Centrality dependence of low-\(p_T\) and high-\(p_T\) particle production in proton-lead collisions with ATLAS

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Introduction

p+A collisions at the LHC provide an opportunity to study the physics of the initial-state of ultra-relativistic A+A collisions

p+A multiplicity measurements:
• $dN_{ch}/d\eta$ – the most basic experimental probe which as a function of centrality can provide understanding of p+A interactions

Z-boson production:
• Clean probe to better understand p+Pb particle production scaling properties and underlying nature of the collision

pp dijet measurements:
• provide a tool to test how underlying event activity correlates with hard scattering kinematics in p+Pb interactions
ATLAS detector

Convection: $y^* = y_{CM} - 0.465 > 0$ is proton-going

- Inner Detector $|\eta| < 2.5$
- EMCal+HCal system $|\eta| < 4.9$
- Pb-going Forward Calorimeter $-4.9 < \eta < -3.2$
Data

- Multiplicity analysis:
  - 2012 p+Pb pilot run is used for the measurements:
    Integrated Luminosity: 1 μb⁻¹

- Z-boson production analysis:
  - $29.1 \pm 1.0$ nb⁻¹ for $Z \rightarrow ee$
  - $27.8 \pm 0.9$ nb⁻¹ for $Z \rightarrow \mu\mu$

- Dijet analysis:
  - pp at 2.76 TeV collisions (2013) with integrated luminosity of 4 pb⁻¹

- Centrality:
  - Pb-going Fcal is used to characterize event centrality
  - Gribov extension is evaluated for the centrality estimations
Centrality and Multiplicity in p+Pb
Multiplicity reconstruction methods

[arXiv:1508.00848]

Pixel tracks:
• $|\eta| < 2.5$
• provide $p_T$ of the particle
• used to reweight HIJING -> Data

Pixel track method is used primarily as a consistency test.

$|\Delta \eta| < 0.015, \ |\Delta \phi| < 0.1, \ |\Delta \eta| < |\Delta \phi|$

Method 1: tracklet = Vertex + 2 hits/clusters (3 layers)
• is chosen as the default result for $dN_{ch}/d\eta$

Method 2: tracklet = Vertex + 2 hits/clusters (2 layers)
• is used for systematic uncertainties
**dN/d\(\eta\) for different centralities**

- \(dN_{\text{ch}}/d\eta\) is measured for \(|\eta| < 2.7\) in eight centrality intervals
- Forward backward asymmetry between p and Pb going directions grows with centrality

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**ATLAS**

\(p+\text{Pb}, \ 1\ \mu\text{b}^{-1}\)

\(\sqrt{s_{\text{NN}}} = 5.02\ \text{TeV}\)

\(y_{\text{cm}} = 0.465\)

\(\eta\) for different centralities

\(\text{Pol2 fit}\)

[arXiv:1508.00848]
dN/d\eta per pair of participants

- To further investigate dN_{ch}/d\eta scaling with N_{part} Z-bosons can be used

- Standard Glauber, used up to now shows increase with \langle N_{part} \rangle
- GGCF with \omega_0=0.11 is almost flat with \omega_0=0.2 even decreases
\( \frac{dN_{ch}}{d\eta}/(\langle N_{part} \rangle/2) \) & \(10^9 N_Z/(\langle N_{coll} \rangle N_{evt})\)

- Similar shape of charged multiplicity and Z-yield
- Agreement in the geometric scaling \(\Rightarrow\) reflecting initial state conditions of the nucleus

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Z-production

ATLAS
\( p+Pb \) 2013, \( L_{\text{int}} = 29 \text{ nb}^{-1} \)
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

- Fit represents \( \langle N_{\text{coll}} \rangle / \langle N_{\text{part}} \rangle \)
- Agreement in the geometric scaling
  \( \implies \) reflecting initial state conditions of the nucleus

\[ 10^6 \langle \frac{dN}{dy} \rangle \langle \frac{d^2N}{d\eta d\phi} \rangle \]

\[ \langle N_{\text{part}} \rangle \]

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[arXiv:1507.06232]
Centrality and Jets in p+Pb:
switching to even higher $p_T$
Jet $R_{pPb}$

- While the $R_{pPb}$ is consistent with unity when evaluated inclusively in centrality, it is not unity when evaluated differentially in centrality.
ATLAS 2013 $p+$Pb data, 27.8 nb$^{-1}$
anti-$k_t$, $R=0.4$, $\sqrt{s_{NN}} = 5.02$ TeV

$0$-$10\%$ / $60$-$90\%$

$p$-going

- $+3.6 < y^* < +4.4$
- $+2.8 < y^* < +3.6$
- $+2.1 < y^* < +2.8$
- $+1.2 < y^* < +2.1$
- $+0.8 < y^* < +1.2$

Pb-going

- $+0.3 < y^* < +0.8$
- $-0.3 < y^* < +0.3$
- $-0.8 < y^* < -0.3$
- $-1.2 < y^* < -0.8$
- $-2.1 < y^* < -1.2$

Jet $R_{CP}$

$R_{CP} / R_{pPb}$ scales with the total momentum of a jet for jets in the positive forward region suggesting a dependence on $x$ of parton in proton.

How much of the centrality dependence (= dependence on $\Sigma E_T$ in the negative forward region) comes from the dependence of $\Sigma E_T$ on $x$ in proton for individual NN collision?
**pp and p+Pb**

- **What is measured**: correlation between the dijet kinematics and the magnitude of the UE in the forward region in **p+p collisions**
- **Motivation**: modeling of particle production, reference measurement to **better understand the centrality in p+Pb**

(a) \( p+Pb \) collision

(b) \( pp \) collision

\[ \Sigma E_T \]

\[ p \quad x_{proj} \quad x_{targ} \quad \eta_1 = +1.5 \quad \eta_2 = +0.5 \]

\[ \Sigma E_T \]

\[ p \quad x_{proj} \quad x_{targ} \quad \eta_1 = +1.5 \quad \eta_2 = +0.5 \]

**Main measurement:**

\[ <\Sigma E_T> \ vs \ p_T^{avg}, \eta^{dijet}, x_{targ}, \ x_{proj} \]
Dijet kinematic variables

- $\Sigma E_T$ corrected to full hadronic scale using a dedicated calibration procedure using PYTHIA8, which accounts for a small offset stemming primarily from out-of-time pileup.

- Jets are reconstructed using anti-kt algorithm with $R=0.4$:
  - $p_{T1}>50$ GeV, $p_{T2}>20$ GeV, $p^{avg}_{T}>50$ GeV
  - $\eta_1 < 3.2$ to match acceptance of jet trigger
  - $\eta_1, \eta_2 > -2.8$ to avoid overlap with the FCal

- The kinematic variables:
  - average quantities for dijet measurements:
    \[
p^{avg}_{T} = (p_{T1} + p_{T2})/2 \quad \quad \quad \eta_{dijet} = (\eta_1 + \eta_2)/2
    \]
  - Bjorken $x_{proj}$ and $x_{targ}$ with the proton defined as the projectile:
    \[
x_{proj} = p^{avg}_{T} \frac{(e^{+\eta_1} + e^{+\eta_2})}{\sqrt{s}}
    \]
    \[
x_{targ} = p^{avg}_{T} \frac{(e^{-\eta_1} + e^{-\eta_2})}{\sqrt{s}}
    \]
Energy production

- Steady decrease with increasing $p_{T}^{\text{avg}}$
- Generators have similar antycorrelation, but vary in overall magnitude
Energy production

ATLAS Preliminary

$pp$, $\sqrt{s} = 2.76$ TeV

- Steady decrease with increasing $p_T^{\text{avg}}$
- Generators have similar antycorrelation, but vary in overall magnitude
Anti-correlation is stronger when \( \eta_{\text{dijet}} \) approaches the \( \Sigma E_T \) measuring region.

This can be evaluated as a function of \( x_{\text{targ}} \) and \( x_{\text{proj}} \) (~ Bjorken x).
x_{proj} and x_{targ}

ATLAS Preliminary

pp, \sqrt{s} = 2.76 TeV

\langle \Sigma E_T \rangle^\text{ref} = \langle \Sigma E_T \rangle(\rho_T^{\text{avg}} \in 50-63 \text{ GeV}, |\eta_{\text{dijet}}| < 0.3)

- Small (10%) drop in \Sigma E_T ratio with \text{x}_{proj}
- Over a factor of two drop in \Sigma E_T ratio with \text{x}_{targ}
- Generators show qualitatively similar behavior
• In pp collisions, $<\sum E_T>$ falls with $x_{targ}$, mostly insensitive to $x_{proj}$
• Effects seen in p+Pb jets are not due to trivial anti-correlation in individual nucleon-nucleon collisions (e.g. “energy conservation”)
Conclusion

• ATLAS measurements of the centrality dependence of the charged particle pseudorapidity distribution, $dN_{\text{ch}}/d\eta$ shows:
  – Significant asymmetry in the rapidity
  – Centrality dependence of $dN_{\text{ch}}/d\eta/(<N_{\text{part}}>/2)$ is sensitive to the model used for centrality determination
  – Comparison to Z-bosons show intriguing similarities between $p+Pb$ observables, and very good consistency with $N_{\text{part}}$ and $N_{\text{coll}}$ scaling

• Presented a measurement of correlation of the underlying event in the backwards region with hard scattering kinematic variables :
  – $<\Sigma E_T>$ is strongly correlated with $x_{\text{targ}}$, but only weakly with $x_{\text{proj}}$
  – The results indicate that the $p+Pb$ jet effect is not a trivial energy conservation
Thank You!
Back Up Slides
pPb interactions produce an additional coherent and photo-nuclear component of events consistent with the excitation of the proton.

- Full coverage $|\eta| < 4.9$ divided into $\Delta \eta = 0.2$ intervals.
- Occupied interval contains reconstructed tracks or calorimeter clusters with $p_T > 200$ MeV.
- $\Delta \eta_{\text{Pb \_ gap}} = \Sigma \Delta \eta_{\text{Pb}}$ Empty interval.
- Electromagnetic or diffractive excitation of the proton typically produce $\Delta \eta_{\text{Pb \_ gap}} > 2$ ($f_{\_ gap} = 6\%$).

Pb-side empty event illustration.
Glauber and Glauber-Gribov models

To model Npart distribution we used:
- standard Glauber with $\sigma_{NN}$ cross section = 70±5mb
- Glauber-Gribov color fluctuation models, with $<\sigma_{NN}>$ cross section = 70±5mb

In Glauber-Gribov model:
- $\sigma_{tot}$ is considered frozen for each event
- parameter $\Omega$ controls the amount of fluctuations
- $\Omega$ is extracted from experimental data: 0.55 [PLB633 (2006) 245–252] and 1.01 [PLB722 (2013) 347–354]
Constructing FCal $\Sigma E_T^{\text{Pb}}$ response

$E_T$ distribution modeled by PYTHIA simulated taking into account FCal response in p+Pb configuration and were approximated by Gamma($k, \theta$) distributions.

Convoluted of $N_{\text{part}}$ Gamma($k, \theta$) was taken as Gamma($k(N_{\text{part}}), \theta(N_{\text{part}})$)

We allowed:

$k(N_{\text{part}}) = k_0 + k_1 \times (N_{\text{part}} - 2)$;

$\theta(N_{\text{part}}) = \theta_0 + \theta_1 \times (\log(N_{\text{part}} - 1))$;

$N_{\text{part}}$ was weighted according to Glauber or Glauber-Gribov model and fitted to the data.
dN_{evt}/dE_T obtained by summing the gamma distributions over different N_{part} values weighted by P(N_{part})

Fits to the measured E^{Pb}_T distributions show reasonable agreement over 3 orders of magnitude in E_T distribution.
- Results produced with models are different
- Standard Glauber has highest fluctuations of produced $E_T$ per participant
- Glauber-Gribov $\Omega = 1.01$ has less $E_T$ fluctuation and therefore gives highest $N_{\text{part}}$
Multiplicty reconstruction methods

- Method 1 is chosen as the default result for \( dN_{\text{ch}}/d\eta \)
- Method 2 is used for systematic uncertainties
- Pixel track method is used primarily as a consistency test
- The correction factor is evaluated as a function of occupancy (O), event vertex (\( z_{\text{vtx}} \)), and \( \eta \) as:

\[
C(O, z_{\text{vtx}}, \eta) \equiv \frac{N_{\text{pr}}(O, z_{\text{vtx}}, \eta)}{N_{\text{rec}}(O, z_{\text{vtx}}, \eta)}
\]

\[
\frac{dN_{\text{ch}}}{d\eta} = \frac{1}{\Delta\eta} \sum \frac{\Delta N_{\text{tr}}(O, z_{\text{vtx}}, \eta) C(O, z_{\text{vtx}}, \eta)}{\sum N_{\text{evt}}(z_{\text{vtx}})}
\]

![Graphs and plots showing multiplicity reconstruction methods for ATLAS, Simulation p+Pb, \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \), \( y_{\text{cm}} = 0.465 \).](image)

\( \frac{dN_{ch}}{d\eta} \) vs alternate centrality

- **ATLAS**
  - \( p+Pb, 1 \mu b^{-1} \)
  - \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
  - \( y_{cm} = 0.465 \)

- Details for different centralities:
  - 0-1%, \( \Sigma E_T^{3.6<\eta_{cm}<4.4} \)
  - 60-90%, \( \Sigma E_T^{3.6<\eta_{cm}<4.4} \)
  - 0-1%, \( \Sigma E_T^{\eta<-4} \)
  - 60-90%, \( \Sigma E_T^{\eta<-4} \)

- Only up to 4% difference

[arXiv:1508.00848]
Z-candidates

- Electrons
  - Trigger e: $E_T > 20$ GeV, $|\eta| < 2.47$
  - Second e: $E_T > 10$ GeV, $|\eta| < 2.47$
  - Forward e: $E_T > 20$ GeV, $2.5 < |\eta| < 4.9$

Select candidates with:
- 66 < $m_{ee}$ < 116 GeV
- 80 < $m_{ee}$ < 100 GeV

- Muons
  - Trigger $\mu$: $p_T > 20$ GeV, $|\eta| < 2.4$
  - Second $\mu$: $p_T > 10$ GeV, $|\eta| < 2.47$

Select candidates with 66 < $m_{\mu\mu}$ < 116 GeV

- To further investigate $dN_{ch}/d\eta$ scaling with $N_{part}$ Z-bosons can be used
Z-production

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

$\text{p+Pb 2013, } L_{\text{int}} = 29 \text{ nb}^{-1}$

- Fit represents $<N_{\text{coll}}>/<N_{\text{part}}>$
- Agreement in the geometric scaling
- Reflecting initial state conditions of the nucleus

ATLAS


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Rapidity Differential Cross-Section

**ATLAS**

\( p+Pb \ 2013, \ L_{int} = 29 \text{ nb}^{-1} \)
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

- Excellent agreement between channels
- \( y_Z^* \) asymmetry observed in the data
- Significant excess at backward rapidity

**Data / MSTW2008 (NNLO)**

**Data / CT10+EPS09 (NLO)**

**Data / CT10 (NLO)**
p+Pb @ LHC and ATLAS

\[ y_{CM} = -0.465 \]

ATLAS C side \( \eta < 0 \)

1.57 TeV/N

ATLAS A side \( \eta > 0 \)

4 TeV
Inner Detector is used for $dN_{ch}/d\eta$ within $|\eta| < 2.7$
Minimum Bias Scintillators used for the event selection $2.1 < |\eta| < 3.9$ (not shown here)
Calorimeters:

- for the electron, jet reconstruction;
- diffractive contribution studies $|\eta|<4.9$
LAr forward (FCal)
Used for the centrality determination
3.2<|\eta|<4.9 (only Pb-going direction)