Exclusive diffractive results from ATLAS, CMS, LHCb, TOTEM at the LHC

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- LHCb results on vector meson production
- ATLAS results (dimuon, diphoton)
- CMS and CMS/TOTEM (dimuon, WW, pion) 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
Measurement of central exclusive production in LHCb

- Measurement of exclusive production of $J/\Psi$ vector meson as an example: Sensitivity to gluon distribution in Pomeron
- **Signal:** Central system with rapidity gaps
- **Background:** Diffractive processes (pomeron remnants not detected, outside detector acceptance)
- **Experimental issue:** Detection of rapidity gaps
- **New detectors in Run II:** HERSCHEL, High Rapidity Shower Counters for LHCb that allow a better suppression of diffractive processes (detection of Pomeron remnants)
pseudorapidity coverage of HeRSCheL: $-10.0 < \eta < -3.5 \quad 5.0 < \eta < 10.0$

pseudorapidity coverage of LHCb (Run 2): $-10.0 < \eta < -1.5 \quad 2.0 < \eta < 10.0$
Event selection and results at 13 TeV

- Veto on forward tracks
- Further cleanup by veto on HERSCHEL signal significance
LHCb results on exclusive $J/\Psi$ and $\Psi(2S)$

- Uncertainties highly correlated between bins
- Preferred model: JMRT NLO (JHEP 11 (2013) 085)
LHCb results on exclusive $J/\Psi$ and $\Psi(2S)$ cross sections

relation between ep (1 amplitude) and pp (2 amplitudes) scattering

$$\frac{d\sigma}{dy_{pp\rightarrow p\nu p}} = r(y) \left[ k_+ \frac{dn}{dk_+} \sigma_{\gamma p\rightarrow \nu p}(W_+) + k_- \frac{dn}{dk_-} \sigma_{\gamma p\rightarrow \nu p}(W_-) \right]$$

$r(y)$: gap survival, $k_\pm$: photon energy, $dn/dk_\pm$: photon flux $W_\pm$: $\gamma p$ mass

- Measure the cross section, get $\sigma(W^-)$ from HERA $\rightarrow$ extract $\sigma(W^+)$ (and vice versa at 7 TeV)
- Kinematic range extended at 13 TeV
- A simple power law does not lead to a good description
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 ($\rho$ contribution)
- Disagreement with theory especially in normalization as expected: MC does not contain proton dissociation events (ArXiv:1706.08310)
- $\sigma_{\pi^+\pi^-} = 26.5 \pm 0.3 (\text{stat}) \pm 5.0 (\text{syst}) \pm 1.1 (\text{lumi}) \, \mu b$
ATLAS/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 two 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!

can be faked by one collision with 2 photons and protons from different collisions
ATLAS/CMS results on exclusive $WW$ production

- Exclusive $WW$ are rare (SM cross section of the order of $96.7 \text{ fb}^{-1}$) → full luminosity needed and reject pile up background
- CMS: 2011 at 7 TeV: $5.05 \text{ fb}^{-1}$; 2012 at 8 TeV: $19.7 \text{ fb}^{-1}$; ATLAS: $20.2 \text{ fb}^{-1}$
- 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 $\gamma \rightarrow \tau\tau$
- CMS: $\sigma(pp \rightarrow pWWp \rightarrow p\mu ep) = 2.2^{+3.3}_{-2.0}$ fb at 7 TeV (SM $4.0 \pm 0.7$ fb) $\sigma(pp \rightarrow pWWp \rightarrow p\mu ep) = 10.8^{+5.1}_{-4.1}$ fb at 8 TeV (SM: $6.2 \pm 0.5$ fb) after correction for proton dissociation, ATLAS $\sigma = 6.9 \pm 2.2(\text{stat}) \pm 1.4(\text{syst})$ fb (SM: $4.4 \pm 0.3$ fb)
- Observed significance for 7 and 8 TeV combination: $3.4 \sigma$ (CMS), $3.0 \sigma$ (ATLAS)
ATLAS/CMS results on exclusive $WW$ production

• Most stringent limits on $\gamma\gamma WW$ quartic anomalous coupling

<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>$a_0^W/\Lambda^2$ ($\Lambda_{\text{cutoff}} = 500$ 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>$a_C^W/\Lambda^2$ ($\Lambda_{\text{cutoff}} = 500$ 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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<tr>
<th>Coupling</th>
<th>$\Lambda_{\text{cutoff}}$</th>
<th>Observed allowed range [GeV$^{-2}$]</th>
<th>Expected allowed range [GeV$^{-2}$]</th>
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<tr>
<td>$a_0^W/\Lambda^2$</td>
<td>500 GeV</td>
<td>$[-0.96 \times 10^{-4}, 0.93 \times 10^{-4}]$</td>
<td>$[-0.90 \times 10^{-4}, 0.87 \times 10^{-4}]$</td>
</tr>
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<td>$a_C^W/\Lambda^2$</td>
<td>500 GeV</td>
<td>$[-3.5 \times 10^{-4}, 3.3 \times 10^{-4}]$</td>
<td>$[-3.3 \times 10^{-4}, 3.1 \times 10^{-4}]$</td>
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<td>$a_0^W/\Lambda^2$</td>
<td>$\infty$</td>
<td>$[-1.7 \times 10^{-6}, 1.7 \times 10^{-6}]$</td>
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**What is AFP/CT-PPS?**

- Tag and measure protons at ±210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All photon-induced cross sections involving anomalous couplings 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 on both sides of CMS: 2016, first data taking (≈ 15 fb⁻¹)
Exclusive $\mu\mu$ production in ATLAS and 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
- ATLAS: rapidity gap selection: Exclusivity selection in presence of pile up vertices ($\mu \sim 13$): Require 0 additional track within 1 mm of $\mu^+\mu^-$ vertex, the challenge being to control the dissociative background, somewhat irreducible
- ATLAS: Fight Drell-Yan and other backgrounds by comparing data and MC background around the $Z$ mass
- CT-PPS: Tag one of the two protons
• Fiducial cross section for $p_T^\mu > 6$ GeV ($12 < m_{\mu\mu} < 30$ GeV); $p_T^\mu > 10$ GeV ($30 < m_{\mu\mu} < 70$ GeV) and corrected for detector inefficiency

• Cross section extracted using binned maximum likelihood fit of $N_{\text{excl}}$, $N_{s\text{-diss}}$: $\sigma_{\gamma\gamma\rightarrow\mu\mu}^{\text{excl., fid}} = 3.12 \pm 0.07(\text{stat}) \pm 0.10(\text{syst})$ pb
ATLAS results on exclusive dimuon production

- Cross section binned in dimuon mass and in dimuon mass divided by center-of-mass energy (ATLAS, ArXiv 1708.04503)
- Look for absorptive effects: Insufficient suppression in Superchic 2 (Khoze, Harland-Lang, Ryskin)
Observation of semi-exclusive dimuon production in CT-PPS

- Observation of semi-exclusive dimuon production in CT-PPS
- First time a near-beam detector operates at a hadron collider at high luminosity (single tag events), Request only one proton tagged (< 1 event expected for double tagged events due to acceptance)
- Main Background is Drell-Yan di-muon production with proton from pile-up event: Data-driven estimate based on sample of Drell-Yan $Z$ events, count number of $Z$ events with $\xi(\mu\mu)$ and $\xi(p)$ within $2\sigma$ and use MC to extrapolate from $Z$ peak to signal region
Observed signal (CT-PPS)

- 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 ($\sim 750$ GeV), the photon induced processes are dominant
- **Conclusion:** Two photons and two tagged protons means photon-induced process
Exclusive diphoton production in ATLAS

- Look for exclusive diphoton production in heavy ion $PbPb$ collisions
- Cross section enhanced by a factor $Z^4$
- In 480 $\mu$b$^{-1}$ of data at $\sqrt{s} = 5.02$ TeV, 13 events observed for $2.6 \pm 0.7$ background events
- For photon $E_T > 3$ GeV, $|\eta| < 2.4$, $M_{\gamma\gamma} > 6$ GeV, $p_T^{\gamma\gamma} < 2$ GeV: $\sigma = 70 \pm 24(stat) \pm 17(syst)$ nb in agreement with SM
- Nature Physics 13 (2017) 852
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$^{-1}$
Conclusion

• Many complementary results concerning exclusive diffraction at the LHC from the different experiments: either using the “rapidity gap” technique or the proton tags

• LHCb: $J/\Psi$ and $\Psi(2S)$ production: preferred model JMRT NLO

• 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: Complementary measurements between CMS-TOTEM and ATLAS (first observation of high-mass exclusive dimuon production)

• $\gamma\gamma\gamma\gamma$ couplings: Observation by ATLAS in heavy ion mode and 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...
Example of ATLAS selection:

1 mm Vertex exclusivity, $p_T^{\mu^+\mu^-} < 1.5$ GeV requirement

Data with typical pileup $\mu \sim 13$. Data-driven $78 \pm 1\%$ veto efficiency.

$p_T$ cut - further single dissociative suppression.