Searches for Quantum Gravity at the LHC

ATLAS

CMS

Outline

- Semi-Classical Black Holes
- String Balls
- Quantum Black Holes

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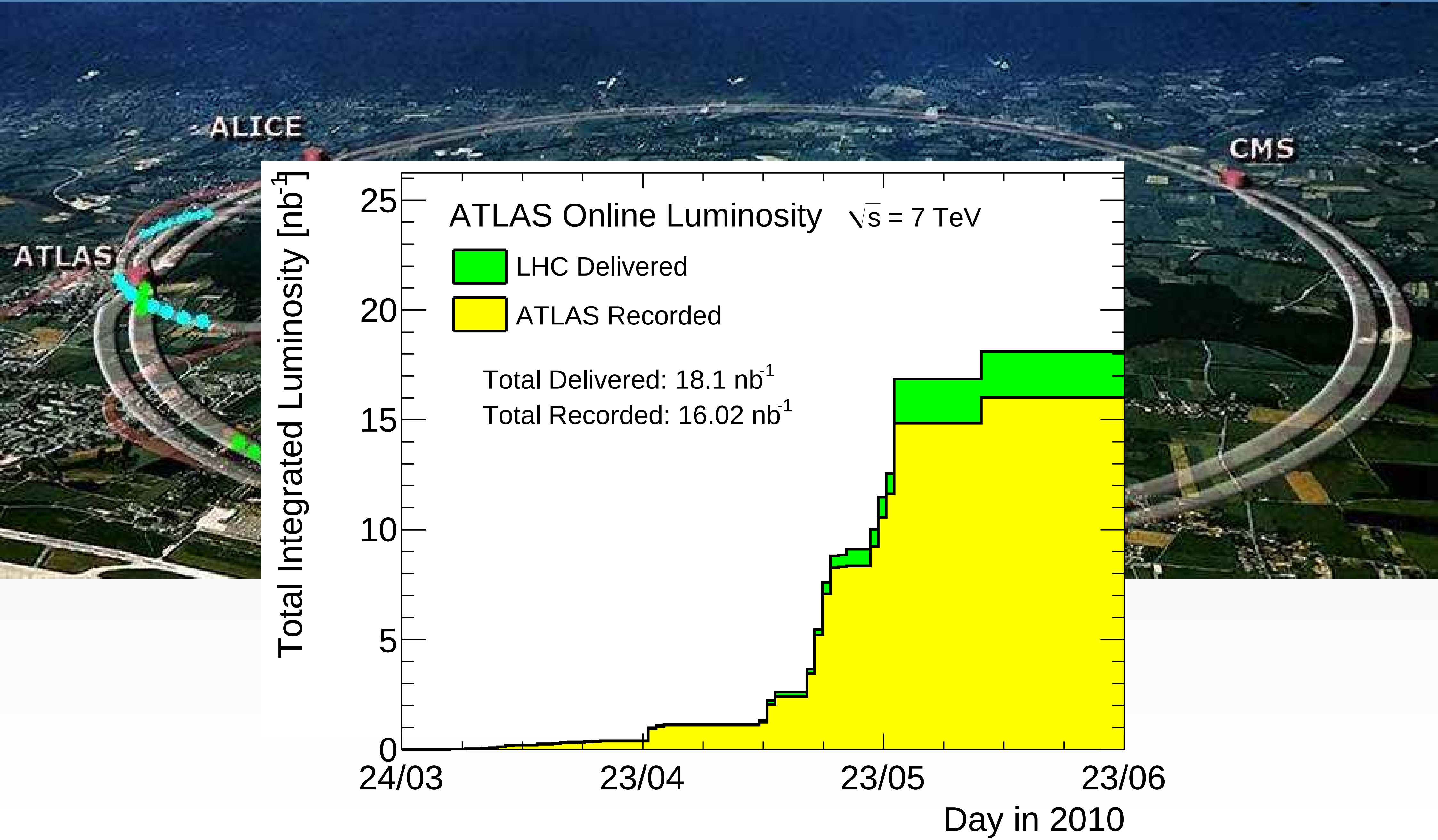
Universität Heidelberg

FSP 101 ATLAS

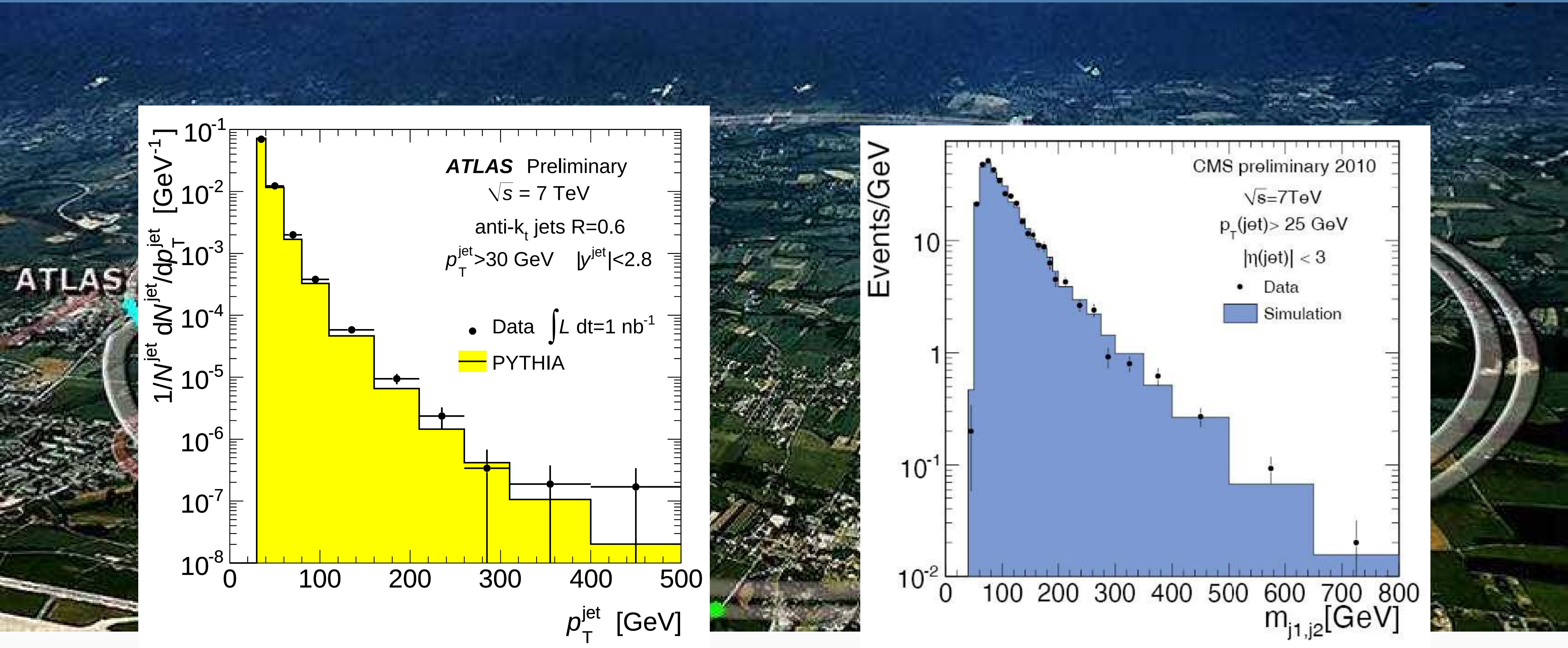
COST Action MP0905
Bonn, 24–25.06.2010

European Science Foundation

Current Status of LHC

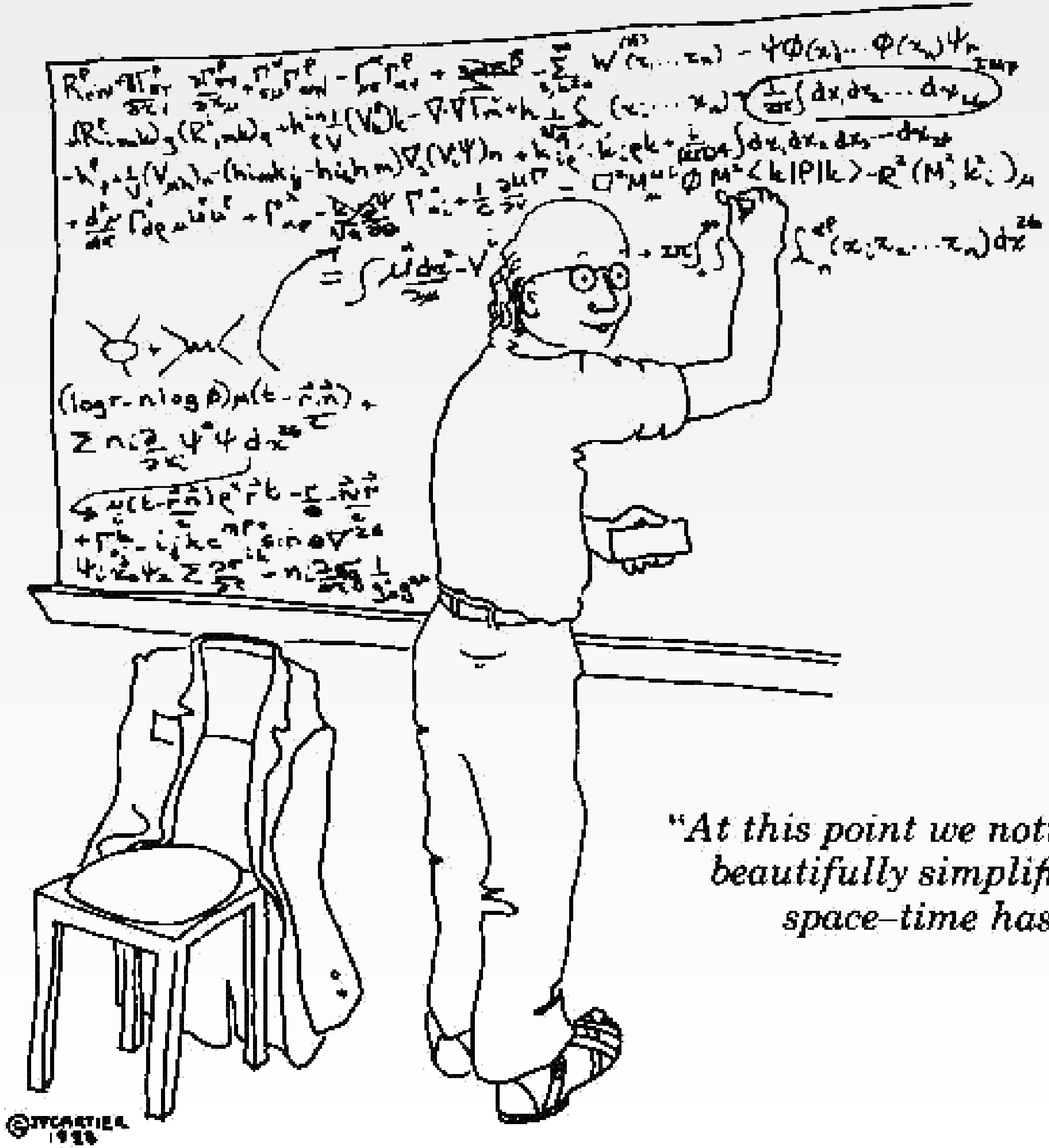


Current Status of LHC



- Detector performance looks better than one might expect for first data
- Good understanding of basic distributions and properties
- First results of searches for new physics are being prepared
- Only MC simulation studies in this talk

Extra Dimensions

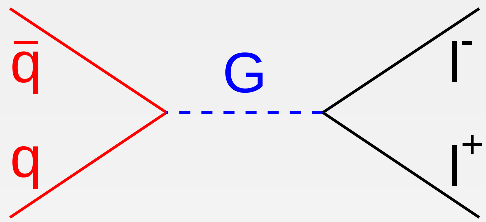


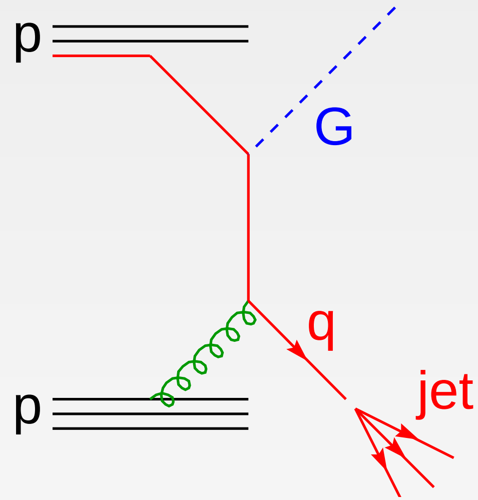
"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

Signatures of Gravity with Extra Dimensions

Perturbative processes

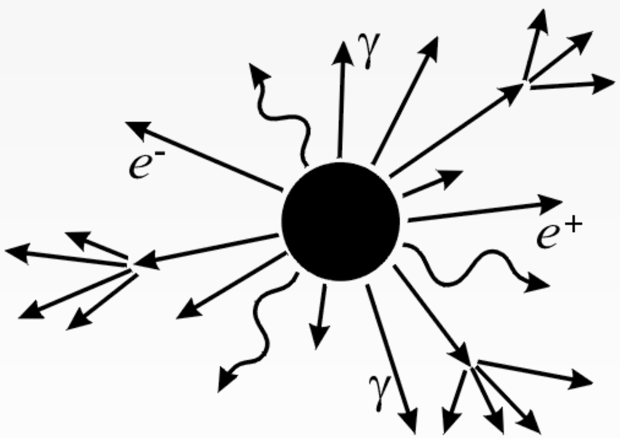
- Exchange of virtual gravitons
- Production of real gravitons

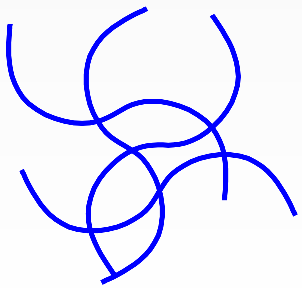


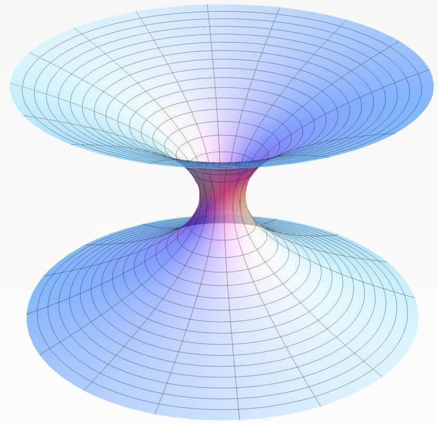


Strong gravity scenarios

- Mini black holes
- String balls
- Time machines
- . . .







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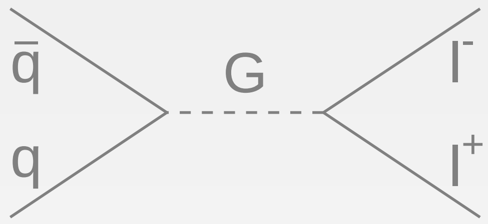

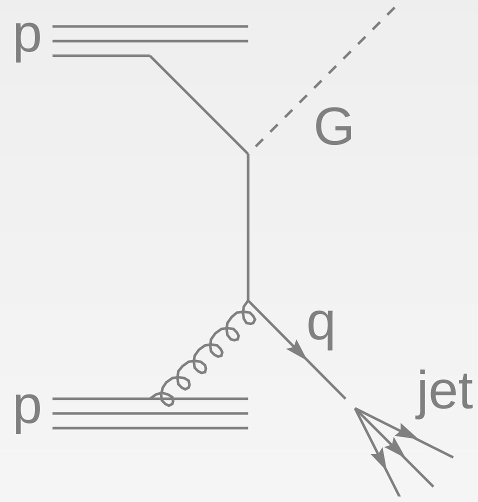

Strong gravity scenarios

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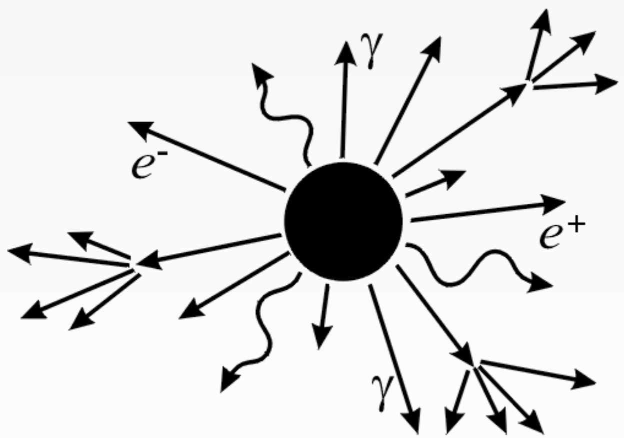
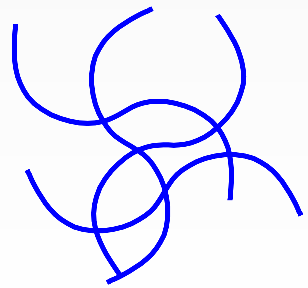
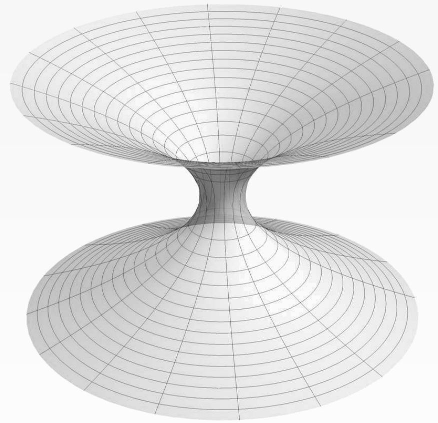
Rest of the talk



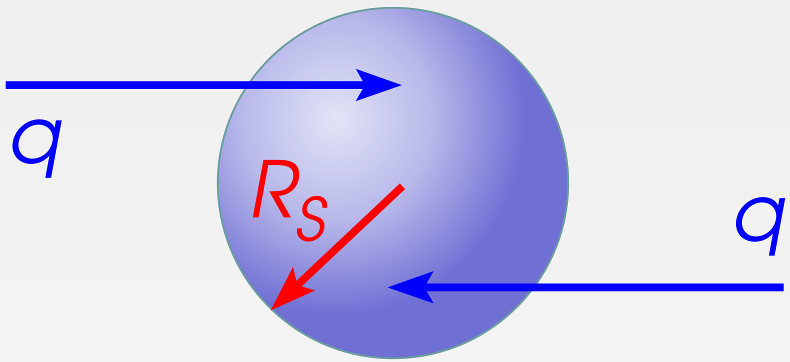




Black Hole Formation @ Hadron Colliders

- 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

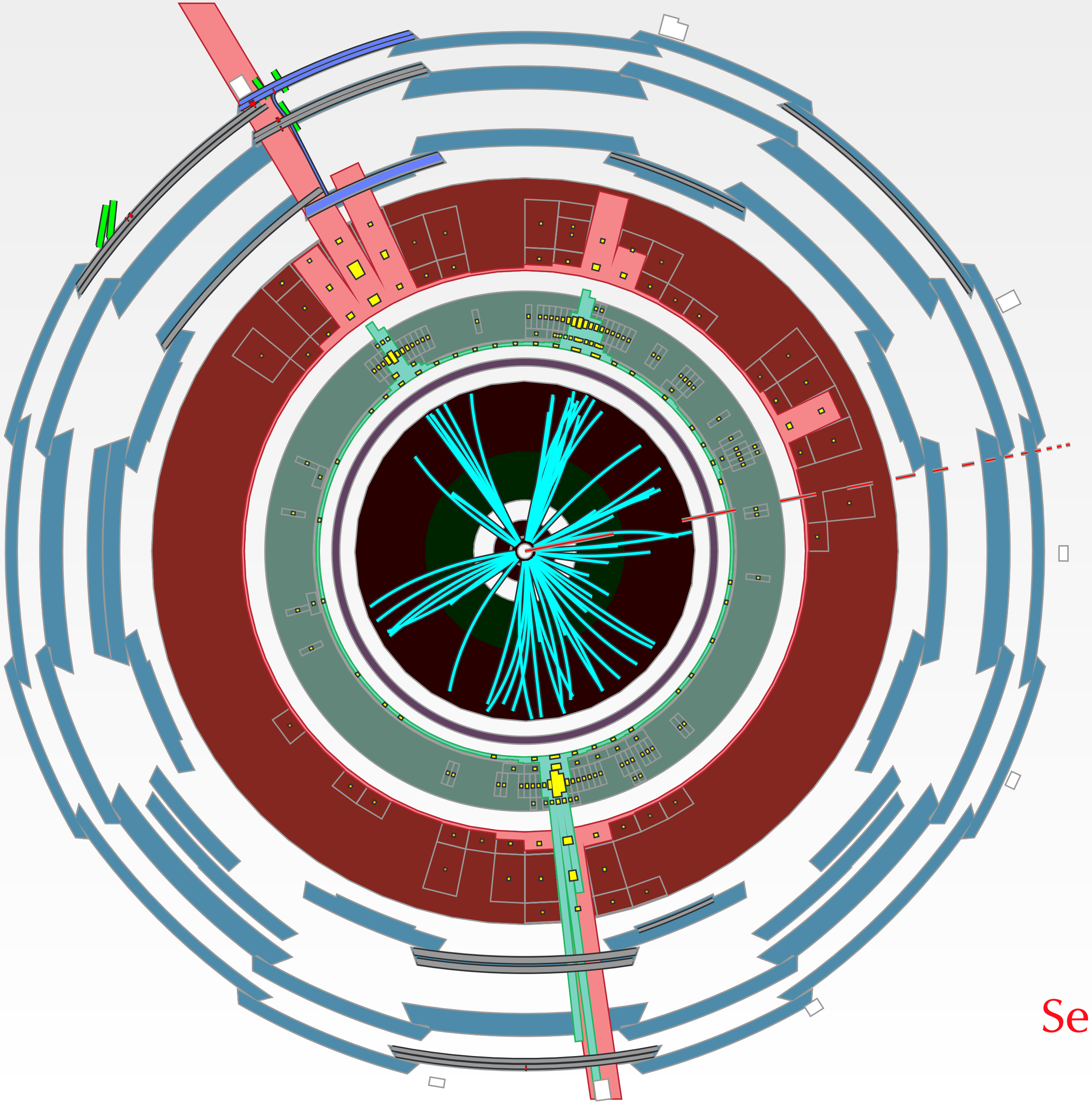
$$R_S \propto \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}}$$

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: $M_{BH} \gtrsim 5M_D$

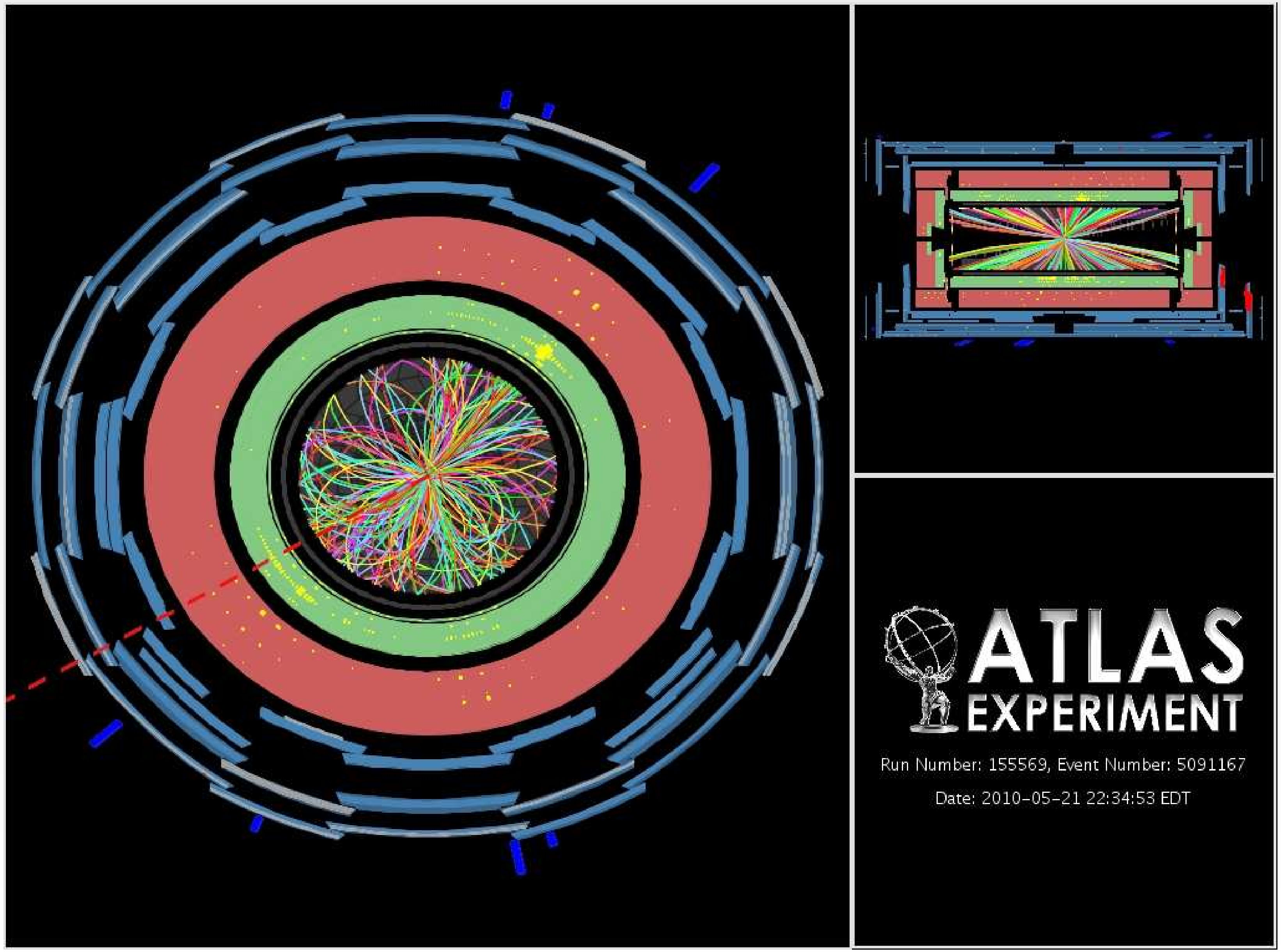
Interesting Event in ATLAS

7 Jets

1 Muon

$\sum E_T > 900\,\text{GeV}$

$E_T^{miss} > 100\,\text{GeV}$



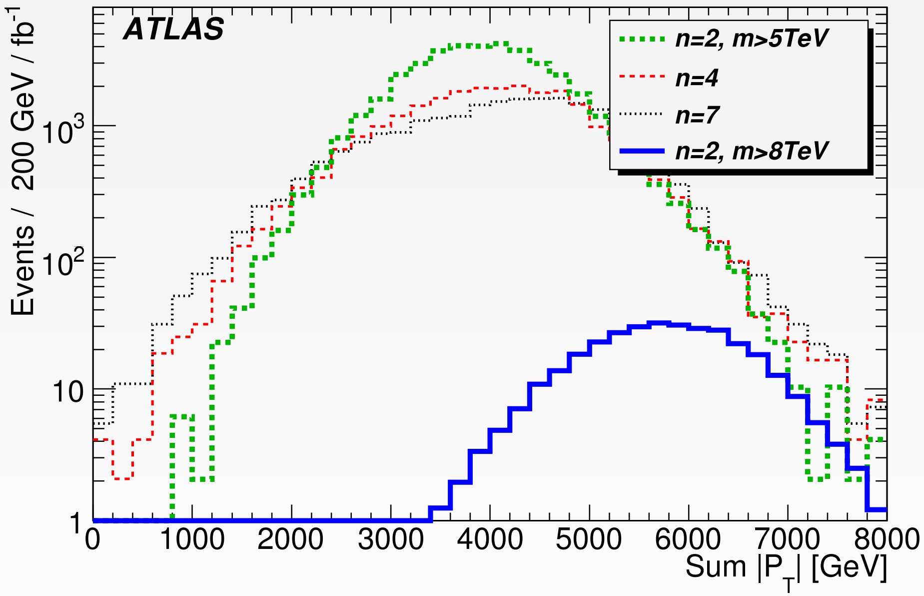
Black Hole Event Selection

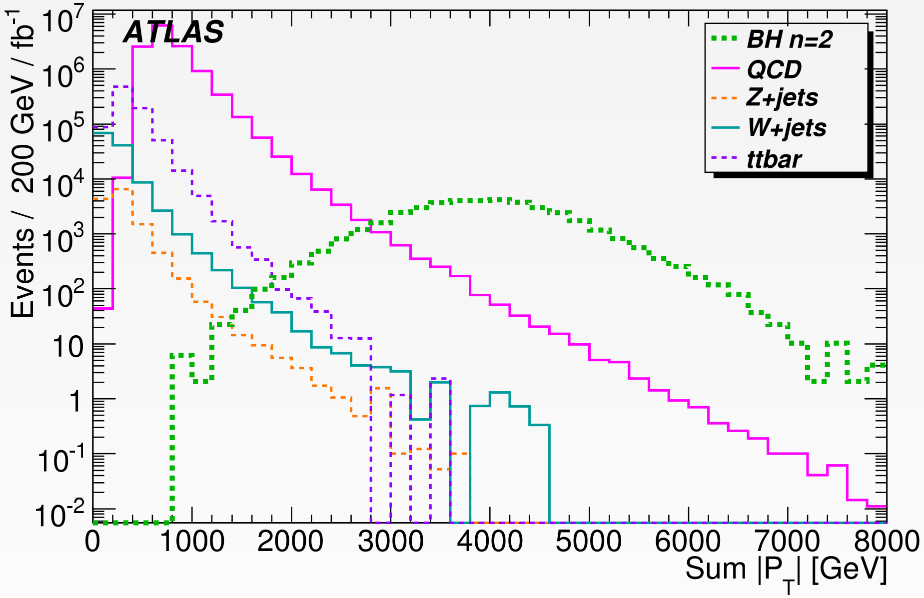
Different strategies exist.

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





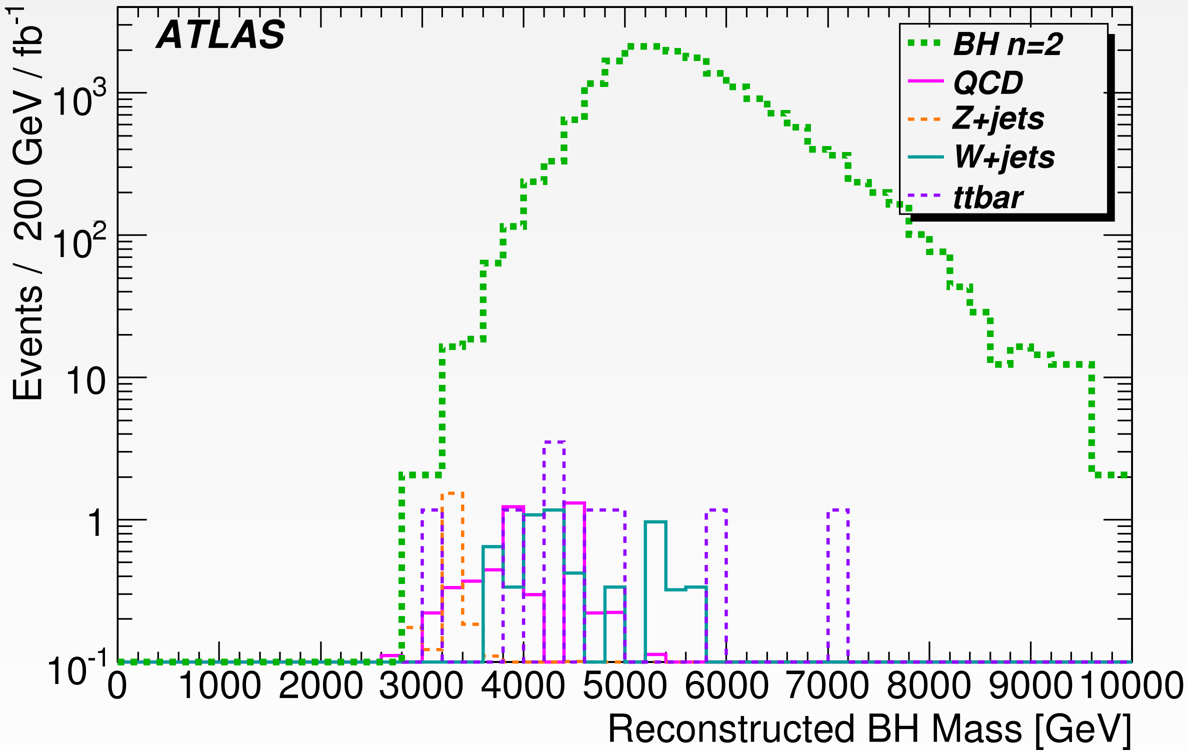
- Require at least one well identified lepton e or μ with $p_T > 50\,\text{GeV}$
  QCD background further reduced by factor ~ 60

Black Hole Mass Reconstruction

ATLAS CSC book, arXiv:0901.0512

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

Example for $M_{\mathrm{BH}} > 5$ TeV, $M_D = 1$ TeV, $\sqrt{s} = 14$ TeV

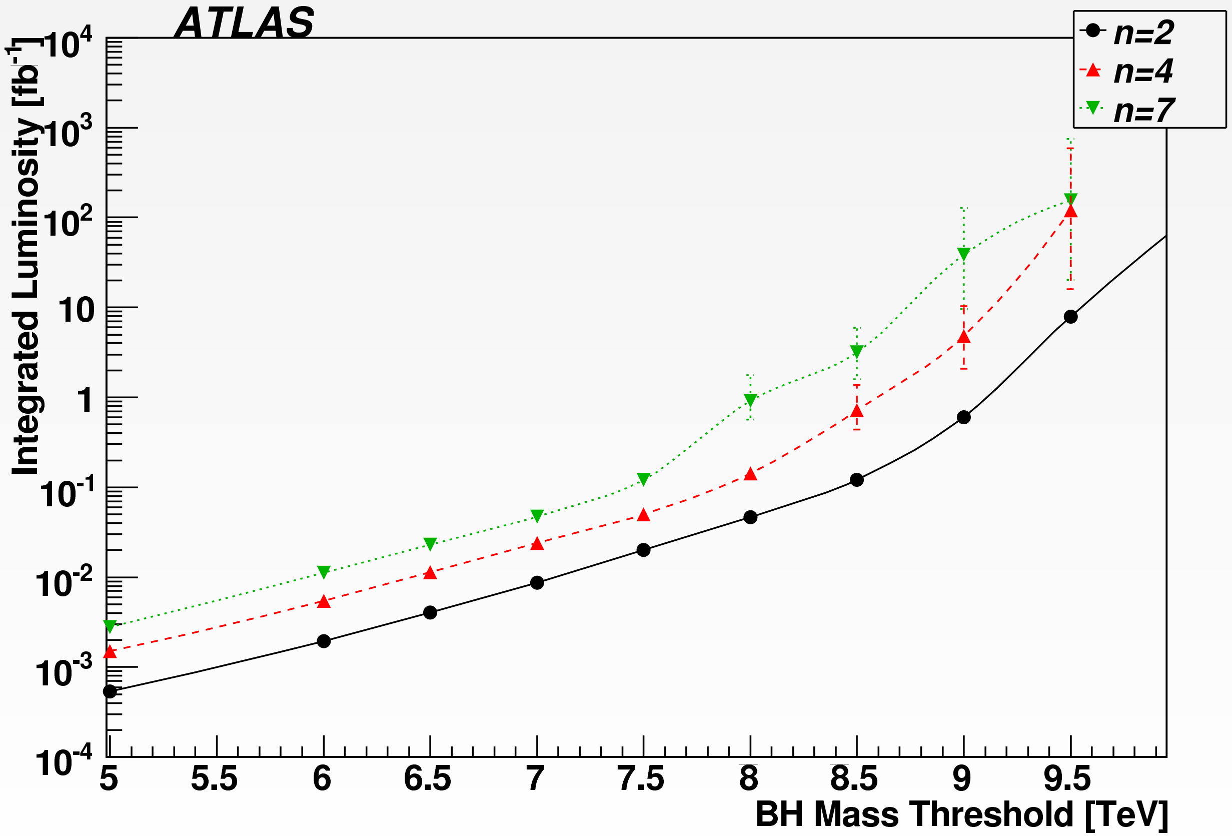


However, turn-on behaviour for $M_{\mathrm{BH}} \gtrsim M_D$ is unknown!

Black Hole Discovery Potential

Robust estimation of discovery potential is difficult, ATLAS CSC book, arXiv:0901.0512
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 $M_{BH} > 5\,\text{TeV}$ with first data at $\sqrt{s} = 7\,\text{TeV}$
  Focus on lower masses
- Turn on of semiclassical BH production is unknown
  If $M_D \sim \mathcal{O}(\text{TeV})$, expect new effects
  Look for high multiplicity events with different objects with $M_{inv} \gtrsim 1\,\text{TeV}$
  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

$$M_s < M_D < \left.\frac{M_s}{g_s^2}\right\} \text{black hole threshold}$$

string scale   Planck scale   string coupling

Cross sections comparable with BH but below GR threshold

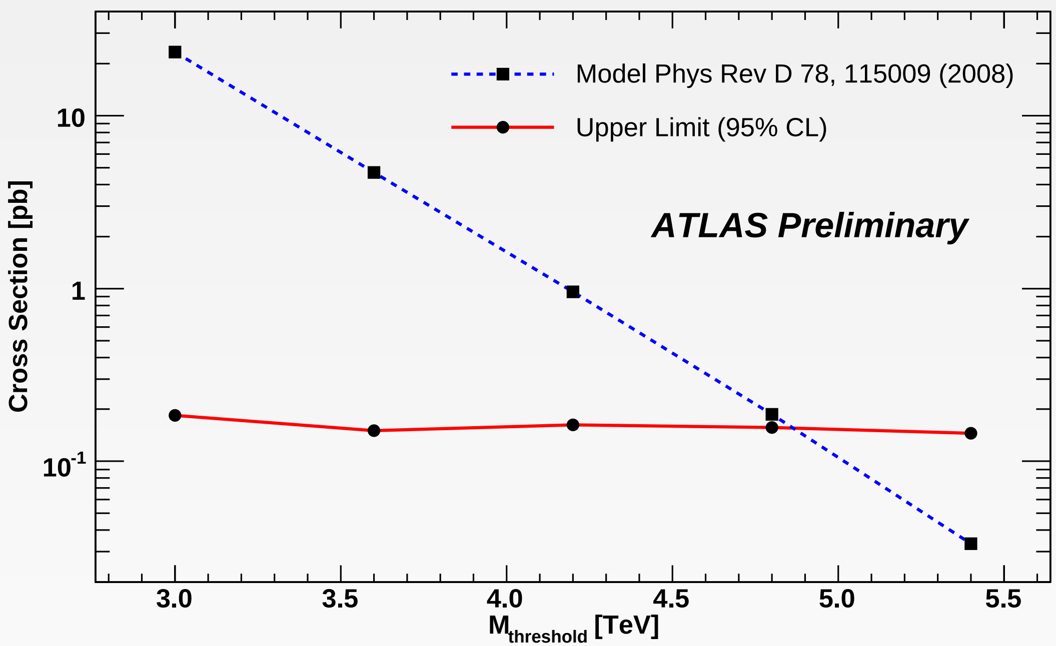
Typical assumption for highly excited string state: $M > 3M_s$

Search for String Balls

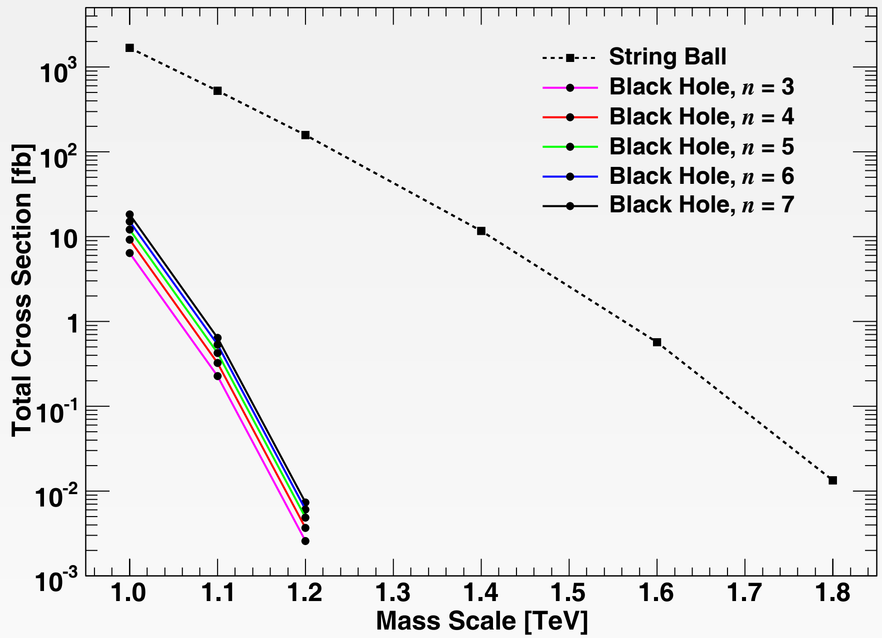
Analysis strategy similar to BH searches

ATLAS-PHYS-PUB-2009-011

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



Cross section at 7 TeV D. Gingrich



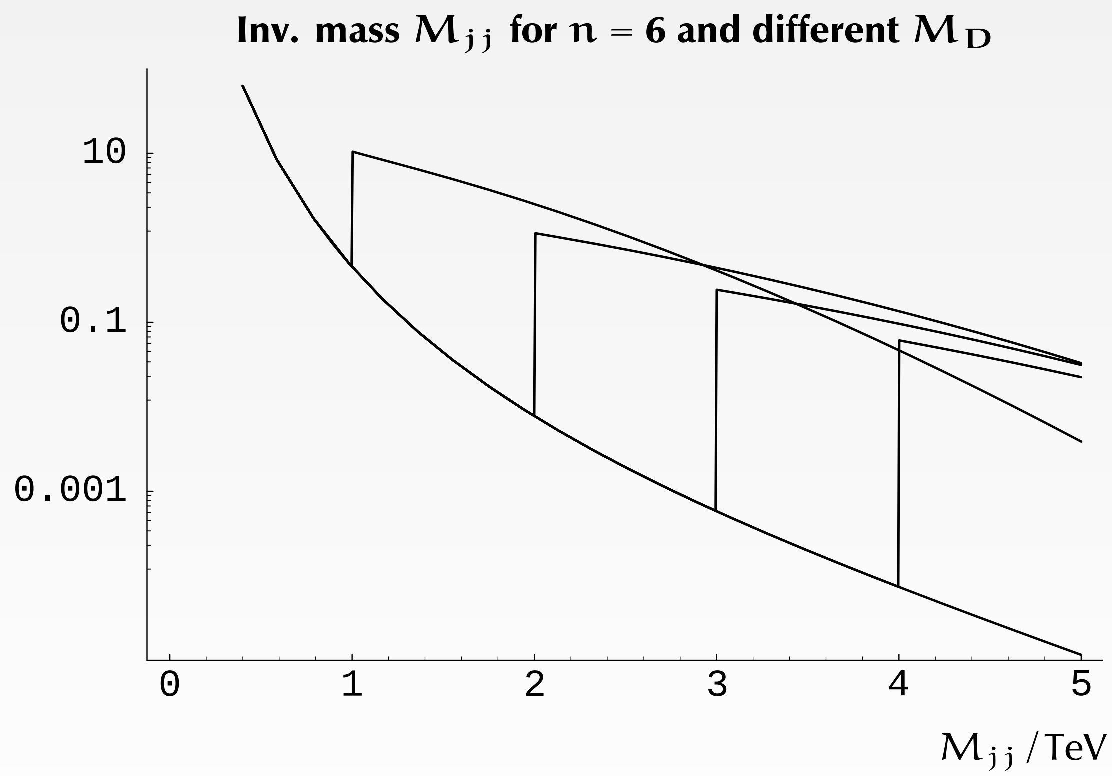
- String Balls can be excluded up to $M \sim 5\,\text{TeV}$ with $100\,\text{pb}^{-1}$ at $\sqrt{s} = 10\,\text{TeV}$
  In this model, this corresponds to $M_S \approx 1.5\,\text{TeV}$ and $M_D \approx 2.4\,\text{TeV}$
- At 7 TeV cross section can still be in pb range for $M > 3\,\text{TeV}$

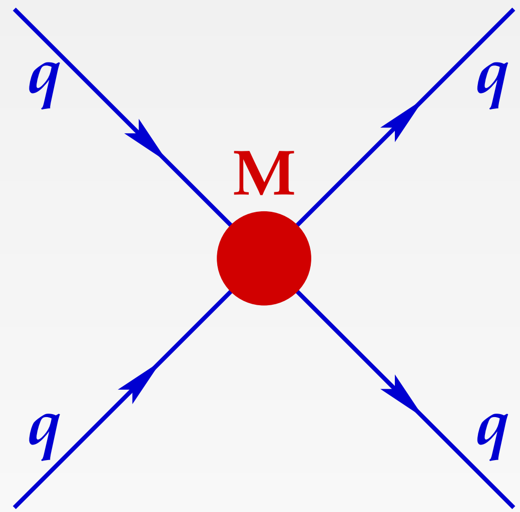
Gravity Effects in Contact Interactions

- 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





Simplified picture
– must be smoothed out.

Still rather sharp turn on
is expected for gravity effects.

- Good candidate for discovery in first data

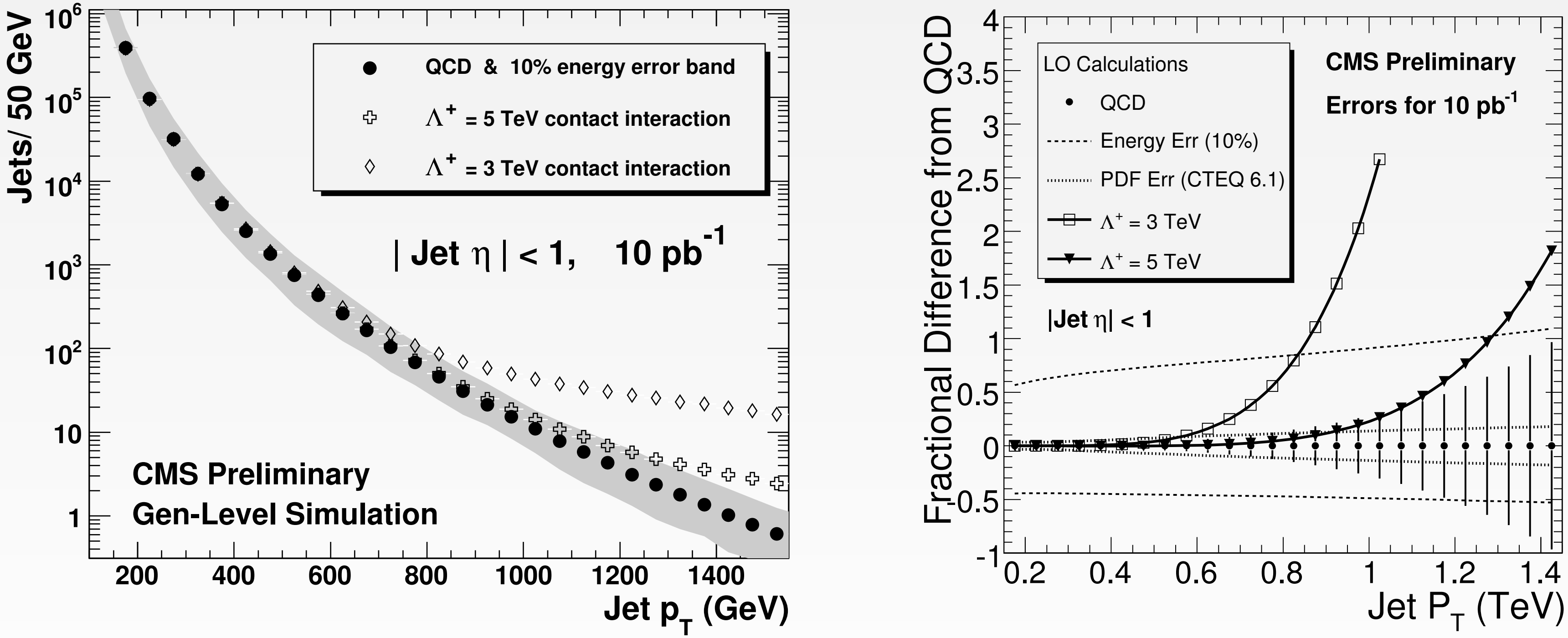
Searches with Dijets

Apply the same techniques as for compositeness searches

CMS-PAS-SBM-07-001

- Look for deviations in inclusive spectra

Pythia simulation at $\sqrt{s} = 14$ TeV



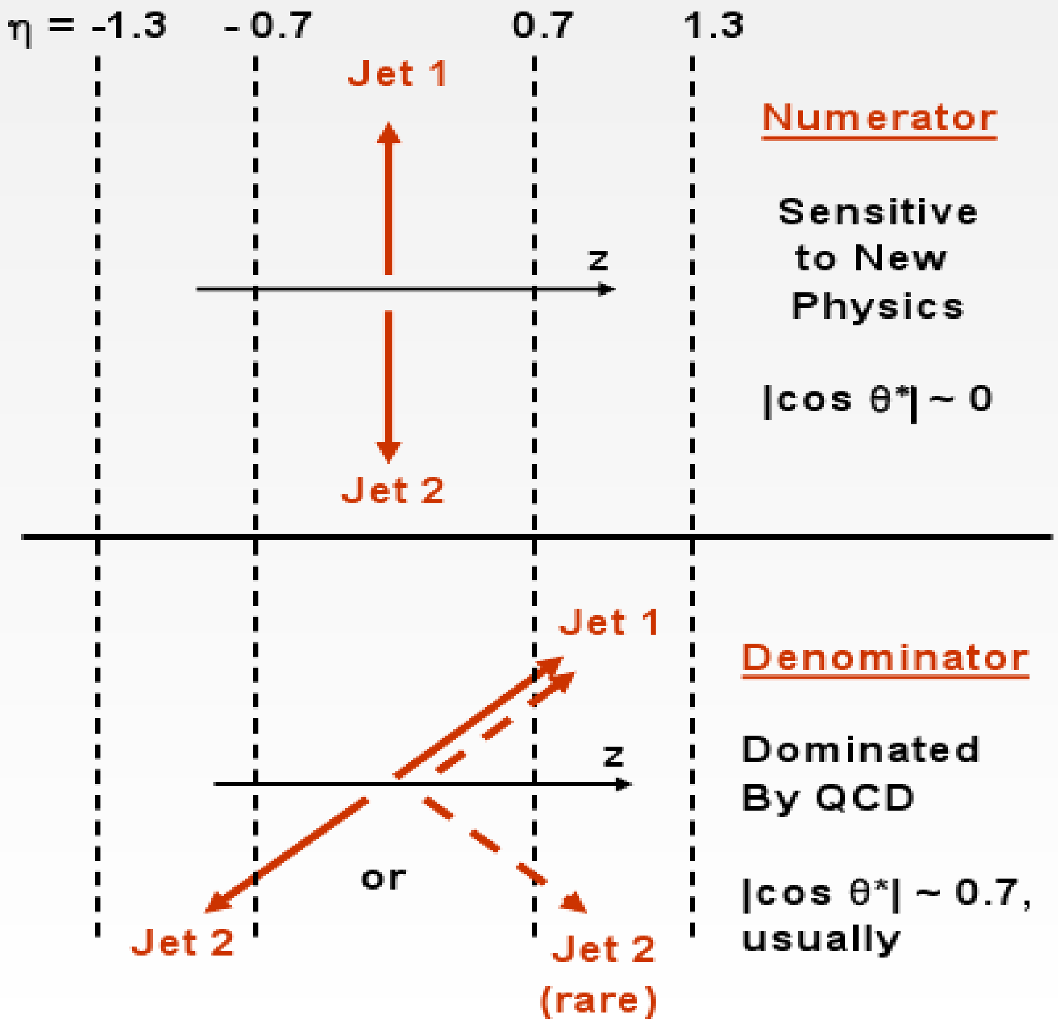
Requires

- Very good detector understanding [small uncertainty of jet energy scale]
- Very good QCD understanding [PDFs, NLO, . . .]

Dijet Angular Distributions

CMS-PAS-SBM-07-001

Example: Dijet ratio $= \dfrac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)}$

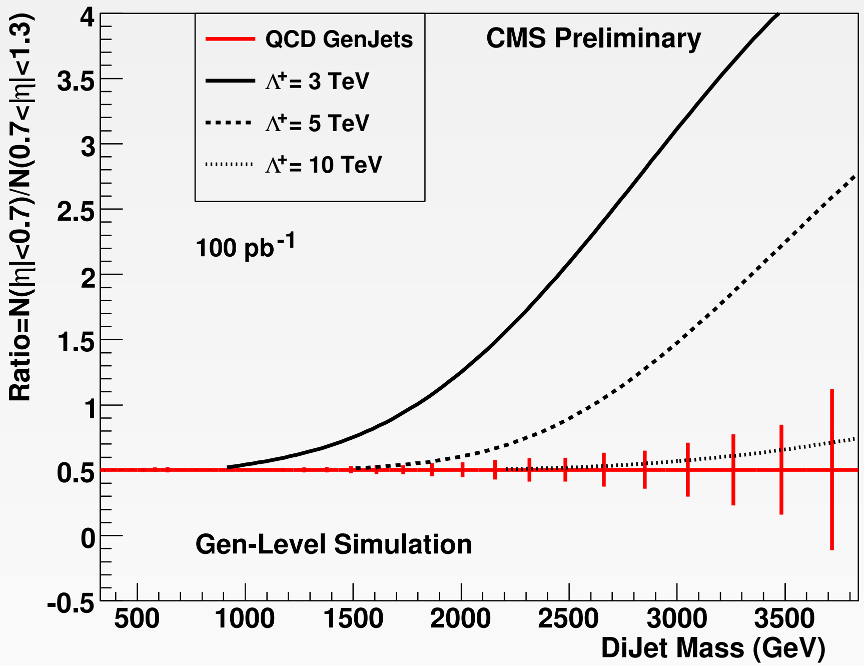


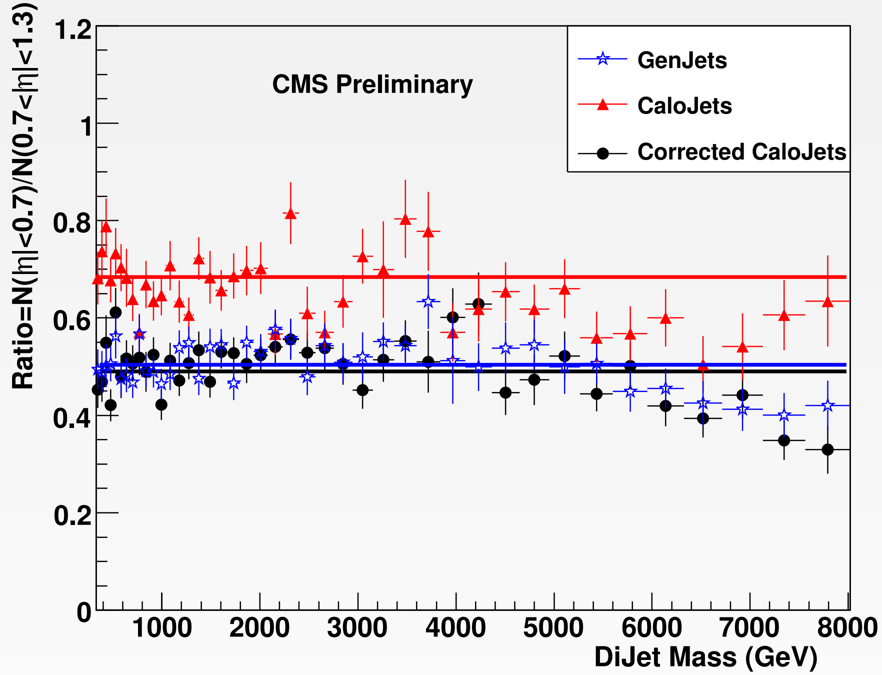
Exclusion or Discovery of Contact Interactions

- Using dijet angular distributions

CMS-PAS-SBM-07-001

Pythia simulation at $\sqrt{s} = 14$ TeV





At $\sqrt{s} = 14$ TeV
with stat. errors only

Excluded Λ (TeV)			Discovered Λ (TeV)		
$10\,\mathrm{pb}^{-1}$	$100\,\mathrm{pb}^{-1}$	$1\,\mathrm{fb}^{-1}$	$10\,\mathrm{pb}^{-1}$	$100\,\mathrm{pb}^{-1}$	$1\,\mathrm{fb}^{-1}$
< 5.3	< 8.3	< 12.5	< 4.1	< 6.8	< 9.9

Conclusions

- With impressive detector performance in first data, ATLAS and CMS are starting first BSM searches

- First interesting exclusion limits may be possible even with $10 - 100\,\mathrm{nb}^{-1}$ [e.g. for geometric cross section of quantum gravity at $M \sim 1$ TeV]

- Evidence for some phenomena is possible with first $1\text{–}100\,\mathrm{pb}^{-1}$ of data
  - Dijets, e.g. quantum black holes in contact interactions
  - Multijet quantum gravity effects

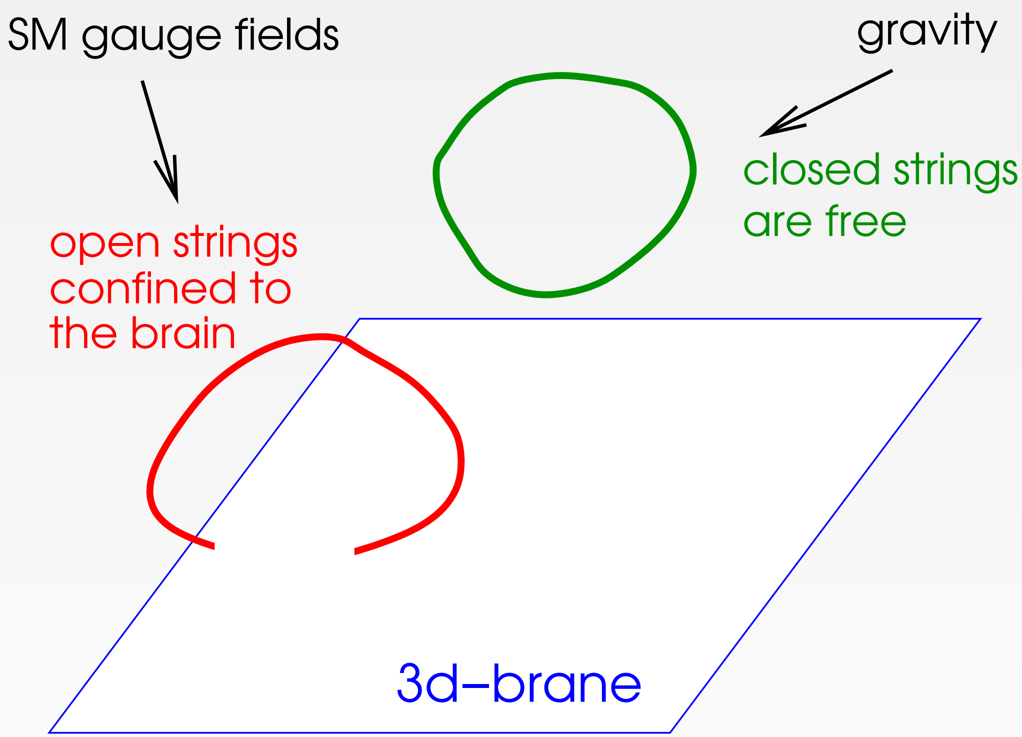
Backup

Additional Information

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

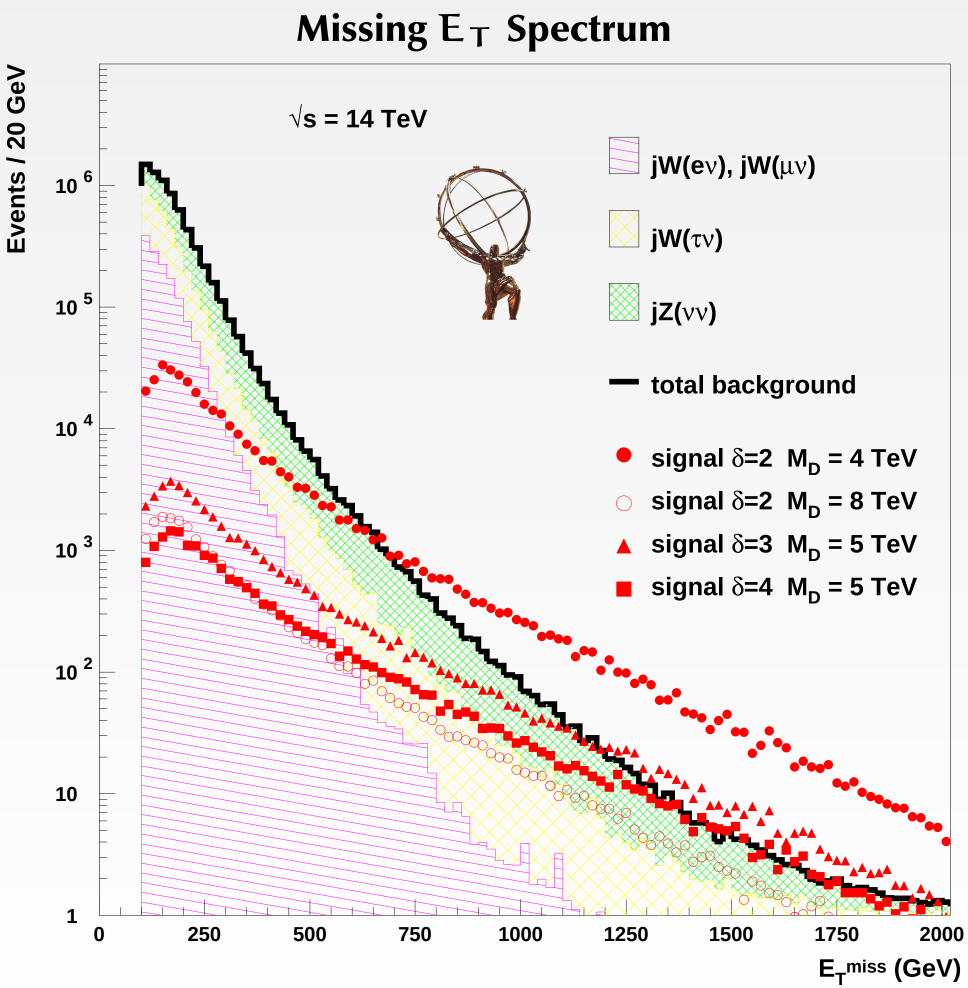


  String theories require 6 – 7 extra dimensions, but not necessary of the same size

- 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 $100\,\mathrm{fb}^{-1}$:

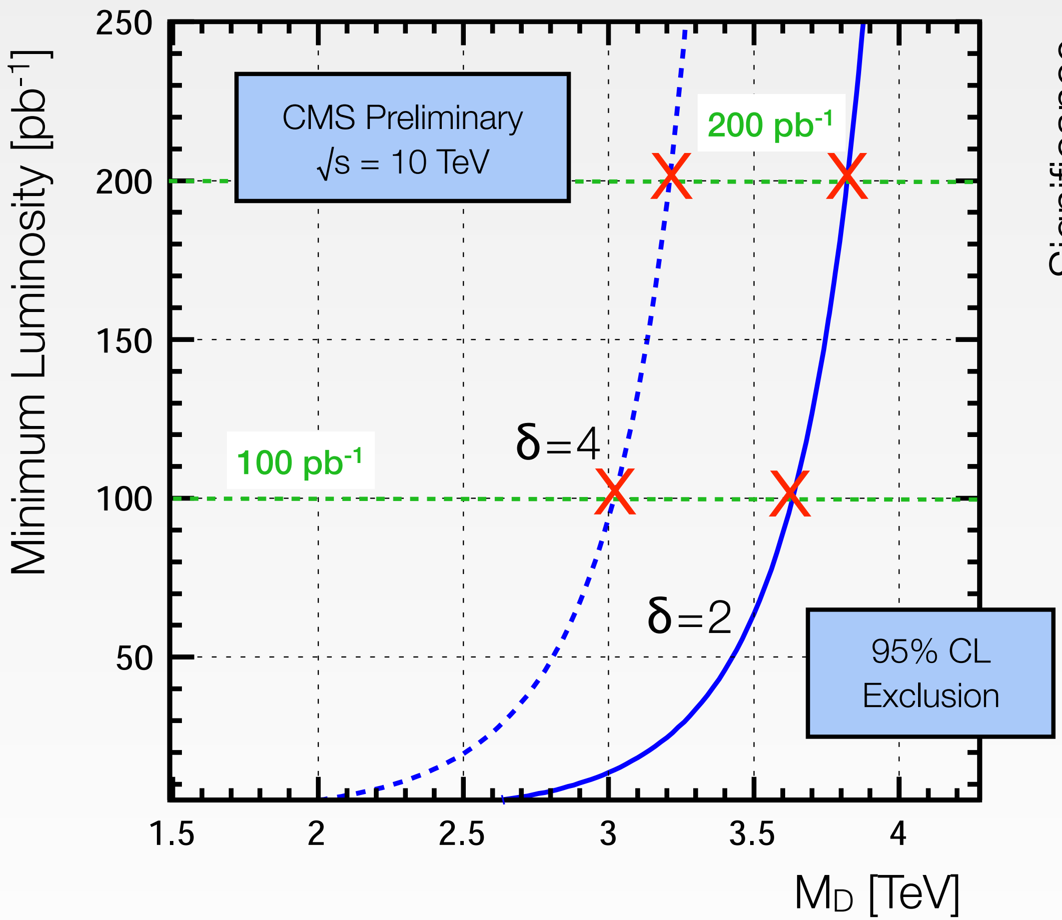
n	2	3	4
M_D / TeV	9	7	6

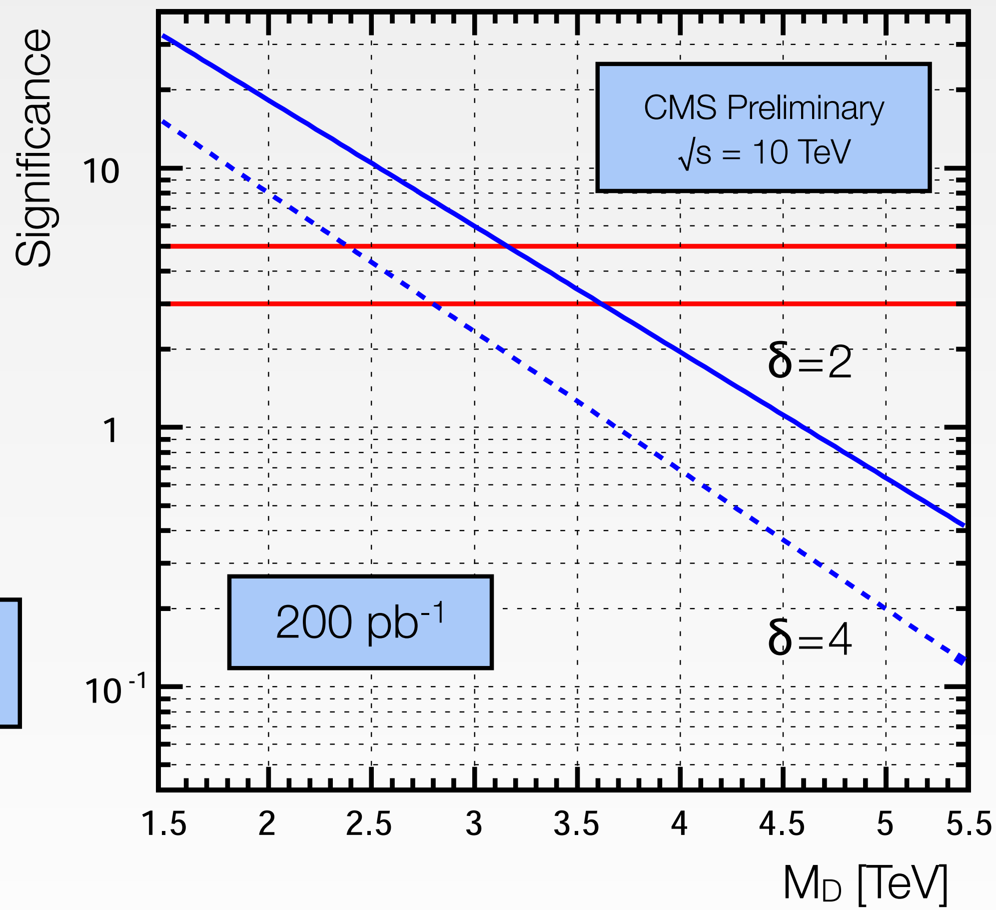
Present limits: 1.4 TeV ($\delta = 2$); 1.0 TeV ($\delta = 4$)

- No instrumentation effects included

Monojets @ CMS

CMS-PAS-EXO-09-013





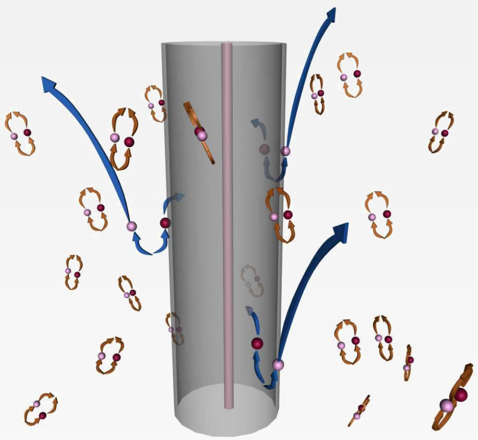
Current limits can be significantly improved with only 5–10 pb^{-1}

Hawking Radiation

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

- Particles have black body spectrum with temperature

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



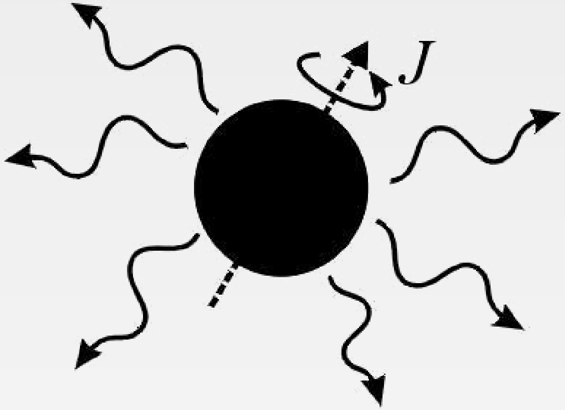
- No chance to discover Hawking radiation of astro black holes
  $T_H < T_{CMB}$

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

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

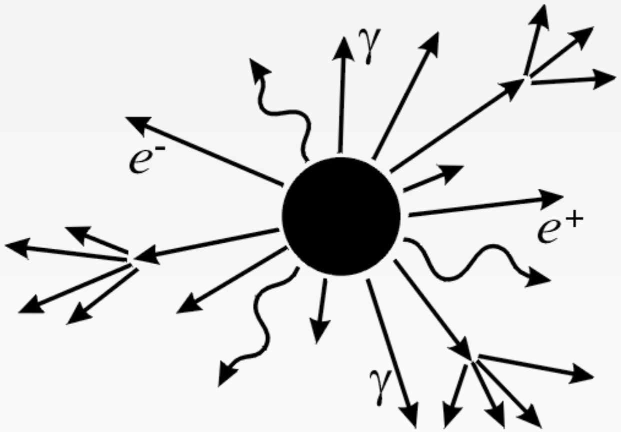
- At high enough T_H massive particles are also produced

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.

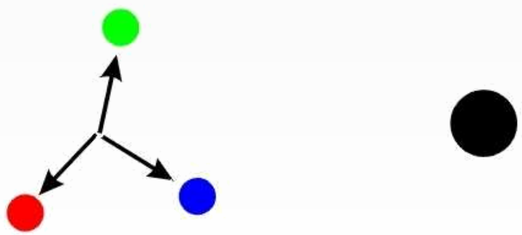
a) spin down – losing angular momentum;

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: $M_{BH} \to M_D$. 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 Trigger

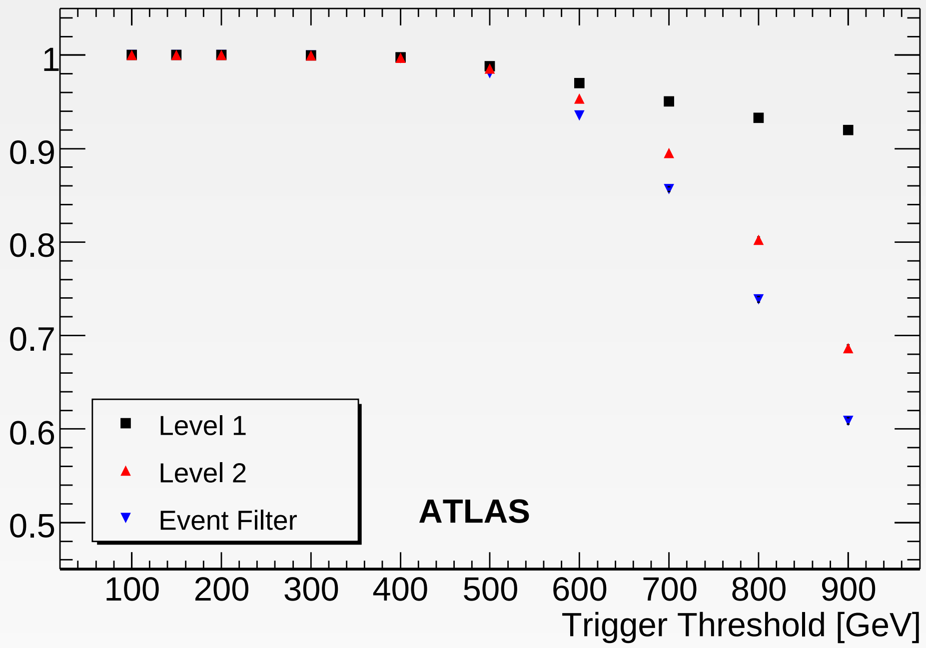
- Single inclusive jet trigger should be very efficient for BH

ATLAS BH CSC report

Eff. ~100% for Thr. $E_T \leqslant 400\,\mathrm{GeV}$

[for current trigger simulation]

- Highest E_T threshold unprescaled
- Trigger menu for $\mathcal{L} = 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$:
  Highest E_T 120 GeV – SM rate ~ 10 Hz
- Trigger menu for $\mathcal{L} = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$:
  Highest E_T 330 GeV – SM rate ~ 10 Hz



- In case of detector problems (noise): 3- or 4-jet trigger

- Alternatively, $\sum E_T$ trigger can be used: $\sum E_T \gtrsim 300\,\mathrm{GeV}$ for first data, $\gtrsim 1\,\mathrm{TeV}$ later
  Especially important for model independent searches

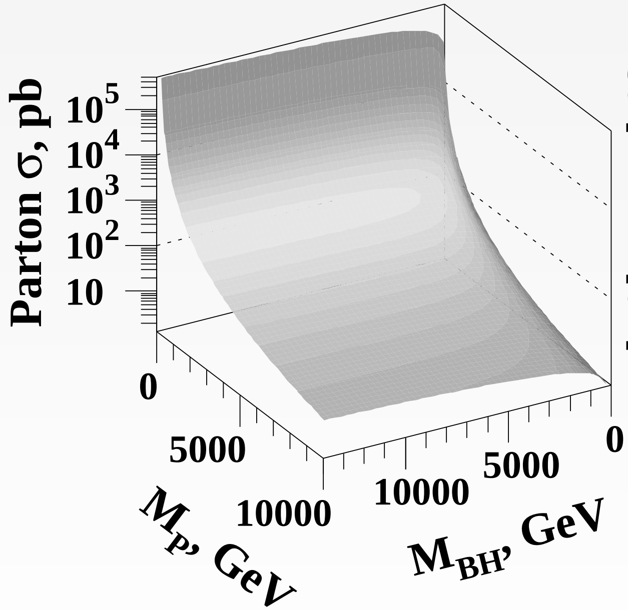
Identifying Black Holes

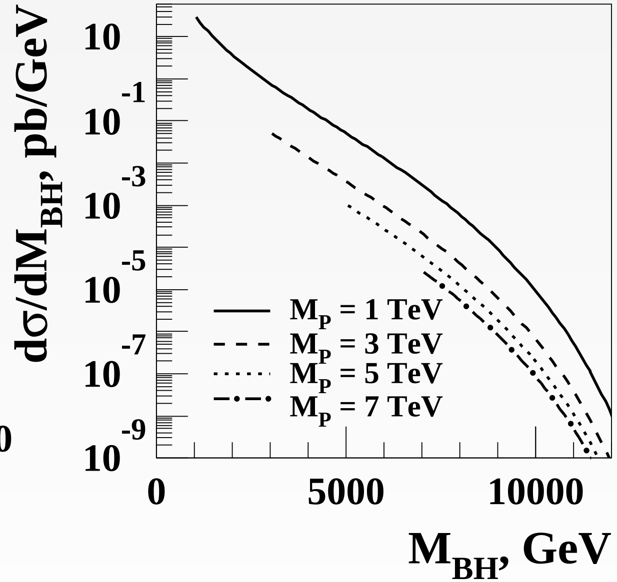
Need several evidences to be sure. Various ideas exist

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

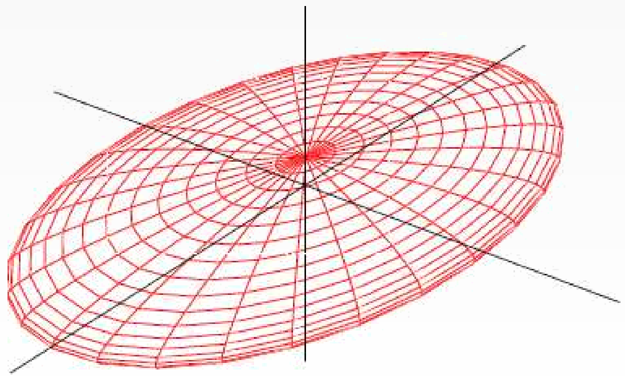
- Hawking radiation ≈ democratic decay in MC
  Look at distributions of particle types: ratios e/μ , e/Z^0 , e/t . . .

- 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

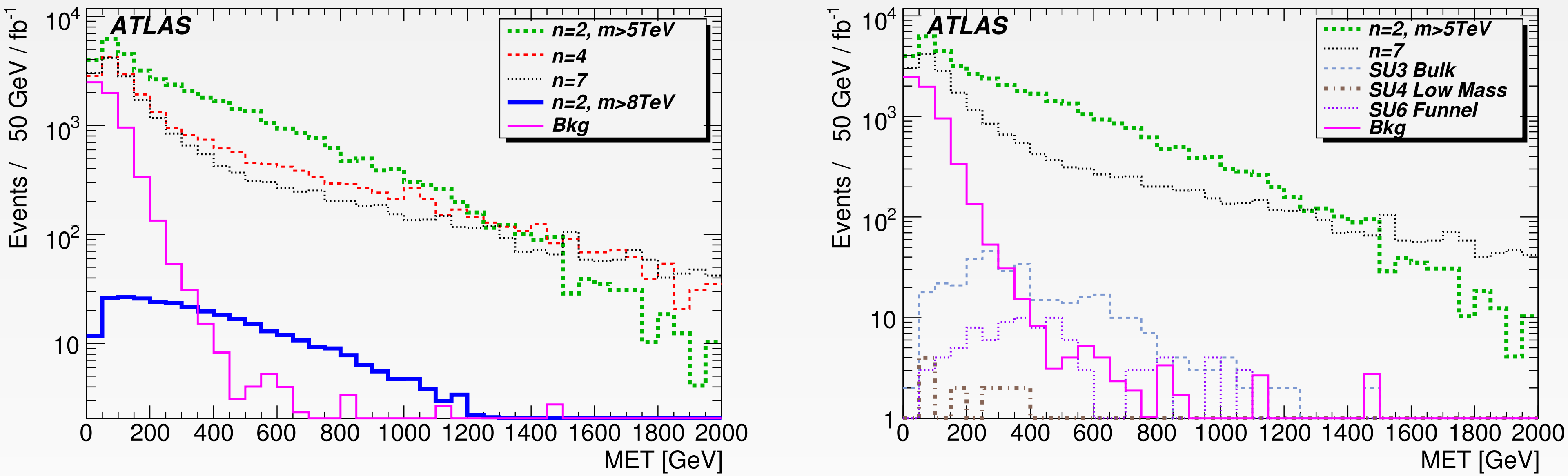


- Look at event shapes (sphericity, (a)planarity, thrust . . .)

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

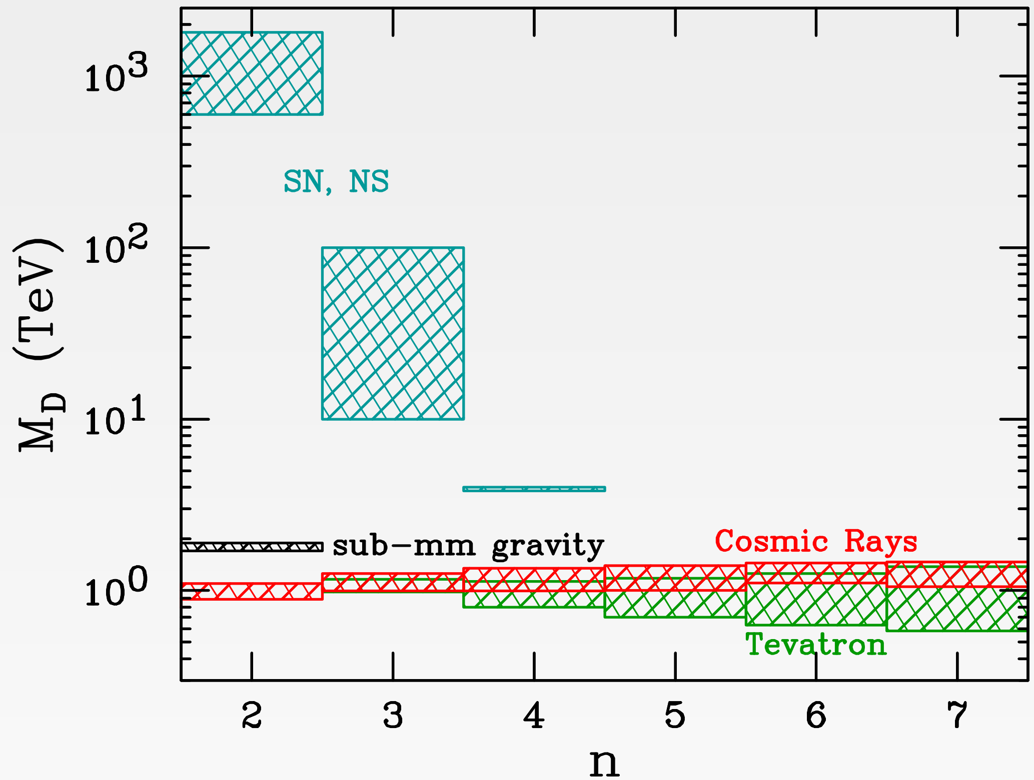
Large uncertainties within "semiclassical" approach.

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

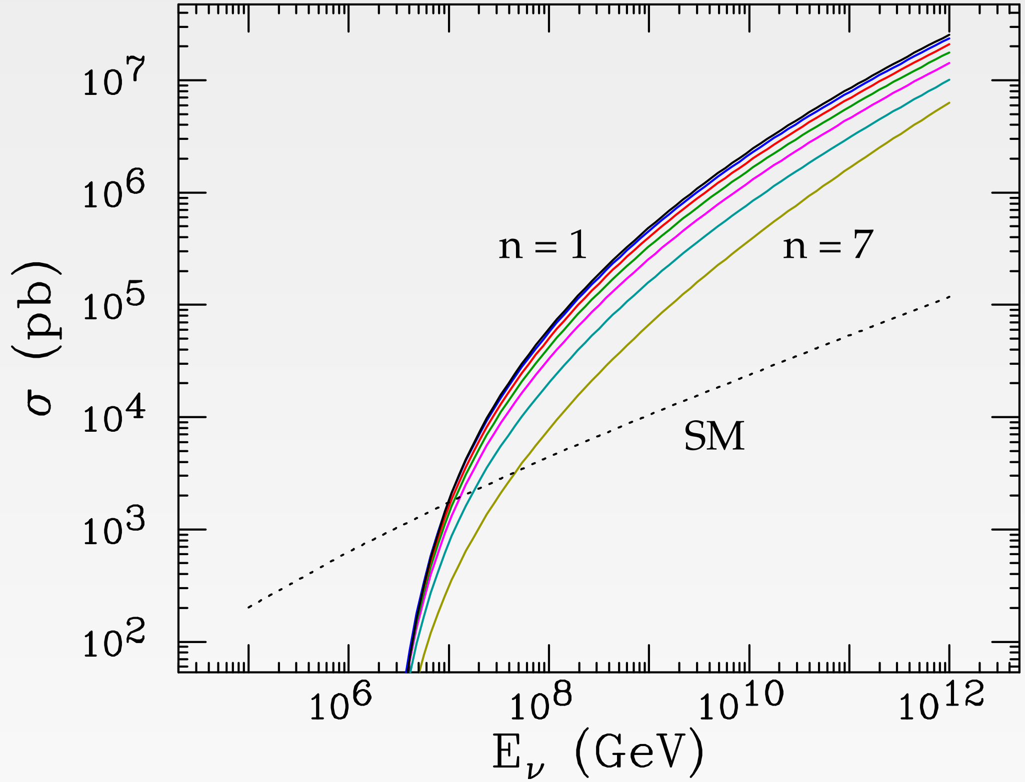
Several analysis strategies are developed for different scenarios.

Limits in ADD Models



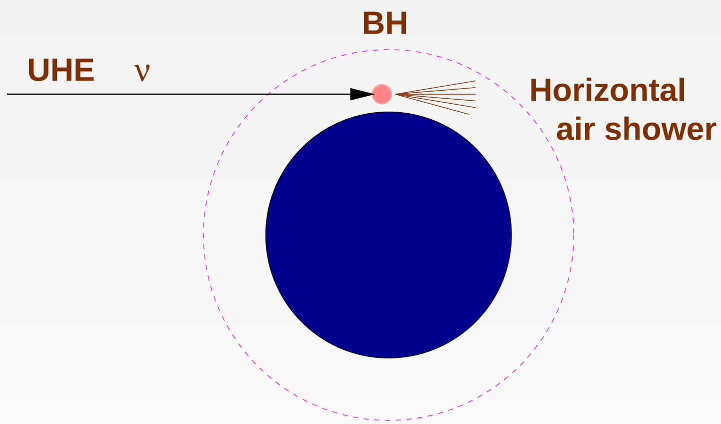
- Astro limits have many uncertainties. Only order of magnitude estimates.
- In general strong astro limits for $n = 2, 3$. Weaker for higher n.
  Colliders can be more sensitive at higher n.
- Astro signals are sensitive to low energy gravitons modes.
  Colliders probe mainly high energy gravitons -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

Black Holes in Cosmic Rays



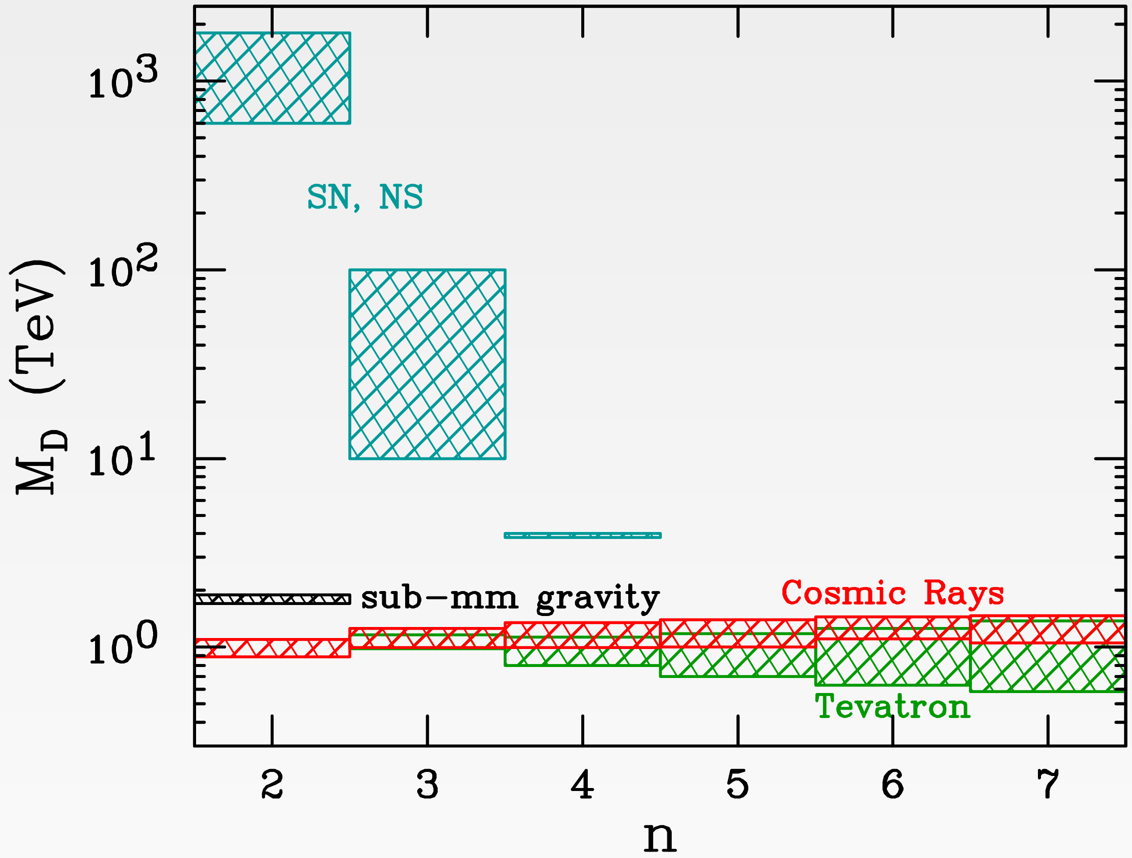
Anchordoqui, Feng, Goldberg, Shapere:

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 $E \sim 100\,\mathrm{TeV}$. They can produce micro black holes deep in atmosphere, leading to quasi-horizontal giant air showers.
- Deep in atmosphere $\longrightarrow$ 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.