SEARCHES FOR BSM PHYSICS IN DIJET AND MULTIJET FINAL STATES AT CMS

SUSY 2016
The University of Melbourne
Melbourne, Australia

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Caltech
MOTIVATION AND OUTLINE

- **Powerful**: LHC in Run 2 is a dijet resonance factory at a new energy scale
- **Broad**: Many BSM phenomena can be searched for
- **Model independent**: search results are applicable to any model that predicts narrow quark-quark, quark-gluon, or gluon-gluon resonances

This talk:
- High-mass search at 13 TeV with 2015 data
- Low-mass search at 8 TeV with "data scouting"
- Data scouting at 13 TeV
EXTENSIVE CMS EXO PROGRAM!

**CMS Preliminary**

- **Leptoquarks**
  - coloron(jj) x2
  - coloron(4j) x2
  - gluino(3j) x2
  - gluino(jjb) x2

- **RS Gravitons**
  - ADD (γ+MET), nED=4, MD
  - ADD (j+MET), nED=4, MD
  - ADD (ee,μμ), nED=4, MS
  - ADD (γγ), nED=4, MS
  - ADD (j), nED=4, MS
  - QBH, nED=6, MD=4 TeV
  - NR BH, nED=6, MD=4 TeV
  - QBH (jj), nED=4, MD=4 TeV
  - Jet Extinction Scale
  - String Scale (jj)

- **Heavy Gauge Bosons**
  - SSM Z'(ττ)
  - SSM Z'(jj)
  - SSM Z'(bb)
  - SSM Z'(ee)+Z'(μμ)
  - SSM W'(jj)
  - SSM W'(lv)

- **Excited Fermions**
  - e* (M=Λ)
  - μ* (M=Λ)
  - q* (qq)
  - q* (qγ)
  - b*

- **Multijet Resonances**
  - ADD (γ+MET), nED=4, MD
  - ADD (j+MET), nED=4, MD
  - ADD (ee,μμ), nED=4, MS
  - ADD (γγ), nED=4, MS
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  - NR BH, nED=6, MD=4 TeV
  - QBH (jj), nED=4, MD=4 TeV
  - Jet Extinction Scale
  - String Scale (jj)

- **Large Extra Dimensions**
  - dijets, Λ+ LL/RR
  - dijets, Λ- LL/RR
  - dimuons, Λ+ LLIM
  - dimuons, Λ- LLIM
  - dielectrons, Λ+ LLIM
  - dielectrons, Λ- LLIM
  - single e, Λ HnCM
  - single μ, Λ HnCM
  - inclusive jets, Λ+

- **Compositeness**
  - dijets, Λ+ LL/RR
  - dijets, Λ- LL/RR
  - dimuons, Λ+ LLIM
  - dimuons, Λ- LLIM
  - dielectrons, Λ+ LLIM
  - dielectrons, Λ- LLIM
  - single e, Λ HnCM
  - single μ, Λ HnCM
  - inclusive jets, Λ-
EXTENSIVE CMS EXO PROGRAM!

**REACH OF DIJET SEARCHES**

**CMS Preliminary**

**Leptoquarks**
- coloron(jj) x2
- coloron(4j) x2
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- gluino(jjb) x2

**Multijet Resonances**
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- ADD (j+MET), nED=4, MD
- ADD (ee,μμ), nED=4, MS
- ADD (γγ), nED=4, MS
- ADD (jj), nED=4, MS
- QBH, nED=6, MD=4 TeV
- NR BH, nED=6, MD=4 TeV
- QBH (jj), nED=4, MD=4 TeV
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**Large Extra Dimensions**
- dijets, L+ LL/RR
- dijets, L- LL/RR
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- dimuons, L- LLIM
- dielectrons, L+ LLIM
- dielectrons, L- LLIM
- single e, L HnCM
- single μ, L HnCM
- inclusive jets, L+
- inclusive jets, L-

**Excited Fermions**
- e* (M=Λ)
- μ* (M=Λ)
- q* (qq)
- q* (qγ)
- b*
LONG HISTORY
EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN-EP/88-54
April 28th, 1988

Two - Jet Mass Distributions at the CERN Proton - Antiproton Collider

UA1 Collaboration, CERN, Geneva, Switzerland
SIGNAL MODELS

- **quark-quark**
  - **axigluons**: axial-vector particles predicted in a model where the QCD symmetry group \( SU(3)_C \) is replaced by the chiral symmetry \( SU(3)_L \times SU(3)_R \)
  - **colorons**: vector particles predicted by the flavor-universal coloron model, in which the \( SU(3)_C \) is embedded in a larger gauge group
  - \( W', Z', ... \)
- **quark-gluon**
  - **excited quarks**: predicted in quark compositeness models
  - **string resonances**, ...
- **gluon-gluon**
  - **RS graviton**: predicted in the RS model of extra dimensions, with 5-dimensional anti de Sitter space and reduced Planck mass
  - \( S_8 \) (color octet scalar) resonances, ...

\( \sqrt{s} = 13 \text{ TeV} \)

Wide jets \( \eta < 2.5, |\Delta \eta| < 1.3 \)

CMS Simulation

Normalized yield / TeV

Dijet mass [TeV]

PRL 116 (2016) 071801
BASICS OF A DIJET SEARCH

- Collect (lots of) data with a trigger based on hadronic activity
- Cluster “wide jets”
- Select events based on wide jet properties
- Search for a bump on a smoothly falling dijet mass spectrum
- Set limits
WIDE JETS

• Jets initially reconstructed with anti-$k_T$ algorithm with $R=0.4$
• “Wide jet” algorithm uses two leading jets as seeds
  • Adds neighboring jets to nearest leading jet if within $\Delta R < 1.1$
  • Recover loss in mass response due to radiation

anti $k_T$ R=0.4 jets \[\rightarrow\] highest $p_T$ seed jets \[\rightarrow\] dijet system
WIDE JETS

- Gluon-gluon resonances are wider than quark-quark resonances due to greater radiation (gluon color factor)
- Mass resolution improved with wide jets even in gluon-gluon case
Dijet Event Selection

- At least one reconstructed vertex with |z| < 24 cm
- Primary vertex is identified as the vertex with the highest sum of $p_T^2$
- At least 2 jets with $p_T > 30$ GeV and $|\eta| < 2.5$
- Wide jets $|\Delta \eta| < 1.3$ to suppress background from t-channel QCD dijet production

$$\Delta \eta_{12} = |\eta_{\text{jet1}} - \eta_{\text{jet2}}| = \ln \left( \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|} \right)$$

- $m_{jj} > 1.2$ TeV to ensure trigger fully efficient
HIGH MASS EVENT

- Highest dijet mass event $m_{jj} = 6.14$ TeV
MODELING DIJET SPECTRUM

- Four-parameter empirical function to model dijet spectrum [1]:
  \[
  \frac{d\sigma}{d \eta_{jj}} = \frac{P_0(1 - x)^{P_1}}{x^{P_2 + P_3 \ln(x)}} , \quad x = m_{jj}/\sqrt{s}
  \]

- How do the parameters affect the shape?
  - Can look at the variations after diagonalizing the covariance matrix from a fit

Dijet mass goodness of fit: $\chi^2 = 31$ for 35 degrees of freedom

Four-parameter function fit (red solid curve)

PYTHIA 8 QCD Monte Carlo (dashed blue curve)

Three signal models with resonance masses corresponding to 95% CL exclusion limit (dash-dotted curves)

Lower panel: difference between the data and the fitted parametrization, divided by the statistical uncertainty

PRL 116 (2016) 071801
Mass limits in Run 2 (13 TeV) show significant improvement in sensitivity over previous Run 1 (8 TeV) limits from CMS.

- String resonances: 5.0 TeV → 7.0 TeV
- Scalar diquarks: 4.7 TeV → 6.0 TeV
- Axigluon/coloron: 3.6 TeV → 5.1 TeV

### Table I. Observed and expected mass limits for analyses that measured to be a smoothly falling distribution. In the

<table>
<thead>
<tr>
<th>Model</th>
<th>Final state</th>
<th>Observed mass limit [TeV]</th>
<th>Expected mass limit [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>String</td>
<td>$qg$</td>
<td>7.0</td>
<td>6.9</td>
</tr>
<tr>
<td>Scalar diquark</td>
<td>$qq$</td>
<td>6.0</td>
<td>6.1</td>
</tr>
<tr>
<td>Axigluon/coloron</td>
<td>$qg$</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Excited quark ($q^*$)</td>
<td>$qq$</td>
<td>5.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Color-octet scalar</td>
<td>$gg$</td>
<td>3.1</td>
<td>3.3</td>
</tr>
<tr>
<td>Heavy $W$ ($W'$)</td>
<td>$qg$</td>
<td>2.6</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Figure 1: 95% CL upper limits
Q: WHAT ABOUT 750 GEV?

- Possible resonance seen at 750 GeV in diphotons; could expect $10 - 10^3 \times$ more events in dijets
- To record events with ~100% trigger efficiency down to $m_{jj} \sim 500$ GeV need to trigger at least $H_T > 400$ GeV

$$\text{BR}(X \rightarrow JJ)/\text{BR}(X \rightarrow \gamma\gamma) \sim (\alpha_s/\alpha)^2 (Q_s/Q)^4 \sim 10 - 10^3$$
TRIGGER SYSTEM

• How can we trigger down to $H_T > 400$ GeV?
• Two limitations:
  • **Bandwidth** = event rate $\times$ event size limited by read-out of $O(100M)$ detector channels, disk storage, and everyone else’s favorite physics channel
  • **CPU time** limited by computing resources for online reconstruction

Total Reco.
BW: $1 \text{ kHz} \times 1 \text{ MB}$
CPU time: 150 ms
D. Anderson "Data Scouting at CMS" 2015 IEEE NSS/MIC

• Technique of data scouting (implemented in 8 TeV and 13 TeV LHC runs)
  • Reconstruct/save only necessary information to perform analysis → record more events

• "PF Scouting" limited by CPU time: allows us to get down to $H_T > 450$ GeV

• Improved in 2015: "Calo Scouting" allows us to get down to $H_T > 250$ GeV

• New in 2016: Saving tracking information around Calo jets to allow us to perform b-tagging down to $H_T > 250$ GeV
RUN 1 DATA SCOUTING RESULT

- Run 1 result already provides constraint at 750 GeV!

limit ~1-3 pb at 750 GeV depending on gg or qq
BEFORE DATA SCOUTING

- Run 1 result also extends sensitivity to $Z'$ in coupling-mass plane to previously uncovered regions!

![Graph showing coupling versus mass](image)

**FIG. 1.** Leading experimental limits in the coupling $g_B$ versus mass $M_{Z'}$ plane for $Z'$ resonances. Values of $g_B$ above each line are excluded at the 95% C.L. This plot would also push sensitivity to lower couplings in the several hundred GeV mass range.

The plot is not extended above $g_B = 2.5$, because the $\Upsilon(1)$ coupling constant is already large, $\alpha_B = g_B^2 / (4 \pi) \approx 0.5$, so that it is difficult to avoid a Landau pole. For that large coupling, the current mass reach is around 2.8 TeV.

The 14 TeV LHC will extend significantly the mass reach, and can probe smaller couplings once enough data is analyzed. Note that couplings of $g_B \approx 0.1$ are typical (the analogous coupling of the photon is approximately 0.3), and even $g_B$ as small as 0.01 would not be very surprising.

We also present the coupling–mass mapping for colorons in Figure 2. For clarity, we only show the envelope of the strongest $\tan \theta$ upper limits from all available analyses at each coloron mass. This mapping is performed again using leading order production. The NLO corrections to coloron production have been computed recently [47], and can vary between roughly $-30\%$ and $+20\%$. We do not take the NLO corrections into account as we do not have an event generator that includes them; furthermore, there is some model dependence in the NLO corrections at small $\tan \theta$ (for example, they are sensitive to the color-octet scalar present in ReCoM [34]).
AFTER DATA SCOUTING

- Run 1 result also extends sensitivity to $Z'$ in coupling-mass plane to previously uncovered regions!
TIME IS A FLAT CIRCLE

higher energy

data scouting

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SUMMARY AND OUTLOOK

• No evidence for new phenomena... yet

• Stringent limits on many new physics models from dijet searches with 2012 and 2015 data

• Data scouting technique allows us to probe lower in the dijet spectrum

• 2016 13 TeV run is ongoing! Lots of data collected

• Search for resonances at low mass (including 750 GeV) with 2015 and 2016 13 TeV data forthcoming!
SEARCHES @ CMS

BACKUP

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Q: WHAT ABOUT 2 TEV?

- Slight excess seen in dijets at ~2 TeV in Run 1 (also in dibosons)
- Not confirmed in Run 2

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**Graph:**
- CMS data with fits and 95% CL upper limits for different resonances.
- Resonance masses and cross-sections presented.
- Dijet mass distribution with W' and q* peaks.
- String, Excited quark, Axigluon/coloron, Scalar diquark, S8, W' SSM, Z' SSM, RS graviton (k/M=0.1).

**QCD MC and JES uncertainty**
- Residuals shown for data and QCD MC fits.

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**Notes:**
- Wide jets (R = 1.1)
- 19.7 fb⁻¹ (8 TeV)

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**Runs:**
- Run 1: Slight excess seen in dijets at ~2 TeV
- Run 2: Not confirmed in Run 2
• String resonances (S), which are Regge excitations of quarks and gluons in string theory and decay predominantly to qq [1, 2].

• Scalar diquarks (D), which decay to qq and ¯q¯q, predicted by a grand unified theory based on the E6 gauge symmetry group [3].

• Mass-degenerate excited quarks (q*), which decay to qg, predicted in quark compositeness models [4, 5]; the compositeness scale is set to be equal to the mass of the excited quark.

• Axial-vector particles called axigluons (A), which decay to q¯q, predicted in a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry SU(3)l × SU(3)r [6].

• Color-octet colorons (C), which also decay to q¯q; these are vector particles predicted by the flavour-universal coloron model, in which the SU(3) gauge symmetry of QCD is embedded in a larger gauge group [7].

• Scalar color-octet resonances (S8) [8] that appear in many dynamical electroweak symmetry breaking models such as Technicolor. We consider the decay channel into a pair of gluons.

• Massive scalar color-octet resonances (S8b) [9] that result from the breaking of an SU(3) × SU(3) gauge symmetry down to the QCD gauge group and that may have generically large couplings to b quarks. We consider the production of a coloron that subsequently decays into an S8b and a light scalar singlet. We fix the singlet mass to 150 GeV. The S8b and scalar singlet have branching fractions (B) of approximately 100% to b¯b and gg, respectively. The tangent of the mixing angle θ between the two SU(3) gauges is set to 0.15. This resonance search is inclusive of extra jets, so the search strategy is insensitive to the decay of the low-mass singlet state.

• New gauge bosons (W' and Z'), that decay to q¯q, predicted by models that include new gauge symmetries [10]; the W' and Z' bosons are assumed to have standard-model-like couplings. Consequently, the ratio between the branching fraction of the Z' to b¯b and the branching fraction to a pair of quarks (excluding the top quark) is approximately 0.22.

• Randall-Sundrum (RS) gravitons (G), which decay to q¯q and gg, predicted in the RS model of extra dimensions [11]. The value of the dimensionless coupling k/Mp is chosen to be 0.1, where k is the curvature scale in the 5-dimensional anti de Sitter space and Mp is the reduced Planck scale. The ratio between the branching fraction of the RS graviton to b¯b and the branching fraction to a pair of quarks (excluding the top quark) or gluons is approximately 0.1 [12].
Setting the scene: this talk on data scouting.

- **Data complexity**
  - Standard data analysis:
    - ATLAS/CMS/LHCb, fully reconstructed data
  - Monitoring:
    - ATLAS TAg Data Analysis
    - ATLAS/CMS/LHCb, Express stream
  - Delayed data analysis:
    - CMS Data Parking
    - ATLAS Delayed Stream

- **Time to access data for analysis**
  - Real-time analysis:
    - LHCb Turbo Stream
    - ATLAS/CMS Data Scouting
  - Data complexity

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LARGE HADRON COLLIDER

Proton-proton collisions at 8 TeV in 2012

CMS

Lake Geneva

CMS

Lake
Geneva

CERN

27 kilometer ring

CMS

Lake
Geneva

CERN
LARGE HADRON COLLIDER

- Proton-proton collisions at 8 TeV in 2012

CMS Integrated Luminosity, pp, 2012, \( \sqrt{s} = 8 \text{ TeV} \)

Data included from 2012-04-04 22:38 to 2012-12-16 20:49 UTC

27 kilometer ring

CMS
LARGE HADRON COLLIDER

- Proton-proton collisions at 13 TeV in 2015
750 GeV $\gamma\gamma$ Resonance?

- Excess seen in CMS ($2.6\sigma$ local, $1.2\sigma$ global at 760 GeV) and ATLAS ($3.6\sigma$ local, $2.0\sigma$ global at 750 GeV)

- Possible resonance is not easily explained within MSSM (tension between preferred small tan$\beta$ and 125 GeV Higgs mass)
**750 GeV $\gamma\gamma$ Resonance?**

- **What do we know?**

  - Can be spin 0 or 2.
    - Completely identical to the argument of the 125 GeV di-photon resonance.
  
  - Spin 0 is much more compelling than spin-2.
    - Very difficult to write down a complete model of spin-2.
How can a neutral particle decay to photons, which only couples to charged particles?

For the SM higgs, they are top quark and W boson

Can top and/or W do it for the X(750)?
• Can top quark and/or W boson do it for X(750)?

- Say X couples to top and or W, with arbitrary coupling.
  - BR(di-photon) is less than $10^{-4}$.
  - 4 fb to di-photon means 10s -100 pb to $t\bar{t}$bar and or WW.
  - A factor of 4 or 5 in the production rates between 8 and 13 TeV.
  - $t\bar{t}$bar and/or WW signal of at least pb at 8 TeV.
750 GeV \( \gamma \gamma \) Resonance?

- Is it possible that there is a \( tt \) or \( WW \) resonance with a cross section of \( \geq 1 \text{ pb} \) in the LHC Run 1 data?

<table>
<thead>
<tr>
<th>final state</th>
<th>700 GeV</th>
<th>750 GeV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( tt ) (narrow)</td>
<td>540 fb</td>
<td>450 fb</td>
<td>CMS [6]</td>
</tr>
<tr>
<td>( tt ) (wide)</td>
<td>620 fb</td>
<td>520 fb</td>
<td>CMS [6]</td>
</tr>
<tr>
<td>( WW (\ell \nu jj) )</td>
<td>60 fb</td>
<td>70 fb</td>
<td>ATLAS [10]</td>
</tr>
</tbody>
</table>

- Must be more new physics in addition to the 750 GeV resonances!!
• What about its production?

  – Unlikely from qqbar.
    ▶ Suppressed by small quark masses, otherwise suffer from severe flavor constraints.

  – Possibly (like the Higgs)

Need more new physics here as well, colored!