Jet Probes of the Initial State at the LHC

Anne M. Sickles on behalf of ALICE, ATLAS & CMS
jets and the initial state

• use the comparison of jet measurements in pPb collisions to measure changes due to the Pb nucleus
  • constrain nuclear parton distribution functions
  • sensitive to parton flavor, x and Q^2
• can we use measurements in pPb to look for final state effects due to the presence of the QGP in pPb collisions?
  • especially central given the extent of correlations observed in pA collisions at RHIC and the LHC
• new measurements of fragmentation of jets opposing photons in PbPb and pp
  • photon unmodified from the initial production

**this talk**: provide an overview of new jet measurements in pp, pPb and PbPb
inclusive jet production in pPb

ALICE jets from charged particles provide lowest $p_T$ jets in pPb

no significant deviation from unity observed
The CMS measurements are compared to a NLO pQCD calculation [57] that is based on the EPS09 nPDFs [19]. The theoretical uncertainties in the pPb and pp measurements. The CMS measurements are compared to a NLO pQCD calculation [57] that is based on the EPS09 nPDFs [19]. The theoretical uncertainties in the pPb and pp measurements.

Figure 8: Inclusive jet nuclear modification factor

ATLAS & CMS $R_{pPb}$ consistent with unity & EPS09 over a wide kinematic range.


**pA versus centrality: RHIC & the LHC**

anti-correlation between centrality measures (α N_{part,Pb}) and very high p_T jets

**pPb motivation:** use proton to study nucleus

**also:** use nucleus to study the proton

---

Perepelitsa, Cole & Strikman PRC 93 (2016) 011902; D. Perepelitsa, QM17

ATLAS PLB748 (2015) 392

PHENIX PRL 116 (2016) 122301
at most, small excess of charged particle $R_{pPb}$ by ATLAS ALICE & CMS
fragmentation functions

- fragmentation functions, jet and charged particle yields are interdependent
- fragmentation functions allow for a closer look at jets than charged particle measurements alone by classifying both high and low $p_T$ particles by the jets from which they come
- no significant deviation from unity over a wide range of jet $p_T$
constraining fragmentation functions in pp

Pythia8 A14 tune with NNPDF23LO provides the best description of the data from the MCs tested

arXiv:1706.02859
constraining fragmentation functions in pp

both calculations use DSS07
paron → charged particle
FFs, hopefully will be
updated soon

Jet substructure using semi-inclusive jet functions in SCET

Hadron Fragmentation Inside Jets in Hadronic Collisions

Zhong-Bo Kang, Felix Ringer and Ivan Vitev

JHEP 1611 (2016) 155

Tom Kaufmann, Asmita Mukherjee, Werner Vogelsang

PRD 92 054015
variation of PDFs and nPDFs slightly different regions of Fig. 1, mean we are mainly interested in studying the modification of the dependence of Fig. 1 for a particular case of two partons colliding without initial state radiation (ISR) or final state radiation (FSR) the nucleon going in the going in the direction. Different configurations of

\[
\eta_{\text{dijet}} = \left( \eta_1 + \eta_2 \right) / 2
\]

\[\sqrt{s_{NN}} = 5.02 \text{ TeV}\]

\[p_{T,1} > 20, p_{T,2} > 30 \text{ GeV}, \Delta \phi_{1,2} > 2\pi/3\]

\[\text{pp 25.8 pb}^{-1}\]

CMS Preliminary

CMS-PAS-HIN-16-003
dijets in pPb & pp @ 5.02 TeV

\[ \eta_{\text{dijet}} = \frac{(\eta_1 + \eta_2)}{2} \]

**pPb collisions**

\[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \]

CMS Preliminary

\[ p_{\text{T},1} > 20, p_{\text{T},2} > 30 \text{ GeV}, \Delta\phi_{1,2} > 2\pi/3 \]

pPb 35 nb\(^{-1}\)

*Ex. Uncer.*

DSSz

EPS09

nCTEQ15

\[ 25 < p_{\text{T}}^{\text{ave}} < 55 \text{ GeV} \]

\[ 55 < p_{\text{T}}^{\text{ave}} < 75 \text{ GeV} \]

\[ 75 < p_{\text{T}}^{\text{ave}} < 95 \text{ GeV} \]

\[ 95 < p_{\text{T}}^{\text{ave}} < 115 \text{ GeV} \]

\[ 115 < p_{\text{T}}^{\text{ave}} < 150 \text{ GeV} \]

\[ p_{\text{T}}^{\text{ave}} > 150 \text{ GeV} \]

CMS-PAS-HIN-16-003
The dependence of the dijet system, where the aims to make a mine the hard scattering process between two incoming partons, because in the case of dijets going in the
tight correlation shows that Fig. 1 for a particular
selecting on ranges of the dijet pseudorapidity defined as
when
The effect of ISR and FSR on this correlation was
differences between pPb and pp dijets constrain nPDF models
updated from previous study done without 5 TeV pp data
• tagging c & b jets changes the flavor sensitivity to nPDF effects
• crucial to quantify in pPb collisions as a baseline for measurements in PbPb collisions where we need to compare the quenching between light, charm and bottom jets
Top quark decay

- Top quark decays to W boson and b quark (BR~100%)
- b quark fragments into a jet with displaced vertex

For this analysis we use the lepton+jets channel:

- $t\bar{t}\to W(l+v)b + W(q+\bar{q})b$

Branching ratio ~30%

Cross section in agreement with expectations based on pp collisions scaled by A

Summary
- First experimental observation of the top quark in nuclear collisions (>5$\sigma$)
- $\sigma_{tt}$ in two channels: $e+$jets and $\mu+$jets
- Combined: $\sigma_{tt}=45\pm8$ nb $\pm17\%$ total uncertainty

CMS now measured $\sigma_{tt}$ at 4 collision energies and in 2 collision systems

CMS

$\chi^2$/dof = 32.1/50
Pb+Pb, $\sqrt{s_{NN}} = 5.02$ TeV
photon + multijet event
$\Sigma E_T^{FCal} = 4.06$ TeV

photon-jet correlations
photon-jet correlations in pp

\[ x_{J\gamma} = \frac{p_{T,jet}}{p_{T,\gamma}} \]

**photons**: \( p_T > 60 \text{ GeV} \); **jets**: \( R = 0.4 \text{ anti-}k_T, p_T > 30 \text{ GeV} \)

**Figures 6, 7**: Measured distributions of the jet-to-photon transverse momentum ratio \( x_{J\gamma} \) in pp collisions (open squares) and PYTHIA 8 simulation (yellow histogram). Each panel shows a different \( p_T \) selection. The vertical bars and the shaded bands show the statistical and systematic uncertainties on the data, respectively.

**Figures 6**: \( 60 < p_T^\gamma < 80 \text{ GeV} \)

**Figures 7**: \( 80 < p_T^\gamma < 100 \text{ GeV} \)

**Figures 8**: \( 100 < p_T^\gamma < 150 \text{ GeV} \)

corrected for backgrounds and jet energy scale, but not for jet energy resolution, which is present in data and MC

- Increasing photon \( p_T \)

ATLAS-CONF-2016-110
photon-jet balance in PbPb

how are these jets modified?

ATLAS-CONF-2016-110

poster: D. Perepelitsa, talk A. Baty
enhanced quark jet contribution compared to inclusive jets

harder fragmentation than inclusive jets; reasonable description by Pythia8 A14 NNPDF23LO
fragmentation of jets opposing photons

\[ \text{CMS-HIN-16-014} \]

\[ \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \]
\[ \text{PbPb} 404 \mu\text{b}^{-1}, \text{pp} 27.4 \text{ pb}^{-1} \]

\[ p_{T}^{\text{jet}} > 1 \text{ GeV/c, anti-}k_{T}, \text{jet } R = 0.3, p_{T}^{\text{\gamma}} > 30 \text{ GeV/c, } |\eta^{\text{\gamma}}| < 1.6 \]
\[ p_{T}^{\text{\gamma}} > 60 \text{ GeV/c, } \eta^{\text{\gamma}} < 1.44, \Delta R^{\gamma} > 0.8 \]

**CMS:** \( p_{T\text{jet}} > 30 \text{ GeV;} p_{T\gamma} > 60 \text{ GeV;} \text{PbPb compared to pp with additional smearing} \)

\( z \) & \( \xi^{\text{jet}} \) determined from the jet kinematics

**ATLAS:** \( 63 < p_{T\text{jet}} < 144 \text{ GeV;} \)
\( 79.6 < p_{T\gamma} < 126 \text{ GeV;} \) fully unfolded for detector effects

**ATLAS Preliminary**

5.02 TeV, \( \gamma \)-tagged jets

- 0-30\% Pb+Pb (\( \times 10^5 \))
- 30-80\% Pb+Pb (\( \times 10^7 \))
- pp (\( \times 10^8 \))

ATLAS-CONF-2017-074
fragmentation of jets opposing photons

$\sqrt{s_{\text{NN}}} = 5.02$ TeV

PbPb 404 $\mu$b$^{-1}$, pp 27.4 pb$^{-1}$

$\gamma$-tagged jets $5.02$ TeV

inclusive jets $2.76$ TeV

$0.4 < T^\gamma < 1.8$,

$T_j > 60$ GeV/c, $|\eta_j| < 1.44$, $|\phi_j - \phi^\gamma| > 4\pi$

Preliminary

CMS-HIN-16-014

Top:

Preliminary

CMS

$\text{PbPb} \, 404 \, \mu \text{b}^{-1}$, $\text{pp} \, 27.4 \, \text{pb}^{-1}$

The centrality dependence of the inclusive fragmentation
distribution for jets associated with an isolated photon for PbPb (full markers) and pp (open markers) collisions.

The ratios of the PbPb to pp distributions. The vertical lines through the points represent statistical uncertainties, while the colored boxes indicate the systematic uncertainties.

ATLAS measurement directly compared to inclusive fragmentation functions

ATLAS & CMS: centrality dependent excess of soft fragments in central collisions compared to pp collisions

$0.8 < N < 1.8$,

$0.4 < T^\gamma < 1.8$,

$T_j > 60$ GeV/c, $|\eta_j| < 1.44$, $|\phi_j - \phi^\gamma| > 4\pi$

Cent. 0 - 10%

Cent. 30 - 50%

Cent. 50 - 100%

$30\text{-}80\%$

$0\text{-}30\%$

$\text{ATLAS \ Preliminary}$

$0\text{-}30\% \ \text{Pb}+\text{Pb} / \text{pp}$

$\text{ATLAS-CONF-2017-074}$
comparison of centrality dependence to inclusive FFs

- **very different** centrality dependence in **photon-tagged jets** than in **inclusive jets**
- **different kinematics**: lower $p_T$ jets in photon-tagged sample than inclusive
- jets which are quenched can remain in the photon-tagged sample with these kinematic selections
- **different flavor composition**
jet quenching in small systems?
**motivation:** correlation measurements in pPb & pp suggest QGP formation; is there jet quenching in small systems?

- $R_{pPb}$ is consistent with unity for jets and charged particles in pPb collisions
- uncertainties associated with the overall normalization might preclude seeing a small quenching in pPb collisions
- additionally it is trivially not possible to define an $R_{pPb}$ for something selected in multiplicity bins as are done in flow inspired measurements
- self normalized measurements which can be done in multiplicity/centrality/$E_T$ selections might be necessary to see any jet quenching (if it is there) in small systems
Fig. 1(b). The measured mean value of criteria are selected for further analysis with an additional requirement on the forward activity. In order to compare results from pPb and PbPb data, PbPb events which pass the same dijet better in the MC simulation by about 120 GeV / c.

As a function of collision centrality (i.e. the degree of overlap of the two colliding nuclei), dijet distributions measured in pPb data, pPb collisions. To characterize the dijet transverse momentum balance (or imbalance) quantitatively for more central events compared to a pp reference [8–10]. The same analysis is performed in

The figure shows the shift in the dijet balance in PbPb was the first jet quenching result at the LHC.

Increasing forward $E_T$

No significance modification of the dijet $p_T$ balance.
Hadron-jet recoil in pPb

Trigger hadron

Recoiling jet

Fully corrected

\[ \Delta_{\text{recoil}} \ (\text{GeV}/c)^{-1} \]

- p–Pb, \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV
- \( y_{\text{NN}} = -0.465 \)
- MB
- ZNA 0–20 %
- ZNA 50–100 %
- Syst. uncert.

Anti-\( k_t \) charged jets, \( R = 0.4 \)
- \( \pi - \Delta \varphi < 0.6 \)
- \( \text{TT}\{12,50\} - \text{TT}\{6,7\} \)

V0A

ALICE Preliminary

Ratios of event activity biased in numerator and other sources

\( R = 0.4 \)

\( \text{V0A} 0-20 \% / 50-100 \% \)

\( p_{\text{T, jet}}^{\text{ch}} \) (GeV/c)

\( p_{\text{T, jet}}^{\text{ch}} \) (GeV/c)

\( R = 0.4 \)

\( \pi - \Delta \varphi < 0.6 \)

\( \text{TT}\{12,50\} - \text{TT}\{6,7\} \)

Again, no significant modification with event activity
The ratio of fragmentation functions as a function of the charged particle pseudorapidity in PbPb collisions understood to be due to QGP.

pPb fragmentation functions show no similar excess.
observables for possible QGP signatures in central $pp$ collisions

Michelangelo L. Mangano$^a$ and Benjamin Nachman$^b$

$^a$Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland
$^b$Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94704, USA

August 29, 2017

1708.08369

- jet quenching might cause modification to substructure of jets in $pp$ (and $pPb$)
- comparison of mass and/or $z_g$ distributions as a function of multiplicity proposed in jets opposite a $Z$
- suggest using the large high energy $pp$ datasets (as in the ATLAS $v2$ in events with a $Z$: talk A. Milov)
summary

• precision measurements of the initial state are needed to quantitatively understand PbPb results
  • direct comparisons between pp, pPb and PbPb are key
  • many 5.02 TeV measurements available for a variety of channels and observables

• centrality dependence at high $p_T$ could provide a unique view of the proton

• thus far no measurement of jet modifications in small systems
  • precision and self normalized observables probably needed for any observation

new 8.16 TeV data sure to provide more insight, high luminosity and collision energy benefit jet probes greatly