Low-x Results from CMS

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(on behalf of the CMS Collaboration)

Low-x Meeting 2016: The 24th Low-x Meeting
6-11 June 2016, Károly Róbert College,
Gyöngyös, Hungary

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Outline

pp @ 13 TeV

Measurement of the pseudorapidity dependence of the energy and transverse energy density
CMS PAS FSQ-15-006 (April, 2016)

Measurement of the energy distribution in the very forward direction
CMS PAS FSQ-16-002 (April, 2016)

Measurement of the very forward inclusive jet cross section
CMS PAS FSQ-16-003 (April, 2016)

pp @ 7 TeV

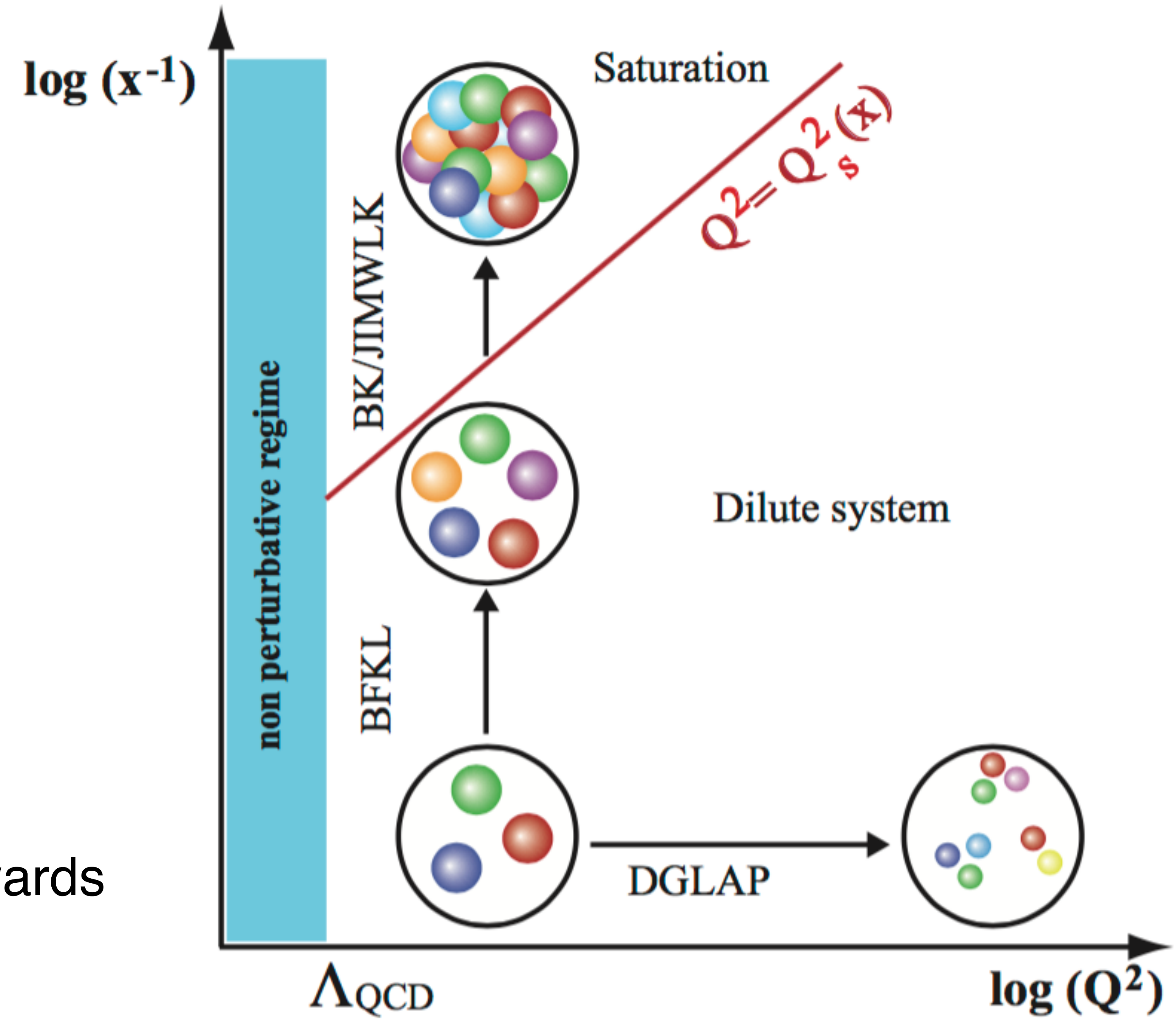
Azimuthal angle decorrelation of jets widely separated in rapidity
arXiv:1601.06713 (submitted to JHEP)

Probing the low-x regions

Low-x dynamics:
parton saturation, BFKL/CCFM dynamics, proton structure, multiparton scattering..

$$x \sim \frac{p_T}{\sqrt{s}} e^{-|y|}$$

low-x = forward rapidity



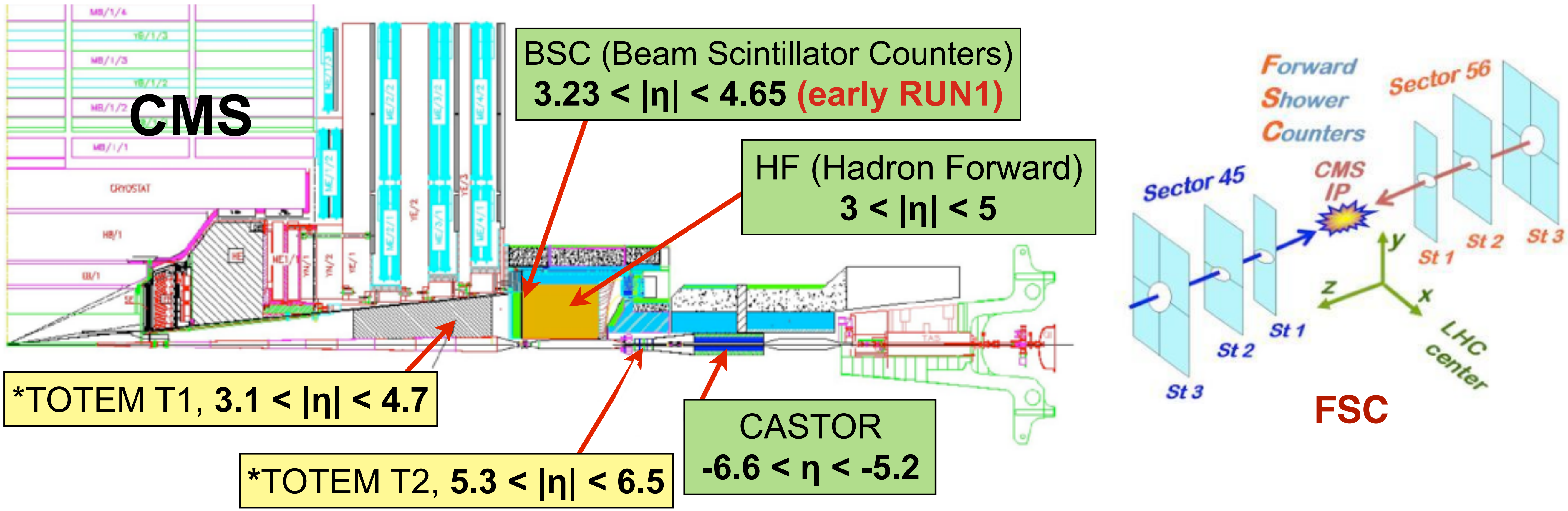
decreasing x ($Q^2 < Q^2_s$) → evolution towards to **high density system**.

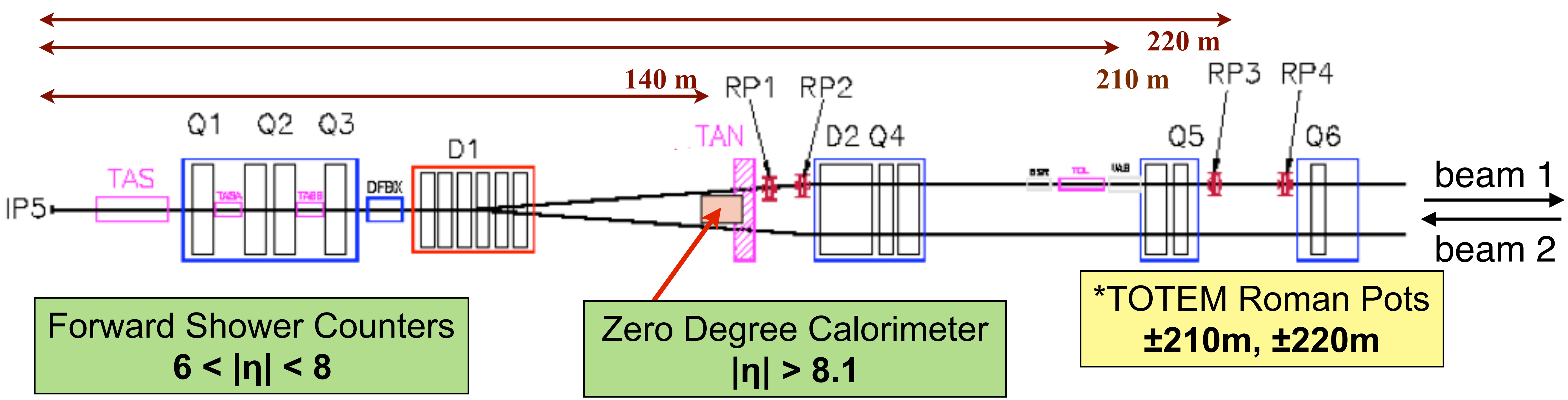
increasing Q^2 ($Q^2 > Q^2_s$): evolution towards the dilute system

saturation scale Q^2

QCD evolution of the structure functions?

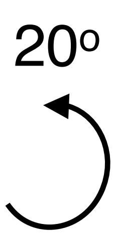
CMS Forward Detectors

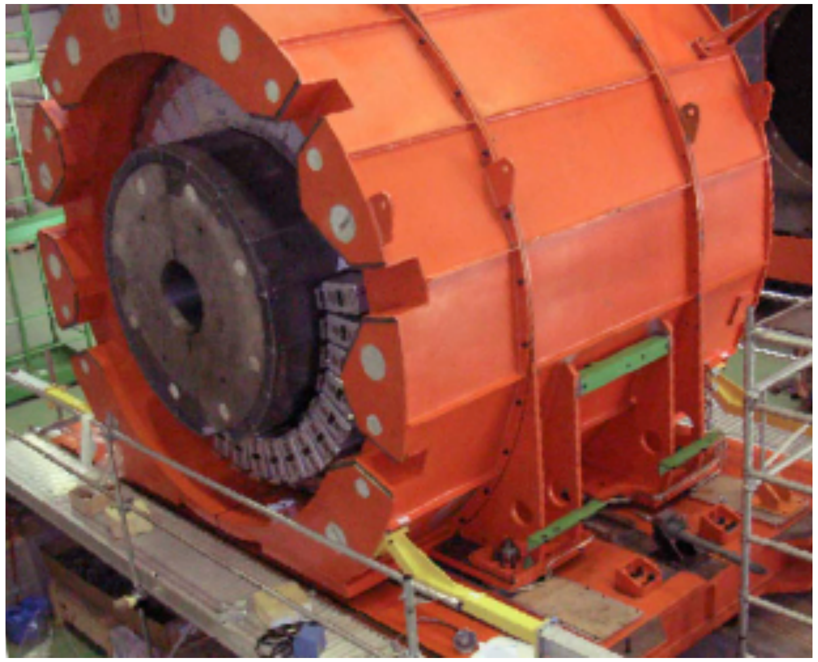




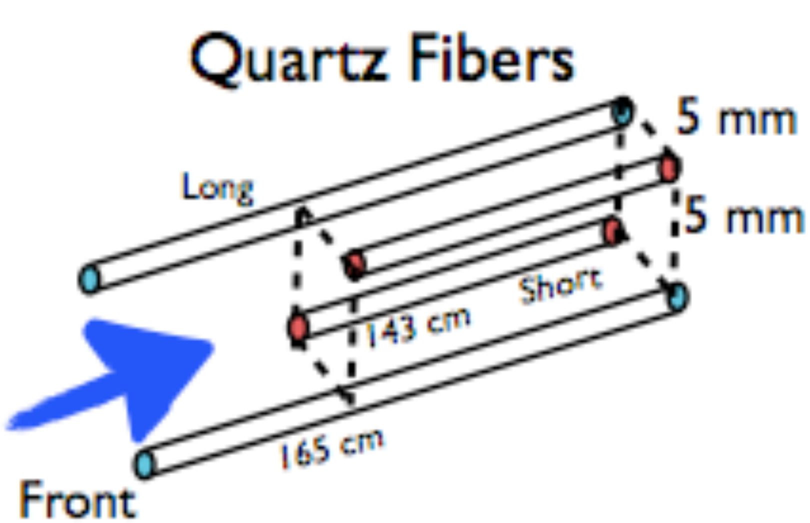
*TOTEM is a separate experiment.

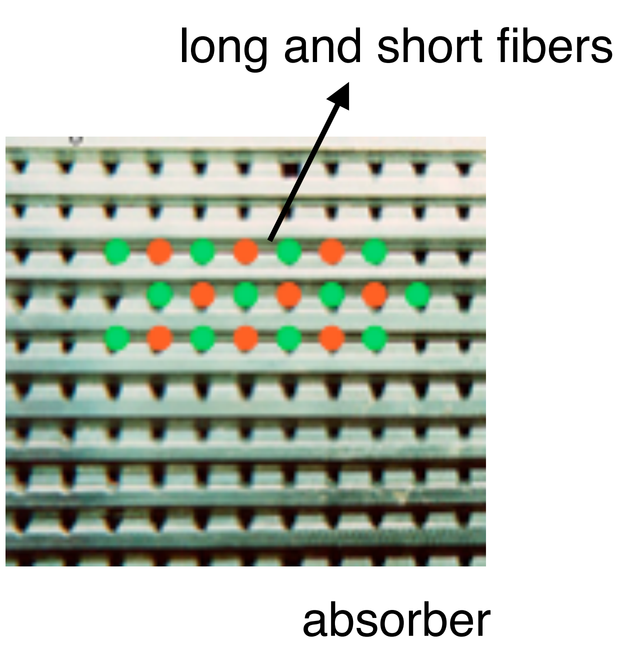
HF: **H**adron **F**orward





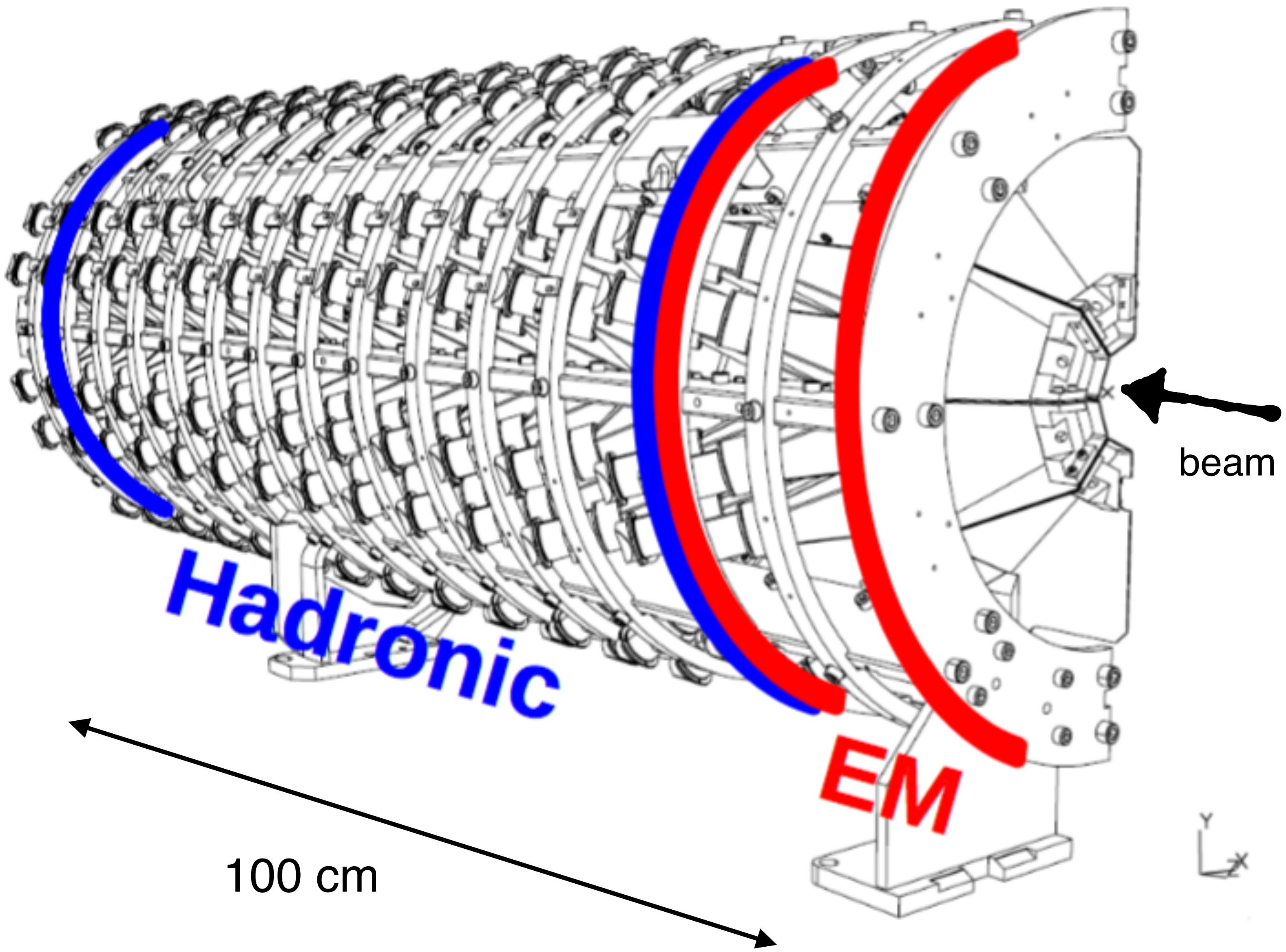
- 11.2 m away from IP5. At both sides of CMS: HF- and HF+
- 18 iron ϕ wedges of 20^{o}.
- Long+short quartz fibres.
  (Electromagnetic and Hadronic)
- Rapidity coverage: **3 < Iηl < 5**
- Energy scale ±10%





CMS Very Forward Calorimeter (CASTOR)

CASTOR: **C**entauro **A**nd **ST**range **O**bjects **R**esearch



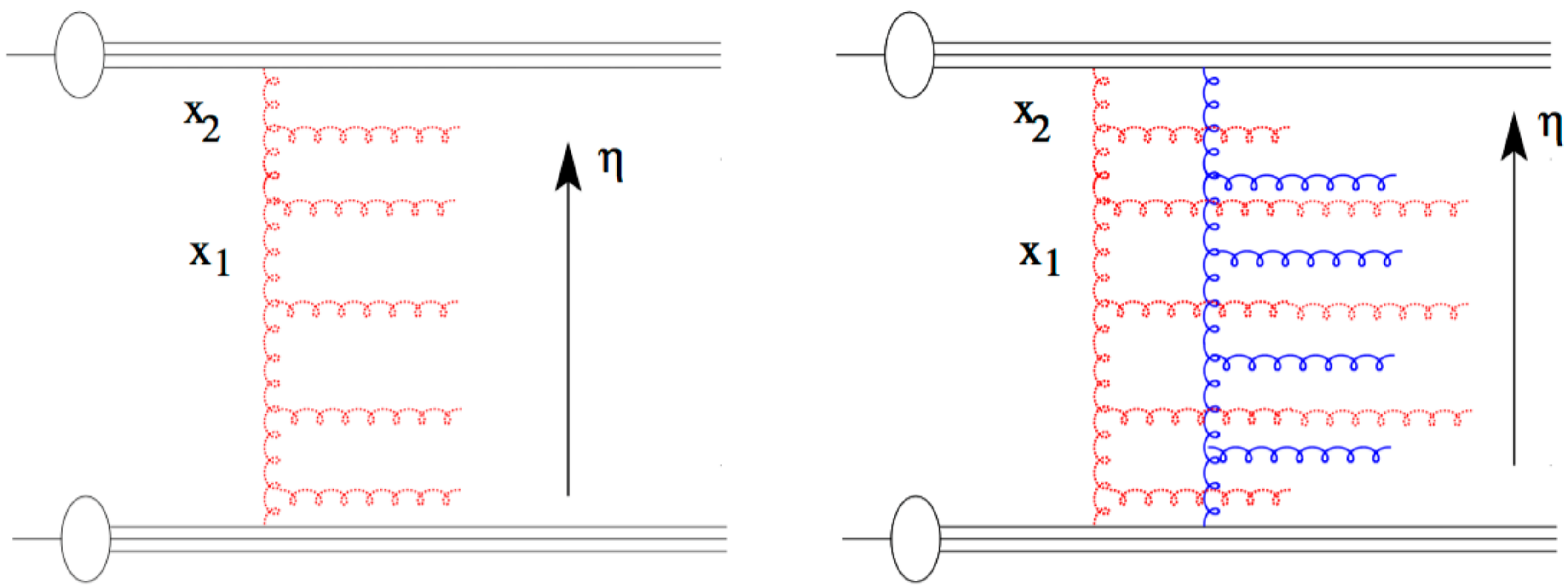
- 14 m away from IP5. Only at minus side.
- Tungsten-Quartz-Cherenkov sampling calorimeter
- No segmentation in η. **-6.6 < η < -5.2**.
- 16-fold segmentation in φ (0.39 rad/section)
- 14-fold segmentation in z.
- Energy scale ±15%.

2 Electromagnetic modules
12 Hadronic modules

Energy and transverse energy density in the forward region

Motivation

- The model predictions differ a lot in the forward region.
- The energy dependence of multiple parton interactions is not well known.
- Study the parton radiation in the forward region.
- Another way to study underlying event. Tune the UE parameters in the forward region.



An earlier measurement from CMS at 0.9 and 7 TeV:
Measurement of energy flow at large pseudorapidities in pp collisions at sqrt(s) = 0.9 and 7 TeV, JHEP 11 (2011) 148.

Measurement

CMS PAS FSQ-15-006

Observables:

- dE / dη (sum of particle energies in each η bin)
- $dE_T / d\eta'$ ($\eta' = \eta$ - ybeam)

The energy flow is measured in $3.15 < |\eta| < 6.6$.

Event classes:

- Soft-inclusive events (single-arm)
- Non-single-diffractive-enhanced (NSD) events (double-arm)

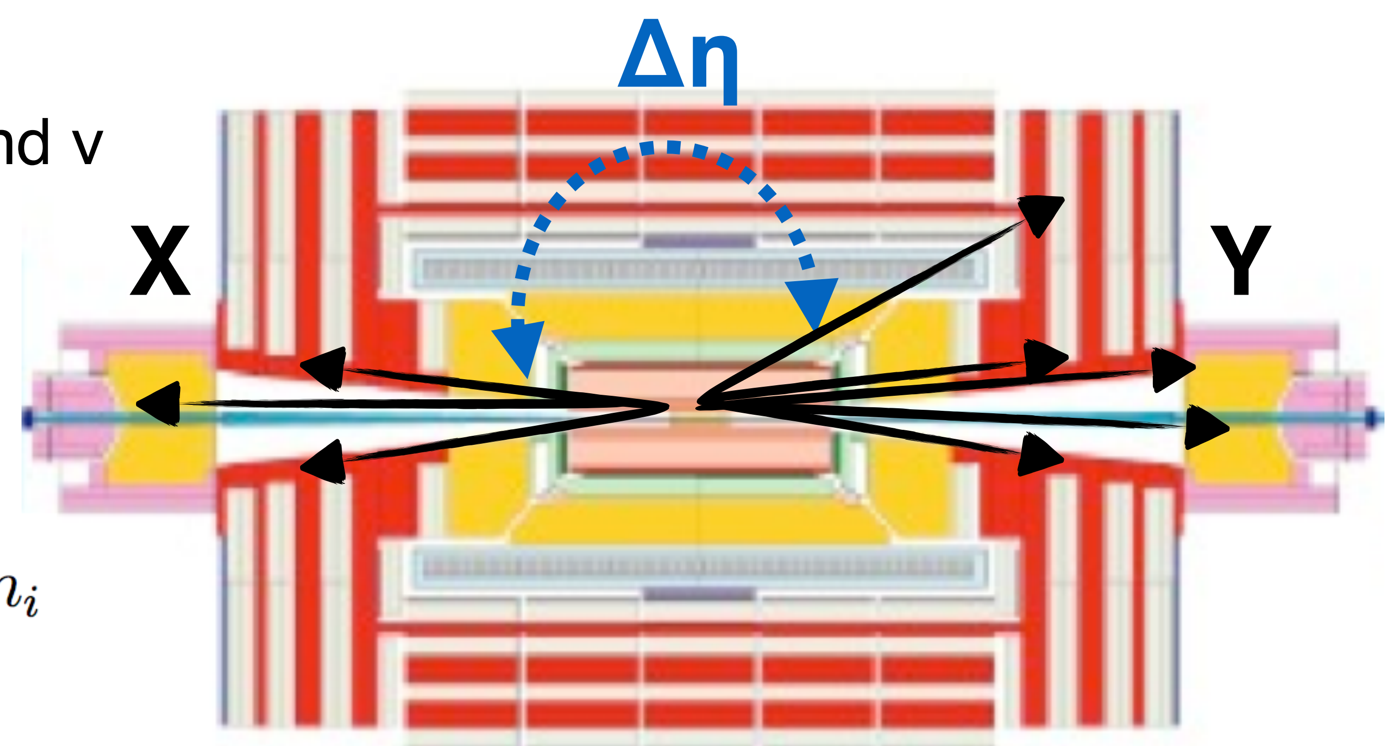
Correction to particle level:

stable particles with cτ > 10 mm, excl. μ and ν

$$\xi_X = \frac{M_X^2}{s}, \qquad \xi_Y = \frac{M_Y^2}{s}$$

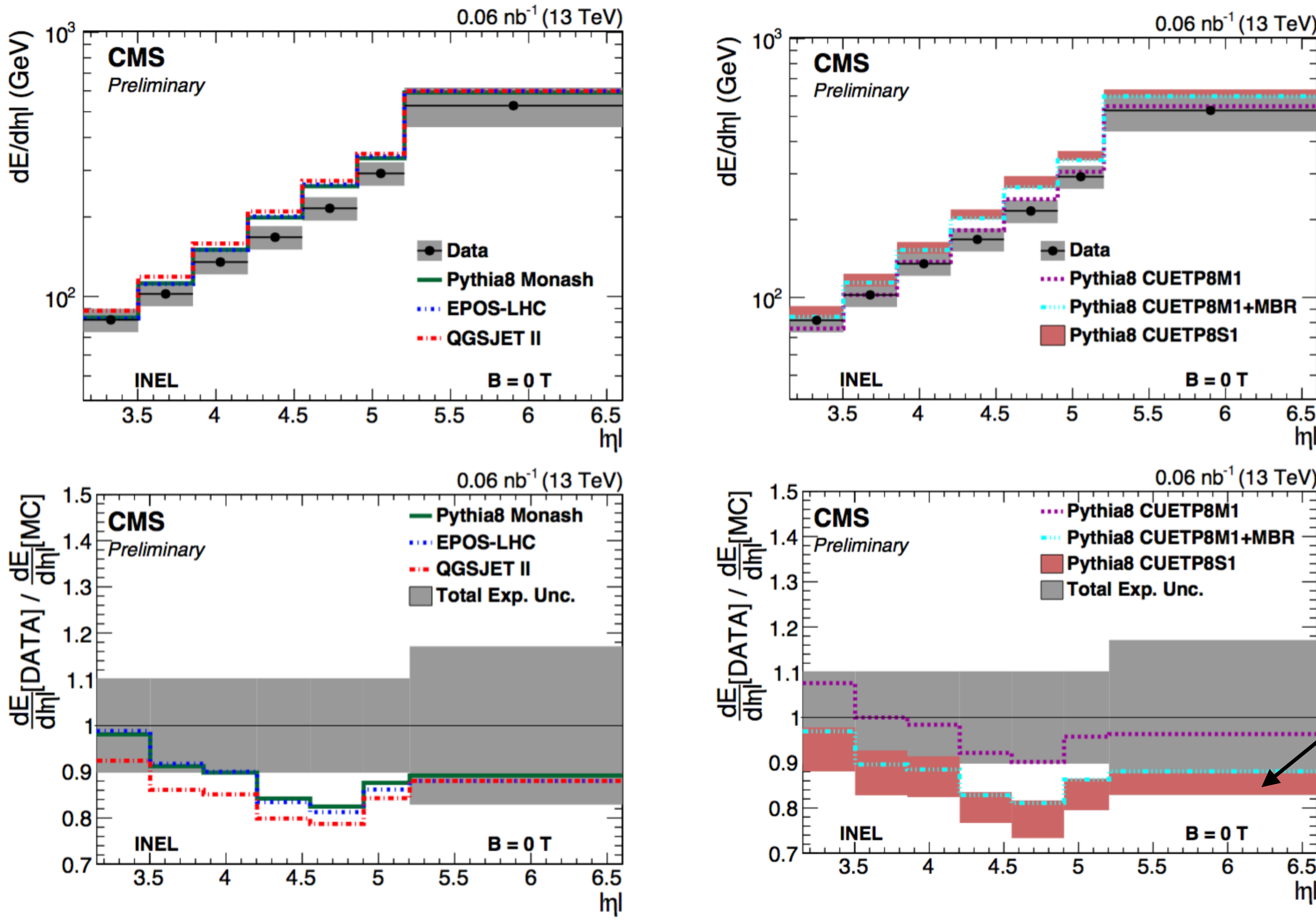
$\xi_{SD} = \max(\xi_X, \xi_Y)$

$$M_X = \sum_i m_i$$



dE/dη Soft-Inclusive Events

CMS PAS FSQ-15-006



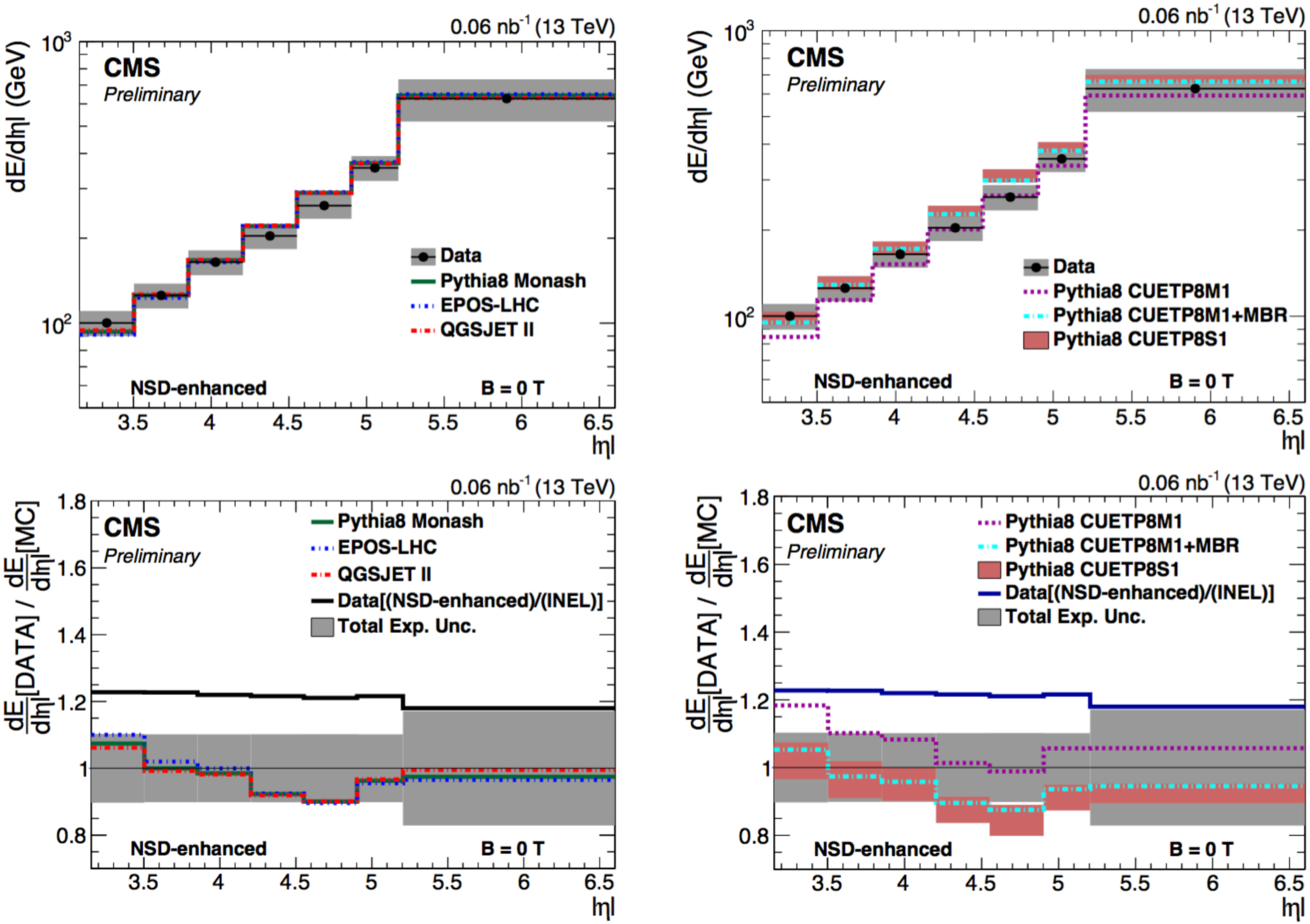
$\xi_{SD} > 10^{-6}$

red band: CUETS1 tune uncertainties

- Large spread of the model predictions in HF region, 3.15 < |η| < 5.2.
- Better description of the data at low η and in the CASTOR region (5.2 < |η| < 6.6).
- PYTHIA8 CUETM1 has the best description of the data.

dE/dη NSD-enhanced Events

CMS PAS FSQ-15-006

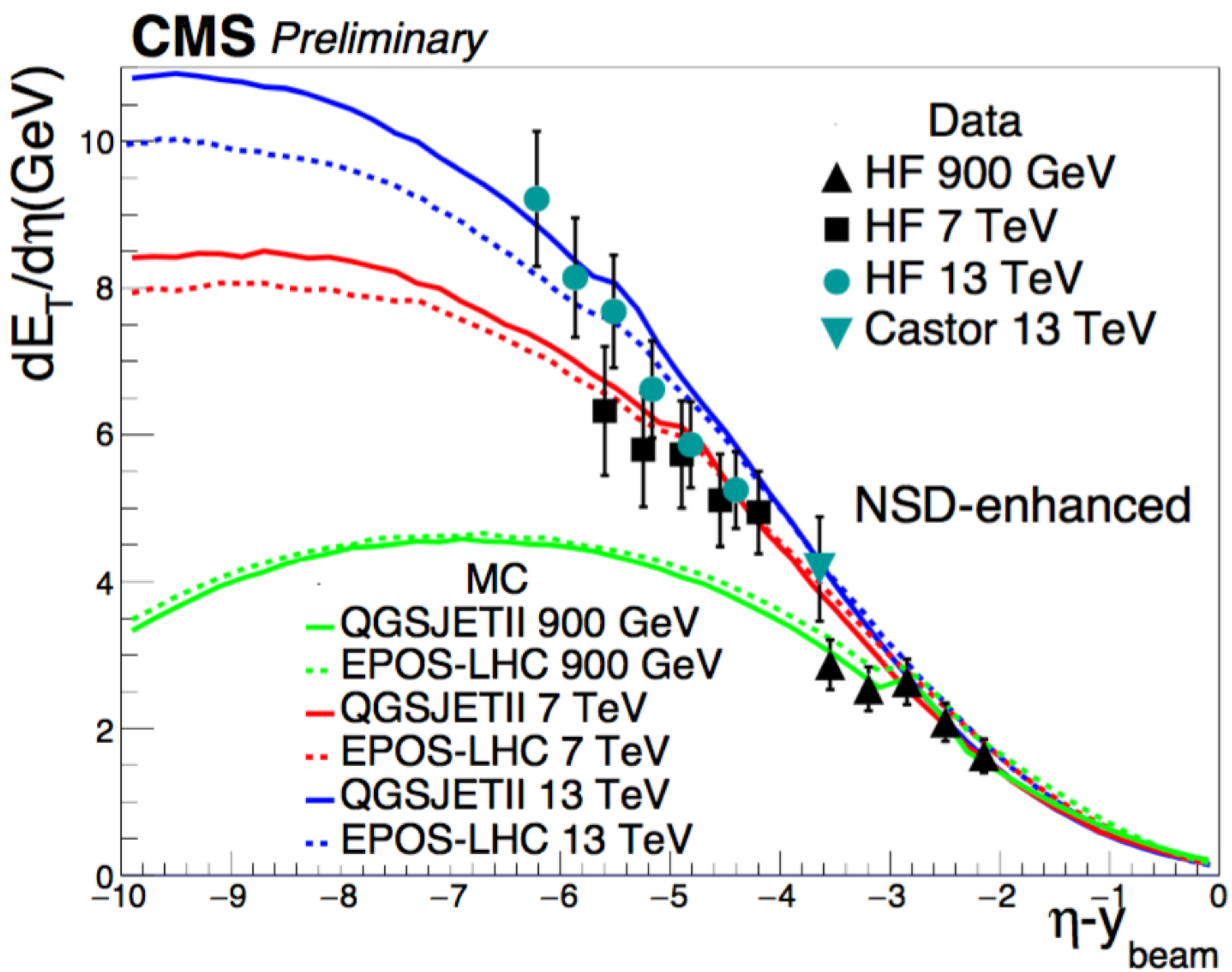


at least one particle (either charged or neutral) at each side of HF acceptance (used 3.15 < |η| < 5.2)

- The spread of model predictions is smaller compared to INEL events.
- EPOS-LHC and QGSJetII describe the data in the whole |η|.
- PYTHIA8 CUETM1 has the best description except at low |η|.

$dE_T/d\eta'$ NSD-enhanced Events

Shifted pseudorapidity variable; $\boldsymbol{\eta' = \eta - y_{beam}}$ (y_{beam} = beam rapidity)

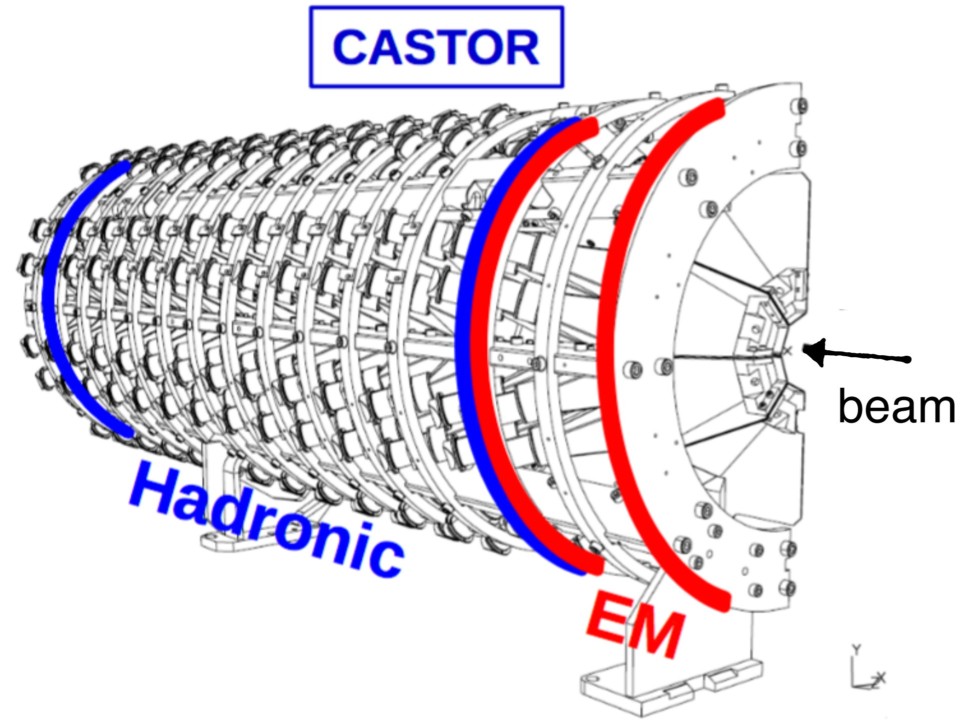


at least two charged particles in $3.9 < |\eta| < 4.4$

- compared to earlier CMS measurement, JHEP 11 (2011) 148.
- The results at different energies (from 900 GeV to 13 TeV) are consistent.

Very forward energy spectra

Measurement



Observable:

- dN / dE

Event classes:

- Soft-inclusive events, $\xi_{SD} > 10^{-6}$ (single-arm)

Total energy spectrum:

Detector level→ energy from all modules

Stable-particle level→ energy from all final state particles except μ and ν.

Electromagnetic energy spectrum:

energy from first 2 modules

energy from e^- and γ (incl. $\pi^0 \to \gamma\gamma$)

Hadronic energy spectrum:

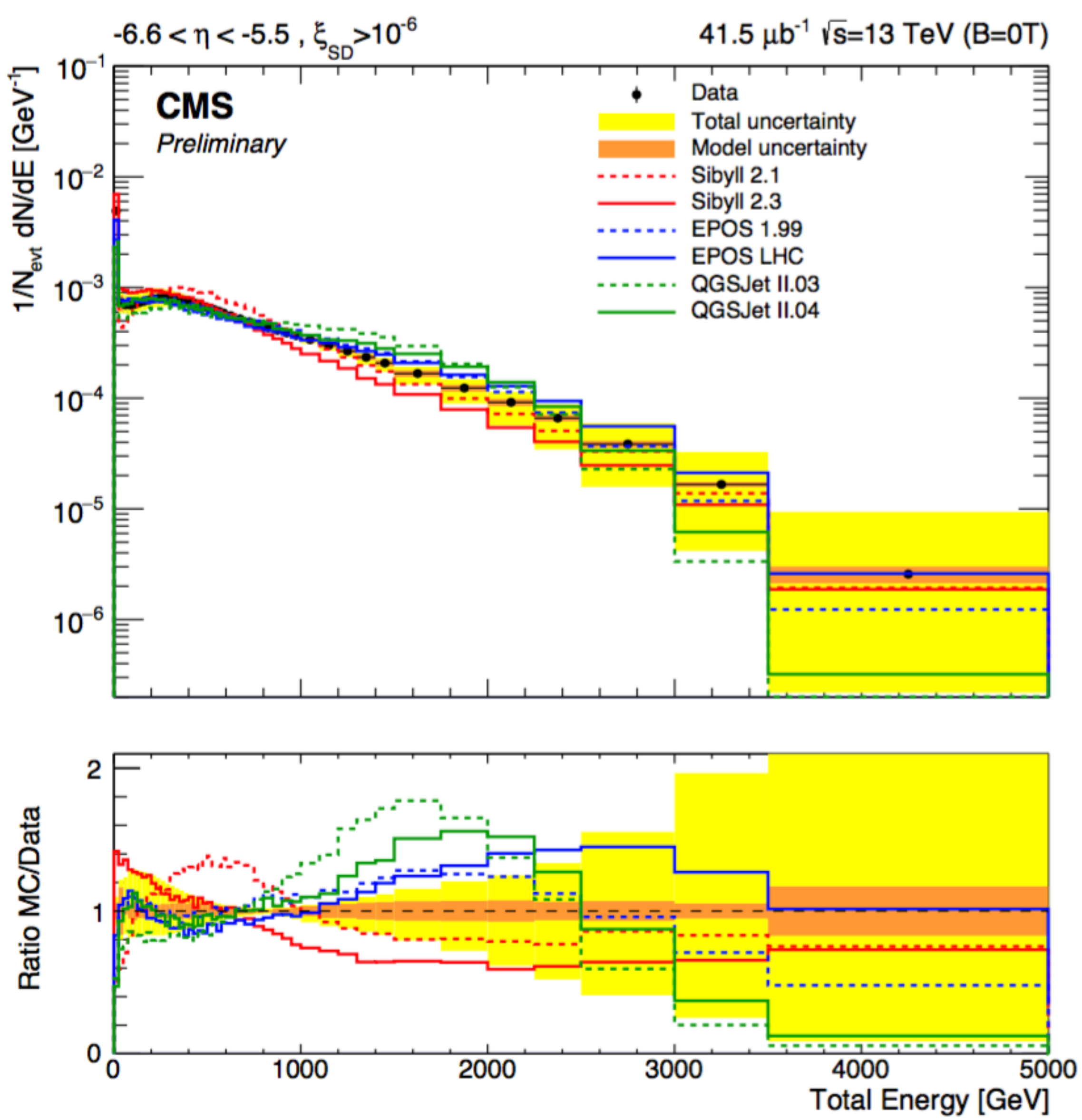
energy from last 12 modules

energy from all final state particles except e^-,γ, μ, and ν.

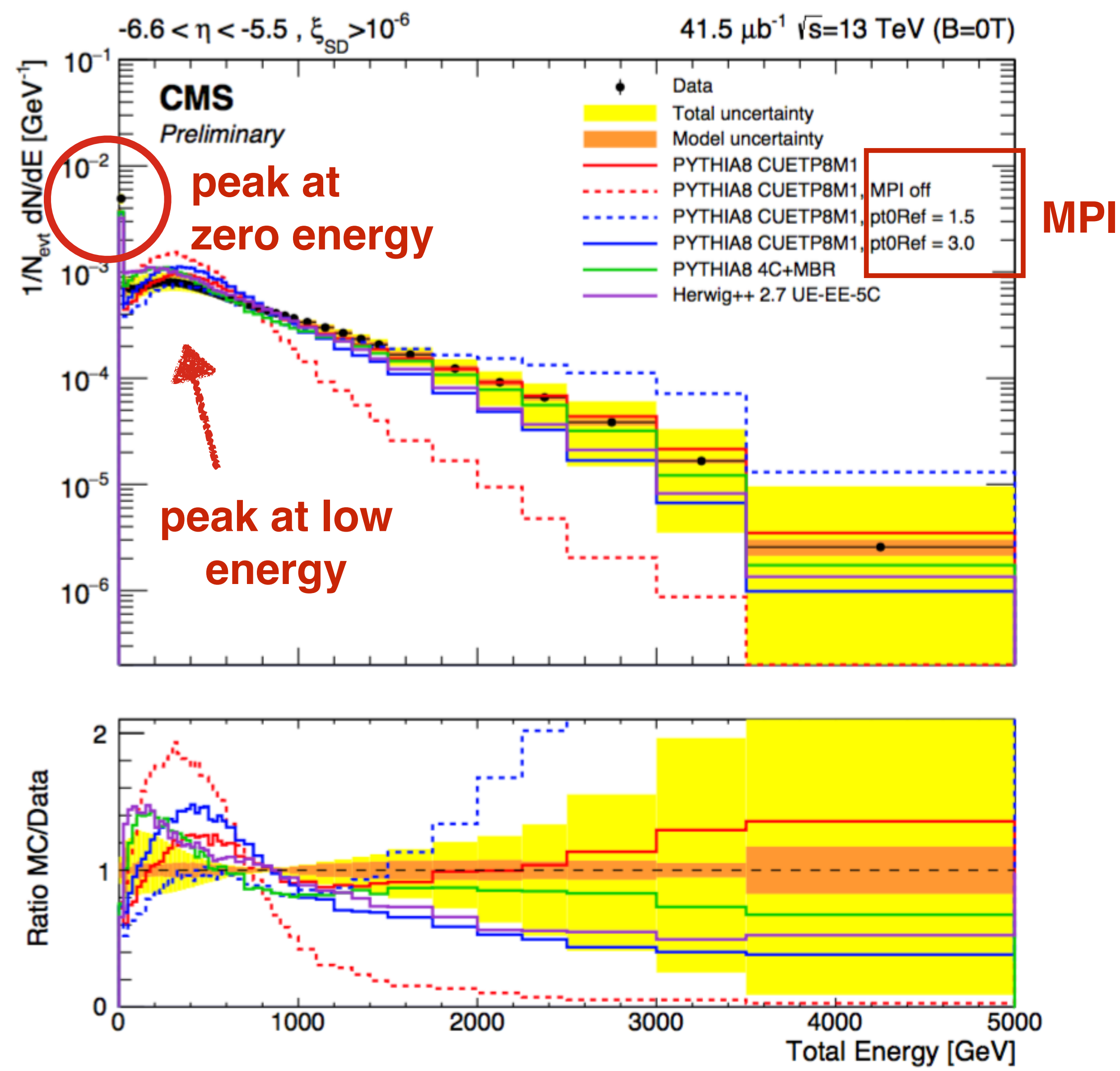
Total Energy Spectrum (dN/dE)

CMS PAS FSQ-16-002

Cosmic Ray models



PYTHIA and Herwig++ (Sensitivity to MPI and UE)

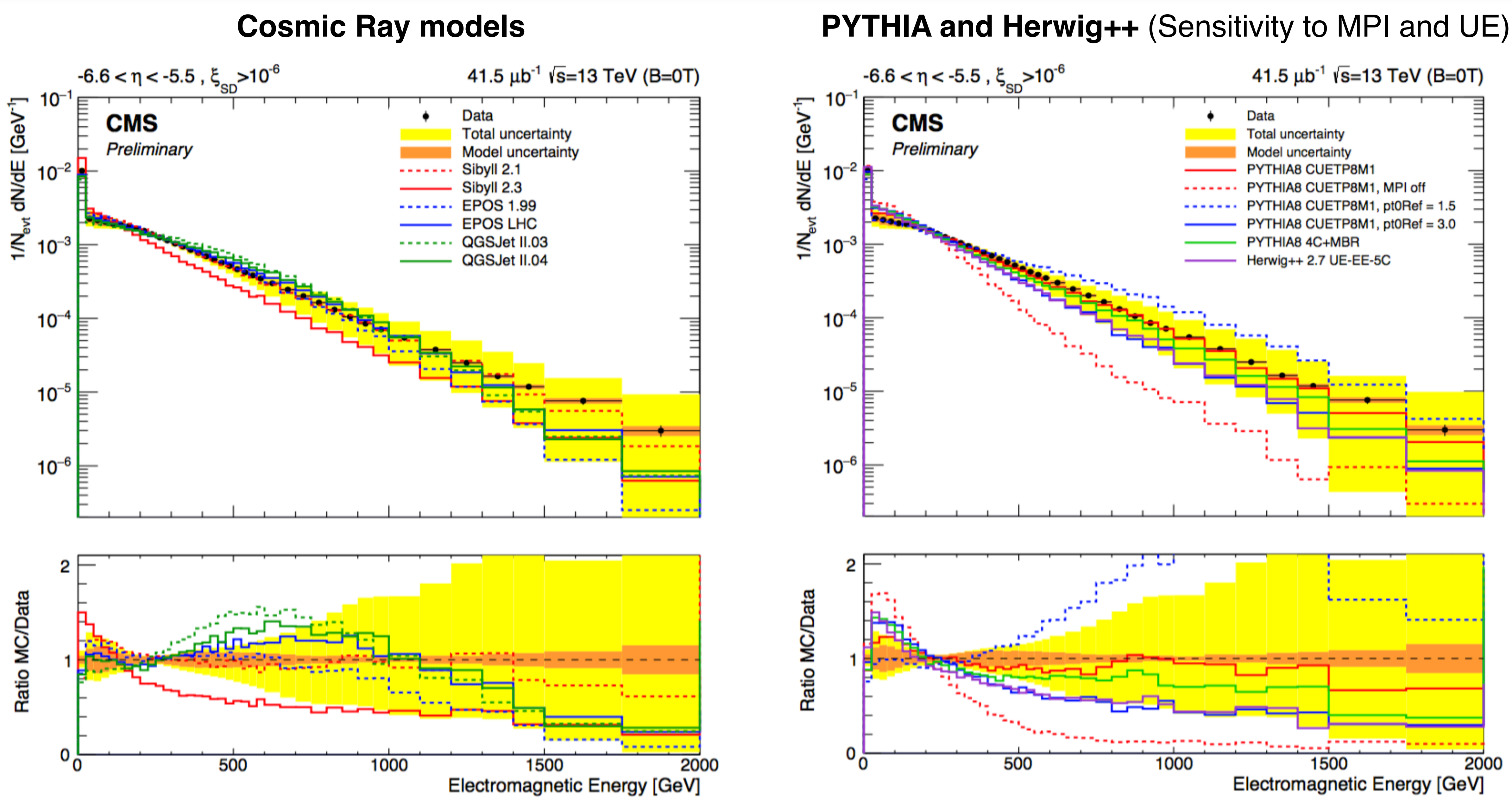


- A sharp peak at zero energy (residual contribution of diffractive events).
- Low energy peak (due to hadronic component) followed by a steep tail towards higher energies.
- None of the model describes the whole spectrum.
- The data is sensitive to MPI and UE.
- CASTOR energy scale is the dominant uncertainty (17%).

pT0Ref ~ MPI p_T cutoff scale. = 2.4024 for CUETM1.

Electromagnetic Energy Spectrum (dN/dE)

CMS PAS FSQ-16-002

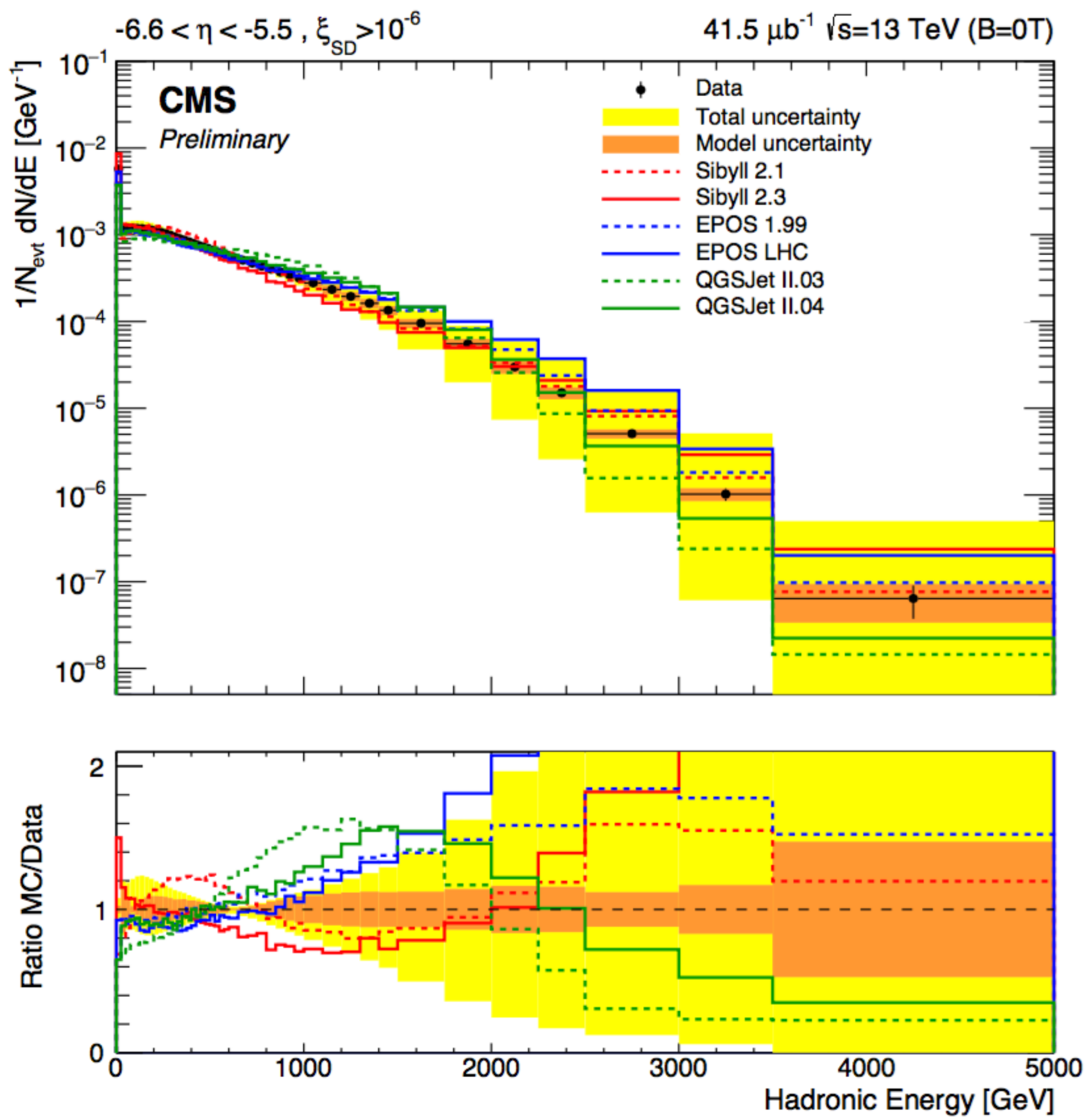


- No bump at low energy.
- Better description of the data by all models.
- The slope in the soft part is not well described by SIBYLL 2.3 and MBR.
- EM spectrum is very sensitive to MPI.

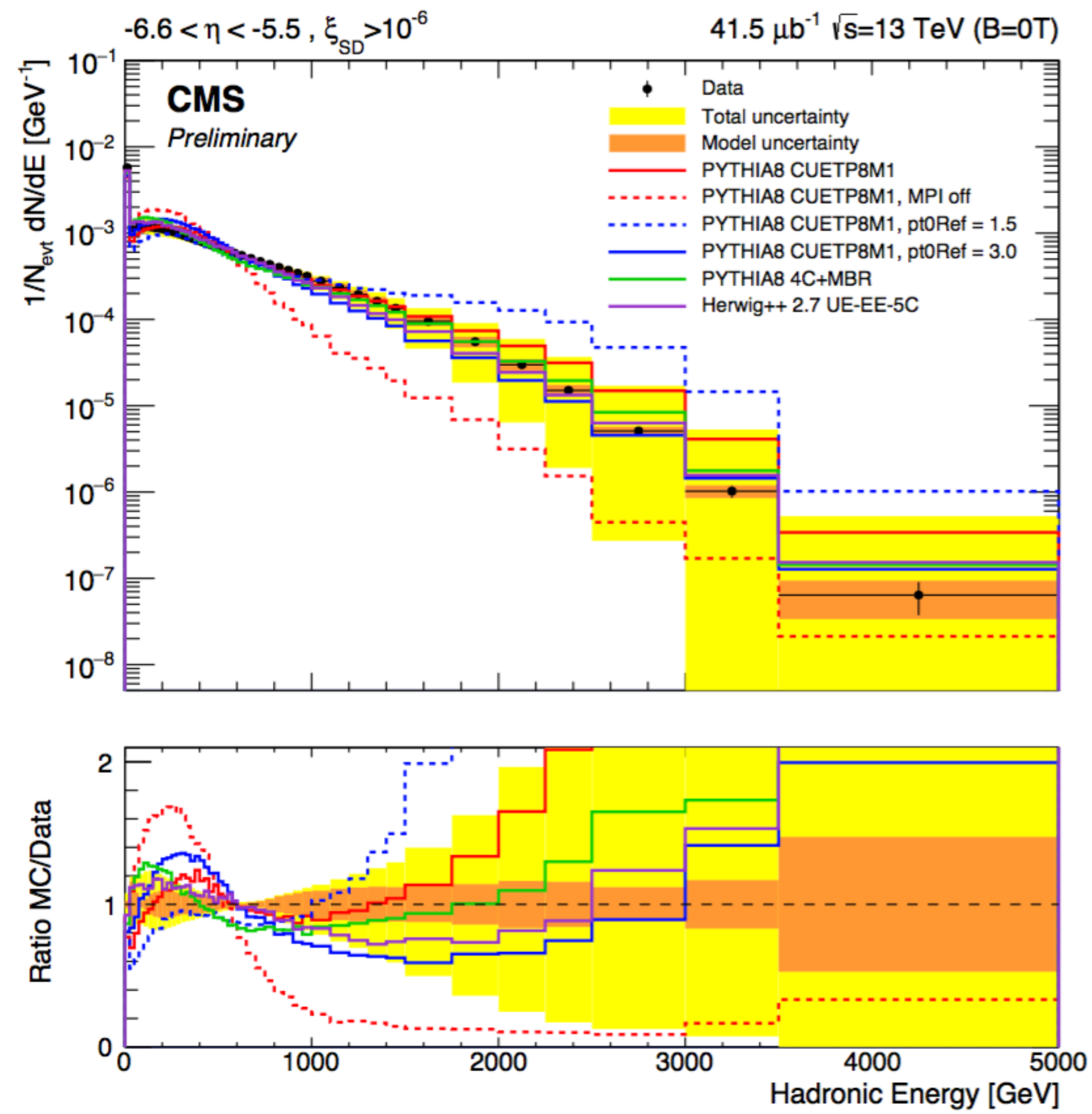
Hadronic Energy Spectrum (dN/dE)

CMS PAS FSQ-16-002

Cosmic Ray models



PYTHIA and Herwig++ (Sensitivity to MPI and UE)



- Peak at low energy. Shows that it is due to hadronic component.
- Sensitivity to MPI in hadronic component is also clearly visible.
- Soft part is reasonably well described by CR models. EPOS-LHC and QGSJetII differ a lot in high energy tail.
- CUETM1 overestimates the data in both low- and high-energy parts. The description is better with MBR and Herwig++.

Very forward inclusive jet cross section

Forward jets

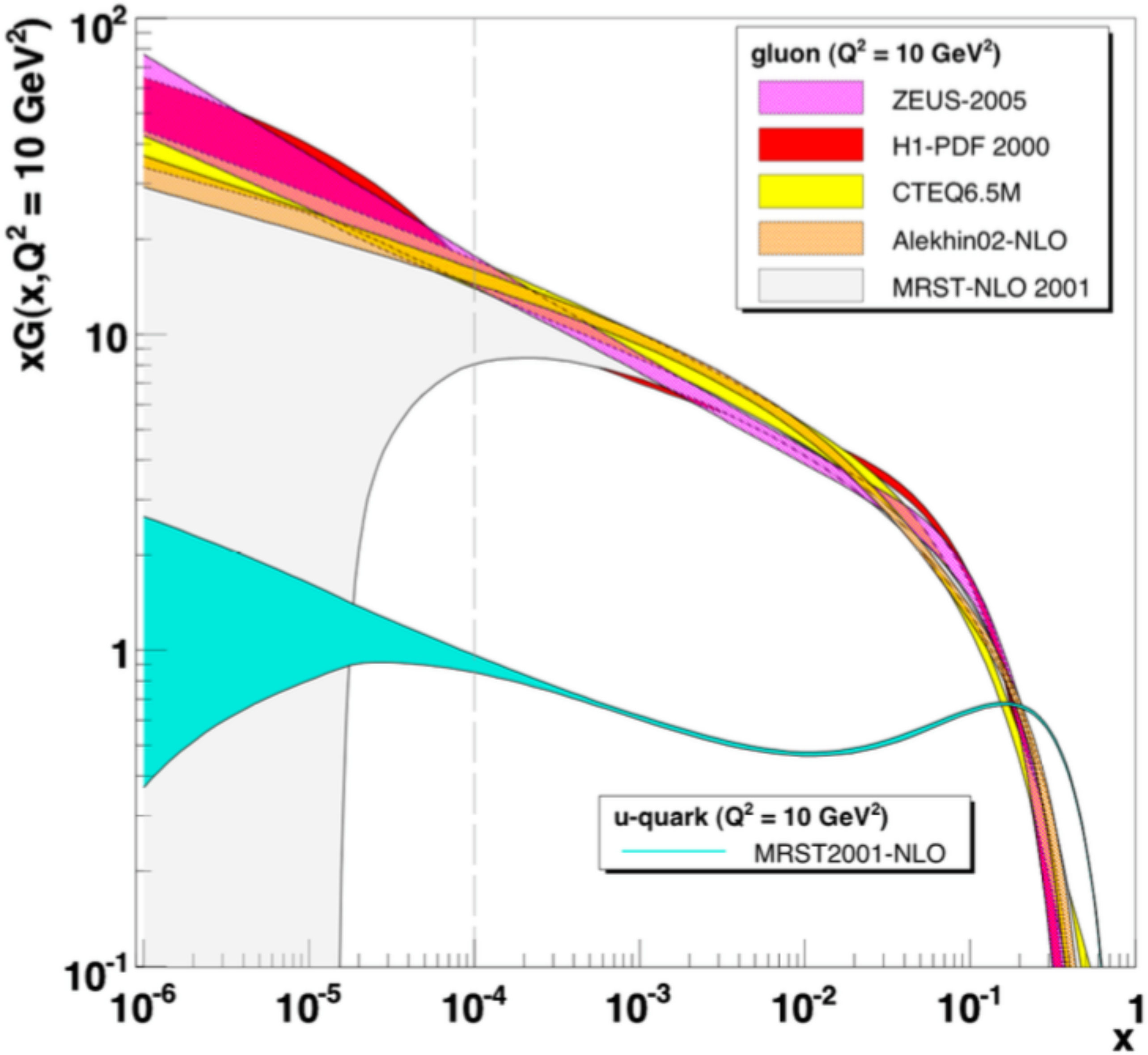
Low-x gluon density in proton is poorly known.

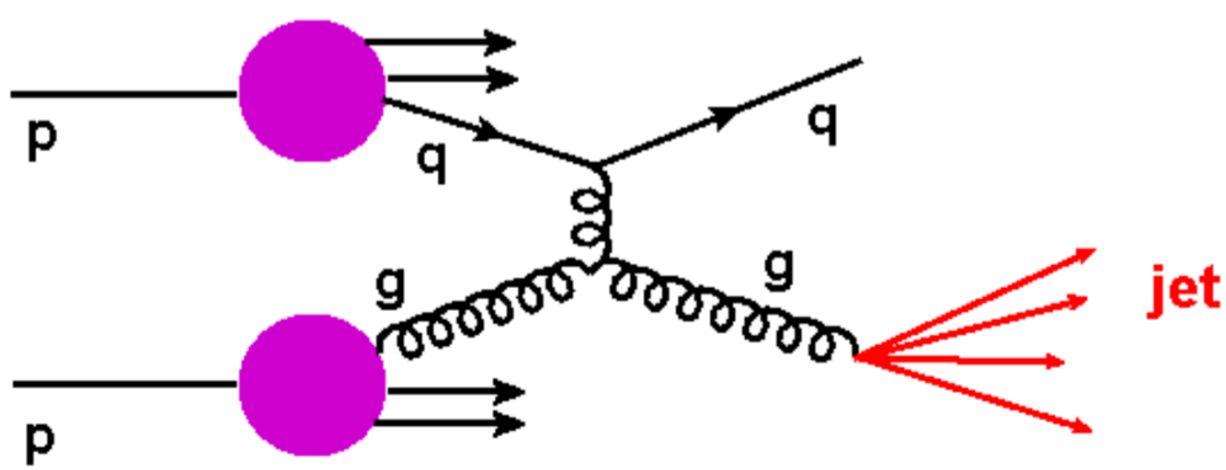
$$x \sim \frac{p_T}{\sqrt{s}} e^{-|y|}$$

high √s → low-x

jet production in CASTOR → $x \sim 10^{-6}$

Forward jet cross sections
constrain low-x gluon PDFs.





$$d\sigma(pp \to jet) = PDF(x_1, Q^2) \otimes PDF(x_2, Q^2) \otimes d\sigma(qg \to jet)$$

Measurement

CMS PAS FSQ-16-003

$E > 150$ GeV or $p_T > 3$ GeV in $-6.6 < \eta < -5.2$

$d\sigma / dp_T$ at 13 TeV:

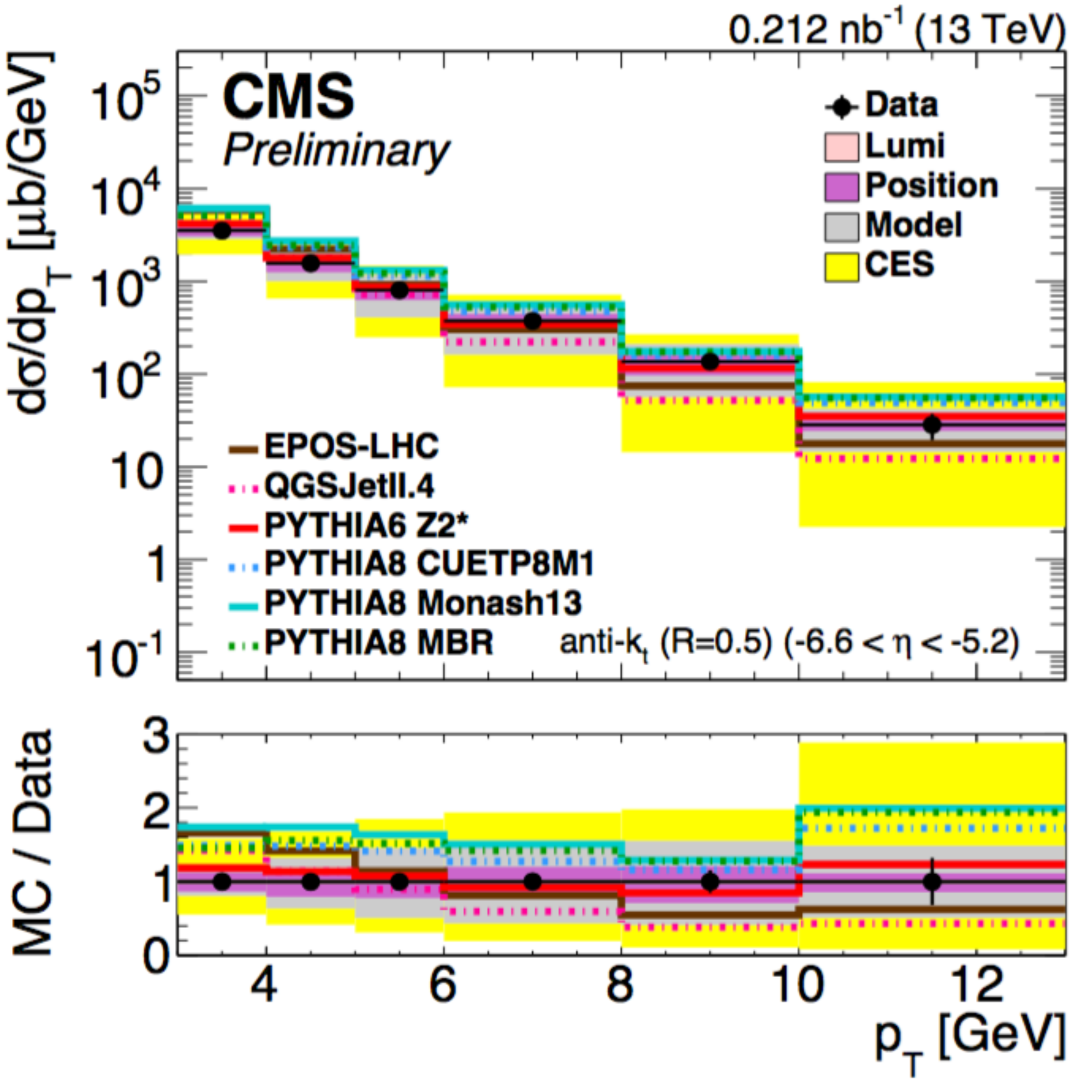
$p_{Tdet} \rightarrow p_{Thadron}$: Lorentz invariant but suffers from η

$\eta = -5.9$

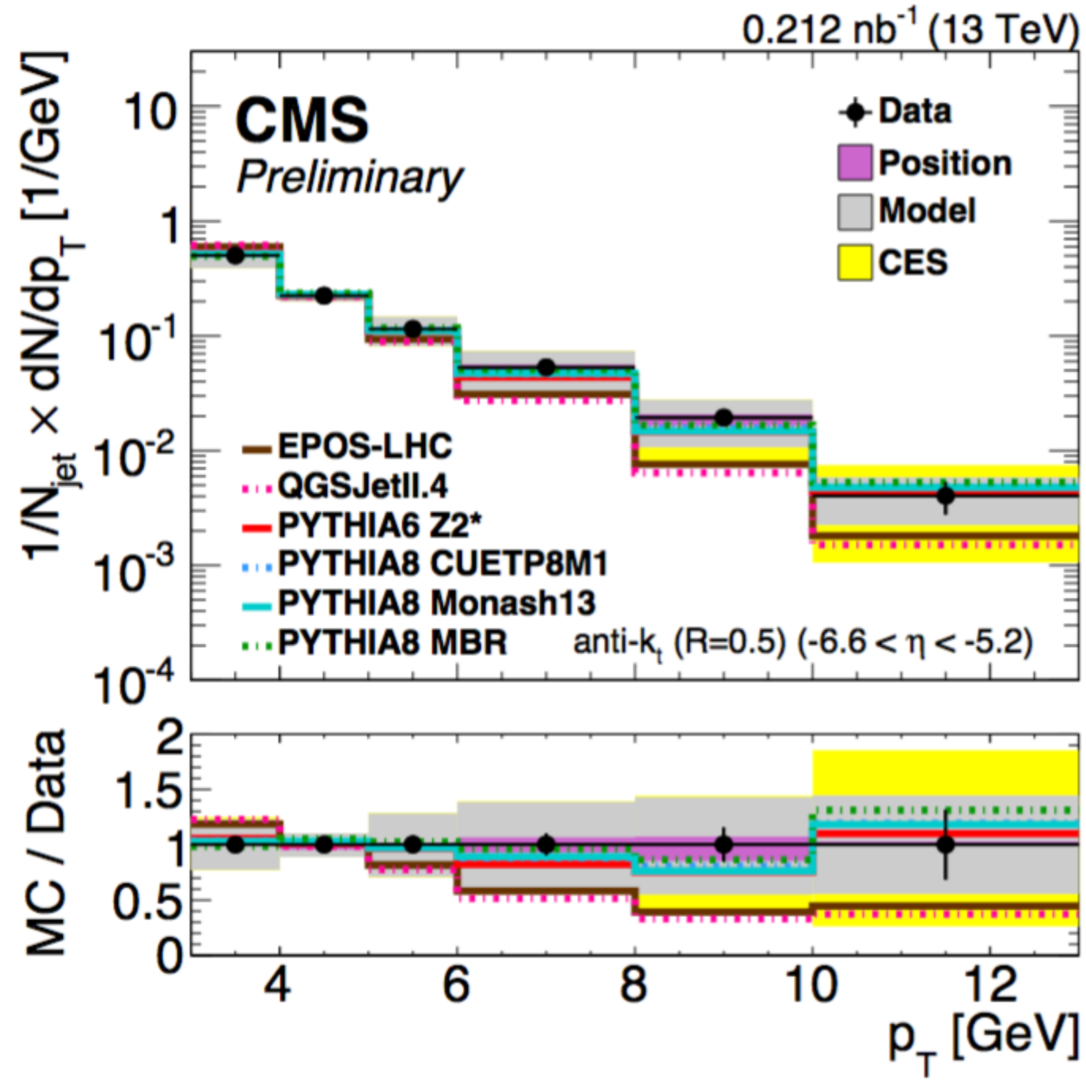
E_{jet} is converted to p_T by cosh(5.9)

Very forward jet cross section at 13 TeV

jet pT spectrum: normalized by $\mathcal{L}$



jet yield: normalized by number of visible jets

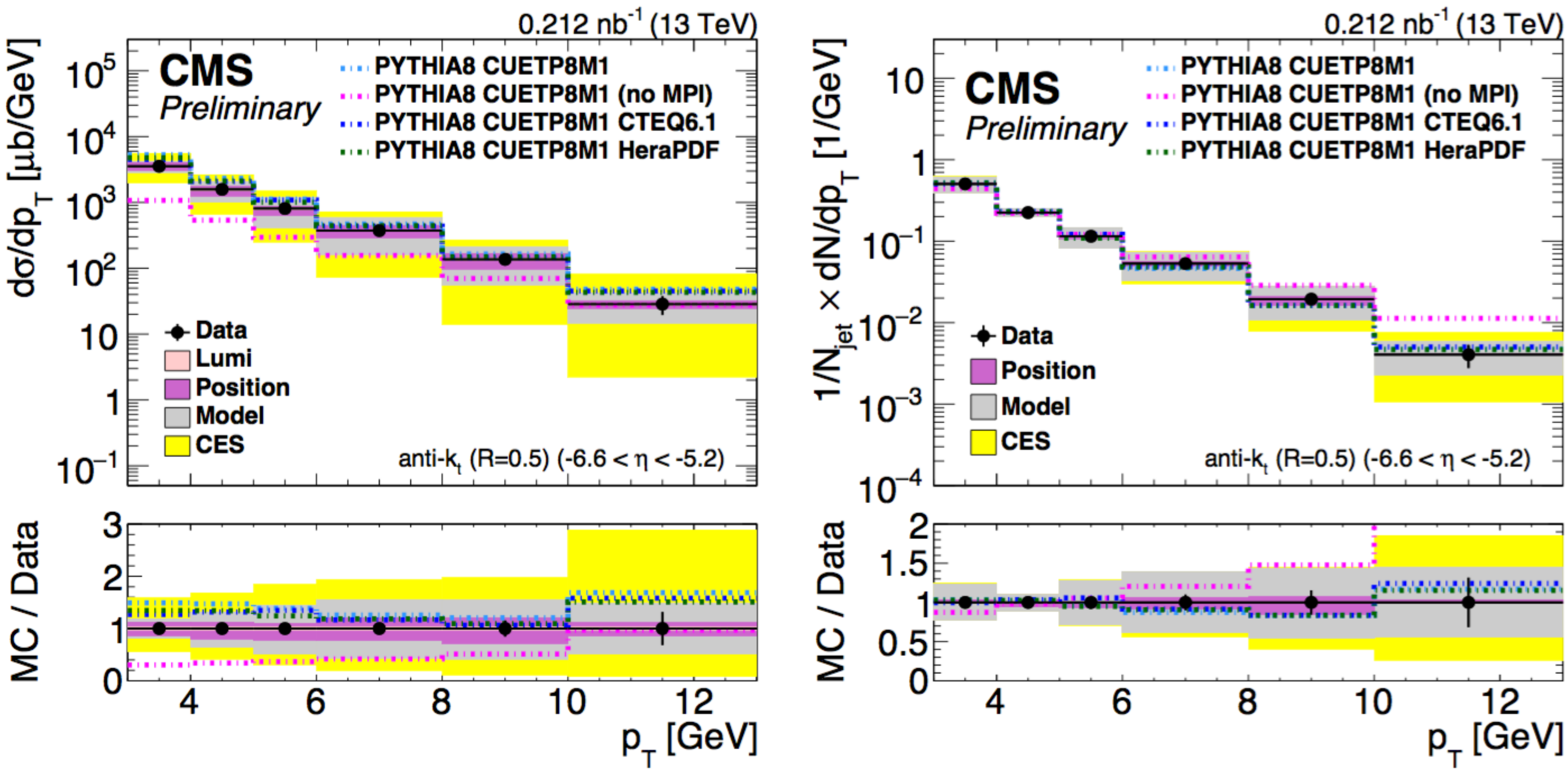


- Large uncertainty in particular due to CES. All models agree with the data within the large uncertainty.
- All PYTHIA flavors slightly overestimate the data while EPOS-LHC and QGSJet have a different trend. They tend to decrease with increasing p_T.

Very forward jet cross section at 13 TeV

CMS PAS FSQ-16-003

Sensitivity to PDF and MPI?



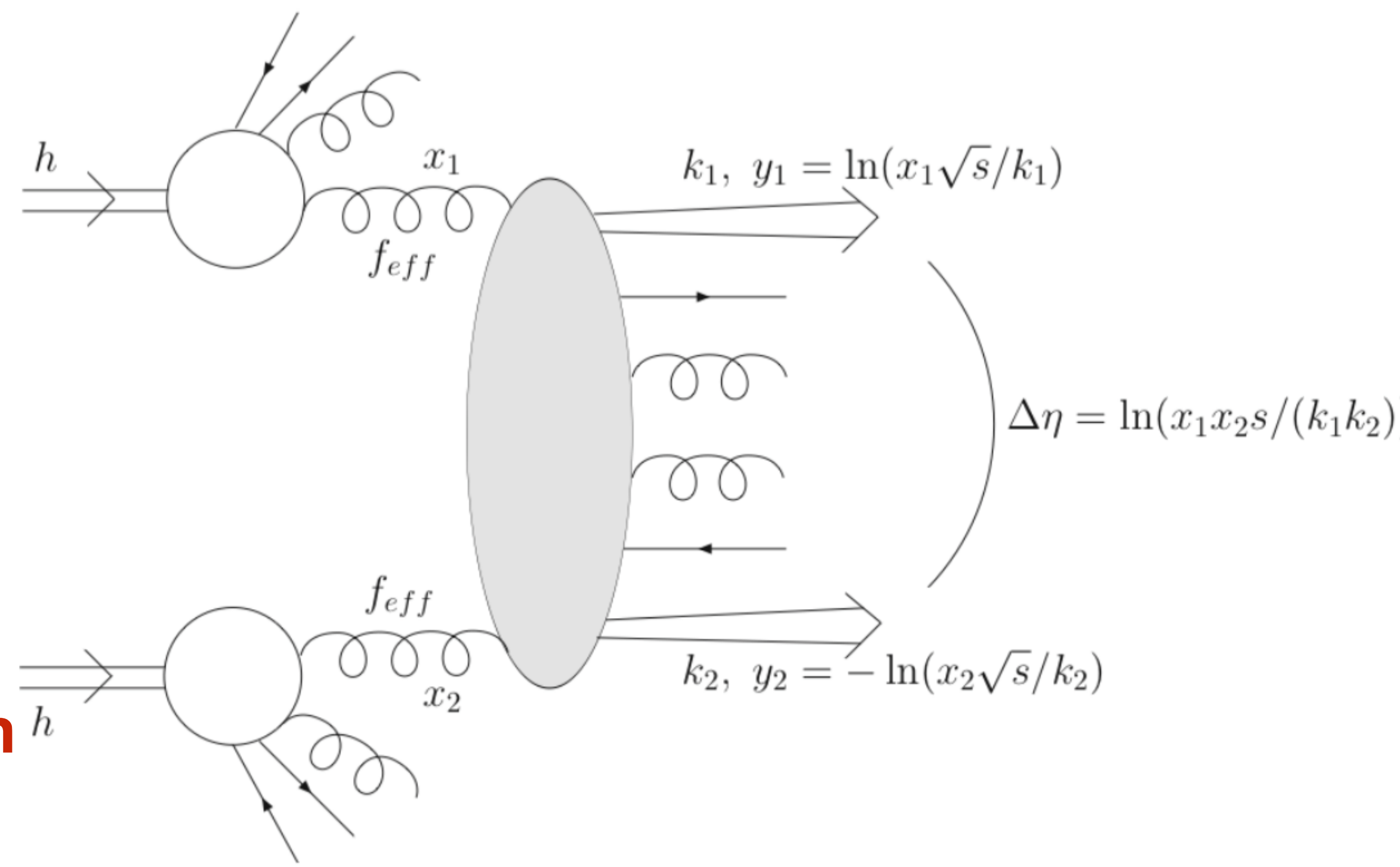
- A moderate sensitivity to PDF set of the model.
- Very sensitive to MPI.
- Smaller experimental uncertainty would make it possible to have further conclusion on PDF sets.

Azimuthal angle decorrelations of jets widely separated in rapidity

Mueller Navelet Jets

A decisive test of BFKL dynamics at hadron colliders.

Mueller-Navelet (MN) jets:
the most forward and the most backward jets in rapidity.



DGLAP (LL): parton emission does not depend on the rapidity separation of MN jets.

BFKL: extra radiation between the 2 jets will smear out back-to-back topology.

Increased azimuthal decorrelation with increasing Δy (w.r.t. DGLAP collinear-factorization)

MN jets cross section as a Fourier series:

decorrelation angle

$$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{\mathrm{Tmin}}) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} C_n(\Delta y, p_{\mathrm{Tmin}})\ \cos(n(\pi - \Delta\phi))\right]$$

CMS measurement

At least two jets; $p_T > 35$ GeV, |y| < 4.7.
Anti-kT, R=0.5, Δy up to 9.4.

Observables:

- ΔΦ as a function of Δy
- The average cosines; $C_N = \langle \cos(N(\pi - \Delta\phi)) \rangle$; N = 1,2,3
- Ratios of the average cosines: C2/C1 and C3/C2

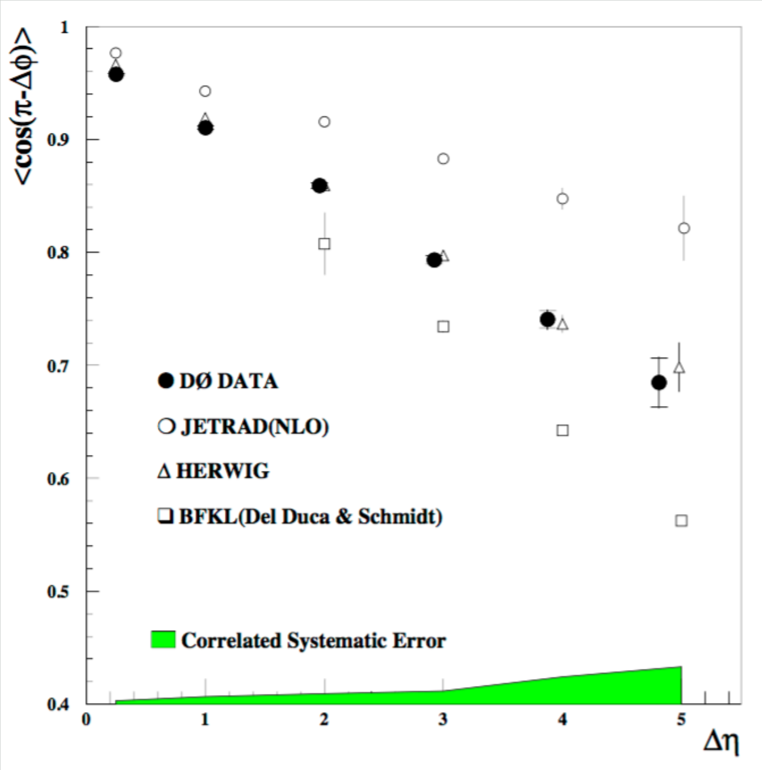
Three bins of rapidity separation between jets

- Δy < 3.0
- 3.0 < Δy < 6.0
- **6.0 < Δy < 9.4 (never measured before)**

D0 measurement

$\sqrt{s}$ = 1.8 TeV, **Δη < 6**, $E_T > 50$ GeV

No significant indication of BFKL



HERWIG (LL) describes the data well
BFKL (LL) too much decorrelation
NLO QCD too little decorrelation

Phys. Rev. Lett. 77, 595-600 (1996)

Monte Carlo Models

arXiv:1601.06713

DGLAP based MCs with LL soft and collinear radiation in parton shower modeling: (MPI is tuned to LHC data)

PYTHIA6 Z2, PYTHIA8 4C, HERWIG++

DGLAP with three-level matrix elements + LL parton showers

SHERPA

NLO terms:

POWHEG, interfaced with PYTHIA

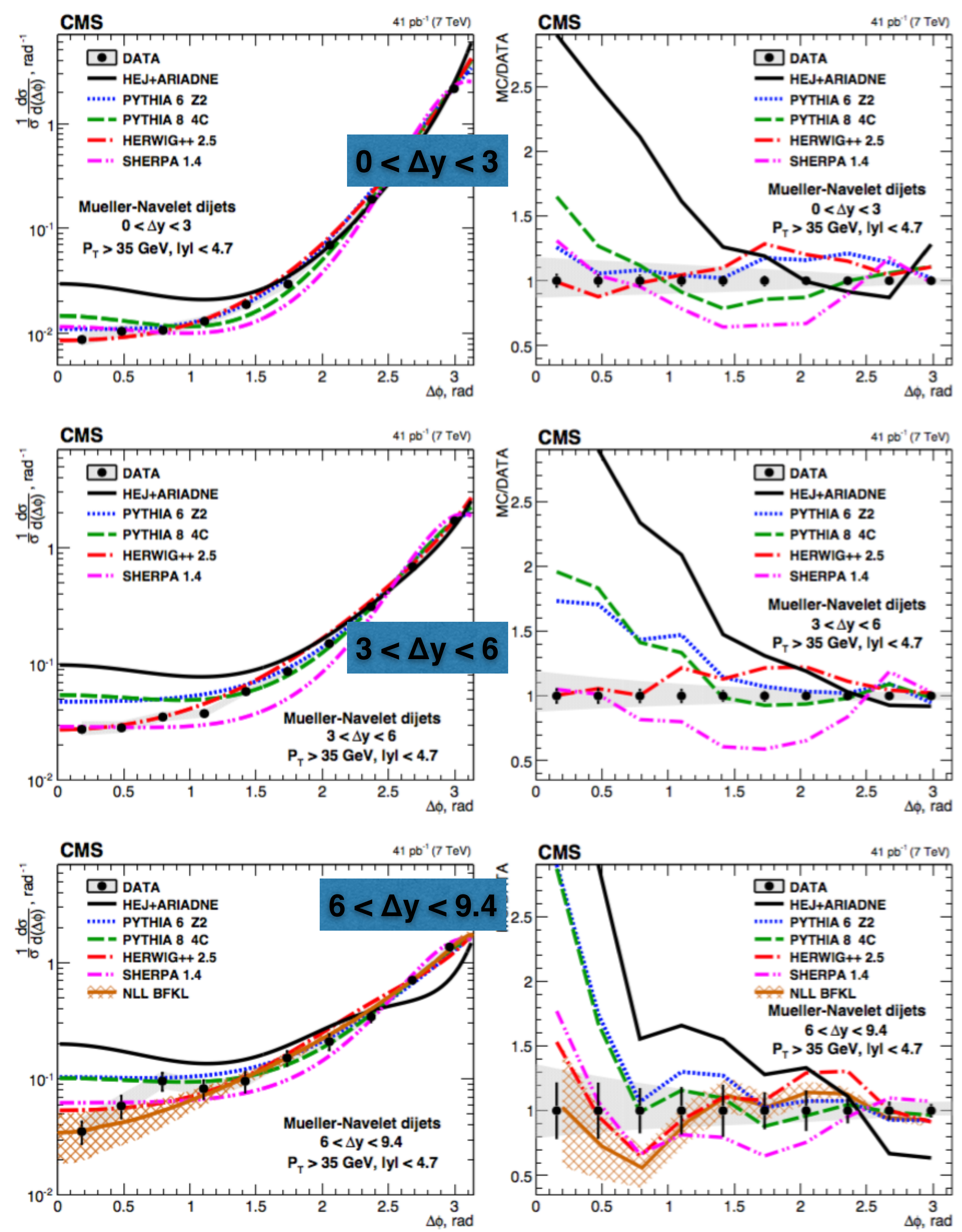
NLL BFKL analytical predictions

Phys. Rev. Lett. 112 (2013) 082003

HEJ (LL BFKL matrix element)**+ARIADNE** (hadronisation and PS)

MN dijets azimuthal decorrelations – ΔΦ

arXiv:1601.06713



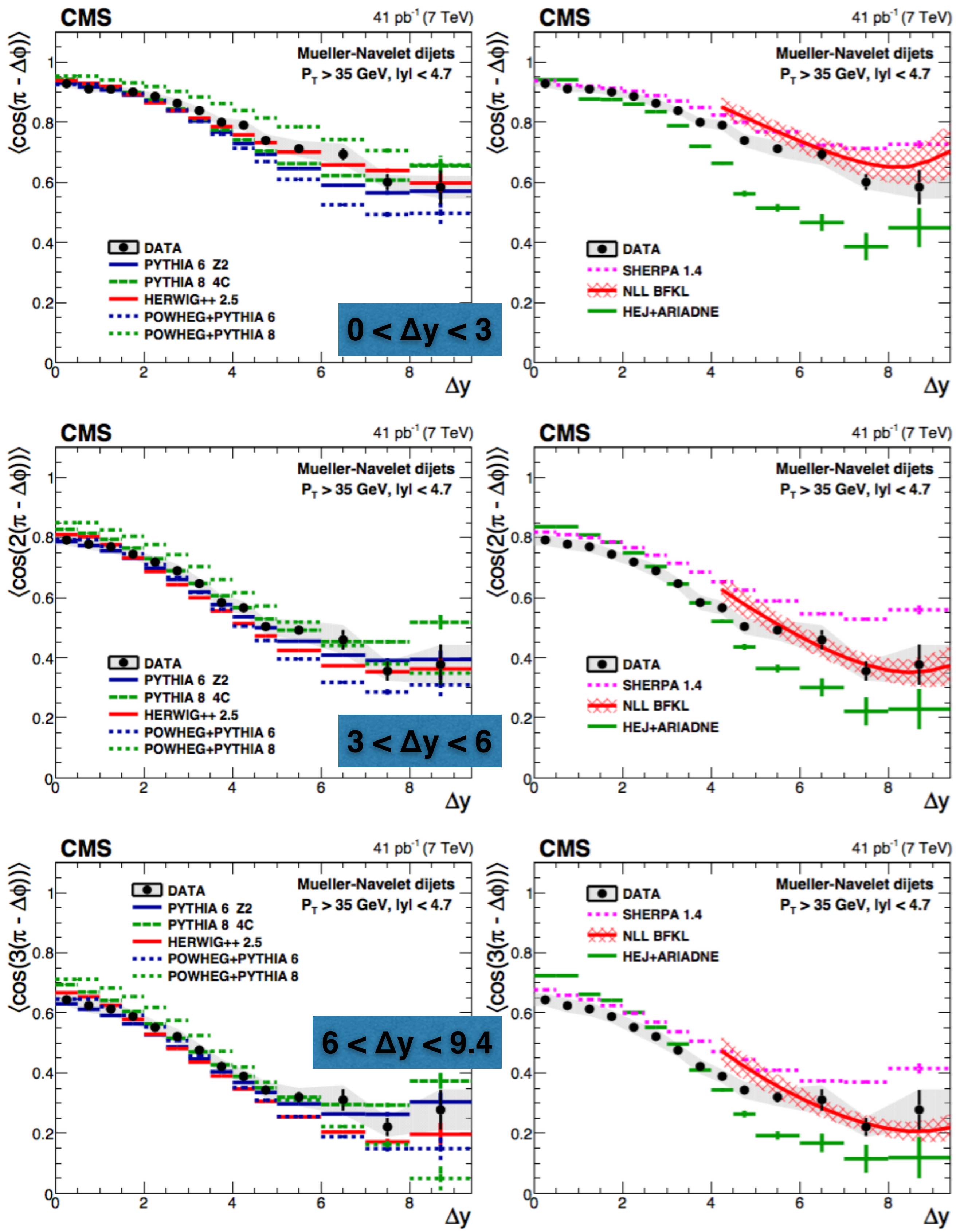
High back-to-back correlation in the central rapidity interval (peak at $\Delta\Phi \approx \pi$).

Larger azimuthal decorrelation with increasing Δy.

PYTHIA and HERWIG describe the data well.

MN dijets average cosines

arXiv:1601.06713



<cos> can be expressed using conformal symmetries in **BFKL**

None of the MC has a good description of the data in all rapidity intervals.

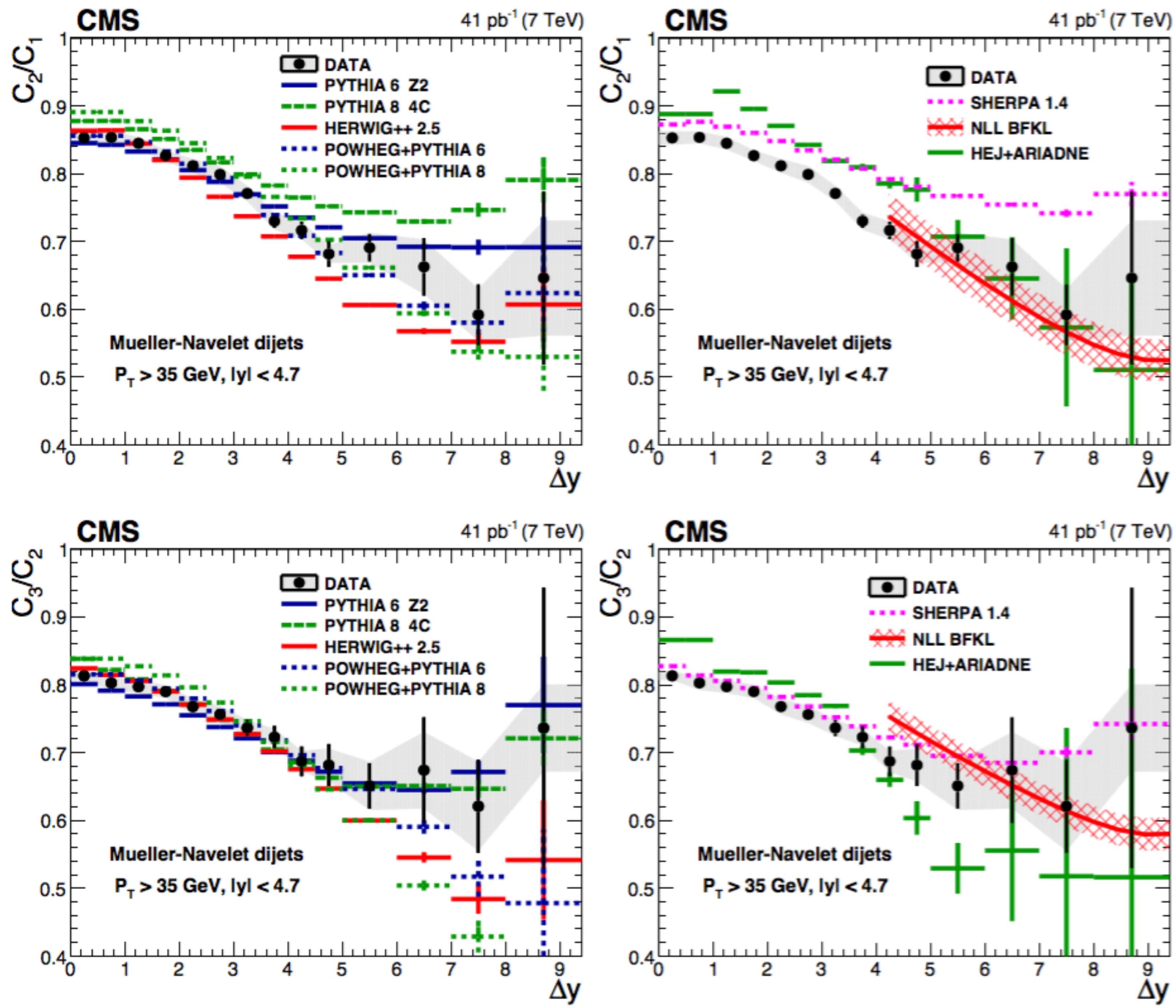
HEJ predicts too much decorrelation.

PYTHIA6 and 8 fair agreement with the data.

MN dijets ratios of average cosines

arXiv:1601.06713

Ratios suppress **DGLAP** contributions and uncertainties of factorization and renormalization scales.



C2/C1 ratios:

PYTHIA, SHERPA underestimates, HERWIG overestimates.

C3/C2 ratios:

PYTHIA and SHERPA consistent with the data. HERWIG overestimates.

NLL **BFKL** agrees with the data both for C2/C1 and C3/C2 ratios.

Summary

- The recent measurements in the forward and very forward rapidities of CMS are presented.
- Some of those measurements are compared to the earlier CMS measurements. The results are found to be consistent.
- All results clearly show the significance of multiple parton interactions and provide a great input for tuning studies in the forward rapidities.
- Data at higher energies might reveal possible BFKL signatures. The kinematical domain of the present study might be in between DGLAP and BFKL

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

Backup

Significance of MPI

Jet production with pT > 20 GeV in |η| < 3 well described by NLO pQCD.

- At low-pT values, total 2→2 cross section becomes larger than total inelastic cross section, σ_{inel}

$$\sigma(p_{\mathrm{T}}^{\mathrm{min}}) = \int_{p_{\mathrm{T}}^{\mathrm{min}}} dp_{\mathrm{T}}^2 d\sigma/dp_{\mathrm{T}}^2$$

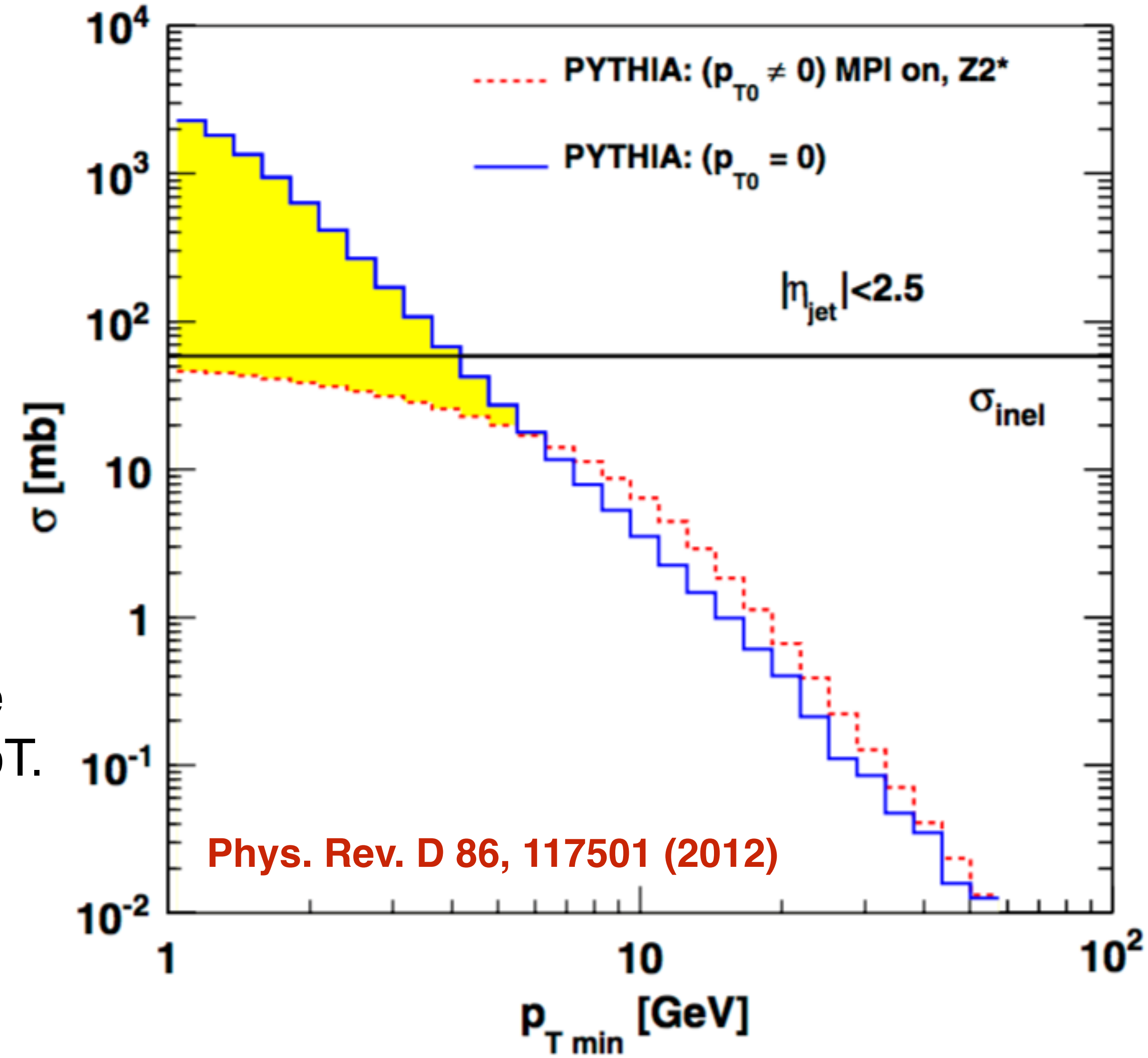
- In PYTHIA, the rise of the 2→2 cross section is controlled by the parameters, p_{T0} and $<n_{MPI}>$.

$$\sigma(p_{T\ min}) \propto \frac{1}{p_{T\ min}^2 + p_{T0}^2}$$

$$< n_{MPI} >= \sigma(p_{T\ min})/\sigma_{inel}$$

- The per-event yields with a leading charged particle or leading jet are sensitive to the saturation at low-pT.

$$r(p_{\mathrm{T}}^{\mathrm{min}}) = \frac{1}{N_{\mathrm{evt}}} \int_{p_{\mathrm{T}}^{\mathrm{min}}} dp_{\mathrm{T}}^{\mathrm{lead}} \left(\frac{dN}{dp_{\mathrm{T}}^{\mathrm{lead}}} \right)$$



Event Selection and Observables

Phys. Rev. D 92, 112001

Trigger:

- Minimum bias events triggered by TOTEM T2 (charged track with $p_T > 40$ MeV in $5.3 < |\eta| < 6.5$)

Vertex requirements:

- Primary vertex reconstruction at CMS. Events with multiple vertices are removed.

Tracks selection:

- $|\eta| < 2.4$ with $p_T > 0.4$ GeV/c.

Track-jets selection:

- Anti-kT, 0.5
- Leading track-jet in $|\eta| < 1.9$ with $p_T > 1$ GeV — input tracks $|\eta| < 2.4$ with $p_T > 0.4$ GeV

Observable: The per-event yields, $r(p_{T,min})$

Normalized integrated charged particle or charged-particle jet event cross sections as a function of $p_{T,min}$ where $p_{T,lead} > p_{T,min}$.

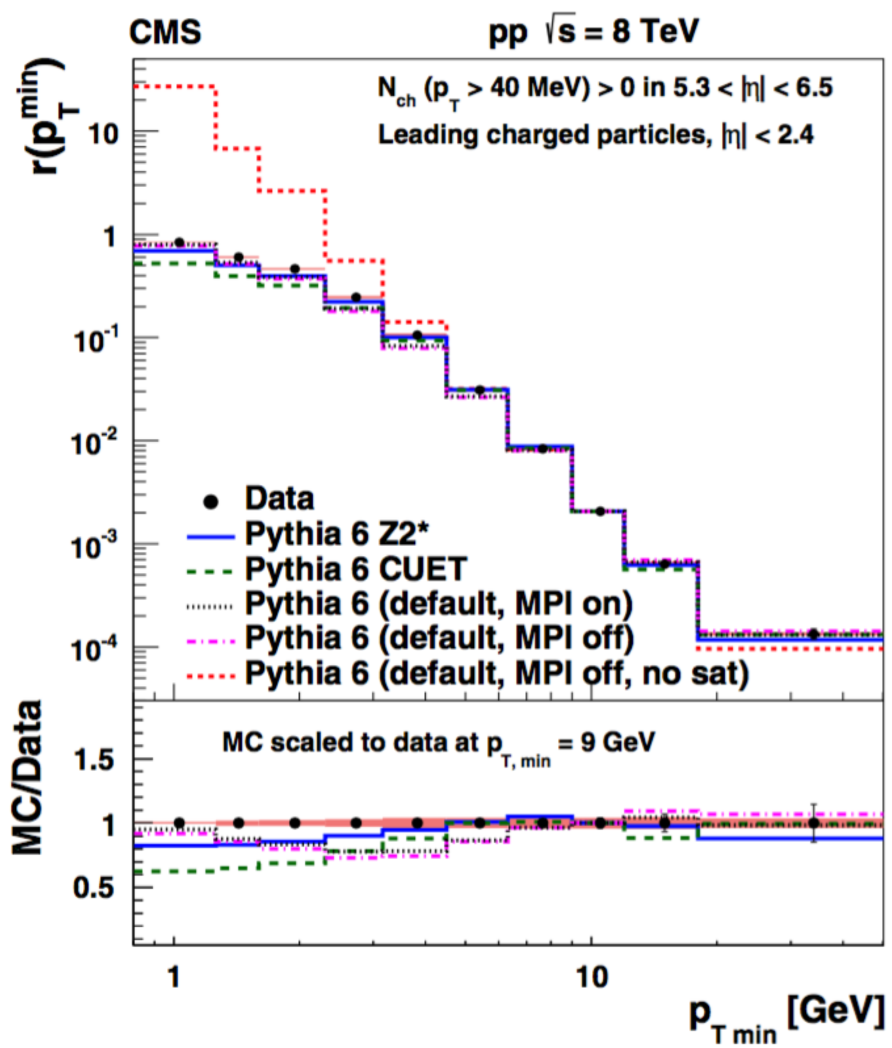
$$r(p_T^{min}) = \frac{1}{N_{evt}} \sum_{p_T^{lead} > p_T^{min}} \Delta p_T^{lead} \left(\frac{\Delta N}{\Delta p_T^{lead}} \right)$$

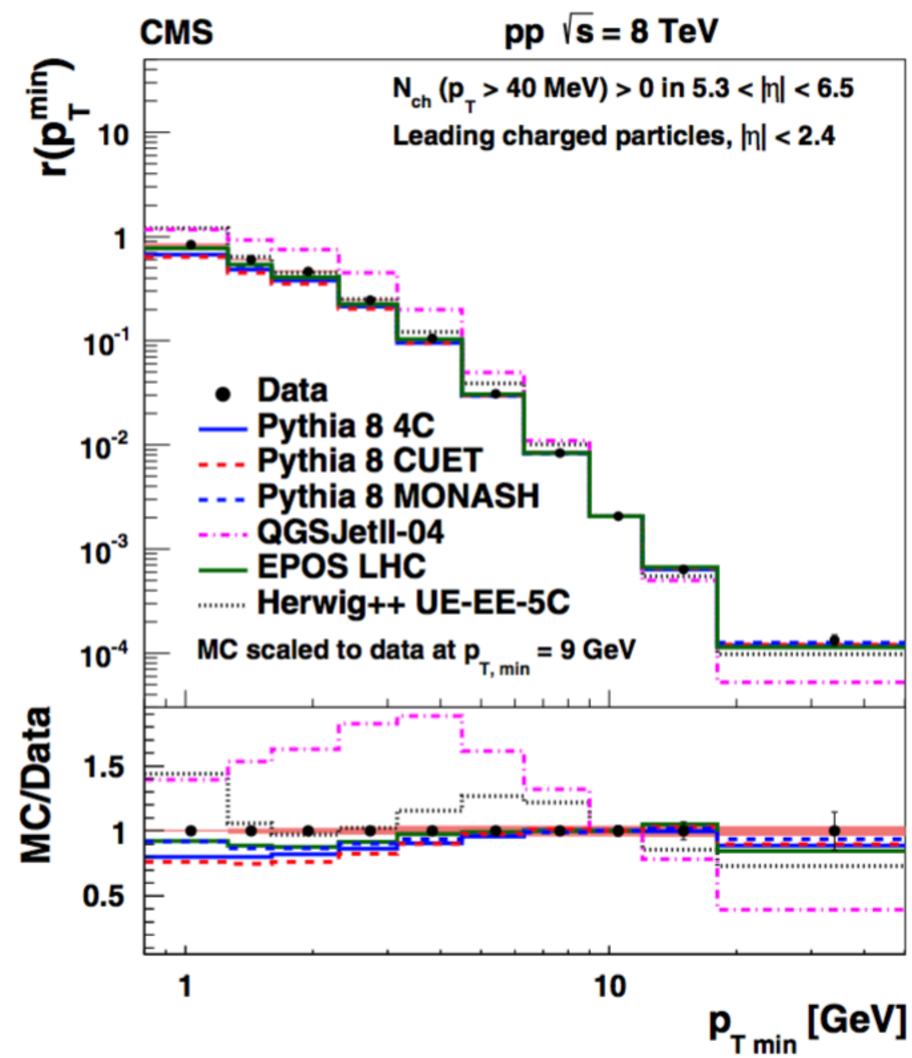
Both the leading charged particle and leading charged-particle jets measurements are normalized to events (N_{evt}) with a leading track in $|\eta| < 2.4$ with $p_T > 0.4$ GeV.

Leading Charged Particles

Phys. Rev. D 92, 112001

Normalized integrated distributions for leading charged particles for events with $p_{T,min} > 0.8$ GeV



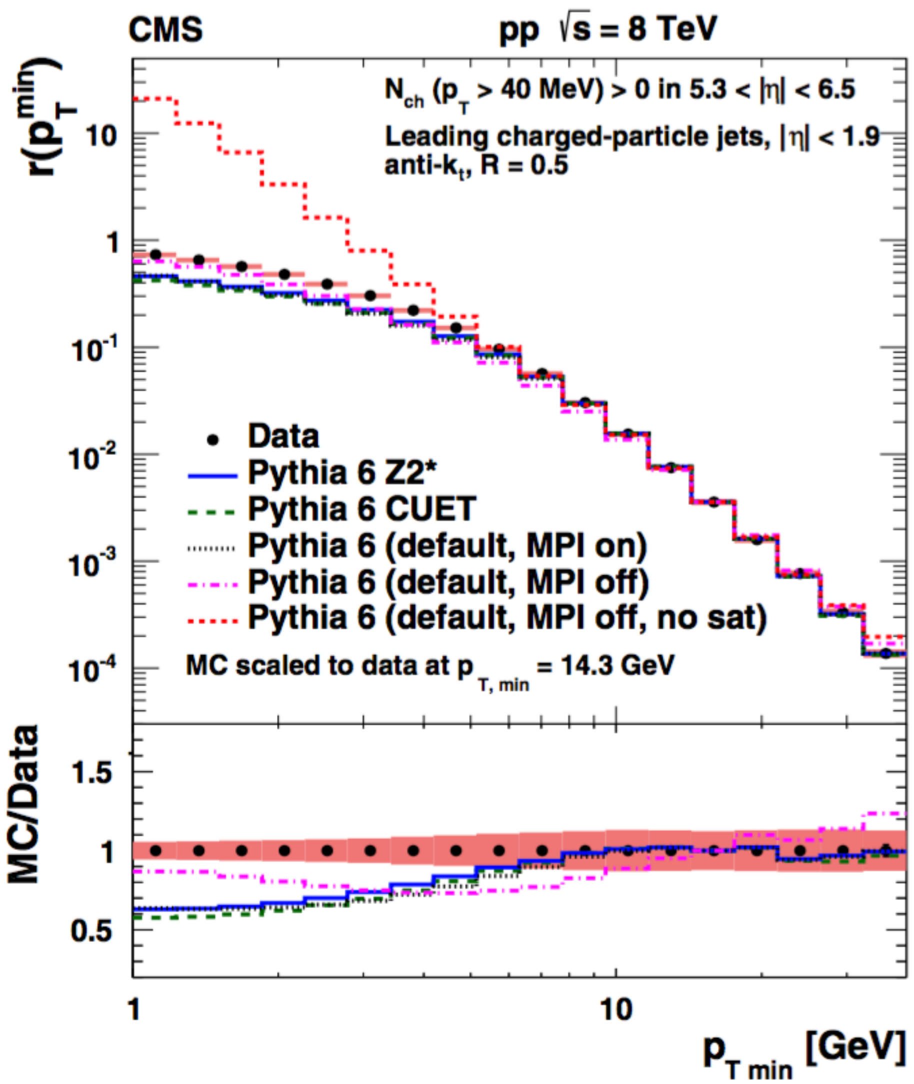


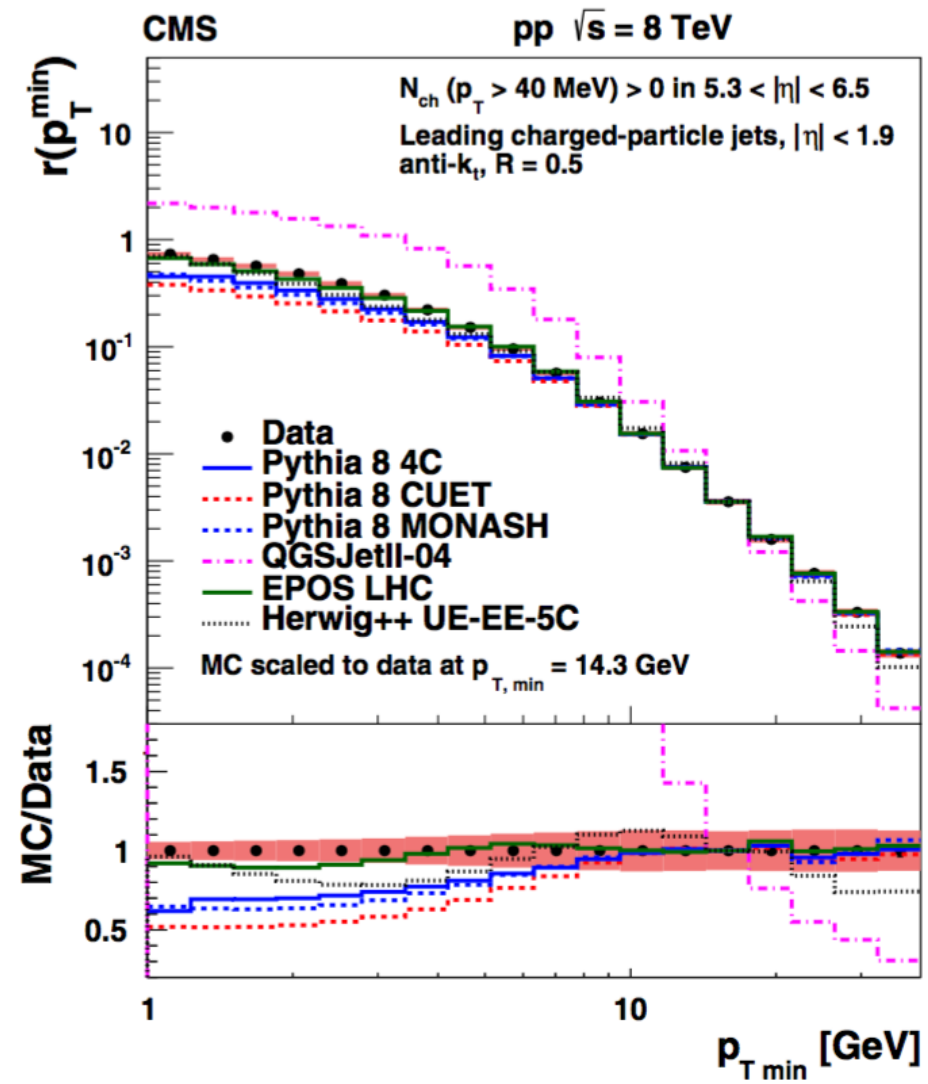
- MC is rescaled to the data at $p_{T,min}$ = 9 GeV.
- The distributions fall steeply at high-p_T. Relatively flat between 1-10 GeV.
- MPI has not a big effect. (When clustering particles into jets MPI becomes more important).
- A large deviation from the data at low-p_T if both MPI and saturation turned off.
- Described well by EPOS. QGSJet fails.

Leading Charged Particle Jets

Phys. Rev. D 92, 112001

Normalized integrated distributions for leading charged-particle jets for events with $p_{T,min} > 1$ GeV





- MC is rescaled to the data at $p_{T,min}$ = 14.3 GeV.
- The turnover point is different: when clustering the particles into jets more energy is collected in the jet cone.
- The PYTHIA6 has a better description of data at low-p_T when MPI is off.
- EPOS has the best description. Large discrepancies between the models.