Measurement of Inelastic, Diffractive, and Exclusive processes in CMS

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The setting: CMS@LHC

- High energy and high luminosity
  - Allows high statistics precision measurements, and sensitivity to “rare” processes (hard diffraction, exclusive production)
  - But high luminosity comes with high “pileup” – average 2-4 extra interactions/crossing in 2010, 5-8 in 2011

- Good detector coverage
  - Tracking to $|\eta| < 2.4$
  - Hadronic calorimeter (HF) to $|\eta| < 5$
  - Forward calorimeters (cover -6.6 < $\eta$ < -5.2 (CASTOR) and $|\eta| > 8.1$ (ZDC)
Measurement of the inelastic cross-section using pileup events
Motivation & method

- Probability of a number interactions occurring in a crossing depends on the total $pp$ cross-section
  - $\Rightarrow$ Turn pileup into an advantage for measuring $\sigma(pp)$

- Method based on counting # of vertices as a function of luminosity
  - Samples collected with high-efficiency triggers (e.g. di-electrons)
  - Data is corrected for vertex merging, and inefficiencies in reconstructing vertices with low track multiplicity
Fitting

- Unfolded distributions are fit to a Poisson distribution for each value of pileup ($\approx N_{\text{vertices}} - 1$) from 0-8
Results (I)

- Nine statistically independent measurements, for each value of the pileup
- Final result from a fit to all nine points
- For 3 tracks with $p_T > 200\text{MeV}$, $|\eta| < 2.4$, the resulting cross-section is:

$$\sigma = 58.7 \pm 2.0 \text{ (Sys)} \pm 2.4 \text{ (Lumi)} \text{ mb}$$
Results (II)

- Measurement is compared to predictions of several models
  - Gives a range of extrapolation factors that can be used to bound the total inelastic cross-section:

\[\sigma_{pp} = 68.0 \pm 2.0 \text{(Sys)} \pm 2.4 \text{(Lumi)} \pm 4.0 \text{(Extr.)} \text{ mb}\]
Diffraction @ 7TeV
Inclusive Diffraction

- Analysis based on 20\(\mu\)b\(^{-1}\) of low-pileup 7TeV data
  - Extends previous CMS results on diffraction at 900GeV and 2.36TeV
  - Trigger with scintillator counters (BSC) and require a vertex consistent with collisions
- Diffractive signal appears as an enhancement near zero in several sensitive variables
  - \(N(\text{HF towers over threshold})\)
  - \(\Sigma E(\text{HF})\)
  - \(\Sigma E-p_Z (~\xi)\), summed over all calorimeter towers
Event distributions

- Select a diffractively enhanced sample by requiring <8 GeV in HF+
- Track multiplicities, track $p_T$ distributions, and energy deposits opposite the gap side compared a range of models
  - Pythia 8 and Phojet better describe the diffractive component, while Pythia 8 and several Pythia 6 tunes perform better for inclusive distributions
- None of the models describe all features of the data
Diffractive W/Z
Introduction and selection

- Part of a larger systematic study of track multiplicity and forward energy flow in W/Z events
- Search for a diffractive component in W/Z events
- Sensitive to multi-parton interactions (MPI), gap-survival probabilities
  - Additional interactions may “fill the gap” in diffractive interactions
- Select W/Z events with a single-vertex to suppress pileup
  - Residual contamination from soft pileup events studied in MC, and in data as a function of average instantaneous luminosity
W/Z with gaps

- Search for a diffractive component in W/Z events
- Define Large Rapidity Gap selection using sum of calorimeter towers in HF (3 < |η| < 5) above 4 GeV
- Excess of events with zero energy compared to Pythia 6 D6T tune
  - But – deficit compared to Pythia 6 Z2, Pythia 8

Fraction of LRG events

\[ W \rightarrow l \nu = 1.46 \pm 0.09 \text{ (stat.)} \pm 0.38 \text{ (syst.)} \% \]
\[ Z \rightarrow ll = 1.60 \pm 0.25 \text{ (stat.)} \pm 0.42 \text{ (syst.)} \% \]
Lepton asymmetry

- Additional sensitivity to diffraction from the charged lepton asymmetry $\eta_{\text{Lepton}}$
  - POMPYT MC predicts leptons from diffractive $W/Z$ are preferentially produced opposite the LRG (small-$x$ diffractive PDF’s)
  - All Pythia tunes predict a flat distribution

- Large asymmetry observed in the LRG sample in data, with best-fit fraction for the diffractive component:
  \[ 50.0 \pm 9.3 \text{ (stat.)} \pm 4.2 \text{ (syst.)\%} \]
Exclusive $\gamma \gamma \rightarrow \mu \mu$
Exclusive production $pp \rightarrow p\mu\mu p$
- QED like “Standard Candle”, proposed as a possible future luminosity measurement

Largest “background” from $\gamma\gamma \rightarrow \mu\mu$ with proton dissociation
- $pp \rightarrow p\mu\mu Y$, or $pp \rightarrow X\mu\mu Y$ with proton remnants undetected
Exclusive dimuons

- Selection based on tracking only, to keep high efficiency with pileup
- Require a $\mu\mu$ vertex, with no other tracks associated
  - Measurement in a restricted phase space $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.1$, $m(\mu\mu) > 11.5$ GeV, to minimize systematic errors and remove $Y$ photoproduction

<table>
<thead>
<tr>
<th>Veto size [cm]</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.9</td>
</tr>
<tr>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

- Efficiency of the track veto is measured in beam-crossing triggered data
  - 92% for full 2010 sample
  - ~70% for events with 8 vertices and 2mm veto size
Exclusive dimuons

- Signal yield and ratio to the prediction obtained from a fit to the $p_T(\mu\mu)$ distribution
  - Signal yield, single $p$-dissociation yield, and a correction to the slope of the $p$-dissociation are free parameters
  - Signal and $p$-dissociation yields are highly anti-correlated

For $p_T(\mu) > 4$ GeV, $|\eta| < 2.1$, $m(\mu\mu) > 11.5$ GeV:

\[ \sigma = 3.38^{+0.58}_{-0.55} \text{ (stat.)} \pm 0.16 \text{ (syst.)} \pm 0.14 \text{ (lum.)} \text{ pb} \]

Ratio = $0.83^{+0.14}_{-0.13} \text{ (stat.)} \pm 0.04 \text{ (syst.)}$
Kinematic distributions compared to LPAIR MC with best fit normalization

- Good agreement with expectations for exclusive $\gamma\gamma \rightarrow \mu\mu$ plus proton dissociation
  - $|1-\Delta\phi(\mu\mu)/\pi|$, $\Delta p_T(\mu\mu)$ peak at ~0, consistent with exclusive production
  - $m(\mu\mu)$ spectrum extends to 76 GeV, no events consistent with $Z \rightarrow \mu\mu$
    (consistent with suppression of spin-1 resonance production $\gamma\gamma$ interactions)
Conclusions

- Inelastic cross-section
  - New measurement based on counting vertices in pileup events
- Inclusive diffraction at 7 TeV
  - No models completely describe calorimeter and charged track distributions
- W/Z
  - No models completely describe energy flow and charged track distributions
  - Study of LRG events, and measurement of diffractive component from $\eta_{\text{lepton}}$
- Exclusive production
  - Observation of $\gamma\gamma \to \mu\mu$ standard candle, data well-described by LPAIR MC
- Inelastic cross-section, diffractive W/Z, exclusive $\gamma\gamma \to \mu\mu$ analyses based on the full 2010 sample (36-40 pb$^{-1}$), including data collected with pileup
  - Stay tuned for new results
Extra
# cross-section systematics

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>$\Delta \sigma_{\text{vtx}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale the luminosity by +4%</td>
<td>-2.3</td>
</tr>
<tr>
<td>Scale the luminosity by -4%</td>
<td>+2.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis parameters</th>
<th>$\Delta \sigma_{\text{vtx}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perform Analysis on a different dataset</td>
<td>+0.9</td>
</tr>
<tr>
<td>Change the fit upper limit from 0.6 to 0.5 $\cdot 10^{30}\text{cm}^{-2}\text{s}^{-1}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Change the fit lower limit from 0.05 to 0.15 $\cdot 10^{30}\text{cm}^{-2}\text{s}^{-1}$: $\Delta \sigma_{\text{vtx}} = -0.3$</td>
<td>-0.3</td>
</tr>
<tr>
<td>Reduce the z-vertex range from 20 to 10 cm</td>
<td>-0.1</td>
</tr>
<tr>
<td>Change the $\epsilon$ correction by 2%</td>
<td>-0.4</td>
</tr>
<tr>
<td>Change the $\epsilon$ correction by -2%</td>
<td>0.3</td>
</tr>
<tr>
<td>Impose the minimum distance of ±1 mm between two vertices</td>
<td>0.1</td>
</tr>
</tbody>
</table>
**$\gamma\gamma \rightarrow \mu\mu$ systematics**

<table>
<thead>
<tr>
<th>Selection</th>
<th>Variation from nominal yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>track veto size</td>
<td>3.6%</td>
</tr>
<tr>
<td>track quality</td>
<td>2.5%</td>
</tr>
<tr>
<td>Drell-Yan background</td>
<td>0.4%</td>
</tr>
<tr>
<td>double $p$—dissociation background</td>
<td>0.9%</td>
</tr>
<tr>
<td>Crossing-angle</td>
<td>1.0%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>0.1%</td>
</tr>
<tr>
<td>Vertexing efficiency</td>
<td>0.1%</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>0.1%</td>
</tr>
<tr>
<td>Efficiency correlations in $J/\psi$ control sample</td>
<td>0.7%</td>
</tr>
<tr>
<td>Muon and trigger efficiency statistical error</td>
<td>0.8%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.8%</strong></td>
</tr>
</tbody>
</table>
Exclusive quarkonia candidates

\[ m = 3.05 \pm 0.03 \text{ GeV} \]
\[ \frac{\Delta \phi}{\pi} = 0.98 \]
\[ \Delta p_T = 0.05 \text{ GeV} \]

\[ m = 9.44 \pm 0.08 \text{ GeV} \]
\[ \frac{\Delta \phi}{\pi} = 0.99 \]
\[ \Delta p_T = 0.20 \text{ GeV} \]
Exclusive $\gamma\gamma \rightarrow \mu\mu$ candidates

\[ m = 20.51 \pm 0.2 \text{ GeV} \]
\[ \frac{\Delta \phi}{\pi} = 0.98 \]
\[ \Delta p_T = 0.48 \]
W/Z Distributions

- Measurements of
  - Energy flow in HF (3 < |\eta| < 4.9), summing calorimeter towes above 4 GeV
  - Track multiplicites (|\eta| < 2.4), for \( p_T > 0.5 \text{ GeV} \) and \( p_T > 1.0 \text{ GeV} \)
  - Correlations – track multiplicites in bins of energy flow, energy deposits in HF+ vs. HF-

- Comparison to a range of Pythia6 and Pythia8 tunes
  - No tune simultaneously describes all multiplicity and energy flow distributions in data
Total cross-section

CMS Model dependent extrapolation

CMS