Forward Physics with the CMS Experiment at LHC

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Outline

- Motivation for Forward Physics
- CMS Detector
- Measurements on the LHC Run 2 data (13 TeV)
  - NEW! – Inelastic pp cross section (CMS PAS FSQ-15-005)
  - NEW! – Pseudorapidity dependence of the energy and transverse energy density (CMS PAS FSQ-15-006)
  - NEW! – Pseudorapidity spectra in different final states (CMS PAS FSQ-15-008)
  - NEW! – Energy distribution in the very forward direction (CMS PAS FSQ-16-002)
  - NEW! – Very forward inclusive jet cross section (CMS PAS FSQ-16-003)
- Summary

- All Forward Physics results at CMS

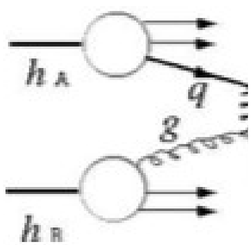
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

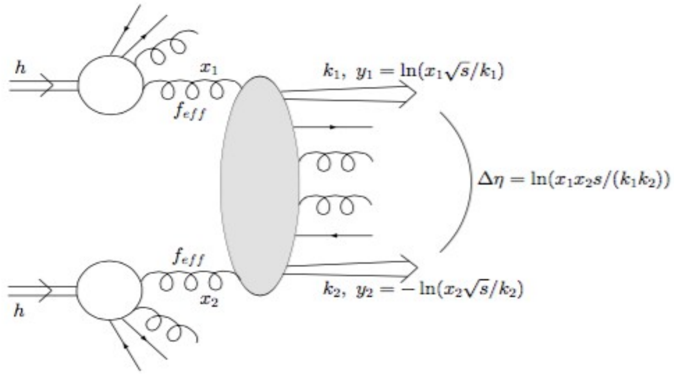
See S. Cerci's talk for results on inclusive jets and strong coupling measurements.

Why Forward Physics?

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

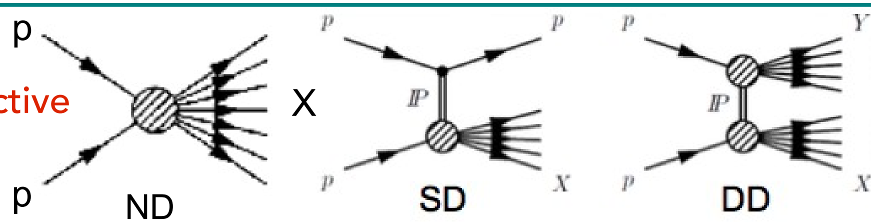
Low-x





- 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).

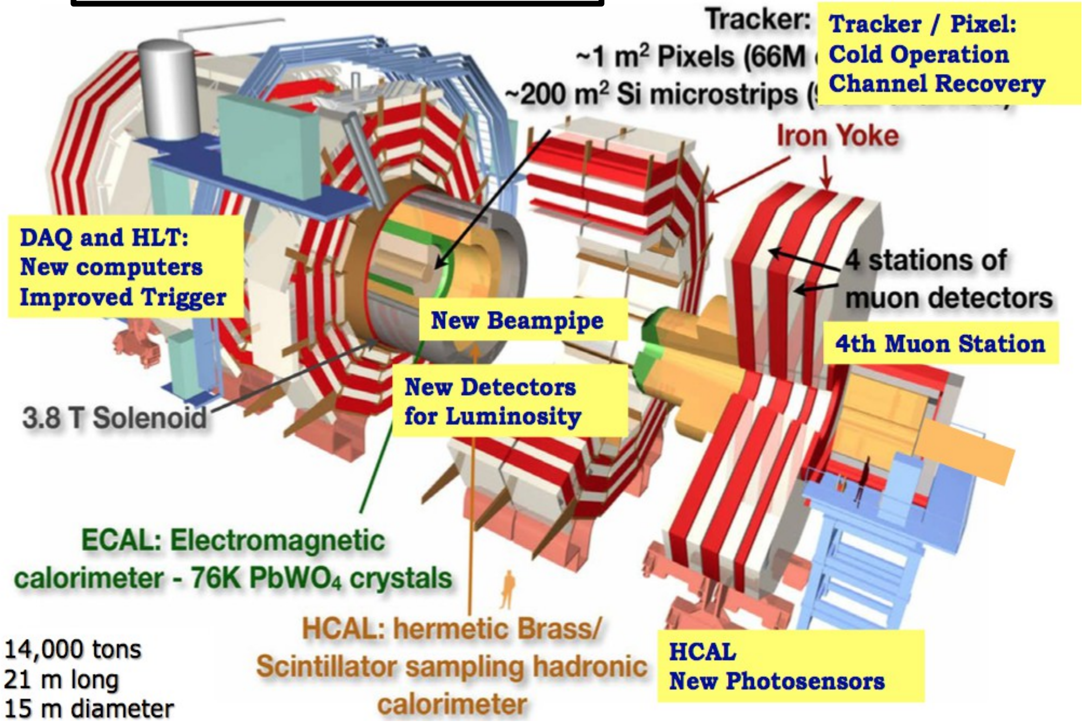
Elastic/diffractive interactions:



- 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)

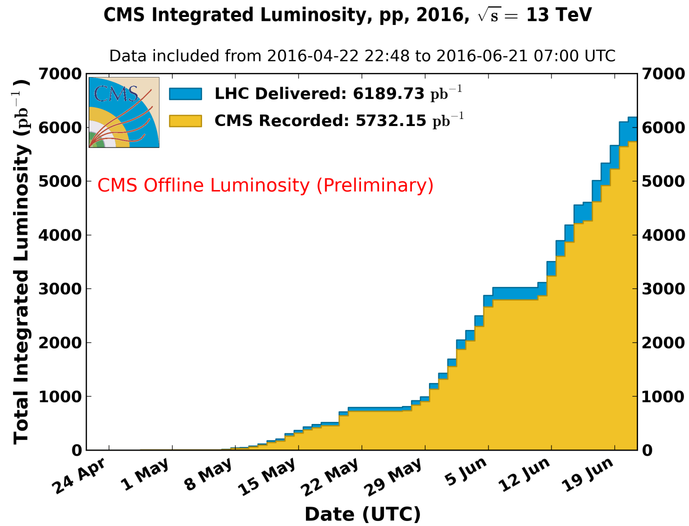
CMS Detector

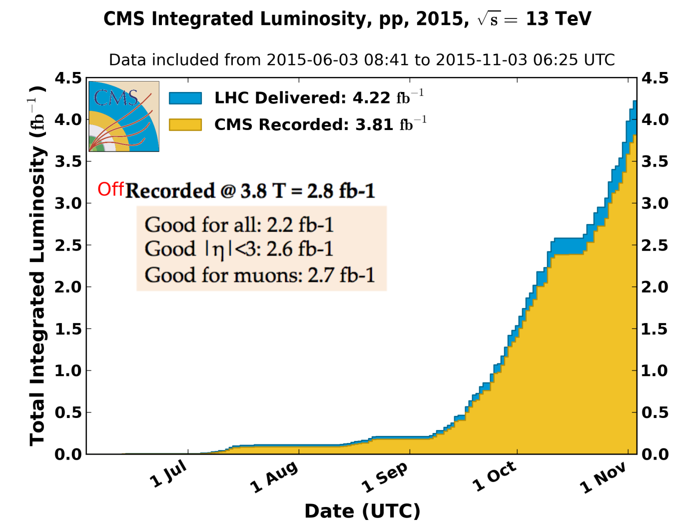
CMS after Long Shutdown 1



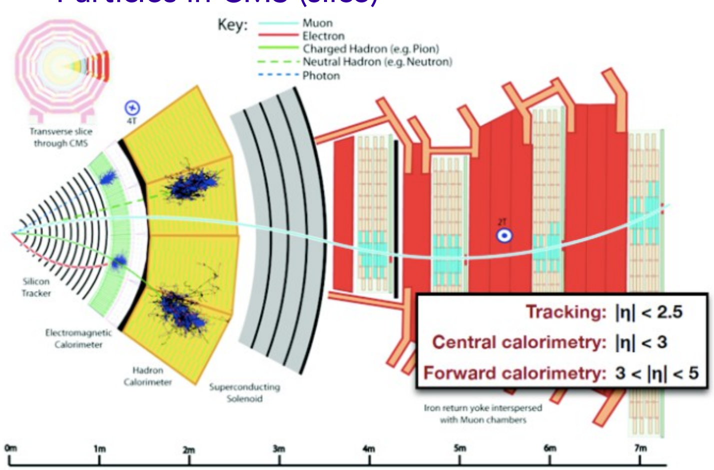
3rd of June 2015: LHC back in business with record pp collision energy of 13 TeV

13 TeV pp data (2015&2016)

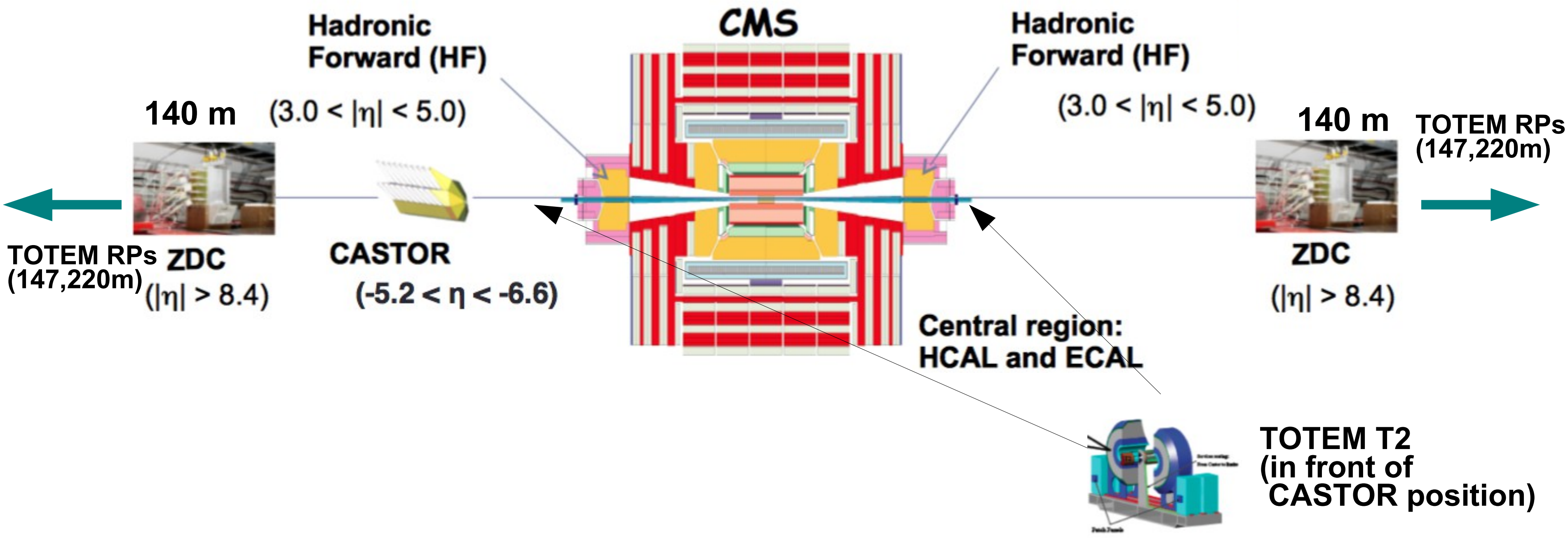




Particles in CMS (slice)



Forward Detectors at CMS

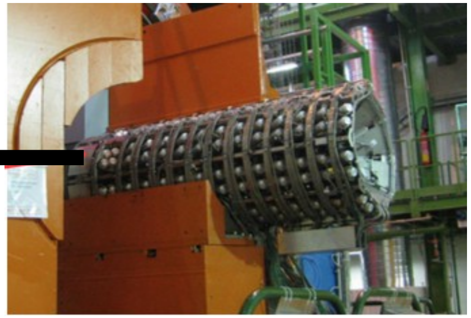


HF Detector

- @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



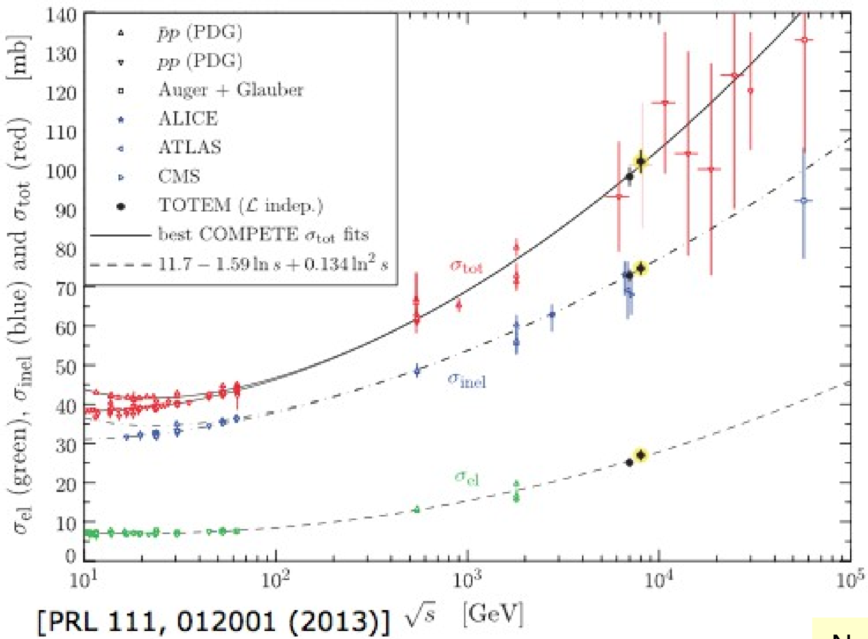
Inelastic pp cross section @ 13 TeV

- Motivation:
  - measure the inelastic pp cross section at 13 TeV in the largest possible phase space that is experimentally accessible
  - extrapolate to the total inelastic phase space domain

$$\sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{inel}(s)$$

$$\boxed{\sigma_{inel}(s) = \sigma_{sd}(s) + \sigma_{dd}(s) + \sigma_{cd}(s) + \sigma_{nd}(s).}$$

  - go more forward and gain information on relative increase
  - reduce extrapolation uncertainty



[PRL 111, 012001 (2013)]

- Results from CMS, ATLAS, ALICE, LHCb @ 7 TeV : σ_{inel} 66.9 - 72.7 mb
- Measurements from TOTEM (with optical theorem)
  - 7 TeV: σ_{inel} = 73.5 ± 1.9 mb
  - 8 TeV: σ_{inel} = 74.7 ± 1.7 mb

CMS PAS FSQ-15-005

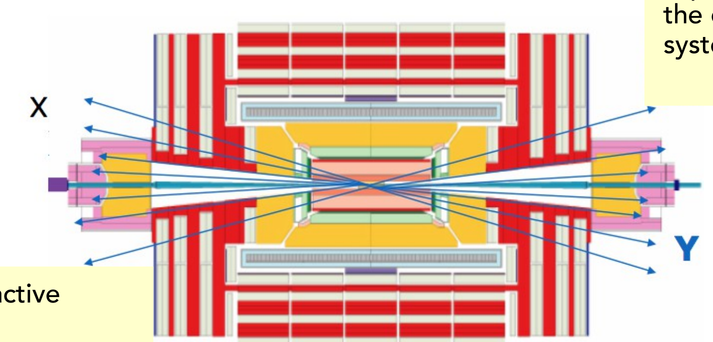
- Analysis strategy:
  - Use low pile-up runs from 2015 with B = 0 T and 3.8 T
  - Trigger: both beams present @ IP
  - Count events with an energy deposit above threshold

HF OR	HF/CASTOR OR
@ least one HF tower above 5 GeV $\xi_X > 10^{-6}$ and $\xi_Y > 10^{-6}$	@ least one HF or CASTOR tower above 5 GeV $\xi_X > 10^{-6}$ and $\xi_Y > 10^{-7}$

$$\xi_X = \frac{M_X^2}{s} \qquad \xi_Y = \frac{M_Y^2}{s} \qquad \xi = \max(\xi_X, \xi_Y)$$

  - 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

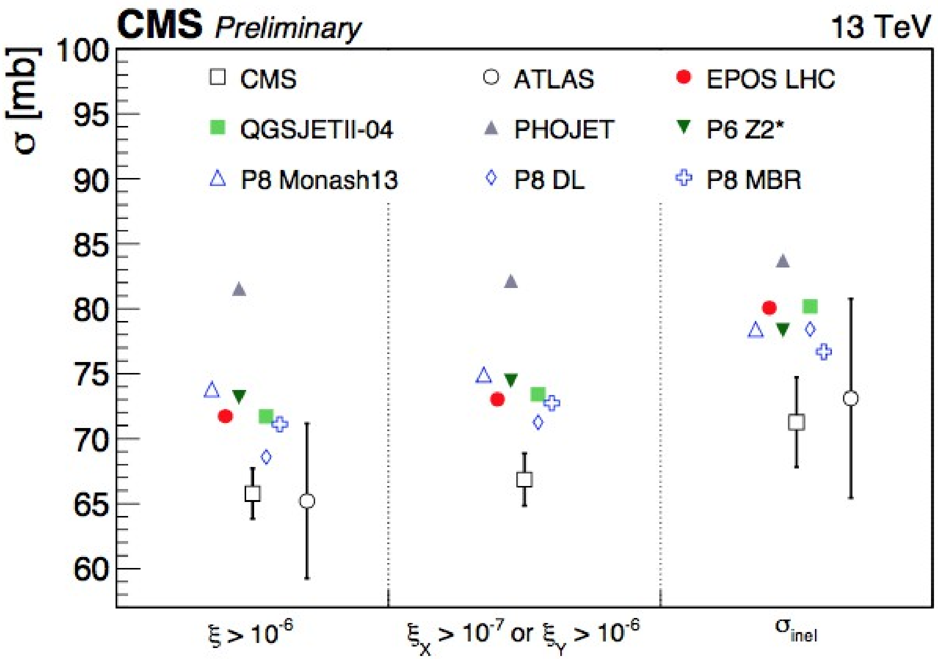
Diffractive events:
- largest gap separates the dissociation systems



Non-Diffractive events:
- Small largest gap
- randomly located

Inelastic pp cross section @ 13 TeV (cont'd)

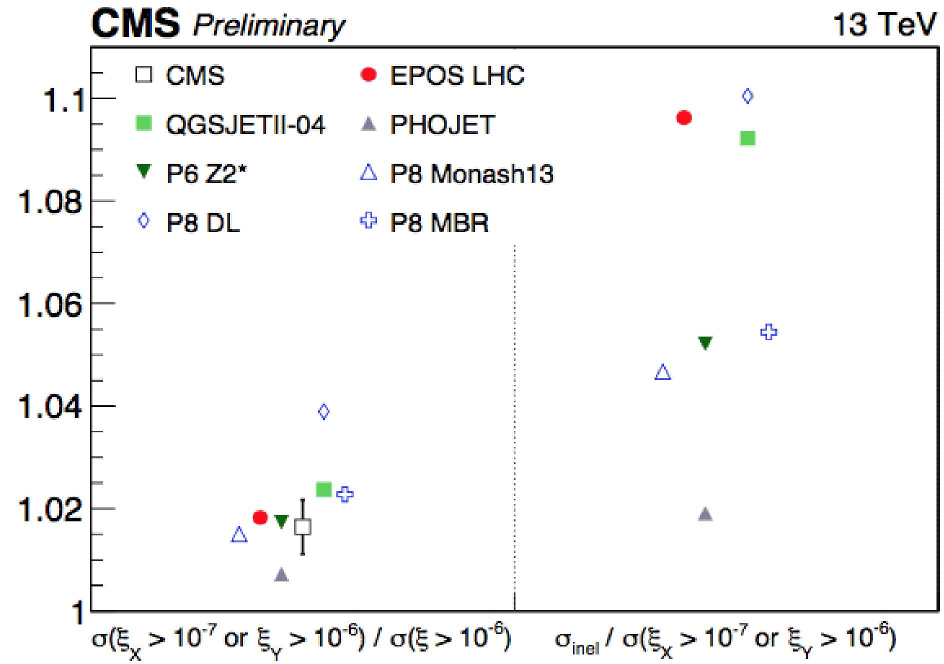
CMS PAS FSQ-15-005



- Most models describe the relative acceptance increase from ($\xi_X>10^{-6}$, $\xi_Y>10^{-6}$) to ($\xi_X> 10^{-7}$, $\xi_Y > 10^{-6}$) well

- The absolute values can not be described by Monte Carlo event generators

Result : σ_{inel} = 71.3 ± 0.5 (exp.) ± 2.1 (lum.) ± 2.7 (ext.) mb



- CMS result consistent with ATLAS [ATLAS-CONF-2015-038]

$\sigma(\xi > 10^{-6})$ = 65.2 ± 0.8 (exp.) ± 5.9 (lum.) mb
σ_{inel} = 73.1 ± 0.9 (exp.) ± 6.6 (lum.) ± 3.8 (ext.) mb

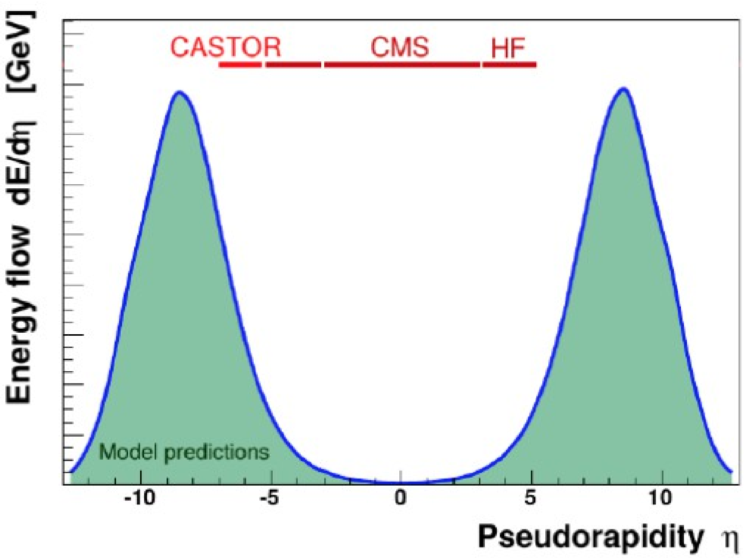
- Both results below the predictions

Forward energy flow & limiting fragmentation @ 13 TeV

CMS PAS FSQ-15-006

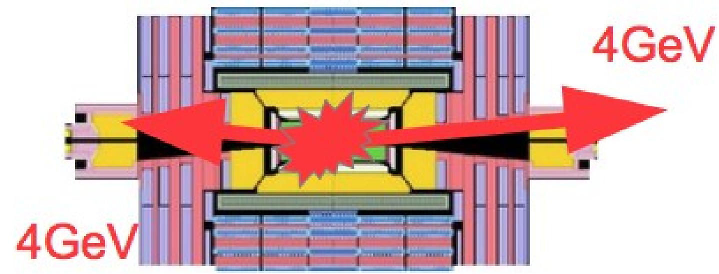
- Motivation:
  - measure the underlying activity for hard processes as well as the new & exciting physics
  - requirement for precision high p_T measurement in QCD and EWK sectors
  - useful input to the tuning of hadronic interaction models
  - better undestanding of QCD dynamics

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

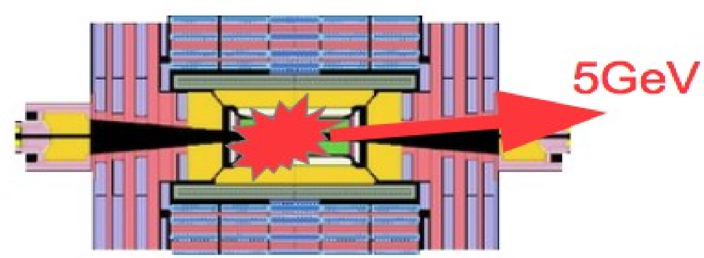


- Analysis strategy:
  - Use low pile-up runs from 2015 with B = 0 T
  - perform the measurement in $3.15 < |\eta| < 6.6$
  - sum up calorimeter energies for two event classes
    - Soft-inclusive events (single-arm)
    - Non-single-diffractive-enhanced (NSD) events (double-arm)
- Observables:
  - $dE / d\eta$ (sum of particle energies in each η bin)
  - $dE_T / d\eta'$ ($\eta' = \eta - y_{beam}$)
- Correction to particle level:
  - stable particles with $c\tau > 10$ mm, excl. μ and ν
  - noise from non-colliding bunches and pile up correction applied

Non-single diffractive events (HF AND)
Double sided collision event activity

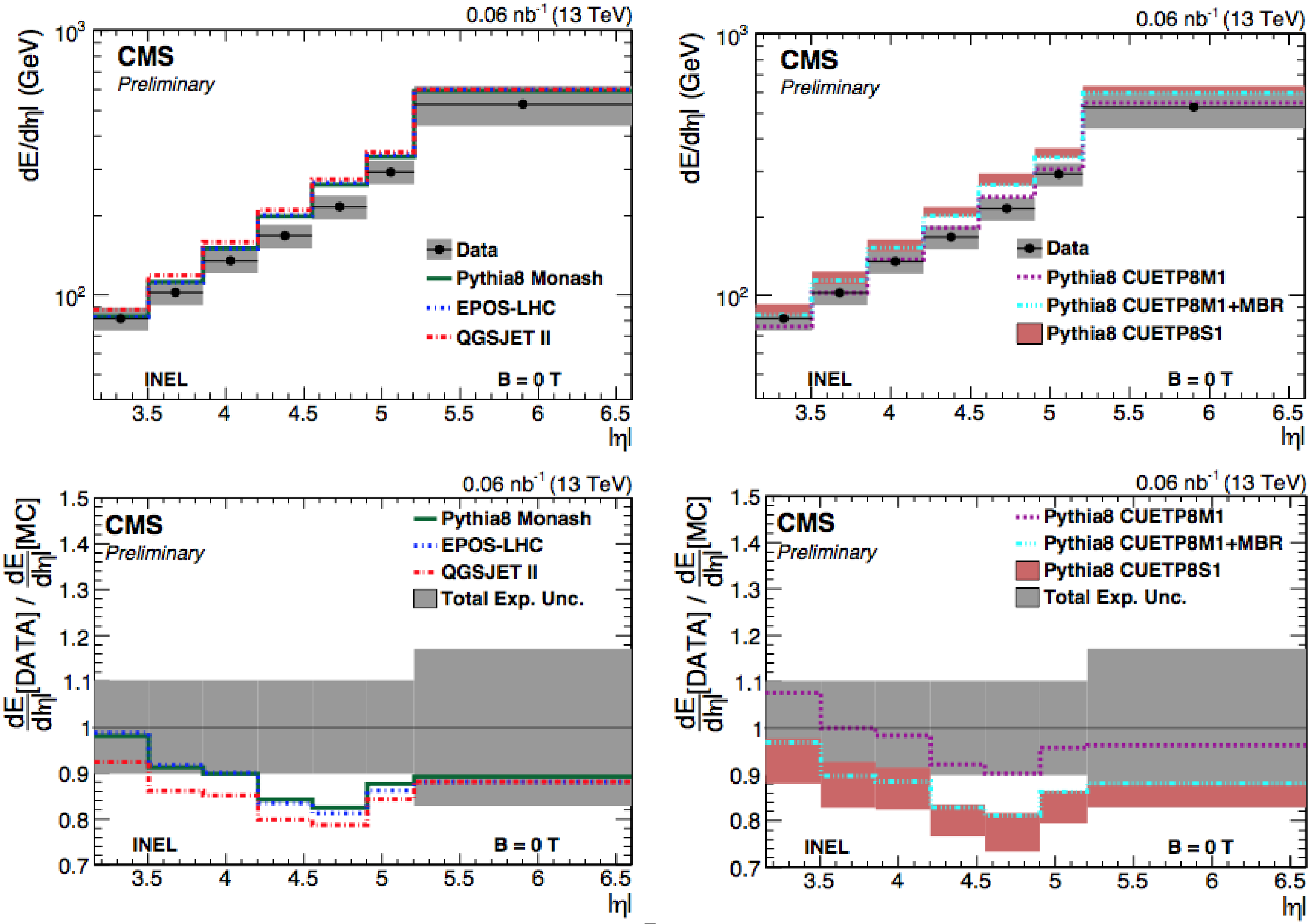


Soft Inclusive Inelastic events (HF OR)
Single sided collision event activity



dE/dη Soft-Inclusive Events

CMS PAS FSQ-15-006

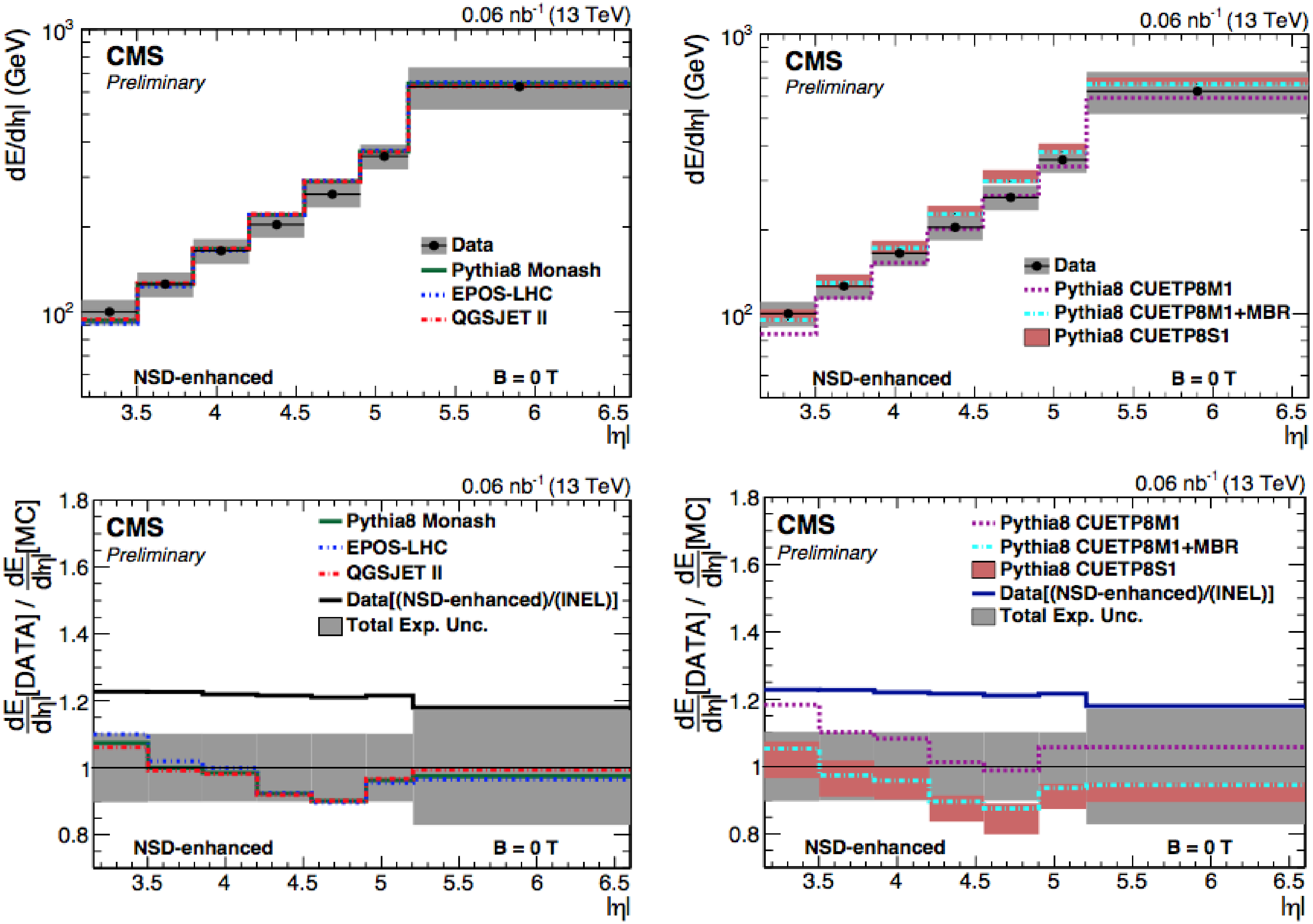


$\xi > 10^{-6}$

- Model predictions show large spread in HF region, 3.15 < |η| < 5.2.
- Best agreement at low η and in the CASTOR region (5.2 < |η| < 6.6).
- Pythia8 Monash vs EPOS/QGSJET: provides comparable result
- CUETP8M1 vs CUETP8M1+MBR: effect of variation of diffractive parameters
- CUETP8S1+uncertainties: dominant contribution from color reconnection parameters

dE/dη NSD-enhanced Events

CMS PAS FSQ-15-006



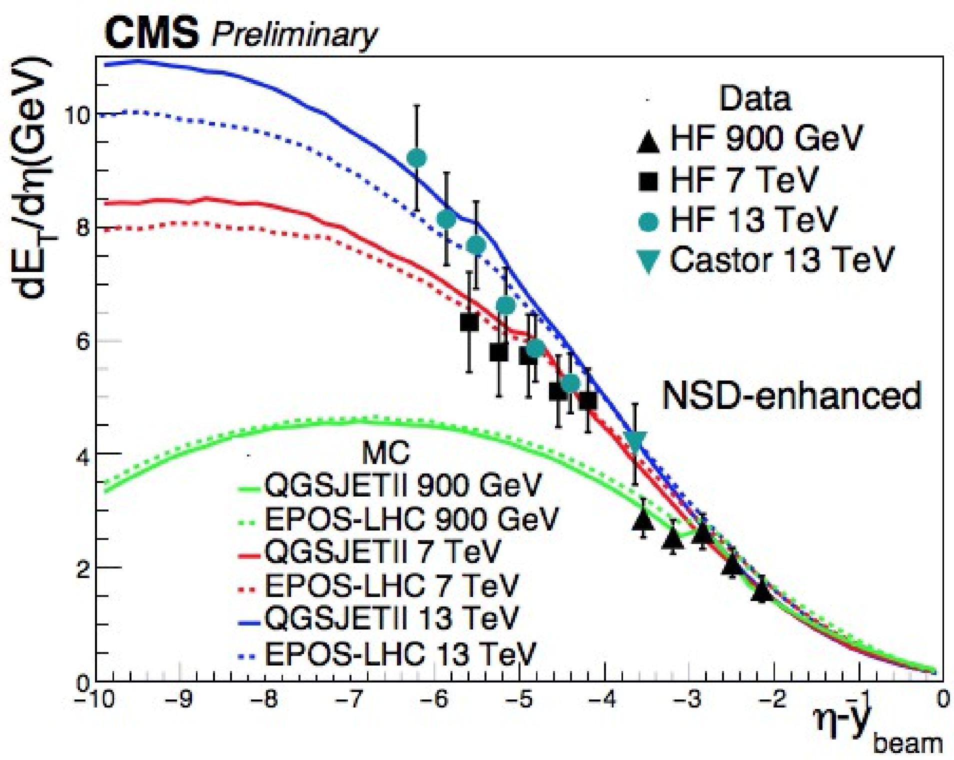
$\xi > 10^{-6}$

- Small spread between the model predictions
- NSD-enhanced (HF-AND) vs. INEL (HF-OR) no significant difference in the spectrum shape
- Overall good description by P8 CUETP8M1 except the first bin
- Cosmic ray MC (EPOS-LHC and QGSJetII) provides good description within the uncertainties for whole eta bins

Limiting fragmentation $dE_T/d\eta'$

CMS PAS FSQ-15-006

- Shifted pseudorapidity variable; $\eta' = \eta - y_{beam}$ (y_{beam} = beam rapidity)
- at least two charged particles in $3.9 < |\eta| < 4$



- Comparison with earlier CMS measurement at different centre-of-mass energies (0.9 and 7TeV), JHEP 11 (2011) 148.
- Simple geometry factors to get E_T from E; particle level definition adjusted to agree with previous data
- Overall consistency with hypothesis of limiting fragmentation

Very forward energy spectra

CMS PAS FSQ-16-002

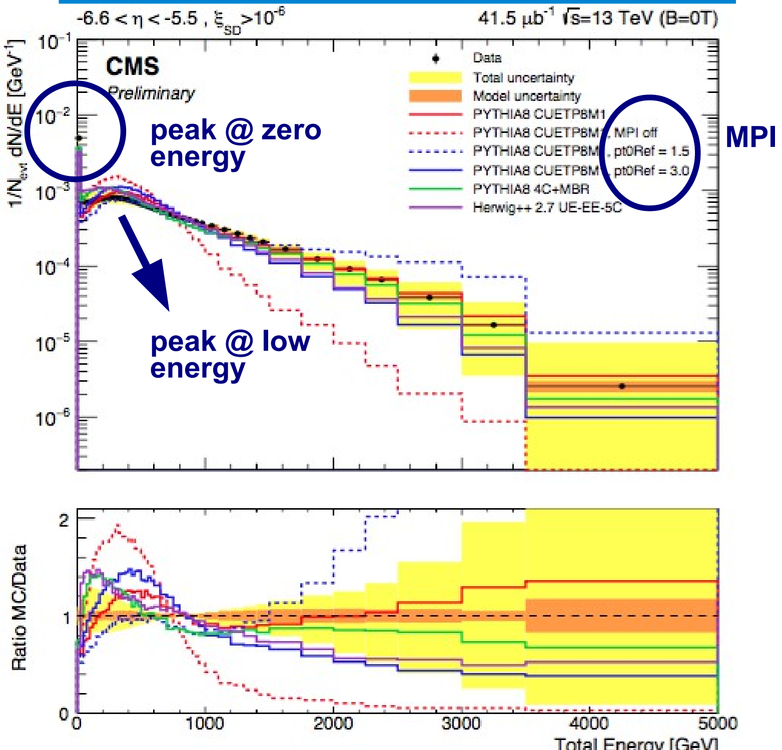
- Motivation:

  - Sensitive to changes in the hadronic interaction parameters such as multiplicity, elasticity or baryon production.

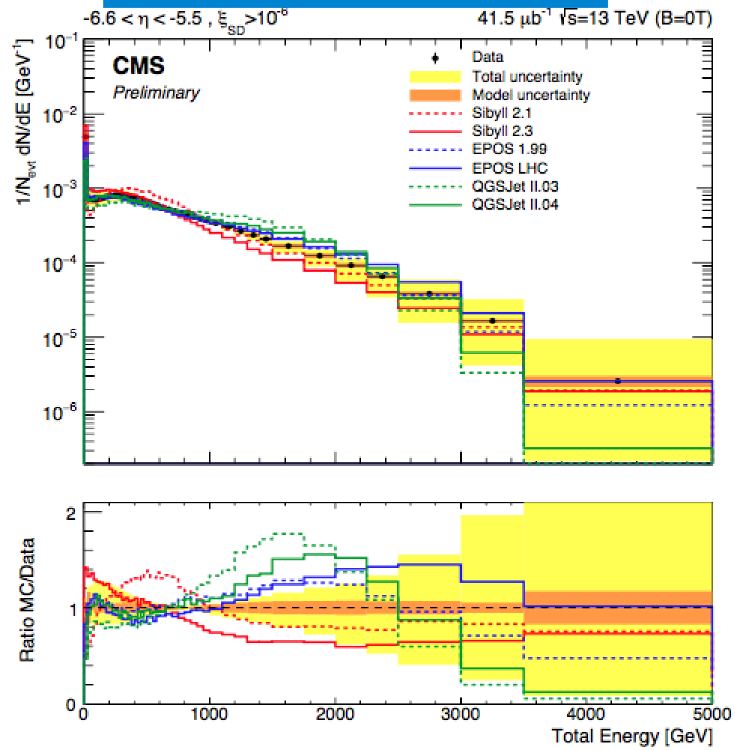
  - The effect is most visible in the structures < 1 TeV

- Analysis strategy:
  - Use low pile-up runs from 2015 with B = 0 T
  - Trigger on beam presence and bunch crossing
    - NSD-enhanced (double-arm)
    - Inclusive inelastic INEL (single arm)
- 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
PYTHIA and Herwig++ (Sensitivity to MPI and UE)



Total Energy Spectrum
Cosmic Ray models



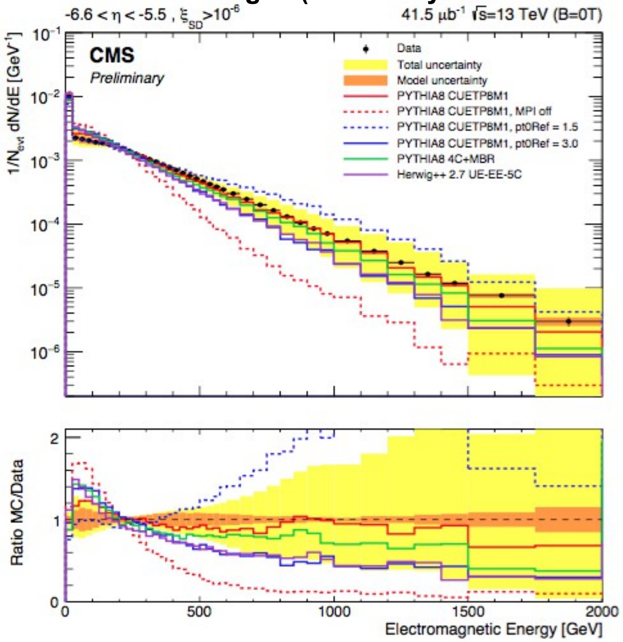
- Visibility of diffractive events as a peak at the lowest energies
- Hadronic component causes low energy peak
- Steep tail towards higher energies

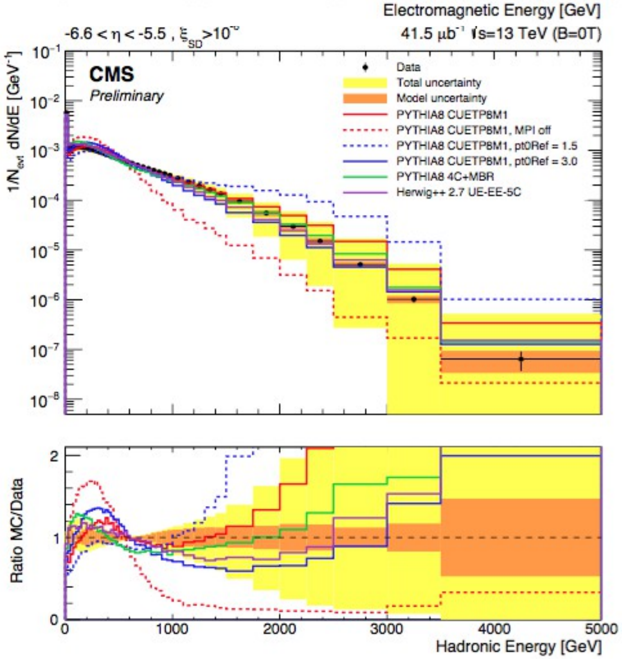
- Dominant unc. Source: CASTOR energy scale (17%)
- Sensitivity seen in data to MPI and UE.

Very forward energy spectra (cont'd)

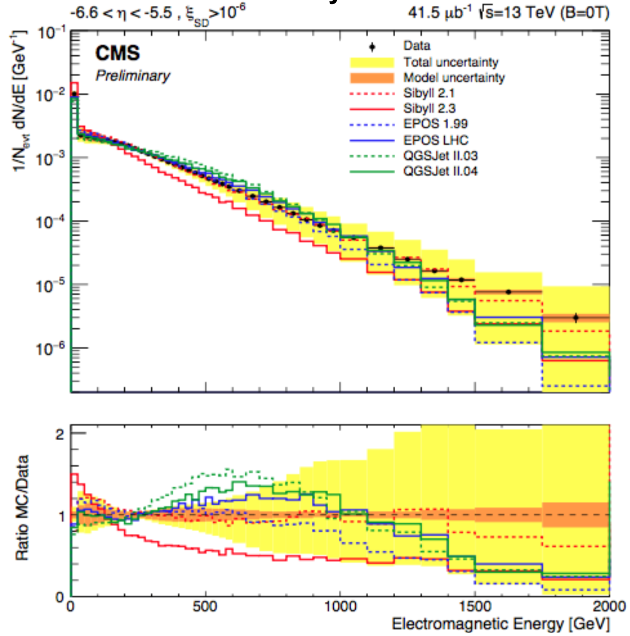
CMS PAS FSQ-16-002

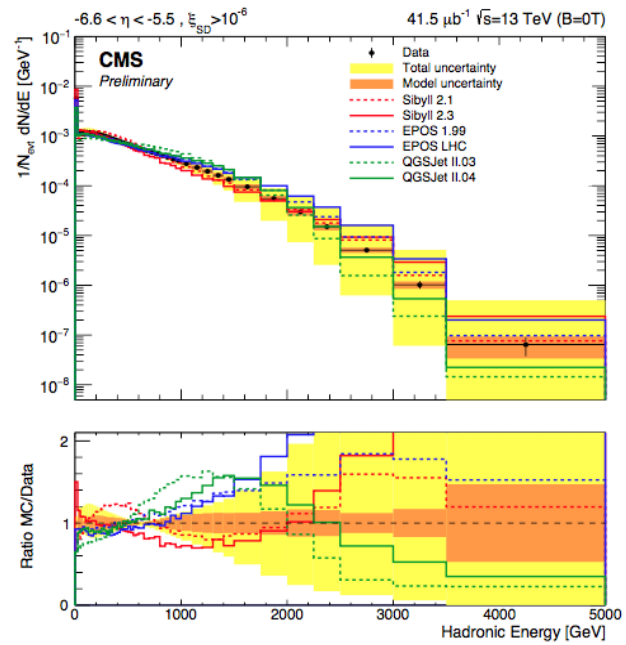
PYTHIA and Herwig++ (Sensitivity to MPI and UE)





Cosmic Ray models





EM spectrum

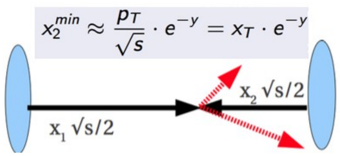
- Data well described by all models
  - except for PYTHIA8 4C+MBR and SIBYLL2.3 : slope in the soft part
- High sensitivity to MPI

Hadronic spectrum

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

Very forward inclusive jet cross section

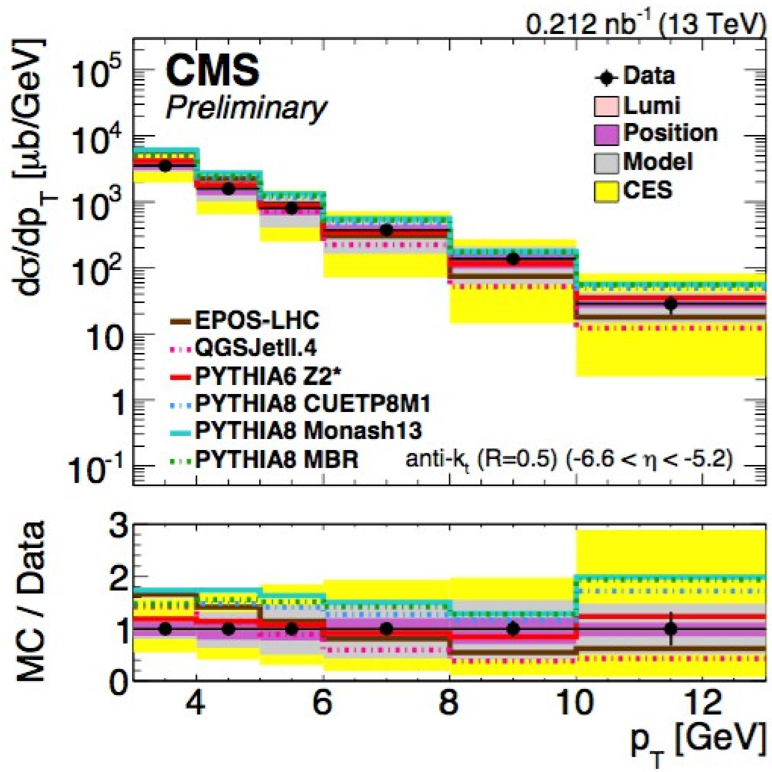
- Motivation:
  - Low x gluon density poorly known
  - Very forward jets allow to probe the low-x domain region sensitive to non-linear QCD effects
  - Constrain low-x gluon PDFs.



CMS PAS FSQ-16-003

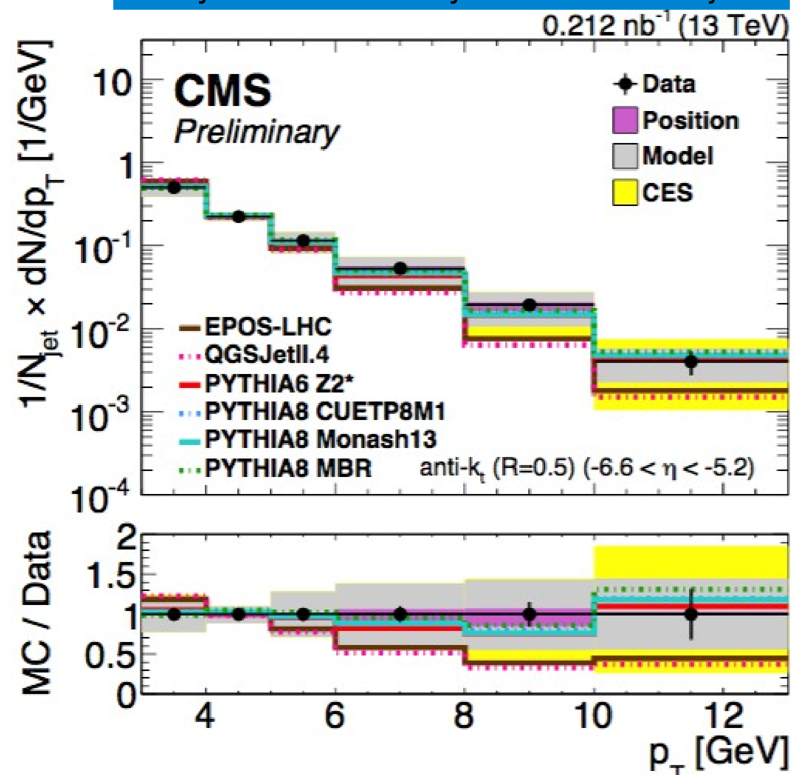
- Analysis strategy:
  - Use low pile-up runs from LHC Run 2 (2015)
  - Phase space definition:
    - E > 150 GeV or p_T > 3 GeV in $-6.6 < \eta < -5.2$
    - $p_{T,det} \rightarrow p_{T,hadron}$: Lorentz invariant but suffers from η
  - Convert E_{jet} to p_T by cosh(η)
- Observables: $d\sigma / dp_T$

Jet p_T spectrum: normalized by Luminosity



- Dominant unc. source: CASTOR energy scale (17%)
- All models show agreement with data within the unc.

Jet yield: normalized by number of visible jets



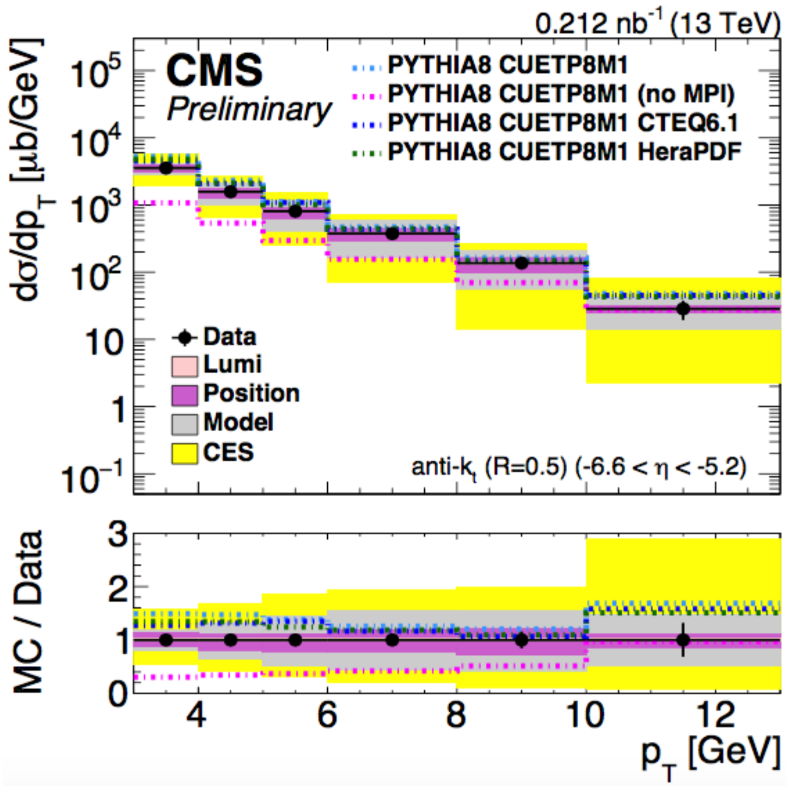
- Overestimation of data by PYTHIA tunes
- EPOS-LHC and QGSJet have tendency of decrease with increasing p_T

Very forward inclusive jet cross section (cont'd)

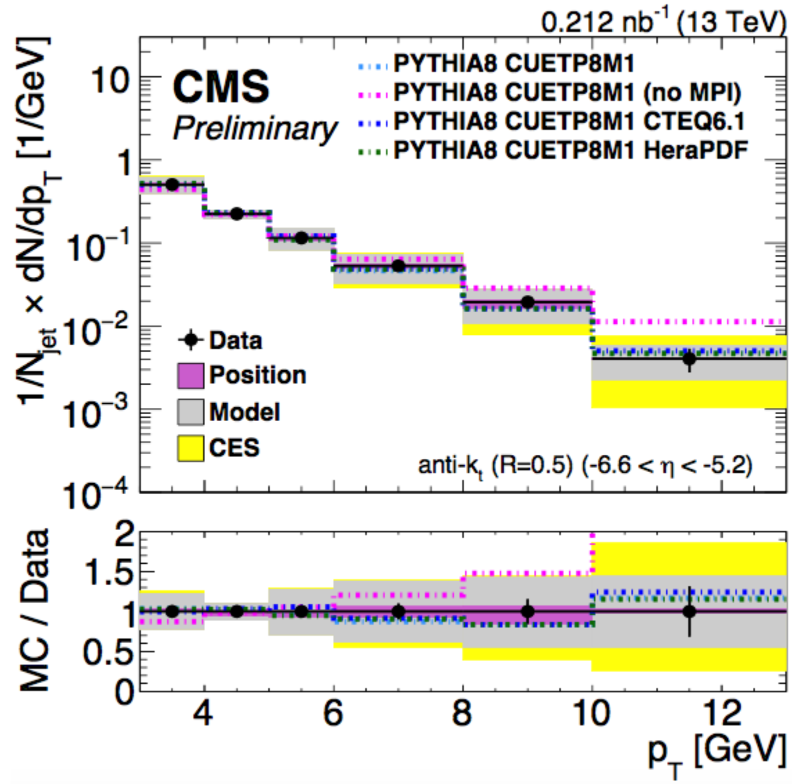
CMS PAS FSQ-16-003

- 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

Pseudorapidity spectra in different final states @ 13TeV

- Motivation:

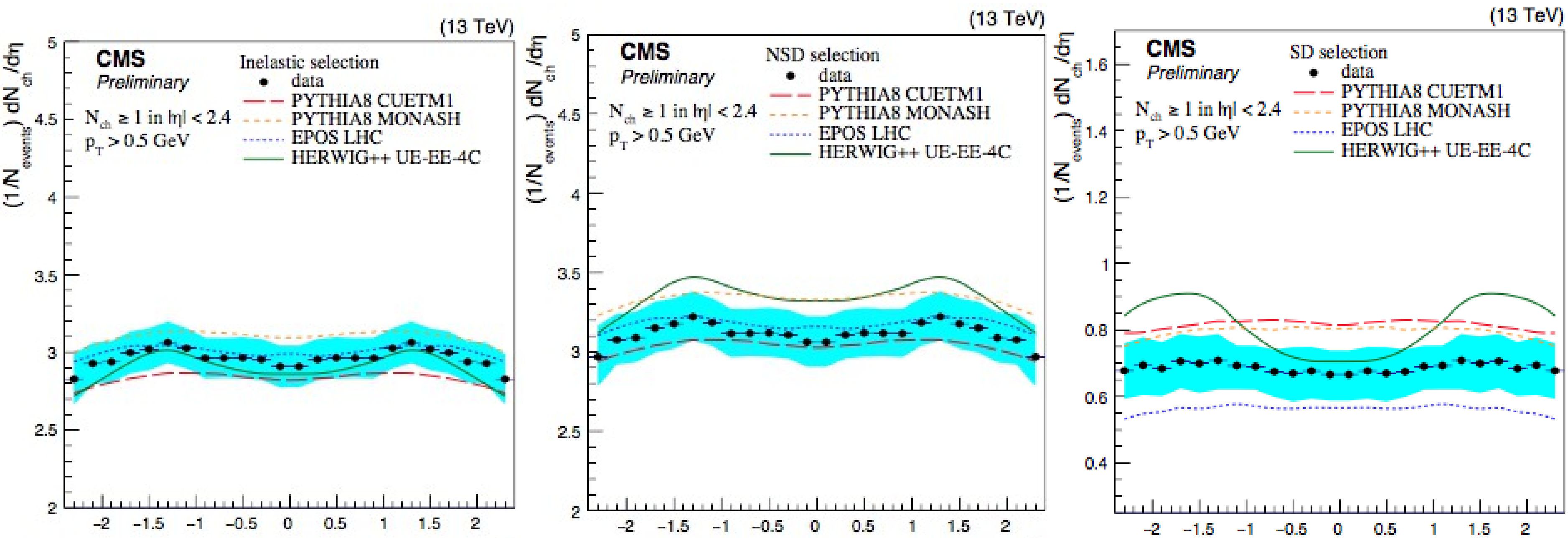
  - Study the different components of particle production
  - Constrain and tune the models
  - Study transition from perturbative to non-perturbative region
  - Measure average number of particles per pseudorapidity unit

CMS PAS FSQ-15-008

- Analysis strategy:
  - Trigger: both beams crossing at the IP

★	: at least 1 charged particle $p_T > 0.5$ GeV $|\eta| < 2.4$
Activity	: at least 1 particle with E > 5 GeV
Veto	: no particle with E > 5 GeV

- Inelastic enhanced : ★ + Activity in at least one Fwd. region
- NSD enhanced : ★ + Activity in both Fwd. Regions
- SD enhanced : ★ + Activity in one Fwd. Region and Veto in the other side



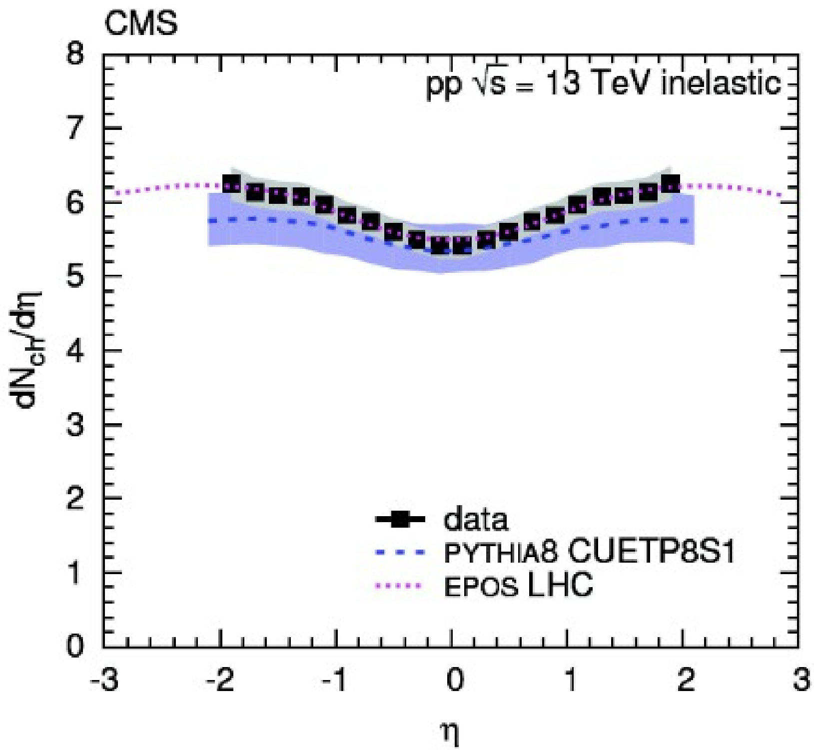
- PYTHIA8 CUETP8M1, EPOS LHC and HERWIG++ describe the inelastic enhanced selection.
- PYTHIA8 MBR with the tune CUETP8M1 give the best description of theNSD enhanced data

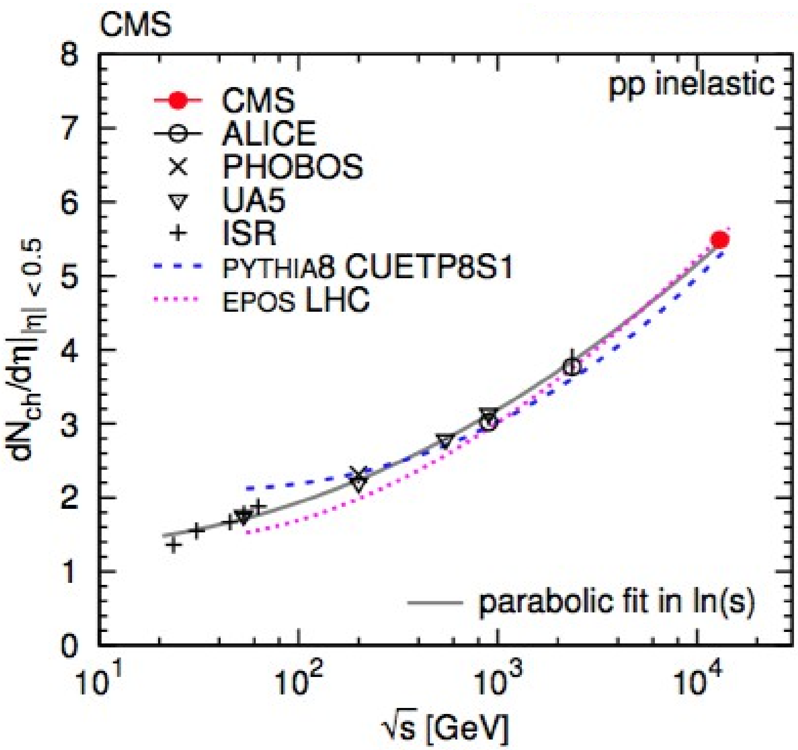
- Total systematic unc. shown as shaded bands around the data points
- EPOS LHC underestimate the SD enhanced data, while PYTHIA8 with the tunes Monash and CUETP8M1 over-estimate the measurements.

dN/dη of charged hadrons @ 13 TeV

Phys.Lett. B751 (2015) 143

- First LHC paper at 13 TeV
- Low pileup 2015 data
- CMS magnet off, B=0 (straight tracks)





- Pseudorapidity density distributions of charged hadrons in the region |η| < 2 for inelastic pp collisions
- Charged hadron multiplicity at midrapidity: 5.49 ± 0.01 (stat.) ± 0.17 (syst.)

- Center-of-mass energy dependence
- PYTHIA8 and EPOS globally reproduce collision-energy dependence of hadron production in inelastic pp collisions. However,
  - EPOS is better than PYTHIA8

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
- CMS collected data with high efficiency during 2015 at 13 TeV center of mass energy
- Ranging from low p_T to high p_T and from inclusive to exclusive observables
- Still more measurements and efforts on-going so new and exciting results are expected soon!

Thank you for your attention!

BACKUP

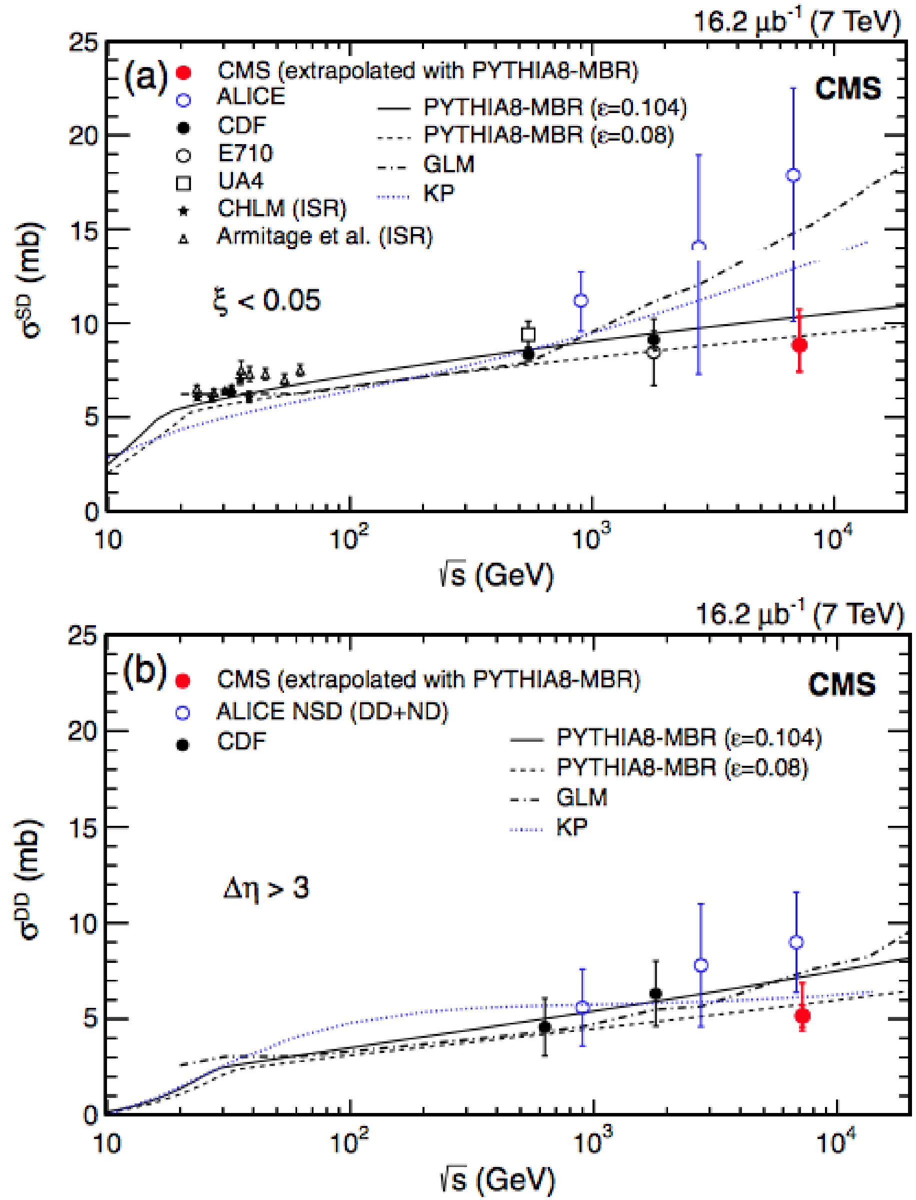
Soft diffraction cross sections @ 7 TeV

PRD 92, 012003

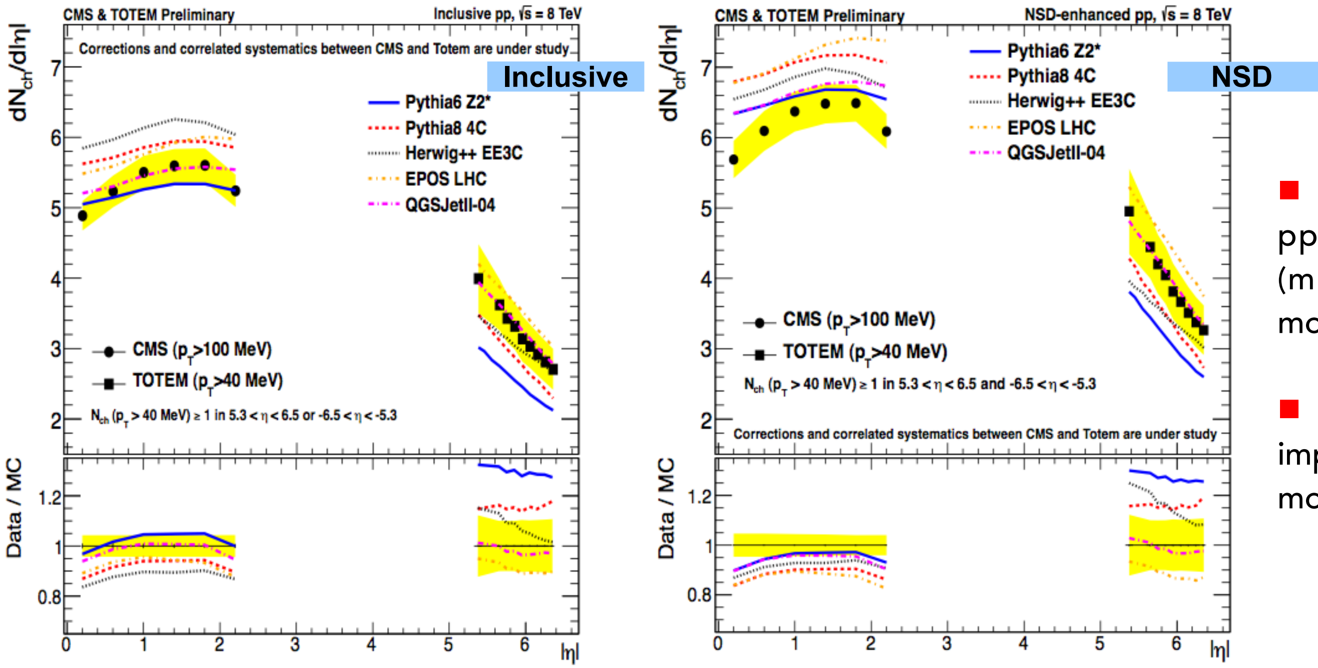
- Diffractive dissociation cross sections in kinematic regions defined by the masses of M_X and M_Y of the two final-state hadronic systems separated by the largest rapidity gap in the event

$$\xi_X = \frac{M_X^2}{s}$$

- Measurements extrapolated to total single (SD, top) and double (DD, bottom) diffractive cross sections:
  - PYTHIA 8 MBR (0.08, 0.104) describes the data well.
  - CMS result is consistent with a SD cross section weakly rising with energy.
  - the data are consistent with a weakly rising cross section with energy, as predicted by the models.



Hadron production in pp @ 8 TeV

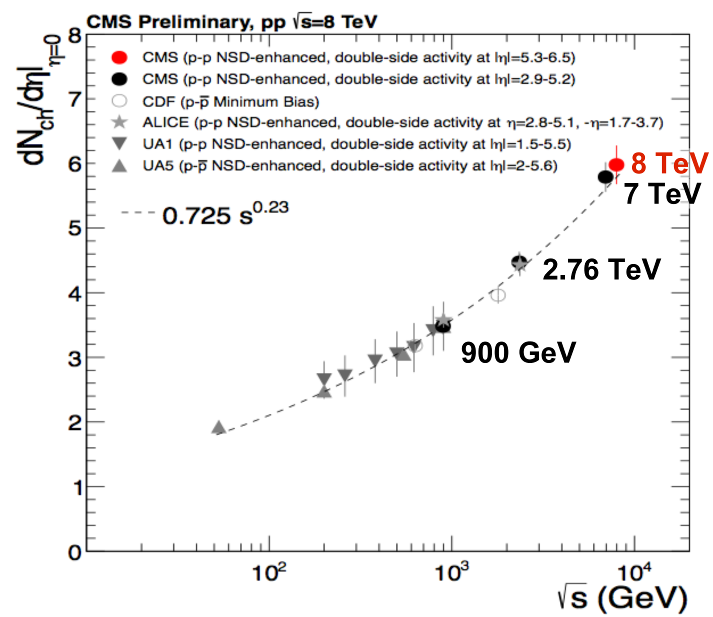


CMS PAS-FSQ-12-026

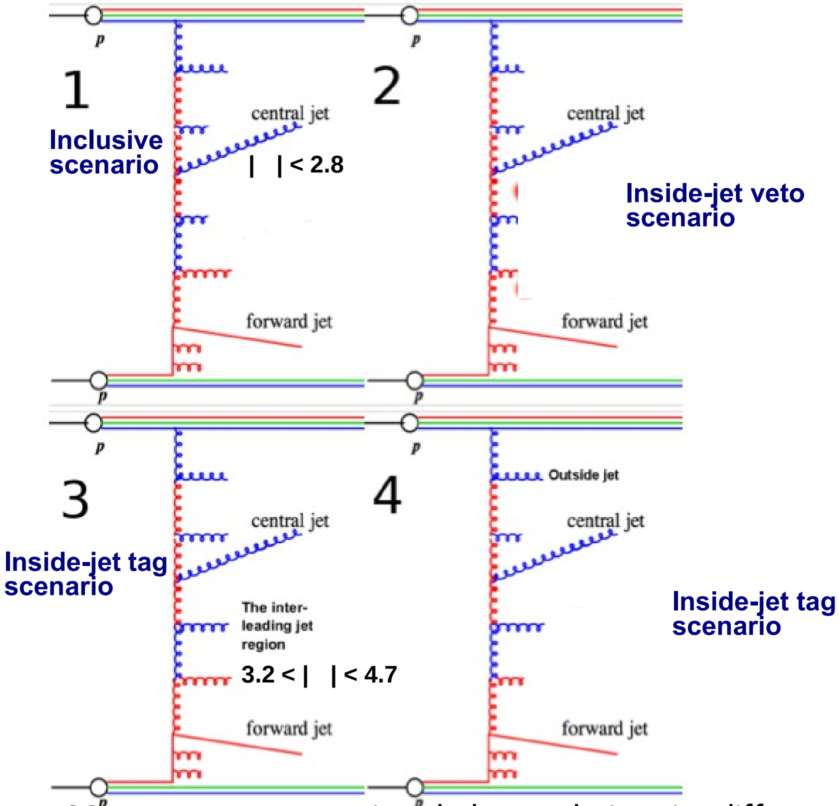
Eur. Phys. J. C 74 (2014) 3053

- Most of the particles produced in pp collisions arise from semi-hard (multi)parton scatterings which are modeled phenomenologically.
- Experimental results provide important input for tuning various MC models and event generators.

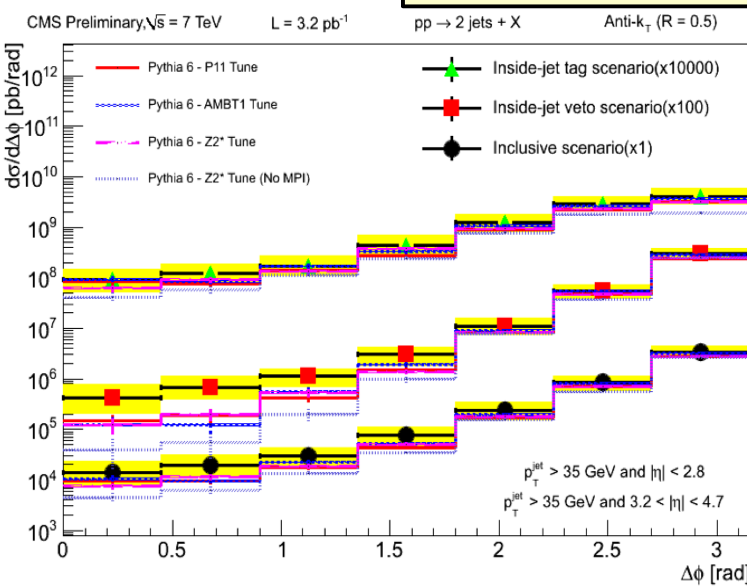
- viiidistributions are measured for different event topologies: either inclusive or dominated by non-single diffractive dissociation (NSD), for charged particles with $p_T > 0.1$ GeV and $p_T > 1$ GeV
- Results: based on different requirements,
  - dominated by different types of collisions
  - focus on the primary charged-particle multiplicity density (dN_{ch}/dvi)ji and the highest-p_T leading track in lvili< 2.4.
- Inclusive setup: poor description by Pythia6 (>30% off @ lvili> 5.2)
- NSD setup:
  - the power-like centre-of-mass energy dependence indicated by previous NSD measurements at different energies
  - generators do not describe the data

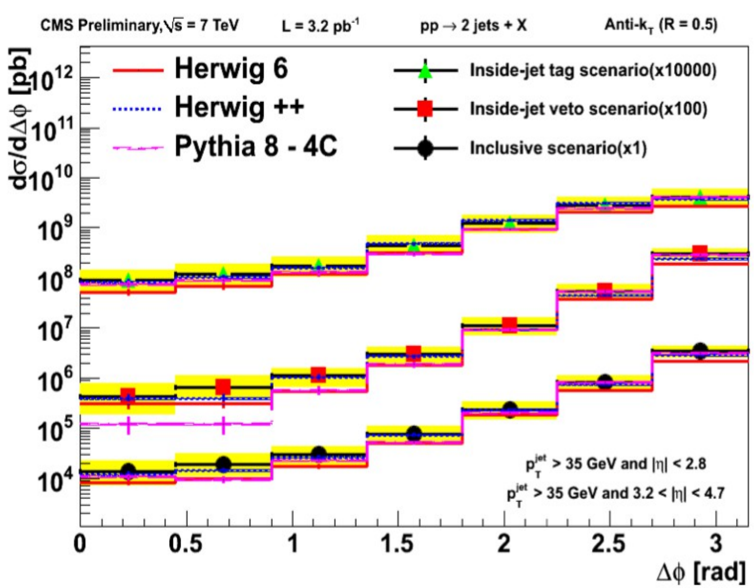


Forward-central jet correlations @ 7 TeV



CMS PAS-FSQ-12-008





- 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++

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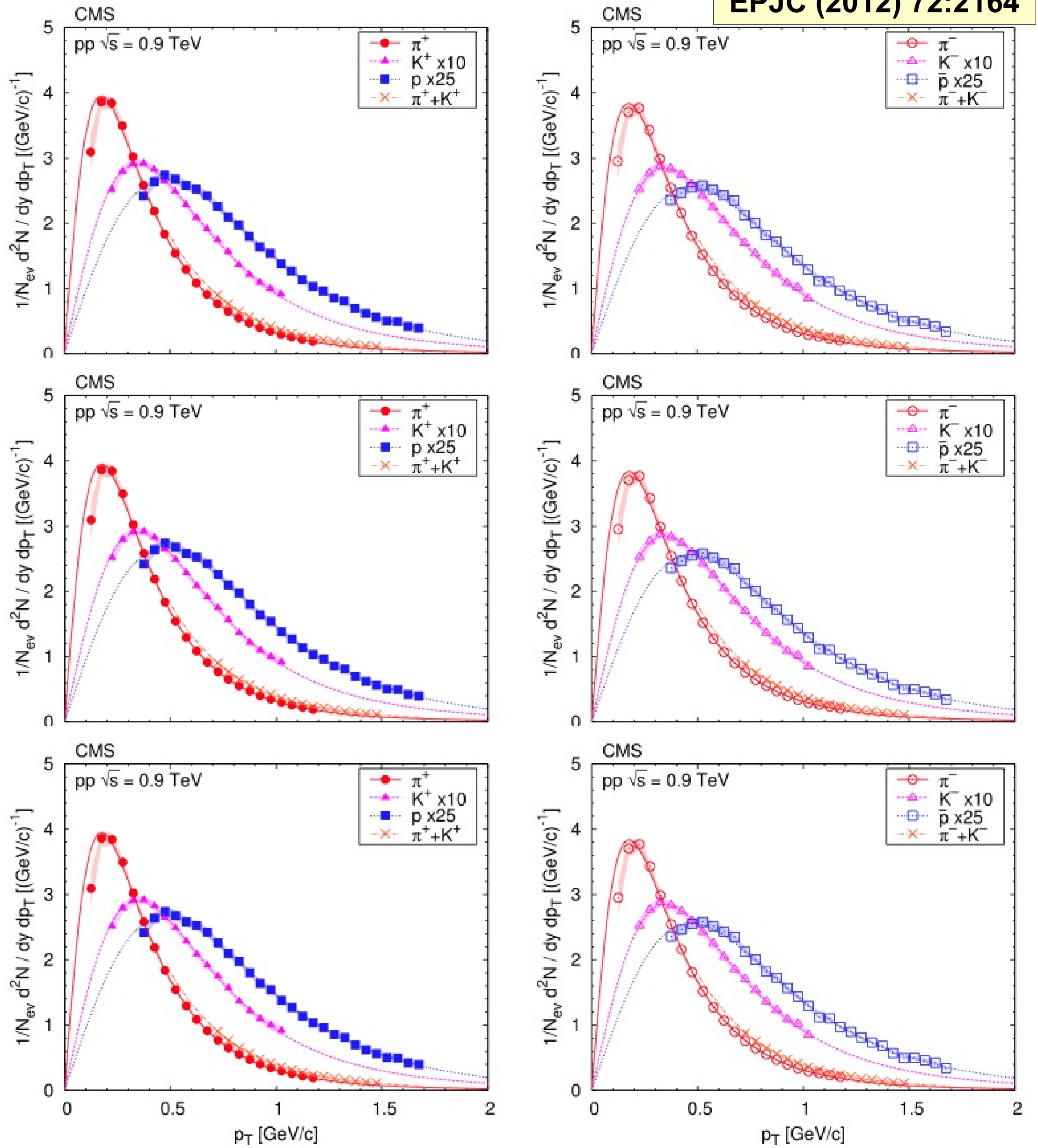
Hadron spectra

– Long history in high energy particle, nuclear and cosmic ray physics
– One of the simplest and most relevant physics quantities
– Scaling properties of particle production; predictions of models and generators



– Particle production at LHC energies is strongly correlated with event multiplicity rather than with the center-of-mass energy of the collision
– Common underlying physics mechanism:
– At TeV energies, the characteristics of particle production are constrained by the amount of initial parton energy that is available in any given collision