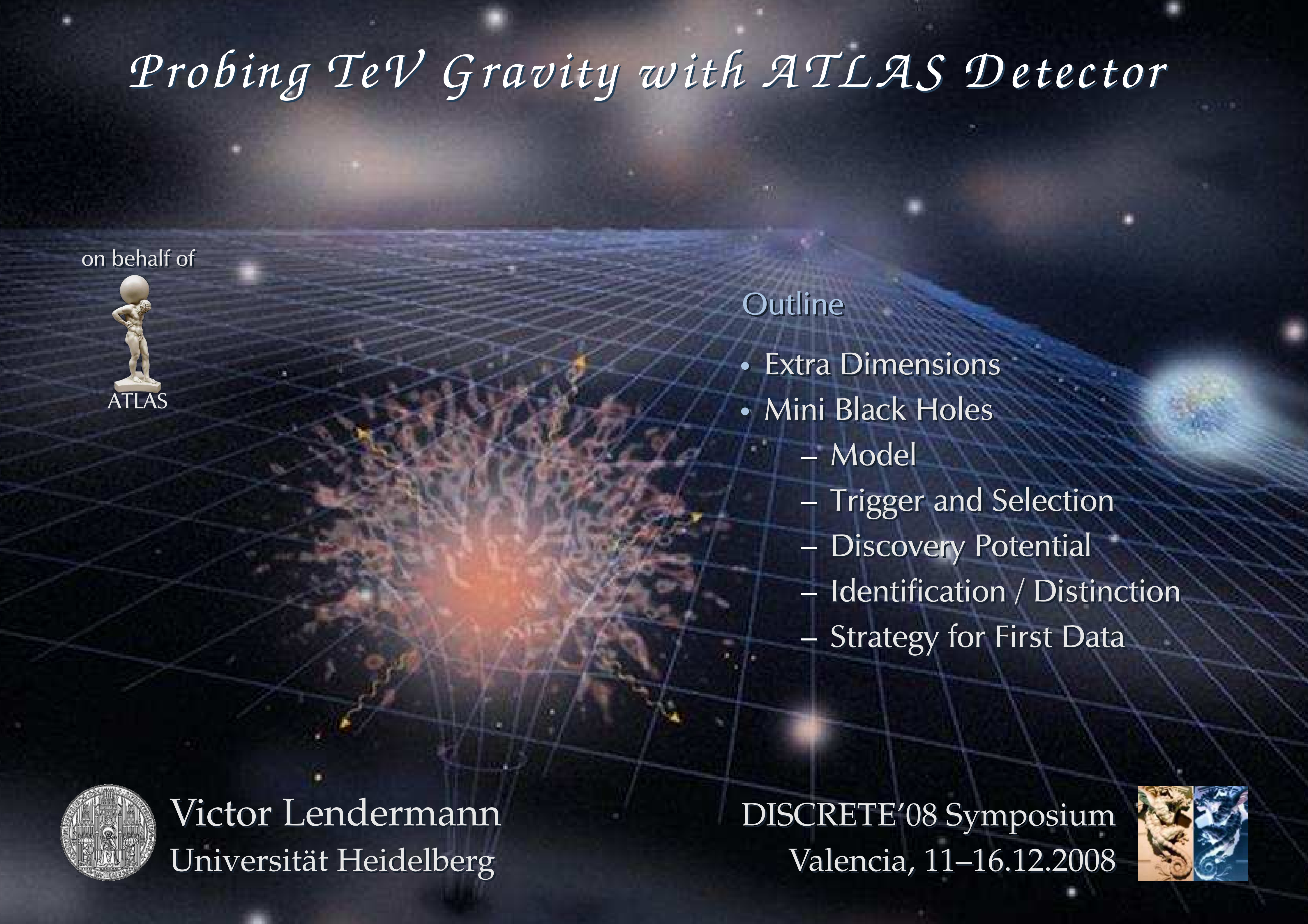
Probing TeV Gravity with ATLAS Detector



on behalf of
ATLAS

Outline

- Extra Dimensions
- Mini Black Holes
    - Model
    - Trigger and Selection
    - Discovery Potential
    - Identification / Distinction
    - Strategy for First Data

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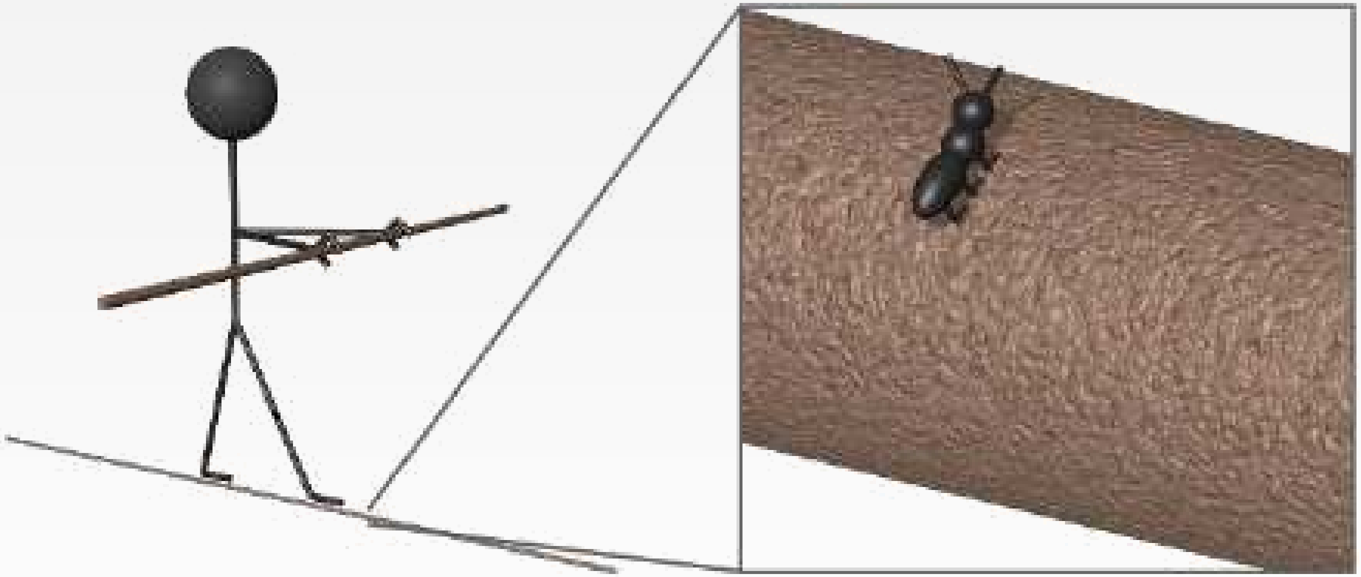
DISCRETE'08 Symposium
Valencia, 11–16.12.2008

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

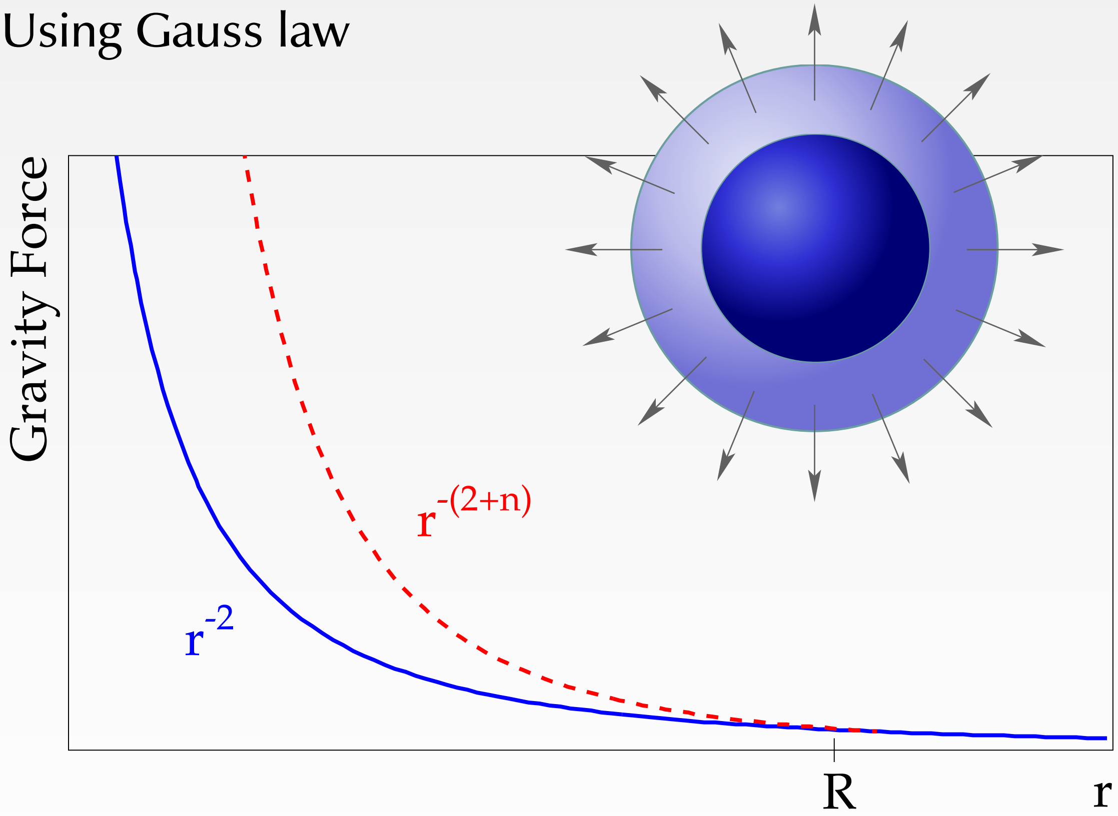
Large Extra Dimensions

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

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

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

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 $2R_S$

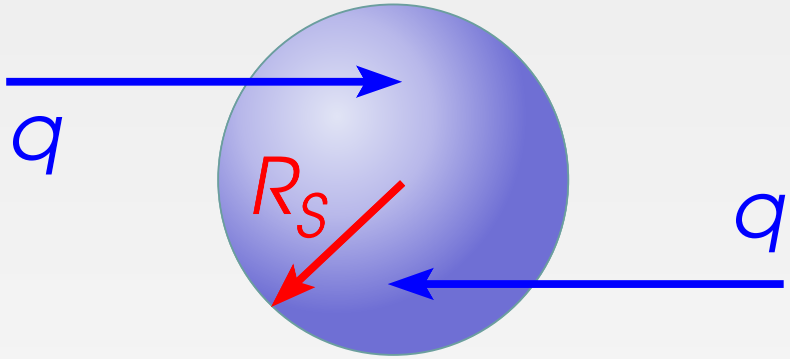
- BH mass $M_{BH}^2 = \hat{s}$
  Continuous mass spectrum starting at some $M \gtrsim M_D$

- 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



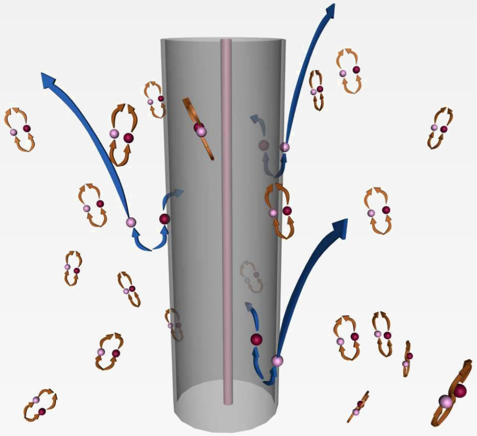
R_S – Schwarzschild radius

Giddings, Thomas: hep-ph/0106219
Dimopolous, 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



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

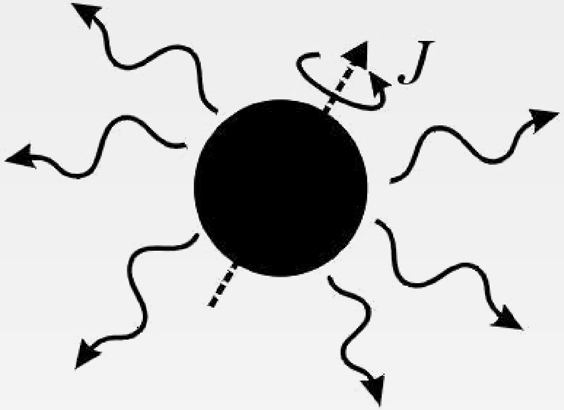
- No chance to discover Hawking radiation of astro black holes
  $T_H \ll T_{CMB}$

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

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

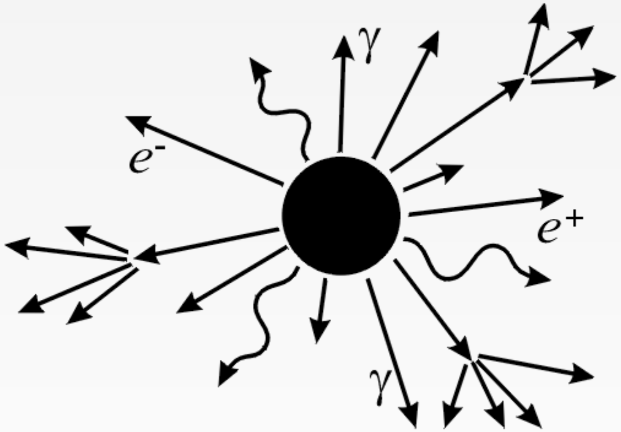
- At high enough T_H massive particles are also produced

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.

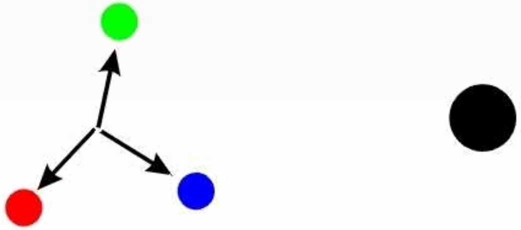
a) spin down – losing angular momentum;

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.

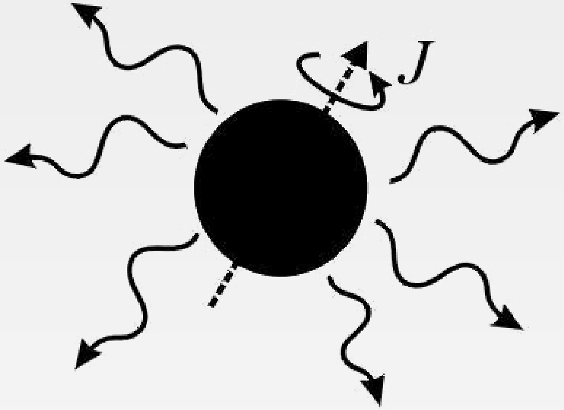
Predictions very difficult.

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

Pictures: backreaction.blogspot.com

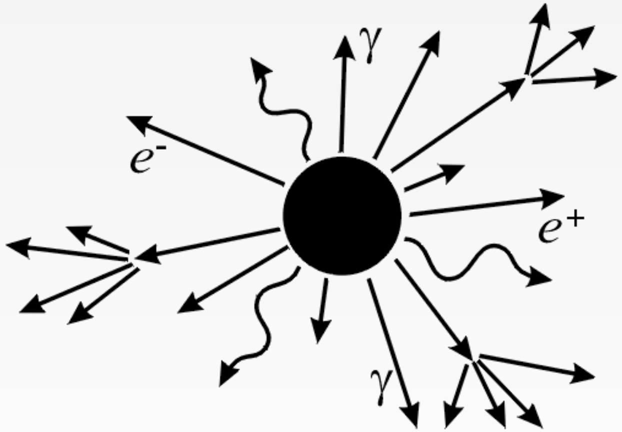
Charybdis MC

Harris, Richardson, Webber: hep-ph/0307305



1. Balding phase: Graviton radiation.

Not simulated

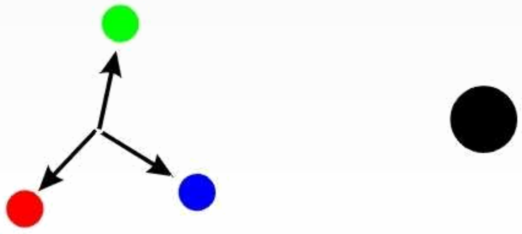


2. Evaporation phase: $M_{BH} \gg M_D$. Hawking radiation.

No spin down.

Only SM particles are generated; no gravitons.

Approximated by democratic decay in SM.

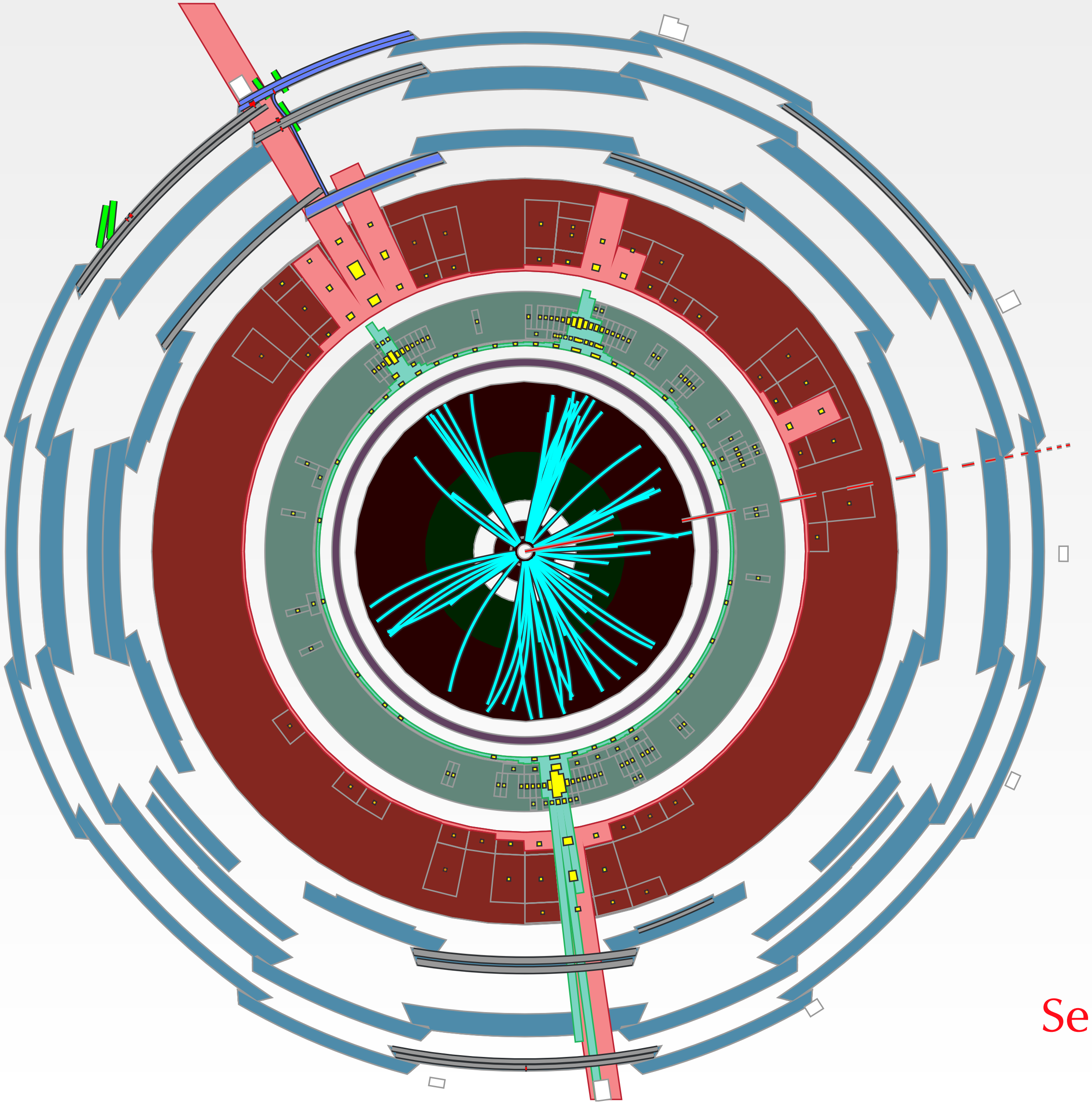


3. Planck phase: $M_{BH} \to M_D$. Regime of quantum gravity.

Only SM particles generated. We use two-body decay.

Current MCs are reasonable for $M_{BH} \gg M_D$ only!

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 Trigger

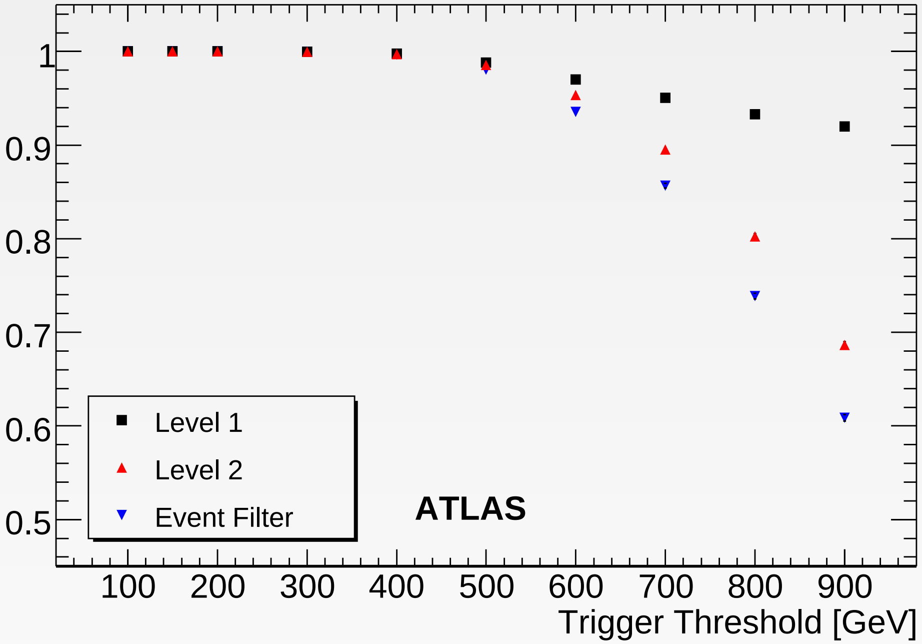
- Single inclusive jet trigger should be very efficient for BH

ATLAS BH CSC report

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

[for current trigger simulation]

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



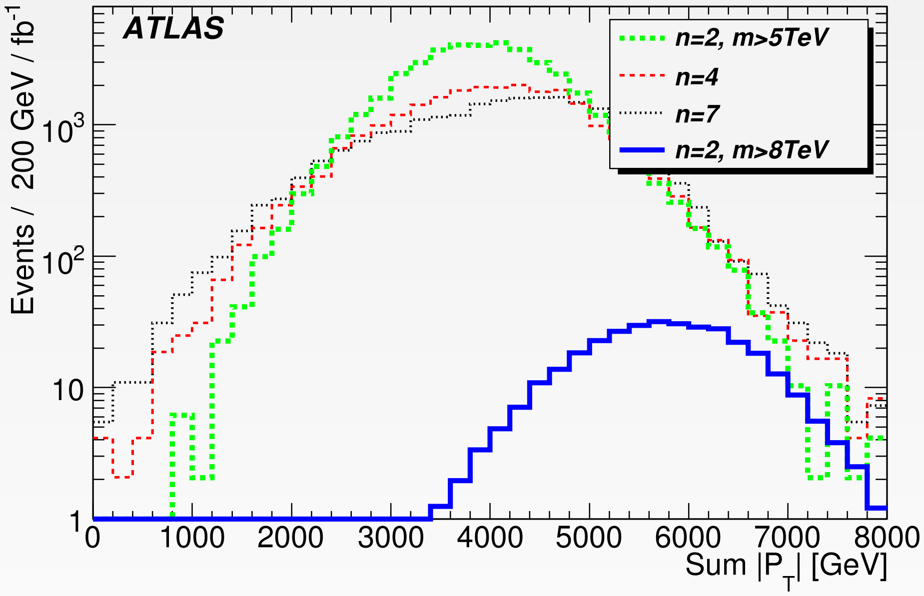
- In case of detector problems (noise): 3- or 4-jet trigger

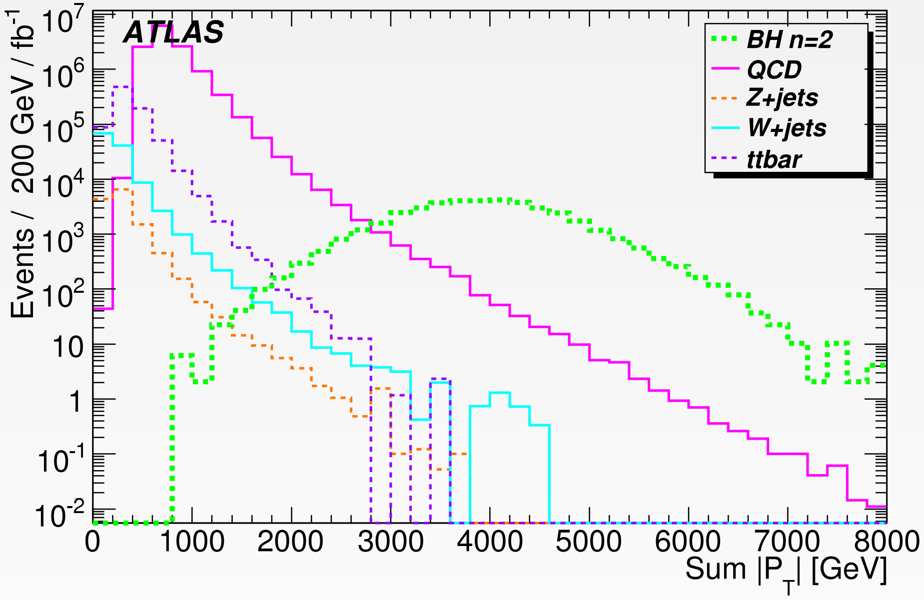
- Alternatively, $\sum E_T$ trigger can be used: $\sum E_T \gtrsim 300\,\text{GeV}$ for first data, $\gtrsim 1\,\text{TeV}$ later
  Especially important for model independent searches

Black Hole Event Selection

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 $p_T > 50\,\text{GeV}$

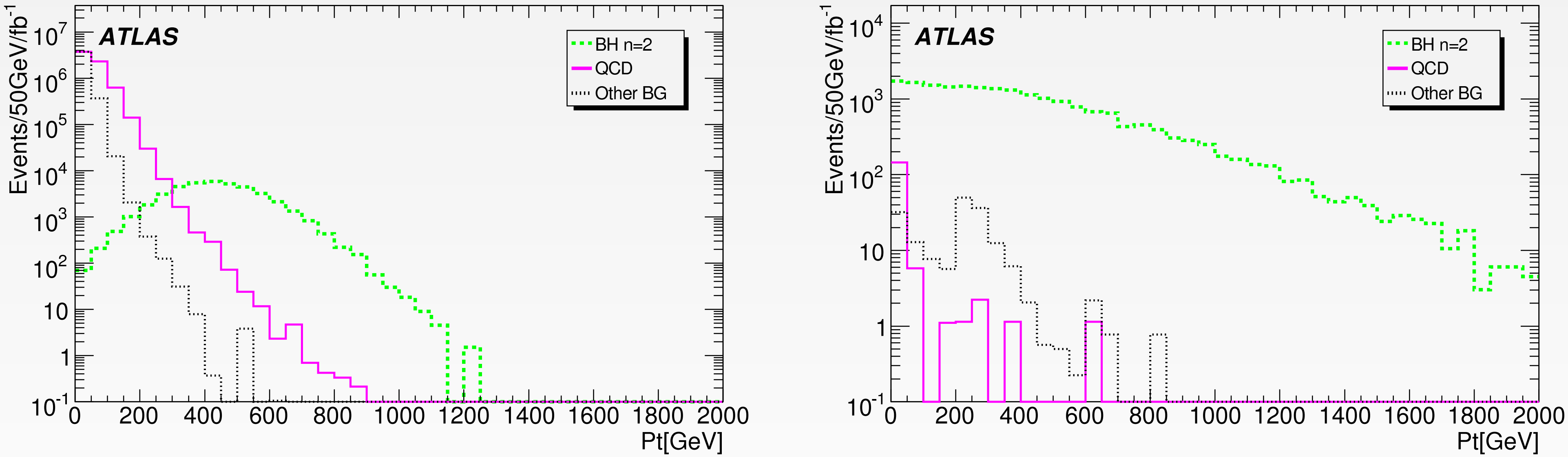
  QCD background further reduced by factor ~ 60

Alternative Selection

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

◆ Require at least 4 objects (jets, e, γ, μ) with $p_T > 200\,\text{GeV}$

4th Object p_T **Lepton p_T**

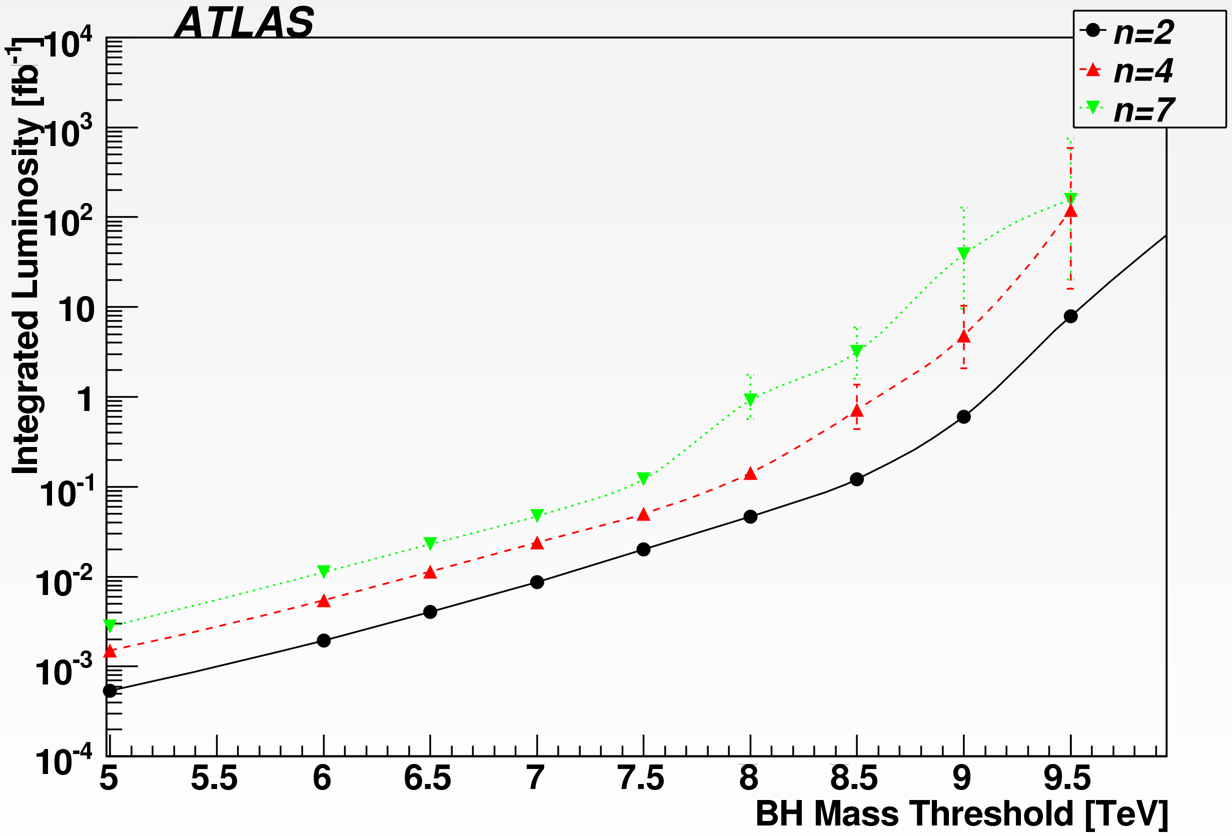


◆ Require at least one well identified lepton e or μ with $p_T > 200\,\text{GeV}$
QCD background further reduced to percent level

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

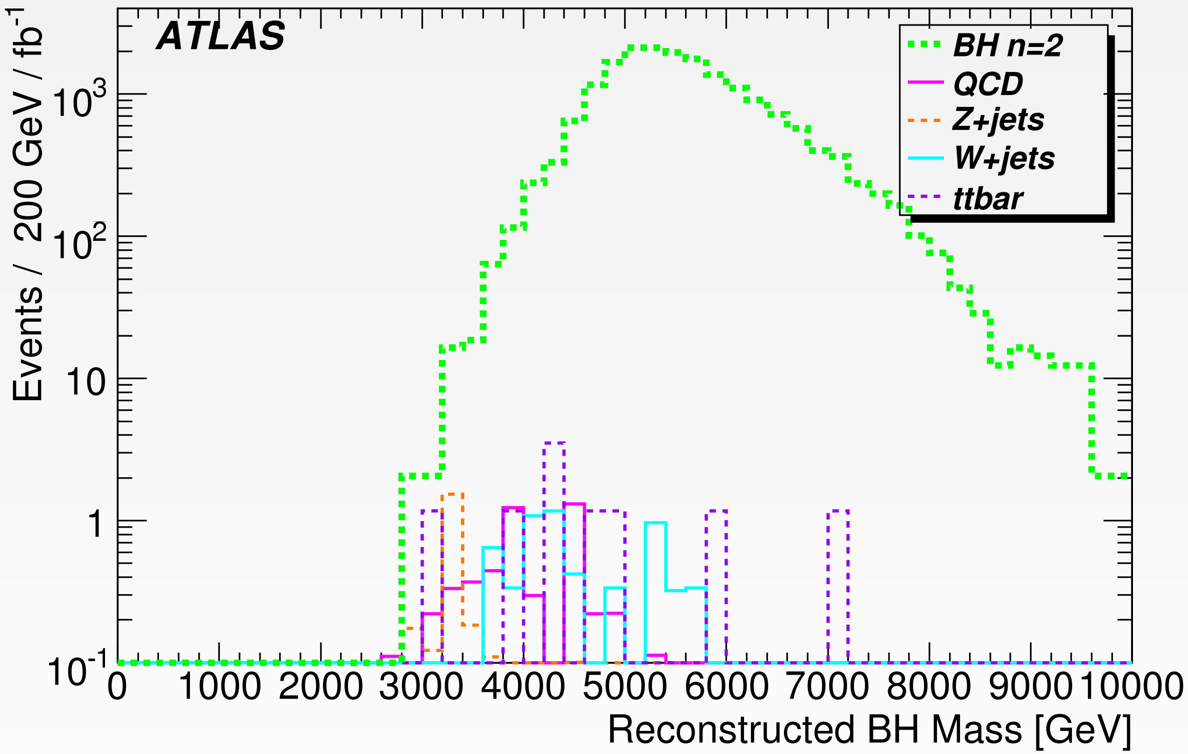
Example: $M_D = 1$ TeV, cut $\sum |p_T| > 2.5$ TeV, lepton requirement



Black Hole Mass Reconstruction

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

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



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

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

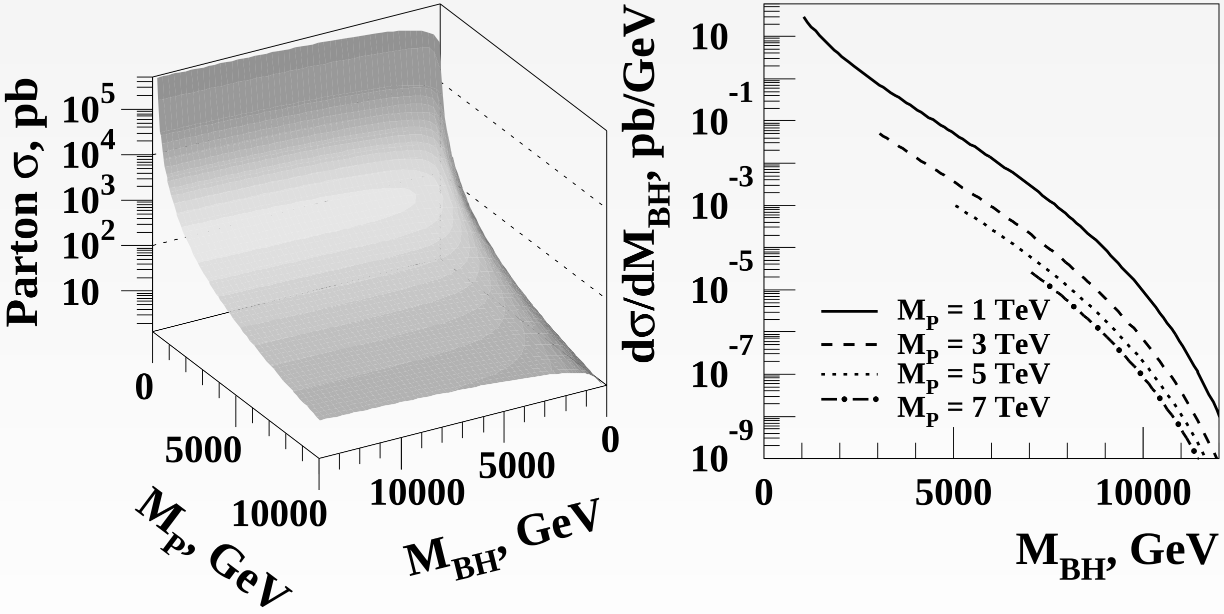
Identifying Black Holes

Need several evidences to be sure. Various ideas exist

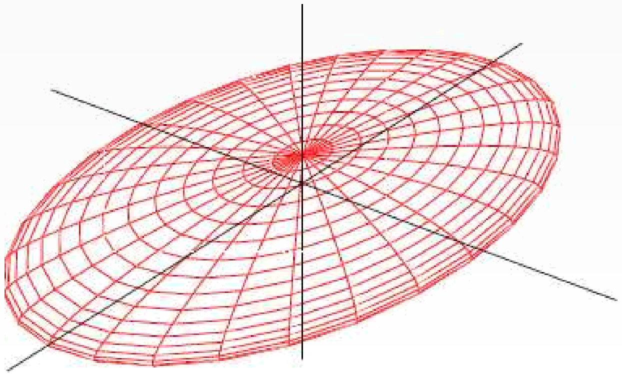
Giddings, Thomas: hep-ph/0106219
Harris et al.: hep-ph/0411022
Roy, Cavaglia: arXiv:0801.3281

- 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
Dimopolous, Landsberg: hep-ph/0106295

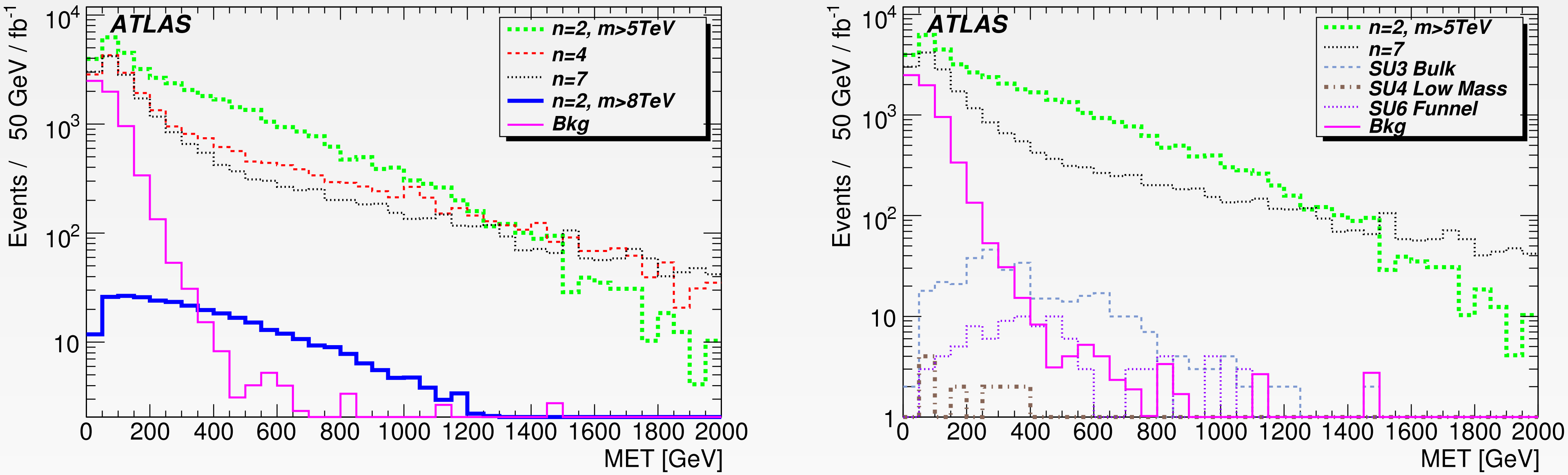


- Look at event shapes (sphericity, (a)planarity, thrust . . .)

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

Black Hole Model Uncertainties

Large uncertainties within “semiclassical” approach

So far simplified simulations are used (e.g. Charybdis MC). 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.

BlackMax	Dai et al.: arXiv:0711.3012
Charybdis	Harris, Richardson, Webber: hep-ph/0307305
Catfish	Cavaglia et al.: hep-ph/0609001
Truenoir	Landsberg: hep-ph/0607297

Search Strategy for First Data

- Little access to $M_{\mathrm{BH}} > 5\,\mathrm{TeV}$ with $100\,\mathrm{pb}^{-1}$ first data at $\sqrt{s} = 10\,\mathrm{TeV}$
  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 $\sum E_T \gtrsim 0.5 - 1\,\mathrm{TeV}$

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

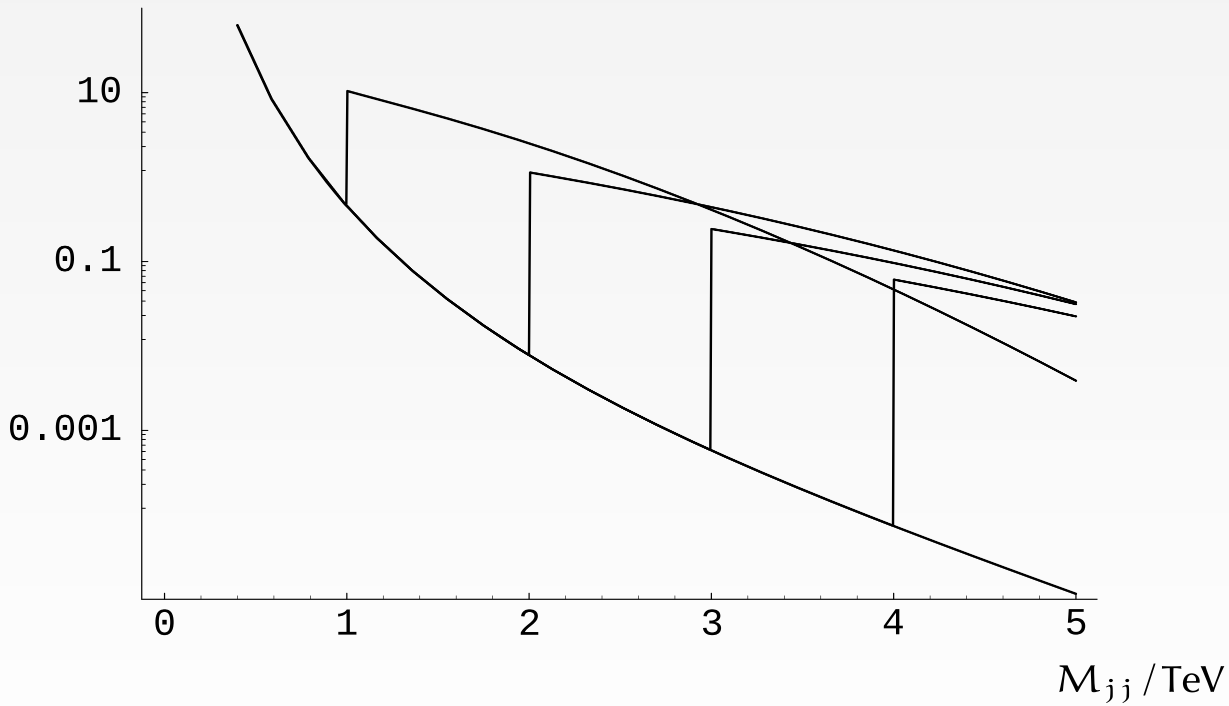
Dimopoulos, Emparan: hep-ph/0108060
Chamblin, Nayak: hep-ph/0206060
Cheung: hep-ph/0205033
Gingrich, Martell: arXiv:0808.2512

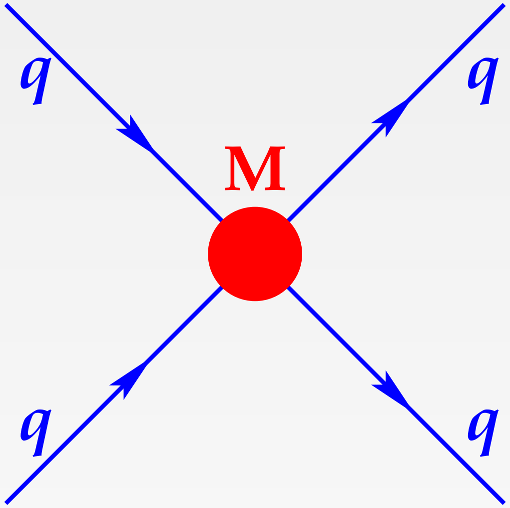
Gravity Effects in Contact Interactions

Meade, Randall: arXiv:0708.3017

- 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
- 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

- Strategy is developed for semiclassical BH: $M_{BH} \gg M_D$
  Triggering, selection, identification, mass reconstruction
  Parameter space is rather limited: $M_D \lesssim 2\,\text{TeV}$

- No quantum gravity theory – many model uncertainties
  More options in simulations become available

- Signal turn-on near Planck scale is unclear
  Little access to $M_{BH} > 5\,\text{TeV}$ with first data at $10\,\text{TeV}$

With first data:

- Look for unusually high multiplicity and high $\sum E_T$
- Look for deviations in dijet and dilepton spectrum

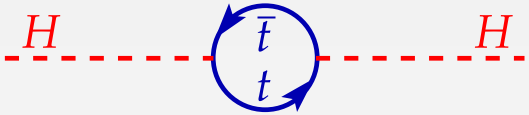
Supported by BMBF

Backup

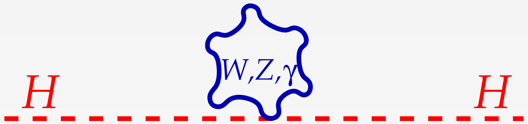
Additional Information

“Fine Tuning” Argument

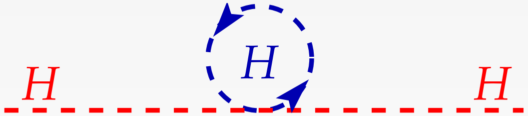
- Higgs self-energy corrections in perturbation theory: $M_H^2 = M_{H,\text{bare}}^2 + \Delta M_H^2$
  Have to integrate over all particle momenta in loops
  ⇒ Loop corrections to Higgs mass rise with UV cut-off Λ^2



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



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



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

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

- Fine tuning to precision $\sim M_H^2/\Lambda^2$ is needed

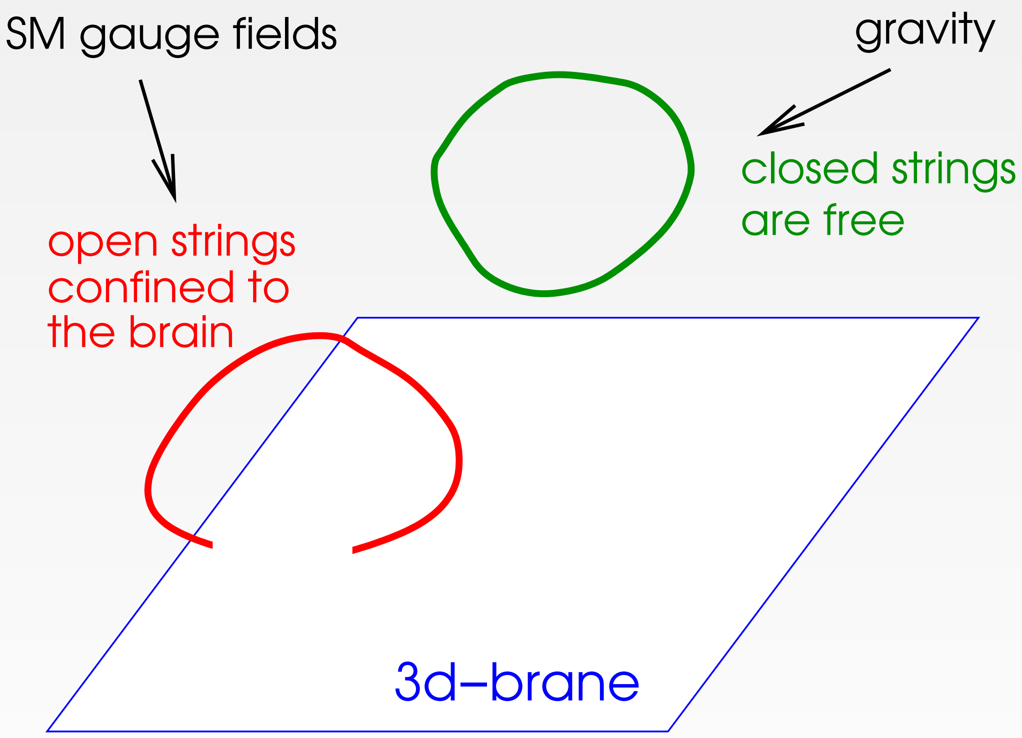
  For $\Lambda = M_{\text{Planck}}$, $M_H \sim 100\,\text{GeV}$: $(\Lambda/M_H)^2 \sim 10^{34}$ – gauge field scale hierarchy

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

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

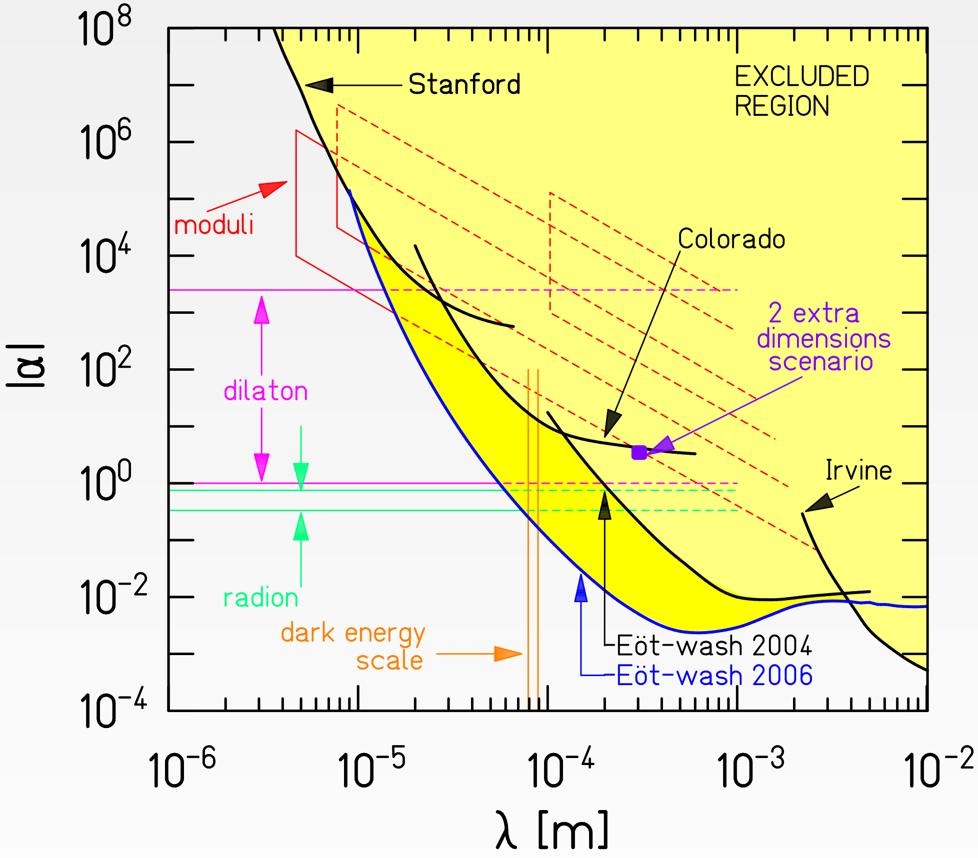
- Why gravity? Because it couples to energy/momentum.
  If gravity cannot go to extra dimensions, then also no other force can.

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.

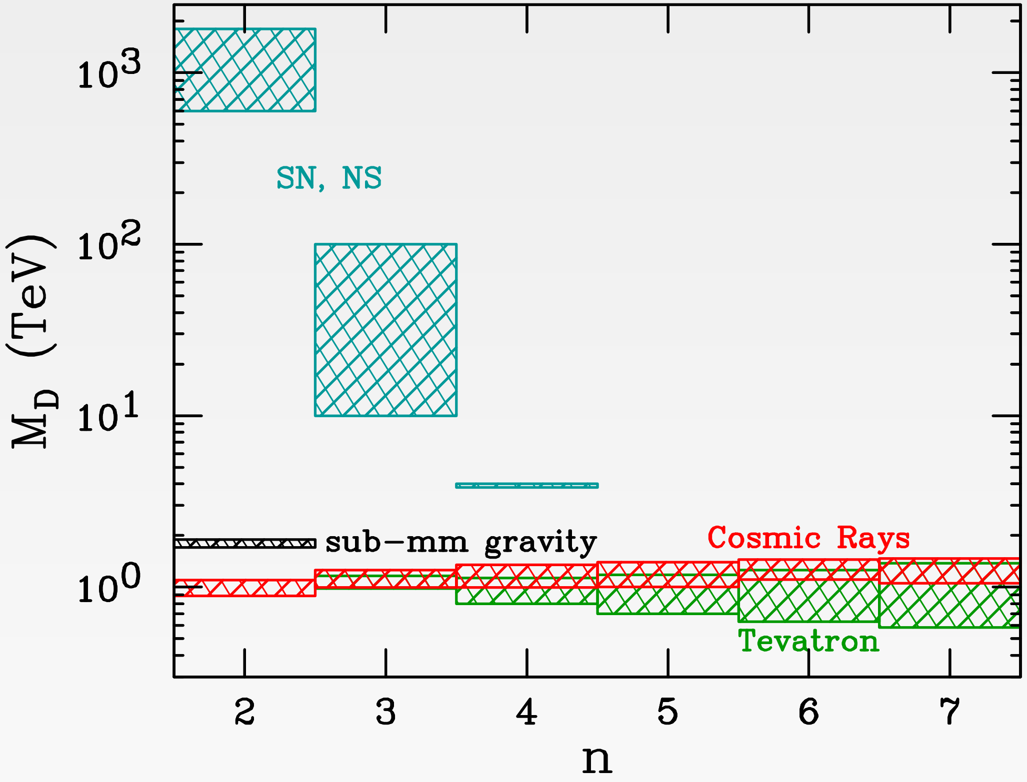


- Modified potential with Yukawa term

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

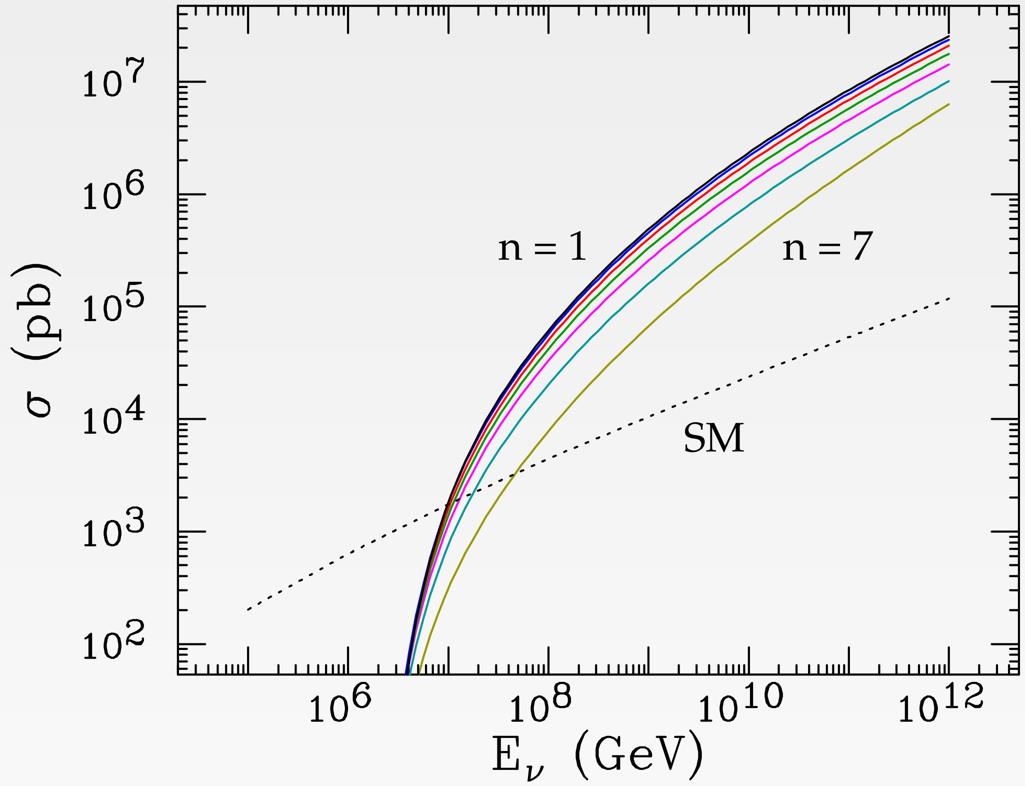
For $n = 2$, this translates into $M_D \gtrsim 3\,\text{TeV}$

Astrophysical Limits in ADD Models



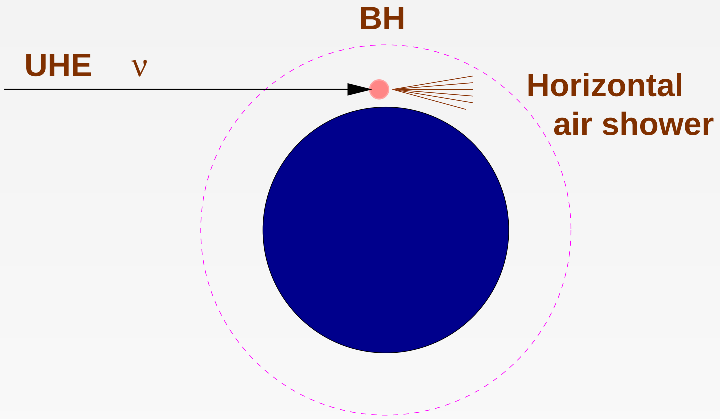
- Astro limits have many uncertainties. Only order of magnitude estimates.
- In general strong astro limits for $n = 2, 3$. Weaker for higher n.
  Colliders can be more sensitive at higher n.
- Astro signals are sensitive to low energy gravitons modes.
  Colliders probe mainly high energy gravitons -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

Black Holes in Cosmic Rays



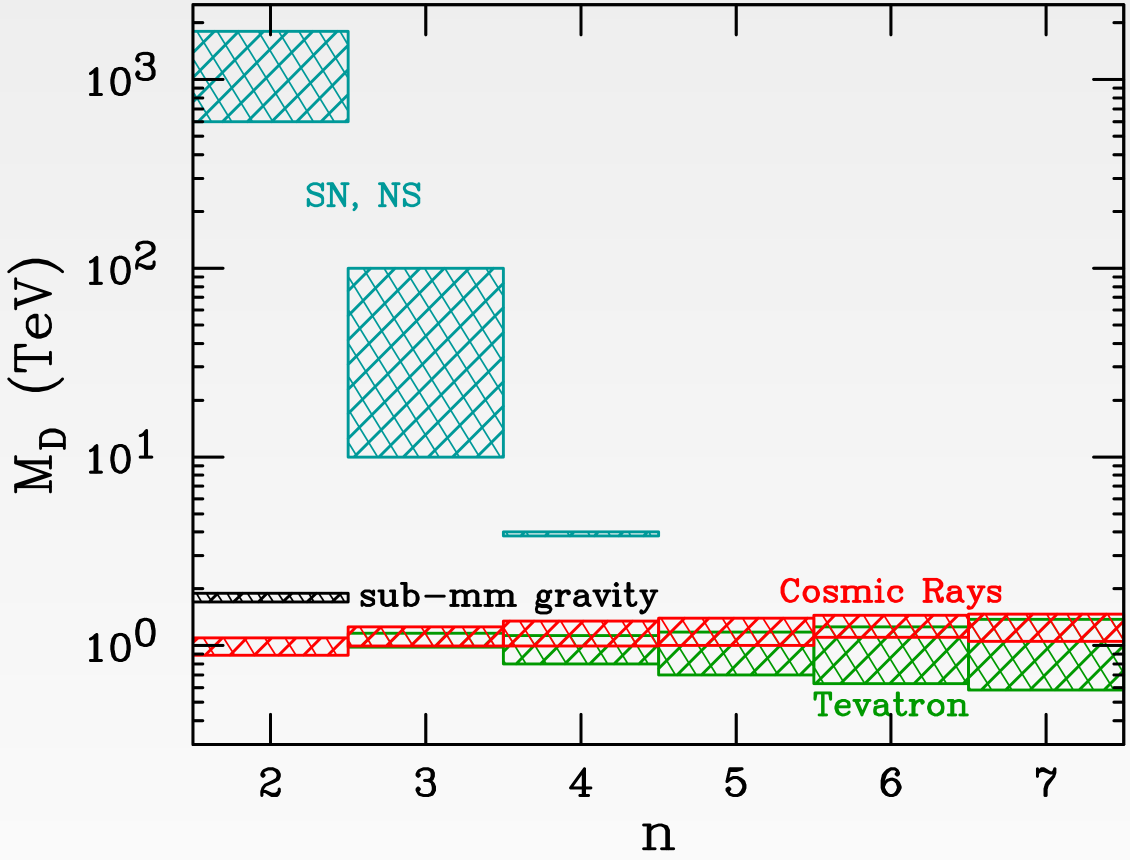
Anchordoqui, Feng,
Goldberg, Shapere:

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 $\longrightarrow$ 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): $M_D > 1 - 1.4\,\mathrm{TeV}$ for $n = 4 - 7$ in ADD.
- So far the only direct bound on micro black holes.