Review of results on forward physics and diffraction by CMS

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On behalf of the CMS Collaboration

University of Kansas

Workshop on Forward Physics & QCD
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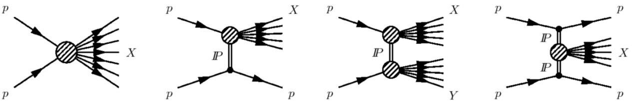
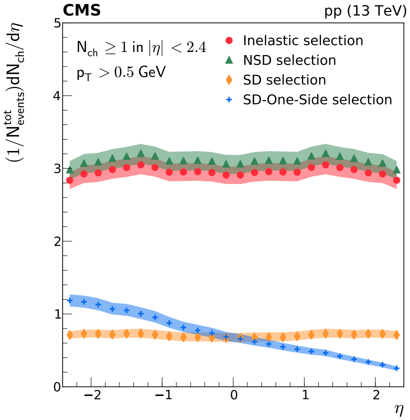
Introduction

- Quantum chromodynamics (QCD), very rich and successful theory of strong interactions!
- Precise understanding of perturbative and non-perturbative QCD necessary for:
  - constraining parton distribution functions in special corners in x and Q^2
  - testing pQCD in unexplored regions of phase-space
  - modeling soft QCD physics
  - all above – interesting in their own right– $\rightarrow$ better SM measurements and searches for physics beyond SM
- We present a summary of recent results by the CMS Collaboration on:
  - Measurement of energy density as a function of pseudorapidity in proton-proton collisions at $\sqrt{s} = 13$ TeV, **Eur. Phys. J. C 79 (2019) 391**
  - Measurement of the underlying event activity in inclusive Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV, **JHEP 07 (2018) 032**
  - Measurement of charged particle spectra in minimum-bias events from proton–proton collisions at $\sqrt{s} = 13$ TeV, **Eur.Phys.J. C78 (2018) no.9, 697**
  - Measurement of inclusive very forward jet cross sections in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV, **JHEP 05 (2019) 043**
  - Azimuthal decorrelation of jets widely separated in rapidity in pp collisions at $\sqrt{s} = 7$ TeV, **J. High Energy Phys. 08 (2016) 139**
  - Study of dijet events with a large rapidity gap between the two leading jets in pp collisions at $\sqrt{s} = 7$ TeV, **Eur. Phys. J. C 78 (2018) 242**
  - Measurement of exclusive Υ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, **Eur. Phys. J. C 79 (2019) 277**
  - Measurement of exclusive $\rho^0(770)$ photoproduction in ultraperipheral pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, **Eur. Phys. J. C 79 (2019) 702**

Charged particle spectra in minimum-bias events at 13 TeV (I)
EPJC78(2018)no.9,697



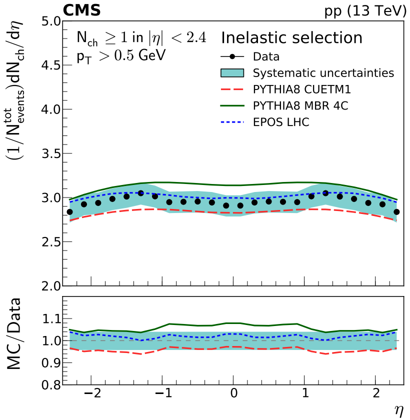


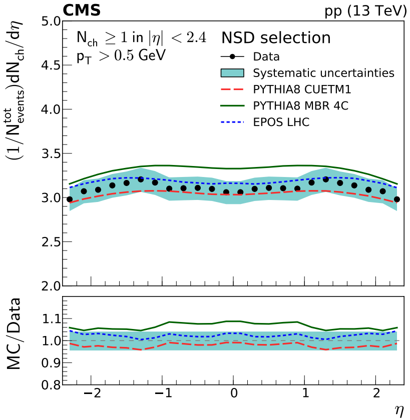
- Study charged particle densities for particles with $p_T > 0.5$ GeV and $|\eta| < 2.4$

Event categories

- Inelastic: At least one calorimeter tower with $E > 5$ GeV in $3 < |\eta| < 5$;
- Non-single diffractive (NSD): At least one calorimeter tower with $E > 5$ GeV in $3 < |\eta| < 5$ in both sides;
- Single-diffractive (SD): At least one calorimeter tower with $E > 5$ GeV in $3 < |\eta| < 5$ in only one side;
- Single-diffractive (exactly one-side)

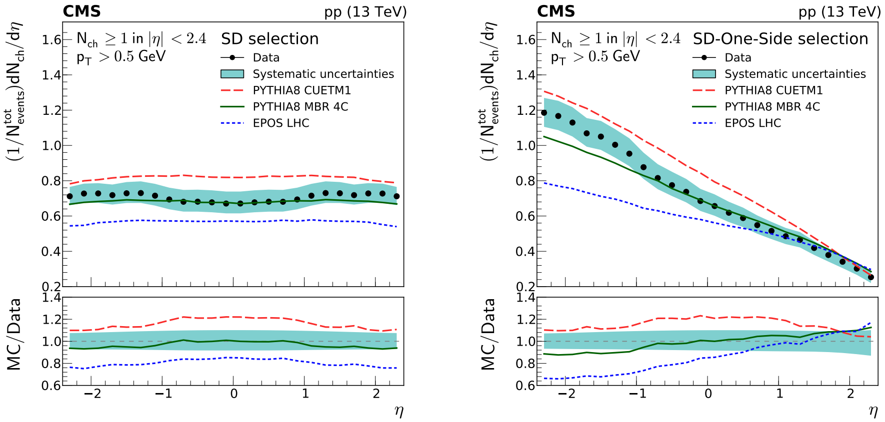
Charged particle spectra in minimum-bias events at 13 TeV (II)





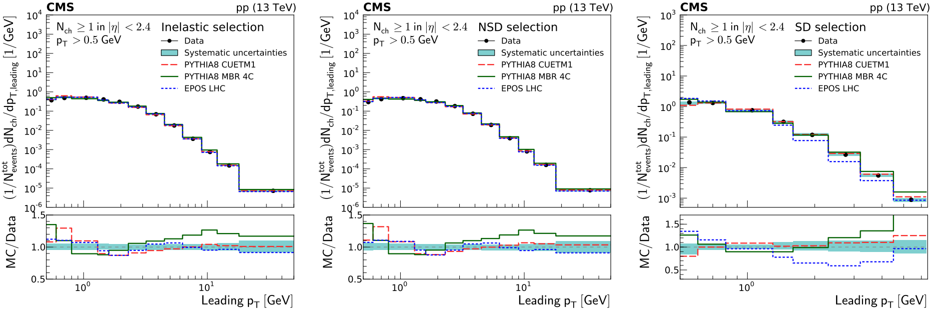
- **PYTHIA8 w/ tunes MBR 4C** and **CUETP8M1** and **EPOS-LHC** show similar agreement with data;
- Difficult to describe simultaneously the density in central and most forward regions

Charged particle spectra in minimum-bias events at 13 TeV (III)



- **PYTHIA8 w/ tune MBR 4C** describes SD enriched samples better than tune **CUETP8M1** and **EPOS-LHC**;
- Difficult to describe simultaneously the density most backward and most forward regions;

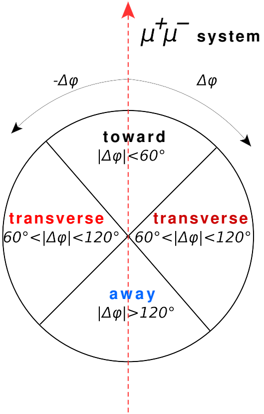
Charged particle spectra in minimum-bias events at 13 TeV (IV)



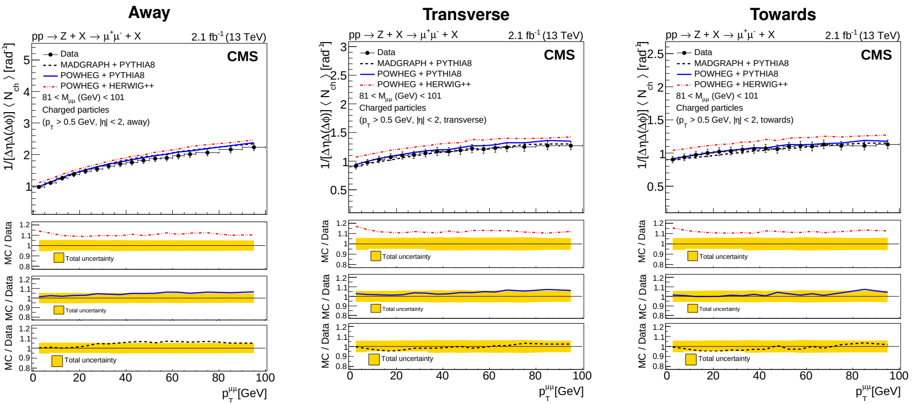
- Difficult to describe leading p_T distribution simultaneously at small-p_T and large-p_T (order 10 GeV);
- **PYTHIA w/ tune CUETP8M1** gives reasonable description across selections and leading p_T spectrum;
- **PYTHIA8 MBR 4C** overestimates data by 10-50% for different selections around leading p_T of 10 GeV;
- **EPOS-LHC** describes data reasonably well for inelastic and NSD selection, but underestimates data for the SD selection by a factor of $\sim$2.

Underlying event in inclusive Z boson in pp collisions at 13 TeV (I)
JHEP 07 (2018) 032

- **Underlying event (UE):** Activity not attributed to hard energy scales: multiparton interactions (MPI), proton remnants interactions.
- **Experimental strategy:** study particle activity relative to a clean hard scattering probe ($Z \to \mu^+\mu^- \to$ Not sensitive to QCD final state radiation).
- Leading and subleading muon with $p_T^\mu > 10$ and 20 GeV, $|\eta^\mu| < 2.4$ and $81 < m_{\mu\mu} < 101$ GeV.
- Study charged particle activity relative to $\mu^+\mu^-$ system.
- One can study the UE in three azimuthal angle regions:
  - **Towards region** ($|\Delta\phi^{\mu\mu,ch}| < 60^\circ$) and **away region** ($|\Delta\phi^{\mu\mu,ch}| > 120^\circ$); dominated by the $\mu^+\mu^-$ system and hadronic recoil;
  - **Transverse region** ($60^\circ < |\Delta\phi^{\mu\mu,ch}| < 120^\circ$): most sensitive to UE activity.

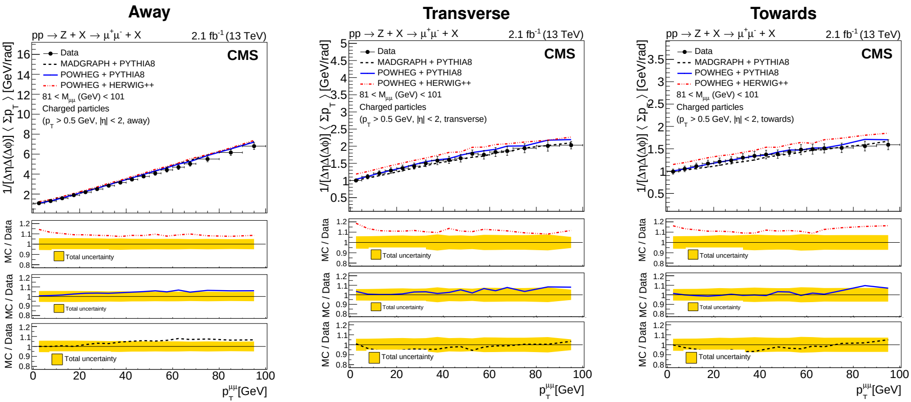


Underlying event in inclusive Z boson in pp collisions at 13 TeV (II)



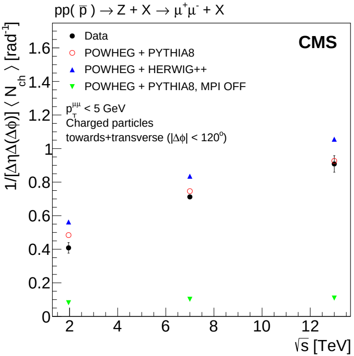
- Slow increase of activity in the transverse and towards regions at higher p_T; sharp increase of activity in the away region (recoiling hadronic activity);
- Similar activities in the 3 regions; different behaviors due to varying initial-state radiation activity.

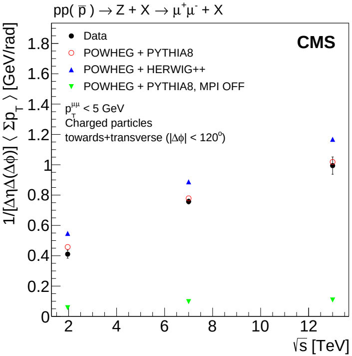
Underlying event in inclusive Z boson in pp collisions at 13 TeV (III)



- **POWHEG + HERWIG++ EE5C:** overestimates by 10-15% in all regions;
- **POWHEG + PYTHIA8 CUETP8M1:** describes data within 5%;
- **MADGRAPH + CUETP8M1:** gives the best description across the 3 regions.

Underlying event in inclusive Z boson in pp collisions at 13 TeV (IV)



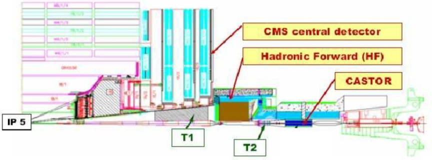


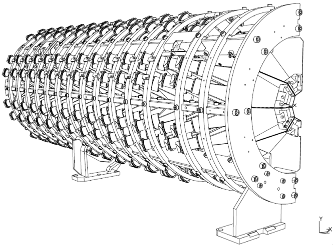
- At low dimuon $p_T^{\mu\mu} < 5$ GeV, UE is dominated by MPI contributions. Expected to be similar in transverse and towards region.
- Average particle and energy densities vs. $\sqrt{s}$ in the combined transverse and towards regions.
- Increase of MPI activity with energy is well reproduced by **POWHEG + PYTHIA8 CUETP8M1** and overestimated by **POWHEG + HERWIG++ EE5C**.

Intermezzo CASTOR: Very forward calorimeter at the LHC

CASTOR

- Electromagnetic-hadronic calorimeter of CMS, covers $-6.6 < \eta < -5.2$;
- 14.37 m w.r.t. interaction point;
- 16-fold segmentation in ϕ, 14-fold segmentation in z; **no segmentation in** η;
- Operational in heavy-ion collisions and in dedicated runs in pp collisions.
- Previous uses in the past:
  - Forward energy flow measurement;
  - Inelastic and diffractive cross section measurements;
  - Jet spectra;





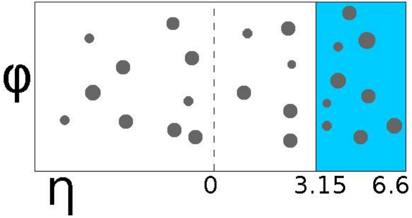
Energy density as function of η in pp collisions at 13 TeV (I)
Eur. Phys. J. C 79 (2019) 391

Analysis strategy

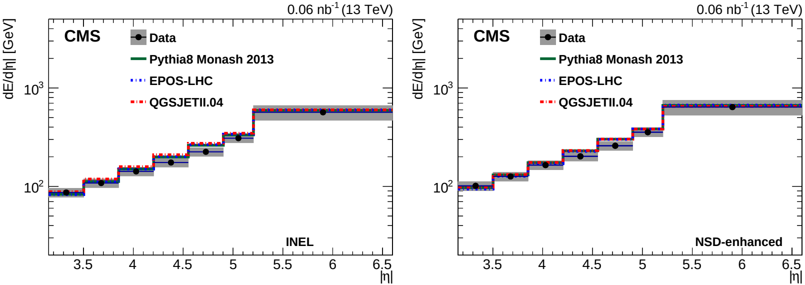
- Measure the average energy density per collision,

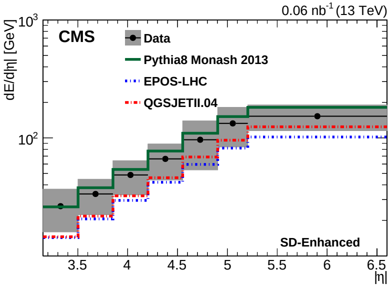
$$\frac{\mathrm{d}E}{\mathrm{d}\eta} = \frac{1}{N_{\mathrm{coll}} \cdot \Delta\eta} \sum_i E_i(\Delta\eta) \qquad (1)$$

- Energy-densities are measured in $3.15 < |\eta| < 5.2$ and with CASTOR $-6.6 < \eta < -5.2$.
- Sensitive to UE and projectile fragmentation.
- Comparison of tranverse energy densities with previous $\sqrt{s} = 0.7$, 7 TeV, for different shifted-intervals $\eta' = \eta - y_{\mathrm{beam}}$.



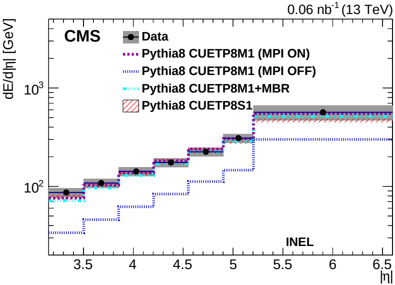
Energy density as function of η in pp collisions at 13 TeV (II)

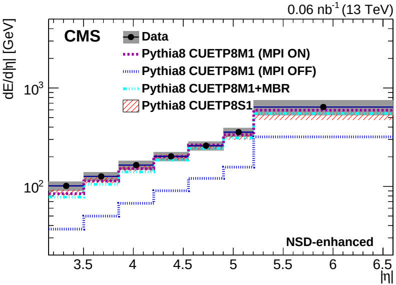




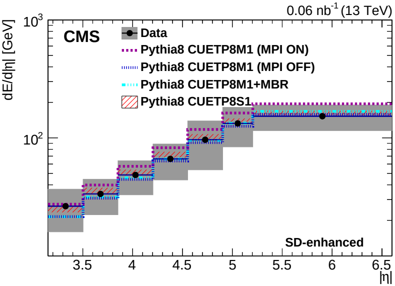
- Good description of $dE/d\eta$ by models in INEL and NSD-Enhanced event categories
- EPOS-LHC and QGSJETII.04 slightly underestimate measured energy densities in SD-enhanced category.

Energy density as function of η in pp collisions at 13 TeV (III)

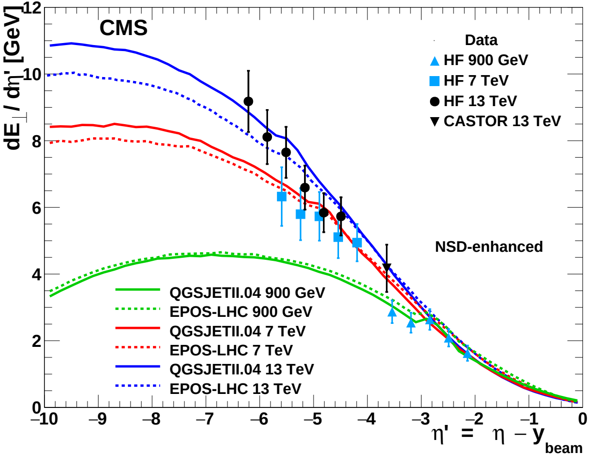




- MPI necessary to describe forward energy densities in INEL and NSD-enhanced categories.
- Absence of MPI does not affect the PYTHIA8 predictions in the SD-enhanced category.
- Similar performance across PYTHIA8 tunes within exp. uncertainties.



Comparison of measurements of transverse energy density $\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta'$ (IV)



- Measurements at $\sqrt{s} = 0.9$, 7, 13 TeV $\rightarrow$ access to different $\eta' = \eta - y_{\text{beam}}$ intervals, with $y_{\text{beam}} = \text{acosh}(\sqrt{s}/2m_p)$.
- Transverse energy $E_\mathrm{T} = E\cosh(\eta)$.
- The data are consistent with QGSJET and EPOS-LHC models within experimental uncertainties.

Intermezzo: Small-x limit of QCD

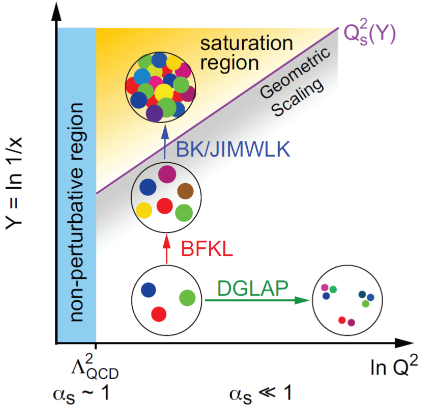


Figure from EIC white paper.

In high-energy limit of QCD, $x \ll 1$ at fixed Q^2, resummation of $\log(1/x)$ to all orders in α_s is necessary.

Linear evolution described by Balitsky-Fadin-Kuraev-Lipatov (**BFKL**) evolution equations.

At some point, parton recombination effects have to be taken into account $\rightarrow$ non-linear evolution, described for example by Balitsky-Kovgechov (**BK**) evolution equation.

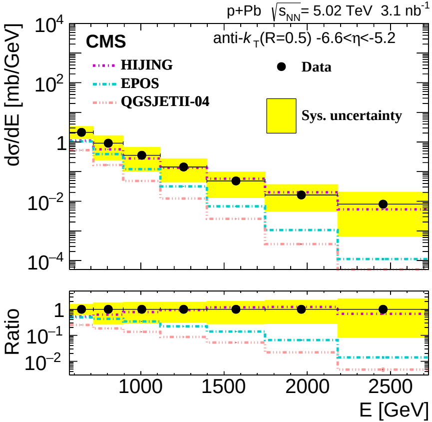
Difficult to observe small-*x* QCD effects!

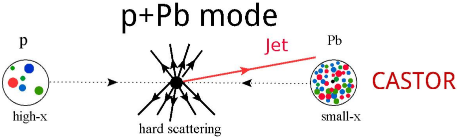
Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution effects, with parton emissions strongly ordered in k_t, describes evolution in most of phase-space covered by experiments.

Inclusive forward jet cross section in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (I) **JHEP05(2019)043**

Study inclusive jet cross section in forward region (CASTOR jets $-6.6 < \eta < -5.2$) in proton-lead and lead-proton collisions. Jets have low-$p_T \gtrsim 5$ GeV.

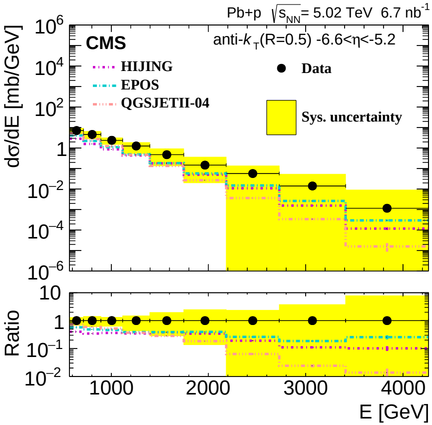
Probes parton densities at $x \sim 10^{-6}$. Saturation scale enhanced by a factor of $A^{1/3} \approx 6$ for proton-lead configuration.

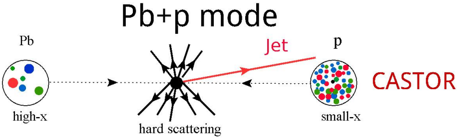




- Large systematic uncertainties, dominated by jet energy scale and model dependence (unfolding);
- **HIJING** describes data well, within uncertainties;
- Reasonable agreement across generators at low energies (around 500 GeV);
- **EPOS** and **QGSJet2** progressively underestimate cross section with increasing energy (about 2 orders of magnitude at 2.5 TeV);

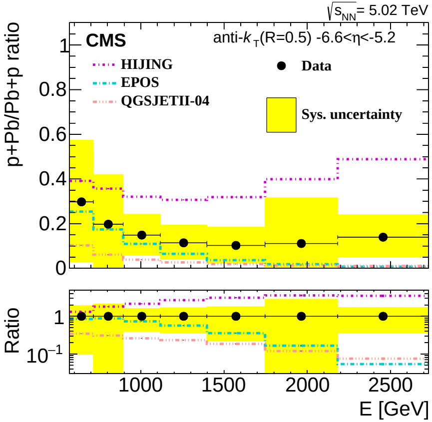
Forward inclusive jet cross section in p-Pb collisions (II)





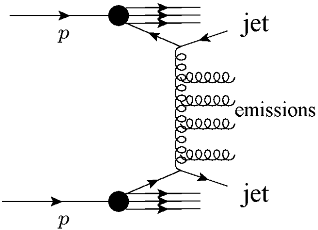
- Large systematic uncertainties, dominated by jet energy scale and model dependence (unfolding).
- **EPOS** and **HIJING** describe spectrum shape reasonably well up to normalization, within uncertainties.

Forward inclusive jet cross section in p-Pb collisions (III)



- Large cancellation of systematic uncertainties; model dependence dominates;
- Caveat: Pb+p and p+Pb are boosted w.r.t. each other;
- **HIJING** describes shape well, but is off by a factor of $\sim$ 2 due to poor Pb+p description;
- **EPOS** and **QGSJet2** are off in shape, with largest discrepancy at 2 TeV;

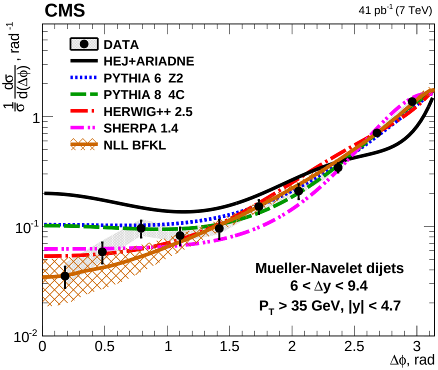
Mueller-Navelet jets in pp collisions at $\sqrt{s} = 7$ TeV (I)
JHEP08(2016)139



Azimuthal angle decorrelations $\Delta\phi$ between the outermost two jets as function of $\Delta y \equiv |y_{\text{jet 1}} - y_{\text{jet 2}}|$.

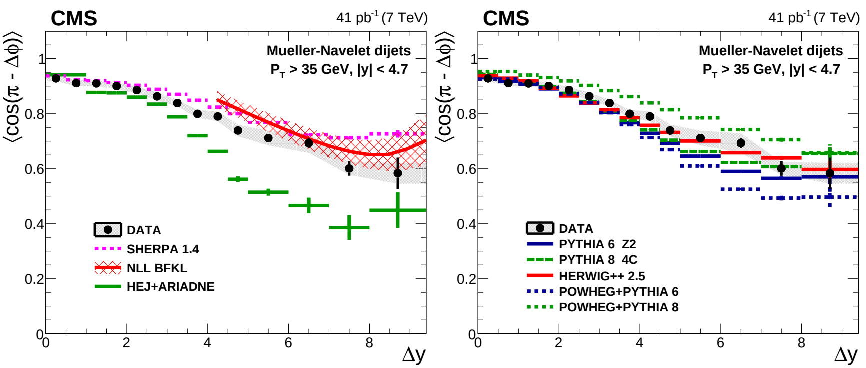
At large Δy, angular decorrelations caused by parton emissions strongly ordered in rapidity $y_1 \gg y_2 \gg \ldots \gg y_{n-1} \gg y_n$, as described by BFKL evolution.

The outermost jets have $p_{\text{T, jet}} > 35$ GeV each, within $|y| < 4.7$.



Normalized differential cross section in $\Delta\phi$

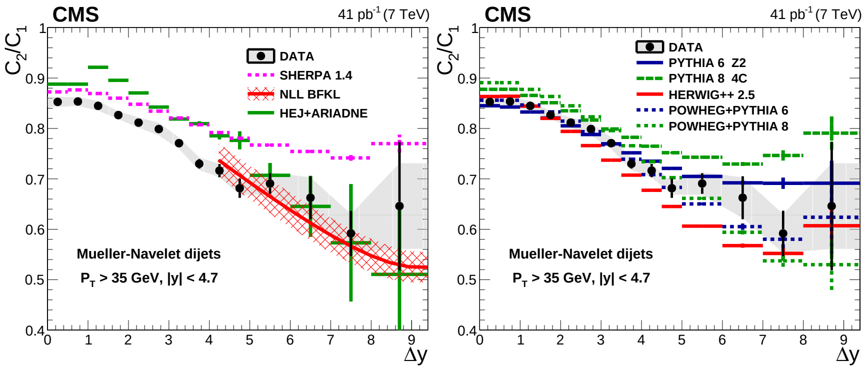
Mueller-Navelet jets in pp collisions at $\sqrt{s} = 7$ TeV (II)



- BFKL at NLL calculations describe data at large Δy within uncertainties.
- HEJ+ARIADNE, based on LL BFKL amplitudes, underestimates data at large Δy.
- PYTHIA8, HERWIG++, SHERPA, based on LO DGLAP calculations, are able to describe data over wide range in Δy within uncertainties.
- POWHEG (NLO matrix elements) supplemented with PYTHIA6 or PYTHIA8 for parton-shower and hadronization effects underestimates or overestimates data at large Δy, respectively.

Mueller-Navelet jets in pp collisions at $\sqrt{s} = 7$ TeV (III)

Ratio of average of cosines $C_2/C_1 = \langle \cos(2[\pi - \Delta\phi]) \rangle / \langle \cos(\pi - \Delta\phi) \rangle$ versus Δy.

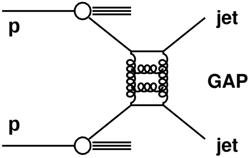


- BFKL at NLL calculations describe data at large Δy within uncertainties.
- HEJ+ARIADNE, based on LL BFKL amplitudes, describe data at large Δy within uncertainties.
- SHERPA overshoots data from medium to large Δy.
- PYTHIA8, HERWIG++, based on LO DGLAP calculations, are able to describe data over wide range in Δy within uncertainties.
- POWHEG (NLO matrix elements) supplemented with PYTHIA6 or PYTHIA8 for parton-shower and hadronization effects describes data at large Δy within uncertainties.

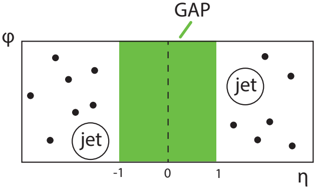
Jet-gap-jet events in pp collisions at $\sqrt{s} = 7$ TeV (I)
EPJC 78 (2018) 242

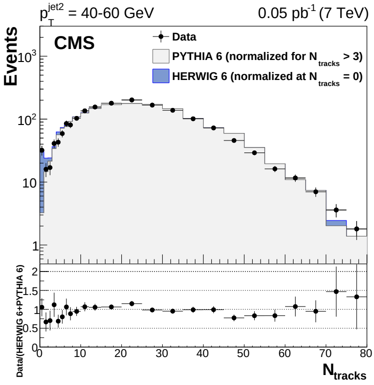
Color-singlet exchange mechanism can be described in terms of BFKL pomeron exchange.

Each of the two jets has $p_T > 40$ GeV, $1.5 < |\eta_{\text{jet}}| < 4.7$, and $\eta_{\text{jet 1}} \cdot \eta_{\text{jet 2}} < 0$.



Rapidity gap is defined as the absence of charged-particle tracks in $|\eta| < 1$.

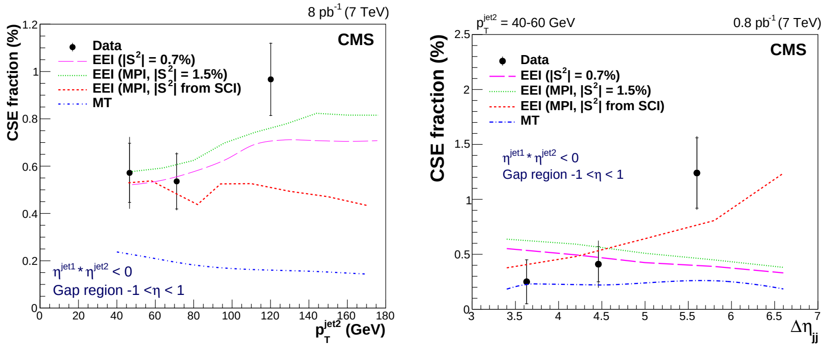




Excess of events in charged-particle multiplicity distribution at $N_{\text{tracks}} = 0 \rightarrow$ **jet-gap-jet events**!

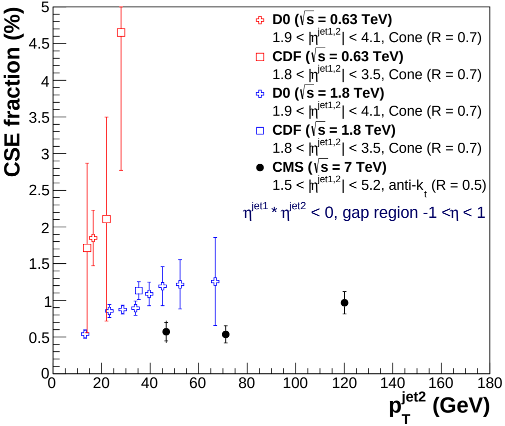
Jet-gap-jet events in pp collisions at $\sqrt{s} = 7$ TeV (II)

Fraction of jet-gap-jet events to inclusive dijet events (**CSE fraction**) versus $p_{T,\,\text{jet }2}$ and $\Delta\eta_{jj}$



- BFKL-LL calculations underestimate the gap fraction value, without soft-rescattering effects taken into account.
- Predictions by Ekstedt-Enberg-Ingelman (EEI) based on BFKL calculations at NLL.
- Different treatments of survival probability: soft-color interaction (SCI), MPI, or constant survival probability factor.
- Difficult to describe all aspects of the measurement simultaneously!

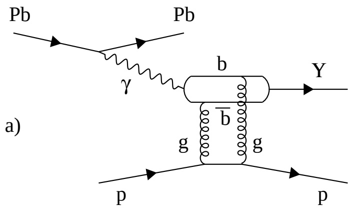
Jet-gap-jet events in pp collisions at $\sqrt{s} = 7$ TeV (III)



- Gap fraction decreases with increasing $\sqrt{s}$: 0.63 **TeV** $\rightarrow$ 1.8 **TeV** $\rightarrow$ **7 TeV**.
- Interpreted in terms of larger soft-rescattering effects contributions with increasing $\sqrt{s}$.
- *Measurement of jet-gap-jet events at 13 TeV under collaboration review.*

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

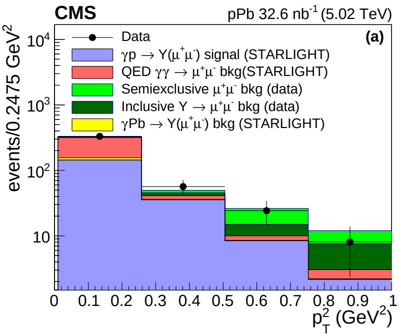
- Photoproduction of quarkonia offers a clean probe of gluon densities of the proton (At LO, $\sigma \sim g^2(x, Q^2)$).
- In particular, one can probe $g(x, Q^2)$ at $x_{\mathrm{Bj}} = 10^{-4} - 10^{-2}$ at $Q^2 \sim m^2_{\Upsilon}$, potentially where saturation effects may play a role.
- Mass of Υ meson provides large hard scale at which the gluon PDF is sampled $\rightarrow$ smaller theoretical uncertainties in pQCD calculations.

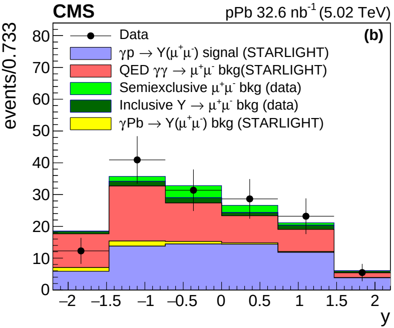


Analysis strategy

- Study $\Upsilon(\mathrm{nS}) \rightarrow \mu^+\mu^-$ decays in UPCs.
- Measure differential cross sections $\mathrm{d}\sigma/\mathrm{d}y_{\Upsilon}$ and $\mathrm{d}\sigma/\mathrm{d}p_T^2$ and $\sigma(\gamma p \rightarrow \Upsilon p)$ as a function of $W_{\gamma p}$

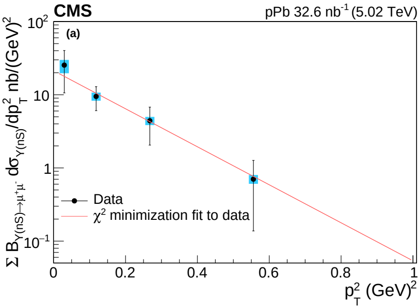
Υ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (II)

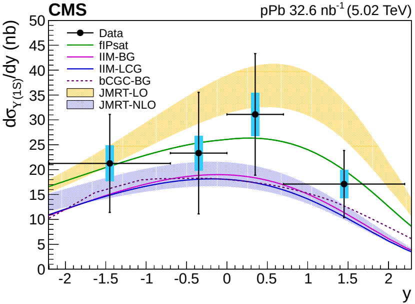




- Photoproduction contributions ($\gamma\gamma \to \mu^+\mu^-$, $\gamma p \to \Upsilon p$, γPb $\to \Upsilon$Pb) are simulated with STARLIGHT generator.
- Inclusive (Drell-Yan) and semi-exclusive Υ residual contaminations are determined from data based on templates built by modifying selection requirements.

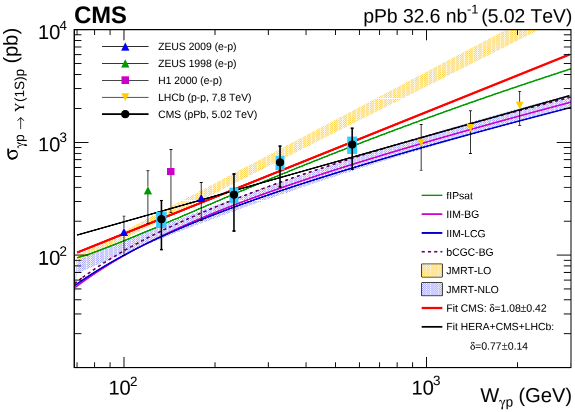
Υ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (III)





- Extract a slope of $b = 6.0 \pm 2.1(\text{stat}) \pm 0.3(\text{syst})\ \text{GeV}^{-2}$ with $\exp(-bp_T^2)$ fit, in agreement with the value measured by ZEUS at lower masses $b = 4.3^{+2.0}_{-1.3}(\text{stat})^{+0.5}_{-0.6}(\text{syst})\ \text{GeV}^{-2}$.
- Predictions by four different theoretical predictions:
  - Jones-Martin-Ryskin-Teubner (JMRT) model.
  - Factorized impact parameter saturation (fIPsat) model.
  - Iancu-Itakura-Munier (IIM) color-dipole formalism.
  - Impact parameter CGC model (bCGC).

Υ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (IV)



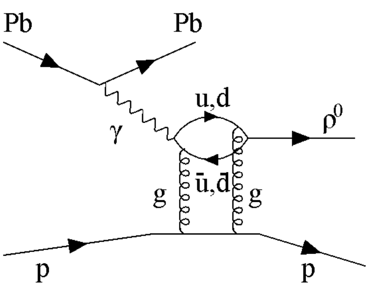
- $W_{\gamma p}$ is related to rapidity of Υ in lab frame via $W_{\gamma p}^2 = 2E_p m_\Upsilon \exp(\pm y)$, where $E_p = 4$ TeV, computed in bins of $\langle y \rangle$
- Photoproduction cross section $\sigma(\gamma \mathrm{p} \to \Upsilon(1S)p)$ extracted from $\frac{\mathrm{d}\sigma}{\mathrm{d}y}(\mathrm{pPb} \to \mathrm{p}\Upsilon(1S)\mathrm{Pb})$
- $\sqrt{s_{NN}} = 5.02$ TeV pPb results with CMS cover region unexplored by H1, ZEUS and LHCb results.
- A fit to the CMS data of the form $A(W_{\gamma p}/400 \text{ GeV})^\delta$ yields $\delta = 1.08 \pm 0.42$, consistent with value by ZEUS $\delta = 1.2 \pm 0.8$.

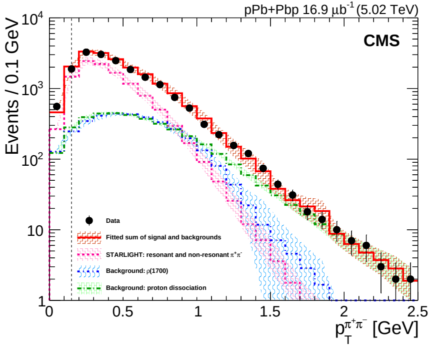
$\rho(770)^0$ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (I), **EPJC79(2019) 702**

Effective color-dipole size of $\rho(770)^0$ meson is larger than with other vector mesons $\rightarrow$ enhancement of parton saturation effects.

Measure production rates of pPb$\rightarrow$ p($\rho(770)^0 \rightarrow \pi^+\pi^-$)Pb.

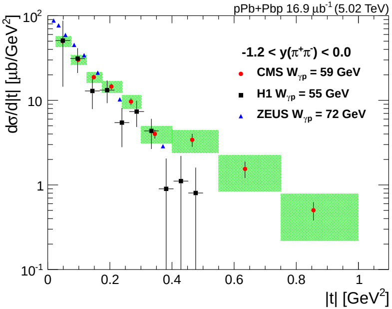
$p_T > 0.4$ (0.2) GeV for leading (subleading) $\pi^\pm$ in $|\eta| < 2$

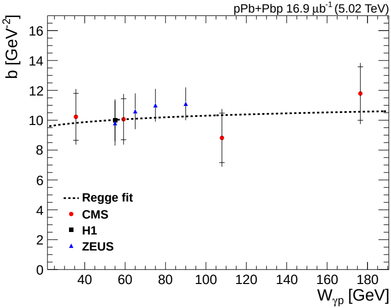




Backgrounds: proton dissociation, resonant $\rho(770)^0$, inclusive $\pi^+\pi^-$, $\rho^0(1700)$, and ω meson production.

$\rho(770)^0$ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (II),





- Good agreement of $-t \approx p^2_{\mathrm{T},\pi^+\pi^-}$ between H1, ZEUS and CMS.
- Shrinkage of diffractive peak with energy (Regge fit):

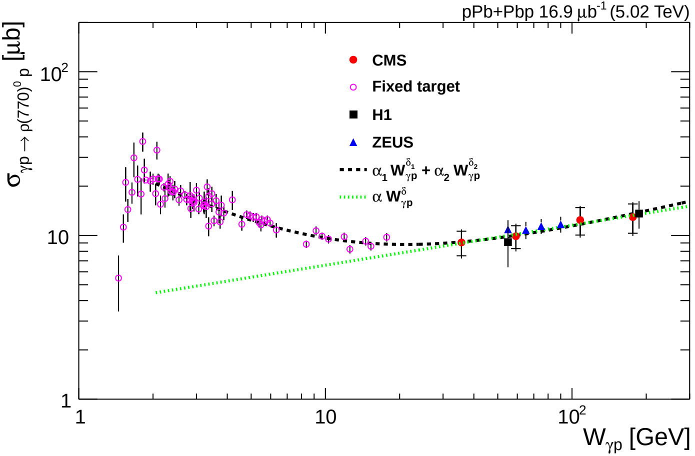
$$b = b_0 + 2\alpha' \ln(W/W_0)^2$$

- Pomeron slope using CMS data:

CMS: $\alpha' = 0.48 \pm 0.33$ (stat) ± 0.12(syst) GeV^{-2}

Consistent with the ZEUS-only value $\alpha' = 0.23 \pm 0.15$ (stat) ± 0.11(syst) GeV^{-2}

$\rho(770)^0$ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (III),



- Power-law fit $W^{\delta}_{\gamma p}$ yields $\delta = 0.23 \pm 0.14$ (stat) ± 0.04 (syst).
- $\sqrt{s_{NN}} = 5.02$ TeV pPb results with CMS cover region unexplored by H1 and ZEUS results.
- Consistent with trend observed with HERA results.

Summary

- The LHC keeps enlarging our access to unexplored phase space to study strong interactions;
- Recent measurements provide important inputs for Monte Carlo generator tuning and constraints on small-x gluon PDFs
- Probes of perturbative and non-perturbative QCD predictions include the results presented today:
  - Measurement of energy density as a function of pseudorapidity in proton-proton collisions at $\sqrt{s} = 13$ TeV, **Eur. Phys. J. C 79 (2019) 391**
  - Measurement of the underlying event activity in inclusive Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV, **JHEP 07 (2018) 032**
  - Measurement of charged particle spectra in minimum-bias events from proton–proton collisions at $\sqrt{s} = 13$ TeV, **Eur.Phys.J. C78 (2018) no.9, 697**
  - Measurement of inclusive very forward jet cross sections in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV, **JHEP 05 (2019) 043**
  - Azimuthal decorrelation of jets widely separated in rapidity in pp collisions at $\sqrt{s} = 7$ TeV, **J. High Energy Phys. 08 (2016) 139**
  - Study of dijet events with a large rapidity gap between the two leading jets in pp collisions at $\sqrt{s} = 7$ TeV, **Eur. Phys. J. C 78 (2018) 242**
  - Measurement of exclusive Υ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, **Eur. Phys. J. C 79 (2019) 277**
  - Measurement of exclusive $\rho^0(770)$ photoproduction in ultraperipheral pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, **Eur. Phys. J. C 79 (2019) 702**
- See contributions by Georgios Krintiras, Michael Albrow, and future opportunities with detector upgrades by Andre Stahl and Margaret Lazarovits.