Recent CMS results in the forward region with the CASTOR detector

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The Forward Instrumentation of CMS
Overview

- CMS has an excellent calorimetric instrumentation in the forward region

![Diagram](https://example.com/diagram.png)

*taken from C. Baus*
HF calorimeters

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

- Tungsten-Quartz-Cherenkov sampling calorimeter
- Segmented in 16 sectors in $\varphi$ and 14 modules in $z$
- No $\eta$-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
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

![Graphs and data plots related to CMS analyses](image-url)

[CERN CDS: 1472732]

[arXiv:1503.08689]

[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 $\sigma_{\text{inel}}$

- 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

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

HF OR CASTOR

- 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 $\sigma_{\text{inel}}$

- Define final state via $\xi$ variable
  - divide final state in two subsystems $X,Y$ relative to the largest rapidity gap
  - calculate invariant masses $M_X, M_Y$ and use
  
  $$\xi_X = \frac{M_X^2}{s}, \quad \xi_Y = \frac{M_Y^2}{s} \quad \text{and} \quad \xi = \max(\xi_X, \xi_Y)$$

- optimal detector acceptance is determined using full MonteCarlo simulation

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

<table>
<thead>
<tr>
<th>HF OR</th>
<th>HF OR CASTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi &gt; 10^{-6}$</td>
<td>$\xi_X &gt; 10^{-7}$ or $\xi_Y &gt; 10^{-6}$</td>
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Measurement of $\sigma_{\text{inel}}$

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

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

\[ \sigma_{\text{inel}} = 71.3 \pm 0.5 \, \text{(exp.)} \pm 2.1 \, \text{(lum.)} \pm 2.7 \, \text{(ext.)} \, \text{mb} \]
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:

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

- Sum of all calorimeter towers above noise level
- Segmentation defined by calorimeter acceptances
- Correction from detector to stable particle level
- Data-driven correction for Pileup
Measurement of $dE/d\eta$

**Left Panel**
- CMS Preliminary
- Data, Pythia8 Monash, EPOS-LHC, QGSJET II
- $B = 0$ T

**Right Panel**
- CMS Preliminary
- Data, Pythia8 CUETP8M1, Pythia8 CUETP8M1+MBR, Pythia8 CUETP8S1
- $B = 0$ T
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 $dE/d\eta$

**CMS Preliminary**

- **Data**
- **Pythia8 Monash**
- **EPOS-LHC**
- **QGSJET II**

**NSD-enhanced**

| $|\eta|$ | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 |
|--------|-----|-----|-----|-----|-----|-----|-----|
| $dE/d\eta$ (GeV) | 10^2 | 10^3 | 10^3 | 10^3 | 10^3 | 10^3 | 10^3 |

**CMS Preliminary**

- **Data**
- **Pythia8 CUETP8M1**
- **Pythia8 CUETP8M1+MBR**
- **Pythia8 CUETP8S1**

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**CMS Preliminary**

- **Pythia8 Monash**
- **EPOS-LHC**
- **QGSJET II**
- **Data**
- **Total Exp. Unc.**

**NSD-enhanced**

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|--------|-----|-----|-----|-----|-----|-----|-----|
| $dE/d\eta$ (GeV) | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 |

**CMS Preliminary**

- **Pythia8 CUETP8M1**
- **Pythia8 CUETP8M1+MBR**
- **Pythia8 CUETP8S1**
- **Data**
- **Total Exp. Unc.**

**NSD-enhanced**

| $|\eta|$ | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 |
|--------|-----|-----|-----|-----|-----|-----|-----|
| $dE/d\eta$ (GeV) | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 |
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 $\sqrt{s}$ 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
    - at least one tower above 5 GeV in either HF+ or HF-
  - soft-inclusive-inelastic
    - $\xi > 10^{-6}$

- 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 $\rightarrow$ total energy sum
- Front $\rightarrow$ electromagnetic component
- Back $\rightarrow$ hadronic component

**soft-inclusive-inelastic**
- all stable particles except $\mu$, $\nu$
- $e$, $\gamma$ (incl. $\pi^0$)
- all stable particles except $\mu$, $\nu$, $e$, $\gamma$

![Diagram of CMS data analysis](image)
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

![Electromagnetic Response](image1)

![Hadronic Response](image2)
Measurement of $1/N_{\text{evt}} \, dN/dE$ in CASTOR

- Measurement confirms the general shape of the spectrum, bump structure at $\sim 350$ 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 $1/N_{\text{evt}} \, dN/dE$ 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

![Graph showing matched GEN-Jet $p_T$ vs. matched RECO-Jet $p_T^{RECO}$]
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

- 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!
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 $\sigma_{\text{inel}}$

<table>
<thead>
<tr>
<th></th>
<th>$\sigma(\xi &gt; 10^{-6})$ (mb)</th>
<th>$\sigma(\xi_X &gt; 10^{-7} \text{ or } \xi_Y &gt; 10^{-6})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model dependence</td>
<td>0.66</td>
<td>0.38</td>
</tr>
<tr>
<td>HF energy scale uncertainty</td>
<td>0.34</td>
<td>0.13</td>
</tr>
<tr>
<td>CASTOR energy scale uncertainty</td>
<td>-</td>
<td>0.04</td>
</tr>
<tr>
<td>CASTOR alignment</td>
<td>-</td>
<td>0.03</td>
</tr>
<tr>
<td>Run-to-run variation</td>
<td>0.15</td>
<td>0.14</td>
</tr>
<tr>
<td>Total</td>
<td>0.76</td>
<td>0.44</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.78</td>
<td>1.96</td>
</tr>
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\[
\sigma(\xi > 10^{-6}) = 65.8 \pm 0.8 \text{ (exp.)} \pm 1.8 \text{ (lum.)} \text{ mb}
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\sigma_{\text{inel}} = 71.3 \pm 0.5 \text{ (exp.)} \pm 2.1 \text{ (lum.)} \pm 2.7 \text{ (ext.)} \text{ mb}
\]
# Measurement of $dE/d\eta$

## Check of systematic effects

<table>
<thead>
<tr>
<th>Source of Systematic Effects</th>
<th>Soft-inclusive inelastic events</th>
<th>Non-single diffractive events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model dependence of correction factor</td>
<td>&lt; 3.5%</td>
<td></td>
</tr>
<tr>
<td>Influence of noise on selection</td>
<td>&lt; 1.75%</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>Influence of noise on energy sums</td>
<td>&lt; 1.2%</td>
<td></td>
</tr>
<tr>
<td>Calorimeter global energy scale in $3.15 &lt;</td>
<td>\eta</td>
<td>&lt; 5.20$</td>
</tr>
<tr>
<td>Calorimeter global energy scale in $5.20 &lt;</td>
<td>\eta</td>
<td>&lt; 6.6$</td>
</tr>
</tbody>
</table>
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.