Search for New Physics in the All-Hadronic Final States at CMS

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on behalf of the CMS Collaboration
Outline

Motivation

The CMS detector and Jet Reconstruction

Monojet + MET

Dijet Resonances

Multijet Resonances

Multijet Transverse Momentum Sum Shape (Black Hole)

Conclusion
Motivation

All hadronic final state is sensitive to new physics from various models
- Strong Dynamics: Jet Resonances
- Extra Dimension: Jet Resonance, Monojet, Black hole
- SUSY: Multijet Resonances (RPV)

A channel with many potential discoveries

Graviton

Dijet resonance
Jet and MET Reconstruction

- Anti-kt (AK) clustering algorithm with cone size of 0.5 (AK5) and 0.7 (AK7)
  - Infrared and collinear safe

Jet types:
- Calorimeter Jets:
  - Reconstructed from energy deposits in the EM and HAD calorimeter, grouped in projective calorimeter towers
- Particle Flow (PF) Jets:
  - Use all detector elements to reconstruct particles and cluster to jets.
- Fat Jets:
  - Clusters of AK5 PF Jets within radius of 1.1, optimize dijet resonance resolution by recombining FSR into the two leading jets

Jet energy corrections: using MC truth information and real data
- Uncertainty on jet energy scale < 3%
- Uncertainty on Jet energy resolution ~10%

MET: negative vector sum of transverse momenta of all particles
Monojet + MET (Direct Graviton)

Signature: Monojet + MET (graviton)
- MET >150 GeV
- At most 2 jets ($p_T > 30$ GeV)
  - $p_T^1 > 110$ GeV, $|\eta_1| < 2.4$
  - $p_T^2 > 30$ GeV, $\Delta \phi_{12} < 2.0$

Data-driven background estimation using $\mu +$jets sample, consistent with QCD MC
- W/Z + jets
- Z(vv) + jets

No significant excess is observed

arXiv:1106.4775 [hep-ex]
**Limit with 36 pb⁻¹**

- Observed and expected limit @95% CL on the ADD parameter $M_D$ (TeV/c²) as functions of $\delta$ (# of extra-dim)

<table>
<thead>
<tr>
<th>$\delta$</th>
<th>NLO Exp</th>
<th>NLO Obs</th>
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<td>2</td>
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<td>2.56</td>
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<td>3</td>
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<td>1.86</td>
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<td>5</td>
<td>1.68</td>
<td>1.74</td>
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<tr>
<td>6</td>
<td>1.62</td>
<td>1.68</td>
</tr>
</tbody>
</table>

- Significant improvement:
  - $\delta = 4$:
    - LEP: 0.94 TeV, D0: 0.85 TeV
    - CDF 1.04 TeV, **CMS: 1.86 TeV**
  - $\delta = 2$:
    - LEP: 1.60 TeV, D0: 0.92 TeV
    - CDF 1.40 TeV, **CMS: 2.56 TeV**

- Observed and expected limit @95% CL on the allowed region of unparticle model parameters $d_U$ and $\Lambda_U$
  - PRD 81 (2010) 056003
  - arXiv:1012.3737
Dijet Resonances Search

- Parton resonances decaying into dijets from various models
- Search for 3 generic types of narrow dijet resonances
  - qq, qg, gg resonances
  - Using fat jet in this result
  - Fat jets shows better resolution due to more recovery of FSR

<table>
<thead>
<tr>
<th>Models</th>
<th>X</th>
<th>Color</th>
<th>J^{P}</th>
<th>\Gamma/(2M)</th>
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<tr>
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<td>q^*</td>
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<td>qg</td>
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<td>E_6 Diquark</td>
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<td>qq</td>
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<td>Coloron</td>
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<td>\bar{q}\bar{q}</td>
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<tr>
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<td>W'</td>
<td>Singlet</td>
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<td>0.01</td>
<td>q\bar{q}</td>
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<td>Mixed</td>
<td>0.003-0.037</td>
<td>qg, \bar{q}\bar{q}, gg</td>
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Dijet Resonances with 1 fb$^{-1}$

- Fat PF Jet, $|\eta| < 2.5$ & $|\Delta \eta| < 1.3$
- Data are in good agreement with QCD
- Fit to a parameterization, good $\chi^2$/d.o.f=27.5/28
- No evidence of new physics

PAS EXO-11-015

\[
\frac{d\sigma}{dm} = \frac{p_0 \cdot (1 - m/\sqrt{s})^{p_1}}{(m/\sqrt{s})^{p_2} + p_3 \ln(m/\sqrt{s})}
\]
*Highest Dijet Mass Event*

- **Run**: 166895
- **Event**: 367873378
- **Dijet Mass**: 3.835 TeV

- **Jet 1**: \(p_T = 1.641\) TeV
- **Jet 2**: \(p_T = 1.522\) TeV

- **Well balanced dijet event**
**Dijet Resonance Limit with 1 fb\(^{-1}\)**

### Models and Exclusions

<table>
<thead>
<tr>
<th>Model</th>
<th>Previous CMS Excluded @95% w/ 3 pb(^{-1}) (TeV)</th>
<th>Excluded @95% CL w/ 1 fb(^{-1}) (TeV)</th>
<th>Expected limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>String Resonance</td>
<td>0.5-2.5</td>
<td>1.0 - 4.00</td>
<td>3.90</td>
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<td>Excited Quark</td>
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<td>Axigluon/Coloron</td>
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<tr>
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<td>1.0 - 3.52</td>
<td>3.28</td>
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<tr>
<td>W’</td>
<td>N/A</td>
<td>1.0 - 1.51</td>
<td>1.42</td>
</tr>
</tbody>
</table>
Search for pair produced R-Parity violating Supersymmetry gluino (no MET) from 6 jet final state

Huge combinatorial background besides QCD background
- 20 triplet combinations from 6 jets

Use a diagonal cut to remove combinatorial background as well as QCD background:
- $m_{jjj} < \Sigma |p_T\text{(triplet)}| - \alpha$ (Offset)

Critical cut in multijet resonances search
No significant excess is observed. Excluded mass limit of RPV gluino at Bayesian 95% CL is between 200 GeV and 280 GeV.

- The highest limit to date and the first limit from pp collisions.

arXiv:1107.3084 [hep-ex]
ADD (Arkani-Hamed, Dimopoulos and Dvali) model’s solution to the hierarchy problem:

\[ M_{\text{PI}}^2 = 8\pi M_D^{n+2} r^n \]
where \( M_{\text{PI}} \) is the Planck scale (\( \sim 10^{16} \) TeV), \( M_D \) is the “true” Planck Scale in 4+n dimension at the electroweak scale.

The parton-level cross section \( \sigma = \pi r_s^2 \), where \( r_s \) (Schwarzschild radius) is defined as:

\[ r_s = \frac{1}{\sqrt{\pi} M_D} \left[ \frac{M_{\text{BH}}}{M_D} \frac{8\Gamma \left( \frac{n+3}{2} \right)}{n+2} \right]^{\frac{1}{n+1}} \]

Signature: high multiplicity, democratic, and highly isotropic decays with the final-state particles carrying hundreds of GeV of energy.

CMS search through \( S_T = \sum E_T(\text{jet, e, } \mu, \gamma) \) w/ \( E_T > 50 \) GeV, MET is included.

- Extract \( S_T \) shape from \( N=2,3 \) samples.
- Normalize to events with multiplicity \( N \geq 3,4,5,6,7,8 \).
Microscopic Black Holes with 1 fb$^{-1}$

Non-QCD standard model backgrounds are negligible

Fit to parameterization

No significant excess is observed

PAS EXO-11-071
Significant improvement comparing with 2010 data
See backup for model dependent limit
CMS hadronic resonance searches have been presented based on 2010 and 2011 data.

No evidence for new physics yet.

Data significantly constrain many models of new physics.

2011 data is quickly supersede 2010 results

- 1 fb\(^{-1}\) on tape
- A few more fb\(^{-1}\) expected this year

Ample space for discoveries.

Stay tuned!
The corresponding black hole mass limit with different black hole parameters: from ~4.1 to ~5.1 TeV

New limit for the first time on string Ball (BLackMax): from 4.1 to 4.5 TeV

- string balls are hypothesized precursors of the semiclassical black holes when the mass of the object is close to the Planck scale.
Fat jets optimize dijet resonance resolution by recombining FSR into the two leading jets

Fat Jets: clusters of AK5 PF Jets
Cluster radius: R=1.1

Fat Jets algorithm

- Select 2 leading AK5 PF jets.
- For AK5 PF jets j from 3 to n:
  - Require:
    - $p_T,j > 10$ GeV
    - $|\eta| < 2.5$
  - If $\Delta R_{1j} < R_{\text{Fat}}$ and $\Delta R_{2j}$.
    - Add j to Fat Jet 1.
  - If $\Delta R_{j2} < R_{\text{Fat}}$ and $\Delta R_{1j}$.
    - Add j to Fat Jet 2.
- $R = 1.1$ is best choice for a single search for $qq$, $qg$ and $gg$ resonances.
Recombination of Radiation

Run: 165993
Event: 1553204810
Dijet Mass: 3.077 TeV

Jet 1 $p_T = 1.414$ TeV
Jet 2 $p_T = 1.389$ TeV

Combined into 1 Fat jet
Dijet Centrality Ratio

\[ R = \frac{\frac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)}}{\frac{N(\text{inner})}{N(\text{outer})}} \]

*Both jets inner or outer.*

- Quantifies the centrality of the dijet angular distribution at a given dijet mass.
  - both leading jets are required to lie in the same \( \eta \) range.
- Important experimental uncertainties cancel because of the ratio (absolute jet energy scale, luminosity).
- “t-channel” scattering for QCD vs “schannel” for most new Physics models
  - roughly flat vs dijet mass for QCD.
  - rises vs dijet mass for contact interactions.
  - “bumps” in dijet mass for dijet resonances.
Dijet Centrality Ratio

Data is agree with the predictions of the standard model. No sign of new physics. Set limit on contact interaction scale $\Lambda$ with modified frequentist approach ($\text{CL}_s$) method. Contact interaction scale excluded for $\Lambda < 4.0$ TeV at 95% CL.

PRL 105, 262001 (2010)
**Background shape for black hole**

Assume the shape (tail) of QCD ST spectrum is invariant for difference multiplicity bins, we can model background from lower multiplicity, and rescale to higher multiplicity.

Fit exclusive multiplicity $= 2/3$ with the following functions, in ST $[800, 2500]$ GeV.

**Parameterizations**

- 0) $P_0 (1+x)^{P_1} / x^{(P_2 + P_3 \times \log(x))}$
- 1) $P_0 / (P_1 + P_2 \times x + x^2)^{P_3}$
- 2) $P_0 / (P_1 + x)^{P_2}$
- 3) $P_0 \times \exp((P_3+(P_1\times\log(x)))+(P_2*(\log(x)^2)))*((P_3+P_4*\log(x)))/x)$
- 4) $P_0 \times \exp(P_1*\log(x) + P_2*x)$

**Normalization**

Rescale the fit to inclusive multiplicity $\geq 3, 4, 5, 6, 7, 8$ in ST $[1800, 2000]$ GeV.