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

Dmitry Sosnov

Petersburg Nuclear Physics Institute NRC KI, Gatchina, Russia

PNPI High Energy Physics Division seminar,
October 20, 2020

The talk is based on recent preliminary CMS results:

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

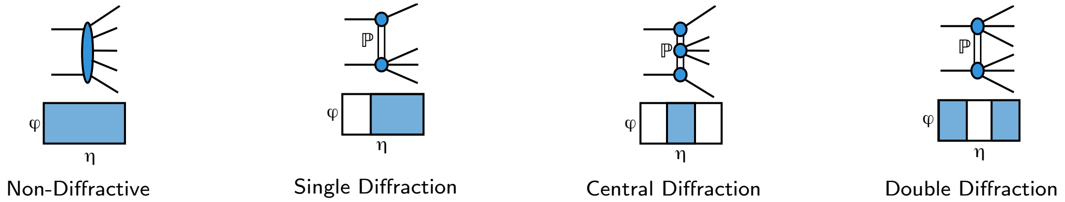
CMS-PAS-HIN-18-019, CERN, June 2020

And also on two talks, presented at:

- The 5th International Conference on Particle Physics and Astrophysics, Moscow, 07.10.2020
- LXX International Conference “NUCLEUS — 2020”, Saint Petersburg, 17.10.2020

Physics relevance

Types of processes:



- 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 (and also by t-channel γ-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
  - Color transparency
- Cross sections of inelastic diffractive processes are very sensitive to nonlinear saturation effects, especially for 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

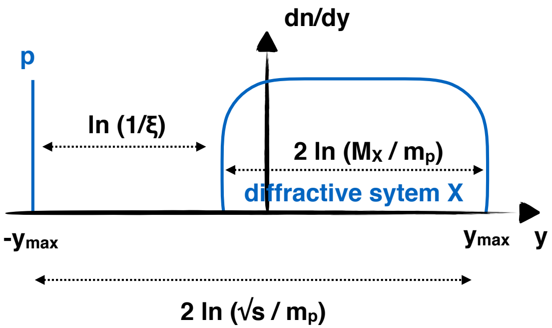
Rapidity Gap in diffractive process

For process $p + p \to h + X$

- $M_X = \sum_i m_i$; $\xi_X = \frac{M_X^2}{s} = 1 - \left(\frac{p_{z,cms}}{p_{z,cms}^{max}}\right)$
- Maximum Rapidity Gap size: $\Delta\eta \sim -ln(\xi_X)$

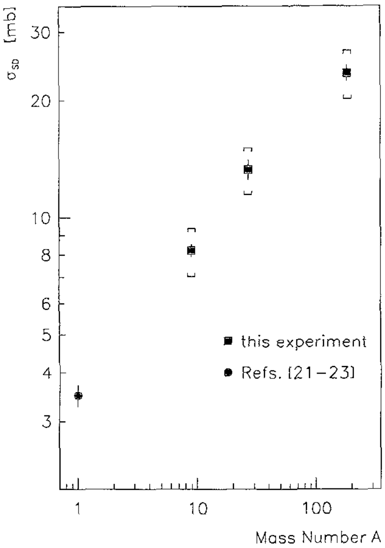
Maximum Rapidity Gap size

- For proton-proton collision at $\sqrt{s} = 13$ TeV:
  - $y_{max} = 9.5$
- For proton-lead collision at $\sqrt{s_{NN}} = 8$ TeV:
  - $y_{max,p} = 9.5$,
  - $y_{max,Pb} = 8.6$,



HELIOS results (Z. Phys. C 49 (1991) 355)

Z. Phys. C 49 (1991) 355

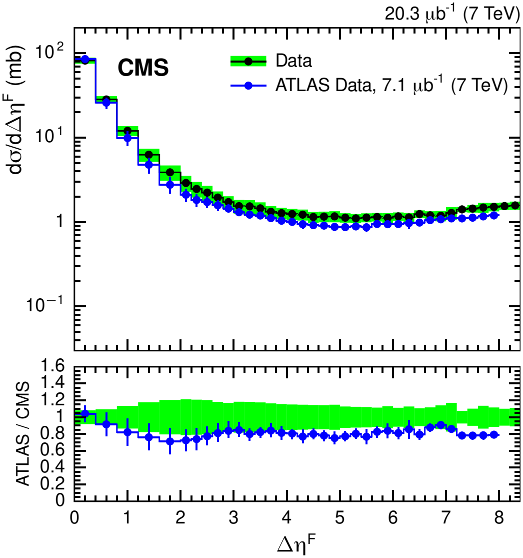


Main HELIOS results

- The cross-section of single diffraction is proportional to the nuclear radius, $\sigma_{SD} \sim A^{1/3}$
- This suggests that diffractive dissociation of nuclei is a peripheral process, predominantly involving nucleons on the rim of the nucleus.

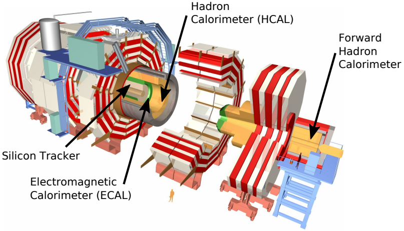
Prior measurements at the LHC in pp collisions

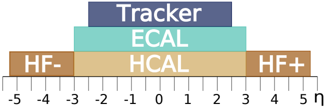
PRD 92 (2015) 012003



- 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

CMS Detector





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

- Zero Degree Calorimeter (ZDC): $|\eta| > 8.5$

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

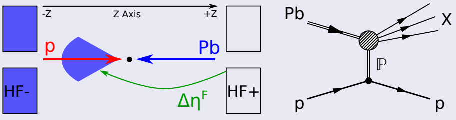
HF Towers

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

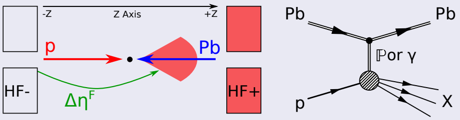
Data and event topologies

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

Event topologies of interest



Lead dissociation



Proton dissociation

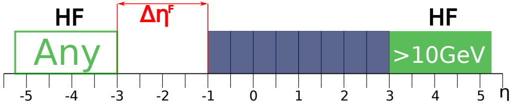
- The photon flux from the Pb is enhanced by a factor of Z^2_{Pb} compared to that of protons

Compared to MC event generators

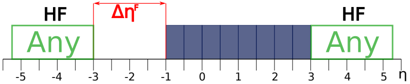
- HIJING v2.1
  - hard parton scatterings: perturbative QCD
  - soft interactions: string excitations
- EPOS-LHC: Gribov-Regge theory for the parton interactions; Gluon saturation — phenomenological implementation
- QGSJET II-04 (generator level only): Gribov-Regge theory for the parton interactions; Gluon saturation via higher order pomeron-pomeron interactions

The generators do not include photon exchange processes

Selection of events with Forward Rapidity Gaps (FRG)



→



Data sample: Minimum Bias data.
Offline selection:

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

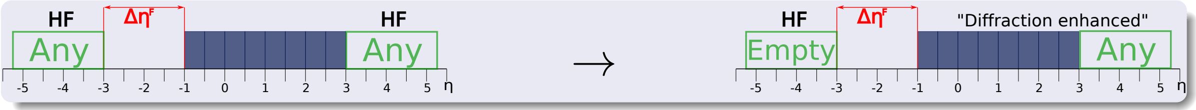
Definition of Rapidity Gap

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

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



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

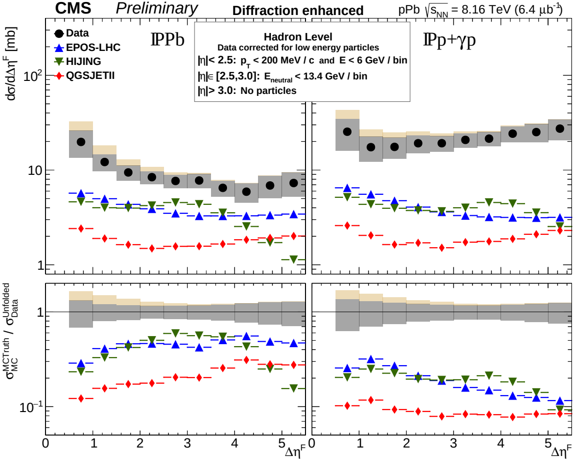
- Data: weighting the original $d\sigma/d\Delta\eta^F$ spectra by the probability for the corresponding HF calorimeter to have no signal
- MC: No detectable particles at the HF acceptance

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

CMS-PAS-HIN-18-019



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

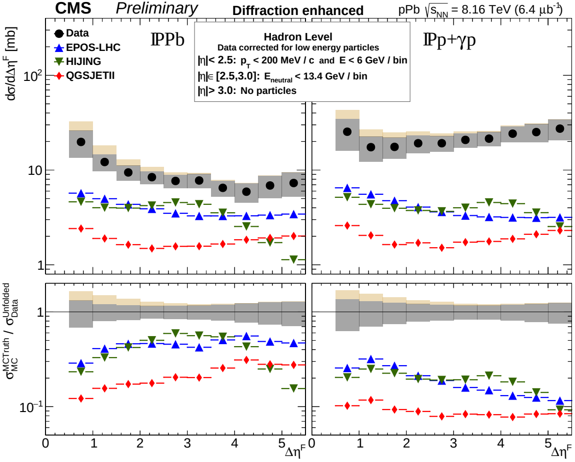
IPPb topology

- 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

Those generators do not include photon exchange processes.

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

CMS-PAS-HIN-18-019



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

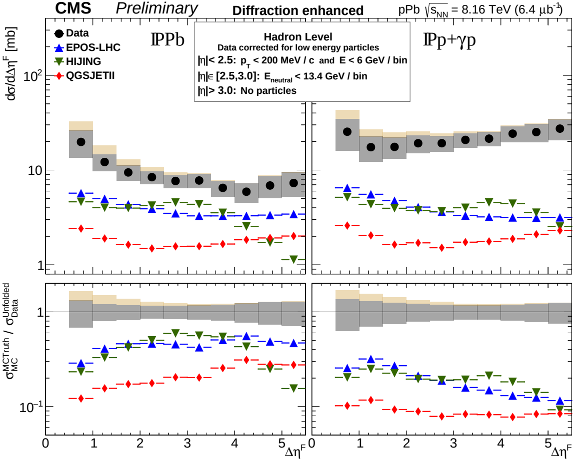
$\mathbb{P}$p topology

- For the $\mathbb{P}$p 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

Those generators do not include photon exchange processes.

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

CMS-PAS-HIN-18-019



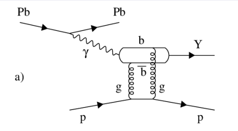
Those generators do not include photon exchange processes.

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

IPp topology

- 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

γp event example: exclusive vector meson production



Presented on QM19:

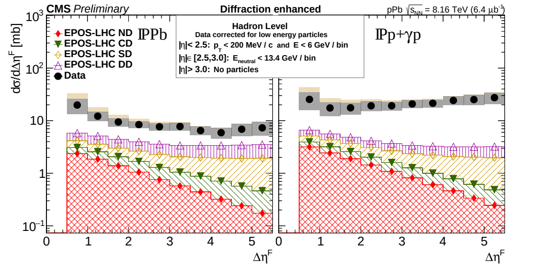
- Υ photoproduction
- $\rho(770)^0$ photoproduction

Contributions of different processes as predicted by EPOS-LHC and QGSJET II

Stacked distributions:

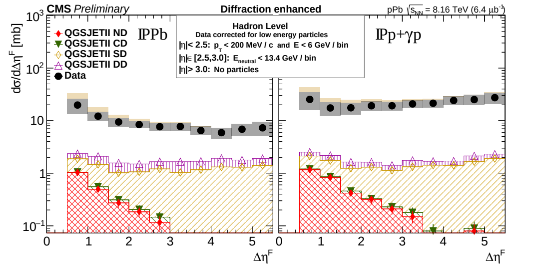
EPOS-LHC

CMS-PAS-HIN-18-019



QGSJET II

CMS-PAS-HIN-18-019



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.

Fraction of events with intact lead

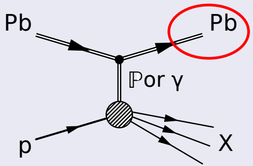
Zero Degree Calorimeter

- 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

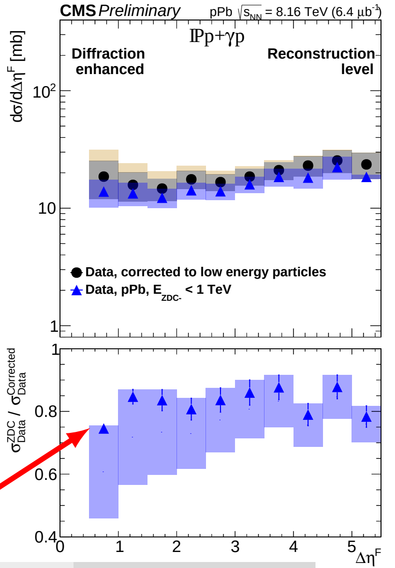
- Events with intact lead selected by requiring ZDC energy on lead-going side below 1 TeV

$\mathbb{P}$p topology



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

CMS-PAS-HIN-18-019



Summary

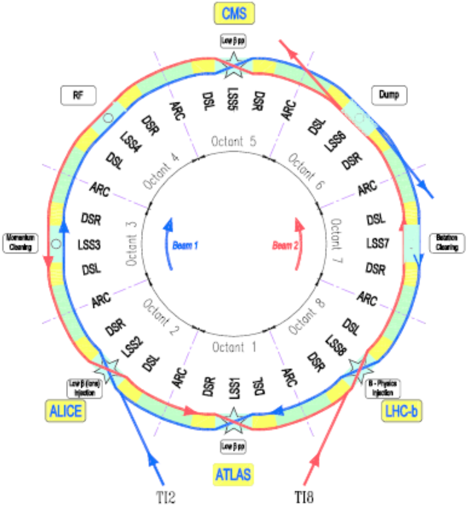
Summary

- 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 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
  - The fraction of 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!

Backup slides

LHC beams and collision modes



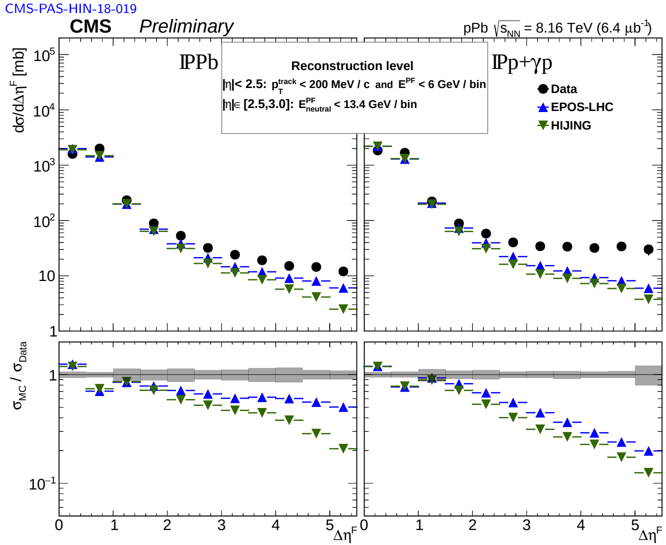
LHC beams

- 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

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



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

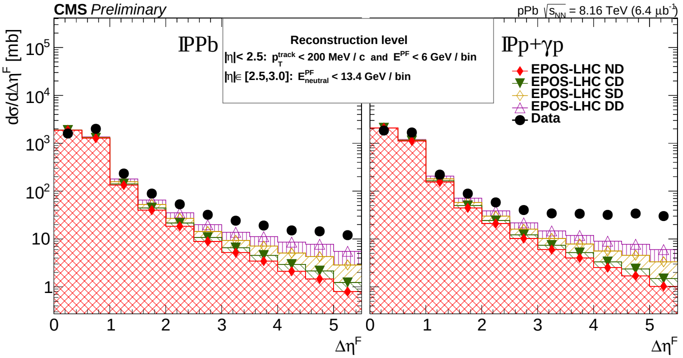
- For both topologies (IPPb and IPp) the spectra fall by a factor of over 50 between $\Delta\eta^F = 0$ and $\Delta\eta^F = 2$
- For $\Delta\eta^F > 2$ the spectra flatten off for both topologies
- The predictions of EPOS-LHC are closer to the data than those of HIJING
- For the IPp MC predictions are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

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

Contributions of different processes predicted by EPOS-LHC

Stacked distributions:

CMS-PAS-HIN-18-019



- 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

Hadron level

Hadron level

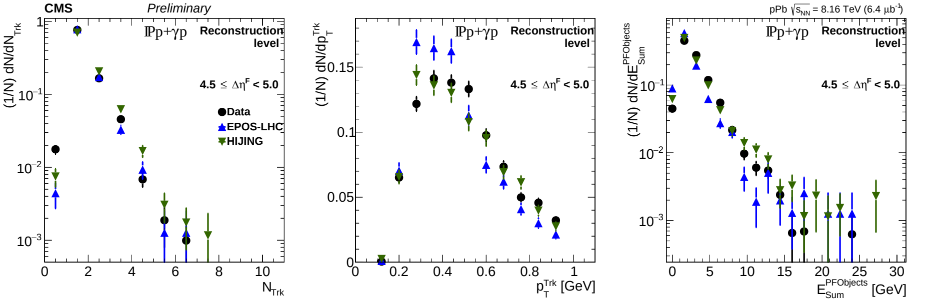
All our corrections correspond to following hadron level definition:

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

Comparison of $\mathbb{P}p$ and γp events

There is a large fraction of γp events, which are not implemented in used event generators

CMS-PAS-HIN-18-019



- 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.

Unfolding to hadron level

Unfolding

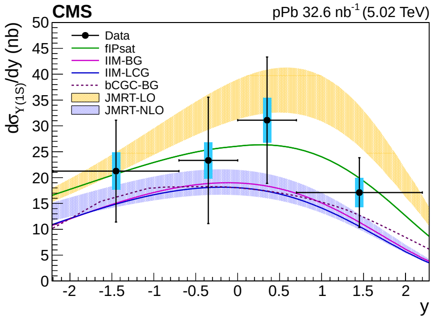
The unfolding was performed:

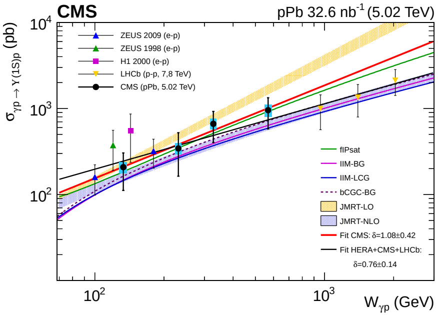
- Using the D'Agostini iteration method with early stopping (in RooUnfold)
- Number of iterations: 2
- Number of iterations was chosen by minimum of the average global correlation coefficient

Exclusive Υ photoproduction in pPb

CMS collaboration,
Measurement of exclusive Υ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
Eur. Phys. J. C 79 (2019) 277

Result: comparison with predictions and other data





- CMS results between previous ZEUS and LHCb data.
- δ (CMS only) $= 1.08 \pm 0.42$
- δ (ZEUS) $= 1.2 \pm 0.8$
- $\sigma \sim W_{\gamma p}^{\delta}$
- δ (CMS + ZEUS + H1) $= 0.99 \pm 0.27$
- δ (CMS + ZEUS + H1 + LHCb) $= 0.77 \pm 0.14$

Go Back

Exclusive $\rho(770)^0$ photoproduction in pPb

CMS collaboration,
Measurement of exclusive $\rho(770)^0$ photoproduction in ultraperipheral pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
Eur. Phys. J. C 79 (2019) 702

Results for $d\sigma/d|t|$

- Fitted as: Ae^{-bt+ct^2}
- $b = 9.2 \pm 0.7$ (stat) GeV^{-2},
  $c = 4.6 \pm 1.6$ (stat) GeV^{-4}
- Regge formula: $b = b_0 + 2\alpha' ln(W_{\gamma p}/W_0)^2$
- $W_0 = 92.6$ GeV
- $\alpha' = 0.28 \pm 0.11$ (stat) ± 0.12 (syst) GeV^{-2}, consistent with ZEUS data and Regge expectations