FRIENDLY BLACK HOLES AT THE MUON COLLIDER

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"The last I heard, Medwick was working on a model black hole in his lab."
Hierarchy problem

Observed Planck scale: $M_{Pl} \sim 10^{19} \text{ GeV}$

Observed EW scale: $M_{EW} \sim 10^2 \text{ GeV}$

Susy? Running couplings?
The approach ‘from below’

- The space time is $D$-dimensional ($D>4$)
- SM fields are confined on a 3-brane in a higher-dimensional space time
- Only gravity propagates in the $n=D-4$ extra dimensions
Brane Universe

\[ S = \frac{M^*_n}{16\pi} \int d^{n+4}x \sqrt{-g} R(g) \]

\[ G_{n+4} = G_4 V_n \]

\[ M_{Pl}^n = M^*_n \]

M. may be very small!!
How do we probe extra-dimensions?
Gravitational effects at the TeV scale

Perturbative effects (Energy $< M_*$)

(Giudice et al. 1998; Mirabelli et al. 1998; Han et al. 1998; Hewett 1999)

- Kaluza-Klein modes
- Virtual graviton exchange

Nonperturbative effects (Energy $\geq M_*$)

(Banks & Fischler 1999; Amati et al. 1987)
All depends on $M$ ... *

If $M \approx 10^{16}$ TeV...

... experimental quantum gravity requires:

Funding unlikely!
If $M^*$ is ~ TeV...

quantum gravity becomes strong at ~ TeV

This may be enough!
Experimental constraints

- **Cavendish experiments:** $n=2$, $M > 1.6$ TeV  
  (Adelberger et al., 2002)

- **Particle collider experiments:** $M/\text{TeV}$ larger than  
  (see e.g. Giudice & Strumia 2002; Peskin 2000)

<table>
<thead>
<tr>
<th></th>
<th>$n=2$</th>
<th>$n=4$</th>
<th>$n=6$</th>
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<tr>
<td>LEP II</td>
<td>0.90</td>
<td>0.33</td>
<td>0.18</td>
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<tr>
<td>Tevatron</td>
<td>0.86</td>
<td>0.39</td>
<td>0.27</td>
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<tr>
<td>LHC</td>
<td>9.4</td>
<td>3.4</td>
<td>2.1</td>
</tr>
</tbody>
</table>

- **Astrophysics and cosmology:** $M/\text{TeV}$ larger than  
  (see e.g. Cullen & Perelstein 1999)

<table>
<thead>
<tr>
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<th>$n=2$</th>
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<td>SN1987A</td>
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<td>Neutron stars</td>
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<tr>
<td>CMBR</td>
<td>65-750</td>
<td>4-32</td>
<td>0.7-4</td>
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<tr>
<td>$C_\gamma$BR</td>
<td>83-263</td>
<td>2.8-7.6</td>
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</tr>
<tr>
<td>UHECR</td>
<td>0.2-0.3</td>
<td>0.2-0.3</td>
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</table>
Nonperturbative effects:

Scattering of two particles with C-o-M energy $>\,\text{TeV}$ and impact parameter $b < r_s$

Black hole forms!
Cross section

(Landsberg & Dimopoulos 2001; Giddings & Thomas 2002)

\[ \sigma_{bh}(s; n) \approx \pi r_s^2 \approx \frac{1}{s_*} \left[ \frac{8 \Gamma((n + 3) / 2)}{(2 + n)} \right]^{\frac{2}{n+1}} \left( \frac{s}{s_*} \right)^{\frac{1}{n+1}} \]

where

\[ M = \sqrt{s} \quad M_* = \sqrt{s_*} \]

♦ Uncharged, non-rotating, spherically symmetric BH
♦ Cross section = black disk (semiclassical regime)
♦ Form factor = 1
If $M \sim \text{TeV} \Rightarrow r_s \sim \text{TeV}^{-1}$

- **UHECR (neutrino-proton to BH):**
  \[
  \sigma_{\nu p \rightarrow bh}(s; n) \approx \sum_i \int dx f_i(x, Q) \sigma_{bh}(xs; n)
  \]

- **LHC (proton-proton to BH):**
  \[
  \sigma_{pp \rightarrow bh}(s; n) \approx \sum_{ij} \int dx \int_{y}^{1} dy f_i(y, Q) f_i(x / y, Q) \sigma_{bh}(xs; n)
  \]

- **Muon collider (muon-muon to BH):**
  \[
  \sigma_{\mu\mu \rightarrow bh}(s; n) \approx \sigma_{bh}(s; n)
  \]
Experimental signatures:

- Very large and steep cross section
  (Landsberg & Dimopoulos 2001; Giddings & Thomas 2002)

- Visible transverse energy / High sphericity events
  (Giddings & Thomas 2002)

- High (?) multiplicity events (hadronic jets + leptons + hard quanta at the end of decay)
  (Giddings & Thomas 2002; Cavaglia 2003)

- Ratio of hadronic to leptonic activity ~ 5:1
  (Giddings & Thomas 2002; Han et al. 2002; Cavaglia 2003)

- Possible large missing energy
  (Cavaglia, Das & Maartens 2003)

- Suppression of hard perturbative scattering processes
**Example**

\[ M_\star = 1 \text{TeV}, \quad n = 6, \quad M_{BH} = 12 \text{TeV} \]

<table>
<thead>
<tr>
<th>Quark</th>
<th>5</th>
<th>Gluon</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged /.</td>
<td>1</td>
<td>W</td>
<td>0</td>
</tr>
<tr>
<td>Neutrino</td>
<td>0</td>
<td>Z</td>
<td>0</td>
</tr>
<tr>
<td>Higgs</td>
<td>0</td>
<td>Graviton</td>
<td>0</td>
</tr>
<tr>
<td>Photon</td>
<td>0</td>
<td></td>
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</tr>
</tbody>
</table>

Quarks and gluons hadronize. H-to-L ratio ~ 5:1
Cross section uncertainties

- **Nonrelativistic limit estimates**
- **Classical photon capture / plunging estimates**
  - (Berti, Cavaglià & Gualtieri 2003)
- **Collisional energy loss/inelasticity**
  - (Yoshino & Nambu, 2003)
- **Angular momentum correction**
  - (Yoshino & Nambu 2003)
- **Charge effects**
  - (Casadio & Harms 2002)
- **Minimal BH formation mass**
  - (Cavaglia`, Das & Maartens 2003)
BH event at CMS

(Model of Landsberg & Dimopoulos, Herwig implementation by C. Harris & P. Richardson, generated by A. de Roeck, simulated & visualised by S. Wynhoff)

Marco Cavaglià  Muon Ring Cooler Workshop, March 12, 2004
The LHC vs the Muon Collider

- LHC: Center-of-mass energy (pp) = 14 TeV
- " (PbPb) = 5.5 TeV

- $\mu$C: Center-of-Mass energy = 4 TeV

- VLHC: Center-of-Mass energy = up to 100 TeV

- VL$\mu$C: Center-of-Mass energy = up to 200 TeV

Disadvantage!
Cross section at the LHC:

**Disadvantage!**

Cross section at the 4 TeV Muon collider:

\[ \sigma \approx 10^2 \text{ pb} \]

Up to \( 10^4 \text{ pb} \)
BH cross section at the LHC:

\[ \sigma_{pp \to bh}(x_m, s; n) \approx \sum_{ij} \int dx \int_{x}^{1} \frac{dy}{y} f_i(y, Q) f_i(x/y, Q) \sigma_{bh}(xs; n) \]

\[ n = 2..7 \text{ from above} \]
BH cross section at the muon collider:

\[
\sigma_{\mu\mu \rightarrow bh} (s; n) \approx \int d^2\epsilon \ f(\epsilon_1) f(\epsilon_2) \sigma_{bh} [s(\epsilon_1, \epsilon_2); n]
\]

\[
f(\epsilon_1) \approx \delta(\epsilon_1 - \epsilon_0), \quad f(\epsilon_2) \approx \delta(\epsilon_2 - \epsilon_0)
\]

If \(\epsilon_m \ll \epsilon_0\), the cross section does not depend on the minimum BH mass.
No uncertainty due to the minimum BH mass
BH collisions at LHC

Proton 7 TeV

Proton 7 TeV

Bunch Crossing 4x10^7 Hz

Proton Collisions 10^9 Hz

Parton Collisions

BH Production

(Adapted from D. Barney)
Differential cross section at the LHC

\[ \frac{d\sigma}{dM_{BH}} (x, s; n) \approx \int_{x}^{y} f_i(y, Q) \frac{dy}{y} f_i(x / y, Q) \sigma_{bh} (xs; n) \]
All BHs have identical mass

\[ \approx \delta (M_{BH} - 4 \, \text{TeV}) \]
What we (want to) do:

♦ Compute the cross section taking into account the beam profile

♦ Systematical analysis of the parameter space

♦ Write an improved montecarlo for BH events at the LHC and at the muon collider

♦ Simulate BH events at the LHC and at the muon collider

♦ Analysis and comparison
Conclusion

- If large extra dimensions exist \(\Rightarrow\) Planck scale \(\sim\) TeV
- Nonperturbative quantum gravity effects at \(E \sim\) TeV
- Creation of black holes & branes at the muon collider!

- If not, constraints on the Planck scale. If yes, new physics at the TeV scale

- Possible tests of strong gravitational effects:
  - Hawking radiation
  - Generalized uncertainty principle