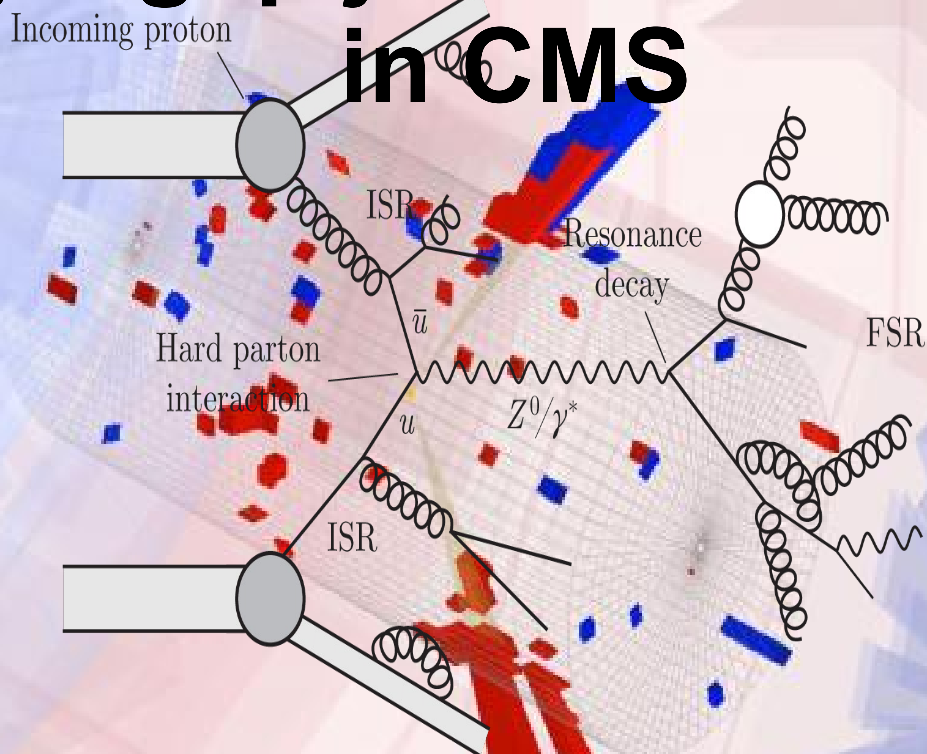
Very forward jet, Mueller Navelet jets and jet gap jet measurements in CMS



Salim CERCI
Adiyaman University
On behalf of the CMS Collaboration

MPI2017: 9th International Workshop on Multiple Partonic Interactions at the LHC

11/12/2017

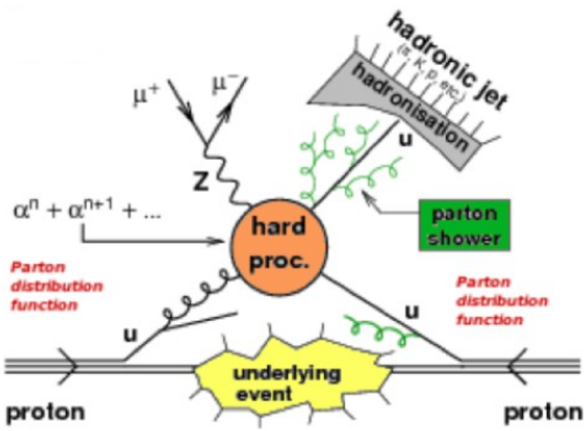
Outline

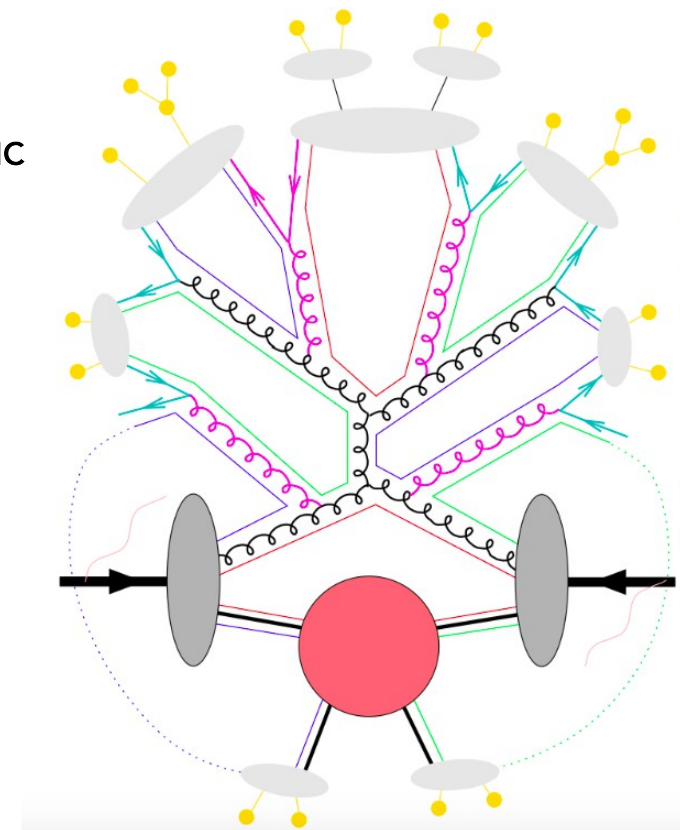
- Motivation
- Overview of most recent forward jet measurements by CMS
  - Inclusive forward jets
  - Very forward jets
  - Mueller-Navelet jets
  - Jet-gap-jet
- Summary

Motivation

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 Δ among the first measurements at each new energy

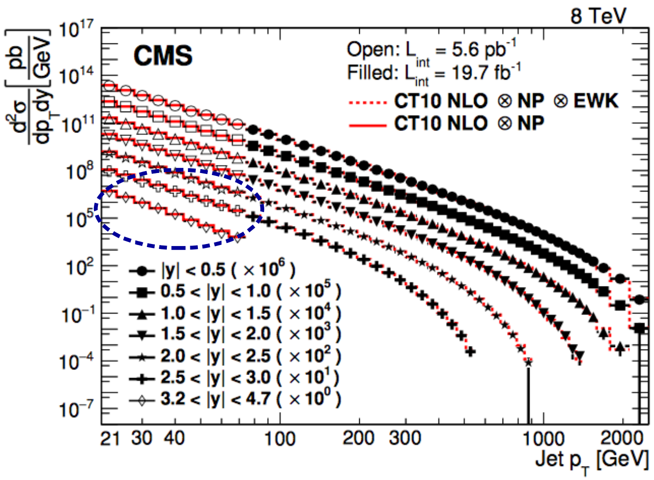


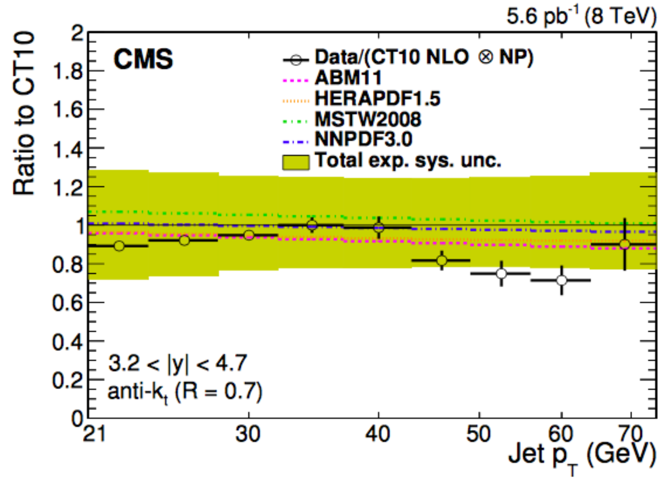


Inclusive Forward Jet Cross Sections @ 8 and 13 TeV

- Jet p_T range measured: [74 , 2500] GeV for |y| < 3 and [21, 74] GeV for 3.2 < |y| < 4.7
- Good agreement over the whole p_T and y range for fixed-order calculations corrected for NP and EW effects
- Comparison with NLO QCD using several PDFs
  (two representative rapidity bins shown)

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \mathcal{L}_{\text{int,eff}}} \frac{N_{\text{jets}}}{\Delta p_T \, (2\Delta|y|)}$$





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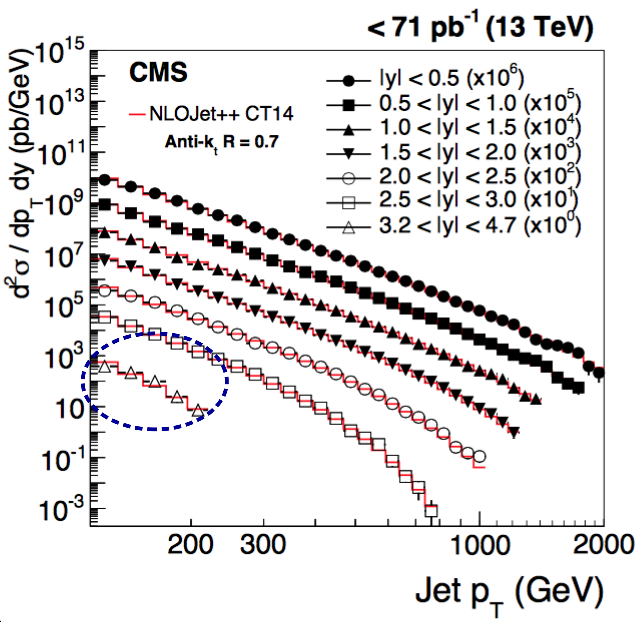
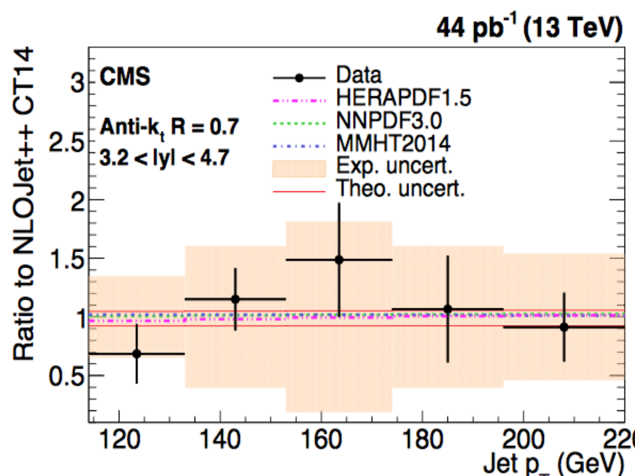
NEW!





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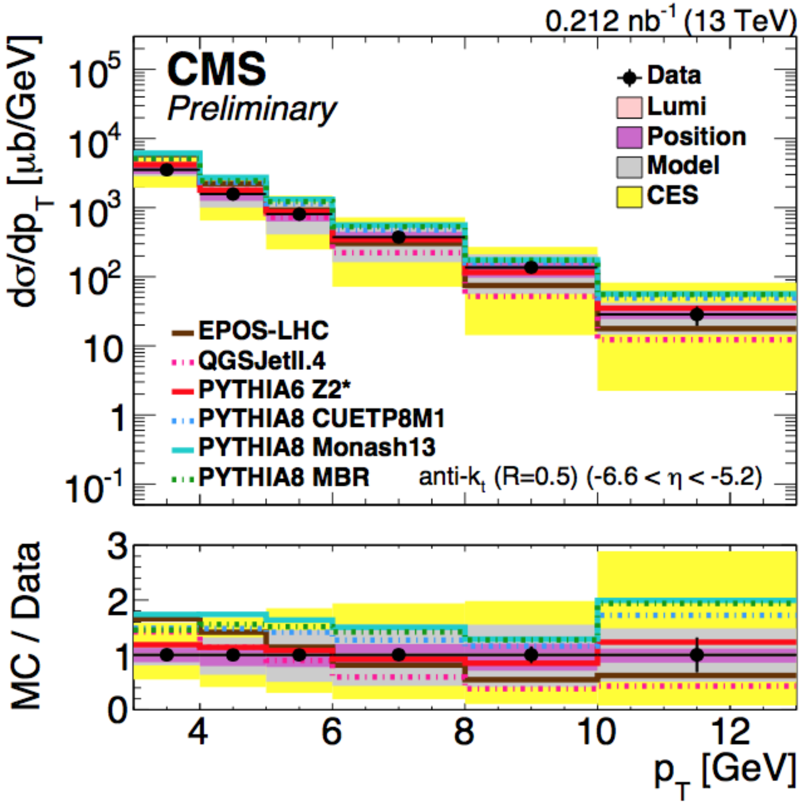
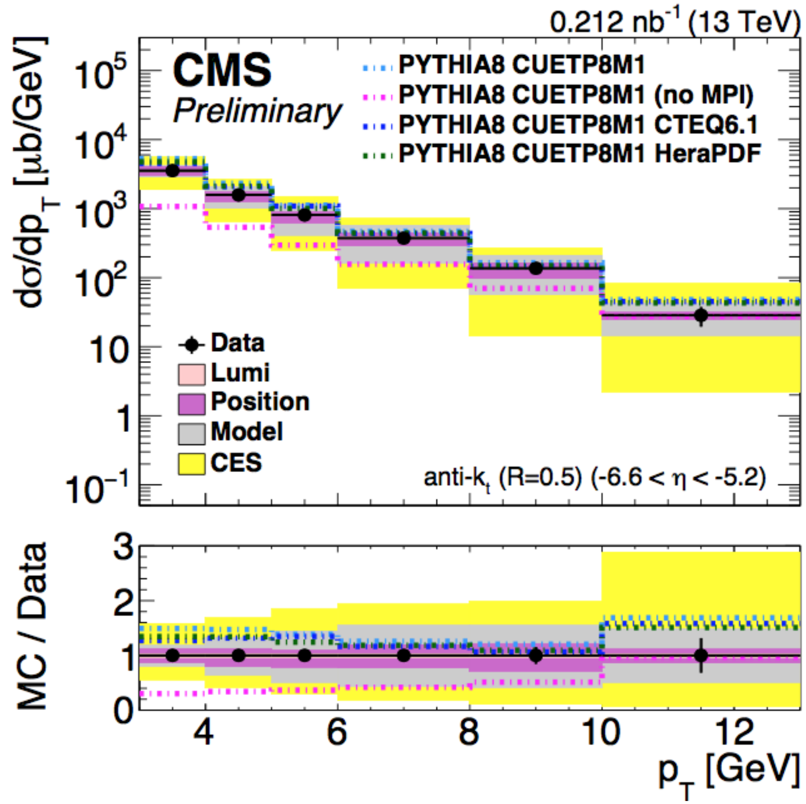
- Jet p_T range measured: [74 , 2500] GeV for |y| < 4.7

Very forward inclusive jets cross section @ 13 TeV

CMS PAS-FSQ-16-003



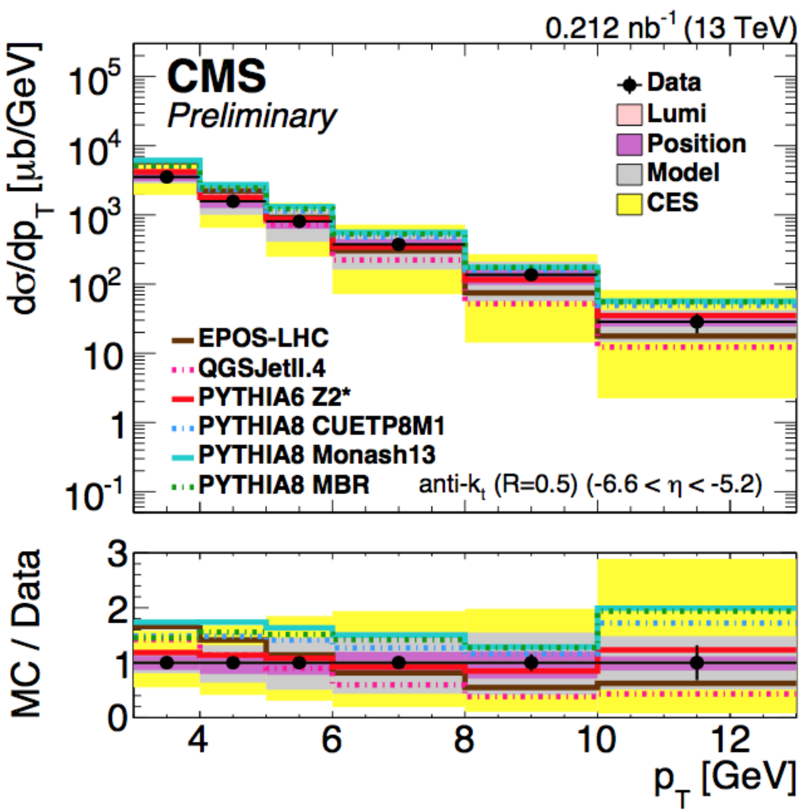


- Dominant uncertainty: jet energy scale (5 – 70%) for normalized distribution
- All models show agreement with data within the unc.
- Overestimation of data by PYTHIA8 tunes
- EPOS-LHC and QGSJet have tendency of decrease with increasing p_T
- Measurement sensitive to MPI in the very forward region

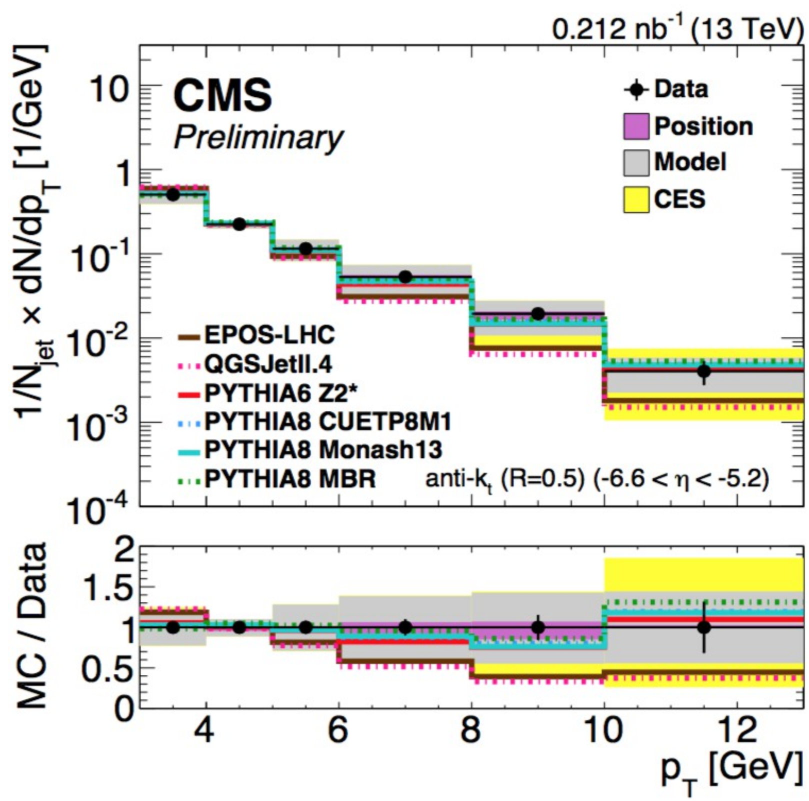
Very forward inclusive jets cross section @ 13 TeV (II)

CMS PAS-FSQ-16-003

Jet pT spectrum: normalized by luminosity



Jet yield: normalized by number of visible jets

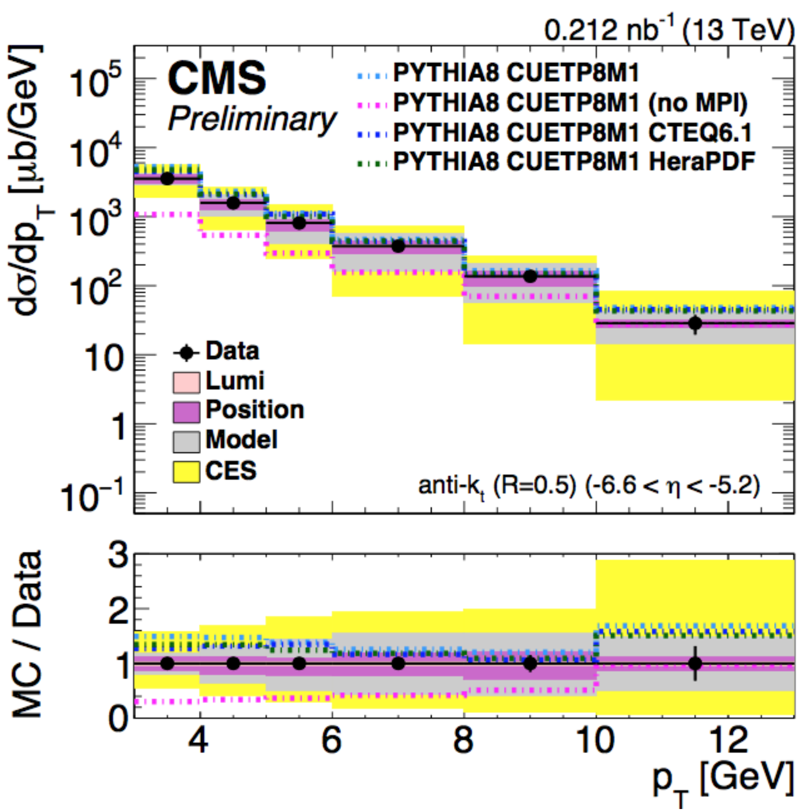


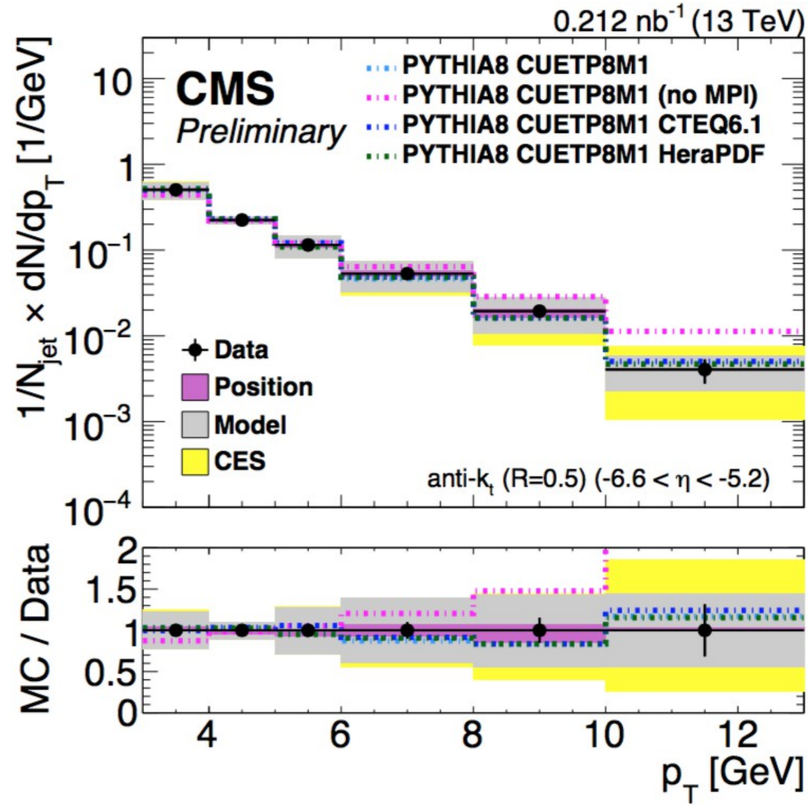
- Dominant unc. source: CASTOR energy scale (17%)
- All models show agreement with data within the unc.
- Overestimation of data by PYTHIA8 tunes
- EPOS-LHC and QGSJet have tendency of decrease with increasing p_T

Very forward inclusive jets cross section @ 13 TeV (III)

CMS PAS-FSQ-16-003

- **Any sensitivity to multiple partonic interaction (MPI) or parton density function (PDF)?**





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

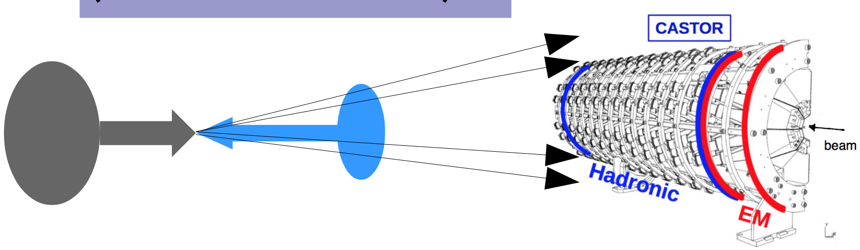
Very forward jets in p+Pb @ 5.02 TeV

CMS PAS FSQ-17-002

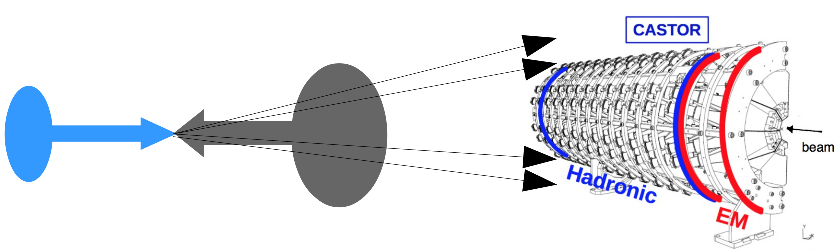
NEW!

- **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- ($3 \leq |\eta| \leq 5.2$)
    - Measure jet energy in CASTOR ($-6.6 < \eta < -5.2$)
  - All results shown in the lab frame!

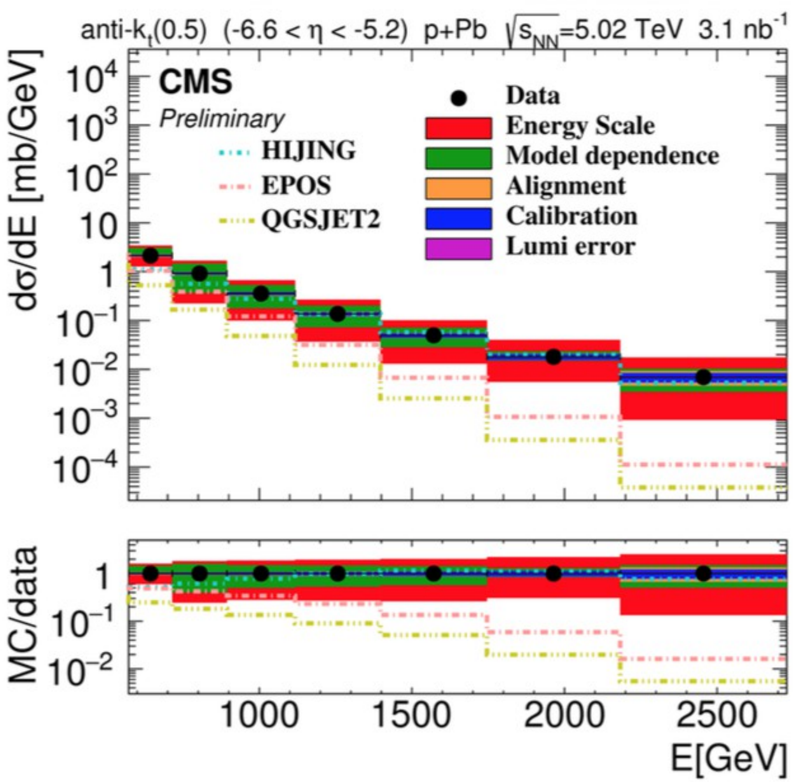
- **Observables:**
  - $d\sigma / dE$ vs. jet energy in p+Pb and Pb+p.
  - Ratio of σ(p+Pb) / σ(Pb+p)

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

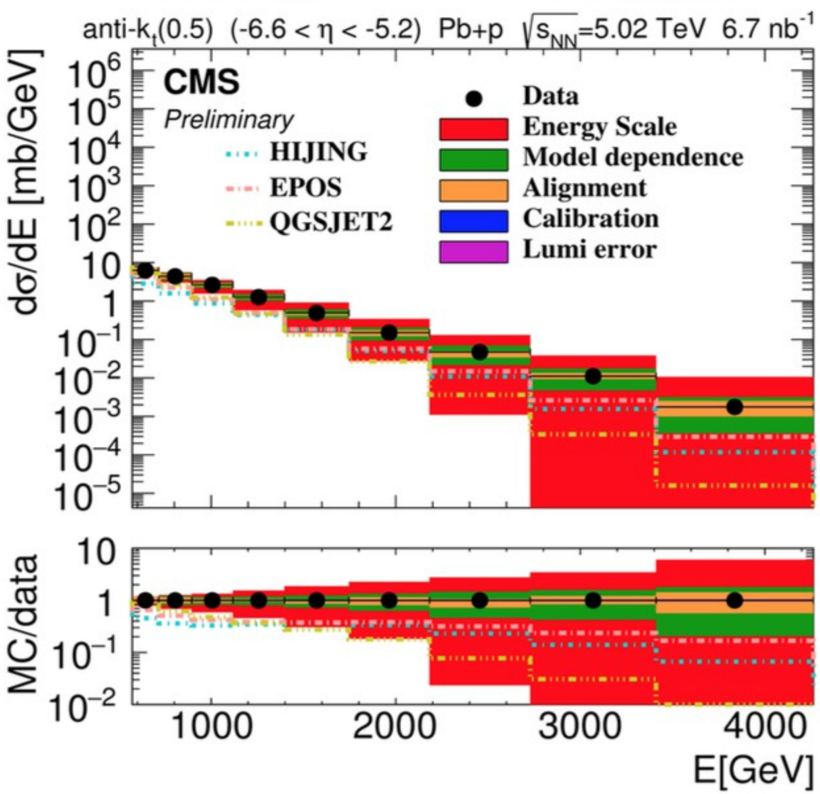
CMS PAS FSQ-17-002

NEW!

p+Pb
(proton towards CASTOR)



Pb+p
(ion towards CASTOR)



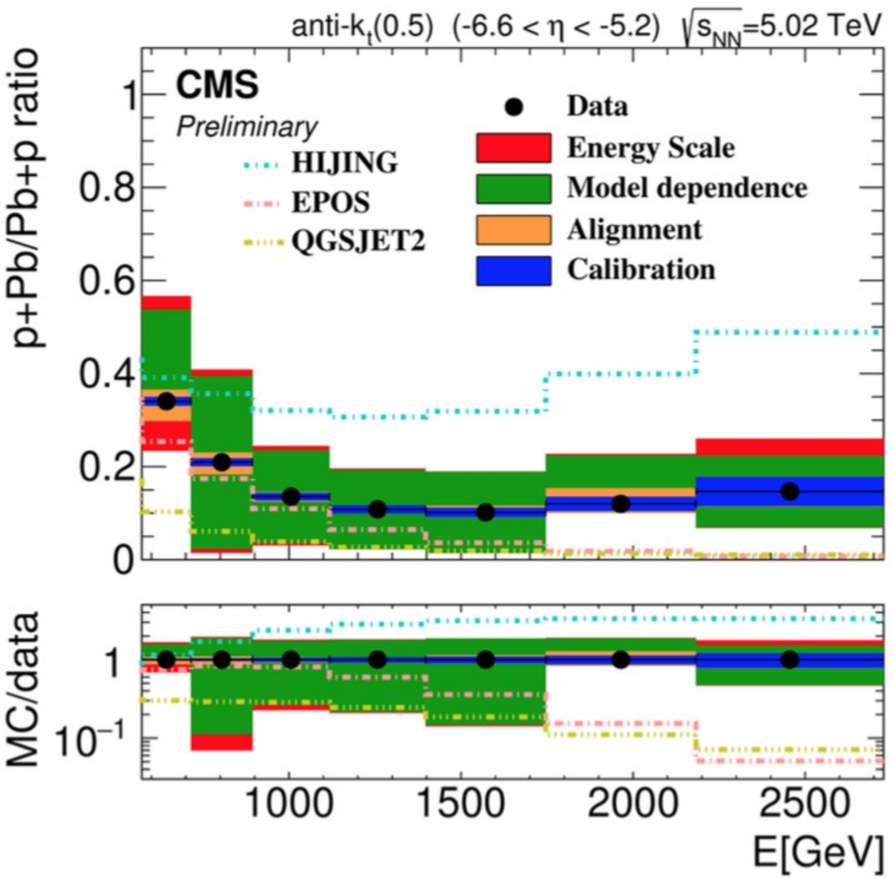
- p+Pb spectrum is well described by HIJING
- EPOS-LHC and QGSJETII-04 underestimate the data progressively with increasing jet energies.

- All models underestimate the data @ lower energy bins in Pb+p spectrum
- 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)

CMS PAS FSQ-17-002



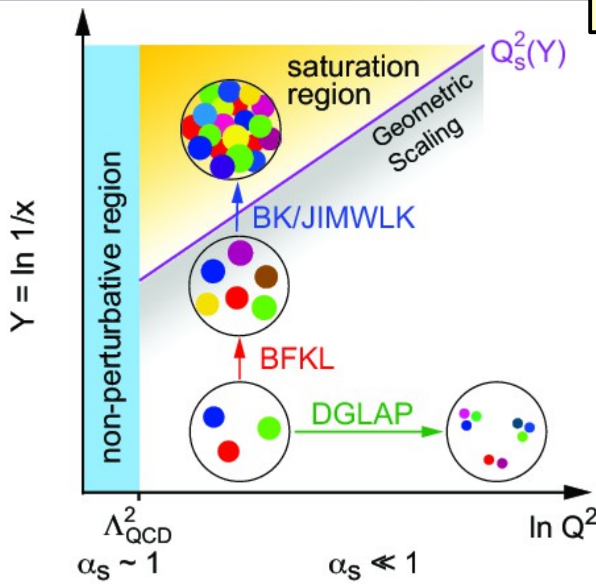
- Energy scale uncertainty largely cancels out
- None of the models describe the data on the whole range.
  - HIJING describes the shape well but is off in normalisation (due to the poor Pb+p description)
- EPOS-LHC and QGSJETII-04 significantly fail to describe the ratio at high energies

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

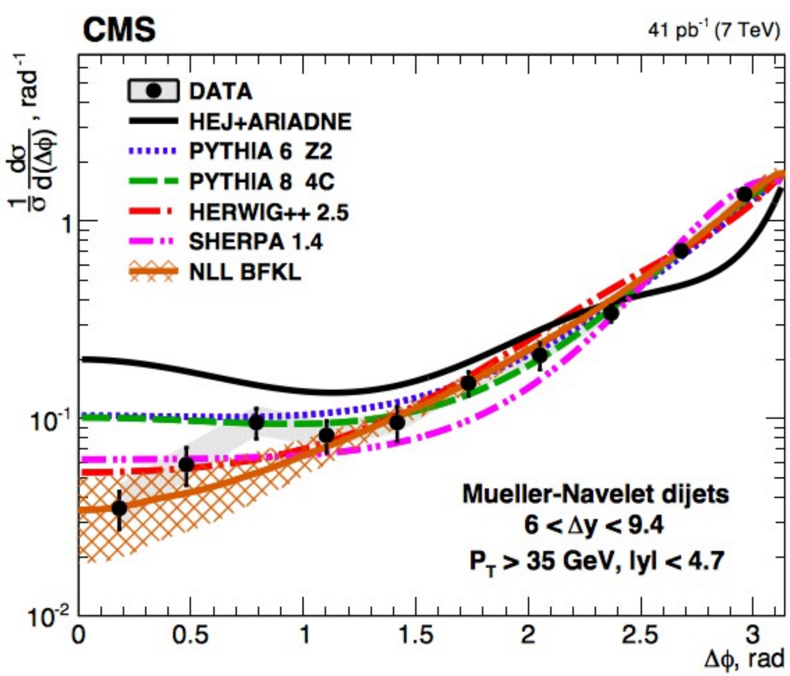
Decorrelation of forward jets at 7 TeV

JHEP 08 (2016) 139

- 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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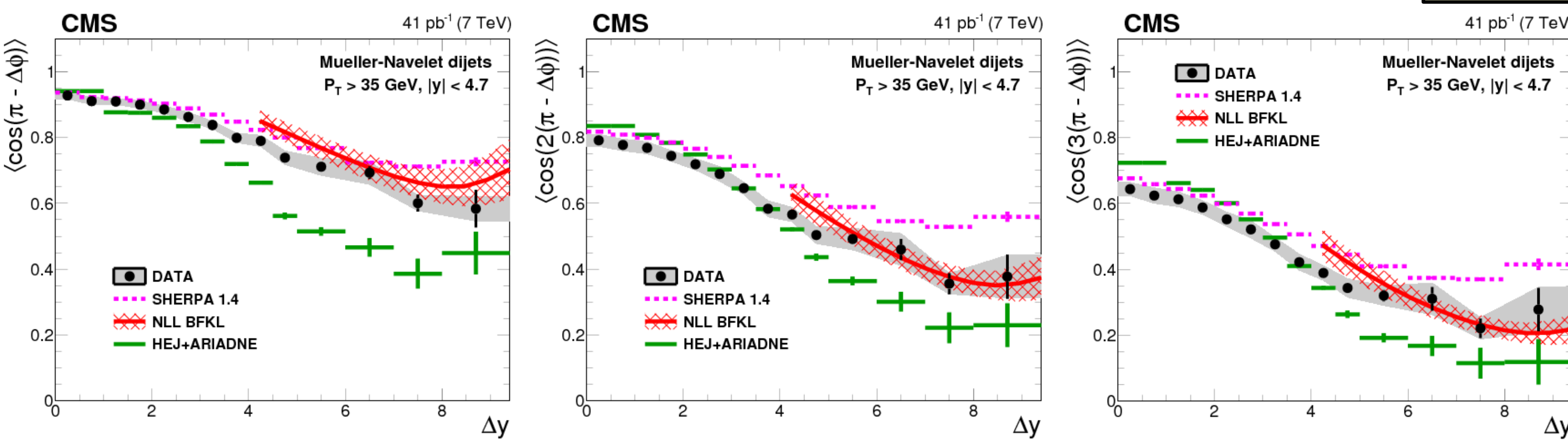
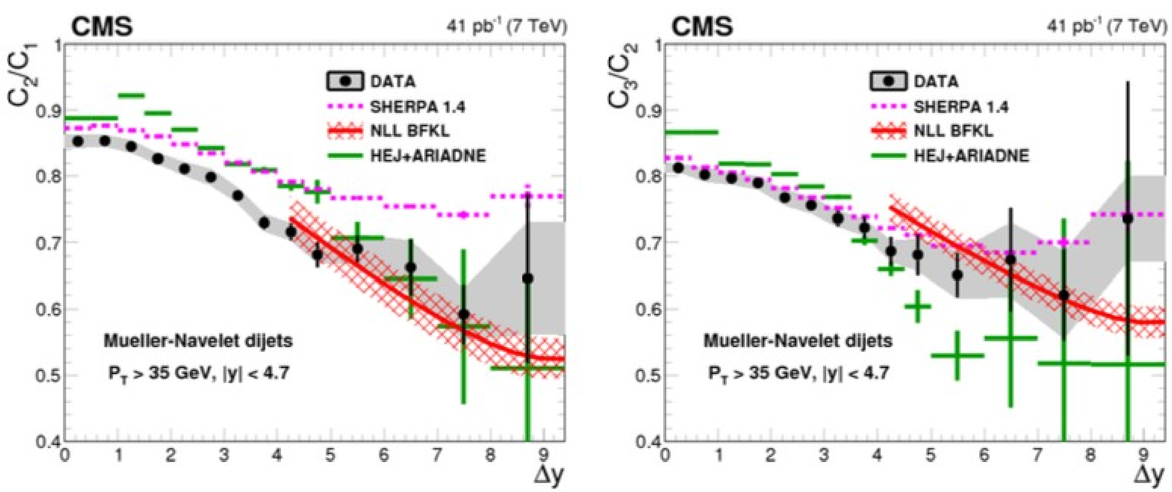




- Mueller-Navelet dijets: pair of jets with the largest rapidity interval
- Decorrelation of Δφ MN pair: sensitive to QCD dynamics
- Cross section vs. Δφ expanded in terms of cos[n(π-Δφ)]
  - expansion coefficients and their ratio depend on Δy
  - region of large Δy probes the BFKL evolution

- 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

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

Dijet events with a large rapidity gap (jet-gap-jet events)

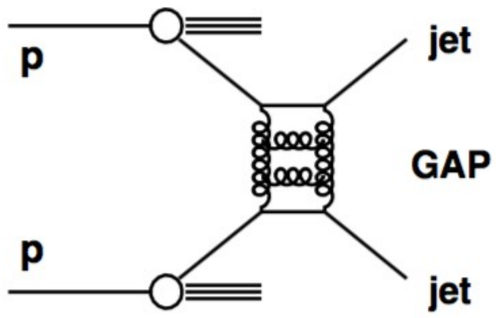
- Jets separated by a large rapidity gap
  - gluon or quark exchange
  - additional particle emissions between jets, **DGLAP (k_T ordered)**
  - absence of particles produced between the jets (color singlet exchange, **CSE**), **BFKL dynamics (ordering in *x*),** rescattering processes
- Events with gaps ~1% observed at Tevatron (CDF, D0) and HERA

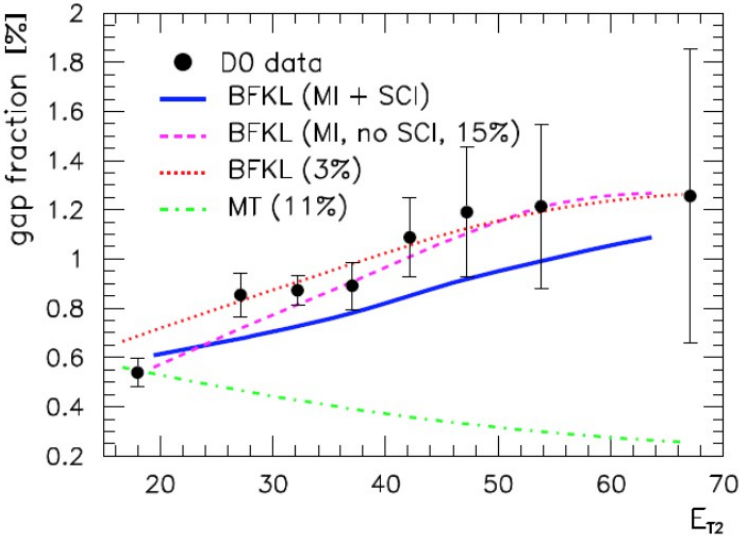
NEW!

arXiv:1710.02586

Submitted to EPJC

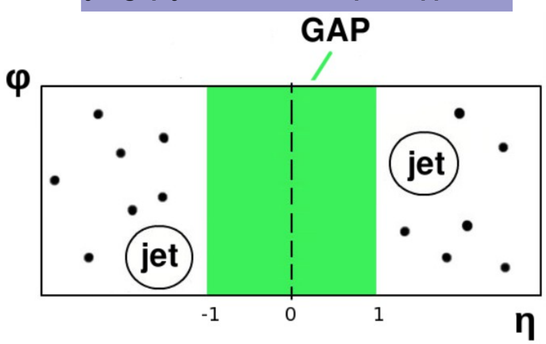
D0 data, compared to Enberg, Ingelman, Motyka model (NLL BFKL + MPI+SCI) **[PLB 524 (2002) 273]**





- **Analysis strategy:**
- Signature: two leading jets with no particles in between
- Jets with p_T > 40 GeV, 1.5 < |y| < 4.7
- Gap particles: |η| < 1, p_T > 0.2 GeV

jet-gap-jet event in the φ vs. η plane.

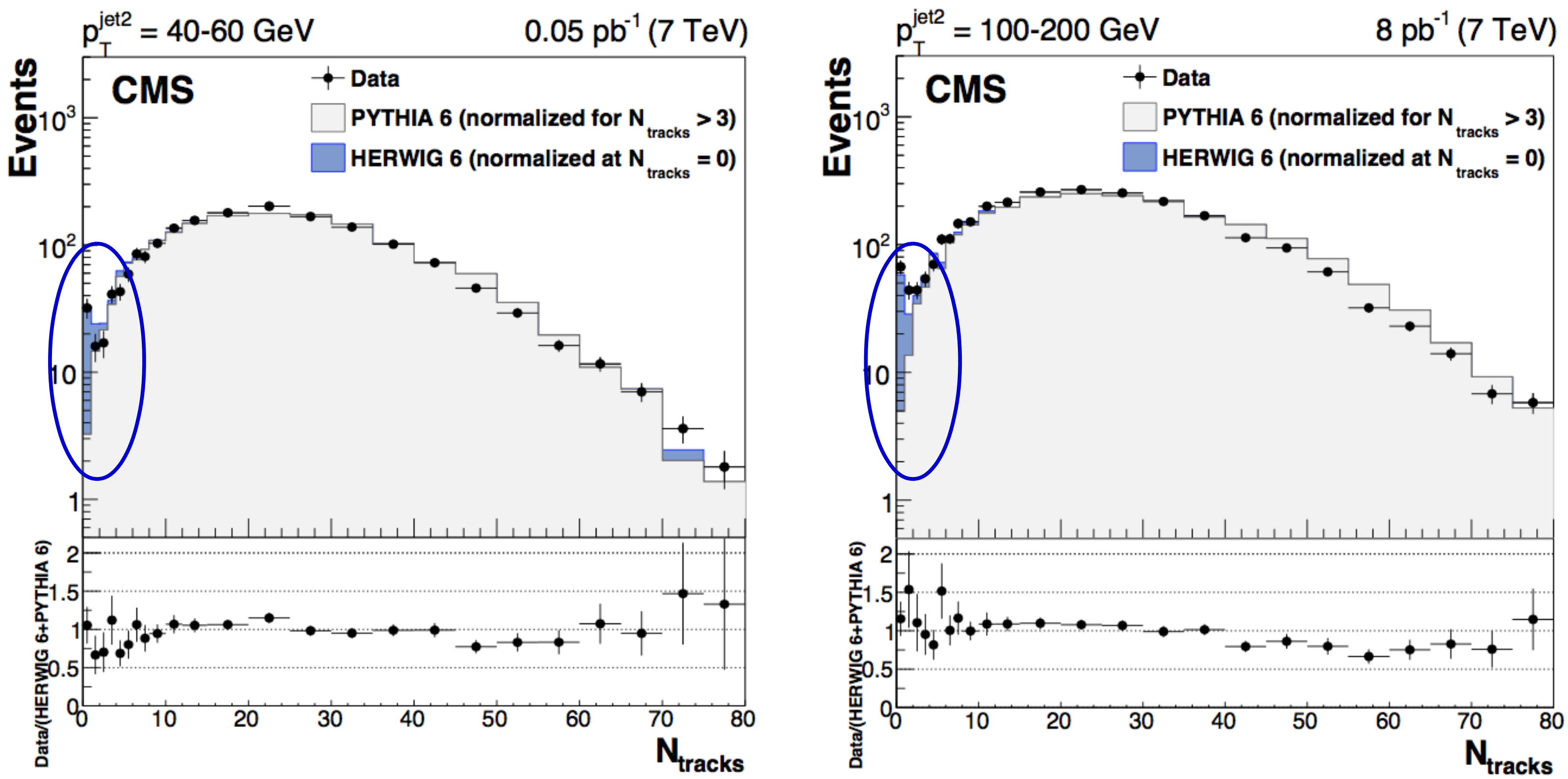


Jet-gap-jet events: number of tracks

NEW!

- Number of central tracks between the two leading jets in events with p_T^{jet2} = 40-60 GeV (left) and 100-200 GeV (right)

arXiv:1710.02586
Submitted to EPJC



- Large excess of gap events over PYTHIA6 prediction (LO DGLAP),
  - this excess well described by HERWIG 6 (LL-BFKL, Mueller-Tang model)

Jet-gap-jet events: p_T

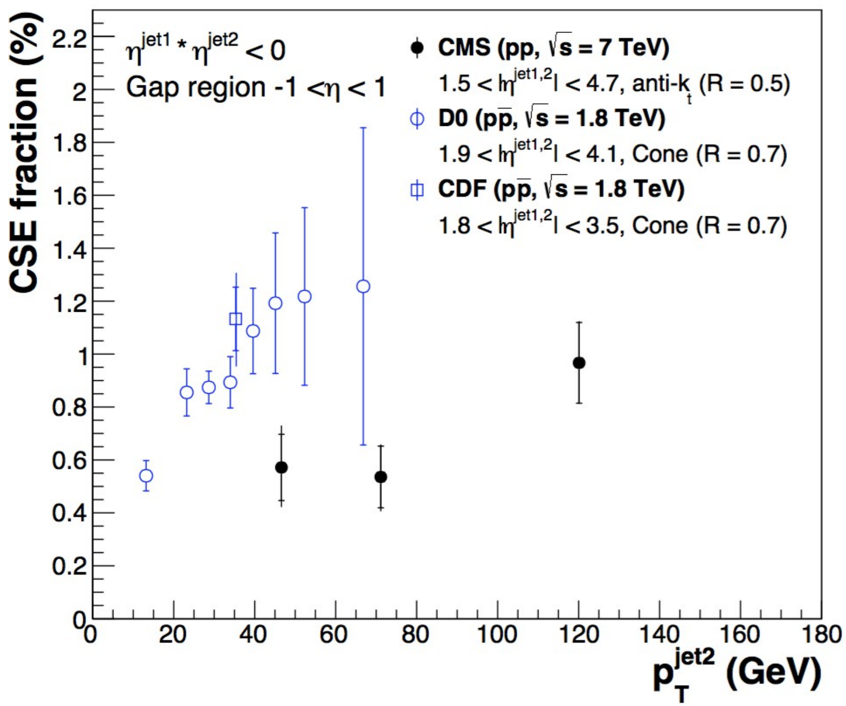
arXiv:1710.02586
Submitted to EPJC

- In order to quantify the contribution from CSE events, CSE fraction

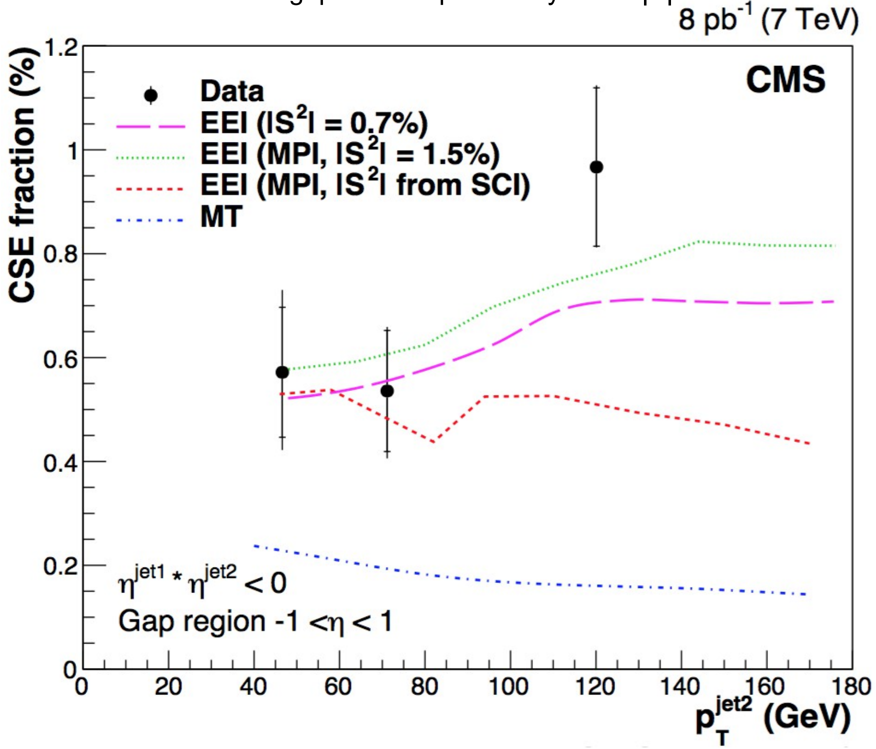
$$f_{CSE} = \frac{N^F_{events} - N^F_{non-CSE}}{N_{events}}$$

  - N^F_{events} : the number of events in the first bins of the multiplicity distribution
  - $N^F_{non-CSE}$: the estimated number of events in these bins originating from non-CSE events
  - N_{events} : the total number of events considered

- f_{CSE} as a function of p_T^{jet2} at $\sqrt{s}$ = 7 TeV, compared to D0 and CDF



- f_{CSE} as a function of p_T^{jet2} at $\sqrt{s}$ = 7 TeV, compared to
Mueller and Tang (MT) model
Estedt, Enberg, and Ingelman (EEI) model with 3 different treatments of the gap survival probability factor $|S|^2$



- A factor ~2 suppression w.r.t. to D0 and CDF data
- At both collision energies f_{CSE} seems to increase with p_T^{jet2}
- The decrease of f_{CSE} with increasing energy: stronger contribution from rescattering processes where the interactions between spectator partons destroy the rapidity gap

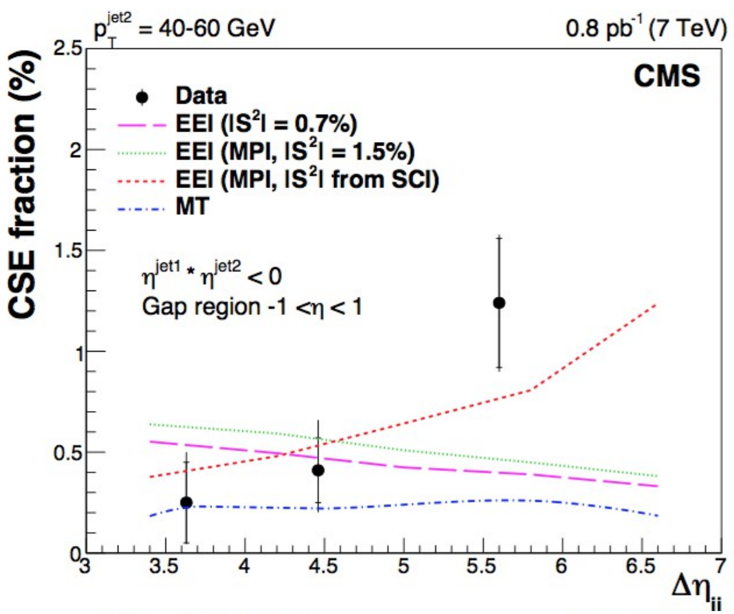
- The MT prediction does not reproduce the increase of f_{CSE}
- BFKL cross section is scaled $|S|^2$ = **0.7%**

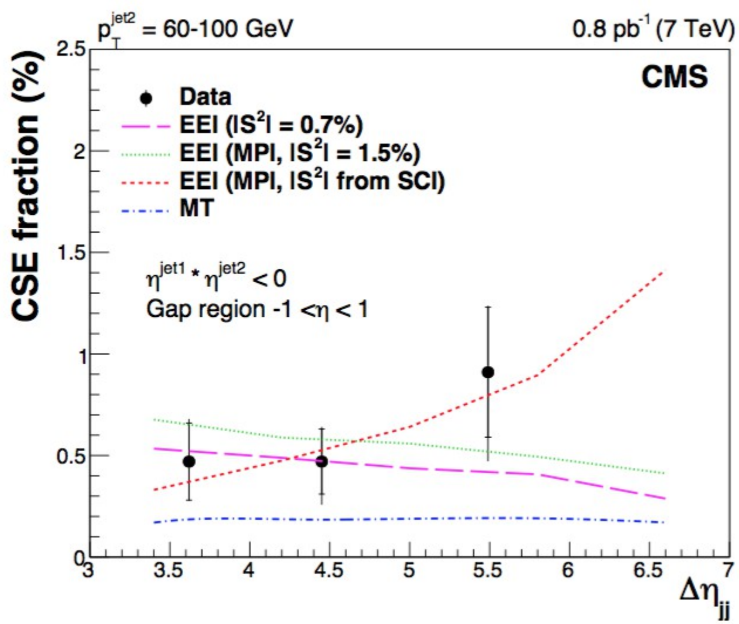
Jet-gap-jet events: GAP/CSE fraction

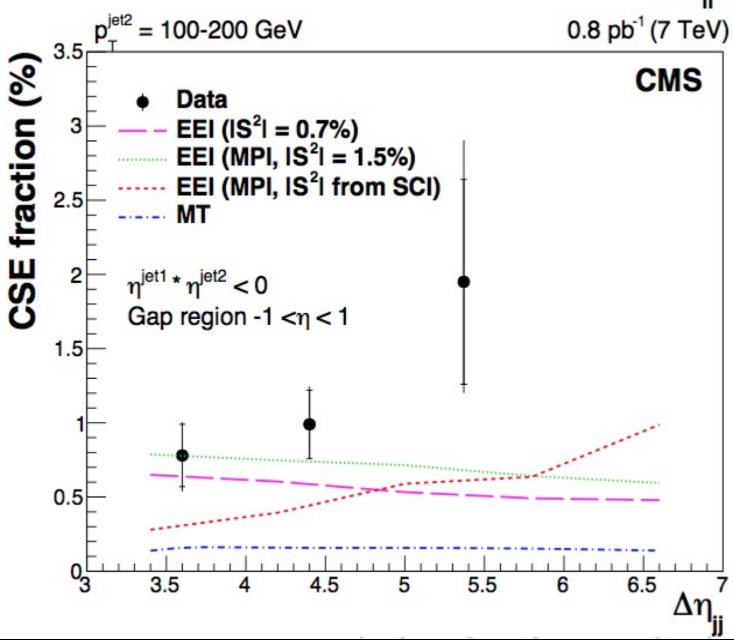
- f_{CSE} as a function of eta in three p_T^{jet2} ranges

arXiv:1710.02586

Submitted to EPJC







- The NLL BFKL calculations of EEI, with three different implementations of the soft rescattering processes, describe many features of the data,

- But none of the implementations is able to simultaneously describe all the features of the measurement.

Summary

- Many interesting results from CMS, reaching new levels of precision and exploring new regions of phase space.
  - wide range of jet measurements at various collision energies, improving our understanding of QCD
  - excellent understanding of the jet reconstruction and energy calibration and together with the high data quality make jet measurements precision physics
- Current results on very forward jets are highly sensitive to UE tuning; weak dependence on PDF
  - No clear sign for saturation yet (p+Pb results need to be further interpreted)
- Mueller-Navelet dijet decorrelations analytical NLL BFKL calculation agrees with data
  - Higher collision energies may be more decisive
- BFKL color singlet exchange measured for the first time at the LHC
  - LO DGLAP does not reproduce dijet events with no particles between them
  - CSE fraction (0.5-1%) rises with p_T but decreases with collision energy

Thank you for your attention!

BACKUP

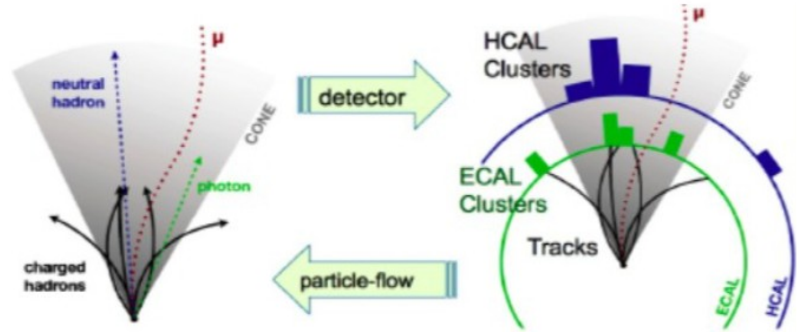
•The gap fractions are plotted relative to the standard LO QCD dijet production rates, calculated with PYTHIA 6 (using tune Z2* for MT, and the default settings with color reconnection features turned off for EEI).

•The MT model prediction is based on the LL BFKL evolution in the asymptotic limit of large rapidity separations between the jets, and is obtained with HERWIG 6 for pure jet-gap-jet events (no simulation of MPI).

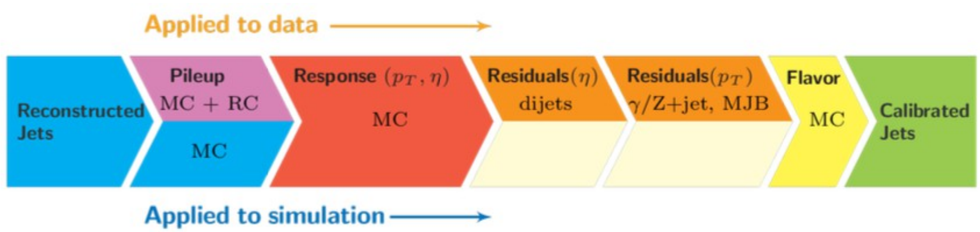
•

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)Δ apply jet finding algorithm Δ 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:



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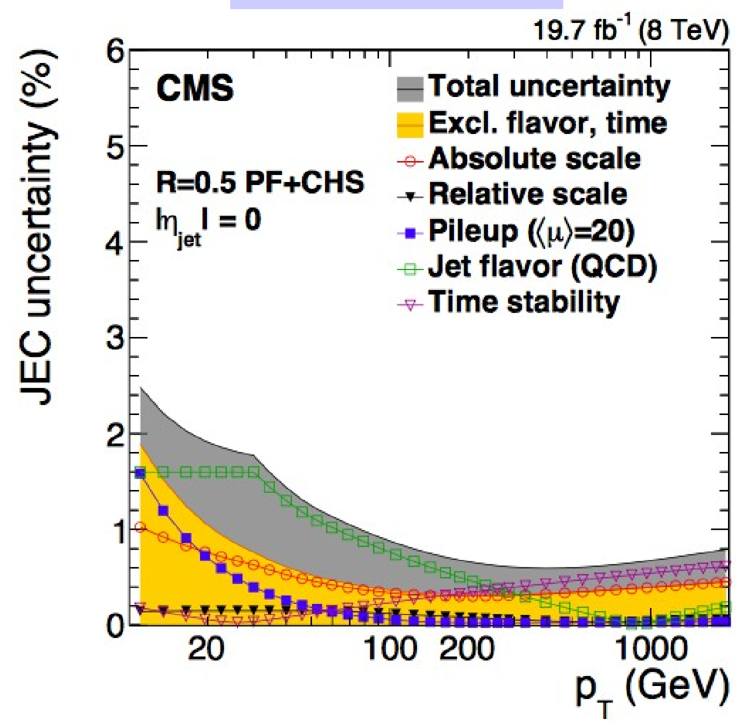

- Pileup → corrects for "offset" energy
- Response → Make jet response flat on η and p_T
- Data/MC residuals → residual differences between data & MC
- Flavor (optional) → corrects dependence on jet flavor