Soft QCD measurements and diffraction in CMS

Grzegorz Brona
(University of Warsaw)
on behalf of
CMS Collaboration

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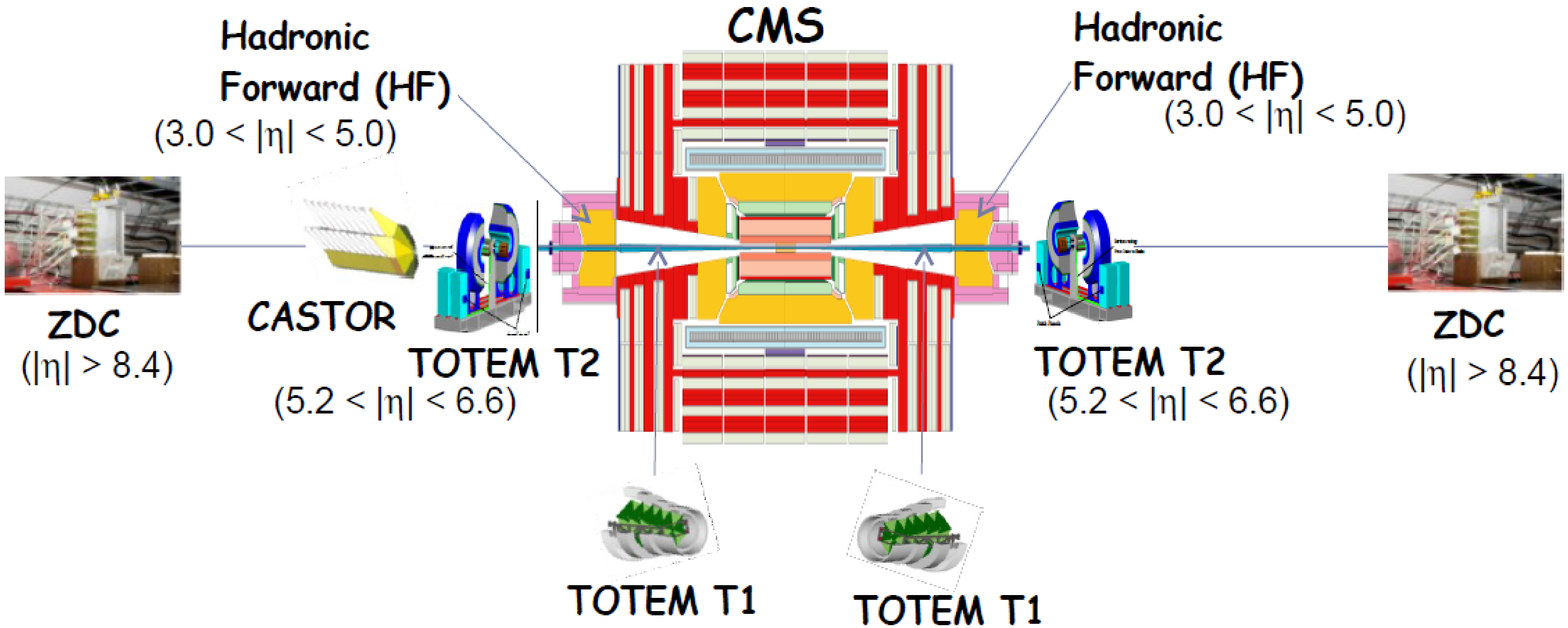
Outline

- Inelastic pp cross section at 13 TeV [FSQ-15-005]
- Forward energy flow [FSQ-15-006]
- Very forward energy flow [FSQ-16-002]
- Underlying activity with leading track/jet [FSQ-15-007]
- Dijets with large rapidity gap [FSQ-12-001]

CMS at Forward Rapidities

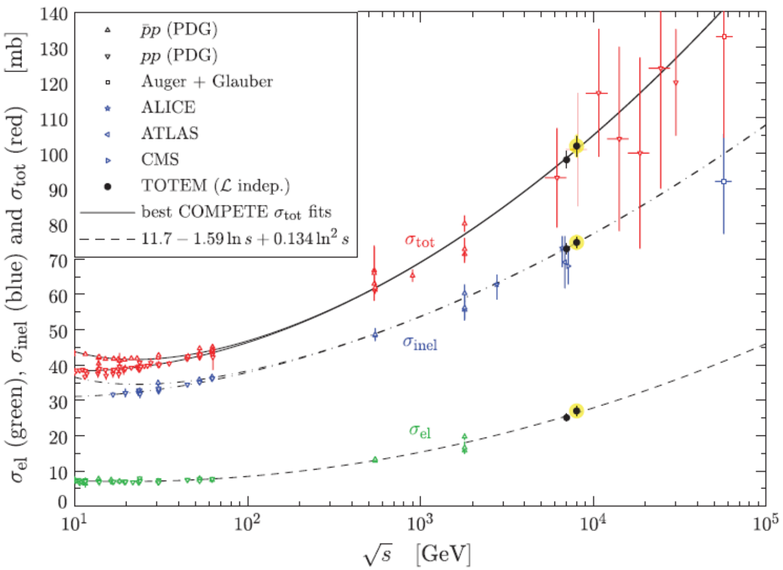


- Tracker $|\eta|<2.4$, $p_T > 100$ MeV
- Electromagnetic calorimeter ECAL
- Hadronic Calorimeter HCAL
- Muon chambers

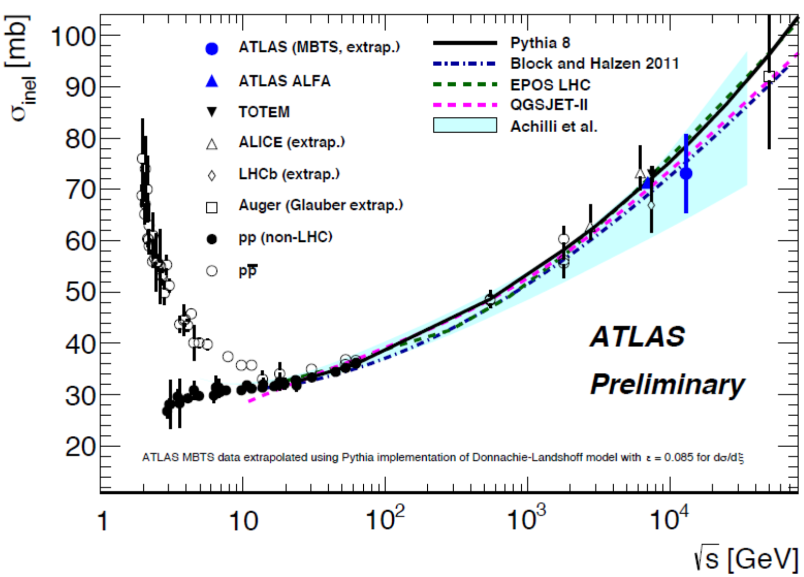
- Hadronic Forward calorimeters (HF)
- Centauro And STrange Objects Research (CASTOR) - calorimeter
- Zero Degree Calorimeter (ZDC)
- Beam Scintillator Counters BSC: $3.2 < |\eta| < 4.7$
- Forward Shower Counters FSC: $6 < |\eta| < 8$

+ Totem (T1/T2 tracking detectors and RP roman pots) separate experiment

Inelastic pp cross section at 13 TeV



- At 7 TeV results from CMS, ATLAS, ALICE, LHCB
- σ_{inel} 66.9 – 72.7 mb central values
- Measurements from TOTEM:
  7 TeV: σ_{inel} = 73.5 ± 1.9 mb
  8 TeV: σ_{inel} = 74.7 ± 1.7 mb



- At 13 TeV result from ATLAS (ATLAS-CONF-2015-038)
- σ_{inel} = 73.1 ± 0.9 (exp) ± 6.6 (lum) ± 3.8 (ext) mb
- Below the predictions

Inelastic pp cross section at 13 TeV

- Low pile-up runs from 2015 with B = 0 T and 3.8 T
- Trigger: both beams present at the interaction point
- Two samples:

  1) HF OR -> at least one HF calorimeter tower above 5 GeV

$$\xi_X > 10^{-6} \text{ and } \xi_Y > 10^{-6}$$

- 2) HF/CASTOR OR -> at least one HF or CASTOR tower above 5 GeV

$$\xi_X > 10^{-6} \text{ and } \xi_Y > 10^{-7}$$

- Correction for noise from no-beam events
- Data driven correction for pile-up events
- Correction to the particle level – different MC models:

PYTHIA8 (D-L and MBR for diffraction), PYTHIA6, EPOS, QGSJET-II, PHOJET

Inelastic pp cross section at 13 TeV

Results:

σ_{inel} (ξ_X>10^{-6}, ξ_Y>10^{-6}) = 65.77 ± 0.03 (stat) ± 0.76 (syst) ± 1.78 (lum) mb

σ_{inel} (ξ_X>10^{-6}, ξ_Y>10^{-7}) = 66.85 ± 0.06 (stat) ± 0.44 (syst) ± 1.96 (lum) mb

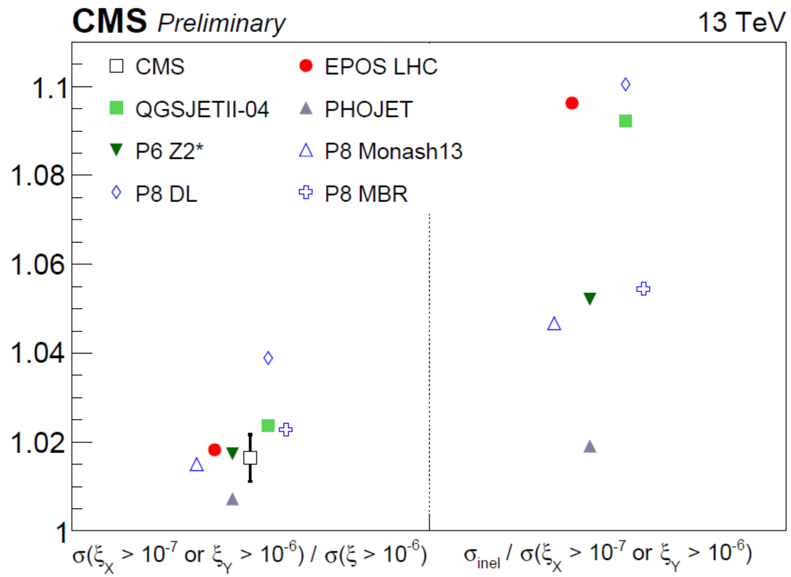
	$\sigma(\xi > 10^{-6})$ (mb)	$\sigma(\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6})$ (mb)
Model dependence	0.66	0.38
HF energy scale uncertainty	0.34	0.13
CASTOR energy scale uncertainty	-	0.04
CASTOR alignment	-	0.03
Run-to-run variation	0.15	0.14
Total	0.76	0.44
Luminosity	1.78	1.96

- The largest uncertainty factor comes from model dependence
- Luminosity uncertainty different in B=0 T and B=3.8 T runs

Extrapolation to full inelastic phase space with corrections from different MC models.

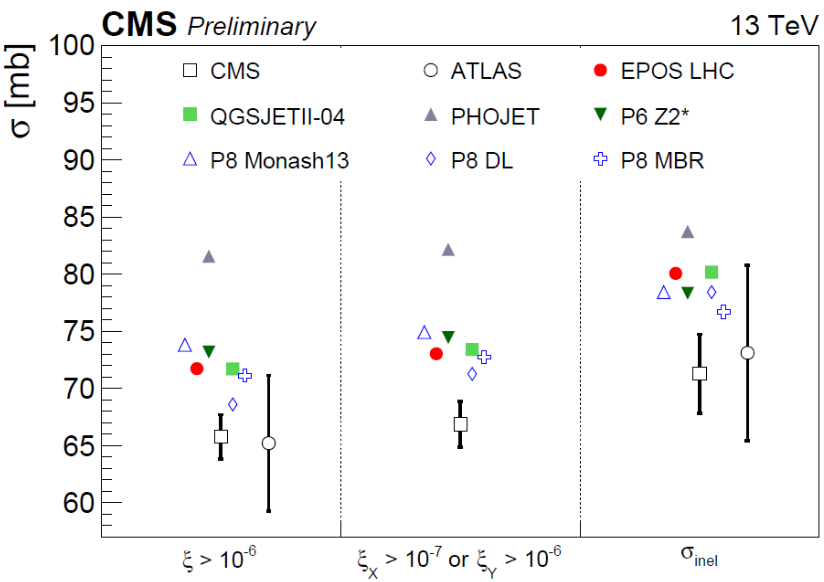
Inelastic pp cross section at 13 TeV

The increase in σ_{inel} when increasing the acceptance from ($\xi_X>10^{-6}$, $\xi_Y>10^{-6}$) to ($\xi_X>10^{-6}$, $\xi_Y>10^{-7}$) reproduced well by models



Correction factor differ (average value taken):

Model	Extrapolation factor
EPOS LHC	1.096
QGSJETII	1.092
PHOJET	1.019
PYTHIA6 Z2*	1.052
PYTHIA8 Monash	1.047
PYTHIA8 DL	1.101
PYTHIA8 MBR	1.054
Average	1.066



- Result

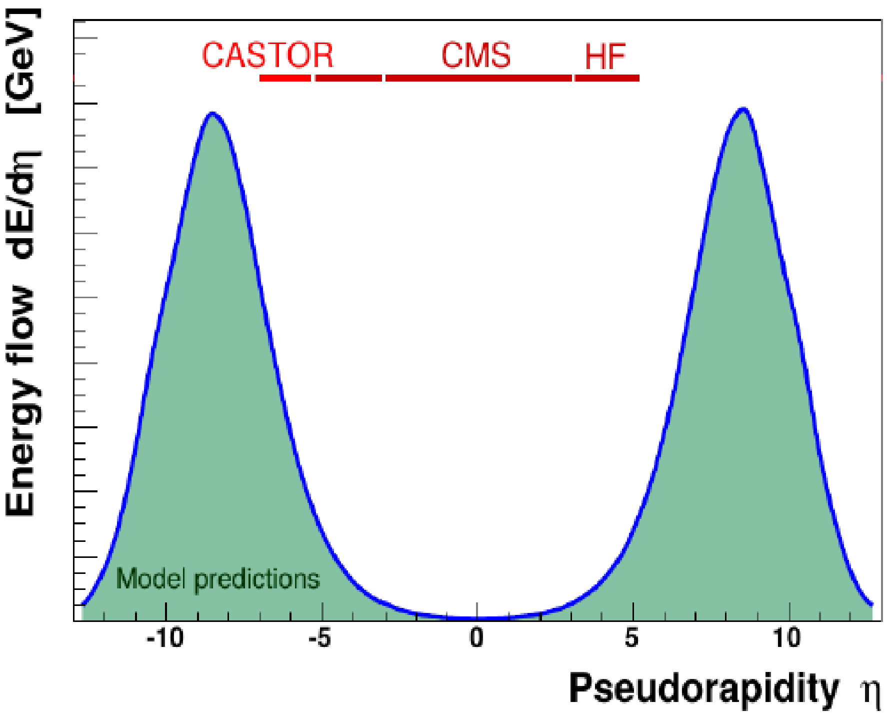
σ_{inel} = 71.26 ± 0.06 (stat) ± 0.47 (syst) ± 2.09 (lum) ± 2.72 (ext.) mb

- CMS result consistent with ATLAS

- Both results below the predictions

Forward energy flow

- Underlying activity for hard processes and new physics
- Requirement for precise measurements in QCD and EW sectors
- Better understanding of QCD dynamics
- Input to the models for cosmic ray physics studies
- Previouse measurements at 0.9 and 7 TeV for pp



Most of the energy in the forward rapidities in HF or CASTOR.

Different models used for comparison:

- PYTHIA8 Monash
- PYTHIA8 CUETP8
- EPOS
- QGSJETII

Forward energy flow

- Two samples:
  1) HF OR -> at least one HF calorimeter tower above 5 GeV
     - inclusive sample

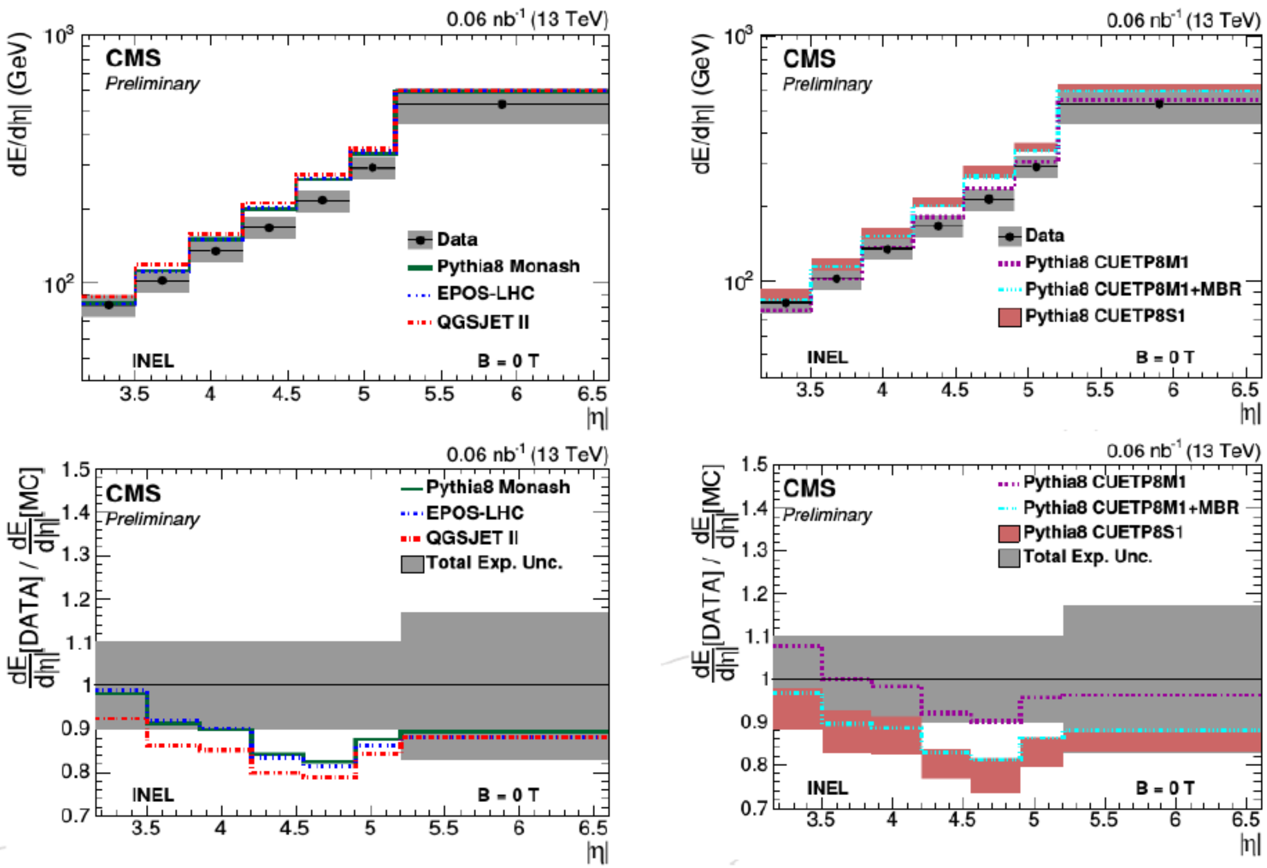
  2) HF AND -> at least one HF tower above 4 GeV at both
     - non-single diffractive enhanced sample

- Observable: sum over calorimeter towers in η bin

- Corrected for pile-up and noise
- Results corrected to particle level
- Largest uncertainty: calorimeter global energy scale 10-17%

Forward energy flow

The same HF-or data, different MC models



HF-OR

P8 Monash and cosmic ray MC provides similar results.

P8 CUETP8M1 (Sch.-Sj) and P8 CUETP8M1 (MBR) exhibits large variations – different diffraction modeling.

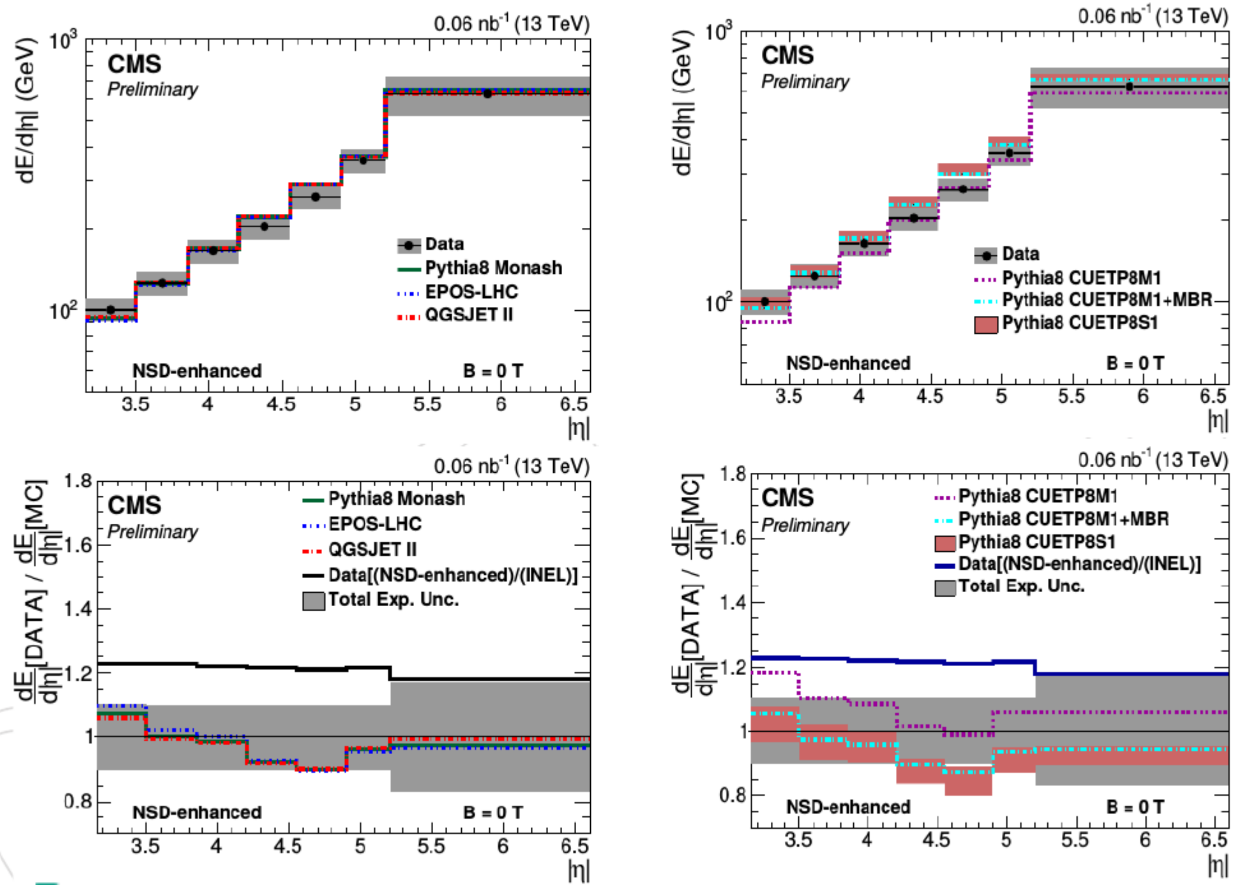
P8 CUETP8M1 works the best

- At lowest η the best agreement
- At higher η bins MC models overestimates the data
- At CASTOR bin the agreement is again better

Forward energy flow

The same HF-and data, different MC models

HF-AND



The spread between models smaller

Cosmic ray MC inside the uncertainities – good description

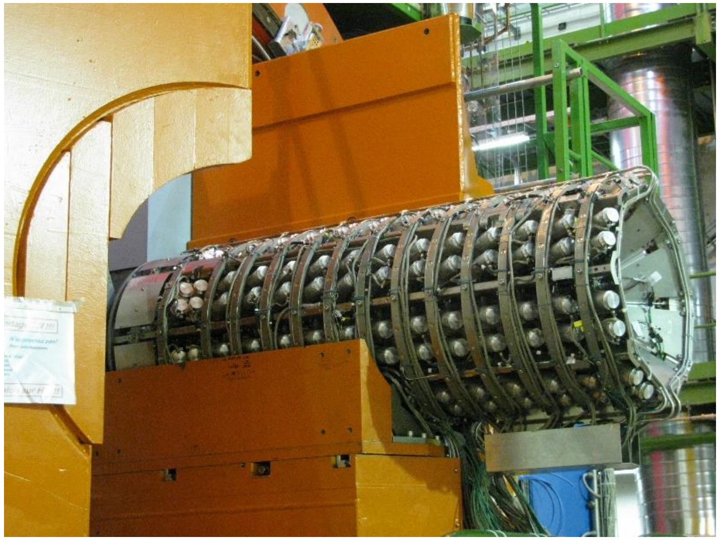
HF-and to HF-or ratio shown – no significant difference in the spectrum shape

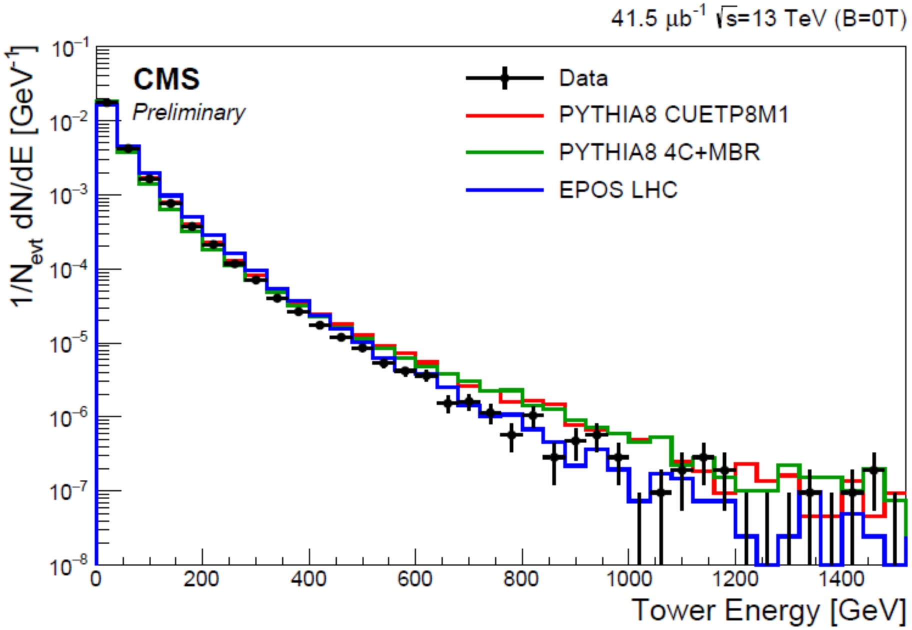
- Good description by P8 CUETP8M1 apart from the first bin

Very forward energy flow

- No segmentation in rapidity
- 14 modules in *z* direction:
  - 2 electromagnetic
  - 14 hadronic

- Selection of events via activity in HF (or) above 5 GeV (tower)



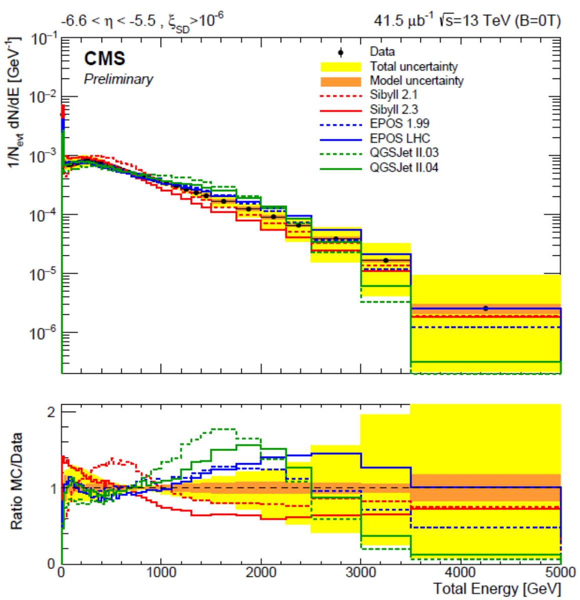


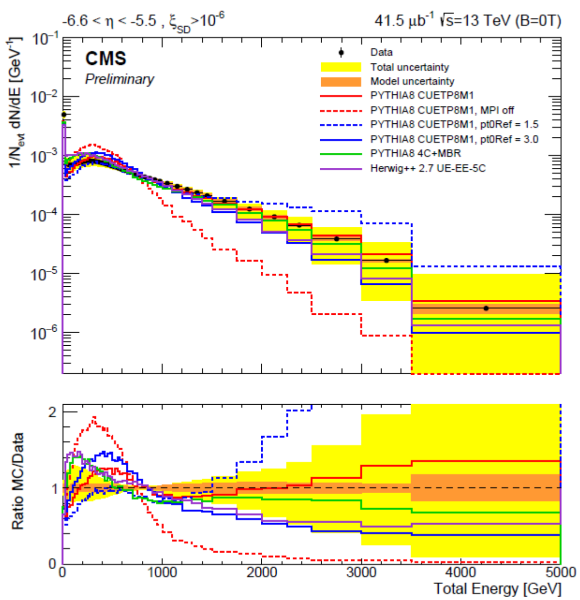
Energy spectrum of single reconstructed CASTOR towers in data well described by MC simulations

The detector level spectra corrected to the stable particle level (with $\xi_{SD}>10^{-6}$ cut)

Very forward energy flow

- Three observables defined:
  1) Total energy in CASTOR per event
  2) Electromagnetic energy (2 modules)
  3) Hadronic energy (12 modules)
- Energy scale uncertainy dominant – 17%



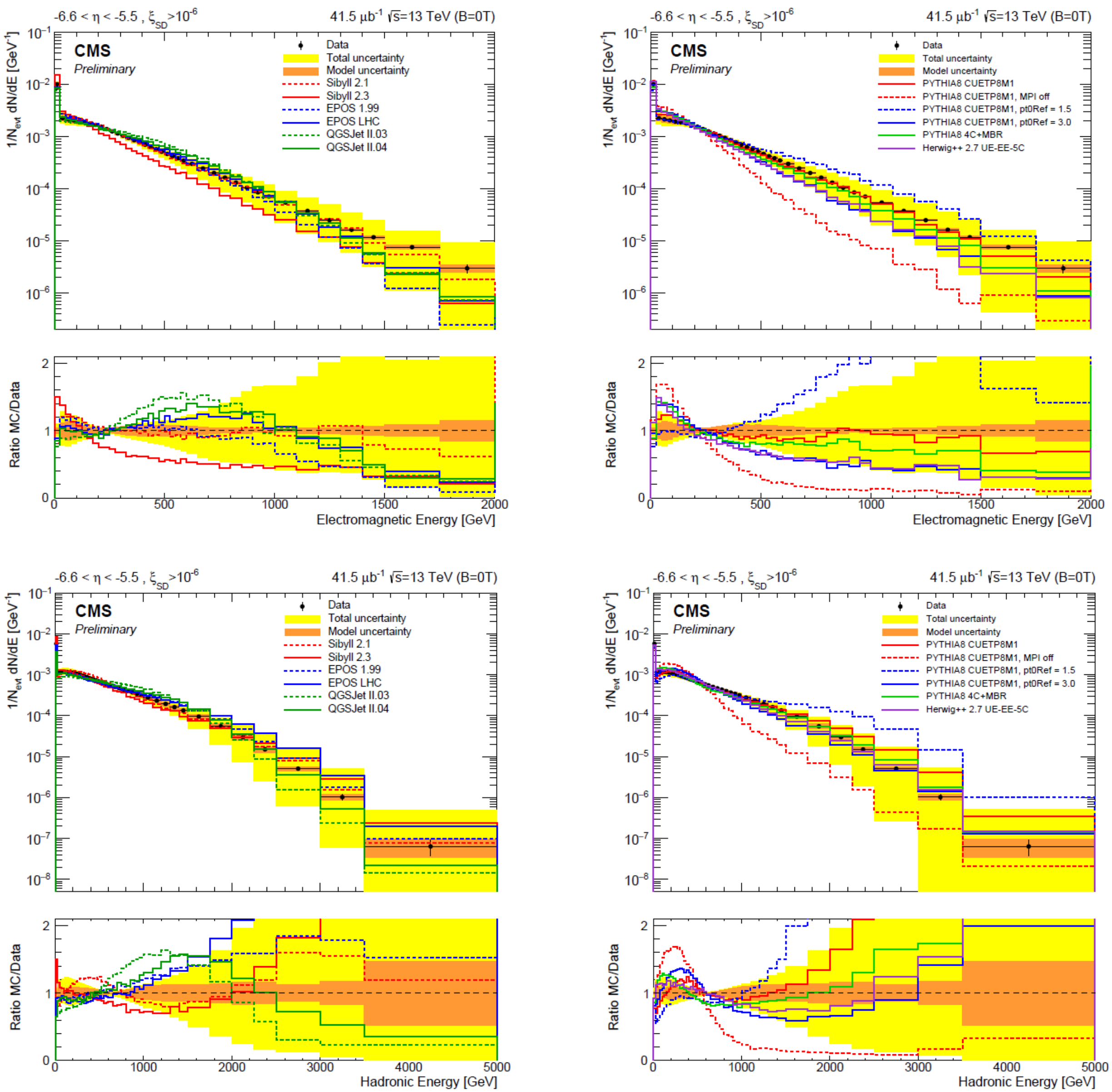


Diffractive events visible as a peak at lowest energies

PYTHIA8/HERWIG tend to overestimate the data in the soft part of te spectrum

The data is very sensitive to MPI and the underlying event parameters

Very forward energy flow



Electromagnetic spectrum well described by all models except for PYTHIA8 4C+MBR and SIBYLL

Sensitivity to the MPI tuning

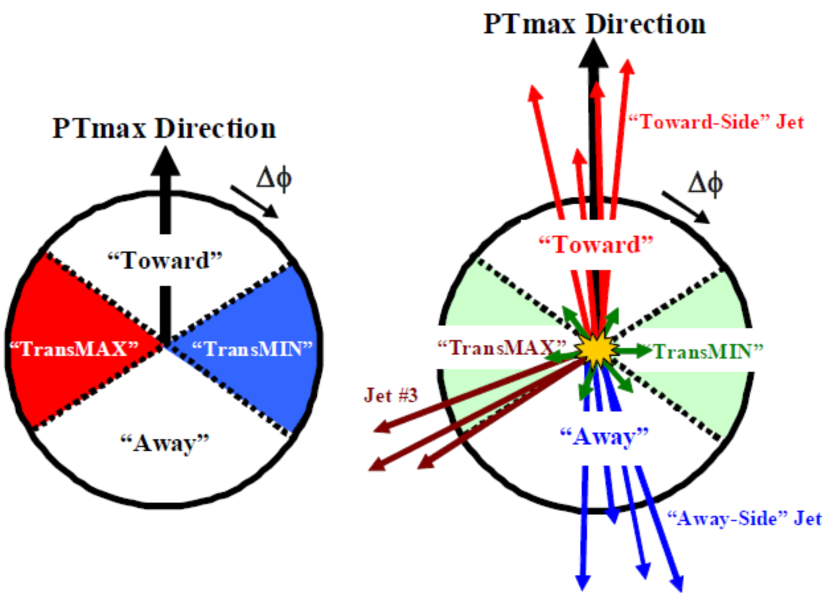
EPOS underestimates the spectrum

QGSJETII overestimates in 0.5-1.8 TeV range and underestimates at larger values

PYTHIA8 tunes overestimate the soft region

Underlying activity with leading track/jet

Leading object in an event (track, jet)



Transverse region divided:

- TransMIN – lower activity, sensitive to MPI + beam-beam remnants
- TransMAX – higher activity, sensitive to MPI + beam-beam remnants + initial and final radiation
- TransDIF = TransMAX – TransMIN, sensitive to initial and final radiation

Leading track:

- $p_T > 0.5$ GeV
- $|\eta|<2$

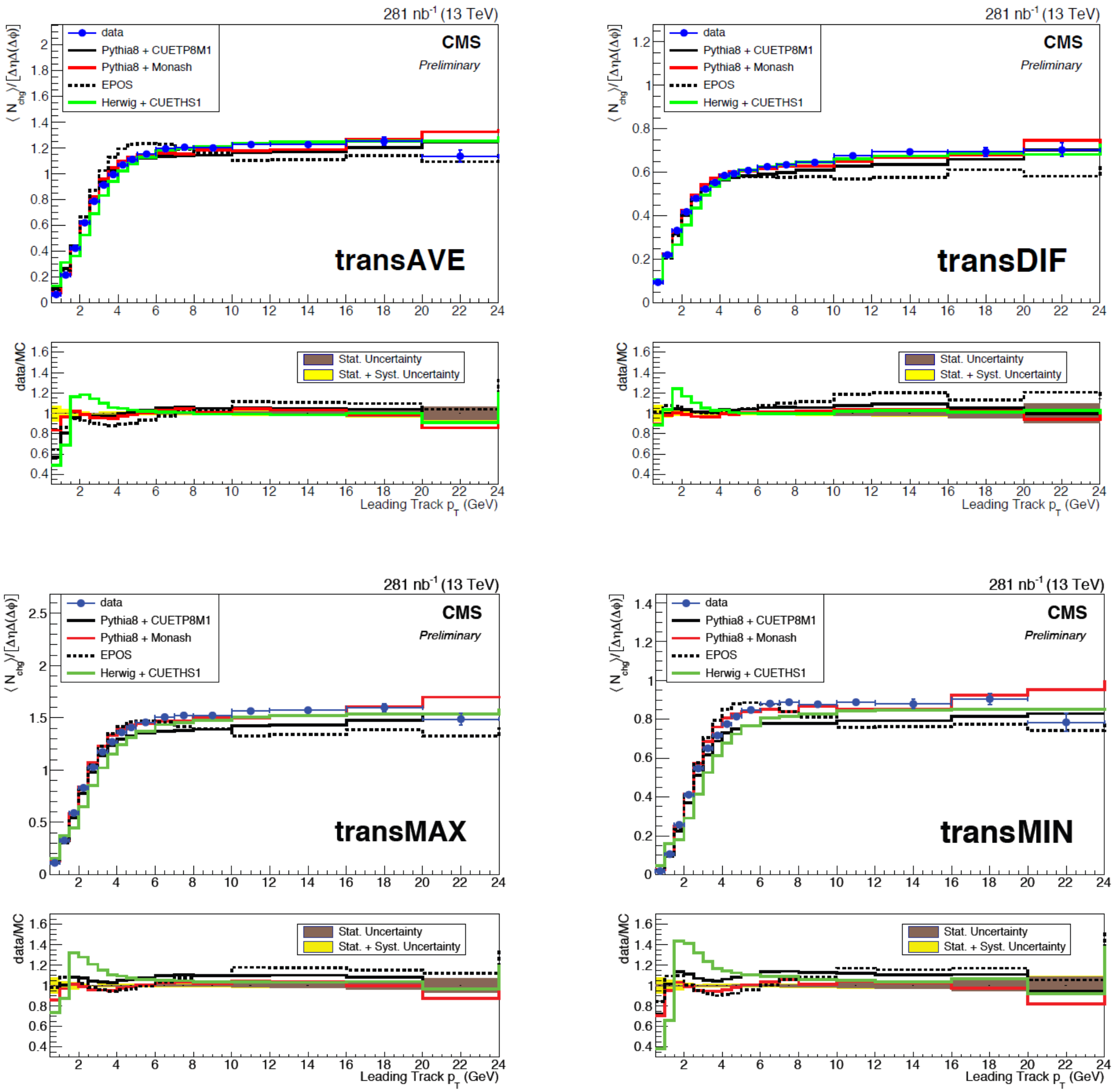
Leading jet:

- $p_T > 1$ GeV
- $|\eta|<2$

Observables:

- The charge density: N_{ch}
- The transverse momentum density: $\sum p_T$

Underlying activity with leading track



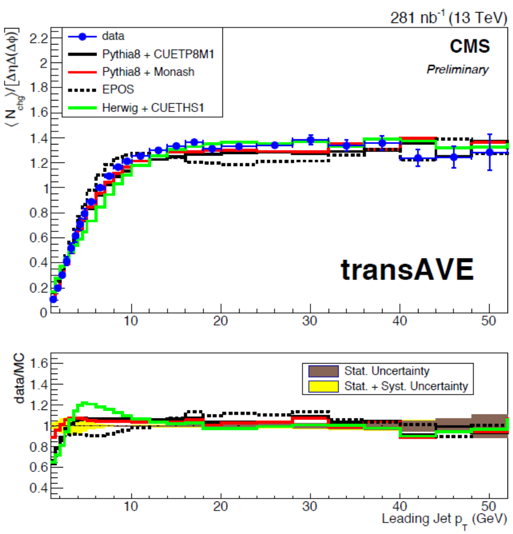
Average charged particle multiplicity density

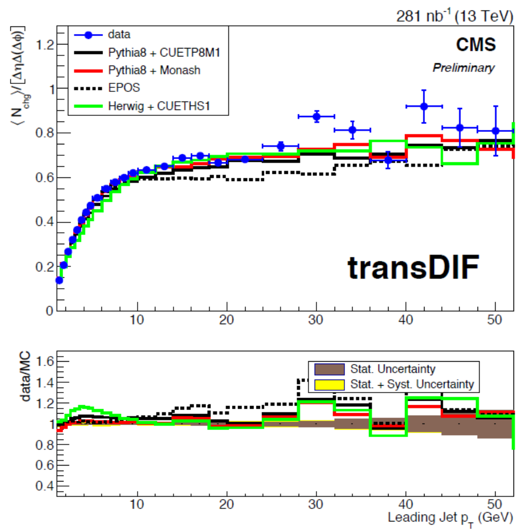
PYTHIA8 Monash, CUETP8M1 are the best

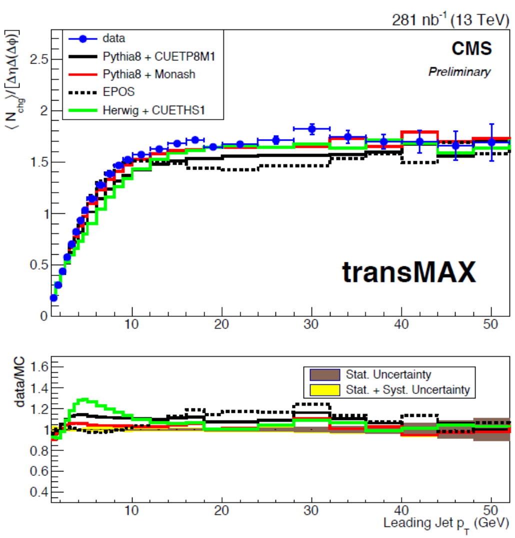
HERWIG do not fit the data at low p_T

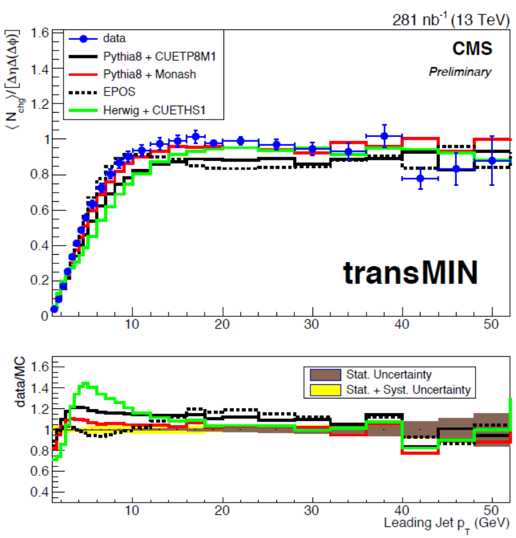
EPOS first above then below the data

Underlying activity with leading jet









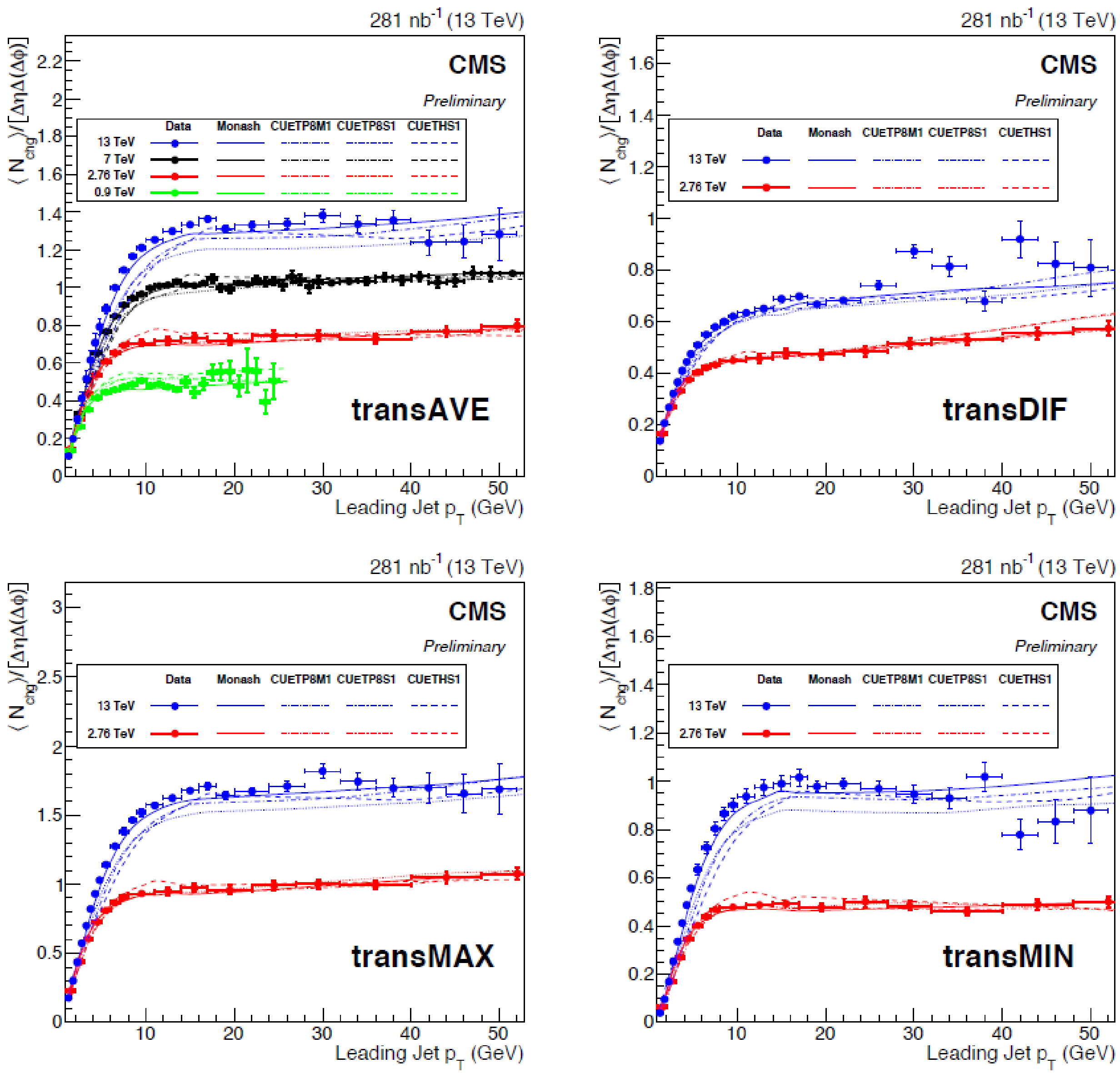
Average charged particle multiplicity density

PYTHIA8 Monash, CUETP8M1 are the best

Higher activity with respect to the leading track spectra

HERWIG again not good at soft region, EPOS underestimates high values

Underlying activity with leading jet



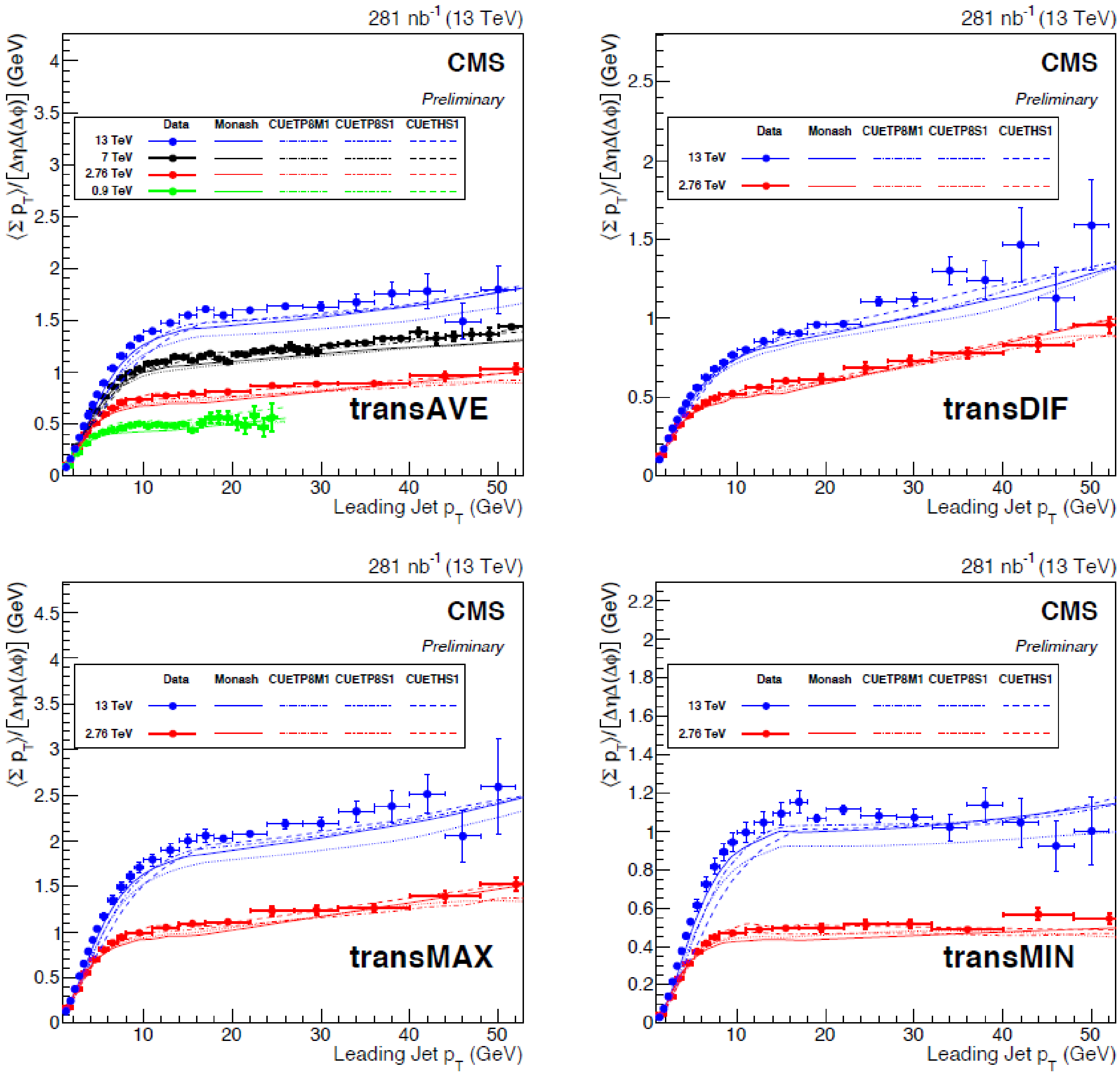
Average charged particle multiplicity density – energy dependence

Rise of UE activity with the rise of the center of mass energy

Rise well desribed by models

transMIN rise faster than transDIF -> MPI activity rises faster than ISR/FSR activity

Underlying activity with leading jet

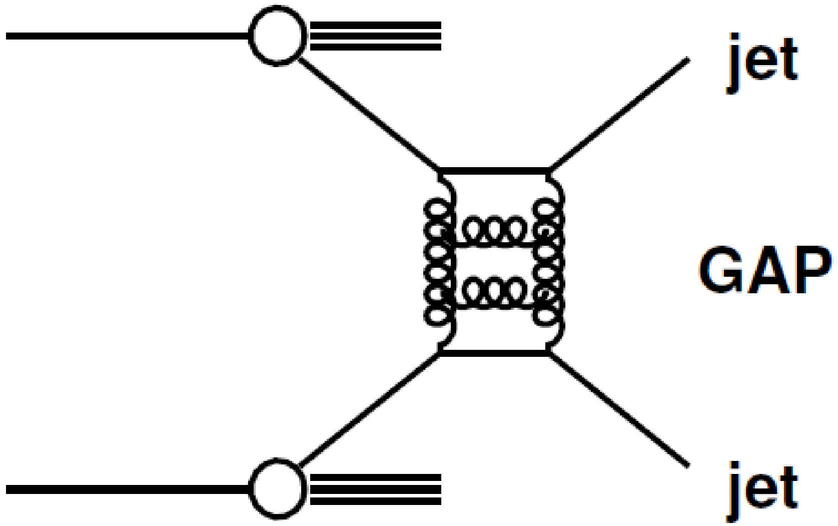


Average transverse momentum density – energy dependence

The same observation

PYTHIA8 Monash, CEUTP8M1 are the best

Dijets with large rapidity gap



- Jets separated by a large rapidity gap
- Color singlet exchange
- Probe BFKL dynamics
- Rescattering processes – rap-gap survival

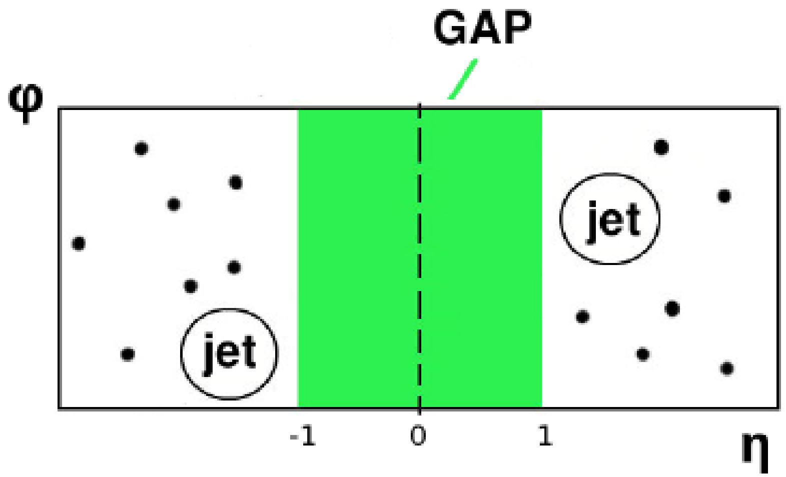
Selection:

- ~8 pb^{-1} of low pile-up data from 2010 at 7 TeV
- Three samples of dijets with the lower energy jet in p_T bins:
  40-60 GeV, 60-100 GeV, 100-200 GeV
- A primary vertex with |z|<24 cm (0, 1 vertices)
- Quality cuts imposed on jets

Dijets with large rapidity gap

Selection:

- η_{jet1} x η_{jet2} < 0 (jets in different hemispheres)
- $|\eta_{jet1,2}|$ > 1.5



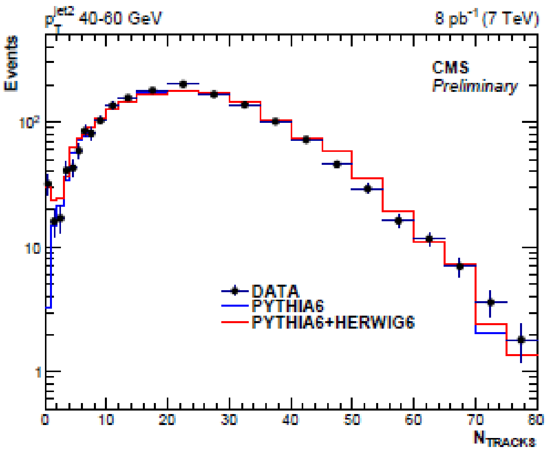
- Number of tracks calculated in $|\eta|$<1 interval
  → tracks with p_T > 0.2 GeV

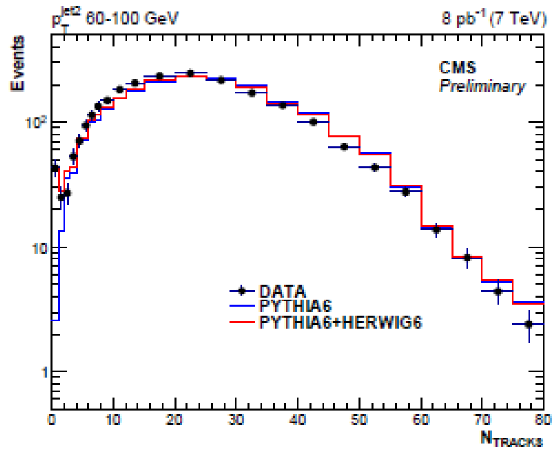
Monte Carlo:

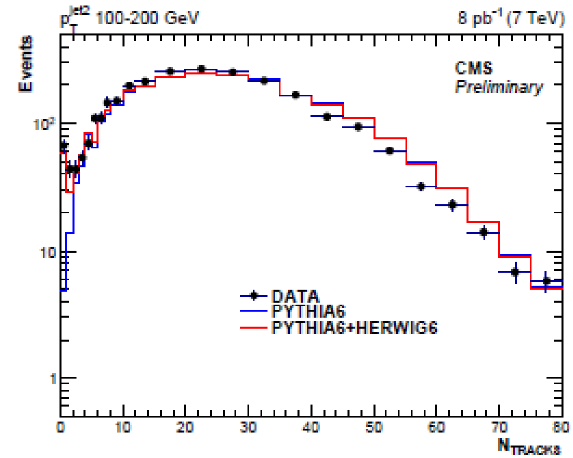
- PYTHIA6-Z2* → LO DGLAP
- HERWIG6 → the hard color-singlet exchange included according to Mueller-Tang model (simplified BFKL calculations containing the LL terms) + JIMMY

Dijets with large rapidity gap

Number of tracks in the central rapidity interval







- Clear excess of gap events over PYTHIA6 predictions – first bins

- Excess can be described with:

$$f_{CSE} = \frac{N_{events}(S) - N_{bkg}(S)}{N_{events}}$$

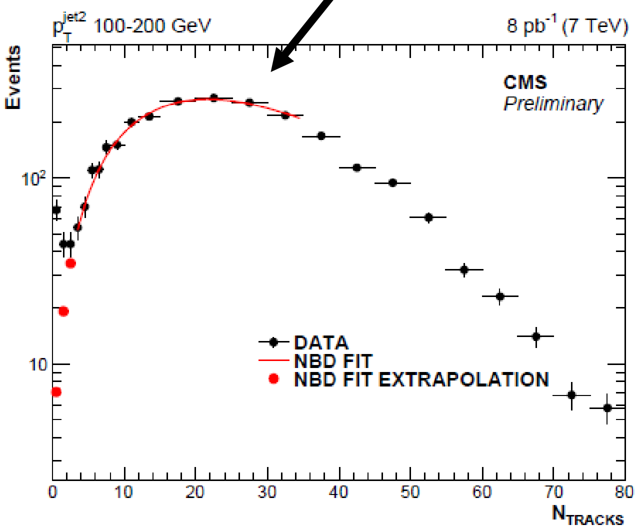
Number of events in first S bins

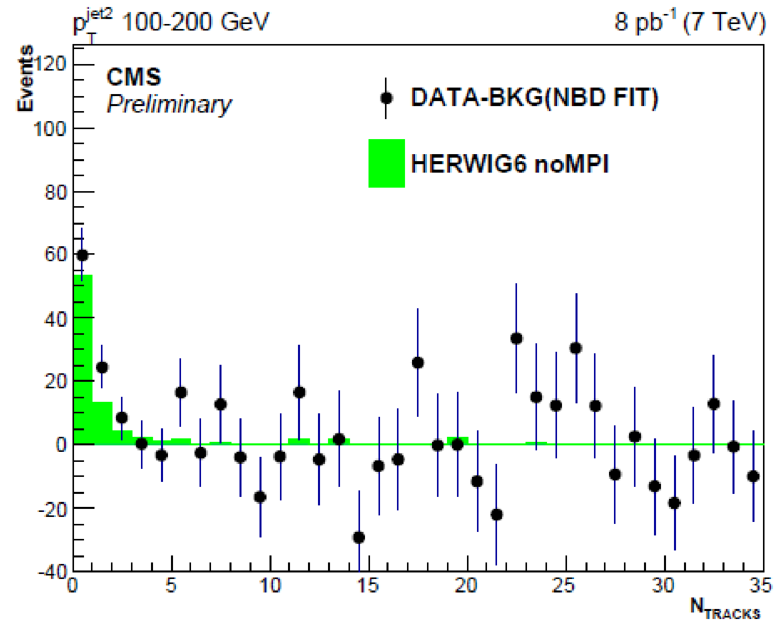
Total number of events

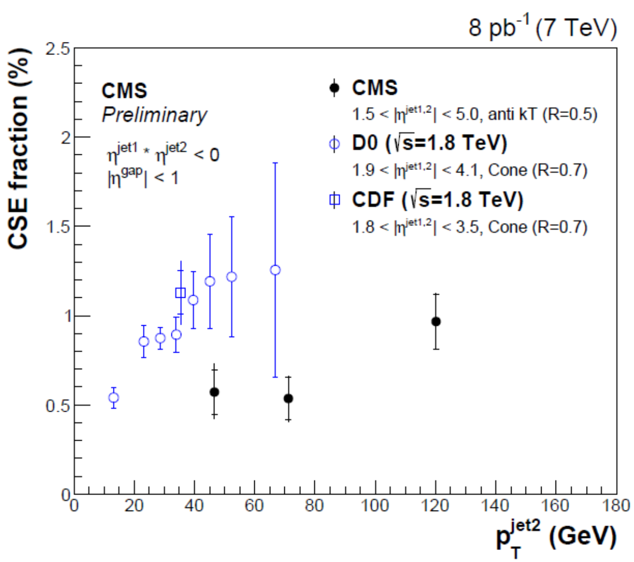
Number of events in first S bins from non Color Singlet Exchange (CSE)

Dijets with large rapidity gap

Negative binomial distribution fitted







f_{CSE} calculated in 2 first bins

- Similar measurements for CDF and D0 (increase with jet2 p_T)
- Suppresion with the center-of-mass energy factor ~2

Summary

- Inelastic pp cross section at 13 TeV measured:

σ_{inel} = 73.26 ± 0.06 (stat) ± 0.47 (syst) ± 2.09 (lum) ± 2.72 (lum) mb
consistent with ATLAS measurement

- Forward energy flow (HF) and very forward energy flow (CASTOR) measured and compared with PYTHIA and cosmic ray models and different tunes

- Underlying activity with leading track/jet measured, center-of-mass energy dependence obtained, PYTHIA8 Monash, CUTEP8M1 fit the best

- Dijets with large rapidity gap observed – indication of BFKL dynamics