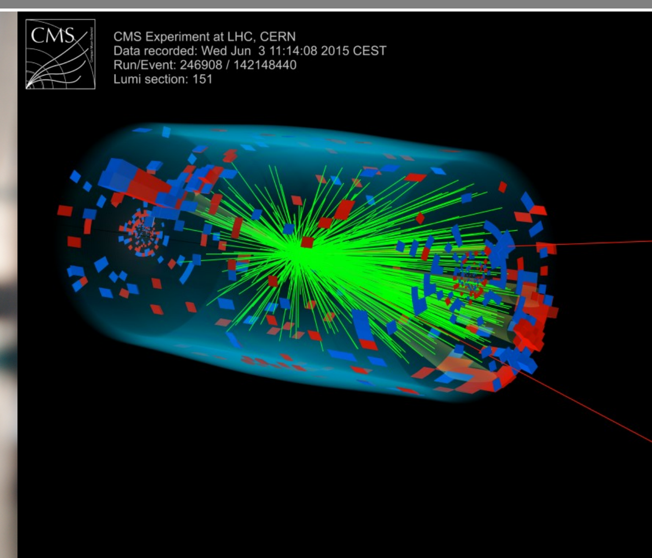
Recent CMS results in the forward region with the CASTOR detector

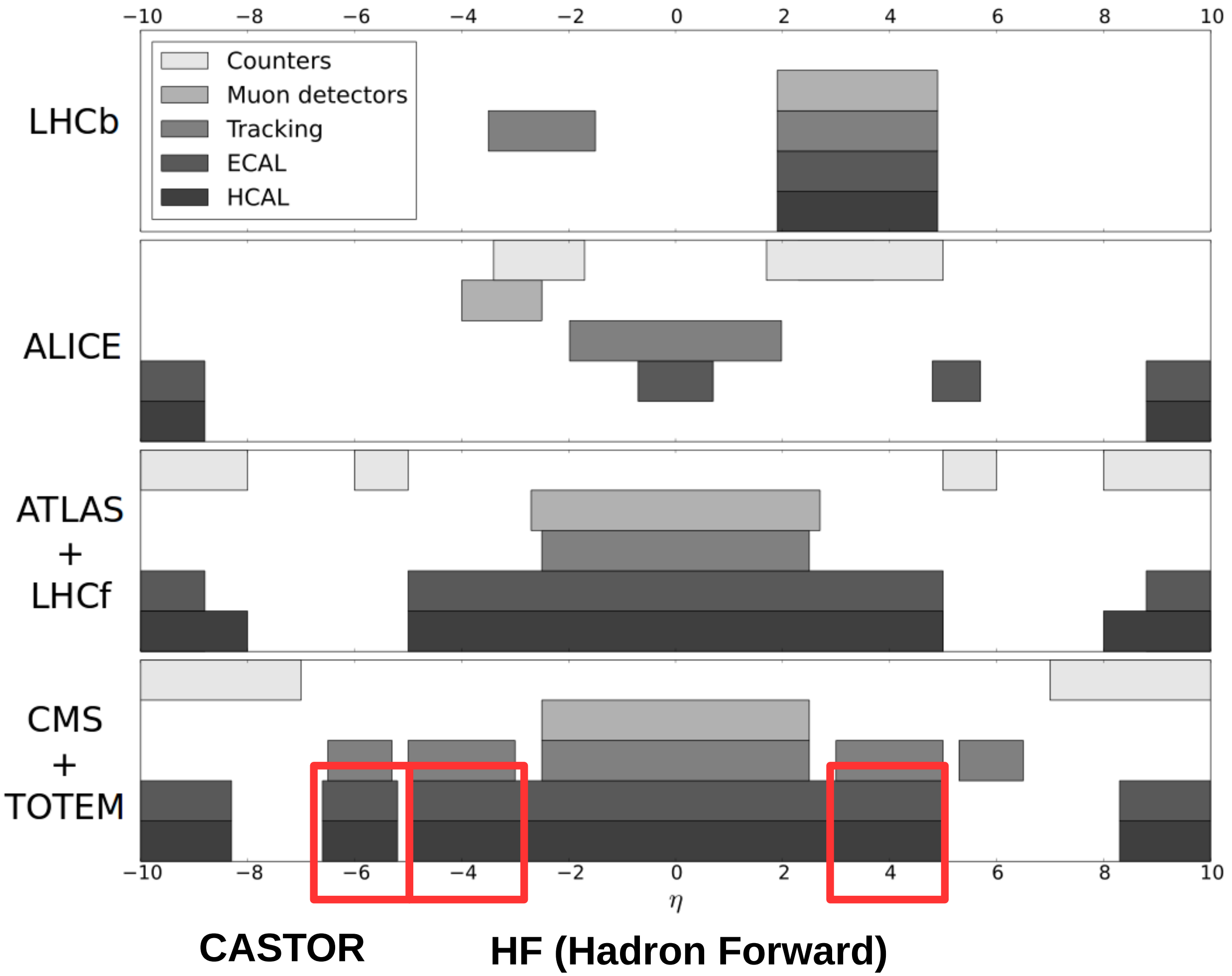
Sebastian Baur for the CMS Collaboration



The Forward Instrumentation of CMS

Overview

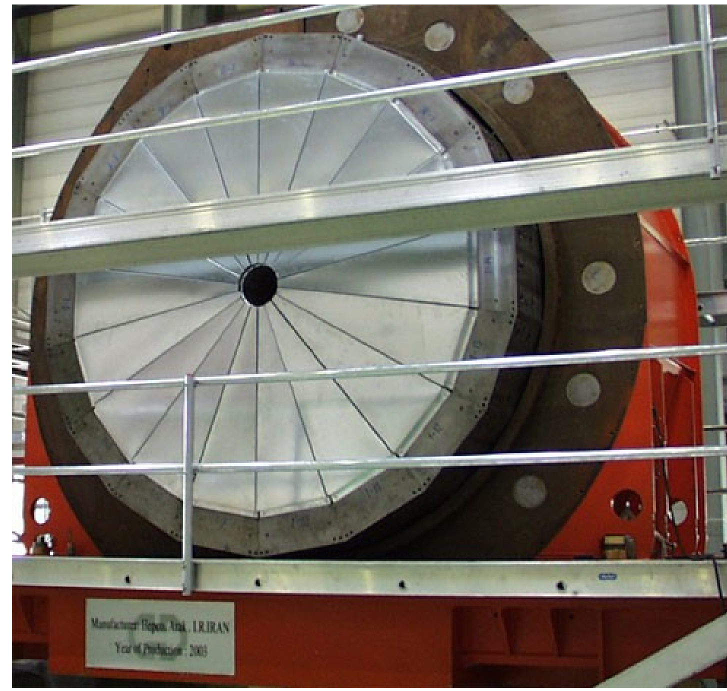
- CMS has an excellent calorimetric instrumentation in the forward region

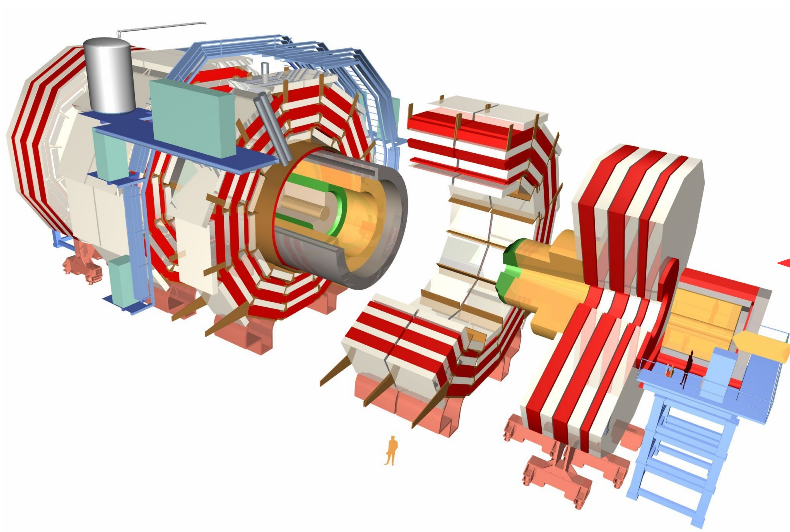


taken from C. Baus

HF calorimeters

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



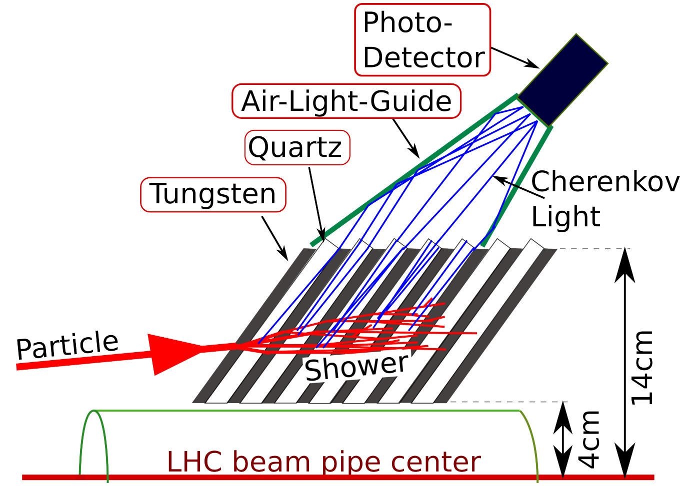


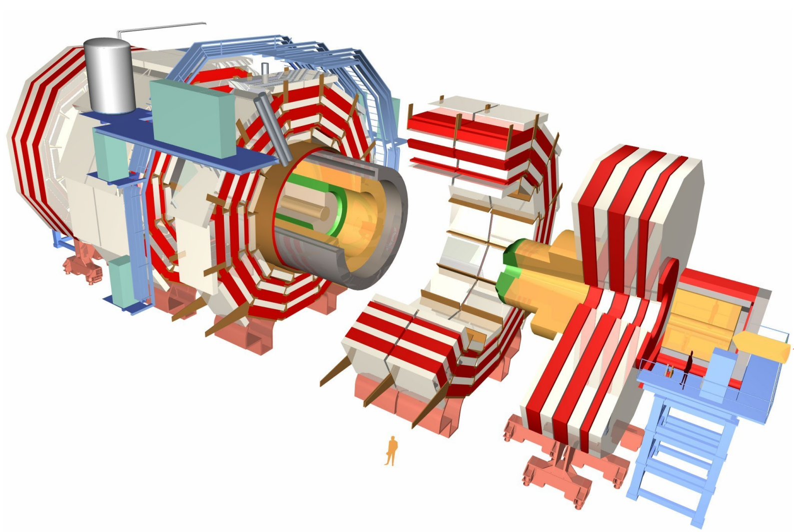
HF (**H**adron **F**orward)

CASTOR in CMS

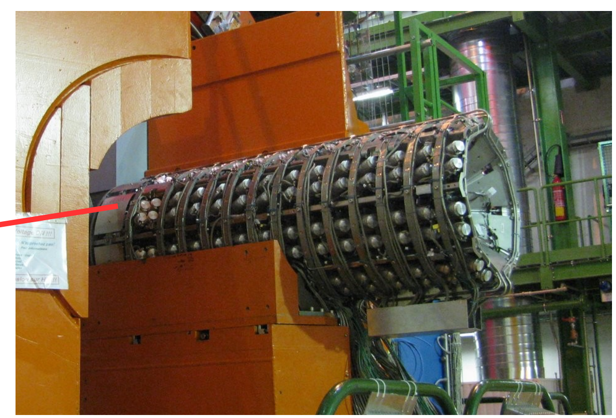
- Tungsten-Quartz-Cherenkov sampling calorimeter
- Segmented in 16 sectors in φ and 14 modules in z
- No η-segmentation: acceptance of $-5.2 < \eta < -6.6$
- Energy scale known to ±17%
- Separated electromagnetic and hadronic sections with depth of $20\, X_0 / 10\, \lambda_{int}$

- Data in 2015: 2 weeks of low-luminosity runs in June



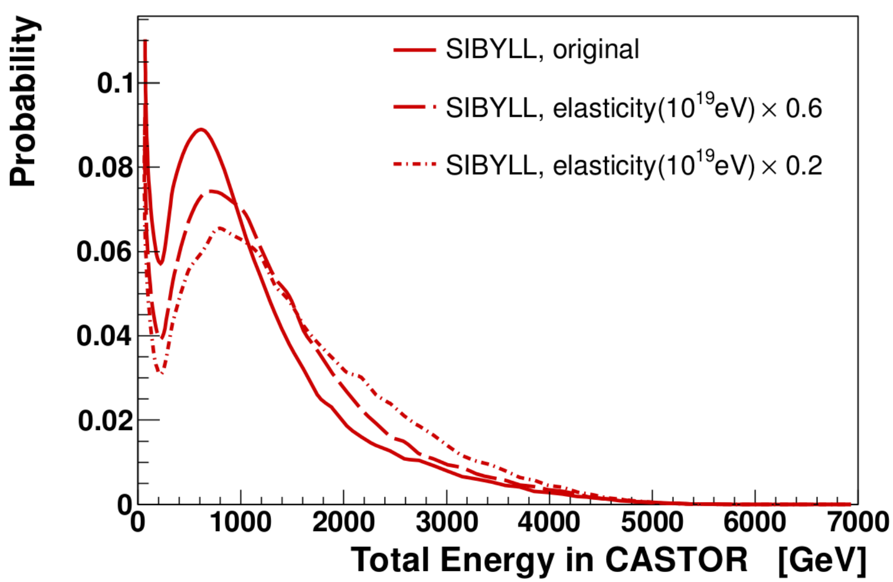


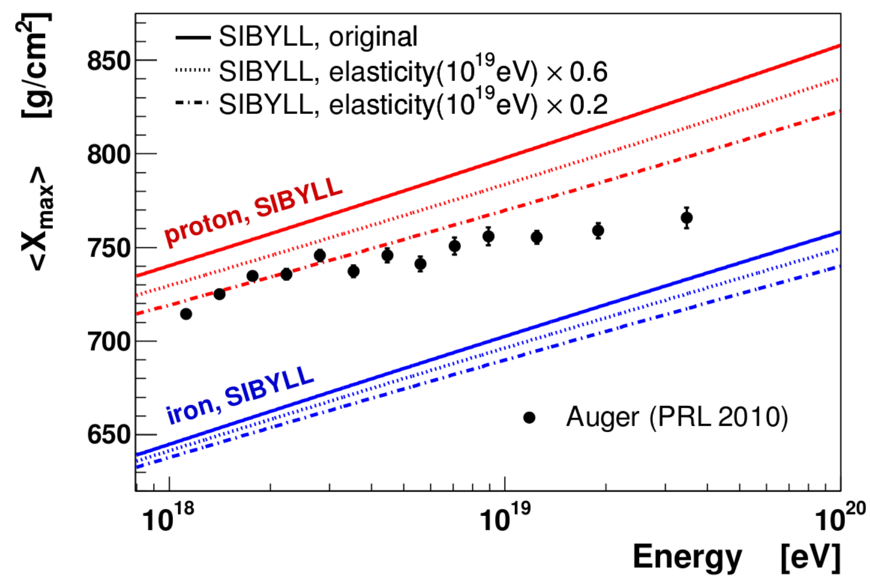
CASTOR



Motivation for forward physics

- Test influence of diffraction on various observables
- Probe proton fragmentation, UE and MPI
- Sensitive to low-x parton dynamics
- Test hypothesis of limiting fragmentation
- Probe cosmic-ray models
- Maximum acceptance to inelastic collisions





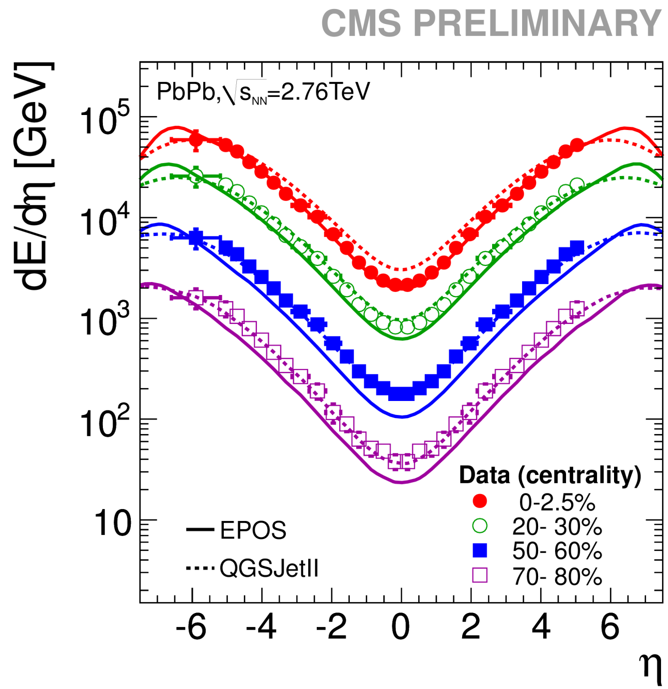
[Simulation study by Ralf Ulrich]

Recent results from CMS forward detectors

Recap: LHC Run 1 analyses

- Measurement of diffractive cross sections
- Measurement of the underlying event
- Energy flow in Pb-Pb collisions

[arXiv:1503.08689]



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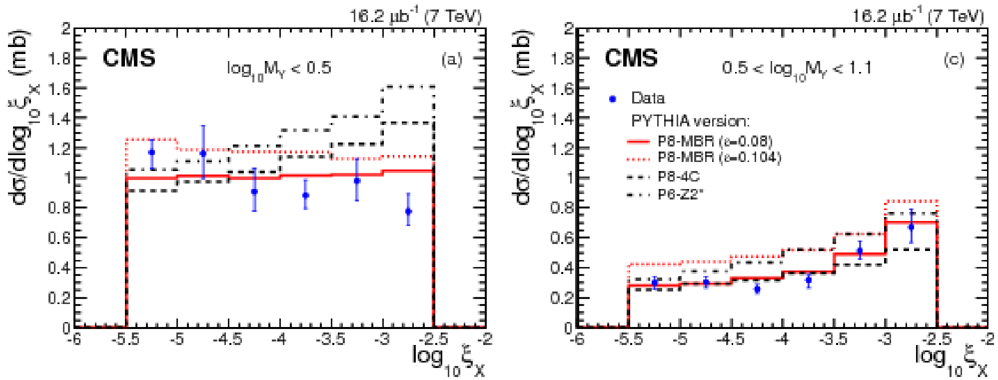
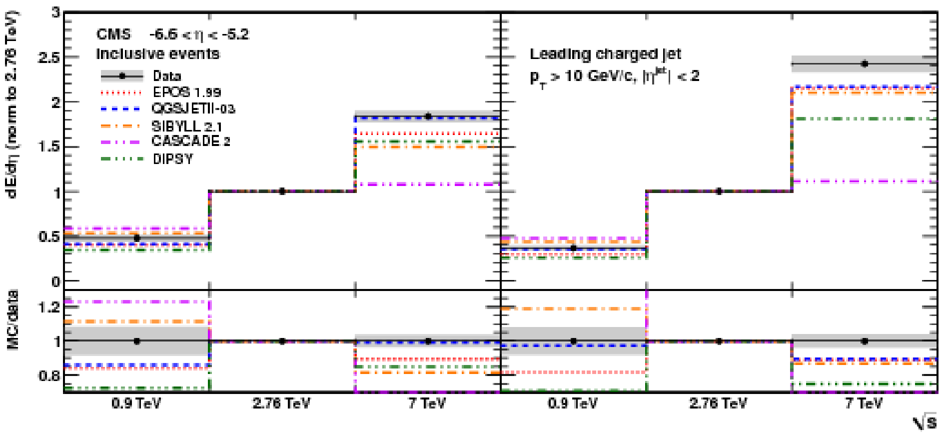




[arXiv:1302.2394]

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

- Focus today: Recently published preliminary results from CMS exploiting the forward instrumentation

  → Measurement of the inelastic cross section (CMS-FSQ-PAS-15-005)
  → Measurement of the forward energy flow (CMS-FSQ-PAS-15-006)
  → Measurement of the very forward energy spectra with CASTOR (CMS-FSQ-PAS-16-002)
  → Measurement of the very forward jet spectrum with CASTOR (CMS-FSQ-PAS-16-003)

Measurement of the inelastic pp cross section

Measurement of σ_{inel}

- Data from various run periods with low PU (5% - 50%) at $\sqrt{s}$ =13 TeV
- Unbiased trigger requiring presence of both beams at the interaction point (ZeroBias)
- Two offline event selections

HF OR	HF OR CASTOR
at least one tower above 5 GeV in either HF+ or HF-	at least one tower above 5 GeV in either HF+ or HF- or CASTOR

- Data-driven correction of noise triggered events and pileup effects
- Correction to the stable particle level with MonteCarlo simulation

Measurement of σ_{inel}

- Define final state via ξ variable
  → divide final state in two subsystems X,Y relative to the largest rapidity gap
  → calculate invariant masses M_X M_Y and use

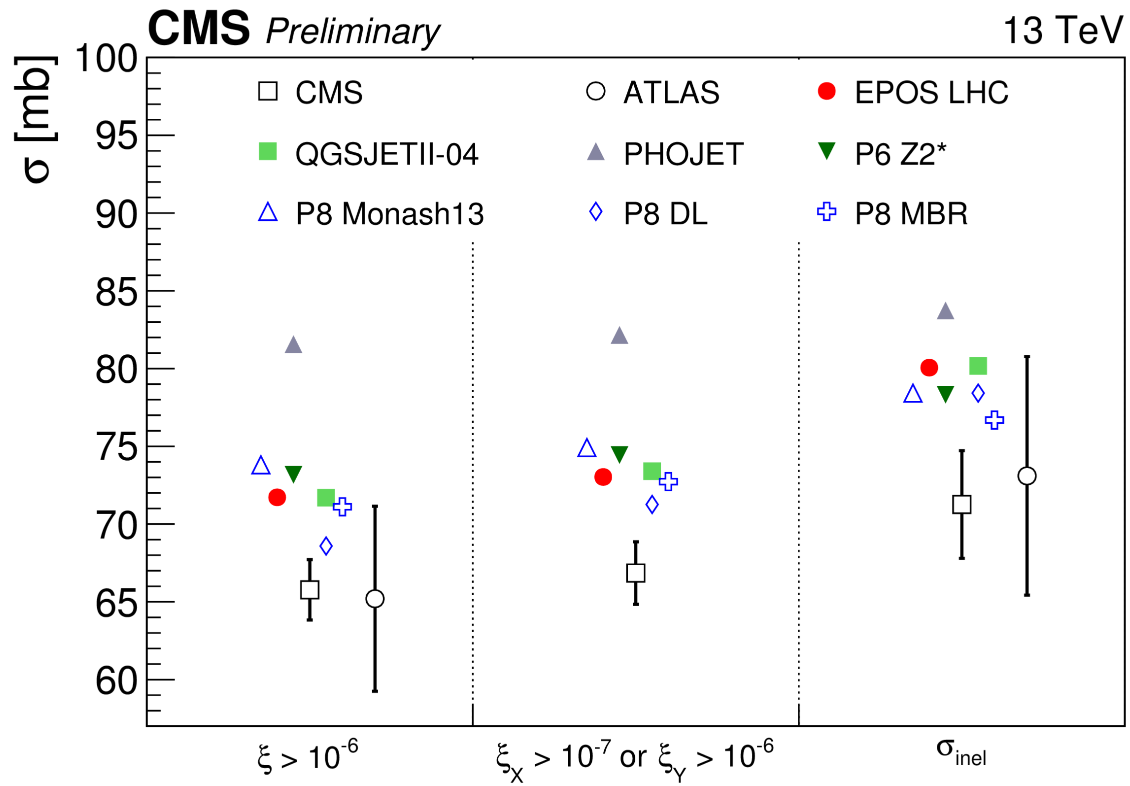
$$\xi_X = \frac{M_X^2}{s}, \xi_Y = \frac{M_Y^2}{s} \text{ and } \xi = \max(\xi_X, \xi_Y)$$

  → optimal detector acceptance is determined using full MonteCarlo simulation

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

- Extrapolation to the full inelastic phase space is done using model-dependent factors, difference is taken as systematic uncertainty

Measurement of σ_{inel}



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

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

$$\sigma_{inel} = 71.3 \pm 0.5\ (\text{exp.}) \pm 2.1\ (\text{lum.}) \pm 2.7\ (\text{ext.})\ \text{mb}$$

Measurement of the forward energy flow

Measurement of $dE/d\eta$

- Average energy density per pseudorapidity
- Unbiased trigger requiring presence of both beams at the interaction point (ZeroBias)
- Two offline event selections:

HF OR

at least one tower above 5 GeV in either HF+ or HF-

HF AND

at least one tower above 4 GeV in both HF+ and HF-

Corrected to stable particle level

soft-inclusive-inelastic

$\xi > 10^{-6}$

Non-single-diffractive-enhanced

at least one particle in HF acceptance on each side of CMS

Measurement of $dE/d\eta$

Average energy density per pseudorapidity:

Correction from detector to stable particle level

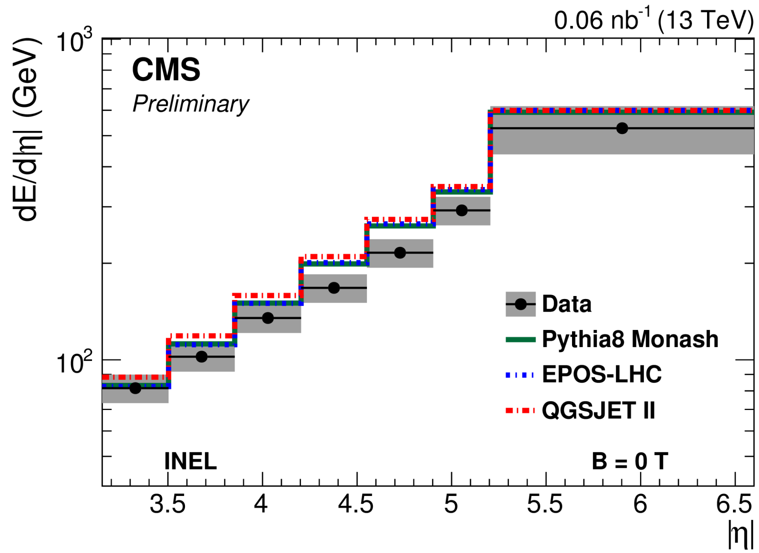
Sum of all calorimeter towers above noise level

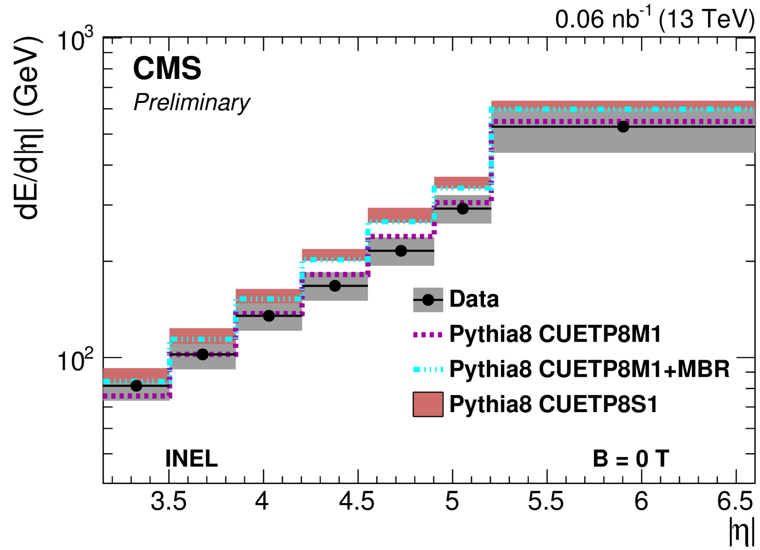
$$\frac{dE}{d\eta}(\eta) = \frac{1}{N}\frac{1}{\Delta\eta}\sum_j E_j \cdot C(PU) \cdot C(\eta)$$

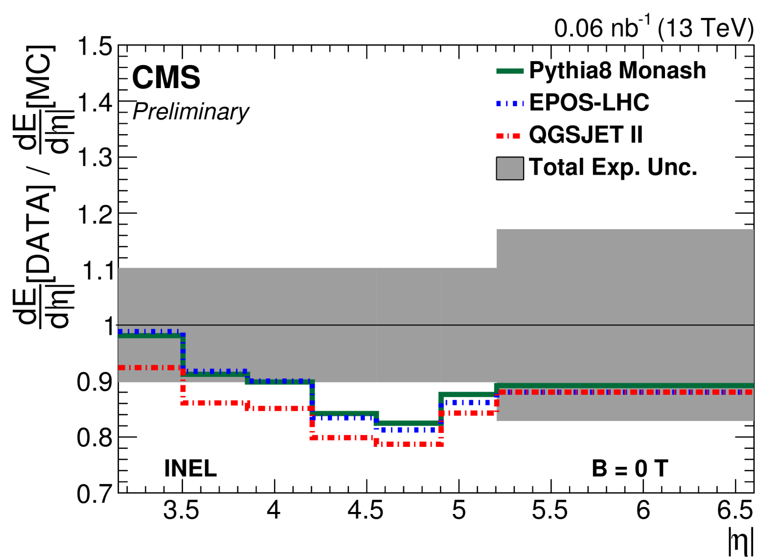
Data-driven correction for Pileup

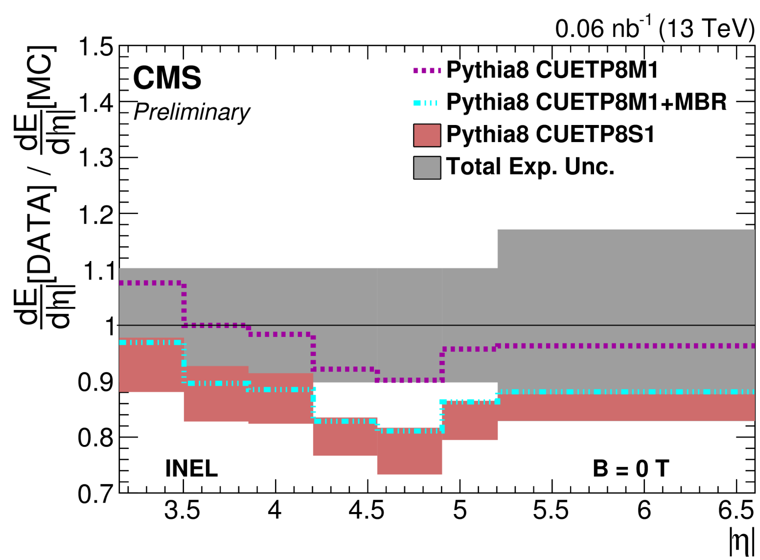
Segmentation defined by calorimeter acceptances

Measurement of $dE/d\eta$



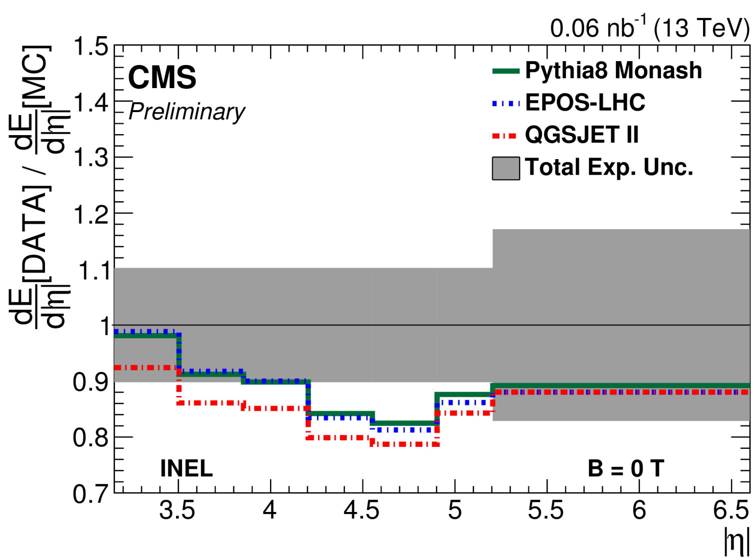


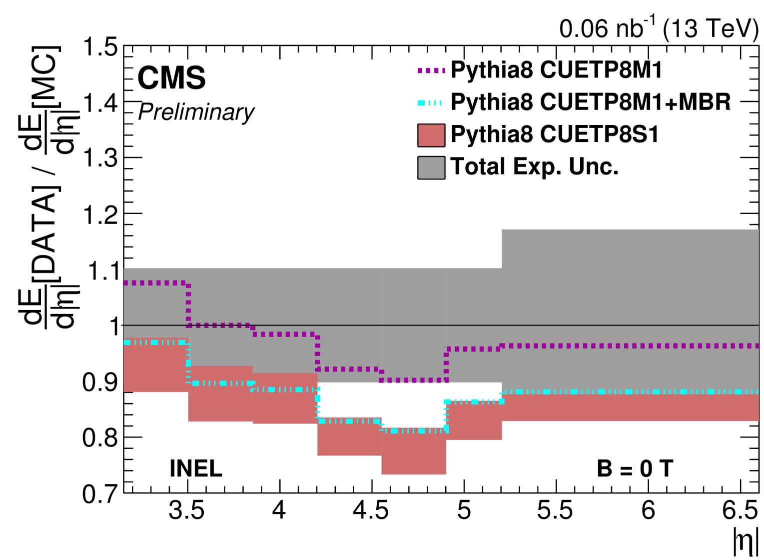




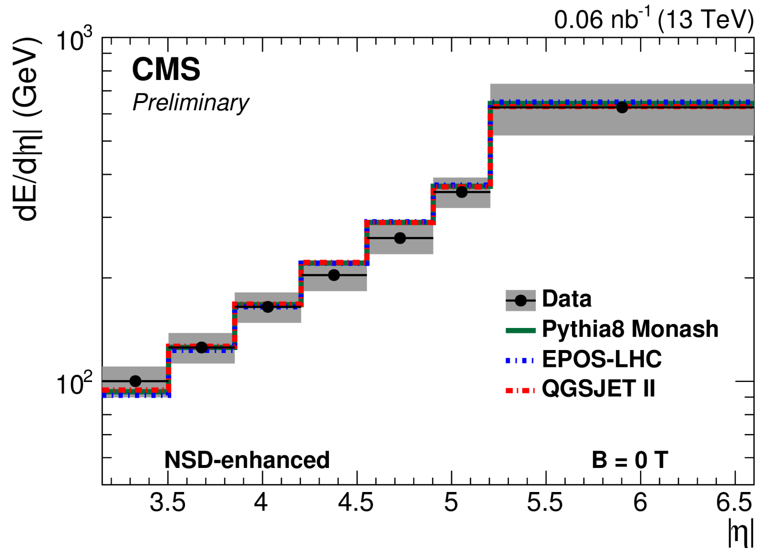
Measurement of $dE/d\eta$

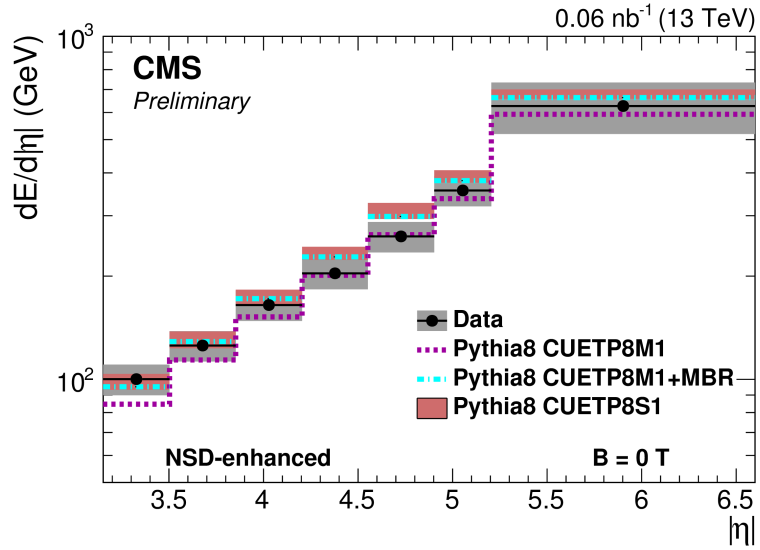
- The spread in the model predictions is large for soft-inclusive-inelastic events
- Predictions are generally a bit too high
- Pythia8 Monash, EPOS LHC, QGSJET: comparable results
- CUETP8M1 vs CUETP8M1+MBR: significant effect of adding the MBR model to the CUET tune
- CUETP8S1+uncertainties: dominant contribution from color reconnection parameters

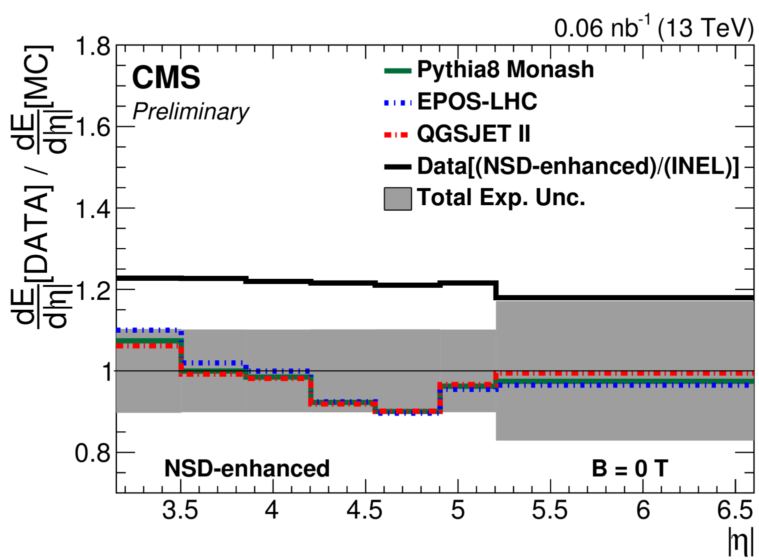


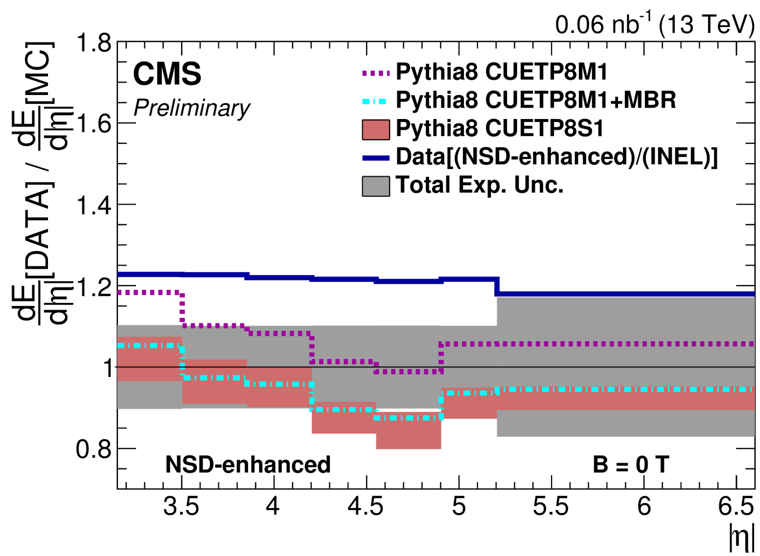


Measurement of $dE/d\eta$



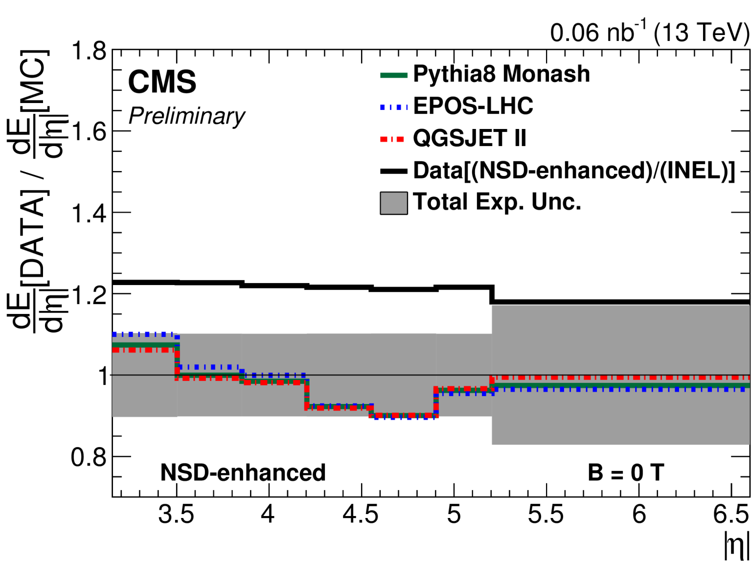


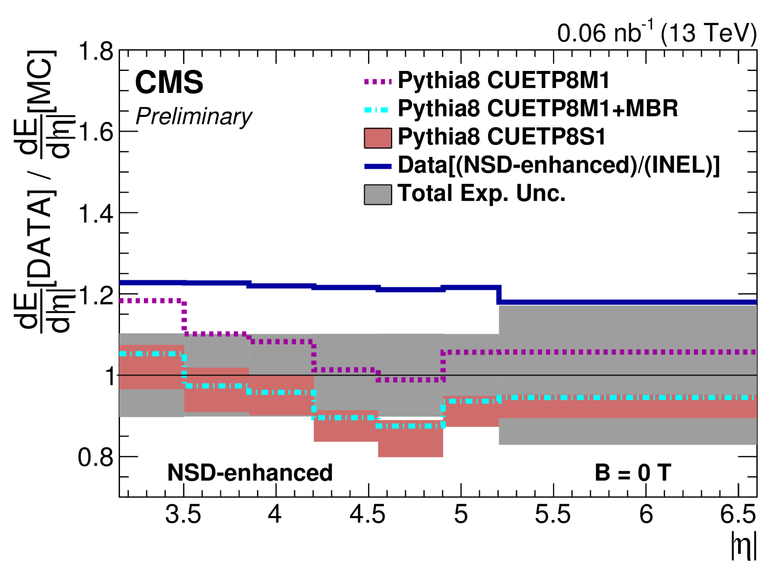




Measurement of $dE/d\eta$

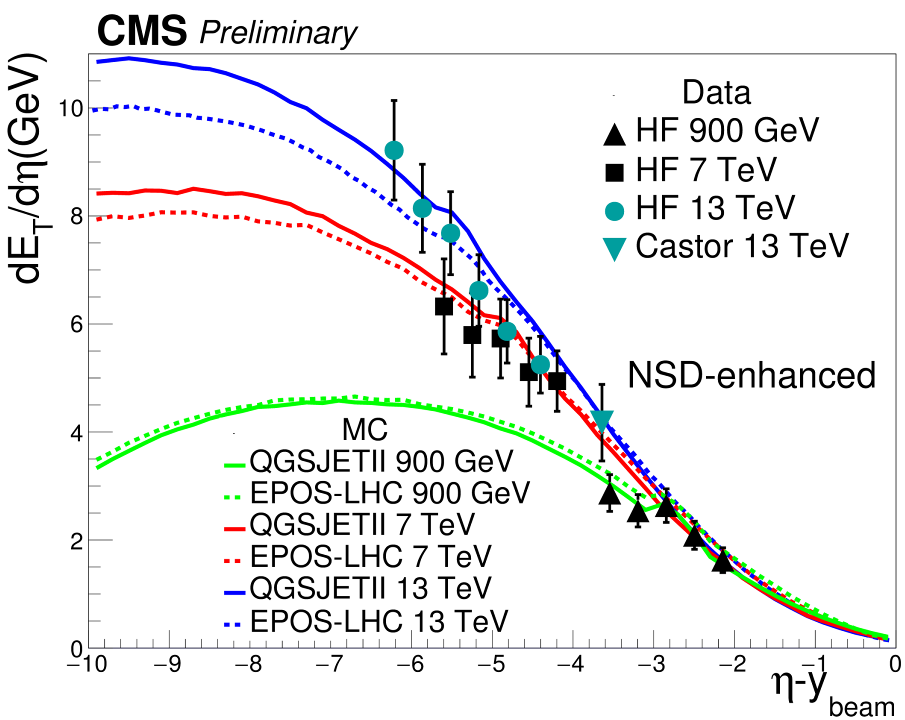
- Non single diffractive energy flow is ~20% higher than the inclusive inelastic
- Smaller spread of model predictions for non-single-diffractive-enhanced
- Overall reasonable description of data by predictions given uncertainties of data





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 the very forward energy spectra

Measurement of $1/N_{evt}\ dN/dE$ in CASTOR

- A more detailed look into the CASTOR acceptance:
  energy deposition probability 1/N dN/dE
- Same event selection as before:
  ZeroBias trigger, offline HF OR selection:

HF OR	→	soft-inclusive-inelastic
at least one tower above 5 GeV in either HF+ or HF-		$\xi > 10^{-6}$

- Furthermore:
  Exploit the design of CASTOR and separate electromagnetic and hadronic energy

Measurement of $1/N_{evt}\ dN/dE$ in CASTOR

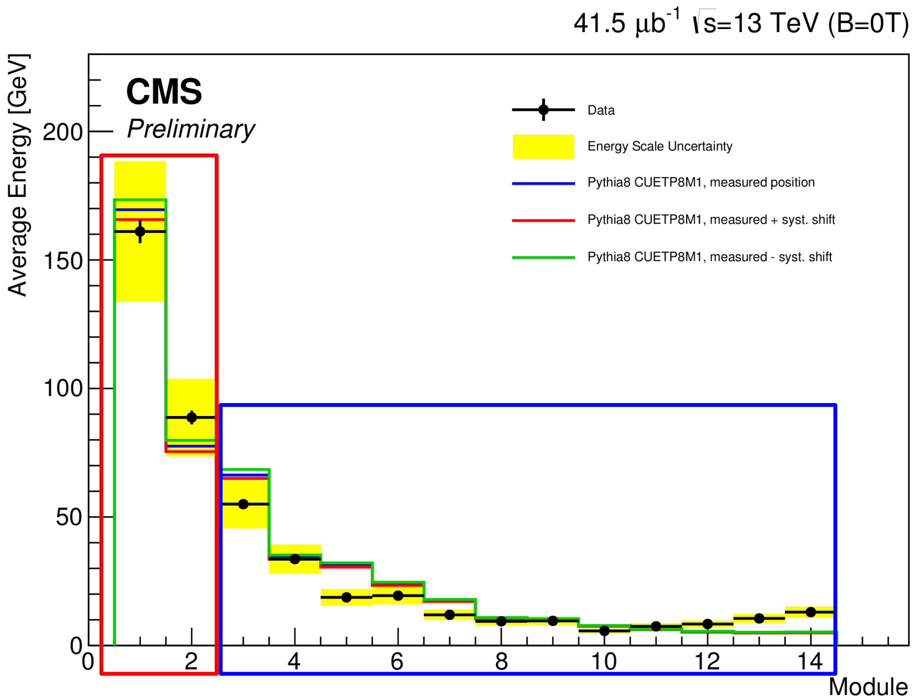
- CASTOR is a combined electromagnetic and hadronic calorimeter
- Signal in the first two modules of CASTOR is sensitive to the electromagnetic component
- Back part measured the hadronic contribution

HF OR

- Whole CASTOR → total energy sum
- Front → electromagnetic component
- Back → hadronic component

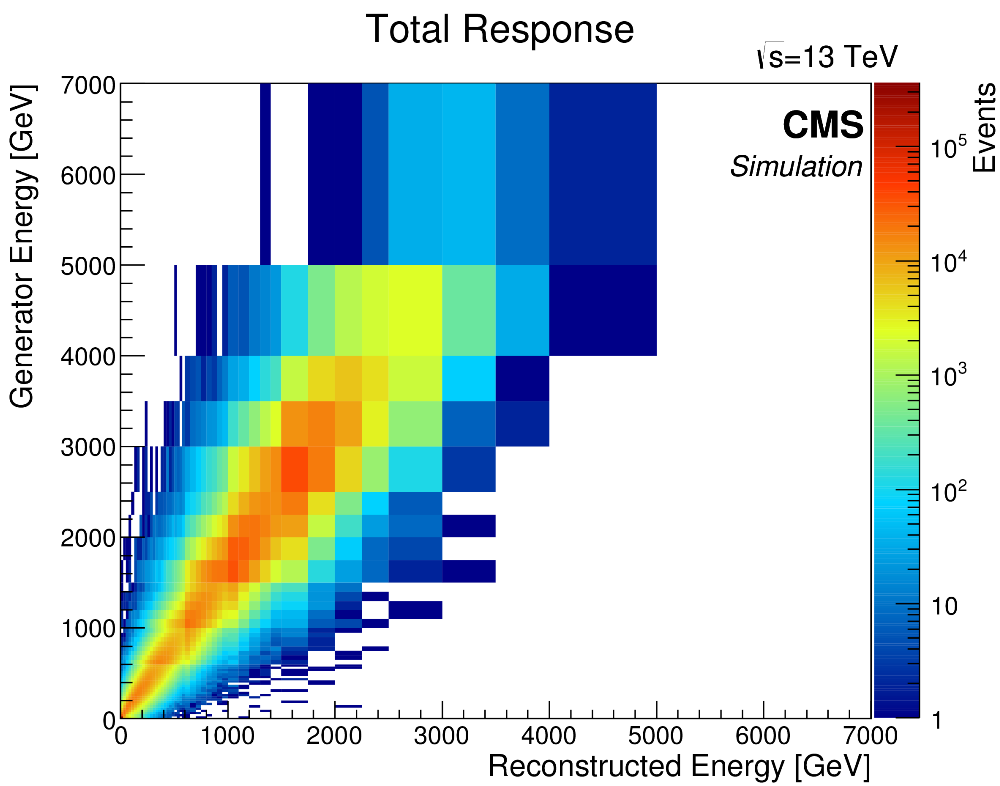
soft-inclusive-inelastic

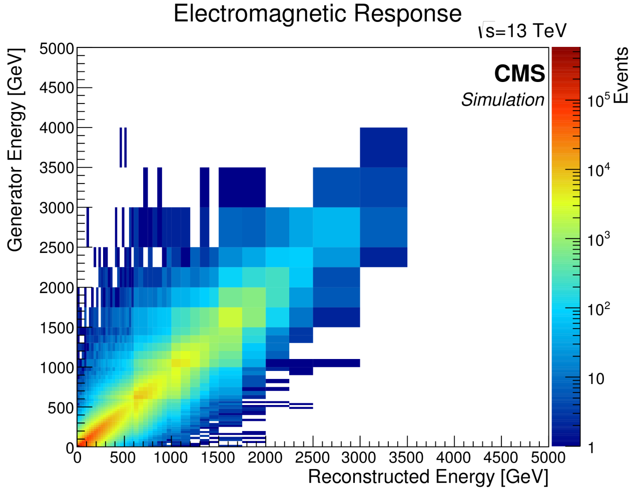
- all stable particles except μ, ν
- e, γ (incl. π^0)
- all stable particles except μ, ν, e, γ

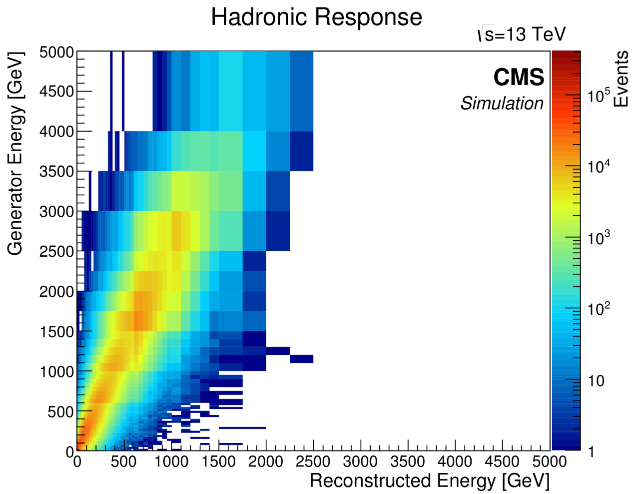


Measurement of $1/N_{evt}\, dN/dE$ in CASTOR

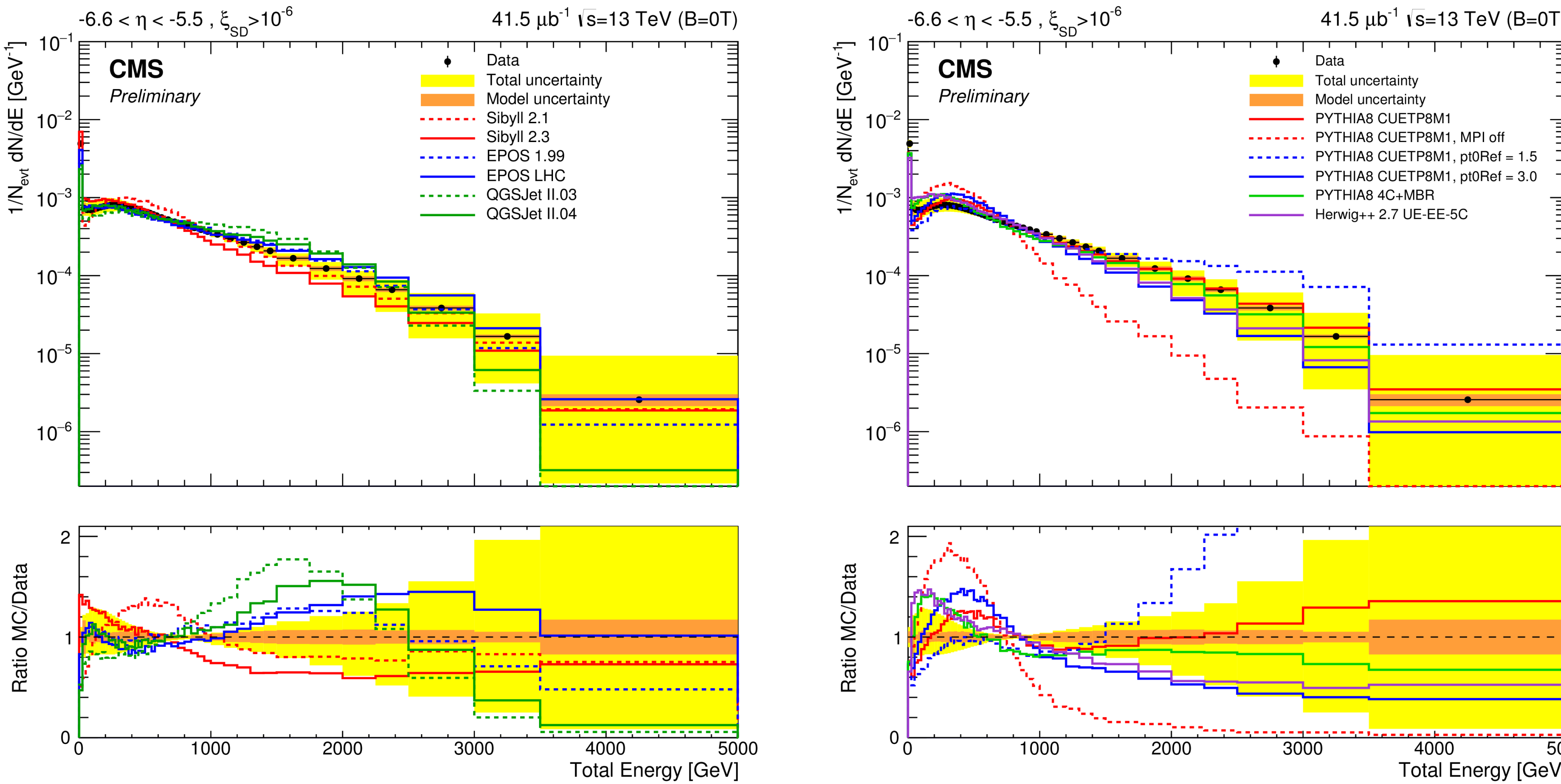
- Residual effects: non-compensation, leakage of em/had energy into back/front part, non-nominal acceptance
  → unfold spectra with d'Agostini iterative with early stopping





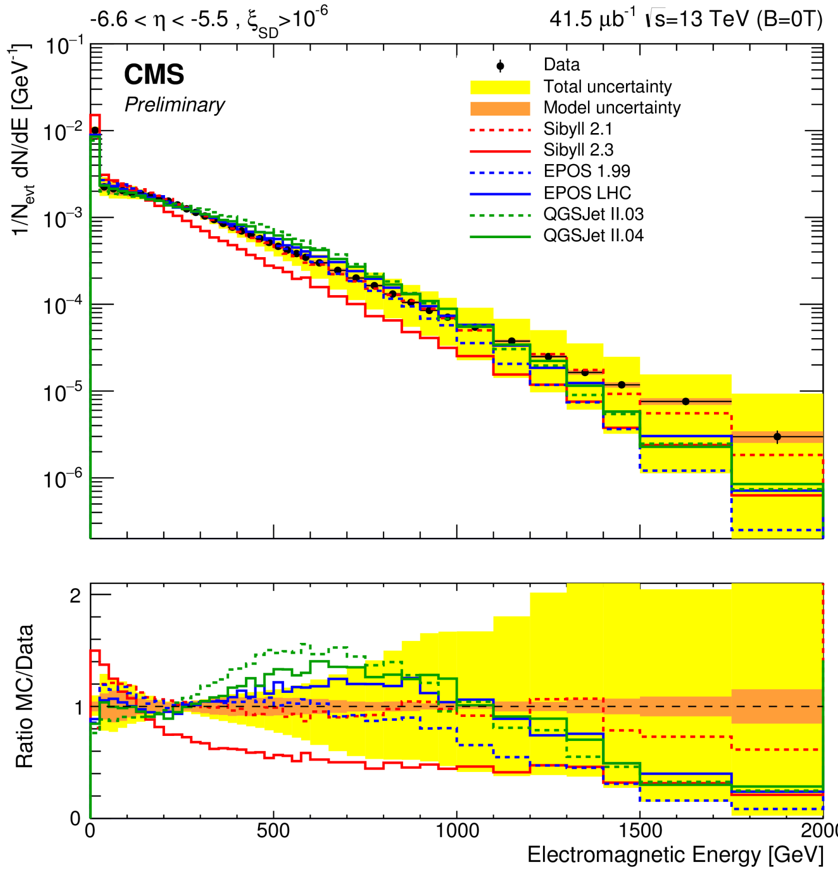


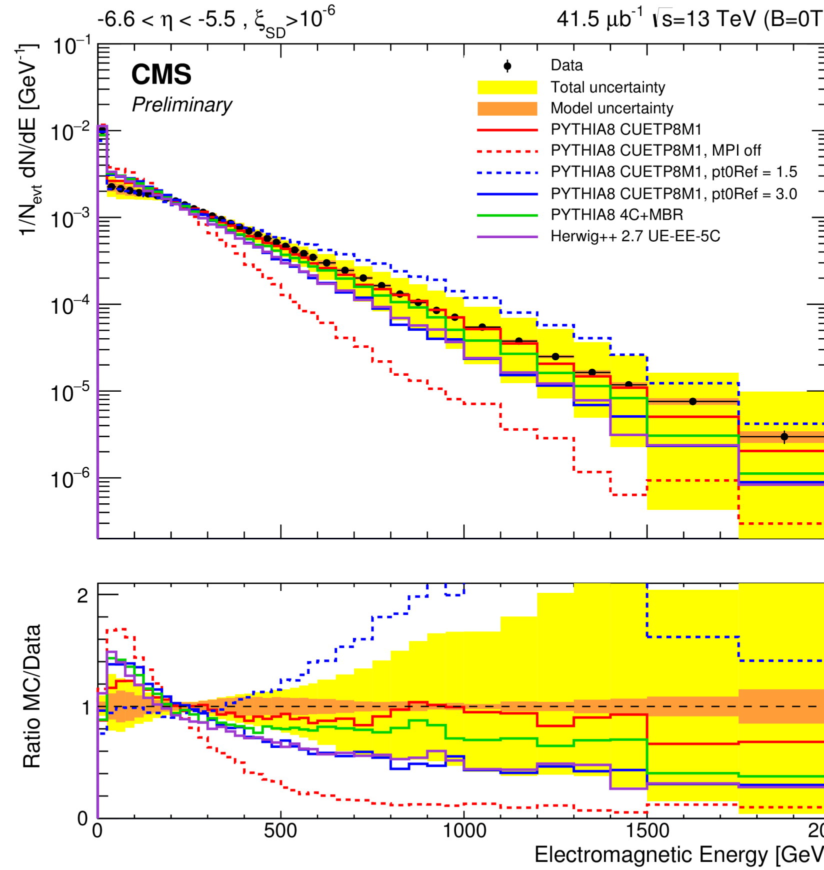
Measurement of $1/N_{evt}\ dN/dE$ in CASTOR



- Measurement confirms the general shape of the spectrum, bump structure at ~350 GeV
- Models perform reasonably well, tuning improvement is seen
- Clear evidence for the importance of MPI, sensitive to pt0Ref parameter

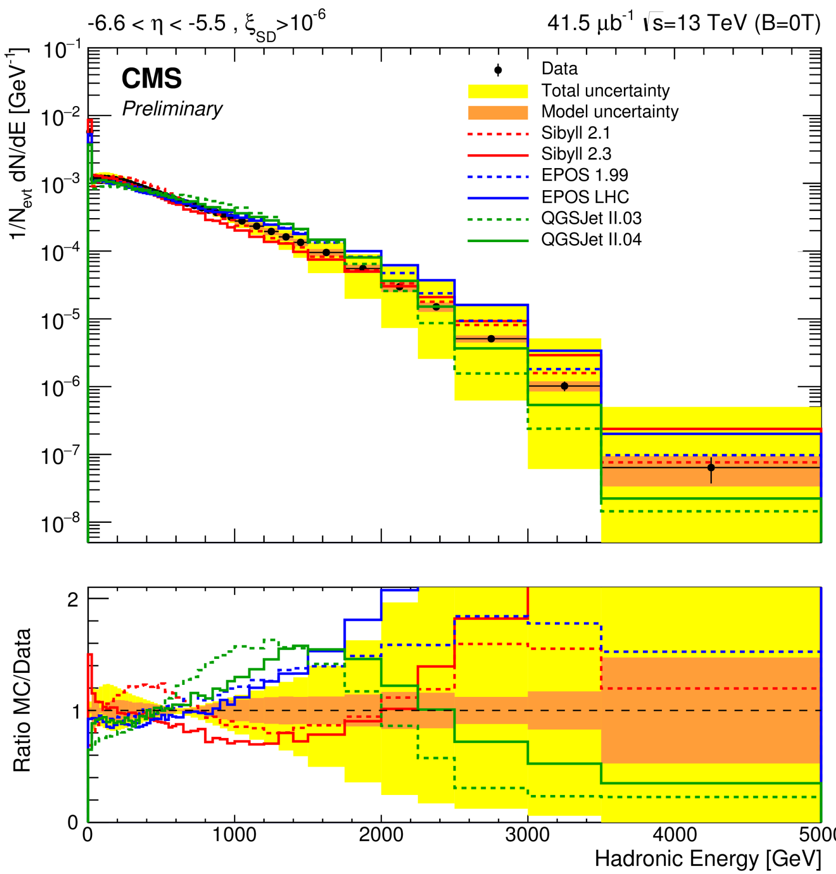
Measurement of $1/N_{evt}\ dN/dE$ in CASTOR

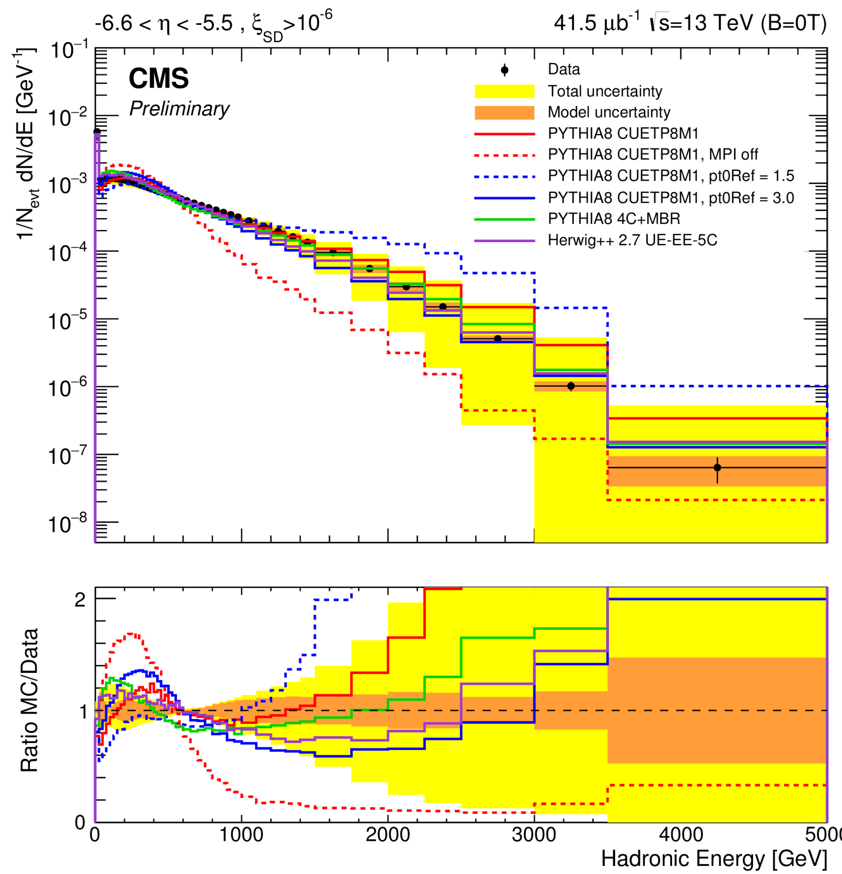




- Better general agreement, despite Sybill 2.3
- Herwig++ UE EE-5C seems to have too strong cutoff on MPI

Measurement of $1/N_{evt}\ dN/dE$ in CASTOR





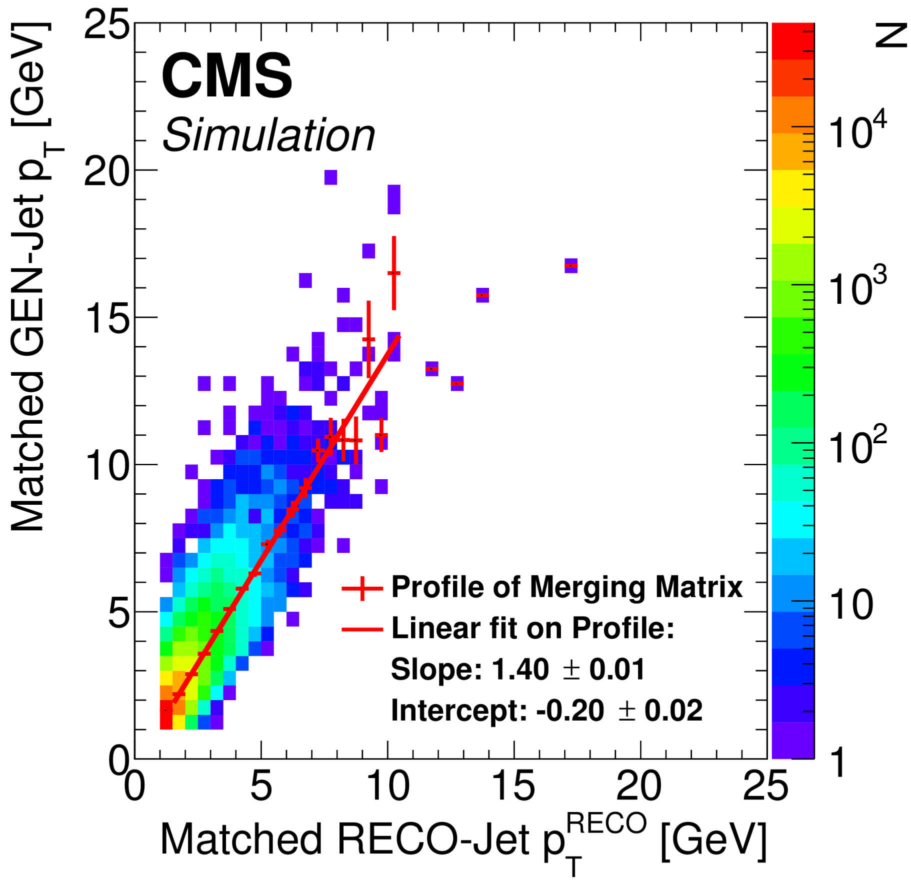
- All models tend to have a too flat spectrum
- Sybill 2.3 shows interesting feature at 0 energy
- General: Shape is rather complex, detailed implications need detailed further studies

Measurement of the very forward jet spectrum

Measurement of very forward jets

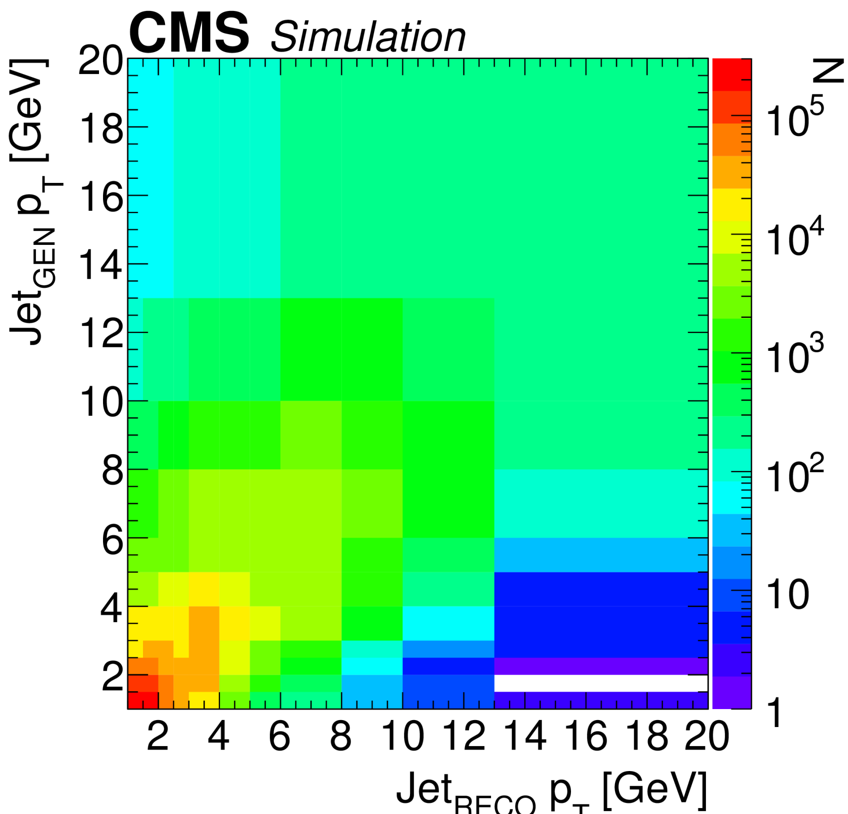
- CASTOR towers are clustered into jets with anti-kt radius 0.5
- Matched to particle level jets also clustered with anti-kt 0.5

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

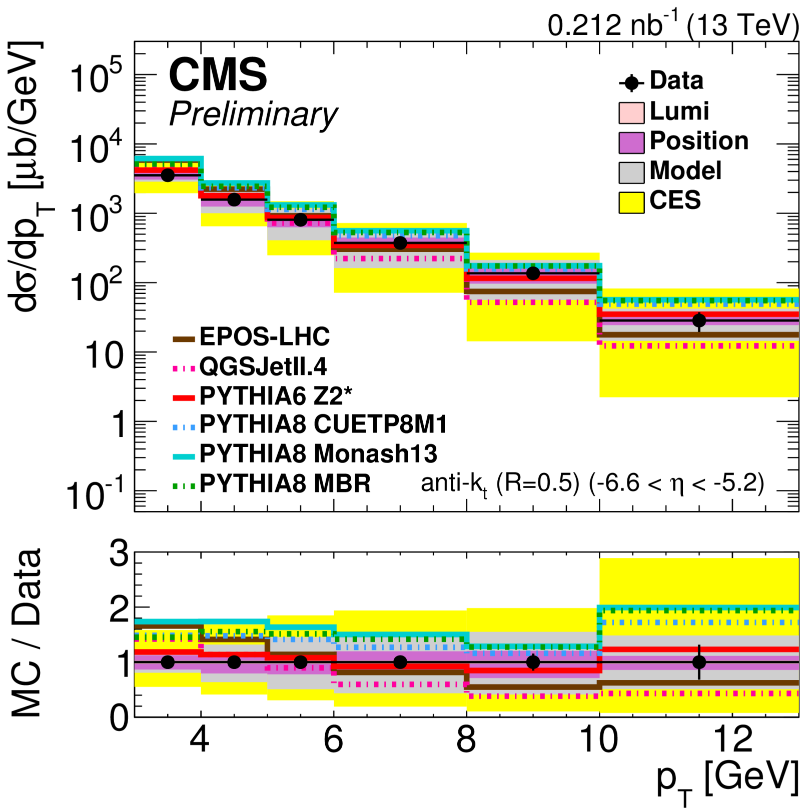


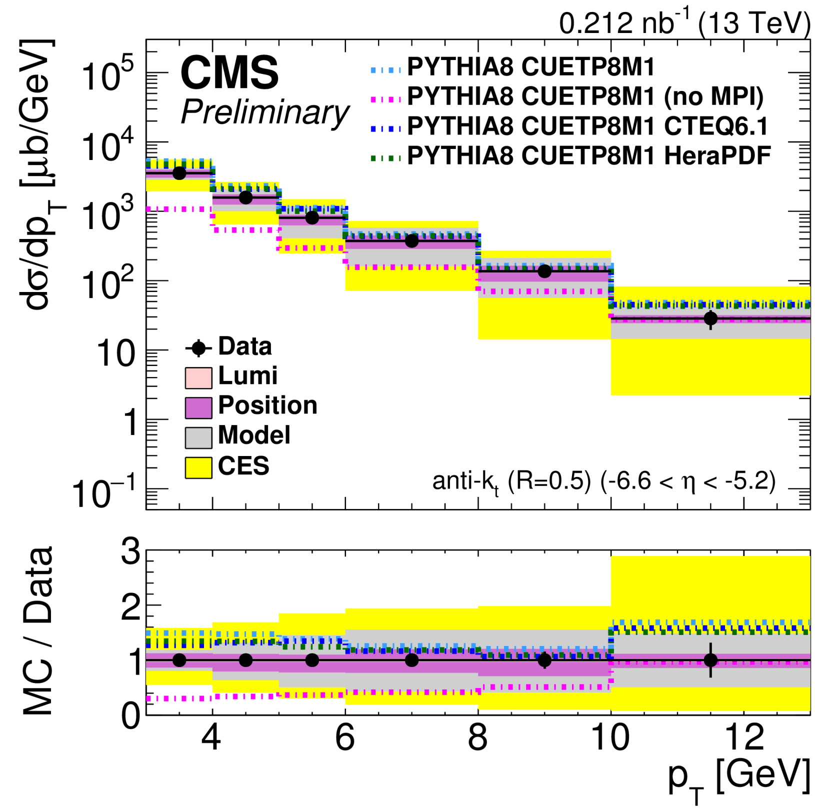
Measurement of very forward jets

- Unfolding of the jet spectrum using d'Agostini iterative method with early stopping
- Correction for border effects (jets hitting the edges of CASTOR), reconstruction inefficiencies and pt resolution
- Broad matrix due to lack of eta segmentation
- Distribution within the CASTOR acceptance influences the result
  → large model dependence
- Main systematic uncertainties:
  - CASTOR energy scale: >50 %
  - CASTOR acceptance uncertainty: 10-30%
  - Model uncertainty: 20-50%
  - Luminosity: 2.9 %



Measurement of very forward jets





- Systematic uncertainties – especially jet energy scale – are very large
- PYTHIA8 gives slightly too large cross sections, proper MPI description is important
- EPOS LHC and QGSJetII seem to be too steep

Summary

Summary

- CMS published recently a nice set of measurements that exploit the forward instrumentation

- The inelastic proton-proton cross section has been measured at 13 TeV and extrapolated to the full phase space
  → Measurement favors a smaller value than most models
  → Most models describe the relative increase from $\xi > 10^{-6}$ to $\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6}$ rather well
  → Results public in CMS-PAS-FSQ-15-005: http://cds.cern.ch/record/2145896

- The energy flow in the forward region, in pseudorapidity range $3.15 < |\eta| < 6.6$, is measured in pp-collisions at 13 TeV for two event classes.
  → In general models provide reasonable description of data, given the uncertainties.
  → Results are studied in terms of shifted pseudorapidity. An overall consistency with hypothesis of limiting fragmentation is found.
  → Results public in CMS-PAS-FSQ-15-006: http://cds.cern.ch/record/2146007

Summary

- Normalized energy spectra in pseudorapidity range $-5.2 < \eta < -6.6$ are measured with CASTOR in pp-collisions at 13 TeV.
  → Models perform quite good in reproducing the spectra shapes
  → Tuning to LHC data improved the description, especially the UE tunes
  → Importance of MPI to describe the energy in the very forward region is shown
  → More concrete interpretations need careful studies
  → Results public in CMS-PAS-FSQ-16-002: http://cds.cern.ch/record/2145374
- For the first time, jets in the very forward region are measured and fully unfolded to the particle level
  → Systematic uncertainties are very large
  → All models agree within the uncertainties
  → Still, some weak conclusions can be drawn
  → Nevertheless, this opens the door for further studies, e.g. jet correlations or ratios to different center-of-mass energies
  → Results public in CMS-PAS-FSQ-16-003: http://cds.cern.ch/record/2146006

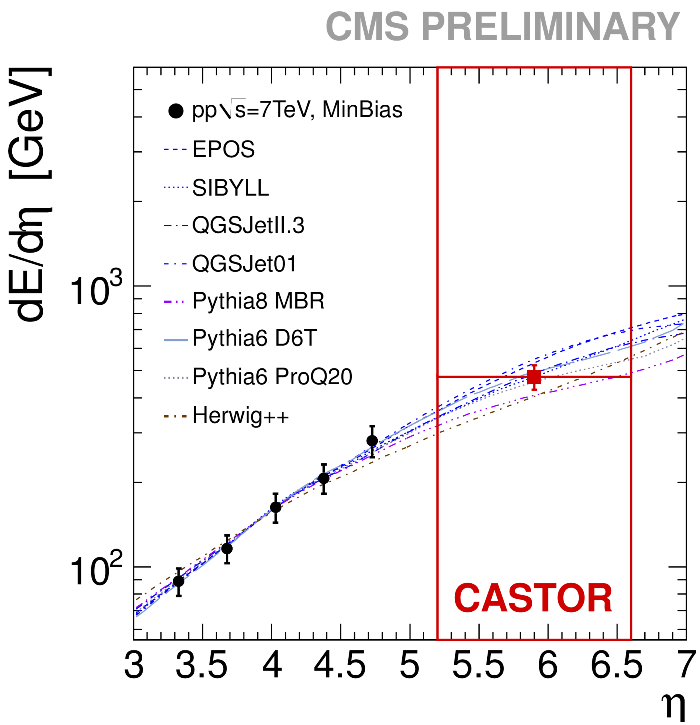
rivet plugins are available upon request for most of the presented analyses

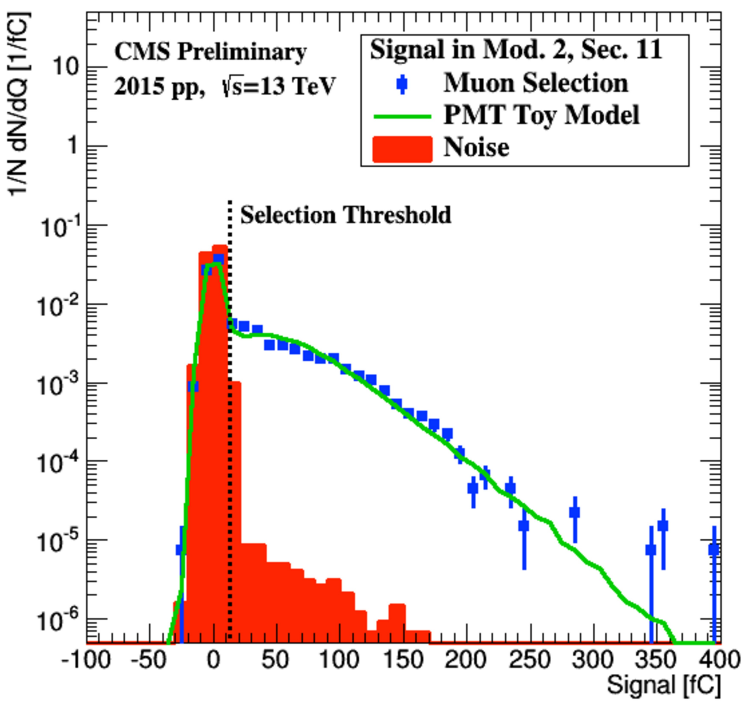
Thank you !

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)

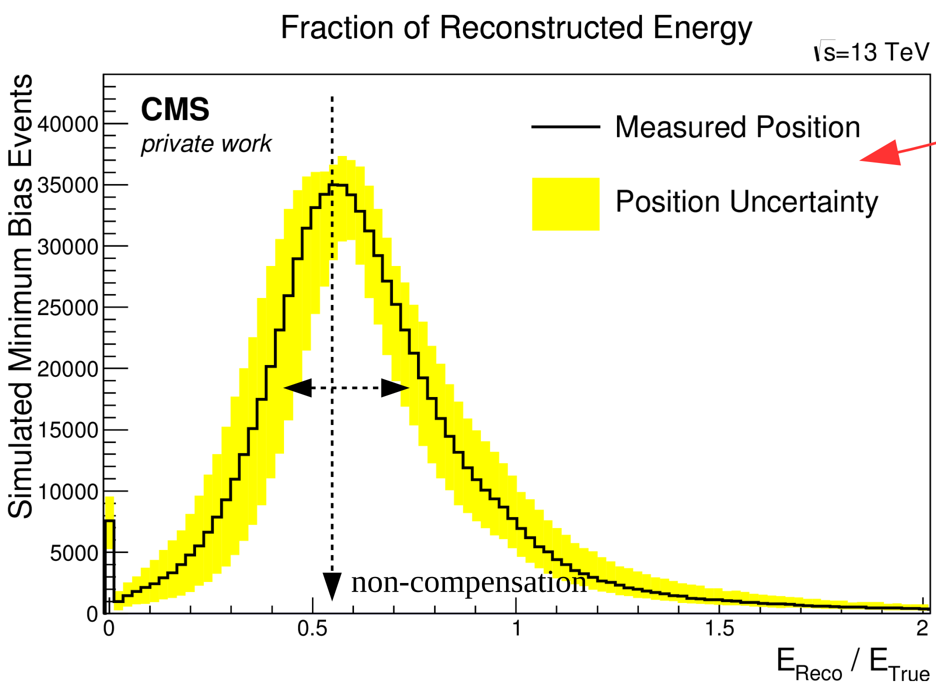


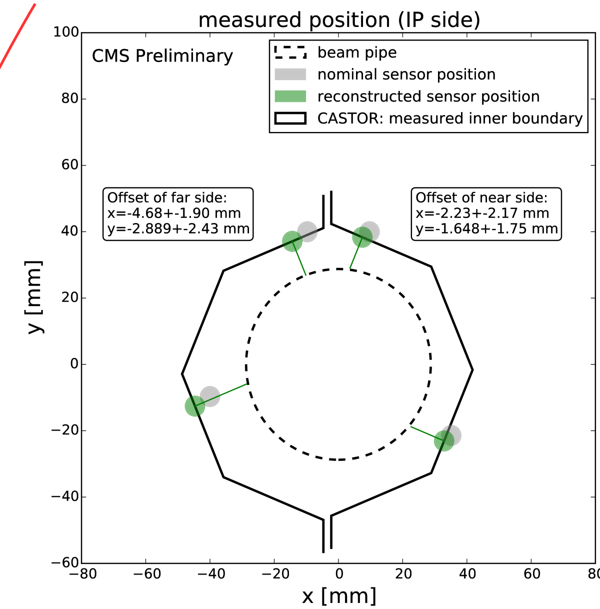


CASTOR energy scale uncertainties

- 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





Measurement of σ_{inel}

	$\sigma(\xi > 10^{-6})$ (mb)	$\sigma(\xi_X > 10^{-7}$ or $\xi_Y > 10^{-6})$ (mb)
Model dependence	0.66	0.38
HF energy scale uncertainty	0.34	0.13
CASTOR energy scale uncertainty	-	0.04
CASTOR alignment	-	0.03
Run-to-run variation	0.15	0.14
Total	0.76	0.44
Luminosity	1.78	1.96

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

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

$\sigma_{inel}= 71.3 \pm 0.5$ (exp.) ± 2.1 (lum.) ± 2.7 (ext.) mb

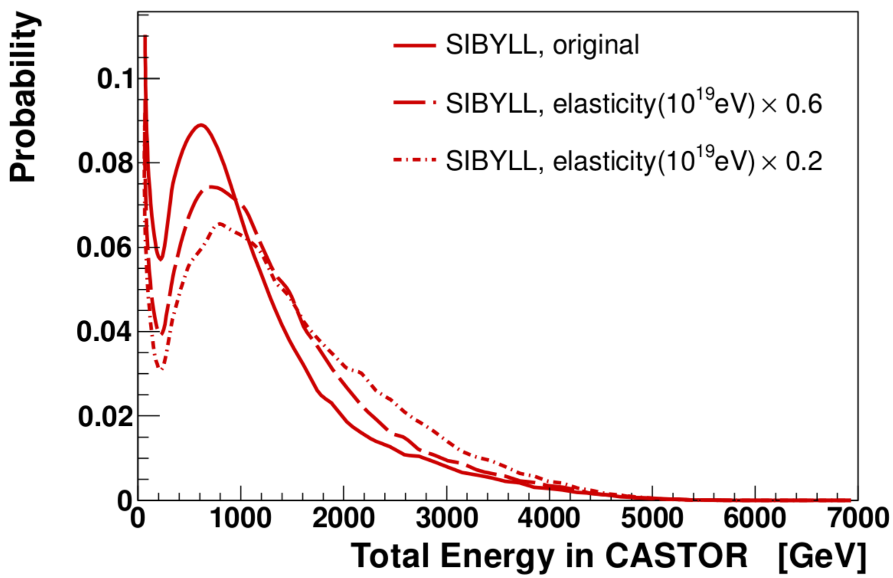
Measurement of $dE/d\eta$

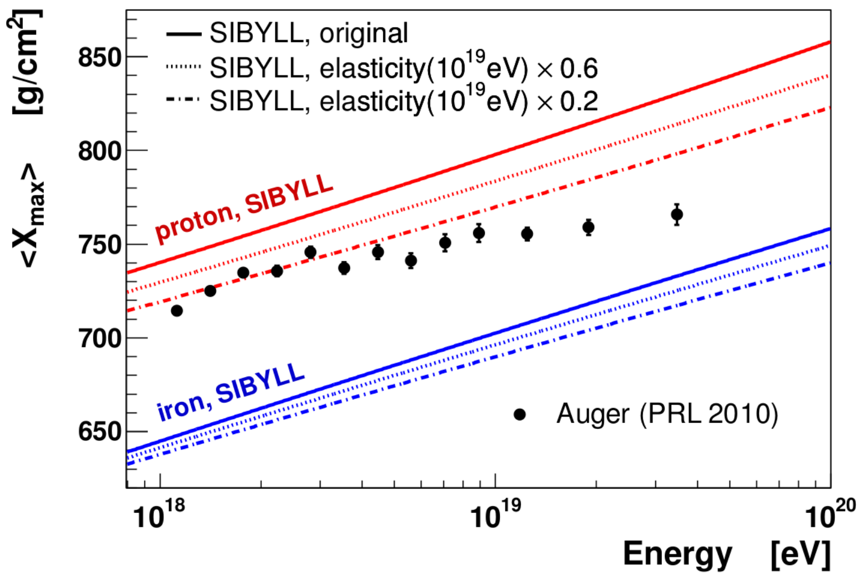
Check of systematic effects

	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%	

Extensive air shower modeling

- Both air shower observables and the very forward energy spectrum are sensitive to changes in the hadronic interaction parameters such as multiplicity, elasticity or baryon production.
- This effect is most visible in the structures below 1TeV.





[Simulation study by Ralf Ulrich]