Forward Energy Measurements with CMS

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On Behalf of the CMS Collaboration

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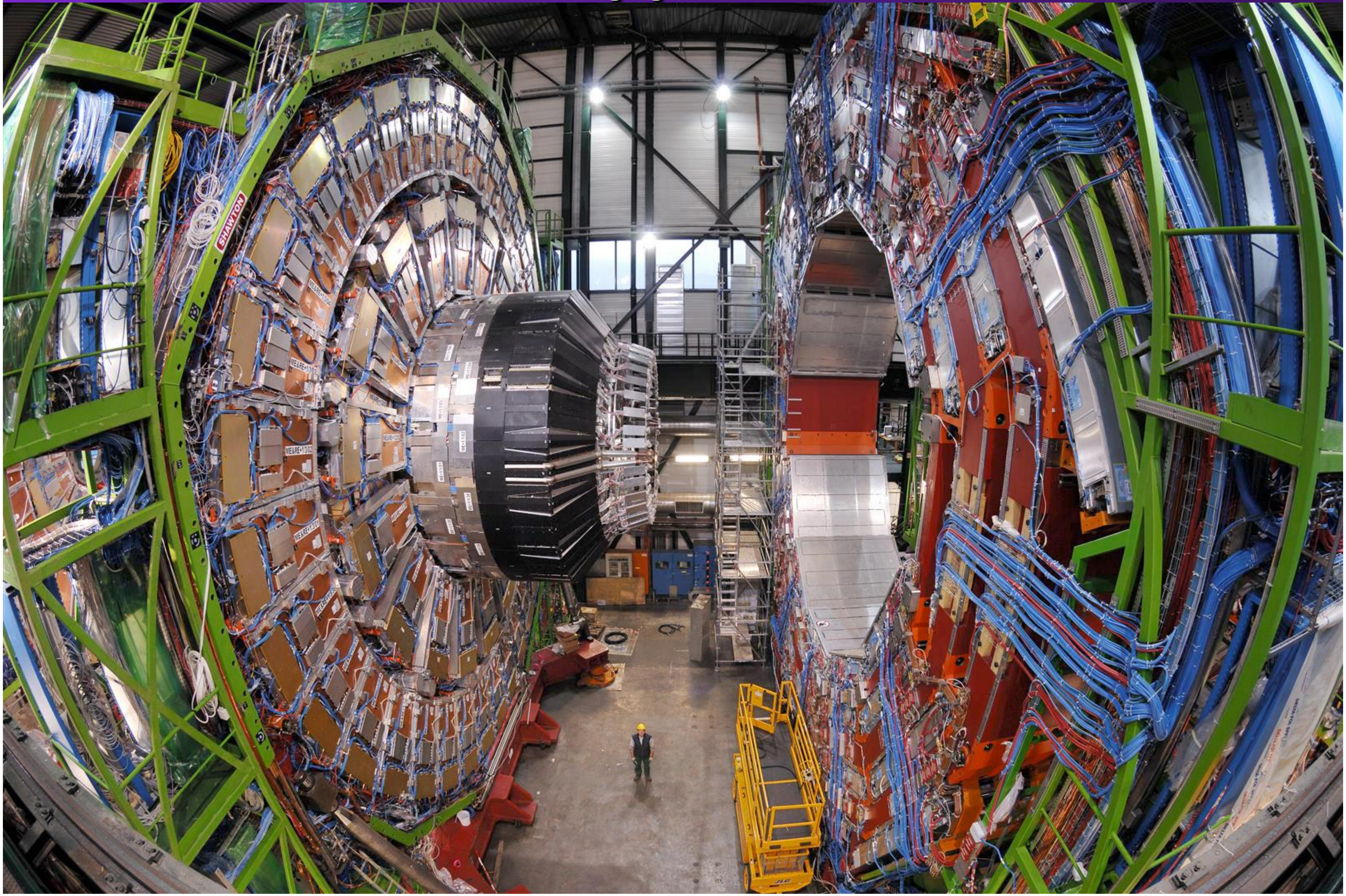
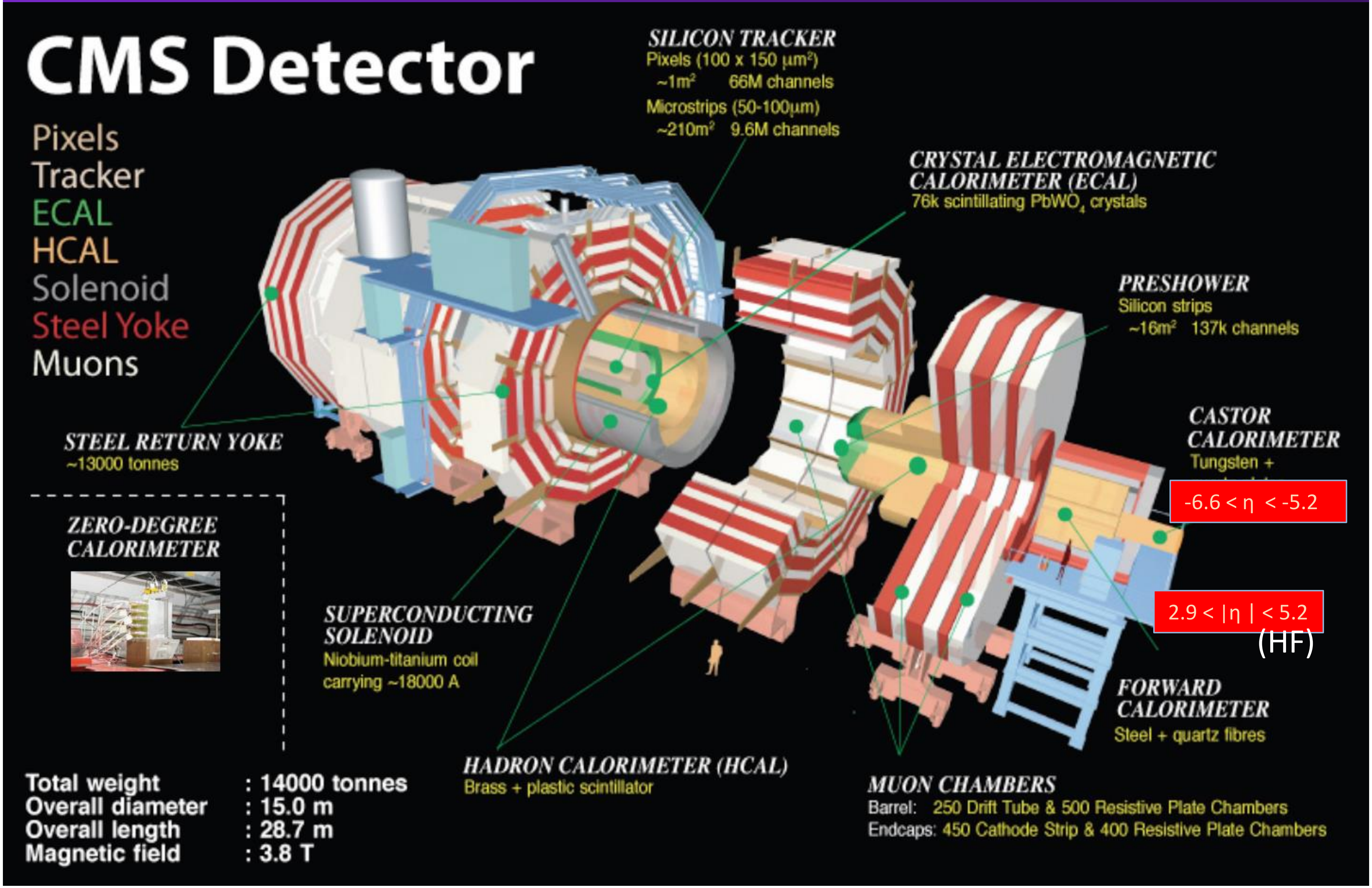
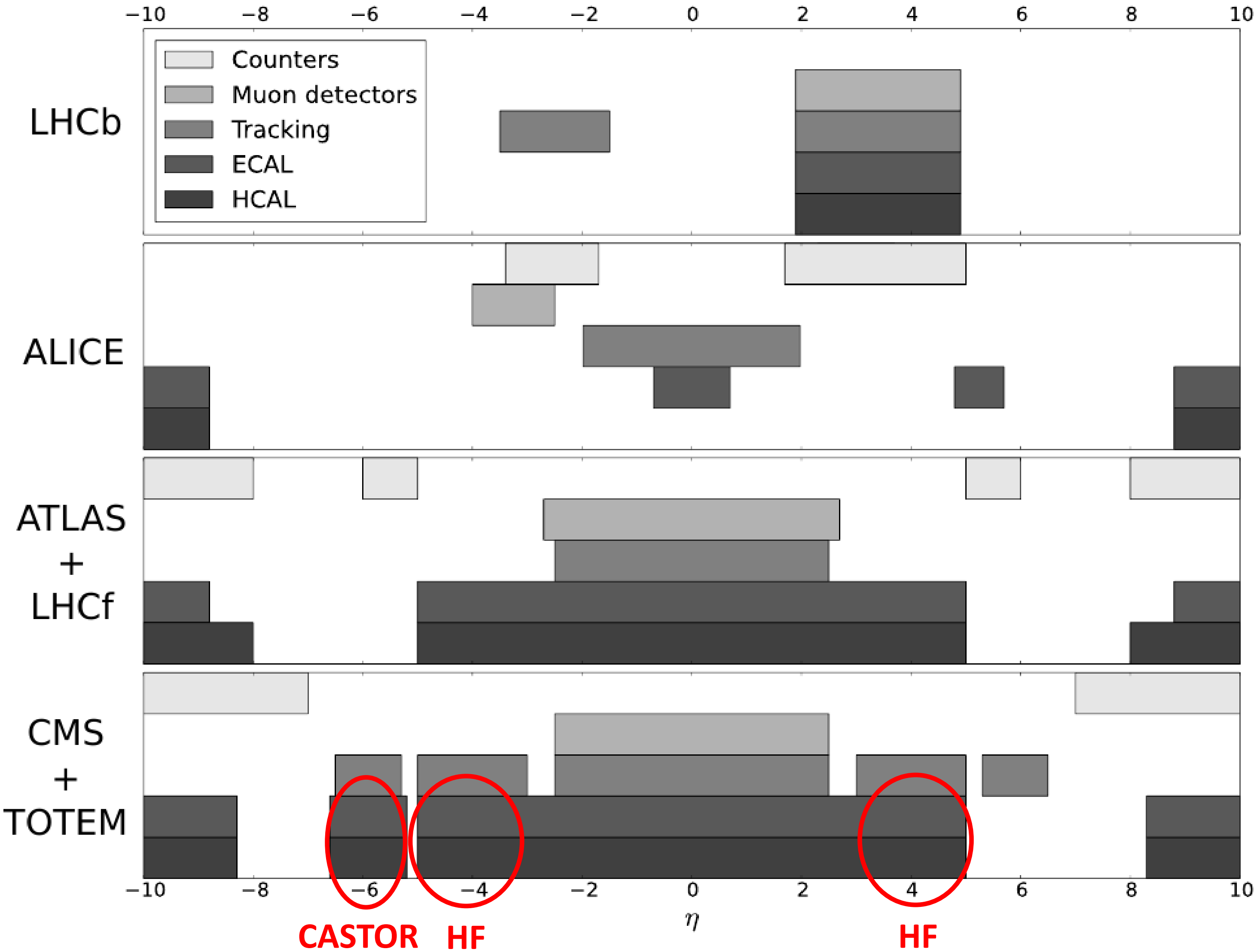
CMS appearance



CMS structure



Pseudorapidity coverage of LHC detectors



[Thesis C.Baus]

Hadronic Forward calorimeters (HF)

- located at 11.2 m from IP on both sides of CMS

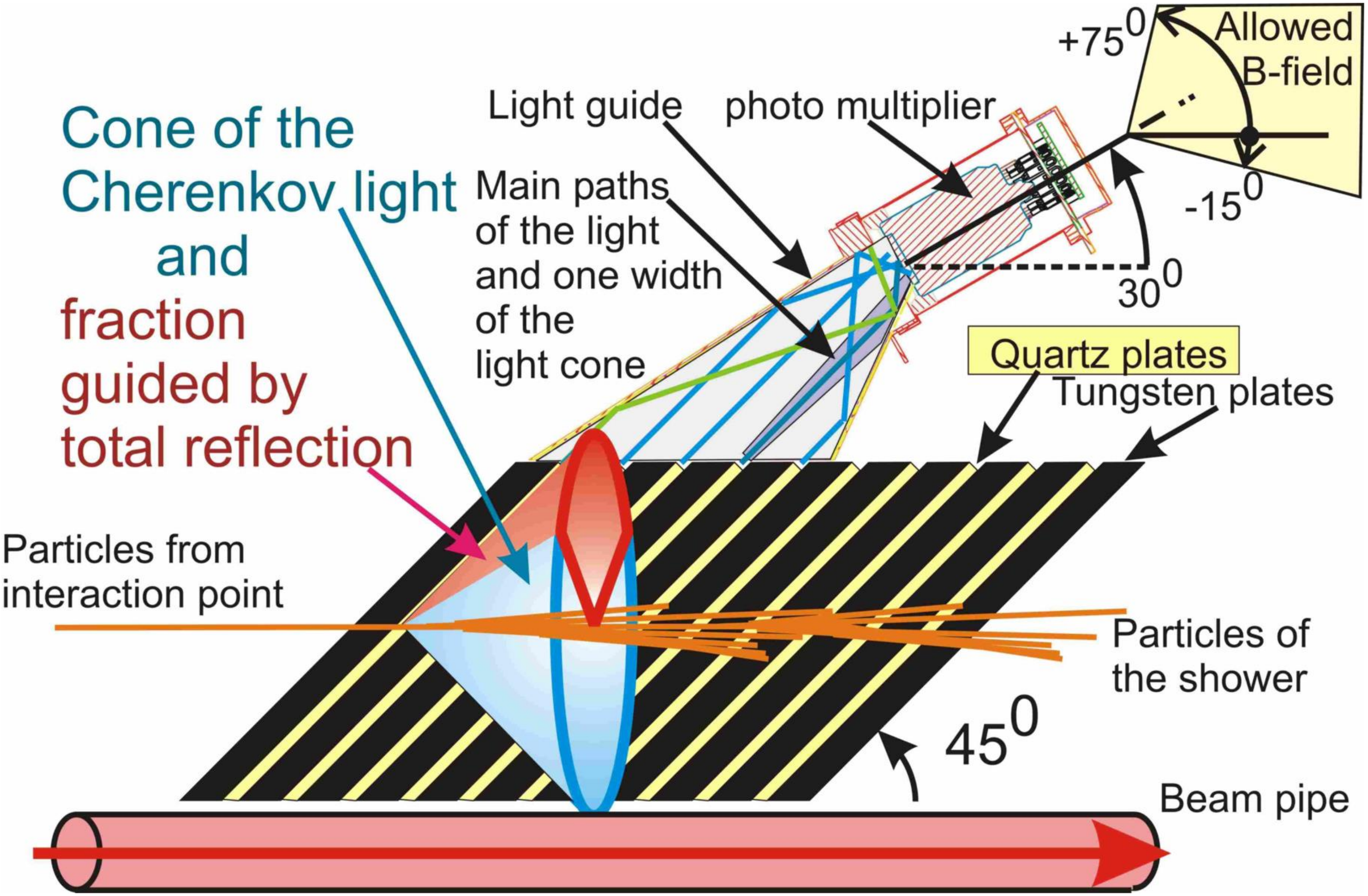
- rapidity coverage $2.9 < |\eta| < 5.2$
- Cerenkov calorimeter made of steel absorbers and embedded radiation-hard quartz fibers, light from the fibers detected by PMT
- 2 types of fibers: long (run over the full depth) and short (start at 22 cm from the front of HF)

→ possible to distinguish showers generated by e/γ from showers generated by hadrons

- 13 rings in η with a segmentation $\Delta\eta = 0.175$ (except for the 2 most inner rings and the most outer one)

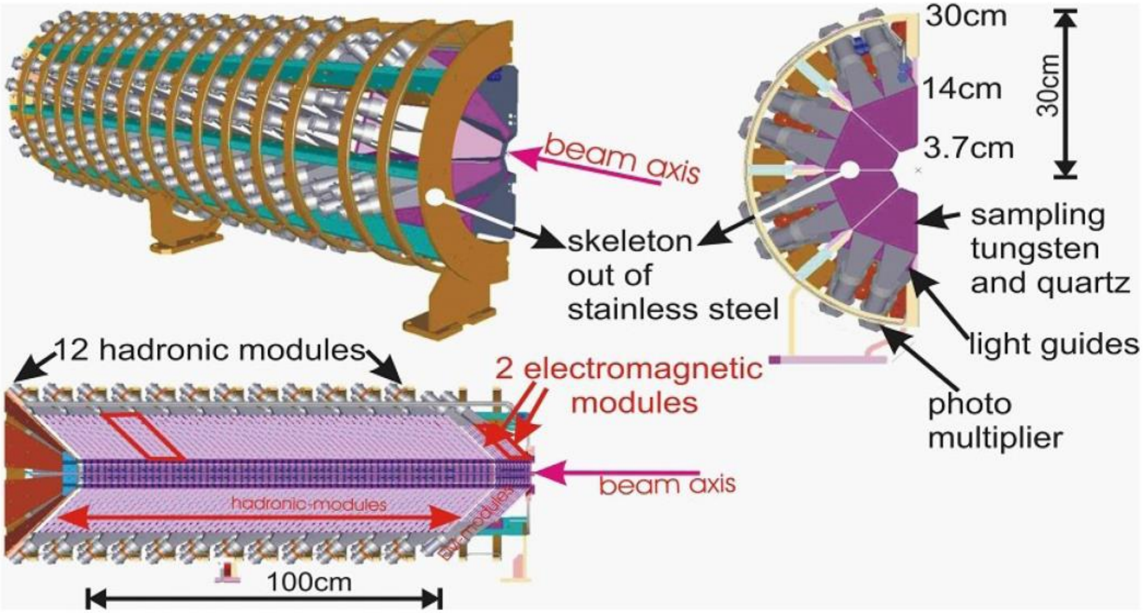
CASTOR calorimeter

Cherenkov sampling calorimeter with quartz plates as active medium and tungsten as absorber



CASTOR calorimeter

- Located at -14.3m from the interaction point
- Covering $-6.6 < \eta < -5.2$
- Electromagnetic and hadronic sections
- 16-fold segmentation in φ; 2(em) + 12(had)-fold segmentation in z
- Very complex environment:
  - magnetic fringe field
  - harsh radiation



Hadronic interaction models

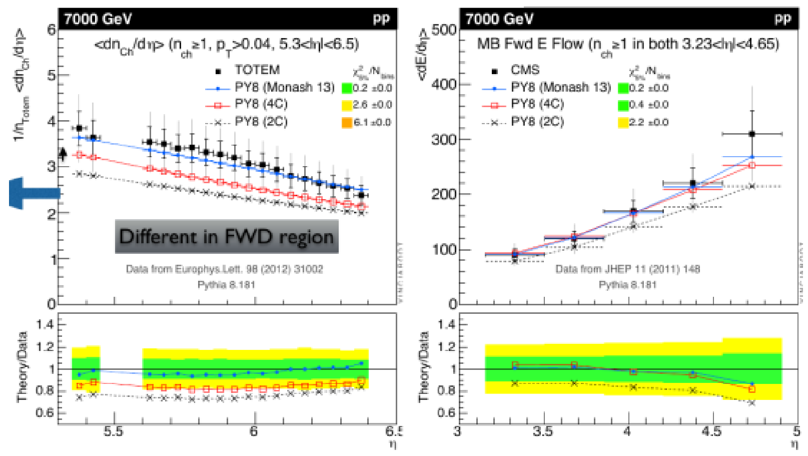
- Pythia8, tuned to LHC Run 1 results:

  Hard scattering matrix elements + parton showering + string fragmentation

  Multitude of adjustable processes & tunable parameters: fragmentation, underlying events, multi-parton interactions/colour reconnections, diffraction

  - Underlying event tune Monash 2013
  - CMS tunes CUETP8M1/CUETP8S1 (MPI)
  - MBR model for diffraction

P.Skands



- EPOS-LHC and QGSJET II-04, tuned to LHC Run 1 results:

  Gribov-Regge pomeron physics + hard pomeron + string fragmentation

  - Commonly used in cosmic ray physics
  - More than Pythia focus on soft interactions
  - QGSJET is more strict in physics
  - EPOS is more 'phenomenological'/'tunable'
  - EPOS includes collectivity/hydrodynamic component in a parametrized form

Event selection

Low pile-up RUN2 runs

Two types of events:

- **Inelastic** (detector level: HF at least in one side)
- **Non-single-diffraction (NSD) enhanced** (HF at both sides)

Inelastic events particle level:

Find largest rapidity gap between particles.

Particles on two sides of the gap create two systems:

system X (negative side) and Y (positive side).

Calculate invariant masses M_X and M_Y, and define:

$$\xi_{\mathrm{X}} = \frac{M_{\mathrm{X}}^2}{s}, \qquad \xi_{\mathrm{Y}} = \frac{M_{\mathrm{Y}}^2}{s}, \qquad \xi = \max(\xi_{\mathrm{X}}, \xi_{\mathrm{Y}})$$

Select events with $\xi > 10^{-6}$

Non-single-diffractive events particle level:

Select events with at least one particle (no energy threshold) in HF pseudorapidity range at both sides

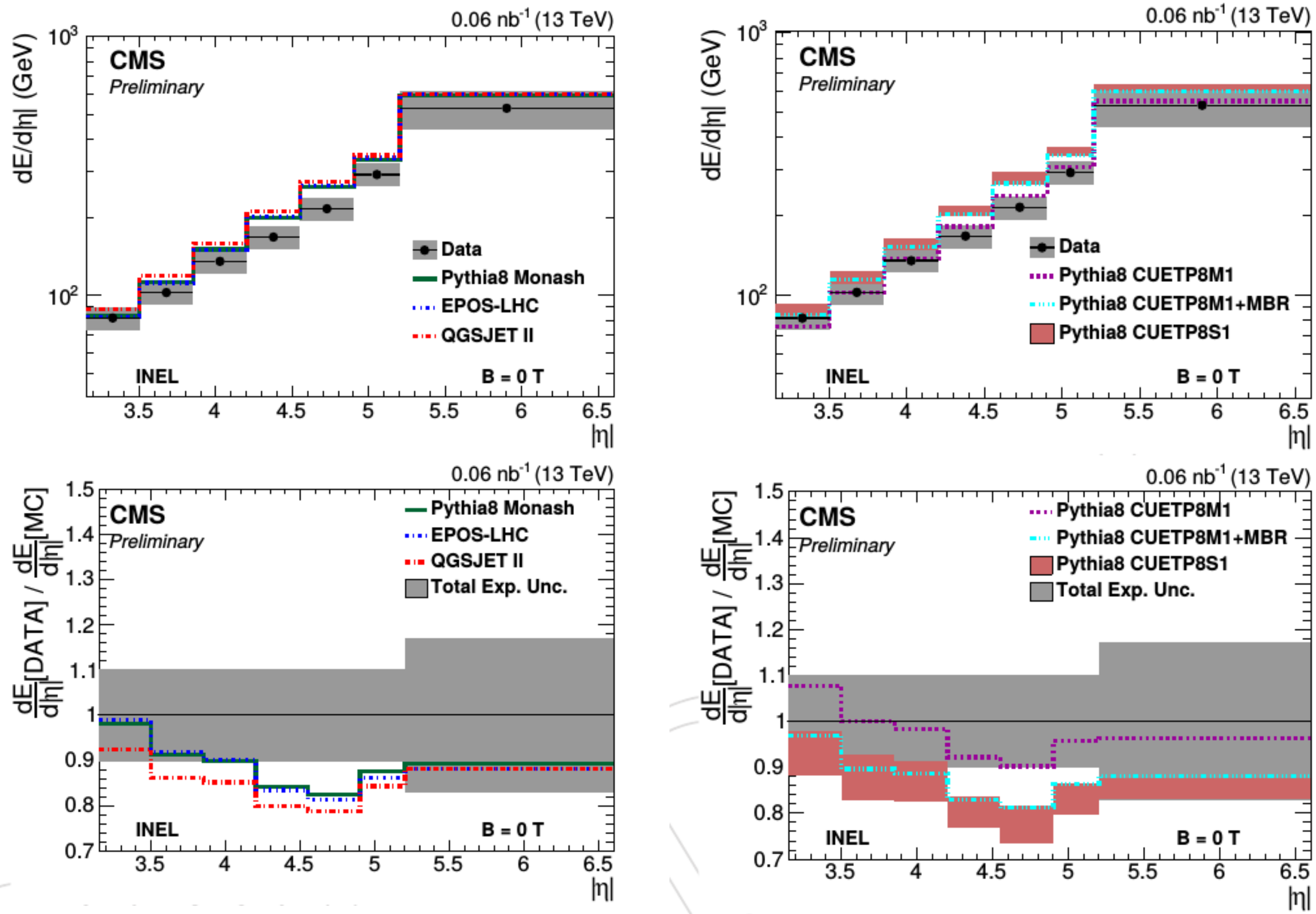
Energies are summed of all particles except muons and neutrinos, without threshold

Systematic effects

	Soft-inclusive inelastic events	Non-single diffractive events
Model dependence of correction factor	< 3.5%	
Influence of noise on selection	< 1.75%	< 0.5%
Influence of noise on energy sums	< 1.2%	
Calorimeter global energy scale in $3.15 < \|\eta\| < 5.20$	10%	
Calorimeter global energy scale in $5.20 < \|\eta\| < 6.6$	17%	

Inelastic events

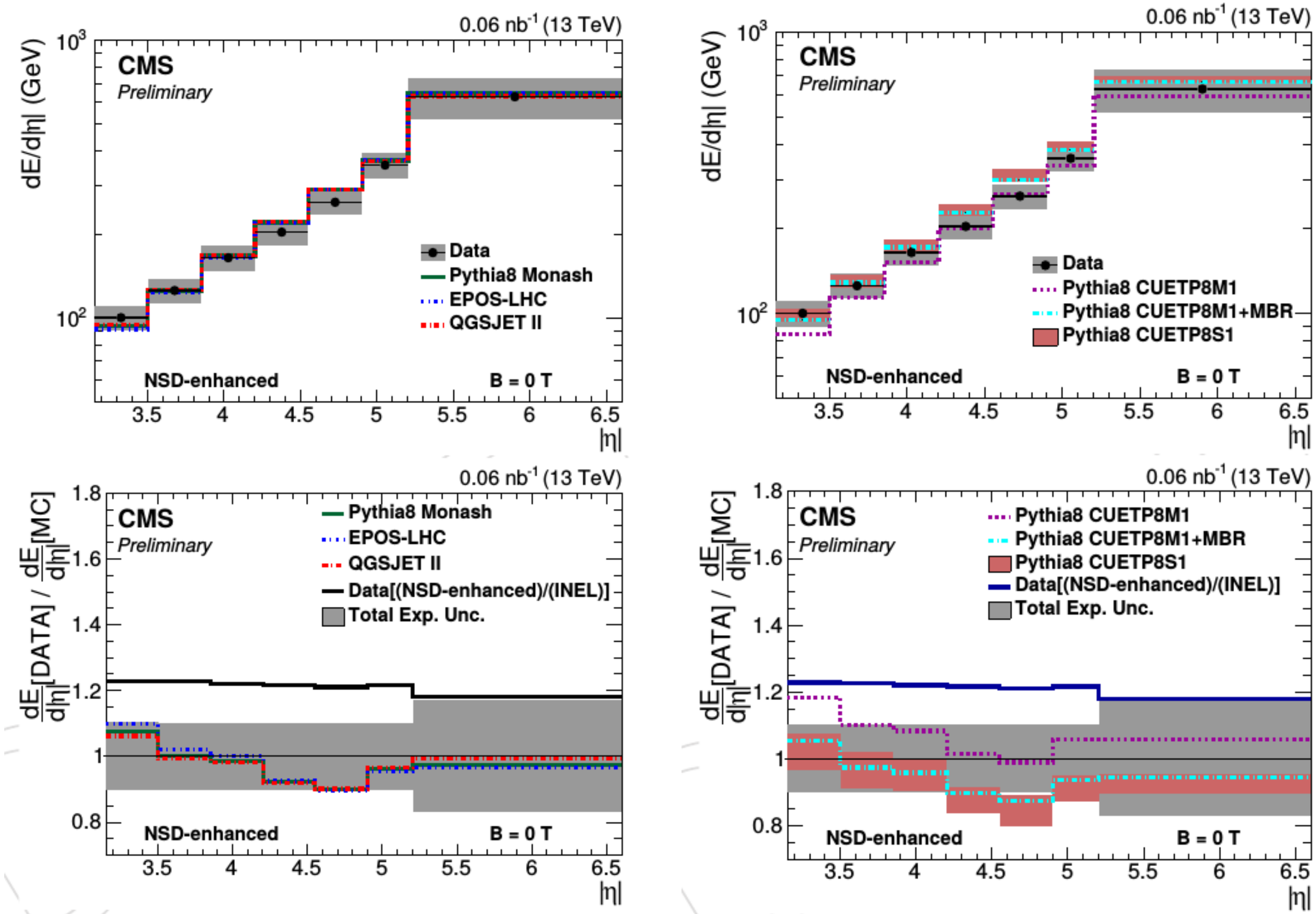
CMS PAS FSQ-15-006



- MC different from data in slope in HF region.
- Pythia8 Monash vs EPOS/QGSJET -> comparable results
- CUETP8M1 vs CUETP8M1+MBR -> effect of variation of diffractive parameters
- CUETP8S1+uncertainties -> effect of variation of color reconnection parameters

NSD-enhanced events

CMS PAS FSQ-15-006

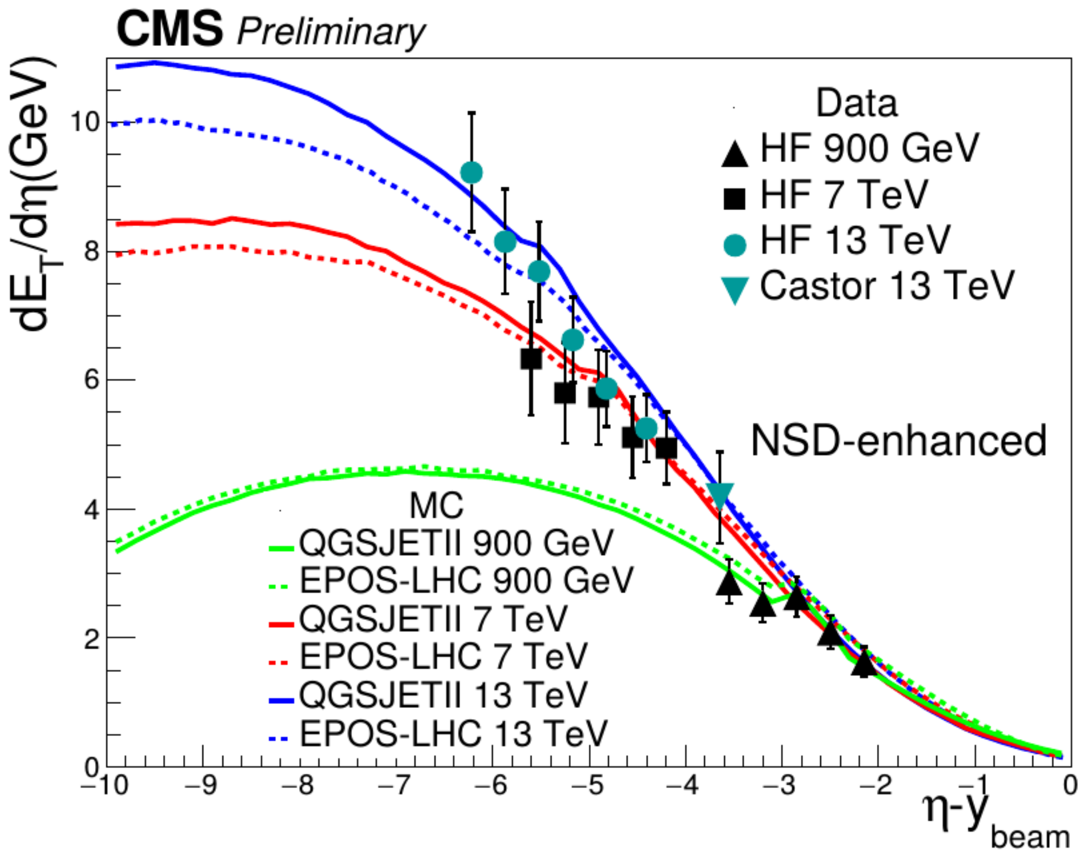


- ❑ MC different from data in slope of η-dependence in HF region.
- ❑ Pythia8 Monash vs EPOS/QGSJET -> practically converge
- ❑ NSD-enhanced vs. INEL -> no significant difference in the spectrum shape, same message

Limiting fragmentation

CMS PAS FSQ-15-006

- Earlier measurements with lower centre-of-mass energies JHEP 11 (2011) 148
- NSD enhanced selection: at least one charged particles in both sides at 3.9 < |η| < 4.4

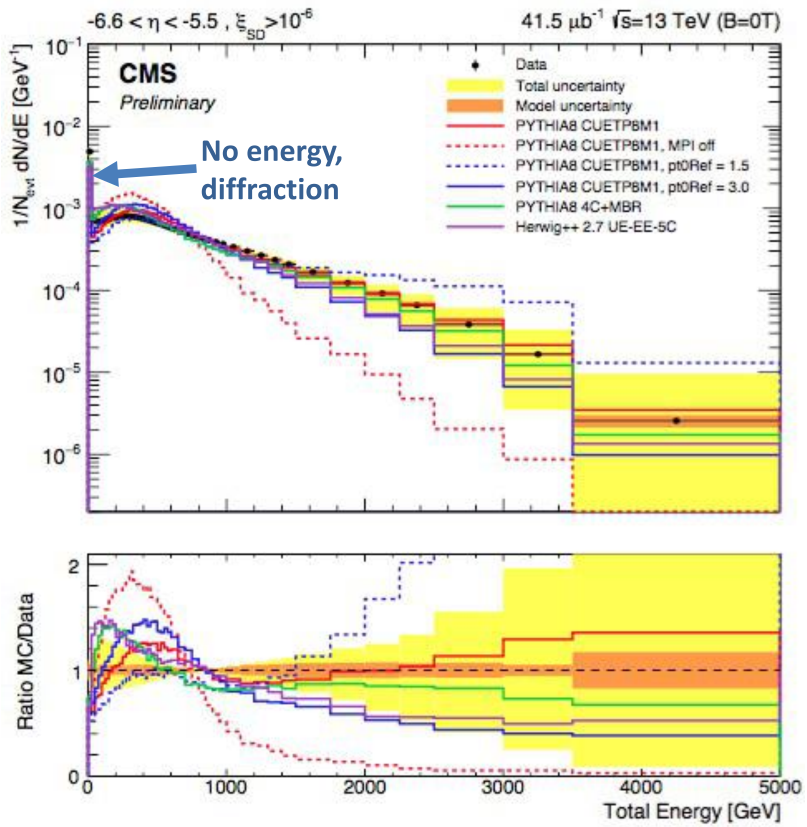


- ❑ Generators successfully reproduce measurements at 900 GeV and 7 TeV
- ❑ Shape of distribution measured at 13 TeV is different from MC
- ❑ Fairly well consistent with hypothesis of limiting fragmentation

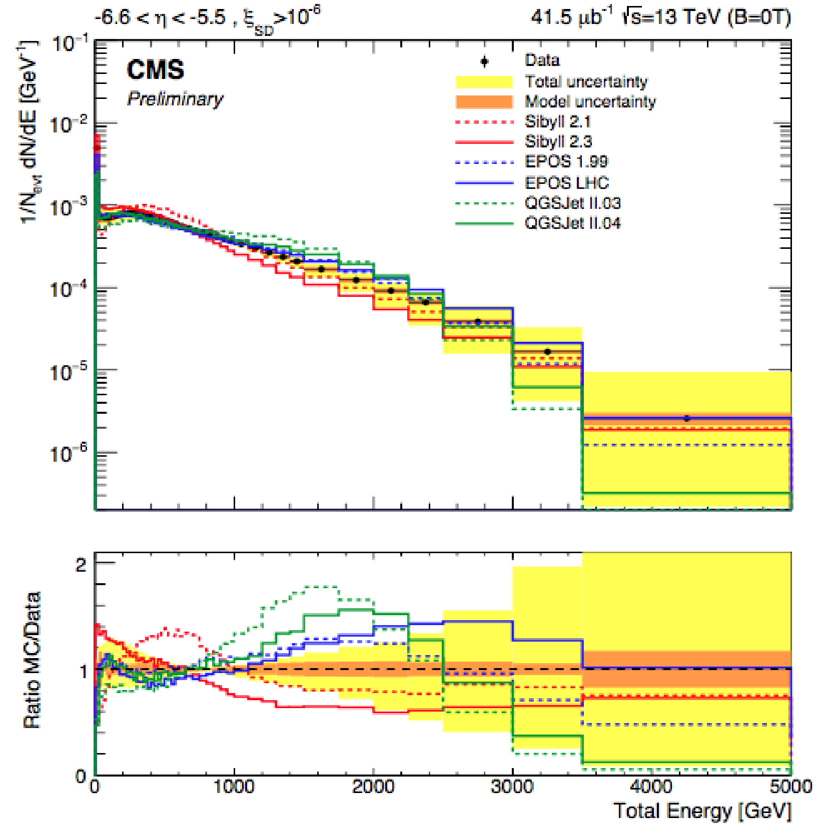
CASTOR energy

CMS PAS FSQ-16-002

Pythia8 and Herwig++ (Sensitivity to MPI and UE)



Cosmic Ray models



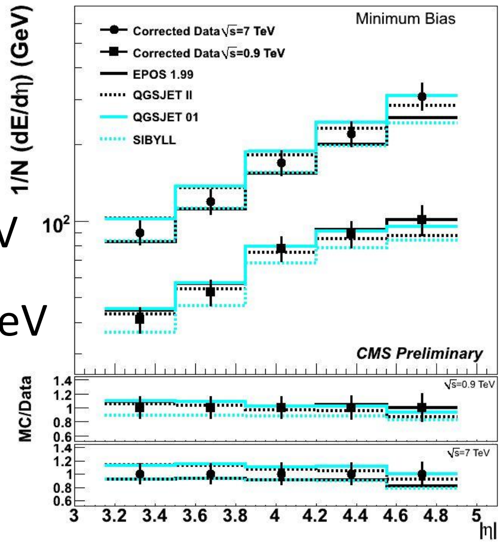
- Allows vetoing of diffraction
- Difference between data and models beyond measurement uncertainty
- Spectra are sensitive to MPI and UE tuning parameters

Other LHC forward measurements

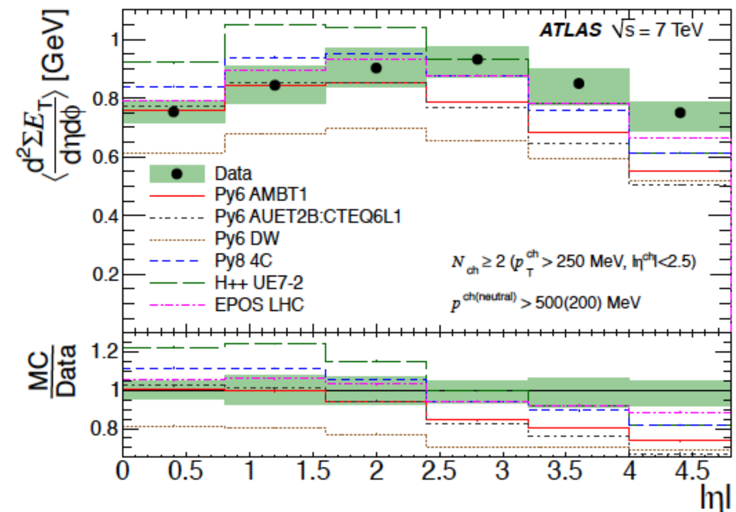
CMS energy flow

7 TeV

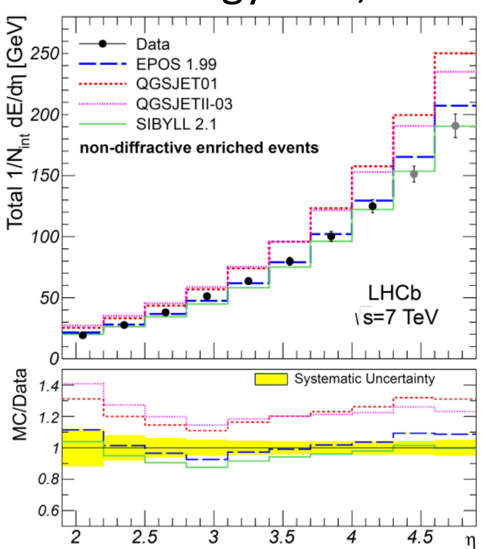
900 GeV



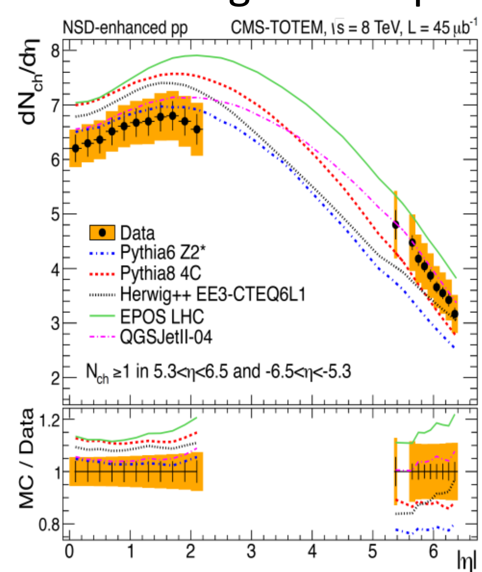
ATLAS energy flow, 7 TeV



LHCb energy flow, 7 TeV

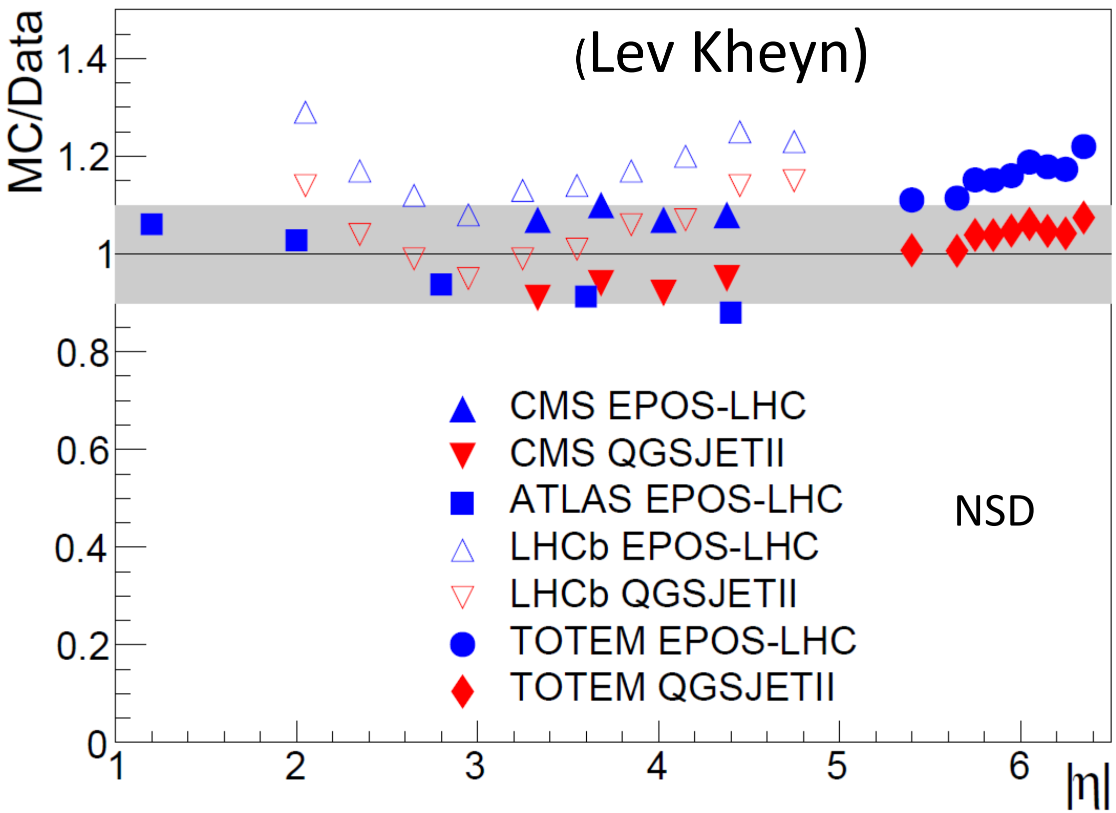


TOTEM charged multiplicity, 8 TeV



Are they compatible?

Ratio of Cosmic Rays Monte Carlo to data



The errors in all measurements are on the level of 10%, they are shown by gray band. Errors are always strongly correlated and usually dominated by general scale uncertainties. Slopes of distributions are influenced to minor extent. Also definition of particle level NSD selection is somewhat different in different experiments which should insert uncertainty while comparing absolute values of the ratios but also should influence to minor extent the slopes. **So difference in slope should be paid attention to.**

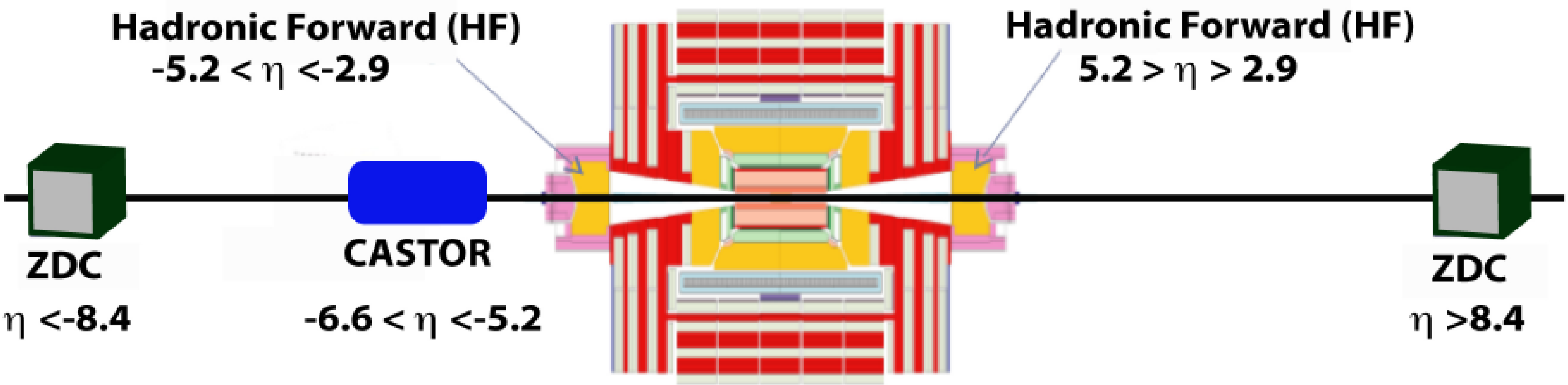
- ATLAS, LHCb and CMS look incompatible in slope
- Totem looks consistent with CMS

Summary

- Energy flow in the forward region of CMS in pp-collisions at 13 TeV as a function of pseudorapidity is studied for two event classes: inclusive and non-single-diffraction enhanced.
- Data are compared to different hadronic interaction models: Pythia8 tunes and Cosmic Ray generators EPOS-LHC and QGSJETII-04.
- The spread in model predictions is large, nevertheless difference in the slope of η dependence between data and all generators is noticeable.
- Results presented in terms of shifted pseudorapidity variable, $\eta - y_{beam}$, are compared to earlier data at 900 GeV and 7 TeV. Fairly well consistent with hypothesis of limiting fragmentation.
- CASTOR energy spectrum allows distinguishing between different models, in particular between different MPI and UE parameterizations.

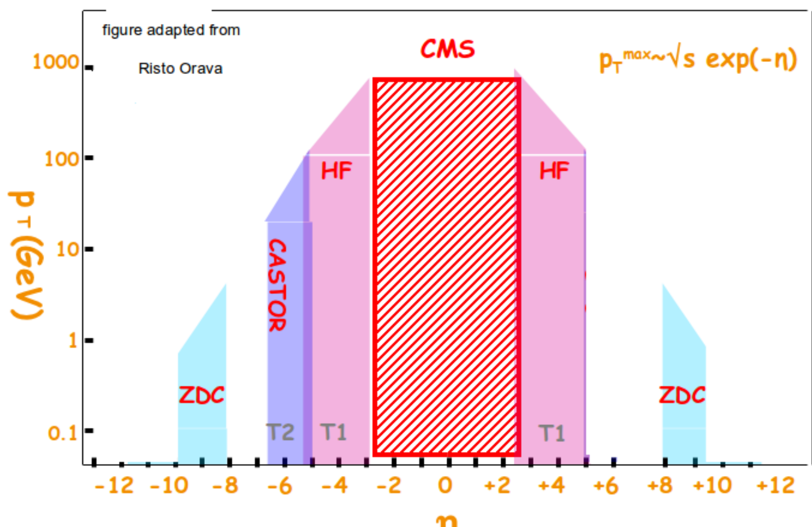
Backups

CMS Forward Detectors

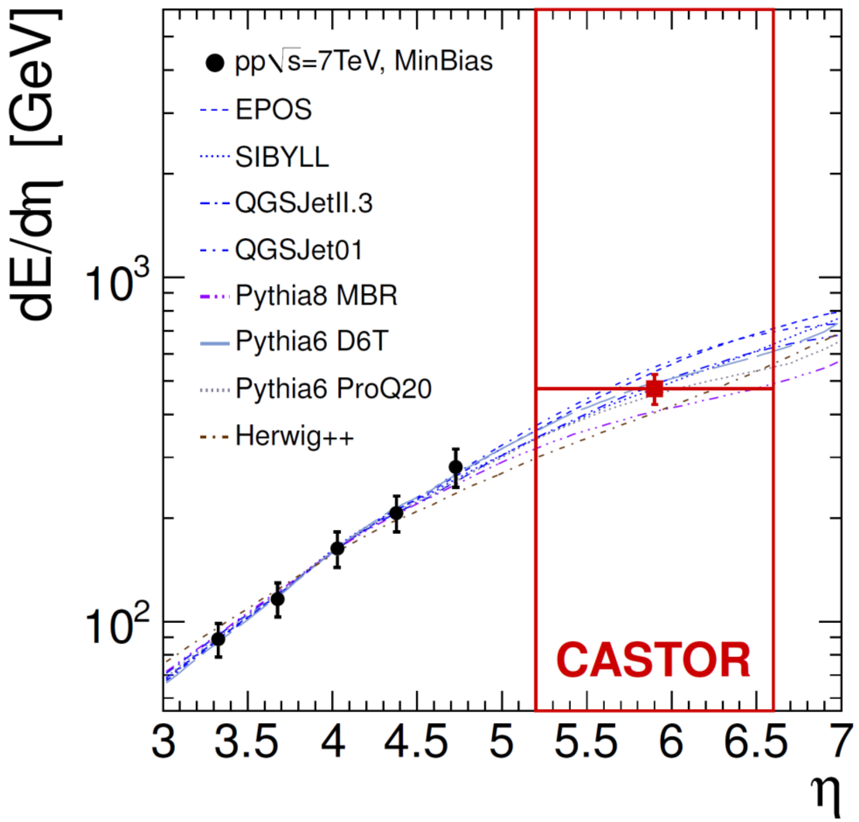


Cherenkov calorimeters:

- HF
  - rapidity coverage: $2.9 < |\eta| < 5.2$
- CASTOR
  - rapidity coverage: $-6.6 < \eta < -5.2$
- ZDC
  - rapidity coverage: $|\eta| > 8.4$



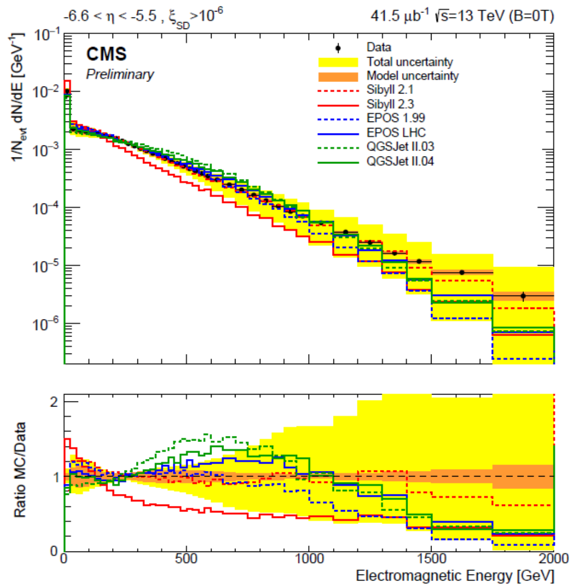
CASTOR absolute calibration

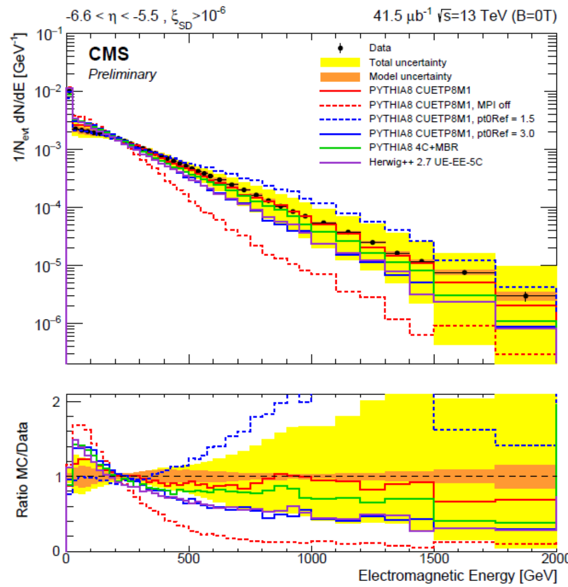


1. Scale models to data in HF range
2. log-linear extrapolation from data points to CASTOR range
3. MC used to correct for deviation from log-linear dependence

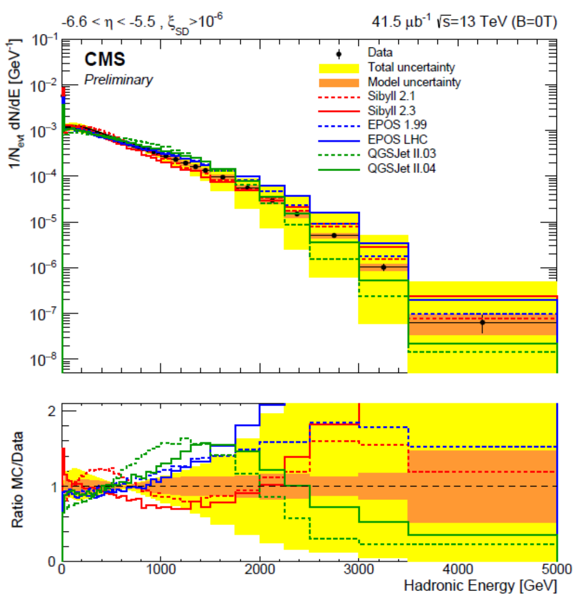
CASTOR energy: electromagnetic & hadronic

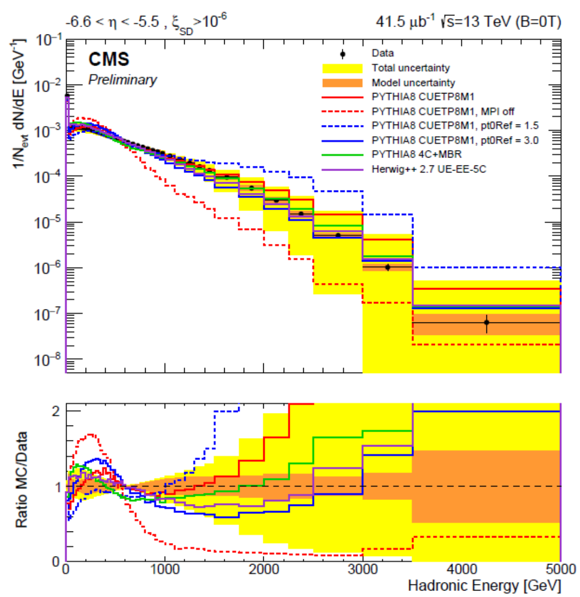
CMS PAS FSQ-16-002





Electromagnetic

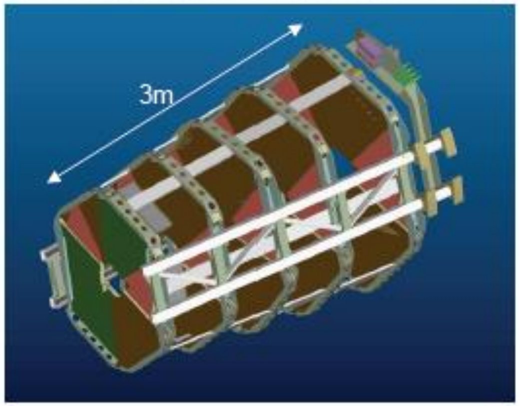


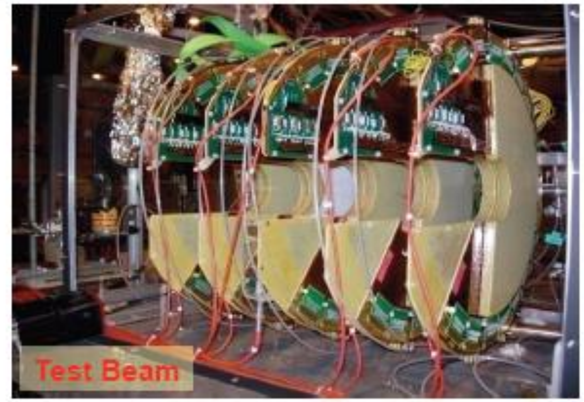


Hadronic

TOTEM

TOTEM T1 & T2





- Cathode Strip Chambers (CSC)
- Mounted in front of HF
- $3.1 < |\eta| < 4.7$
- 5 planes with 3 coordinates/plane
- 6 trapezoidal CSC detectors/plane
- Resolution: $\sigma \sim 0.8$mm

- Gas Electron Multiplier (GEM)
- Mounted in front of CASTOR
- $5.3 < |\eta| < 6.5$
- 10 planes formed by 20 GEM semi-circular modules
- Resolution: $\sigma_{strip} \sim 70\mu$m

TOTEM: Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC

Limiting fragmentation

Charged multiplicity

Thesis Yen-Jee Lee