Contents

- Proton tagging at the LHC
- Pomeron structure
- BFKL resummation effects
- Beyond standard model: Anomalous coupling
What is the CMS-TOTEM Precision Proton Spectrometer (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)
- Similar detectors: ATLAS Forward Proton (AFP)
Detecting intact protons in ATLAS/CMS-TOTEM at the LHC

- Tag and measure protons at ±210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)
- All diffractive cross sections computed using the Forward Physics Monte Carlo (FPMC)
- Complementarity between low and high mass diffraction (high and low cross sections): special runs at low luminosity (no pile up) and standard luminosity runs with pile up
**Diffraction at LHC: kinematical variables**

- $t$: 4-momentum transfer squared
- $\xi_1, \xi_2$: proton fractional momentum loss (momentum fraction of the proton carried by the pomeron)
- $\beta_{1,2} = x_{Bj,1,2}/\xi_{1,2}$: Bjorken-$x$ of parton inside the pomeron
- $M^2 = s\xi_1\xi_2$: diffractive mass produced
- $\Delta y_{1,2} \sim \Delta \eta \sim \log 1/\xi_{1,2}$: rapidity gap
Hard diffraction at the LHC

- Understanding better the structure of the exchanged colorless object, the Pomeron
- Dijet production: dominated by $gg$ exchanges
- $\gamma +$ jet production: dominated by $qg$ exchanges
- Jet gap jet in diffraction: Probe proton structure at high gluon densities
Inclusive diffraction at the LHC: sensitivity to gluon density

- Predict DPE dijet cross section at the LHC in PPS acceptance, jets with $p_T > 20$ GeV, reconstructed at particle level using anti-$k_T$ algorithm

- Sensitivity to gluon density in Pomeron especially the gluon density on Pomeron at high $\beta$: multiply the gluon density by $(1 - \beta)^\nu$ with $\nu = -1, ..., 1$

- Measurement possible with $10 \text{ pb}^{-1}$, allows to test if gluon density is similar between different accelerators (HERA and LHC) (universality of Pomeron model)

- Dijet mass fraction: dijet mass divided by total diffractive mass ($\sqrt{\xi_1 \xi_2 S}$)

Inclusive diffraction at the LHC: sensitivity to quark densities

- Predict DPE $\gamma+\text{jet}$ divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to quark density in Pomeron, and of assumption: $u = d = s = \bar{u} = \bar{d} = \bar{s}$ used in QCD fits at HERA
- Measurement of $W$ asymmetry also sensitive to quark densities
Looking for low $x$ resummation effects

- Dokshitzer Gribov Lipatov Altarelli Parisi (DGLAP): Evolution in $Q^2$
- Balitski Fadin Kuraev Lipatov (BFKL): Evolution in $x$

**Aim:** Understanding the proton structure (quarks, gluons)

$Q^2$: resolution inside the proton (like a microscope)

$X$: Proton momentum fraction carried away by the interacting quark
Jet gap jet events in diffraction

- Study BFKL dynamics using jet gap jet events in DPE
Search for $\gamma\gamma WW$, $\gamma\gamma\gamma\gamma$ quartic anomalous coupling

- Study of the process: $pp \rightarrow ppWW$, $pp \rightarrow ppZZ$, $pp \rightarrow pp\gamma\gamma$
- Standard Model: $\sigma_{WW} = 95.6 \text{ fb}$, $\sigma_{WW}(W = M_X > 1 \text{ TeV}) = 5.9 \text{ fb}$
- Process sensitive to anomalous couplings: $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
**γγ exclusive production: SM contribution**

- QCD production dominates at low $m_{γγ}$, QED at high $m_{γγ}$
- Important to consider $W$ loops at high $m_{γγ}$
- At high masses (> 200 GeV), the photon induced processes are dominant
- **Conclusion:** Two photons and two tagged protons means photon-induced process
Motivations to look for quartic $\gamma\gamma$ anomalous couplings

- Two effective operators at low energies

$$\mathcal{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

- $\gamma\gamma\gamma\gamma$ couplings can be modified in a model independent way by loops of heavy charged particles $\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$ where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$ depends on the spin of the particle. This leads to $\zeta_1$ of the order of $10^{-14}$-$10^{-13}$
Motivations to look for quartic $\gamma\gamma$ anomalous couplings

Two effective operators at low energies

$$\mathcal{L}_{A\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}$$

$\zeta_1$ can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon) $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where $f_s$ is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle; for instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$
Search for quartic $\gamma\gamma$ anomalous couplings

- Search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...
- Anomalous coupling events appear at high di-photon masses
Search for quartic $\gamma\gamma$ anomalous couplings

- No background after cuts for 300 fb$^{-1}$: sensitivity up to a few $10^{-15}$, better by 2 orders of magnitude with respect to “standard” methods
- Exclusivity cuts using proton tagging needed to suppress backgrounds

<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>$</td>
<td>0.015 &lt; \xi_{1,2} &lt; 0.15, \text{PT}_{1,2} &gt; 200, (100) \text{ GeV}</td>
<td>$</td>
<td>65</td>
<td>18 (187)</td>
<td>0.13</td>
<td>0.2</td>
</tr>
<tr>
<td>$m_{\gamma\gamma} &gt; 600 \text{ GeV}$</td>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
<td>0.2</td>
<td>1023</td>
</tr>
<tr>
<td>$</td>
<td>\text{PT}<em>{2}/\text{PT}</em>{1} &gt; 0.95,</td>
<td>\Delta \phi &gt; \pi - 0.01$</td>
<td>64</td>
<td>17 (186)</td>
<td>0.10</td>
<td>0</td>
</tr>
<tr>
<td>$\sqrt{\xi_1 \xi_2 \xi_3} = m_{\gamma\gamma} \pm 3%$</td>
<td>61</td>
<td>16 (175)</td>
<td>0.09</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>60</td>
<td>12 (169)</td>
<td>0.09</td>
<td>0</td>
</tr>
</tbody>
</table>

Forward Physics with proton tagging at the LHC
Look for $Z\gamma$ anomalous production

$Z$ can decay leptonically or hadronically: the fact that we can control the background using the mass/rapidity matching technique allows us to look in both channels (very small background)

Best expected reach at the LHC by about three orders of magnitude

Forward Physics with proton tagging at the LHC
Anomalous couplings studies in $WW$ events

- Reach on anomalous couplings studied using a full simulation of the ATLAS detector, including all pile-up effects; only leptonic decays of $W$s are considered
- Signal appears at high lepton $p_T$ and dilepton mass (central ATLAS) and high diffractive mass (reconstructed using forward detectors)
- Cut on the number of tracks fitted to the primary vertex: very efficient to remove remaining pile-up after requesting a high mass object to be produced (for signal, we have two leptons coming from the $W$ decays and nothing else)
Effective anomalous couplings correspond to loops of charged particles, Reaches the values expected for extradim models (C. Grojean, J. Wells)

<table>
<thead>
<tr>
<th>Cuts</th>
<th>Top</th>
<th>Dibosons</th>
<th>Drell-Yan</th>
<th>W/Z+jet</th>
<th>Diff.</th>
<th>$\alpha_0^W / \Lambda^2 = 5 \cdot 10^{-6}$ GeV $^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>timing &lt; 10 ps</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{lep1} &gt; 150$ GeV</td>
<td>5198</td>
<td>601</td>
<td>20093</td>
<td>1820</td>
<td>190</td>
<td>282</td>
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<tr>
<td>$p_T^{lep2} &gt; 20$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M(ll) &gt; 300$ GeV</td>
<td>1650</td>
<td>176</td>
<td>2512</td>
<td>7.7</td>
<td>176</td>
<td>248</td>
</tr>
<tr>
<td>nTracks ≤ 3</td>
<td>2.8</td>
<td>2.1</td>
<td>78</td>
<td>0</td>
<td>51</td>
<td>71</td>
</tr>
<tr>
<td>$\Delta \phi &lt; 3.1$</td>
<td>2.5</td>
<td>1.7</td>
<td>29</td>
<td>0</td>
<td>2.5</td>
<td>56</td>
</tr>
<tr>
<td>$m_\gamma &gt; 800$ GeV</td>
<td>0.6</td>
<td>0.4</td>
<td>7.3</td>
<td>0</td>
<td>1.1</td>
<td>50</td>
</tr>
<tr>
<td>$p_T^{lep1} &gt; 300$ GeV</td>
<td>0</td>
<td>0.2</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 9.5. Number of expected signal and background events for 300 fb$^{-1}$ at pile-up $\mu = 46$. A time resolution of 10 ps has been assumed for background rejection. The diffractive background comprises production of QED diboson, QED dilepton, diffractive WW, double pomeron exchange WW.

Improvement of “standard” LHC methods by studying $pp \rightarrow l^\pm \nu \gamma \gamma$ (see P. J. Bell, ArXiV:0907.5299) by more than 2 orders of magnitude with 40/300 fb$^{-1}$ at LHC (Reach up to $1.3 \times 10^{-6}$)
Conclusion

- Better understanding of diffraction in QCD (pomeron structure) and also BFKL resummation at low $x$
- $\gamma\gamma\gamma, \gamma\gamma ZZ, \gamma\gamma WW, \gamma\gamma\gamma Z$ anomalous coupling studies
  - photon-induced processes $pp \rightarrow p\gamma\gamma p$ (gluon exchanges suppressed at high masses):
  - Theoretical calculation in good control (QED processes with intact protons), not sensitive to the photon structure function
  - "Background-free" experiment and any observed event is signal
  - NB: Survival probability in better control than in the QCD (gluon) case
- CT-PPS/AFP allows to probe BSM diphoton production in a model independent way: sensitivities to values predicted by extradim or composite Higgs models
- See talk by Cristian about ALPs
Workshop on Forward Physics and QCD at the LHC, EIC and cosmic ray physics

- Workshop on Forward Physics and Instrumentation: from Colliders to Cosmic Rays: Guanajuato, Mexico, November 18-21 2019
- Discuss aspects of forward physics, saturation in $pp$, $pA$, $AA$ collisions at LHC, EIC, and links with cosmic ray physics
- Web page: https://indico.cern.ch/event/823693/
Search for axion like particles

- Production of ALPs via photon exchanges and tagging the intact protons in the final state complementary to the usual search at the LHC ($Z$ decays into 3 photons): sensitivity at high ALP mass, C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, ArXiv 1803.10835, JHEP 1806 (2018) 131; See talk by C. Baldenegro

- Complementarity with Pb Pb running: sensitivity to low mass diphoton, low luminosity but cross section increased by $Z^4$
Search for axion like particles: complementarity with heavy ion runs

- Production of ALPs via photon exchanges in heavy ion runs: Complementarity to $pp$ running
- Similar gain of three orders of magnitude on sensitivity for $\gamma\gamma\gamma Z$ couplings in $pp$ collisions: C. Baldenegro, S. Fichet, G. von Gersдорff, C. R., JHEP 1706 (2017) 142