Recent Exotic Searches with CMS

Conor Henderson (University of Alabama)
On behalf of the CMS Collaboration

Les Rencontres de Physique de la Vallée d'Aoste
La Thuile, 1-7 March 2015
BSM Searches in Many Final States

(Borrowing the metaphor from F. Riva this morning)

- Our goal when searching for BSM physics in many final states …
BSM Searches in Many Final States

- Try to eat as much as we can!

Inspired by F. Riva this morning
Outline of This Talk

- BSM Physics - trying to eat as much as we can …

Heavy resonances

Dark Matter

Long-Lived
Heavy Resonances – Brief Overview

- Heavy resonance would be unambiguous signal of new physics
- Many possible BSM sources; a common one is:
  - $Z'$:
    - mediator of some new U(1) gauge field
    - frequent signature of BSM enlarged symmetry groups breaking down to $\text{SM} = \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$

- (Can also interpret high-mass spectrum in terms of non-resonant excesses, eg Large Extra Dimensions (ADD), via virtual graviton exchange)
Dijet Resonance Search (EXO-12-059)

- Jet $p_T > 30$ GeV; inclusive jets and b-tagged jets categories
- Uses “wide jets” - less sensitive to gluon radiation
- No evidence for resonance in dijet mass

arXiv:1501.04198
Dijet Limits

- Can set limits on many possible new physics scenarios producing dijets
- Example: “coloron” (new massive strongly-interacting gauge boson) excluded with masses below 3.7 TeV

EXO-12-059

CMS

$\sigma \times B \times A \ (pb)$

$\times 10^4$

$\times 10^3$

$\times 10^2$

$\times 10^1$

$\times 10^0$

$\times 10^{-1}$

$\times 10^{-2}$

$\times 10^{-3}$

$\times 10^{-4}$

$\times 10^{-5}$

19.7 fb$^{-1}$ (8 TeV)

Resonance mass (GeV)

95% CL upper limits

- Gluon-gluon
- Quark-gluon
- Quark-quark

String
- Excited quark
- Axigluon/coloron
- Scalar diquark
- S8
- W' SSM
- Z' SSM
- RS graviton (k/M=0.1)
Search for New Physics in Dilepton Mass

- Dielectron and dimuon channels
- Resonant signal in dilepton mass possible from Z' or Randall-Sundrum graviton; non-resonant excesses from Large Extra Dimensions (ADD) or Contact Interactions
- Main background from Drell-Yan; also ttbar and diboson processes produce two real leptons in final state

arXiv:1412.6302
Dilepton Limits (EXO-12-061)

- 95% CL exclusion limits set on:
  - $Z'_{\text{SSM}} \, M > 2.90$ TeV
  - RS graviton $M_1 > 2.73$ TeV ($k/M_{\text{Pl}}=0.1$)
  - ADD: $\Lambda_T > 4.14$ TeV (GRW convention)
ττ in eμ Decay Channel (EXO-12-046)

- ττ in eμ decay channel, with Missing E_T (MET) from ν

- 95% CL: Z'_SSM M > 1.3 TeV

- ADD Extra dim.:
Top-Antitop Resonance in Dilepton Channel (B2G-12-007)

- $tt \rightarrow bWbW, \ W \rightarrow l\nu$
- Identify b-jets by secondary vertex
- Consider both narrow and wide resonances
- Exclusion limits:
  - Narrow Z', $M > 1.5$ TeV
  - Wide Z', $M > 2.0$ TeV
Z-Higgs Resonance Search (EXO-13-007)

- $Z \rightarrow qq$, $H \rightarrow \tau\tau$
- $Z \rightarrow qq$ reconstructed as single “Z-jet”
- $\tau$ pair from $H$ highly boosted; $e$, $\mu$ and hadronic decay channels all considered
- Exclude $\sigma \times$ BR of $27.8$ fb $-$ $0.9$ fb, for $M_{ZH} 800$-$2500$ GeV
Dark Matter at the LHC

- Dark Matter (existence inferred from galaxy rotation curves, gravitational lensing, etc) - comprises 23% of the universe, but is not compatible with any SM particle

- But a stable particle of mass ~0.1-1 TeV and weak-scale interactions would be a good DM candidate – the “WIMP Miracle”!

- Several BSM theories predict such a particle … could we observe DM production in LHC collisions?

Bullet Cluster
Monophoton Search (EXO-12-047)

- Photon $E_T > 145$ GeV; MET > 140 GeV; veto leptons
- Dominant background at high MET: $Z(\rightarrow \nu\nu)\gamma$
- Data found to be consistent with background prediction …
- (Can also interpret as limit on ADD: real graviton emission)

$\text{arXiv:1410.8812}$
Monophoton Limits

- Translate results to limit on DM-nucleon scattering cross-section, compare with DM direct detection experiments

- Spin-independent and spin-dependent DM interactions
Long-lived new physics can give novel detector signatures – new reconstruction and analysis techniques needed for these
Stopped R-Hadrons (EXO-12-036)

- Long-lived colored particle (gluino or top squark) can form 'R-hadron'; large dE/dx, can come to rest in detector, then decay at some later time

- Signature: large energy deposit in calorimeter, in time interval *between* LHC collisions!

- Background: brem from cosmic or beam halo muons; noise

<table>
<thead>
<tr>
<th>Period</th>
<th>Trigger livetime (h)</th>
<th>$N_{\text{noise}}^{\text{bkg}}$</th>
<th>$N_{\text{cosmic}}^{\text{bkg}}$</th>
<th>$N_{\text{halo}}^{\text{bkg}}$</th>
<th>$N_{\text{total}}^{\text{bkg}}$</th>
<th>$N_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>253</td>
<td>$0.0^{+2.3}_{-0.0}$</td>
<td>$4.8 \pm 3.6$</td>
<td>—</td>
<td>$4.8^{+4.3}_{-3.6}$</td>
<td>2</td>
</tr>
<tr>
<td>2012</td>
<td>281</td>
<td>$0.0^{+2.6}_{-0.0}$</td>
<td>$5.2 \pm 2.5$</td>
<td>$8.0 \pm 0.4$</td>
<td>$13.2^{+3.6}_{-2.5}$</td>
<td>10</td>
</tr>
</tbody>
</table>

- Data events consistent with background – assuming R-hadron interaction model, exclude gluino $M < 1000$ GeV, top squark $M < 525$ GeV, for lifetimes $1 \mu s – 1000s$

*arXiv:1501.05603*
CMS EXO Results Summary

- **Leptoquarks**
  - LQ1(ej) x 2
  - LQ1(ej)+LQ1(vj)
  - LQ2(μj) x 2
  - LQ2(μj)+LQ2(vj)
  - LQ3(vb) x 2
  - LQ3(τb) x 2
  - LQ3(ττ) x 2
  - LQ3(vτ) x 2

- **RS Gravitons**
  - RS1(γγ), k=0.1
  - RS1(σσ, ηη), k=0.1
  - RS1(θθ), k=0.1
  - RS1(WW→4j), k=0.1

- **CMS Preliminary**
  - SSM Z(ττ)
  - SSM Z(jj)
  - SSM Z(θθ)
  - SSM Z(σσ, ηη)
  - SSM W(jj)
  - SSM W(γγ)
  - SSM W(WZ→μμμ)
  - SSM W(WZ→μμτ)

- **Heavy Gauge Bosons**
  - ADD (γγ), n=4, MS
  - ADD (σσ, ηη), n=4, MS
  - ADD (θθ), n=4, MD
  - ADD (W+, MET), n=4, MD
  - QbH, n=4, MD=4 TeV
  - NR BH, n=4, MD=4 TeV
  - Jet Extinction Scale
  - String Scale (j)

- **Excited Fermions**
  - e⁺ (M=L)
  - μ⁺ (M=L)
  - q⁺ (qg)
  - q⁺ (qτ)
  - b⁺
  - coloron(jj) x 2
  - coloron(4j) x 2
  - gluino(3j) x 2
  - gluino(4j) x 2

- **Multijet Resonances**
  - dijets, Λ⁺ LL/RR
  - dijets, Λ⁻ LL/RR
  - dimuons, Λ⁺ LLIM
  - dimuons, Λ⁻ LLIM
  - dielectrons, Λ⁺ LLIM
  - dimuons, Λ⁻ LLIM
  - single e, Λ⁺ ΛnCM
  - single μ, Λ⁺ ΛnCM
  - inclusive jets, Λ⁺
  - inclusive jets, Λ⁻

- **Stopped Gluino (Cloud)**
  - stopped gluino (cloud)
  - HSCP gluino (cloud)
  - HSCP stop (cloud) q=2/3e
  - HSCP q=3e

- **Long-Lived Particles**
  - neutralino, cτ=25 cm, ECAL time

- **Dark Matter**
  - j+MET, SI DM=100 GeV, Λ
  - j+MET, SD DM=100 GeV, Λ
  - γ+MET, SI DM=100 GeV, Λ
  - γ+MET, SD DM=100 GeV, Λ
  - Λ+MET, ζ=+1, SI DM=100 GeV, Λ
  - Λ+MET, ζ=+1, SD DM=100 GeV, Λ
  - Λ+MET, ζ=−1, SI DM=100 GeV, Λ
  - Λ+MET, ζ=−1, SD DM=100 GeV, Λ

- **Large Extra Dimensions**
  - Dijets, Λ⁺ LL/RR
  - Dijets, Λ⁻ LL/RR
  - Dimuons, Λ⁺ LLIM
  - Dimuons, Λ⁻ LLIM
  - Dielectrons, Λ⁺ LLIM
  - Dimuons, Λ⁻ LLIM
  - Single e, Λ⁺ ΛnCM
  - Single μ, Λ⁺ ΛnCM
  - Inclusive Jets, Λ⁺
  - Inclusive Jets, Λ⁻

- **Compositeness**
  - CMS Exotica Physics Group Summary – ICHEP 2014

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B2G Results Summary

CMS Searches for New Physics Beyond Two Generations (B2G)
95% CL Exclusions (TeV)

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Summary

- LHC Run 1 complete, ~20 fb\(^{-1}\) collected at 8 TeV
- CMS has performed many searches for BSM physics, results can be found at:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
- Many final states explored, but no evidence yet for Beyond-SM physics
Outlook

- LHC Run 2: increase collision energy to 13 TeV and increase rate of accumulating data
- The race to discover new physics beyond the Standard Model …
Outlook

New Physics Finish Line
Outlook

Tevatron?

New Physics Finish Line
Tevatron? LHC, 7 TeV?

New Physics Finish Line
Outlook

Tevatron?  LHC, 7 TeV?  LHC, 8 TeV?

New Physics Finish Line
Outlook

Tevatron?  LHC, 7 TeV?  LHC, 8 TeV?  LHC at 13 TeV?
In evjj channel, with selection optimised for LQ mass=650 GeV, 2.6 sigma excess of data over bkg – spread out, no peak in m_{ej}
Dilepton trigger 17+8 GeV; offline e,μ pT>20 GeV; MET> 20 GeV

To more effectively distinguish between lower mass backgrounds from tau lepton pairs from new particle production, the visible tau decay products and the $E_T$ are used to reconstruct the mass:

$$M(\mu, e, E_T) = \sqrt{(E_{\mu} + E_e + E_T)^2 - (p_{\mu}^2 + p_e^2 + E_T^2)^2}.$$  \hspace{1cm} (5)

Table 1: Number of observed events in data and estimated background events, for different $M(\mu, e, E_T)$ mass ranges. The errors on the estimated background events represent the statistical uncertainty from the MC samples.

<table>
<thead>
<tr>
<th>$M(\mu, e, E_T)$ (GeV)</th>
<th>[50,100]</th>
<th>[100,150]</th>
<th>[150,200]</th>
<th>[200,250]</th>
<th>[250,300]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected bkg Data</td>
<td>3480 ± 120</td>
<td>4250 ± 130</td>
<td>1010 ± 70</td>
<td>396 ± 19</td>
<td>230 ± 24</td>
</tr>
<tr>
<td></td>
<td>3428</td>
<td>4296</td>
<td>1000</td>
<td>388</td>
<td>198</td>
</tr>
<tr>
<td>$M(\mu, e, E_T)$ (GeV)</td>
<td>[300,400]</td>
<td>[400,600]</td>
<td>[600,900]</td>
<td>[900,1500]</td>
<td>[0,1500]</td>
</tr>
<tr>
<td>Expected bkg Data</td>
<td>217 ± 13</td>
<td>82 ± 5</td>
<td>20 ± 4</td>
<td>2.7 ± 1.6</td>
<td>9680 ± 190</td>
</tr>
<tr>
<td></td>
<td>176</td>
<td>98</td>
<td>20</td>
<td>3</td>
<td>9607</td>
</tr>
</tbody>
</table>
Z-Higgs Resonance Search (EXO-13-007)
Dark Matter + ttbar (B2G-14-004)

- Scalar DM-quark interaction small due to light quark mass
- Motivates search for DM + top quark pair → ttbar + MET
- Increases LHC sensitivity to scalar DM interaction

\[ L_{\text{int}} = \frac{m_q}{M_\chi^3} \bar{q}q\bar{\chi}\chi \]
Displaced Dilepton Pairs (EXO-12-037)

- Pair of charged leptons from a displaced vertex – would indicate long-lived particle decay
- Seek displaced vertex lepton pairs 12 std dev from primary vertex – no such events seen in data arXiv:1411.6977
- Color-octet, weak-triplet, neutral scalar boson $\Theta^0$
- Pair-produced,
- decaying to $b\bar{b}$ and $Z+g$

![Graph showing mass distributions and limits](image.png)
New BSM Fermion States

- “Vector-like” quarks:
  - 4th generation quarks, but “non-chiral” (SM quarks are chiral, i.e., only LH state couples to Weak interaction)

- Heavy Majorana Neutrinos:
  - A heavy neutrino which is its own anti-particle
Consider TT → bWbW and QQ → qWqW (one W hadronic, other W leptonic decay)

Hadronic W highly boosted – use 'jet-pruning'

Exclude T, M<912 GeV and Q, M<788 GeV
Heavy Majorana Neutrino (EXO-12-057)

- Signature: same-sign dimuon pair (only possible if heavy neutrino N is Majorana) +2jets
- Set limits on $V_{\mu N}$, mixing element of N with SM $\nu_\mu$, as function of N mass
- $\mu$ $p_T > 20.15$ GeV, 2 jets $p_T > 20$ GeV
- Veto 3$^{rd}$ $\mu$, to suppress WZ bkg; veto b-tag jet to suppress ttbar bkg
- Additional refinement based on on-shell Ws, for low-mass and high-mass separately
- Major bkg are: WZ, ZZ etc; W+jets, dijets, with jet faking muon (via heavy flavour decay, usually); the contribution from charge-mis-measured muons at CMS is negligible for this $p_T$ range
LHC Run 2: increase collision energy to 13 TeV and increase rate of accumulating data

We look forward to exciting times in this new frontier!