Exclusive diffraction at the LHC

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- Exclusive pion, $J/\Psi$, $\Psi(2S)$ production
- Exclusive dilepton production (with/without proton tagging)
- Exclusive $\gamma\gamma$ and $WW$ productions
- Prospects: ALPs, anomalous coupling studies
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 (Khoze Martin Ryskin)
  - Photon exchange
- 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 larger than 2 TeV
Measurement of central exclusive production in LHCb

- Measurement of central exclusive production of $J/\Psi$ and $\Psi(2S)$ vector mesons at 13 TeV: 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)
The HERSCHEL detector - LHCb

pseudorapidity coverage of HeRSChel: $-10.0 < \eta < -3.5$  $5.0 < \eta < 10.0$
pseudorapidity coverage of LHCb (Run 2): $-10.0 < \eta < -1.5$  $2.0 < \eta < 10.0$
$J/\psi$ and $\psi(2S)$ production at 13 TeV

- Event selection requires 2 muons within $2 < \eta < 4.5$ and veto on additional forward track and energy
- for 204 pb$^{-1}$ in 2015: 14753 $J/\psi$ and 440 $\psi(2S)$
- Further cleanup by veto on HERSCHEL signal significance: purity of $0.755 \pm 0.015$ for $J/\psi$ and $0.726 \pm 0.061$ for $\psi(2S)$
LHCb results on exclusive $J/\psi$ and $\Psi(2S)$

- Uncertainties highly correlated between bins
- Preferred model: JMRT NLO (JHEP 11 (2013) 085)
- $\sigma(J/\psi \rightarrow \mu^+\mu^-)(2 < \eta < 4.5) = 435 \pm 18 \pm 11 \pm 17$ pb,
  $\sigma(\Psi(2S) \rightarrow \mu^+\mu^-)(2 < \eta < 4.5) = 11.1 \pm 1.1 \pm 0.3 \pm 0.4$ pb (JHEP 1810 (2018) 167)
LHCb results on exclusive $J/\Psi$ and $\Psi(2S)$ cross sections

Measure the cross section, get $\sigma(W^-)$ from HERA $\rightarrow$ extract $\sigma(W^+)$ (and vice versa at 13 TeV)

A simple power law does not lead to a good description

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

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

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

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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 (at 13 and 5.02 TeV): no pile up, high cross section
- Experimental signature: only two opposite tracks from the same primary vertex; no additional signal in calorimeter; $p_T(\pi) > 0.2\,\text{GeV}; |y(\pi)| < 2.4$
- Background computed directly using data and same sign events (pure background sample)
Data compared to the predictions from DIME MC (DPE) and STARLIGHT MC (\(\rho\))

Disagreement with theory especially in missing resonances and in normalization as expected: MC does not contain proton dissociation events (ArXiv:1706.08310)

\[
\sigma_{\pi^+\pi^-}(13\text{ TeV}) = 19.0 \pm 0.6(\text{stat}) \pm 3.2(\text{syst}) \pm 0.01(\text{lumi}) \, \mu b;
\]

\[
\sigma_{\pi^+\pi^-}(5.02\text{ TeV}) = 19.6 \pm 0.4(\text{stat}) \pm 3.3(\text{syst}) \pm 0.01(\text{lumi}) \, \mu b
\]
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, $M_{e\mu} > 20 \text{ GeV}$ to avoid low mass resonances, $p_T^{e\mu} > 30 \text{ GeV}$ to remove Drell Yan and $\gamma \rightarrow \tau\tau$
ATLAS/CMS results on exclusive $WW$ production

- CMS: $\sigma(pp \rightarrow pWWp \rightarrow p\mu\nu p) = 2.2^{+3.3}_{-2.0}$ fb at 7 TeV (SM $4.0 \pm 0.7$ fb)
  $\sigma(pp \rightarrow pWWp \rightarrow p\mu\nu p) = 10.8^{+5.1}_{-4.1}$ fb at 8 TeV (SM: $6.2 \pm 0.5$ fb) after correction for proton dissociation, ATLAS $\sigma = 6.9 \pm 2.2(stat) \pm 1.4(syst)$ 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>$7 \mathrm{TeV} \times 10^{-4} \mathrm{GeV}^{-2}$</th>
<th>$8 \mathrm{TeV} \times 10^{-4} \mathrm{GeV}^{-2}$</th>
<th>$7+8 \mathrm{TeV} \times 10^{-4} \mathrm{GeV}^{-2}$</th>
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<tbody>
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<td>$a_W^0/\Lambda^2$ ($\Lambda_{\text{cutoff}} = 500 \mathrm{GeV}$)</td>
<td>$-1.5 &lt; a_W^0/\Lambda^2 &lt; 1.5$</td>
<td>$-1.1 &lt; a_W^0/\Lambda^2 &lt; 1.0$</td>
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<td>$a_W^2/\Lambda^2$ ($\Lambda_{\text{cutoff}} = 500 \mathrm{GeV}$)</td>
<td>$-5 &lt; a_W^2/\Lambda^2 &lt; 5$</td>
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Exclusive $\mu\mu$ production in ATLAS and in CMS-TOTEM

- 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
- CMS TOTEM-Precision Proton Spectrometer: Tag one of the two protons
**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)
- Dominant uncertainty from template fit to acoplanarity shape
- Results compatible with SM expectation (taking into account ~20 % of proton dissociation)
Proton detectors in CMS-TOTEM/ATLAS-AFP: Running at high luminosity

- Tag and measure protons at ±210 m CMS-TOTEM Precision Proton Spectrometer (PPS), ATLAS Forward Proton (AFP)
- Detectors: measure proton position (3D pixel or strip Silicon detectors) and time-of-flight (Ultrafast Si, diamond detectors)
- About 110 fb$^{-1}$ of data have been accumulated
- Many analyses in progress
Good acceptance at high mass

Roman pots inserted routinely in every store without issues
Request pair of opposite sign muons or electrons with $p_T > 50$ GeV and $M_{ll} > 110$ GeV above the $Z$ boson peak.

To suppress background: Veto additional tracks around dimuon/dielectron vertex (within 0.5 mm) and require back-to-back muons/electrons $|1 - \Delta \Phi/\pi| < 0.006$ for electrons (0.009 for muons).
Observed signal

- First measurement of semi-exclusive dilepton process with proton tag
- PPS works as expected (validates alignment, optics determination...)
- 17 (res. 23) events are found with protons in the PPS acceptance and 12 (resp. 8) $< 2\sigma$ matching in the $\mu\mu$ (res. $ee$) channel
- Significance $> 5\sigma$ for observing 20 events for a background of 3.85
  $(1.49 \pm 0.07(stat) \pm 0.53(syst) \text{ for } \mu\mu \text{ and } 2.36 \pm 0.09(stat) \pm 0.47(syst) \text{ for } ee)$
Search for extra dimensions in the universe using $\gamma$ induced processes

- Additional channels: $WW$, $ZZ$, $\gamma Z$, dilepton production ($\gamma \gamma$ described in more detail as an example)

- Search for production of two photons and two intact protons in the final state: $pp \rightarrow p\gamma\gamma p$

- Possible larger number of events than expected in SM due to extra-dimensions, composite Higgs models, dark matter particles

- Anomalous couplings can appear via loops of new particles coupling to photons or via resonances decaying into two photons
Removing pile up at the LHC

- **Negligible background** after matching invariant mass and rapidity of diphoton system to prediction from protons (S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert. JHEP 1502 (2015) 165)

- Use fast timing detectors in the case of $WW$ production and $W$s decaying leptonically.

Exclusive diffraction at the LHC
Sensitivity to anomalous couplings at medium and high lumi LHC

- With 300 fb$^{-1}$ (Run III), gain of sensitivity by more than 2 orders of magnitude with respect to "usual" LHC sensitivity (similar for $\gamma Z$, $ZZ$ and $WW$)
- Run 4 (HL-LHC): Assuming similar proton acceptance as in Run 3, sensitivity further increased by about one order of magnitude with $\sim 3000$ fb$^{-1}$ (CERN-LPCC-2018-03)
- For exclusive diphoton production, timing detectors are not crucial
Application of exclusive $\gamma\gamma$: Looking for Axion Like Particles (ALPs)

- **ALPs decaying into two $\gamma$s**

- Same analysis: two photons and two intact protons: sensitivity improved by 2 (resp. 3) orders of magnitude with 300 (resp. 3000) fb$^{-1}$ (C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, JHEP 1806 (2018) 131)

- Searching for high mass ALPs coupling to $\gamma$ without PPS: Difficult to perform, usually combines couplings to gluons, quarks, leptons, $\gamma$
Look for exclusive diphoton production in heavy ion \( \text{PbPb} \) collisions

Cross section enhanced by a factor \( Z^4 \)

In 480 \( \mu b^{-1} \) of data in 2015 at \( \sqrt{s} = 5.02 \) TeV, 13 events observed for 2.6 ± 0.7 background events

More data in 2018: 1.7 \( \text{nb}^{-1} \): 59 events (background of 12±3)

For photon \( E_T > 3 \text{ GeV}, |\eta| < 2.37, \quad M_{\gamma\gamma} > 6 \text{ GeV}, \quad p_T^{\gamma\gamma} < 2 \text{ GeV}: \quad \sigma = 78 \pm 13(\text{stat}) \pm 8(\text{syst}) \text{ nb in agreement with SM (49 ± 5 nb)}

• Production of ALPs via photon exchanges in heavy ion runs: Complementarity to $pp$ running

• Sensitivity to low mass ALPs: low luminosity but cross section increased by $Z^4$, C. Baldenegro, S. Hassani, C.R., L. Schoeffel, ArXiv:1903.04151

• Similar gain of three orders of magnitude on sensitivity for $\gamma\gamma Z$ couplings in $pp$ collisions: C. Baldenegro, S. Fichet, G. von Gersdorff, C. R., JHEP 1706 (2017) 142
Many complementary results concerning exclusive diffraction at the LHC from the different experiments: either using “rapidity gap” technique or 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...
- **More details about anomalous couplings, ALPs... in Justin’s talk**
Summary of 20 candidates properties

- Dimuon invariant mass vs rapidity distributions in the range expected for single arm acceptance
- No event at higher mass that are double tagged: The two dielectron events in the acceptance region are compatible with pile up contamination (2.36 events expected)
- Highest mass event: 917 GeV
SM exclusive diphoton production negligible at high diphoton mass

- $\gamma$ selection: High $p_T$ photon ($>150$ GeV), back-to-back, high mass di-photon (above 500 GeV)

- Proton selection: in the acceptance of the forward proton detectors (mass above 400 GeV)

- Only background remaining after cuts: pile up