Very forward energy flow and jets in pp and pA at CMS

Pierre Van Mechelen
on behalf of the CMS Collaboration

Single inclusive jet transverse momentum and energy spectra at very forward rapidity in pp collisions at $\sqrt{s}$ = 7 and 13 TeV

Krzysztof Kutak, Hans Van Haevermaet, and Pierre Van Mechelen

Low x Workshop, Bari, June 2017

Outline

- A few words on CASTOR and very forward jet reconstruction in CMS…

- Measurement of the inclusive energy spectrum in the very forward direction in proton-proton collisions at $\sqrt{s}$ = 13 TeV
- Measurement of the very forward inclusive jet cross section in pp collisions at $\sqrt{s}$ = 13 TeV
- Very forward inclusive jet cross sections in p+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

on behalf of CMS

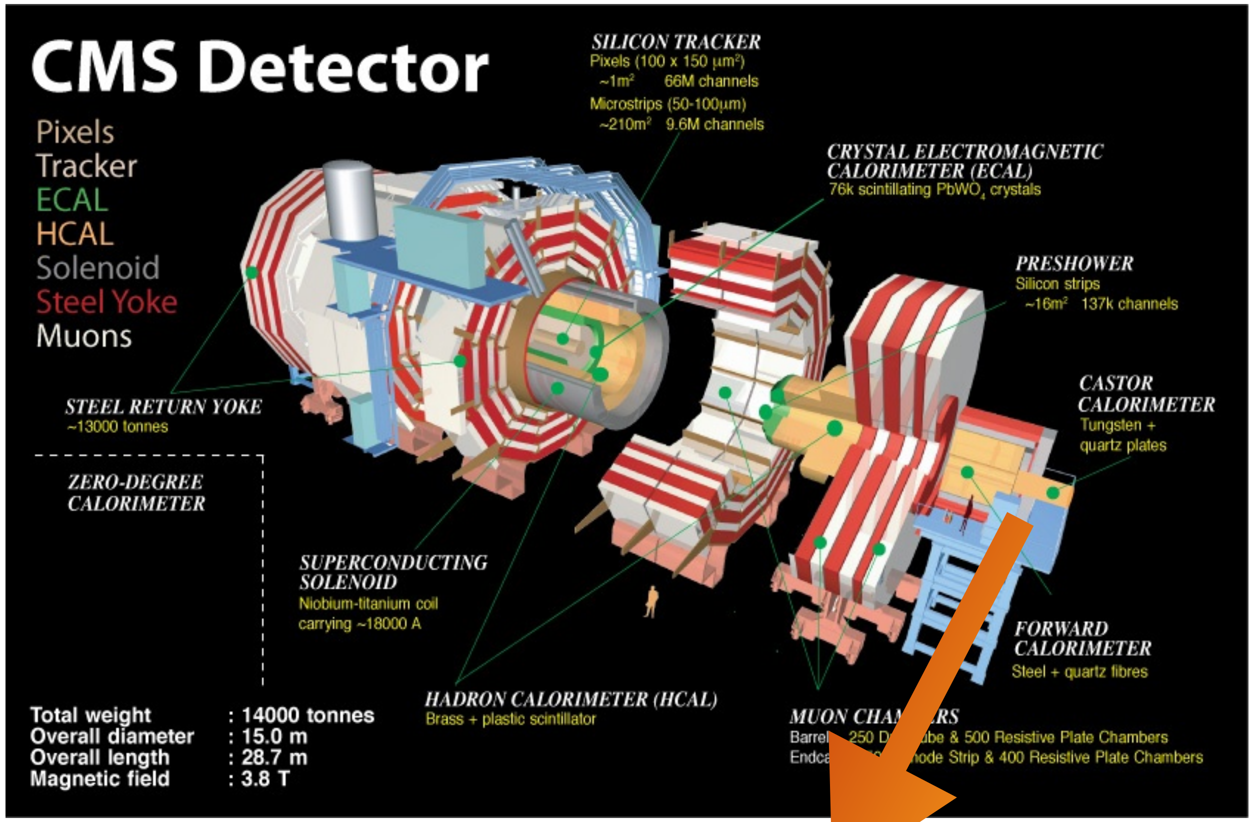
- Single inclusive jet transverse momentum and energy spectra at very forward rapidity in pp collisions at $\sqrt{s}$ = 7 and 13 TeV

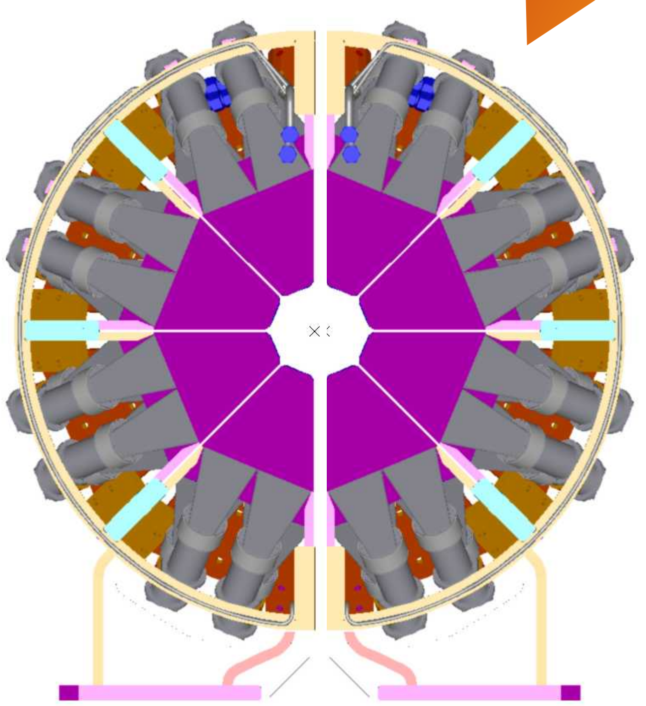
K. Kutak, H. Van Haevermaet, P. Van Mechelen

The CASTOR calorimeter

Very forward energy measurement

- Extends the coverage in forward direction to $-6.6 < \eta < -5.2$
- 14.37m from the interaction point
- Octagonal cylinder with inner radius 3.7 cm, outer radius 14 cm and total depth 10.5 Λ_I
- Signal collection through Čerenkov photons transmitted to PMTs through air core light guides
- W absorber and quartz plates sandwich, with 45° inclination with respect to the beam axis
- Electromagnetic and hadronic sections
- 16-fold segmentation in φ, 14-fold segmentation in z, **no segmentation in η**
- Has been taking pp, pA and AA data in 2010, 2011, 2013, 2015, and 2016

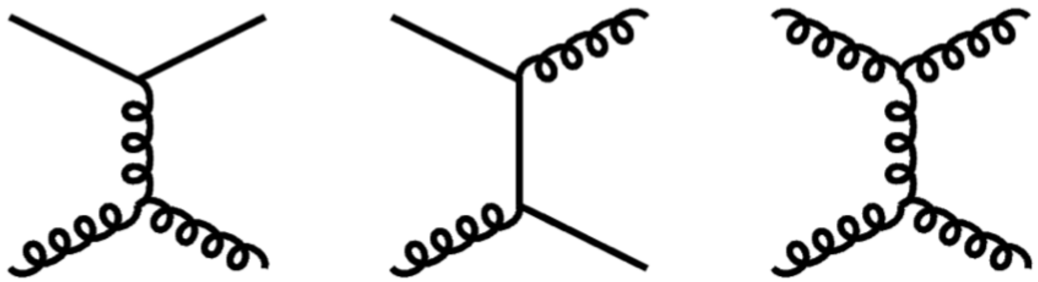




Forward jet kinematics

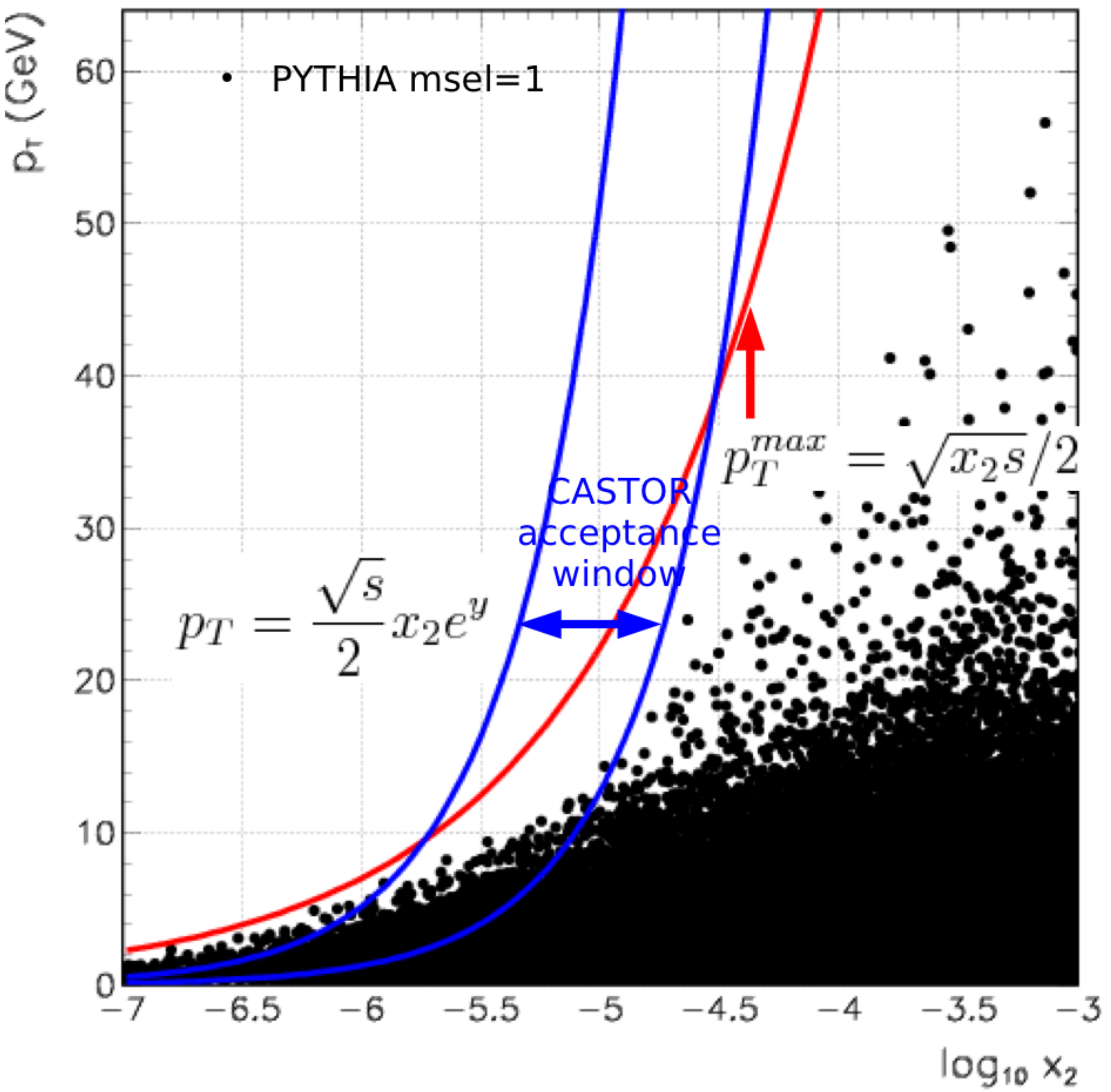
PYTHIA6 generator level study for pp collisions at √s = 7 TeV

- MSEL=1: jets from *t*-channel exchange processes



- Basic kinematics from "hard" subprocess

$$p_T^{max} \sim M/2$$
$$M^2 = x_1 x_2 s$$
$$y = \frac{1}{2} \ln x_1/x_2$$



Forward jet kinematics

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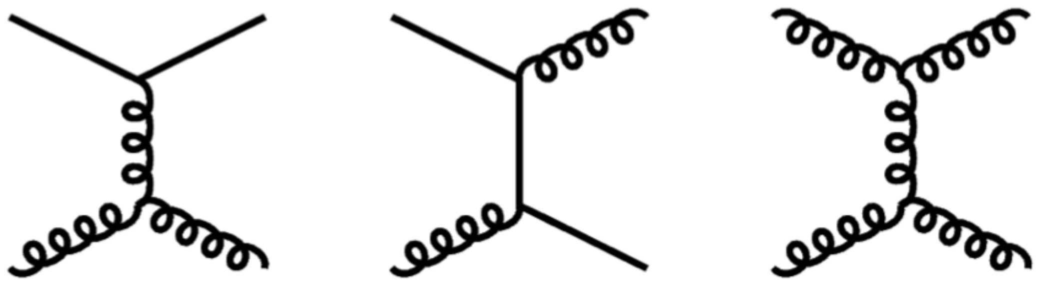
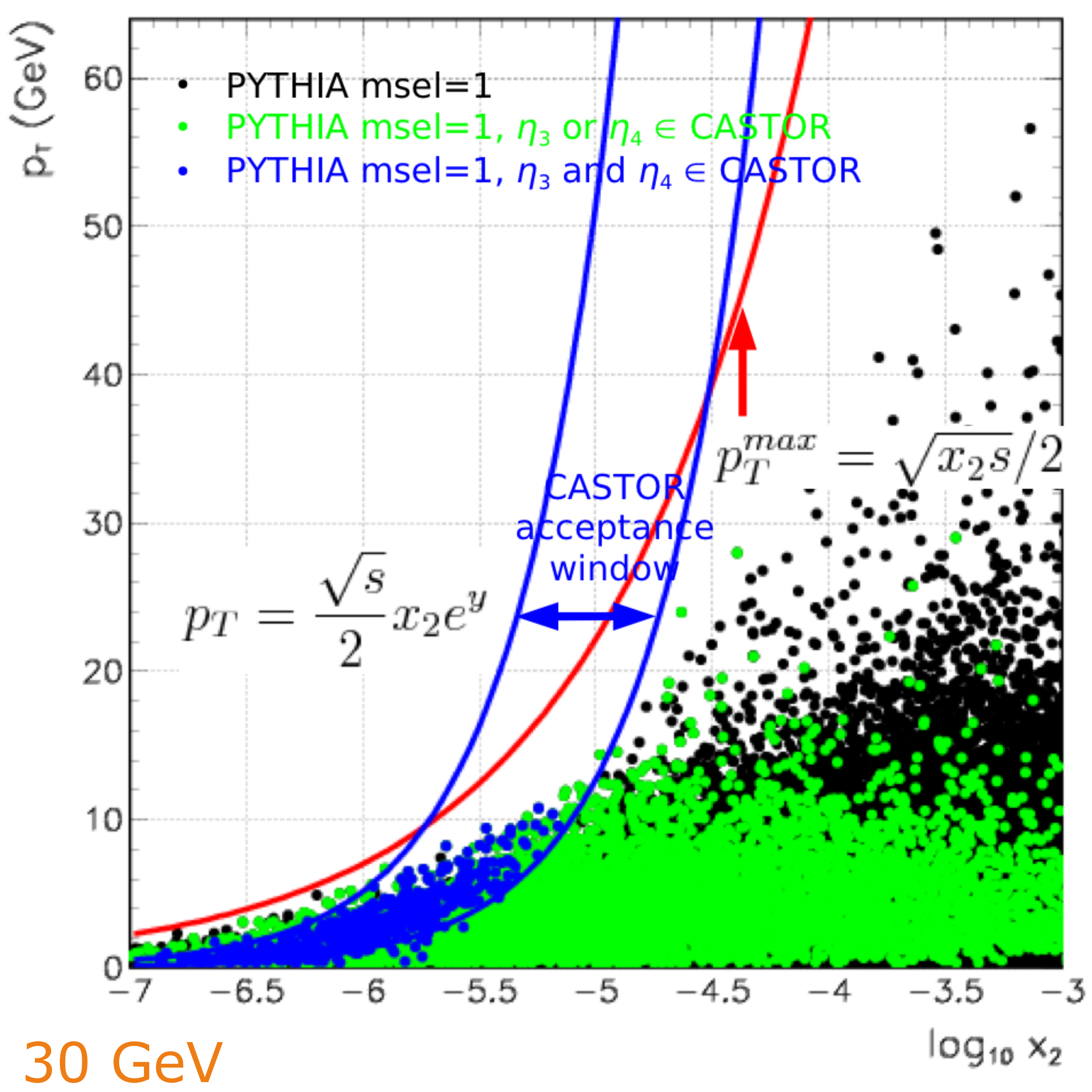




- Basic kinematics from "hard" subprocess

$$p_T^{max} \sim M/2$$
$$M^2 = x_1 x_2 s$$
$$y = \frac{1}{2} \ln x_1/x_2$$

- Caveat: not all jets come from hard subprocess with *y* in CASTOR (due to jet opening angle)

→ Maximum p_T for jets in CASTOR ~ 30 GeV

→ Reach in *x*-Bjorken down to 10^{-6}

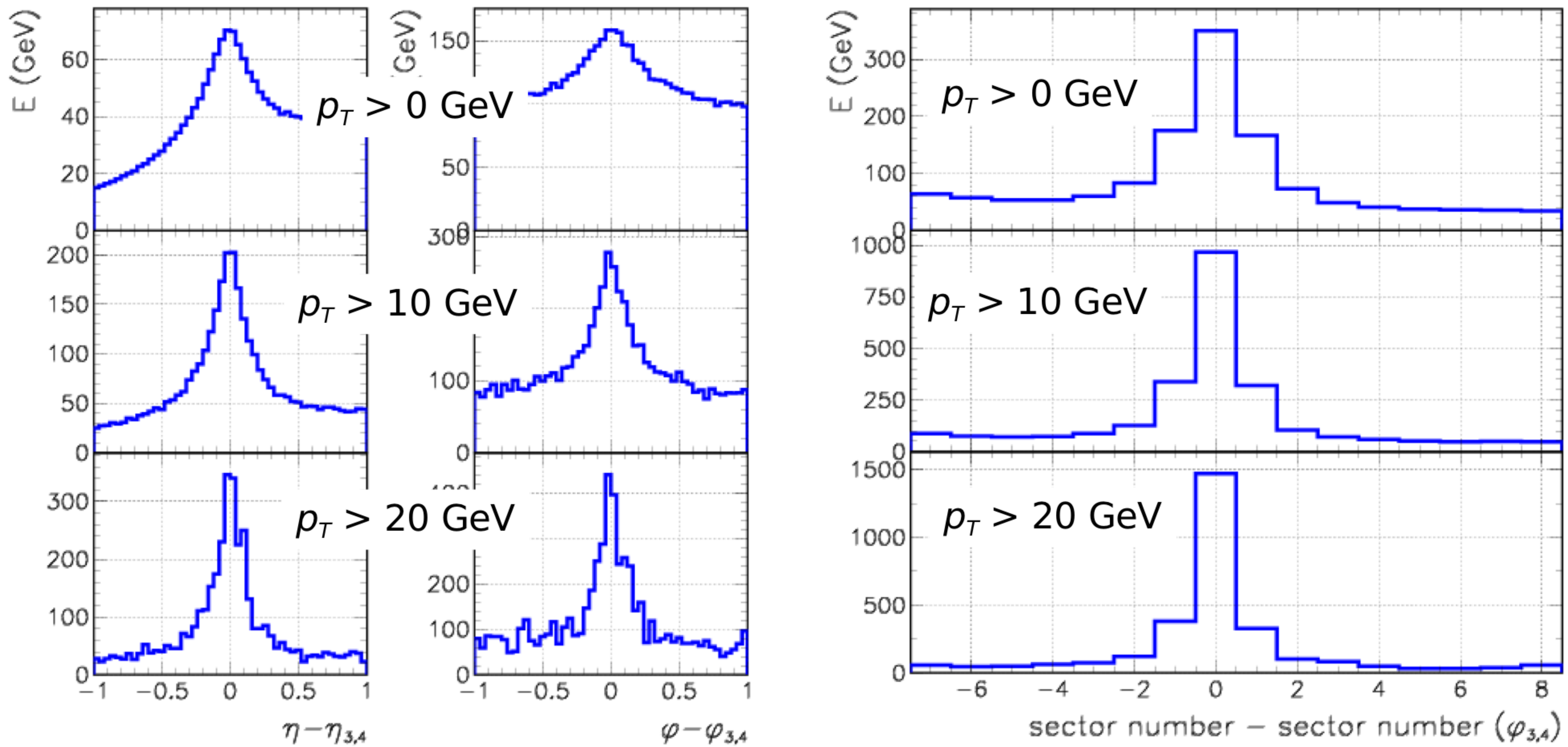
Forward jet kinematics

PYTHIA6 generator level study for pp collisions at √s = 7 TeV

- Detector signature: Jet profiles

Hadron level

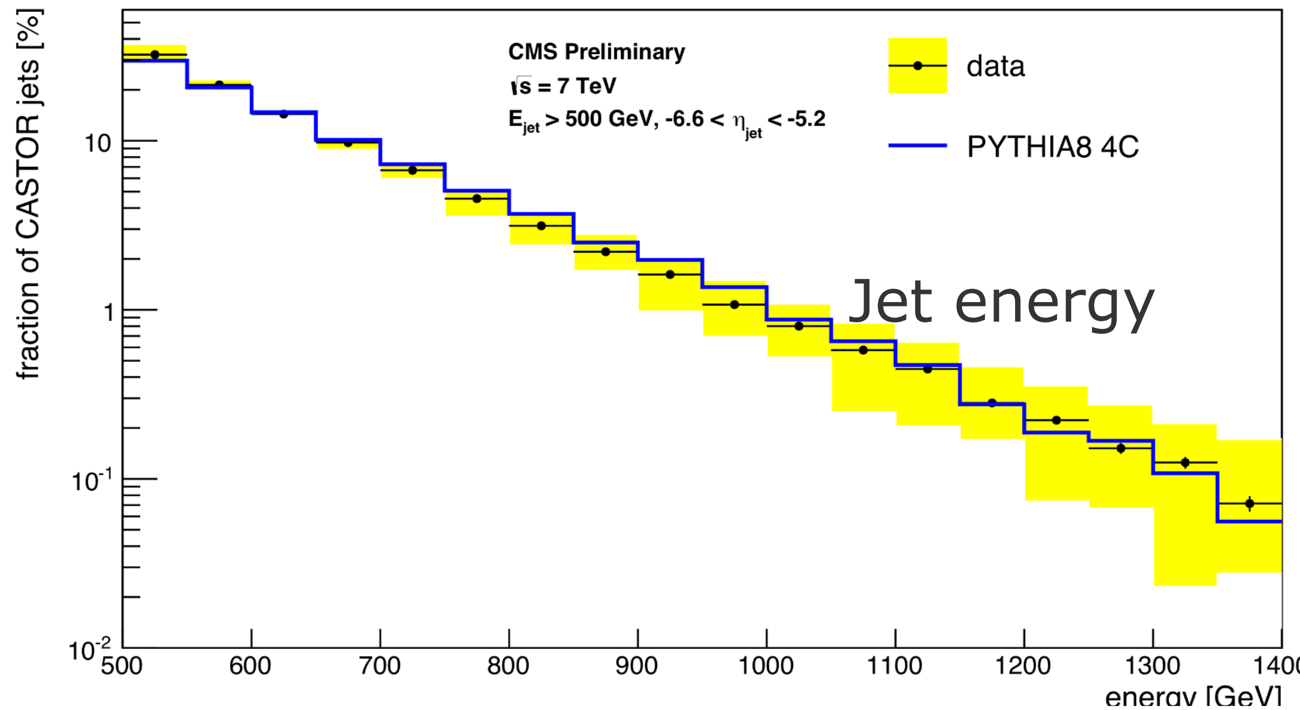
"Detector" level

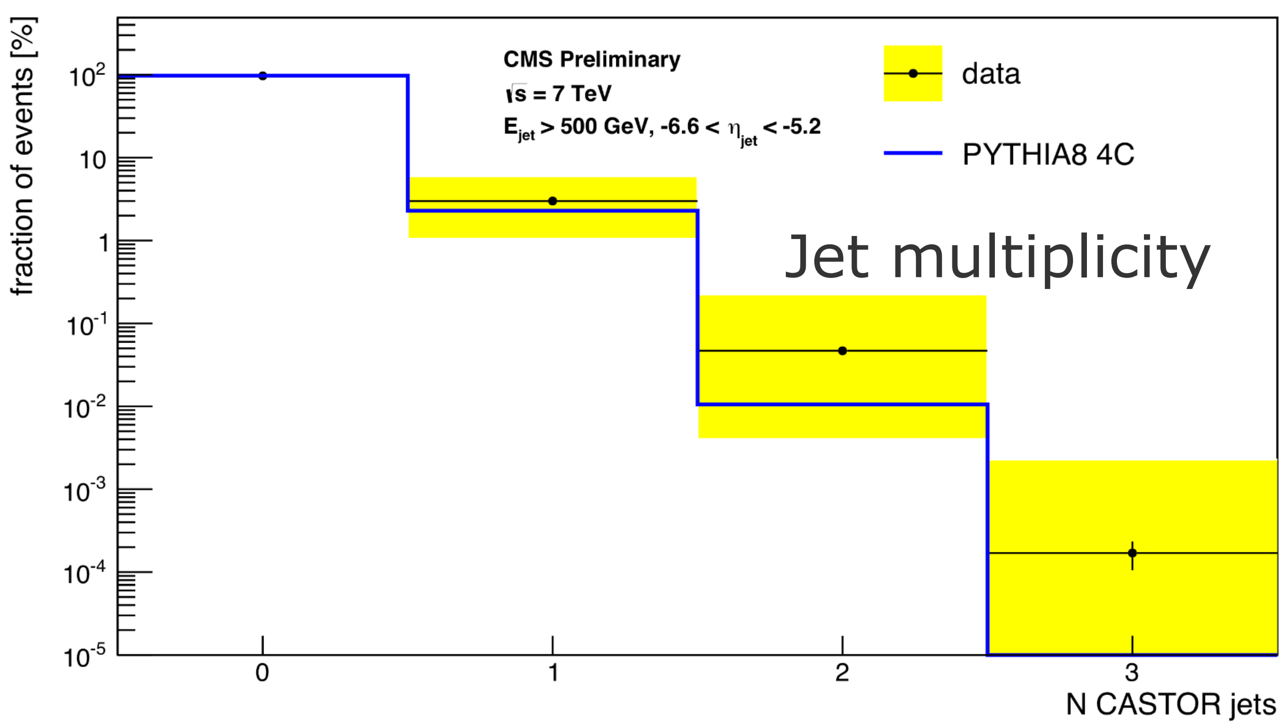


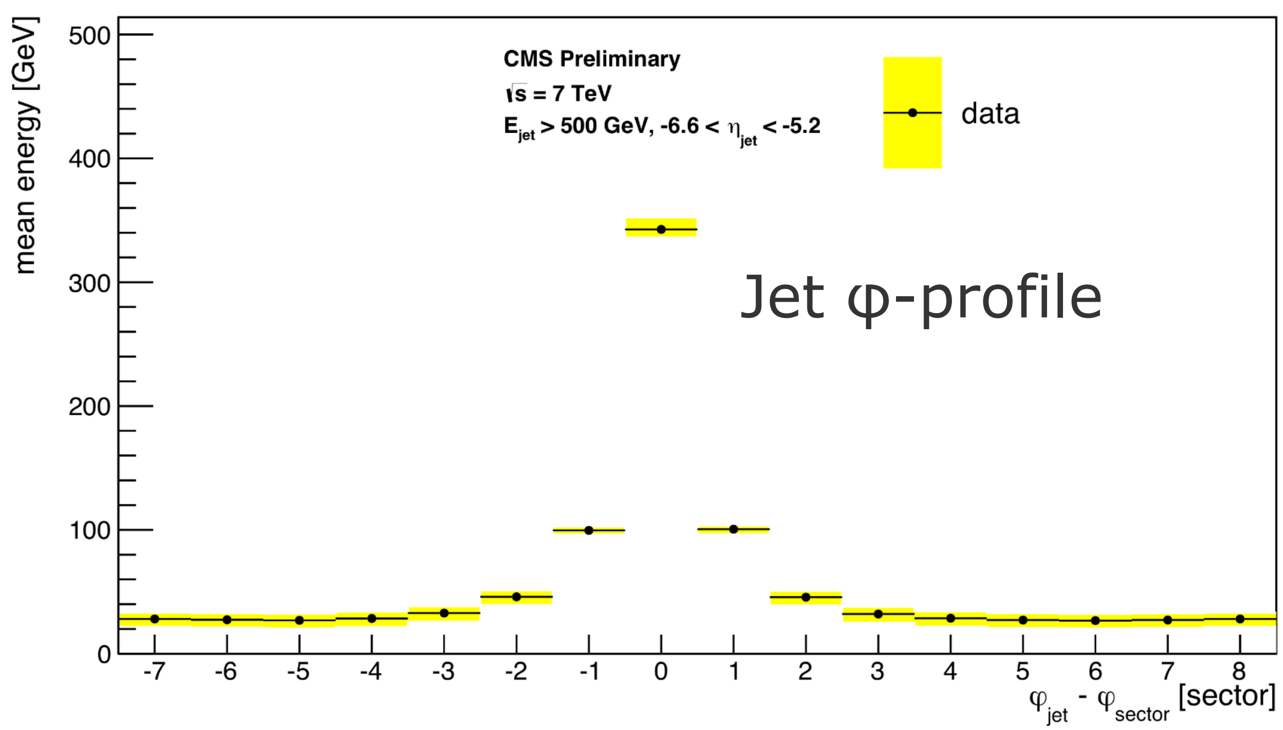
First look at jets in CASTOR

From 2010, low pile-up data

- Minimum-bias trigger
- Anti-k_T (R=0.5) track-jet (jet made of charged particles only)
  - require p_T > 1 GeV, $|\eta|$ < 2
- Anti-k_T (R=0.7) jet clustering in CASTOR
  - require E > 0.5 TeV
- All plots normalized to unity







CMS DP-2014/022

Measurement of the inclusive energy spectrum in the very forward direction in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS-FSQ-16-002
arXiv:1701.08695
submitted to JHEP

Forward energy flow

Why?

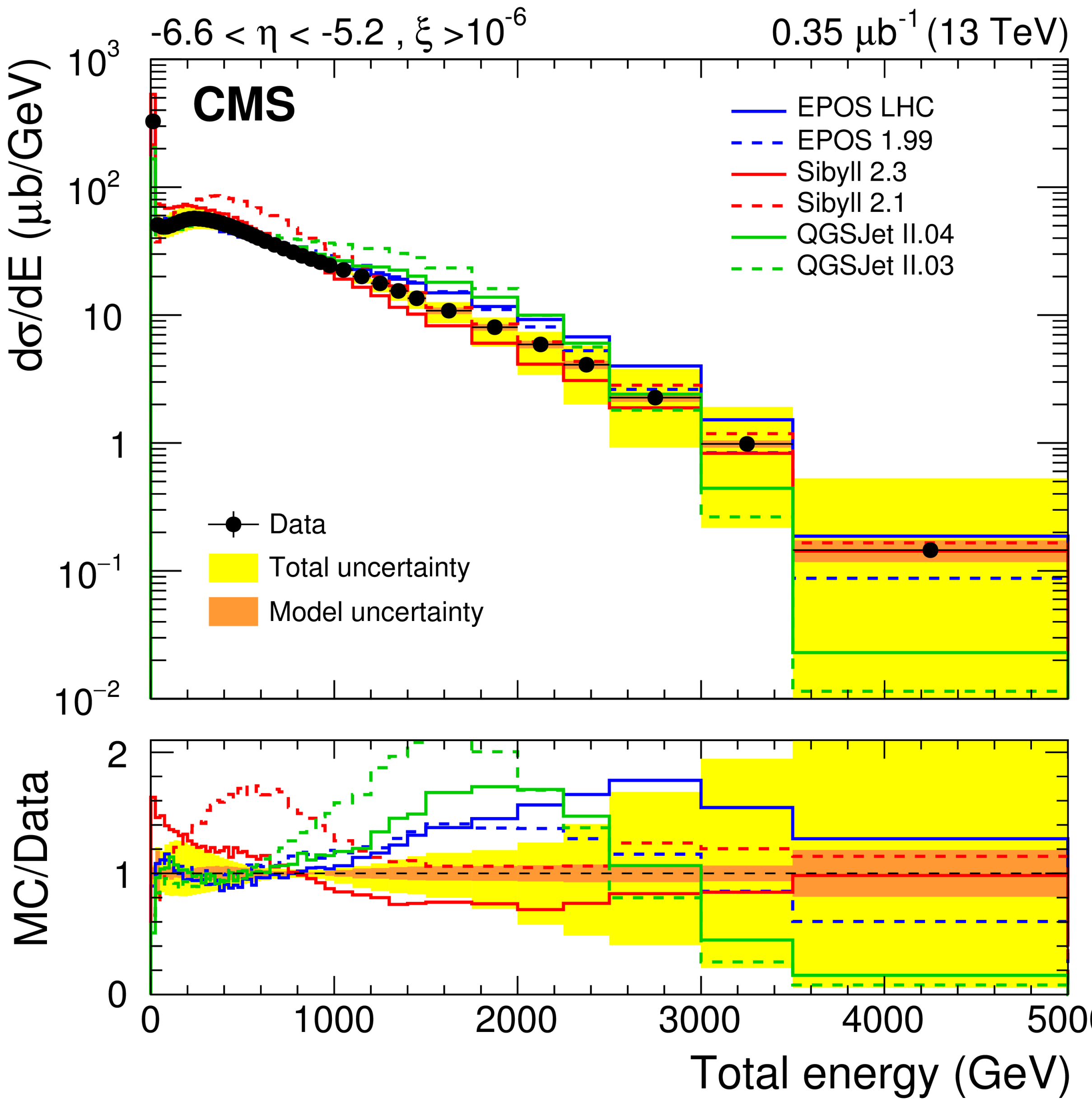
- Sensitive to Underlying Event (MPI and beam remnants)
- Important for a complete description of pp interactions and simulation of extensive air showers induced by high energy cosmic rays
(c.f. observed excess of muon yield in air showers)

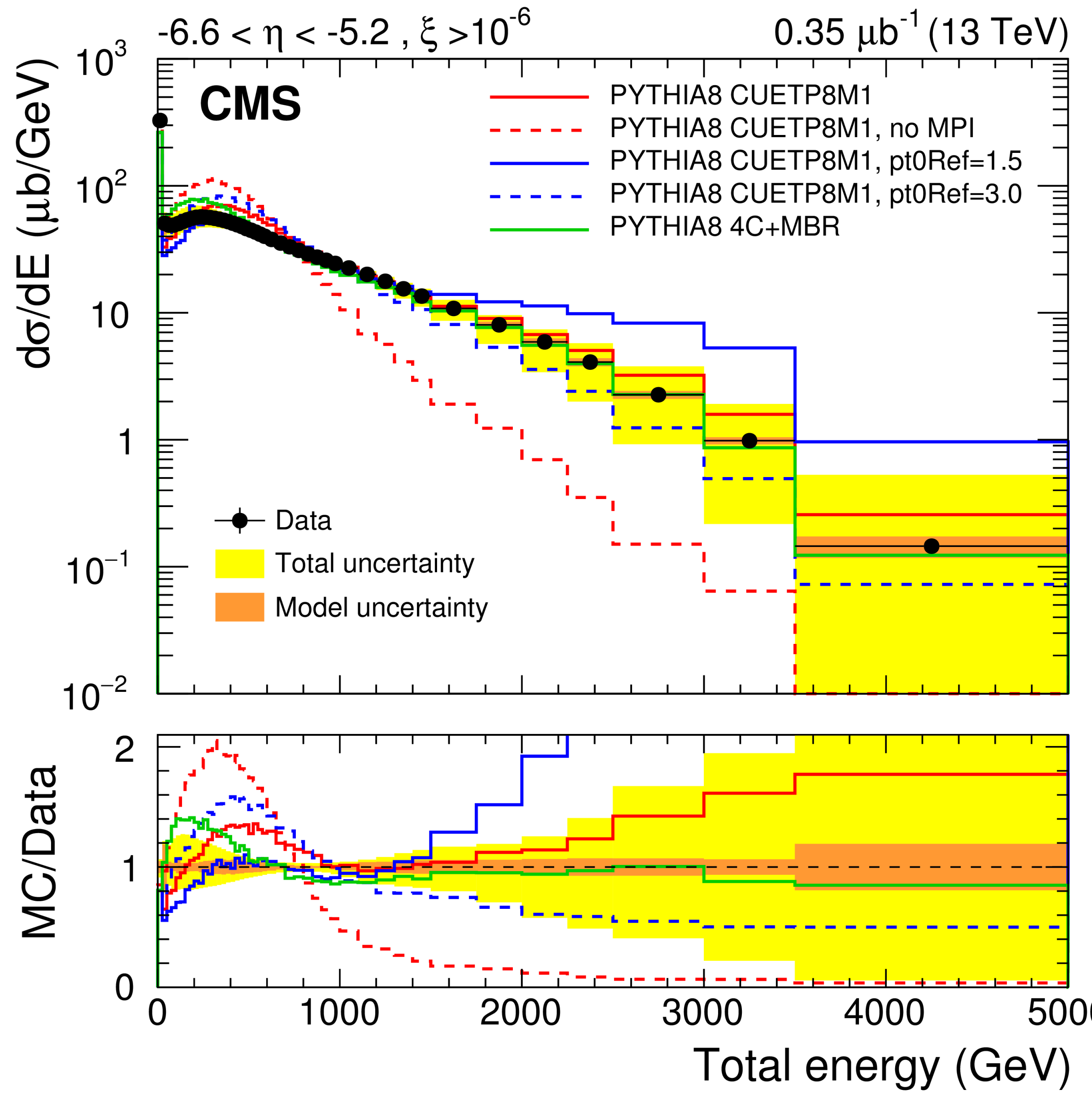
What?

- Energy spectra unfolded to particle level
  - for proton-proton interactions at $\sqrt{s}$ = 13 TeV with $\xi > 10^{-6}$
  - energy from particles with $-6.6 < \eta < -5.2$
  → total energy = Σ particle energies (except μ/ν)
  → electromagnetic energy = Σ e+γ energies (including $\pi^0 \to \gamma\gamma$)
  → hadronic energy = Σ all other particle energies (except μ/ν)
- Energy scale uncertainty yields the dominant systematic uncertainty

Forward energy flow

TOTAL ENERGY

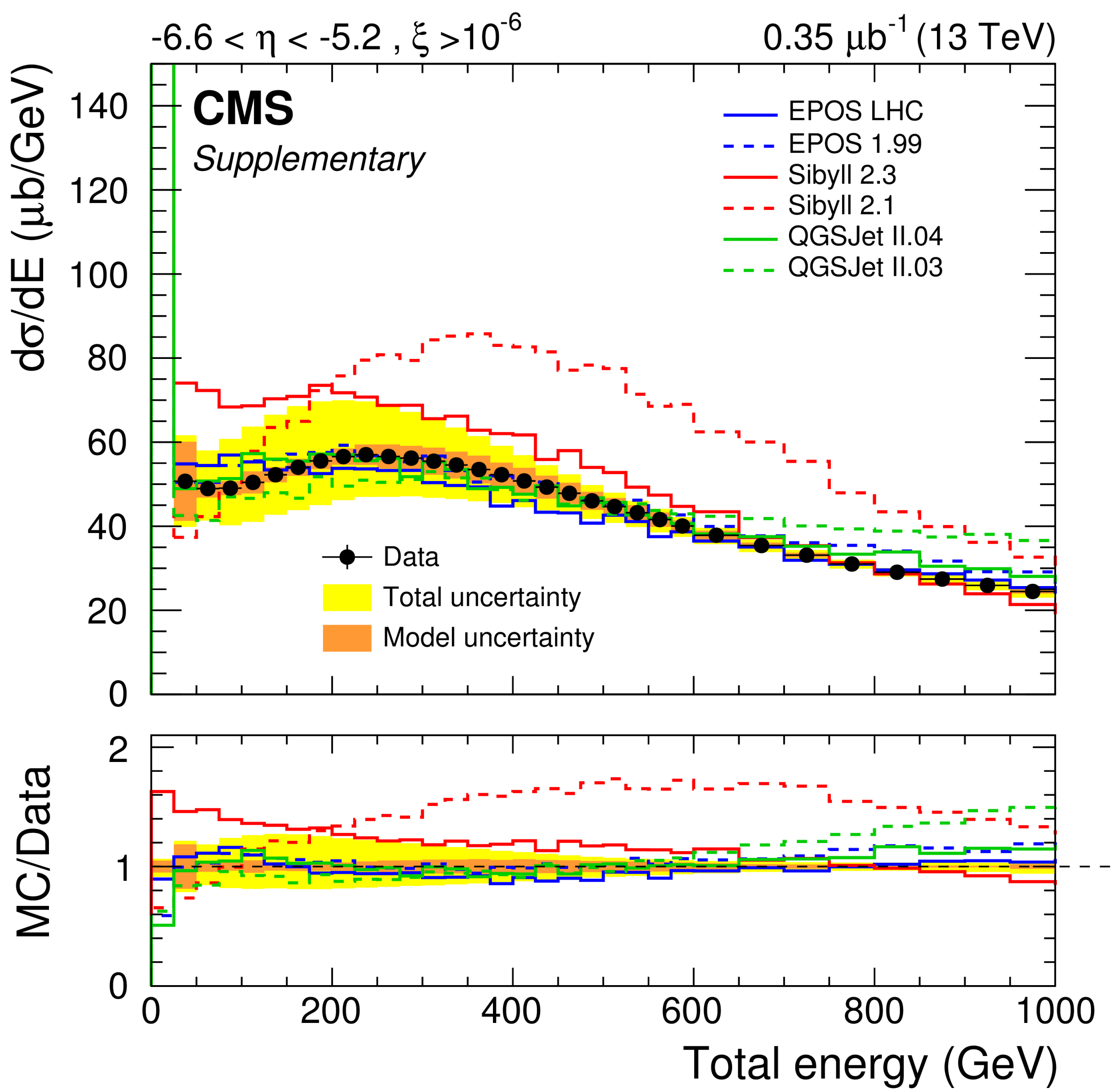


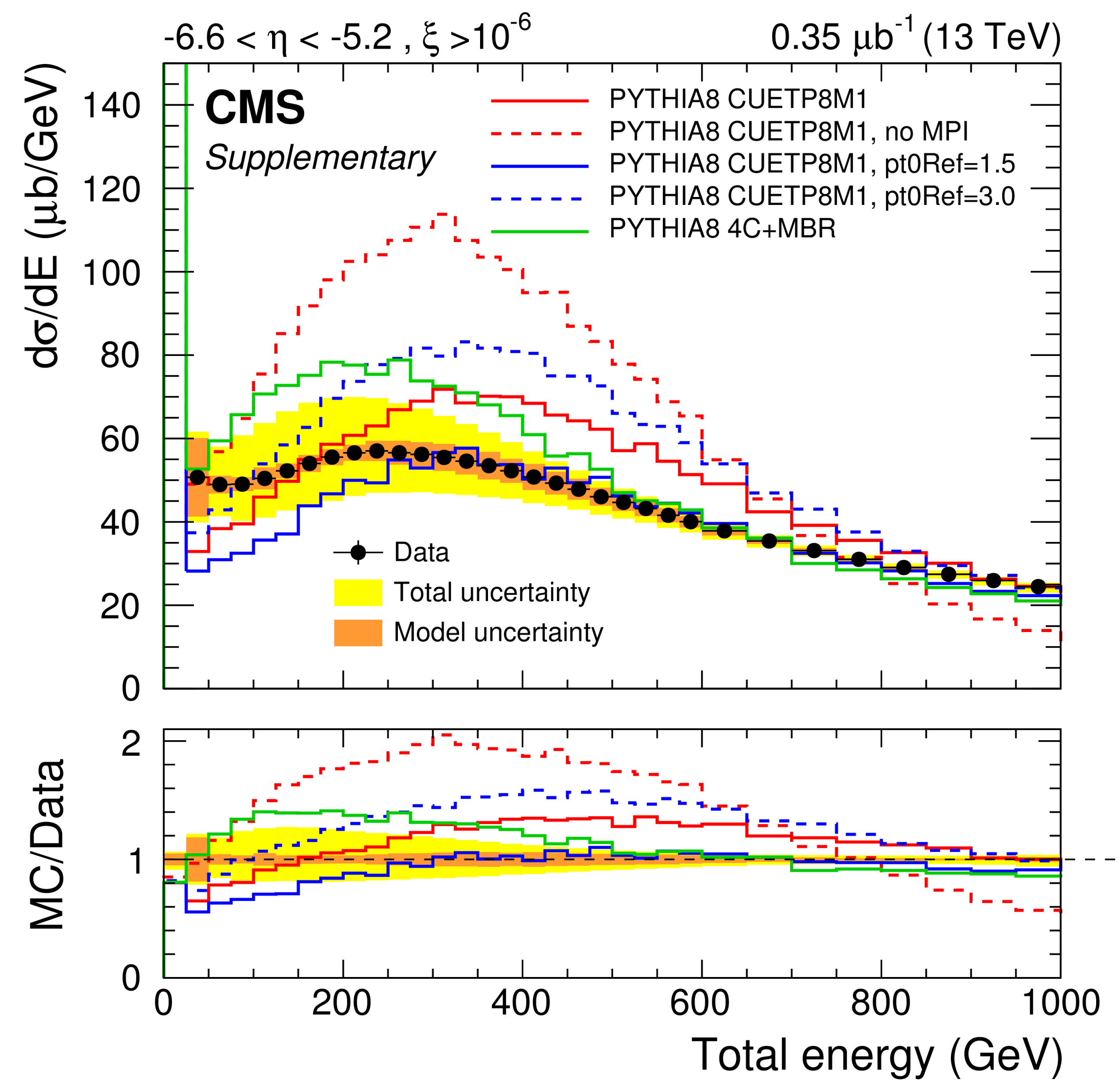


- Diffractive peak at $E = 0$
- High energy tail very sensitive to MPI

Forward energy flow

TOTAL ENERGY - ZOOM



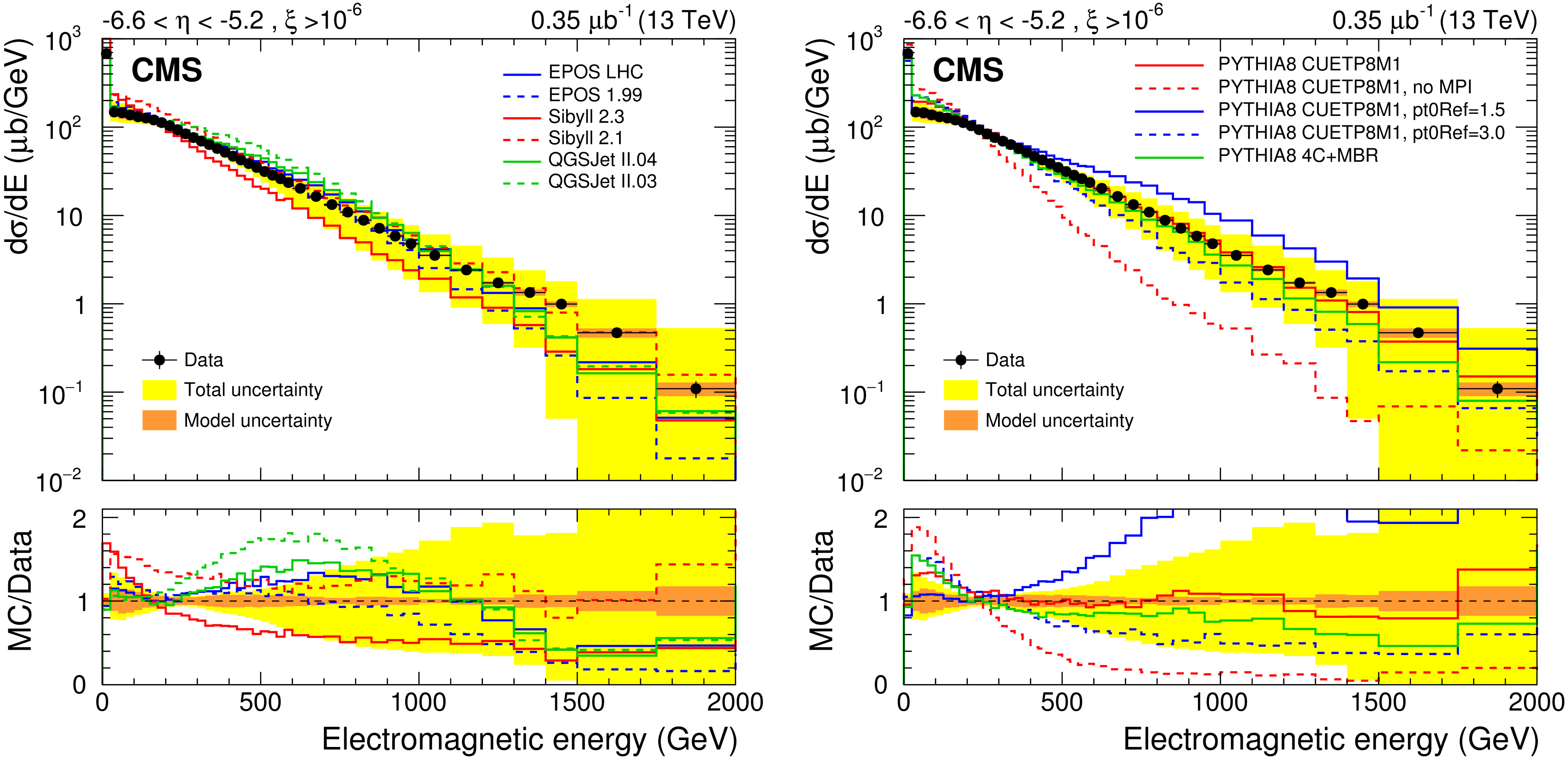


- Diffractive peak at $E = 0$
- High energy tail very sensitive to MPI
- Zoom of low energy distribution: better described by some of the "Cosmic Ray" models

http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ-16-002/index.html

Energy flow in pp (e.m.)

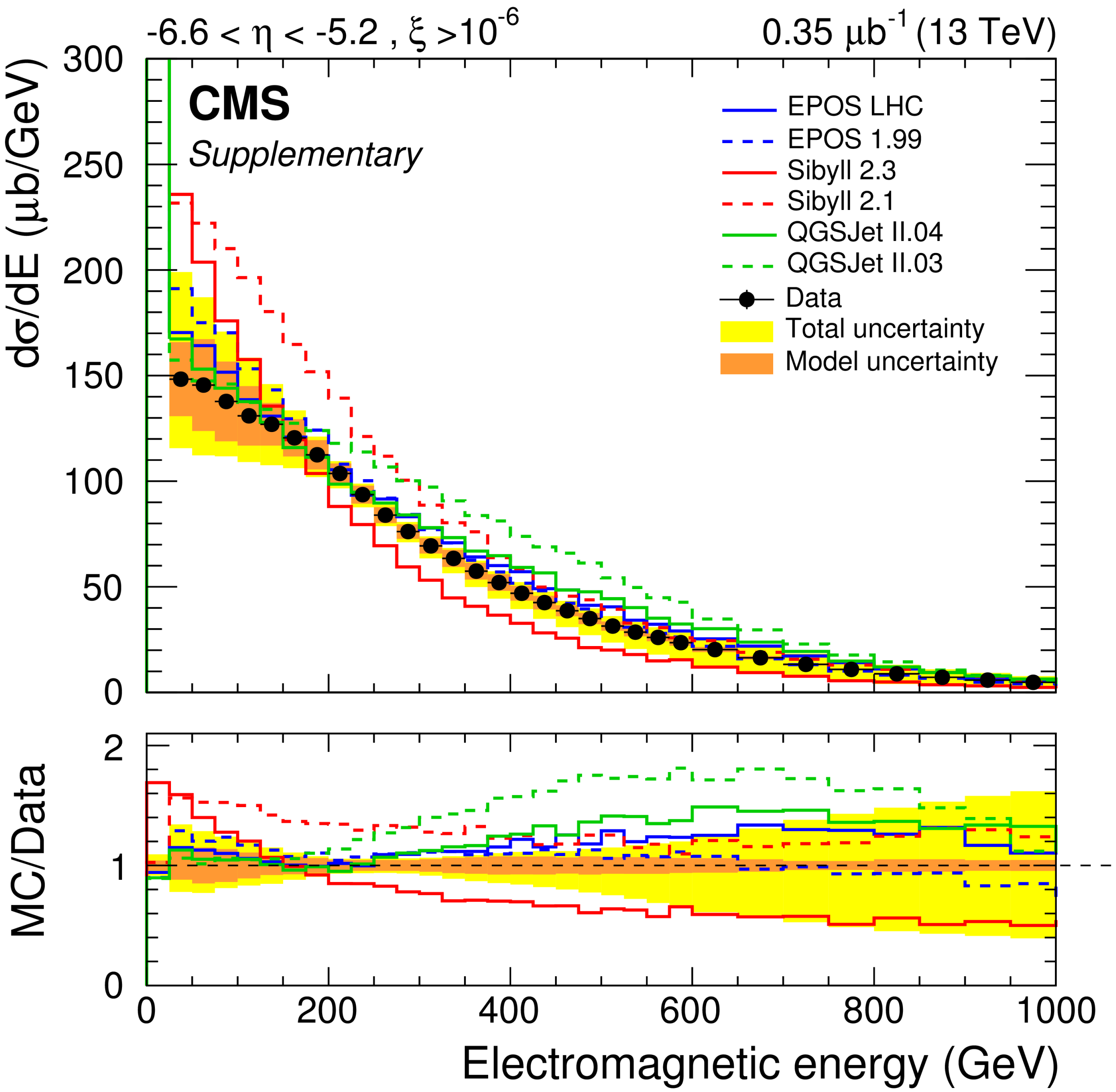
ELECTROMAGNETIC ENERGY

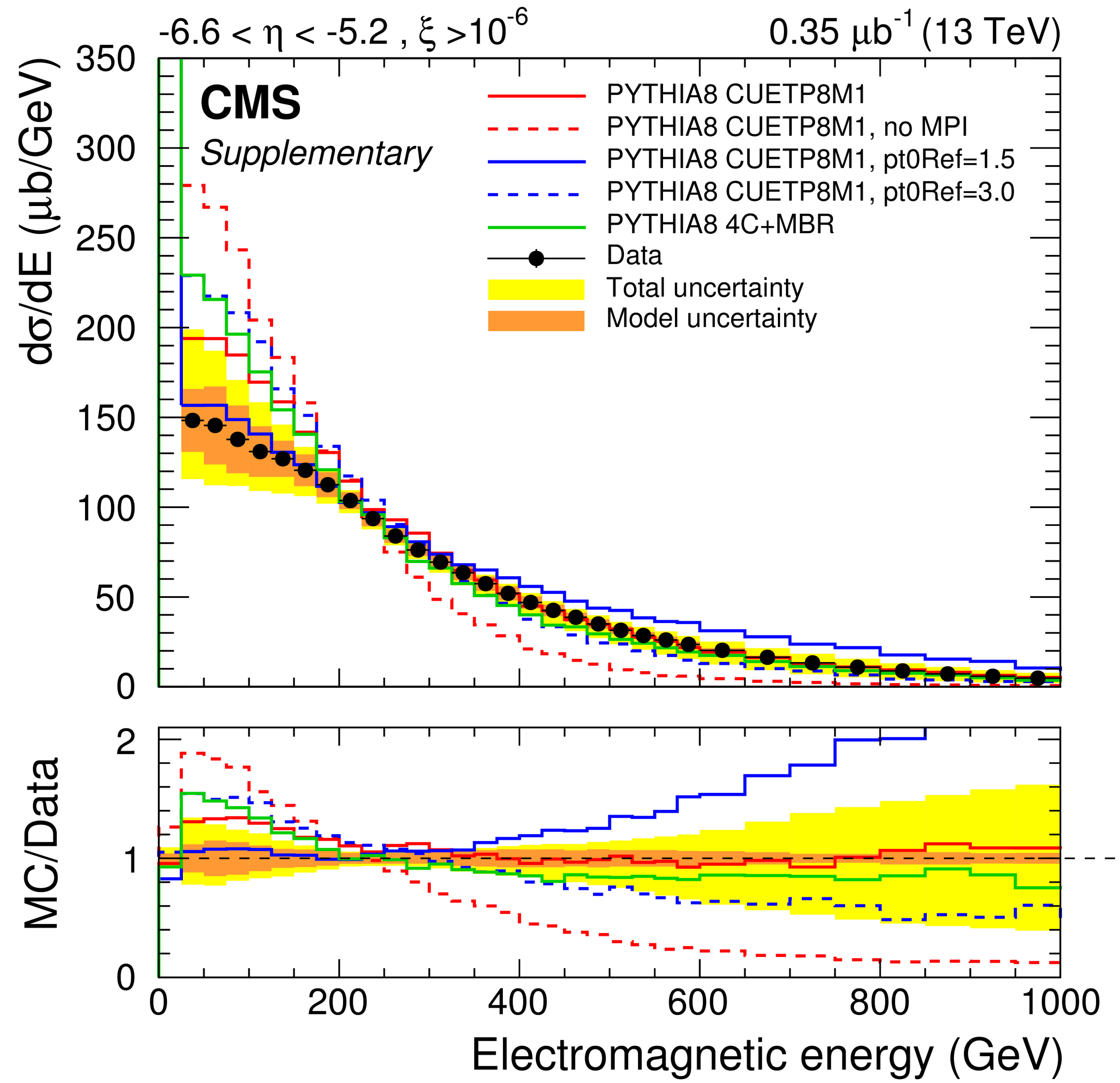


- High energy tail is still sensitive to MPI modeling
- Overall good description by most models

Energy flow in pp (e.m.)

ELECTROMAGNETIC ENERGY - ZOOM



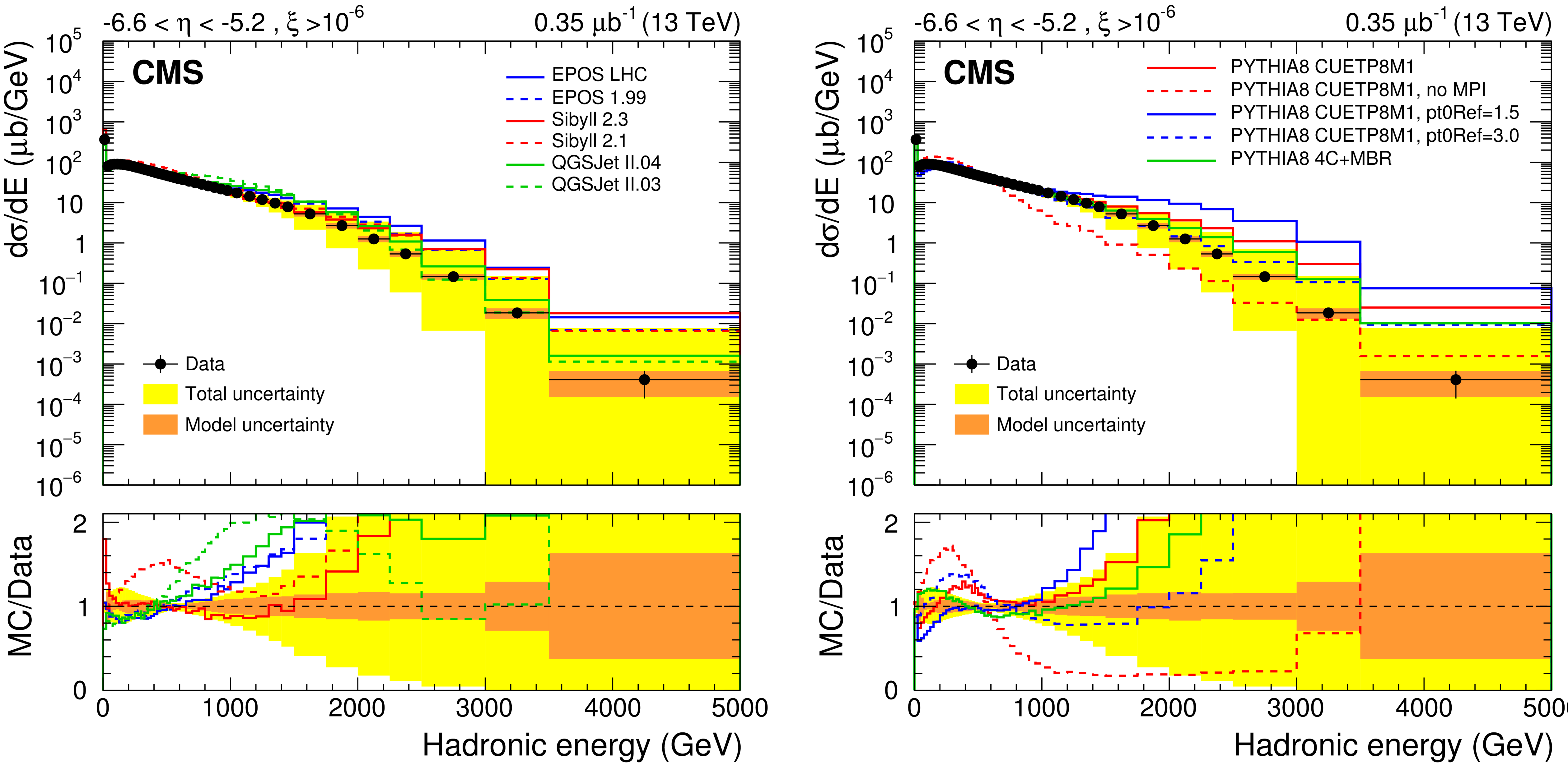


- High energy tail is still sensitive to MPI modelling
- Overall reasonable description by most models
- Zoom of low energy distribution: PYTHIA MBR and Sibyll describe data less well

http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ-16-002/index.html

Forward energy flow

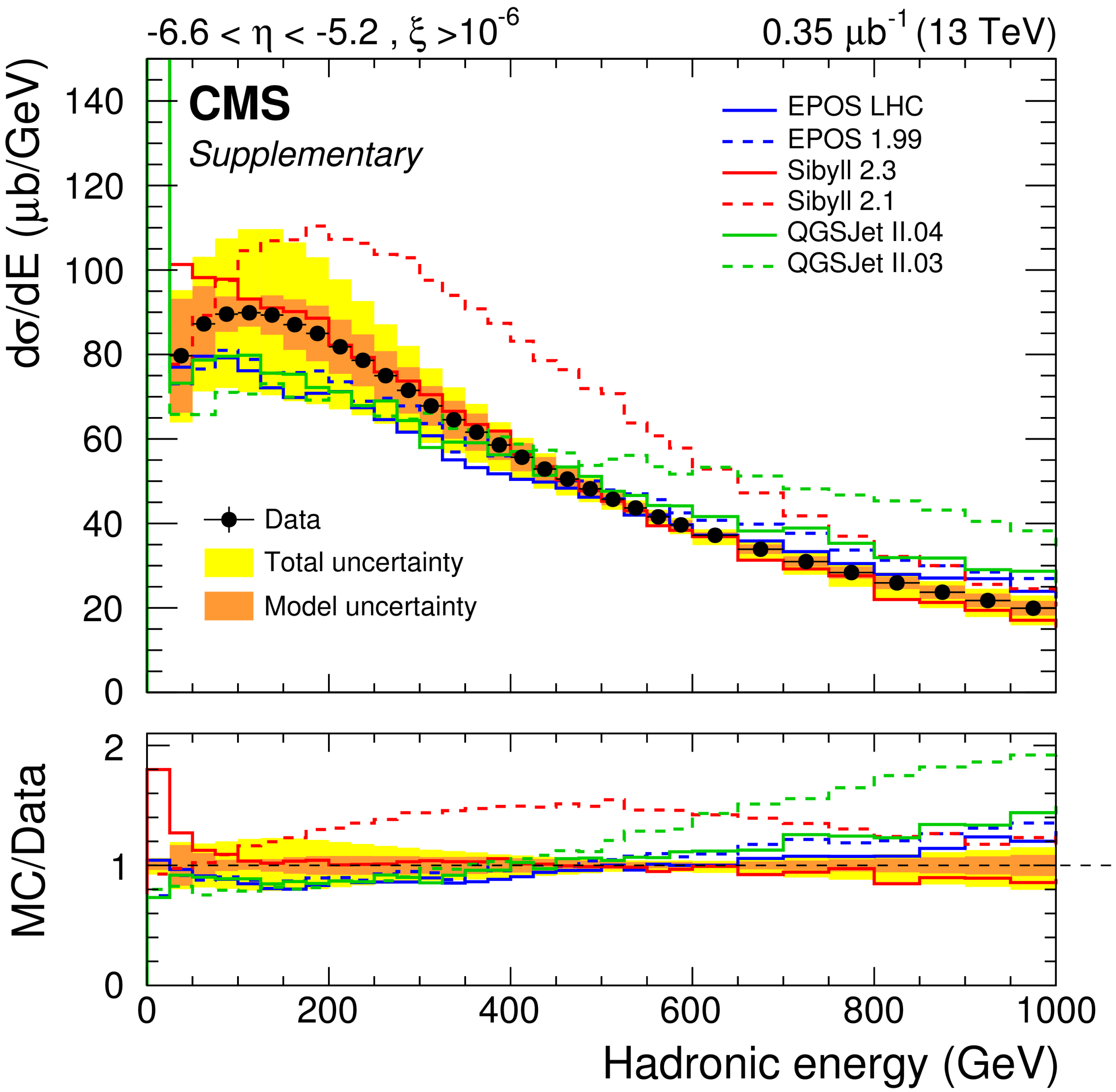
HADRONIC ENERGY

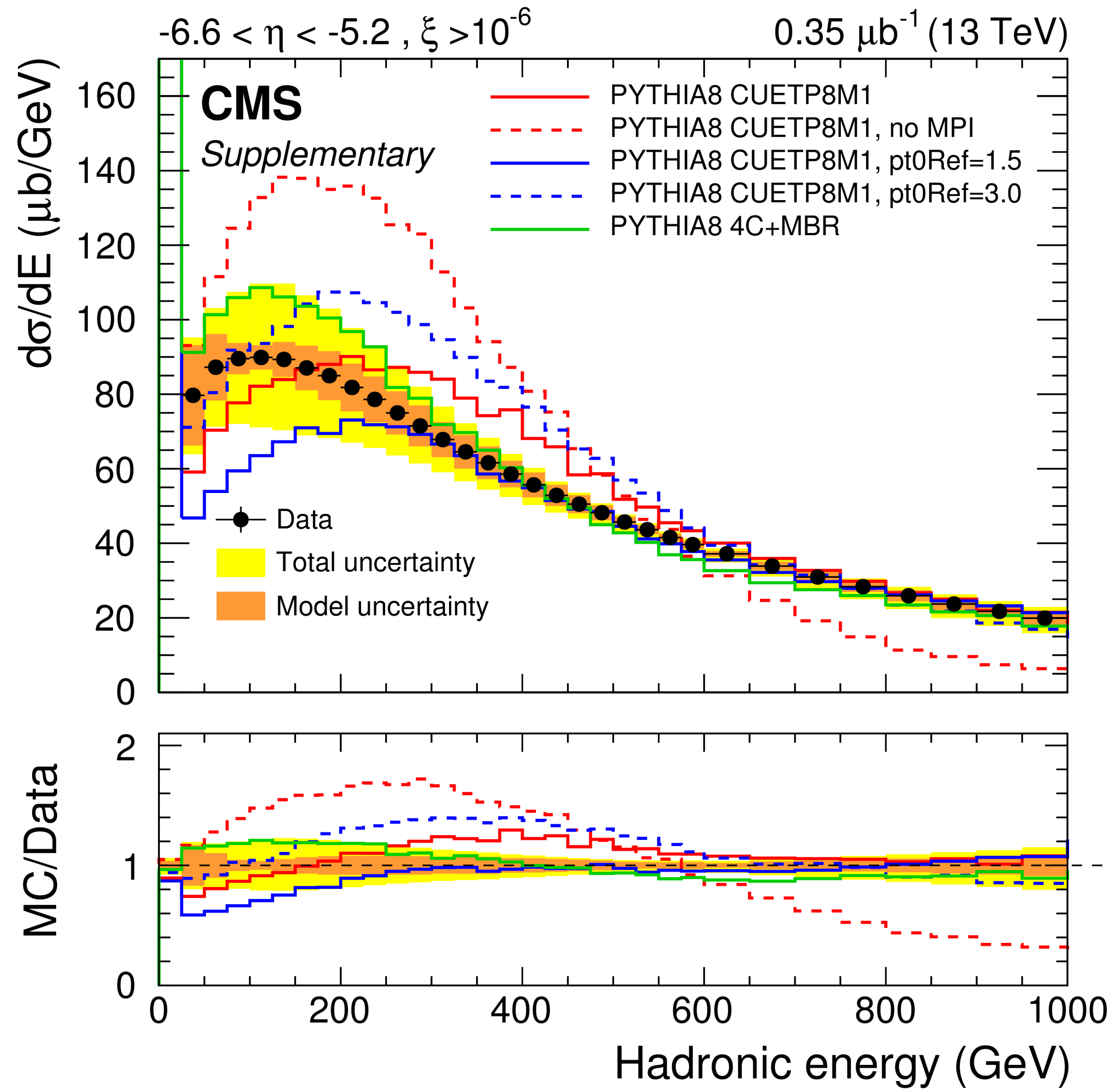


- All models overestimate the high-energy tail

Forward energy flow

HADRONIC ENERGY - ZOOM





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- All models overestimate the high-energy tail
- Zoom of low energy distribution: confirms conclusion from total energy spectrum

Measurement of
the very forward inclusive jet cross section
in pp collisions at $\sqrt{s}$ = 13 TeV

CMS-PAS-FSQ-16-003

Forward jets in pp

Why?

- Powerful benchmark for QCD model predictions

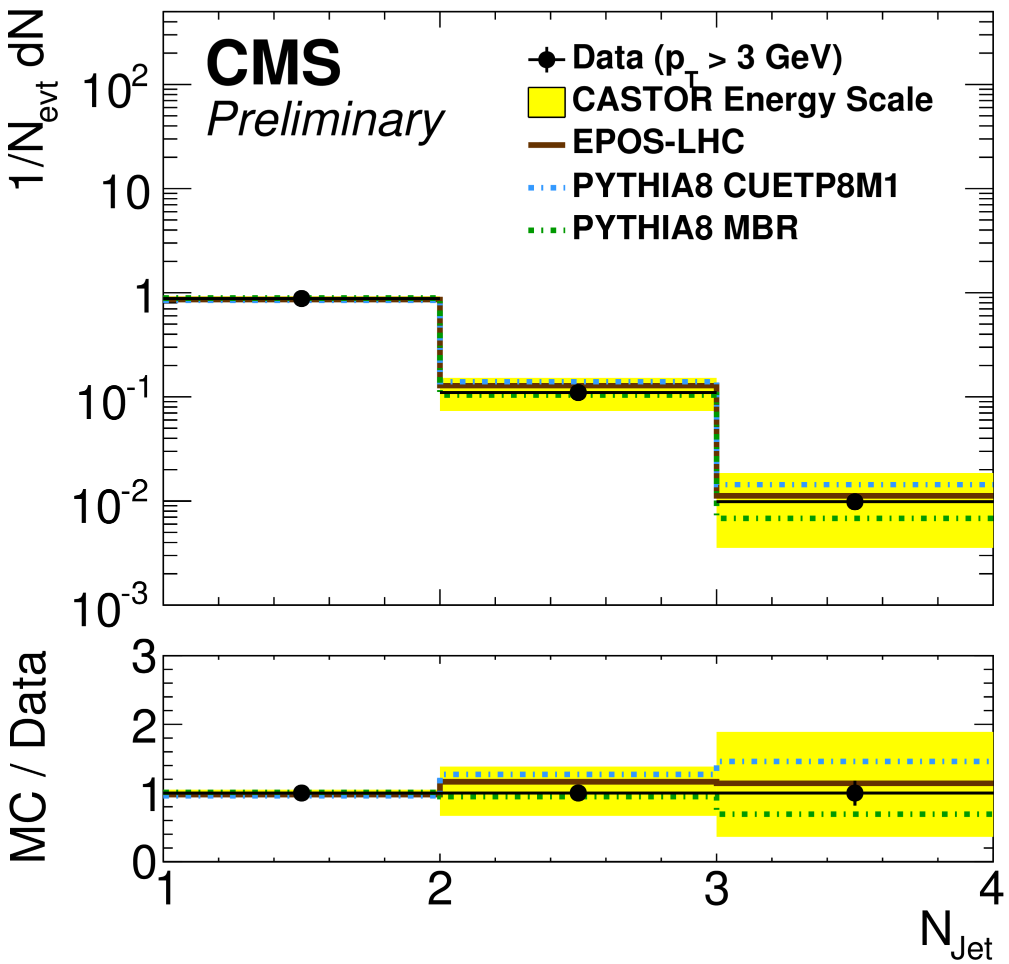
$$x = \frac{p_T\, e^{-\eta}}{\sqrt{s}}$$ → forward, low p_T jets give access to low x

- Sensitive to parton evolution dynamics (DGLAP/BFKL/CCFM)
- Possibly sensitive to parton saturation (nonlinear evolution)?

What?

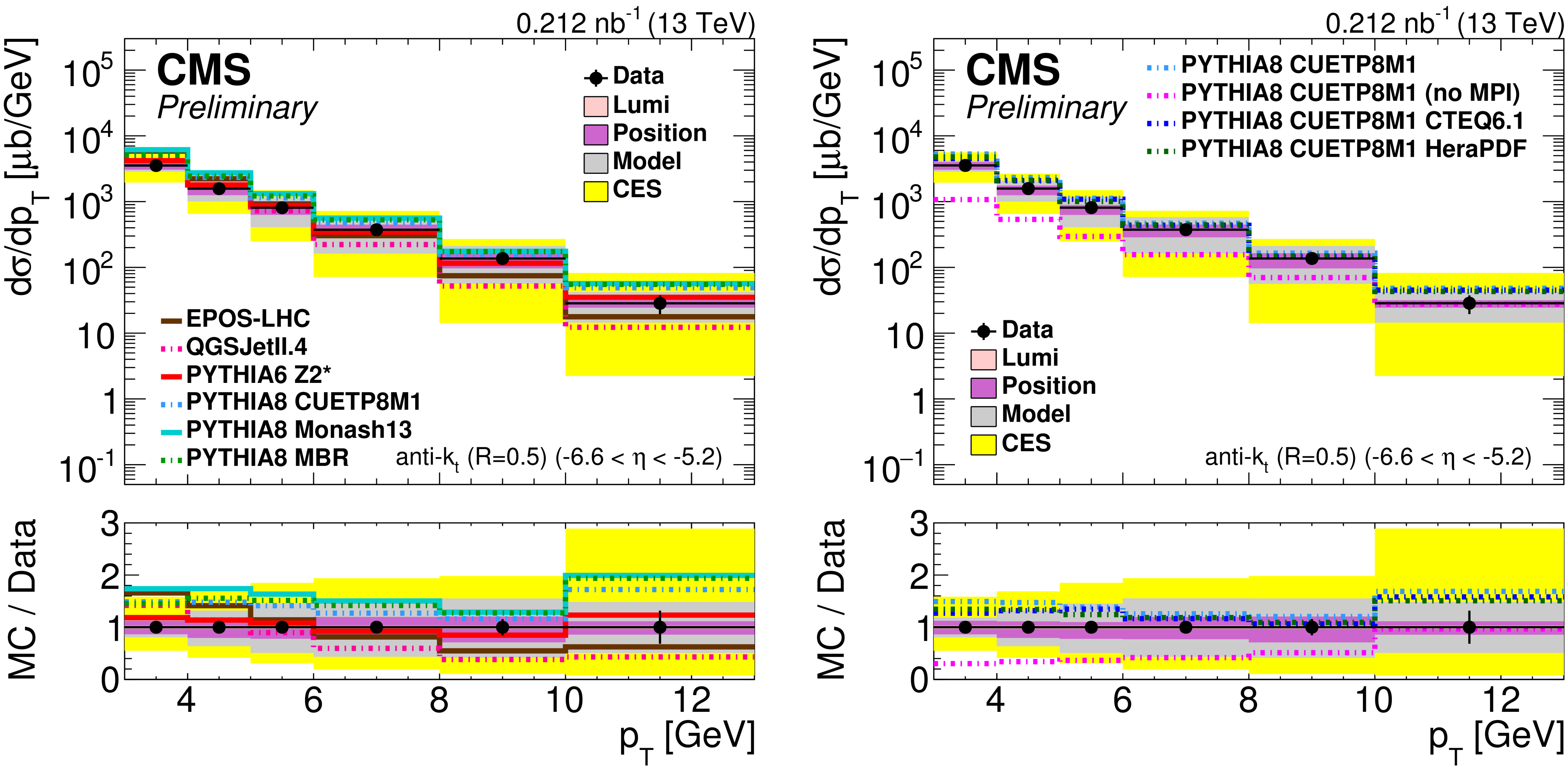
- Fully corrected inclusive jet cross sections and jet yields normalized to number of visible jets as function of jet p_T
  - anti-k_T jets with $R = 0.5$
  - $-6.6 < \eta < -5.2$
  - p_T unfolded from $E \cdot \cosh \eta$, with $\eta = -5.9$
- Energy scale uncertainty yields the dominant systematic uncertainty

DETECTOR LEVEL JET MULTIPLICITY



Forward jets in pp

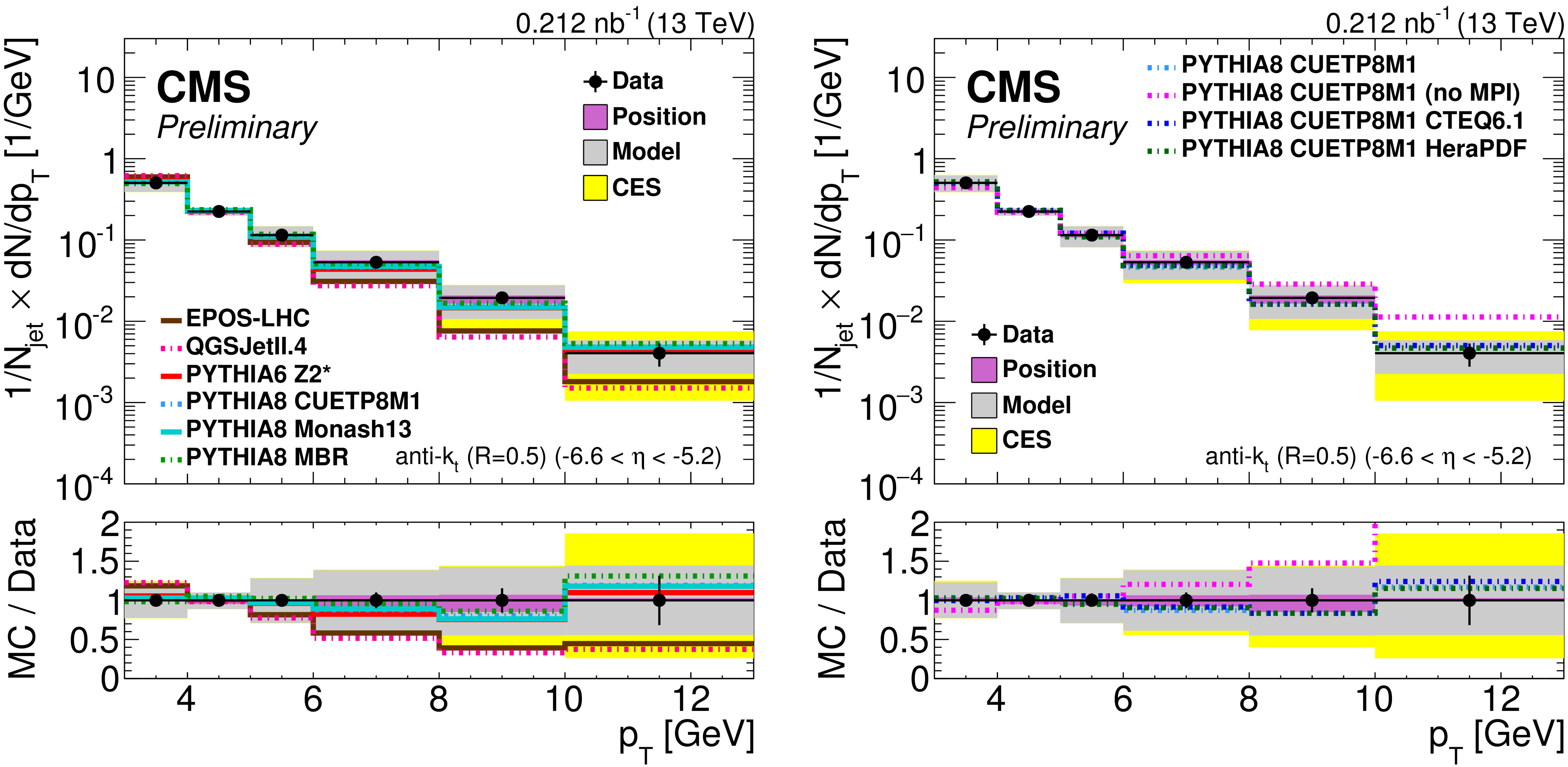
CROSS SECTION



- All models are compatible with data within uncertainties
- Weak dependence on underlying PDF
- Large sensitivity to MPI modelling

Forward jets in pp

JET YIELD



- Smaller energy scale uncertainty when the jet yield is normalized by the number of visible jets
- EPOS and QGSJet are a bit softer than the data indicate

Very forward inclusive jet cross sections in p+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

CMS-PAS-FSQ-17-001

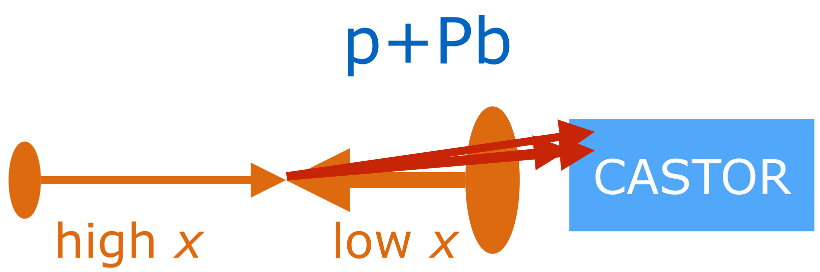
Forward jets in p+Pb/Pb+p

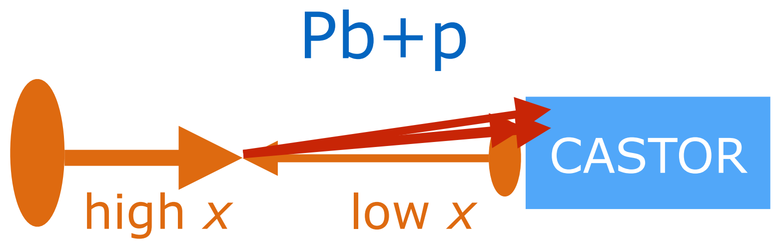
Why?

- Enhanced saturation (and nuclear) effects in collisions with heavy ions
- Saturation scale in collisions with ions more perturbative with respect to saturation scale in proton collisions

What?

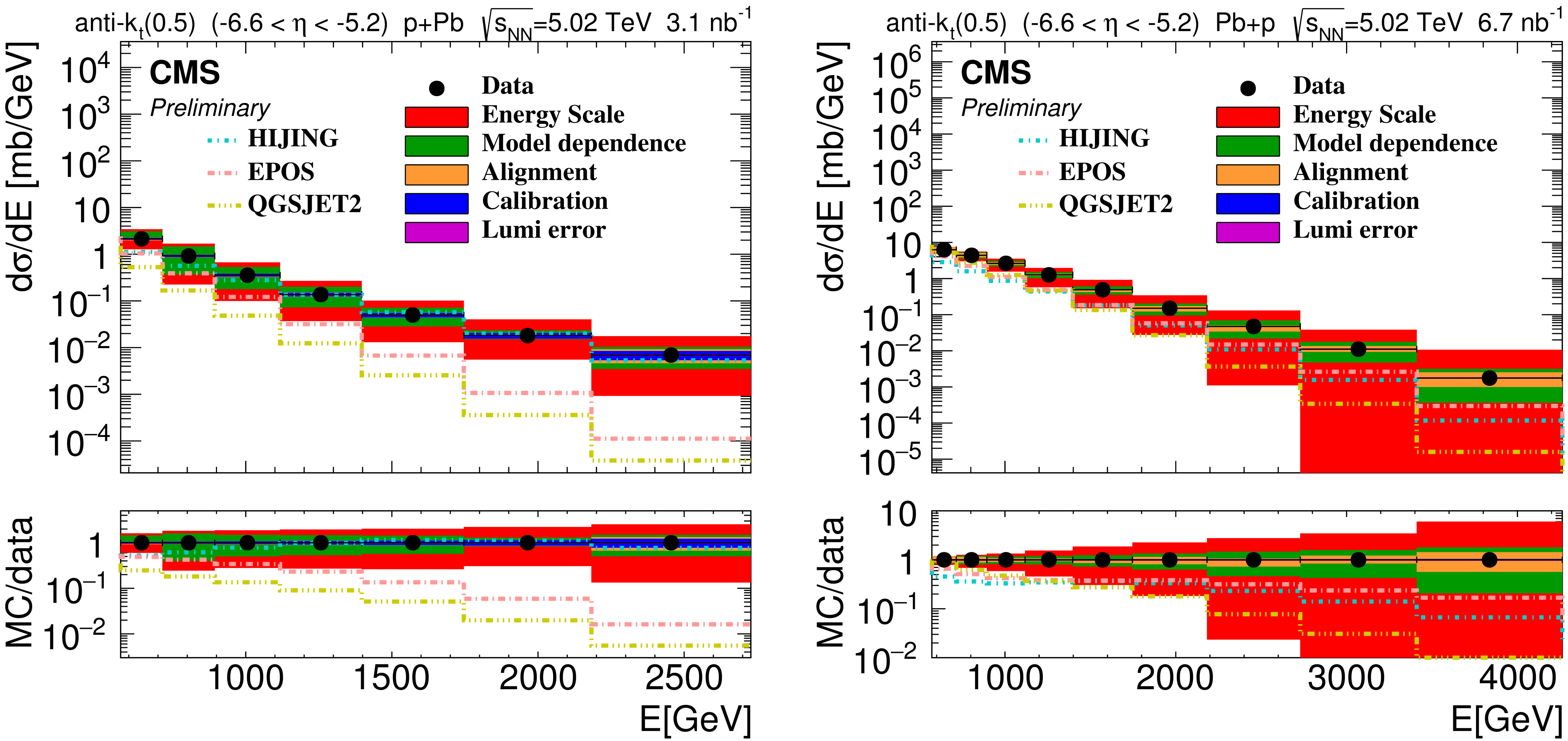
- Fully corrected inclusive jet cross sections in p+Pb (proton towards CASTOR) and Pb+p (ion towards CASTOR) as function of jet energy
  - double-sided event selection to suppress photon-induced and diffractive interactions
  - anti-k_T jets with R = 0.5
  - -6.6 < η < -5.2
- Ratio of p+Pb/Pb+p cross section as function of energy
- Dominant systematic uncertainty:
  - energy scale for absolute cross section
  - model dependence for cross section ratio





Forward jets in p+Pb/Pb+p

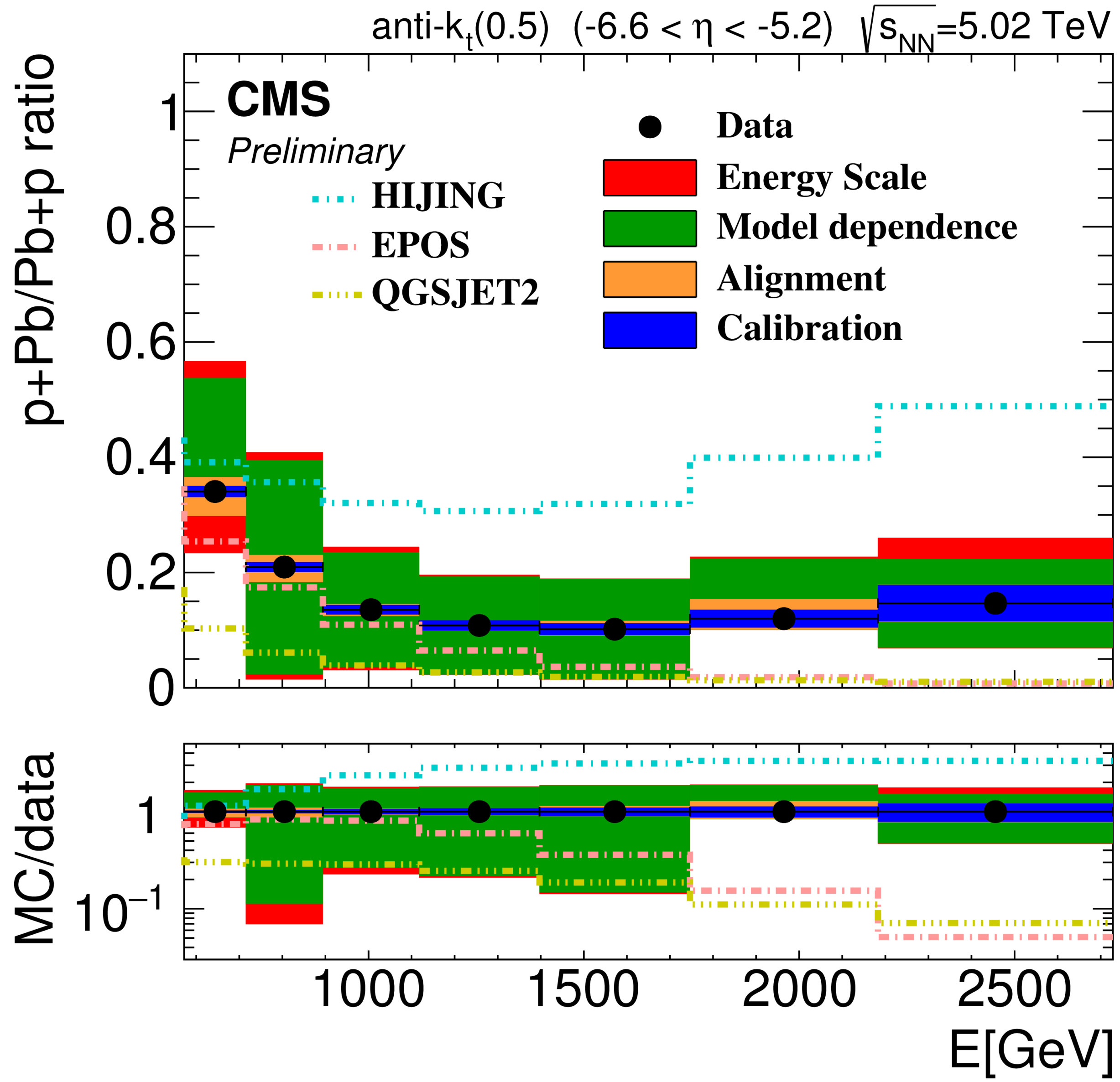
CROSS SECTION FOR p+Pb and Pb+p **LAB frame**



- p+Pb: HIJING describes data well; EPOS and QGSJet2 underestimate the cross section
- Pb+p: models underestimate low-energy tail, but are within large uncertainty at high energy

Forward jets in p+Pb/Pb+p

CROSS SECTION RATIO p+Pb/Pb+p **LAB frame**



- Saturation expected in p+Pb, but not in Pb+p
  → depletion at low energy?
- Caveat: asymmetric beams lead to different boost factors and different acceptance windows
- Cancellation of energy scale uncertainty allows for better discrimination between data and models

Single inclusive jet transverse momentum and energy spectra at very forward rapidity in pp collisions at $\sqrt{s}$ = 7 and 13 TeV

K. Kutak, H. Van Haevermaet,
P. Van Mechelen

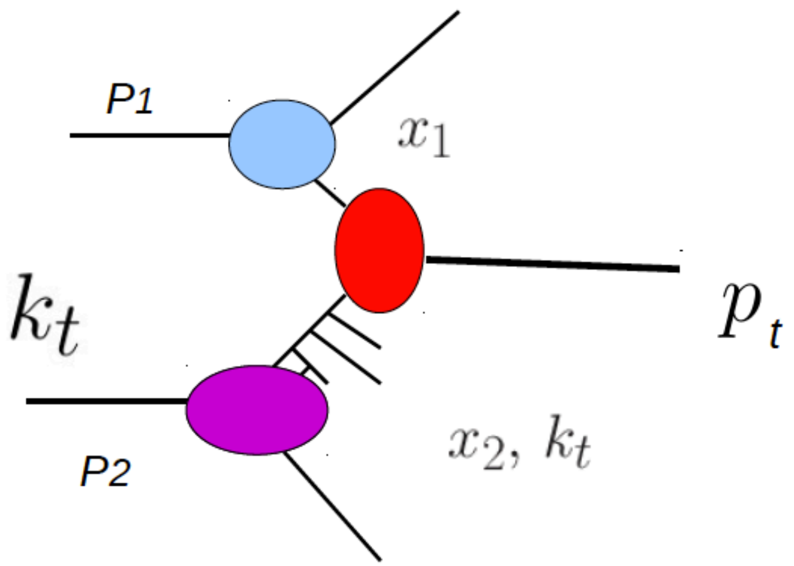
arXiv:1701.07370
PLB 770 (2017) 412

High-energy factorisation (HEF)

"Hybrid" approach for inclusive forward jet production

- High-*x* parton from conventional, linear PDF
- Low-x gluon from off-shell, k_T -dependent PDF
- p_T of the final state jet = k_T of off-shell gluon
- In collinear factorization, the 2→1 matrix element with 3 on-shell partons is zero
- Unintegrated PDF from
  - "extended" BFKL ≡ Kutak-Sapeta (KS) linear PDF
  - "extended" BK ≡ KS nonlinear PDF

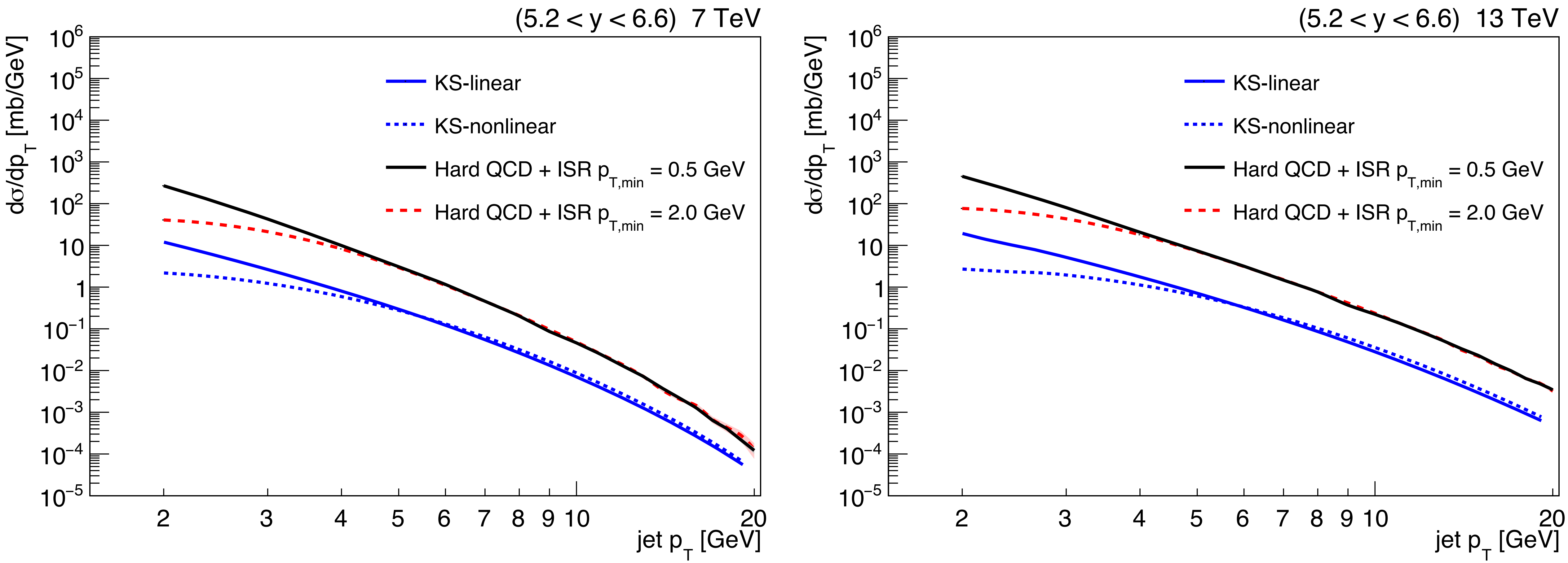
$$p_t = k_t$$



$$x_1 = \frac{p_t\, e^{y}}{\sqrt{S}} \qquad x_2 = \frac{p_t\, e^{-y}}{\sqrt{S}}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y\,\mathrm{d}p_\mathrm{T}} = \frac{1}{2}\,\frac{\pi\, p_\mathrm{T}}{(x_1 x_2 s)^2}\left[\sum_{\mathrm{q}(\bar{\mathrm{q}})} \overline{|\mathcal{M}_{\mathrm{g^*q(\bar{q})\to q(\bar{q})}}|}^2 x_1 f_{\mathrm{q(\bar{q})/A}}(x_1,\mu^2)\,\mathcal{F}^{\mathrm{F}}_{\mathrm{g^*/B}}(x_2,p_\mathrm{T}^2,\mu^2)\right.$$
$$\left. + \overline{|\mathcal{M}_{\mathrm{g^*g\to g}}|}^2 x_1 g_{\mathrm{g/A}}(x_1,\mu^2)\,\mathcal{F}^{\mathrm{A}}_{\mathrm{g^*/B}}(x_2,p_\mathrm{T}^2,\mu^2))\right]$$

HEF predictions for forward jets in pp

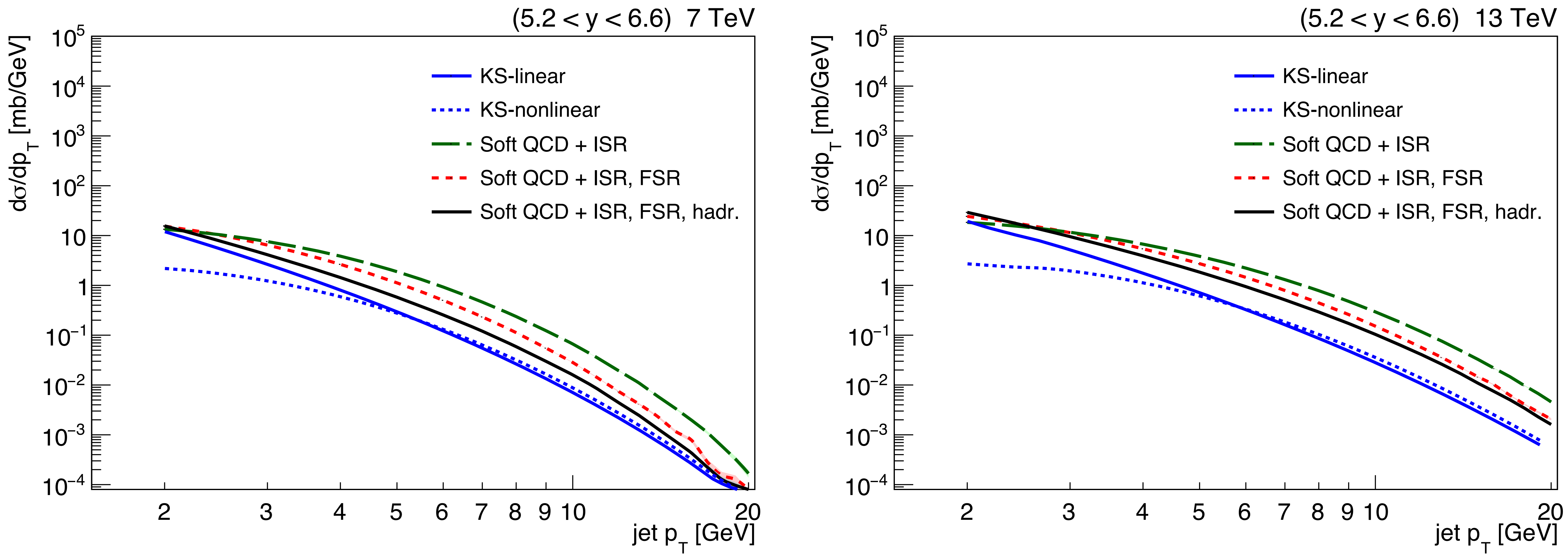


Comparison of HEF framework to PYTHIA

- Remarkable similarity in shape between KS-linear and PYTHIA (ME+ISR) with soft regularization cut
- Remarkable similarity in shape between KS-nonlinear and PYTHIA (ME+ISR) with hard regularization cut
- Significant differences in normalization

→ no effects from low-*x* resummation?

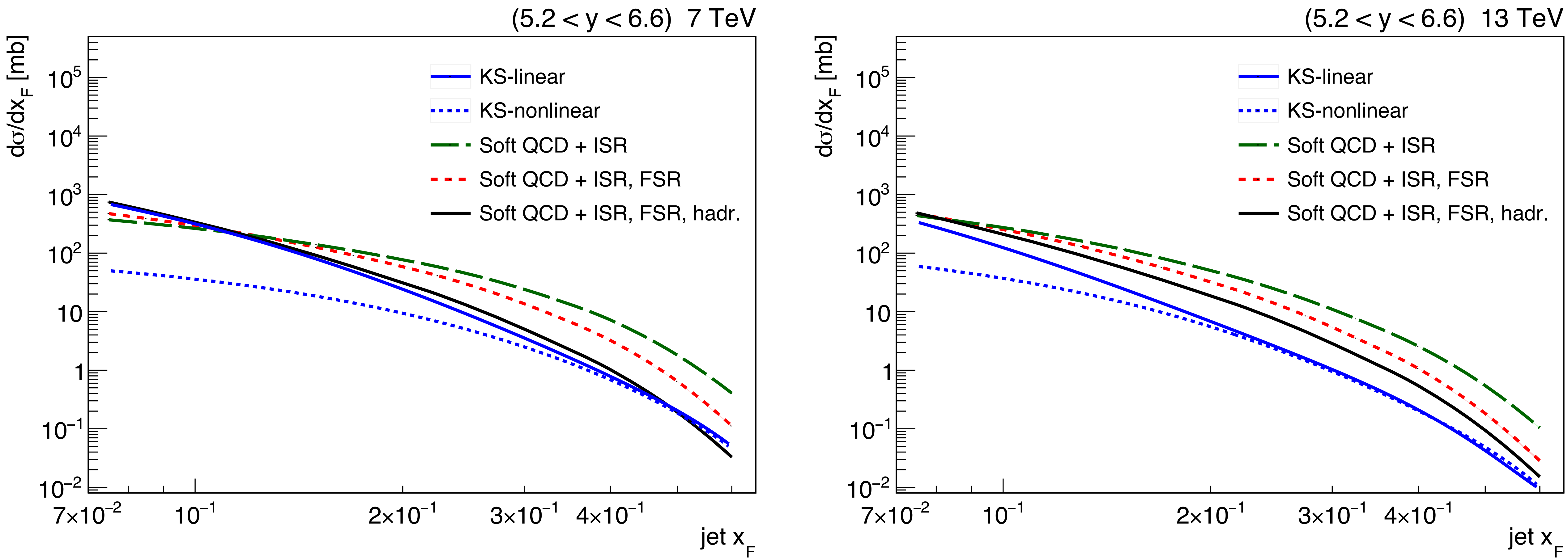
HEF predictions for forward jets in pp



Comparison of HEF framework to PYTHIA

- Underlying event (soft QCD ≡ regularization+MPI, Final State Radiation, and hadronization) change PYTHIA prediction significantly
- Full PYTHIA yields results that are close to HEF prediction with KS-linear PDFs

HEF predictions for forward jets in pp



Comparing cross section at $\sqrt{s}$ = 7 and 13 TeV

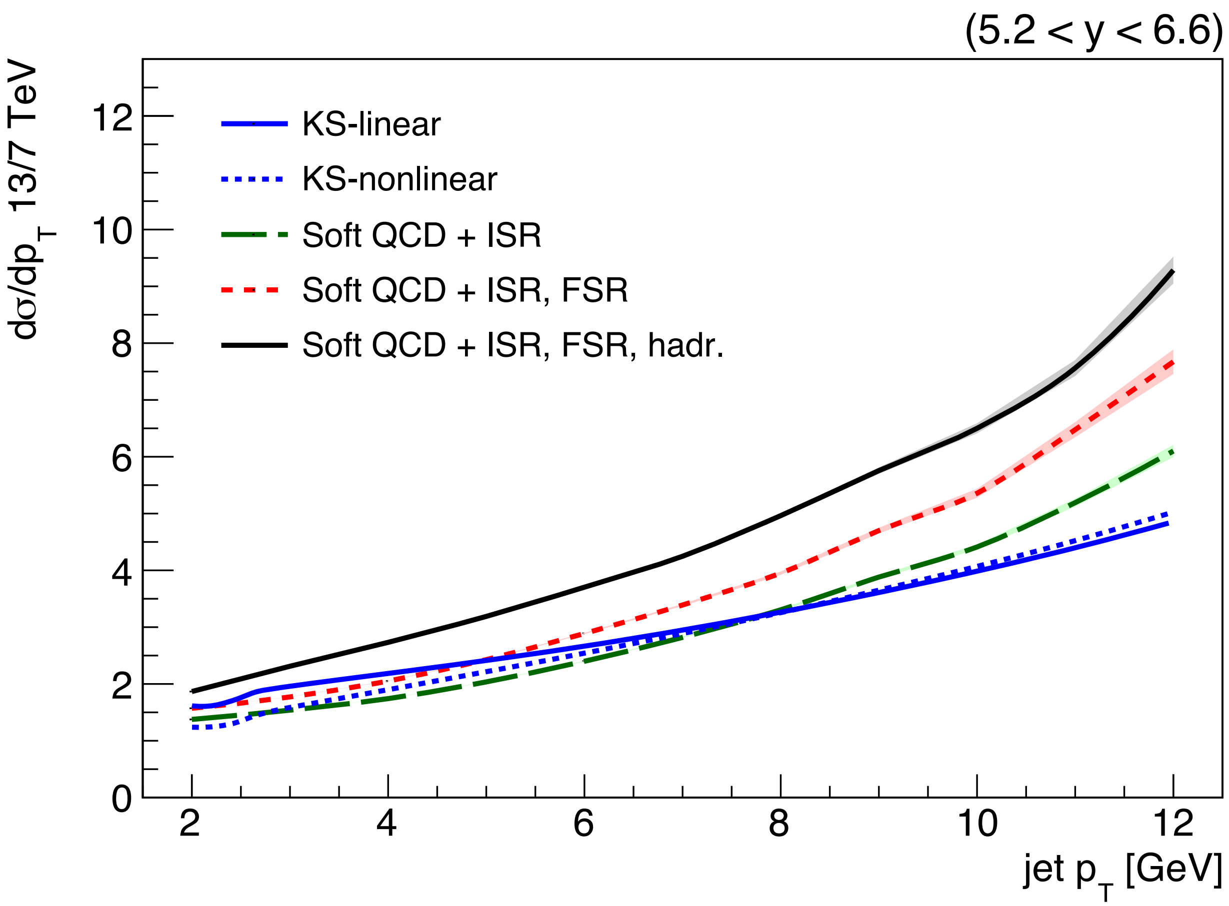
- Feynman-x allows to compare jet cross section at different $\sqrt{s}$

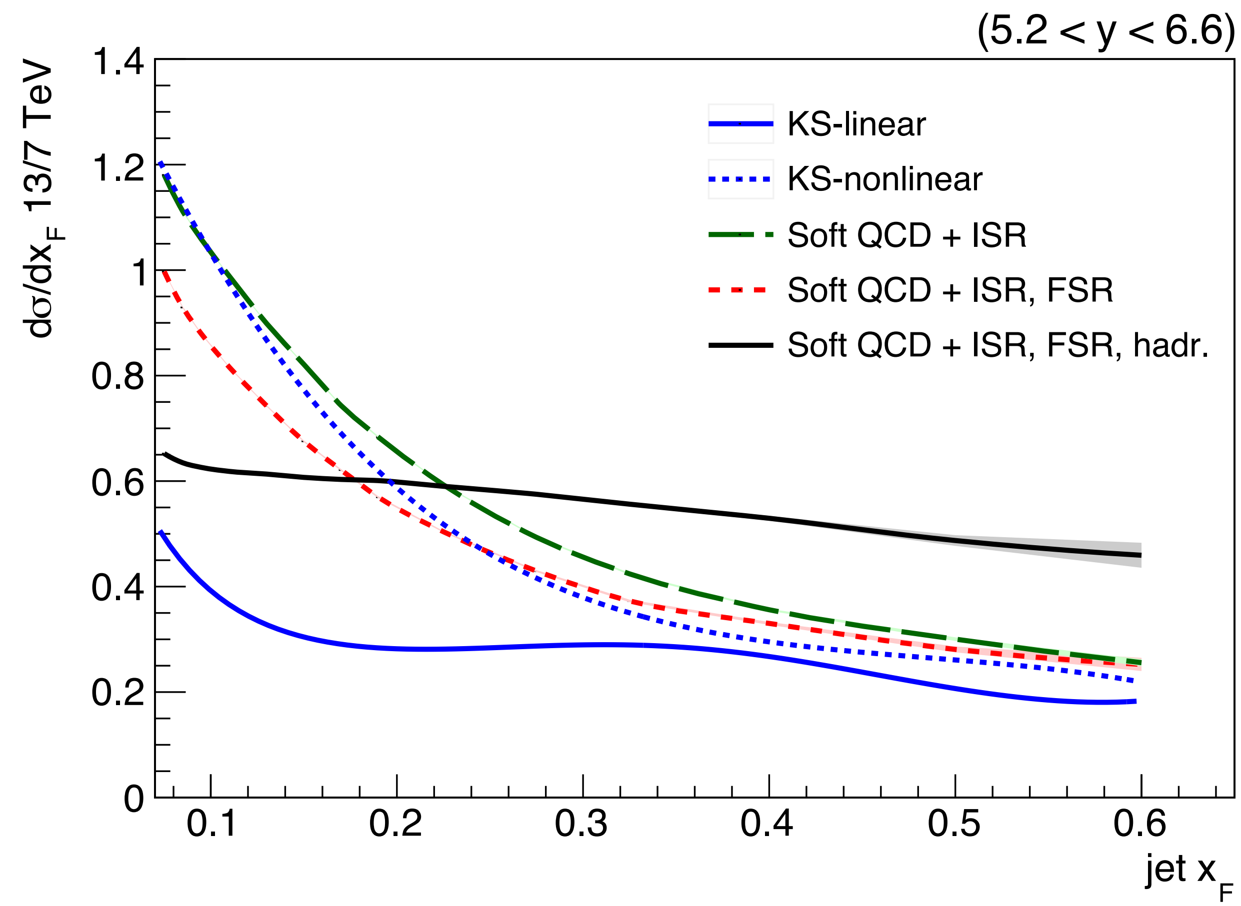
$$x_{\rm F} = \frac{2p_{\rm L}}{\sqrt{s}}$$

  Measures asymmetry in the longitudinal direction
  This observable is easily accessible with CASTOR

- Similar conclusions as for p_T spectra

HEF predictions for forward jets in pp





Ratio of cross section at $\sqrt{s}$ = 13 and 7 TeV

- KS-linear and KS-nonlinear
  - very similar ratio as function of p_T
  - very different ratios as function of x_F

  → **optimal observable to look at saturation**

- PYTHIA predicts a ratio that is a factor 2 larger than HEF

Summary

- Measurements of **jets in the very forward region** (-6.6 < η < -5.2) at CMS are a reality!
- Major challenge: energy scale uncertainty
  → inventive procedures for cancelation of uncertainties are being developed

- Current results on energy flow and forward jets highly sensitive to Underlying UE tuning; weak depedence on PDF
- No clear sign for saturation yet (p+Pb results need to be further interpreted)

- **Hybrid factorisation framework** allows to make accurate prediction in the forward region and is very helpful for the interpretation of experimental results