Forward energy flow and jet production in p+p and p+A collisions at the LHC with CMS

ICHEP, Seoul

Merijn van de Klundert on behalf of the CMS collaboration[1]
mvandekl@cern.ch

[1]DESY, Germany

July 2, 2018

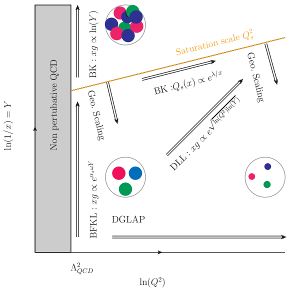
Motivation

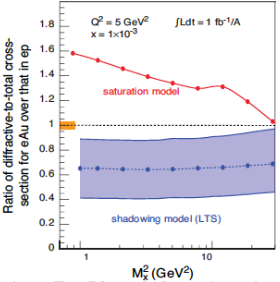
Signals of nonlinear QCD

- At very small momentum fractions x transition from dilute to dense medium. Nonlinear QCD behaviour expected
  - Relevant to cosmic-ray and heavy ion physics
- Saturation scale: $Q_s^2(x) \approx \frac{\alpha_s x g(x, Q_s^2)}{\pi R^2_{had.}}$
  - Geometric interpretation: gluons with area $r^2 \approx 1/Q^2$ "fill up" the hadron area. Fusion reactions ($gg \rightarrow g$) expected when overlap occurs
- Saturation has been extensively analysed in past, constitutes a key incentive for future EIC

Status of gluon saturation

- Analyses key measurements comply with saturation hypothesis
- Interpretation of important results diffused though:
  - HERA e+p measurements: the saturation scale close to perturbative limit
  - RHIC d+Au measurements: hard partons projectile at kinematic limit
- LHC results appear to comply with saturation
  - No "smoking gun" signature observed yet though





Graph from **Eur.Phys.J. A. 52 (2016) no.9, 268**

Saturation at LHC

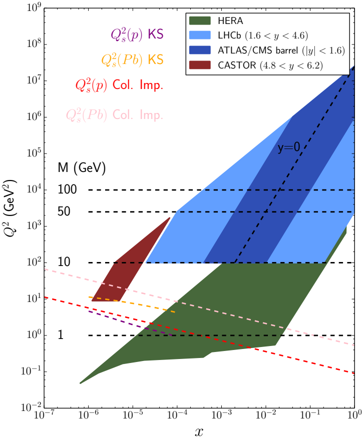
Optimal saturation signals

- Saturation scale in ion $\approx N^{1/3}$ larger than proton, ≈ 6 for lead)
- For a jet in leading order approximation: $x \approx \frac{p_T \exp^{-\eta}}{\sqrt{s}}$
  $\rightarrow$ Forward low p_T jets in p+Pb collisions sensitive to saturation effects

Forward low pt jets in CASTOR at CMS

- CMS equiped with CASTOR calorimeter:
  - Acceptance: $-6.6 < \eta < -5.2$
  - For jets: $p_T \geq 3$ GeV

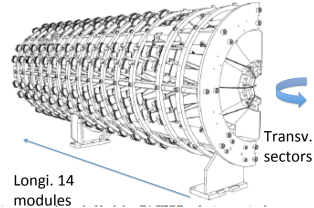
  $\rightarrow$ Measurement potentially higly sensitive to saturation, and circumvent adversities previous analyses



Focus of presentation

- Measurement of single-inclusive jet energy spectrum in p+Pb collisions in CASTOR
  - For proton (p+Pb) and ion (Pb+p) to CASTOR
- Interpret results with dedicated saturation models

The CASTOR calorimeter at CMS



CASTOR at CMS

- CASTOR: EM-hadronic tungsten-quartz calorimeter at CMS. Unique acceptance!
  $\rightarrow$ Most forward conventional calorimeter deployed at the LHC, at 14 m from interaction point
- CASTOR has no η segmentation! Measure energy of jets instead of p_{T}, in its acceptance
- Preliminary results on jets in CASTOR:
  - p+p collisions at $\sqrt{s}$ =7 TeV (**CMS-PAS-FSQ-12-023**
  - p+p collisions at $\sqrt{s}$ =13 TeV **CMS-PAS-FSQ-16-003**)
  - p+Pb collisions at $\sqrt{s}$ =5 TeV (**CMS-PAS-FSQ-17-001**)
    $\rightarrow$ Presented in this talk!
  - More CASTOR and general references in backup slide

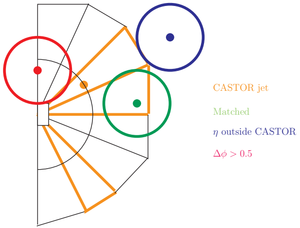
Source of systematic uncertainty

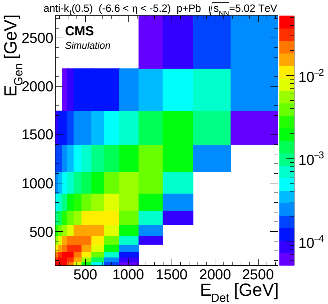
Sources of sys.uncertainty (by magnitude):

- CASTOR energy scale: 15% uncertainty
- Model uncertainty
- Alignment CASTOR known within 2 mm
- Calibration procedure
- Luminosity

Consequences jet matching procedure

- For CASTOR, can only match jets in ϕ
- Two profound consequences:
  - Broad response matrix $\rightarrow$ need regularised unfolding
  - Large mis and fake fractions $\rightarrow$ substantial model dependence unfolding procedure
- NB: unfolding needs 28 Bayesian iterations

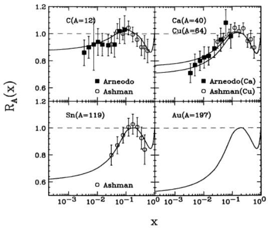




Strategy towards interpreting the data

Two saturation models using Hybrid factorisation:

- Hybrid factorisation for forward production
  - Hard parton via collinear factorisation and DGLAP evolution
  - Soft parton via unintegrated pdf and rcBK equation
- AAMQS: model soft updf with Colour Glass Condensate assumptions **Phys. Rev. D 94 (2016) 054004**
- Katie KS
  - Use Katie program for offshell matrix elements **Comput. Phys. Commun. 224 (2018) 371**
  - Interfaced with Kutak-Sapeta linear and nonlinear updfs. Evolve with extended BFKL and rcBK equation **Phys. Rev. D 86 (2012) 094043**

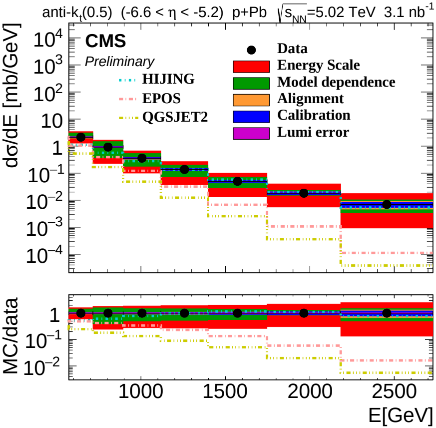


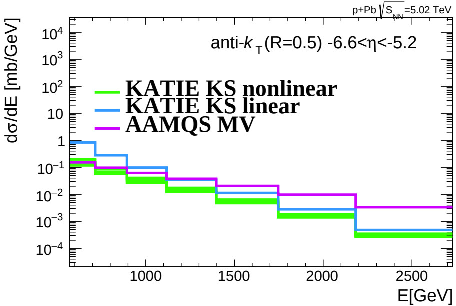
Nuclear modification of structure function from nuclear DIS data used by Hijing. **Phys. Lett. B 202, 603 (1988), ibid. 211, 493 (1988)**

Other event generators:

- Hijing. Applies DGLAP parton evolution via Pythia. Shadowing implemented via suppression of nuclear gluon pdf. Suppressed with fit to nuclear sea quark DIS data **Comput.Phys.Commun.83:307,1994**
- EPOS and QGSJetII_04. CR model. Hard amplitudes via DGLAP, soft with Regge-Gribov theory. Phenomenological implementations of saturation **Phys. Rev. C 92, 034906 (2015)**, **Phys.Rev. D83 (2011) 014018**

The key result: the p+Pb spectrum. Probe ion glue with proton





Observations

- Hijing describes data well
- EPOS and QGSJet too soft. Deviations of 2.5 orders!

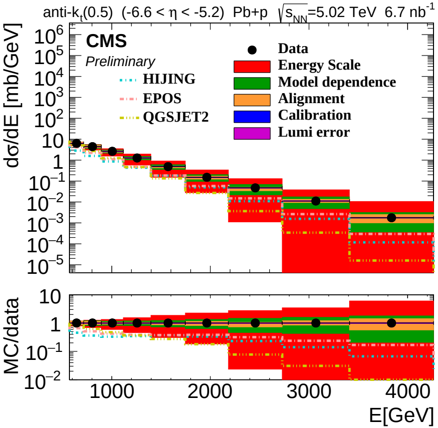
Katie KS

- Measurement potentially highly sensitive to saturation

AAMQS prediction

- Shape appears rather hard

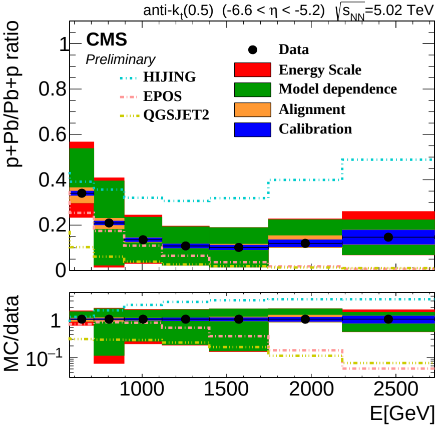
The unfolded Pb+p spectrum



Observations

- Jet algorithm picks contributions beam remnant
- Large sys. uncertainty
- EPOS and Hijing describe shape data reasonably well but norm is off. QGSJet worst description data

The unfolded ratio p+Pb/Pb+p



Data-driven interpretation hard

- Divide results from different cms-frame acceptance
- Ion debris and nuclear effects distort picture

Optimal resolution

- Scale uncertainty partially cancels
- Hijing describes shape well but norm off, due to Pb+p
- EPOS and QGSJet have wrong shape, partially describe data

Physics interpretation

- Data potentially highly sensitive to saturation effects
  $\rightarrow$ Exploring available saturation models (KaTie, AAMQS) to compare with measured data.
- Hijing, based on collinear factorisation and nuclear shadowing, describes p+Pb
  $\rightarrow$ Suggestive k_{T} factorisation may not be needed here. Nuclear effects modelled rather on nucleon that parton level

Experimental progress

- presented first measurement of very forward jets with CASTOR in proton-lead collisions
- CASTOR collected many dataset for different beam setups. Great potential to future (refined) studies

... Thanks for your attention!

Next steps/discussion

Models

- Discrepancy between AAMQS and Katie non-linear predictions need clarification
  - Dipole amplitude vs offshell matrix elements, effect MPI, hadronisation method, ...
- Shadowing:
  - Currently implemented via fit to data in Hijing
  - Estimate of magnitude effect important

Data-driven conclusion desirable but not straightforward!

- Jets in CASTOR in p+Pb suffer from boost. Can't correct
- Logical next steps (input welcome!)
  - Analyse 5 TeV p+p reference run
  - Study centrality dependence (different dependence shadowing/saturation?)
  - Study of dijets and correlation may enhance sensitivity

Content

- References for presentation
- 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

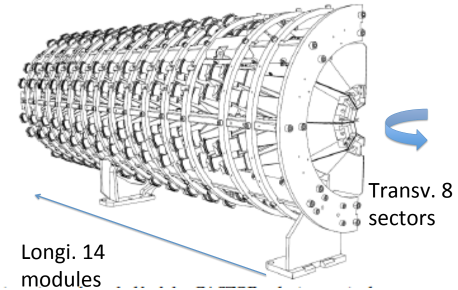
- As cross check, 7 TeV p+p NTuples analysed within p+Pb framework. Convergence reached
- For most parameters, values found are same or comparable with CASTOR p+p jet analyses at 7 and 13 TeV
- Result cross section and systematic uncertainties are reasonably consistent with p+p analyses
- Behaviour on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

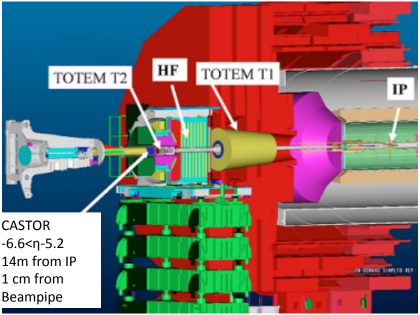
List of papers, CMS PAS (Physics Analysis Summary) and performance notes with CASTOR

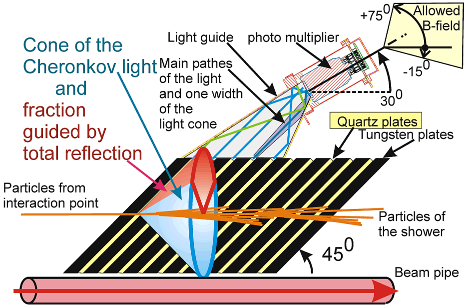
- Underlying event at forward rapidity at 0.9, 2.76, and 7 TeV p+p: **JHEP 04 (2013) 072**
- Forward energy flow at 13 TeV p+p: **JHEP 08 (2017) 046**
- η and centrality dependence of the forward energy density in PbPb collisions at $\sqrt{s}$=2.76 TeV: **CMS-PAS-HIN-12-006**
- Diffractive Dissociative Cross section at 7 TeV p+p: **Phys. Rev. D 92, 012003 (2015)**
- 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**

Theory predictions

- Katie-KS predictions:
  - Katie: textbfComput. Phys. Commun. 224 (2018) 371
  - Kutak-Sapeta updf: textbfPhys. Rev. D 86 (2012) 094043
- AAMQS predictions:
  - The predictions are based on the framework described in **Phys. Rev. D 94 (2016) 054004**

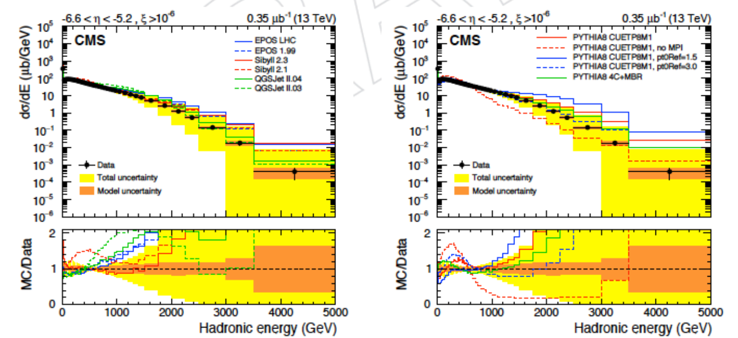

Transv. 8 sectors
Longi. 14 modules


TOTEM T2
HF
TOTEM T1
IP
CASTOR
-6.6<η-5.2
14m from IP
1 cm from
Beampipe


+75^0
Allowed B-field
Light guide
photo multiplier
Cone of the Cheronkov light and fraction guided by total reflection
Main pathes of the light and one width of the light cone
-15^0
30^0
Quartz plates
Tungsten plates
Particles from interaction point
Particles of the shower
45^0
Beam pipe

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 JHEP 08 (2017) 046



Condition number definition

Results

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