Search for narrow high-mass resonances in the dielectron + dimuon final states at CMS
(CMS-PAS-EXO-11-019)

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For the CMS Collaboration
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But first... $Z' \rightarrow \tau\tau$ search with 36 pb$^{-1}$

$Z'$ with SM-like couplings decaying into $\tau\tau$: $M > 468$ GeV @ 95 C.L.
Introduction

• Search for new physics: extra narrow high-mass resonances.
  – E.g. new gauge bosons $Z'$ or Randall-Sundrum gravitons $G_{KK}$.

• Generic shape-based search: no assumptions on absolute background rate.

• Results normalized to the $Z^0$ peak:

$$ \frac{\sigma \times BR(Z')}{\sigma \times BR(Z^0)} = \frac{N(Z')}{N(Z^0)} \times \frac{A(Z^0)}{A(Z')} \times \frac{\epsilon(Z^0)}{\epsilon(Z')} $$

Benefits:
  – Luminosity uncertainty irrelevant
  – Other systematic effects cancel or are reduced

Example from MC studies done for CMS Physics TDR (2006): bump from $Z'$ on SM background
**CMS: the Compact Muon Solenoid**

Fine-grained ECAL for precise measurement of EM energies – ultimately, $\Delta E/E < 0.5\%$ for $E > 100$ GeV.

$\rightarrow$ Excellent $m_{ee}$ resolution, but challenge is on id of electrons vs. jets!

Inner tracker in 3.8 T magnetic field, plus muon system for triggering, id, and to improve high-$p_T$ measurement – $\Delta p_T/p_T < 10\%$ at $p_T \sim 1$ TeV.

$\rightarrow$ Muon id much easier than electron id, $m_{\mu\mu}$ resolution is the challenge!
Dilepton selection

- As in $Z^0$ cross section measurement, adapted for high $E_T$ or $p_T$.
  - Differences $\rightarrow$ small extra systematic uncertainties.

- Trigger: double EM clusters with $E_T > 33$ GeV, single muons with $p_T > 30$ GeV.

- Offline: require two isolated leptons with $E_T$ or $p_T$ above trigger turn-on, with further quality cuts.

- Total efficiency in simulation is $>85\%$ for $m_{ll} > 1$ TeV.
  - Checked lepton efficiency in data using $Z^0$ tag+probe up to $p_T \sim 100$ GeV; for muons, also use cosmic-ray events.
  - Ratio of efficiencies from low to high mass, rather than absolute efficiencies, is important in this analysis.
Dielectron/dimuon differences

- **Looser muon selection**: smaller background from jets for muons.
- **Smaller dielectron acceptance**: no endcap-endcap electron pairs allowed, gap between ECAL barrel and endcap.
- **Opposite charges required for dimuons**, but not for dielectrons.
- **Cosmic-ray muons** used to aid in understanding high-$p_T$ collision muons.
Muon momentum/dimuon mass resolution

Narrow peak broadened by mass/momentum resolution.

Adding muon system hits to tracker-only fit helps for $p_T > \sim 200$ GeV:

But:

High-$p$ muons’ E loss in steel yoke + showers in muon chambers can spoil fit.

→ Use muon hits selectively: e.g. take only first station with hits, drop incompatible hits in chambers flooded by showers.

3.8 T in Si tracker, 2 T in muon system

High-$p$ resolution $\sim 1/(BL^2)$

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Optimizing measurement of high-$p_T$ muons

- Improve on these algorithms by making “cocktail” of fits: for each muon, choose based on e.g. goodness-of-fit criteria.
- Gauge impact in data using cosmic-ray muons: reconstruct the same muon separately in opposite halves of CMS then compare results.

\[ R(q/p_T) = \frac{(q/p_T)^{\text{upper}} - (q/p_T)^{\text{lower}}}{\sqrt{2(q/p_T)^{\text{lower}}}} \]
Dilepton backgrounds

- Dominant: irreducible Drell-Yan (DY) production – use DY shape from sim. in search.
- Next biggest (10% of DY above 120 GeV): ttbar and other sources of “prompt” leptons – check in data using eμ events.
- Dileptons from misidentified jets:
  - For dimuons, negligible (<1% of DY rate above 120 GeV).
  - Dielectrons suffer more: about 5% of the DY rate above 120 GeV.
  - Estimate in data by loosening cuts (e.g. isolation).
- Cosmic-ray muons: using sidebands, estimate less than 0.1 remaining dimuon event above 120 GeV.
\textbf{e\textmu method for ttbar, other prompt leptons}

- Expect two e\textmu events for every ee or \mu\mu event, then scale by different e,\mu efficiencies.
- Extract scale factor N(ee, \mu\mu)/N(e\textmu) from MC in bins of dilepton mass.
- \textbf{Currently just a cross-check} – but good agreement between data and MC.

<table>
<thead>
<tr>
<th>Mass range</th>
<th>N(e\textmu), data</th>
<th>e\textmu-predicted N(ee)</th>
<th>MC-predicted N(ee)</th>
<th>e\textmu-predicted N(\mu\mu)</th>
<th>MC-predicted N(\mu\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 120 GeV</td>
<td>999</td>
<td>420 ± 14</td>
<td>400 ± 64</td>
<td>578 ± 25</td>
<td>560 ± 71</td>
</tr>
<tr>
<td>&gt; 200 GeV</td>
<td>300</td>
<td>139 ± 8</td>
<td>124 ± 20</td>
<td>194 ± 15</td>
<td>171 ± 22</td>
</tr>
</tbody>
</table>
Dielectron jet background

- Measure probability for jet reconstructed as an electron (with loosened cuts) to pass rest of selection.
  - Require exactly one reconstructed electron to remove $Z^0 \rightarrow ee$ events.
  - Use simulation to subtract $W+jet$, $\gamma+jet$, $Z^0 \rightarrow ee$ contamination.

- Apply to ee events to get dielectron-from-jets spectrum – compatible with simulation within target uncertainty.

- Similar strategy in dimuon channel using isolation cut.
Dielectron mass spectrum

Other prompt leptons: VV, tW, t\(\tau\), Z\(\rightarrow\tau\tau\).

Jets: QCD dijets, W+jets.

MC distributions normalized to NLO cross sections, then overall to the data at Z peak in 60-120 GeV.

Uncertainties in table: statistical ⊕ systematic.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(120 – 200 GeV)</td>
</tr>
<tr>
<td>CMS data</td>
<td>3410</td>
</tr>
<tr>
<td>Total background</td>
<td>3375 ± 161</td>
</tr>
<tr>
<td>Z/(\gamma^*)</td>
<td>2992 ± 149</td>
</tr>
<tr>
<td>(t\bar{t}) + other prompt leptons</td>
<td>275 ± 41</td>
</tr>
<tr>
<td>Multi-jet events</td>
<td>107 ± 43</td>
</tr>
</tbody>
</table>

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Opposite-sign dimuon mass spectrum

Other prompt leptons: VV, tW, Z→ττ.
Jets: QCD dijets, W+jets.
MC distributions normalized to NLO cross sections, then overall to the data at Z peak in 60-120 GeV.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(120 – 200) GeV</td>
</tr>
<tr>
<td>CMS data</td>
<td>5216</td>
</tr>
<tr>
<td>Total background</td>
<td>5537 ± 250</td>
</tr>
<tr>
<td>Z/γ*</td>
<td>5131 ± 246</td>
</tr>
<tr>
<td>t̅t + other prompt leptons</td>
<td>404 ± 46</td>
</tr>
<tr>
<td>Multi-jet events</td>
<td>3 ± 3</td>
</tr>
</tbody>
</table>

Uncertainties in table: statistical ⊕ systematic.
Resonance search: bump hunt

- Simple signal + background pdf, with shape parameters from MC; fit explores the difference in shapes.
- Use likelihood ratio to calculate uncorrected significance $S_L$ as a function of the dimuon mass $M$.
- Correct for probability of getting at least as extreme of a fluctuation from background-only ("look-elsewhere effect", LEE) in the range 600-2000 GeV.

\[ L \sim \prod_{i} f_{\text{signal}} + f_{\text{background}} \]

\[ f_{\text{signal}} \sim \text{Breit-Wigner}(m|M, \Gamma) \otimes \text{Gaussian}(m|M, w) \]

\[ f_{\text{background}} \sim \exp\left(-am\right)/m^b \]

\[ S_L = \sqrt{2 \ln \frac{L_{S+B}^{\text{max}}(f_s)}{L_B}} \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Most sig. bump at $M$ (GeV)</th>
<th>Local $Z$ ($\sigma$)</th>
<th>LEE-corrected $Z$ ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>950</td>
<td>2.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>1080</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Combined</td>
<td>970</td>
<td>2.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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Dilepton mass limits on benchmark models

Set limits on ratio of cross sections

\[ R_{\sigma} = \frac{\sigma(pp \rightarrow Z' + X \rightarrow \ell\ell + X)}{\sigma(pp \rightarrow Z + X \rightarrow \ell\ell + X)} \]

using a Bayesian method. 95% CL limits:

<table>
<thead>
<tr>
<th>Channel</th>
<th>µµ</th>
<th>ee</th>
<th>µµ+ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z_{SSM}</td>
<td>1780 GeV</td>
<td>1730 GeV</td>
<td>1940 GeV</td>
</tr>
<tr>
<td>Z_{\psi}</td>
<td>1440 GeV</td>
<td>1440 GeV</td>
<td>1620 GeV</td>
</tr>
<tr>
<td>G_{KK}, c = 0.05</td>
<td>1240 GeV</td>
<td>1300 GeV</td>
<td>1450 GeV</td>
</tr>
<tr>
<td>G_{KK}, c = 0.1</td>
<td>1640 GeV</td>
<td>1590 GeV</td>
<td>1780 GeV</td>
</tr>
</tbody>
</table>
Conclusions

- Data/MC agreement is good – still waiting for a bump.
- Cross-checks/systematic studies show backgrounds are under control.
- 2011 data has piled in fast – expecting to have 400% more by the end of the year.
- Thanks to CMS and the LHC, and...
- Thanks to you for listening!
Backup information
Electron selection

<table>
<thead>
<tr>
<th>variable</th>
<th>barrel</th>
<th>endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T$</td>
<td>&gt; 35 GeV</td>
<td>&gt; 40 GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta_{sc}</td>
<td>$ seed</td>
</tr>
<tr>
<td></td>
<td>ECAL seeded</td>
<td>ECAL seeded</td>
</tr>
<tr>
<td>missing hits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta\eta_{in}$</td>
<td>= 0</td>
<td>= 0</td>
</tr>
<tr>
<td>$\Delta\phi_{in}$</td>
<td>&lt; 0.005</td>
<td>&lt; 0.007</td>
</tr>
<tr>
<td>$H/E$</td>
<td>&lt; 0.09</td>
<td>&lt; 0.09</td>
</tr>
<tr>
<td>$E^{2x5}/E^{5x5}$</td>
<td>&gt; 0.94 OR $E^{1x5}/E^{5x5}$ &gt; 0.83</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>$\sigma_{\eta\eta}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>isol Em + Had Depth 1</td>
<td>&lt; 2 + 0.03 x $E_T$ GeV</td>
<td>&lt; 2.5 GeV for $E_T$ &lt; 50 GeV</td>
</tr>
<tr>
<td>isol Had Depth 2</td>
<td>&lt; 7.5 GeV/c</td>
<td>&lt; 2.5 + 0.03 x ($E_T - 50$) GeV</td>
</tr>
<tr>
<td>isol Pt Tracks</td>
<td></td>
<td>&lt; 0.5 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 15 GeV/c</td>
</tr>
</tbody>
</table>
Dielectron energy scale/resolution

- Fit $Z^0 \rightarrow ee$ peak in data and simulation and compare.
- Take resolution at high mass from simulation, applying additional smearing derived at $Z^0$ peak:

Fit is Crystal Ball convoluted with Breit-Wigner.
Dielectron eff. scale factor

Data/simulation scale factor, measured at $Z^0$:

EB: $1.008 \pm 0.001^{\text{stat}} \pm 0.011^{\text{sys}}$

EE: $1.017 \pm 0.002^{\text{stat}} \pm 0.010^{\text{sys}}$

Extrapolate to high mass:

EB: $1.002 \pm 0.011^{\text{stat}} \pm 0.018^{\text{sys}}$

EE: $1.030 \pm 0.024^{\text{stat}} \pm 0.021^{\text{sys}}$
Example Tevatron dilepton limits
40 pb$^{-1}$ CMS dilepton limits
\[
\mathcal{L}(m|\mathcal{R}_\sigma, M, \Gamma, w, \alpha, \kappa, \mu_B) = \frac{\mu^N e^{-\mu}}{N!} \prod_{i=1}^{N} \left( \frac{\mu_S(\mathcal{R}_\sigma)}{\mu} f_S(m_i|M, \Gamma, w) + \frac{\mu_B}{\mu} f_B(m_i|\alpha, \kappa) \right)
\]

with:

- \(m_i\) = observed mass spectrum;
- \(f_S(m_i|M, \Gamma, w)\) = signal pdf, Breit-Wigner of width \(\Gamma\) and mass \(M\), convoluted with Gaussian with width \(w\);
- \(f_B(m_i|\alpha, \kappa) \sim \exp(-\alpha m)m^{-\kappa}\) = background pdf;
- \(\mathcal{R}_\sigma = \frac{\sigma(pp \rightarrow Z' + X \rightarrow \ell\ell + X)}{\sigma(pp \rightarrow Z + X \rightarrow \ell\ell + X)}\) = the cross section ratio, which goes into the likelihood function as part of the signal Poisson mean \(\mu_S = \mathcal{R}_\sigma \cdot \mu_Z \cdot \mathcal{R}_\epsilon\), where \(\mu_Z\) is the Poisson mean number of \(Z^0 \rightarrow \text{ee}\) or \(\mu \mu\) events, and \(\mathcal{R}_\epsilon\) is the ratio of total efficiency for \(Z'\) and \(Z^0\) decays;
- \(\mu_B\) is the Poisson mean of the total background yield, \(\mu = \mu_S + \mu_B\), and \(N\) is the total number of events with mass above 600 GeV.
Dilepton systematics

• 3% (8%) on the acceptance times efficiency ratio evolution from low to high mass for dimuons (dielectrons), which includes PDF uncertainties (relevant to the acceptance) and the mass dependence of K-factors.

• For dimuons, sensitivity study to mass scale uncertainty (affecting only the region below 1250 GeV where there are events) showed negligible impact up to the maximum possible from alignment effects; for dielectrons, study at Z⁰ peak results in 1% for barrel and 3% for endcap.

• For dimuons, effect of possible $\chi^2$-invariant “weak mode” in alignment, which corresponds to a muon tracking curvature bias, folded into estimate of Gaussian width for signal pdf.

• Shape systematics explored:
  – include an extra background shape representing the ttbar component and varying its amplitude;
  – trying a different functional form for the background pdf;
  – and changing the low-mass cut-off point for the DY shape fit from 200 GeV down to 150 GeV, which changes the background shape parameters.
RSG diphoton search with 36 pb$^{-1}$

![Graph showing diphoton mass distribution and cross-sections.]

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