Exclusive processes from CMS

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On behalf of the CMS Collaboration
Outline

• Introduction

• Proton-proton collisions
  • Exclusive $\gamma\gamma \rightarrow W^+W^-$ production
    • Limits on anomalous quartic gauge couplings
  • Exclusive $\pi^+\pi^-$ production
    • Differential and integrated cross-sections

• Proton-lead collisions
  • Exclusive photoproduction of Upsilon in pPb collisions at $\sqrt{s} = 5.02$ TeV
    • estimate the $|t|$ dependence of the cross-section
    • photonuclear cross-section

• Ongoing analyses and future prospects
  • Using CMS-TOTEM data to extend studies of central exclusive production
  • Vector meson production in pPb
The CMS Experiment

EM and Hadron calorimeters
Muon Chambers

Pb
(1.58 TeV)

Proton
(4 TeV)

Inner tracker

LHC Runs
pp 7, 8, 13 TeV
pPb 5.02, 8 TeV
Exclusive electroweak boson pairs
Motivation: Exclusive electroweak boson pairs

- The exclusive production of W pairs is sensitive to anomalous quartic gauge couplings (aQGC)

- The electroweak sector of Standard Model predicts QGC

- Any deviation from SM expectations can reveal a sign of new physics

- Objective: Measure SM cross section and look for aQGC.

- aQGC are introduced via effective Lagrangian

$$\mathcal{L}^0_6 = \frac{-e^2}{8} \frac{a^W_0}{\Lambda^2} F^\mu_\nu F^{\mu\nu} W^{+\alpha} W^-_{\alpha}$$

$$\mathcal{L}^C_6 = \frac{-e^2}{16} \frac{a^W_C}{\Lambda^2} F^{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W^-_{\beta} - W^{-\alpha} W^+_{\beta})$$

Anomalous coupling constant for quartic vertex

\(\Lambda\) : Scale for New Physics
Exclusive $\gamma\gamma \rightarrow W^+ W^-$: event selection

- Exclusive production of $W$ pairs
  
  \[ pp \rightarrow p^{(*)} W^+ W^- p^{(*)} \]
  
  $p^{(*)}$: Elastic + Inelastic contributions

- 2011 pp collision data at 7 TeV with 5.05 fb$^{-1}$

- 2012 pp collision data at 8 TeV with 19.7 fb$^{-1}$

- Offline exclusive $\gamma\gamma \rightarrow W^+ W^-$ signal selection
  
  - Opposite-sign $e\mu$ pair (final state) originating from common primary vertex
  
  - No extra tracks at $e\mu$ vertex \textbf{to remove inclusive background}
  
  - Invariant mass ($e\mu$) $> 20$ GeV to get rid of any low mass resonances
  
  - $p_T (e\mu) > 30$ GeV \textbf{to suppress DY and $\gamma\gamma \rightarrow \tau^+ \tau^-$}

- Proton dissociation factor from $\mu\mu$ sample
Exclusive $\gamma\gamma \rightarrow W^+W^-$ production at 7 and 8 TeV

SM signal region: N extra tracks = 0, $p_T(e\mu) > 30$ GeV

Cross section times branching fraction

$\sigma(pp \rightarrow p^*(\gamma)W^+W^-(\gamma)p^*) \rightarrow p^*\mu^{\pm}e^{\mp}p^*) = 2.2^{+3.3}_{-2.0}$ fb

SM Prediction: $4.0 \pm 0.7$ fb

The observed significance for 7 and 8 TeV combination is $3.4\sigma$
Exclusive $\gamma \gamma \rightarrow W^+ W^-$: aQGC limit

- Used shape of $p_T (e\mu)$ distribution to search for sign of anomalous quartic gauge couplings
- $p_T (e\mu) > 100$ GeV used at 7 TeV
- Two bins at 8 TeV
  - $30 < p_T (e\mu) < 130$ GeV and $p_T (e\mu) > 130$ GeV
- Region outside solid line is excluded at 95% CL
- The most stringent limit so far, two orders of magnitude more stringent than LEP

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### Table

<table>
<thead>
<tr>
<th>Dimension-6 AQGC parameter</th>
<th>7 TeV ($\times 10^{-4}$ GeV$^{-2}$)</th>
<th>8 TeV ($\times 10^{-4}$ GeV$^{-2}$)</th>
<th>7+8 TeV ($\times 10^{-4}$ GeV$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{0}^{W}/\Lambda^2 (\Lambda_{\text{cutoff}} = 500 \text{ GeV})$</td>
<td>$-1.5 &lt; a_{0}^{W}/\Lambda^2 &lt; 1.5$</td>
<td>$-1.1 &lt; a_{0}^{W}/\Lambda^2 &lt; 1.0$</td>
<td>$-0.9 &lt; a_{0}^{W}/\Lambda^2 &lt; 0.9$</td>
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<tr>
<td>$a_{C}^{W}/\Lambda^2 (\Lambda_{\text{cutoff}} = 500 \text{ GeV})$</td>
<td>$-5 &lt; a_{C}^{W}/\Lambda^2 &lt; 5$</td>
<td>$-4.2 &lt; a_{C}^{W}/\Lambda^2 &lt; 3.4$</td>
<td>$-3.6 &lt; a_{C}^{W}/\Lambda^2 &lt; 3.0$</td>
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</table>
Exclusive $\pi^+\pi^-$ production
Exclusive $\pi^+\pi^-$ production: Experimental signature

- Exclusive production of hadrons at central rapidities phenomenologically described in terms of “DPE” Double Pomeron Exchange when the mass of central system is low, or pertubatively in “CEP”

- **Experimental signature:**
  - Only two opposite sign tracks ($\pi^{\pm}$) from the same primary vertex
  - No additional signal in calorimeters
  - $p_T(\pi) > 0.2$ GeV
  - $|y(\pi)| < 2$
Exclusive $\pi^+\pi^-$ production: Background estimation

→ **Signal:** (Zero-bin with opposite-sign (OS) events)

→ **Background:**
  
  → Make “data-driven”
  
  → Both normalization and shape for different distributions
  
  → Use the sample with all cuts applied, but require 1-5 towers above threshold
  
  → Take the background normalization from the average of these 5 bins
  
  → Take the shapes from events in these 5 bins
  
  → Use the same procedure on same-sign (SS) events (purely background)
Exclusive $\pi^+\pi^-$ production: Signal distribution

- Using the sideband region in the tower multiplicity distribution
- For the nominal background estimate, use the control sample with 1-5 extra calorimeter towers above threshold, and all other selection criteria applied
- The non-exclusive background shapes obtained from this method are shown, with a normalization given by the average number of events per bin of tower multiplicity

Background is $\pi^+\pi^-$ events but with additional activity
Exclusive $\pi^+\pi^-$ production: Results $d\sigma/dM$

Differential cross section:

- with $p_T(\pi) > 0.2$ GeV and $|y(\pi)| < 2$
- Compared to the predictions of DPE production from the Dime MC (red/green curves), and STARLIGHT (dash). (Here: Dime MC & Starlight are stacked)
- The shaded blue band shows the overall systematic uncertainty, and the thin error bar indicates the statistical uncertainty
- The results are plotted on a linear scale (left) and a logarithmic scale (right)
Exclusive $\pi^+\pi^-$ production: Results $d\sigma/dp_T, d\sigma/dy$

Differential cross sections as a function of $p_T$ and rapidity:

- with $p_T(\pi) > 0.2$ GeV and $|y(\pi)| < 2$

- Compared to the predictions of DPE production from the Dime MC (red/green curves), and STARLIGHT (dash).

(Here: Dime MC & Starlight are stacked)
The shaded blue band shows the overall systematic uncertainty, and the thin error bar indicates the statistical uncertainty

- The results are plotted on a logarithmic scale (top) and a linear scale (bottom)

$\sigma_{vis} = 20.5 \pm 0.3(stat.) \pm 3.1(sys.) \pm 0.8(lumi) \mu b$
Exclusive vector meson production in pPb
Motivation: Exclusive vector meson production in pPb

- The exclusive production is studied in ultraperipheral pPb collisions
- Ions interact via photons
- The photon flux grows with the square of the charge, $Z^2$
Motivation: Exclusive vector meson production in pPb

- The exclusive production is studied in ultraperipheral pPb collisions
- Ions interact via photons
- The photon flux grows with the square of the charge, $Z^2$
- Photoproduction process is sensitive to the gluon density squared in the nucleon (nucleus)

$$\frac{d \sigma_{\gamma p, A \rightarrow V p, A}}{dt} \bigg|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3 \alpha M_v^5} \times 16 \pi^3 \left[ xG(x, Q^2) \right]^2$$

$$\sigma_{\gamma p \rightarrow \gamma p} = \frac{1}{b} \frac{d \sigma_{\gamma p, A \rightarrow V p, A}}{dt} \bigg|_{t=0}$$

- Probe gluon distributions in the proton at low $x$ ($10^{-4}$ to $2 \cdot 10^{-2}$)

$$x = \left( \frac{M_Y}{W_{\gamma p}} \right)^2$$

- Photonuclear cross-section shows power law dependence with $W_{\gamma p}$

$$\sigma \propto W_{\gamma p}^{-\delta}$$
Motivation: Exclusive $\gamma$ production

- Energy of the photon-proton collision

\[ W_{\gamma p}^2 = 2 \cdot E_p \cdot M_{VM} \cdot \exp(-y) \]

$E_p$ - proton beam energy

$M_{VM}$ - Mass of the Vector meson

$y$ – Rapidity of the vector meson

<table>
<thead>
<tr>
<th>CMS</th>
<th>HERA</th>
<th>LHCb</th>
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<tbody>
<tr>
<td>$E_p$ [GeV]</td>
<td>4000</td>
<td>820</td>
</tr>
<tr>
<td>y-range</td>
<td>(-2.2;2.2)</td>
<td>(-1.5;1.5)</td>
</tr>
<tr>
<td>$W_{\gamma p}$ [GeV]</td>
<td>91-826</td>
<td>60-220</td>
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</table>
Exclusive upsilon production

• 2013 pPb data at 5.02 TeV with 32.6 nb\(^{-1}\)

• Offline exclusive \(pPb \rightarrow \Upsilon(\gamma p) \rightarrow \mu^+\mu^-\) signal selection
  • Invariant mass (\(\mu\mu\)): 9.12 – 10.64 GeV
  • Opposite-sign \(\mu\mu\) pair (final state) originating from common primary vertex
  • No extra tracks at primary vertex to remove non-exclusive background
  • Upsilon \(p_T\): 0.1-1 GeV to suppress QED and proton dissociation
  • Upsilon |\(y| < 2.2\) high muon finding efficiency

\[\chi^2/\text{ndf}=0.582150\]

\begin{align*}
N(\text{Upsilon}(1S)) &= 24.3 \pm 6.7 \\
N(\text{Upsilon}(2S)) &= 19.1 \pm 6.3 \\
N(\text{Upsilon}(3S)) &= 7.4 \pm 4.9 \\
N(\text{two-photon events}) &= 183 \pm 16
\end{align*}
Exclusive upsilon production

- Data compared to simulation (contains different contributions)
- Low $p_T$: QED elastic background, estimated by STARLIGHT
- High $p_T$: Non-exclusive background estimated from data
- Starlight MC: $\gamma Pb$ (small contribution) and reweighted $\gamma p$ contribution

Good agreement between data and MC
Photoproduction cross-section as a function of $|t|$  

- The differential cross section is calculated according to

$$\frac{d\sigma_Y}{dt} = \frac{N_{sig}^{Unfolded}}{L \cdot \Delta t}$$

- $N_{sig}$, the background subtracted, unfolded and acceptance corrected number of upsilon events in each $|t|$ bin.

- $d\sigma/dt$ fitted with an exponential function, provides the information on the transverse profile of the interaction region.

\[\begin{array}{c|c|c}
\chi^2 / \text{ndf} & 0.98 / 3 \\
\text{Constant} & 2.9 \pm 0.45 \\
\text{Slope} & -4.5 \pm 1.7 \\
\end{array}\]

CMS Results

$b = 4.5 \pm 1.7 \text{ (stat.)} \pm 0.6 \text{ (syst.) GeV}^{-2}$

Data is in agreement with ZEUS measurements and consistent with predictions based on pQCD models

\[\begin{array}{c}
\text{ZEUS for } \Upsilon(1S) \\
\text{b} = 4.3^{+2.0}_{-1.3} \text{ (stat)} \\
\end{array}\]

Cross-section as a function of $W_{\gamma p}$

- The cross section is estimated by
  \[
  \sigma_{\gamma p \rightarrow \Upsilon(1S)p} = \frac{1}{\Phi} \frac{d\sigma_{\Upsilon(1S)}}{d y}
  \]
- Rapidity distribution of $\Upsilon(1S+2S+3S)$ used to estimate $\sigma_{\Upsilon(1S)}$ vs $W_{\gamma p}$
- The cross-section is corrected for muonic branching ratio, feed-down, upsilon (1S) fraction

A fit with power-law $A X (W/400)^{\delta}$ to the CMS data
\[
\delta = (0.96 \pm 0.43), \quad A = 655 \pm 196
\]
Data compatible with power-law dependence of $\sigma(W_{\gamma p})$, disfavours LO pQCD predictions

ZEUS
\[
\delta = 1.2 \pm 0.8
\]
PLB 680(2009) 4-12
Future prospects
Future prospects: Joint CMS-TOTEM run @13 TeV

- Joint CMS-TOTEM $\beta^* = 90\text{m}$ runs in October 2015
- About 0.4/pb of low-pileup ($\mu = 0.06$-$0.15$) data at 13 TeV
- Events with central system in CMS and diffractive protons in TOTEM Roman Pots
- Separate DAQ systems with trigger exchange
- CMS and TOTEM data reconstructed separately, then merged offline (event by event based on the same orbit and bunch crossing)
- Dedicated CMS track reconstruction tune, to assure high track-finding efficiency for low-$p_T$ tracks and high vertex-finding efficiency for 2-track events

**Trigger:** Two scattered protons in the TOTEM Roman Pots (RP), no activity in the TOTEM T2 telescopes, at least 5 clusters in the CMS pixel detector
Future prospects: Joint CMS-TOTEM run @13 TeV

Transverse momenta $p_Y$ of the scattered protons detected in Roman Pots (TOTEM) vs transverse momenta of two pion tracks measured in the central tracking system (CMS) for the $pp \rightarrow pp\pi^+\pi^-$ production. Events on the diagonal correspond to the exclusive $\pi^+\pi^-$ production.

**Adding tagged protons from TOTEM greatly helps to select exclusive $pp \rightarrow pp\pi^+\pi^-$ process with no proton-dissociation**

The three distinct regions along the $p_Y^{TOTEM}$ axis correspond to the top-top, diagonal and bottom-bottom proton configurations.
Future prospects: cross-section as a function of $W_{\gamma p}$

- Energy of the photon-proton collision

$$W_{\gamma p}^2 = 2 \cdot E_p \cdot M_{VM} \cdot \exp(-y)$$

- $E_p$ - proton beam energy
- $M_{VM}$ - Mass of the Vector meson
- $y$ – Rapidity of the vector meson

- The proton beam energy at LHC is much higher compared to HERA
  CMS Run-I and Run-II data extend measurements performed at HERA

- CMS covers both forward and backward rapidity regions
  It is a unique possibility to cover the energy region between HERA experiments and LHCb data
Future prospects: $|t|$-distributions

Appearance of diffractive dips are signature of gluon saturation according to b-CGC and IP-Sat models.

Both H1 and ZEUS measured only low $|t|$ region.

It is necessary to extend the measurement to higher $t$-values.

Summary

• Exclusive $\gamma\gamma \rightarrow W^+W^-$
  • 2 events observed at 7 Tev, 13 events observed at 8 Tev in SM region
  • No indication of aQGC found

• Exclusive $\pi^+\pi^-$
  • Differential cross-sections above exclusive $\pi^+\pi^- + \rho$ photoproduction predictions for high-pt
  • The invariant mass spectrum shows some features not included in the purely non-resonant predictions

• Exclusive $\Upsilon$ in pPb
  • The first measurement of exclusive $\Upsilon$ photoproduction in pPb collisions at 5.02 TeV has been presented
  • Data compatible with power-law dependence of $\sigma_{\Upsilon(1S)}(W_{\gamma p})$ and previous measurements by HERA and LHCb
  • The differential cross-section $d\sigma/dt$ in agreement with earlier measurements and consistent with predictions based on pQCD models

• More exciting exclusive results to be presented this year
  • Both in pp and pPb data (and even in PbPb!)
Additional slides
Requirements of the transverse momentum balance $|p_Y^{CMS} + p_Y^{TOTEM}| < 2\sigma_{dpY}$ and $|p_X^{CMS} + p_X^{TOTEM}| < 2\sigma_{dpX}$ are applied to reject background and select events of central exclusive production, $pp \rightarrow ppX$ with $X=\pi^+\pi^-, K^+K^-, \pi^+\pi^-\pi^+\pi^-, K^+K^-K^+K^-$, ...
Left: the x position of the event vertex for pp-$\to$pp$\pi^+\pi^-$ events reconstructed from an extrapolation of the proton tracks measured in the right ($z>0$) vs left ($z<0$) TOTEM Roman Pot.

Right: The CMS vs TOTEM measurement of the x position of the event vertex for pp-$\to$pp$\pi^+\pi^-$ events. The CMS value is measured in the CMS reference frame, while the TOTEM value is measured in the LHC reference frame.

The $\beta^*=90m$ optics has parallel-to-point focusing for the y plane – the RP measurement in y has no sensitivity on the vertex (only on the scattering angle).
Future prospects: Joint CMS-TOTEM run @13 TeV

Requirements of the vertex compatibility $|x_{\text{VTX}}^{p \text{right}} - x_{\text{VTX}}^{p \text{left}}| < 2\sigma_{d\text{xVTX}}^{\text{TOTEM}}$ and $|x_{\text{VTX}}^{\text{CMS}} - x_{\text{VTX}}^{\text{TOTEM}} - x_0| < 2\sigma_{d\text{xVTX}}$ are applied to reject background and select events of central exclusive production, $pp \rightarrow ppX$ with $X=\pi^+\pi^-, K^+K^-, \pi^+\pi^-\pi^+\pi^-, K^+K^-K^+K^-$, ...