Forward energy flow and jet measurements with CMS

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on behalf of the CMS collaboration

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Why study forward energy flow?

- Study QCD and its (low $x$ parton) dynamics
- Kinematic range relevant for cosmic air showers
  - use to test and/or tune cosmic ray air shower models
- In most LHC interactions, most of energy goes forward
  - good coverage for total inelastic cross section measurement
- Wide rapidity coverage
  - good coverage of large rapidity gaps,
    test colour singlet exchange
How to do this in CMS?

- CMS is nicely equipped for benchmark energy flow measurements.
Measurements with CASTOR

very forward energy measurement: $-6.6 < \eta < -5.2$

14-fold segmentation in $z$, 16-fold segmentation in $\phi$, no segmentation in $\eta$
Forward jet $p_T$ spectrum @ 13 TeV

PYTHIA8 (CUETP8M1) gives consistent description

Multi-Parton-Interactions important
Forward jet $p_T$ spectrum @ 13 TeV

Jet $p_T$

cosmic ray shower generators EPOS and QGSJetII give reasonable description
Forward particle production @ 13 TeV

**Total energy of all particles**

Significant check of performance of different generators and tunes. None reproduces all features.

OT runs

**Cosmic air shower generators**

**PYTHIA tunes**

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Forward particle production @ 13 TeV

electromagnetic (mainly $\pi^0$)  hadronic (mainly $\pi^\pm$)

overall, EPOS seems to do best for electromagnetic ($\pi^0$) and hadronic ($\pi^\pm$) energy fractions

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Forward jet production in pPb and Pb+p @ 5 TeV

CMS PAS FSQ-17-001, to be published soon

p+Pb (p \rightarrow \text{CASTOR}) \quad \text{Pb+p (lead \rightarrow \text{CASTOR})}

distributions at RECO level (norm. to cross section); test “saturation”

data slope for p\rightarrow\text{CASTOR} not well described by models

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Forward jet production in pPb and PbP @ 5 TeV

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before

after unfolding to particle level

ratio p+Pb/Pb+p

anti-\kappa(0.5) (-6.6 < \eta < -5.2) \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}

before                             after unfolding to particle level

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\end{figure}

none of generators performing well, can use unique data to improve!
Measurements with HF (and CAL endcaps)
Forward energy/unit rapidity in pp @ 13 TeV

inelastic events
(>= one side HF)

reasonably described by predictions
Non-Single-Diffractive enhanced events
(both sides HF)

center-of-mass energy dependence well described, consistent with limiting fragmentation hypothesis
Total inelastic cross section @ 13 TeV

use HF and/or CASTOR to define inelastic events

$\xi_X = \frac{M_X^2}{s}$

$\xi_Y = \frac{M_Y^2}{s}$

$\xi = \max(\xi_X, \xi_Y)$

results from HF and HF+CASTOR are consistent

CMS and ATLAS results are consistent

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Dijet events with large rapidity gaps

@ 7 TeV
jet 1: -4.7 < \eta < -1.5  
jet 2: 1.5 < \eta < 4.7  
no tracks  
-1 < \eta < 1 (GAP)

HERWIG 6 describes data with gap (includes colour-singlet exchange)
PYTHIA 6 describes data w/o gap (no colour-singlet simulation)
Dijet events with large rapidity gaps


Colour-Singlet-Exchange fraction

comparison to Tevatron

trend 0.63 $\rightarrow$ 1.8 TeV confirmed by

trend 1.8 $\rightarrow$ 7 TeV consistent with rapidity gap suppression models

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Dijet events with large rapidity gaps

EEI model (Ekstedt, Enberg and Ingelmann) (NLL BFKL+gap suppr.) works better than MT model (Mueller and Tang) (LL)

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Conclusions

- Measurements of forward energy or jet production at LHC are a great tool to test QCD and its dynamics, and to calibrate cosmic ray air shower simulations.

- Measurements in CASTOR rapidity range $-6.6 < \eta < -5.2$ in both pp and pPb are unique to CMS. Reasonably described by QCD. Discriminate between different "air shower" models and PYTHIA tunes. Significant room for improvement of proton+lead interaction simulations.

- Conclusions consistent with differential measurements in "more central" calorimeters (HF and endcaps). Also give access to total inelastic cross section, consistent with ATLAS and dijets with large rapidity gap, first LHC measurement, checks BFKL-based colour singlet exchange and gap suppression models.