Soft and forward physics results by CMS

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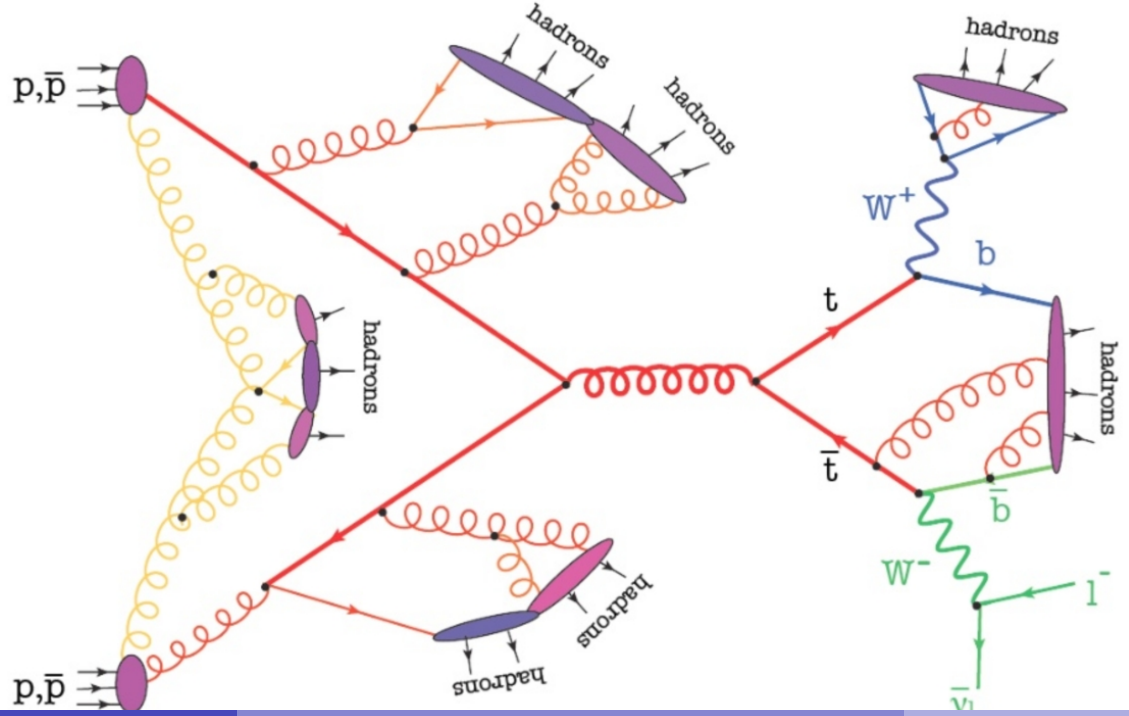
Introduction

- Quantum chromodynamics (QCD), very rich and successful theory of strong interactions!
- Precise understanding of perturbative and non-perturbative QCD necessary for:
  - testing pQCD in unexplored regions of phase-space
  - modelling soft QCD physics
  - constraining parton distribution functions
  - all above $\rightarrow$ better SM measurements and searches for physics beyond SM
- We present a summary of recent results by the CMS Collaboration on the following topics:
  - Measurement of the average very forward energy as a function of track multiplicity at central pseudorapidities in proton-proton collisions at $\sqrt{s} = 13$ TeV, Submitted to EPJC, **arXiv:1908.01750**
  - 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 exclusive Υ photoproduction from protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, **Eur. Phys. J. C 79 (2019) 277**

Measurement of the average very forward energy as a function of track multiplicity at central pseudorapidities in proton-proton collisions at $\sqrt{s} = 13$ TeV, Submitted to EPJC, arXiv:1908.01750

Motivation

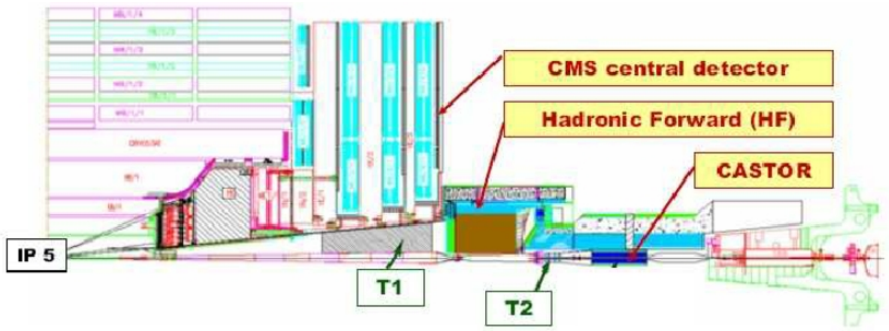
- Study correlations of particle activity at central rapidities and forward rapidities in proton-proton collisions.
- The energy carried by particles emitted in very forward region can be studied up to $-6.6 < \eta < -5.2$ using the CASTOR calorimeter of CMS.
- Measurements over a very large rapidity interval may provide additional information on the underlying event activity compared to previous studies at central rapidities.
- This information can improve event generators used in simulations of extensive air showers induced by cosmic rays at ultra-high energies.

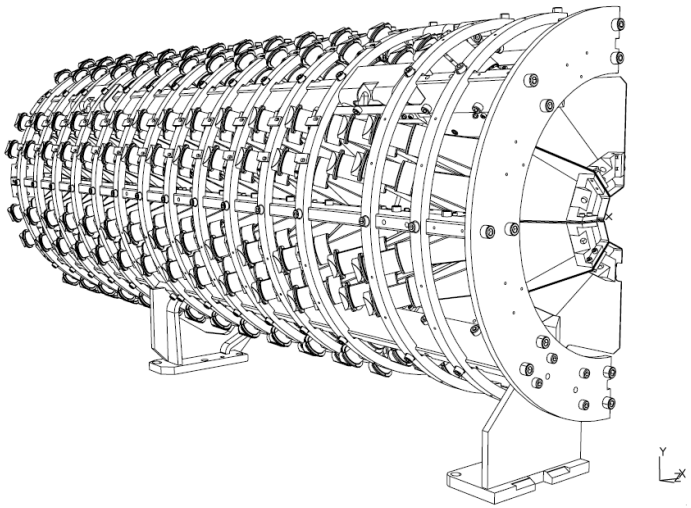


CASTOR: Very forward calorimeter at the LHC

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;





Analysis strategy

Measure the average total, electromagnetic and hadronic energy per event in CASTOR as a function of track multiplicity.

Compare with various MC generators predictions with different parameter tunes and physics approaches:

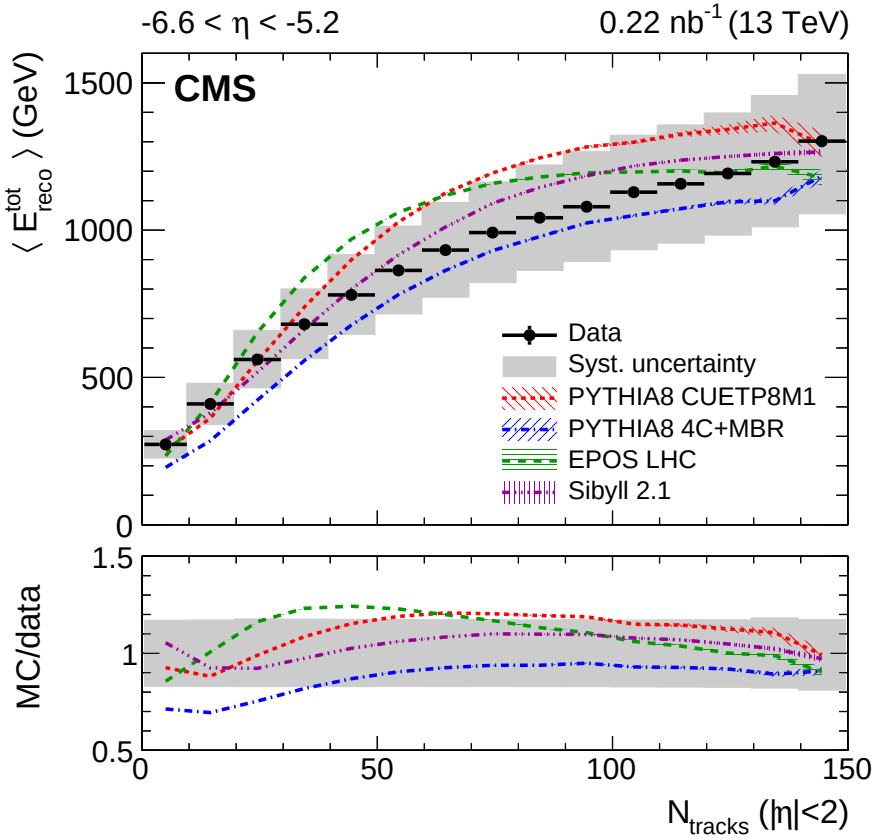
- PYTHIA8 with tunes CUETP8M1, 4C, and MBR, HERWIG 7.1
- EPOS-LHC, QGSJETII.04, SIBYLL 2.1, SIBYLL 2.3c

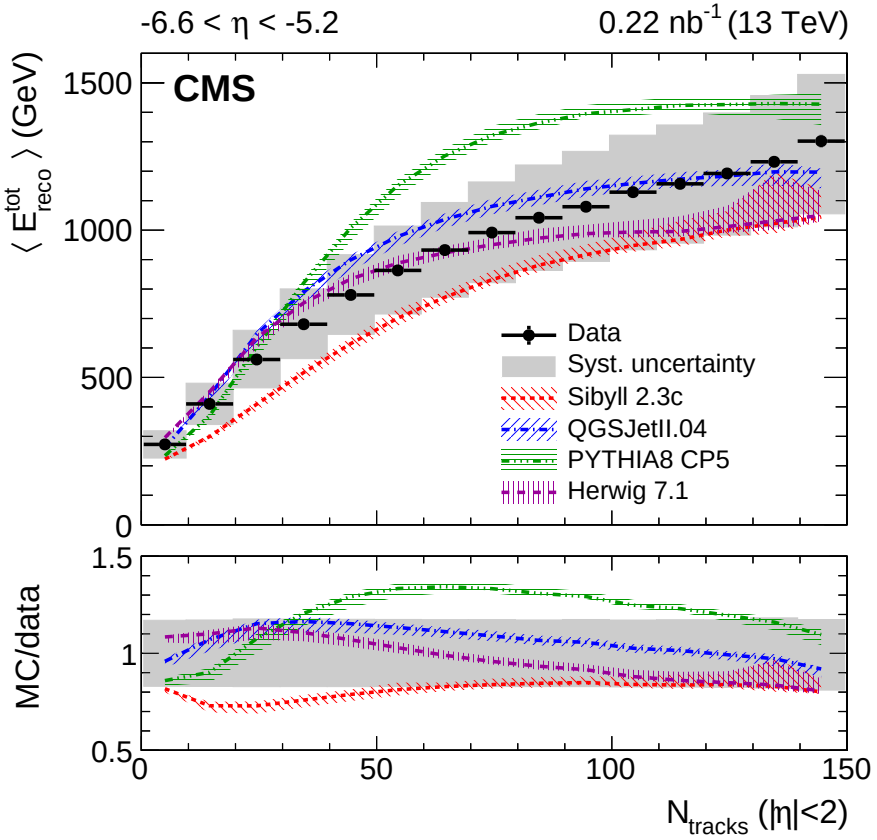
Data sample

Low pileup (30%) pp collisions at 13 TeV in June 2015, 0.22 nb^{-1}.

Selection

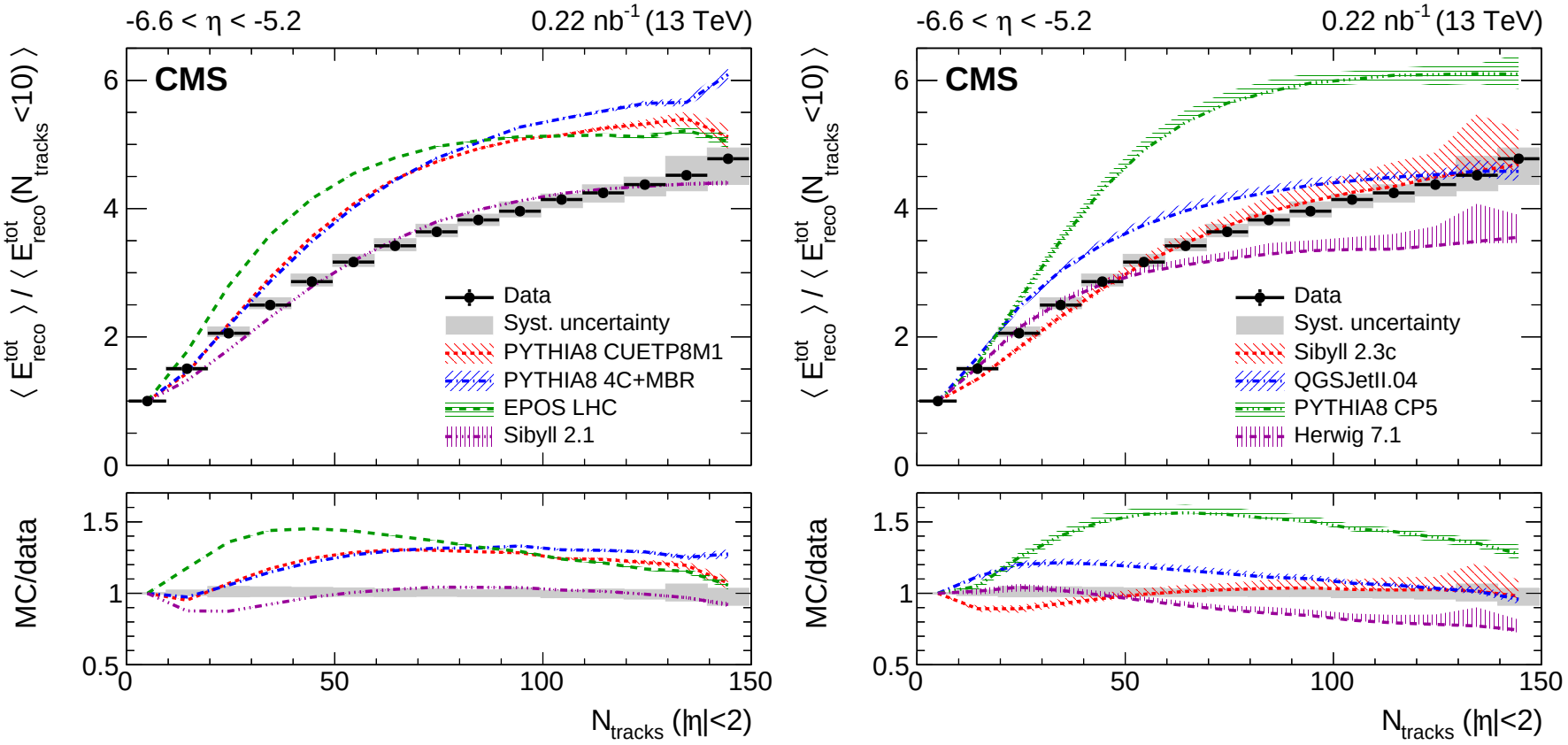
- For online trigger, the Beam Pickup Timing for the eXperiment (BPTX) devices were used (non-empty two colliding bunches)
- Offline, at least one calorimeter-tower in $3 < |\eta| < 5.2$ and at least one reconstructed track within $|\eta| < 2$.
- Total energy in CASTOR is the sum of calorimeter-towers w/ energy above noise-level $E > 2$ GeV.





Observations

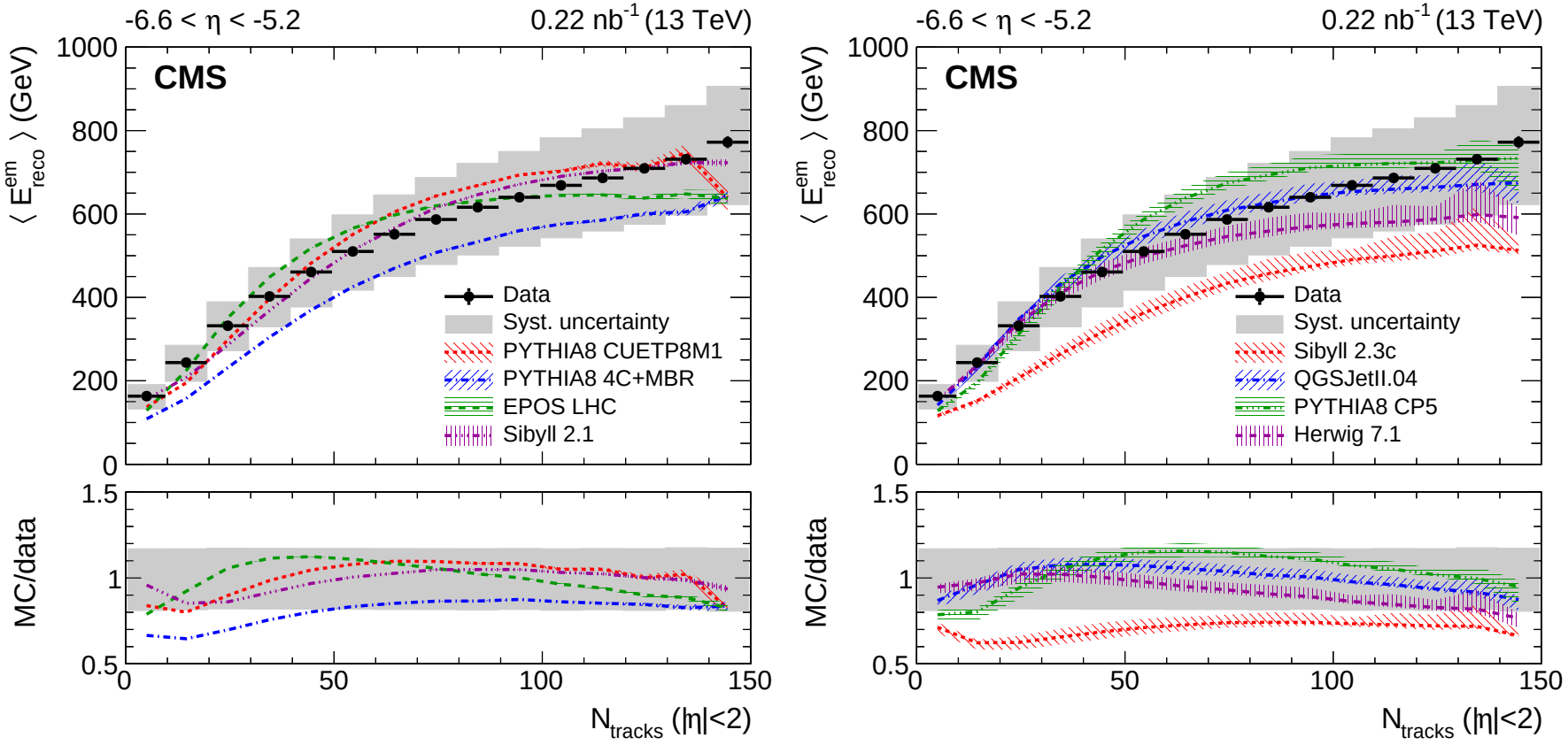
- UE tunes determined at central rapidities seem to be valid also at forward rapidities.
- PYTHIA8 4C + MBR and SIBYLL 2.3c predictions underestimate total energy at low multiplicities.
- PYTHIA8 5C overshoots data at intermediate multiplicities.



Observations

- Average total energy $\langle E_{\text{tot}} \rangle$ is normalized to total energy in $N_{\text{Tracks}} < 10$ to suppress experimental uncertainties.
- PYTHIA8 tunes yield very similar shapes, which are inconsistent with the one in data.
- EPS-LHC, QGSJETII.04, and HERWIG 7.1 predict saturation $\langle E_{\text{tot}} \rangle$ at intermediate multiplicities, which is not observed in data.
- SIBYLL provides predictions in agreement with data.

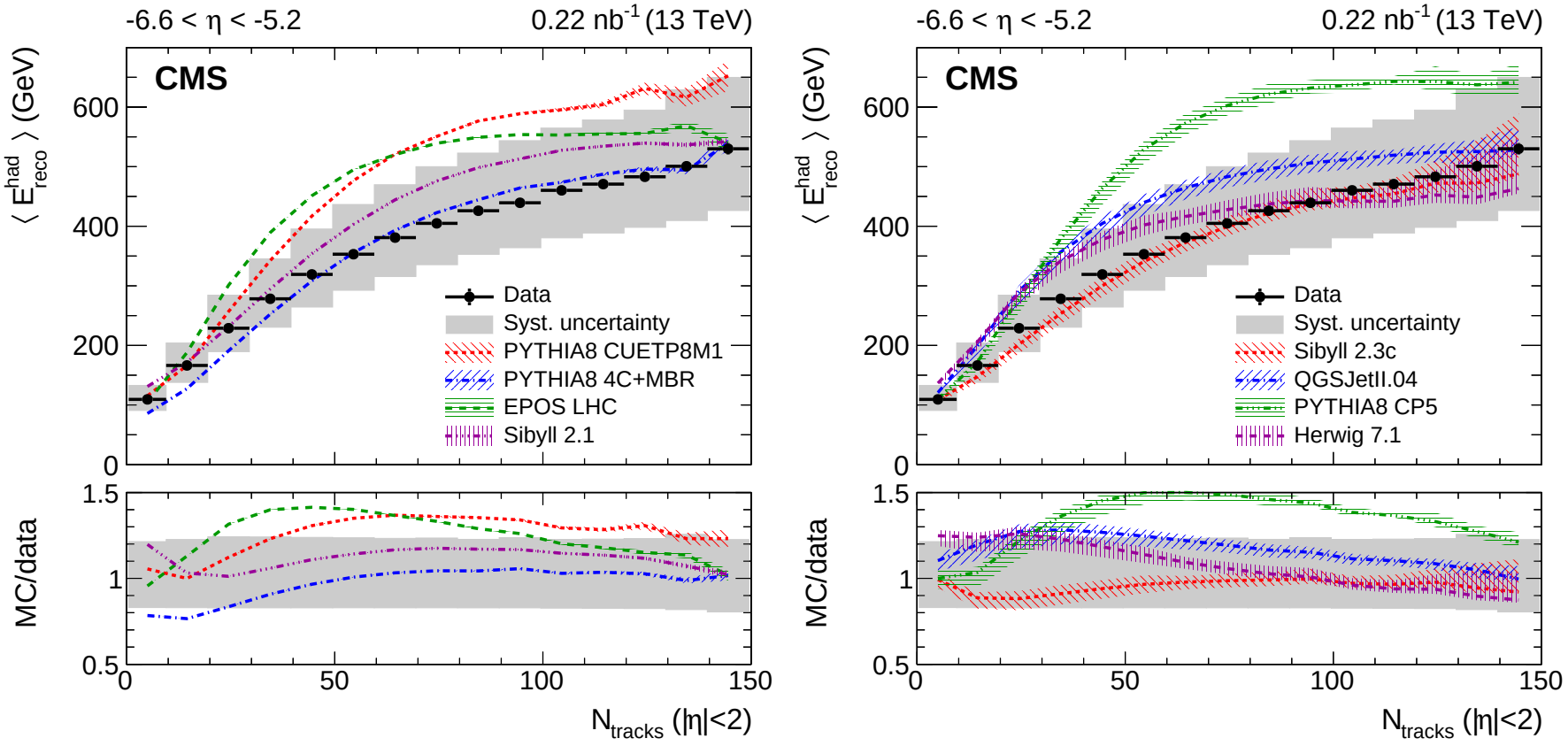
Individual average electromagnetic energy distributions $\langle E_{em} \rangle$



Observations

- Most models describe the electromagnetic energy distribution over the full track multiplicity spectra.
- SIBYLL 2.3c systematically underestimates the measured $\langle E_{em} \rangle$ in data.
- PYTHIA8 4C+MBR slightly underestimates $\langle E_{em} \rangle$ at low multiplicities.

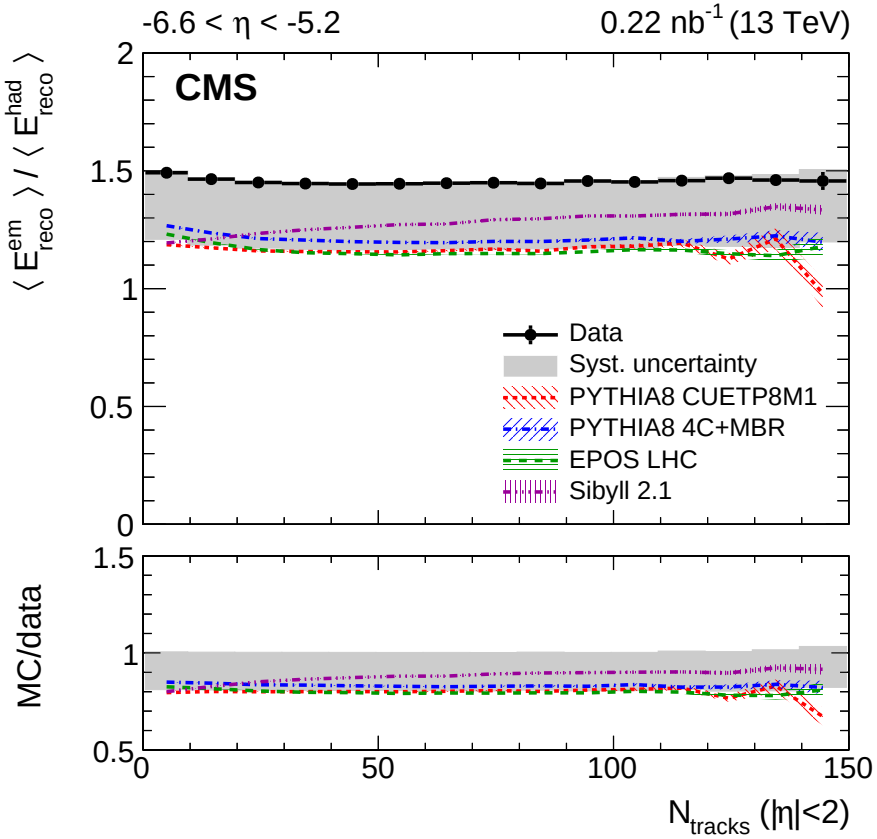
Individual average hadronic energy distributions $\langle E_{\text{had}} \rangle$

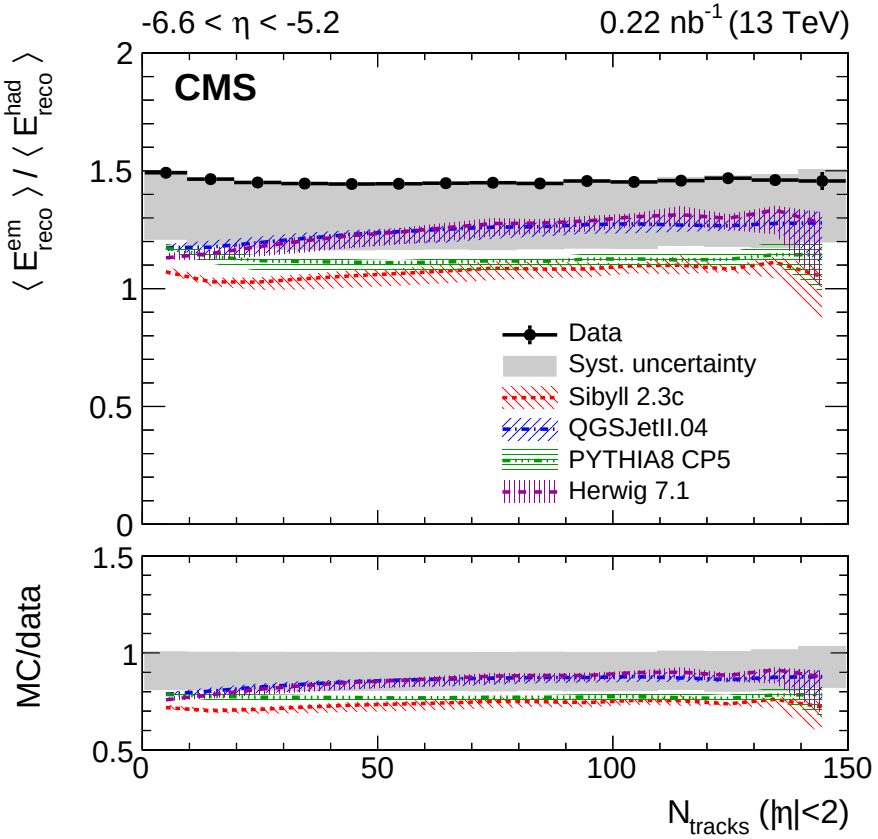


Observation

- EPOS LHC, PYTHIA8 tune CUETP8M1 and CP5 overestimate $\langle E_{\text{had}} \rangle$ relative to the data at medium multiplicities.
- The rest of the models describe the hadronic component well.

Ratio $\langle E_{em} \rangle / \langle E_{had} \rangle$





- Measured ratio is approximately uniform over the whole multiplicity range.
- Model predictions are generally lower than the data.
- QGSJETII.04, SIBYLL 2.1 and HERWIG 7.1 proivde the best description of the ratio.

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**

Motivation

- Inelastic proton-proton colisions are described by a combination of hard- and soft-exchanges between the proton's constituents.
- Hard collisions are complemented by multiple parton interactions (MPI) and projectile fragmentation effects.
- Studies of energy densities in pseudorapidity, $\mathrm{d}E/\mathrm{d}\eta$ measured in pp collisions at the LHC can help test many of the associated parametrizations of underlying event activity.
- Valuable input for tuning of Monte Carlo event generators used to describe high-energy hadronic interactions employed in cosmic-ray physics measurements.

Analysis strategy

Measure the average energy density per collision,

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

Energy-densities are measured in $3.15 < |\eta| < 5.2$ and with CASTOR $-6.6 < \eta < -5.2$.

Comparison with various MC generator predictions: EPOS-LHC, QGSJETII.04, PYTHIA8.

Comparison of tranverse energy densities with previous $\sqrt{s} = 0.7$, 7 TeV, for different shifted-intervals $\eta' = \eta - y_{\text{beam}}$.

Data sample

Low pileup ($\sim$ 5%) pp collisions at 13 TeV during 2015, with CASTOR forward calorimeter operating ($-6.6 < \eta < -5.2$) and 0.06 nb^{-1} of data.

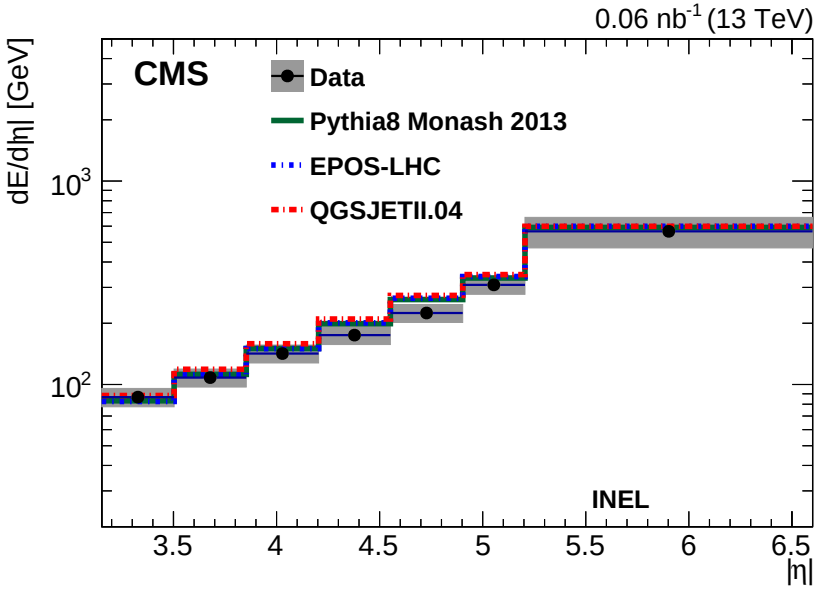
Selection

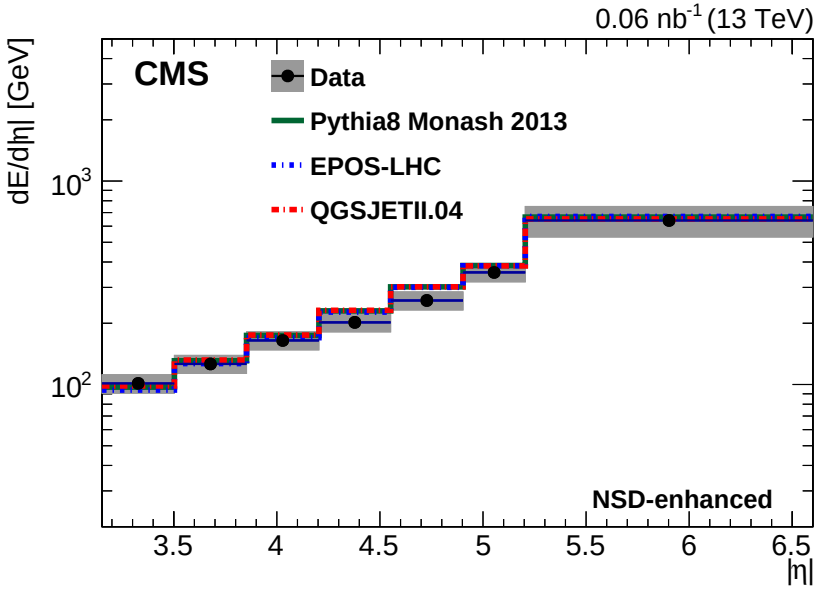
Online, events are selected by triggering the DAQ with BPTX devices of CMS.

Event categories defined in terms of forward-particle production above noise-level:

- Inelastic (**INEL**): Energy deposition of $E > 5$ GeV in $3 < |\eta| < 5.2$ on either hemisphere of CMS
- Non-single-diffractive enhanced (**NSD-enhanced**): Energy deposition of $E > 5$ GeV in $3 < \eta < 5.2$ and $-5.2 < \eta < -3$
- Single-diffractive enhanced (**SD-enhanced**): Energy deposition of $E > 5$ GeV in $3\eta < 5.2$ and energy deposition of at most $E < 5$ GeV in $-5.2 < \eta < -3$, or viceversa.

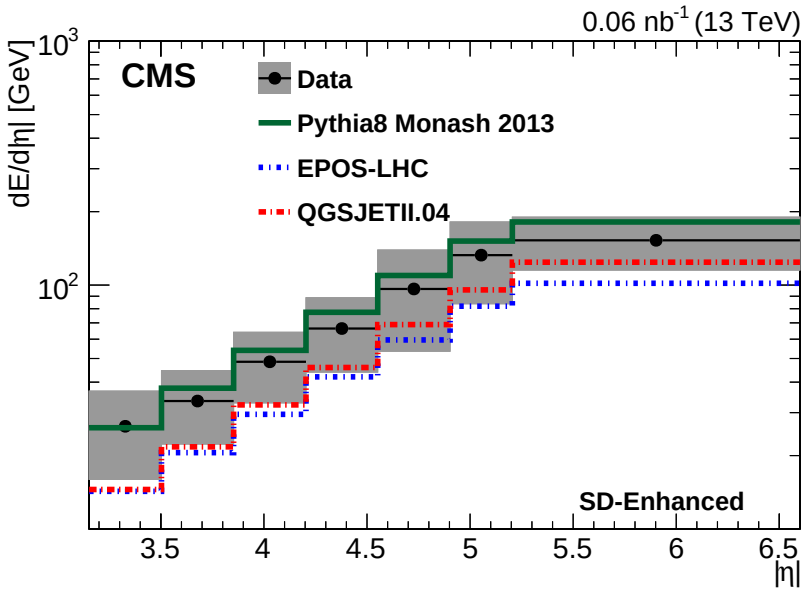
Results

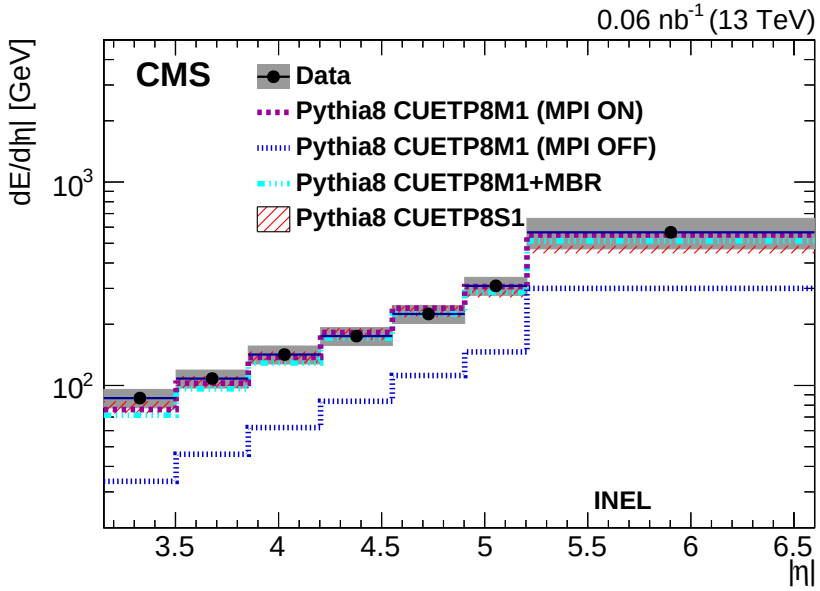


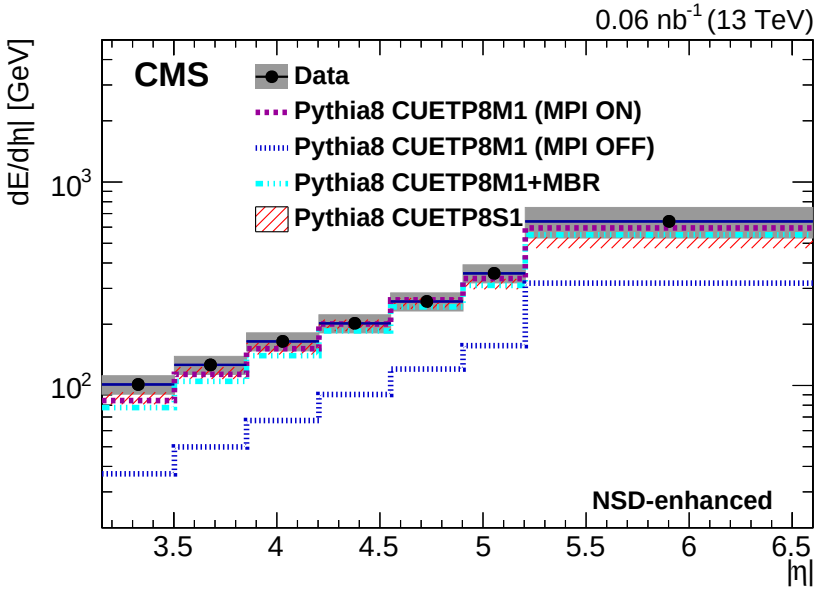


Observations

- 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.

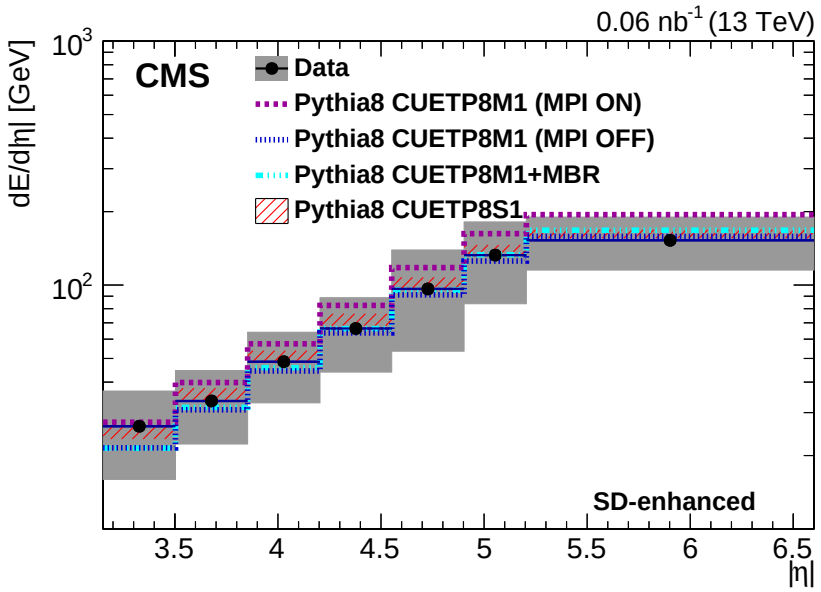




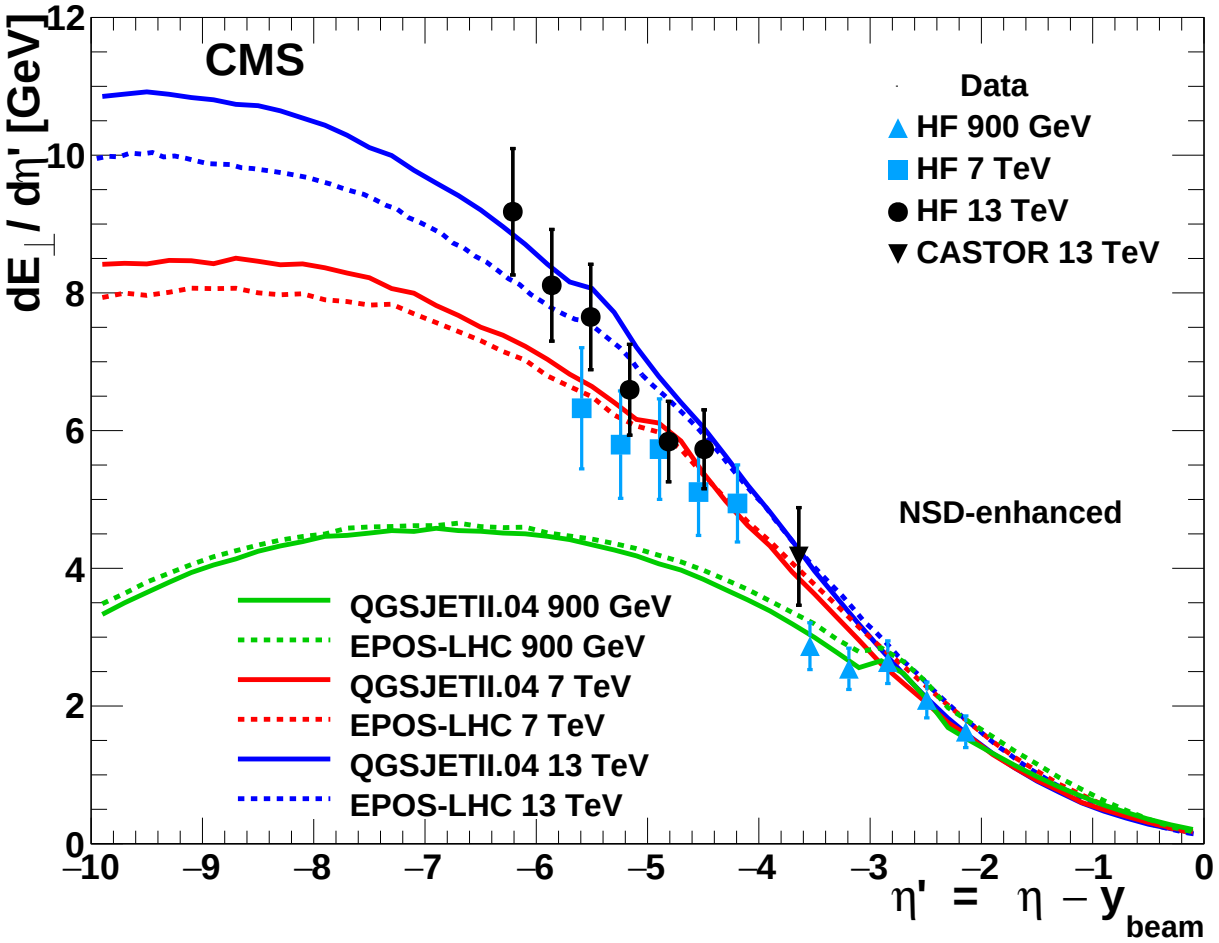


Observations

- 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.

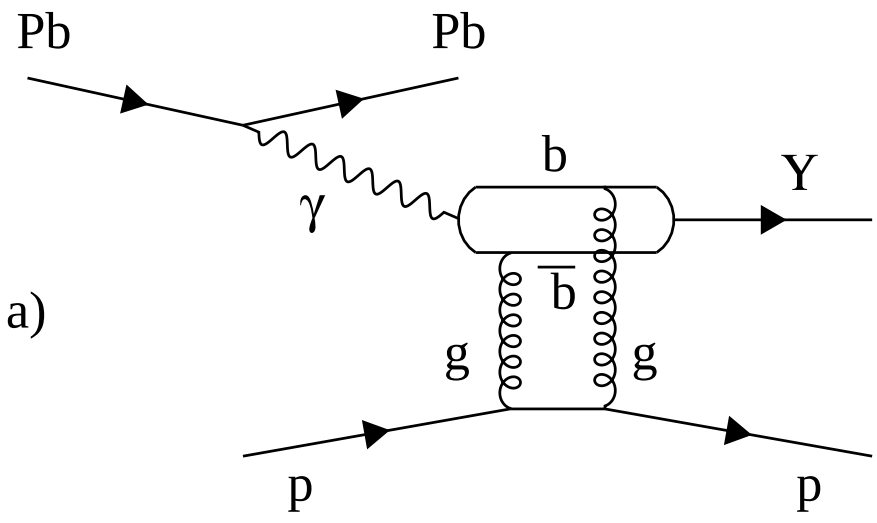


Comparison of measurements of transverse energy density $\mathrm{d}E_\mathrm{T}/\mathrm{d}\eta'$



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

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



- Exclusive photoproduction of vector bosons can be studied in ultraperipheral pPb collisions.
- Photoproduction of quarkonia offers a clean probe of gluon densities of the proton at $x_{\mathrm{Bj}} = 10^{-4} - 10^{-2}$ at $Q^2 \sim m_{\Upsilon}^2$, potentially where saturation effects may play a role.
- The larger mass of the Υ meson provides a larger perturbative scale at which the gluon PDF is sampled, thereby reducing theoretical uncertainties in pQCD calculations.

Analysis strategy

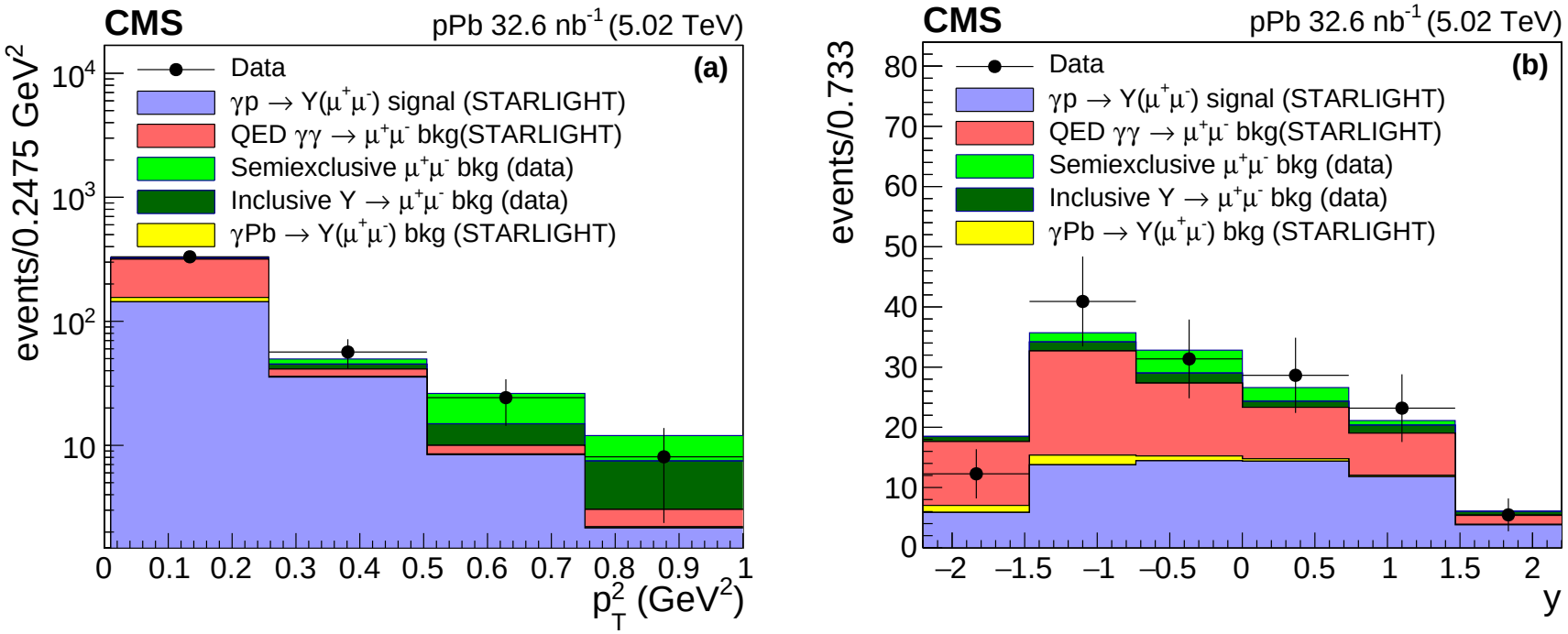
- Study Υ(nS) $\rightarrow \mu^+\mu^-$ decays in UPCs.
- Measure differential cross sections $\mathrm{d}\sigma/\mathrm{d}y_\Upsilon$ and $\mathrm{d}\sigma/\mathrm{d}p_T^2$ and $\sigma(\gamma p \rightarrow \Upsilon p)$ as a function of $W_{\gamma p}$
- Comparison of results with previous measurements at H1, ZEUS and LHCb
- Comparison of results with various treatments of low-x_{Bj} gluon densities

Data sample

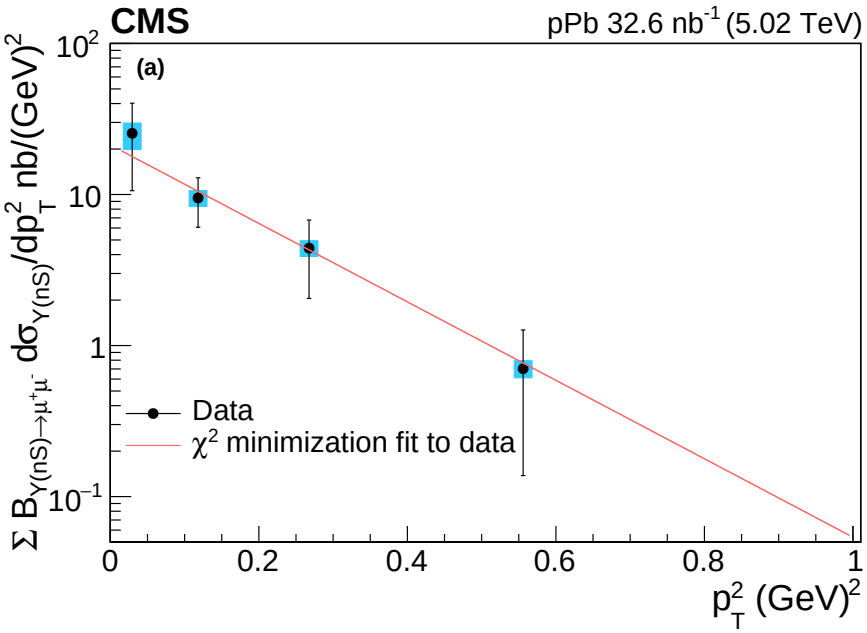
pPb (Pbp) collisions at $\sqrt{s_{NN}} = 5.02$ TeV and 32.6 nb^{-1} of data by CMS

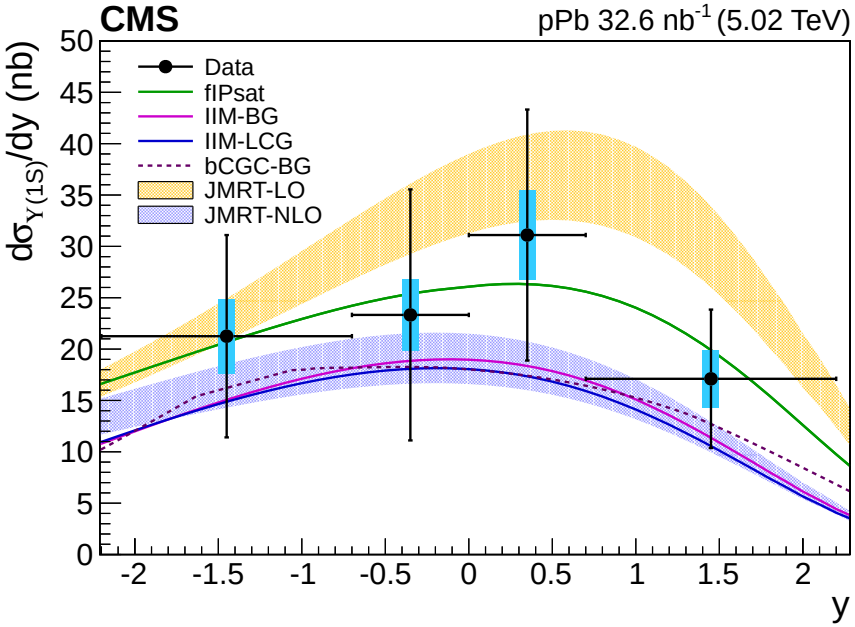
Selection

- High-level trigger requirement: $n_\mu \geq 1$ and $1 \geq N_{Track} \geq 6$
- Offline requirements:
  - Two oposite-charge muon pair with a single vertex and no extra charged-particles with $p_{\mathrm{T}} > 0.1$ GeV.
  - Offline, each muon has $p_{\mathrm{T}}^{\mu} > 3.3$ GeV and $|\eta^{\mu}| < 2.2$ in the lab frame.
  - No calorimeter-energy deposits with $E > 5$ GeV in $3 < |\eta| < 5.2$ in forward region.
  - $\Upsilon(nS)$ mass window restricted to $9.1 < m_{\mu\mu} < 10.6$ GeV, for $n = 1, 2, 3$.

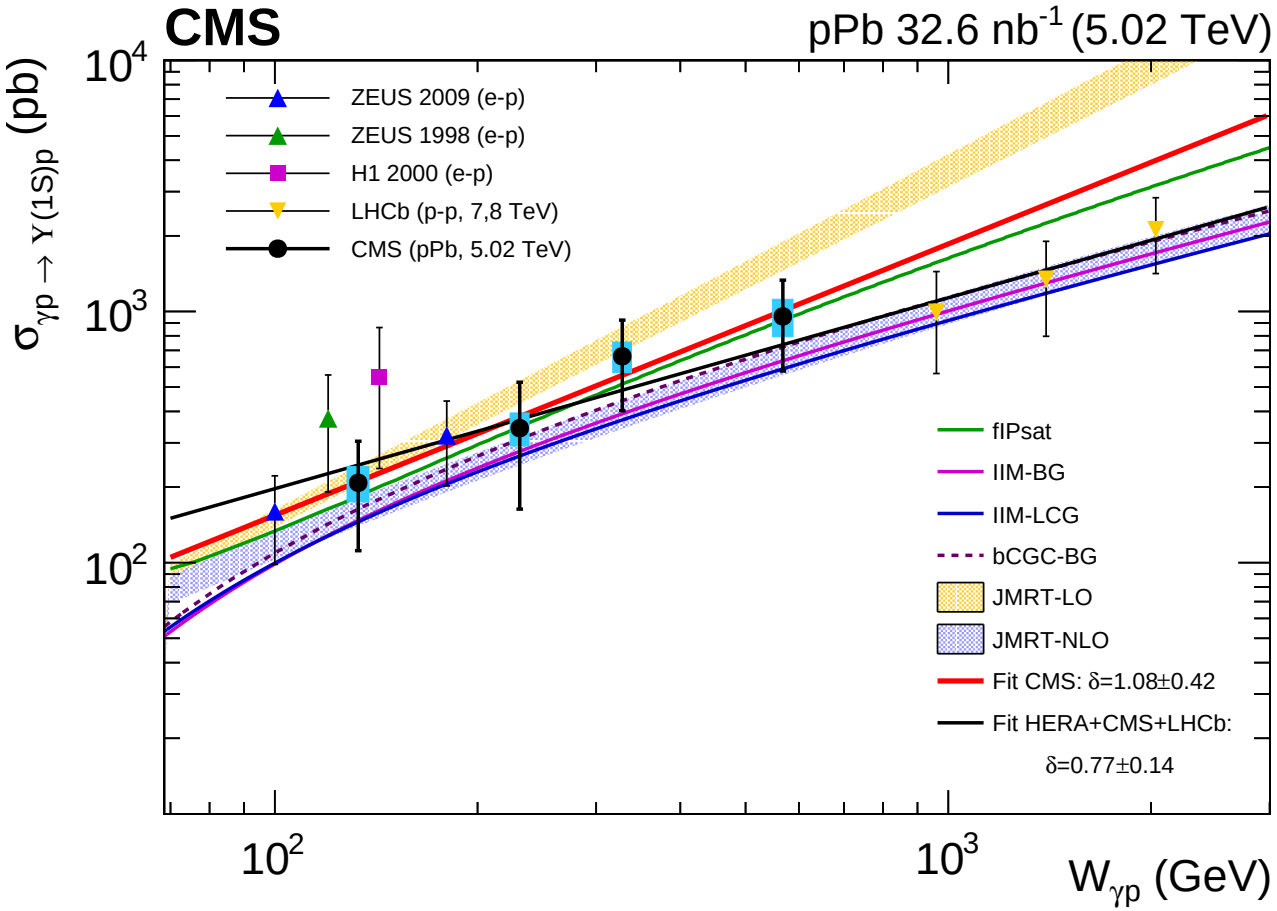


- Photoproduction contributions ($\gamma\gamma \to \mu^+\mu^-$, $\gamma p \to \Upsilon p$, γPb $\to \Upsilon$Pb) are simulated with STARLIGHT generator.
- Inclusive (Drell-Yan) and semi-exclusive Υ residual contaminations are determined from data based on templates built by modifying selection requirements.





- Extract a slope of $b = 6.0 \pm 2.1(\text{stat}) \pm 0.3(\text{syst})$ GeV^{-2} with $\exp(-bp_T^2)$ fit, in agreement with the value measured by ZEUS at lower masses $b = 4.3^{+2.0}_{-1.3}(\text{stat})^{+0.5}_{-0.6}(\text{syst})$ 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).



- $W_{\gamma p}$ is related to rapidity of Υ in lab frame via $W^2_{\gamma p} = 2E_p m_\Upsilon \exp(\pm y)$, 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 $A(W_{\gamma p}/400\ \mathrm{GeV})^\delta$ yields $\delta = 1.08 \pm 0.42$, consistent with value by ZEUS $\delta = 1.2 \pm 0.8$.

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 the average very forward energy as a function of track multiplicity at central pseudorapidities in proton-proton collisions at $\sqrt{s} = 13$ TeV, Submitted to EPJC, arXiv:1908.01750
  - 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**
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