First observation of diffraction in proton-lead collisions at the LHC with the CMS detector

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Abstract. We present the first measurements of diffraction processes in proton-lead collisions at LHC with CMS at $\sqrt{s_{NN}} = 8.16$ TeV. The very large angular coverage of CMS is used to tag rapidity gaps in the forward regions on both the proton-going and lead-going sides to identify both pomeron-lead and pomeron-proton topologies. The present data provide essentially unique information for understanding the high energy limit of QCD and modeling cosmic ray air showers since the previous measurement of these processes was done at energy almost 300 times lower ($\sqrt{s_{NN}} = 30$ GeV). The results are compared to predictions from the EPOS-LHC, QGSJET II and HIJING event generators.

1. Introduction
For high energy particle collisions, the exchange of objects with vacuum quantum numbers, named pomerons ($\mathbb{P}$) [1,2], is responsible for the diffraction and contains a large fraction of events at the LHC [3–7]. Diffractive scattering is deeply connected to the fundamental nature of QCD [8–13].

Pomerons can participate in elastic, diffractive and non-diffractive processes. The diffractive processes are characterized at the final state by large gaps in the rapidity distributions, often measured from the very forward region of the detector.

The hadronic diffractive processes in hadron-nuclear collisions may involve specific effects due to Gribov inelastic screening contributions [14] which are not included in the Glauber approach. Diffraction in hadron-nuclear collisions is also relevant for cosmic-ray physics [15].

In this talk, the first measurement of diffractive proton-nucleus cross sections at the LHC is presented. The measurement [16] was done with the CMS detector with forward rapidity gap studies at $\sqrt{s_{NN}} = 8.16$ TeV. The previous measurements of the forward rapidity gap cross-section were done by the ATLAS [3] and CMS [4] collaborations for the proton-proton collisions at center-of-mass energy of 7 TeV and by HELIOS [17] collaboration for proton-nuclear collision at p-N center-of-mass energy of about 30 GeV.

2. Analysis and results
The measurement of diffractive pPb collisions was performed with the CMS detector [18] at $\sqrt{s_{NN}} = 8.16$ TeV with 6.4 $\mu$b$^{-1}$ of data collected in 2016 [16]. The results were compared to the EPOS-LHC [19], HIJING v2.1 [20] and QGSJET II-04 [21] event generators.

The performed analysis is based on the detection of a large forward rapidity gap (FRG, $\Delta\eta^F$) from the proton or lead ion side.
The difference in the flux of coherent quasi-real photons for the lead ion side compared to the proton side leads to a significant contribution of electromagnetic $\gamma p$ processes to the sample of events with a large gap on the lead ion side [22–26].

Figure 1 shows Feynman diagrams and schematic topologies of single diffractive pomeron-lead (IPPb) and pomeron-proton (IPp) processes for pPb collisions.

![Feynman diagrams and topologies](image)

**Figure 1.** Feynman diagrams (top) and topologies (bottom) of pPb events with large rapidity gaps for IPPb (a) and IPp or $\gamma p$ (b). The blue (a) and red (b) cones indicate the products of diffractive dissociation for the lead ion and proton respectively. The regions free of final state particles, $\Delta \eta^F$, are marked with green arrows. It is possible for $\gamma p$ interactions to mimic the topology on the left but these are much suppressed compared to the $\gamma p$ case.

For this analysis, FRG is calculated from $|\eta| = 3.0$ and the phase space within $|\eta| = 3.0$ is divided into 12 bins. The detector-level FRG distribution is shown on figure 2 with the EPOS-LHC and HIJING predictions for the IPPb (left) and IPp (right) topologies. On the bottom plots the ratios of EPOS-LHC and HIJING predictions to data are shown.

For both topologies spectra fall at the first two bins and flatten after $\Delta \eta^F = 2.0$, which may be explained by the dominance of non-diffractive events for the low $\Delta \eta^F$. For the IPp topology the difference between data and MC predictions is caused by a significant contribution of $\gamma p$ events, while for the IPPb topology predictions for EPOS-LHC and HIJING are much closer to data.

To obtain the $\frac{d\sigma}{d\Delta \eta^F}$ distribution with increased sensitivity to diffraction events by extending the rapidity gap size to asymmetric proton-lead cases (called hereafter “diffraction enhanced distribution”) on the figure 3, every bin for the detector-level $\frac{d\sigma}{d\Delta \eta^F}$ distribution was reweighted to the probability to have no signal in $3.15 < |\eta| < 5.2$ region and unfolded to hadron level using EPOS-LHC response matrices.

The statistical and systematic uncertainties for the data are added in quadrature. In figure 3 the full uncertainty is shown as yellow band, and the full uncertainty excluding the error introduced with the correction for the undetectable energy in region $3.15 < |\eta| < 5.2$ is shown as gray band. The obtained FRG distribution is compared with EPOS-LHC, HIJING and QGSJET II predictions.

For the IPPb topology the shape of the FRG distribution for HIJING differs from the data while the EPOS-LHC and QGSJET II predictions have a shape similar to the CMS results.
Figure 2. Top: the detector-level $\frac{d\sigma}{d\Delta \eta^F}$ distribution for the CMS data [16] (black) with the predictions of the EPOS-LHC [19] (blue) and HIJING [20] (green) event generators. The distributions are shown for the IPp (a) and IPp (b) topologies. Bottom: ratio between generator predictions and CMS data.

However, the EPOS-LHC and QGSJET II prediction is two and four times lower than data, respectively. The difference between data and generator predictions for the IPp topology is suggestive of the large $\gamma p$ contribution to the selected events.

On the figure 3, the hadron level “diffraction enhanced” predictions from EPOS-LHC and QGSJET II are split into non-diffractive, single, central and double diffractive events. Both the EPOS-LHC and QGSJET II predictions show that for the “diffraction enhanced” $\frac{d\sigma}{d\Delta \eta^F}$ distribution the diffractive events become dominant after $\Delta \eta^F = 1.0$.

3. Summary

For the first time, the forward rapidity gap cross-section spectra $\frac{d\sigma}{d\Delta \eta^F}$ for proton-lead collisions at the LHC were measured with the CMS detector at the energy $\sqrt{s_{NN}} = 8.16$ TeV for the IPp and IPp topologies. For the IPp topologies the shape of EPOS-LHC and QGSJET II distributions is similar to data, but the predicted cross-section is two and four times lower than data, respectively. HIJING predicts significantly lower distributions for the large $\Delta \eta^F$. For the IPp topology the data distribution is significantly higher than event generator predictions, which suggests a large contribution of $\gamma p$ events that are not incorporated in the used generators.
Figure 3. Top: the hadron-level $\frac{d\sigma}{d\Delta\eta}$ distribution with increased sensitivity to diffraction events for the CMS data [16] (black) with the predictions of the EPOS-LHC [19] (blue), HIJING [20] (green) and QGSJET II [21] (red) event generators. The distributions are shown for the $\text{PbPb}$ (a) and $\text{Pp}$ (b) topologies. Bottom: ratio between generator predictions and CMS data.
**Figure 4.** The hadron-level $\frac{d\sigma}{d\Delta \eta^F}$ distribution with increased sensitivity to diffraction events for the EPOS-LHC [19] (top) and QGSJET II [21] (bottom) generators, broken down to non-diffractive (red), single (magenta), central (green) and double (yellow) diffractive events compared to CMS data [16] (black).
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