Search for new Physics in the dijet mass spectrum
and dijet ratio in pp Collisions at $\sqrt{s} = 7$ TeV

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On behalf of the CMS Collaboration

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Outline

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Motivation

- We study the inclusive dijet final state using the **dijet mass spectrum** and the **dijet centrality ratio** observables.
- Together the Dijet Mass and Ratio provide a **test of QCD** and a **sensitive search** for new physics beyond the Standard Model.

- **Dijet mass distribution** is a simple check of rate vs dijet mass from QCD and PDFs.
- **Dijet centrality ratio** is a detailed measure of QCD dynamics from angular distribution.

- **Dijet mass** provides most sensitive “bump” hunt for new particles decaying to dijets.
- **Dijet centrality ratio** can confirm that a “bump” is not QCD fluctuation.

- **Dijet centrality ratio** is more sensitive than the dijet mass to contact interactions from quark compositeness.
- When all experimental uncertainties are considered.
Specific Dijet Resonance Models

- Parton resonances decaying to dijets are predicted by various theory models:
  - Axigluons
  - Colorons
  - Excited Quarks
  - $E_6$ Diquarks
  - Randal-Sundrum Gravitons
  - New vector bosons ($Z', W'$)

- Recent theoretical development: String Resonances
  - Regge excitations of quarks and gluons
  - Much higher cross-section than excited quark models by a factor $\sim 25$ (due to color, spin and chirality effects)

<table>
<thead>
<tr>
<th>Model Name</th>
<th>X</th>
<th>Color</th>
<th>$J^P$</th>
<th>$\Gamma / (2M)$</th>
<th>Final-state Partons</th>
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</thead>
<tbody>
<tr>
<td>String</td>
<td>S</td>
<td>mixed</td>
<td>mixed</td>
<td>0.003-0.037</td>
<td>$q\bar{q}$ $qg$ and $gg$</td>
</tr>
<tr>
<td>Axigluon</td>
<td>A</td>
<td>Octet</td>
<td>$1^+$</td>
<td>0.05</td>
<td>$q\bar{q}$</td>
</tr>
<tr>
<td>Coloron</td>
<td>C</td>
<td>Octet</td>
<td>$1^-$</td>
<td>0.05</td>
<td>$q\bar{q}$</td>
</tr>
<tr>
<td>Excited Quark</td>
<td>q*</td>
<td>Triplet</td>
<td>$1/2^+$</td>
<td>0.02</td>
<td>$qg$</td>
</tr>
<tr>
<td>$E_6$ Diquark</td>
<td>D</td>
<td>Triplet</td>
<td>$0^+$</td>
<td>0.004</td>
<td>$qq$</td>
</tr>
<tr>
<td>RS Graviton</td>
<td>G</td>
<td>Singlet</td>
<td>$2^+$</td>
<td>0.01</td>
<td>$q\bar{q}$, $gg$</td>
</tr>
<tr>
<td>Heavy W</td>
<td>W'</td>
<td>Singlet</td>
<td>$1^-$</td>
<td>0.01</td>
<td>$q\bar{q}$</td>
</tr>
<tr>
<td>Heavy Z</td>
<td>Z'</td>
<td>Singlet</td>
<td>$1^-$</td>
<td>0.01</td>
<td>$q\bar{q}$</td>
</tr>
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</table>

String resonances would produce a spectacular “bump” in the dijet invariant mass spectrum.
The CMS Detector

Pixels Tracker
ECAL
HCAL
Solenoid Steel Yoke
Muons

**STEEL RETURN YOKE**
~13000 tonnes

**SUPERCONDUCTING SOLENOID**
Niobium-titanium coil carrying ~18000 A

**HADRON CALORIMETER (HCAL)**
Brass + plastic scintillator

**SILICON TRACKER**
Pixels (100 x 150 μm²)
~1m²  66M channels
Microstrips (50-100μm)
~210m²  9.6M channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
76k scintillating PbWO₄ crystals

**PRESHOWER**
Silicon strips
~16m²  137k channels

**FORWARD CALORIMETER**
Steel + quartz fibres

**MUON CHAMBERS**
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

<table>
<thead>
<tr>
<th>Total weight</th>
<th>14000 tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall diameter</td>
<td>15.0 m</td>
</tr>
<tr>
<td>Overall length</td>
<td>28.7 m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>3.8 T</td>
</tr>
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</table>
Jets are reconstructed from energy depositions in the Electromagnetic and Hadron calorimeters, grouped in projective towers.

- **Anti-\(k_T\)** clustering algorithm with distance parameter \(R=0.7\).
  - infrared and collinear safe, sequential recombination algorithm.
  - essentially behaves like a cone algorithm.

- Jet energy calibration from Monte Carlo truth.
  - preliminary in-situ measurements with \(\gamma+\text{jet } p_T\) balancing and of single particle response, indicate that the jet energy scale is known to better than 10%.

- Jet \(p_T\) resolution in the simulation agrees with in-situ measurement.
Events are well balanced, as expected from the dijet topology.

Events have low MET/SumET due to finite jet resolution, consistent with the QCD expectation.

- unphysical backgrounds would show-up at MET/SumET ~ 1.

- Jets are “back-to-back” in azimuth \( \varphi \).
Highest Dijet Mass Event

Run: 138919  
Event: 32253996  
Dijet Mass: 2.130 TeV

Jet 1 $p_T$: 585 GeV

Jet 2 $p_T$: 557 GeV

Jet 2 $p_T$: 557 GeV
We use a jet trigger requiring a single jet with $E_T > 50$ GeV uncorrected.

- We measure the dijet mass spectrum where the trigger is fully efficient.
- The dijet mass spectrum with both jets in the range $|\eta_1|,|\eta_2| < 1.3$, extends to 2.13 TeV with 120 nb$^{-1}$.
- The data is in good agreement with the full CMS simulation of QCD from PYTHIA.
Smooth Fit of the Data

Good fit of the data with only 3 parameters ($\chi^2/\text{ndf} = 13/20$).
- No indication of new Physics.
- String resonances have large cross-section and provide the highest search sensitivity.

$$\frac{d\sigma}{dm} = P_0 \frac{(1 - m/\sqrt{s})^P_1}{m^{P_2}}$$
Resonance shapes are produced with PYTHIA + CMS simulation.

The 3 types of resonances (qq, qg, gg) have different shapes, mainly due to FSR.

- The width of the dijet resonance increases with increasing number of gluons because they emit more radiation than the quarks.

- Gaussian core of dijet mass resolution for qg resonances varies from 11% at 0.5 TeV to 6% at 2.5 TeV.

- We search for these 3 generic types of narrow dijet resonances in the data.
We have **generic, cross-section upper limits** on quark-quark, quark-gluon and gluon-gluon resonances.

The upper limits are compared to the expected cross-section for 7 resonance models.

- We exclude **excited quarks** (qg resonance) with mass $M < 0.59$ TeV. Tevatron limit is 0.87 TeV.
- We exclude **Axigluons/Colorons** (qq resonance) with $M < 0.52$ TeV. Tevatron limit is 1.25 TeV.
- We exclude a **string resonance with mass $M<1.67$ TeV**
  - string resonance decays predominantly to qg (75%).
  - we have taken into account its branching ratio to gg (12%) and qqbar (13%) as well.
  - more stringent than the Tevatron limit on string resonances of about 1.4 TeV (our evaluation of cross-section).
The Dijet Centrality Ratio

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

- 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.
  - “t-channel” scattering for QCD vs “s-channel” for most new Physics models
  - approximately flat vs dijet mass for QCD.
  - rises vs dijet mass for contact interactions.
  - “bumps” in dijet mass for dijet resonances.
- The analysis of the dijet angular distribution is complimentary to the spectrum analysis.
- The dijet centrality ratio is used to confront the QCD prediction and search for new Physics.
Data compared to theory predictions.

Important experimental uncertainties cancel because of the ratio (absolute jet energy scale, luminosity).

NLO theory uncertainty dominated by the factorization/renormalization scale and the non pert. correction.

The data agree well with the NLO+non pert. correction prediction.
Limits with the Dijet Centrality Ratio

** CMS Preliminary \( \Lambda = 1.5 \text{TeV} \)
\( \sqrt{s} = 7 \text{ TeV} \)

- Data 120 nb\(^{-1}\)
- NLO+Non-Pert. Correction
- Contact Interactions
- Excited Quarks

Log Likelihood Ratio

\[ \Lambda \text{ (GeV)} \]

- Ratio is flat, no sign of new physics.
- Contact interaction scale excluded for \( \Lambda < 1.9 \text{ TeV} \) at 95% CL.
- Tevatron excludes \( \Lambda < 2.8 \text{ TeV} \)

CMS Preliminary \( \sqrt{s} = 7 \text{ TeV} \)
Limit: 1900 GeV

ICHEP 2010, Paris
Konstantinos Kousouris
Future Prospects

Expected resonance mass limits from dijet spectrum

Expected contact interaction scale limits from dijet centrality ratio

✧ Expected limits indicate that we should reach the Tevatron q* limit of 870 GeV with 400 nb⁻¹.
✧ The Tevatron limit of \( \Lambda > 2.8 \text{ TeV} \) (D0, 1fb⁻¹) is expected to be surpassed with 4 pb⁻¹.
✧ CMS is now exploring new territory, beyond the Tevatron String Resonance limit.
Summary

✦ The dijet mass spectrum extends to $2.13\text{ TeV}$ with $120\text{ nb}^{-1}$ for $|\eta_{1,2}|<1.3$.
✦ The dijet mass spectrum is in good agreement with a full CMS simulation of QCD from PYTHIA.
✦ The dijet centrality ratio is in good agreement with the QCD perturbative prediction at NLO with non pert. corrections.
✦ We have limits on dijet resonance cross-sections, for qq, qg and gg resonances.
✦ We exclude string resonances with mass $M < 1.67\text{ TeV}$ at 95% CL.
  ◦ Beyond the Tevatron limit of 1.4 TeV.
✦ We exclude excited quarks with mass $M < 0.59\text{ TeV}$ and axigluons with mass $M < 0.52\text{ TeV}$ at 95% CL.
✦ We exclude contact interactions for $\Lambda < 1.9\text{ TeV}$ at 95% CL.
✦ Expected limits indicate that we should reach the Tevatron $q^*\text{ limit}$ of $870\text{ GeV}$ with $400\text{ nb}^{-1}$ and surpass the $\Lambda > 2.8\text{ TeV}$ limit with $4\text{ pb}^{-1}$.
References

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

(1) “Search for Dijet Resonances in the Dijet Mass Distribution in $pp$ Collisions at $\sqrt{s} = 7$ TeV”,
**Physics Analysis Summary: EXO-10-001**

(2) “Search for New Physics with the Dijet Centrality Ratio”,
**Physics Analysis Summary: EXO-10-002**

(3) “Jet Performance in $pp$ Collisions at $\sqrt{s} = 7$ TeV”,
**Physics Analysis Summary: JME-10-003**

(4) “Single Particle Response in the CMS Calorimeters”,
**Physics Analysis Summary: JME-10-008**

(5) “The CMS physics reach for searches at 7 TeV”,
**CMS NOTE-2010/008**
Measurement of the dijet invariant mass spectrum and the dijet centrality ratio, in the fiducial region $|\eta|<1.3$, using the two highest $p_T$ jets in an event.

Comparison to the Monte Carlo (PYTHIA + CMS simulation) and perturbative QCD at NLO prediction, to check the overall agreement.

Fit of the measured spectrum with a smooth function and search for resonances.

Look at the dijet centrality ratio for resonance-like or compositeness-like deviations from the theory prediction.
The Anti-\(k_T\) Clustering Algorithm

\[
d_{ij} = \min \left( k_{T,i}^{-2}, k_{T,j}^{-2} \right) \frac{\Delta R_{ij}^2}{R^2}
\]

\[
\Delta R_{i,j}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
\]

✧ New development in the jet clustering theory.
✧ Tends to cluster the energy around the hardest particles.
  ▶ essentially behaves like a cone algorithm giving perfectly round jet areas
✧ Belongs to the "\(k_T\)" family.
  ▶ merging of 4-vector pairs based on transverse momentum weighted distance in \(y-\phi\) plane.
  ▶ the clustering terminates when the weighted distance between particles is greater than a specific value \(R\) (resolution parameter).
  ▶ the quantity \(R\) is of the order of unity.
✧ infrared and collinear safe (suitable for theory calculations).
We combine the fine mass bins at high mass to eliminate bins with 0 events.

- the horizontal position of the points is found using the QCD spectrum.
- this provides the fairest comparison between QCD and the data.
- but these mass bins are too coarse to be used for resonance search.

\[ \sqrt{s} = 7 \text{ TeV} \]

anti-\(k_T\) R = 0.7 CaloJets

\( M_{jj} > 354 \text{ GeV} \)

\( |\eta_1, \eta_2| < 1.3 \)
Uncertainties on the Cross-Section Limits

Sources of systematic uncertainty

- Jet Energy Scale
- Jet Energy Resolution
- Background Parametrization
- Luminosity

Total systematic uncertainty on the cross section limit varies between 16% and 43% depending on resonance mass and type.

- JEC is the dominant systematic uncertainty.

We include the total systematic uncertainty in the limit using a conservative convolution technique.

- This increases our cross section limits between 10% and 38% depending on resonance mass and type.
Preliminary measurement of the single particle response indicates that the data vs MC agreement is better than 3% in the barrel.

the level of accuracy of the single particle response simulation, shows that the assigned 10% JES uncertainty is safe.

Preliminary measurement of the jet energy response using the MPF method shows good agreement between data and MC.

Direct measurement of the relative jet energy scale with dijet $p_T$ balance shows that the uncertainty of the relative scale across $\eta$ is less than 2%.