First measurement of the forward rapidity gap distribution in proton-lead collisions at LHC energy $\sqrt{s_{\mathrm{NN}}} = 8.16\ \mathrm{TeV}$ with the CMS experiment

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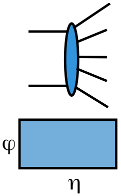
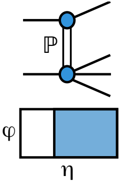
Physics relevance

Physics processes:



Non-Diffraction

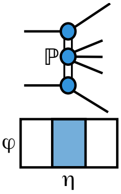


Single Diffraction

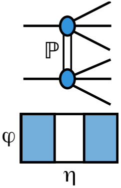
- Diffractive collisions – inelastic collisions with no quantum numbers are exchanged between colliding particles
- Characterized: by a Rapidity Gap, which is caused by t-channel pomeron(s) exchange.

- Most important problems of QCD which can be studied with diffraction:
  - Nature of the pomeron ($\mathbb{P}$) in QCD
  - Small-x problem and "saturation" of parton densities
- Cross sections of inelastic diffractive processes are very sensitive to nonlinear saturation effects, which get more important for scattering off nuclei.
- Diffraction of hadrons on nuclear targets at very high energies is also relevant for cosmic-ray physics.
- The latest measurements on diffraction in pA were done by HELIOS with $\sqrt{s} = 27$ GeV Z. Phys. C 49 (1991) 355

Physics processes:



Central Diffraction



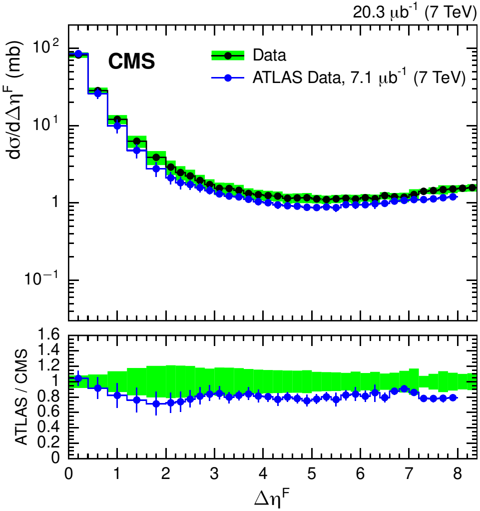
Double Diffraction

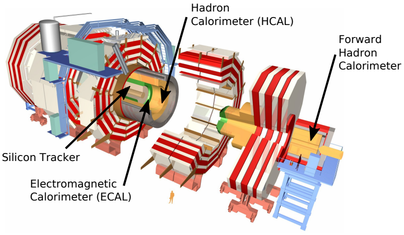
- Rapidity Gap ($\Delta\eta$) - the rapidity regions free of final state particles
- Forward Rapidity Gap (FRG, $\Delta\eta^{\mathrm{F}}$) distribution is one of the most inclusive way to study diffraction
- Until now only pp diffraction at LHC is observed
- FRG was studied with pp collisions data by ATLAS EPJC 72 (2012) 1926, CMS PRD 92 (2015) 012003

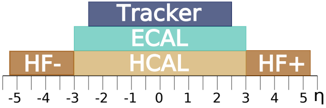
Analysis

CMS collaboration, "First measurement of the forward rapidity gap distribution in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV" CMS-PAS-HIN-18-019

PRD 92 (2015) 012003







CMS pseudorapidity coverage

- Silicon tracker: $|\eta| < 2.5$
- ECAL and HCAL: $|\eta| < 3.0$
- Forward Hadron Calorimeter (HF): $3.0 < |\eta| < 5.2$
- Zero Degree Calorimeter (ZDC): $|\eta| > 8.5$

Triggers

- Minimum Bias (MB): Requires the presence of proton and lead beams and an energy of HF Tower higher then approximately 7 GeV in either of the HF calorimeters
- Zero Bias (ZB): Requires the presence of proton and lead beams in the CMS detector
- Analysis was done on MB and ZB was used for the cross section corrections

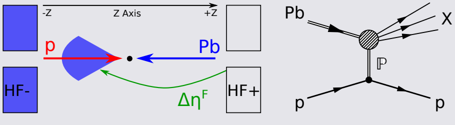
HF Towers

- HF has fine segmentation in η and ϕ into 432 HF Towers

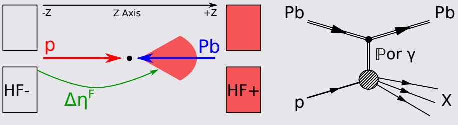
Data and event topologies

Data: CMS, pPb $\sqrt{s_{NN}} = 8.16$ TeV, $6.4\ \mu b^{-1}$ (2016)

Event topologies of interest



Lead dissociation



Proton dissociation

- The photon flux from the Pb is enhanced by a factor of Z^2_{Pb} compared to that of protons

Compared to MC event generators

HIJING v2.1

- hard parton scatterings: perturbative QCD
- soft interactions: string excitations

EPOS-LHC:

- Gribov-Regge theory for the parton interactions; Gluon saturation — phenomenological implementation

QGSJET II-04 (generator level only):

- Gribov-Regge theory for the parton interactions; Gluon saturation via higher order pomeron-pomeron interactions

The generators do not include photon exchange processes

Selection of events with Forward Rapidity Gaps (FRG)

Offline selection:

- At least one HF tower with energy at least 10 GeV
- Events with 0 or 1 vertex.

Definition of Rapidity Gap

- At least one HF tower with energy at least 10 GeV in HF opposite to FRG
- In bins of 0.5 in η
- For $|\eta| < 2.5$:
  - No track with $p_T > 200$ MeV
  - Total energy of all PF candidates less then 6 GeV
- For $2.5 \leq |\eta| < 3.0$:
  - Total energy of all PF hadronic candidates less then 13.4 GeV

Correction to total inelastic cross section

Zero Bias data used to normalize to cros section of events with at least one track with $p_T > 200$ MeV and eny energy in opposite HF

FRG cross section at *detector level* for $|\eta| < 3.0$

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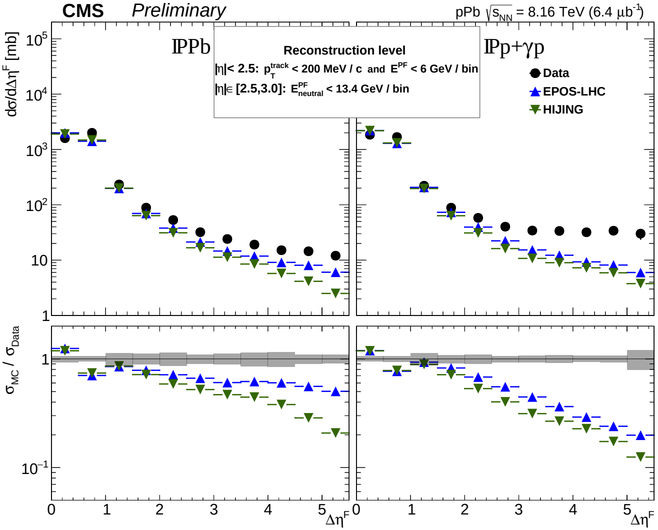

The Monte Carlo spectra are normalized to the total visible cross section of the data.

- For both topologies (IPPb and IPp) the spectra fall by a factor of over 50 between $\Delta\eta^F = 0$ and $\Delta\eta^F = 2$
- For $\Delta\eta^F > 2$ the spectra flatten off for both topologies
- The predictions of EPOS-LHC are closer to the data than those of HIJING
- For the IPp MC predictions are significantly below the data in the region $\Delta\eta^F > 2$ due to γp events

FRG cross section at detector level for $|\eta| < 3.0$ predicted by EPOS-LHC

Stacked distributions:

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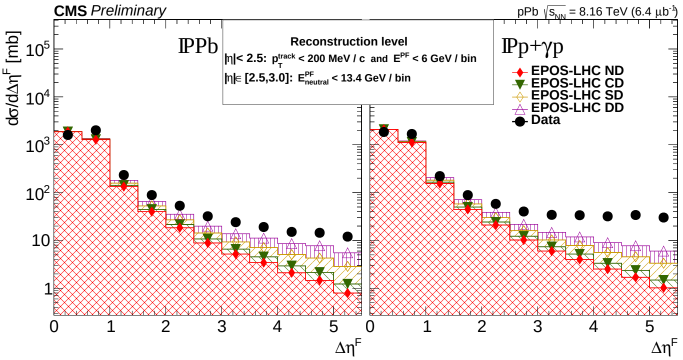
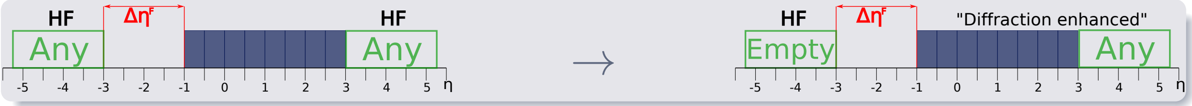


- Non-diffractive processes dominate at $\Delta\eta^F < 3.0$
- Extending the FRG acceptance would allow to be more sensitive to the diffractive processes

- ND: Non-Diffractive
- CD: Central Diffractive
- SD: Single Diffractive
- DD: Double Diffractive

"Diffraction enhanced" subsample: extending over HF region adjacent to FRG



To extend FRG over the HF region ($3.0 < |\eta| < 5.2$):

- Data: weighting the original $d\sigma/d\Delta\eta^F$ spectra by the probability for the corresponding HF calorimeter having no signal
- MC: No detectable particles within the HF acceptance

Weighting procedure

- We want to find the fraction of events without energy deposition at HF
- We normalize maximal the HF tower energy distribution of non-colliding bunch events to the low-energy part at the same distribution for the data with selected FRG
- This we do for each FRG bin separately on the ZeroBias data

Unfolding to hadron level

Hadron level

All our corrections correspond to following hadron level definition:

- Inelastic collision events
- FRG in the central region (**the same as detector level**):
  - In bins of 0.5 in η
  - For $|\eta| < 2.5$:
    - ★ No charged particles with $p_T > 200$ MeV
    - ★ The total energy of all particles should not exceed 6 GeV
  - For $2.5 \leq |\eta| < 3.0$:
    - ★ The total energy of neutral hadrons should not exceed 13.4 GeV
- No detectable particles at the HF acceptance on the side of FRG

Hadron-level FRG cross section at diffractive enhanced subsample for $|\eta| < 3.0$

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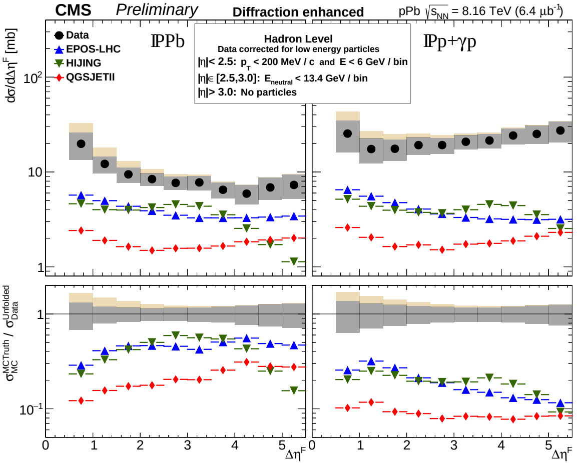


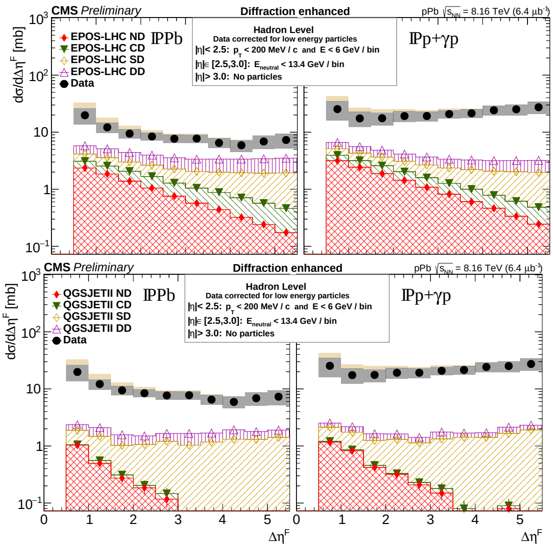
Those generators do not include photon exchange processes.

The Monte Carlo spectra are normalized to the total visible cross section of the data.

- For the IPPb topology case, (γ-exchange contribution should be negligible), predictions of EPOS-LHC is about a factor of 2 and QGSJET II a factor of 4 are below the data
- However for both of those generators the shape of the $\frac{d\sigma}{d\Delta\eta^F}$ spectrum is similar to that of the data
- The rapidity spectrum from the HIJING generator falls at large $\Delta\eta^F$ in contradiction to the data

- For the IPp case all the generators are more than a factor of 5 below the data
- This suggests a very strong contribution from γp events which is not yet implemented in the considered event generators

The contribution from different processes as predicted by EPOS-LHC and QGSJET II



Stacked distributions:

- ND: Non-Diffractive
- CD: Central Diffractive
- SD: Single Diffractive
- DD: Double Diffractive

- Transition to diffractive enhanced sample suppressed contribution of non-diffractive processes.
- The considered event generators do not fully describe the data.

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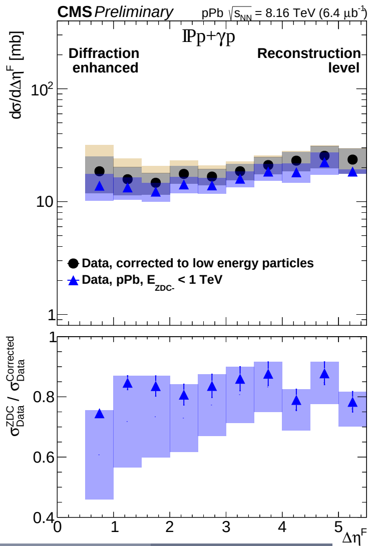
Zero Degree Calorimeter

- ZDC calorimeters are located 140 m away from the CMS interaction point
- Consist of tungsten absorber and quartz fibers
- Allows to exclude events with neutrons produced due to a lead break-up ($\mathbb{P}p$ topology only)

ZDC veto requirement

- Events with intact lead selected by requiring ZDC energy on lead-going side below 1 TeV



The fraction of events with intact lead is independent of the FRG size

Summary

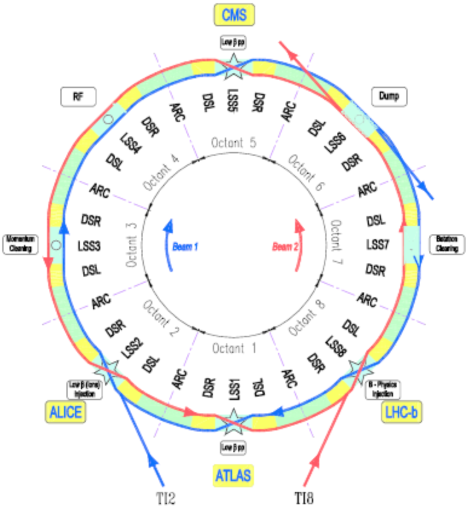
Summary

- Forward rapidity gap distribution $\frac{d\sigma}{d\Delta\eta^F}$ from proton-lead collisions at the LHC ($\sqrt{s_{NN}} = 8.16$ TeV) have been measured for the first time for both pomeron-lead and pomeron-proton topologies
- For the $\mathbb{P}$Pb topology case, where the γ-exchange contribution should be negligible:
  - Predictions of EPOS-LHC are about a factor of 2 and QGSJET II a factor of 4 below the data
  - However for both of those generators the shape of the $\frac{d\sigma}{d\Delta\eta^F}$ spectrum is similar to that of the data
  - The rapidity spectrum from the HIJING generator falls at large $\Delta\eta^F$ contrary to the data
- For the $\mathbb{P}$p case:
  - The cross section of EPOS-LHC and QGSJET II are lower than data by more than a factor of 5
  - This suggests a very strong contribution from γp events which is not yet implemented in the considered event generators
  - The fraction of $\mathbb{P}$p events with intact lead is independent of the FRG size
- These data may be of significant help in modeling ultrahigh-energy cosmic ray air showers

Thank you for attention!

Backup slides

LHC beams and collision modes

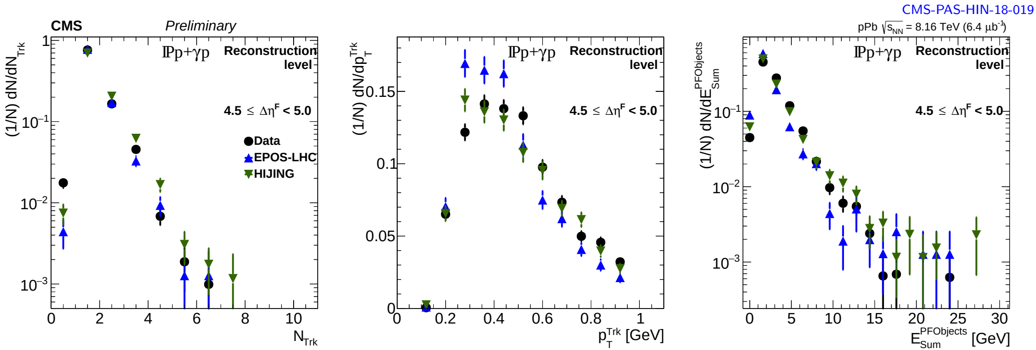


LHC beams

- Beam 1 circulates clockwise
- Beam 2 goes counter-clockwise

Collision modes

- During data taking beam direction was reversed.
- Pbp: beam 1 — protons, beam 2 — lead ions
- pPb: beam 1 — lead ions, beam 2 — protons



- To test the appropriateness of using these generators for the unfolding, distribution of:
  - Number of tracks,
  - p_T distribution of tracks
  - Sum of energy of all PF candidates

  in a bin was studied
- For each $\Delta\eta^F$ bin, the distributions are in a good agreement.