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

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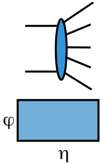
The talk is based on recent preliminary CMS results:

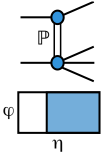
CMS collaboration,
First measurement of the forward rapidity gap distribution in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

CMS-PAS-HIN-18-019, CERN, June 2020

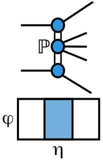
Types of processes:



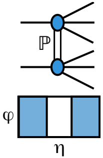
Non-Diffractive



Single Diffraction



Central Diffraction

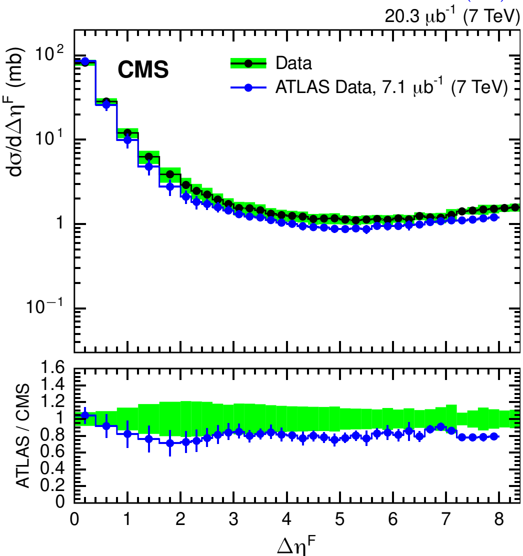


Double Diffraction

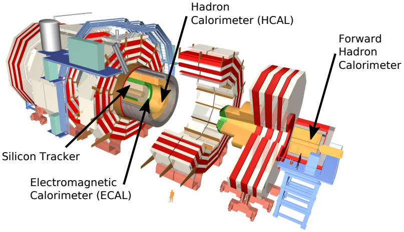
- Diffractive collisions are defined as special inelastic collisions in which no quantum numbers are exchanged between colliding particles
- A diffractive process is characterized by a Rapidity Gap, which is caused by t-channel pomeron(s) exchange.

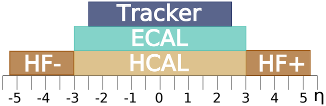
- Most important problems of QCD which can be studied with diffraction:
  - Nature of the pomeron in QCD
  - Small-x problem and "saturation" of parton densities
- Cross sections of inelastic diffractive processes are very sensitive to nonlinear saturation effects, which get more important for scattering 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 (1999) 355

PRD 92 (2015) 012003



- Rapidity Gap - the rapidity regions free of final state particles
- Forward Rapidity Gap (FRG) 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





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

Calorimetry + tracking = Particle Flow (PF) objects

Triggers

- Minimum Bias (MB): Requires the presence of proton and lead beams and an energy of HF Tower more 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 made on Minimum Bias and Zero Bias used for the cross section corrections

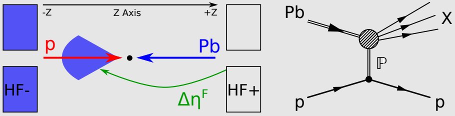
HF Towers

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

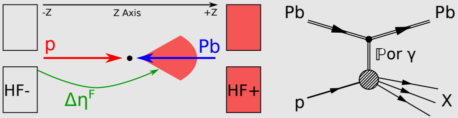
Data and event topologies

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

Event topologies of interest



Lead dissociation



Proton dissociation

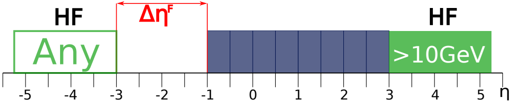
- The photon flux from the Pb is enhanced by a factor of Z^2_{Pb} compared to that of protons

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)



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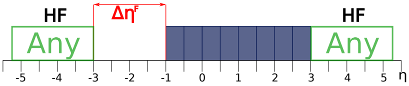

Data sample: Minimum Bias data.
Offline selection:

- 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 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
- At least one track with $p_T > 200$ MeV

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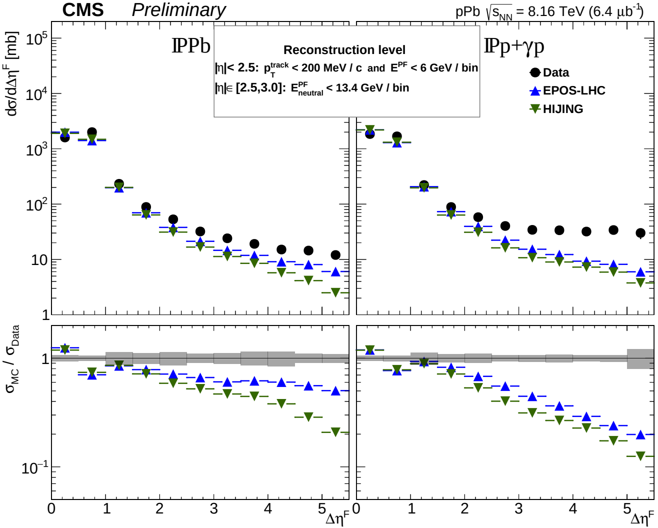
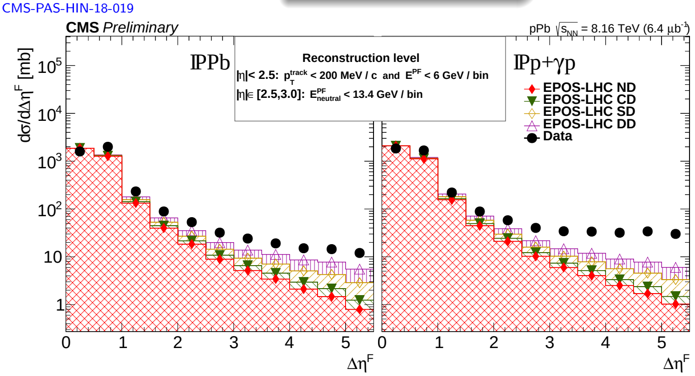


The Monte Carlo spectra are normalized to the total visible cross section of the data.

- 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

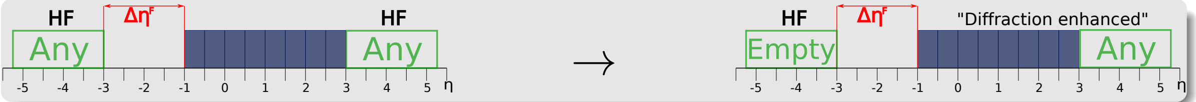
Contributions of different processes predicted by EPOS-LHC

Stacked distributions:



- 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



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 to have no signal
- MC: No detectable particles at the HF acceptance

Weighting procedure

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

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 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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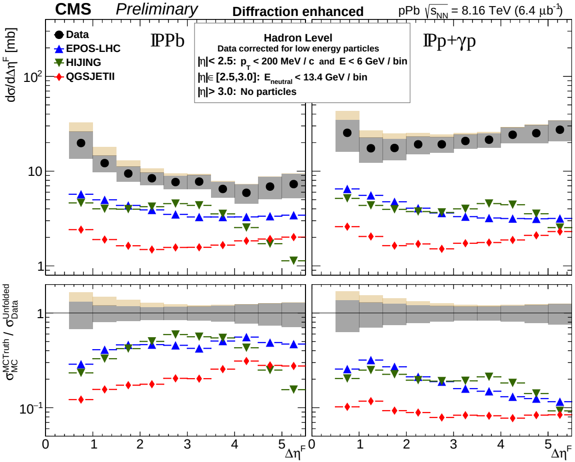

Those generators do not include photon exchange processes.

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

Stacked distributions:

EPOS-LHC

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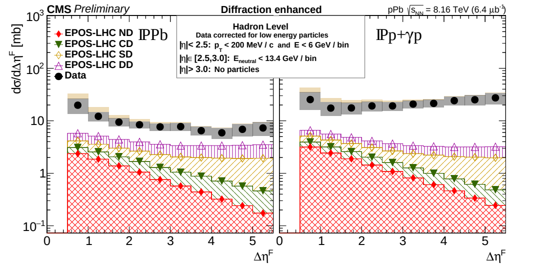

QGSJET II

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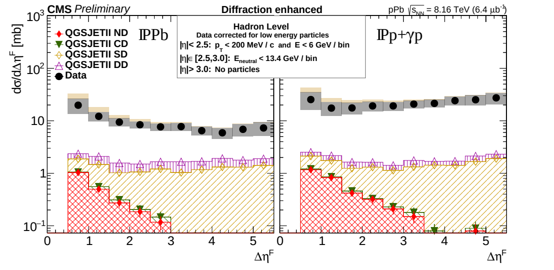


ND: Non-Diffractive CD: Central Diffractive SD: Single Diffractive DD: Double Diffractive

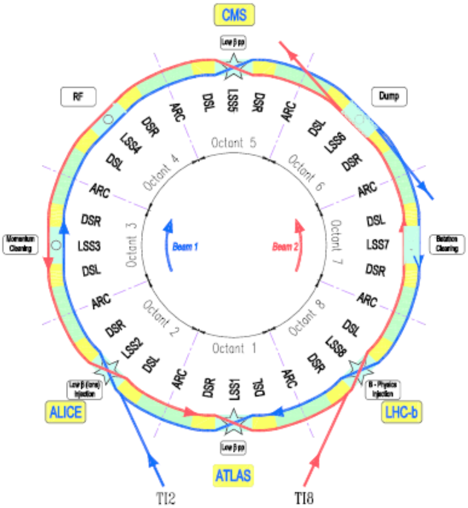
- Transition to diffractive enhanced sample suppressed contribution of non-diffractive processes.
- The considered event generators do not fully describe the data.

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 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 $\mathbb{P}$p case:
  - All used 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
- These data may be of significant help in modeling ultrahigh-energy cosmic ray air showers

Thank you!

Backup slides

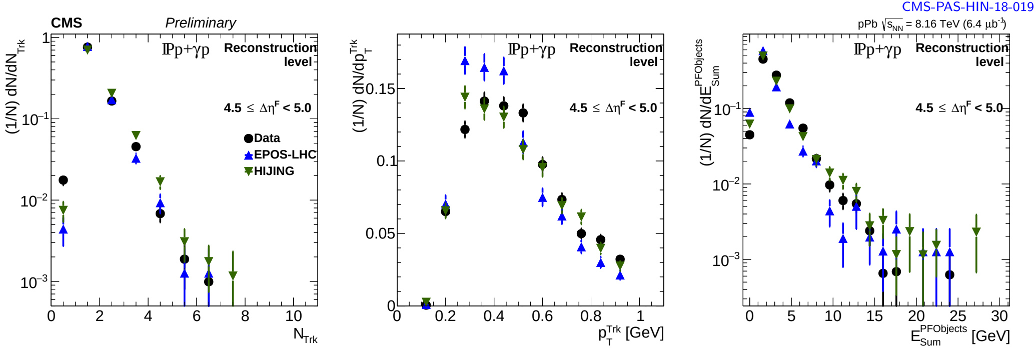


LHC beams

- 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.