Searches for Quantum Gravity at the LHC

Outline

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

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Current Status of LHC

ATLAS Online Luminosity
\[ \sqrt{s} = 7 \text{ TeV} \]

Total Delivered: 18.1 nb\(^{-1}\)
Total Recorded: 16.02 nb\(^{-1}\)
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

Victor Lendermann, *Searches for Quantum Gravity at the LHC*
“At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions.”
Perturbative processes
♦ Exchange of virtual gravitons
♦ Production of real gravitons

Strong gravity scenarios
♦ Mini black holes
♦ String balls
♦ Time machines
♦ ...
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
- ...

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. $\implies$ BH are charged and coloured

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

Hawking radiation
- High multiplicity
- High sphericity

Democratic decay example

<table>
<thead>
<tr>
<th>Decay</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>q, g</td>
<td>72%</td>
</tr>
<tr>
<td>e, µ, τ</td>
<td>11%</td>
</tr>
<tr>
<td>W±, Z</td>
<td>8%</td>
</tr>
<tr>
<td>ν</td>
<td>6%</td>
</tr>
<tr>
<td>H</td>
<td>2%</td>
</tr>
<tr>
<td>γ</td>
<td>1%</td>
</tr>
</tbody>
</table>

h/l activity 5 : 1

Semi-classical model: $M_{BH} \gtrsim 5M_D$
Interesting Event in ATLAS

7 Jets
1 Muon
\[ \sum E_T > 900 \text{ GeV} \]
\[ E_{\text{miss}} > 100 \text{ GeV} \]
Different strategies exist.

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 $\mu$ with $p_T > 50 \text{ GeV}$

QCD background further reduced by factor $\sim 60$
Black Hole Mass Reconstruction

\[ p_{BH} = \sum p_i + (E_T, E_T \cdot x, E_T \cdot y, 0) \quad \rightarrow \quad M_{BH} = \sqrt{p_{BH}^2} \]

Example for \( M_{BH} > 5 \text{ TeV}, \quad M_D = 1 \text{ TeV}, \quad \sqrt{s} = 14 \text{ TeV} \)

However, turn-on behaviour for \( M_{BH} \gtrsim M_D \) is unknown!
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 $\Rightarrow$ conservative estimation

$$M_D = 1 \text{ TeV}, \sum |p_T| > 2.5 \text{ TeV}, \text{ lepton requirement, } \sqrt{s} = 14 \text{ TeV}$$
Search Strategy for First Data

- Little access to $M_{\text{BH}} > 5$ TeV with first data at $\sqrt{s} = 7$ TeV
  Focus on lower masses

- Turn on of semiclassical BH production is unknown
  If $M_{\text{D}} \sim \mathcal{O}(\text{TeV})$, expect new effects
  Look for high multiplicity events with different objects with $M_{\text{inv}} \gtrsim 1$ TeV
  If geometric $\hat{\sigma} = \pi R_s^2$ starts at $M \sim 1$ TeV, cross section would be in nb range

- **Example:** string balls
String balls – excited string states in weakly-coupled string theory

\[ M_s < M_D < \frac{M_s}{g_s^2} \]  \quad \text{black hole threshold}

string scale \quad \text{Planck scale} \quad \text{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

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 $M > 3\,\text{TeV}$
Black holes at $M \sim M_D$ may appear in contact interactions. This can be any quantum gravity effect or resonance.

Expect excess at high $p_T$ in dijet and dilepton distributions.

Good candidate for discovery in first data.
Searches with Dijets

Apply the same techniques as for compositeness searches

♦ 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

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

\[\eta = -1.3 \quad -0.7 \quad 0.7 \quad 1.3\]

Jet 1

\[\text{Numerator}\]

Sensitive to New Physics

|cos \theta^*| \sim 0

Jet 2

Jet 1

\[\text{Denominator}\]

Dominated By QCD

|cos \theta^*| \sim 0.7, usually

Jet 2 (rare)
Exclusion or Discovery of Contact Interactions

Using dijet angular distributions

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

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

<table>
<thead>
<tr>
<th>Excluded $\Lambda$ (TeV)</th>
<th>Discovered $\Lambda$ (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 pb$^{-1}$</td>
<td>10 pb$^{-1}$</td>
</tr>
<tr>
<td>100 pb$^{-1}$</td>
<td>100 pb$^{-1}$</td>
</tr>
<tr>
<td>1 fb$^{-1}$</td>
<td>1 fb$^{-1}$</td>
</tr>
<tr>
<td>$&lt; 5.3$</td>
<td>$&lt; 4.1$</td>
</tr>
<tr>
<td>$&lt; 8.3$</td>
<td>$&lt; 6.8$</td>
</tr>
<tr>
<td>$&lt; 12.5$</td>
<td>$&lt; 9.9$</td>
</tr>
</tbody>
</table>

Victor Lendermann, *Searches for Quantum Gravity at the LHC*
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 $10 - 100 \text{ nb}^{-1}$ [e.g. for geometric cross section of quantum gravity at $M \sim 1 \text{ TeV}$]

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


Missing $E_T$ Spectrum

ATLAS fast MC studies

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

<table>
<thead>
<tr>
<th>$n$</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_D$ / TeV</td>
<td>9</td>
<td>7</td>
<td>6</td>
</tr>
</tbody>
</table>

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

No instrumentation effects included
Current limits can be significantly improved with only 5–10 pb$^{-1}$
Steven Hawking (1975):

Pairs of virtual particles appear at event horizon with one particle escaping.

Particles have black body spectrum with temperature

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

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.
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.
Single inclusive jet trigger should be very efficient for BH

Eff. $\sim 100\%$ for Thr. $E_T \leq 400$ GeV
[for current trigger simulation]

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

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

Alternatively, $\sum E_T$ trigger can be used: $\sum E_T \gtrsim 300$ GeV for first data, $\gtrsim 1$ TeV later
Especially important for model independent searches
Identifying Black Holes

Need several evidences to be sure. Various ideas exist

♦ Hawking radiation \(\simeq\) democratic decay in MC
  Look at distributions of particle types: ratios \(e/\mu\), \(e/Z^0\), \(e/t\) . . .

♦ 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 . . .)
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.
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.
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 $\rightarrow$ distinguish from hadronic showers
- Cross section should be very large
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.