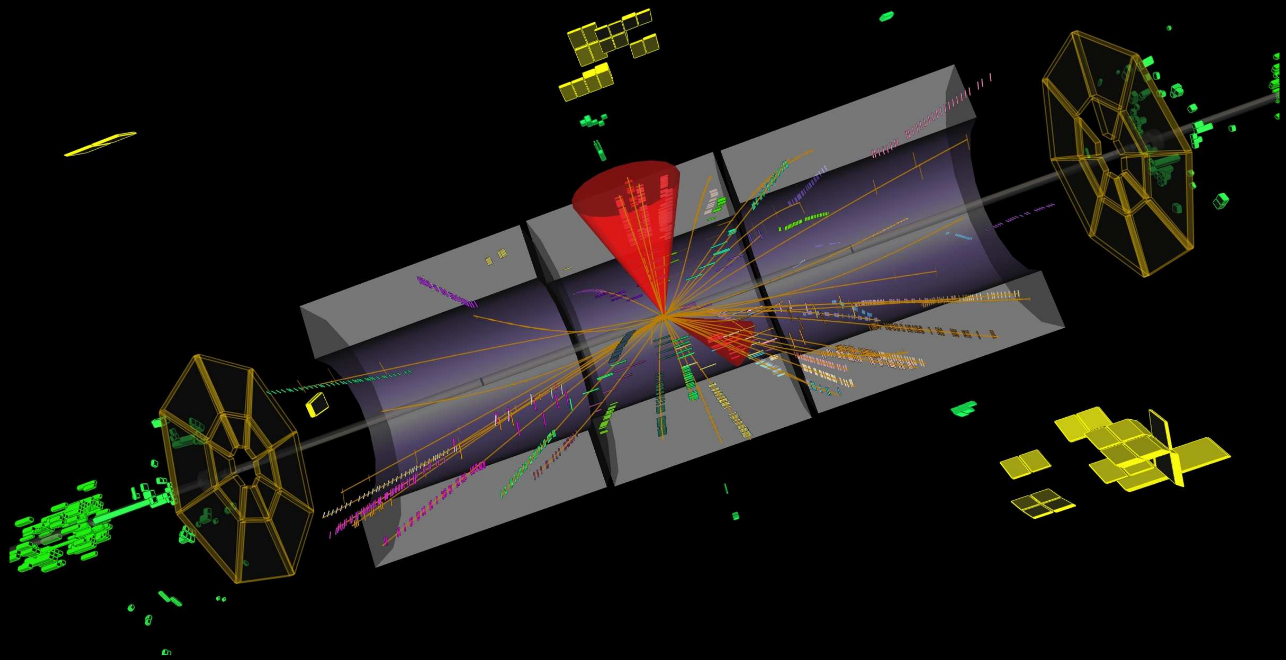
Early Searches with Jets with the ATLAS detector at the LHC

on behalf of
ATLAS Collaboration



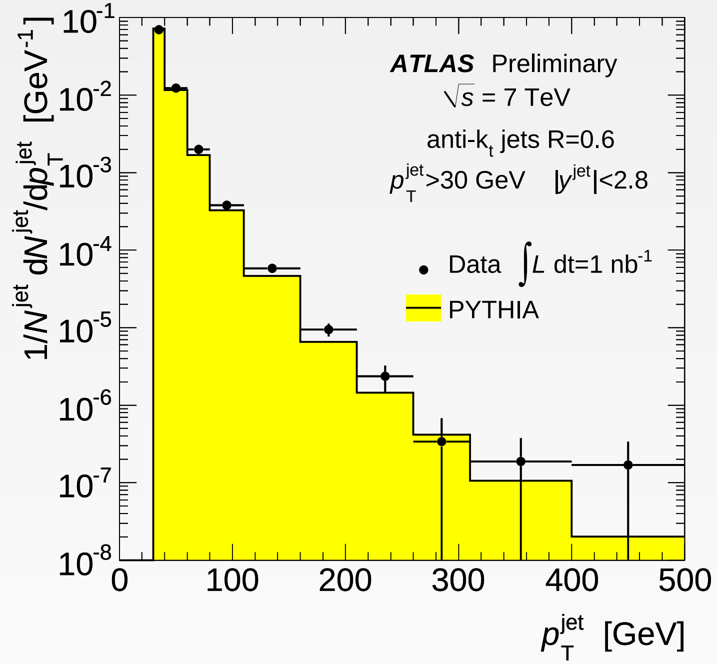
Victor Lendermann
Universität Heidelberg

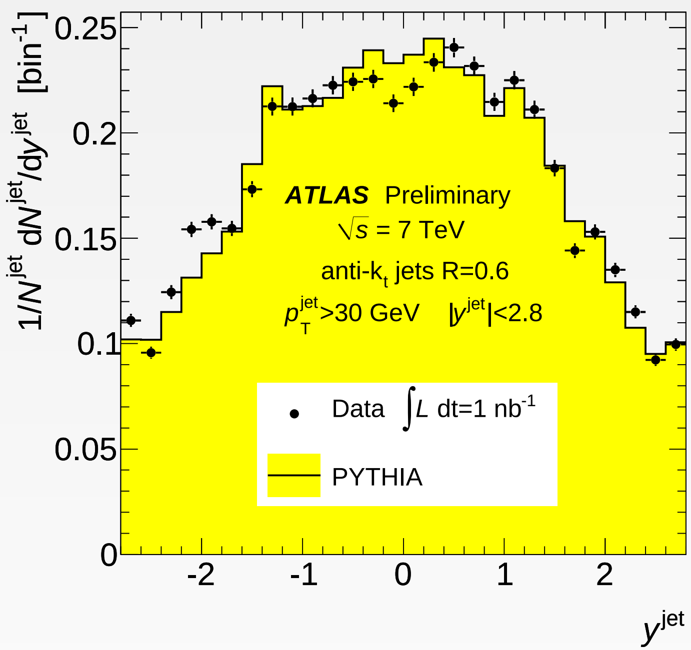
Physics at the LHC
Hamburg, 07–12.06.2010

Jets in ATLAS

Detector performance looks better than one might expect for first data

Good understanding of jet distributions and properties $\longrightarrow$ talk by E. Feng





What can we do with first 1 nb^{-1} – 100 pb^{-1}? For example

- Quantum gravity multijet searches
- Inclusive SUSY searches
- Exotic dijet searches

Large Extra Dimensions

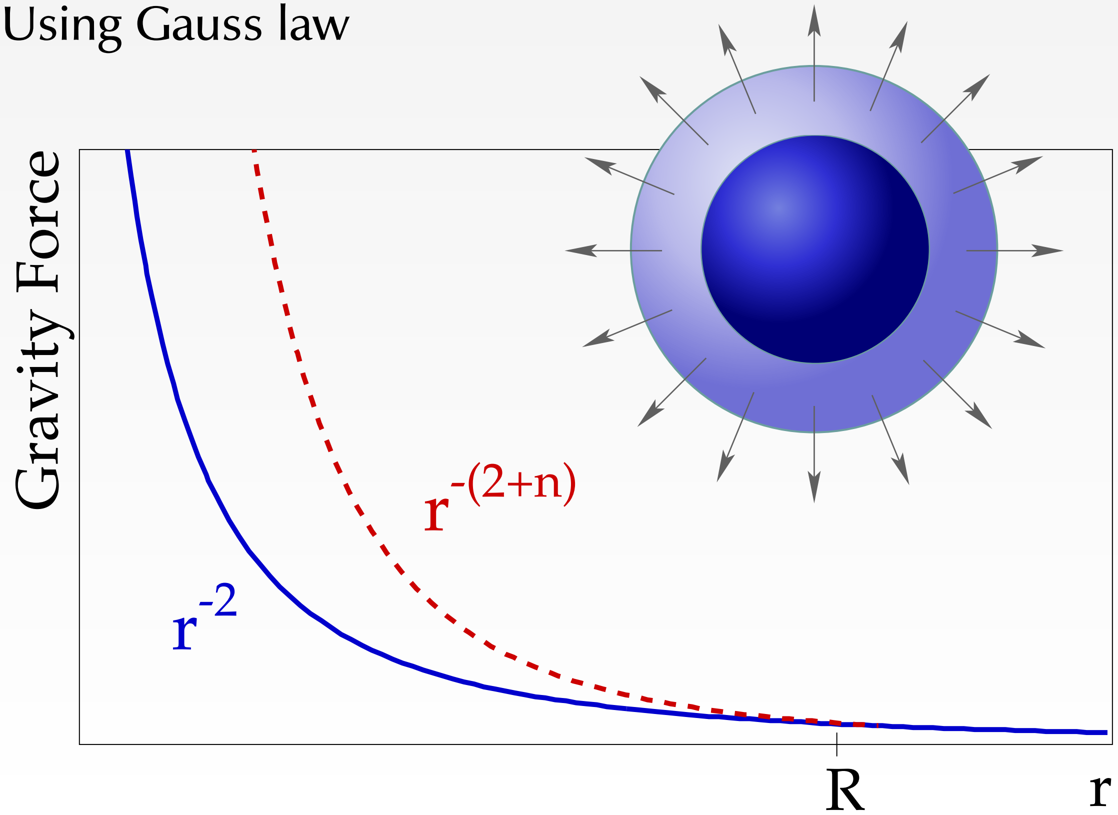
Hierarchy problem: $M_{EW} \sim 100\,\text{GeV}$ $\quad M_{Pl} = \sqrt{\frac{\hbar c}{G}} \sim 10^{19}\,\text{GeV}$

ADD approach

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

- n compactified extra dimensions of same size R
- Only gravity can propagate in extra dimensions

Using Gauss law



Fundamental scale M_D:

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

Large R $\Longleftrightarrow$ Small M_D

Assume $M_D \sim 1\,\text{TeV}$
to solve hierarchy problem

Black Hole Formation @ Hadron Colliders

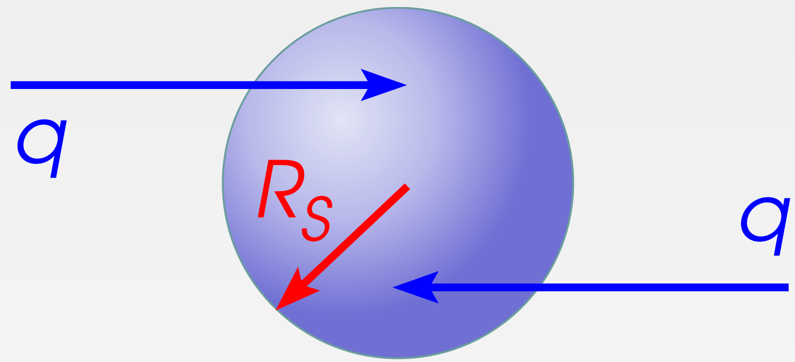
- Big energies $\Longleftrightarrow$ small distances.
  BH forms if partons come closer than $2R_S$

- 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 semi-classical "black disc" approximation:

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

- Possible for any combination of quarks and gluons.
  $\Longrightarrow$ BH are charged and coloured



R_S – Schwarzschild radius

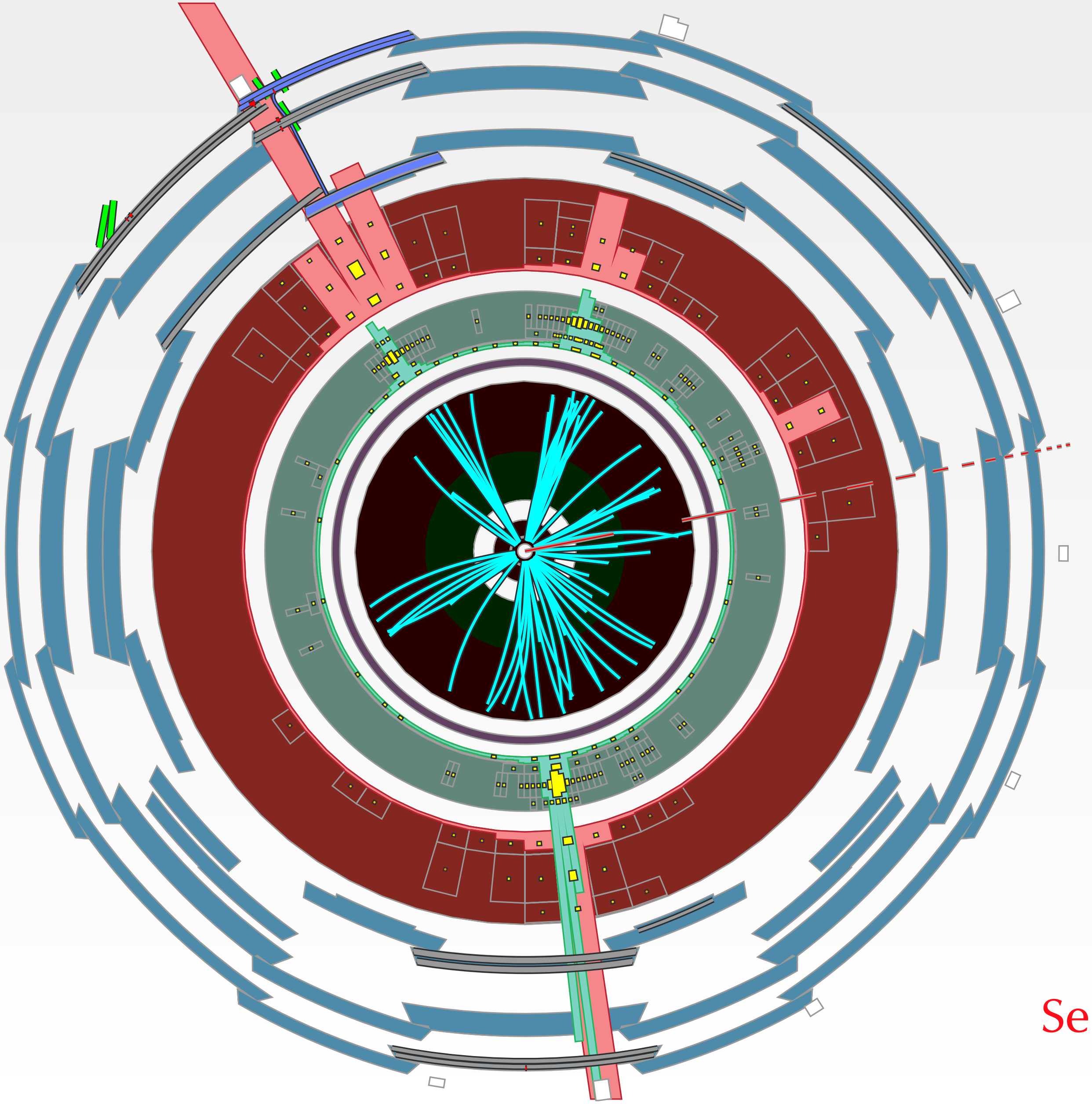
$$R_S \propto \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}}$$

Banks, Fischler: hep-th/9906038

Giddings, Thomas: hep-ph/0106219

Dimopoulos, Landsberg: hep-ph/0106295

Black Hole Event Simulation



Hawking radiation

- 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

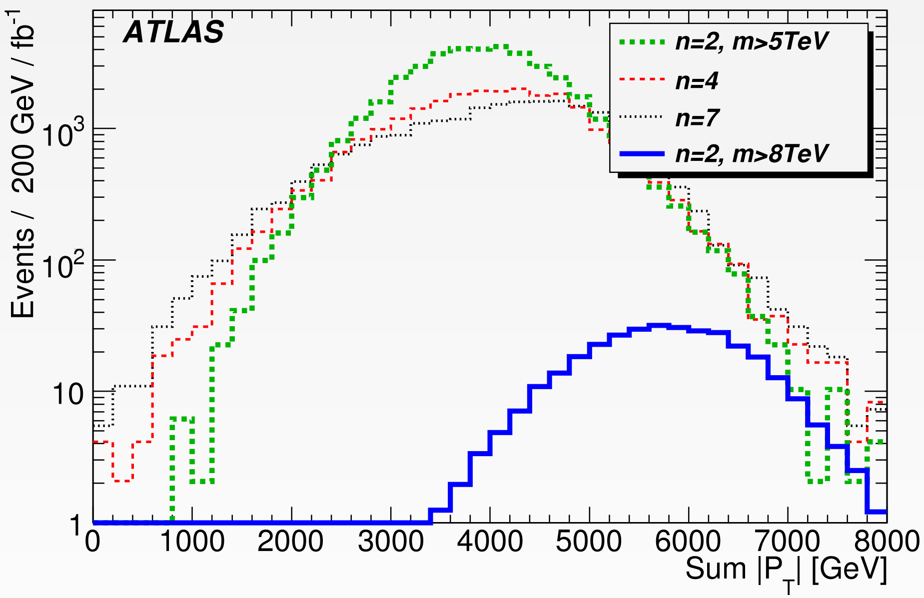
Semi-classical model: $M_{BH} \gtrsim 5 M_D$

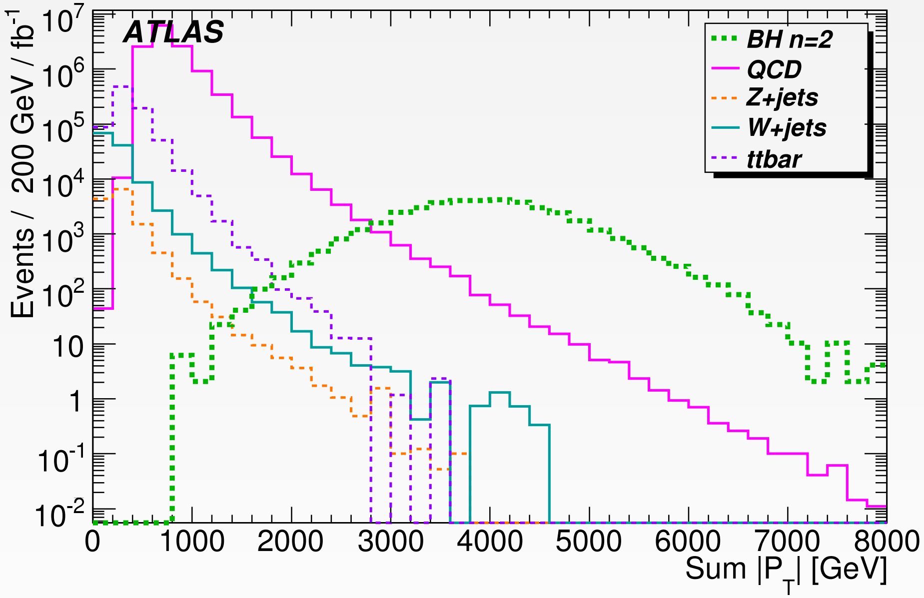
Black Hole Event Selection

Different strategies exist. ATLAS CSC book, arXiv:0901.0512

Example for $M_{BH} > 5\,\text{TeV}$, $M_D = 1\,\text{TeV}$, $\mathcal{L} = 1\,\text{fb}^{-1}$ at $\sqrt{s} = 14\,\text{TeV}$

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



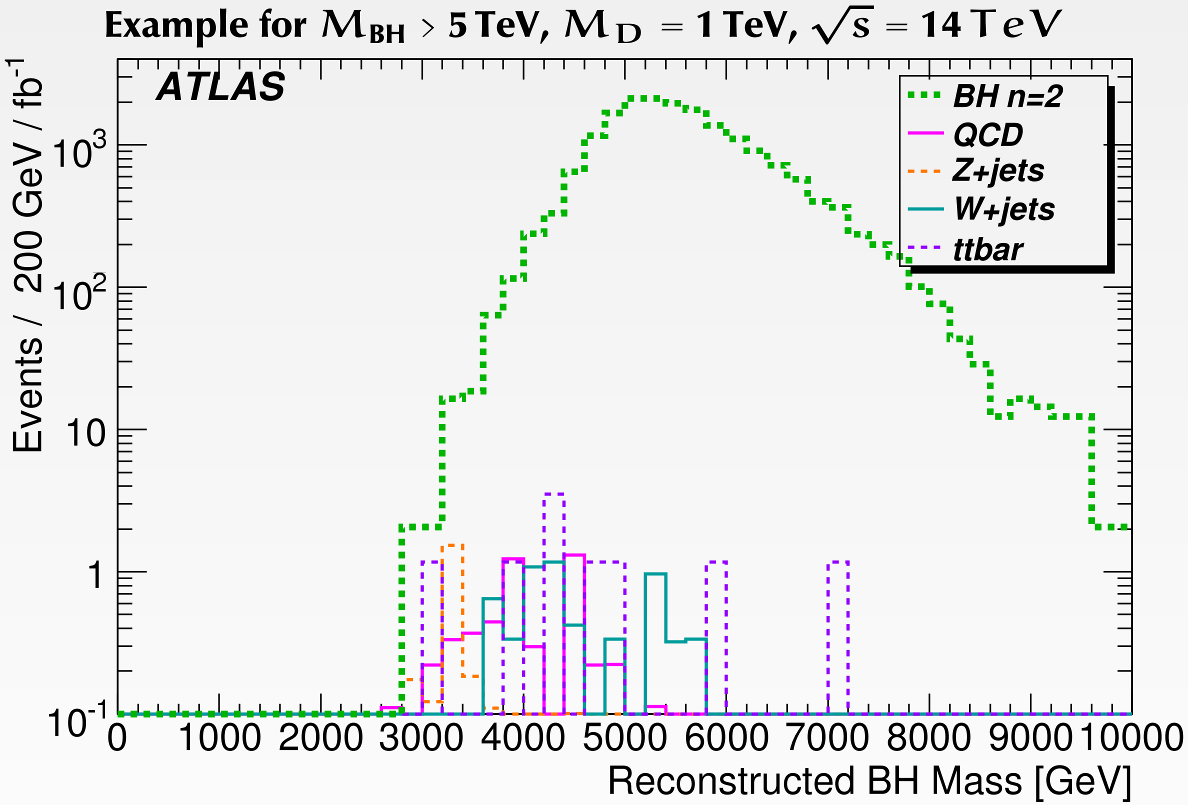


- Require at least one well identified lepton e or μ with $p_T > 50\,\text{GeV}$

  QCD background further reduced by factor ~ 60

Black Hole Mass Reconstruction

$$\mathbf{p}_{BH} = \sum \mathbf{p}_i + (\not{E}_T, \not{E}_{T_x}, \not{E}_{T_y}, 0) \longrightarrow M_{BH} = \sqrt{\mathbf{p}_{BH}^2}$$

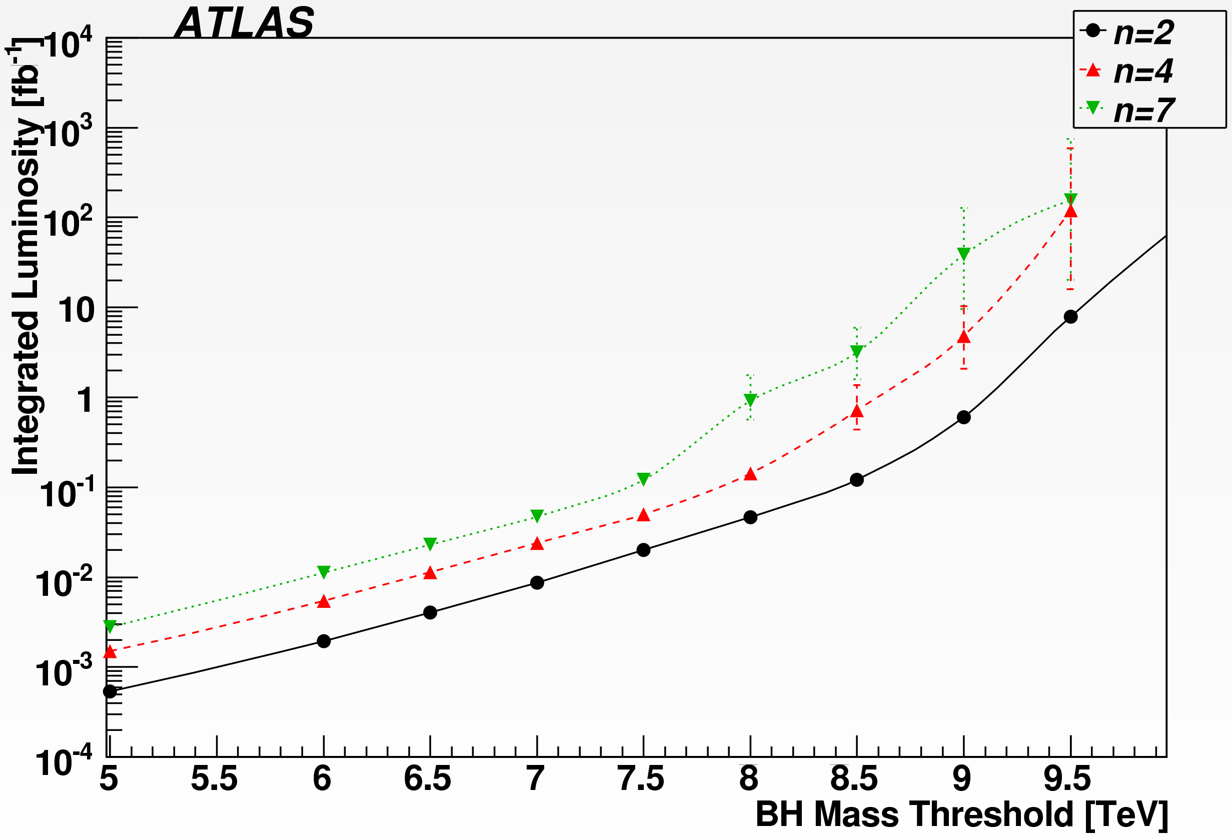


However, turn-on behaviour for $M_{BH} \gtrsim M_D$ is unknown!

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

$M_D = 1$ TeV, $\sum |p_T| > 2.5$ TeV, lepton requirement, $\sqrt{s} = 14$ TeV



Search Strategy for First Data

- Little access to $M_{\rm BH} > 5\,\text{TeV}$ with first data at $\sqrt{s} = 7\,\text{TeV}$
  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 $M_{\rm inv} \gtrsim 1\,\text{TeV}$
  If geometric $\hat{\sigma} = \pi R_S^2$ starts at $M \sim 1\,\text{TeV}$, cross section would be in nb range
- **Example**: string balls

String Balls

String balls – excited string states in weakly-coupled string theory

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

$$M_s < M_D < \frac{M_s}{g_s^2}$$ } black hole threshold

string scale — Planck scale — string coupling

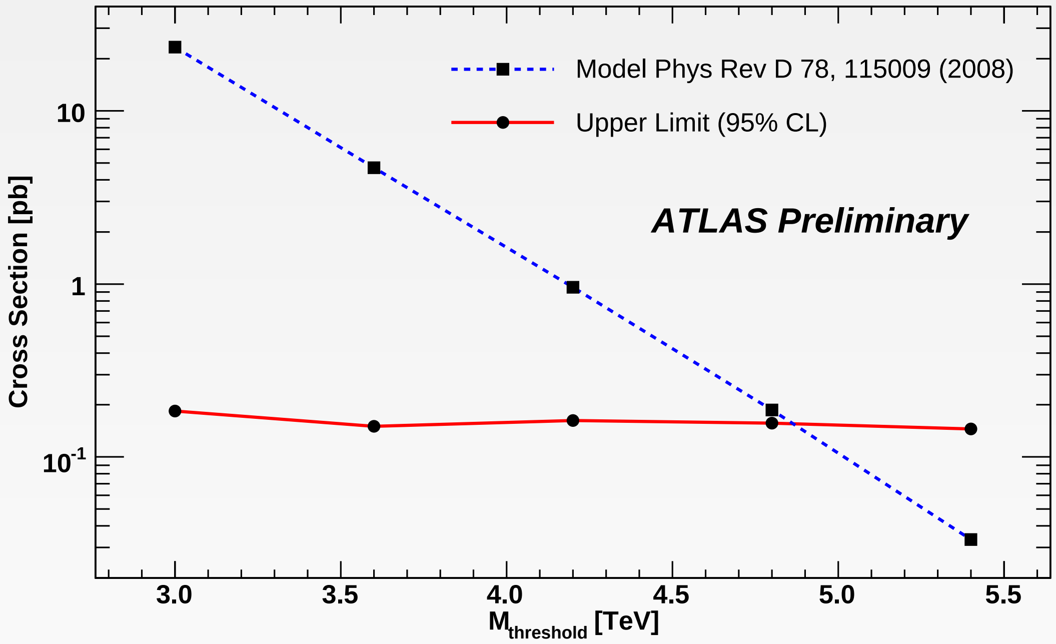
Cross sections comparable with BH but below GR threshold
Typical assumption for highly excited string state: $M > 3M_s$

Search for String Balls

Analysis strategy similar to BH searches

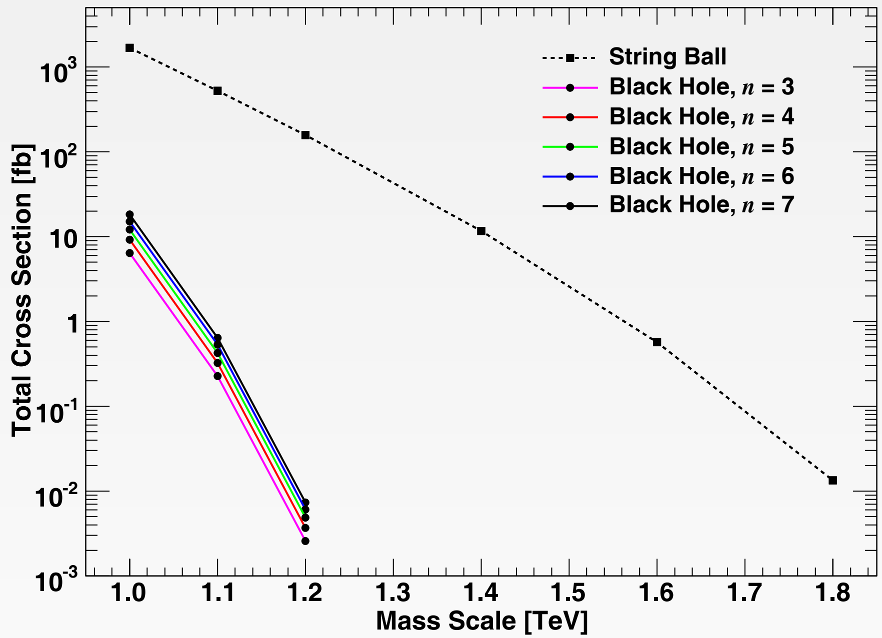
ATLAS-PHYS-PUB-2009-011

Cross section upper limit for 100 pb^{-1} at 10 TeV



Cross section at 7 TeV

D. Gingrich

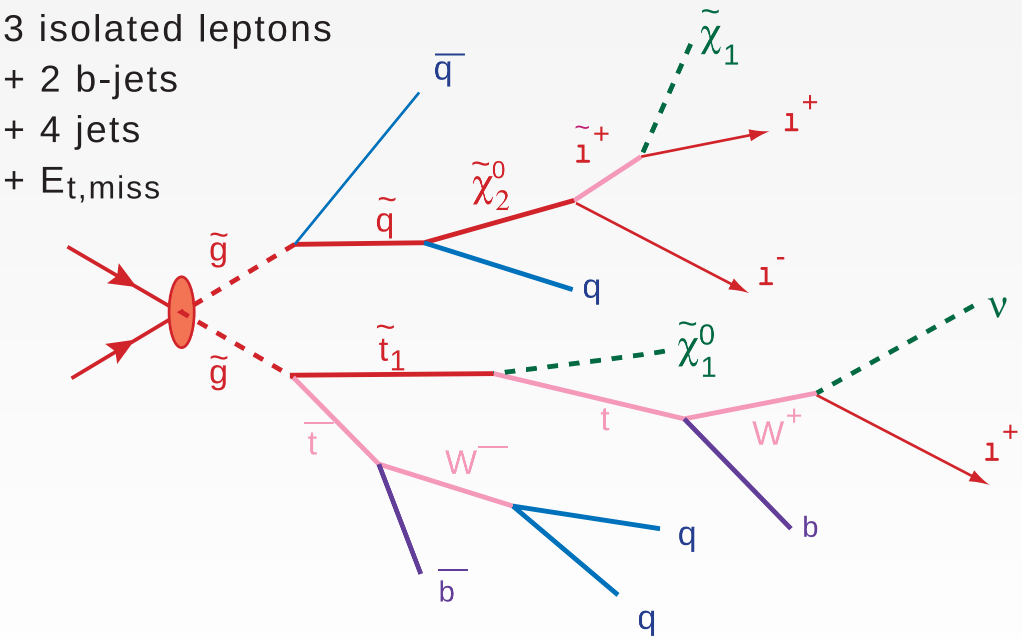


- String Balls can be excluded up to $M \sim 5\,\text{TeV}$ with $100\,\text{pb}^{-1}$ at $\sqrt{s} = 10\,\text{TeV}$
  In this model, this corresponds to $M_S \approx 1.5\,\text{TeV}$ and $M_D \approx 2.4\,\text{TeV}$
- At 7 TeV cross section can still be in pb range for $M > 3\,\text{TeV}$

SUSY Signatures at the LHC

Long decay cascades down to LSPs

- High E_T jets from $\tilde{q} \to q\tilde{\chi}_i^0$, $\tilde{q} \to q'\tilde{\chi}_i^\pm$, $\tilde{g} \to q\tilde{q}$
- Large Missing E_T due to invisible LSPs
- isolated leptons from $\tilde{\chi}_2^0 \to l\tilde{l}$, $\tilde{l} \to l\tilde{\chi}_1^0$



ATLAS study at $\sqrt{s} = 10\,\text{TeV}$

- "Standard" mSUGRA signals
- Phenomenological MSSM
  - 19 free soft SUSY breaking parameters
  - 200 points allowed by LEP, Tevatron and dark matter searches

SUSY Analysis Strategy

ATL-PHYS-PUB-2009-084

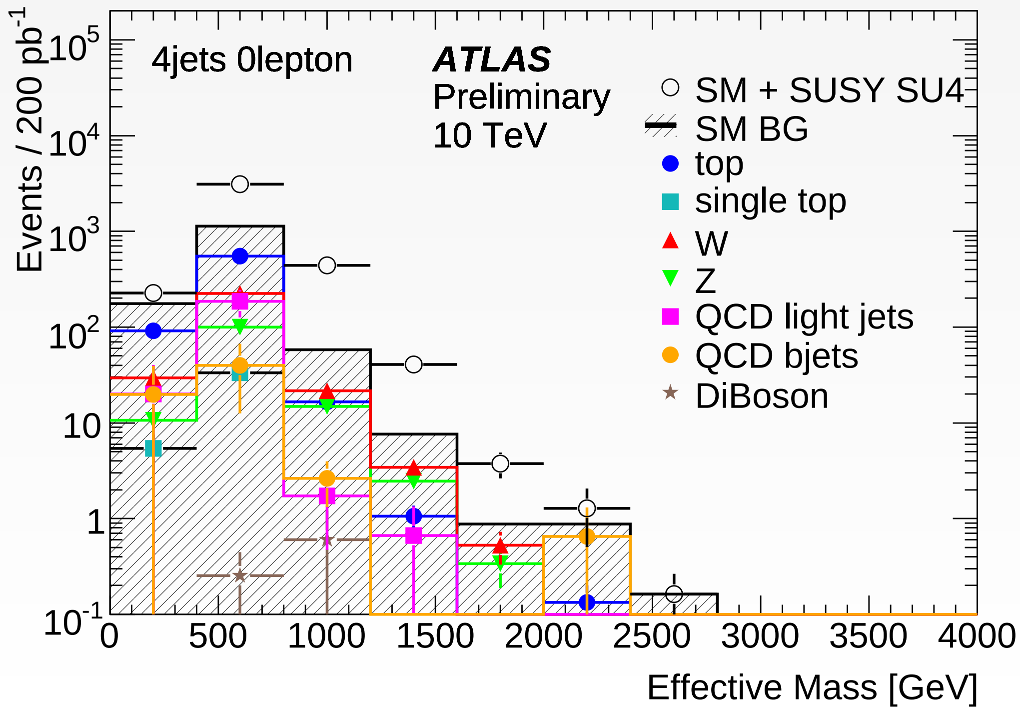
- **Event Selection**
  - Select $\geqslant 2$, $\geqslant 3$, $\geqslant 4$ jets with $p_T > 40 - 50\,\text{GeV}$
  - Select exactly 0, 1, 2 SS, 2 OS leptons with $p_T > 20\,\text{GeV}$
  - Require $E_T^{miss} > 80\,\text{GeV}$ and $E_T^{miss} > f \times M_{eff}$
  - Further cuts suppressing certain background topologies

- **Search for deviations from SM** in

$$M_{eff} = \sum_{jets} |p_T| + \sum_{leptons} |p_T| + E_T^{miss}$$

- **Crucial issues**
  - Background suppression
  - Background understanding using control regions
  - Understanding of E_T^{miss}

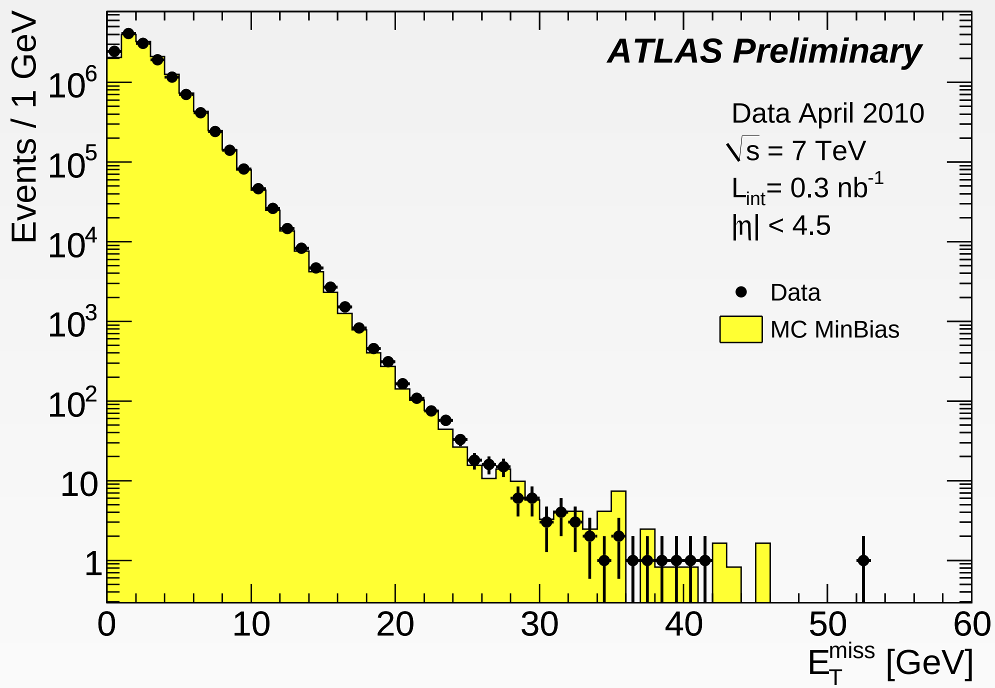
Example: SU4, $\geq$4 jets and 0 leptons

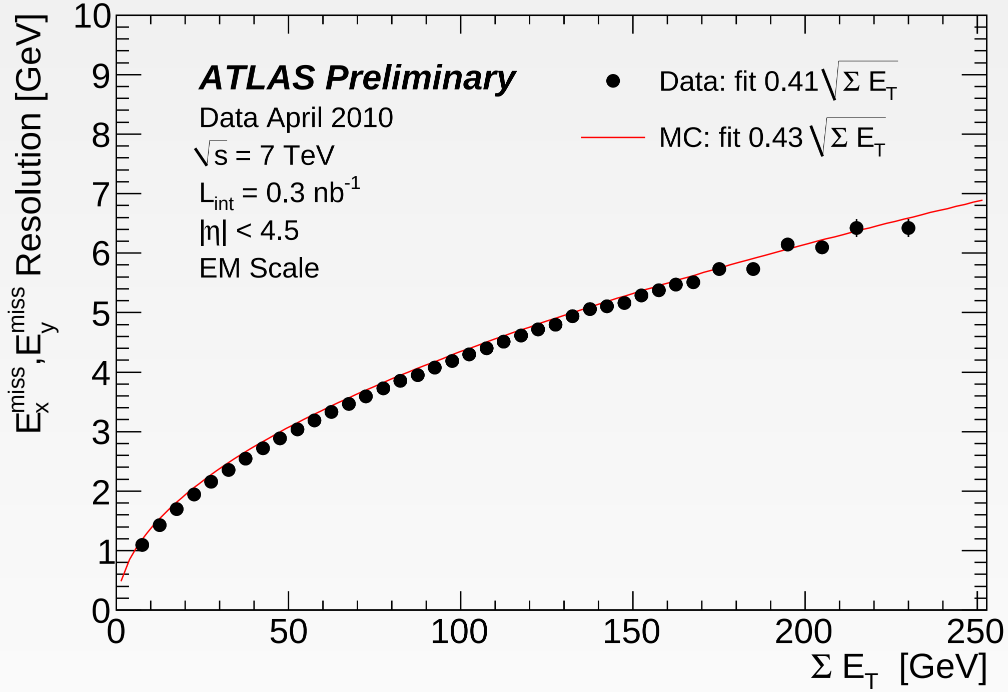


Missing E_T Performance in Data at $\sqrt{s} = 7$ TeV

Min.bias data

Cells in topological clusters at uncorrected electromagnetic scale

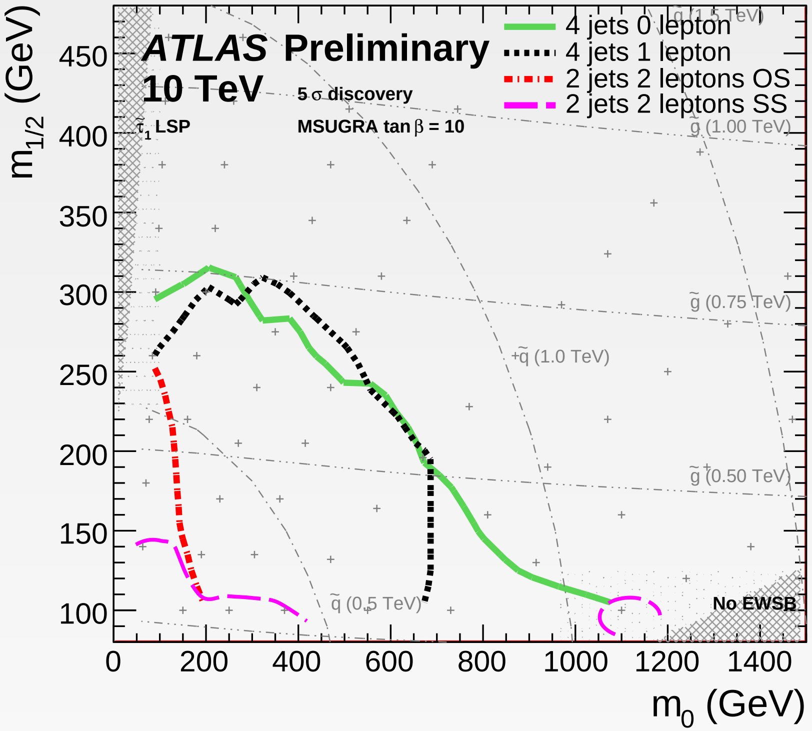


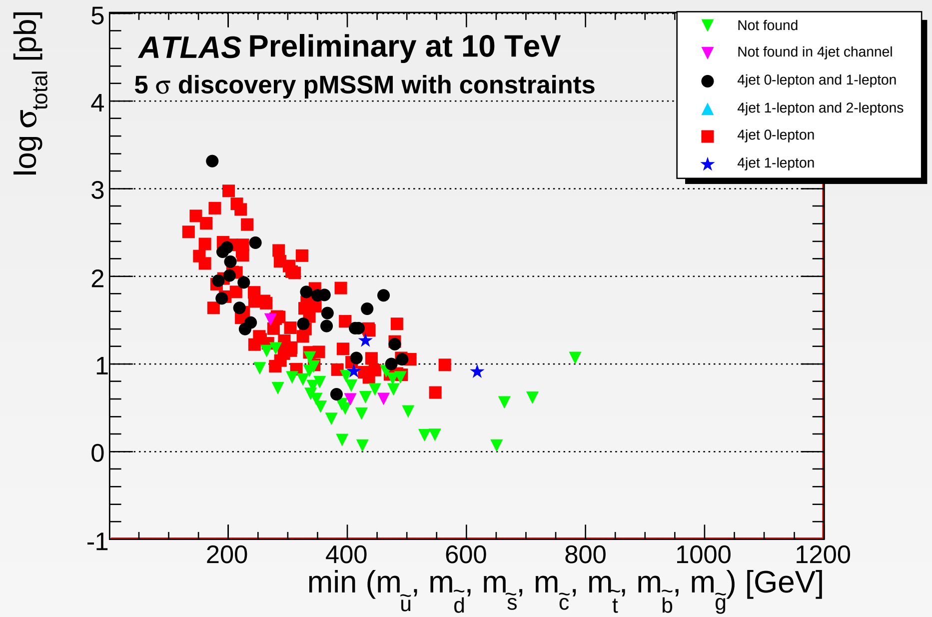


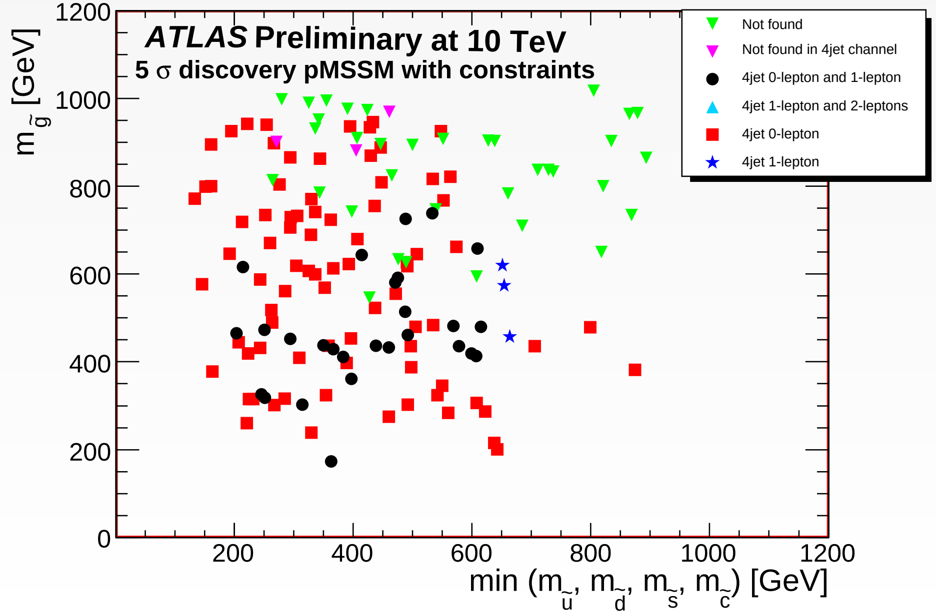
E_T^{miss} tails and resolution are in good agreement with the simulation

⟶ talk by A. Yurkewicz

SUSY Discovery Reach







- Most pMSSM signals can be discovered in 4-jet channel if $\sigma > 10\,\text{pb}$
- Typical mass range at $\sqrt{s} = 10\,\text{TeV}$: $m_{\tilde{q},\tilde{g}}$ up to $600 - 800\,\text{GeV}$
- Reach in $1\,\text{fb}^{-1}$ at 7 TeV is similar to $200\,\text{pb}^{-1}$ at 10 TeV

Conclusions

- With impressive detector performance in first data, ATLAS is starting first searches in jet signatures

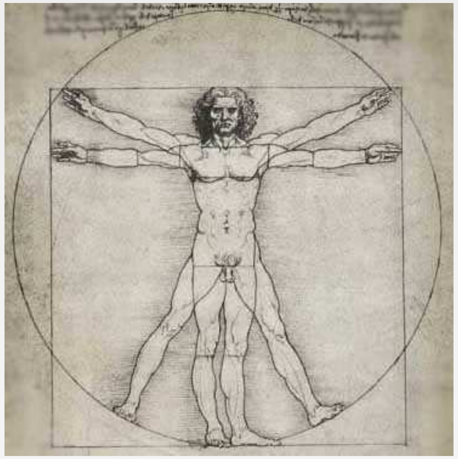
- First competetive exclusion limits may be possible even with a few nb^{-1} [e.g. for geometric cross section of quantum gravity at $M \sim 1$ TeV]

- Evidence for some phenomena is possible with first 1–100 pb^{-1} of data
  - Dijets [contact interactions, resonances]
  - Multijet quantum gravity effects
  - SUSY

FSP 101 ATLAS

Additional Information

Possible Sizes of Extra Dimensions



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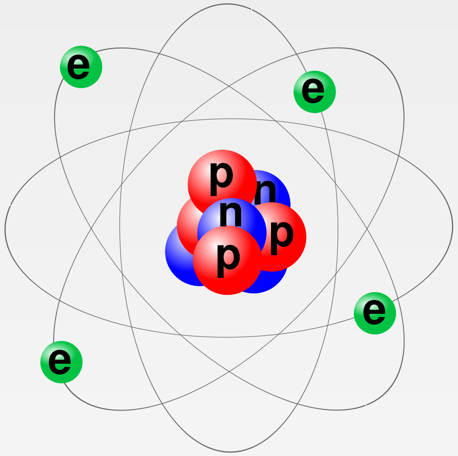

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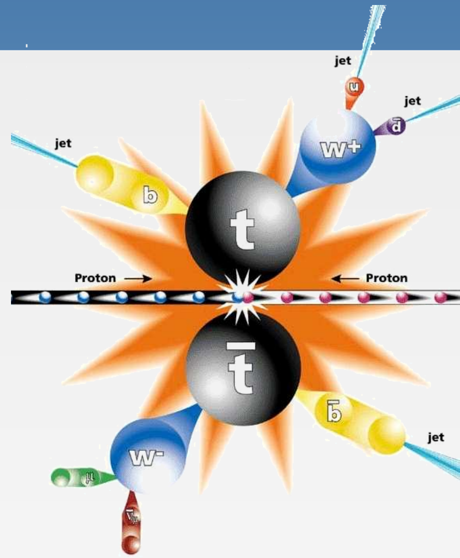


1 m 0.05 mm 10^{-10} m 10^{-20} m

Newton's gravity law | . . . . .changes? . . . .

direct gravity tests

hep-ph/0611184

Size R_C for $M_D = 1$ TeV

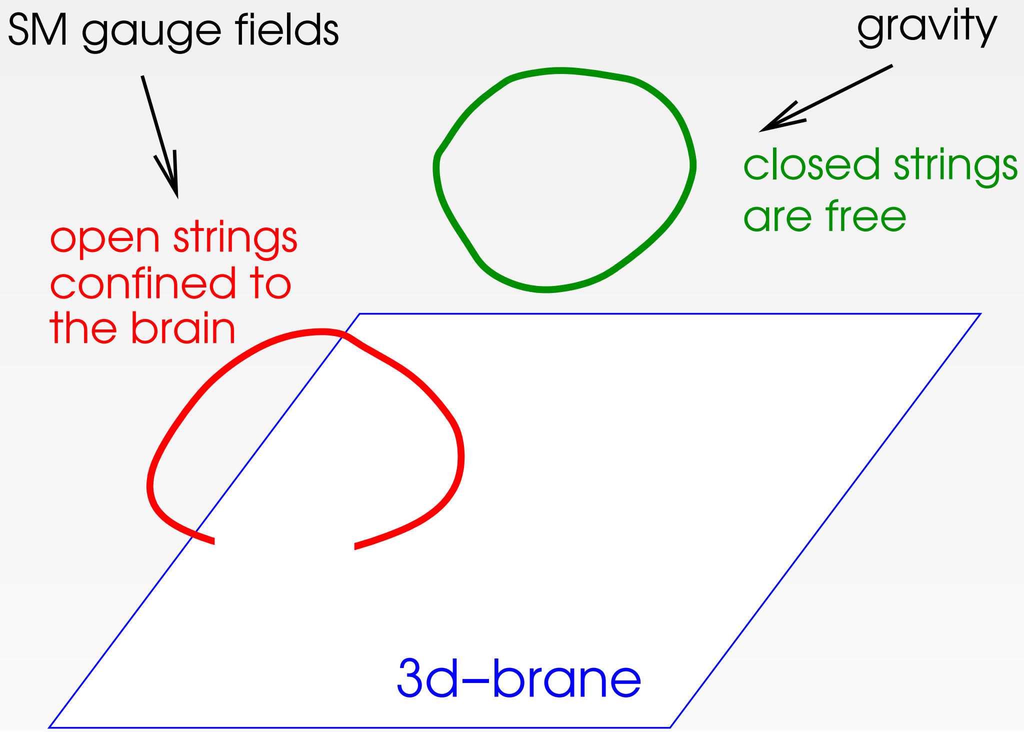
n	1	2	3	...	7
R_C	10^{10} km	1 mm	1 nm	...	1 fm

↑ $\mathcal{O}$(Solar system)

↖ ↑ ↗ "large" compared to HEP scales

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

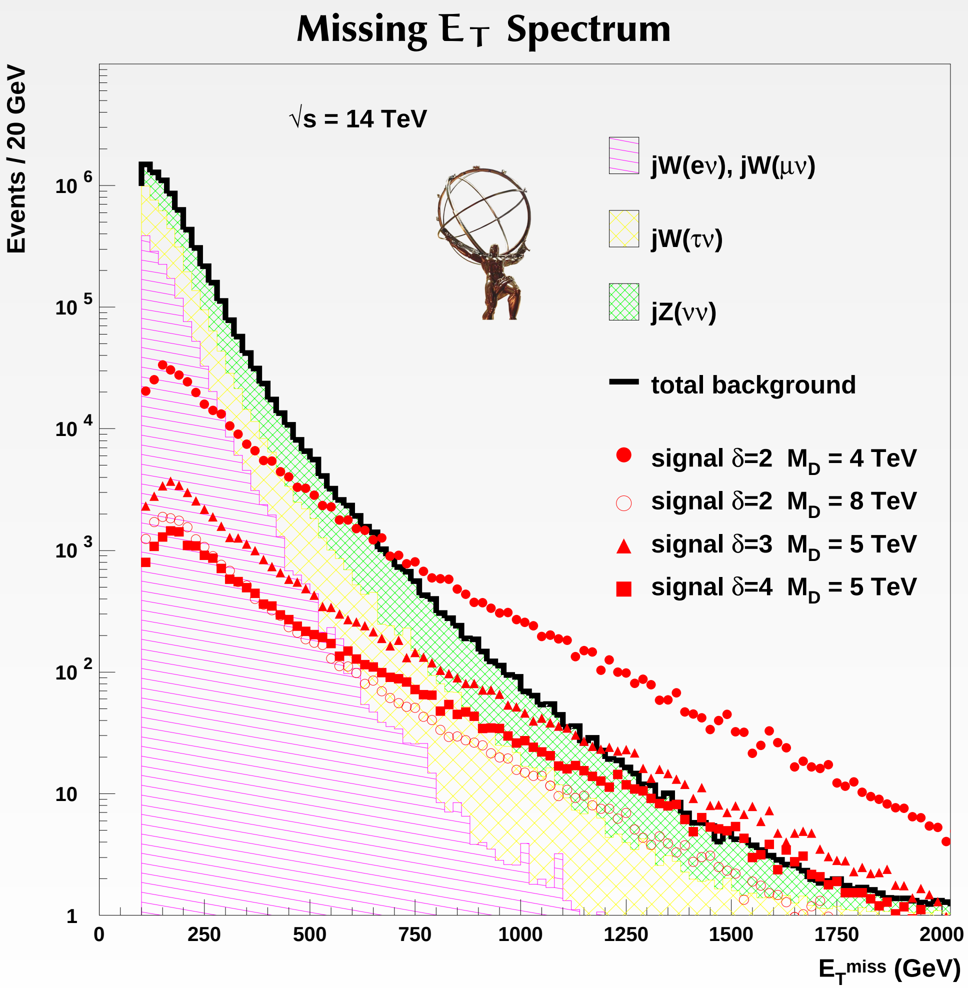


String theories require 6 – 7 extra dimensions, but not necessary of the same size

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

Monojets @ ATLAS

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



- ATLAS fast MC studies
- 5σ discovery sensitivity for $100\,\mathrm{fb}^{-1}$:

n	2	3	4
M_D / TeV	9	7	6

Present limits: 1.4 TeV ($\delta = 2$); 1.0 TeV ($\delta = 4$)

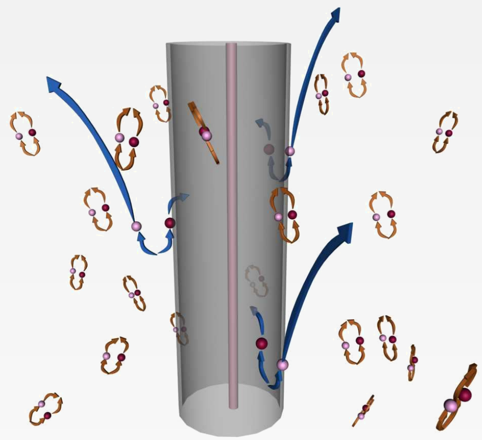
- No instrumentation effects included

Hawking Radiation

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

- Particles have black body spectrum with temperature

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



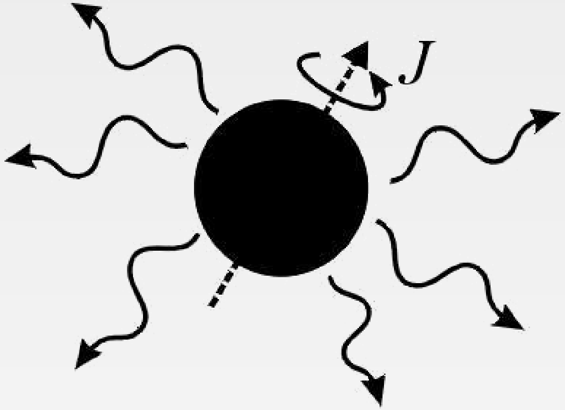
- No chance to discover Hawking radiation of astro black holes
  $T_H \ll T_{CMB}$

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

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

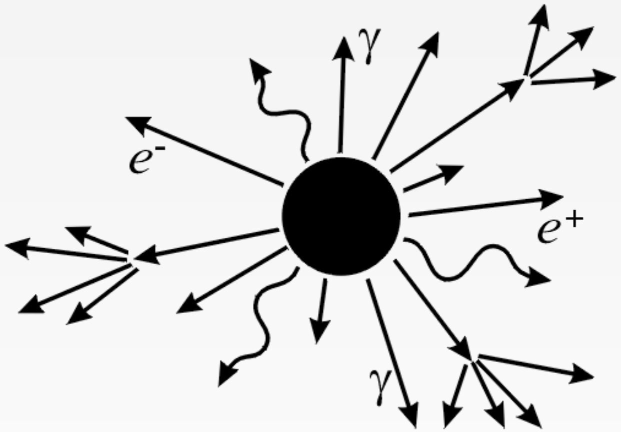
- At high enough T_H massive particles are also produced

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.

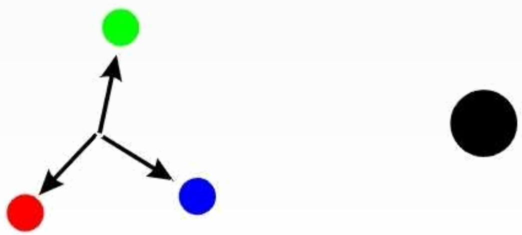
a) spin down – losing angular momentum;

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

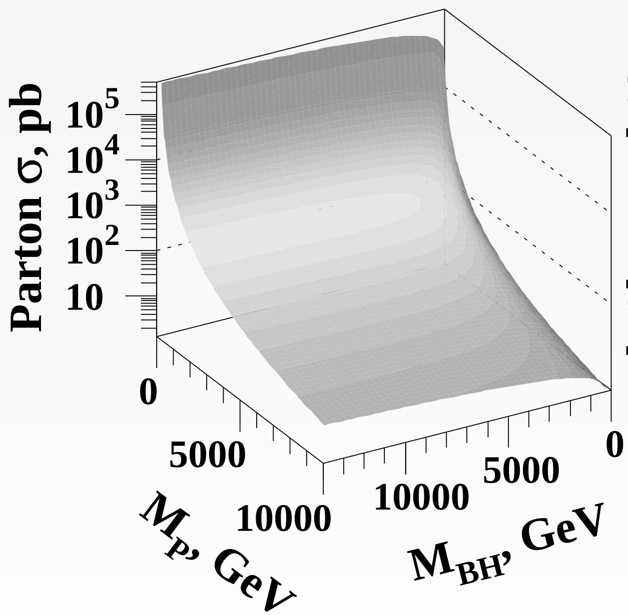
Identifying Black Holes

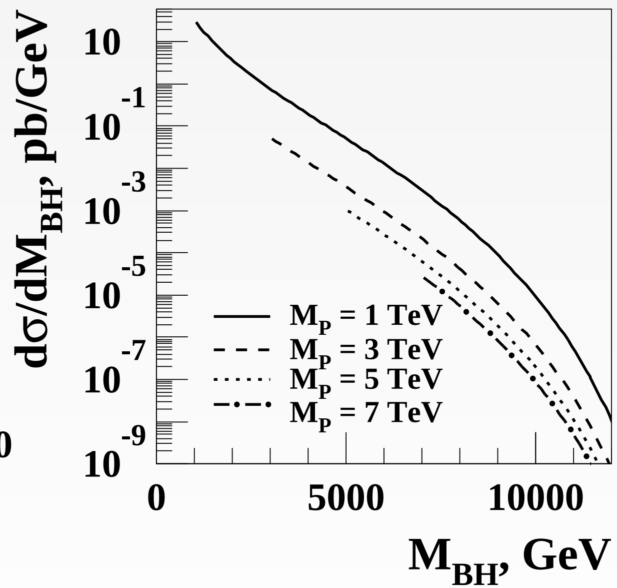
Need several evidences to be sure. Various ideas exist

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

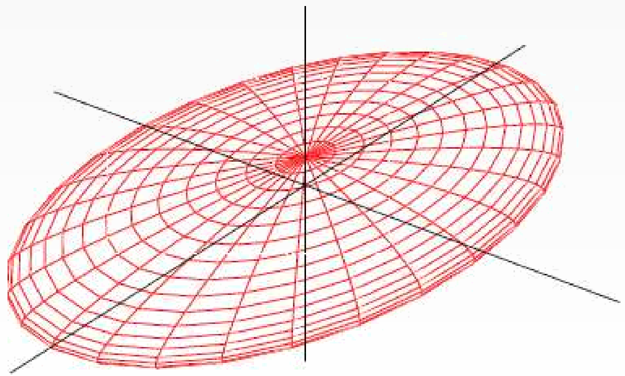
- Hawking radiation ≈ democratic decay in MC
  Look at distributions of particle types: ratios e/μ , e/Z^0 , e/t . . .

- 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

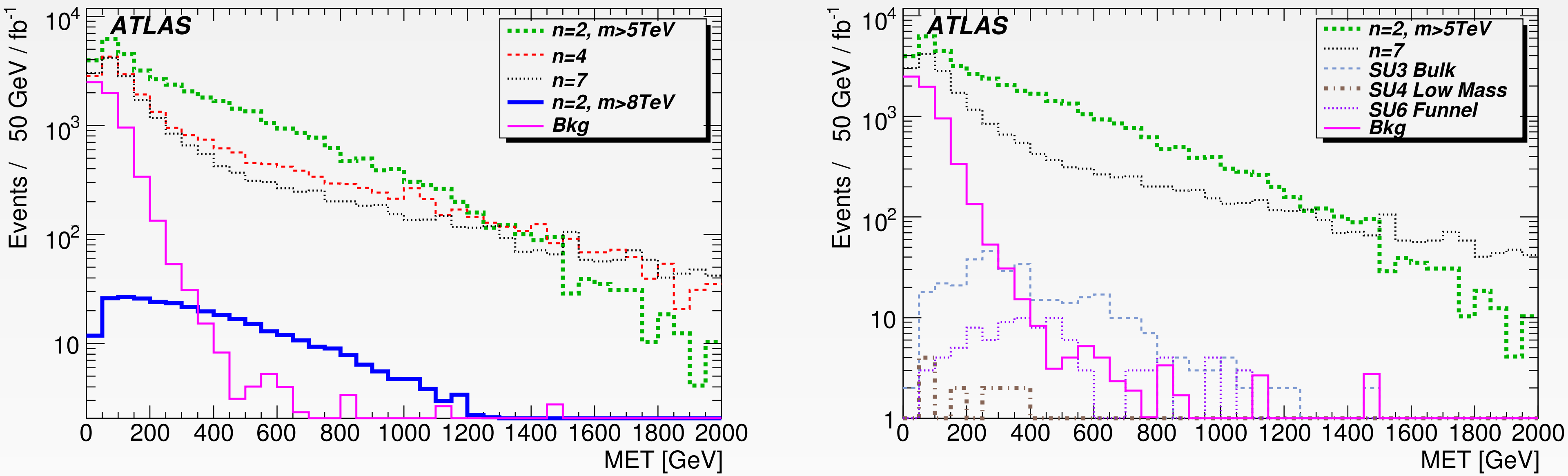


- Look at event shapes (sphericity, (a)planarity, thrust . . .)

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, as graviton radiation was not simulated
- Such high $\not{E}_T$ are not typical for SUSY – would require high mass neutralino LSP

Black Hole Model Uncertainties

Large uncertainties within "semiclassical" approach.

Previously missing features are implemented in new MC versions:

- Gravition emission
- Rotation
- Possible brane tension
- Conservation of quantum numbers (lepton, flavours)
- More elaborated final burst models

Several analysis strategies are developed for different scenarios.

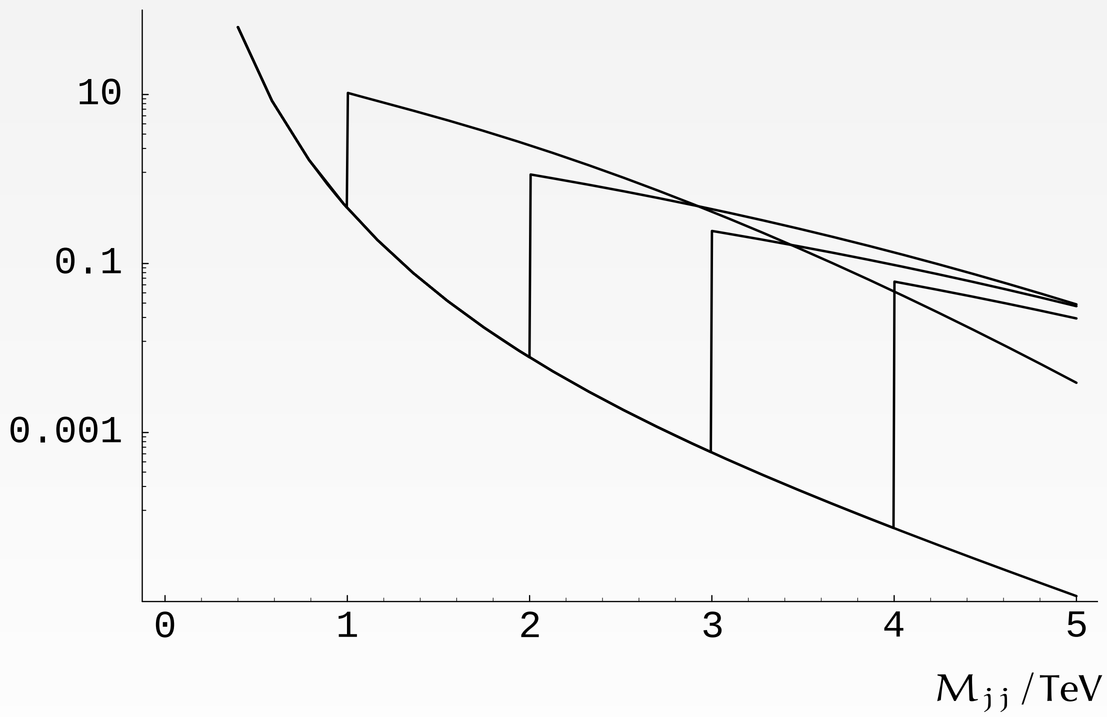
Gravity Effects in Contact Interactions

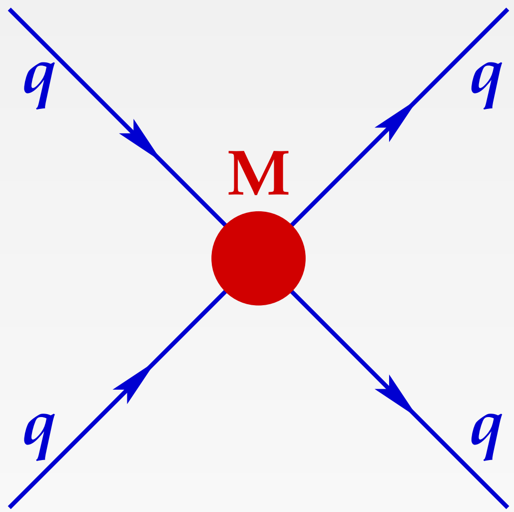
- Black holes at $M \sim M_D$ may appear in contact interactions
  This can be any quantum gravity effect or resonance

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.

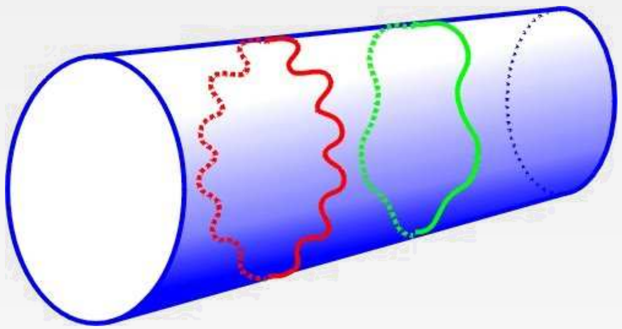
- Good candidate for discovery in first data

Universal Extra Dimensions

Allow all SM particles to go in extra dimensions

Appelquist, Cheng, Dobrescu:
hep-ph/0012100

- Kaluza–Klein excitations of all SM particles
  All masses are of order $1/R_C$



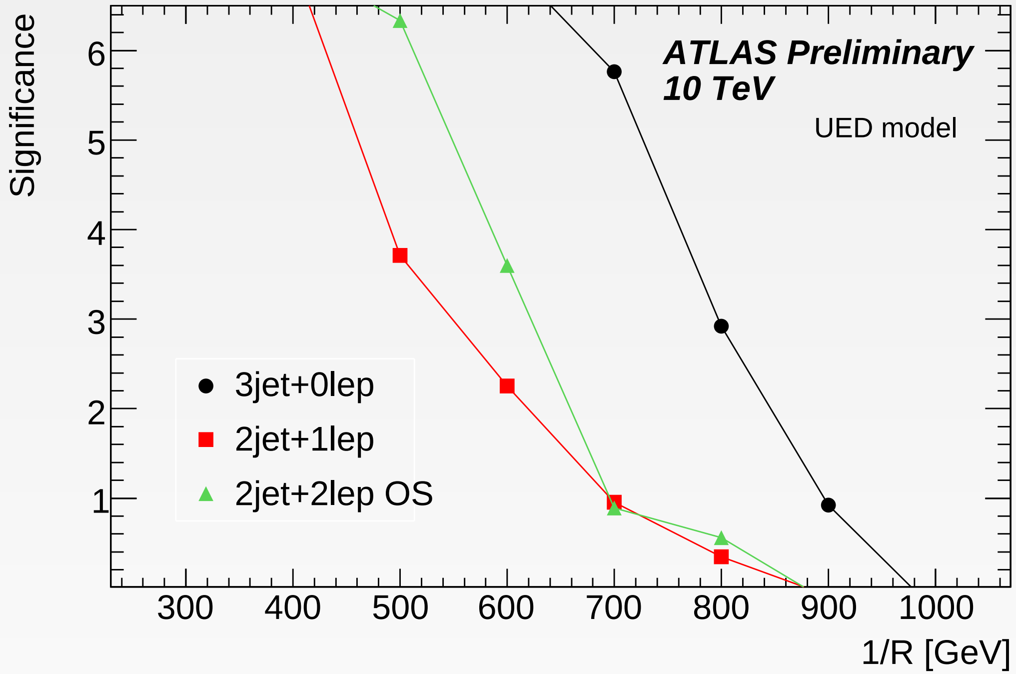
- Momentum in bulk must be conserved
  as no particle is kept on the 3D-brane
  $\longrightarrow$ KK states are produced in pairs – as in MSSM
  $\longrightarrow$ Introduce KK parity – similar to R-parity
- Current constraints: $1/R_C \gtrsim 300 - 500\,\mathrm{GeV}$
- Reach phenomenology similar to SUSY with squized mass spectra
  $\longrightarrow$ Long decay channels
  $\longrightarrow$ Lightest KK excitation is stable – missing E_T

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

UED Discovery Reach

Similar analysis strategy as for SUSY

ATL-PHYS-PUB-2009-084



UED can be discovered for $R \lesssim 700\,\mathrm{GeV}$ with $200\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 10\,\mathrm{TeV}$