Searches in CMS for new physics in final states with jets

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Motivation

• The Standard Model (SM) of particle physics is incomplete:
  ➢ Why is there an imbalance of matter and antimatter in the universe?
  ➢ How does gravity fit into our model?
  ➢ Why do quarks and leptons come in three generations? Are they elementary particles?
  ➢ Why are gauge couplings so different, are they unified at a higher scale? Are there more forces in nature?
  ➢ What is 95% of the Universe made of?

• Many models of physics that extend the SM often require new particles that couple to quarks and/or gluons and decay to jets.
There is a variety of recent resonance searches in CMS, with jets in final states using data from Run II (2016-2018) with an integrated luminosity of 138 fb$^{-1}$: CMS EXO public results

A selection of recent Full Run II results will be discussed in this talk:

- Search for VBF production of SS muons through Majorana neutrinos or the Weinberg operator (CMS-EXO-21-003)

- Search for high-mass resonances decaying to a jet and a Lorentz-boosted resonance (CMS-EXO-20-007)

- Search for resonant and nonresonant production of pairs of dijet resonances (CMS-EXO-21-010)

- Search for LQs decaying to tau and b (CMS-EXO-19-016)

There is a dedicated talk on displaced jet analyses by Celia Fernandez Madrazo.
Search for $VBF \rightarrow \mu^+\mu^-$ through Majorana $N$ or the Weinberg operator

**Experimental Signature:**
- Two SS $\mu$’s and two jets.
- The cross section of VBF t-channel process decreases more slowly with increasing $m_N$ compared with the traditional $N$ hunting strategy ($s$-channel production $q\bar{q}$ annihilation).

**Backgrounds:**
- **Main**: $WZ$ and non-prompt leptons estimated using CRs.
- **Others**: $WW$, $ZZ$, $tZq$, $ttW$, $ttZ$, and $VVV$

**Signal Models:**
- VBF HMN at Seesaw type I
- Weinberg operator Dim.5
  - Wilson coefficient $C_5^{\ell\ell'} \sim |m_{\mu\mu}|$

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CMS-EXO-21-003

13 TeV LHC


$\sigma / \sigma_{SM}$ vs $m_N$ [GeV]
Results on $\text{VBF} \rightarrow N \rightarrow \mu\mu$ through Majorana N or the Weinberg operator

- Discriminating variable for both analyses is $H_T/p_T(\mu_1)$.

- The first search for Majorana N at several TeV: reaching very high $m_N$ up to 23 TeV.

- A first probe of the Weinberg operator at the LHC: upper limit on effective $|m_{\mu\mu}|$: obs (exp) 10.8 (12.8) GeV.
Di-tri-jets Search

Experimental Signature:
Two large-radius (wide) resolved jets, one coming from R2 (R2-jet) and one coming from the third parton (P3-jet):
- \( pp \rightarrow R1 \rightarrow R2+P3 \rightarrow (P1+P2) +P3 \)
- \( P1, P2, P3 \) are gluons

Main backgrounds:
Multijet QCD production estimated with a data-driven method, using several parametric functional forms. Discrimination between signal and QCD background, by exploiting jet substructure information and kinematics of the decay.

Signal Models:
Warped extra dimensions where R1 is a KK gluon (GKK), R2 is a radion (\( \phi \))
- \( GKK \rightarrow \phi g \rightarrow ggg \) (trijet)
Search largely model independent.

22 SRs defined in the \( m(R2)/m(P3) \) plane.
Results on Di-tri-jets

- Maximum likelihood fit in the dijet mass performed in the SRs.
- Excess: 1.8 $\sigma$ global (3.2 $\sigma$ local) $\rightarrow$ look into it in Run III.
- By exploring a novel experimental signature, we extend significantly the experimental exclusion of this benchmark model of new physics at the LHC.
Paired Dijet Search

Experimental Signature:
Four or two resolved jets paired to same mass resonances.

Main backgrounds:
Multijet QCD production estimated with a data-driven method, using several parametric functional forms.

Signal Models:
Two modes of pair production of dijet resonances:

• **Resonant** → Benchmark model: Diquark decaying to vector-like quarks which decay to an up quark and gluon.

  \[ uu \rightarrow S \rightarrow \chi \chi \rightarrow (u g)(u g) \]

• **Non-resonant** → Benchmark model: R-parity violating stop pairs decaying to a d and s quark.

  \[ pp \rightarrow \tilde{t} \tilde{t}^* \rightarrow (d \bar{s})(d s) \]

Search largely model independent.
Results of resonant search

- Maximum likelihood fit in the four jet mass performed in the SRs.
- Excess: 1.6 $\sigma$ global (3.9 $\sigma$ local) $\rightarrow$ look into it in Run III.

- These are the first LHC limits on resonant pair production of dijet resonances via high mass intermediate states.
Results of nonresonant search

- Maximum likelihood fit in the **average dijet mass** performed in the SRs.

Excess: 2.5 $\sigma$ global (3.6 $\sigma$ local) $\rightarrow$ look into it in Run III.
- Results significantly extend the previous limits.
Search for LQs → τb
...motivated by B-anomalies

Experimental Signature:
2 τ’s and 1 or 2 b tag jets

Channels:
τhτh, eτh, μτh, and μμ, eμ

Backgrounds:
Main: Z → ττ, t ¯t (constrained by μμ and eμ channel respectively), j → τh fake (estimated by the Fake Factor method) Others: diboson, single top

Signal Models:
• Scalar & vector LQ signals
• Production modes: LQ pair, nonres, single
• coupling strength λ = 1-2.5
• For vector LQ:
  κ = 1,0: (non) minimal coupling

See also Olena Karacheban’s talk
Results on LQs $\rightarrow \tau b$

Event categories: $\geq 1$ jet (0 or 1 b tag) and 0 jet (3 $m_{vis}$ bins)

$S_T^{\text{MET}} \equiv p_T^1 + p_T^2 + p_T^{\text{met}}$

$\chi = e^{\Delta \eta}$

- Simultaneous maximum likelihood fit of LQ signals in $\chi$ and $S_T^{\text{MET}}$.
- Reorder bins by $S/(S+B)$ from fit with total signal.

~3$\sigma$
Upper limits placed on the third-generation scalar LQ production cross section and on coupling strength as a function of the LQ mass.

We observe a $\sim 3\sigma$ excess above $m_{LQ} > 1800$ GeV driven by the non-resonance mode $\rightarrow$ look into it in Run III.
Summary

- Hadronic final states offer great sensitivity to many models of new physics.

- Searches for hadronic resonances in CMS were presented:
  - No significant deviations from SM so far but several excesses to keep an eye and to drive us where to look next.
  - Constraints in several benchmark models.

- Significant improvements due to
  - Data driven methods to estimate the background.
  - Jet sub-structure techniques.
  - Increased luminosity with full Run II datasets.
  - New final states are explored.

- Hope that with all the improvements and advancements on reconstruction, trigger, analysis approaches and techniques, we should be able to fully exploit the Run III discovery potential and either make a discovery, or improve limits beyond luminosity scaling.
Thank you!

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Back up
Paired Dijet Search
Search for $LQ_3$ (scalar) $\rightarrow b\tau$
Search for $\text{LQ}_3 \rightarrow b \tau$

$\lambda$: coupling strength of the LQ-lepton-quark vertex
Table 2: Best-fit LQ cross sections $\sigma$ for various masses and coupling strengths $\lambda$, and the corresponding significance $z$ (given in standard deviations) for different production modes individually, as well as their combination.

<table>
<thead>
<tr>
<th>Signal</th>
<th>$m_{LQ} = 1400 \text{ GeV}$</th>
<th>$m_{LQ} = 2000 \text{ GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma \text{ [pb]}$</td>
<td>$z$</td>
</tr>
<tr>
<td><strong>Scalar</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pair</td>
<td>$0.24^{+0.47}_{-0.45}$ 0.5</td>
<td>$0.22^{+0.41}_{-0.39}$ 0.0</td>
</tr>
<tr>
<td>Single, $\lambda = 1$</td>
<td>$1.15^{+0.95}_{-0.92}$ 1.3</td>
<td>$0.64^{+0.68}_{-0.65}$ 1.0</td>
</tr>
<tr>
<td>Single, $\lambda = 2.5$</td>
<td>$9.1^{+5.6}_{-5.3}$ 1.7</td>
<td>$18^{+11}_{-11}$ 1.7</td>
</tr>
<tr>
<td>Nonres.</td>
<td>$70^{+13}_{-22}$ 3.4</td>
<td>$63^{+120}_{-19}$ 3.5</td>
</tr>
<tr>
<td>Total, $\lambda = 1$</td>
<td>$1.7^{+1.9}_{-1.8}$ 0.9</td>
<td>$9.6^{+6.2}_{-5.9}$ 1.7</td>
</tr>
<tr>
<td>Total, $\lambda = 2.5$</td>
<td>$43^{+16}_{-15}$ 2.9</td>
<td>$62^{+20}_{-19}$ 3.4</td>
</tr>
<tr>
<td><strong>Vector, $\kappa = 0$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pair</td>
<td>$0.24^{+0.46}_{-0.44}$ 0.0</td>
<td>$0.24^{+0.41}_{-0.39}$ 0.0</td>
</tr>
<tr>
<td>Single, $\lambda = 1$</td>
<td>$1.00^{+0.89}_{-0.85}$ 1.2</td>
<td>$0.60^{+0.66}_{-0.63}$ 1.0</td>
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<tr>
<td>Nonres.</td>
<td>$58^{+18}_{-17}$ 3.5</td>
<td>$51^{+16}_{-15}$ 3.5</td>
</tr>
<tr>
<td>Total, $\lambda = 1$</td>
<td>$1.2^{+1.5}_{-1.4}$ 0.8</td>
<td>$7.7^{+5.1}_{-4.8}$ 1.7</td>
</tr>
<tr>
<td>Total, $\lambda = 2.5$</td>
<td>$12.2^{+7.1}_{-6.8}$ 1.8</td>
<td>$43^{+15}_{-14}$ 3.1</td>
</tr>
<tr>
<td><strong>Vector, $\kappa = 1$</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Total, $\lambda = 1$</td>
<td>$0.42^{+0.69}_{-0.66}$ 0.0</td>
<td>$1.3^{+1.5}_{-1.4}$ 0.5</td>
</tr>
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</tbody>
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Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state

- The **bosons** that are **highly Lorentz-boosted** they form a single large-radius jet.

- **Novel machine learning techniques** are employed to distinguish jets from W, Z, and H boson decays from other jets.

- In a HVT model, spin-1 $Z'$ and $W'$ resonances with masses below 4.8 TeV are excluded at the 95% CL.

- These limits are the best to date.

- Limits also on graviton model, boson production through VBF etc.

Local (global) significance of 3.6 (2.3) $\sigma$ for mild excesses of events at masses of 2.1 and 2.9 TeV → Look into it in Run 3