Exclusive diffractive results from CMS and TOTEM at the LHC

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On behalf of the CMS and TOTEM collaborations

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- Pion pair production
- $WW$ pair production
- Observation of exclusive $\mu\mu$ production in CT-PPS and prospects
What do we call Exclusive Diffraction / $\gamma$ exchange events?

- **Left diagram:** Double Pomeron Exchange: some energy is “lost” in Pomeron remnants
- **Next three diagrams:** Exclusive production: the full energy is used to produce dijets, vector mesons, no energy loss
  - Dijet production via gluon exchange, QCD process (KMR)
  - Photon exchange
  - Vector meson production
- **Possibility to reconstruct the properties of the object produced exclusively (via photon and gluon exchanges) from the tagged proton:** system completely constrained
- **Central exclusive production is a potential channel for BSM physics:** sensitivity to high masses up to 1.8 TeV
CMS results on exclusive pion production

- Exclusive pion production in CMS
- Soft Pomeron exchange is dominant at low mass: Photon exchange contribution is much suppressed
- Measurement can be performed in special runs at low luminosity: no pile up, high cross section
- Experimental signature: only two opposite tracks from the same primary vertex; no additional signal in calorimeter; $p_T(\pi) > 0.2 GeV$; $|y(\pi)| < 2$
- Background computed directly using data and same sign events (pure background sample)
CMS results on exclusive pion production

- Data compared to the predictions from DIME MC (DPE) and STARLIGHT MC (ρ contribution)
- Disagreement with theory especially in normalization as expected: MC does not contain proton dissociation events (ArXiv:1706.08310)
- $\sigma_{\pi^+\pi^-} = 26.5 \pm 0.3\,(stat) \pm 5.0\,(syst) \pm 1.1\,(lumi)\ \mu b$
CMS results on exclusive $WW$ production

- Look for $WW$ exclusive production
- Motivation: sensitive to $\gamma\gamma WW$ quartic anomalous couplings that could be a sign of new physics
- Quartic gauge anomalous $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings parametrised by $a_W^0, a_Z^0, a_C^W, a_C^Z$

\[
\mathcal{L}_6^0 \sim -\frac{e^2}{8} \frac{a_W^0}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W^{-\alpha} - \frac{e^2}{16 \cos^2(\theta_W)} \frac{a_Z^0}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^\alpha Z_\alpha
\]

\[
\mathcal{L}_6^C \sim -\frac{e^2}{16} \frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F_{\mu\beta} (W^{+\alpha} W^{-\beta} + W^{-\alpha} W^{+\beta})
- \frac{e^2}{16 \cos^2(\theta_W)} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F_{\mu\beta} Z^\alpha Z_\beta
\]

- Anomalous parameters equal to 0 for SM
One aside: what is pile up at LHC?

A collision with 2 protons and 2 photons

- Due to high number of protons in one packet, there can be more than one $pp$ interaction when the packets collide
- Typically up to 50 pile up events in Run II (about 25-30 now)
- Analyses at high luminosity because of lower production cross section (exclusive $WW, \gamma\gamma...$): need to fight pile up!
CMS results on exclusive $WW$ production

- **Exclusive $WW$** are rare (SM cross section of the order of 97 fb$^{-1}$ → full luminosity needed and reject pile up background

- **2011** $pp$ data at 7 TeV: 5.05 fb$^{-1}$

- **2012** $pp$ data at 8 TeV: 19.7 fb$^{-1}$

- **Exclusive selection:** opposite sign $e\mu$ from common primary vertex, no extra track from vertex, $M_{e\mu} > 20$ GeV to avoid low mass resonances, $p_T^{e\mu} > 30$ GeV to remove Drell Yan and $\gamma \rightarrow \tau\tau$

- $\sigma(pp \rightarrow pWWp \rightarrow p\mu ep) = 2.2^{+3.3}_{-2.0}$ fb at 7 TeV (SM 4.0 ± 0.7 fb) and $\sigma(pp \rightarrow pWWp \rightarrow p\mu ep) = 10.8^{+5.1}_{-4.1}$ fb at 8 TeV (SM: 6.2 ± 0.5 fb) after correction for proton dissociation

- **Observed significance for 7 and 8 TeV combination:** 3.4 $\sigma$
CMS results on exclusive $WW$ production

- Most stringent limits on $\gamma\gamma WW$ quartic anomalous coupling
- JHEP08 (2016) 119
What is CT-PPS?

- Tag and measure protons at ±210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All anomalous coupling cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Sensitivity to high mass central system, X, as determined using AFP/CT-PPS: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements
What is CT-PPS?

- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795
- LHC magnets bend scattered protons out of the beam envelope
- Detect scattered protons a few mm from the beam (both sides of CMS)
- First data taking in 2016: ~ 15 fb$^{-1}$
Exclusive $\mu\mu$ production in CT-PPS

- Turn the LHC into a $\gamma\gamma$ collider: flux of quasi-real photons under the Equivalent Photon Approximation, dilepton production dominated by photon exchange processes
- Observation of exclusive dimuon production in CT-PPS
- First time a near-beam detector operates at a hadron collider at high luminosity
- Request only one proton tagged ($< 1$ event expected for double tagged events due to acceptance)
- Data-driven background estimate
- **Step 1 - Absolute alignment**: Use elastic $pp \rightarrow pp$ events in a special alignment run where both horizontal and vertical roman pots get very close to the beam.

- **Step 2 - Relative alignment**: Use inclusive sample of protons triggered by CMS in standard runs and match distribution of proton track position to that of alignment runs.
Observation of semi-exclusive dimuon production in CT-PPS: Strategy

- In order to select exclusive events: Look for correlation between direct proton $\xi$ measurement using CT-PPS and using the dimuon system in CMS:

$$\xi^\pm = \frac{1}{\sqrt{s}}(p_T^{\mu_1} e^{\pm \eta_1} + p_T^{\mu_2} e^{\pm \eta_2})$$

($\pm \eta$ solutions correspond to the protons in the $+z$ and $-z$ direction)

- Expected backgrounds:

![Drell-Yan](image1.png) ![Double dissociation](image2.png) + pileup proton

will fake signal (overlap with pile up or beam halo protons)
**Event selection**

- Request pair of opposite sign muons with $p_T > 50$ GeV and $M_{\mu\mu} > 110$ GeV above the $Z$ boson peak

- **To suppress background:** Veto additional tracks around dimuon vertex (within 0.5 mm) and require back-to-back muons $|1 - \Delta \Phi/\pi| < 0.009$
**Data driven background estimate**

- Use sample of background protons from $Z$-peak events (data)

- **Drell-Yan contribution:** Count number of $Z$-peak events with $\xi(\mu\mu)$ and $\xi$(proton) correlated within $2\sigma$ and use MC to extrapolate from $Z$-peak region to signal region

- **Double dissociative contribution:** Mix double dissociative simulated events (LPAIR) and protons from data to derive number of matching events

- **Total number of expected matching background events:** $1.47 \pm 0.06$ (stat) $\pm 0.52$ (syst)
**Observed signal**

- First measurement of semi-exclusive di-muon process with proton tag
- CT-PPS works as expected (validates alignment, optics determination...)
- 17 events are found with protons in the CT-PPS acceptance and 12 \(< 2\sigma\) matching
- Significance for observing 12 events for a background of \(1.47 \pm 0.06\text{(stat)} \pm 0.52\text{(syst)}\): 4.3 \(\sigma\)
Summary of 12 candidates properties

- Dimuon invariant mass vs rapidity distributions in the range expected for single arm acceptance
- No event at higher mass that would be in the acceptance for double tagging
- Highest mass event: 341 GeV
- CMS-PAS-PPS-17-001
Additional photon exchange processes: diphoton production

- SM QCD production dominates at low $m_{\gamma\gamma}$, QED at high $m_{\gamma\gamma}$
- Important to consider $W$ loops at high $m_{\gamma\gamma}$
- At high masses ($> 300$ GeV), the photon induced processes are dominant
- **Conclusion:** Two photons and two tagged protons means photon-induced process
Search for quartic $\gamma\gamma$ anomalous couplings in AFP/CT-PPS

- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- No background after cuts for 300 fb$^{-1}$
Search for quartic $\gamma\gamma$ anomalous couplings

<table>
<thead>
<tr>
<th>Cut / Process</th>
<th>Signal (full)</th>
<th>Signal with (without) f.f (EFT)</th>
<th>Excl.</th>
<th>DPE</th>
<th>DY, di-jet + pile up</th>
<th>$\gamma\gamma$ + pile up</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[0.015 &lt; \xi_{1,2} &lt; 0.15, \not{p}<em>T</em>{1,2} &gt; 200, (100) \text{ GeV}]$</td>
<td>130.8</td>
<td>36.9 (373.9)</td>
<td>0.25</td>
<td>0.2</td>
<td>1.6</td>
<td>2968</td>
</tr>
<tr>
<td>$m_{\gamma\gamma} &gt; 600 \text{ GeV}$</td>
<td>128.3</td>
<td>34.9 (371.6)</td>
<td>0.20</td>
<td>0</td>
<td>0.2</td>
<td>1023</td>
</tr>
<tr>
<td>$[pT_2/pT_1 &gt; 0.95,</td>
<td>\Delta\phi</td>
<td>&gt; \pi - 0.01]$</td>
<td>128.3</td>
<td>34.9 (371.4)</td>
<td>0.19</td>
<td>0</td>
</tr>
<tr>
<td>$\sqrt{\xi_1 \xi_2} = m_{\gamma\gamma} \pm 3%$</td>
<td>122.0</td>
<td>32.9 (350.2)</td>
<td>0.18</td>
<td>0</td>
<td>0</td>
<td>2.8</td>
</tr>
<tr>
<td>$</td>
<td>y_{\gamma\gamma} - y_{pp}</td>
<td>&lt; 0.03$</td>
<td>119.1</td>
<td>31.8 (338.5)</td>
<td>0.18</td>
<td>0</td>
</tr>
</tbody>
</table>

- Exclusivity cuts needed to reject background
- Exclusivity cuts using proton tagging needed to suppress backgrounds (Without exclusivity cuts using CT-PPS: background of 80.2 for 300 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Luminosity</th>
<th>300 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pile-up ($\mu$)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>coupling (GeV$^{-4}$)</td>
<td>$\geq 1$ conv. $\gamma$ 5 $\sigma$</td>
<td>$\geq 1$ conv. $\gamma$ 95% CL</td>
<td>all $\gamma$ 95% CL</td>
<td>all $\gamma$ 95% CL</td>
</tr>
<tr>
<td>$\zeta_1$ f.f.</td>
<td>$8 \cdot 10^{-14}$</td>
<td>$5 \cdot 10^{-14}$</td>
<td>$3 \cdot 10^{-14}$</td>
<td>$2.5 \cdot 10^{-14}$</td>
</tr>
<tr>
<td>$\zeta_1$ no f.f.</td>
<td>$2.5 \cdot 10^{-14}$</td>
<td>$1.5 \cdot 10^{-14}$</td>
<td>$9 \cdot 10^{-15}$</td>
<td>$7 \cdot 10^{-15}$</td>
</tr>
<tr>
<td>$\zeta_2$ f.f.</td>
<td>$2 \cdot 10^{-13}$</td>
<td>$1 \cdot 10^{-13}$</td>
<td>$6 \cdot 10^{-14}$</td>
<td>$4.5 \cdot 10^{-14}$</td>
</tr>
<tr>
<td>$\zeta_2$ no f.f.</td>
<td>$5 \cdot 10^{-14}$</td>
<td>$4 \cdot 10^{-14}$</td>
<td>$2 \cdot 10^{-14}$</td>
<td>$1.5 \cdot 10^{-14}$</td>
</tr>
</tbody>
</table>

- Reaches the values predicted by extra-dim or composite Higgs models
Background of about 3.1 events for 300 fb$^{-1}$, and about 25 events of signal for a coupling of $4 \times 10^{-13}$ GeV$^{-4}$.

Reach better by three orders of magnitude with respect to standard methods at the LHC: Looking at Z boson decay into 3 photons.

Conclusion

• Many complementary results concerning exclusive diffraction at the LHC from CMS and TOTEM (CT-PPS) either using the “rapidity gap” technique or the proton tags

• CMS exclusive pion production: disagreement with theoretical expectations probably due to the fact that proton dissociation is not included in models

• Best limits on $\gamma\gamma WW$ anomalous couplings in CMS

• Exclusive di-muon production: First observation of high-mass exclusive dimuon production:. 17 events are found with protons in the CT-PPS acceptance and 12 with $< 2\sigma$ matching, which leads to a significance for observing 12 events for a background of $1.47 \pm 0.06^{(stat)} \pm 0.52^{(syst)}$ of 4.3 $\sigma$

• $\gamma\gamma\gamma\gamma$ couplings: Nice prospects for AFP and CT-PPS, highest possible sensitivities to $\gamma\gamma\gamma\gamma, \gamma\gamma WW, \gamma\gamma ZZ, \gamma\gamma\gamma Z$ anomalous couplings due to new resonances, extra-dim. or composite Higgs...