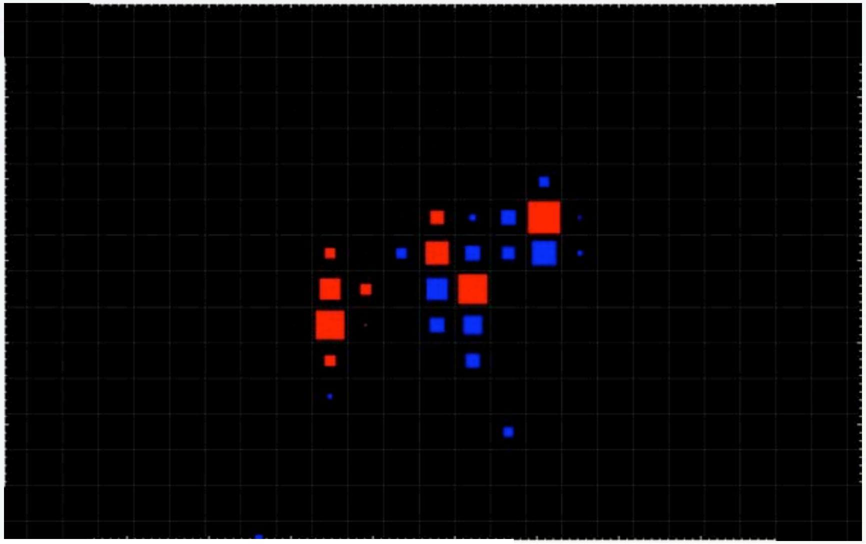

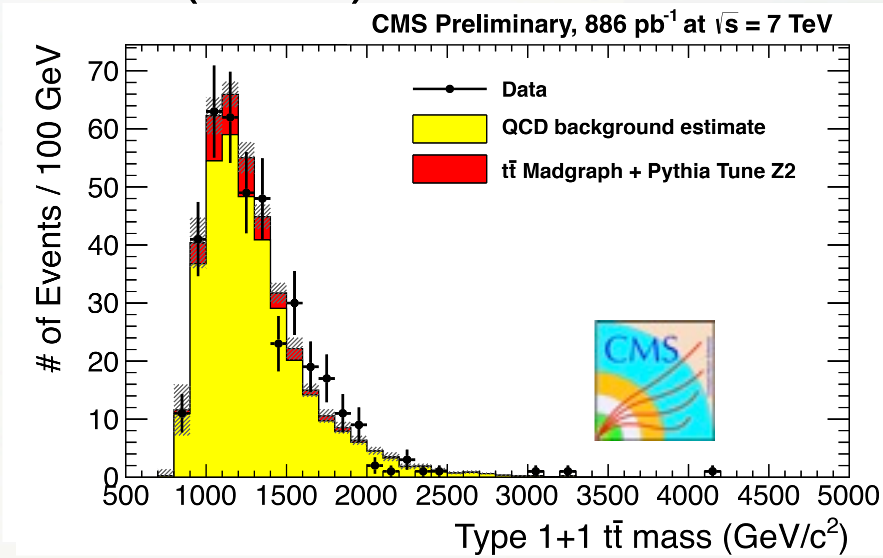

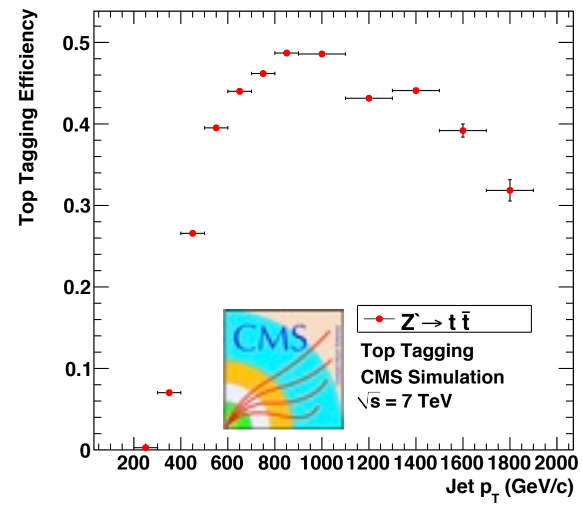

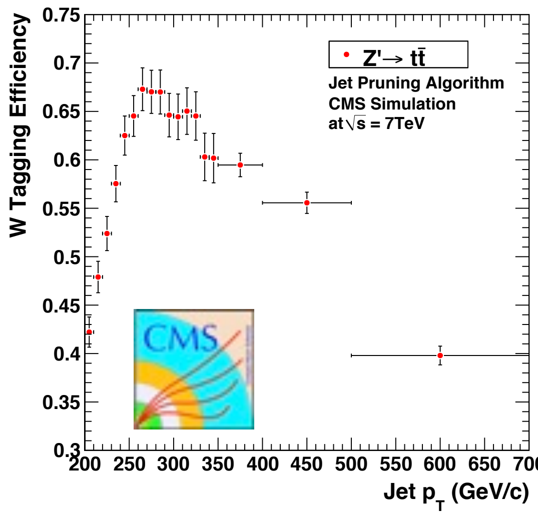

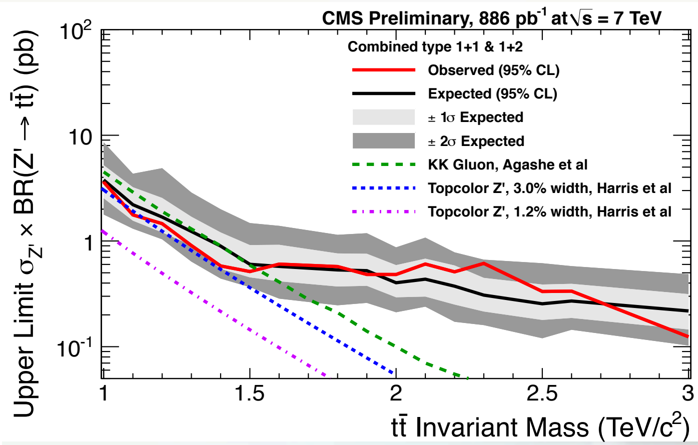

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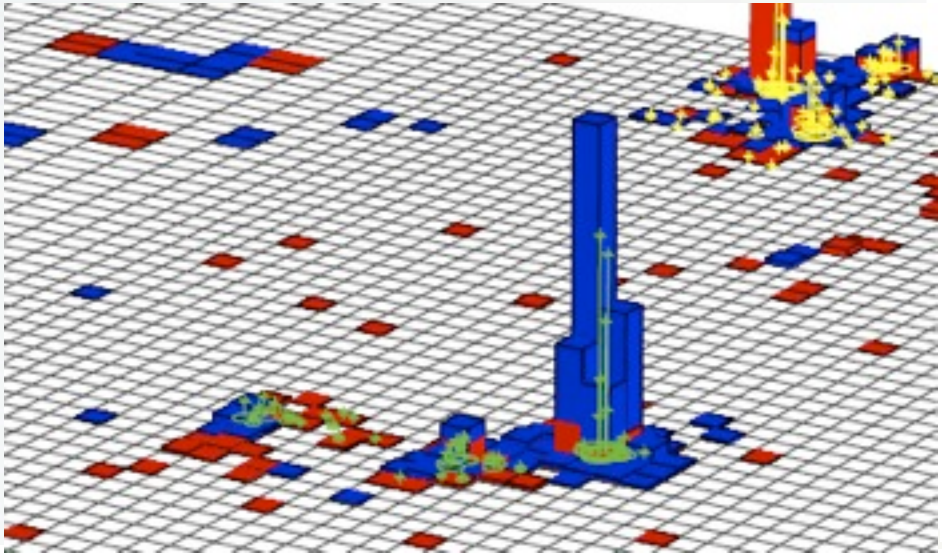

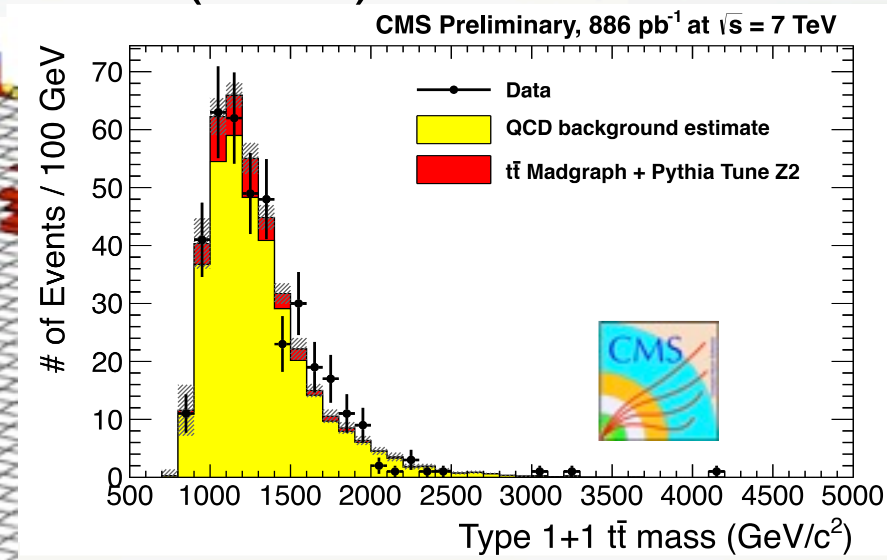

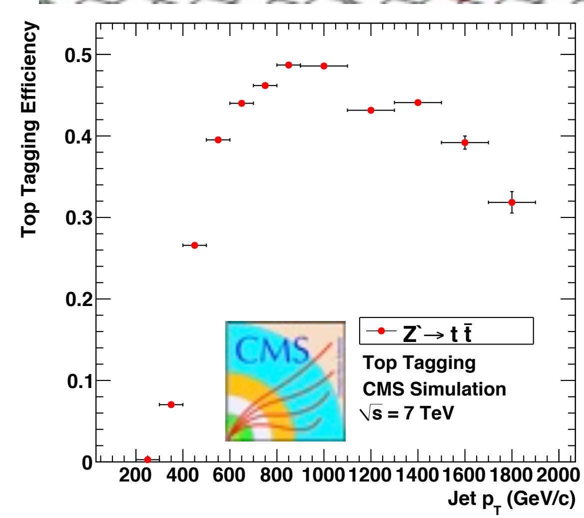

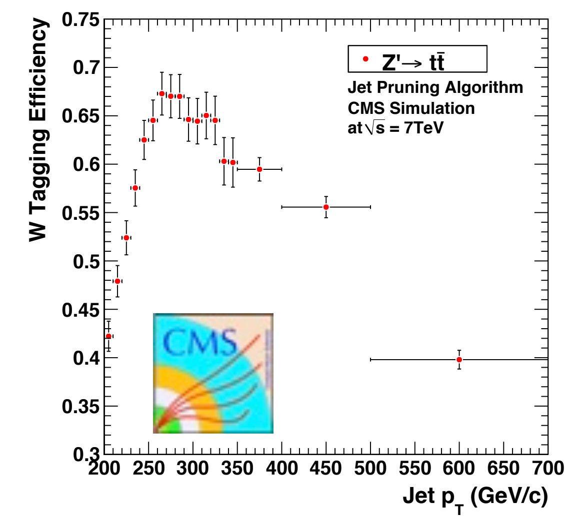

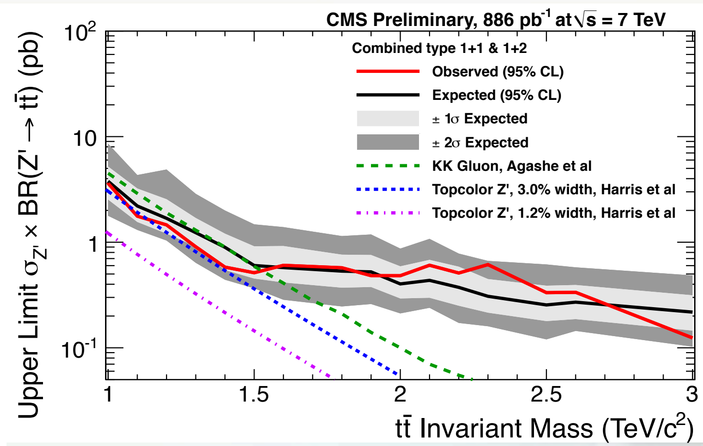

CMS PAS-EXO-11-006

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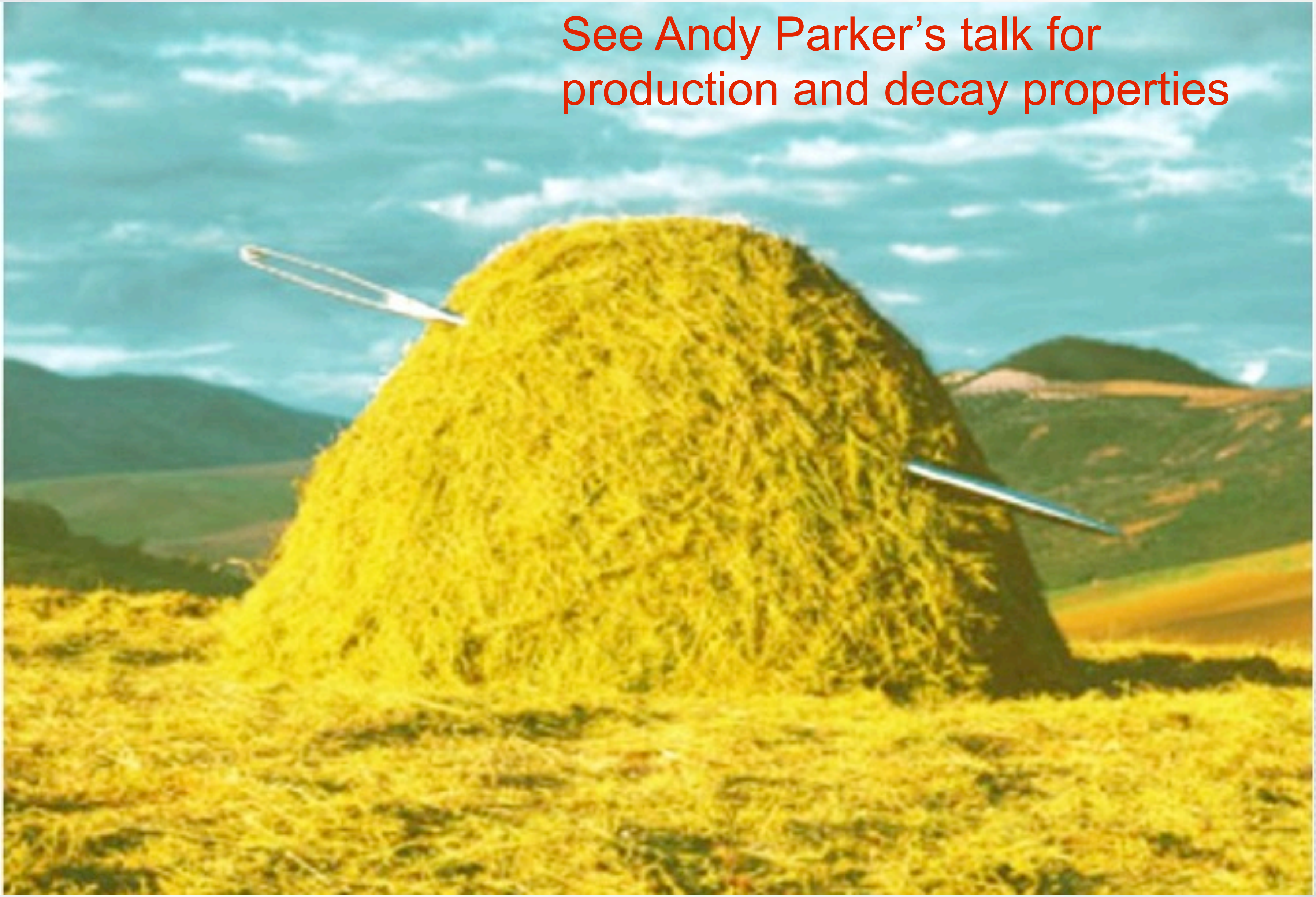
Black Holes at the LHC?

See Andy Parker's talk for production and decay properties



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
  - Meade/Randall [arXiv:0708.3017] used a different characteristic scale: $\overline{M}_{\rm Pl} e^{-k\pi r}$, which results in a more conservative cross section estimate

RS to ADD Mapping

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

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

- The Schwarzschild radius: $R_S = \frac{1}{\pi M e^{-k\pi R_C}} \sqrt{\frac{M_{BH}}{3 M e^{-k\pi R_C}}}$

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

  where $\tilde{k} \equiv k / \overline{M}_{Pl}$

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

- 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)

String Balls at the LHC

- Dimopoulos/Emparan, hep-ph/0108060 – 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:

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

  into a similar democratic mix of particles, with perhaps a larger bulk component

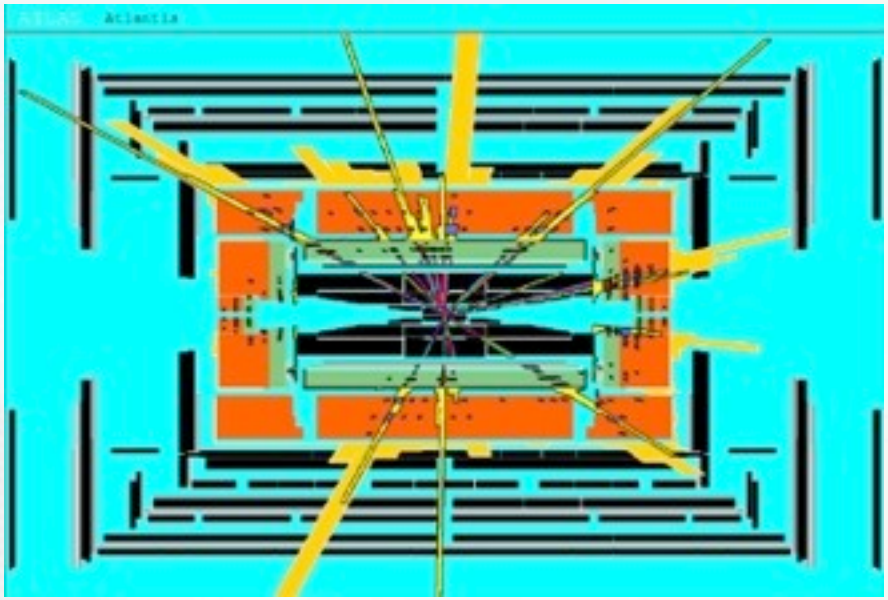
- Cross section of the string ball production is numerically similar to that of BH, due to the absence of a small coupling parameter:

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

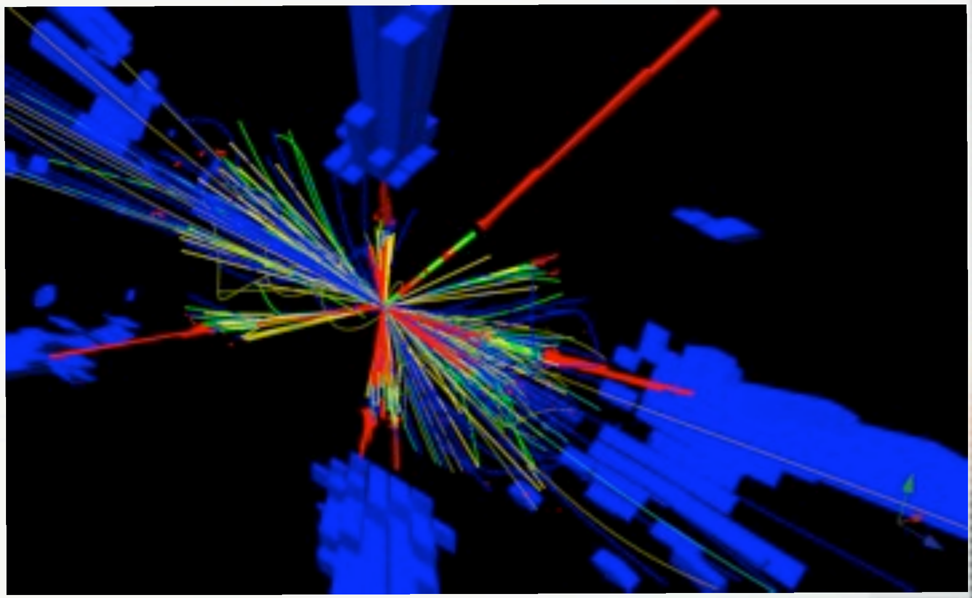
- It might be possible to distinguish between the two cases by looking at the missing energy in the events, as well as at the production cross section dependence on the total mass of the object
- Very interesting idea; more studies of that kind to come!

Black Hole Event Simulation

- Advanced Monte Carlo generators are available: CHARYBDIS2 (HERWIG-based generator with an elaborated decay model by Harris/Richardson/Webber); CATFISH (Cavaglia); BLACKMAX (Dai et al.); QBH (Gingrich)



Simulated black hole event in the ATLAS detector



Simulated black hole event in the CMS detector

Black Holes in CMS

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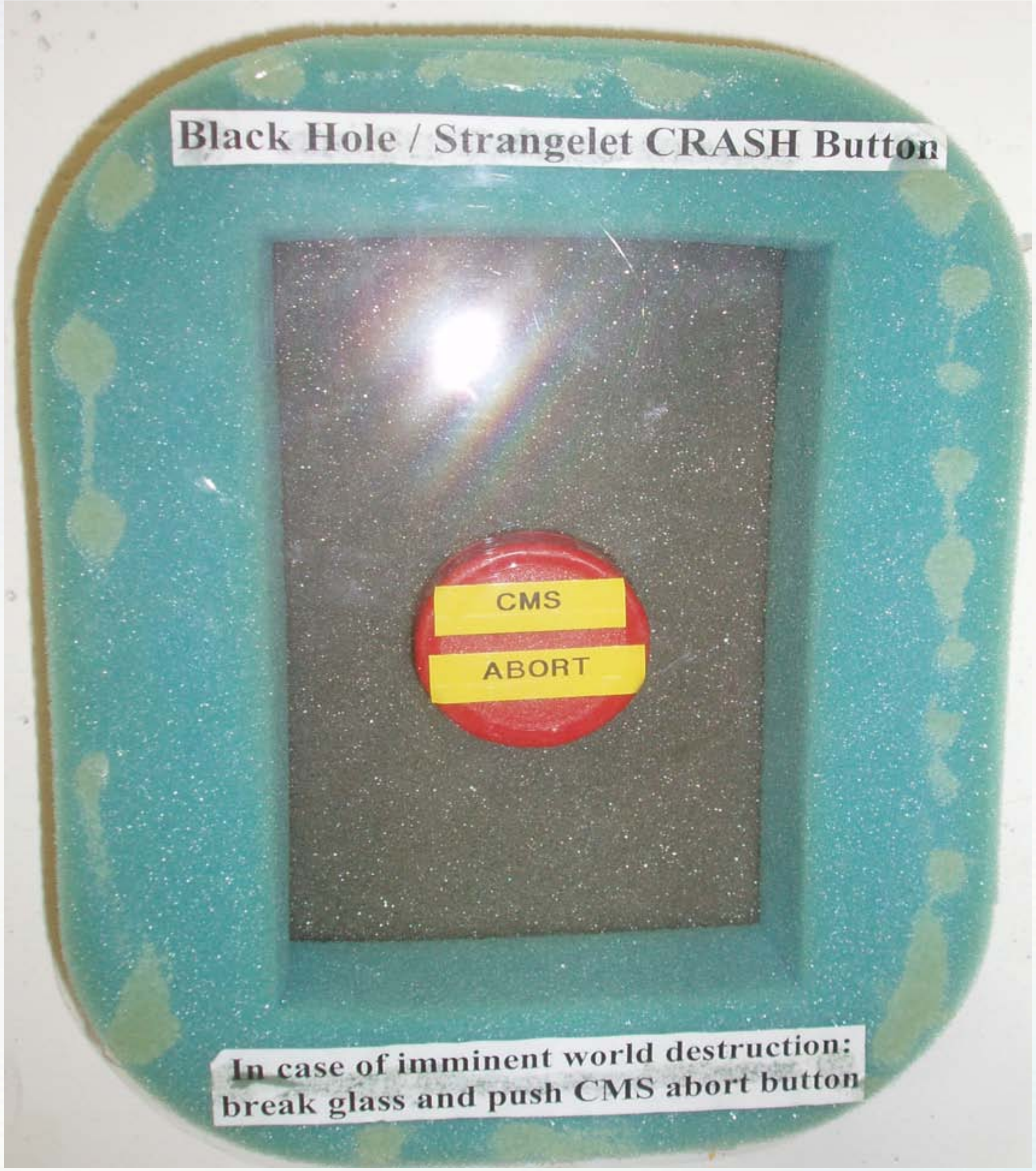
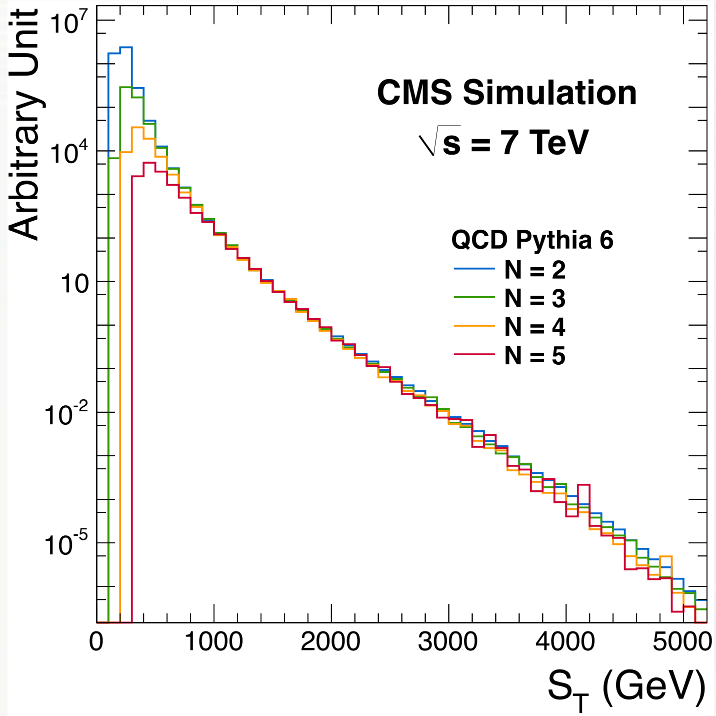


Search for Black Holes in CMS

- First dedicated collider search based on the 2010 data published earlier this year [Phys. Lett. **B697** (2011) 434]
- Based on $S_T = \Sigma E_T$, where the sum is over all the objects with $E_T > 50$ GeV, including ME_T - very robust against the fine details of evaporation
- Completely data-driven QCD background determination using a novel technique: S_T-invariance of the final state multiplicity
- Empirically found and tested with various MC generators (PYTHIA, ALPGEN) up to high jet multiplicity
  - Came as an initial surprise to all the theorists we mentioned it to - now trying to explain it from basic QCD principles!
  - Note that one naively would expect such scaling for the invariant mass, which is simply the sum of total energy in the detector
    - Does work as well: object minimum E_T thresholds, pile-up!



Also see Andy Parker's talk

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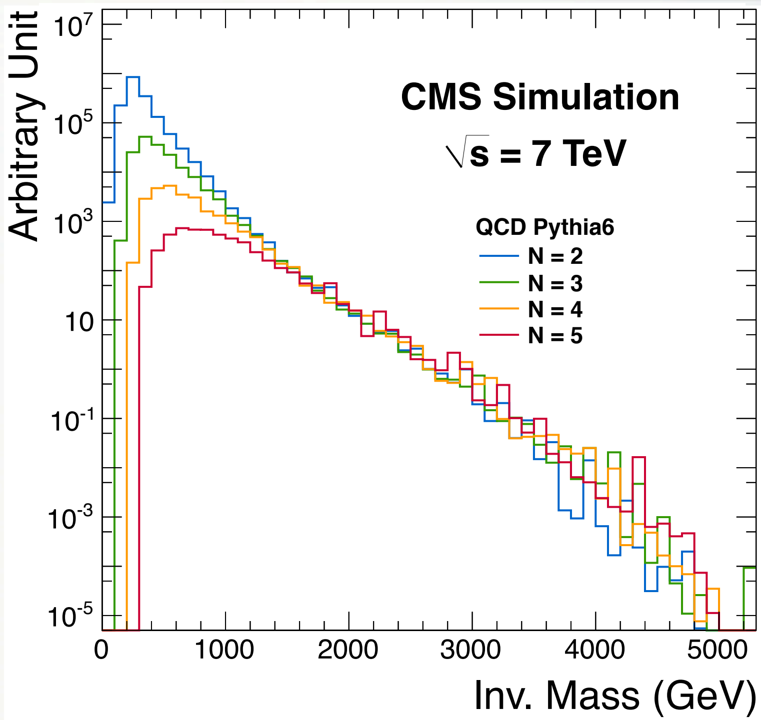

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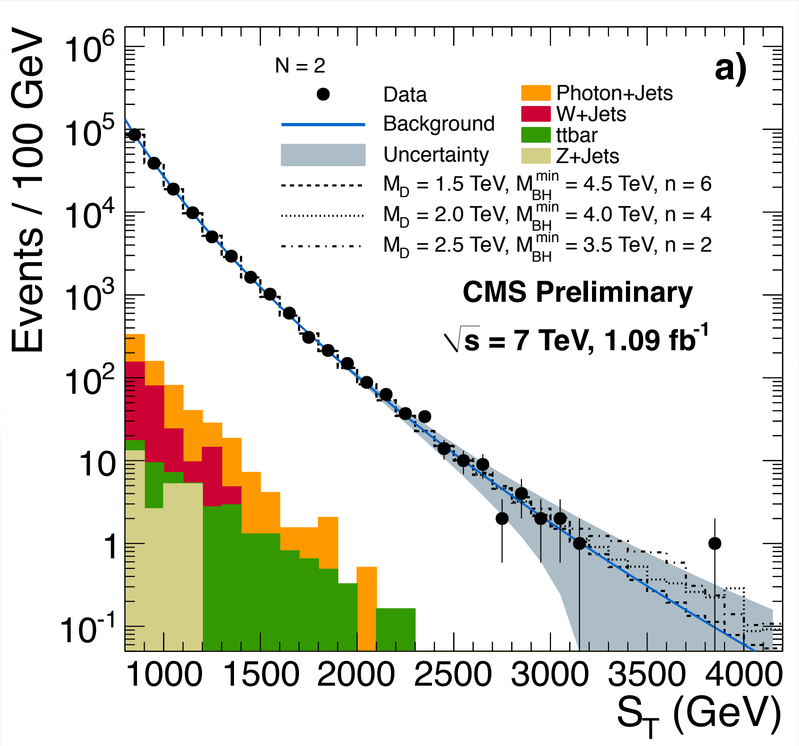
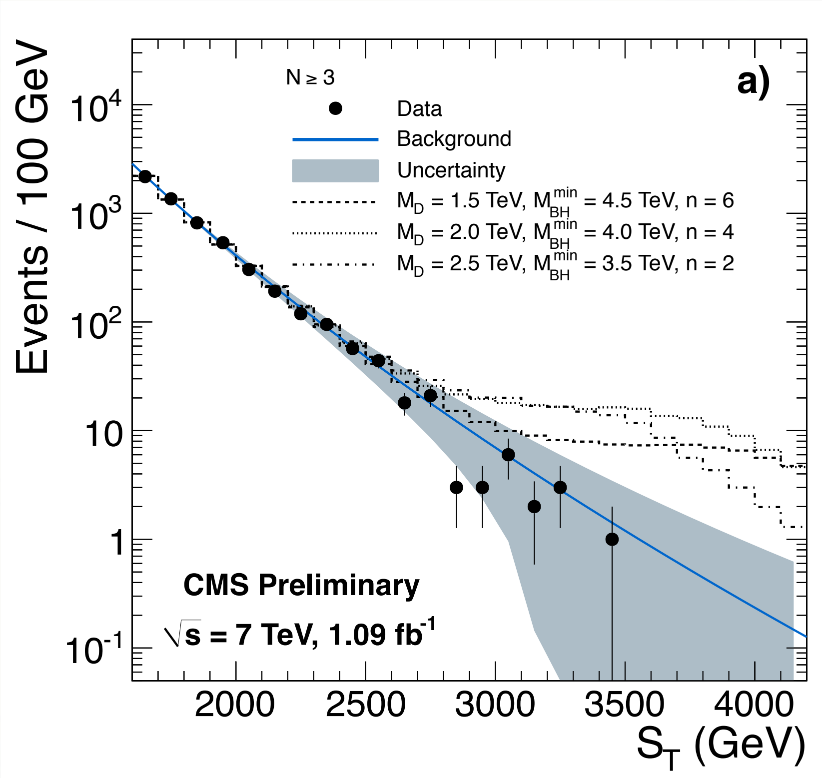
New Analysis with 2011 Data (1/fb)

- Established the empirical scaling with the data, using exclusive N = 2 and 3 multiplicities
- Assign shape uncertainty due to fit parameter variation and template function choice





CMS PAS EXO-11-071

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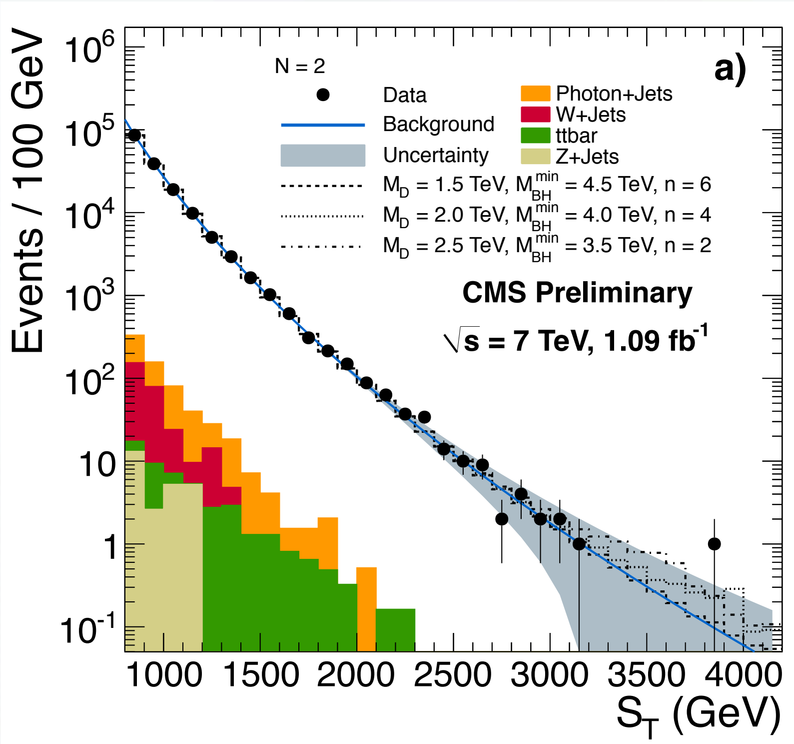
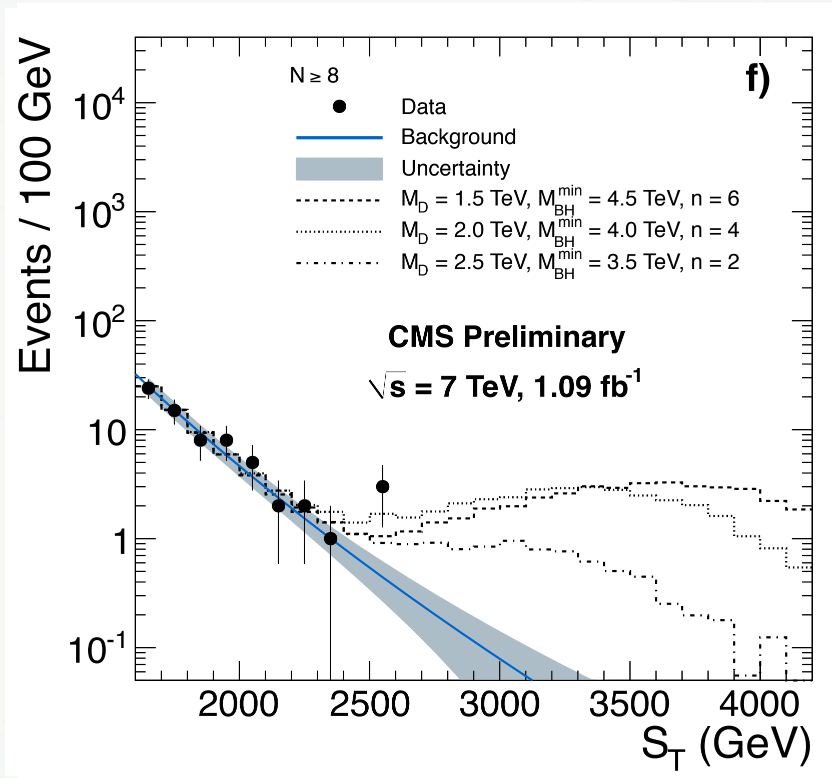
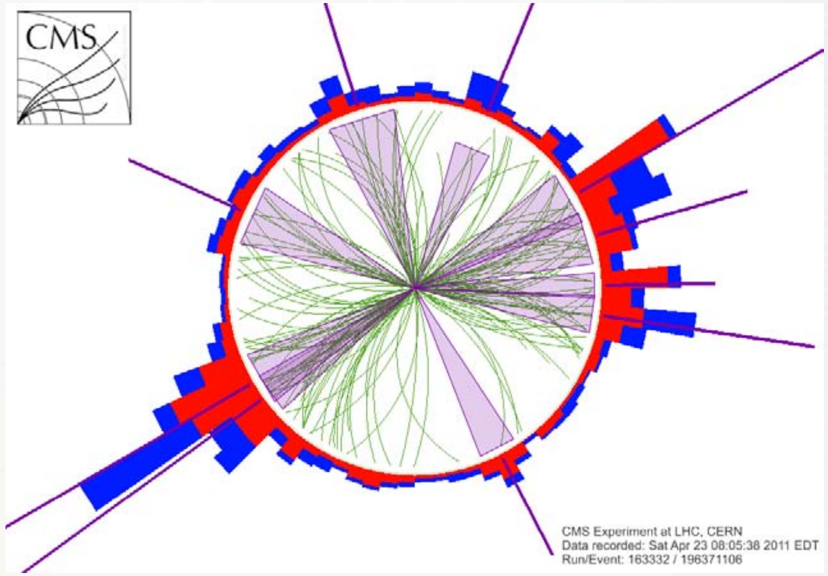


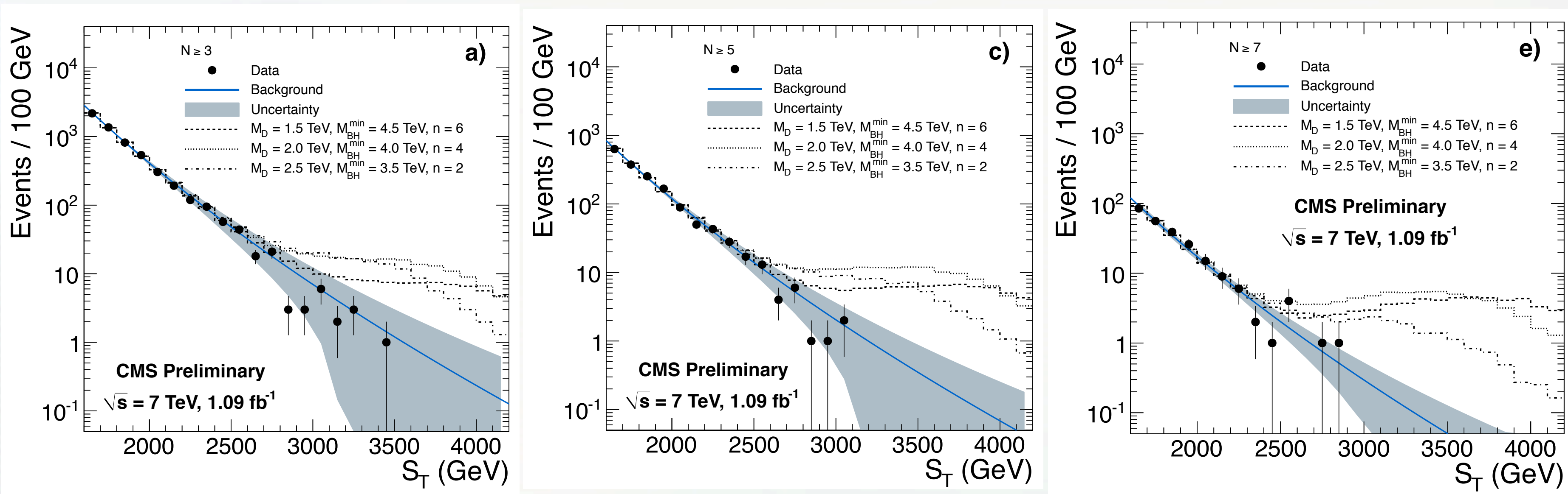


CMS PAS EXO-11-071

Limits on Black Holes

- Used the N=2 shape with its uncertainties, to fit higher multiplicities, where the signal is expected to be most prominent
- Given no excess, set limits on the minimum BH mass
- Despite lack of excess, see some truly spectacular events!





Sunday, September 4, 11

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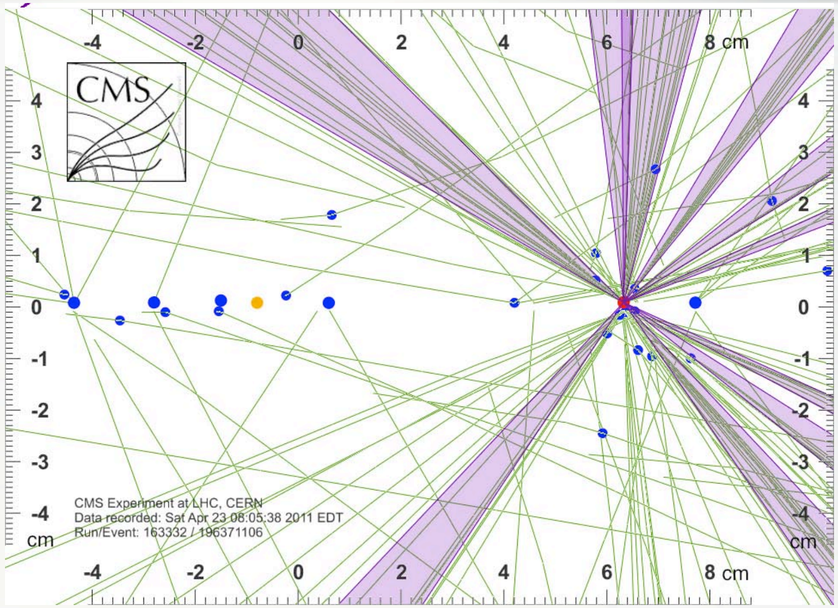
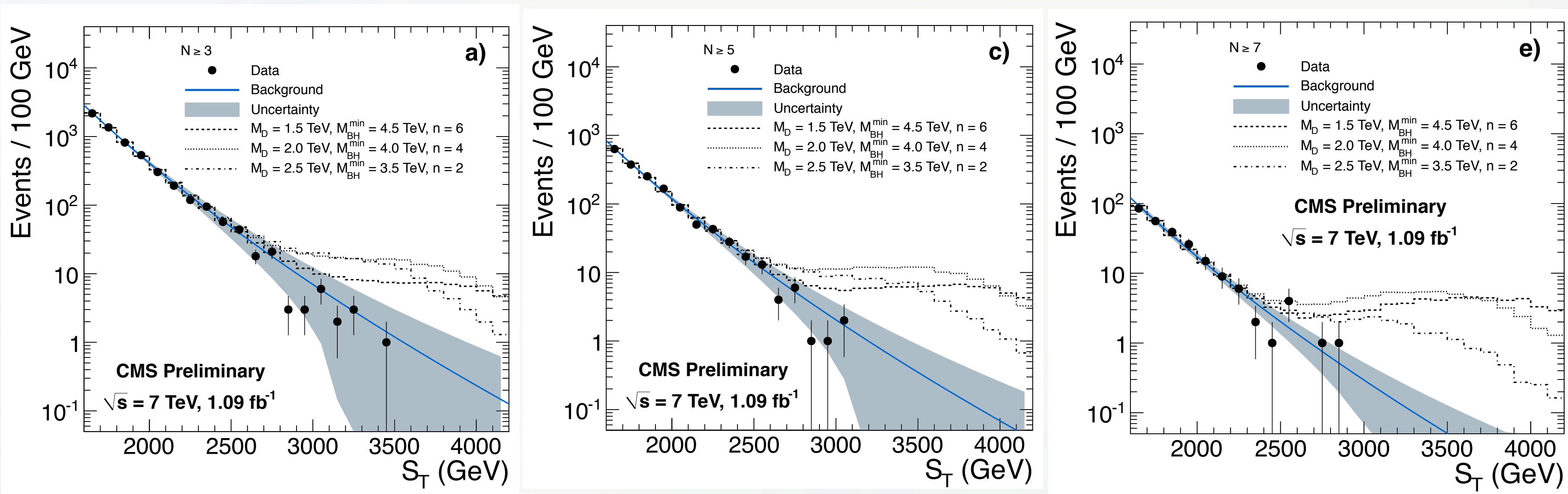
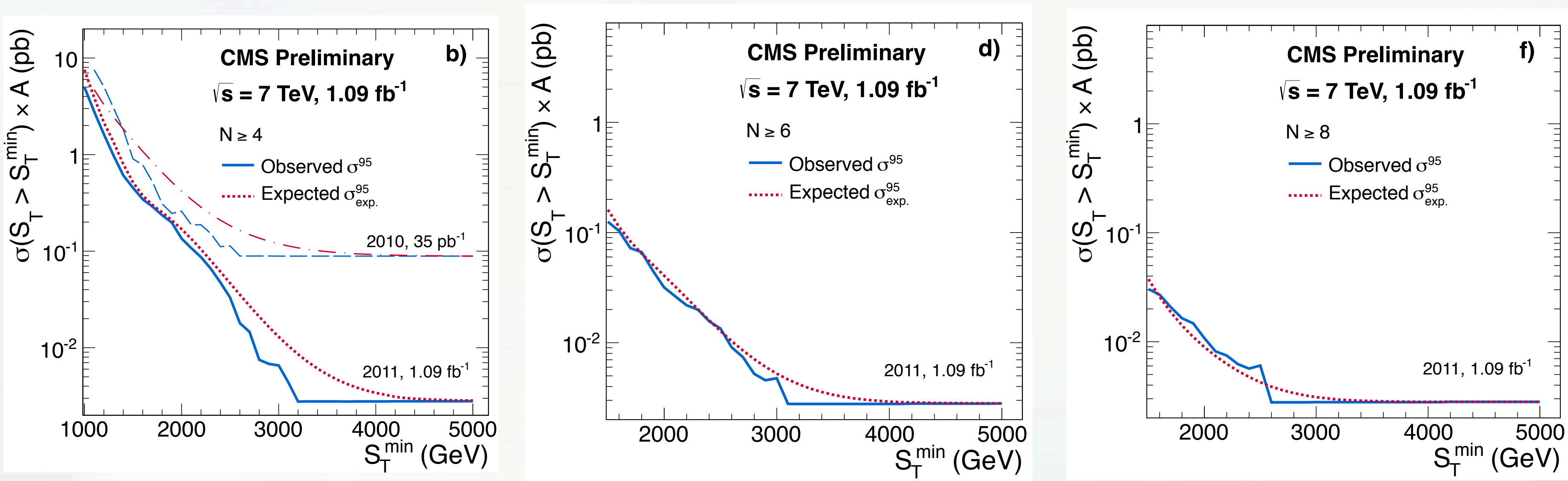




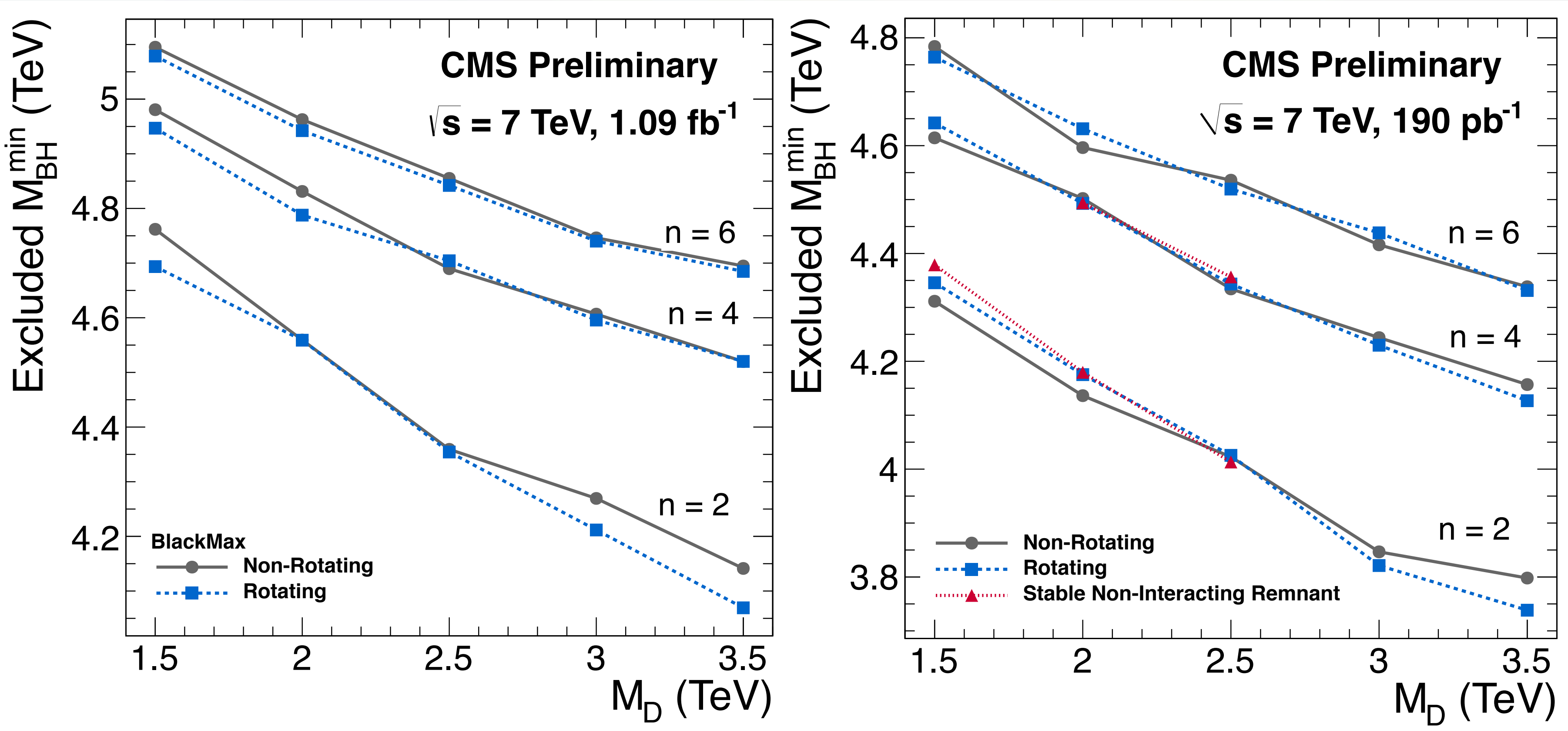
Model-Independent Limits

- First, set generic model-independent limits on new physics decaying to high-mass, high-multiplicity final states, with $S_T > S_T^{min}$
- These limits, as a function of S_T^{min} are in a 1 fb range and can be used to probe generic black hole models, including trapped surface losses, bulk radiation, etc.
- They are also useful for other models of new physics, e.g. heavy resonances decaying into multijet states



Semi-Classical Limits

- Not very useful at these relatively low masses, but give one an idea on the typical mass reach
- Important point is low sensitivity on the parameters of the production and decay model, such as remnant, rotation, etc.



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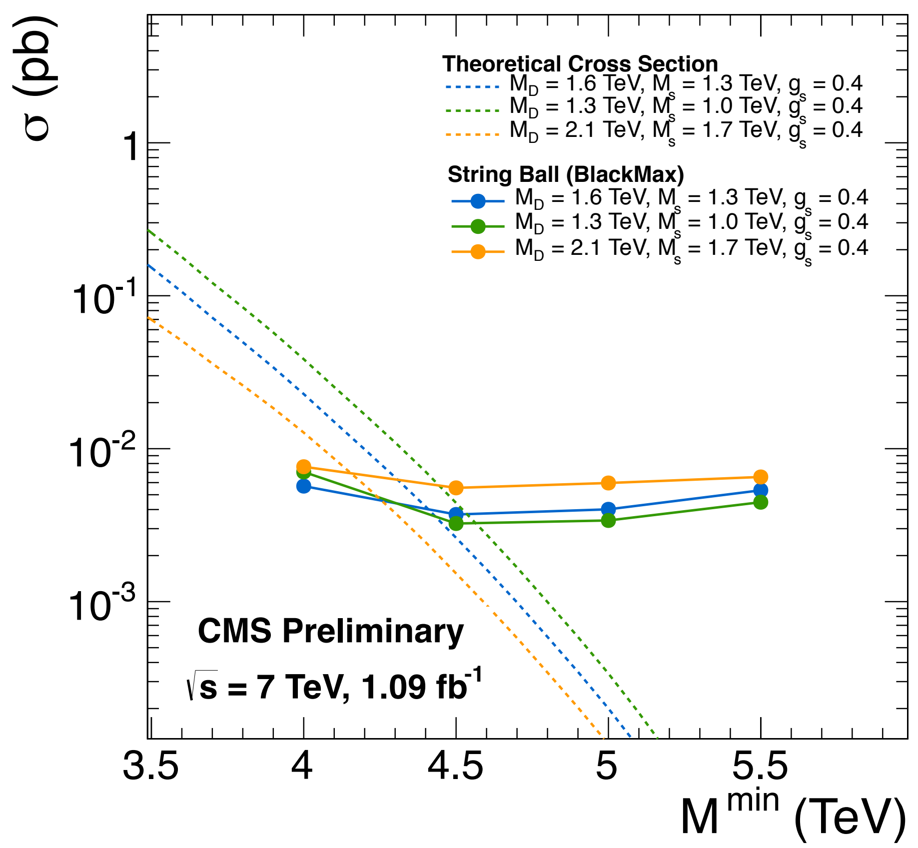
String Balls Limits

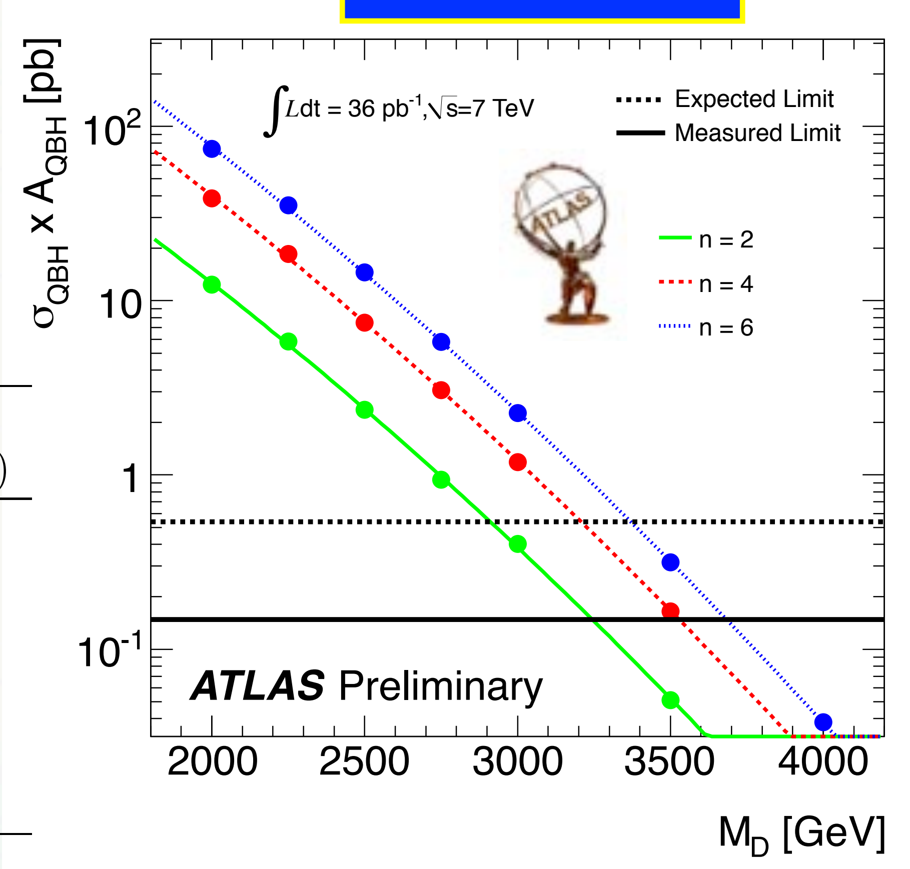
- An attempt to see the sensitivity of our results to quantum effects is to interpret our limits in terms of string balls - quantum precursors of black holes
- First limits on string balls from a collider experiment



ATLAS Search for Quantum BH

- Decay very fast, possibly before thermalization
- Dominant decay mode: 2 jets (Meade-Randall model)
- Search for bumps in the dijet mass spectrum and an excess of central events using dijet angular distribution
- See Vicki Moeller's talk for other channels

arXiv:1103.3864



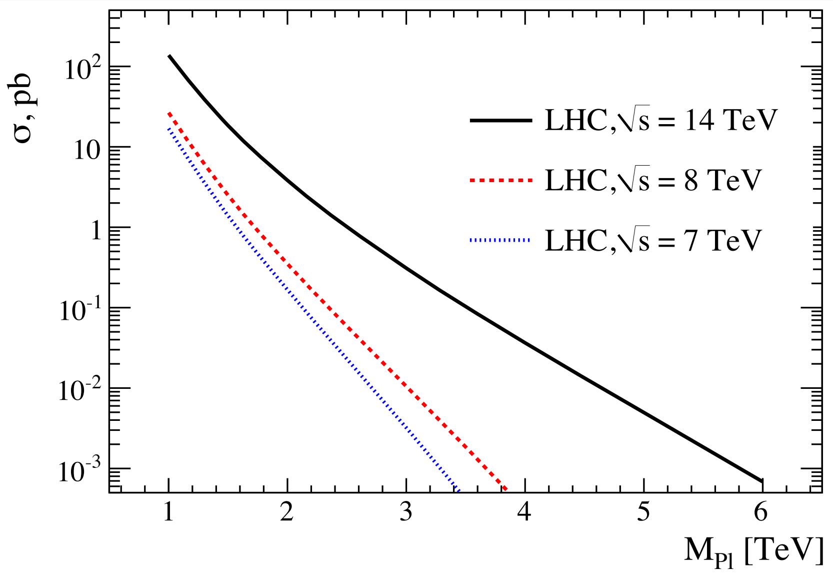
n Extra Dimensions	Expected Limit (TeV)	Observed Limit (TeV)
2	2.91	3.26
3	3.08	3.41
4	3.20	3.53
5	3.29	3.62
6	3.37	3.69
7	3.43	3.75

QBH and Vanishing Dimensions

- In some models, the space-time may be lower-dimensional at short distances, perhaps just 1+1-dimensional
- In this case, the black hole cross section is given by [Calmet/GL, arXiv:1008.3390]:

$$\sigma_{QBH} = \frac{1}{16\pi \bar{M}_P^2} \theta(\sqrt{\hat{s}} - \bar{M}_P).$$

- This is large cross section and the LHC will be able to probe this case as well



Kerr Black Holes

- Black holes produced in particle collisions generally have a non-zero angular momentum:

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

- While L is small for $M_{BH} = M_{Pl}$, it grows with M_{BH} and can reach ~10 (in the units of $\hbar$), which is non-negligible
- Such a spinning black hole is described by the Kerr solution and has an enhanced emission of gravitons (super-radiance)
- Unfortunately, the grey-body factor for spin-2 particles for the case of Kerr black hole in d > 3 dimensions has not been calculated, so it's hard to quantify the effect
- This is important for collider searches, as gravitons result in large missing transverse energy and reduced observable energy in the detector

Where We Stand?

- We haven't seen any signs of TeV-scale gravity yet
  - The LHC became the key player in this field in the just past 9 months
- The fantastic machine and detector performance allowed us to probe TeV-scale Planck scale up to ~3-4 TeV thus significantly extending previous limits
- We have excluded various classes of black holes and their precursors with masses less than ~4-5 TeV
- There is little chance left that we can see quantum gravity effects at the 7 TeV machine
  - This chapter has been simply closed in the last few months!
- The 14 TeV LHC upgrade and new high-energy run of ~2015 would allow to probe significantly higher scales and ultimately decide if TeV-scale gravity can be a solution to the hierarchy problem
- However given the existing constraints, it is clear that if we produce black-hole-like objects at 14 TeV, they will be highly non-classical
- Possible description of these objects is where the theoretical effort should be focused in order to lead us in the new chapter on this

Thank You!