Final states containing jets are an integral part of searches for New Physics at CMS.

Many predicted New Physics outside the SM live in this sector:

Dedicated analyses with jets probe all of these final states using 2010 LHC data (up to 36 pb$^{-1}$)

*This talk highlights just a few of these searches. For a comprehensive list:

\[\text{twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO}\]
Multi-Jets
Dijets
b’
Lepto-Quarks
Black Holes

"The road to discovery"
New Physics in the Dijet Mass Spectrum

**Signature Selection**

Leading 2 jets in event:
- \( M_{jj} > 220 \text{ GeV} \)
- \(|\eta_{1,2}| < 2.5, |\Delta\eta_{1,2}| < 1.3\)

**Narrow resonances decaying to dijets (3 initial-state models):**
- Quark-quark, quark-gluon, gluon-gluon

**Diagram:**

- CMS Data (2.9 pb\(^{-1}\))
- Fit
- 10% JES Uncertainty
- QCD Pythia + CMS Simulation
- Excited Quark
- String

\( \sqrt{s} = 7 \text{ TeV} \)

\(|\eta| < 2.5 \, \text{ and } |\Delta\eta| < 1.3\)

\( q^* (0.5 \text{ TeV}) \)

\( q^* (1.5 \text{ TeV}) \)

\( S (1 \text{ TeV}) \)

\( S (2 \text{ TeV}) \)
Model-independent limits tested for 7 benchmark resonances

Bayesian approach is used to set separate limits for gg, qg and qq

<table>
<thead>
<tr>
<th>Model</th>
<th>Exclusion regions [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>String resonance (qg, q\bar{g}, gg)</td>
<td>0.50 – 2.50</td>
</tr>
<tr>
<td>Excited quark (qg)</td>
<td>0.50 – 1.58</td>
</tr>
<tr>
<td>Axigluon/Coloron (q\bar{q} / q\bar{q})</td>
<td>0.50 – 1.17 &amp; 1.47 – 1.52</td>
</tr>
<tr>
<td>E6 diquark (qq)</td>
<td>0.50-0.58, 0.97-1.08, &amp; 1.45-1.60</td>
</tr>
</tbody>
</table>

CMS Data (2.9 pb⁻¹)
\( \sqrt{s} = 7 \) TeV
|η| < 2.5 & |Δ| η| < 1.3

Resonance Models
- String
- Excited Quark
- Axigluon/Coloron
- E6 Diquark
- W⁻
- Z’
- RS Graviton
New Physics in dijet angular distributions:

- $\chi$ is related to scattering angle $\theta^*$ as

$$\chi = e^{2y^*} = \exp(|y_1 - y_2|)$$

- Background from QCD is flat in $\chi$
- Isotropic new physics peaks at low $\chi$

**Benchmark Model:** quark compositeness

**Signature Selection**

Leading 2 jets in event:

- $M_{jj} > 250$ GeV
- $|\eta_{1,2}| < 2.5$
- $y_{\text{BOOST}} = \frac{1}{2}(y_1 + y_2) < 1.11$
- $y^* = \frac{1}{2}|y_1 - y_2| < 1.39$

**CMS Simulation**

- $2200 < M_{jj}$ [GeV]
- QCD
- $\Lambda = 5.0$ TeV
Dijet $\chi$: Data and Limits

Good agreement between data and NLO QCD found

$\rightarrow$ Limits set using modified frequentist approach:

$$CL_s = \frac{P_{QCD+CL}(Q \geq Q_{obs})}{1 - P_{QCD}(Q \leq Q_{obs})}$$

Observed limit: $\Lambda > 5.6$ TeV
Expected limit: $\Lambda > 5.0$ TeV
Searching for strongly coupled resonances decaying to three-jets

Benchmark model: R-parity violating gluino decays
(pair-produced + strongly coupled to uds quarks)

Signature Selection
High Jet Multiplicity (≥ 6 Jets)
Large event scalar sum $p_T$ ( > 425 GeV)
No requirement on leptons or MET

Construct Jet $M_{jjj}$ Triplets (20 Combinations)

For all jet triplets, plot:
$M_{jjj}$ vs. $\Sigma |p_T^{\text{jet}}|$

Require each to pass:
$M_{jjj} < \Sigma |p_T^{\text{jet}}| - \Delta$ (Offset)
Largest excess seen at 390 GeV/c² → significance of 1.9σ (with look-elsewhere effect)

• 1st limits from the LHC
• Highest limits to date on gluino RPV decays!
Expanding the toolbox
For searches past jet-only final states, we include additional objects for more discriminating power!

– Define new variable $S_T$

\[ S_T = \sum_{\text{Selected\ Objects}} \left| p_T \right| + \text{MET} \]

– Lepton requirements:
  • Charge pairing of $\mu/e$: Same-Sign (SS) and Opposite Sign (OS)
  • Isolation to reject QCD background

– Large Missing $E_T$
Searches for Leptoquarks

Leptoquarks
- Predicted by many extensions to the SM (TC, GUTs, and more)
- Couple to both quarks and leptons with interaction scale $\lambda$
- 3 types of final states possible through pair production: ($llqq$, $l_{\nu}qq$, $\nu\nuqq$)

$\beta$ is the branching fraction $\text{Br}(LQ \rightarrow lq)$

- $\beta^2$
- $\beta(1-\beta)$
- $(1-\beta)^2$
1\textsuperscript{st} Generation Leptoquarks ($e^+e^-jj$)

**Pre-Selection**
- At least 2 isolated electrons, each $p_T > 30$ GeV
- At least two jets, each $p_T > 30$ GeV
- $M_{T(e,e)}$ greater than 50 GeV
- $S_T$ (2 electrons, 2 jets, MET) > 250 GeV

**Full Selection**
- $M_{T(e,e)} > 125$ GeV
- $S_T > f(x)$, where $x$ is LQ mass hypothesis

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**Graphs**

**CMS**

- Data, 33.2 pb\(^{-1}\)
- $Z/\gamma^* +$ jets
- $t\bar{t}$
- Other backgrounds
- LQ, $M = 400$ GeV

**Histograms**

1. **$M_{ee}$ (GeV)**
2. **$S_T$ (GeV)**

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**References**

arXiv:1012.4031 (hep-ex)
Accepted by PRL
1st Generation Leptoquarks \((e^+\nu^-jj)\)

**Pre-Selection**
- Exactly 1 isolated electron with \(p_T > 35\) GeV
- At least two jets, each \(p_T > 30\) GeV
- Missing \(E_T\) greater than 45 GeV
- \(|\Delta\Phi(MET,e)| > 0.8\) and \(|\Delta\Phi(MET,jet)| > 0.5\)
- No good muons with \(p_T > 10\) GeV
- \(S_T (e, 2\) jets MET) \(> 250\) GeV

**Full Selection**
- \(M_T(e, MET) > 125\) GeV
- \(\min(p_T(e), MET) > 85\) GeV
- \(S_T > f(x)\), where \(x\) is LQ mass hypothesis
2nd Generation Leptoquarks ($\mu^+\mu^-jj$)

**Pre-Selection**
- At least 2 isolated muons, each $p_T > 30$ GeV
- At least two jets, each $p_T > 30$ GeV
- $M_{T(\mu,\mu)}$ greater than 50 GeV
- $S_T$ (2 muons, 2 jets, MET) > 250 GeV

**Full Selection**
- $M_{T(\mu,\mu)} > 115$ GeV
- $S_T > f(x)$, where $x$ is LQ mass hypothesis
2nd Generation Leptoquarks ($\mu^+\nu^-jj$)

EXO-10-008

Pre-Selection
- Exactly one muon with $p_T > 35$ GeV
- At least two jets, each $p_T > 30$ GeV
- Missing $E_T$ greater than 45 GeV
- No good electron with $p_T > 15$ GeV
- $S_T$ (muon, 2 jets MET) > 250 GeV

Full Selection
- $M_T(\mu, \text{MET}) > 125$ GeV
- $\min(p_T(\mu), \text{MET}) > 85$ GeV
- $S_T > f(x)$, where $x$ is LQ mass hypothesis
Leptoquark limits

Limits for both 1\textsuperscript{st} and 2\textsuperscript{nd} generation Leptoquarks outperform Tevatron limits for all but very low $\beta$

New combined limits:

$M_{LQ1} > 384, 340 \text{ GeV/c}^2$, $\beta = 1, 0.5$

New limit from the $\mu\mu jj$ channel:

$M_{LQ2} > 394 \text{ GeV/c}^2$
Search for b’
arXiv:1102.4746 (hep-ex)

Pair produced 4\textsuperscript{th} generation heavy quarks
b’ → tW → bWW

**Signature Selection**

- 2 (3) Leptons with $p_T > 20$ GeV
- At least 2 (4) Jets with $p_T > 25$ GeV
- 2 SS leptons (3 leptons: 2OS + 1 extra)
- Large Missing $E_T$ > 425 GeV
- Large $S_T$ > 350 GeV

Closing in on Tevatron limit ($m_{b'} > 385$ GeV) with just 34 pb\textsuperscript{-1}
Search for Black Holes

PLB 697 (2011), 434

Microscopic Black Holes

Lifetimes of $\sim 10^{-27}$ seconds
Decays into wide range of particles
Mostly quarks and gluons
But also $\gamma$, $e^+$, $e^-$, $\mu^+$, $\mu^-$, $W$, $Z$ and more
Cross section proportional to $\pi \cdot R_s^2$
($R_s$ is the Schwartzchild Radius)
And with extra dimensions ($n > 0$)
Cross sections accessible at LHC

Signature Selection

Large amount of total energy expected:
Construct $S_T$ using all objects with $p_T > 50$ GeV (jets and isolated $\gamma^0/e^+/\mu^+$)
Events divided into object multiplicity bins

CMS, 35 pb$^{-1}$
$\sqrt{s} = 7$ TeV

$N = 2$

Data

Background

Uncertainty

Photon+Jets

W+Jets

ttbar

Z+Jets

$M_D = 1.5$ TeV, $M_{BH}^{\text{min}} = 3.0$ TeV, $n = 6$

$M_D = 2.0$ TeV, $M_{BH}^{\text{min}} = 3.0$ TeV, $n = 4$

$M_D = 3.0$ TeV, $M_{BH}^{\text{min}} = 3.0$ TeV, $n = 2$
Black Holes: Limits

CMS, 35 pb\(^{-1}\) \(\sqrt{s} = 7\) TeV

- Non-rotating Black Holes
  - \(M_B = 3.0\) TeV, \(n = 2\)
  - \(M_B = 2.0\) TeV, \(n = 4\)
  - \(M_B = 1.5\) TeV, \(n = 6\)

Theoretical Cross Section
- \(M_D = 3.0\) TeV, \(n = 2\)
- \(M_D = 2.0\) TeV, \(n = 4\)
- \(M_D = 1.5\) TeV, \(n = 6\)

95% CL Black Hole Exclusion Limit
- Bayesian Technique with flat prior
- \(M_{BH}\): from 3.5 – 4.5 TeV for
- \(M_D\): from 1.5 – 3.5 TeV

No excess observed in data
Limits are set based on:
- Black Hole Mass (\(M_{BH}\))
- True Planck Scale (\(M_D\))

First direct limits on BH production at hadron colliders
No discoveries yet for hadronic resonances using 2010 data, however...

- Well understood backgrounds and data-driven techniques
- Competitive limits are set in all analyses, and in many cases world’s best limits are set
- Already plans for updating results with 2011 data and extending analyses into new channels

Potential for New Physics is right down the road!