Search for Monojets and Black Holes with CMS

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on behalf of the CMS Collaboration
• The ADD Model and its consequences
• The CMS detector @ LHC
• The Black Holes search
• Looking for Monojet events:
  ➔ Topology and selections
  ➔ Background estimate from data
  ➔ Significance and exclusion limits
• Conclusions and outlook
The ADD Model

- The Hierarchy problem between the Electroweak ($M_{EW} \sim 100$ GeV) and the Planck ($M_{Pl} \sim 10^{19}$ GeV) scales is one of the motivations to look for theories Beyond the Standard Model

- In 1998, Arkani-Hamed, Dimopoulos and Dvali proposed a theory which introduced $\delta$ Large Extradimensions of the order of 0.1 mm, compactified on a $M_D \sim$TeV scale (or a radius $R$)

- The relationship between $M_D$ and $M_{Pl}$ can be found using the $4+\delta$ gravitational potential:

$$V(r) \approx \frac{1}{M_D^{\delta+2}} \frac{m_1 m_2}{r^{\delta+1}} \quad r \gg R$$

$$\Rightarrow V(r) \approx \frac{m_1 m_2}{M_D^{\delta+2}} \frac{1}{R^\delta} \frac{1}{r} \quad \Rightarrow M_D^{\delta+2} R^\delta \equiv M_{Pl}$$

- The fundamental scale of Gravity is so lowered to the TeV scale

- SM model particles can propagate only in the 4d space (brane) while Gravitons freely travels in all the 4+\delta spacetime (bulk)
BH Production

- The Schwarzschild radius in Extradimensional theories is smaller than its 4d version:

\[ r_{S(4+\delta)} = \frac{1}{\sqrt{\pi} M_D} \left[ \frac{M_{BH}}{M_D} \left( \frac{8 \Gamma((\delta+3)/2)}{\delta+2} \right) \right]^{\frac{1}{\delta+1}} \]

- Parton level cross sections for e.g. \( M_D \sim 2 \text{ TeV} \) are in the pb range:

\[ \sigma(BH) = \pi r_{S(4+\delta)} \]

- Due to Hawking radiation, BH has short lifetime (~10^{-27} s) and decays “democratically” in all SM particles

Graviton Production

- Gravitons propagate in the bulk as Kaluza-Klein towers. In the brane they appear as massive spin-2 particles

- They gravitationally couples to SM matter

- In collider experiments, they “appear” as *Missing Tranverse Energy (MET)*

- The cross section is:

\[ \sigma \sim \frac{1}{M_D^2} \left( \frac{\sqrt{s}}{M_D} \right)^\delta \]
The proposed studies are performed @LHC, with a 14 TeV center-of-mass energy

- $10^{30}$-$10^{32} \text{ cm}^{-2}\text{s}^{-1}$ initial luminosity
- $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ designed luminosity

The CMS detector offers:

- 4T solenoidal magnetic field
- Good charged particles momentum resolution and reconstruction
- Good MET and Jet resolution, with an hermetic ($|\eta|<5$) and fine-grained hadronic calorimeter
- Electromagnetic calorimeter with wide coverage ($|\eta|<2.5$) and good energy resolution
ADD Black Holes

• The democratic nature of BH evaporation leads to final states with high multiplicity of (usually) high-$p_T$ leptons and jets

• The ratio between jets and leptons can be estimated as 5:1

• CHARYBDIS event generator was used to produce the BH samples with benchmark parameters:
  • $M_D = 2$ TeV, $\delta=3$
  • BH mass between 4 TeV and 14 TeV

• The Fast Simulation of the CMS detector has been used after a validation with the GEANT-based detailed simulation

• Possible backgrounds are: QCD jets, top production and boson plus jets production

• The BH mass is correlated to the invariant mass of all the produced particles
ADD Black Holes

- The thermal nature of Hawking radiation requires that the sphericity distribution of BH products is ≠ 0
- Events are counted if the total sum of \( p_T \) is greater than 2.5 TeV

### Selections

<table>
<thead>
<tr>
<th>Cut</th>
<th>Signal</th>
<th>tt+nJ</th>
<th>W+nJ</th>
<th>Z+nJ</th>
<th>QCD Dijet</th>
<th>WW+nJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Section (pb)</td>
<td>18.85</td>
<td>371</td>
<td>896</td>
<td>781.84</td>
<td>33076.8</td>
<td>269.91</td>
</tr>
<tr>
<td>Events (10 fb⁻¹)</td>
<td>188500</td>
<td>3.71×10⁶</td>
<td>8.96×10⁶</td>
<td>7.82×10⁶</td>
<td>3.31×10⁸</td>
<td>2.70×10⁶</td>
</tr>
<tr>
<td>( M_{\text{Inv}} &gt; 2 \text{ TeV/c}^2 )</td>
<td>18.71</td>
<td>13.29</td>
<td>6.53</td>
<td>3.85</td>
<td>2634.94</td>
<td>20.53</td>
</tr>
<tr>
<td>Tot. Multiplicity &gt; 4</td>
<td>17.72</td>
<td>13.25</td>
<td>6.43</td>
<td>3.84</td>
<td>2613.18</td>
<td>20.42</td>
</tr>
<tr>
<td>Sphericity &gt; 0.28</td>
<td>9.27</td>
<td>1.60</td>
<td>0.23</td>
<td>0.10</td>
<td>53.74</td>
<td>0.07</td>
</tr>
<tr>
<td>Final No. Events (10 fb⁻¹)</td>
<td>92740</td>
<td>15990</td>
<td>2328</td>
<td>982</td>
<td>537391</td>
<td>740</td>
</tr>
</tbody>
</table>

- The minimum integrated luminosity \( \mathcal{L} \) for 5σ discovery for this benchmark point is \( \sim 2 \text{ pb}^{-1} \).
- For \( M_D \) of 2-3 TeV, \( M_{BH} \leq 4 \text{ TeV} \) and \( \delta = 2-6 \) the necessary \( \mathcal{L} \) can be of \( O(100 \text{ pb}^{-1}) \)
- Significance sensibility to PDF uncertainties is 12% (benchmark point)
ADD Monojets

• One of the most interesting channels is ADD model is the G+jet emission:

- The signature is the presence of a single energetic jet back-to-back to MET

• Samples with $M_D = 2$-7 TeV and $\delta = 2$-4 were produced using the SHERPA event generator and the CMS Fast Simulation (after validation) with CTEQ5L and jet $p_T > 200$ GeV

• Backgrounds: $Z(\nu\nu)$+jets, $W(l\nu)$+jets, top production, QCD jets. Simulated with Detailed CMS simulation

• Iterative Cone jets with $R=0.5$ were used. No corrections applied to Jets and MET

• Analysis performed for 100 pb$^{-1}$ of integrated luminosity

\[
\begin{array}{|c|c|c|}
\hline
&M_D = 2$ TeV & $M_D = 4$ TeV & $M_D = 6$ TeV \\
\hline
\delta = 2 & 49.246 \pm 0.056 & 18.914 \pm 0.022 & 0.862 \pm 0.001 \\
\delta = 4 & 4.253 \pm 0.005 & 0.998 \pm 0.001 & 0.109 \pm 0.001 \\
\hline
\end{array}
\]

Values in pb
Monojet Selections

- **Trigger:**
  - L1: $H_T > 200$ GeV, $p_T^0 = 10$ GeV
  - HLT: $H_T > 250$ GeV, $M_{H_T} > 100$ GeV with $p_T^0 = 20$ GeV
  
  $$H_T = \sum_{p_T(j) > p_T^0} |\vec{p}_T(j)|$$
  $$M_{H_T} = \left| \sum_{p_T(j) > p_T^0} \vec{p}_T(j) \right|$$

- **Jets:** $p_T > 40$ GeV, $|\eta| < 3$
- **MET:** $> 400$ GeV
- **Lepton cleaning:**
  - Jet Electromagnetic Fraction (JEMF) $< 0.9$
  - No isolated tracks with $p_T > 15$ GeV

- **First Jet:** $p_T > 350$ GeV, $|\eta| < 1.7$
- At maximum 2 jets in the event
- $\Delta \phi$(first jet, MET) $> 2.8$
- $\Delta \phi$(second jet, MET) $> 0.5$
# Estimate of Z(\(\nu\nu\)) + jets

<table>
<thead>
<tr>
<th></th>
<th>(tt)</th>
<th>(Z(\nu\nu) + \text{jets})</th>
<th>QCD</th>
<th>(W(\nu\nu) + \text{jets})</th>
<th>(W(\mu\nu) + \text{jets})</th>
<th>(W(\tau\nu) + \text{jets})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>3860</td>
<td>1280</td>
<td>4.92 \times 10^5</td>
<td>1199</td>
<td>1617</td>
<td>1488</td>
</tr>
<tr>
<td>(E_T^{\text{miss}} &gt; 400,\text{GeV})</td>
<td>36.6</td>
<td>54.8</td>
<td>17.9</td>
<td>19.5</td>
<td>63.7</td>
<td>36.3</td>
</tr>
<tr>
<td>(</td>
<td>EMF</td>
<td>&lt; 0.9)</td>
<td>32.0</td>
<td>52.4</td>
<td>17.2</td>
<td>8.8</td>
</tr>
<tr>
<td>(TIV &lt; 0.1)</td>
<td>12.2</td>
<td>46.3</td>
<td>14.2</td>
<td>4.3</td>
<td>5.9</td>
<td>13.0</td>
</tr>
</tbody>
</table>
| \(p_T(\text{jet 1}) > 350\,\text{GeV},\)
| \(|\eta(\text{jet 1})| < 1.7\) | 9.8    | 36.6                          | 11.8 | 3.3             | 4.5             | 9.9             |
| Number of jets < 3 | 2.2    | 28.9                          | 4.6  | 2.3             | 2.8             | 6.9             |
| \(\Delta\phi(\text{jet 1}, E_T^{\text{miss}} > 2.8,\)
| \(\Delta\phi(\text{jet 2}, E_T^{\text{miss}} > 0.5)\) | 0.5    | 25.7                          | < 0.6 | 2.0             | 2.0             | 5.5             |

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<table>
<thead>
<tr>
<th></th>
<th>(\delta = 2)</th>
<th>(\Delta = 6,\text{TeV})</th>
<th>(\delta = 2)</th>
<th>(\Delta = 6,\text{TeV})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>3060</td>
<td>54.4</td>
<td>1190</td>
<td>7.98</td>
</tr>
<tr>
<td>(E_T^{\text{miss}} &gt; 400,\text{GeV})</td>
<td>691</td>
<td>12.1</td>
<td>244.7</td>
<td>3.05</td>
</tr>
<tr>
<td>(</td>
<td>EMF</td>
<td>&lt; 0.9)</td>
<td>658.6</td>
<td>11.6</td>
</tr>
<tr>
<td>(TIV &lt; 0.1)</td>
<td>539.2</td>
<td>9.5</td>
<td>185.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>
| \(p_T(\text{jet 1}) > 350\,\text{GeV},\)
| \(|\eta(\text{jet 1})| < 1.7\) | 343.1          | 6.5            | 117.1          | 1.6            |
| Number of jets < 3 | 286.8          | 5.4            | 98.3           | 1.2            |
| \(\Delta\phi(\text{jet 1}, E_T^{\text{miss}} > 2.8,\)
| \(\Delta\phi(\text{jet 2}, E_T^{\text{miss}} > 0.5)\) | 261.5          | 4.9            | 90.1           | 1.1            |

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**CMS Preliminary**

- \(W+\text{jets}\)
- \(Z(\nu\nu)+\text{jets}\)
- \(t\bar{t}\)
- QCD
- ADD \(M_D=2\,\text{TeV}\)

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Leonardo Sala

PANIC08, Eilat (Israel). 10/11/2008
Estimate of $Z(\nu\nu)+\text{jets}$

- It is an *irreducible* background, and also the main one. Better if estimated from data.
- At high bosons $p_T$, the ratio between $W(\mu\nu)+1\text{jet}$ and $Z(\nu\nu)+1\text{jet}$ is $\sim 1.3$. PDF dependence $\sim 1\%$.
- A ~pure $W(\mu\nu)$ control sample is selected with:
  - A single isolated muon with $p_T > 20$ GeV
  - All signal selections (single muon excluded from Track Veto).
- This sample is further corrected by Trigger and Isolation efficiency. Systematic effects taken into account.
- The contamination by $W(\tau\nu)$ events ($\sim 16\%$) is estimated by the $\text{Br}(\tau \rightarrow \mu)$. The top pair contamination ($\sim 10\%$) is treated as a systematic contribution.
- Result: $21.9 \pm 4.9\,(\text{stat})^{+2.1}_{-1.4}\,(\text{syst})$
Results

- The MC prediction for W background will be normalized to the measured $W(\mu \nu)$ in the control sample. The top pair prediction will be normalized to the measured top pair production.

- The total background will be:

\[ N_B = 30.7 \pm 6.8 \, (stat)_{-1.5}^{+2.7} \, (syst) \]

- Systematic effects on signal prediction:
  - PDF: $+8.6\%/-6.6\%$
  - Scale dependence: $+11\%/-13\%$
  - Luminosity: 10\% assumed
  - Jet Energy Scale: 10\% assumed on jet 4-momentum, which is translated in a $-0.8\%/-4\%$ effect on the number of selected events
  - MET: evaluated as $+17.5\%/-15.9\%$ with a shift by $\sigma(MET)$
  - Jet Energy and angular resolution: found of $O(1\%)$
Discovery and Exclusion

Previous results

<table>
<thead>
<tr>
<th>δ</th>
<th>LEP</th>
<th>DØ</th>
<th>CDF</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>γ + $E_T^{miss}$</td>
<td>γ + $E_T^{miss}$</td>
<td>jet + $E_T^{miss}$</td>
<td>γ + $E_T^{miss}$</td>
</tr>
<tr>
<td>2</td>
<td>1.600</td>
<td>0.921</td>
<td>1.310</td>
<td>1.080</td>
</tr>
<tr>
<td>3</td>
<td>1.200</td>
<td>0.877</td>
<td>1.080</td>
<td>1.000</td>
</tr>
<tr>
<td>4</td>
<td>0.940</td>
<td>0.848</td>
<td>0.980</td>
<td>0.970</td>
</tr>
<tr>
<td>5</td>
<td>0.770</td>
<td>0.821</td>
<td>0.910</td>
<td>0.930</td>
</tr>
<tr>
<td>6</td>
<td>0.660</td>
<td>0.810</td>
<td>0.880</td>
<td>0.900</td>
</tr>
</tbody>
</table>

CMS reach for 100 pb$^{-1}$

<table>
<thead>
<tr>
<th>δ</th>
<th>3 σ</th>
<th>95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.58</td>
<td>4.61</td>
</tr>
<tr>
<td>4</td>
<td>2.63</td>
<td>3.46</td>
</tr>
</tbody>
</table>
Conclusions and Outlook

- The ADD model introduces Extradimensions in order to solve the Hierarchy Problem
- One of its manifestations can be the evaporation of Black Holes, which can be detected at the CMS detector also with $O(pb^{-1})$ statistics thanks to the spectacularity of the event
- Another interesting channel is the Monojet+MET one, where the Graviton does not interact with the detector
- Current limits on ADD Extradimensions can be significantly extended already with 100 $pb^{-1}$ of integrated luminosity
- Procedures for estimating backgrounds from data are provided
- We are ready for data!
Backup
Significance estimator

- The Profile Likelihood estimator has been used (arXiv:physics/0702156v3)

\[ S_{PL} = \sqrt{2} \left[ n_{on} \ln \frac{n_{on}^{1+\tau}}{n_{on}+n_{off}} + n_{off} \ln \frac{n_{off}^{1+\tau}}{\tau(n_{on}+n_{off})} \right]^{1/2} \]

- It can be computed from a likelihood ratio, where the likelihood function is a Poisson distribution for the total number of observed event \((N_S + N_B)\), multiplied by a Gaussian with \(N_B\) as mean and the total background error \(\Delta B\) as sigma. We took the analytic expression of the estimator. It is tailored for an on/off problem (background estimated from the sidebands of a signal region). To convert it to the actual problem, here it is assumed \(\tau = N_B / (\Delta B)\), \(n_{off} = \tau N_B\) and \(n_{on} = N_S + N_B\)
Previous results

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$Z(\nu\nu) + \text{jets estimate}$