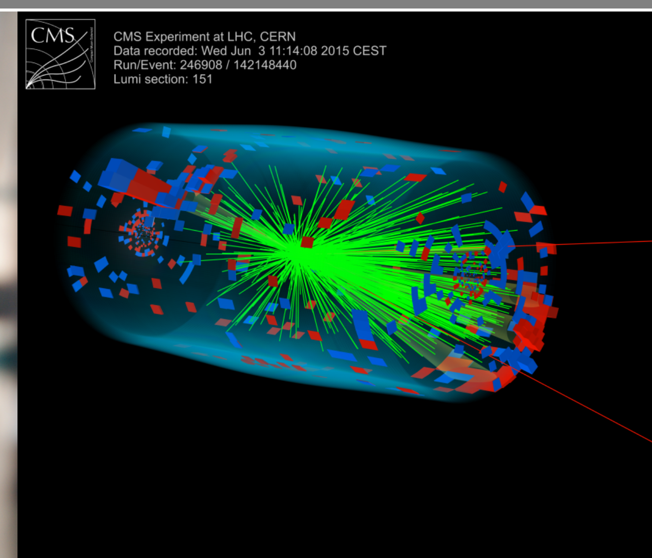
Measurements of very-forward energy with the CASTOR calorimeter of CMS

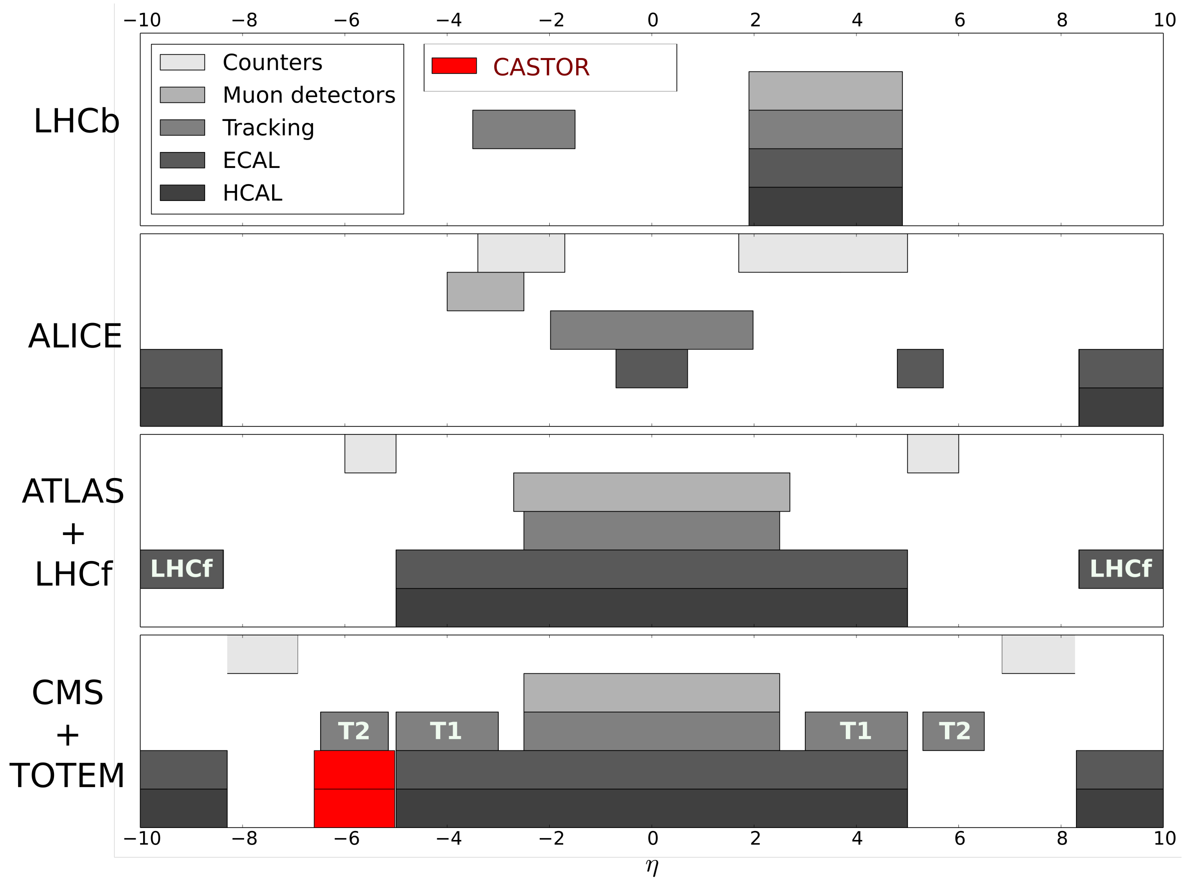
Sebastian Baur for the CMS Collaboration



Detector overview and physics motivation

Overview

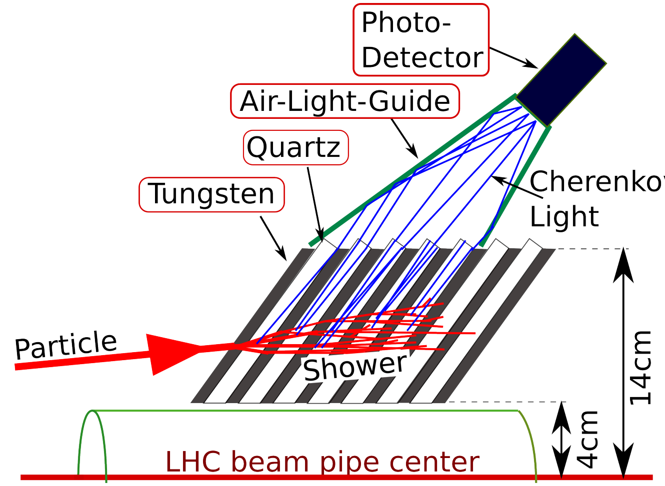
CMS has an excellent calorimetric instrumentation in the forward region with CASTOR as a unique instrument

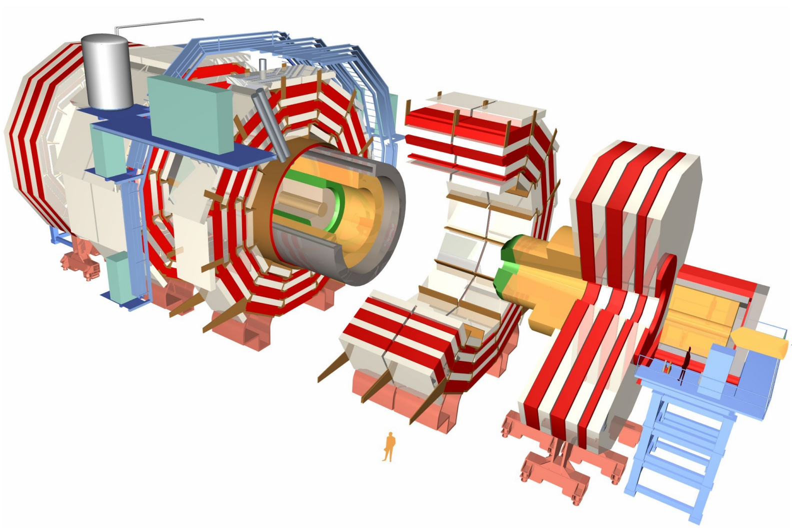


picture modified from C. Baus

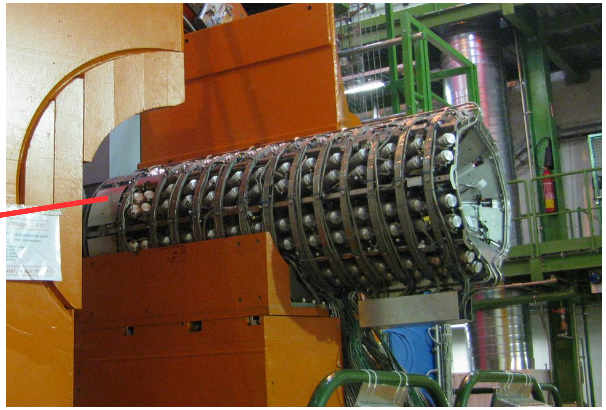
CASTOR in CMS

- Tungsten-Quartz sampling calorimeter
- Acceptance of $-6.6 < \eta < -5.2$
- Segmentation in φ and z
- Separated electromagnetic and hadronic sections with depth of $20\ X_0\ /\ 10\ \lambda_{int}$
- Energy scale known to ±15%



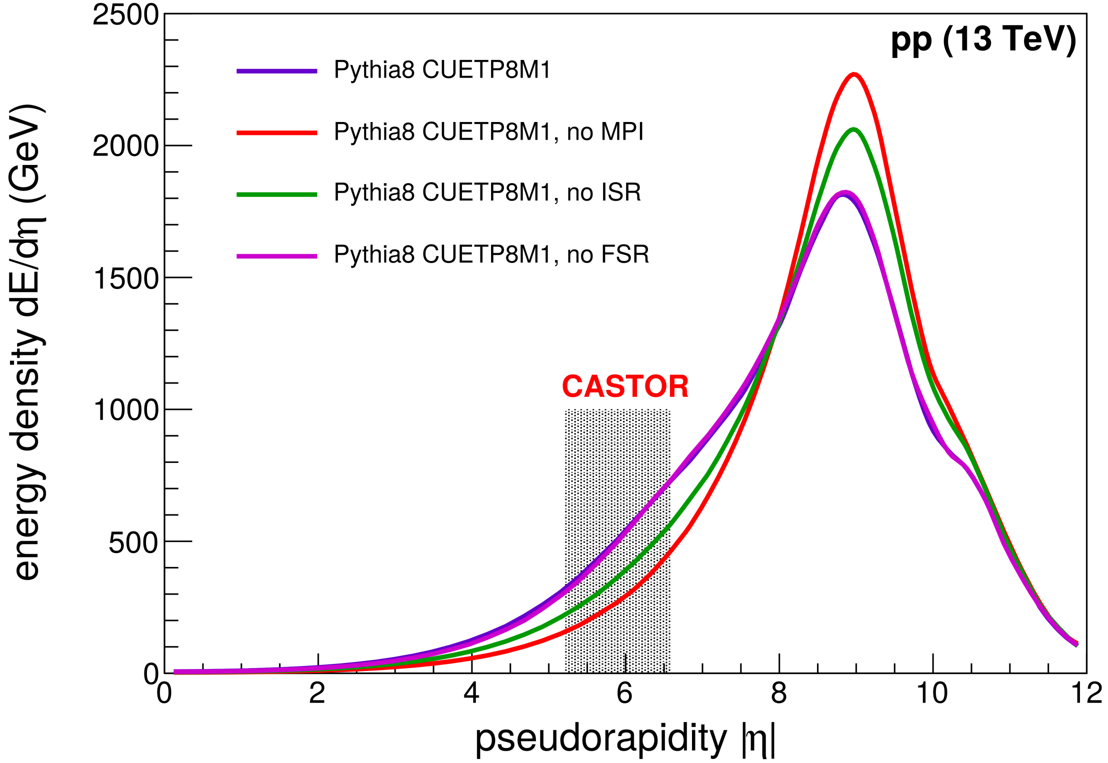


CASTOR



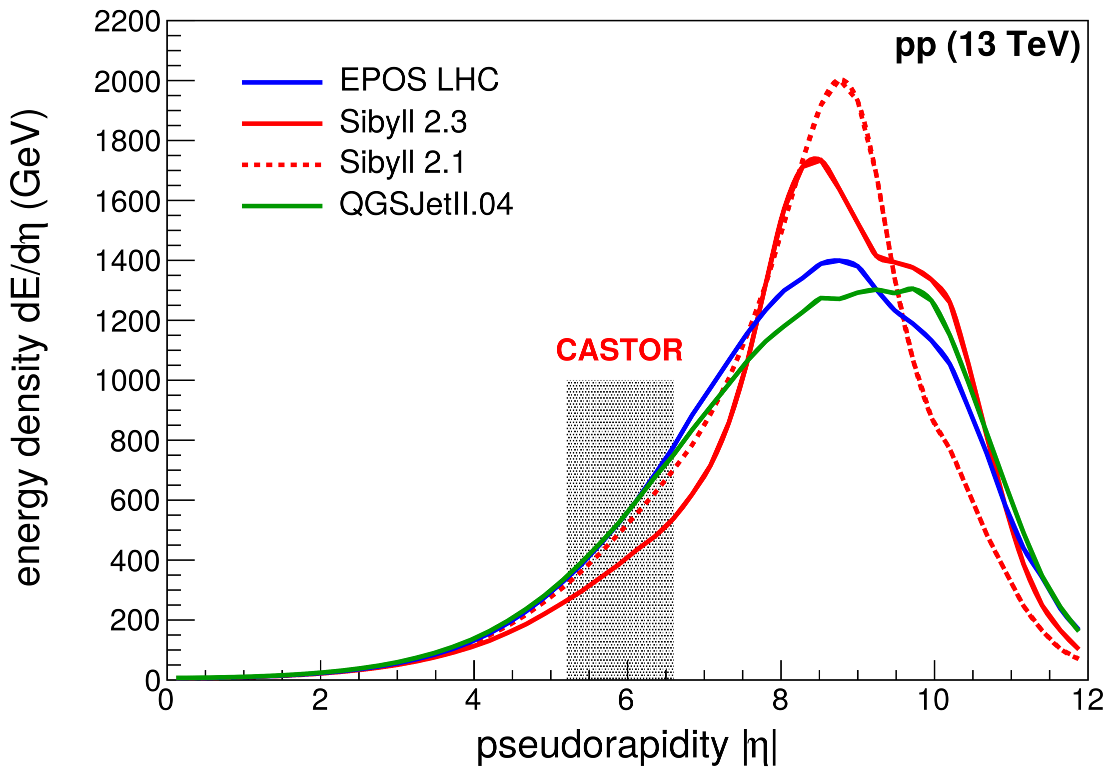
Forward physics with CASTOR

- Highest energy densities dominated by soft interactions
- Probe underlying event and especially Multiparton Interactions (MPI)



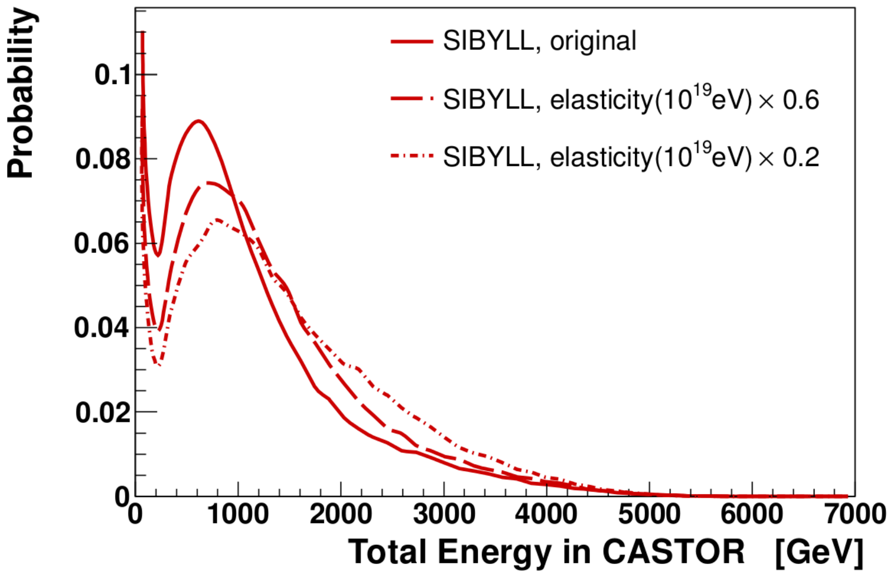
Forward physics with CASTOR

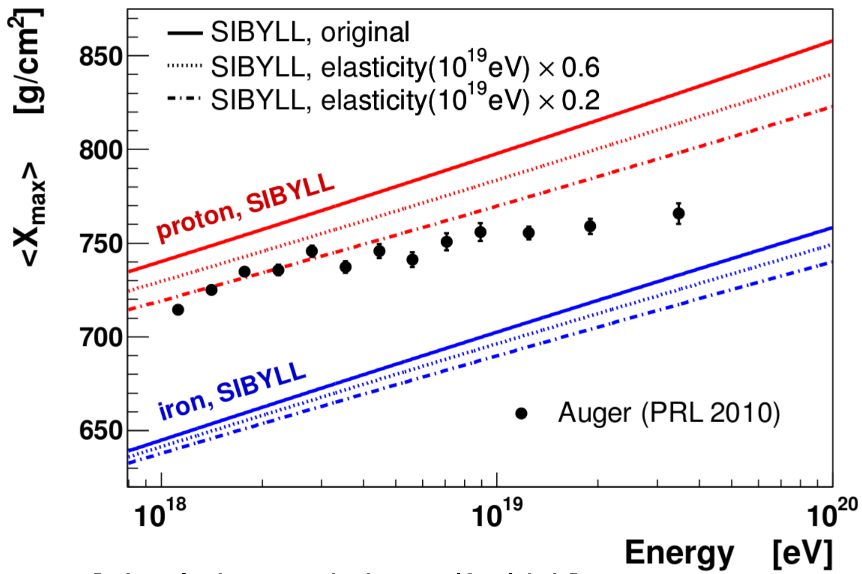
- Highest energy densities → relevant for air shower development
- Probe models for cosmic-ray air showers



Forward physics with CASTOR

- Highest energy densities → relevant for air shower development
- Probe models for cosmic-ray air showers
- Example: elasticity in Sibyll 2.1





[Simulation study by Ralf Ulrich]

Highlighted results with CASTOR

LHC Run 1: 900 GeV → 7 TeV

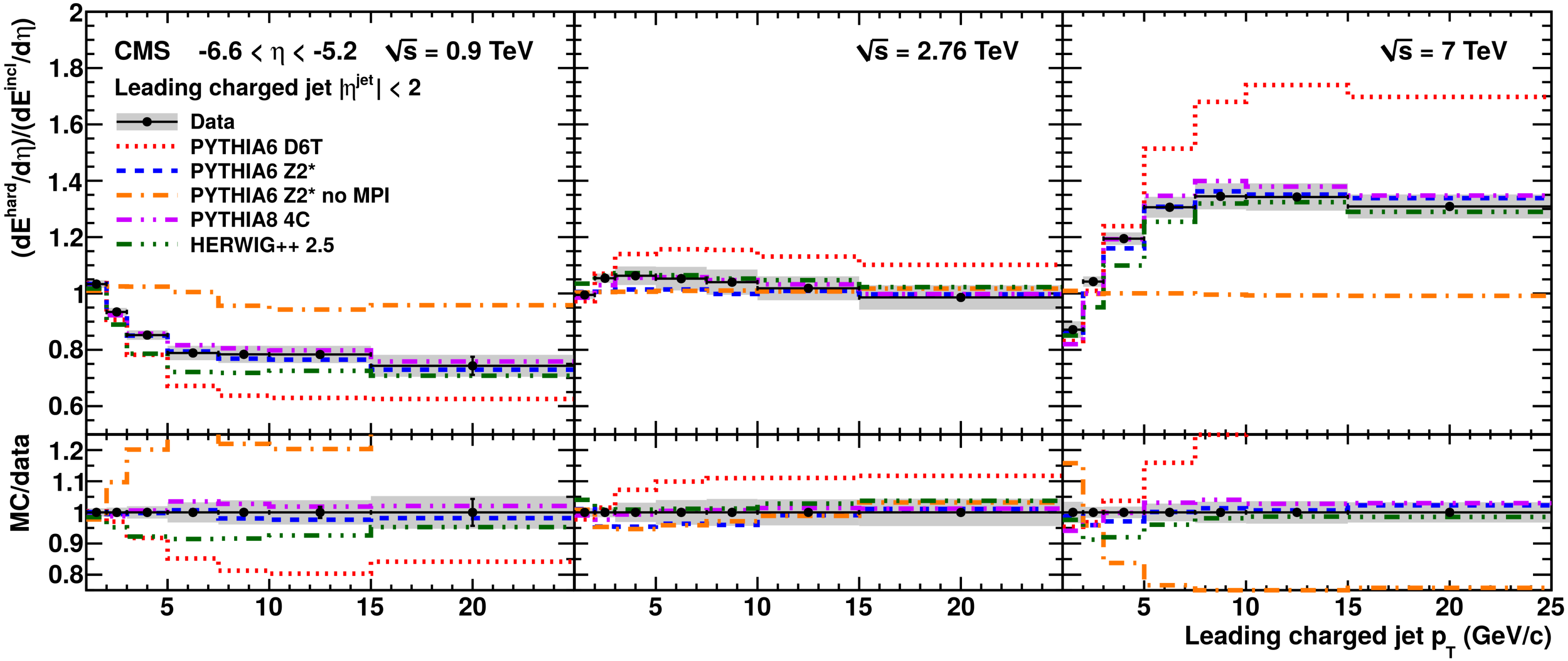
- "Study of the underlying event at forward rapidity" [JHEP 04 (2013) 072]

- Study of the CASTOR energy density
  → as function of leading jet $p_T(|\eta|<2)$ at central acceptance
    → relative to the inclusive energy density
  → as function of $\sqrt{s}$

- Mostly pre-LHC models used

Underlying event with CASTOR

[JHEP 04 (2013) 072]



decrease with collision scale

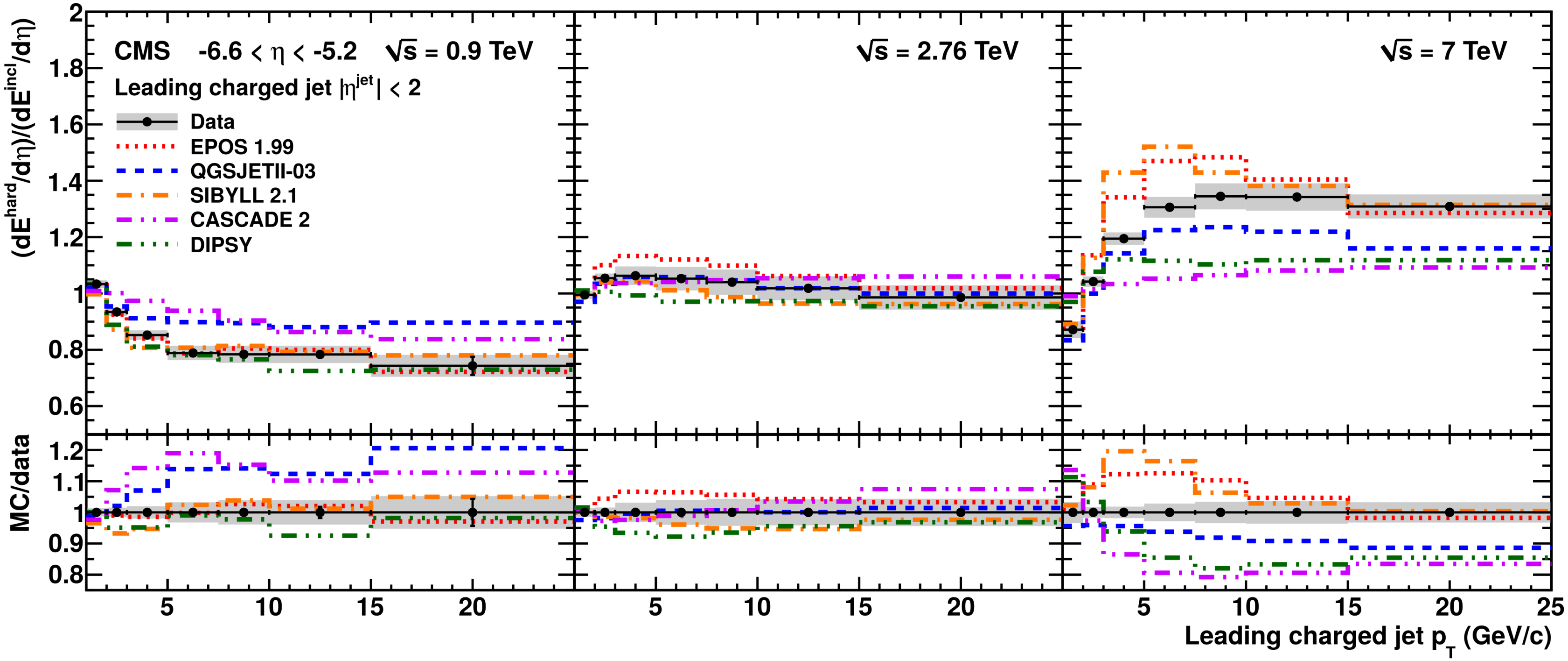
increase with collision scale

remnant fragmentation

MPI

Underlying event with CASTOR

[JHEP 04 (2013) 072]



decrease with
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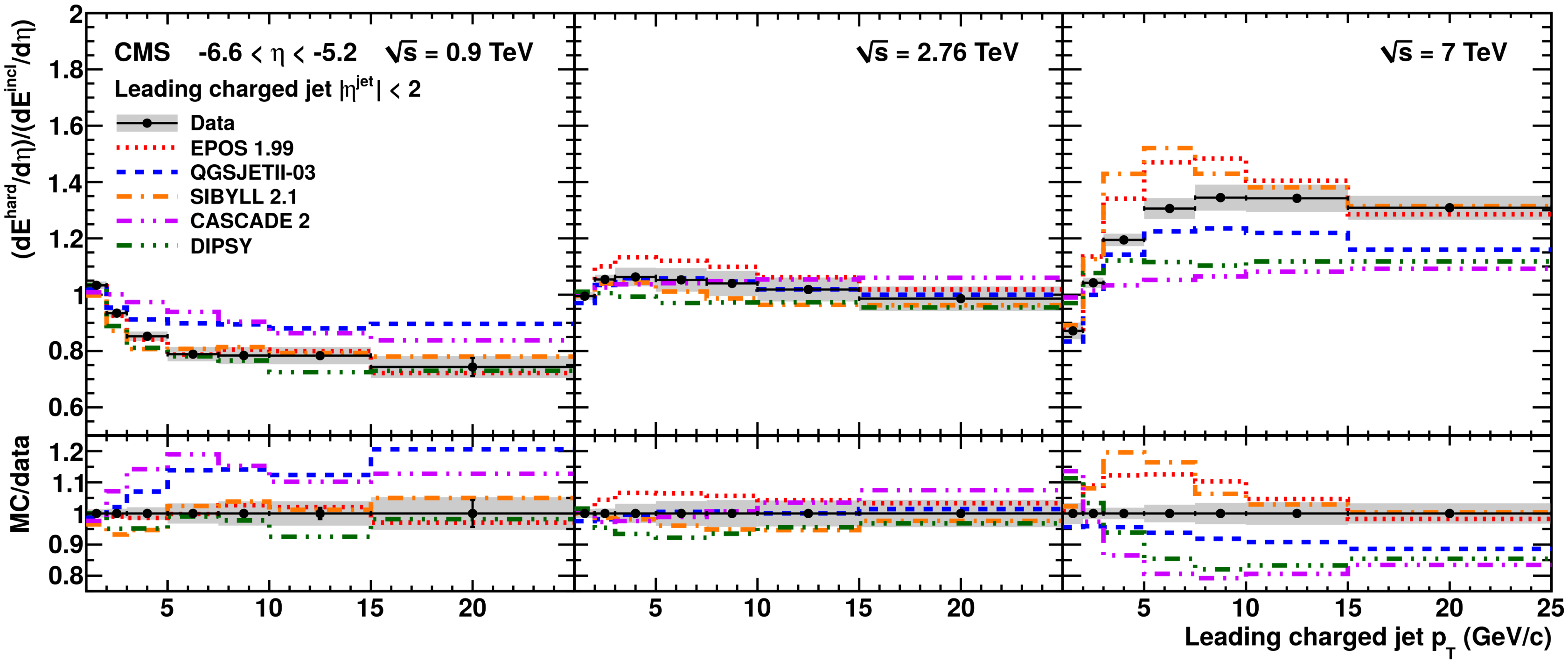
MPI

Underlying event with CASTOR

[JHEP 04 (2013) 072]

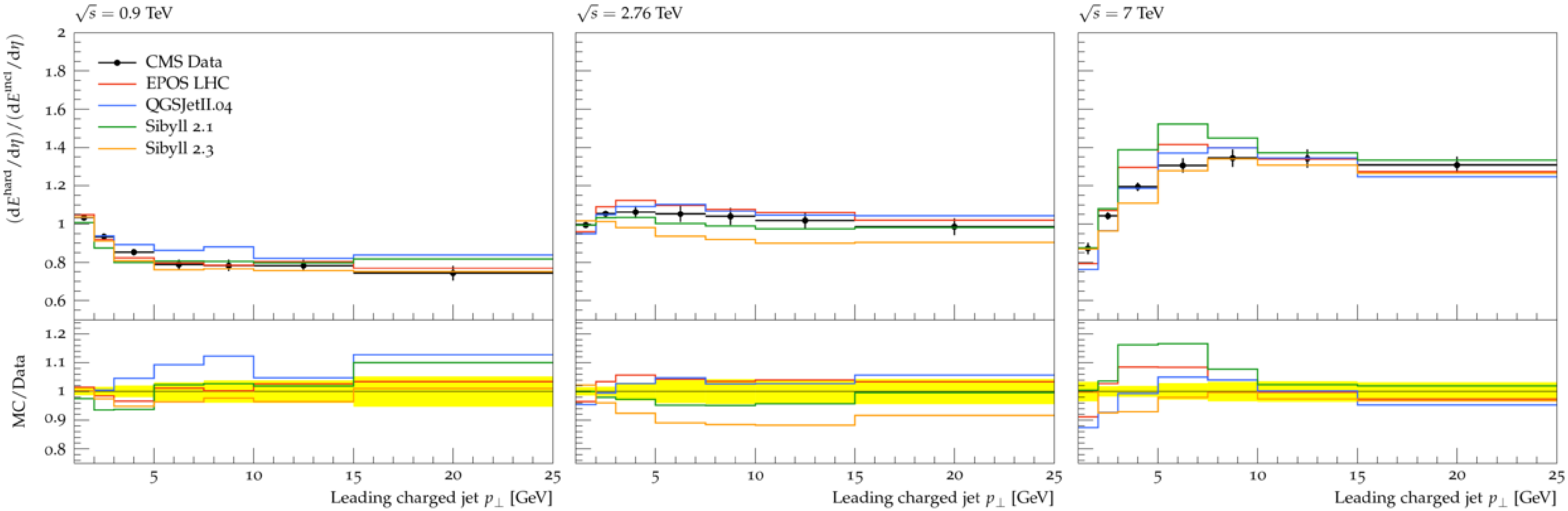


Evolution is

- Well matched by (LHC tuned) PYTHIA 6/8
- Underestimated by QGSJetII.03
- Overestimated by Sibyll 2.1 and EPOS 1.99

Underlying event with CASTOR

Compared to updated models *(using Rivet plugin CMS_2013_I1218372)*:



- No significant changes from EPOS 1.99 to EPOS LHC
- Better description by new versions
  - QGSJetII.04 and
  - Sibyll 2.3

LHC Run 2: 13 TeV pp

- Strong combined effort in CMS to exploit early 13 TeV low pileup data
- Number of MinimumBias analyses with consistent event selections and particle 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

$\xi > 10^{-6}$

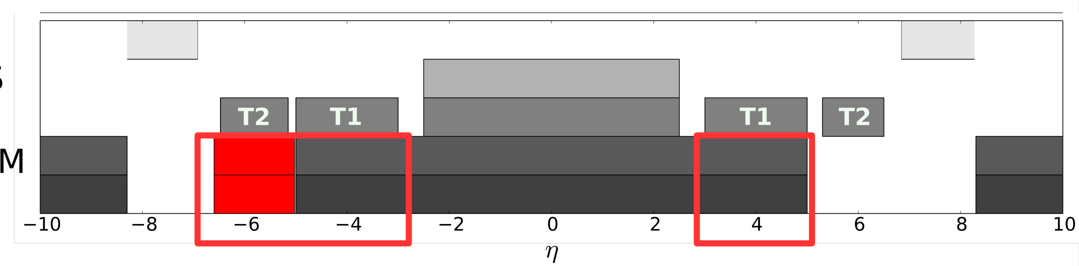
Measurement of forward $dE/d\eta$

Average energy density per pseudorapidity:
→ CMS-PAS-FSQ-15-006, CERN CDS 2146007

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

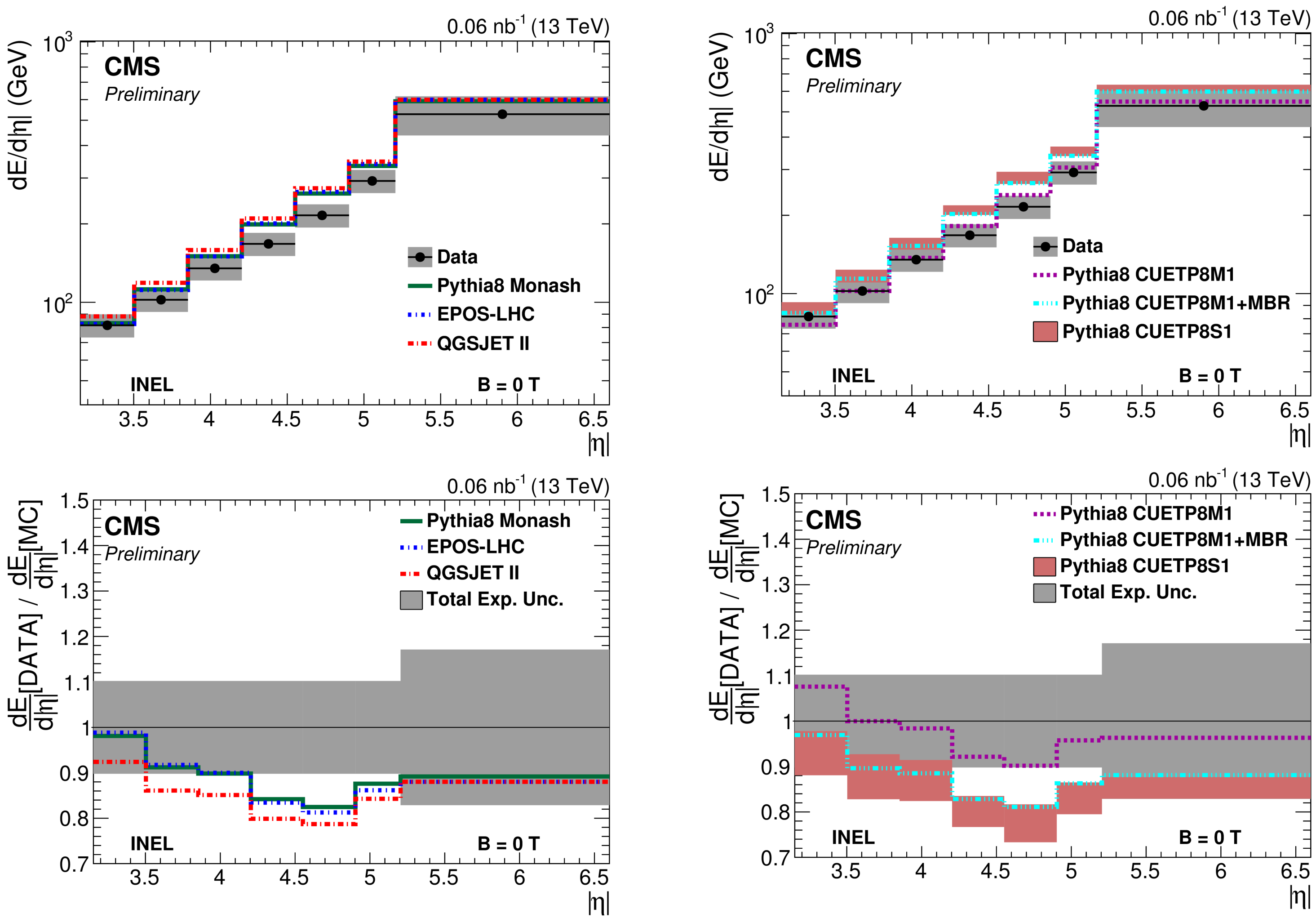
Sum of all calorimeter towers above noise level

Segmentation defined by calorimeter acceptances



Combining HF and CASTOR acceptances
→ $3.15 < |\eta| < 6.6$

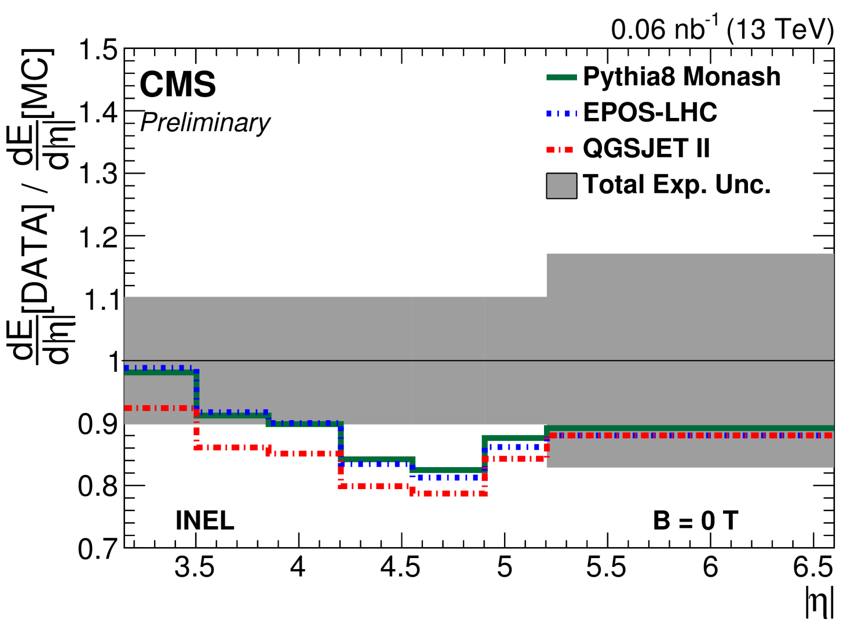
Measurement of forward $dE/d\eta$

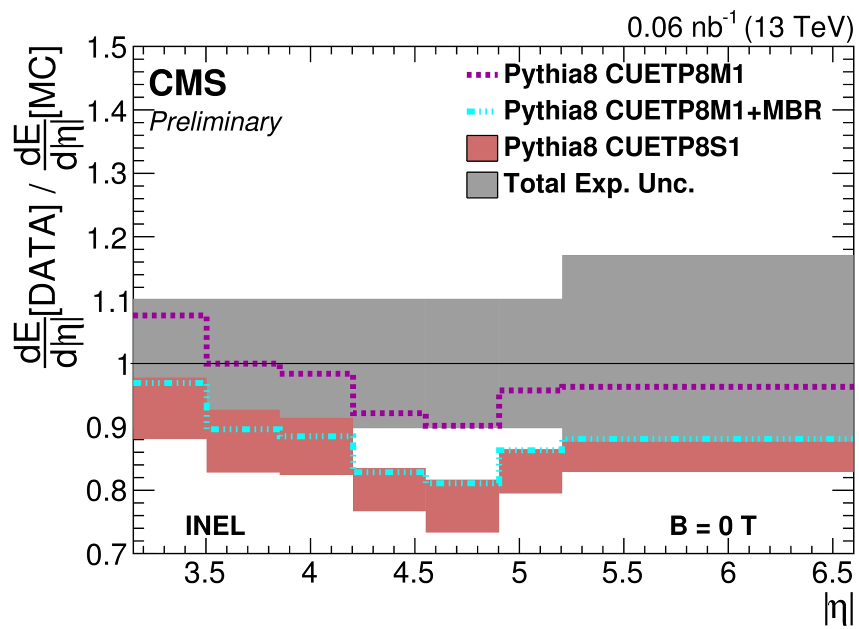


[CMS-PAS-FSQ-15-006]

Measurement of $dE/d\eta$

- Predictions are generally a bit too high
- PYTHIA8 Monash, EPOS LHC, QGSJetII.04: comparable results
- CUETP8M1 and CUETP8S1 differ in PDF choice
  → spread is larger than tuning uncertainties





[CMS-PAS-FSQ-15-006]

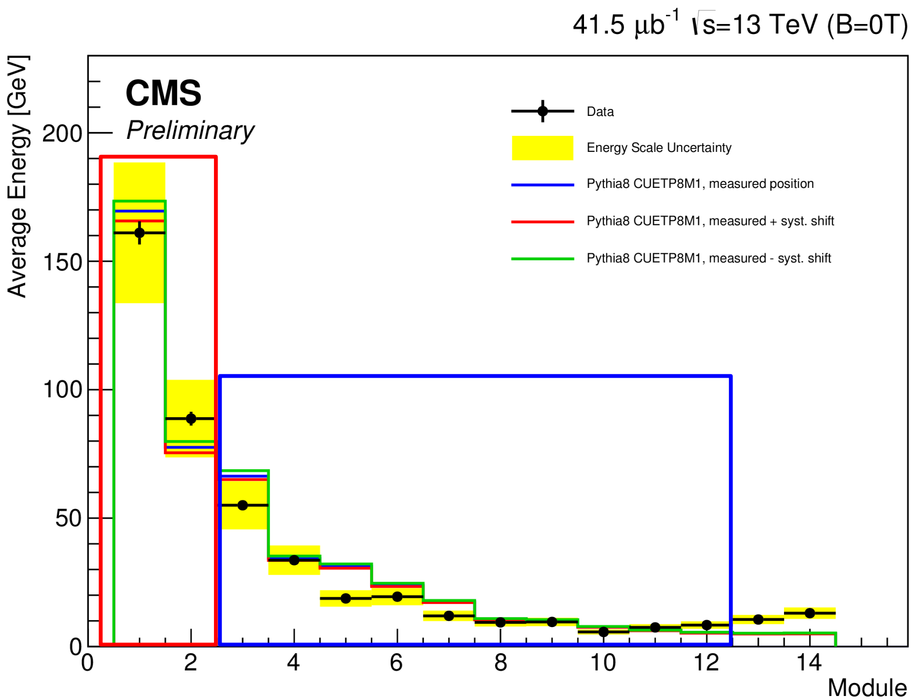
Measurement of energy spectra $d\sigma/dE$

- Total energy: Sum all calorimeter towers above noise threshold
- Signal in the first two modules of CASTOR is sensitive to the electromagnetic component
- Back part measures the hadronic contribution

Three spectra:
(normalized to the cross section)

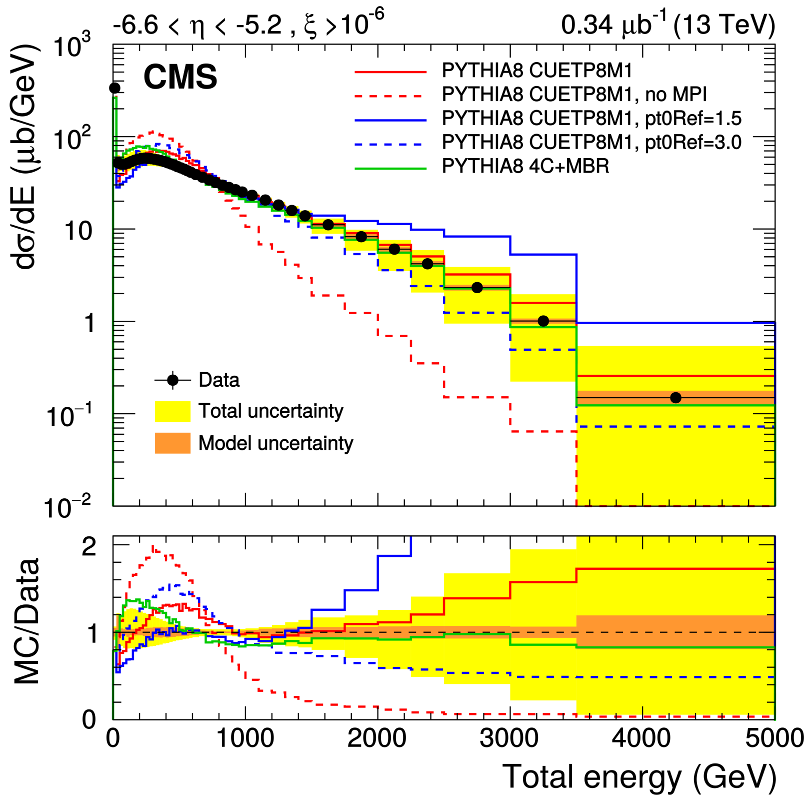
Energy sum of
- all stable particles except μ, ν
- e, γ (incl. π^0)
- all stable particles except μ, ν, e, γ

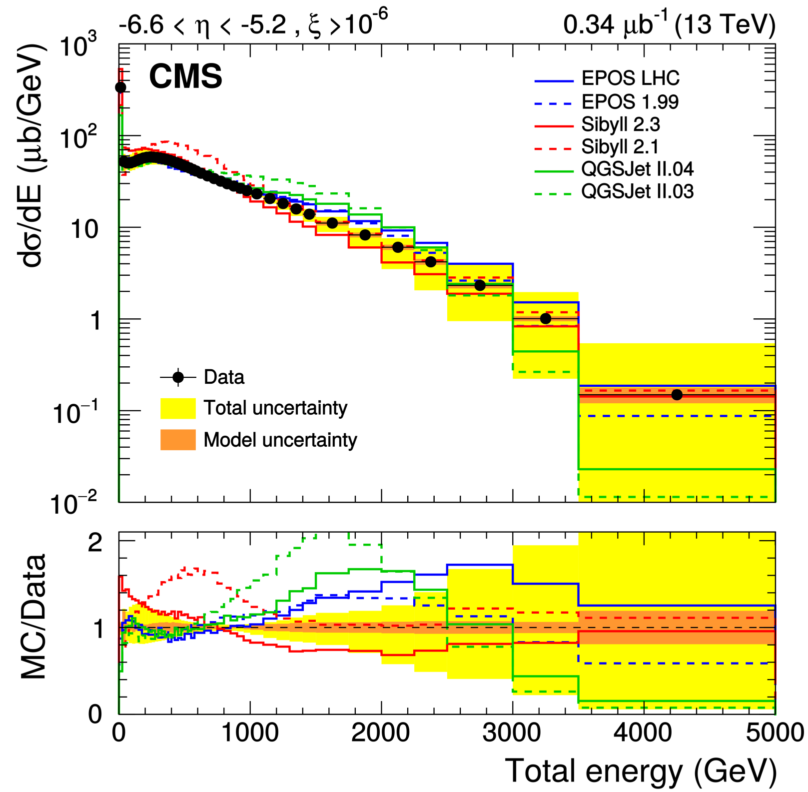
[JHEP 08 (2017) 046]



Measurement of energy spectra *dσ/dE*

[JHEP 08 (2017) 046]

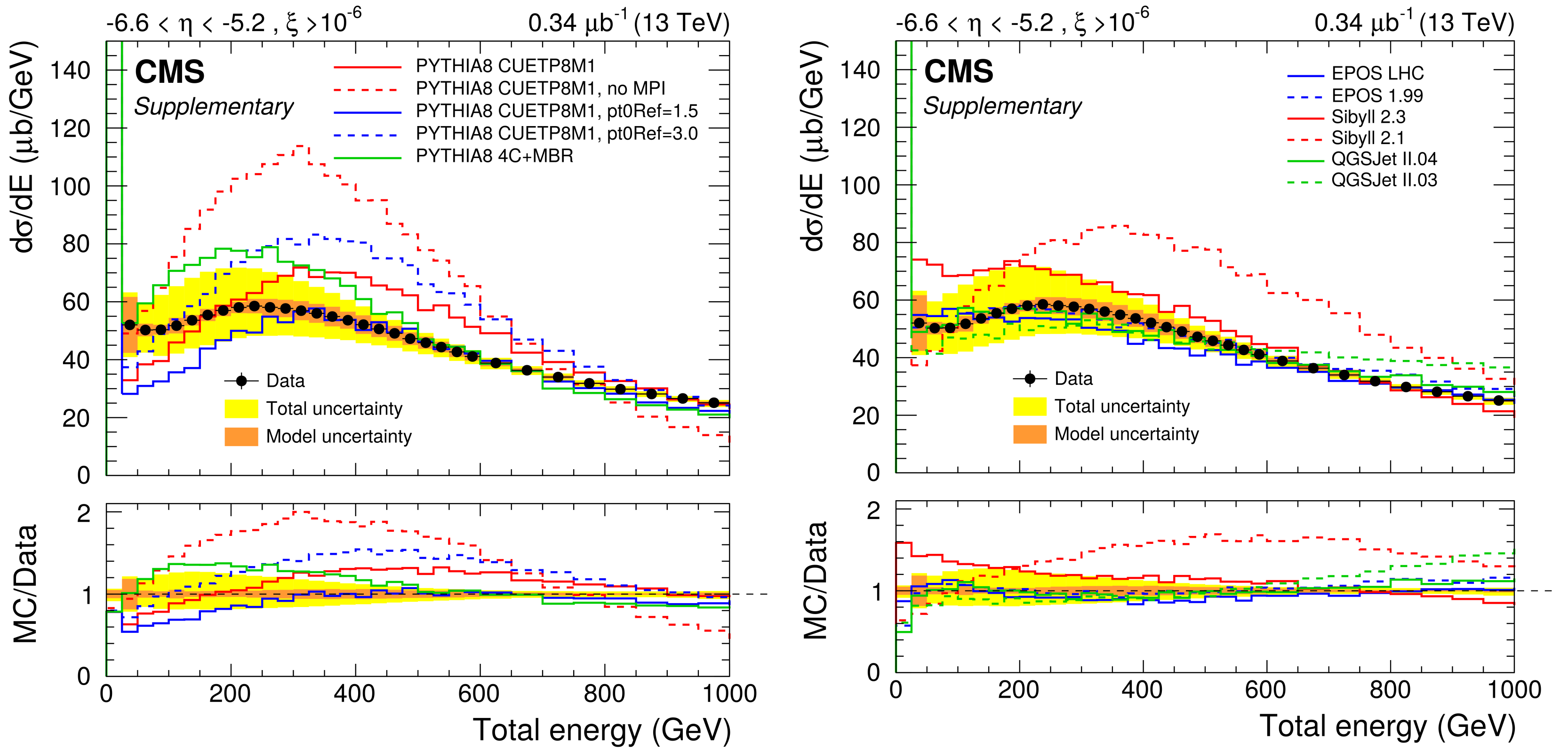




- Strong sensitivity for MPI modeling in PYTHIA 8
- Strong constraints for cosmic-ray models, generally good performance
- Low energy distribution sensitive to diffraction and collision elasticity

Measurement of energy spectra *dσ/dE*

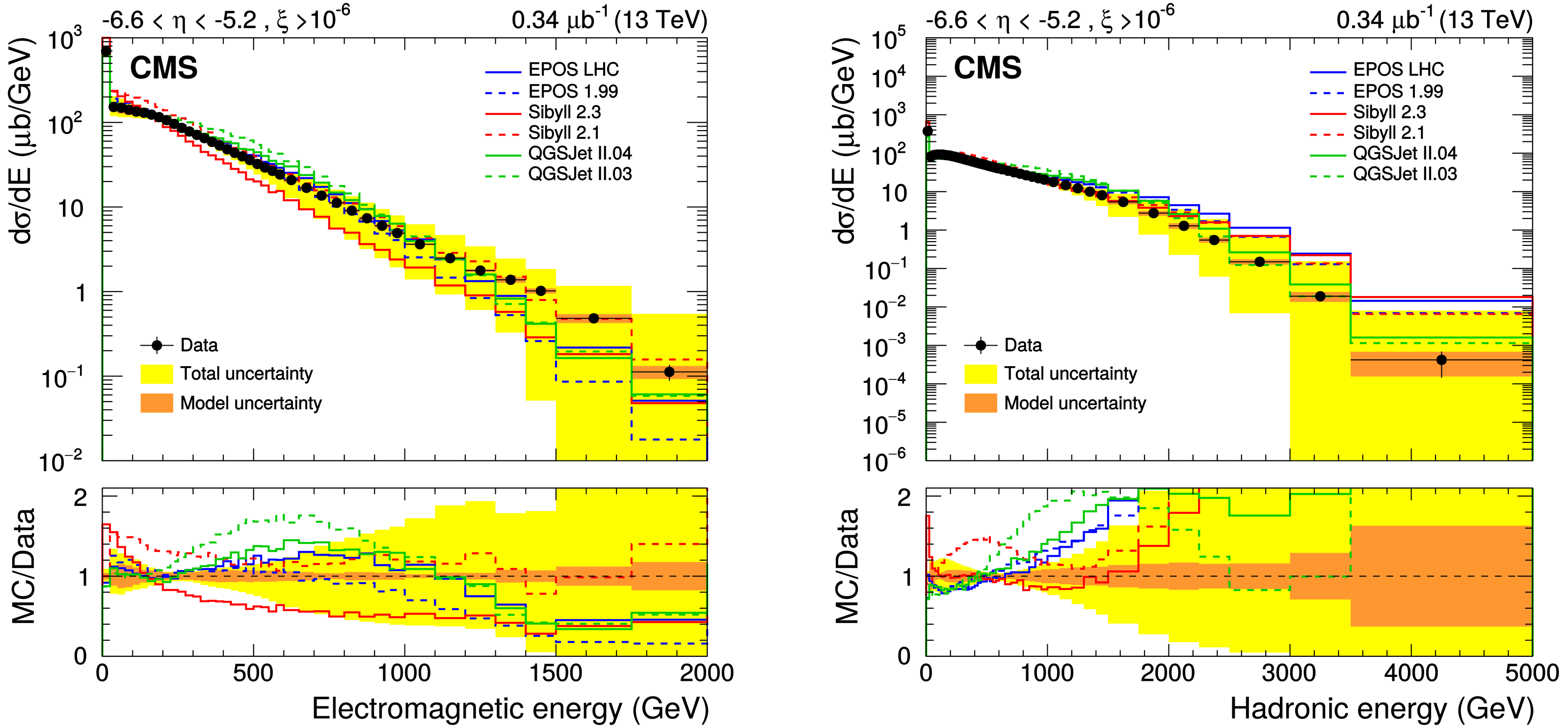
[JHEP 08 (2017) 046]



- Low energy distribution sensitive to diffraction and collision elasticity
  PYTHIA8 4C+MBR ↔ CUETP8M1
  EPOS / QGSJetII / Sibyll 2.1 ↔ Sibyll 2.3

Measurement of energy spectra *dσ/dE*

[JHEP 08 (2017) 046]



- Electromagnetic energy in general very well described;
  Sibyll 2.3 has significantly less e.m. energy than Sibyll 2.1 and as data
- Hadronic energy: All models are on the upper edge of the uncertainties
- No room to boost muon production

Summary

- CMS has a unique and well understood forward instrumentation
- Especially CASTOR provided some very interesting set of measurements:

→ Relative energy density as function of central jet p_T [JHEP 04 (2013) 072]

  → probe UE strength at different center-of-mass energies

  → transition between remnant fragmentation and MPI dominated regime

→ Forward energy density in $3.15 < |\eta| < 6.6$ [CMS-PAS-FSQ-15-006]

  → Already good agreement found

  → sensitive to MPI tunes and PDF

→ Inclusive energy spectra in CASTOR acceptance [JHEP 08 (2017) 046]

  → Relevant for MPI modeling and air-shower predictions

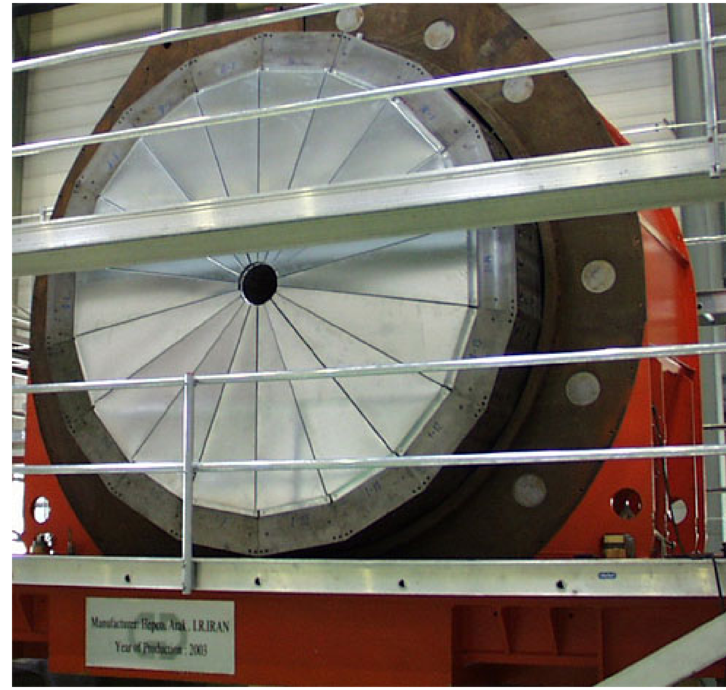
  → Sensitive to diffraction,

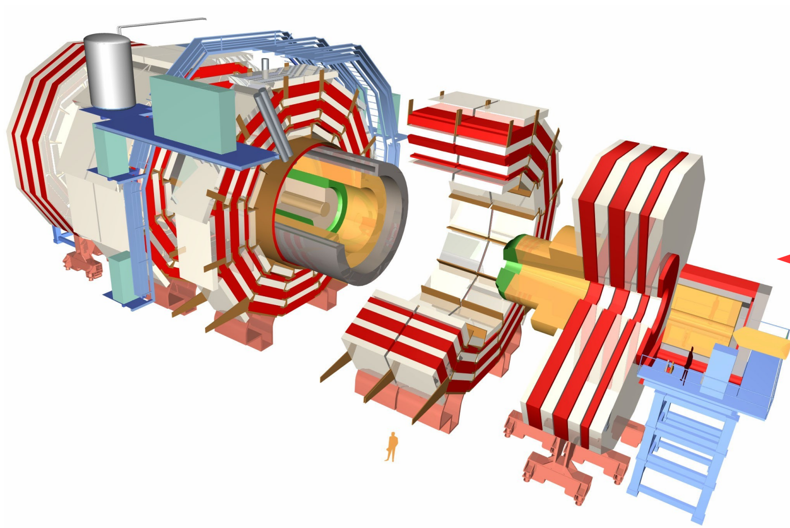
  → First em/had separation with CASTOR

Backup

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%

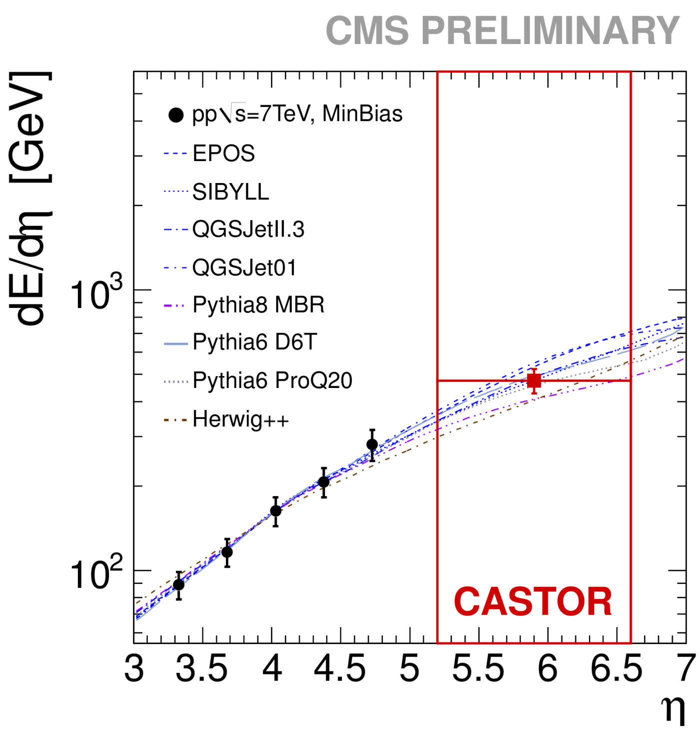


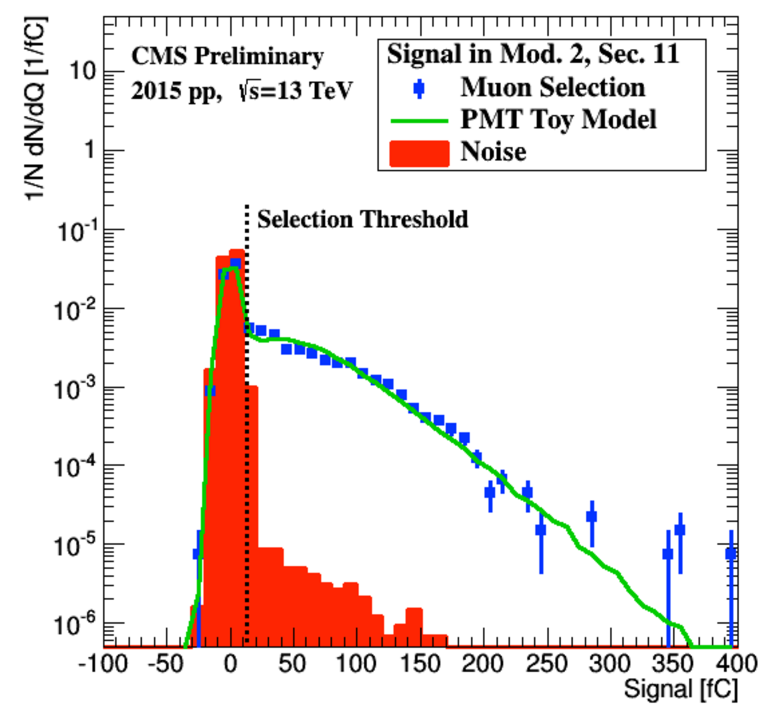


HF (**H**adron **F**orward)

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)

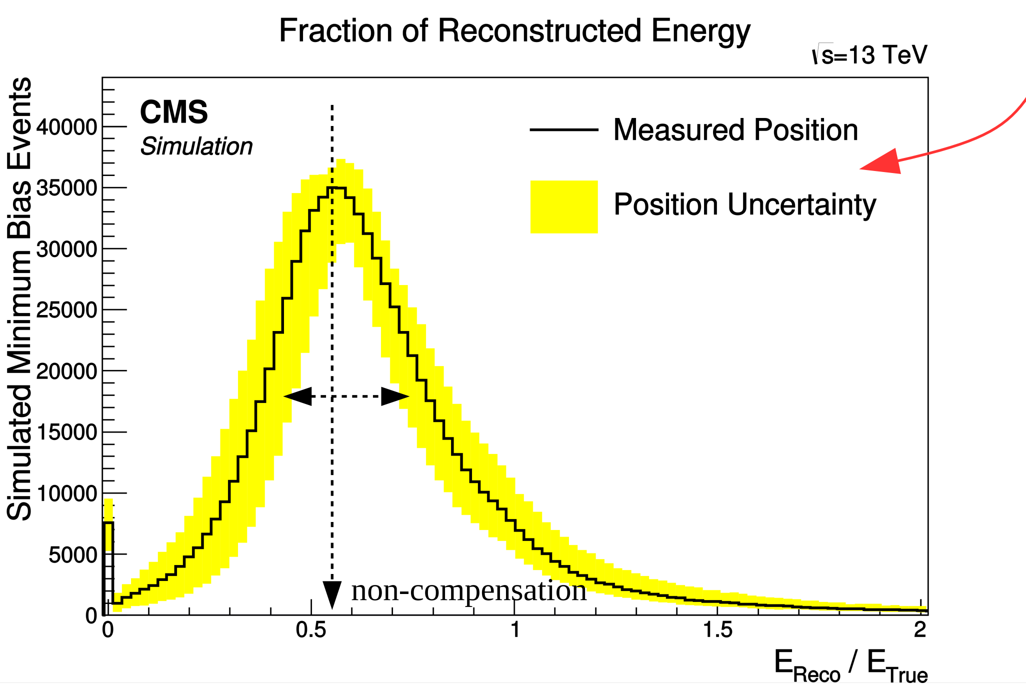


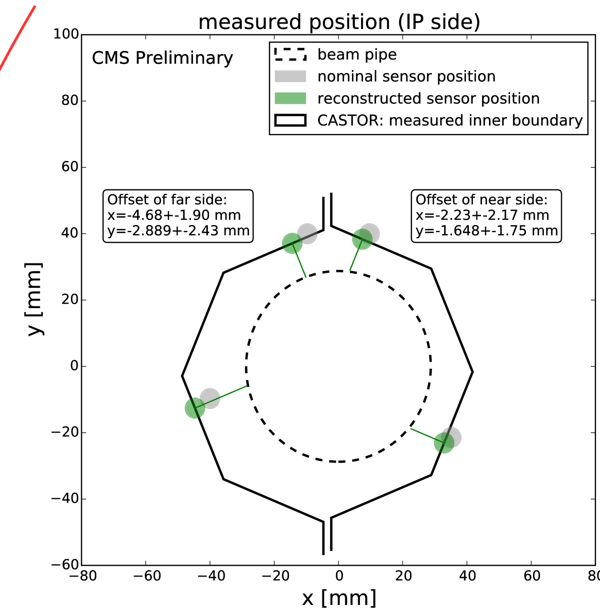


CASTOR energy scale uncertainty

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

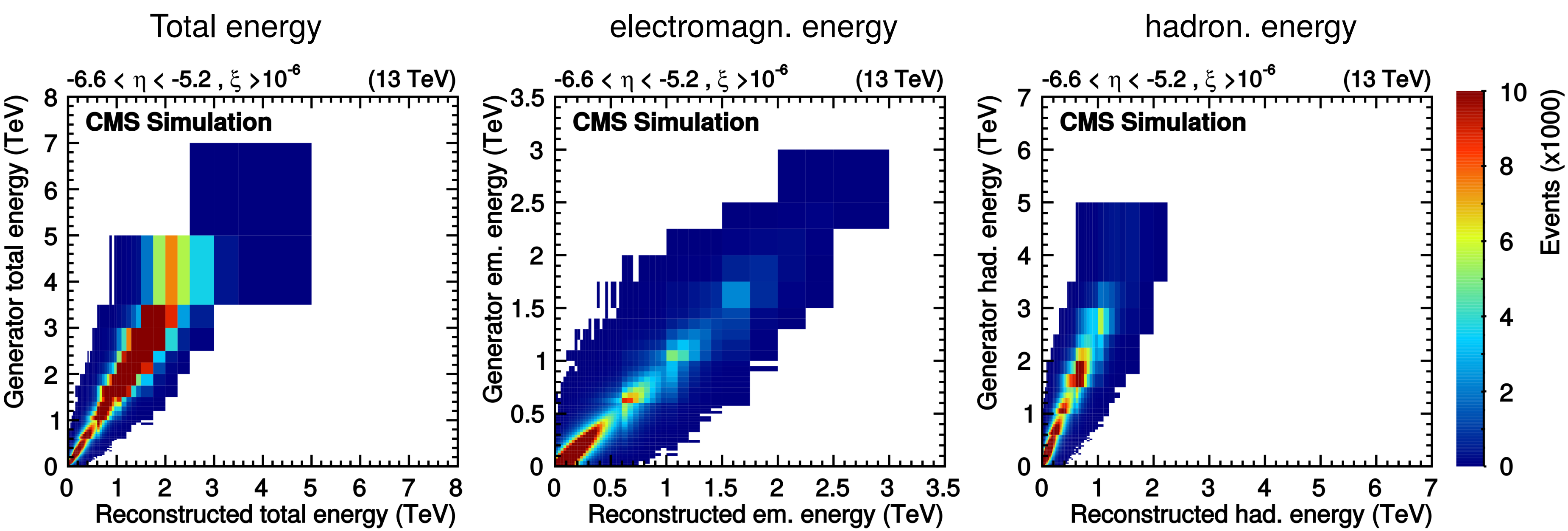
Alignment is done with infrared sensors with respect to the beampipe with precision of ~2mm





Energy reconstruction in CASTOR

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



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