Very forward inclusive jet cross sections in p+Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV

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Motivation

Signals of nonlinear QCD

- At very small momentum fractions $x$ transition from dilute to dense medium. Nonlinear QCD behaviour expected

- For a jet in leading order approximation: $x \approx \frac{p_t \exp^{-\eta}}{\sqrt{s}}$
  - Forward low $p_t$ jets serve as probe for small $x$

- Parton density (and saturation scale) in heavy ion larger than in proton
  - Gluon density in ion $\approx N^{1/3}$ larger than proton, $\approx 6$ for lead
  - Forward jet spectrum in proton lead collisions excellent observable for signals nonlinear QCD

- Present new, unprecedented measurement of forward jet spectra in proton lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV at CMS!
  - Can we observe signals of nonlinear QCD? Which models provides good description?
CASTOR at CMS

- CASTOR: EM-hadronic calorimeter at CMS:
  \[-6.6 \leq \eta \leq -5.2\]
  → Most forward conventional calorimeter deployed at the LHC, at 14 m from interaction point

- CASTOR has no \( \eta \) segmentation! Present energy spectra instead of \( p_t \)

- CASTOR measures energy deposits, jets, and rapidity gaps

- CASTOR successfully extended acceptance for measurements (references in backup):
  - Inelastic and diffractive cross sections
  - Forward energy flow and underlying event
  - Jet spectra
In proton lead collisions various reactions occur:
  ▶ Elastic scattering, photon-induced events, diffractive collisions, inelastic hadronic collisions
  ▶ This analysis deploys a non-diffractive, hadronic event selection

**Event selection detector level**
  ▶ Online: require beams in CMS interaction point and a central track with $p_t \geq 0.4$ GeV ($|\eta| \leq 2.5$)
  ▶ Offline: require minimally one calotower above 4 GeV in HF+ and HF- ($3 \leq |\eta| \leq 5.2$) (HF is Hadronic Forward calorimeter)
    ★ Effectively suppresses diffractive and photon-induced events, see PAS FSQ-13-006
  ▶ Require maximally one good primary vertex, to avoid event pileup

**Event selection generator level**
  ▶ Require minimally one particle above 4 GeV in HF+ and HF- acceptance
  ▶ Require minimally one charged particle above 0.4 GeV in tracker acceptance
    → We’ll unfold to a spectrum for this event selection

**Analyse proton lead collisions delivered to CMS in 2013. p+Pb: proton towards CASTOR. Pb+p: ion to CASTOR**

**In lab. frame: proton beam energy is 4 TeV, ion beam energy is 1.6 TeV (per nucleon). All results presented are in the lab frame!**
Jets in CASTOR in data and simulation

Event simulation

- Propagate generator particles through CMS detector volume 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

Constructing CASTOR jets

- CASTOR is segmented into 16 towers (a tower is a longitudinal summation of channels)
  - Cluster the towers with anti-$k_t$ algorithm into CASTOR jets
- CASTOR jets possess various systematical uncertainties
  - Energy scale uncertainty: 15%
  - Calibration uncertainty (explanation in backup)
  - Alignment uncertainty: the position of CASTOR is known to only 2 mm
- All results are for single inclusive jet spectra

Comparing CASTOR jet spectra on detector level

Proton to CASTOR

CASTOR jet spectra normalised to a cross section

- Energy scale uncertainty propagates into large uncertainty on spectrum
- Alignment sys. uncertainty simulated per model
- HIJING describes data well
- EPOS and QGSJet underestimate data progressively with energy, up to nearly 2 orders of magnitude
Comparing CASTOR jet spectra on detector level

Ion to CASTOR

- At low energies all models underestimate the data
- From $\approx 2$ TeV onwards, systematic uncertainties become prohibitive on model distinction

CASTOR jet spectra normalised to a cross section
Comparing CASTOR jet spectra on detector level

Ratio $p+Pb/Pb+p$ of spectra

Energy scale uncertainty largely cancels

Ratio significantly overestimated by HIJING

EPOS and QGSJet underestimate data progressively with energy up to an order of magnitude
Unfolding CASTOR jet spectra

Motivation

- Presented CASTOR jet spectra on detector level
- Cannot compare such results between experiments directly. Comparison to future models problematic
  → Unfold detector level spectra to particle level jets

Determining the response of CASTOR to jets in proton lead collisions

- Define acceptance generator level jets. Extend CASTOR acceptance by $\Delta \eta$. Found $\Delta \eta = 0$ gives optimal response matrix
- Maximal distance in $\phi$ between jets. $\Delta \phi = 0.5$ gives minimal number unmatched jets (aka miss and fake jets)
The response matrices

The response matrices for Hijing

- For $\Delta \phi = 0.5$, $\Delta \eta = 0$
- Left: $p+Pb$. Right: $Pb+p$
- Response matrices rather broad, reflected in large condition number (in backup)
Unfolding the spectra

- Unfolding performed by the d'Agostini iterative procedure.
  - Unfolding uses response matrix and spectra of misidentified jets
  - Unfolding cannot compensate for miss and fake spectra, while these are model dependent!
    → Fake and miss spectra unconventional large at CASTOR since no $\eta$ resolution

- All systematic uncertainties evaluated with Hijing
- Model uncertainty evaluated by using EPOS and QGSJet
- The maximal uncertainty is always taken
  → Conservative approach!
The unfolded p+Pb spectrum

Observations

- Large sys. uncertainty, significant contribution from model dependence
- Hijing describes data (very!) well
- EPOS and QGSJet have wrong slope and underestimate the data progressively with energy. At 2.5 TeV data and QGSJet deviate by 2.5 orders of magnitude!
  → Forward inclusive jet spectrum in p+Pb has strong discriminative power!
The unfolded Pb+p spectrum

Observations
- Large sys. uncertainty
- EPOS and Hijing describe shape data reasonably well but norm is off. QGSJet worst description data
- Lower error bound of last 2 bins extends to 0
The key result: the unfolded ratio $p+Pb/Pb+p$

- $p+Pb$ cross section order of magnitude smaller than $Pb+p$
- Ratio is quite flat, scale uncertainty largely cancels → Ratio opportune observable
- Hijing describes shape well but an overall factor $\approx 2$ off, due to poor $Pb+p$ description
- EPOS and QGSJet have wrong shape, partially describe data

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Conclusions: physics interpretation

Physics interpretation

- Compared three models with different implementation saturation to data
  - Cannot draw an unambiguous conclusion on model comparison at this point
    - Compare to generators with saturation turned on and off. Possible for Hijing (and Herwig?), not for EPOS and QGSJet
      - What physics is in Hijing suppression?
    - Compare to calculations in Coloured Glass framework and Hybrid Factorisation
      - See talk from dr. Kutak last Tuesday the calculation for p+p 13/7 TeV ratio!
    - Use different input pdf’s with different implementation nuclear shadowing
  - Data driven conclusions. p+Pb: probe glue of heavy ion with hard partons of proton; Pb+p reverse. Expect stronger effect saturation in p+Pb
    - Compromised by boost of centre of mass frame
      - Effect must be understood
      - Ratio p+Pb/p+p would provide good reference, and smaller effect due to boost
- ... Jet spectra in CASTOR in proton lead collisions appear to have good resolution for hypothesis testing!

Nuclear modification of structure function from nuclear DIS data. Hijing employs the fitted function for nuclear suppression

... Thanks for your attention!

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Content

- Conclusions on Data and model comparison
- Note on validity results
- References CASTOR papers
- Recent results on forward energy flow
- Detail picture of a CASTOR channel
Conclusions: data and model comparison

Data and model comparison

- Uncertainties for p+Pb and Pb+p large. Scale largely cancels for ratio
  - Max scale uncertainty pA: 145% / 71%
  - Max scale uncertainty Ap: 170% / 81%
  - Max scale uncertainty pA/Ap: 57% / 29%
- p+Pb: significant deviations, progressively larger with jet energy
- Pb+p: model discrepancies smaller than p+Pb, but significant at lower energies
- Ratio: not described by any model. Hijing deviates significantly, through Pb+p deviations
- The RECO level spectra have enhanced discriminative power due to absence model uncertainty
Brief note validity

Validity procedure

- As cross check, 7 TeV p+p NTuples analysed within p+Pb framework. Convergence reached
- For most parameters, values found are same or comparable with CASTOR p+p jet analyses at 7 and 13 TeV
- Result cross section and systematic uncertainties are reasonably consistent with p+p analyses
- Behaviour on unfolded spectra reasonably comparable with RECO level spectra
- p+Pb actually described by models at low energies
- ... No internal inconsistencies observed
List of papers, CMS PAS (Physics Analysis Summary) and performance notes with CASTOR

- Underlying event at forward rapidity at 0.9, 2.76, and 7 TeV p+p: **JHEP 04 (2013) 072**
- Forward energy flow at 13 TeV p+p: **CMS PAS FSQ-16-003**
- $\eta$ and centrality dependence of the forward energy density in PbPb collisions at $\sqrt{s}=2.76$ TeV: **CMS-PAS-HIN-12-006**
- Inelastic cross section at 13 TeV p+p: **CMS PAS FSQ-15-005**
- Inclusive CASTOR jet cross section at 13 TeV p+p: **CMS PAS FSQ-16-003**
- Inclusive CASTOR jet cross section at 7 TeV p+p: **CMS-PAS-FSQ-12-023**
- Inclusive CASTOR jet cross section at 5 TeV p+Pb: **CMS-PAS-FSQ-17-001**
Measuring Energy Flow at Forward rapidity at $\sqrt{s} = 13$ TeV

**Results**

- Energy flow $\frac{dN}{dE}$ measured at CASTOR at 13 TeV proton+proton collisions
- Measurement possesses large systematics error (mainly due to scale). Nonetheless, none of models describes all features of the data
- Cosmic Ray models tuned to LHC give best description
- Spectra very sensitive to MPI cutoff.
  - Forward energy flow measurement at CASTOR allows for tuning MPI and improving understanding muon production in air showers
- Results can be found at arXiv:1701.08695, submitted to Journal!

Left: Ratio of the energy deposited in CASTOR for events with a central charged-particle jet with respect to inclusive events, as a function of the jet $p_t$. Right: energy in CASTOR for inclusive events and events with central jets above 10 GeV.
Condition number definition

Results

- Condition number is a reflection of how broad the response matrix is.
- \( \text{cond}(K) = \sigma_{\text{max}} / \max (0, \sigma_{\text{min}}) \), where \( \sigma_{\text{max}} \) is the largest and \( \sigma_{\text{min}} \) is the smallest singular value of \( K \).
- Large condition number implies many Bayesian iterations are needed for sufficient regularization.