Very Forward Jets in CMS with CASTOR

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On behalf of the CMS Collaboration
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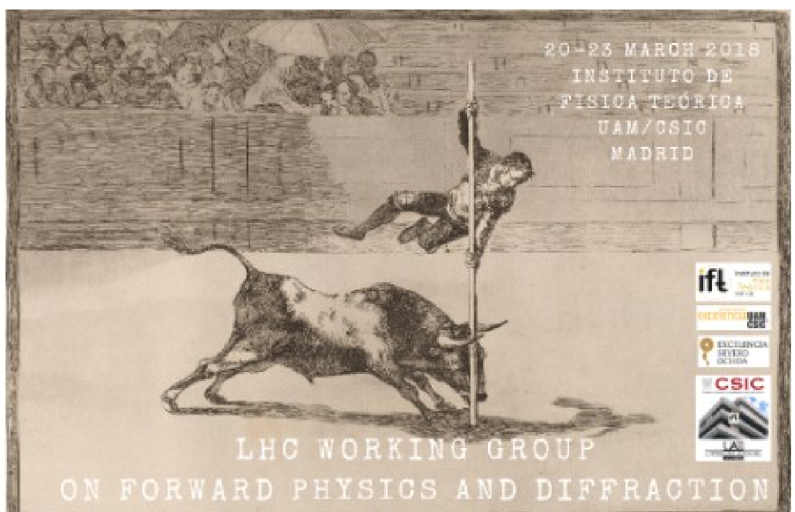
Madrid, Spain



Outline

- Motivation for Forward Physics
- CMS Detector
- Measurements on the LHC Run 2 data (13 TeV)

  - Measurement of the very forward inclusive jet cross section in pp collisions at $\sqrt{s}$ = 13 TeV (CMS PAS FSQ-16-003)

  NEW! - Very forward inclusive jet cross sections in p+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (CMS PAS FSQ-17-001)

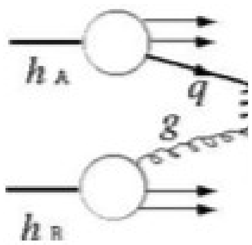
- Summary

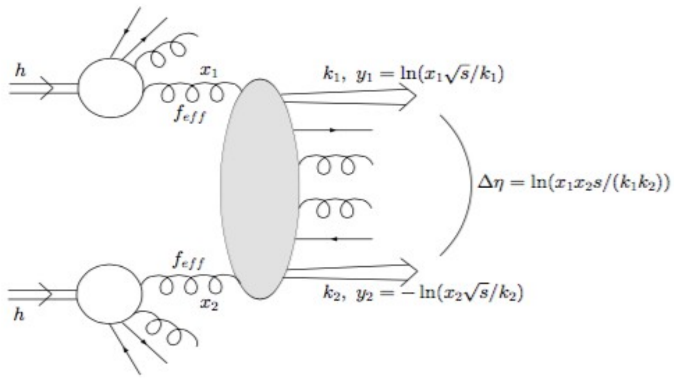
- All Forward Physics results at CMS
  https://cms-results.web.cern.ch/cms-results/publicresults/publications/FSQ/index.html

Why Forward Physics?

- To understand the pp collisions depend on a wide range of phenomena by looking at low p_T or forward y
- Many interesting (mostly colorsinglet exchange) scattering processes at the LHC are characterized by forward particle production:

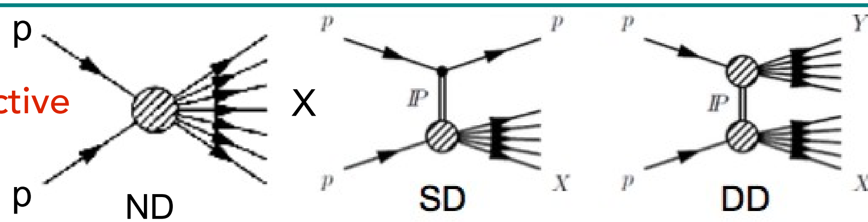
Low-x





- Small fraction of proton momentum carried by an interacting parton.
- Test of pQCD evolution (DGLAP vs BFKL dynamics);
- Tool to study small-x QCD are forward jets – jets emitted at small angle with respect to the beam (large rapidity).

Elastic/diffractive interactions:



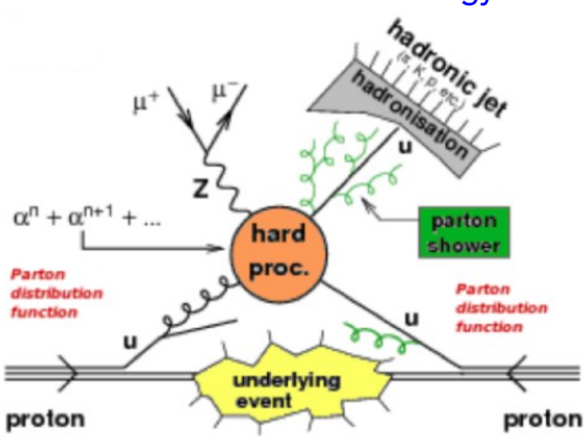
- Soft diffraction (X=anything):
  - Dominated by soft QCD → SD, DPE vs. s, t, M_X
  - provide valuable info of non-perturb. QCD.
  - Contributions to pileup pp events.
- Hard diffraction (X = jets, W's, Z's ...):
  - Calculable (in principle) in pQCD → Info on proton structure (dPDFs,GPDs),multiparton interactions (MPI), discovery physics (DPE Higgs, beyond SM)

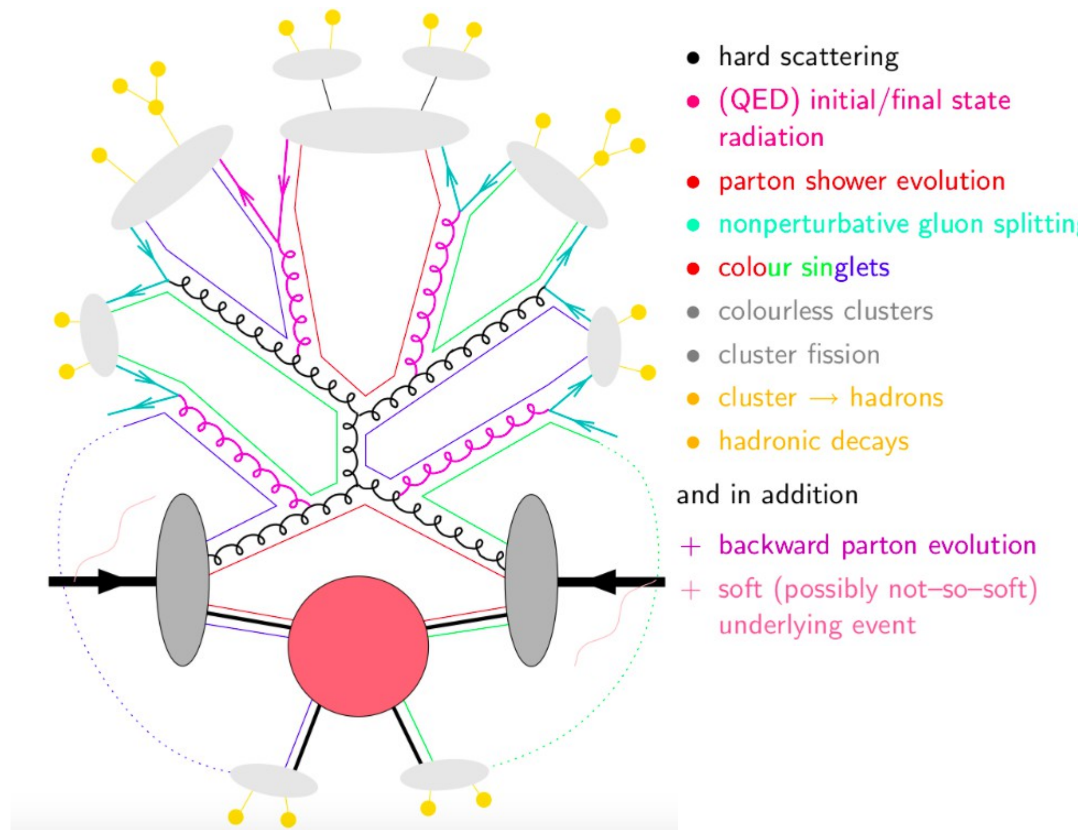
- Cosmic ray physics:
  - Forward energy & particle flows / min. bias events (p-p,p-A,A-A)
  - Exotica: "Centauro" events (DCCs, strangelets)

Why jets?

Jets:

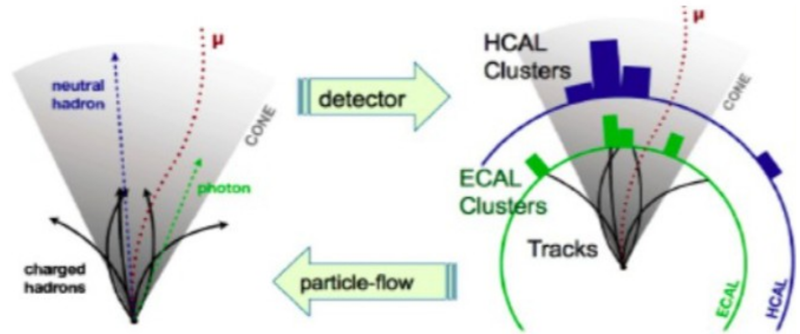
- Key component to extend our understanding of the Standard Model physics
- Invaluable objects to probe QCD
  - soft QCD - low p_T multiparton scattering, fragmentation, underlying event, etc.
  - hard QCD - high p_T: PDFs, strong coupling, perturbation theory, ISR & FSR, parton shower, (subjets)
- Measure and understand the main background to many new physics searches.
- Check SM predictions at high energy scales.
- Abundantly produced at hadron colliders like LHC
  - LHC is a jet factory!
- Jet and photon cross section measurements are also important for validating the detector/trigger/reconstruction chain, and are "legacy" measurements for the future → among the first measurements at each new energy



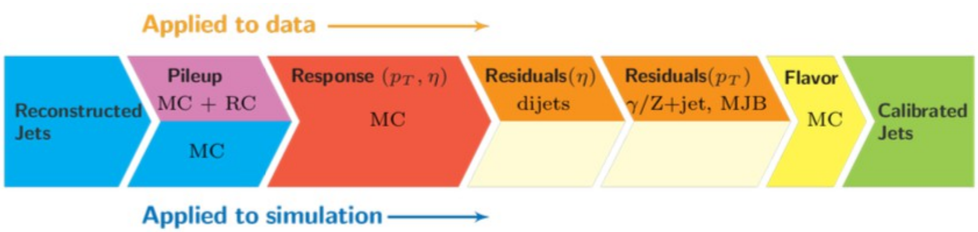


Jet Reconstruction and Jet Calibration @ CMS

- A jet in CMS is seen as a bunch of particles in the detector
- Jet reconstruction procedure: input objects (e.g. particles)→ apply jet finding algorithm → jet reconstruction
- Anti-k_t algorithm (infrared and collinear safe) is used
- Particle Flow (PF) Jets: Clustering of Particle Flow candidates constructed by combining information from all sub-detector systems.



- Factorized Jet Energy Correction approach in CMS:



- ► **Pileup → corrects for "offset" energy**
- ► **Response → Make jet response flat on η and p_T**
- ► **Data/MC residuals → residual differences between data & MC**
- ► **Flavor (optional) → corrects dependence on jet flavor**

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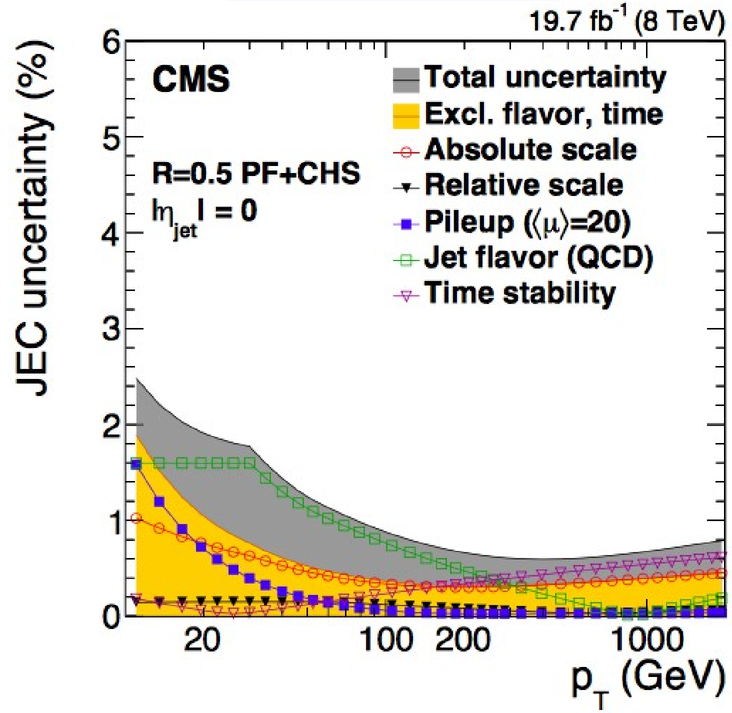
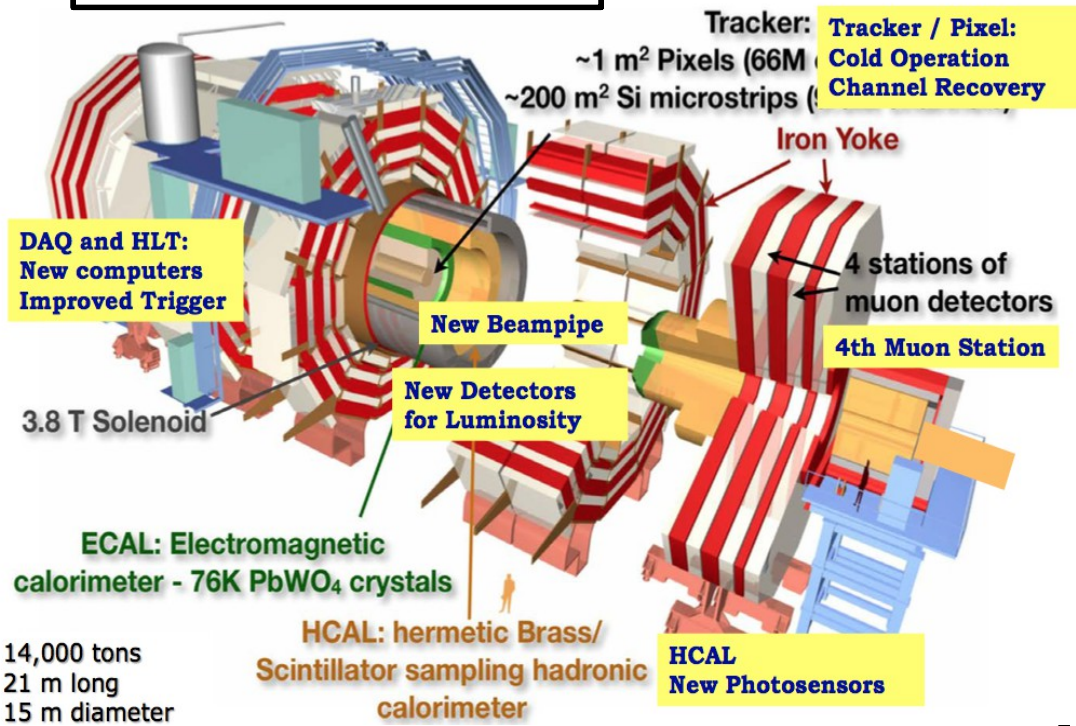


CMS Detector

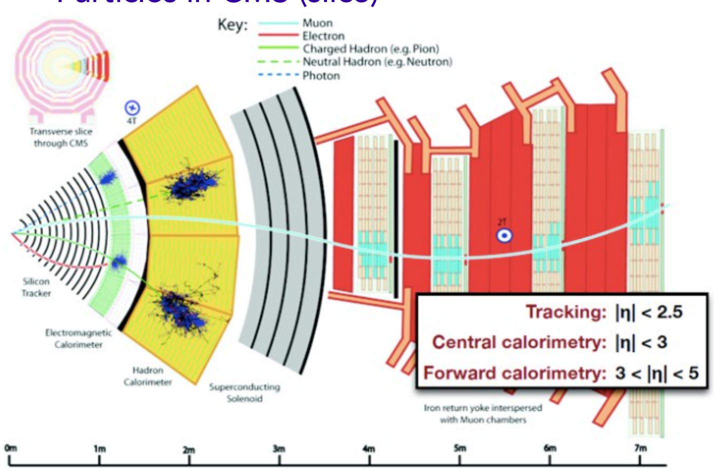
CMS after Long Shutdown 1



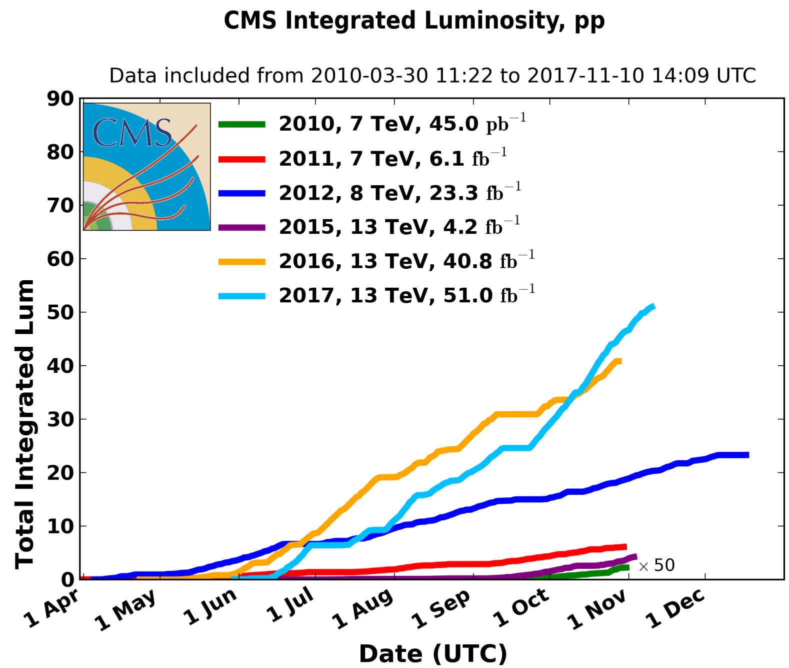
14,000 tons
21 m long
15 m diameter

3[rd] of June 2015: LHC back in business with record pp collision energy of 13 TeV

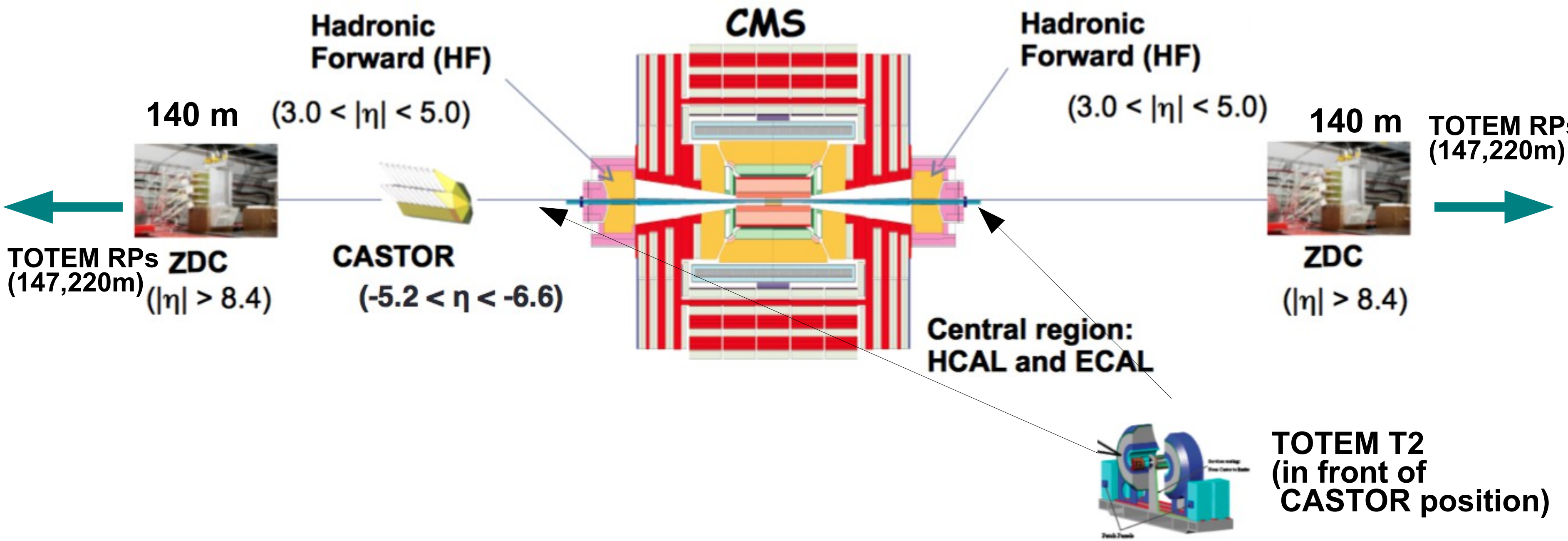
Particles in CMS (slice)



Run I and II pp collisions



Forward Detectors at CMS

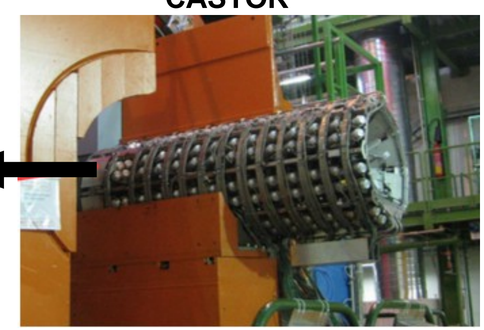


HF Detector

- @11.2 m from interaction point
- Rapidity coverage: **3 < |η| < 5**
- Steel absorbers/quartz fibers (Long+short fibers)
- 0.175x0.175 η/φ segmentation

- Tungsten-Quartz-Cherenkov sampling calorimeter
- Octagonal cylindrical shape
- Segmented in 16 sectors in φ and 14 modules in z
- Separated electromagnetic and hadronic sections
- Located at 14.4 m from IP in CMS

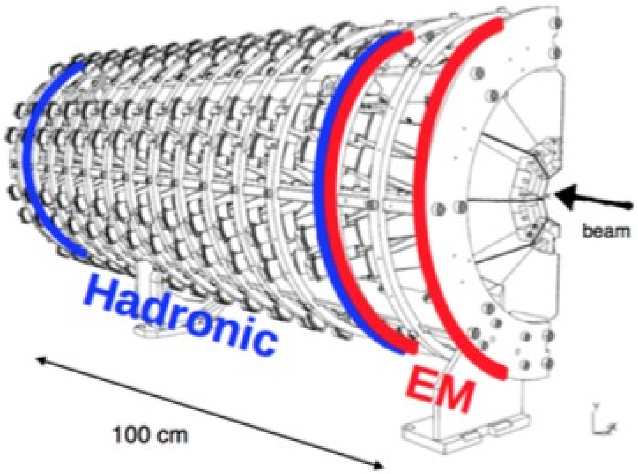
CASTOR

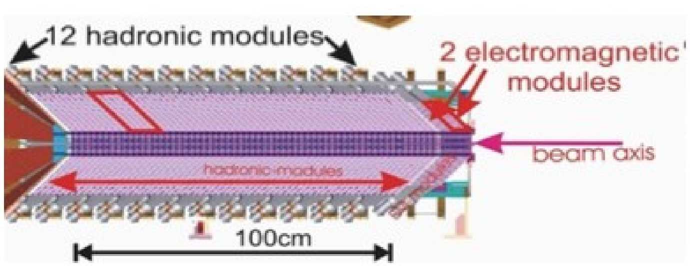


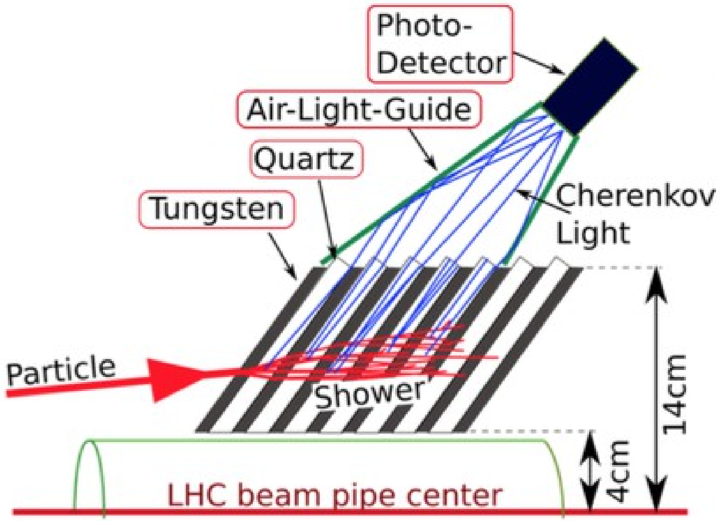
CMS Very Forward Calorimeter (CASTOR)

- Centauro And STrange Objects Research (CASTOR)
- Tungsten-Quartz-Cherenkov sampling calorimeter
- 14.37 m away from Interaction Point (IP). Only at minus side.

- Segmented in 16 sectors in ϕ
- 14–fold segmentation in z: 2 electromagnetic modules, 12 hadronic modules
- Very forward accceptance: $-6.6 < \eta < -5.2$
- No segmentation in η: all jets $\eta = -5.9$



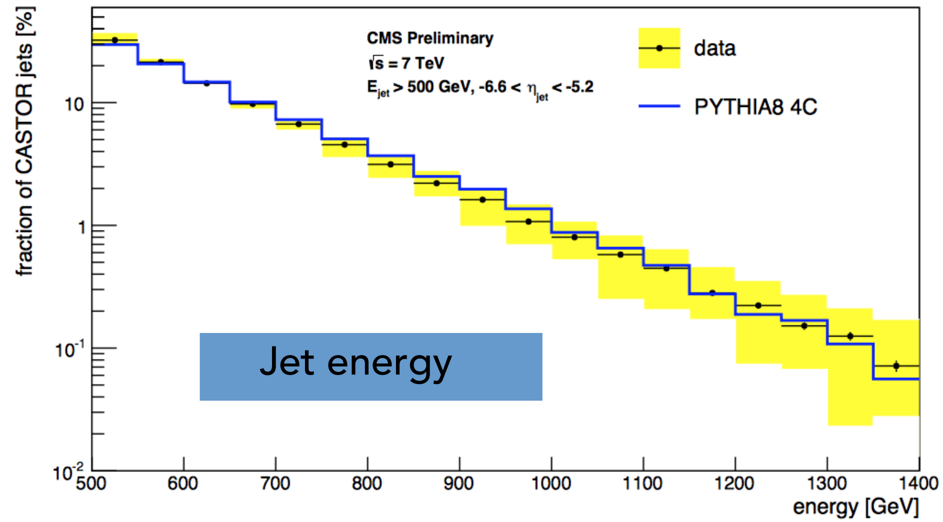


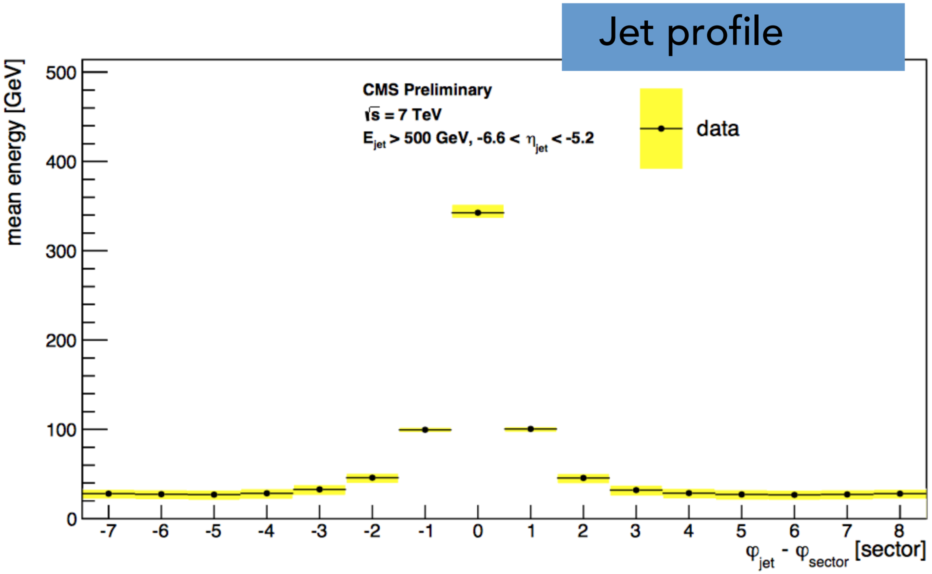


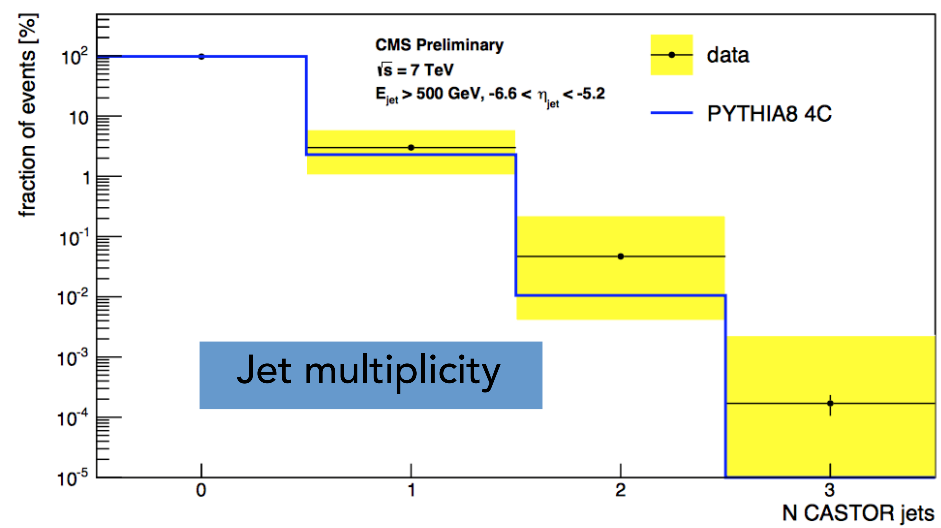
Jet Measurement with CASTOR: First look

CMS DP-2014/022

- **Motivation:**
  - First measurement of jets inside the CASTOR
- **Analysis strategy:**
  - Very low pile-up sample of pp collisions @ $\sqrt{s}$=7 TeV taken in 2010 Run I period
  - Minimum Bias trigger
  - Require central leading track-jet (jet made of charged particles only): p_T > 1 GeV/c and $|\eta| < 2$
  - Anti-k_T (R = 0.5) with high purity input tracks: $|\eta| <$ 2.5 and p_T > 300 MeV
  - Jet in CASTOR E_{jet} > 500 GeV
  - Plots normalized to unity
  - Comparison with Pythia8 4C





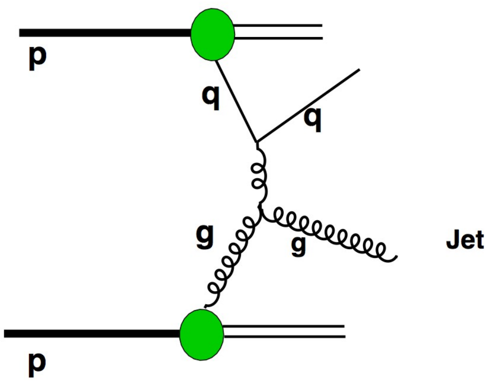


Very forward jets in pp

- Powerful benchmark for QCD model predictions
- Forward and low p_T jet production provides access to low -x
- Sensitive to parton evolution dynamics (DGLAP/BFKL/CCFM)

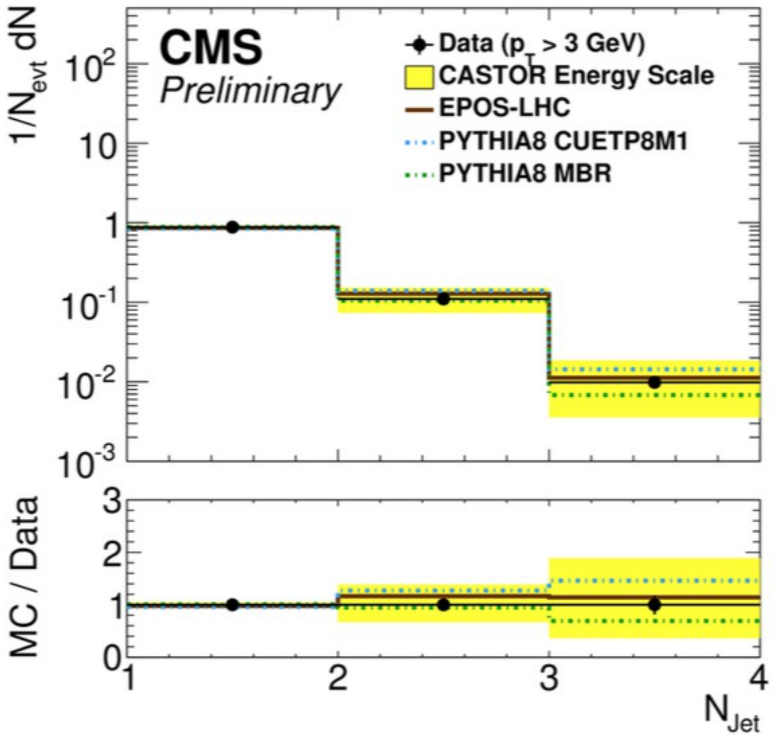
  $d\sigma(pp \rightarrow jet) = PDF(x_1, Q^2) \otimes PDF(x_2, Q^2) \otimes d\sigma(qg \rightarrow jet)$

- Possibly sensitive to parton saturation (nonlinear evolution)?



CMS PAS FSQ-16-003

Jet multiplicity @ detector level

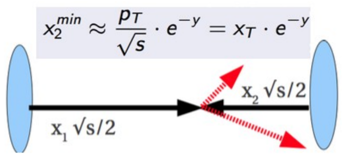


- Very forward jet measurement performed with 13 TeV data
- Fully corrected inclusive jet cross sections and jet yields normalized to number of visible jets as function of jet p_T
  - anti-k_T jets with $R = 0.5$
  - $-6.6 < \eta < -5.2$
  - p_T unfolded from $E \cdot \cosh \eta$, with $\eta = -5.9$
- Energy scale uncertainty yields the dominant systematic uncertainty

Very forward inclusive jet cross section

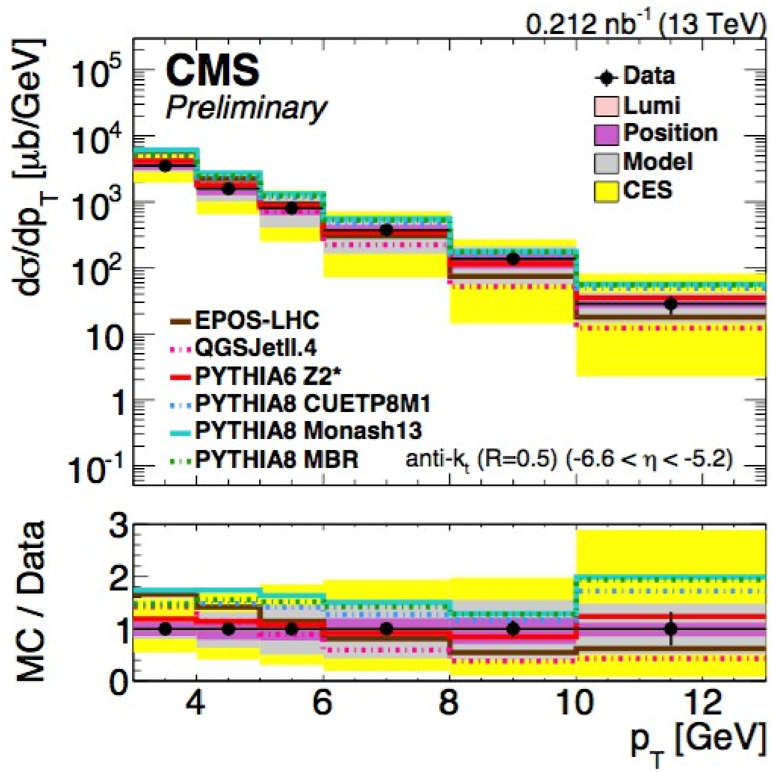
CMS PAS FSQ-16-003

- Motivation:
  - Low x gluon density poorly known
  - Very forward jets allow to probe the low-x domain region sensitive to non-linear QCD effects
  - Constrain low-x gluon PDFs.

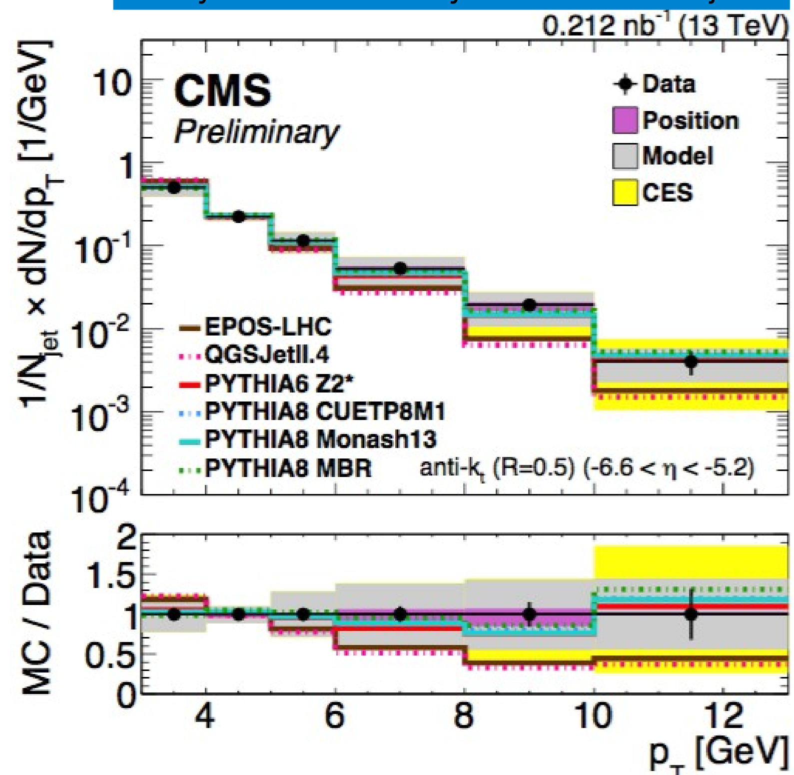


- Analysis strategy:
  - Use low pile-up runs from LHC Run 2 (2015)
  - Phase space definition:
    - E > 150 GeV or p_T > 3 GeV in $-6.6 < \eta < -5.2$
    - $p_{T,det} \rightarrow p_{T,hadron}$: Lorentz invariant but suffers from η
  - Convert E_{jet} to p_T by $\cosh(\eta)$
- Observables: $d\sigma / dp_T$

Jet p_T spectrum: normalized by Luminosity



Jet yield: normalized by number of visible jets



- Dominant unc. source: CASTOR energy scale (15%)
- All models show agreement with data within the unc.

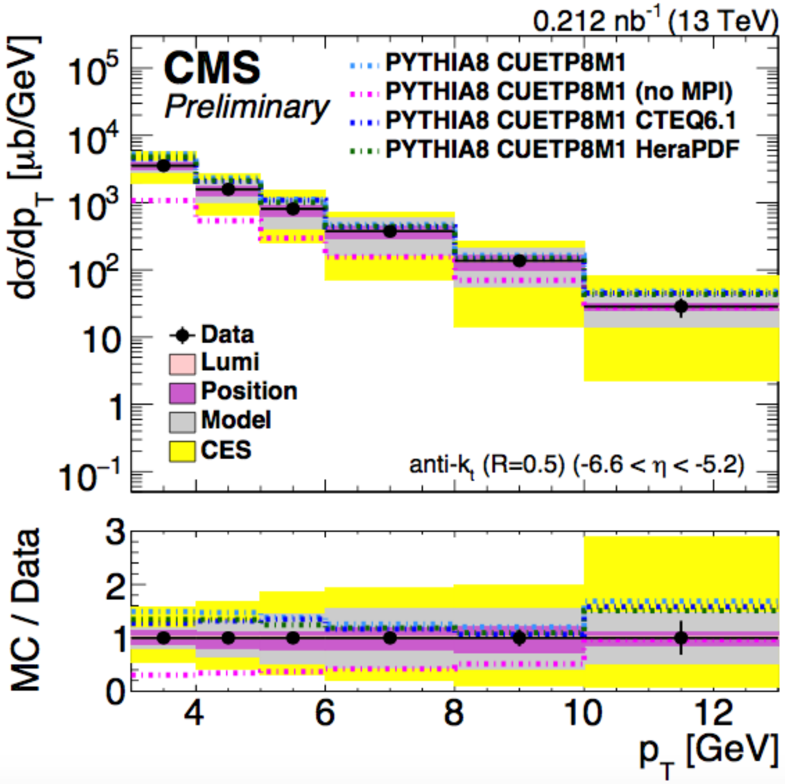
- Overestimation of data by PYTHIA tunes
- EPOS-LHC and QGSJet have tendency of decrease with increasing p_T

Very forward inclusive jet cross section (cont'd)

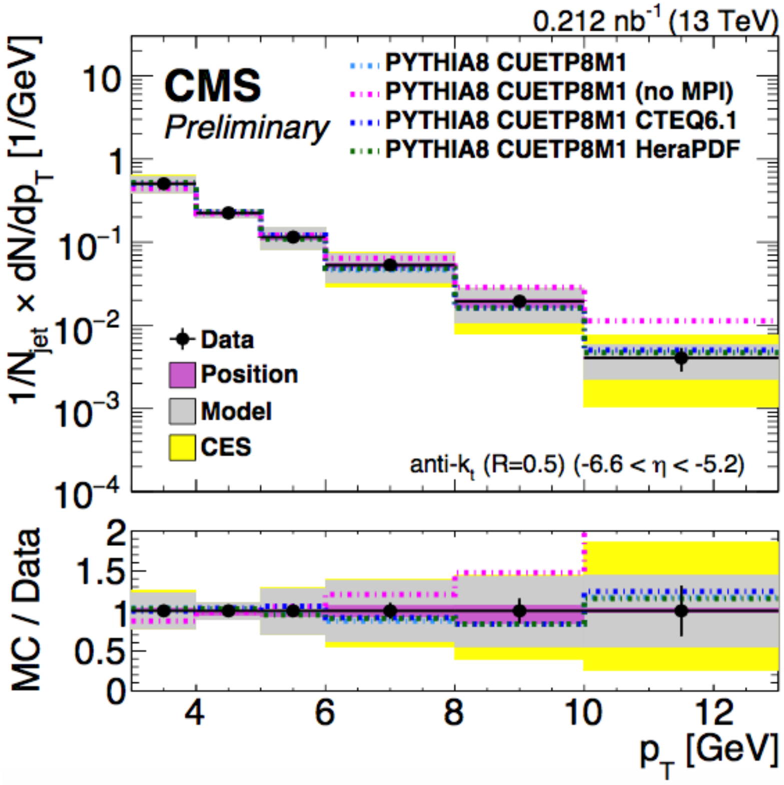
CMS PAS FSQ-16-003

- Any sensitivity to MPI or PDF?

Jet p_T spectrum: normalized by Luminosity



Jet yield: normalized by number of visible jets



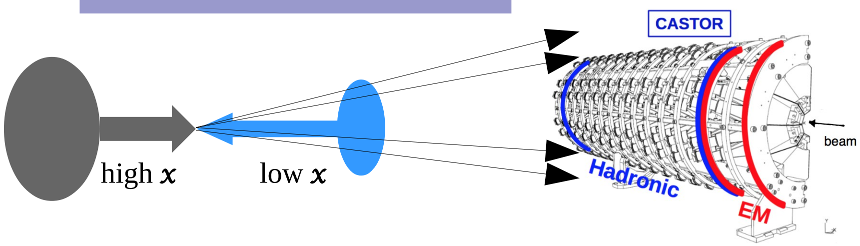
- Moderate sensitivity to the underlying PDF set of the model
- Very sensitive to MPI

Very forward jets in p+Pb @ 5.02 TeV

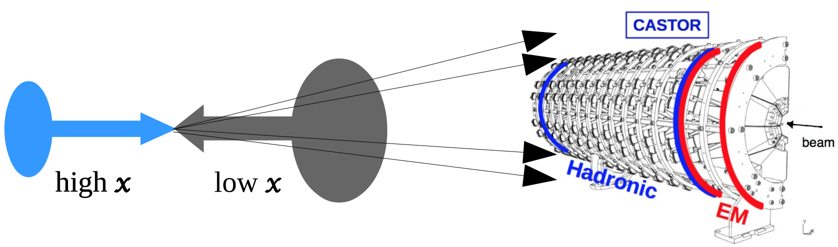
CMS PAS FSQ-17-001

- **Motivation:**
  - At very low-x transition from dilute to dense medium.
    - Non-linear QCD behaviour expected
  - Gluon density in heavy ion larger than proton
  - More perturbative saturation scale (Q_S) compared to saturation scale in pp collisions.
  - Sensitivity to non-DGLAP (BFKL?) evolution scheme.

Pb+p
(ion towards CASTOR)



p+Pb
(proton towards CASTOR)



- **Analysis strategy:**
  - Use proton lead collisions data in 2013.
    - p+Pb: proton towards CASTOR.
    - Pb+p: ion to CASTOR
  - non-diffractive, hadronic event selection
  - Event selection
    - Online: require beams in CMS IP & a track with $p_T \geq 0.4$ GeV ($|\eta| \leq 2.5$)
    - Offline: require $E_{tower} > 4$ GeV in HF+ and HF- ($3 \leq |\eta| \leq 5.2$)
    - Use anti-k_T jets with R = 0.5
    - Measure jet energy in CASTOR ($-6.6 < \eta < -5.2$)
  - All results shown in the lab frame!
- **Observables:**
  - Fully corrected inclusive jet cross sections $d\sigma / dE$ vs. jet energy in p+Pb and Pb+p.
  - Ratio of σ(p+Pb) / σ(Pb+p) as function of energy

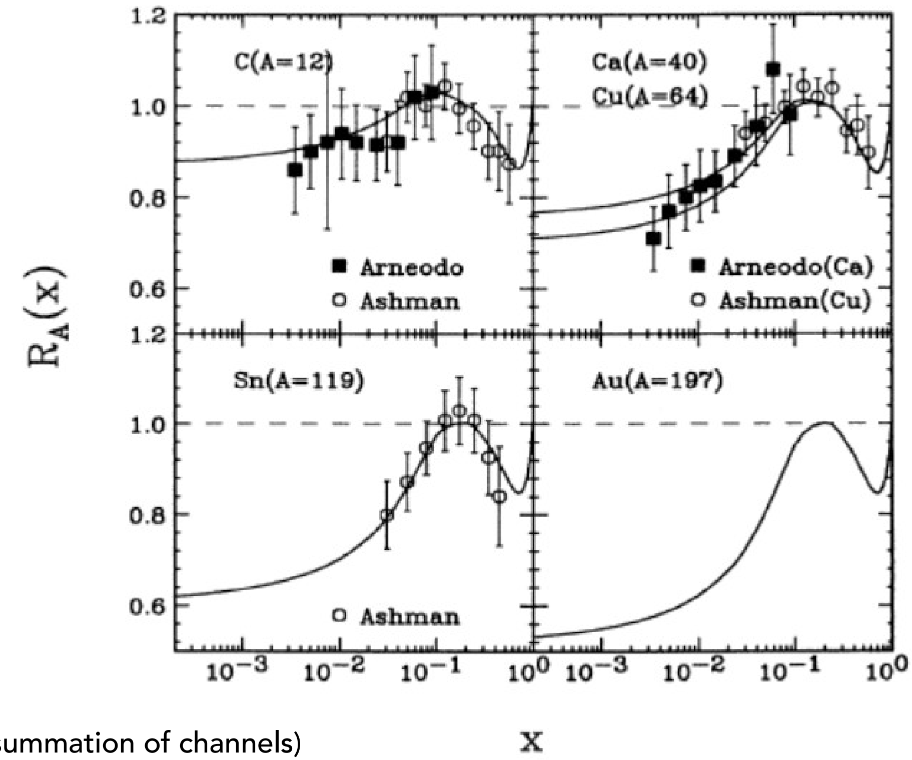
MC Generators

CMS PAS FSQ-16-002

CMS PAS FSQ-17-001

- Simulation of events:
  - Propagate generator particles through CMS detector using GEANT4
- Generators used:
  - HIJING:
    - Applies DGLAP parton evolution via PYTHIA.
    - Shadowing implemented via suppression of nuclear gluon pdf.
    - Suppressed with fit to nuclear sea quark DIS data
  - EPOS:
    - Combination of parton model with pomeron exchange with hydrodynamic model.
    - Effective screening occurs via interference terms
  - QGSJETII04:
    - Similar to EPOS, but implements saturation via phenomenological model
    - no hydrodynamics on-DGLAP (BFKL?) evolution scheme.

Phys. Lett. B 202, 603 (1988)



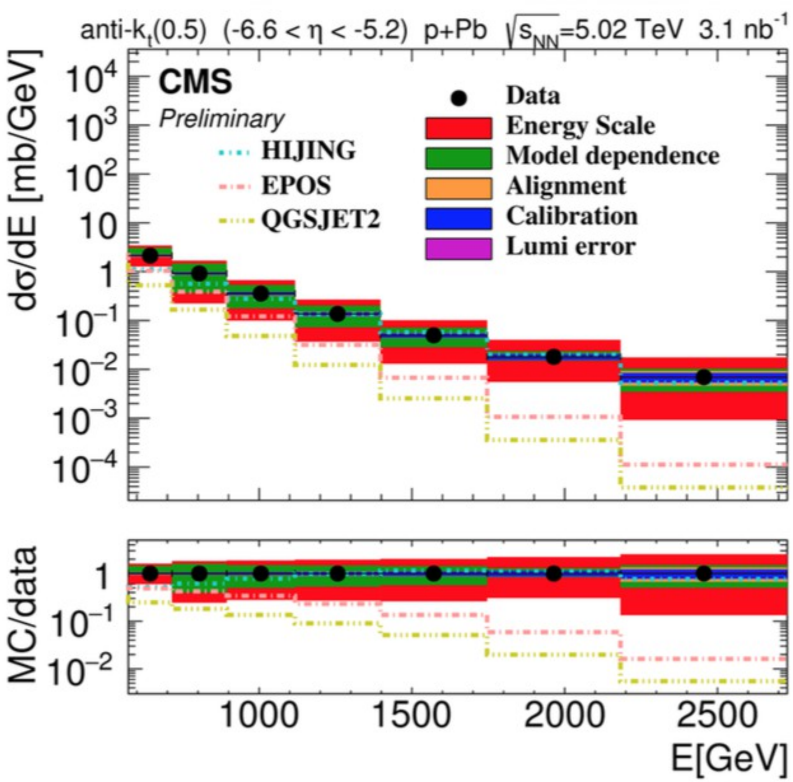
- Reconstruction of jets in CASTOR:
  - CASTOR is segmented into 16 towers (a tower is a longitudinal summation of channels)
  - Anti-k_t algorithm used for reconstruction of CASTOR jets
- Systematic uncertainties
  - Jet energy scale uncertainty + Alignment unc. (the position of CASTOR is known to only 2 mm) : 17%
  - Calibration uncertainty

Jet energy cross section for p+Pb and Pb+p

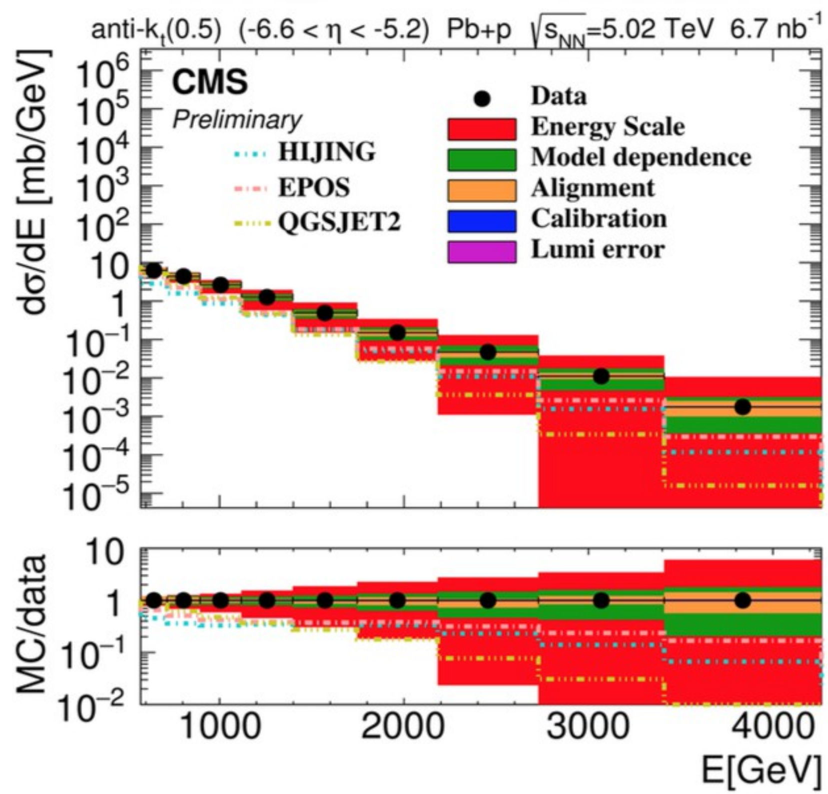
CMS PAS FSQ-17-001

LAB frame

p+Pb
(proton towards CASTOR)



Pb+p
(ion towards CASTOR)



- p+Pb spectrum is well described by HIJING
- EPOS-LHC and QGSJETII-04 underestimate the data progressively with increasing jet energies
  - hard component in data and HIJING?

- All models underestimate low-energy tail for Pb+p spectrum
- But from ~1.2 TeV onwards, all models are in agreement with the data

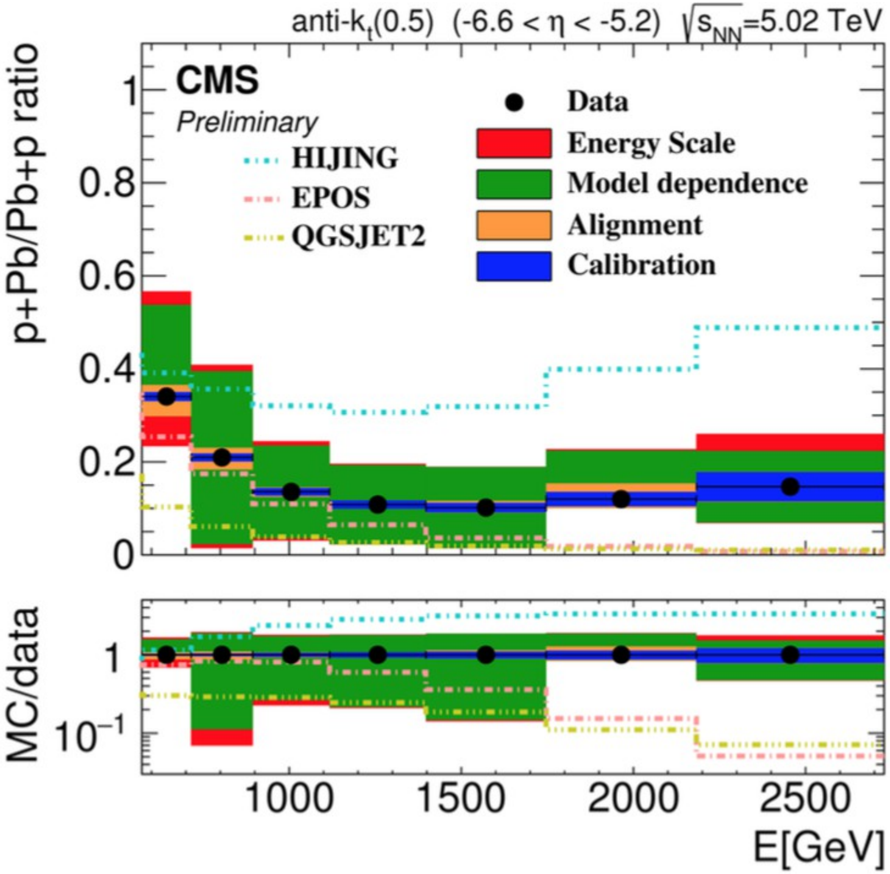
- Energy scale uncertainty is the dominant uncertainty for both p+Pb and Pb+p spectra.

Ratio: σ(p+Pb) / σ (Pb+p)

NEW!

CMS PAS FSQ-17-001

LAB frame



- Cancellation of energy scale uncertainty allows for better discrimination between data and models

- None of the models describe the data on the whole range.
  - HIJING describes the shape well but is off in normalisation (due to the poor Pb+p description)

- EPOS-LHC and QGSJETII-04 significantly fail to describe the ratio at high energies

- Saturation expected in p+Pb, but not in Pb+p ⇒
  - depletion at low energy?

Summary

- LHC provides access to a large phase space as well as the highest energy reached ever
- CMS has very rich and active forward physics program provides the perfect testing ground for QCD models and theory
  - unique forward detector instrumentation
- Very forward jets measurements at CMS are a reality!
  - challenge is energy scale uncertainty
  - efforts on-going for cancelation of uncertainties
- Very forward jets
  - highly sensitive to Underlying Event settings and provide valuable inputs for tuning
  - But weak dependence on PDF
- No clear sign for saturation yet
  - p+Pb results need to be further interpreted

Thank you for your attention!

BACKUP

Decorrelation of forward jets at 7 TeV

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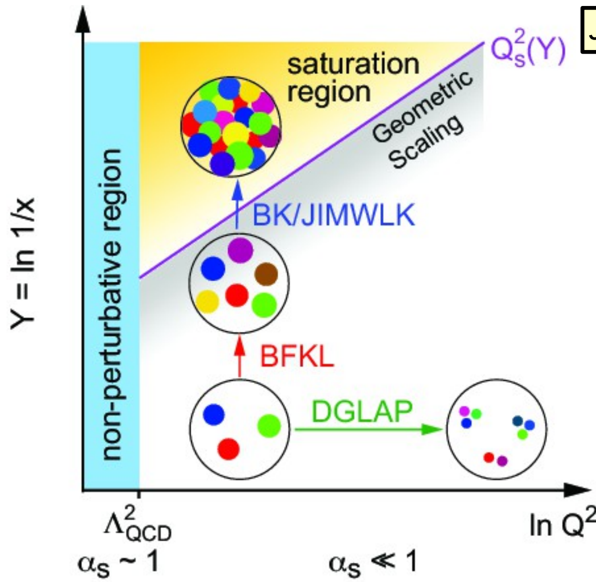
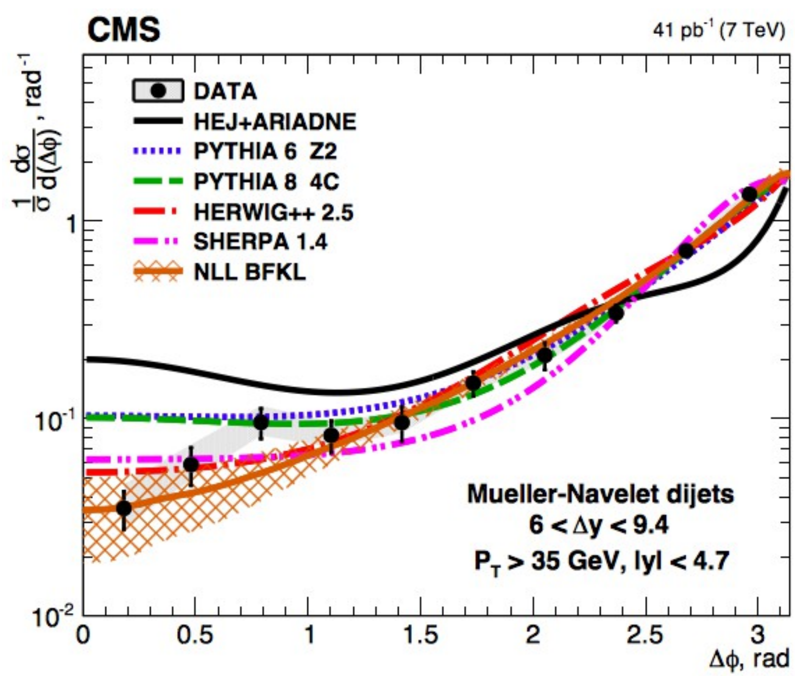
- Approaches to higher-order calculations:
  - DGLAP approach: resummation in terms of $\ln(Q^2)$
  - BFKL approach: resummation in terms of $\ln(1/x)$



- Most forward and most backward jets with $p_T > 35$ GeV
- Results given for up to $|\Delta y| = 9.4$
- Compared to predictions
  - DGLAP-based LO MCs
  - HEJ: LL BFKL-based MC
  - NLL BFKL prediction
- Angular variables also studied as a function of Δy



Mueller-Navelet dijet azimuthal decorrelations

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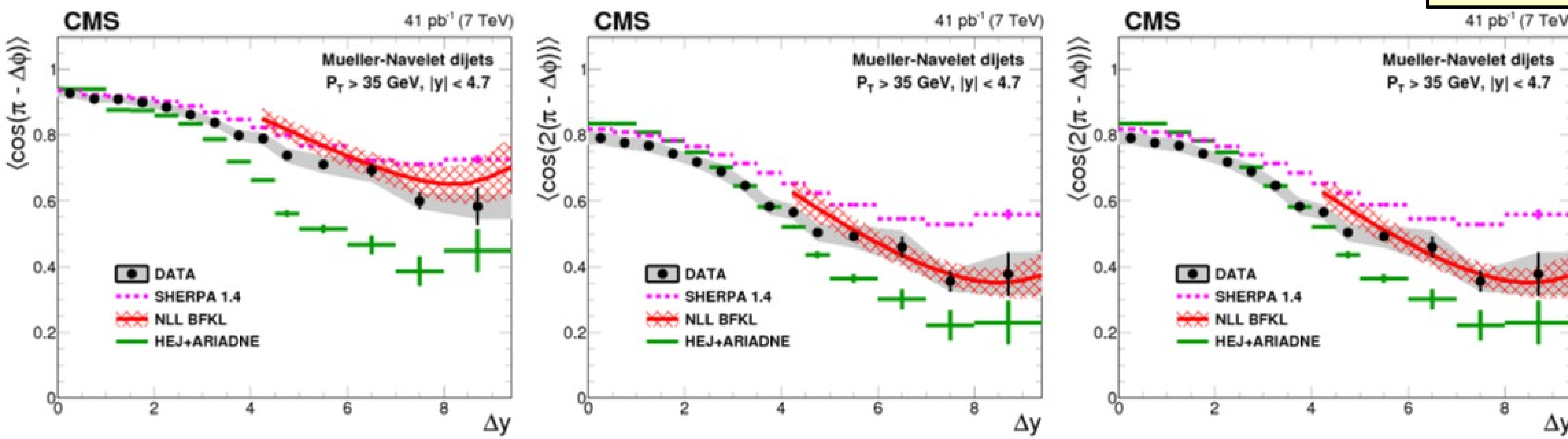
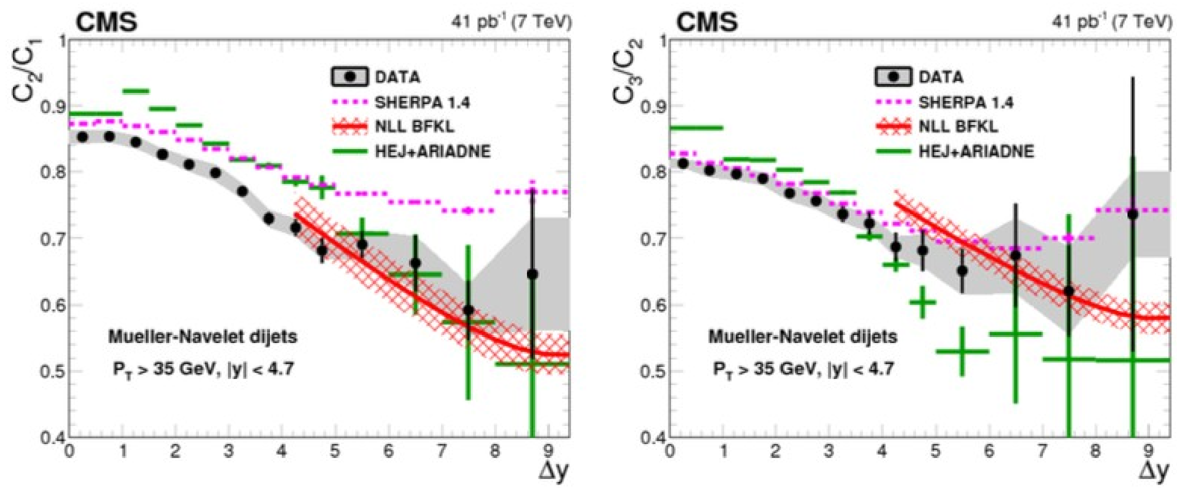




- Mueller-Navelet dijets: pair of jets with the largest rapidity interval
- Decorrelation of Δφ MN pair: sensitive to QCD dynamics
- Cross section vs. Δφ expanded in terms of cos[n(π-Δφ)]
  - expansion coefficients and their ratio depend on Δy
  - region of large Δy probes the BFKL evolution

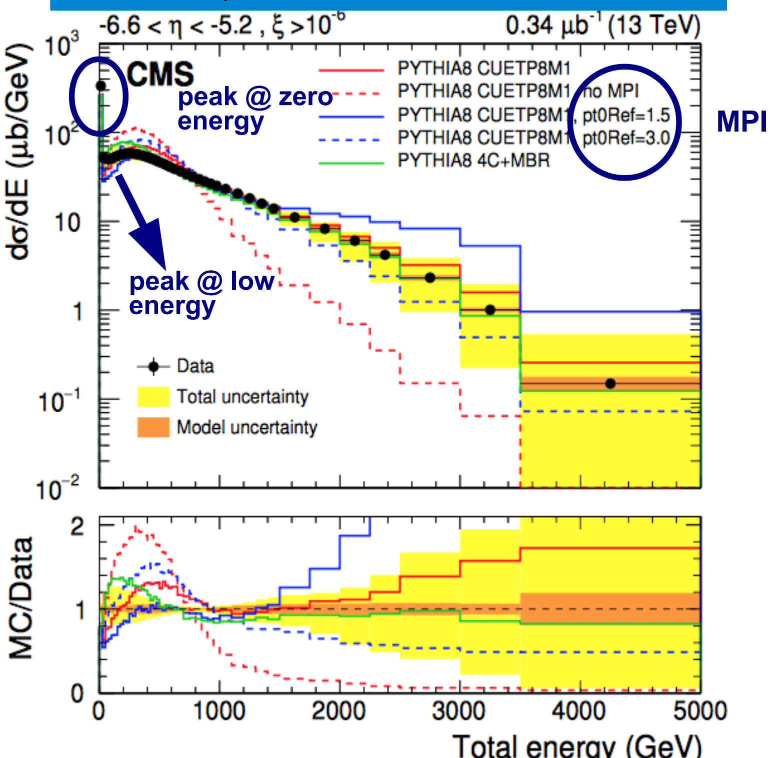
- Good data-theory agreement: NLL BFKL analytical calculations at large Δy
- BFKL NLL calculations, parton level (small effects from hadronization) (JHEP 1305(2013) 096) sensitivity to MPI and angular ordering

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

Very forward energy spectra

- Motivation:
  - Sensitive to changes in the hadronic interaction parameters such as multiplicity, elasticity or baryon production.
  - The effect is most visible in the structures < 1 TeV

Total Energy Spectrum: PYTHIA (Sensitivity to MPI and UE)



- Visibility of diffractive events as a peak at the lowest energies
- Hadronic component causes low energy peak
- Steep tail towards higher energies

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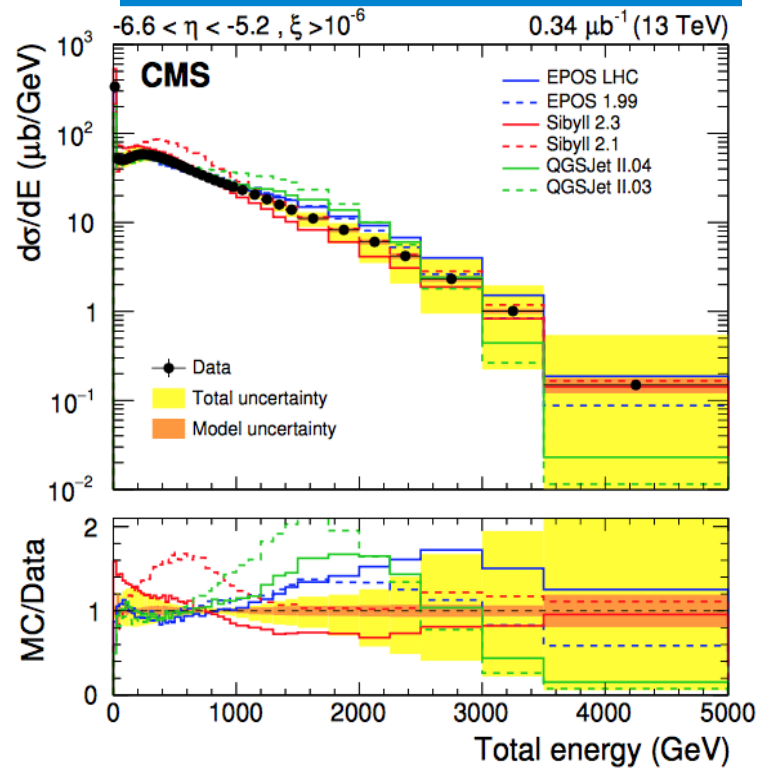
- Analysis strategy:
  - Use pp collisions @13 TeV, low pile-up runs from 2015 with B = 0 T
  - Trigger on beam presence and bunch crossing
    - Soft inclusive events (single arm selection)
- Observables:
  - Total energy measured by CASTOR (dN / dE)
  - Separate spectrum as
    - Electromagnetic (energy from first 2 modules)
    - hadronic (energy from last 12 modules)

Total Energy Spectrum: Cosmic Ray models



- Dominant unc. Source: CASTOR energy scale (17%)
- Sensitivity seen in data to MPI and UE.

Very forward energy spectra (cont'd)

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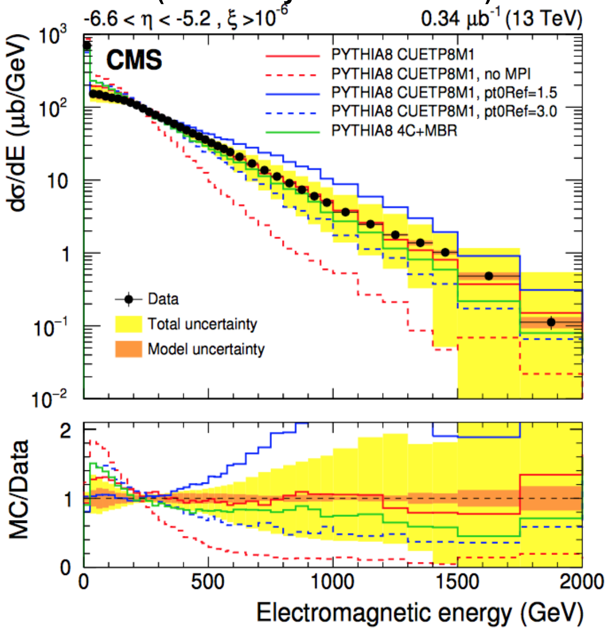
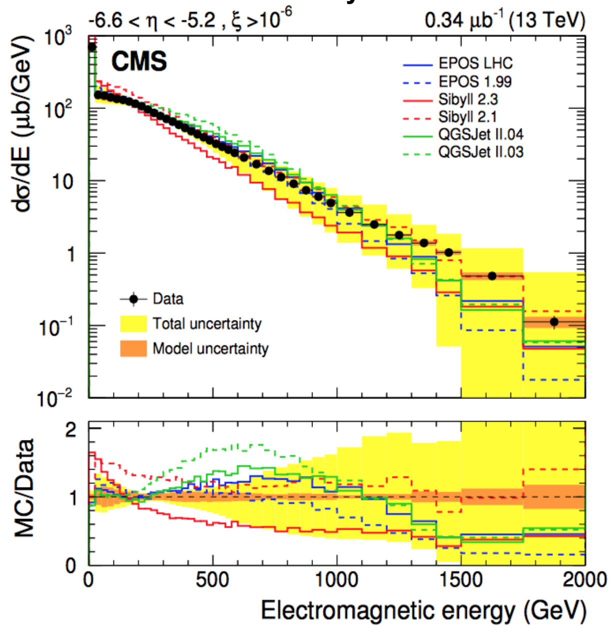
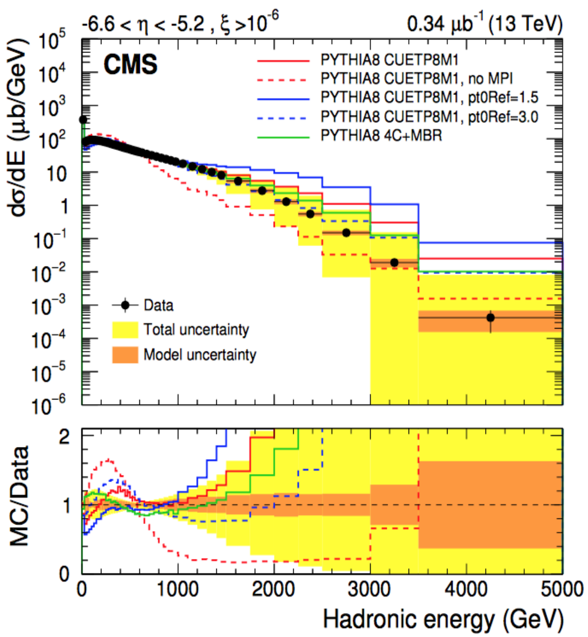
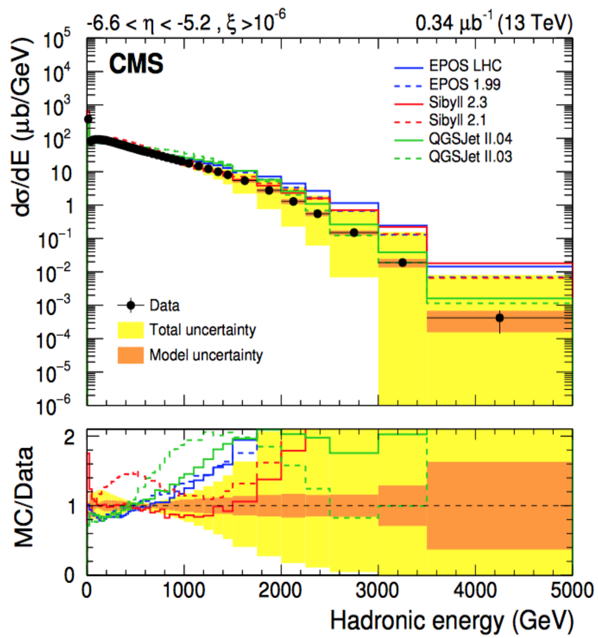
PYTHIA8 (Sensitivity to MPI and UE)



Cosmic Ray models







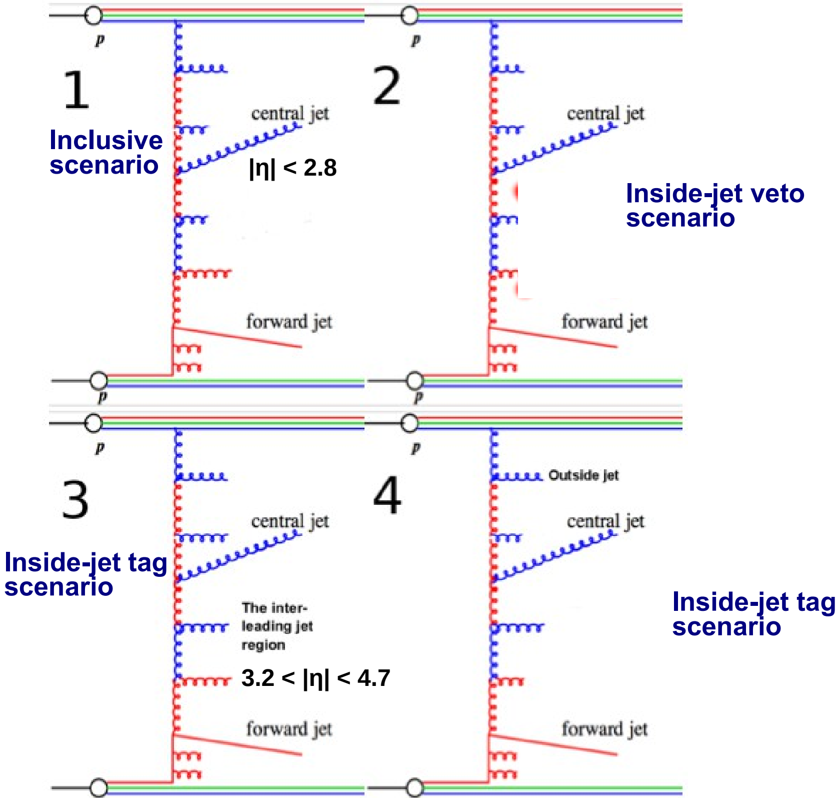
EM spectrum

- Data well described by all models
  - except for PYTHIA8 4C+MBR and SIBYLL2.3 : slope in the soft part
- High sensitivity to MPI

Hadronic spectrum

- Cosmic ray models perfom well
  - EPOS LHC and QGSJETII shows large differences in high energy tail
- PYTHIA8 tunes overestimate the soft region

Forward-central jet correlations @ 7 TeV



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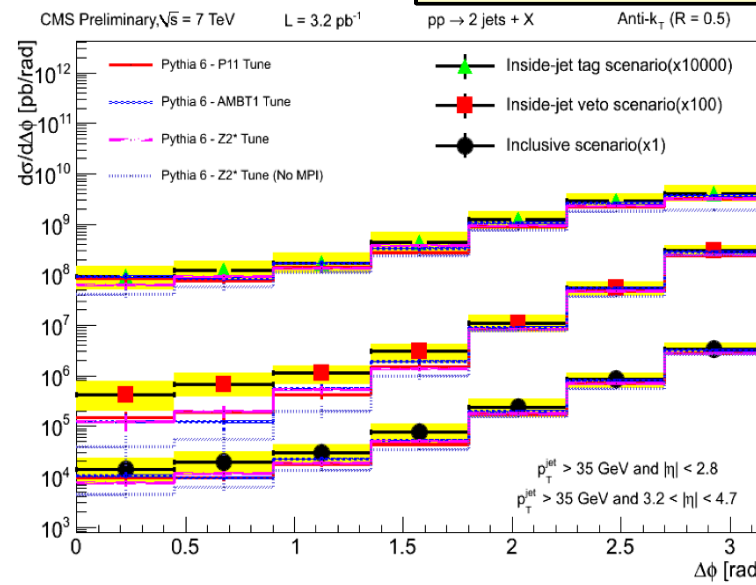

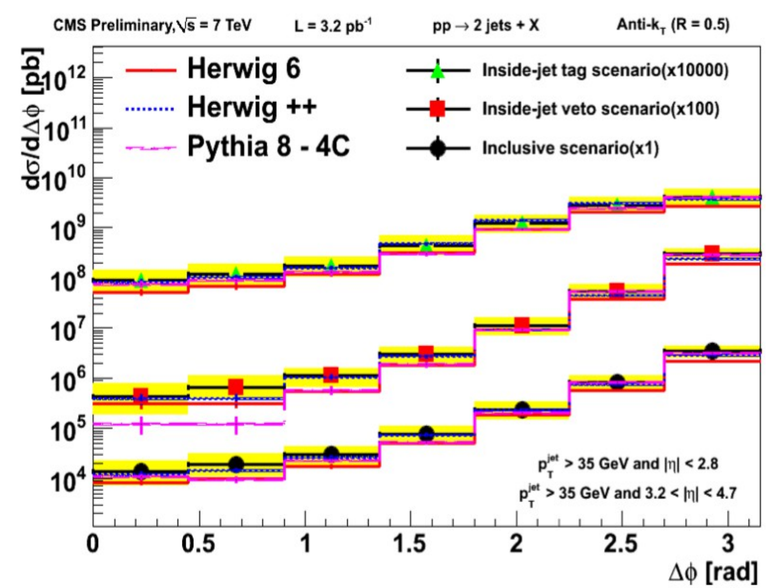

- Measurement on azimuthal correlation in different scenarios, for different rapidity separation,
  - Probe high and low–x regions, q & g ladders
  - Large viidifference between jets

  higher order emissions : high sensitivity to QCD and parton dynamics
  - Sensitivity to UE and MPI
- DGLAP MCs describe the observables very well
  - Overall Herwig performs better than Pythia
  - the best description by Herwig++