CMS Highlights on Searches for New Physics in Final States with Jets

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on behalf of the CMS Collaboration
Introduction

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  - ...yet incomplete...
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  − New **dimensions**?
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  New Physics in the form of:
  - New **gauge bosons**?
  - New **dimensions**?
  - **Compositeness**?
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  – New gauge bosons?
  – New dimensions?
  – Compositeness?

• New, simple or elaborate ideas to probe even more beyond the SM.
  – New ways of using common experimental objects
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  - New dimensions?
  - Compositeness?

- New, simple or elaborate ideas to probe even more beyond the SM.
  - New ways of using common experimental objects: Jets.

Novel analyses at CMS
Search for a high mass dimuon resonance associated with b quark jets at $\sqrt{s} = 13$ TeV

CMS-PAS-EXO-22-016
Analysis Motivation

- Search for new neutral vector boson $Z' \rightarrow \mu\mu$ in association with $\geq 1$ b-jet.
  - $350 \text{ GeV} \leq m_{Z'} \leq 2.5 \text{ TeV}$
  - $Z'$ coupling to b & s quarks $\Rightarrow$ Implications to low energy $b \rightarrow sll$ observables[1].

- Simplified lepton flavor-universal lagrangian[2]:
  \[
  \mathcal{L}_{BSM} = Z'_\eta \left( g_\ell \sum_{f=e,\mu,\tau} \bar{f} \gamma^n P_L f + g_\nu \sum_{f=\nu_e,\nu_\mu,\nu_\tau} \bar{f} \gamma^n P_L f + g_b \left[ \bar{b} \gamma^n P_L b + \delta_{bs} (\bar{s} \gamma^n P_L b + \text{h.c.}) \right] \right)
  \]

- Full Run 2 CMS data set in a different light $\rightarrow$ Enhanced sensitivity by:
  - Explicit event _categories based on $N_b$._
  - $tt$ _killer veto_: Suppress the dominant SM background.

[1]: JHEP 04 (2023) 033
[2]: PTEP 2022 (2022) 083C01
Optimizing Selection & Categorization

- **Select high-p_T dimuon pair:**
  - Muons with $p_T(\mu) > 53$ GeV & $|\eta(\mu)| < 2.4$.
  - Global high-p_T muon ID.
  - Tight tracker isolation & impact parameter requirements.

- **Select $\geq 1$ tight b-tagged jet:**
  - $p_T > 20$ GeV, $|\eta| < 2.5$
  - Medium b-tagging WP for other b-tagged jets.

- **Veto events with:**
  - **Cosmics** → 3D angle btw. muons $< \pi - 0.02$.
  - Extra leptons (e & $\mu$) & isolated tracks ($\tau$ leptons).
  - Significant muon or b-jet mismeasurements, i.e.:
    - $\text{MET} > 250$ GeV & ($|\Delta\phi_{\text{MET,}\mu/b}| < 0.3$ || $|\Delta\phi_{\text{MET,}\mu/b}| > \pi - 0.3$)

- **Categorize selected events:**
  - $N_b = 1$
  - $N_b \geq 2$

\[ \min(m_{\mu b}) > 175 \text{ GeV} \]
Going Fully Data-Driven

- **Background parametrization:**
  PDF envelope of exponential, power law & bernstein polynomial functions.
  - Fit $m_{\mu\mu}$ within $m_{Z'} \pm 10 \sigma_{mass}$.
  - Unbinned likelihood fits directly in data $\Rightarrow$ No dependence on SM simulation.

- **Signal parametrization:**
  Double-sided Crystal Ball + Gaussian.
  - Signal shape parameters from simulation $\rightarrow$ Dependence vs. $m_{Z'}$.

![Graphs showing data and fits for different backgrounds and signal shapes](image-url)
Results

- No significant excess.
- **Model independent limits** on number of signal events with \( N_b \geq 1 \).
  - Easily reinterpretable for any neutral resonance model!
  - Vary relative fraction of events in \( N_b \geq 2 \) category, \( f_{2b} \) ⇒ Probe different signal hypotheses.
  - Dimishing background for increasing masses and/or \( f_{2b} \) ⇒ More stringent limits.
Results

• Narrow-width resonance ⇒
  Restrict to parameter space where $\Gamma_{Z'} < \sigma_{\text{mass}} / 2$.

• Interpretation for the simplified lepton flavor-universal lagrangian ($g_\ell = g_\nu$).

• Set constraints on B$_3$–L$_2$ model of Ref. [1]:
  - $g_{Z'} =$ coupling of $Z'$ to SM fermions.
  - $\theta_{23} =$ mixing angle between 2$^{\text{nd}}$ & 3$^{\text{rd}}$ generation quarks.

Global-fit preferred parameter space completely excluded for some masses!
Search for high-mass resonances decaying to a jet and a Lorentz-boosted resonance in proton-proton collisions at \( \sqrt{s}=13\text{TeV} \)

CMS-PAS-EXO-20-007
Phys. Lett. B, 832, 137263

Intermission for context
Analysis Motivation

- Physics cases:
  - **Cascade decay** (Res1 → Res2...)
    - Extra dimensions KK gauge boson: $G_{KK} \rightarrow \phi g \rightarrow ggg$\[^3\]
    - $m_{Res2} / m_{Res1} = \rho_m \leq 0.2 \Rightarrow$
      One jet + one **boosted** jet pair $\Rightarrow$ This analysis.

- Reconstruction strategy:
  - **AK15 jets** to recover:
    - Both jets from **Res2**.
    - Hard gluon radiation from isolated $g$.
  - Exploit **N-subjettiness**:
    - Jet with low $\tau_{21} \rightarrow \text{Res2 candidate}$!

Analysis Strategy

- **Event selection:**
  - 2 AK15 jets ($p_T > 100$ GeV & $|\eta| < 2.5$).
  - $\Delta\eta_{jj} < 1.3$ (QCD suppression)
  - $m_{jj} > 1.6$ TeV (trigger selection)

- **Categorization:**
  - Optimize signal significance:
    - $m_{\text{Res2}} \leq 0.6$ TeV $\Rightarrow$ 22 categories
    - $0.6 < m_{\text{Res2}} \leq 1.2$ TeV $\Rightarrow$ 9 categories
    - $m_{\text{Res2}} > 1.2$ TeV $\Rightarrow$ 1 categories
  - Also recovers wrong $\text{Res2}$-jet assignment.

- **Parametrization:**
  - **Signal:** Double-sided Crystal Ball from simulation.
  - **Background:** Smoothly falling function from data.
Results

• Signal extraction:
  - Binned, simultaneous MLL fit on $m_{jj}$.
    ➢ Binning determined by $m_{jj}$ resolution (~5%).
  - Fit range $0.65m_{\text{Res1}} \leq m_{jj} \leq 1.15m_{\text{Res1}}$
    ➢ Lower bound adjusted/category rejected based on existence of $m_{jj}$ turn-on near signal peak.

• No significant excess observed:
  - Max local(global) significance = 3.2σ(<1.8σ).

• 1\textsuperscript{st} search to probe 3-parton final state using a dijet signature:
  - Significantly extend excluded parameter space for $G_{KK}$ model (~1 TeV).
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• 1st search to probe 3-parton final state using a dijet signature:
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Can we go higher? Can we complement?
Search for narrow trijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV on CMS

CMS-PAS-EXO-22-008
Analysis Motivation

- **1st generic search for 3-jet resonances!**
- **Physics cases:**
  - **Direct 3-body decay**
    - Benchmark model: \( Z_R \rightarrow ggg^{[4]} \)
    - \( \Gamma \sim 3\times10^{-3}\% \) for nominal(narrow) hypothesis.
  - **Cascade decay** (\( Res1 \rightarrow Res2... \))
    - Extra dimensions KK gauge boson: \( G_{KK} \rightarrow \phi g \rightarrow ggg^{[3]} \)
    - Compositeness excited quarks: \( q^{*} \rightarrow W' q \rightarrow qqq^{[3]} \)
    - \( 0.2 \leq \rho_m \leq 0.8 \Rightarrow \) Three *resolved* jets \( \Rightarrow \) This analysis.
- Analysis based on full Run 2 CMS data set.

[4]: arXiv:1612.00047
**Trijet Selection**

- Final state gluons ⇒ Energy outside the AK4 cone.
  - Add AK4 jets to recover energy:
    - **Seeds:** 3 jets ($p_T > 100$ GeV & $|\eta| < 2.5$).
    - **Combine:** Jets ($p_T > 30$ GeV & $|\eta| < 2.5$) within $\Delta R < 1.1$.
    - **Result:** 3 wide-jets used for selection.

- **Selection:**
  - Optimized by $S/\sqrt{B}$ studies ⇒
    - $\max(\Delta\eta_{jj}) < 1.6$
    - $\max(\Delta R_{jj}) < 3.0$
  - Limited by trigger selection ⇒
    - $m_{jjj} > 1.50$ TeV for 2016.
    - $m_{jjj} > 1.76$ TeV for 2017/2018.
Signal & Bkg Modelling

• **Signal extraction:**
  Binned, MLL fit on $m_{jjj}$.
  - Binning determined by $m_{jjj}$ resolution (2–4%).

• **Signal modelling:**
  Simulation templates.
  - Interpolated using the morphing method:
    - 50 GeV, $m_{jjj} \leq 3$ TeV
    - 100 GeV, $3 < m_{jjj} \leq 5$ TeV
    - 200 GeV, $m_{jjj} > 5$ TeV

• **Background modelling:**
  PDF envelope of empirical functions fit on data.
  - $f_A(x; N) = p_0 \times \frac{(1-x)p_1}{(x)^{\sum_{i=2}^{N} p_i \log^{i-2}(x)}}$
  - $f_B(x; N) = p_0 \times \frac{e^{-p_1(x)}}{(x)^{\sum_{i=2}^{N} p_i \log^{i-2}(x)}}$
  - $f_C(x; N) = p_0 \times (x)^{\sum_{i=1}^{N} p_i \log^{i-1}(x)}$
  - Order determined by Fisher test.
Results

- **1st search of its kind →** Extended parameter space explored!
- **No significant excess observed:**
  - Max local(global) significance = 2.2σ(0.36σ).
- **Exclusion limits:**
  - No reach for $Z_R$ with current dataset.
  - $\text{Res1} \rightarrow \text{Res2}g \rightarrow ggg$ excluded up to 3.1 TeV.
  - $\text{Res1} \rightarrow \text{Res2}q \rightarrow qqq$ excluded up to 6.0 TeV.
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Highlights Summarized

• **Major CMS effort to probe New Physics!**

• **Examples of BSM models:**
  – Z’ boson.
  – Warped dimensions.
  – Compositeness.

• **Utilizing all tools** available in novel ways.
  – In this talk: **Jets** as the common tool.

• **What the future holds:**
  – More models to probe!
  – More tools to use!
  – More data to explore!

⇒ More analyses being prepared!