Very Forward Jets in CMS with CASTOR

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Outline

- Motivation for Forward Physics
- CMS Detector
- Measurements on the LHC Run 2 data (13 TeV)
  - Measurement of the very forward inclusive jet cross section in pp collisions at $\sqrt{s} = 13$ TeV (CMS PAS FSQ-16-003)
  - Very forward inclusive jet cross sections in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (CMS PAS FSQ-17-001)
- Summary

All Forward Physics results at CMS
Why Forward Physics?

- To understand the pp collisions depend on a wide range of phenomena by looking at low $p_T$ or forward $y$
- Many interesting (mostly colorsinglet exchange) scattering processes at the LHC are characterized by forward particle production:

**Low-x**

- Small fraction of proton momentum carried by an interacting parton.
- Test of pQCD evolution (DGLAP vs BFKL dynamics);
- Tool to study small-$x$ QCD are forward jets – jets emitted at small angle with respect to the beam (large rapidity).

**Elastic/diffractive interactions:**

- Hard diffraction ($X = \text{jets, W's, Z's...}$):
  - Calculable (in principle) in pQCD $\rightarrow$ Info on proton structure (dPDFs, GPDs), multiparton interactions (MPI), discovery physics (DPE Higgs, beyond SM)

**Soft diffraction ($X=\text{anything}$):**

- Dominated by soft QCD $\rightarrow$ SD, DPE vs. $s, t, M_X$
- provide valuable info of non-perturb. QCD.
- Contributions to pileup pp events.

**Cosmic ray physics:**

- Forward energy & particle flows / min. bias events (p-p, p-A, A-A)
- Exotica: “Centauro” events (DCCs, strangelets)
Why jets?

- Key component to extend our understanding of the Standard Model physics
- Invaluable objects to probe QCD
  - soft QCD - low $p_T$ multiparton scattering, fragmentation, underlying event, etc.
  - hard QCD - high $p_T$: PDFs, strong coupling, perturbation theory, ISR & FSR, parton shower, (subjets)
- Measure and understand the main background to many new physics searches.
- Check SM predictions at high energy scales.
- Abundantly produced at hadron colliders like LHC
  - LHC is a jet factory!
- Jet and photon cross section measurements are also important for validating the detector/trigger/reconstruction chain, and are "legacy" measurements for the future among the first measurements at each new energy

Jets:

- hard scattering
- (QED) initial/final state radiation
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays

and in addition
- backward parton evolution
- soft (possibly not-so-soft) underlying event
A jet in CMS is seen as a bunch of particles in the detector.

Jet reconstruction procedure: input objects (e.g. particles) → apply jet finding algorithm → jet reconstruction.

- Anti-$k_t$ algorithm (infrared and collinear safe) is used.

- Particle Flow (PF) Jets: Clustering of Particle Flow candidates constructed by combining information from all sub-detector systems.

- Factorized Jet Energy Correction approach in CMS:
  - Pileup → corrects for “offset” energy
  - Response → Make jet response flat on $\eta$ and $p_T$
  - Data/MC residuals → residual differences between data & MC
  - Flavor (optional) → corrects dependence on jet flavor
Very Forward Jets in CMS with CASTOR, Forward Physics and Diffraction 2018

CMS after Long Shutdown 1

3rd of June 2015: LHC back in business with record pp collision energy of 13 TeV

Run I and II pp collisions

CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:22 to 2017-11-10 14:09 UTC

- 2010, 7 TeV, 45.0 pb\(^{-1}\)
- 2011, 7 TeV, 6.1 fb\(^{-1}\)
- 2012, 8 TeV, 23.3 fb\(^{-1}\)
- 2015, 13 TeV, 4.2 fb\(^{-1}\)
- 2016, 13 TeV, 40.8 fb\(^{-1}\)
- 2017, 13 TeV, 51.0 fb\(^{-1}\)
Forward Detectors at CMS

**TOTEM RPs** (147,220m) (|η| > 8.4)

**CASTOR** (-5.2 < η < -6.6)

Central region: HCAL and ECAL

**HF Detector**

- @11.2 m from interaction point
- Rapidity coverage: 3 < |η| < 5
- Steel absorbers/quartz fibers (Long+short fibers)
- 0.175x0.175 η/φ segmentation

**CASTOR**

- Tungsten-Quartz-Cherenkov sampling calorimeter
- Octagonal cylindrical shape
- Segmented in 16 sectors in φ and 14 modules in z
- Separated electromagnetic and hadronic sections
- Located at 14.4 m from IP in CMS
CMS Very Forward Calorimeter (CASTOR)

- Centauro And STrange Objects Research (CASTOR)
- Tungsten-Quartz-Cherenkov sampling calorimeter
- 14.37 m away from Interaction Point (IP). Only at minus side.

- Segmented in 16 sectors in $\phi$
- 14-fold segmentation in $z$: 2 electromagnetic modules, 12 hadronic modules
- Very forward acceptance: $-6.6 < \eta < -5.2$
- No segmentation in $\eta$: all jets $\eta = -5.9$
Motivation:
- First measurement of jets inside the CASTOR

Analysis strategy:
- Very low pile-up sample of pp collisions @ $\sqrt{s}=7$ TeV taken in 2010 Run I period
- Minimum Bias trigger
- Require central leading track-jet (jet made of charged particles only): $p_T > 1$ GeV/c and $|\eta| < 2$
- Anti-$k_T$ ($R = 0.5$) with high purity input tracks: $|\eta| < 2.5$ and $p_T > 300$ MeV
- Jet in CASTOR $E_{\text{jet}} > 500$ GeV
- Plots normalized to unity
- Comparison with Pythia8 4C

Jet energy

Jet profile

Jet multiplicity
Very forward jets in pp

- Powerful benchmark for QCD model predictions
- Forward and low $p_T$ jet production provides access to low-$x$
- Sensitive to parton evolution dynamics (DGLAP/BFKL/CCFM)

$$d\sigma(pp\rightarrow\text{jet}) = \text{PDF}(x_1, Q^2) \otimes \text{PDF}(x_2, Q^2) \otimes \sigma(qg\rightarrow\text{jet})$$

- Possibly sensitive to parton saturation (nonlinear evolution)?

Very forward jet measurement performed with 13 TeV data
- Fully corrected inclusive jet cross sections and jet yields normalized to number of visible jets as function of jet $p_T$
  - $-6.6< \eta <-5.2$
  - $p_T$ unfolded from $E\cdot \cosh \eta$, with $\eta = -5.9$
- Energy scale uncertainty yields the dominant systematic uncertainty
Motivation:
- Low x gluon density poorly known
- Very forward jets allow to probe the low-x domain region sensitive to non-linear QCD effects
- Constrain low-x gluon PDFs.

Analysis strategy:
- Use low pile-up runs from LHC Run 2 (2015)
- Phase space definition:
  - \( E > 150 \text{ GeV} \) or \( p_T > 3 \text{ GeV} \) in \(-6.6 < \eta < -5.2\)
  - \( p_{T,\text{det}} \rightarrow p_{T,\text{hadron}} \): Lorentz invariant but suffers from \( \eta \)
- Convert \( E_{\text{jet}} \) to \( p_T \) by \( \cosh(\eta) \)

Observables: \( \frac{d\sigma}{dp_T} \)

Dominant unc. source: CASTOR energy scale (15%)
All models show agreement with data within the unc.
Any sensitivity to MPI or PDF?

- Moderate sensitivity to the underlying PDF set of the model
- Very sensitive to MPI
**Motivation:**

- At very low-x transition from dilute to dense medium.
  - Non-linear QCD behaviour expected
- Gluon density in heavy ion larger than proton
- More perturbative saturation scale ($Q_s$) compared to saturation scale in pp collisions.
- Sensitivity to non-DGLAP (BFKL?) evolution scheme.

**Analysis strategy:**

- Use proton lead collisions data in 2013.
  - p+Pb: proton towards CASTOR.
  - Pb+p: ion to CASTOR
- Non-diffractive, hadronic event selection
- Event selection
  - Online: require beams in CMS IP & a track with $p_T \geq 0.4$ GeV ($|\eta| \leq 2.5$)
  - Offline: require $E_{\text{tower}} > 4$ GeV in HF+ and HF- (3 ≤ |$\eta$| ≤ 5.2)
  - Use anti-$k_T$ jets with R = 0.5
  - Measure jet energy in CASTOR (-6.6 < $\eta$ < -5.2)
- All results shown in the lab frame!

**Observables:**

- Fully corrected inclusive jet cross sections $d\sigma / dE$ vs. jet energy in p+Pb and Pb+p.
- Ratio of $\sigma(p+Pb) / \sigma(Pb+p)$ as function of energy
**MC Generators**

- Simulation of events:
  - Propagate generator particles through CMS detector using GEANT4

- Generators used:
  - HIJING:
    - Applies DGLAP parton evolution via PYTHIA.
    - Shadowing implemented via suppression of nuclear gluon pdf.
    - Suppressed with fit to nuclear sea quark DIS data
  - EPOS:
    - Combination of parton model with pomeron exchange with hydrodynamic model.
    - Effective screening occurs via interference terms
  - QGSJETII04:
    - Similar to EPOS, but implements saturation via phenomenological model
    - no hydrodynamics on-DGLAP (BFKL?) evolution scheme.

- Reconstruction of jets in CASTOR:
  - CASTOR is segmented into 16 towers (a tower is a longitudinal summation of channels)
  - Anti-\( k_T \) algorithm used for reconstruction of CASTOR jets

- Systematic uncertainties
  - Jet energy scale uncertainty + Alignment unc. (the position of CASTOR is known to only 2 mm) : 17%
  - Calibration uncertainty

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Jet energy cross section for p+Pb and Pb+p

- p+Pb spectrum is well described by HIJING
- EPOS-LHC and QGSJETII-04 underestimate the data progressively with increasing jet energies
  - hard component in data and HIJING?
- All models underestimate low-energy tail for Pb+p spectrum
  - But from ~1.2 TeV onwards, all models are in agreement with the data

Energy scale uncertainty is the dominant uncertainty for both p+Pb and Pb+p spectra.
Cancellation of energy scale uncertainty allows for better discrimination between data and models.

- None of the models describe the data on the whole range.
  - HIJING describes the shape well but is off in normalisation (due to the poor Pb+p description)

- EPOS-LHC and QGSJETII-04 significantly fail to describe the ratio at high energies

- Saturation expected in p+Pb, but not in Pb+p
  - Depletion at low energy?
LHC provides access to a large phase space as well as the highest energy reached ever

CMS has very rich and active forward physics program provides the perfect testing ground for QCD models and theory
  - unique forward detector instrumentation

Very forward jets measurements at CMS are a reality!
  - challenge is energy scale uncertainty
  - efforts on-going for cancelation of uncertainties

Very forward jets
  - highly sensitive to Underlying Event settings and provide valuable inputs for tuning
  - But weak dependence on PDF

No clear sign for saturation yet
  - p+Pb results need to be further interpreted
Thank you for your attention!
BACKUP
Decorrelation of forward jets at 7 TeV

- Approaches to higher-order calculations:
  - DGLAP approach: resummation in terms of $\ln(Q^2)$
  - BFKL approach: resummation in terms of $\ln(1/x)$

- Most forward and most backward jets with $p_T > 35$ GeV
- Results given for up to $|\Delta y| = 9.4$
- Compared to predictions
  - DGLAP-based LO MCs
  - HEJ: LL BFKL-based MC
  - NLL BFKL prediction
- Angular variables also studied as a function of $\Delta y$
Mueller-Navelet dijet azimuthal decorrelations

- Mueller-Navelet dijets: pair of jets with the largest rapidity interval
- Decorrelation of $\Delta \phi$ MN pair: sensitive to QCD dynamics
- Cross section vs. $\Delta \phi$ expanded in terms of $\cos[n(\pi-\Delta \phi)]$
  - expansion coefficients and their ratio depend on $\Delta y$
  - region of large $\Delta y$ probes the BFKL evolution

Good data-theory agreement: NLL BFKL analytical calculations at large $\Delta y$

BFKL NLL calculations, parton level (small effects from hadronization) (JHEP 1305(2013) 096) sensitivity to MPI and angular ordering
**Very forward energy spectra**

**Motivation:**
- Sensitive to changes in the hadronic interaction parameters such as multiplicity, elasticity or baryon production.
- The effect is most visible in the structures < 1 TeV

**Analysis strategy:**
- Use pp collisions @13 TeV, low pile-up runs from 2015 with B = 0 T
- Trigger on beam presence and bunch crossing
- Soft inclusive events (single arm selection)

**Observables:**
- Total energy measured by CASTOR (dN / dE)
- Separate spectrum as
  - Electromagnetic (energy from first 2 modules)
  - Hadronic (energy from last 12 modules)

**Visibility of diffractive events as a peak at the lowest energies**
- Hadronic component causes low energy peak
- Steep tail towards higher energies

**Dominant unc. Source: CASTOR energy scale (17%)**
- Sensitivity seen in data to MPI and UE.
Very forward energy spectra (cont'd)

PYTHIA8 (Sensitivity to MPI and UE)

- Data well described by all models except for PYTHIA8 4C+MBR and SIBYLL2.3: slope in the soft part
- High sensitivity to MPI

Cosmic Ray models

- Cosmic ray models perform well
  - EPOS LHC and QGSJETII shows large differences in high energy tail
  - PYTHIA8 tunes overestimate the soft region

EM spectrum

Hadronic spectrum
Measurement on azimuthal correlation in different scenarios, for different rapidity separation,
- Probe high and low-x regions, q & g ladders
- Large $|\eta|$ difference between jets
  - high order emissions: high sensitivity to QCD and parton dynamics
- Sensitivity to UE and MPI

DGLAP MCs describe the observables very well
- Overall Herwig performs better than Pythia
- the best description by Herwig++