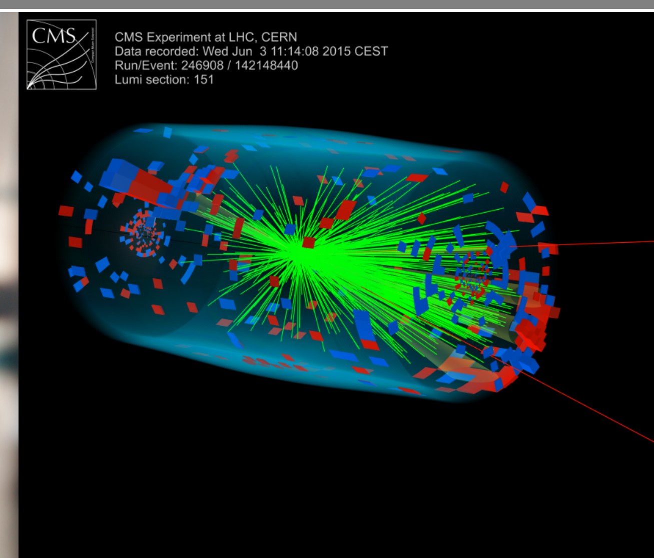
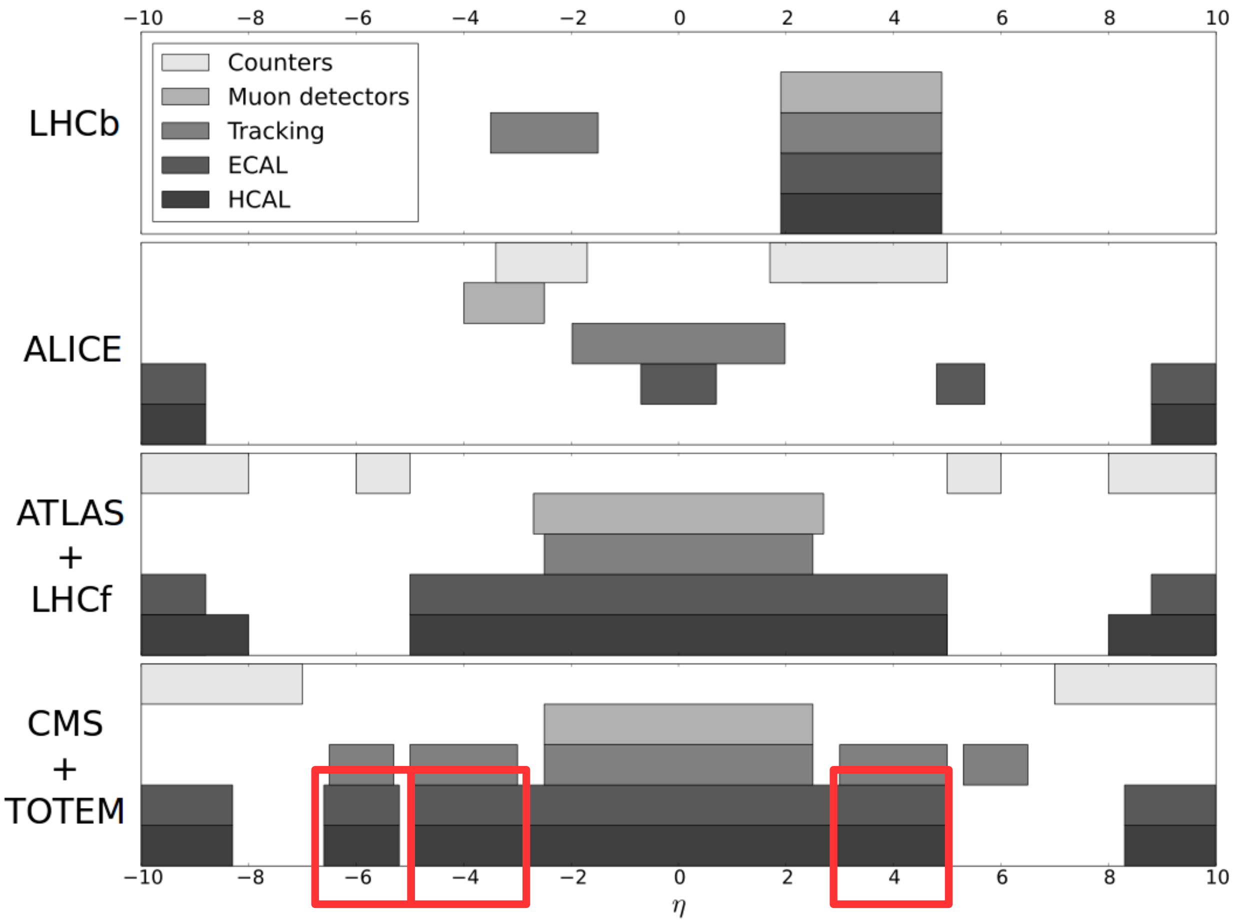
Forward physics with CASTOR in CMS

Sebastian Baur for the CMS Collaboration



Overview

CMS has an excellent calorimetric instrumentation in the forward region

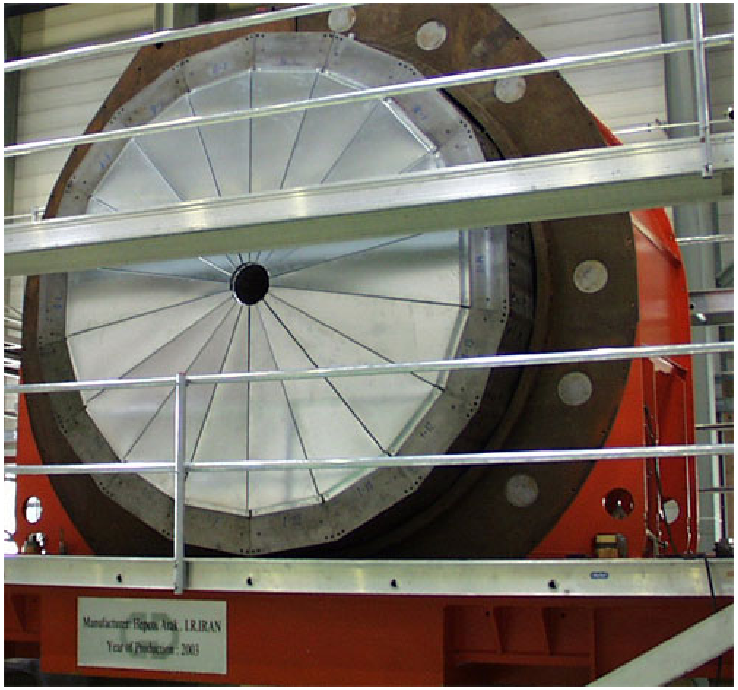


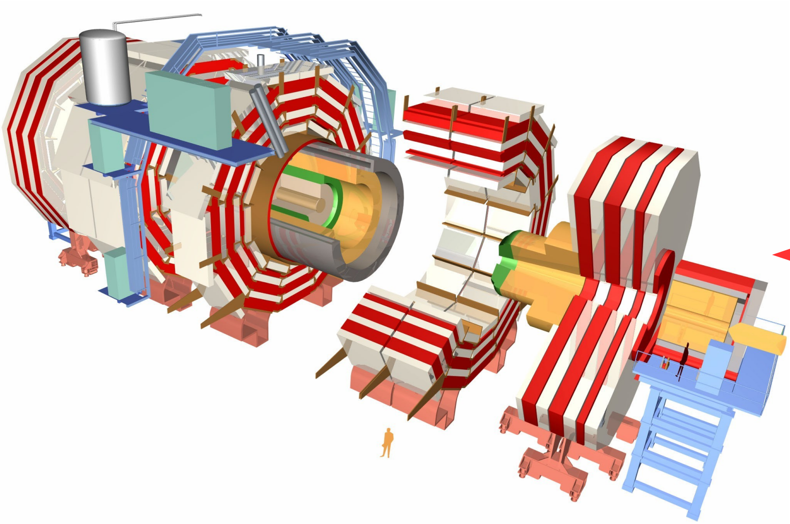
CASTOR **HF (Hadron Forward)**

picture from C. Baus

HF calorimeters

- iron wedges and quartz fibers,
- 13 segments in η: $3.152 < |\eta| < 5.205$
- at both sides of CMS: HF- and HF+
- Energy scale known to ±10%

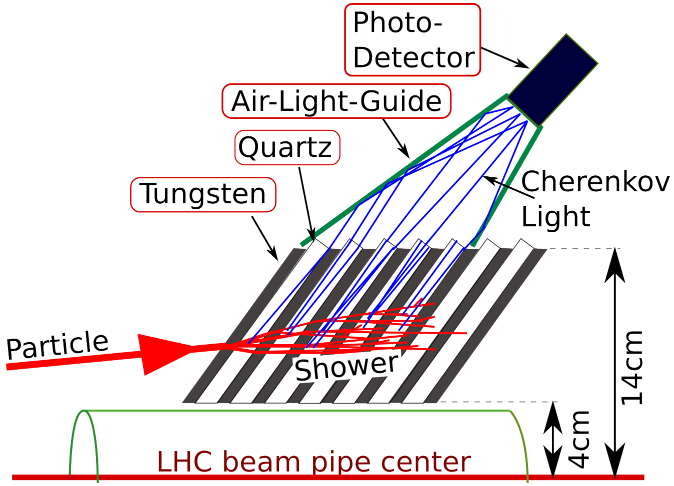


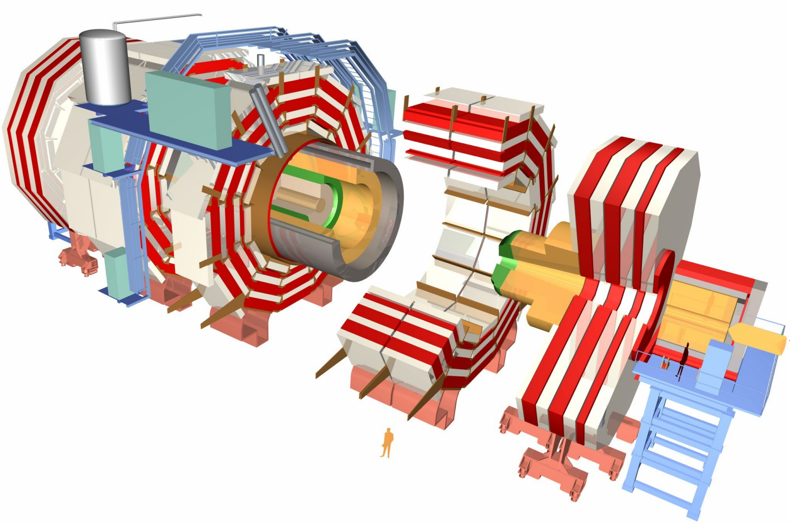


HF (**H**adron **F**orward)

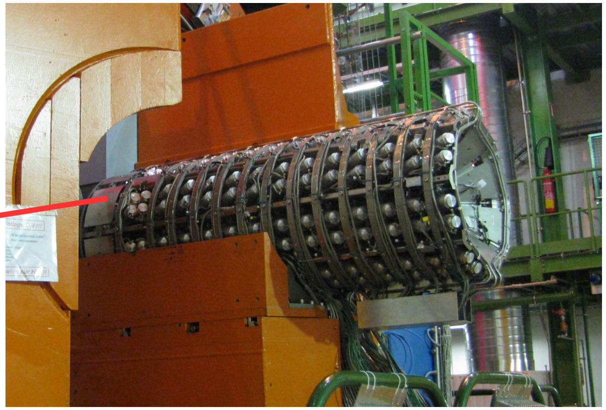
CASTOR in CMS

- Tungsten-Quartz sampling calorimeter
- acceptance of $-5.2 < \eta < -6.6$
- Energy scale known to ±17%
- Separated electromagnetic and hadronic sections with depth of $20\ X_0\ /\ 10\ \lambda_{int}$



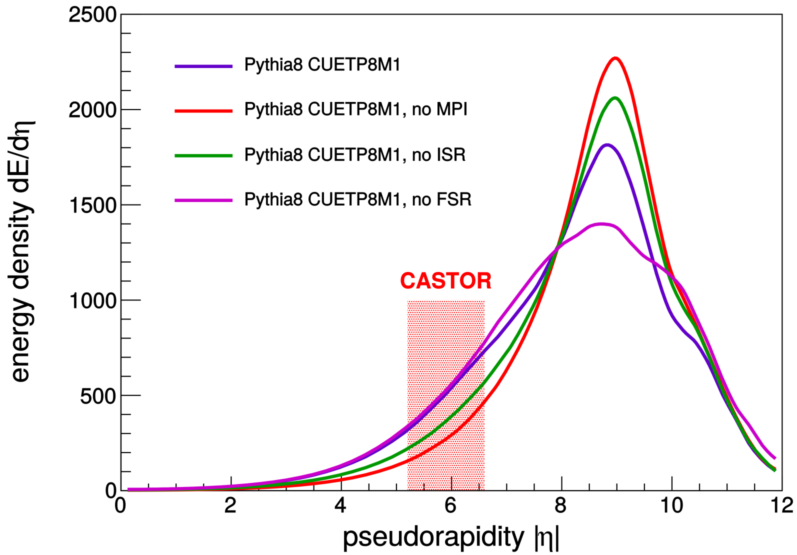


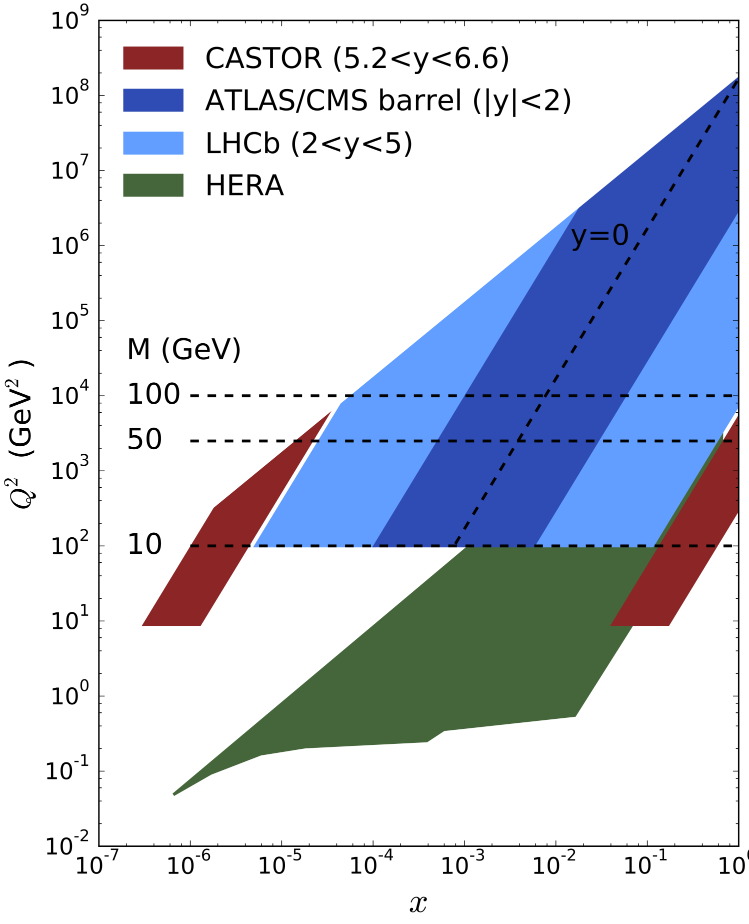
CASTOR



Forward Physics With CASTOR

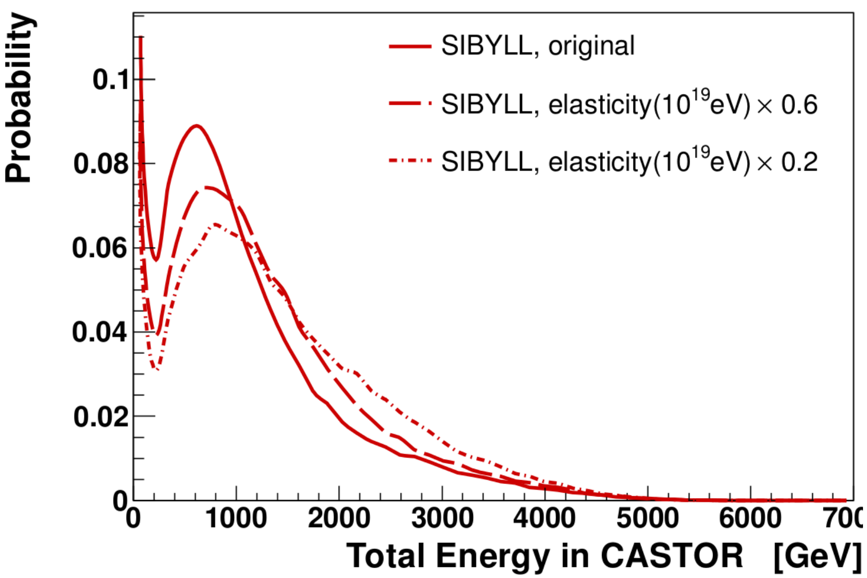
- Highest energy densities dominated by soft interactions
- Sensitive to low-x parton dynamics,
- Probe proton fragmentation, UE and Multiparton Interactions (MPI)

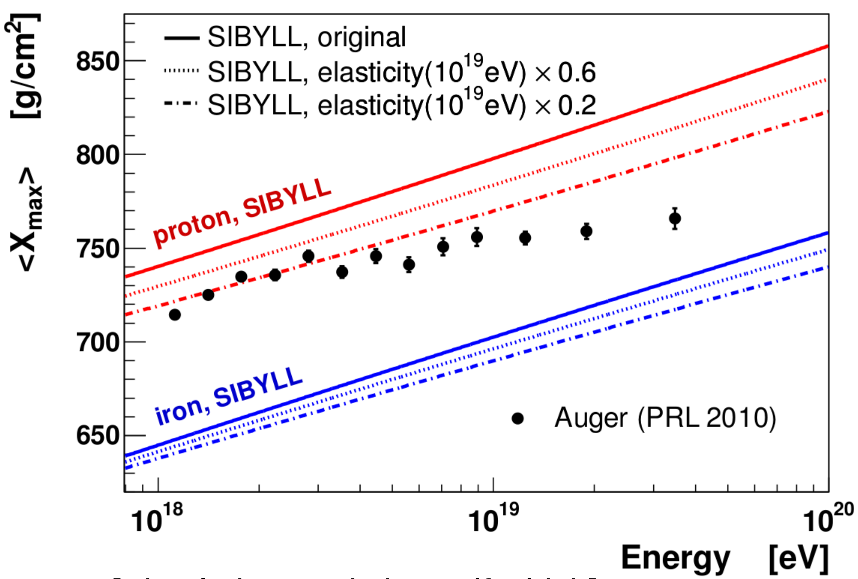




Forward Physics With CASTOR

- Highest energy densities
  → relevant for air shower development
- Probe models for cosmic-ray air showers
- Example: elasticity in Sibyll2.1



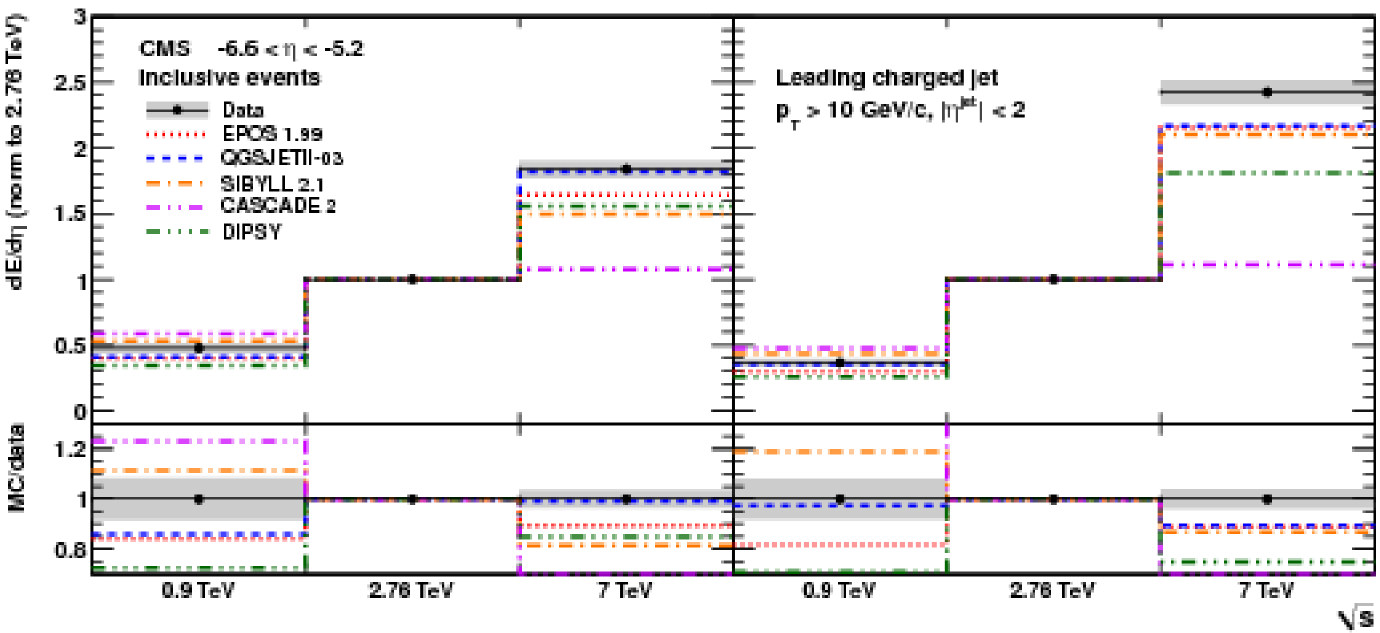


[Simulation study by Ralf Ulrich]

Highlighted 13 TeV results with CASTOR

Recap: LHC Run 1 analyses

- Measurement of diffractive cross sections — arXiv:1503.08689
- Measurement of the underlying event — arXiv:1302.2394
- Energy flow in Pb-Pb collisions — CERN CDS: 1472732
- Inclusive jet Spectra in 5 TeV p-Pb — CERN CDS: 2258273



Analysis effort with 13 TeV data

- Strong combined effort in CMS to exploit early 13 TeV low pileup data
- Number of MinimumBias analyses with similar event selections and hadron level definitions

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

HF OR

$\xi > 10^{-6}$

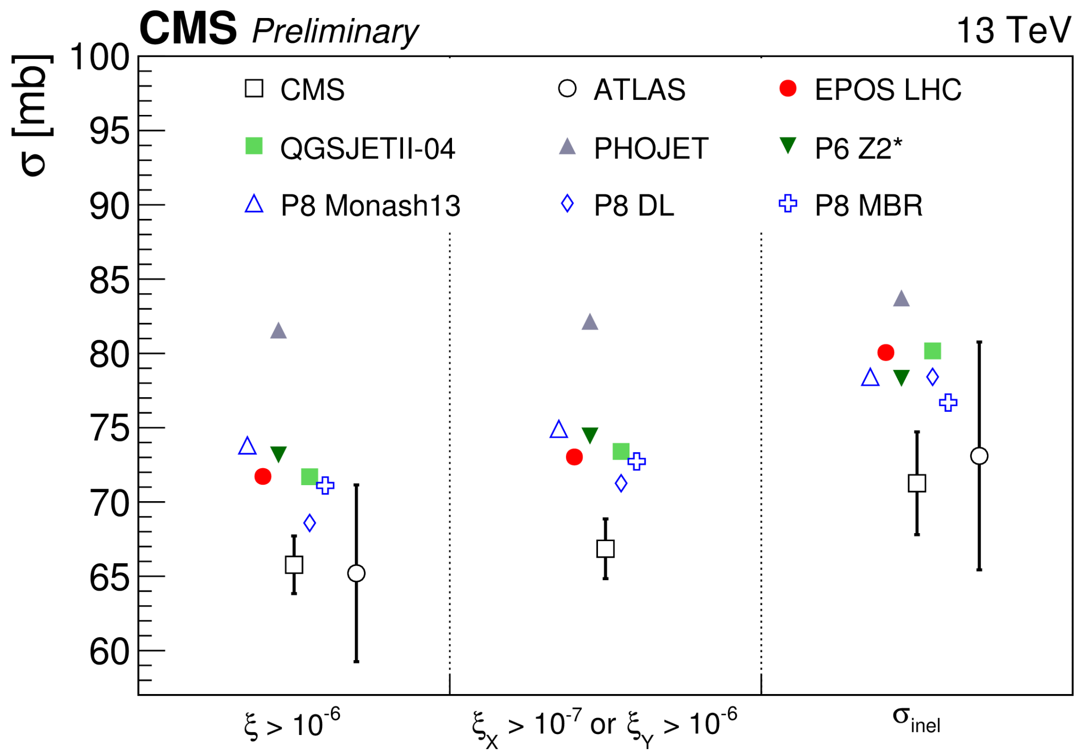
Measurement of σ_{inel}

- Two acceptances, HF only and HF or CASTOR

HF OR	HF OR CASTOR
$\xi > 10^{-6}$	$\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}$

- With CASTOR
  - Experimental uncertainties are reduces
  - Covered phase space in increased
  - Smaller extrapolation uncertainties

Measurement of σ_{inel}



$\sigma(\xi > 10^{-6}) = 65.8 \pm 0.8\ (\text{exp.}) \pm 1.8\ (\text{lum.})\ \text{mb}$

$\sigma(\xi_X > 10^{-7} \text{ or } \xi_Y > 10^{-6}) = 66.9 \pm 0.4\ (\text{exp.}) \pm 2.0\ (\text{lum.})\ \text{mb}$

Measurement of forward $dE/d\eta$

Average energy density per pseudorapidity:

Sum of all calorimeter towers above noise level

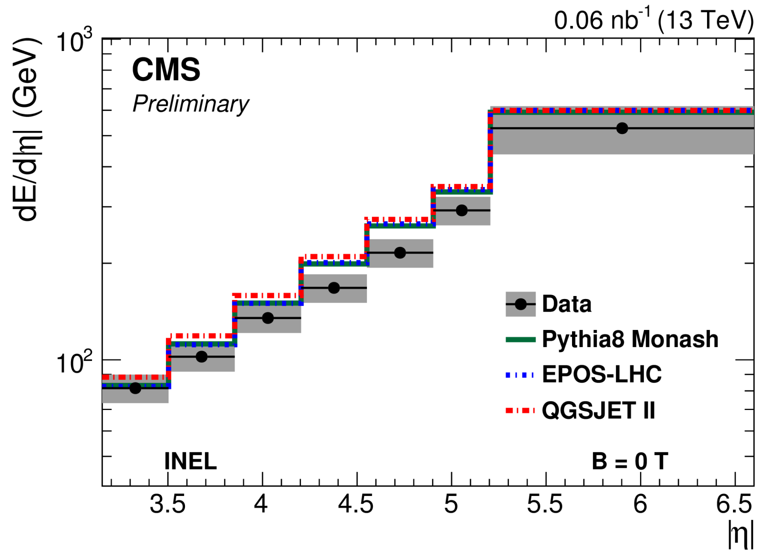
Correction from detector to stable particle level

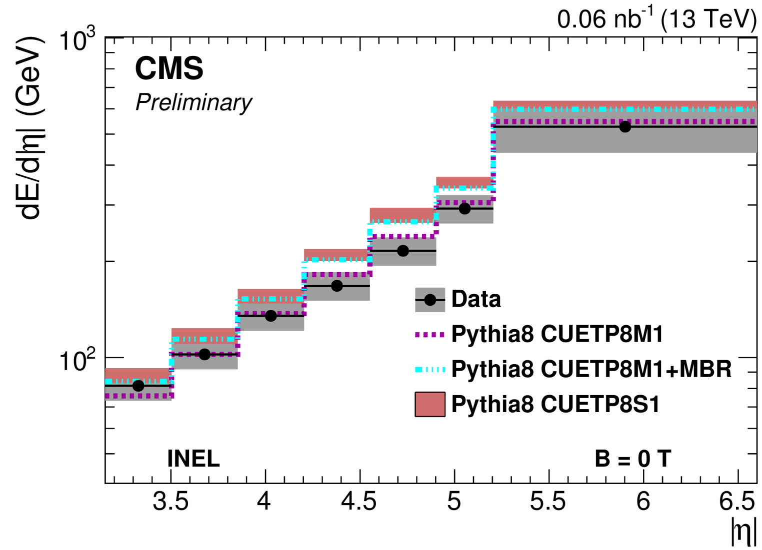
$$\frac{dE}{d\eta}(\eta) = \frac{1}{N}\frac{1}{\Delta\eta}\sum_j E_j \cdot C(PU) \cdot C(\eta)$$

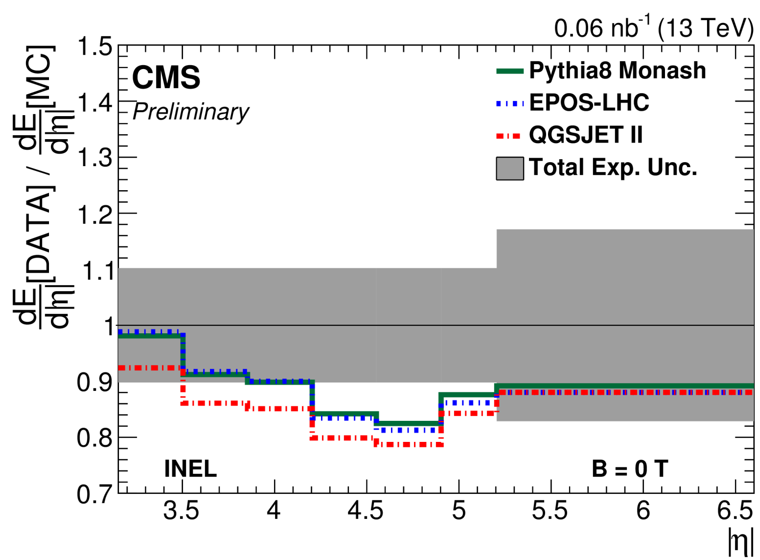
Segmentation defined by calorimeter acceptances

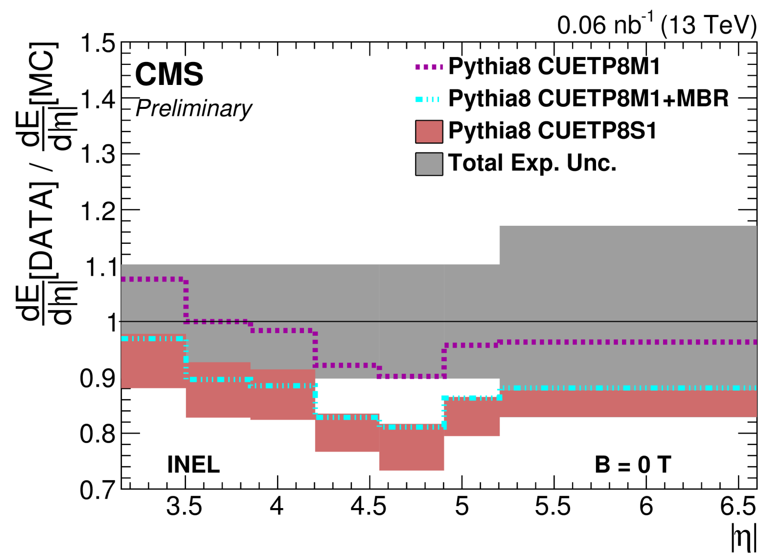
Data-driven correction for Pileup

Measurement of forward $dE/d\eta$



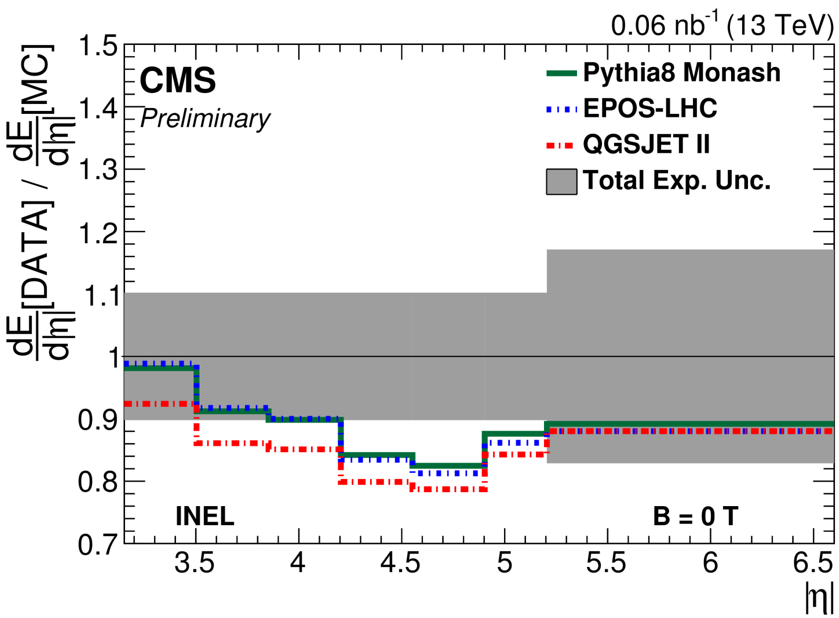


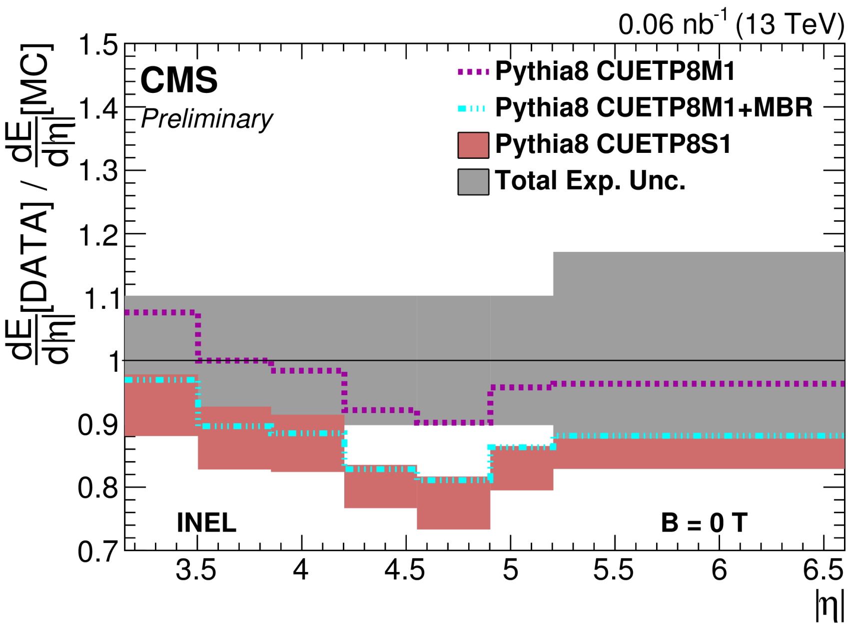




Measurement of *dE/dη*

- The spread in the model predictions is larger than tuning uncertainties
- Predictions are generally a bit too high
- Pythia8 Monash, EPOS LHC, QGSJET: comparable results





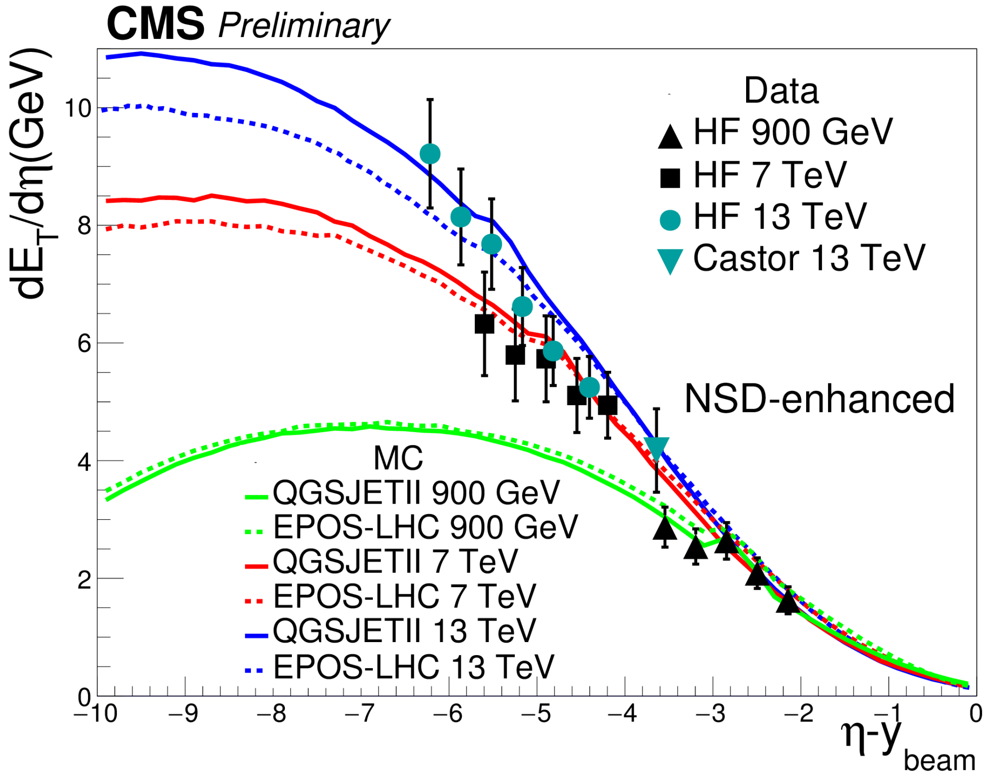
Measurement of $dE/d\eta$

Test of limiting fragmentation with new and old data:

→ Transverse energy flow as function of (pseudo-)rapidity shifted by the beam rapidity

→ converges for different √s towards 0

→ confirmed !

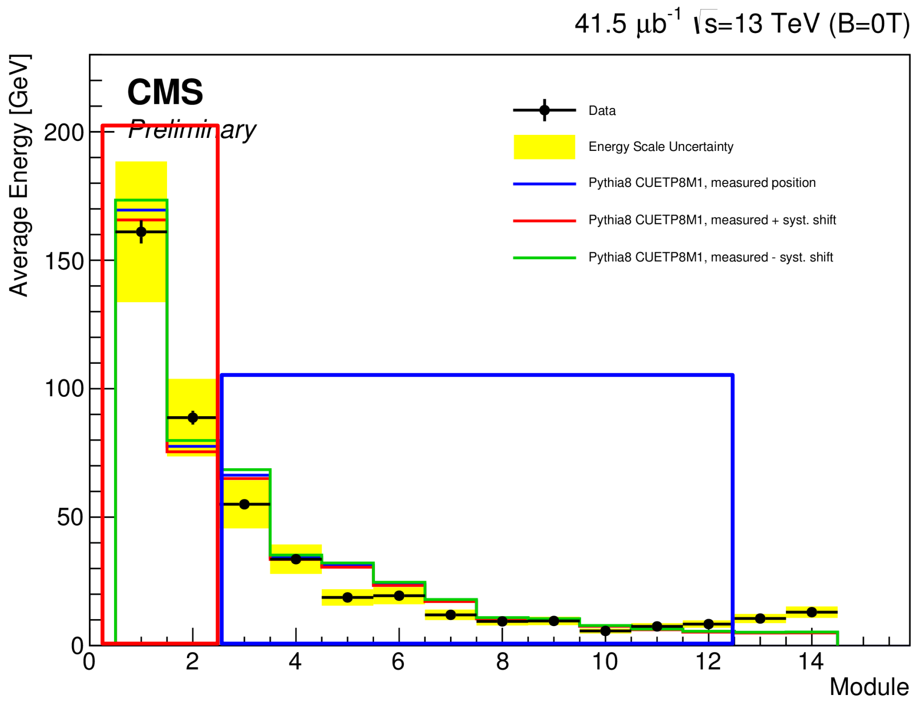


Measurement of energy spectra $d\sigma/dE$

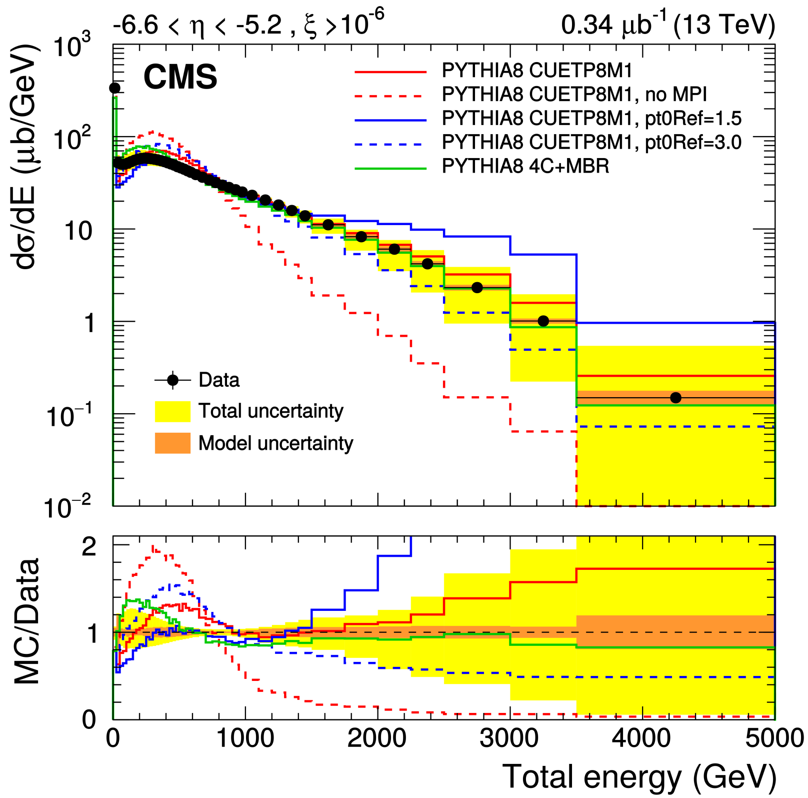
- Signal in the first two modules of CASTOR is sensitive to the electromagnetic component
- Back part measures the hadronic contribution

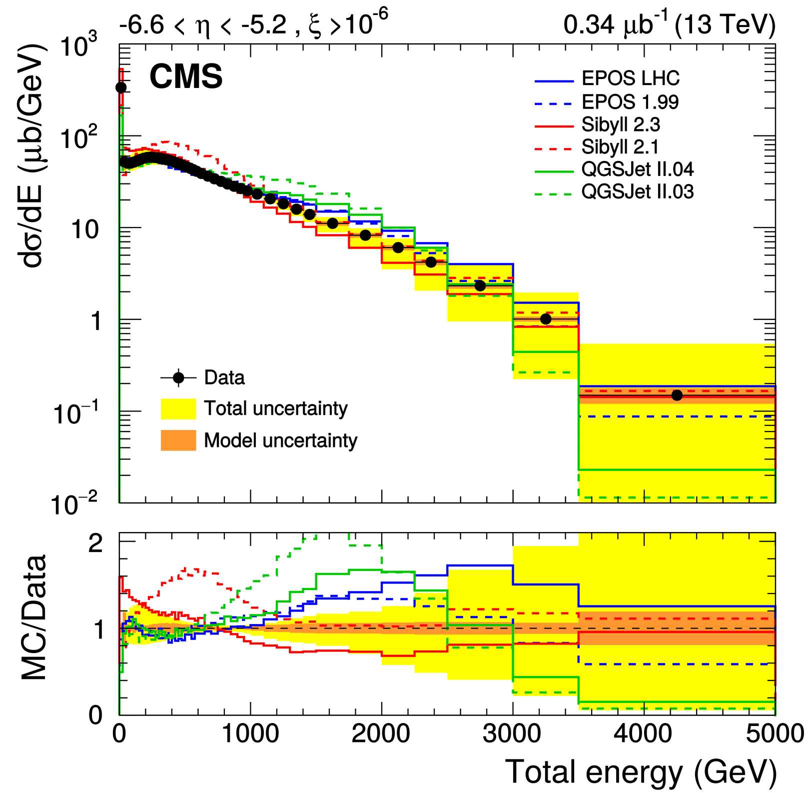
Three spectra:

Energy sum of
- all stable particles except μ, ν
- e, γ (incl. π^0)
- all stable particles except μ, ν, e, γ



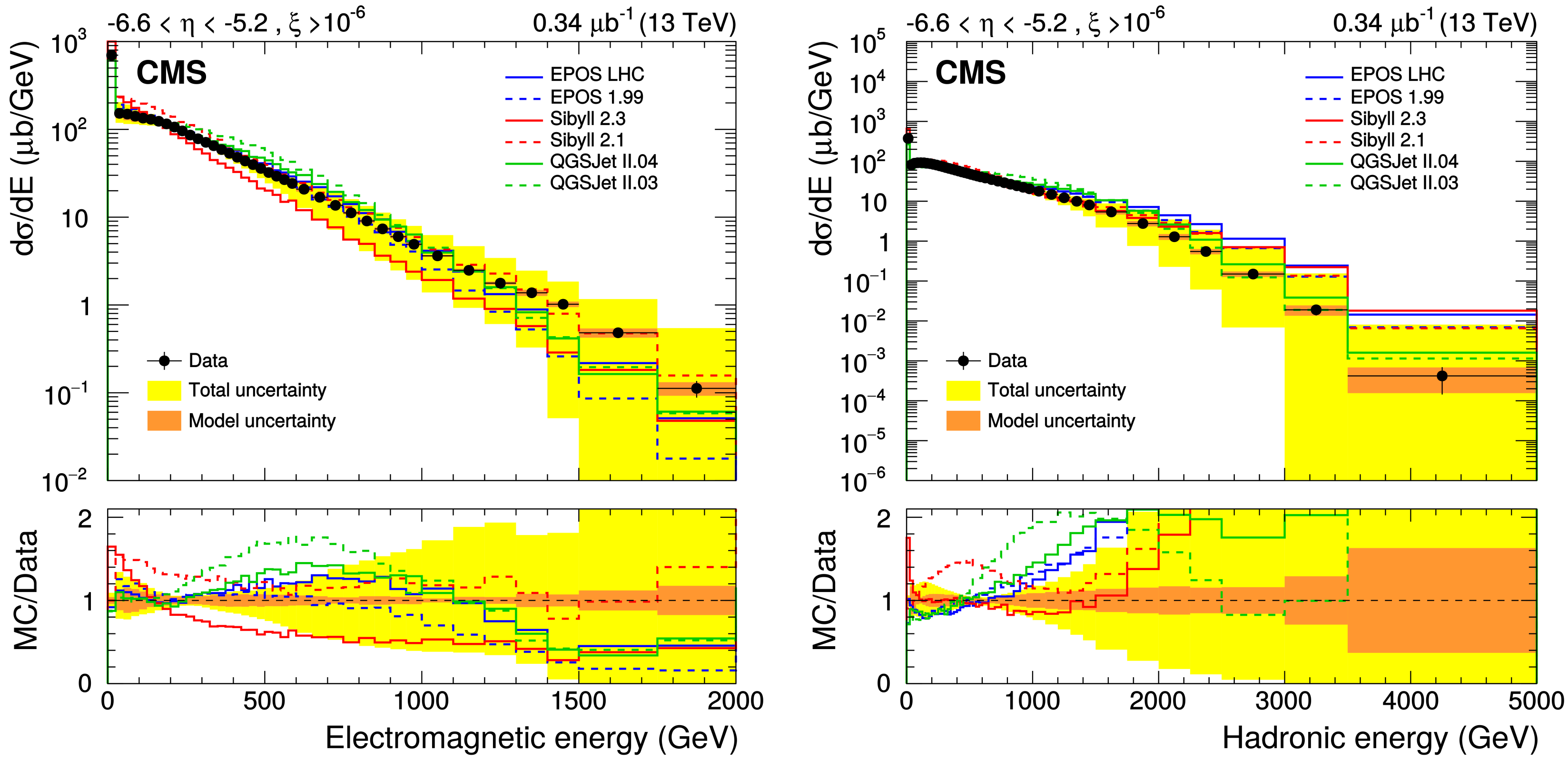
Measurement of energy spectra *dσ/dE*





- Strong sensitivity for MPI modeling in PYTHIA 8
- Strong constraints for cosmic-ray models, e.g. Sibyll 2.3
- Low energy distribution sensitive to diffraction and collision elasticity

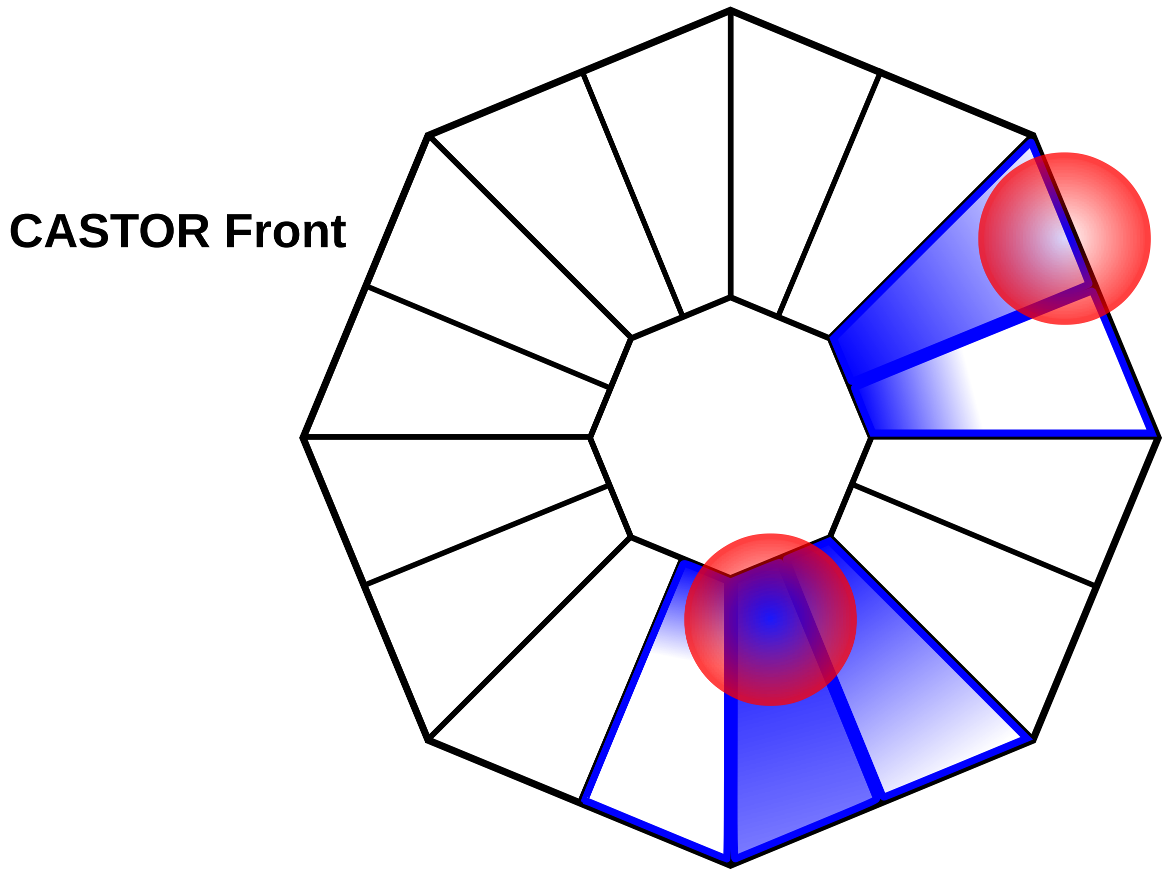
Measurement of energy spectra *dσ/dE*



- Separation into electromagnetic and hadronic energy reveals more features of the models

Measurement of very forward jets

- CASTOR towers are clustered into jets with anti-kt radius 0.5
- Matched to particle level jets also clustered with anti-kt 0.5



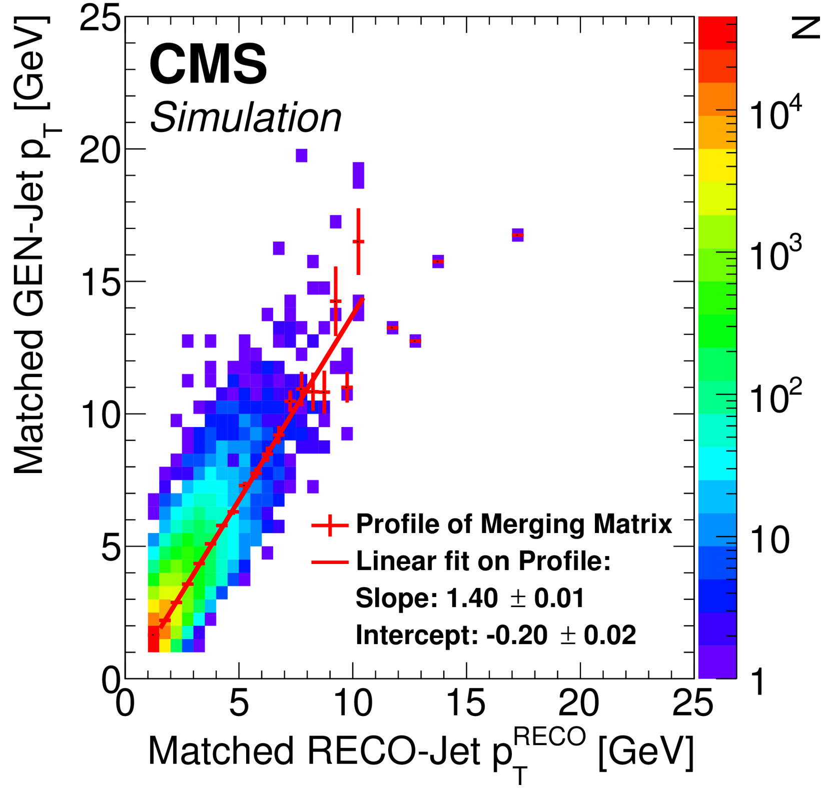
$$p_{\mathrm{t}} > 3\,\mathrm{GeV}$$

$$-5.2 > \eta > -6.6$$

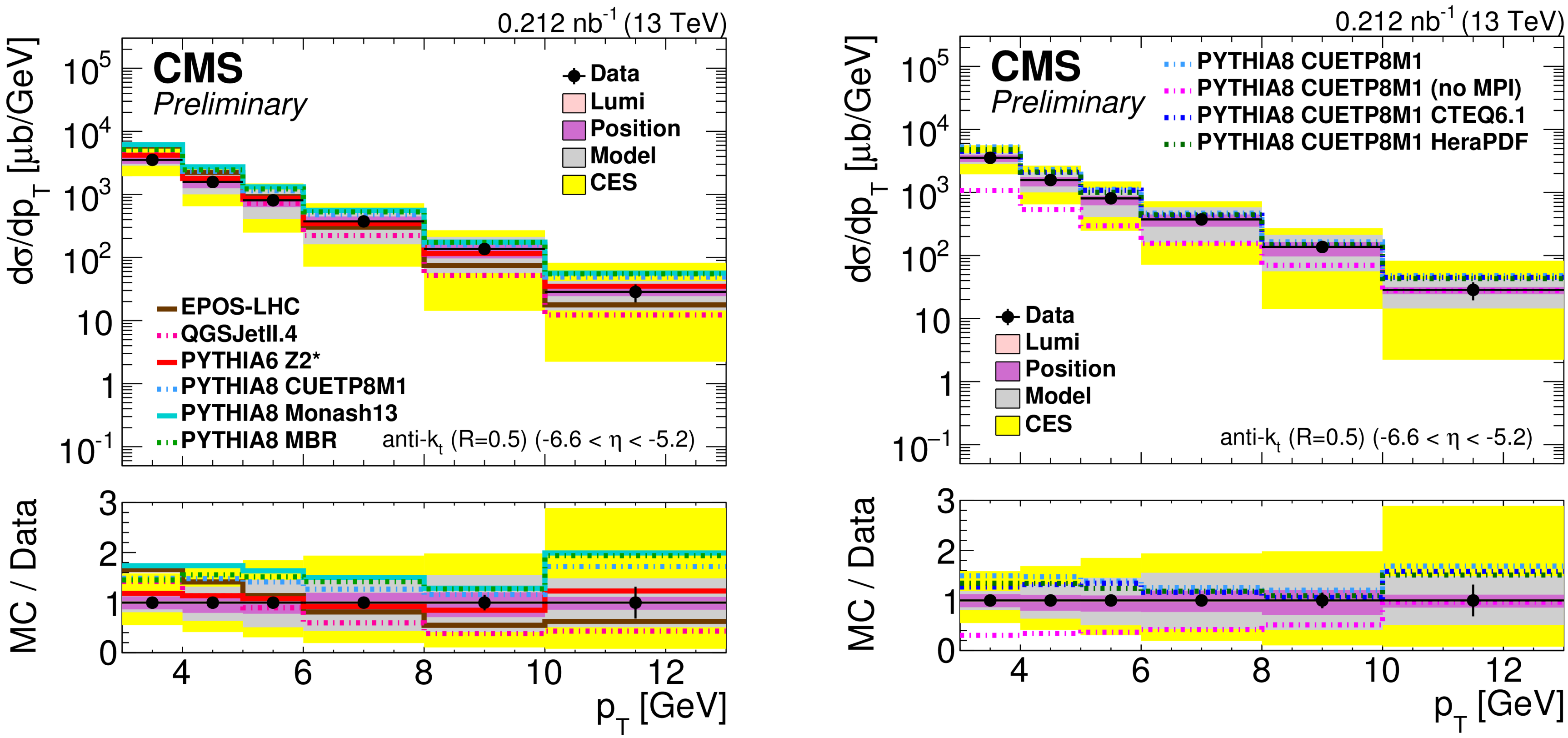
Measurement of very forward jets

- First order Jet Energy Calibration:
  → Simulation based correction
  for first order detector effects

- Followed by full unfolding of the measured spectra



Measurement of very forward jets



- Systematic uncertainties – especially jet energy scale – are very large
- proper MPI description in PYTHIA8 is important to describe low-pt part
- EPOS LHC and QGSJetII seem to be too steep

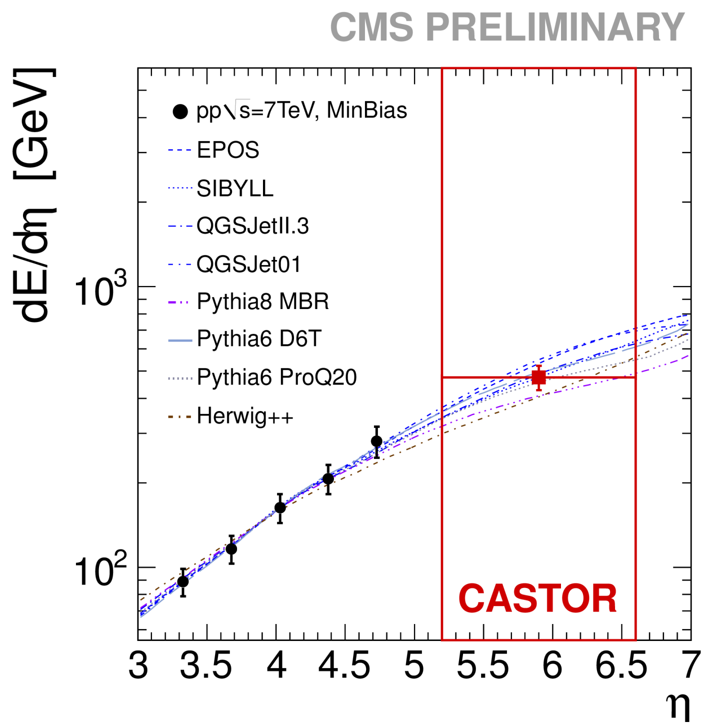
Summary

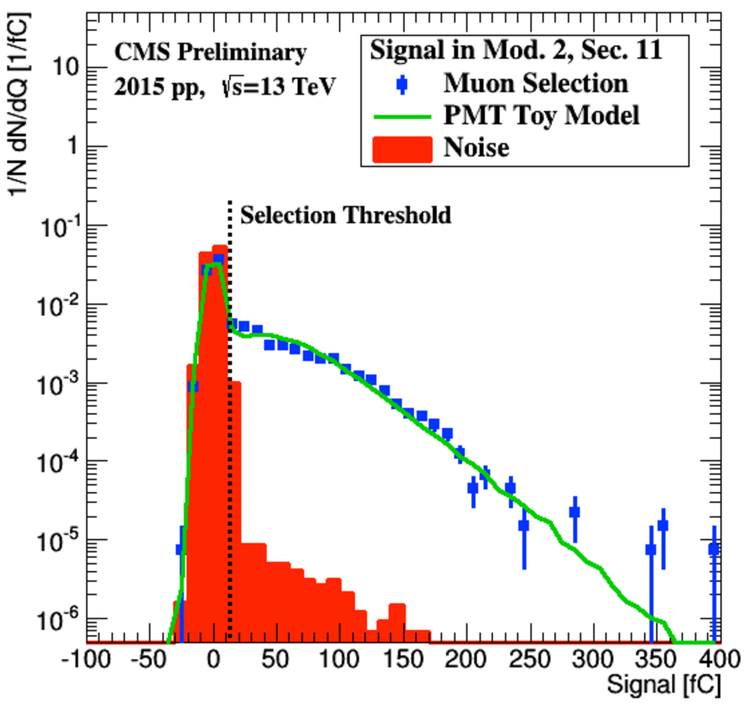
- CMS has a rich physics program in the forward phase space
  → published a nice set of measurements
- Measurement of the inelastic cross section profits from the extended phase space with CASTOR
  → Preliminary results public on http://cds.cern.ch/record/2145896 paper out soon
- The energy flow in $3.15 < |\eta| < 6.6$
  → Preliminary results public on http://cds.cern.ch/record/2146007 paper out soon
- Energy spectra in CASTOR acceptance
  → Important for MPI modeling and air-shower predictions
  → Published in [JHEP 1708 (2017) 046]
- Inclusive CASTOR jet spectra
  → Published in http://cds.cern.ch/record/2146006

Backup

Calibration of CASTOR

- Challenging calibration procedure due to exposed position
- Data-driven absolute calibration based on HF scale with independent dataset
- Channel-wise intercalibration with beam halo muons (dedicated trigger)

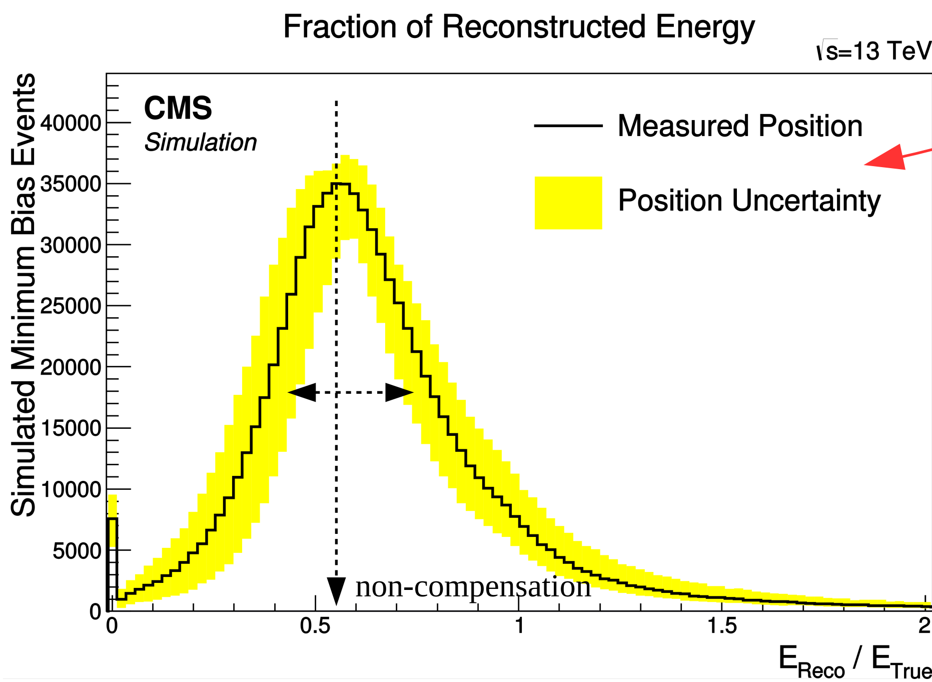


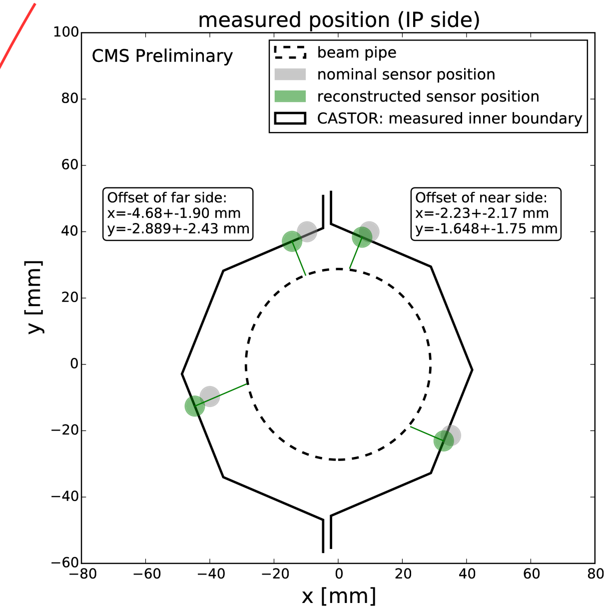


CASTOR energy scale uncertainties

- Systematic uncertainty of the energy scale:
  - → HF calibration: 10%
  - → model & extrapolation uncertainty: 10%
  - → non-compensation: 5%
  - → position uncertainty: 7%
  - → **total: 17%**

Alignment is done with infrared sensors with respect to the beampipe with precision of ~2mm

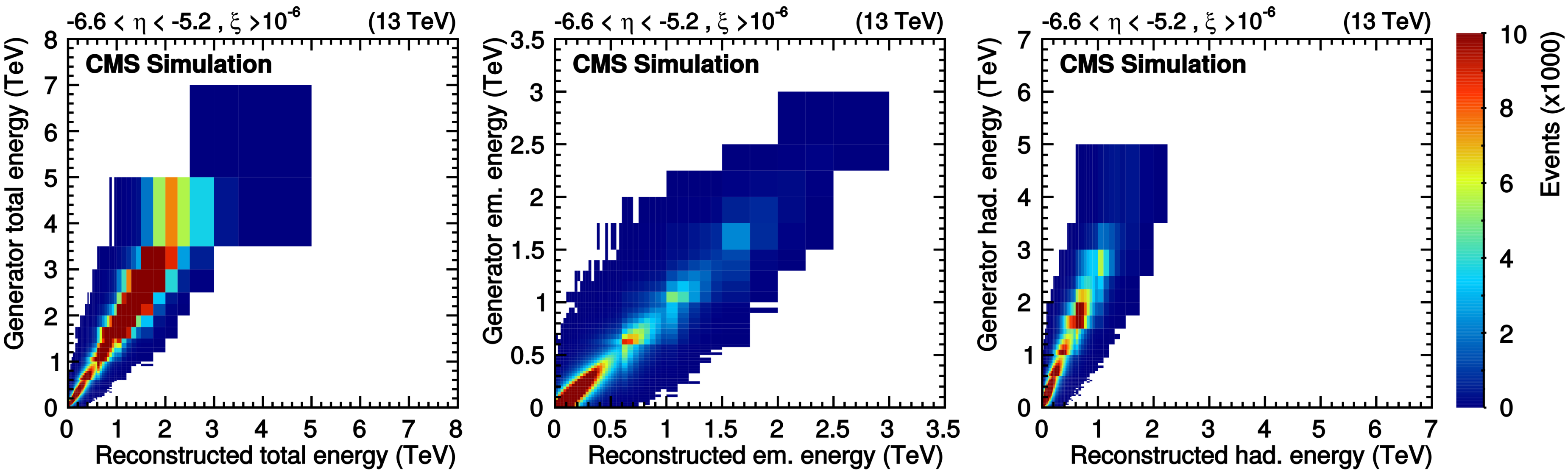




Energy reconstruction in CASTOR

- Energy resolution and calibration affected by non-compensation
- Large MonteCarlo corrections needed

Total energy | electromagn. energy | hadron. energy



$\langle E_{\text{reco}}/E_{\text{gen}}\rangle \approx 0.6$ | $\langle E_{\text{reco}}/E_{\text{gen}}\rangle \approx 1$ | $\langle E_{\text{reco}}/E_{\text{gen}}\rangle \approx 0.3$