Searches for new heavy resonances in final states with leptons and photons

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Outline

- CMS published results with 13 TeV data
  - 2015 and 2016 data
  - Analysis with 2017 data still in progress.

- Fully reconstructed final states:
  - Diphoton (with all the gory details)
  - $Z'$ boson in dielectron and dimuon
  - $Z$+gamma (leptonic decay)
  - Electron-muon high mass resonances

- One example of non fully reconstructed final state:
  - $W'$ boson in lepton plus missing transverse momentum

- Conclusions
Motivation

Fully reconstructed final state signatures at higher center-of-mass energy is the golden way to discover new particles and phenomena beyond the SM.


Final states with leptons and photons → good invariant mass resolution.

- Very clear signature: peak over a smooth background
- Experimentally robust
- Small systematic effects
- Model independent probe to new physics
Past discoveries

J/Psi

Z

Higgs
Large Hadron Collider performances (Run1-Run2)

2010-12: LHC Run1

2013-14: LS1 (Long Shutdown 1)

2015-17(18): LHC Run2

From Run1 to Run2

- 7/8 TeV → 13 TeV increasing $\sqrt{s}$ extends the reach of Run1

- Up to $2 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$ Higher event rate and larger PileUp; challenging for trigger and reconstruction.
High mass resonances in diphoton final state

**PLB 767 (2017) 147**

- Data sample: 12.9 fb\(^{-1}\) taken in 2016 at \(\sqrt{s} = 13\) TeV combined with
  - 3.3 fb\(^{-1}\) taken in 2015 at \(\sqrt{s} = 13\) TeV
  - 19.7 fb\(^{-1}\) taken in 2012 at \(\sqrt{s} = 8\) TeV

- Analysis built on SM Higgs search experience
- Robust and model-independent cut based analysis

Benchmark models:

- **Spin-0 analysis**: extended Higgs sector (2HDM)
  - Scalar and/or pseudo-scalar can have sizable branching ratio to diphoton

- **Spin-2 analysis**: Randall-Sundrum graviton
  - Model predicts tower of Kaluza-Klein states with TeV mass scale; mass of the RS graviton is the mass lightest KK excitation
Diphoton vertex identification

- Spread of primary vertex position is \(~ 5 \text{ cm in } z\)
- If vertex is located within 1 cm, contribution to the mass resolution from angle negligible
- The vertex is selected using recoiling tracks (and reconstructed conversion when present)
- Multivariate approach for optimal performance
  \[ \sum p_T^2, p_T(\gamma\gamma) \text{ vs } p_T(\text{tracks}), z_{\text{conv}} \]

- Average probability is \(~ 90\%\).
- Performance validated in data with Z\(\rightarrow\mu\mu\) events
Event selection

Cut-based event selection
(same selection for both benchmark models)

- HLT: 2 photons, $E_T > 60$ GeV
- Offline selection:
  - $E_T > 75$ GeV
  - ECAL fiducial region
  - dedicated photon selection
    (isolation, H/E, shower shape)
- 2 event categories:
  - EBEB: both $\gamma$ in the barrel
  - EBEE: one $\gamma$ in EB, one in EE

10-15% improvement from adding the barrel-endcap category

Per-photon efficiency in the barrel (endcaps): $\sim 90\%$ ($\sim 85\%$).

Zee to check efficiencies

- data/MC scale factors compatible with 1, constant at high $p_T$
High mass resonances in diphoton final state

$m(\gamma\gamma) \sim 750$ GeV
Shape of the signal: combination of the intrinsic width of the resonance and the ECAL detector response.

Detector response modeled on fully simulated signal sample with negligible intrinsic width.

<table>
<thead>
<tr>
<th>$m$ (GeV)</th>
<th>$\frac{\sigma_{FWHM}^{3.8\gamma}}{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>$0.94 \times 10^{-2}$</td>
</tr>
<tr>
<td>1000</td>
<td>$0.94 \times 10^{-2}$</td>
</tr>
<tr>
<td>2000</td>
<td>$0.96 \times 10^{-2}$</td>
</tr>
<tr>
<td>4500</td>
<td>$1.11 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Background $m_{\gamma\gamma}$ shape:
- Parametric fit to data $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\log(m_{\gamma\gamma})}$

Background composition is measured in data with template fits:
- Direct $\gamma\gamma$ SM production; two prompt photons $\rightarrow$ irreducible. Dominant component (>80%)
- Dijets and $\gamma$+jets production $\rightarrow$ reducible. (10-20%)
High mass resonances in diphoton final state

$m_{\gamma\gamma}$ spectra of selected events in the two categories
Interpretation: exclusion limits

Observed limits on Graviton cross section x diphoton BR:

- \( m_G < 1.95 \text{ TeV} \) excluded in the narrow-width scenario (detector resolution is dominant, \( k = 0.01 \))
- \( m_G < 4.45 \text{ TeV} \) excluded in the broad scenario (intrinsic width is dominant, \( k = 0.2 \))

Most stringent limits on RS graviton production to date.

- Expected and observed limits in good agreement.
- Similar limits for spin-0 benchmark model.

\[ \Gamma_G / m_G \sim 6\% \]
Interpretation: p value

Excess observed by CMS and ATLAS at 750 GeV in 2015 data:
- Local significance was 3.4σ (CMS) and 3.9σ (ATLAS)

Excess not confirmed with 4 times more data analyzed in 2016.
- The largest excess in CMS dataset is at 0.9 TeV with a local significance of 2.2σ.
- The excess at 750 GeV is now reduced to 1.9σ.
High mass resonances in $Z(\text{ee}/\mu^+\mu^-)+\gamma$ final states

**CMS PAS EXO-17-005 (arXiv:1712.03143 - submitted to JHEP)**

Data sample: 35.9 fb$^{-1}$ taken in 2016 at $\sqrt{s} = 13$ TeV

- Two isolated electrons with $E_T > 65/10$ GeV and one photon with $E_T > 65$ GeV all in the acceptance $|\eta| < 2.5$

- Two isolated muons with opposite charge, $E_T > 52/10$ GeV and $|\eta| < 2.4$ and one photon with $E_T > 40$ GeV and $|\eta| < 2.5$

- Invariant mass of the dilepton system between 50 and 130 GeV.

- Dominant backgrounds:
  - continuum SM $Z\gamma$ production (irreducible)
  - leptonic decays of the $Z$ boson with FSR and $Z$+jet with jet misidentified as photon (reducible)

- The photon is required to have a distance $\Delta R > 0.4$ from each of the two leptons, to minimize the effect of lepton FSR.

- Benchmark: narrow/broad spin-0 resonances (assuming no interference with SM non resonant $Z\gamma$ production)

- Signal acceptance depends weakly on the spin of the resonances.
The SM background is described by the function \( f(m_{Z\gamma}) = m_{Z\gamma}^{a+b \log m_{Z\gamma}} \)
fitting directly on data events. No significant excess over the background-only hypothesis.
The results from leptonic channels are combined with hadronic channel.

The observed limits for narrow (broad) spin-0 resonances with masses between 0.35 and 4.0 TeV, ranging from 50 (100) to 0.3 (1.5) fb.

These are the most stringent limits on such resonances to date.
High mass resonances in dielectron final state

**CMS PAS EXO-16-031** - Data sample: 12.4 fb\(^{-1}\) taken in 2016 at \(\sqrt{s} = 13\) TeV

- Two isolated electrons with \(E_T > 35\) GeV and at least one electron in the central region: \(|\eta| < 1.44\) (CMS electron acceptance \(|\eta| < 2.5\))
- Efficiency (reco+ID) of 1 TeV electron pair within the detector acceptance: BB 69±8\% and BE 66±10\%
High mass resonances in dimuon final state

**CMS PAS EXO-16-031** - Data sample: 13.0 fb⁻¹ taken in 2016 at √s = 13 TeV

- Two isolated muons with opposite charge, E_T > 53 GeV and |η| < 2.4 coming from the same vertex and not perfectly back-to-back (to reject cosmic rays)
- Dimuon pair invariant mass resolution at 2 TeV is ~5% with both muons in the central region (<2% for dielectron pair).
High mass resonances in $ee/\mu^+\mu^-$ final states

- Search for a new spin 1 neutral narrow resonance: intrinsic width negligible w.r.t. experimental resolution.
- Signal model: Breit-Wigner convoluted with a Gaussian.
- Observations consistent with SM expectations.

Upper limits at 95% of CL on:
- Sequential Standard Model (additional U(1) symmetries)
- GUT inspired models with a $Z'_\psi$ boson with narrow width

<table>
<thead>
<tr>
<th>Channel</th>
<th>$Z'_{SSM}$ Obs. (TeV)</th>
<th>$Z'_{\psi}$ Obs. (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>3.65</td>
<td>3.10</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>3.75</td>
<td>3.20</td>
</tr>
<tr>
<td>ee + $\mu^+\mu^-$</td>
<td>4.0</td>
<td>3.50</td>
</tr>
</tbody>
</table>
High mass resonances in LFV $e\mu$ final states

**CMS PAS EXO-16-058** - Data sample: 35.9 fb$^{-1}$ taken in 2016 at $\sqrt{s} = 13$ TeV

- One isolated electron with $E_T > 35$ GeV, $|\eta| < 2.5$ and one isolated muon with $E_T > 53$ GeV, $|\eta| < 2.4$
- Signal efficiency ranges from 55% to 66% for different benchmark and resonance mass of 1-4 TeV.

**Benchmark models:**

- **tau sneutrino**: the Lightest Supersymmetric Particle in R-parity violating (RPV) SUSY
  - limits on $\lambda$ (coupling with $e\mu$ pair) and $\lambda'$ (coupling with $d\bar{d}$bar pair)
- **$Z'$ gauge boson** in LFV models
  - Assuming BR = 10% for LFV decay and width/mass = 0.03
- **QBH**: spin-0, colourless, neutral quantum black holes
High mass resonances in LFV \( e\mu \) final states

Data consistent with SM expectation in the whole mass range.

- Four events observed with invariant mass > 1.5 TeV.
- SM expectation: 
  \[ 4.2 \pm 0.35(\text{stat.}) \pm 0.91(\text{syst.}) \]

Invariant mass resolution:
\[ 2.2\% \ (3.1\%) \text{ at } 200 \text{ GeV (3 TeV)} \]

QBH signal is a broad distribution with a threshold mass smeared out by the detector resolution.
High mass resonances in LFV $e\mu$ final states

LFV tau sneutrino mass limit: 1.7 TeV to 3.8 TeV for different couplings.

$Z'$ mass limit: 4.4 TeV

QBH threshold mass limit: 3.6 TeV (one extra-dim.) to 5.6 TeV (n=6)
W’ gauge boson in lepton plus missing transverse momentum.

**PLB 770 (2017) 278** - Data sample: 2.3 fb⁻¹ taken in 2015 at √s = 13 TeV

- Large missing transverse momentum and one isolated electron (E_T > 130 GeV to suppress non-prompt electrons and misidentified jets and |η| < 2.5) or one isolated muon (E_T > 53 GeV and |η| < 2.4).
- Two additional requirements in the selection are: |Δφ(\vec{p}_T^\ell, \vec{p}_T^{\text{miss}})| > 2.5 and 0.4 < p_T^\ell/E_T^{\text{miss}} < 1.5
- The main discriminating variable is:

  \[ M_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos[\Delta\phi(\vec{p}_T^\ell, \vec{p}_T^{\text{miss}})])} \]
Sequential standard model (SSM): new massive boson with same couplings as the SM W boson. The decay channel $W' \rightarrow tb$ is also allowed.

Exclusion limits are also set for the production of generic $W'$ boson using a model-independent approach.

* 95% CL limit on SSM $W'$ mass:
  - electron channel 3.6 TeV
  - muon channel 3.9 TeV
  - combined 4.1 TeV (4.0 TeV expected)

Tighter limits than those obtained from Run 1 data.
Conclusions

- No sign of new heavy resonances in the very first 13 TeV data.
- CMS (with ATLAS) is setting stringent limits on BSM scenarios.
- ~40 fb\(^{-1}\) @ 13 TeV analysed so far; will be >150 fb\(^{-1}\) at the end of Run2.
- Still 2900 fb\(^{-1}\) to be taken or analysed during Run3 @ 14 TeV and HL-LHC.
Backup
Total weight: 14000 t
Overall diameter: 15 m
Overall length: 28.7 m
CL limit procedure

\[ \mathcal{L}(\text{data} \mid \mu, \theta) = \text{Poisson} \left( \text{data} \mid \mu \cdot s(\theta) + b(\theta) \right) \cdot p(\hat{\theta} \mid \theta). \]

\[ \tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(\text{data} \mid \mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data} \mid \hat{\mu}, \hat{\theta})}. \]

\[ p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} \mid \text{signal+background}) = \int_{\tilde{q}_\mu^{\text{obs}}}^{\infty} f(\tilde{q}_\mu \mid \mu, \hat{\theta}_\mu^{\text{obs}}) \, d\tilde{q}_\mu \]

\[ 1 - p_b = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} \mid \text{background-only}) = \int_{\tilde{q}_\mu^{\text{obs}}}^{\infty} f(\tilde{q}_\mu \mid 0, \hat{\theta}_0^{\text{obs}}) \, d\tilde{q}_\mu \]

and calculate \( \text{CL}_s(\mu) \) as a ratio of these two probabilities \(^1\)

\[ \text{CL}_s(\mu) = \frac{p_\mu}{1 - p_b} \]
Systematic errors in diphoton analysis

Signal model:
✓ Luminosity: 6.2% on signal normalization
✓ Trigger and photon selection: 6% on signal normalization
✓ Photon energy scale: 1%
✓ Photon energy resolution: 0.5%
✓ PDF: 6% on signal normalization

Background model:
✓ Bias term only
✓ Parameter coefficients: unconstrained nuisance parameters contribute to statistical error
Combination with 8 TeV results in narrow width hypothesis
✓ different acceptance and categorizations
✓ most sensitive 8 TeV analysis in each mass range considered

Likelihood of fits to S+B hypothesis vs 13 TeV equivalent cross-section:
✓ 8 TeV limits scaled by xsec ratio
✓ S=RS Graviton, $m_G=750$ GeV, $k=0.01$
  ✓ production: 90% gg, 10% qqbar
  ✓ $xsec(8\text{TeV})/xsec(13\text{TeV})=1/4.2=0.24$

• **Compatible equivalent cross-sections within uncertainties**
• **13 TeV result not in contradiction with 8 TeV**