Impact of LHC data on ultra-high energy cosmic-ray physics

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Outline

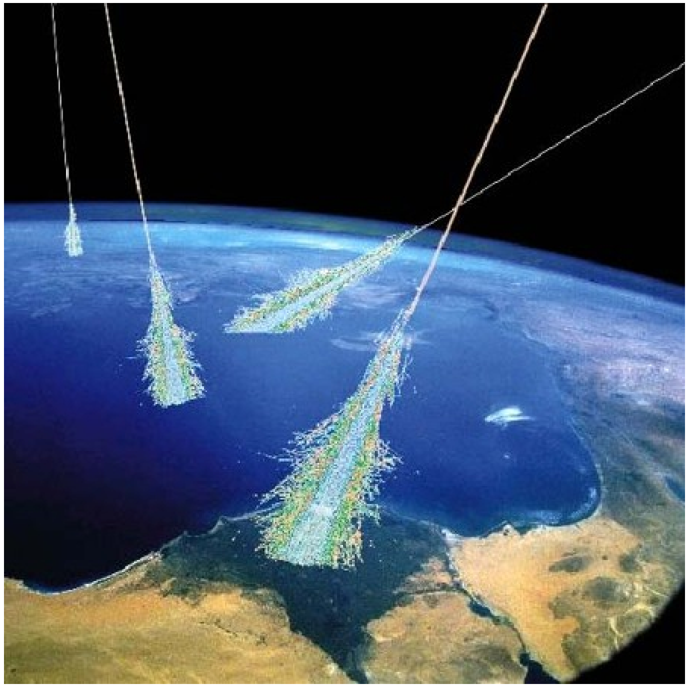
- Introduction to CR physics
- Overview of LHC experiments
- Recent measurements from CMS
- Summary

Introduction: Cosmic-Rays (CR)

- CR are particles reaching the Earth atmosphere from the outer space.

- In astroparticle physics, the identification and understanding of the sources of high-energy CR is one of the most important open problems.

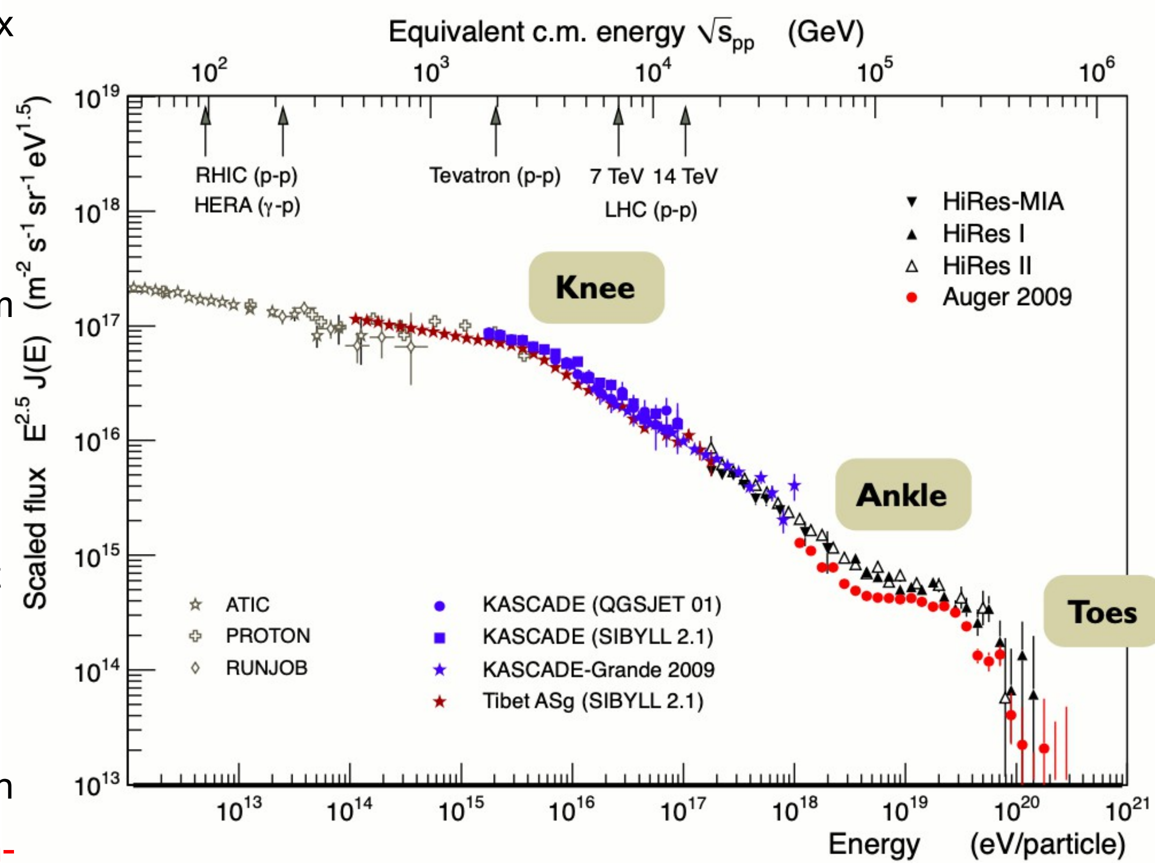
- One of the main goals of the CR experiments is the study of the energy and composition of the primary CR



Introduction: Cosmic-Rays (CR)

- A compilation of recent flux measurements of CR is shown in Fig.
- CR flux falls very rapidly with energy (power-law: E^{-n}):

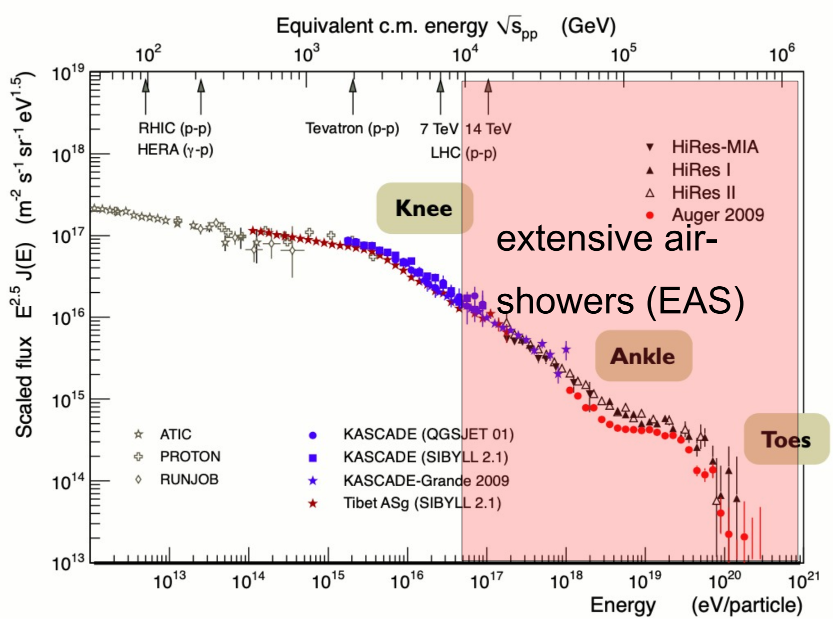
- The power law of the energy spectrum of CR changes at about 10^{15} eV (***Knee***)
- The ***ankle*** in the energy spectrum at Ѓ 10^{18} eV is often assumed to be the imprint of the change from galactic to extragalactic sources
- The suppression of the flux at ultra-high energies could be due to Greisen-Zatsepin-Kuzmin GZK-energy loss effect or to the fact that the sources have reached their maximum energy or both.



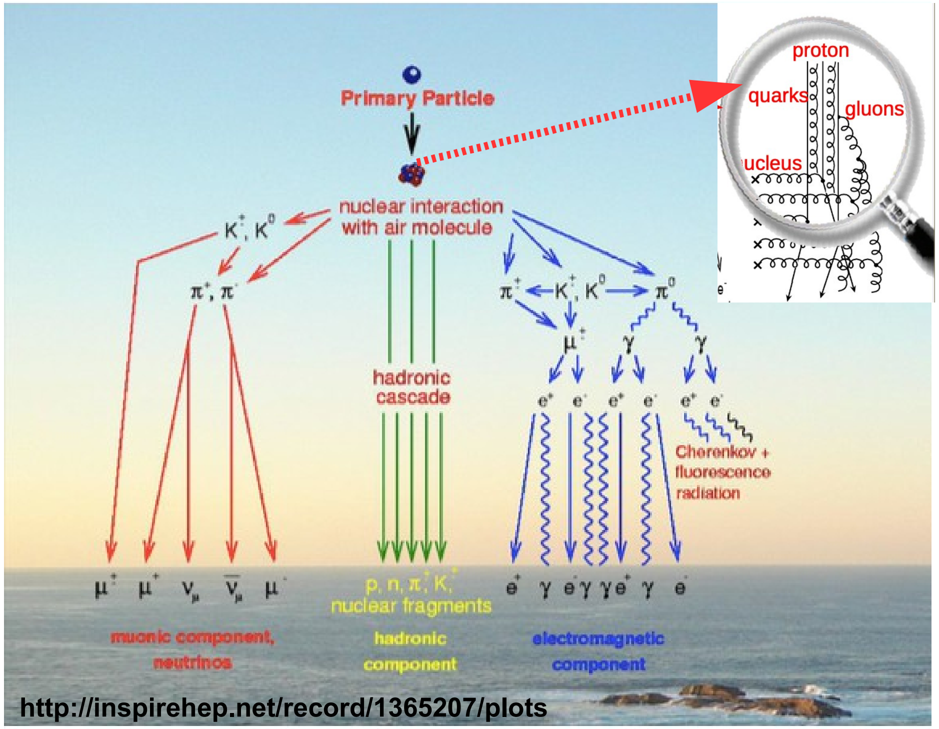
- CR observed up to energies $E \sim 10^{20}$eV (GZK-cutoff)

Energy Spectrum of CR and colliders

- CR can be measured only indirectly above an energy of 10^{14} eV through the cascades of secondary particles, called extensive air-showers (EAS), that they produce in the atmosphere

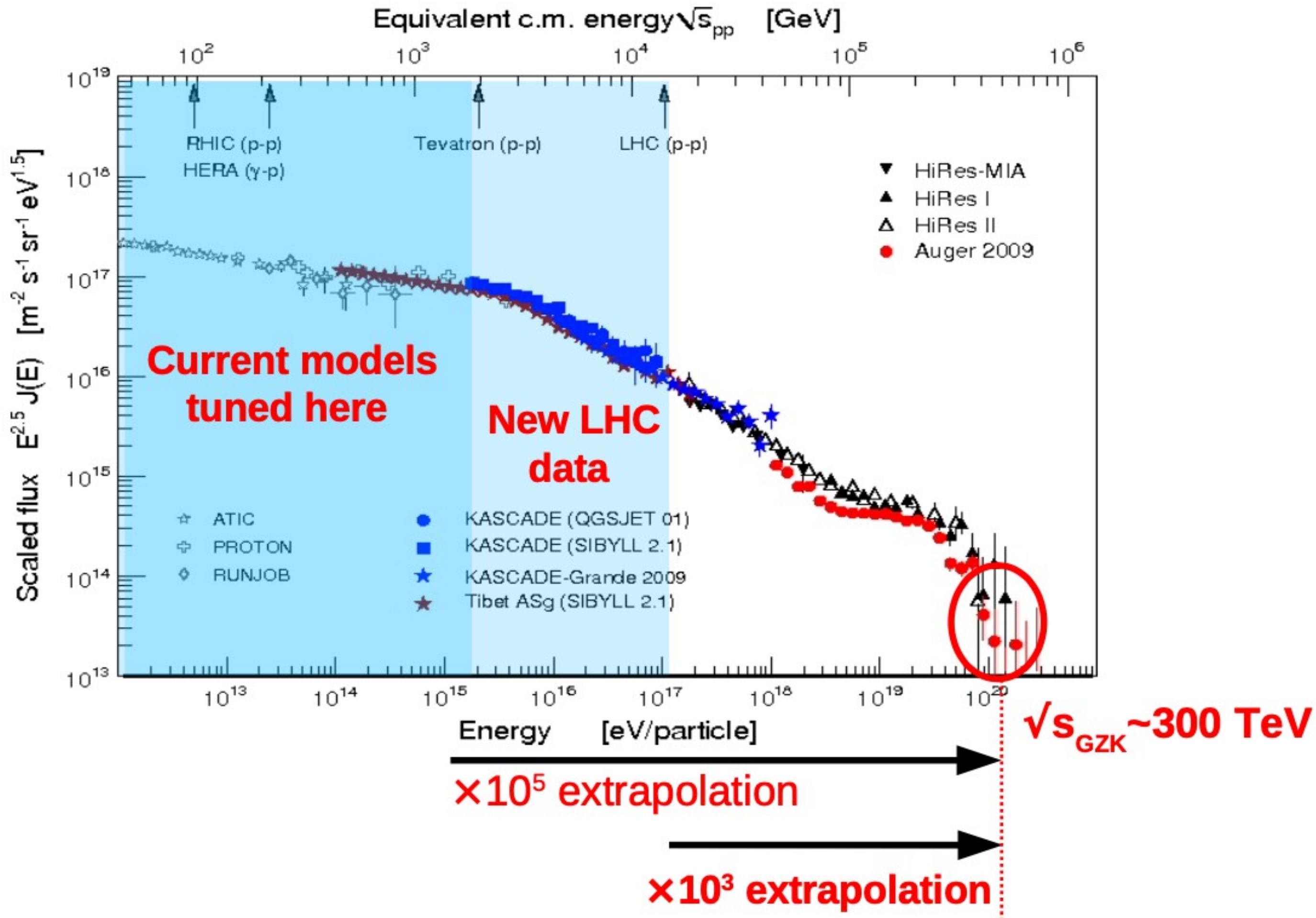


- Only by simulating the generation of EAS and comparing the predictions with measurements one can draw conclusions on the primary mass composition of the arriving particles
- CR energy & mass determined via hadronic+transport Monte Carlos:
- MCs tuned with **data obtained from accelerators**.



http://inspirehep.net/record/1365207/plots

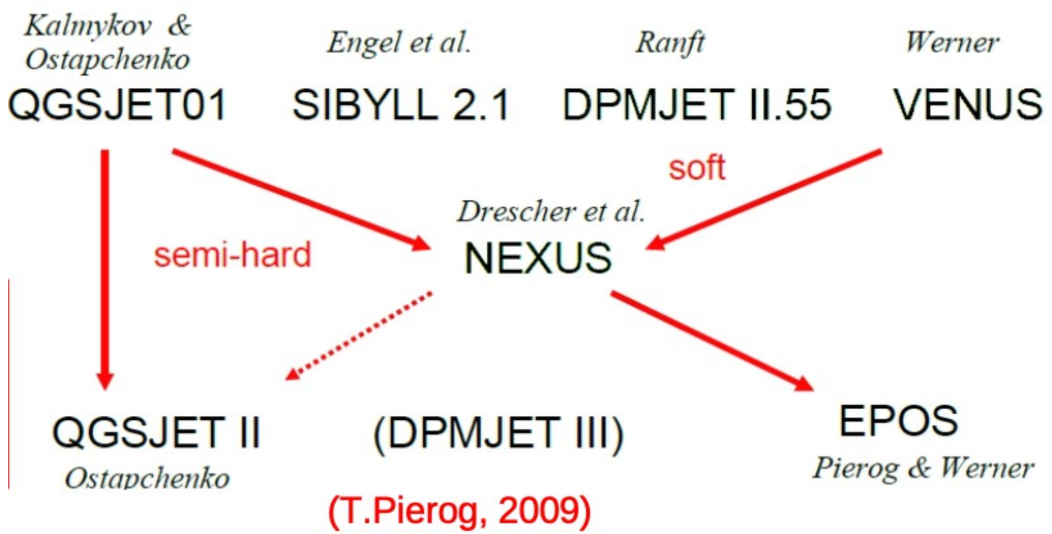
Tuning of hadronic MC models with collider data



- The LHC at the CERN laboratory allows us to access for the first time the energy region above the knee in the laboratory.
- Therefore an analysis of inclusive particle data taken at the LHC is particularly interesting for constraining existing hadronic interaction models and for testing possible new mechanisms of hadron production
- The LHC data can provide a significant constrain for hadronic MCs for UHCR

Hadronic interaction models @ high energy

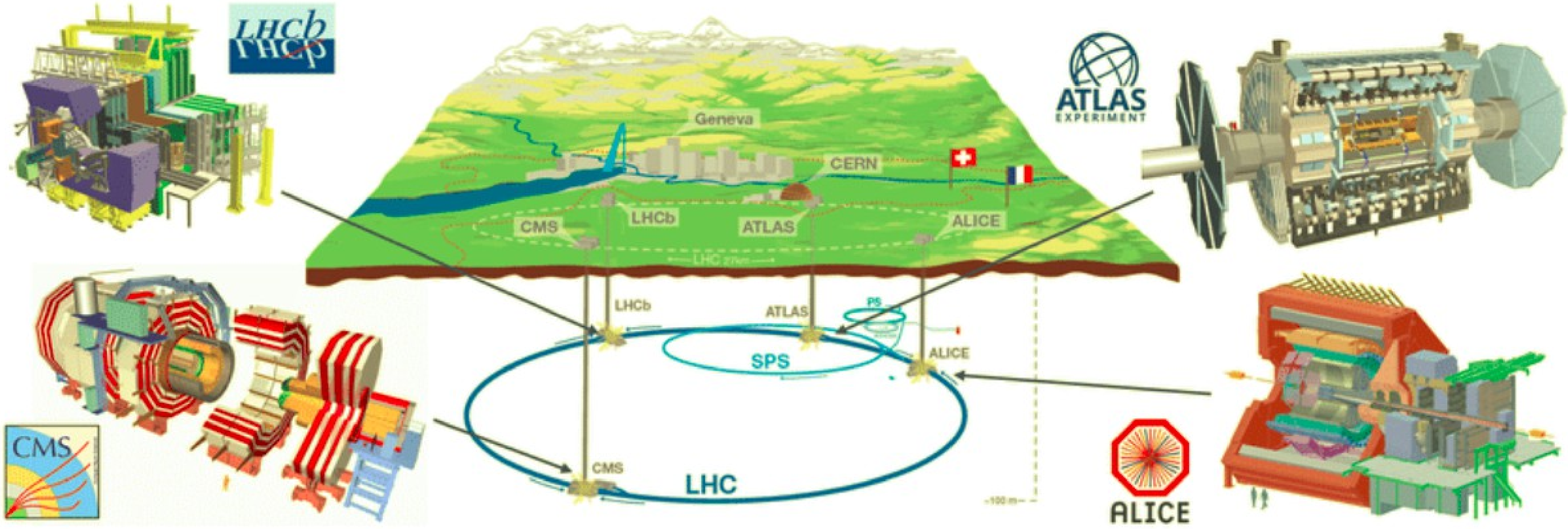
- Calculating predictions for the bulk of produced particles in hadronic interactions is not possible yet within first- principles QCD.
- One has to resort to phenomenological models that combine fundamental principles of QFT – such as unitarity, analyticity and crossing – together with perturbative QCD predictions including phenomenological fits (e.g. accounting for the parton-to-hadron fragmentation) to experimental hadron spectra.
- General-purpose hadronic interaction models used in HEP, such as **PYTHIA, HERWIG and SHERPA**, are developed to learn and interpret the data measured in accelerator experiments with an emphasis on hard-scattering measurements (signals and backgrounds) rather than on the bulk of hadron production at lower p_T.
- In contrast, interaction models commonly used in cosmic-ray physics such as **QGSJET01, QGSJETII and SIBYLL,** are supposed to predict hadronic interactions as realistically as possible with the emphasis on reproducing existing accelerator measurements and providing a reasonable extrapolation to higher energy and to phase-space regions where no data are available.
- In between these two generic categories there are models such as **PHOJET/DPMJET and EPOS,** which are designed to be more universal and approach the sophistication of HEP models regarding some aspects of hard processes.



Large Hadron Collider (LHC) @ CERN

- LHC is the world's largest and most powerful particle accelerator.

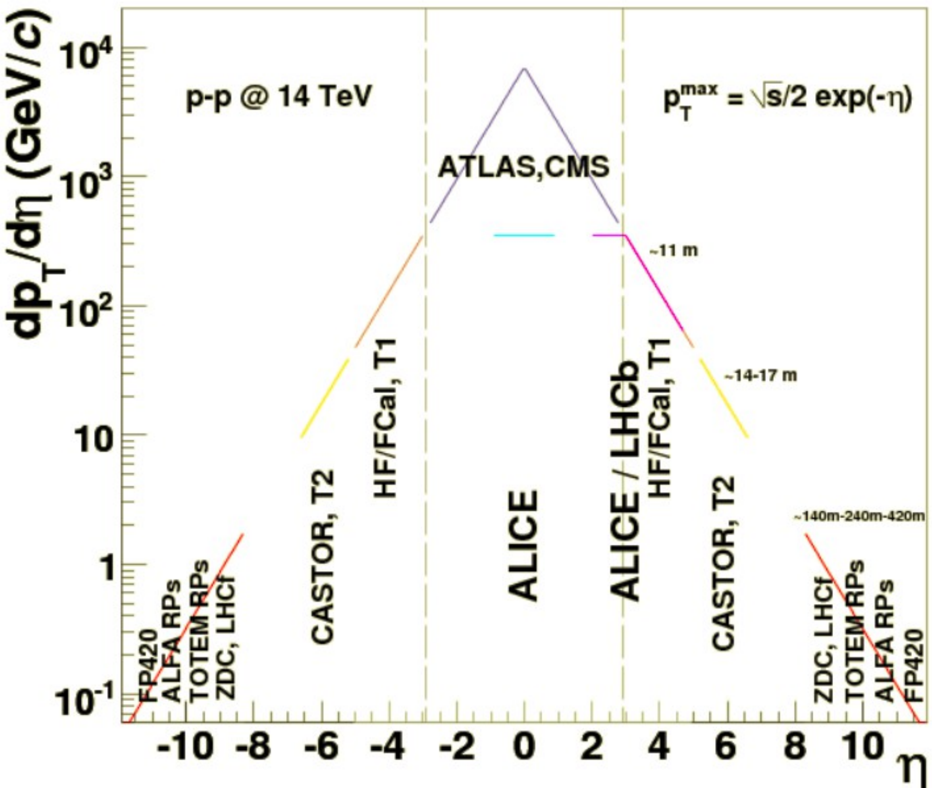
- It consists of a 27-km ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way.



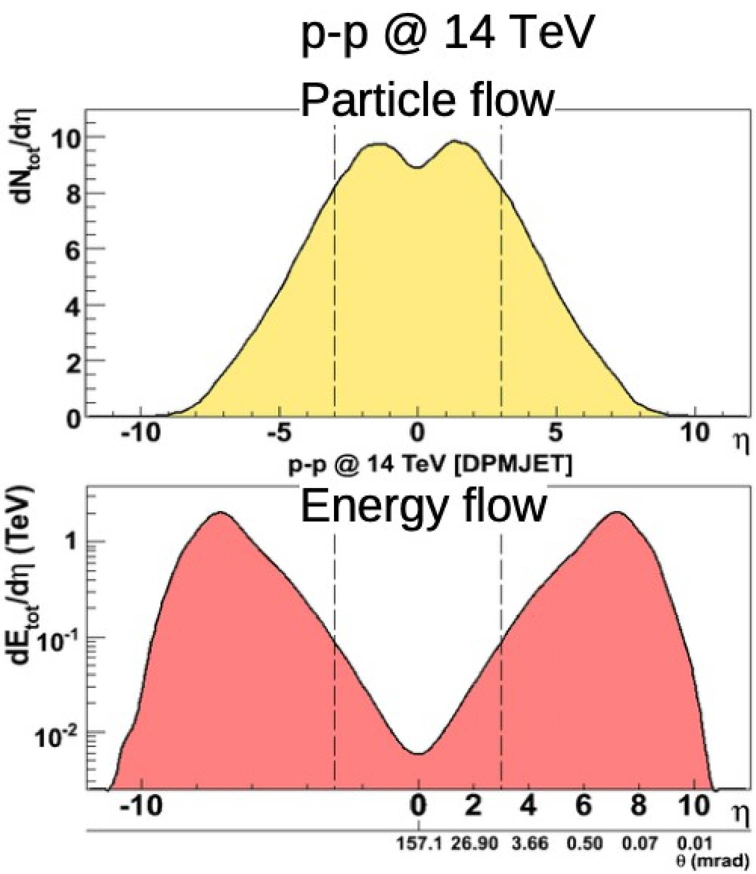
Acceptance of LHC experiments

- The number of particles in an air-shower is roughly proportional to the energy of the primary particle, the most energetic outgoing particles of an interaction, emitted in **the very forward region of a collider experiment,** are the most important ones for understanding air-showers

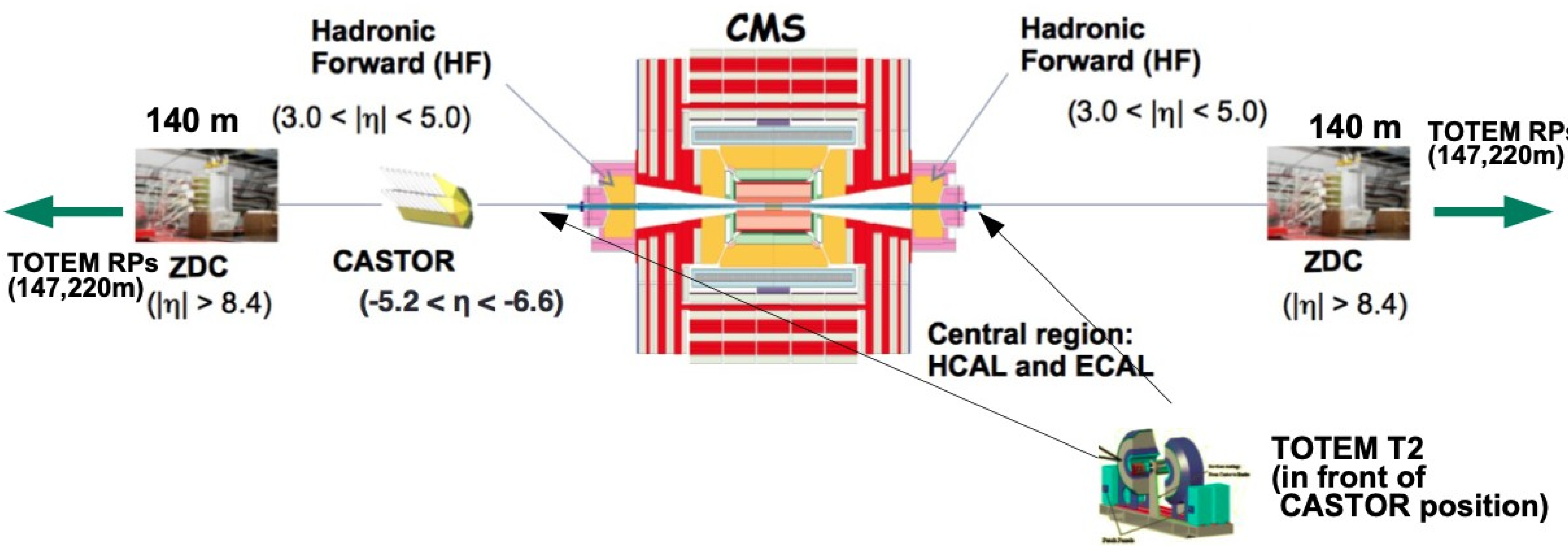
p_T and η acceptance



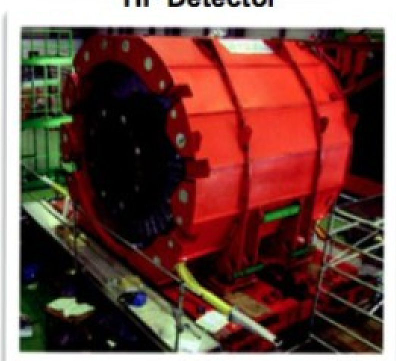
d'Enterria, David - arXiv:0911.1273



Forward detectors @ 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

Charged particle density

- **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

- **Analysis strategy:**

  - Trigger: both beams crossing at the IP

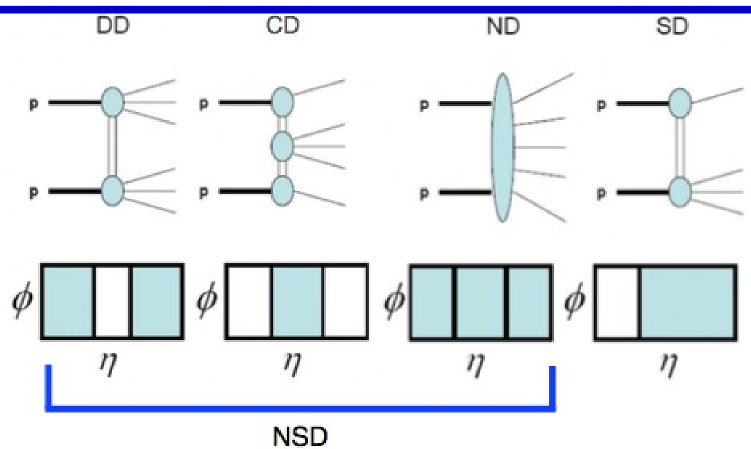
★ :at least 1 charged particle $p_T > 0.5$ GeV $|\eta| < 2.4$

Activity : at least 1 particle with E > 5 GeV

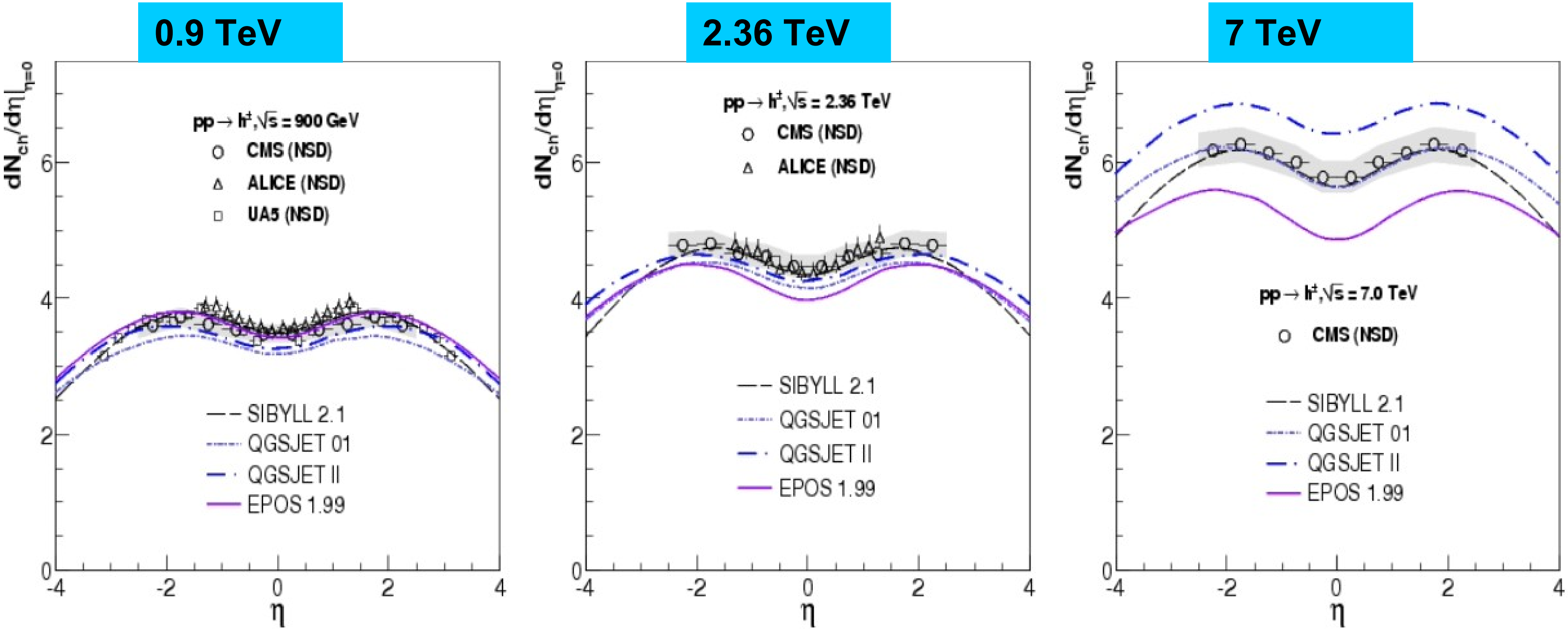
Veto : no particle with E > 5 GeV

- **Four different event selections based on activity in forward region**

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



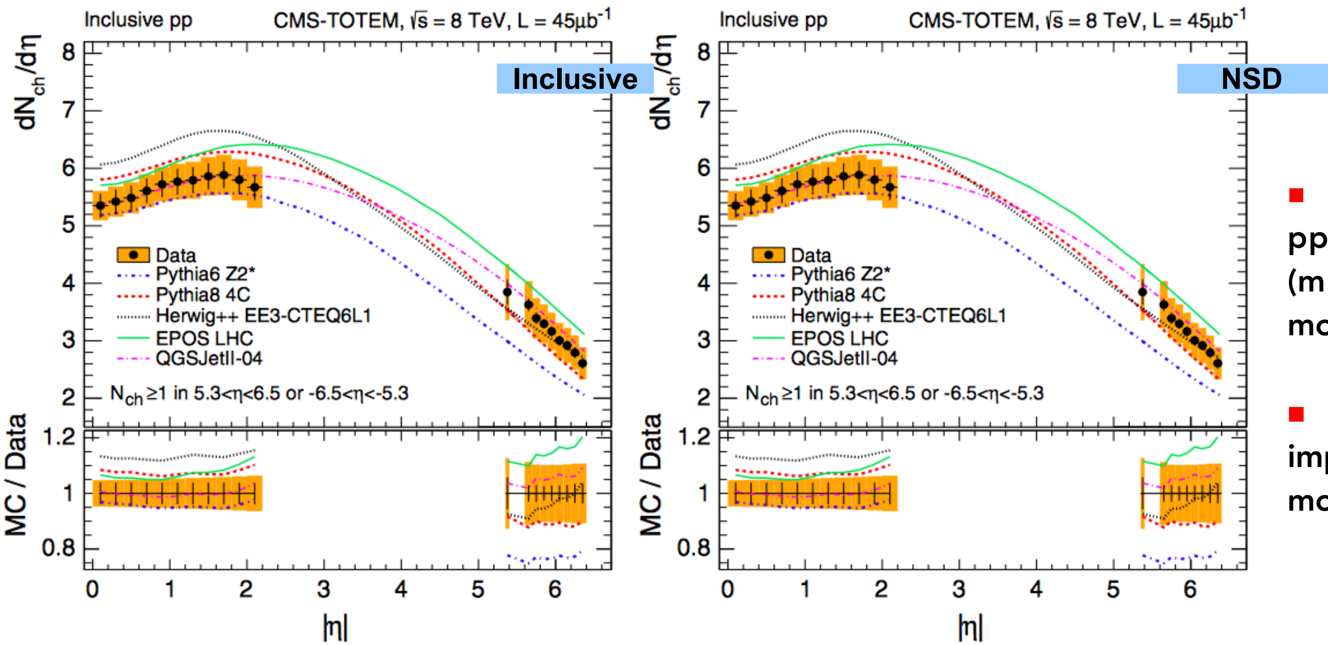
Charged particle density



D.d'Enterria, R. Engel, T. Pierog, S. Ostapchenko, K. Werner [https://doi.org/10.1016/j.astropartphys.2011.05.002]

- Comparison of 0.9, 2.36, and 7 TeV charged-hadron data to CR MCs:
  - Particle multiplicity not completely well predicted at 7.0 TeV:
  - "Simplest" models: QGSJET-01, SIBYLL 2.1 better than more complete ones

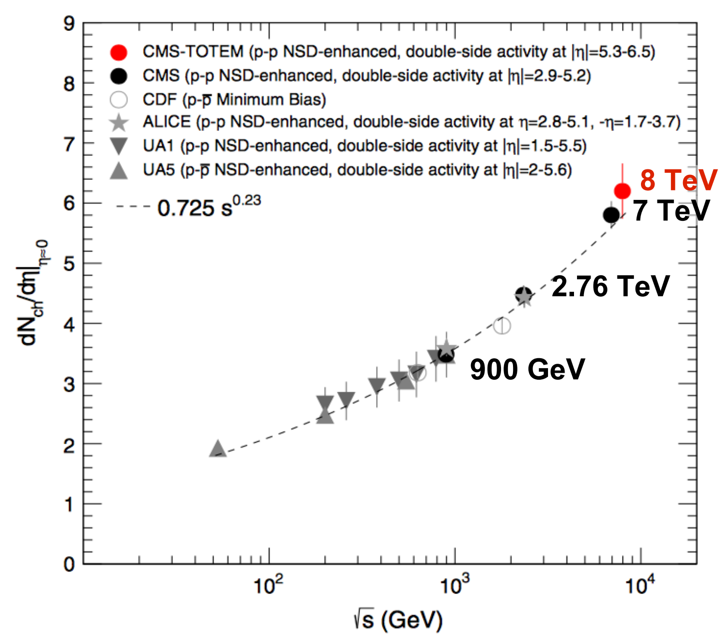
Hadron production in pp @ 8 TeV



EPJ 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.

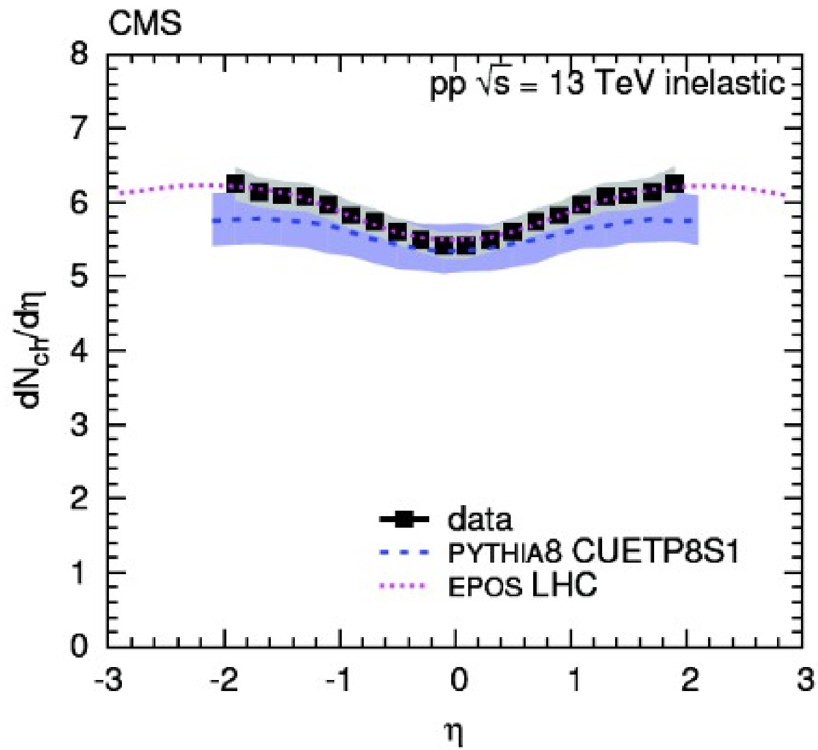
- η distributions are measured for different event topologies: either inclusive or dominated by non-single diffractive dissociation (NSD), for charged particles with $p_T > 0.1$ GeV and $p_T > 1$ GeV
- Results: based on different requirements,
  - dominated by different types of collisions
  - focus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

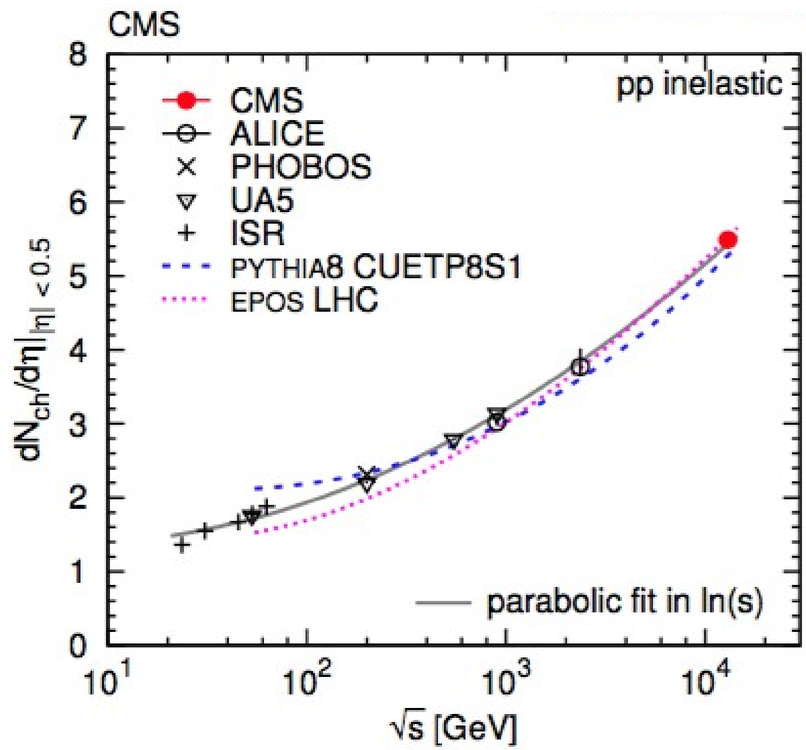


Charged hadrons @ 13 TeV

Phys.Lett. B751 (2015) 143-163

- First LHC paper at 13 TeV
- Datasets:
  - data taken June 7, 2015
  - number of collisions per bunch crossing: ~0.05
  - CMS tracker and pixel detectors ON
  - CMS magnet off, B=0 (straight tracks)





- Pseudorapidity density distributions of charged hadrons in the region $|\eta| < 2$ 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

Energy density measurement @ 13 TeV

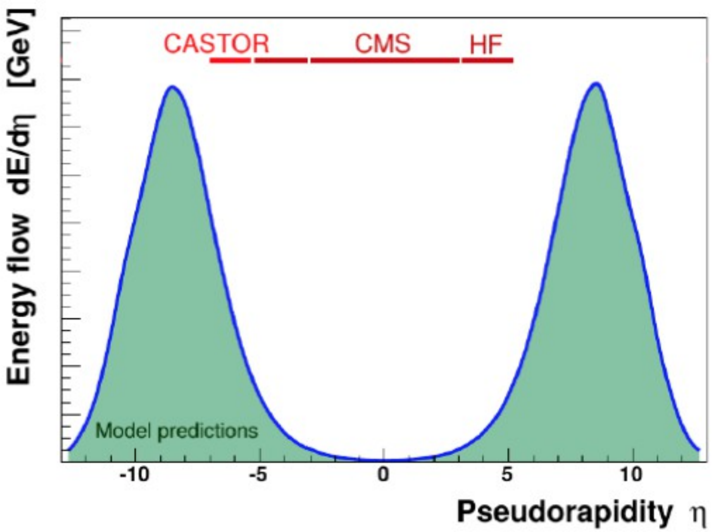
Eur. Phys. J. C 79 (2019) 391

- **Motivation:**
  - useful input to the tuning of hadronic interaction models
  - better understanding of QCD dynamics
  - measure the energy density in pp collisions @ √s = 13 TeV

- **Observables:**
  - dE / dη (sum of particle energies in each η bin)
  - The average energy density per collision is defined as

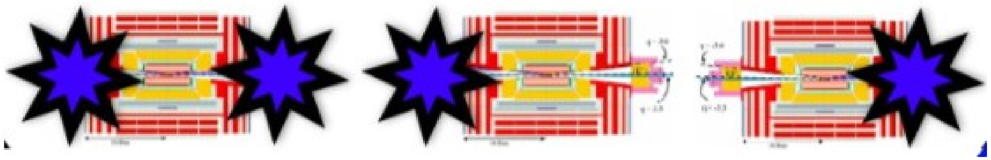
$$\frac{dE}{d\eta} = \frac{1}{N_{coll}} \sum_i E_i \frac{c(\eta)}{\Delta\eta}$$

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

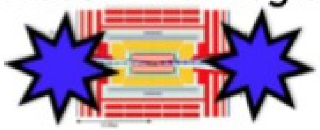


- Different event categories based on activity in forward region

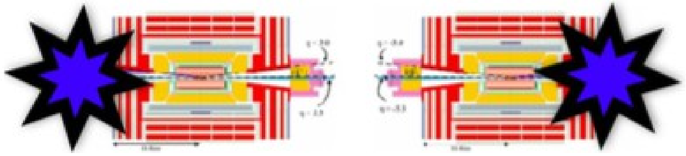
- Inelastic: Activity in at least one Fwd. Region



- NonSingle Diffractive (NSD) enhanced : Activity in both Fwd. Regions



- **Single Diffractive (SD) enhanced: Activity in one Fwd. Region and Veto in the other side**



Energy density measurement @ 13 TeV (II)

- EPOS-LHC and QGSJetII show agreement with the data within the uncertainties over the whole |η| range.

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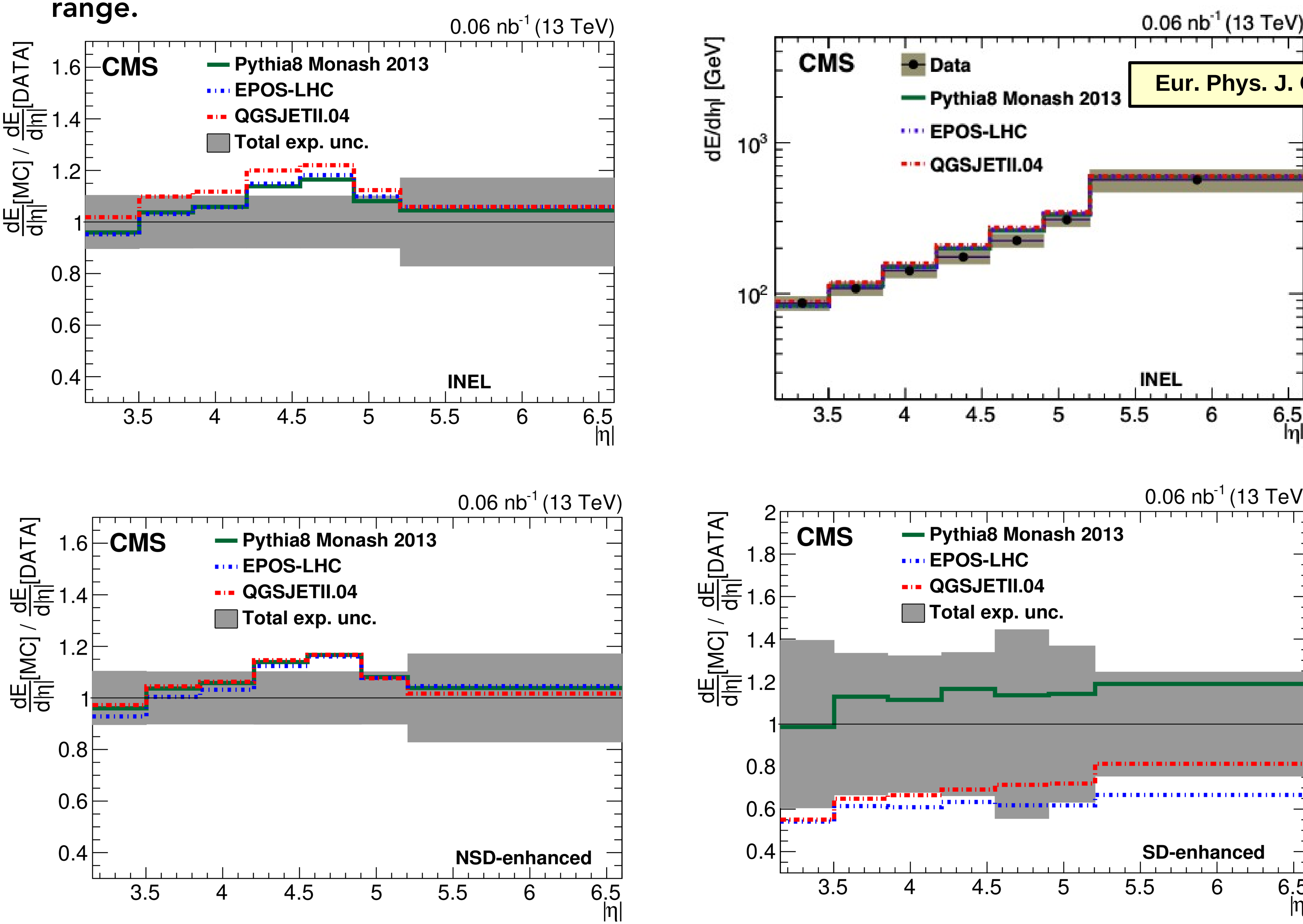

Energy density measurement @ 13 TeV (III)

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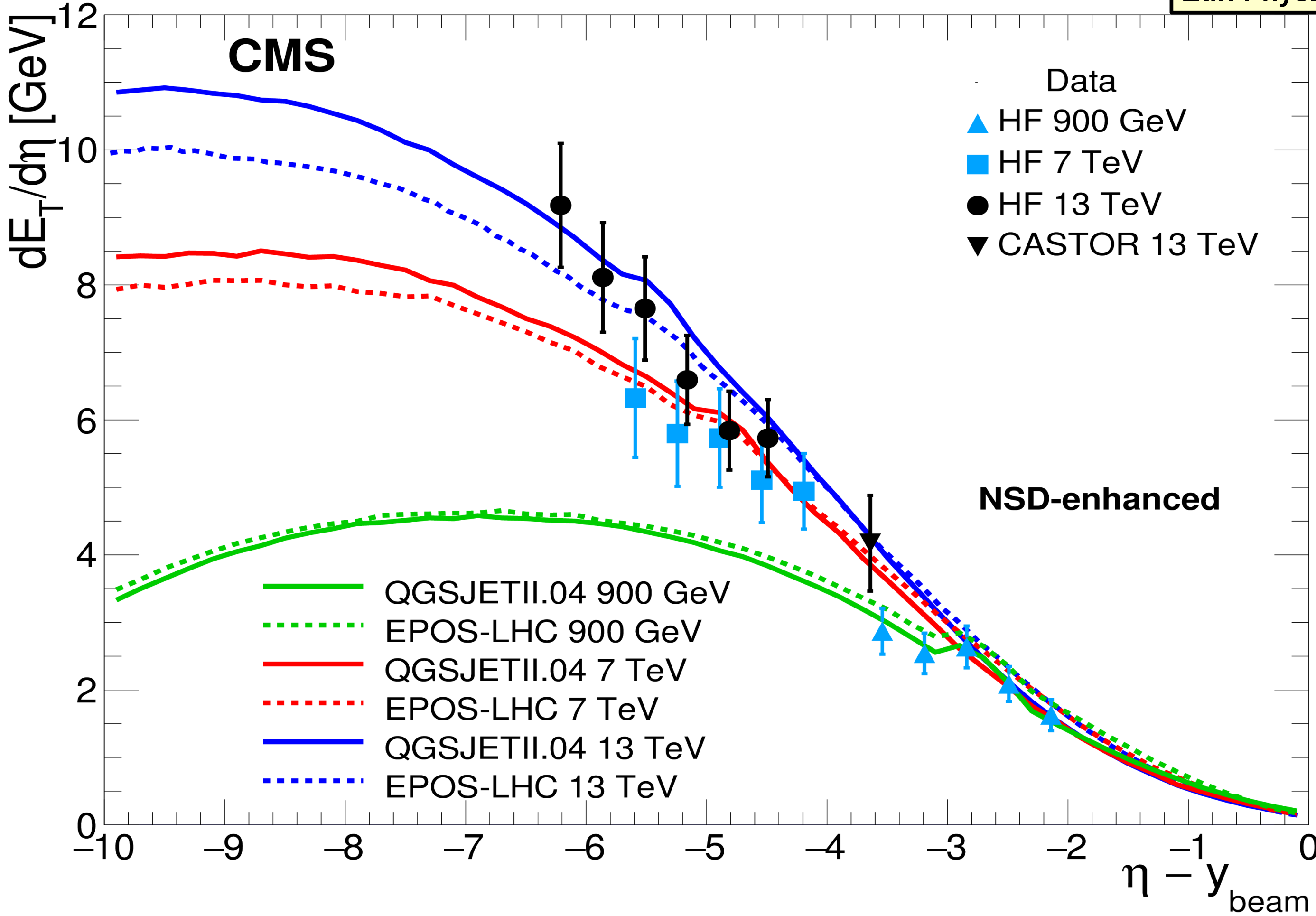


- $dE_T / d\eta'$ ($\eta' = \eta$ | y_{beam})
- The hypothesis of limiting fragmentation suggests that particle production reveals longitudinal scaling, i.e. the dependence of very forward particle production on the centre-of-mass energy vanishes in the region $\eta' \approx 0$.
- In this study, the hypothesis of limiting fragmentation is tested in collisions at $\sqrt{s}$ from 0.9 to 13 TeV.

Total pp cross section @ LHC

- Total cross-sections at the LHC:

$$\sigma_{tot} = \sigma_{el} + \sigma_{in}$$

$$\sigma_{in} = \sigma_{parton} + \sigma_{SD} + \sigma_{DD} + \sigma_{DPE}$$

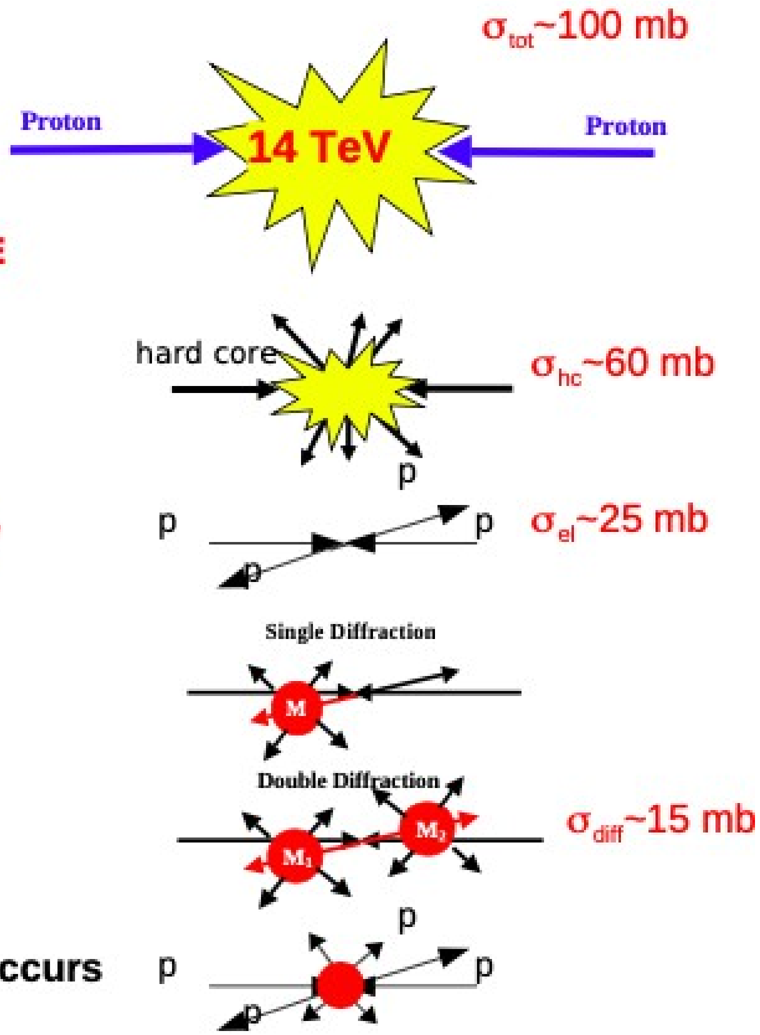
~60% of the time a **"hard"** collision occurs

~25% of the time the protons **scatter elastically**

~10% of the time **single diffraction** occurs

~1% of the time **double diffraction** occurs

~1% of the time **central (exclusive) diffraction** occurs



David d'Enterria, 2011

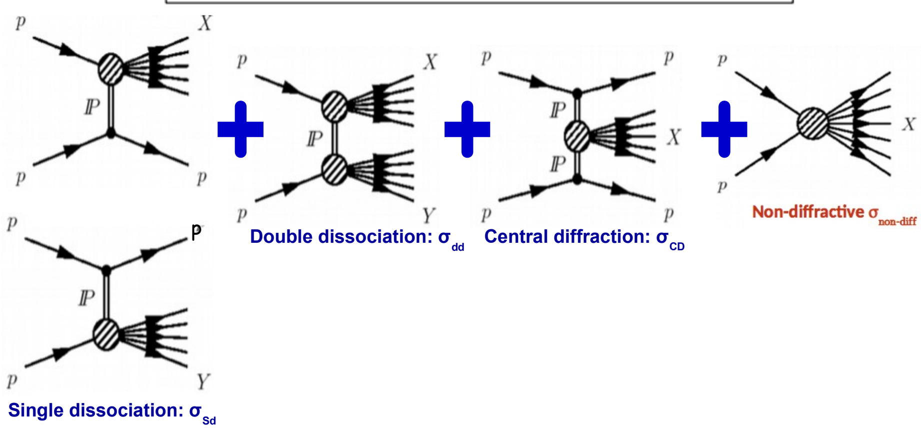
pp cross section

JHEP 07 (2018) 161

- **Motivation:**
  - measure the inelastic pp cross section @ 13 TeV in the largest possible phase space that is experimentally accessible
  - the total pp cross section

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

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



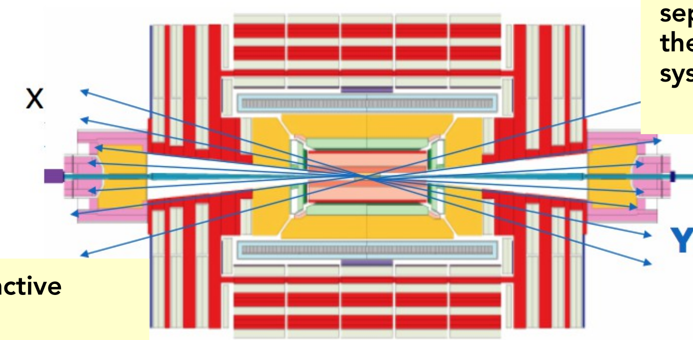
- go more forward and gain information on relative increase
- reduce extrapolation uncertainty
- provide valuable input for phenomenological hadronic interaction models and Monte Carlo (MC) tuning
- Inelastic cross section required for the modelling of pileup.

- **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
  - @ least one HF tower above 5 GeV ($\xi > 10^{-6}$)
  - @ least one HF or CASTOR tower above 5 GeV($\xi_X > 10^{-7}$ OR $\xi_Y > 10^{-6}$

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

  - 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

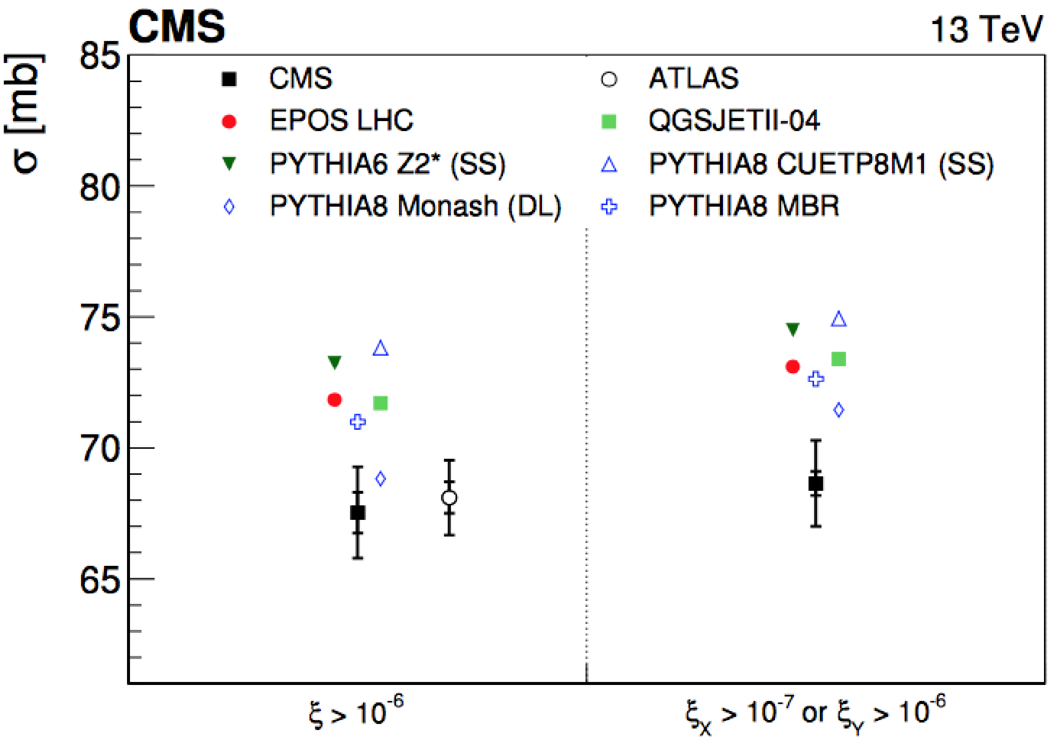
Diffractive events:
- largest gap separates the dissociation systems



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

Inelastic pp cross section

JHEP 07 (2018) 161



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

	Relative cross section increase in %
Data	1.64 ± 0.53
EPOS LHC	1.76
QGSJETII-04	2.36
PYTHIA 6 Z2* (SS)	1.74
PYTHIA 8 CUETP8M1 (SS)	1.52
PYTHIA 8 Monash (DL)	3.83
PYTHIA 8 MBR	2.32

HF only: $\sigma(\xi > 10^{-6}) = 67.5 \pm 0.8$ (syst) ± 1.6 (lumi) mb

HF or CASTOR: $\sigma(\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}) = 68.6 \pm 0.5$ (syst) ± 1.6 (lumi) mb

- The measured cross sections are smaller than those predicted by the majority of models for hadron-hadron scattering.

Summary

- LHC is the first collider reaching an energy higher than the knee in the energy spectrum of cosmic rays.

- Many measurements are made for UHCR at the LHC

  - The comparison to LHC data is an important benchmark for the quality of the models and hence the reliability of air shower simulations currently used to interpret cosmic ray (CR) data.
  - The quality of the LHC data description varies from model to model and differs for different observables.
  - Re-tuning of model parameters to match LHC data will improve the reliability of air shower simulations.

- A new period of data taking of LHC begins with 13.6 TeV, providing greater precision and discovery potential than ever before.

  - Future measurements at the LHC will further cross-check interaction models and help to understand better the underlying hadron production processes.

THANKS FOR YOUR ATTENTION!

BACKUP

- Knee the origin of which is still under debate.
  - Theoretical explanations have been put forward based on a change of slope in the source spectra, effects of leakage from the Galaxy, the assumption of changes in hadronic interactions or the production of exotic new particles

Their exact extragalactic sources and their nature, protons or heavier ions, remain still open questions today [1, 2]. When reaching earth, they collide with N,O nuclei in the upper atmosphere at c.m. energies, $\sqrt{s} = \sqrt{m_{CR}^2 + m_{N,O}^2 + 2 \cdot E_{CR} \cdot m_{CR}} \approx \sqrt{2 \cdot 10^9 \cdot E_{CR}(eV)} \approx 14$–450 TeV, up to 30 times larger than those ever reached in

In experimental particle physics, **pseudorapidity**, η, is a commonly used spatial coordinate describing the angle of a particle relative to the beam axis. It is defined as

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

where θ is the angle between the particle three-momentum $\mathbf{p}$ and the positive direction of the beam axis.[1] Inversely,

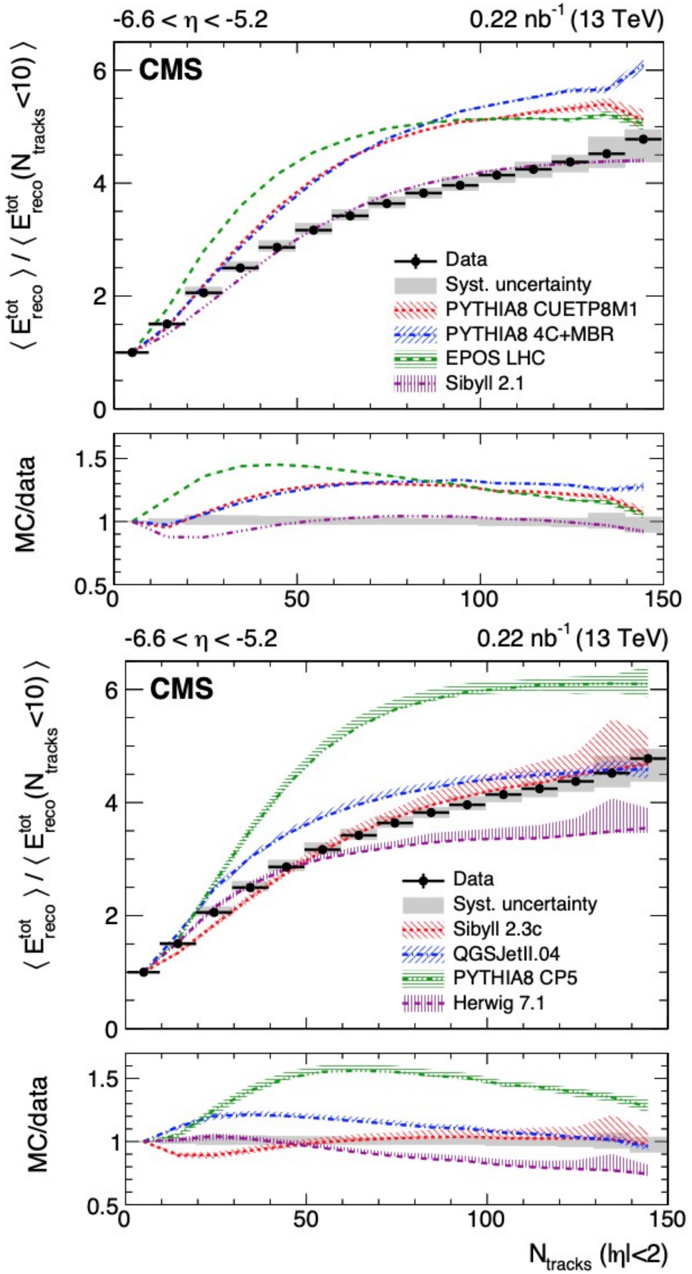
24

Average very forward energy @ 13 TeV

EPJ C 79 (2019) 893

- **Motivation:**
  - Energy carried by particles produced in the very forward region powerful probe
    - to study UE activity
    - to validate MPI models and tuning
  - First correlation study of hadron activity at very forward & central rapidities performed @13 TeV

- **Analysis strategy:**
  - Average energy reconstructed in $-6.6 < \eta < -5.2$ as a function of the track multiplicity
  - Activity in @ least one tower of HF calorimeter
  - At-least one track reconstructed in CMS tracker with $|\eta| < 2$
  - Apply a cut on reco. vertex multiplicity--> reduce PU events



▶ Comparison with models and high energy cosmic ray air showers

▶ Increase with N_{tracks}

▶ UE parameter tunes determined at central rapidity can be safely extrapolated to the very forward region!

▶SIBYLL 2.1 gives the best description

The EPOS-LHC and QGSJETII.04 generators are commonly used to describe extensive air showers in the atmosphere initiated by cosmic ray particles, where soft physics is of pri- mary importance. A combination of Gribov–Regge multiple scattering perturbative QCD, and string fragmentation are the cornerstones of both models. While QGSJETII.04 includes a small number of fundamental parameters, the phenomenology implemented in EPOS-LHC of- fers more opportunities for tuning. In EPOS-LHC a hydrodynamic, or collective, component is included in a parametrised form