Searches for Extra Dimensions with the ATLAS Detector at the LHC

Outline

- Introduction
- Large Extra Dimensions
- Warped Extra Dimensions
- TeV^{-1} Extra Dimensions
- Universal Extra Dimensions
- Mini Black Holes

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GDR Terascale Workshop
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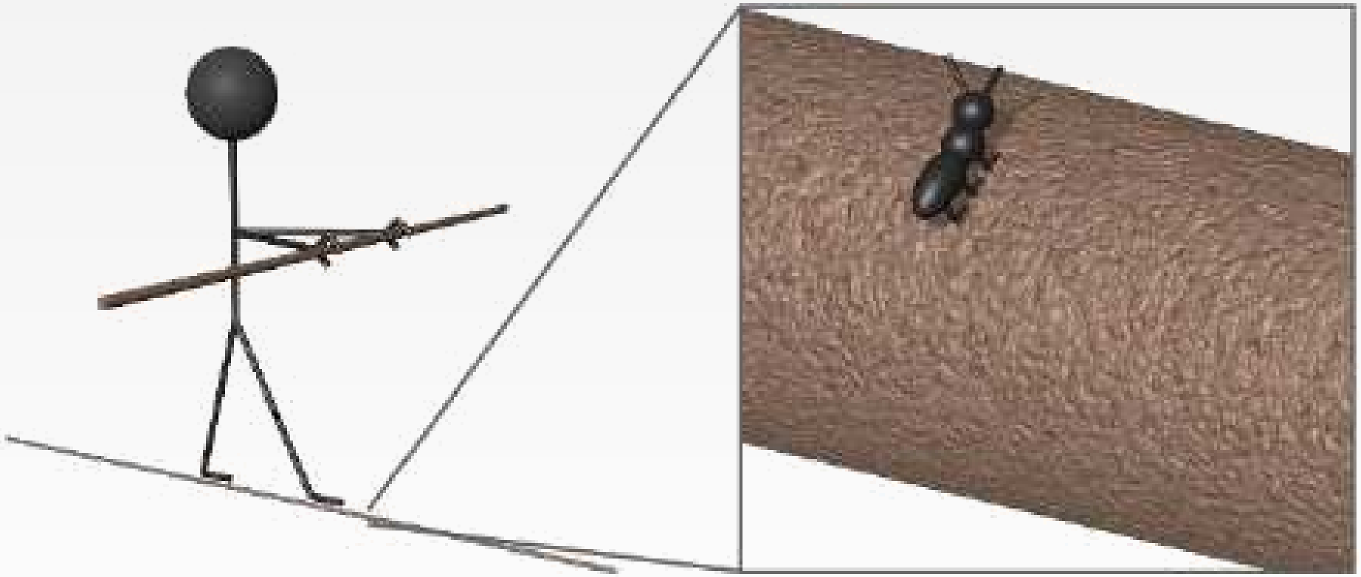
Compactified Extra Dimensions

Hierarchy problem: $M_{EW} \sim 100\,\text{GeV}$ $\quad M_{Pl} = \sqrt{\frac{\hbar c}{G}} \sim 10^{19}\,\text{GeV}$

Compactified Extra Dimensions can provide a solution



Planck scale can be close to EW scale $\sim$ 1TeV

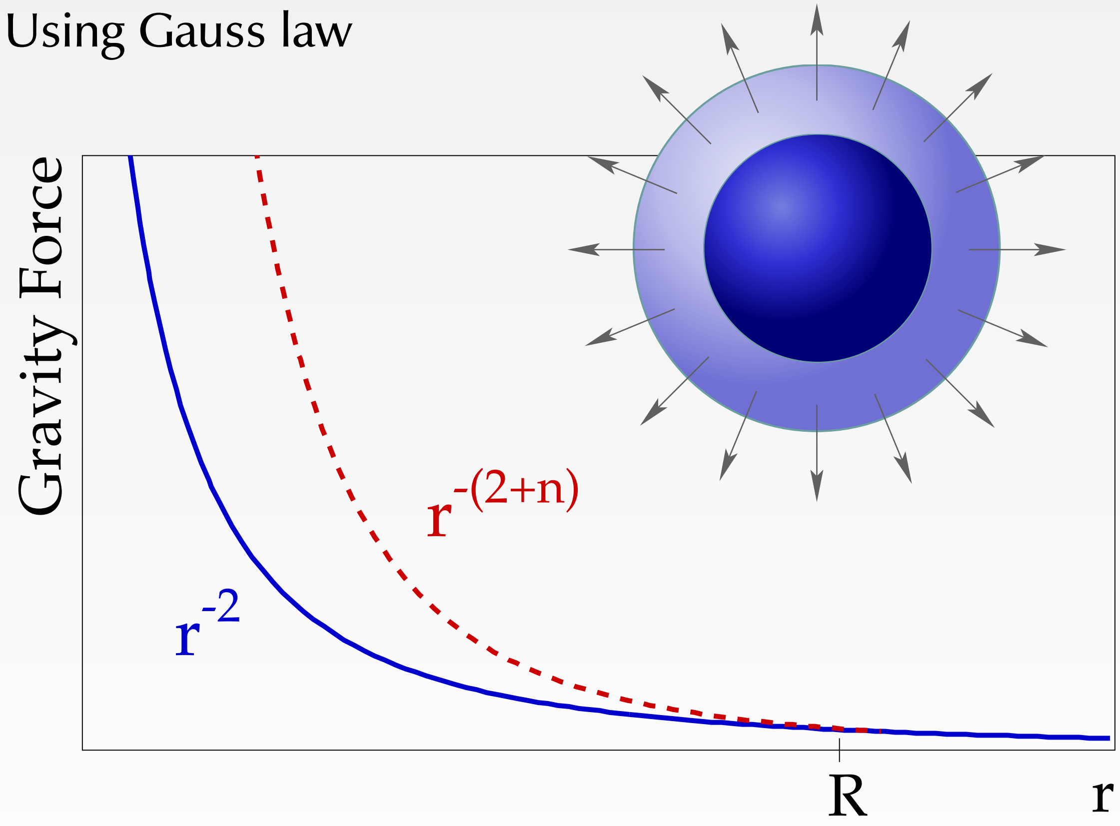
Large Extra Dimensions

ADD approach Antoniadis, Arkani-Hamed, Dimopoulos, Dvali: hep-ph/9803315, 9804398, 9807344

There are n compactified extra dimensions of same size R

Only gravity can propagate in extra dimensions

Using Gauss law



$$F \propto \frac{G}{r^2} \longrightarrow F \propto \frac{G'}{r^{2+n}}$$

For $r \gg R$: $F \propto \dfrac{G'}{r^2 R^n}$

For a smooth transition: $G' \sim G R^n$

$$M_{Pl} = \sqrt{\frac{\hbar c}{G}} \quad \Rightarrow \quad M_{Pl}^2 \sim M_D^{n+2} R^n$$

Large $R \iff$ Small M_D

Assume $M_D \sim 1$ TeV to solve hierarchy problem

How Large Can Extra Dimensions Be

$$R_C \sim \frac{1}{M_D}\left(\frac{M_{Pl}}{M_D}\right)^{\frac{2}{n}}$$

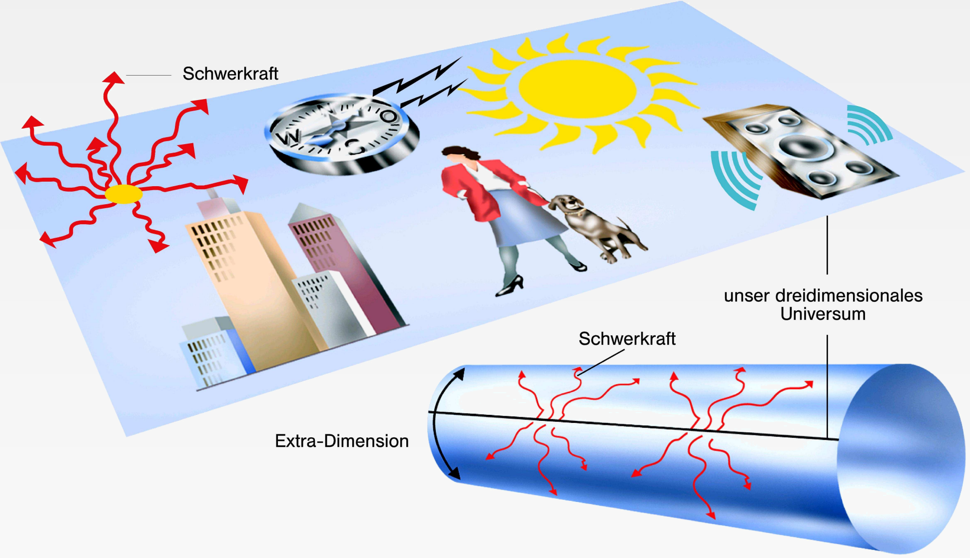
Size for $M_D = 1\,\text{TeV}$:

n	1	2	3	...	7
R_C	10^{10} km	1 mm	1 nm	...	1 fm

↑ $\mathcal{O}$(Solar system)

↖ ↑ ↗ “large”

compared to HEP scales



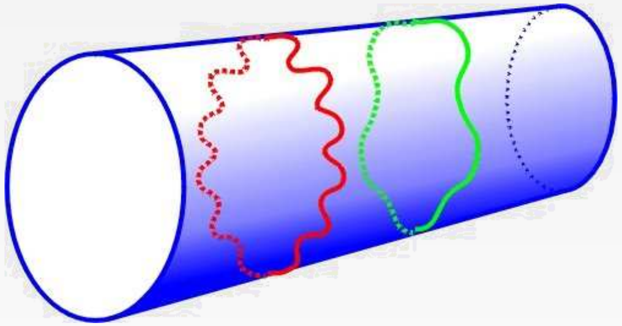
SM gauge fields cannot go to extra dimensions at such scales.
This is ruled out by HEP experiments. But gravity can.

Exp. limits for gravity law: $r \lesssim 50\,\mu\text{m}$ (hep-ph/0611184)

Kaluza–Klein Modes

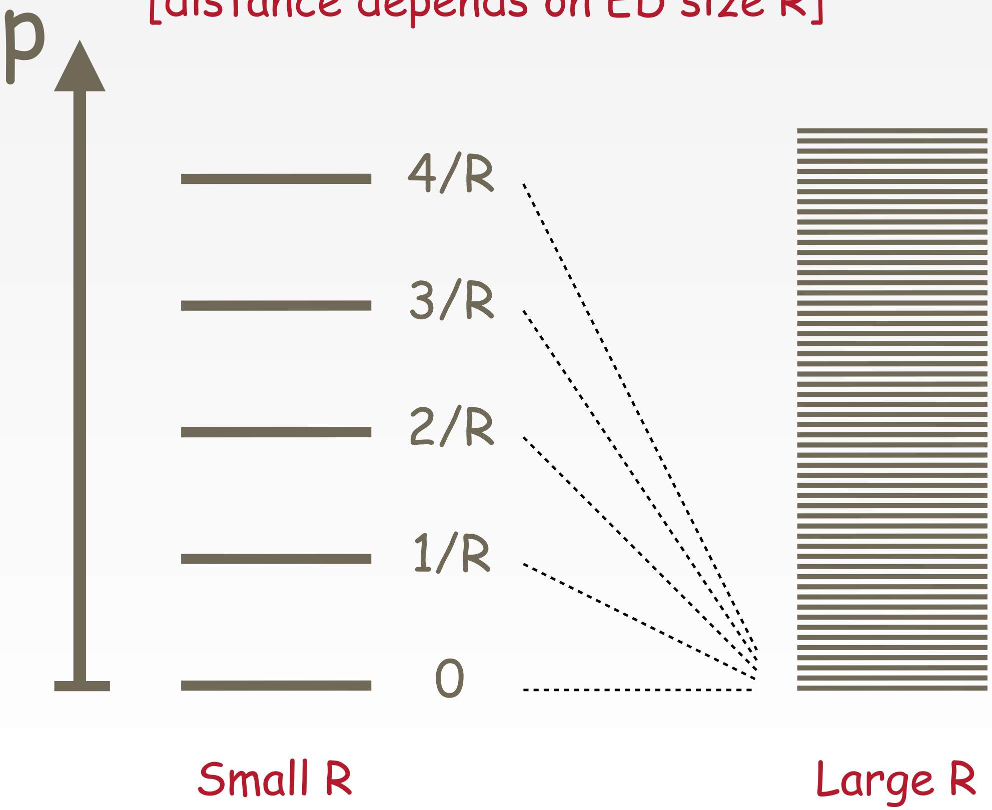
$$E^2 = p_x^2 + p_y^2 + p_z^2 + \underbrace{p_{\text{extra}}^2 + m^2}_{\substack{\text{extra mass states}\\ \text{in 4-dim. space-time}}}$$

- ♦ Winding modes



- ♦ Energy spacing $\sim 1/R_C$

KK-Towers
[distance depends on ED size R]

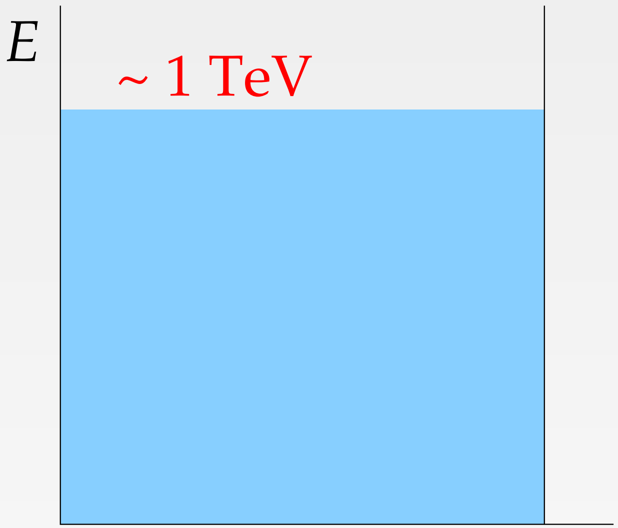


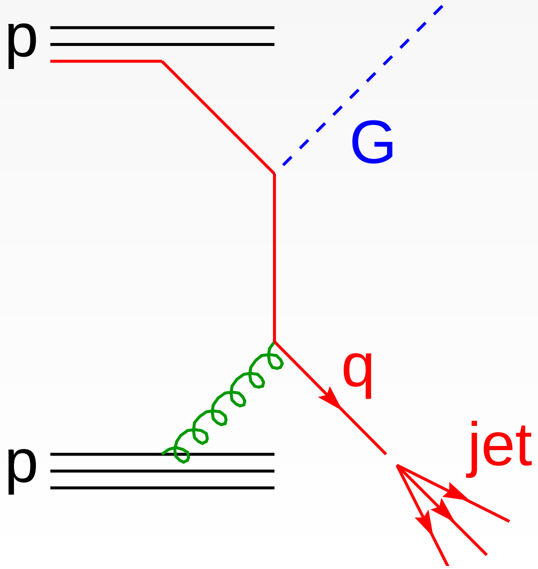
Kaluza–Klein Gravitons in ADD

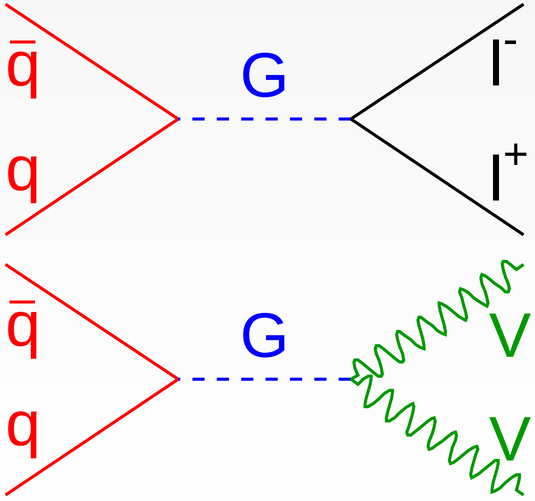
- Energy spacing $\sim 1/R_C \sim 1\,\text{meV} - 100\,\text{MeV}$ (large ED)
  Appear as continuous spectrum in experiment

- Coupling: G_N per mode;
  compensated by large number of modes

- Search for production of
  - real gravitons → monojets, monophotons
  - virtual gravitons → e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$

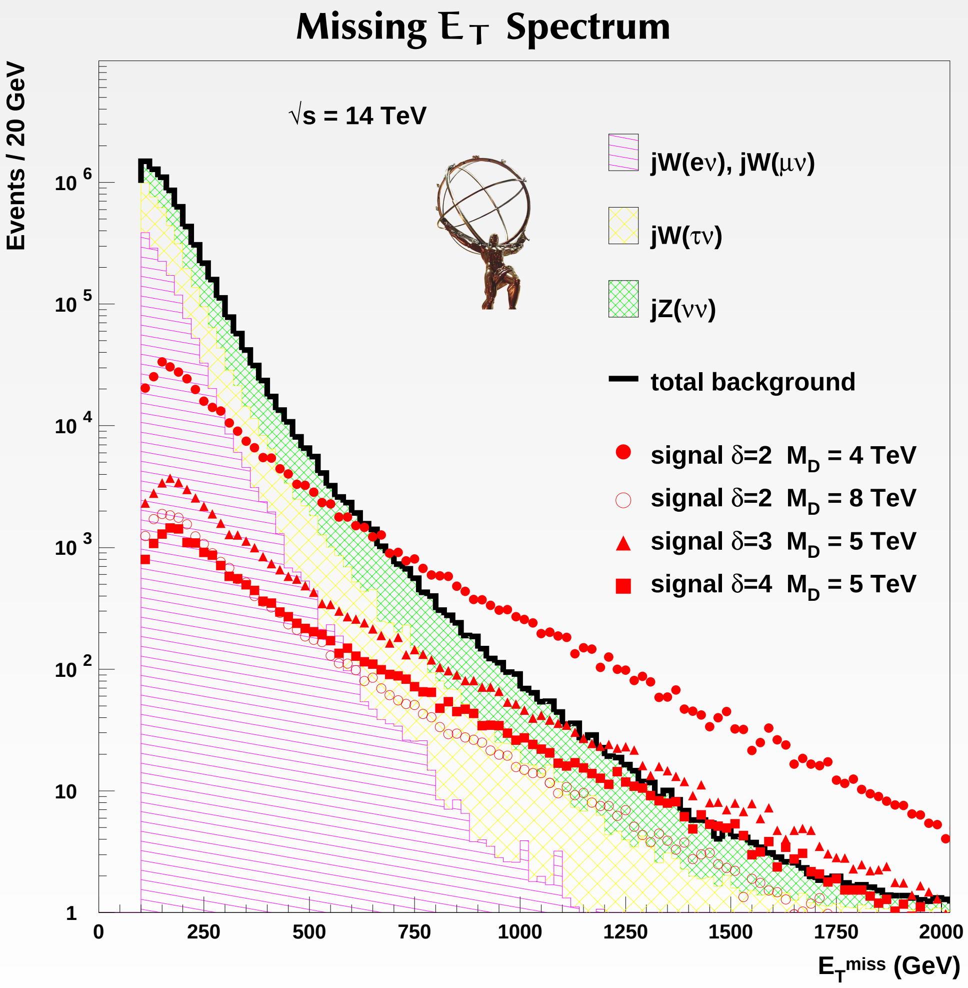






Monojets @ LHC

Vacavant, Hinchliffe: ATLAS-PHYS-2000-016, SN-ATLAS-2001-005



- ATLAS fast MC based studies

  5σ discovery sensitivity for 100 fb^{-1}:

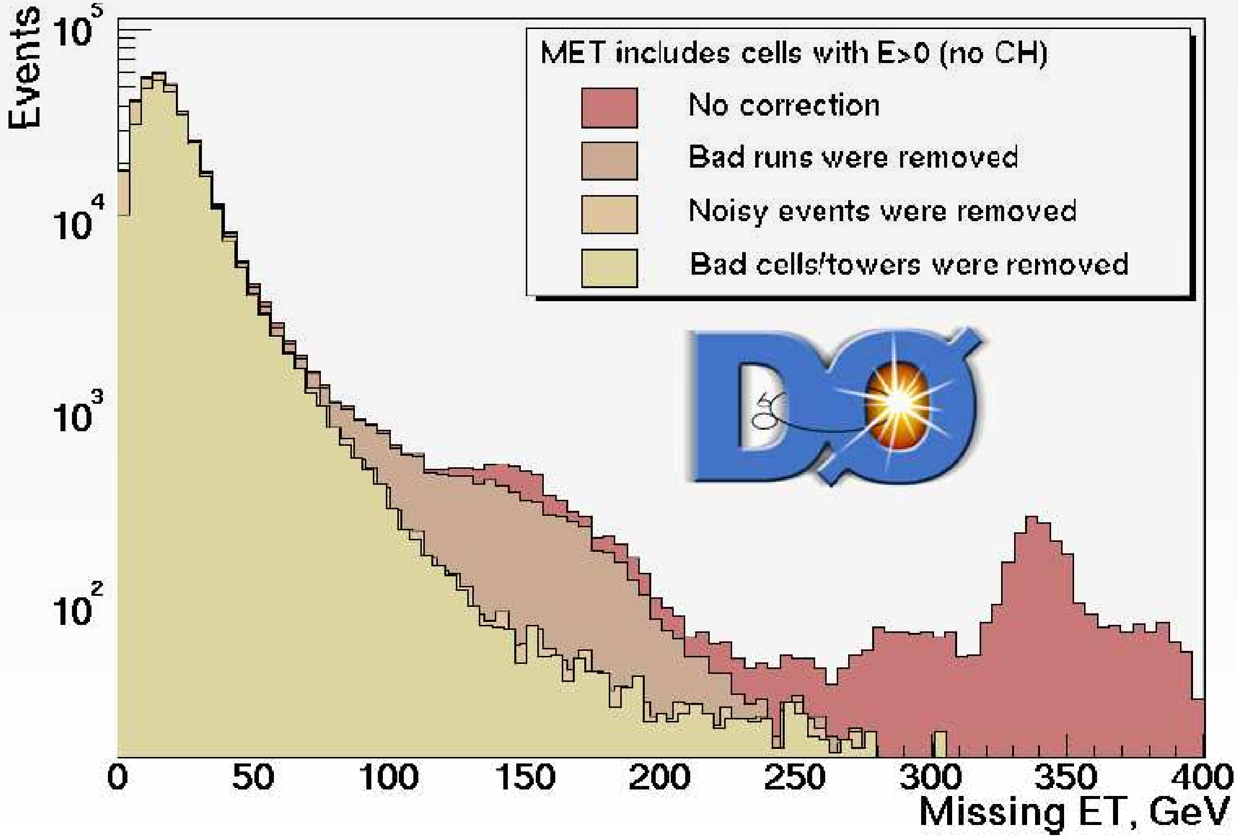
n	2	3	4
M_D / TeV	9	7	6

- No instrumentation effects included
- Study on full simulation confirmed the result for fully working detector

Monojets

Backgrounds

- Irreducible: Jet + $Z \to \nu\nu$
- Partially reducible: Jet + $W \to \nu e, \nu\mu, \nu\tau$ with lepton lost
- Instrumentation
  - QCD dijets with one jet lost in dead region
  - Beam induced signals
  - Calorimeter noise
  - Cosmics

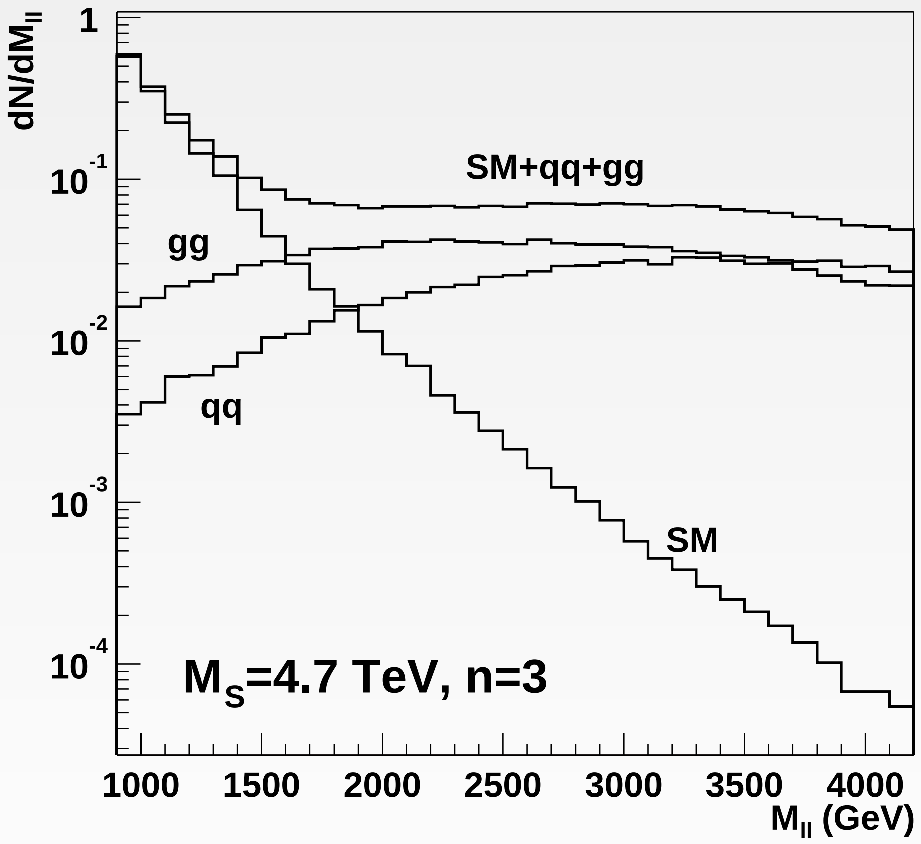


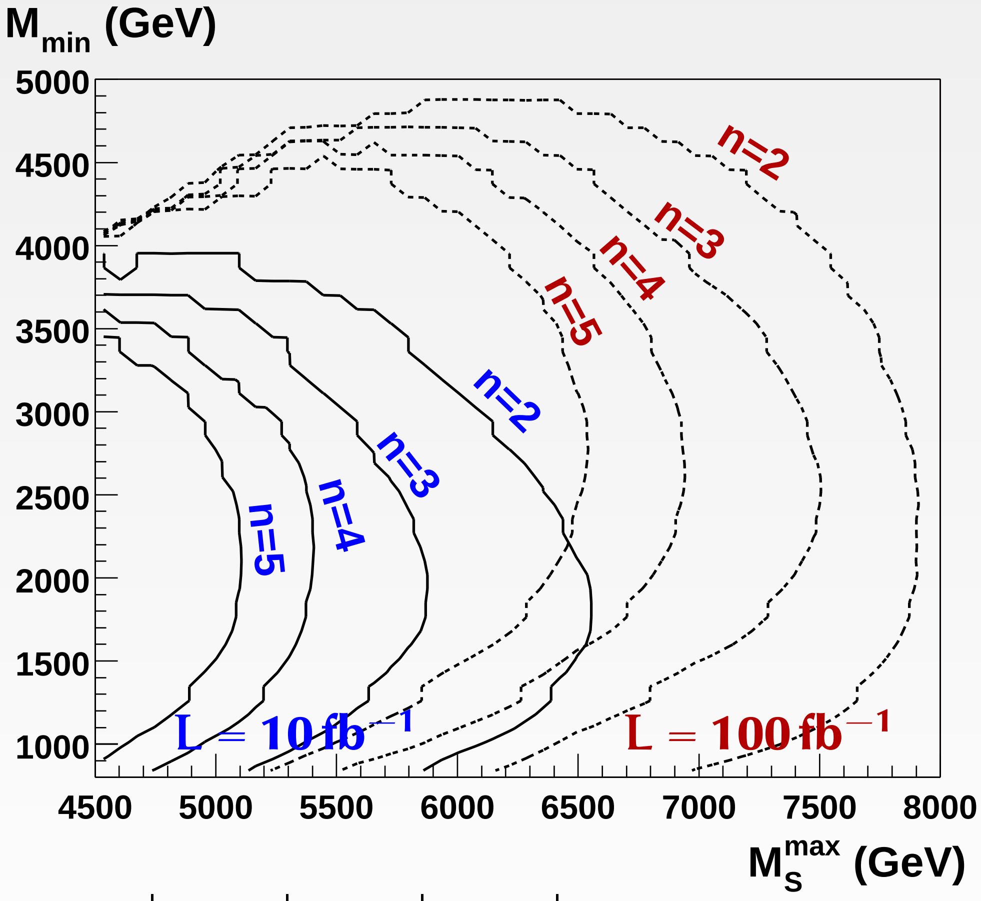
Can be very challenging

Virtual KK Graviton Exchange

Kabachenko, Miagkov, Zenin: ATLAS-PHYS-2001-012,

Example: G → ll (ATLFAST)





Combined reach in $\gamma\gamma + ll$ for M_D / TeV:

$n =$	2	3	4	5
10 fb^{-1}	7.0	6.3	5.7	5.4
100 fb^{-1}	8.1	7.9	7.4	7.0

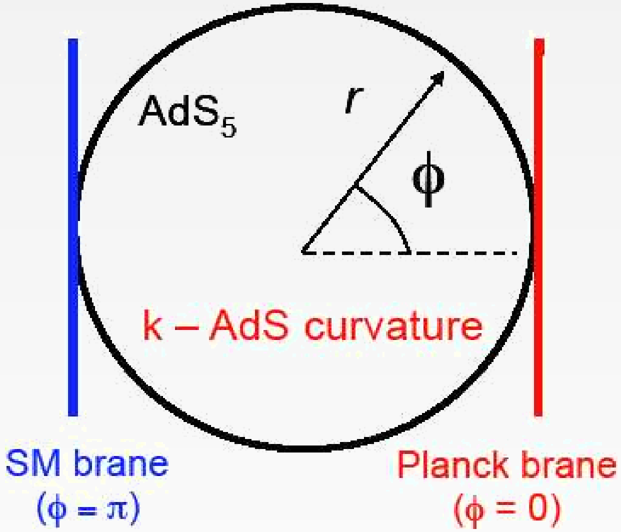
Warped Extra Dimensions

Criticism on ADD: gauge field hierarchy is replaced by hierarchy of length scales

Alternative – RS model

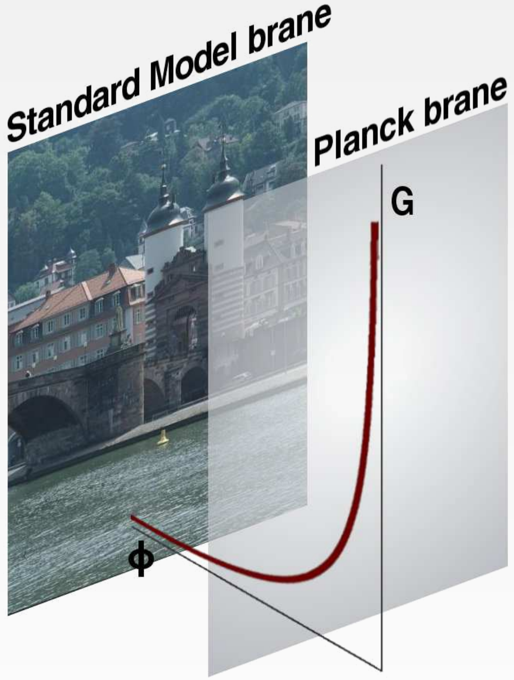
Randall, Sundrum: hep-ph/9905221

Two 3D-branes separated by one compactified extra dimension



Anti-deSitter space-time metric

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



Gravity is strong on Planck brane

On SM brane it is attenuated by exponential "warp" factor

$$\Lambda_\pi \sim M_{Pl}e^{-\pi k r_c}$$

For $kr_c \sim 10$: $\Lambda_\pi \sim 1$ TeV and hierarchy problem is solved naturally

Kaluza–Klein Gravitons in RS

- Particle in a box with AdS metric
- Energy eigenvalues are given by roots of Bessel function J_1

$$M_n = kx_n e^{-kr_C\pi} \qquad \text{e.g. } x_1 = 3.83$$

- Coupling $1/\Lambda_\pi^2$ for $i > 0$
- May be accessible as narrow resonances
  Search in e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$, ZZ
- Energy spacing would be model confirmation

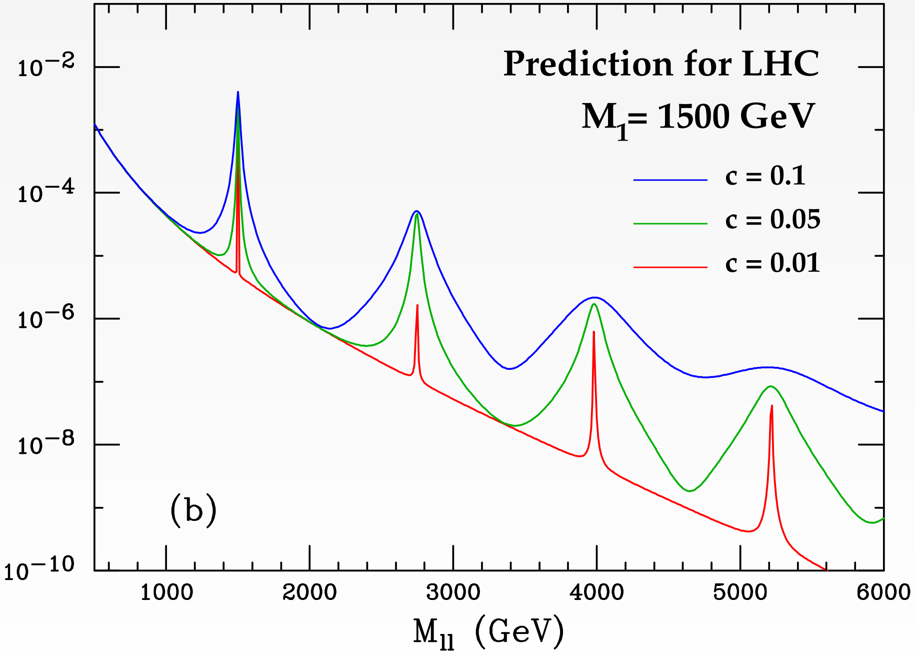
  Davoudiasl, Hewett, Rizzo: hep-ph/0006041

Model has 2 free parameters. Choose these:

$$M_1 \quad \text{and} \quad c = \frac{M_1}{x_1 \Lambda_\pi}$$

Theoretically “reasonable” range: $0.01 < c < 0.1$

For $kr_C = 12$: $r_C = 10^{-32}$ m

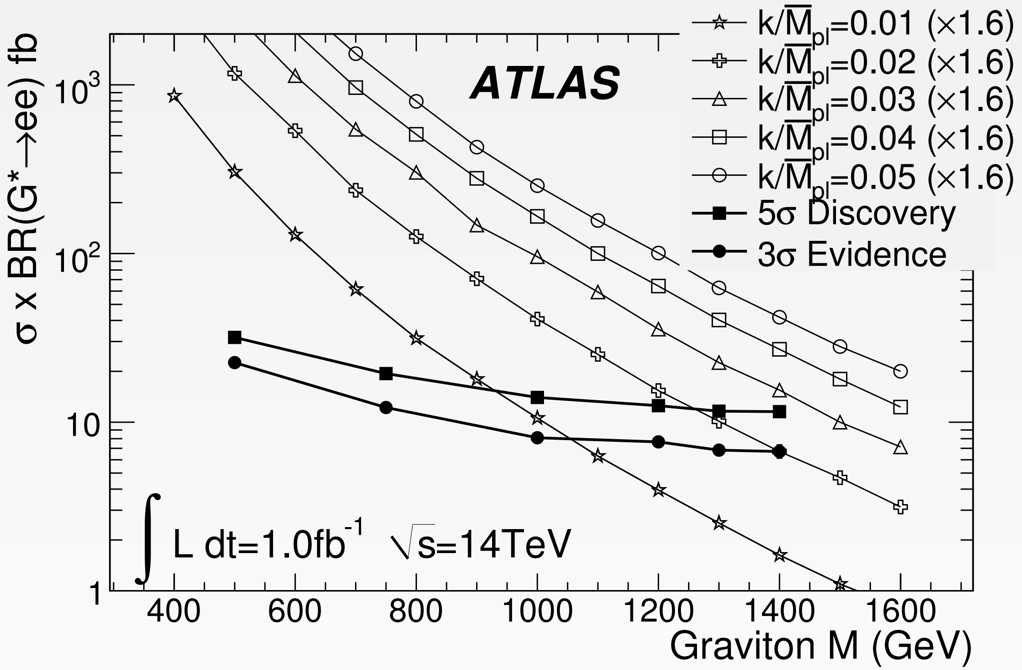


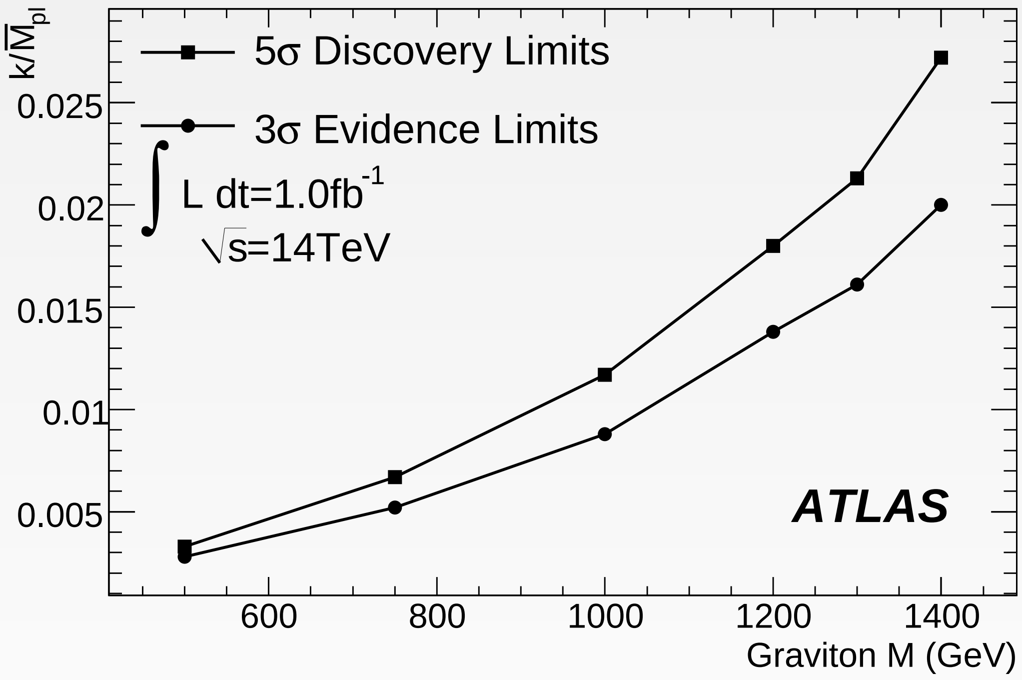
KK Gravitons in RS: Reach @ LHC

Recent ATLAS studies with full simulation:
more realistic detector effects, trigger, particle ID

ATLAS CSC book, arXiv:0901.0512

$\mathbf{G \rightarrow e^+e^-}$





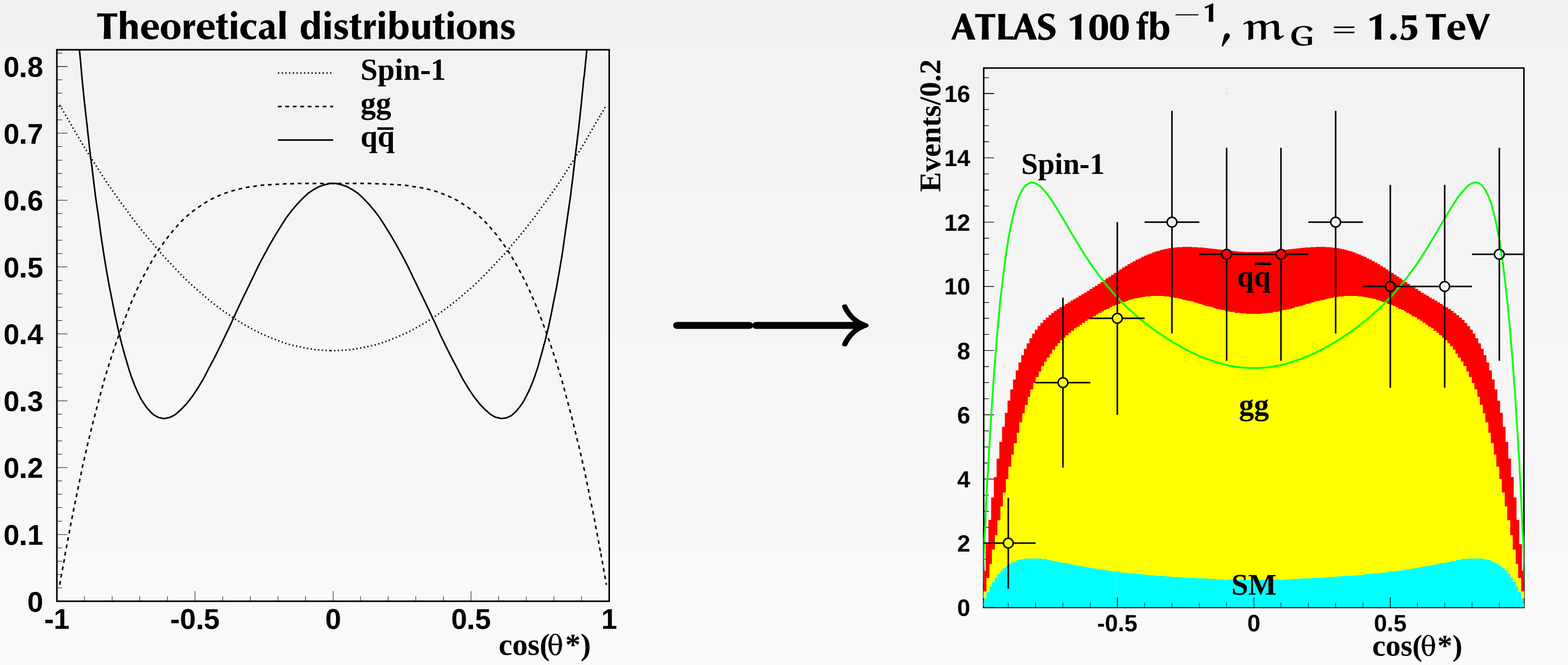
Note: assume $\Lambda_\pi < 10\,\text{TeV}$ for natural solution of hierarchy problem

Then e.g. for $M_1 = 1\,\text{TeV}$: $c > 0.025$

LHC should be able to cover the whole region of interest with $< 100\,\text{fb}^{-1}$

Distinguish RS Graviton and Any Z_{KK}/Z'

- Determine spin of the resonance: $S_G = 2$, $S_{Z'} = 1$
- Different angular distributions $\cos\theta^*$ in lepton-lepton (= parton-parton) cms frame



$G \to e^+ e^-$

Allanach, Odagiri, Parker, Weber:

hep-ph/0006114

- Need clean samples with small backgrounds ⇒ hard cuts
- Need large statistics
- Understand corrections for detector acceptance

TeV^{-1} Extra Dimensions

Allow all SM force carriers γ, Z, W, g (, G) to go in extra dimensions

Change running of couplings

Similar to ADD, but focus on GUT scale not Planck scale

Achieve Great Unification at TeV scale

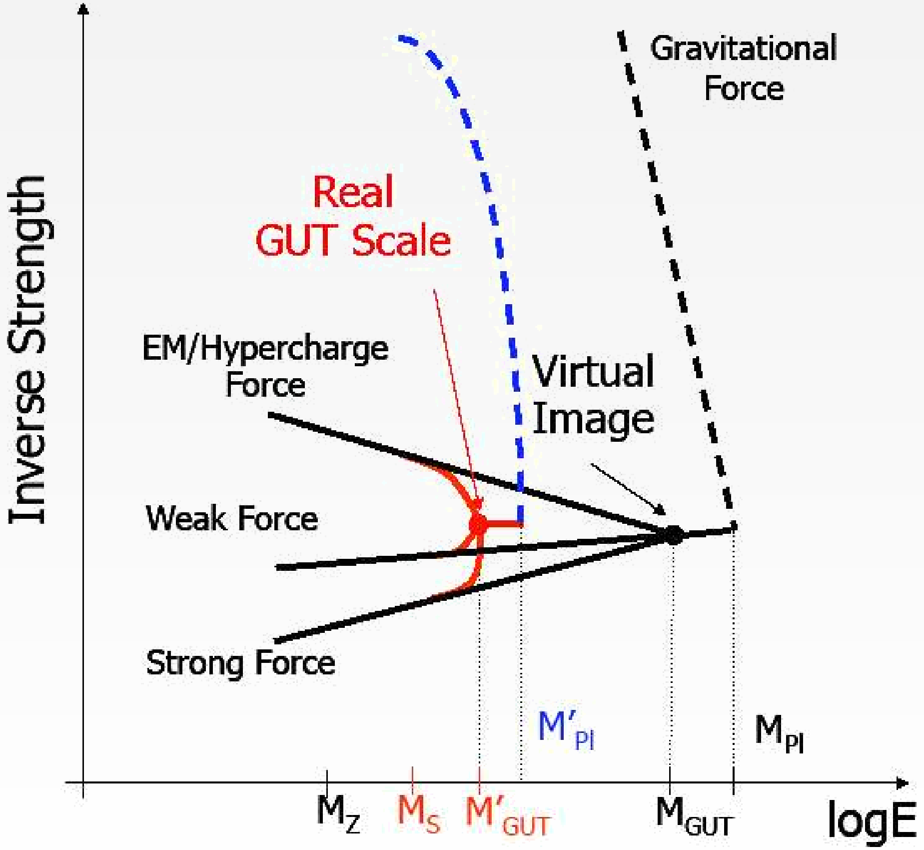
These ED cannot be large:

$$R_C \sim \text{TeV}^{-1} \sim 10^{-19}\,\text{m}$$

From EW precision measurements:

$$1/R_C \gtrsim 6\,\text{TeV}$$

Gravity gets larger but still relatively weak

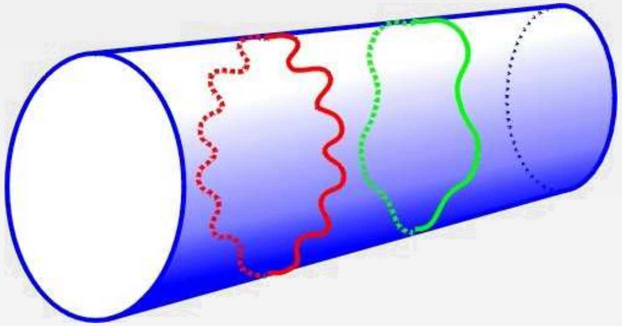


Antoniadis: PLB 246 (1990) 377

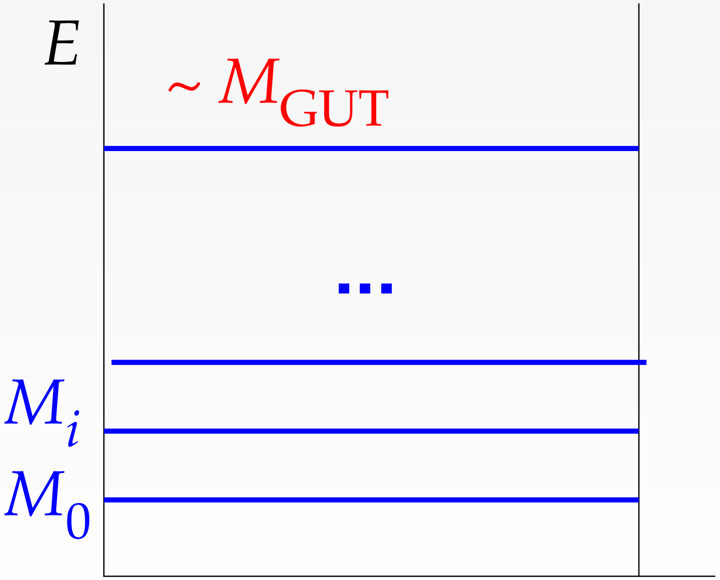
Dienes, Dudas, Gherghetta: hep-ph/9803466

Kaluza–Klein Modes in TeV^{-1} ED

- Winding modes with nearly equal energy spacing $1/r_C \sim \mathrm{TeV}^{-1}$



- Search for massive resonances at LHC:
  γ_{KK}, Z_{KK}, W_{KK}, g_{KK}
  in general Z', W' ...
  typical early searches

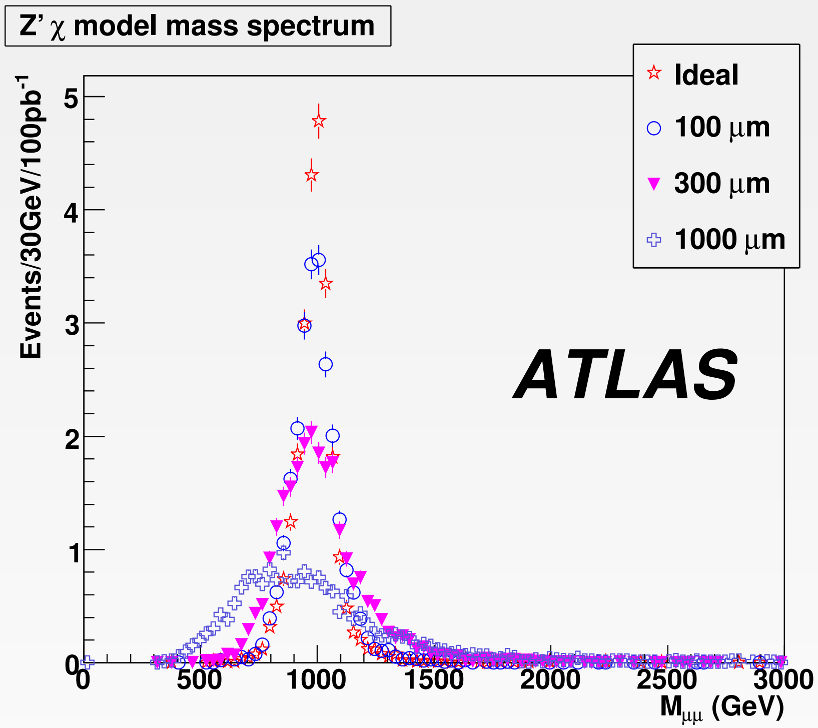


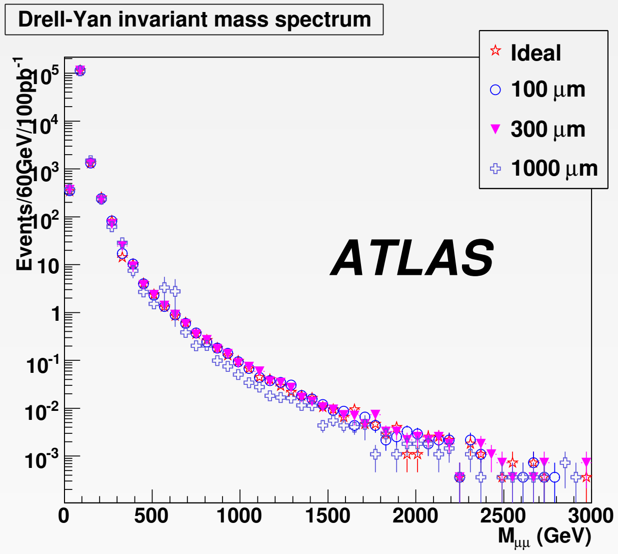
Example: $Z' \to \mu\mu$ – Effects of Misalignment

Full simulation

ATLAS CSC book, arXiv:0901.0512

- **Loss of resolution**





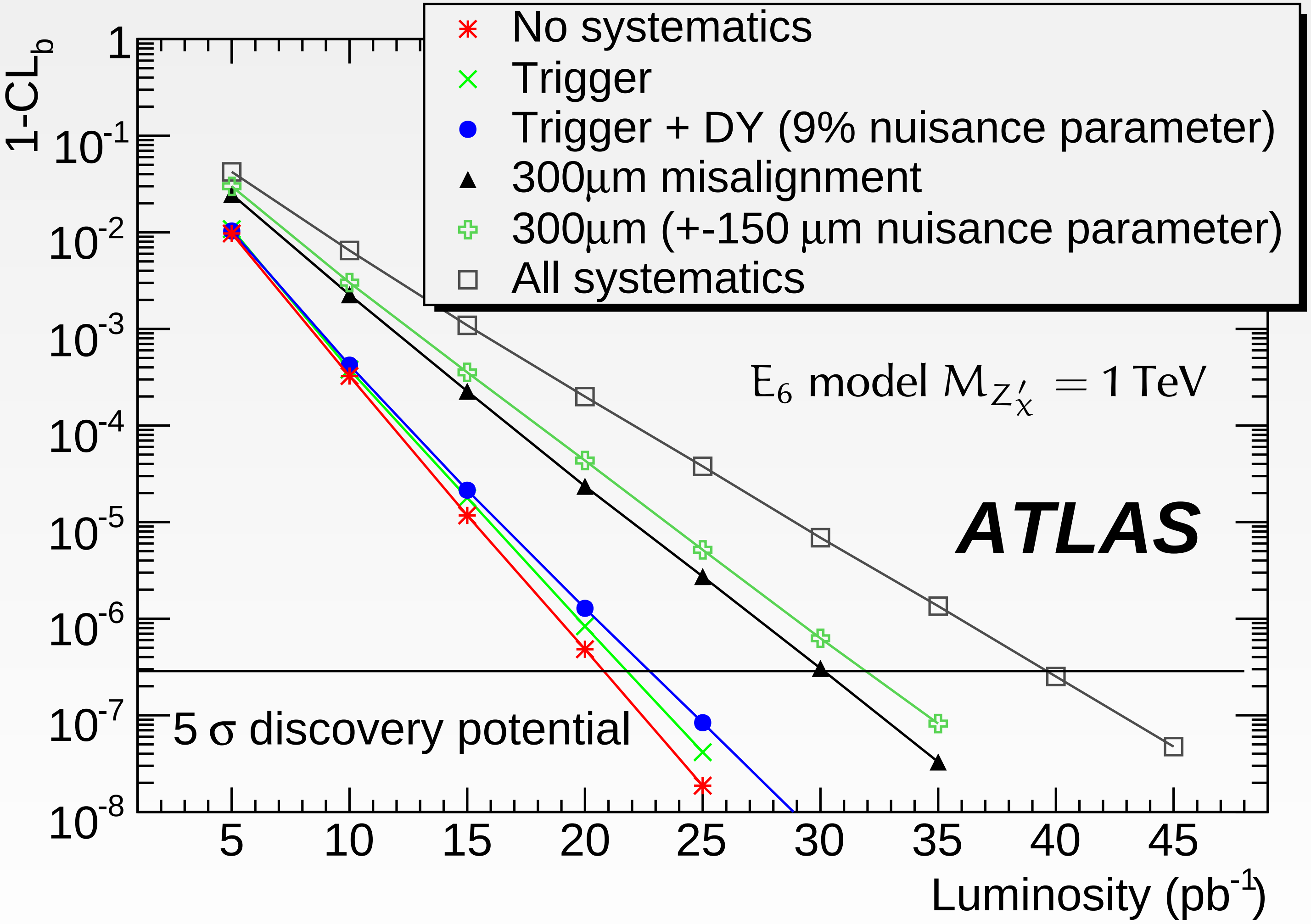
- **Loss of efficiency due to charge misidentification**

Misalignment (μm)	Ideal	40	100	200	300	500	700	1000
Relative efficiency	0.984	0.984	0.984	0.98	0.973	0.948	0.918	0.877

$Z'_\chi \to \mu\mu$ *Discovery Potential*

Full simulation

ATLAS CSC book, arXiv:0901.0512



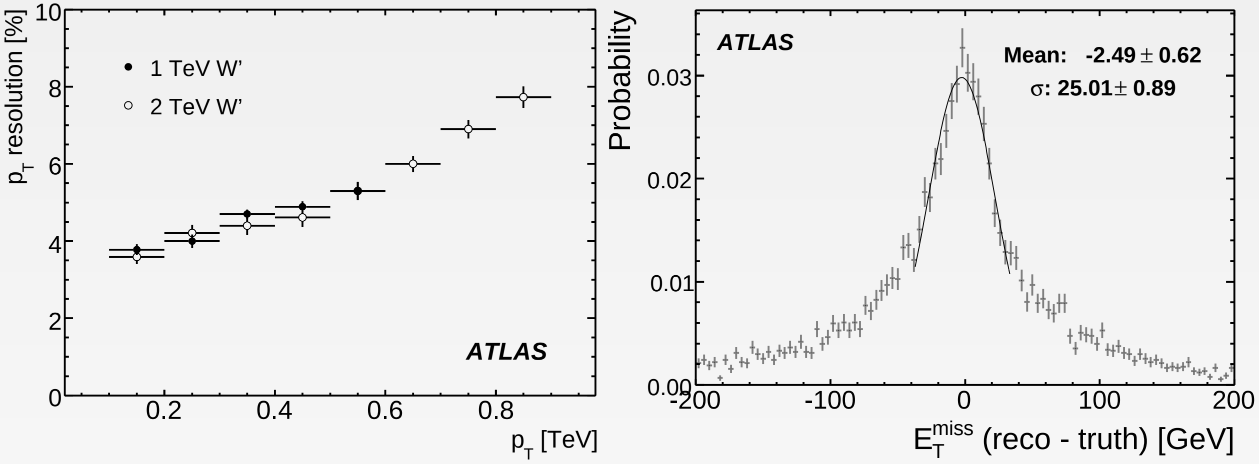
see also Schäfer, Ledroit, Trocme: ATLAS-PHYS-PUB-2005-010 for Z_{KK} studies

Example: $W' \to \mu\nu$ Reconstruction

Full simulation

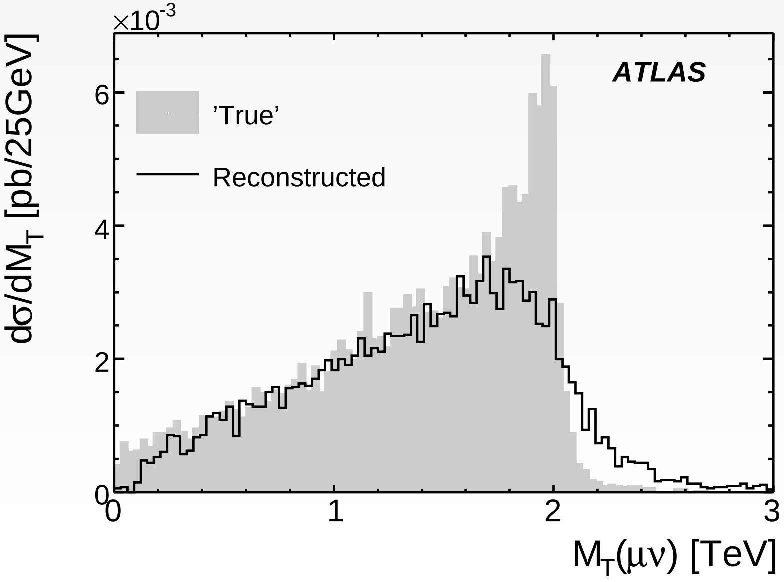
ATLAS CSC book, arXiv:0901.0512

- Require muon $p_T > 50\,\text{GeV}$ and $E_T^{miss} > 50\,\text{GeV}$



- Reconstruct transverse mass

$$m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos \Delta\phi_{l, E_T^{miss}})}$$

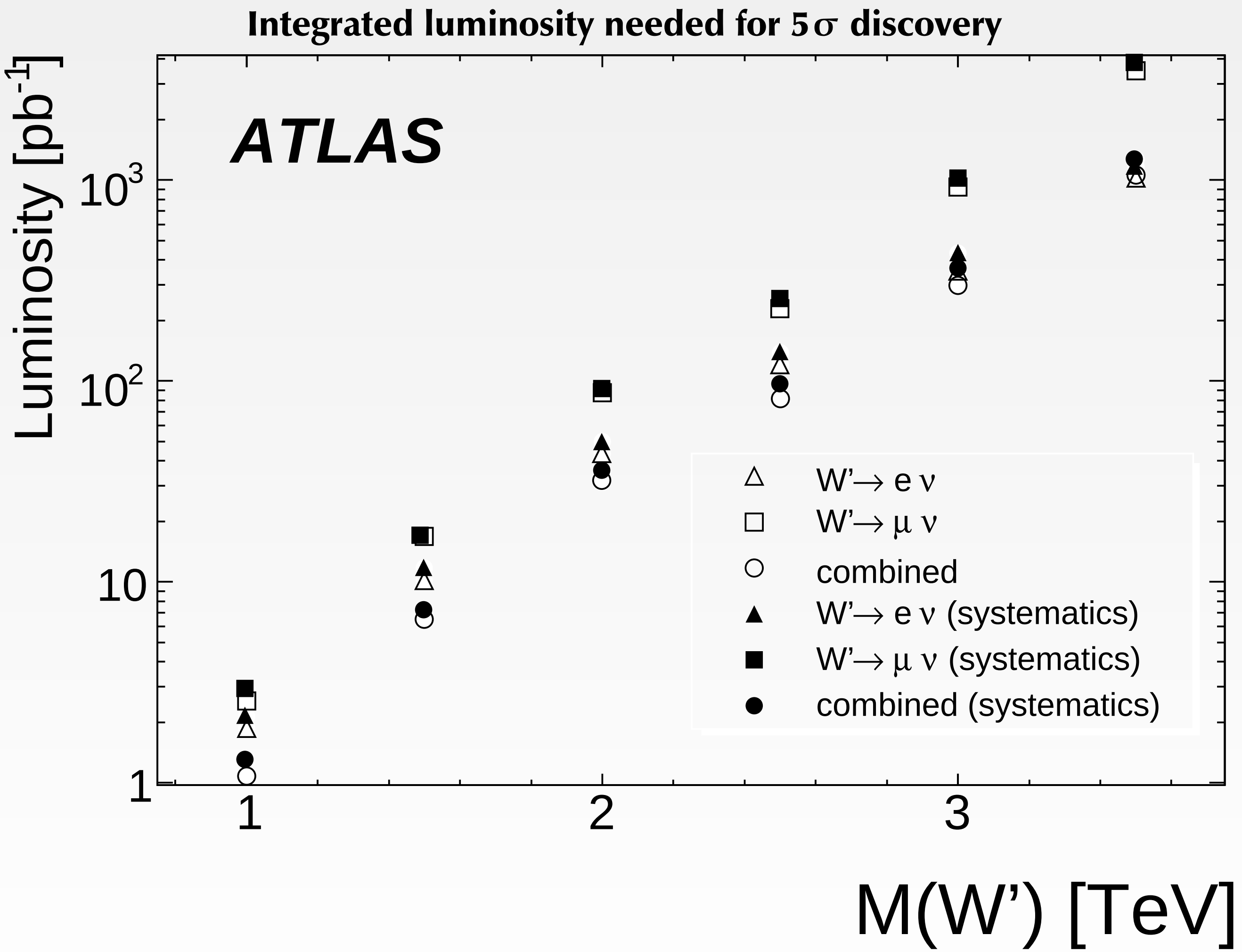


$M_{W'} = 2\,\text{TeV}$

W' Discovery Potential

Full simulation

ATLAS CSC book, arXiv:0901.0512



Integrated luminosity needed for 5σ discovery

Systematics included: lepton ID, energy scales and resolutions, lumi error, NLO, PDFs, . . .

Universal Extra Dimensions

Allow all SM particles to go in extra dimensions

Further extension of TeV^{-1}

Appelquist, Cheng, Dobrescu:
hep-ph/0012100

- Momentum in bulk must be conserved!
  as no particle is kept on the 3D-brane
  → KK states are produced in pairs – as in MSSM
  → Introduce KK parity – similar to R-parity
- Due to KK-parity much weaker constraints: $1/R_C \gtrsim 300 - 500\,\text{GeV}$
- Expect for LHC: $1/R_C \sim 1.5\,\text{TeV}$
- Reach phenomenology similar to SUSY
  → Long decay channels
  → Lightest KK excitation is stable – missing E_T
  → Candidate for dark matter

Cheng, Matchev, Schmaltz
hep-ph/0204342, hep-ph/0205314

Example ATLAS studies

Beauchemin, Azuelos: ATL-PHYS-PUB-2005-003

Black Holes

- Black Holes are predicted in general relativity theory
- Karl Schwarzschild solution (1916) for static non-spinning massive object – metric with singularity at Schwarzschild radius

$$R_S = \frac{2M_{BH}G}{c^2} \propto \frac{1}{M_{Pl}} \frac{M_{BH}}{M_{Pl}}$$

If radius of object $r < R_S$, black hole with event horizon at R_S is formed

- Generalisation by Myers and Perry (1986) for $D = 4 + n$ dimensions

$$R_S \propto \frac{1}{M_D} \left(\frac{M_{BH}}{M_D} \right)^{\frac{1}{n+1}}$$

For small M_D: R_S is large

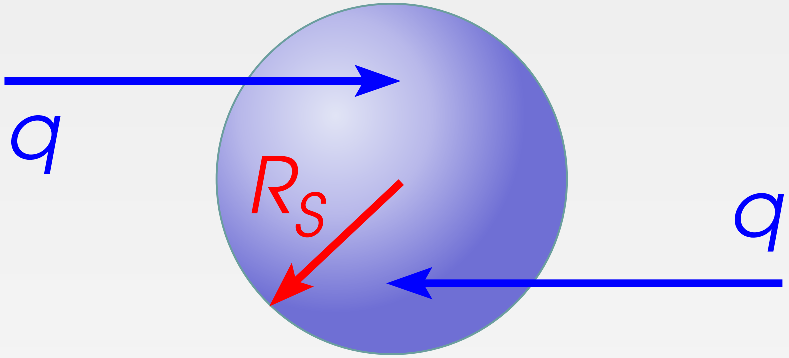
Black Hole Formation @ Hadron Colliders

- Big energies $\Longleftrightarrow$ small distances.
  BH forms if partons come closer than $2R_S$
- BH mass $M_{BH}^2 = \hat{s}$
  Continuous mass spectrum starting at some $M \gtrsim M_D$
- Exact cross section needs quantum gravity theory.
  Use quasi-classical "black disc" approximation:

  $\hat{\sigma} = f\pi R^2$ with formation factor $f \sim 1$

  Parton level cross section grows with energy

  Non-perturbative! – valid for $M_{BH} \gg M_D$
- Possible for any combination of quarks and gluons.
  All gauge and spin quantum numbers are allowed
  $\Longrightarrow$ BH are charged and coloured



R_S – Schwarzschild radius

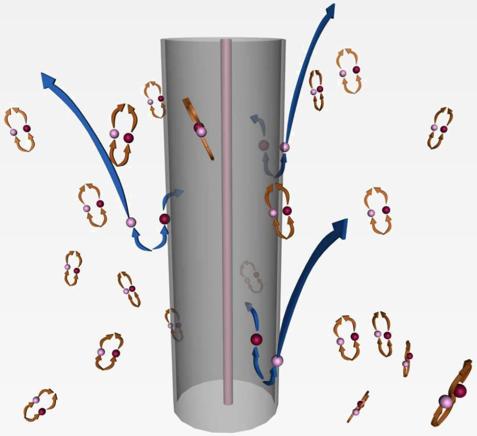
Banks, Fischler: hep-th/9906038
Giddings, Thomas: hep-ph/0106219
Dimopoulos, Landsberg: hep-ph/0106295

Hawking Radiation

- Steven Hawking (1975):
  Pairs of virtual particles appear at event horizon with one particle escaping

- Particles have black body spectrum with temperature

$$T_H = \frac{\hbar c}{4\pi k_B R_S} = \frac{1}{4\pi R_S} \propto M_{Pl} \frac{M_{Pl}}{M_{BH}}$$



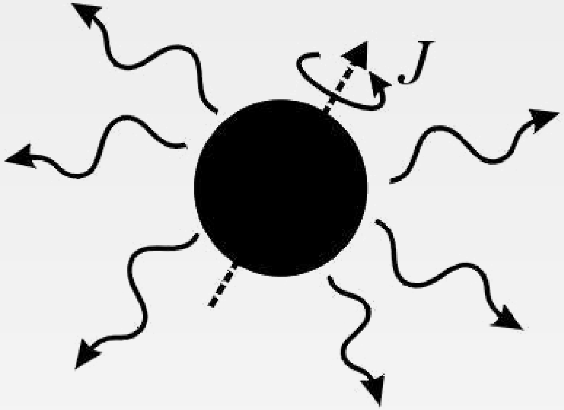
- No chance to discover Hawking radiation of astro black holes
  $T_H \ll T_{CMB}$

- In $D = 4 + n$ dimensions (Myers, Perry, 1986)

$$T_H = \frac{n+1}{4\pi R_S} \propto M_D \left(\frac{M_D}{M_{BH}}\right)^{\frac{1}{n+1}} (n+1)$$

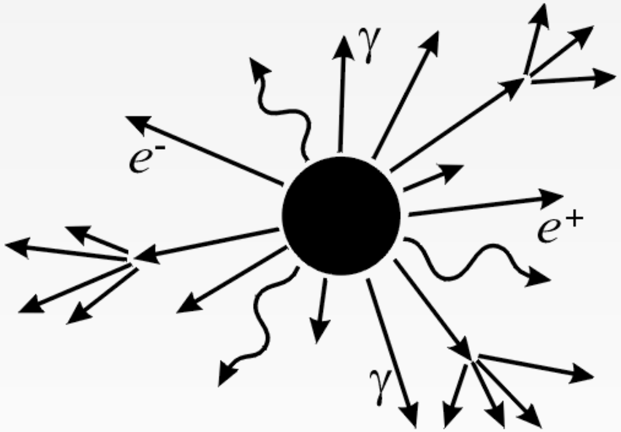
- At high enough T_H massive particles are also produced

Black Hole Decay



1. Balding phase: Graviton radiation.

multipole moments are radiated and BH settles down in hairless state.



2. Evaporation phase: $M_{BH} \gg M_D$. Hawking radiation.

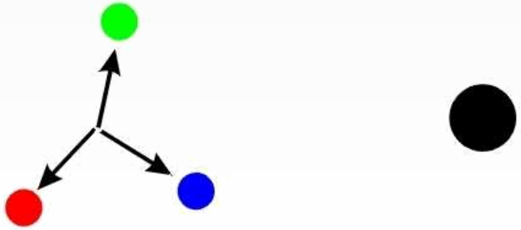
a) spin down – losing angular momentum;

b) black body radiation – emission of thermally distributed quanta.

Most of initial energy is emitted during this phase.

Mostly in SM particles.

All SM particles on our brane; gravitons also in ED.



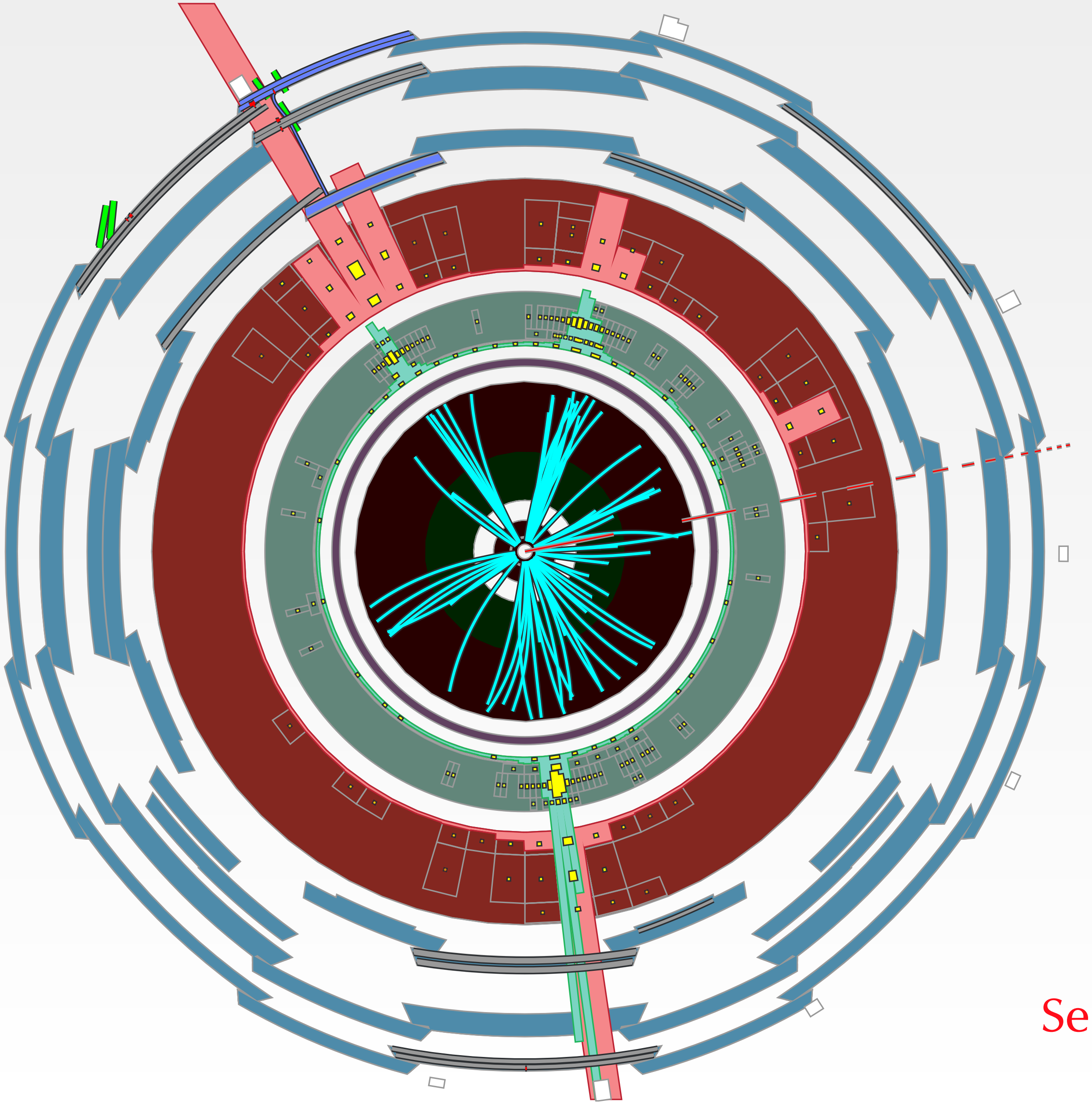
3. Planck phase: $M_{BH} \rightarrow M_D$. Regime of quantum gravity.

Predictions very difficult.

BH decays in some last few SM particles or leaves stable remnant.

Pictures: backreaction.blogspot.com

Black Hole Event Simulation



- High multiplicity
- High sphericity

Democratic decay example

q, g	72%
e, μ, τ	11%
$W^{\pm}, Z$	8%
ν	6%
H	2%
γ	1%
h/l activity	5 : 1
h/γ activity	100 : 1

Semi-classical model: $M_{BH} \gtrsim 5M_D$

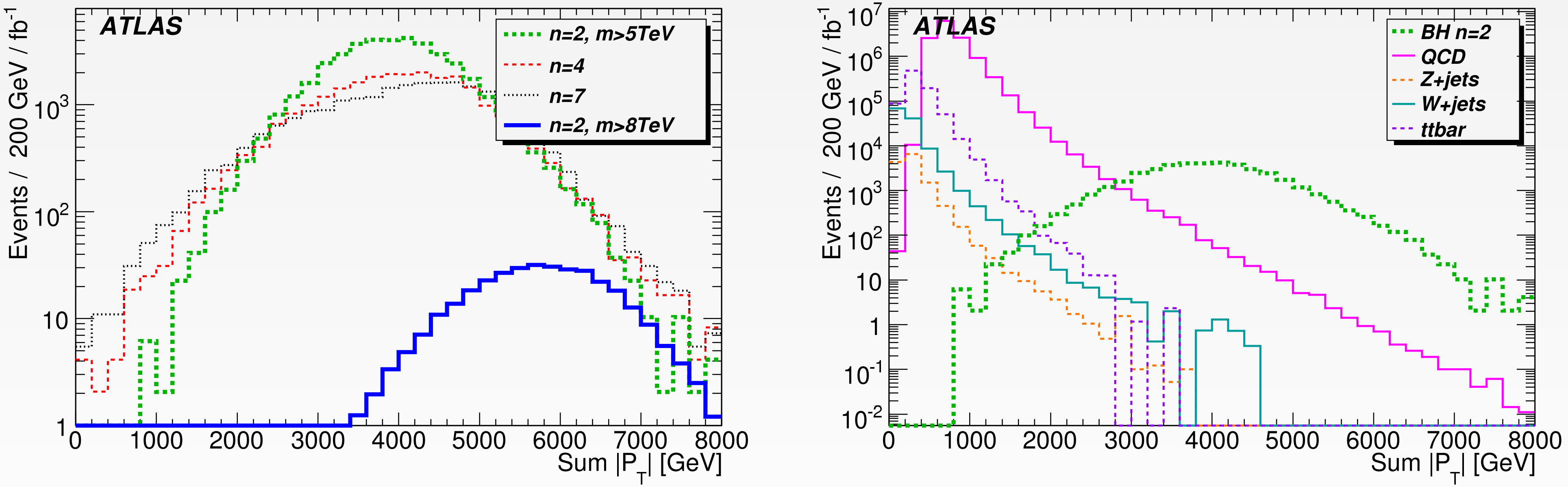
Black Hole Event Selection

Different strategies exist.

ATLAS CSC book, arXiv:0901.0512

Example for $M_{BH} > 5\,\text{TeV}$, $M_D = 1\,\text{TeV}$, $\mathcal{L} = 1\,\text{fb}^{-1}$

- Cut $\sum |p_T| > 2.5\,\text{TeV}$



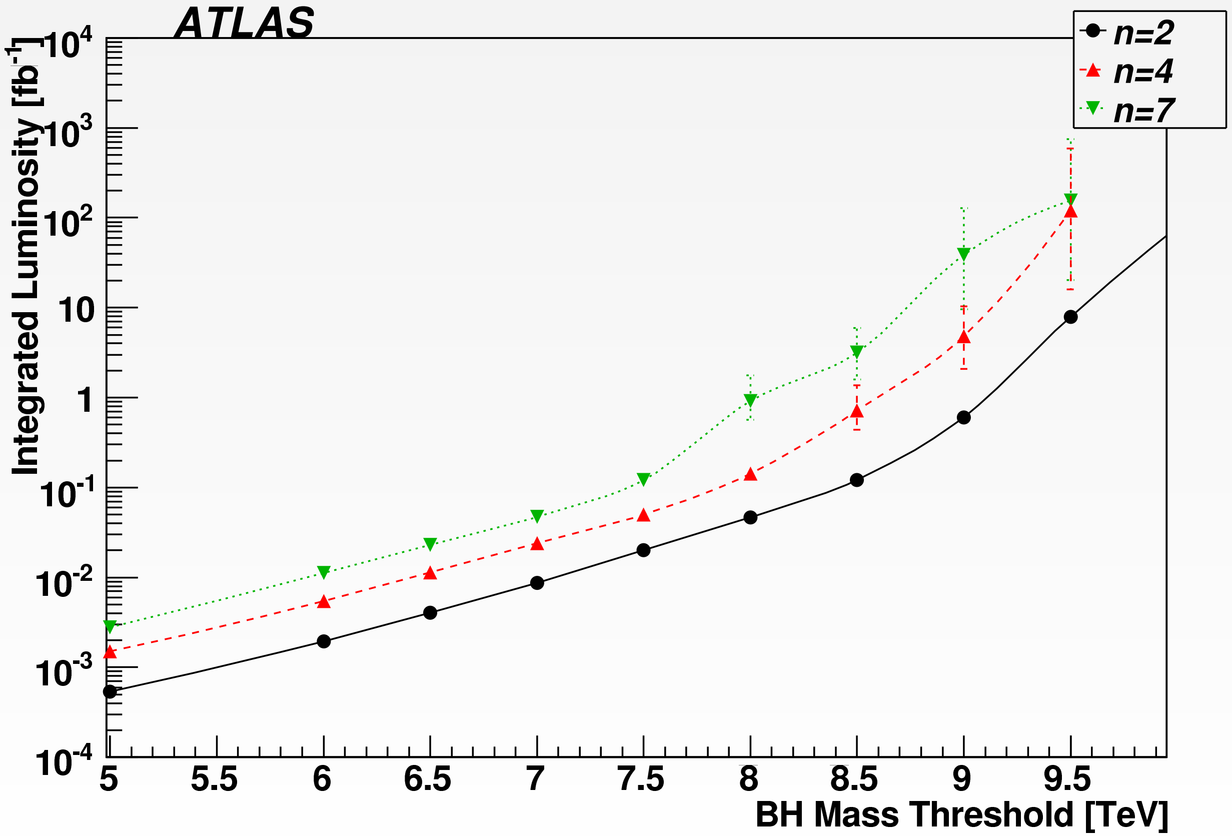
- Require at least one well identified lepton e or μ with $p_T > 50\,\text{GeV}$

  QCD background further reduced by factor ~ 60

Black Hole Discovery Potential

Robust estimation of discovery potential is difficult,
because semi-classical model assumptions are valid only for $M_{BH} \gg M_D$.
Introduce artificial mass cut-off in generated samples $\Longrightarrow$ conservative estimation

Example: $M_D = 1$ TeV, cut $\sum |p_T| > 2.5$ TeV, lepton requirement



Black Hole Model Uncertainties

Large uncertainties within “semiclassical” approach.

So far simplified simulations are used. Previously missing features:

- Grey body factors (e.g. due to gravition emission)
- Rotation
- Recoil due to radiation
- Possible brane tension
- Conservation of quantum numbers (baryon, lepton, flavours)

More effects are implemented in new MC versions.

Several analysis strategies are developed for different scenarios.

Search Strategy for First Data

- Little access to $M_{BH} > 5\,\text{TeV}$ with $100\,\text{pb}^{-1}$ first data at $\sqrt{s} = 10\,\text{TeV}$
  Focus on lower masses

- Turn on of semiclassical BH production is unknown
  If $M_D \sim \mathcal{O}(TeV)$, expect new effects
  Look for high multiplicity events with different objects with $\sum E_T \gtrsim 0.5 - 1\,\text{TeV}$

Example: string balls – excited string states in low string scale models

Dimopoulos, Emparan: hep-ph/0108060
Chamblin, Nayak: hep-ph/0206060
Cheung: hep-ph/0205033
Gingrich, Martell: arXiv:0808.2512

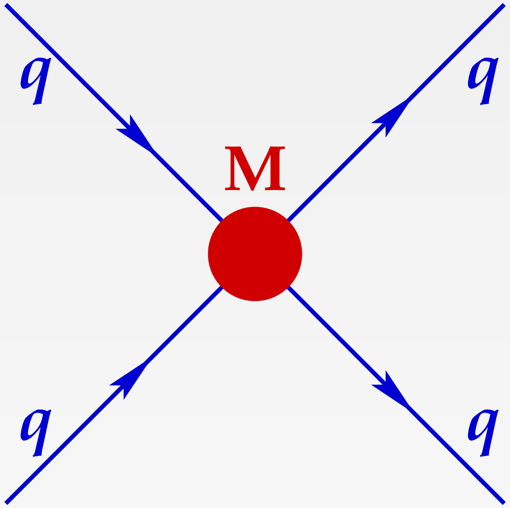
Gravity Effects in Contact Interactions

- Black holes at $M \sim M_D$ may first appear in contact interactions

  Similar to compositeness

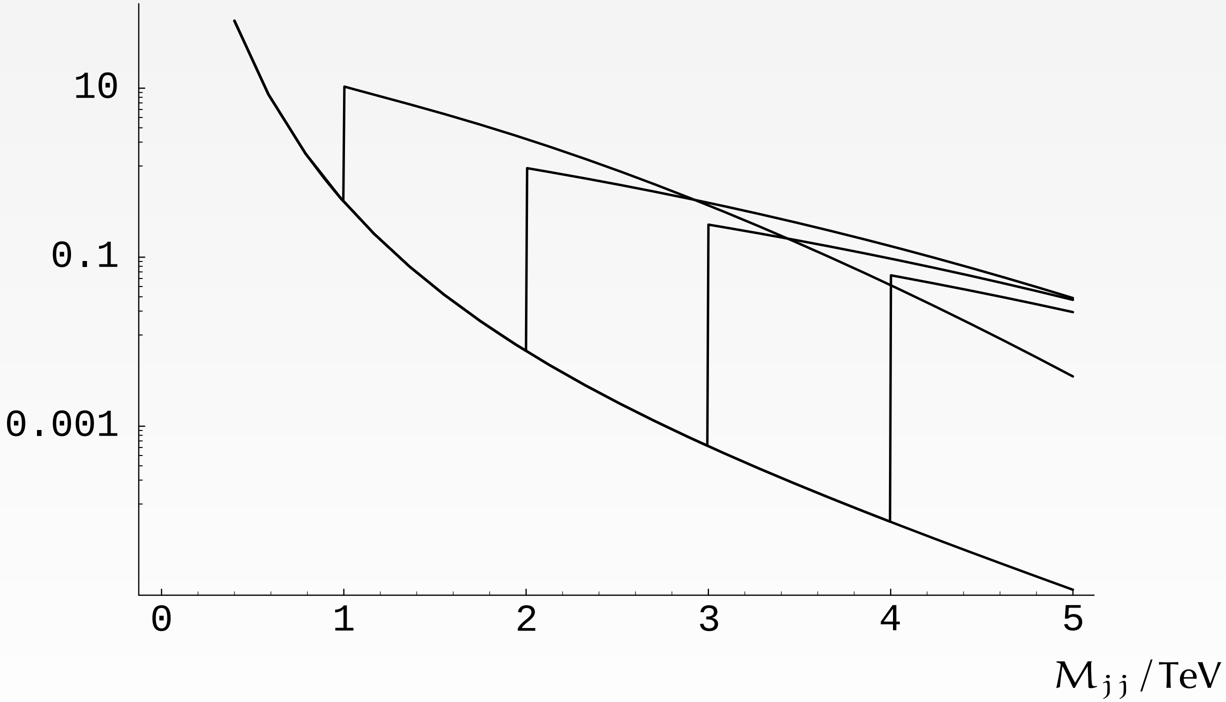
  This can be any quantum gravity effect or resonance

Meade, Randall: arXiv:0708.3017



- Expect excess at high p_T in dijet and dilepton distributions

Inv. mass M_{jj} for $n = 6$ and different M_D



Simplified picture – must be smoothed out.
Still rather sharp turn on is expected for gravity effects.

Conclusions

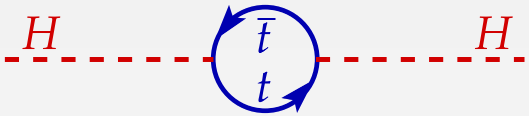
- Many striking signatures for extra dimensions
  - Kaluza-Klein excitations
  - Mini black holes and other non-perturbative objects
- Many MC studies for discovery reach were performed
- Evidence possible with first 100 pb^{-1} of data
  We only need to collect it . . .

Backup

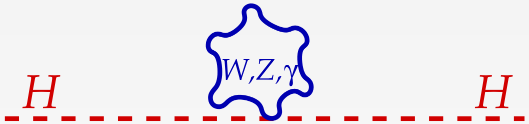
Additional Information

“Fine Tuning” Argument

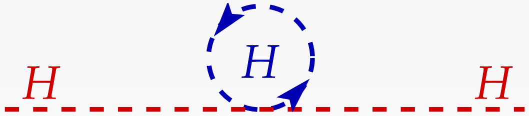
- Higgs self-energy corrections in perturbation theory: $M_H^2 = M_{H,\mathrm{bare}}^2 + \Delta M_H^2$
  Have to integrate over all particle momenta in loops
  ⇒ Loop corrections to Higgs mass rise with UV cut-off Λ^2



$$\Delta M_{H,1}^2 = -\frac{3}{8\pi^2} g_f^2 \Lambda^2$$



$$\Delta M_{H,2}^2 = \frac{1}{16\pi^2} g^2 \Lambda^2$$



$$\Delta M_{H,3}^2 = \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

$$V(\phi) = -\mu^2|\phi^\dagger\phi| + \lambda|\phi^\dagger\phi|^2$$

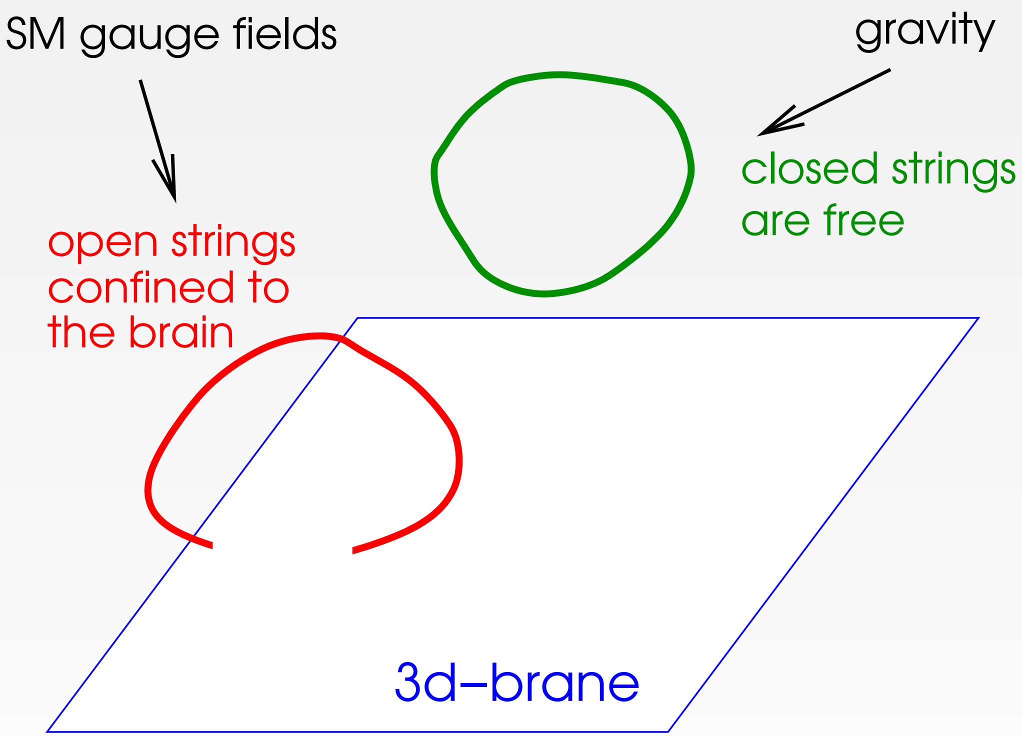
- Fine tuning to precision $\sim M_H^2/\Lambda^2$ is needed
  For $\Lambda = M_{\mathrm{Planck}}$, $M_H \sim 100\,\mathrm{GeV}$: $(\Lambda/M_H)^2 \sim 10^{34}$ – gauge field scale hierarchy

$$M_H^2 = M_{H,\mathrm{bare}}^2 + \underbrace{\frac{1}{16\pi^2}(-6g_t^2 + g^2 + \lambda^2)\cdot 10^{34} M_H^2}_{\text{SM}} - \underbrace{\quad\dots\quad}_{\text{New Physics}} \simeq (130\,\mathrm{GeV})^2$$

Possible Explanation in String Theory

- SM gauge fields cannot go to extra dimensions at such scales.
  This is ruled out by HEP experiments. But gravity can!

- String theory



String theories require 6 – 7 extra dimensions, but not necessary of the same size

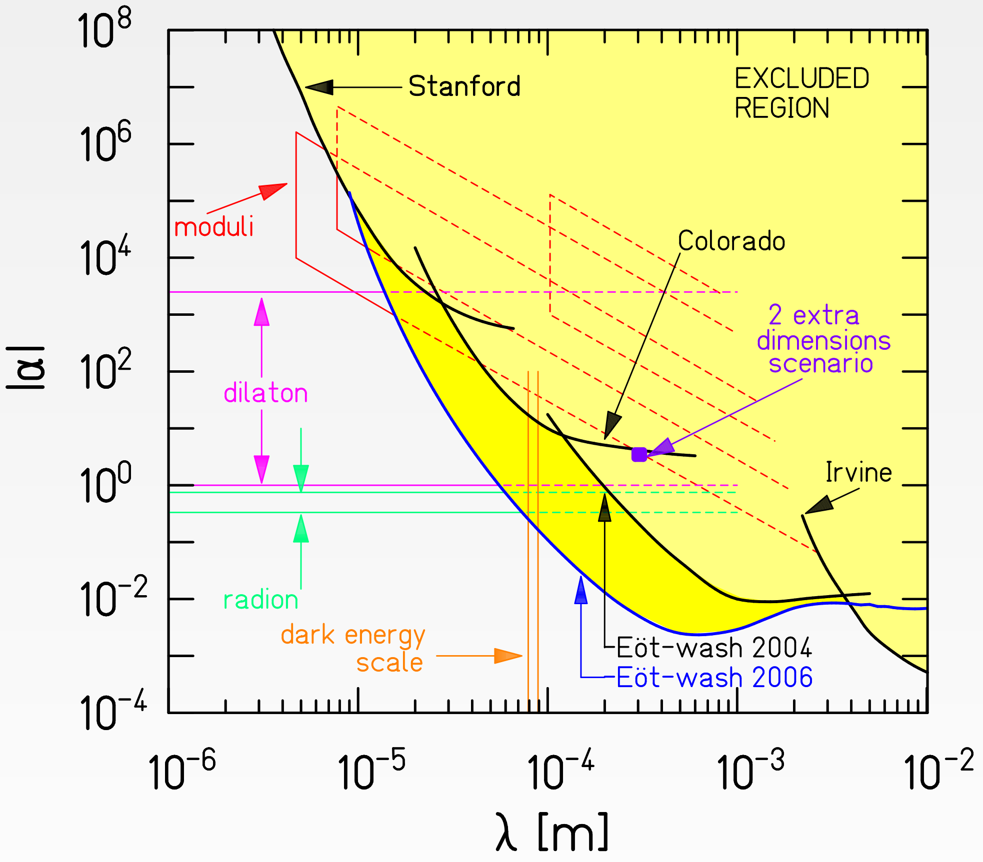
- Why gravity? Because it couples to energy/momentum.
  If gravity cannot go to extra dimensions, then also no other force can.

Tabletop Experiments

At present, Newton's gravity law is tested down to 50 µm

Adelberger et al.: hep-ph/0611184

- Torsion balance experiments –
  high-tech remake of Cavendish exp.

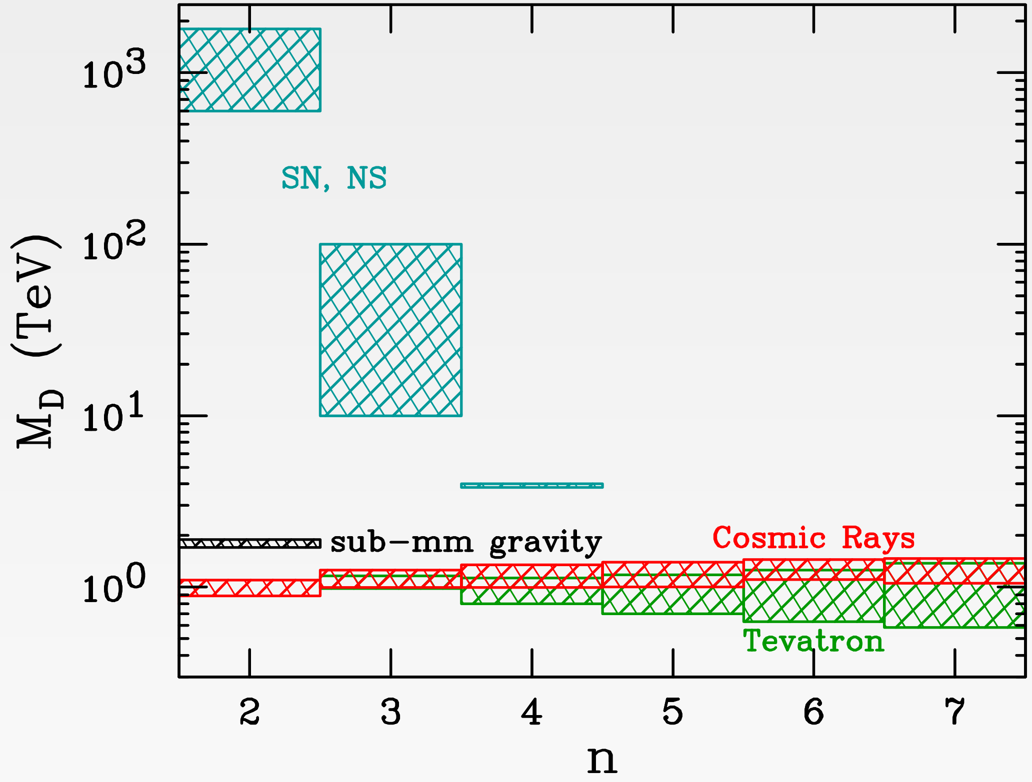


- Modified potential with Yukawa term

$$V(r) = -G\frac{m_1 m_2}{r}\left[1 + \alpha e^{-r/\lambda}\right]$$

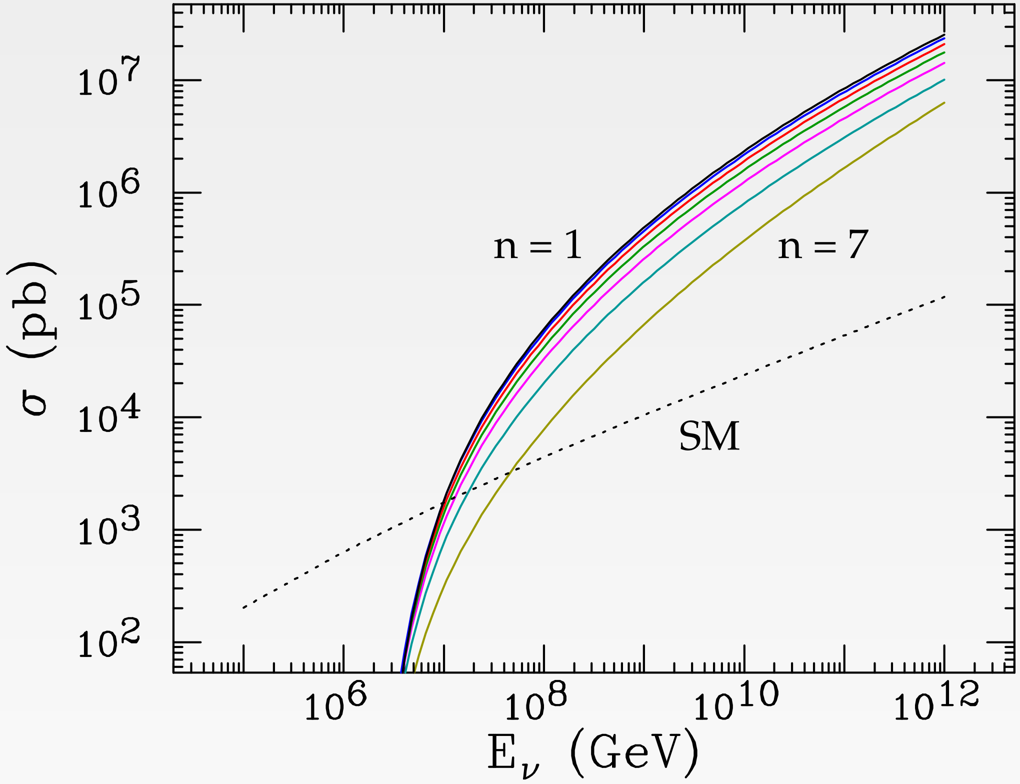
For $n = 2$, this translates into $M_D \gtrsim 3\,\text{TeV}$

Astrophysical Limits in ADD Models



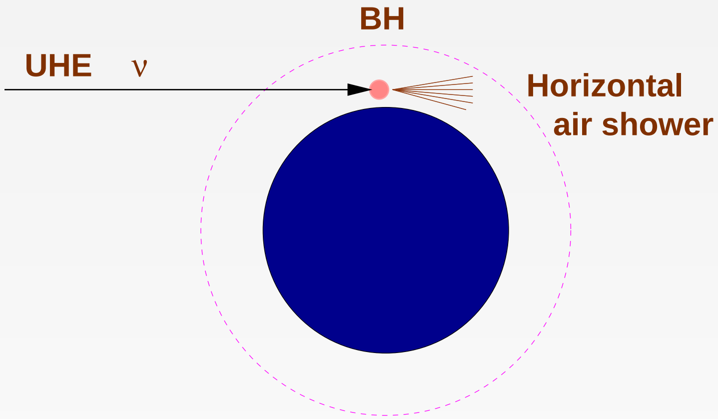
- Astro limits have many uncertainties. Only order of magnitude estimates.
- In general strong astro limits for $n = 2, 3$. Weaker for higher n.
  Colliders can be more sensitive at higher n.
- Astro signals are sensitive to low energy gravitons modes.
  Colliders probe mainly high energy gravitons - complementary measurements.

Black Holes in Cosmic Rays



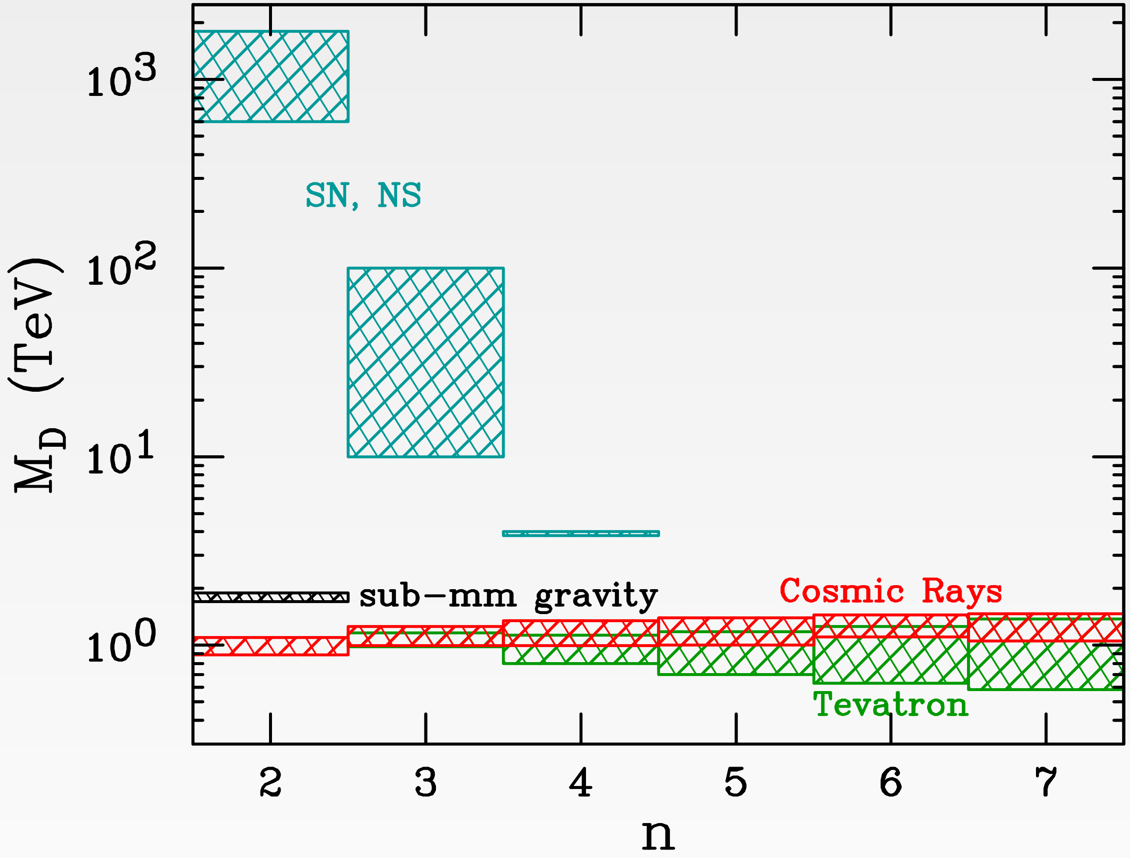
Anchordoqui, Feng,
Goldberg, Shapere:

hep-ph/0307228, 0112247



- Ultra high-energy cosmic-ray neutrinos, $E_\nu \lesssim 10^{19}$ eV, interact with atmosphere and Earth's crust with cms $E \sim 100$ TeV. They can produce micro black holes deep in atmosphere, leading to quasi-horizontal giant air showers.
- Deep in atmosphere ⟶ distinguish from hadronic showers
- Cross section should be very large

Cosmic Ray Bounds in ADD



Anchordoqui, Feng,
Goldberg, Shapere:

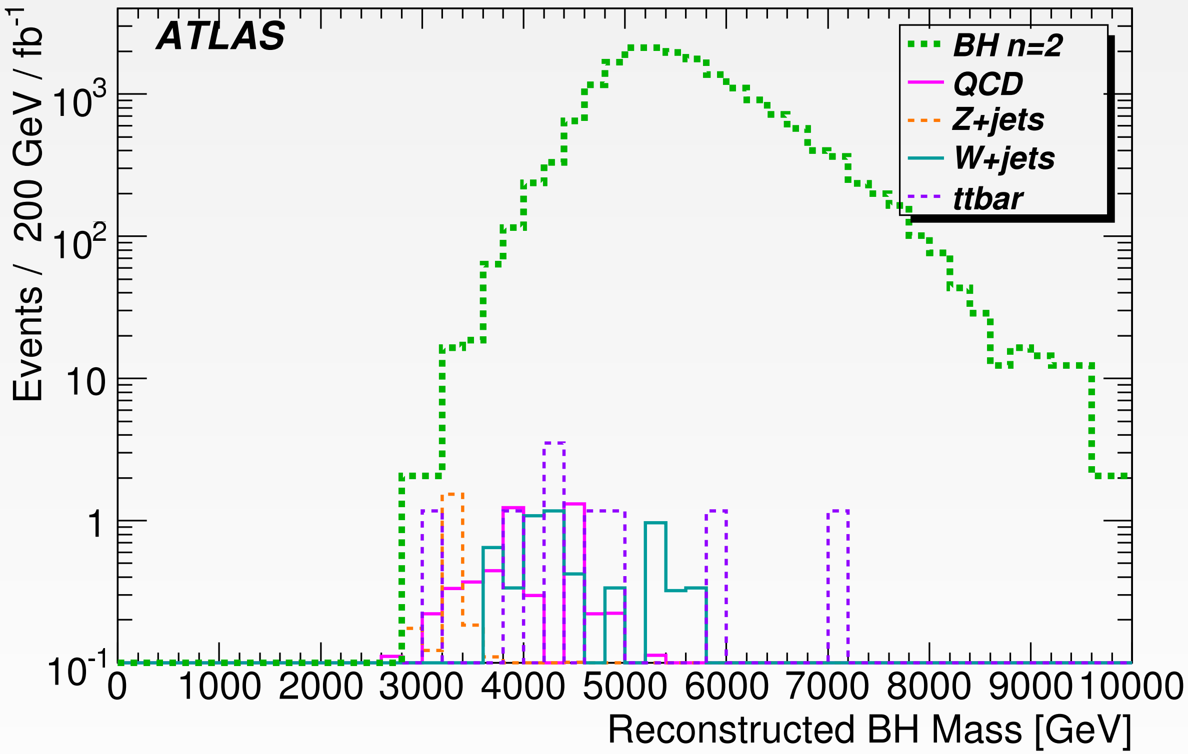
hep-ph/0307228, 0112247

- Using data of Akeno Giant Shower Array (AGASA), Fly's Eye, High Resolution Fly's Eye (HiRes) and Radio Ice Cerenkov Experiment (RICE): $M_D > 1 - 1.4\,\text{TeV}$ for $n = 4 - 7$ in ADD.
- So far the only direct bound on micro black holes.

Black Hole Mass Reconstruction

$$p_{BH} = \sum p_i + (\not{E}_T, \not{E}_{T_x}, \not{E}_{T_y}, 0) \qquad \longrightarrow \qquad M_{BH} = \sqrt{p_{BH}^2}$$

Example for $M_{BH} > 5\,\text{TeV}$, $M_D = 1\,\text{TeV}$



For high statistics mass resolution may be improved with additional cuts, e.g. $\not{E}_T < 100\,\text{GeV}$

However, turn-on behaviour for $M_{BH} \gtrsim M_D$ is unknown!

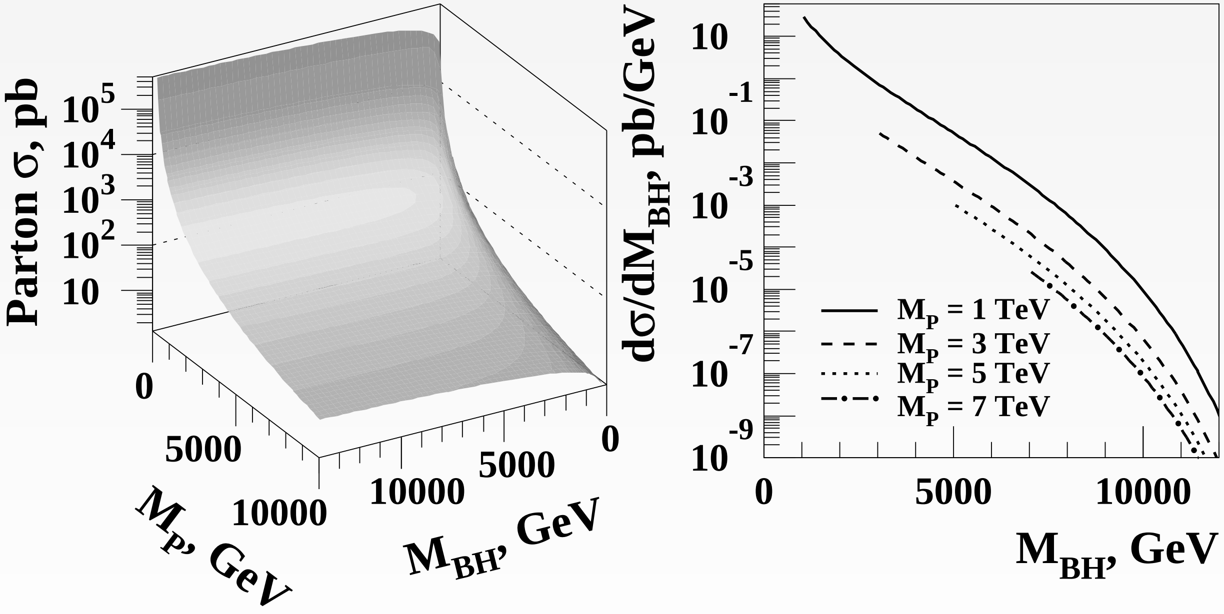
Identifying Black Holes

Need several evidences to be sure. Various ideas exist

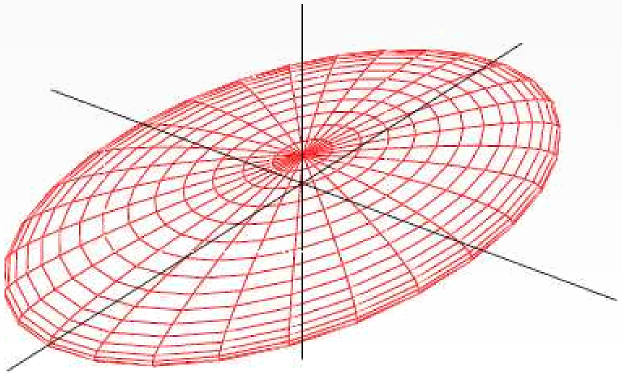
Giddings, Thomas: hep-ph/0106219
Harris et al.: hep-ph/0411022
Roy, Cavaglia: arXiv:0801.3281

◆ Hawking radiation ≈ democratic decay in MC
Look at distributions of particle types: ratios e/μ , e/Z^0 , e/t , Z^0/t . . .

◆ Extract parton cross section and prove that it grows with $\hat{s} = M_{BH}$
Depends on resolution and on turn-on behaviour



plots from
Dimopoulos, Landsberg: hep-ph/0106295

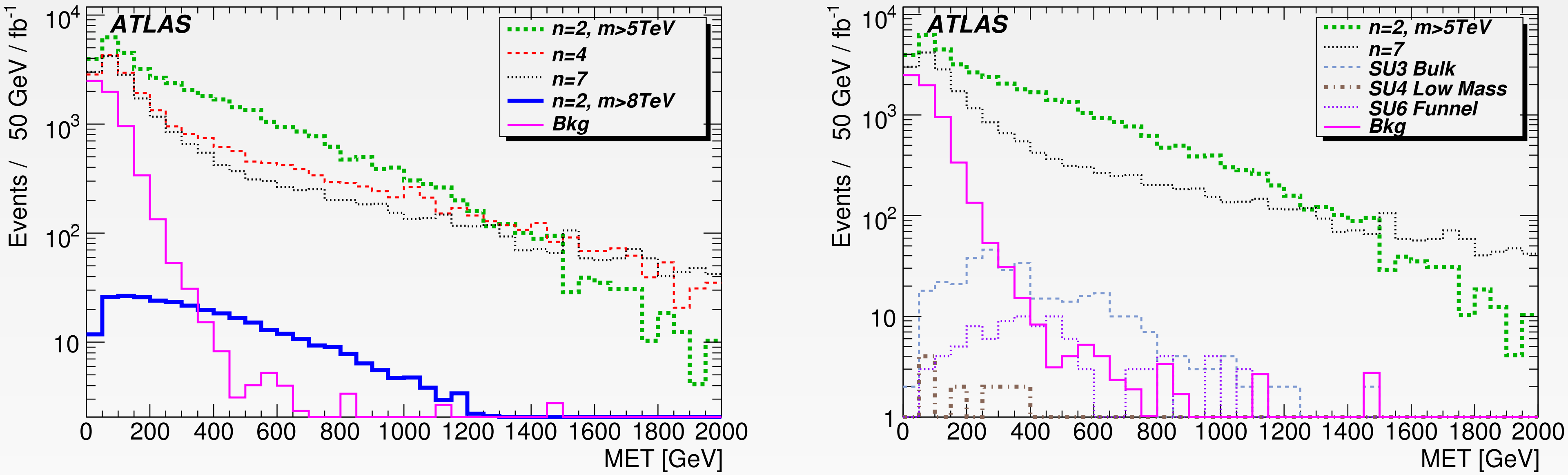


◆ Look at event shapes (sphericity, (a)planarity, thrust . . .)

Identifying BH – Distinction from SUSY

- BH are characterised by large $\not{E}_T$ tail

Example: cut $\sum |p_T| > 2.5$ TeV, no lepton requirement



- Should be underestimated in Charybdis, as graviton radiation is not simulated
- Such high $\not{E}_T$ are not typical for SUSY – would require high mass neutralino LSP