Centrality dependence of low-p_T and high-p_r 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 $_{ch}$ /dn – 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

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

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 μμ

- 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:

- $|η|$ < 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, $|\Delta \varphi|$ < 0.1, $|\Delta \eta|$ < $|\Delta \varphi|$

Method 1: tracklet = Vertex + 2 hits/clusters (3 layers) Tracklet method 2 • Use only 2 layers.

 \cdot is chosen as the default result for dN $_{ch}$ /dn

Method 2: tracklet = Vertex + 2 hits/clusters (2 layers)

• is used for systematic uncertainties

dN/dη **for different centralities**

[arXiv:1508.00848]

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

dN/dη **per pair of participants**

[arXiv:1508.00848]

• To further investigate dN_{ch}/dη scaling with N_{part} Z-bosons can be used

- Standard Glauber, used up to now shows increase with $\langle N_{part} \rangle$
- GGCF with ω_{σ} =0.11 is almost flat with ω_{σ} =0.2 even decreases

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

Z-production

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

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The XXVth International Conference on Nucleus-Nucleus Collisions

<u>[arXiv:1507.06232]</u>

Centrality and Jets in p+Pb: switching to even higher p_T

Jet R_{pPb} $\overline{}$ -**- -**>pPb

• While the $\mathsf{R}_{\mathsf{pPb}}$ is consistent with unity when evaluated inclusively in centrality, it is not unity when evaluated differentially in centrality

- R_{CP}/R_{DPb} 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 ΣE_T in the negative forward region) comes from the dependence of ΣE_T on x in proton for individual NN collision?

pp and p+Pb

- = +0.5 2 η the magnitude of the UE in the forward region **in p+p collisions** • **What is measured**: correlation between the dijet kinematics and
- Motivation: modeling of particle production, reference measurement to **better understand the centrality in p+Pb**

(a) *p*+Pb collision

(b) *pp* collision

p p

p p

nucleus, and the P*E*^T is measured in the forward calorimeter downstream of the target proton. Due to the symmetric nature of *pp* collisions, each event can also be interpreted by exchanging the roles of the target and projectile between the two protons, and measuring the P*E*^T in the opposite forward nucleus, and the P*E*^T is measured in the forward calorimeter downstream of the target proton. Due to the symmetric nature of *pp* collisions, each event can also be interpreted by exchanging the roles **DIJET KINEMATIC VARIABIES** and the protons, and the protons, and the protons, and the protons, and the opposite f calorimeter module. To keep the same convention in this case, the pseudorapidity, the pseudorapidity, the pseudorapidity, in the pseudorapidity, the pseudorapidity, the pseudorapidity, in the pseudorapidity) of the pseudor **Dijet kinematic variables** calorimeter module. To keep the same convention in the *z* and the pseudorapidity in the pseudorapidity in the p
Same convention in the pseudorapidity in the pseudorapidity of *z axis (and thus thus thus thus thus thus thu* **Dijet kinematic variables**

- Due to the symmetric nature of *pp* collisions, each event can also be interpreted by exchanging the roles of the target and projectile between the two protons, and measuring the P*E*^T in the opposite forward procedure doing. This co, which decoding for a sinal onse stemming primarily in sime at or time pricap $\Sigma \mathsf{E}_\tau$ 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 $\;$ Due to the symmetric nature of *pp* collisions, each event can also be interpreted by exchanging the roles of the target and projectile between the two protons, and measuring the P*E*^T in the opposite forward procedure doing. This co, which decoding for a sinal of stemming primarily in om sat of this preap \cdot ΣE_T corrected to full hadronic scale using a dedicated calibration procedure using PYTHIA8, which accounts for a small offset
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stemming primarily from out-of-time pileup \bullet - 2E_T CONTECTED TO TUIL HAUNOTIC SCAIL USING a GEOFATCH CAINTATION \bullet \cdot ΣE _T corrected to full hadronic scale using a dedicated calibration stemming primarily from out-of-time pileup Pair Shoot both β performed by the full analysis is performed separately using each for the separately using each form β is intertwere variables within the summer within the system are determined with the system as shown in the and the fig. 1. The form is also formed separate separately using the formulation.
Procedure using PYTHIA8, which accounts for a small offset • ΣE_T corrected to full hadronic scale using a dedicated calibration
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Attest are reconstructed using anti-kt algorithm with R=0. P*E*Ti measurement from each side. This • Jets are reconstructed using anti-kt algorithm with R=0.4: $\,$ • Jets are reconstructed using anti-kt algorithm with $R=0.4$: ^o Jets are reconstructed using anti-kt algorithm with R=0.4: increases the statistic of the measurement by $\frac{1}{t}$ and $\frac{1}{t}$ also allow with $D-D$ and $\frac{1}{t}$ • Jets are reconstructed using anti-kt algorithm with R=0.4:
- p_{T1} >50 GeV, p_{T2} >20 GeV, p^{avg}_{T} >50 GeV or simplicity, and the detector energy state in the selection cuts and the selection cuts and the selection cuts
• **p_{T1}>50 GeV, p_{T2}>20 GeV, p^{avg}_T >50 GeV**
- $\begin{array}{lll} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{array}$ external by up to match acceptance of iet trigger \cdot n_1 < 3.2 to match acceptance of jet trigger increases the statistics of the measurement by up to a factor of two while also allowing for an important n_{T1} and n_{T2} and n_{T2} are n_{T1} and n_{T2 • n_1 < 3.2 to match acceptance of jet trigger
• n_1 , n_2 > -2.8 to avoid overlap with the FCal
	- Jets are reconstructed using anti-kt algorithm with R=0.4 • η_1 < 3.2 to match acceptance of jet trigger
• η_1 , η_2 > -2.8 to avoid overlap with the FCal ⁶⁶ event generatots are described below. in the results described below are always presented according to the convention where P*E*^T is measured \cdot η_1 , η_2 \ge -2.8 to avoid overlap with the FCal • η_1 < 3.2 to match acceptance of jet trigger
• η_2 , η_3 > -2.8 to avoid overlap with the FCal ⁶⁶ event generatots are described below. in the results described below are always presented according to the convention where P*E*^T is measured \cdot n₁, n₂ > -2.8 to a $\frac{1}{11}$ \sim 3.2 to material exceptance or jet trigger
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• The kinematic variables: α and α results are also reported as a function of two kinematic quantities α function of two kinematic α ariables: $\frac{1}{2}$ • The kinematic variables: **in the formard calorimeters. Example the formatic value of** \mathbf{F} ⁶⁶ event generatots are described below.
	- Average quantities, more familiar in dijet measurements $p_{\rm T}^{\rm avg}$ p_T^{avg} es (p_T^{avg}) d'average $(\eta_1 + \eta_2)/2$ · average quantities for dijet measurements;
average also appliced for dijet measurements; $\vert p \vert$ \cdot average quantities for dijet measurements: P_{reported} as function of the assessment of the assessment of the above • $\frac{1}{2}$ average quantities for dijet measurements:
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• a gyerage quantities for dijet measurements:
- \bullet Bjorken x_proj and x_targ with the proton defined as the projectile: $\mathcal{L}_{\mathcal{L}}$ and $\mathcal{L}_{\mathcal{L$ between studied in die die verschieden in der die verschieden in der die verschieden in der die verschieden in $\begin{bmatrix} \mathbf{y} & \mathbf{y} & \mathbf{y} \\ \mathbf{y} & \mathbf{y} & \mathbf{y} \\ \mathbf{y} & \mathbf{y} & \mathbf{y} \end{bmatrix}$ $\frac{1}{2}$ 4442 44444 80 region and x/h $10T$ as (1959 H) and x_{drag} with the proton of x_{proj} and x_{drag} with the proton of x_{proj} y_{eff} $y_{$ ^T ⁷⁰ > 50 GeV, the jets were required to have ⌘1,² > 2.8 to separate them by 0.4 units in pseudorapidity From the P 71 **P 71 PART REGION REGION REGION REGION REGION REGION CONSTRUCTION** $\frac{2}{\pi}$
 $\frac{2}{\pi}$ *x*proj and *x*targ, with *x*proj defined by *p* ^T (*e*+⌘¹ ⁺ *^e*+⌘²)/ 1415) show that we have a set of the set of t $\chi_{\text{a}} = \sqrt{\frac{1}{2}} \exp\left[\frac{1}{2} \int \frac{d^2 y}{dx^2} \right] \left(e^{-\frac{1}{2} \frac{dy}{dx}} \right)$ \mathcal{L} $\mathcal{$ *s*, (1) \overline{A} <u>liting the set of the set</u> he proton defined as the pr
ረ*!\! ***T**I \bullet Bjorken x_{proj} and x_{targ} with the proton defined as the projectile: $\frac{2}{x}$ /₁ \sqrt{x} $\frac{\lambda}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ of the hard-scattered participation in the beam-proton with positive (negative) rapidity. Such estimates of the beam-proton of the beam-proton of the beam-proton of the beam-proton of the such estimates of the such estimat \mathcal{L} $\mathcal{$ **been studied in die verschieden die verschieden der alternatione der alternatione der alternatione der alternatione** ⁶⁹ corresponds to events where the transverse momenta of the jets were *p*T,¹ > 50 GeV, *p*T,² > 20 GeV, and *p* avg p *p* avg ^T (*e*+⌘¹ ⁺ *^e*+⌘²)/ avg γ arate the γ by ϕ , γ , γ in γ ⁷² acceptance of the central jet trigger. Results are also reported as a function of two kinematic quantities p_T $\overline{\mathbf{B}}$ (p_T) $\overline{\mathbf{B}}$ (p_T) and χ_{targ} with the proton χ_{rarg} $\overline{\mathbf{C}}$ $\$ avg *x*proj = *p* avg ^T (*e*+⌘¹ ⁺ *^e*+⌘²)/ p $T = \frac{V}{1} \cdot \frac{1}{a} \frac{1}{\psi} \frac$ te The PT by θ _r T_ufnits hype $\frac{1}{2}$ ance are $\frac{1}{2}$ and $\frac{1}{2}$ $\frac{1}{2}$ *x*projection *x* and *x*_p and **by** *p* ^T (*e*+⌘¹ ⁺ *^e*+⌘²)/ **2019#w region and when** \mathcal{A}^{\dagger} , $\mathcal{C}^{\dagger}\mathcal{D}^{1/2}$ \mathcal{A}^{\dagger} $\overline{\mathbf{C}}$ **y** $\overline{\mathbf{C}}$ **y** $\overline{\mathbf{C}}$ \mathbf{C} \mathbf{C} \mathbf{C} \mathbf{C} \mathbf{C} \mathbf{C} e projectile: $\sum_{n=1}^{r} \sum_{i=1}^{r} \sum_{j=1}^{r}$ avg ^T (*e*⌘¹ ⁺ *^e*⌘²)/ $\frac{x}{10}$ and $\frac{y}{10}$ and $\frac{y}{100}$ correspondence to the Bjorkenof the secretaries parties (negative) rapidity. Such estimates of the positive (negative) rapidity. Such estima $\frac{1}{2}$ includes $\frac{1}{2}$ and $\frac{1}{2}$ with the proton defined as the projectile: \mathcal{P} and \mathcal{P} and \mathcal{P} and \mathcal{P} and \mathcal{P} and \mathcal{P} and \mathcal{P} are \mathcal{P} and \overline{B} been studied in die measurements werden studied in different studies werden studies and \overline{B} \cdot Bjorken x_{proj} and x_{targ} with the proton defined as the projectile:
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region and whe $\frac{1}{2}$ s_n $\overline{\mathcal{U}}$ \mathcal{L} In a perturbative approach, at leading order, *x*proj (*x*targ) corresponds approximately to the Bjorken-*x* t ¹ bjorken x_{proj} $\sum_{x}^{y} \sum_{\text{real}}^{y} \prod_{i=1}^{p}$ de the funcional values of the transverse momental of the term in the *jets* were *p*
M, **HNO pUH**, $T_{\rm 494}^{\rm 5123}$ $\frac{1}{2}$
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• Bjorken x_{proj} and x_{targ} with the proton defined as the projectile: $\begin{bmatrix} 0 & \text{if} & \$ from the P 71 was also region of the leading in the leading in the leading in the leading to the leading to the l \int_{0}^{∞} $\tilde{\mathbf{v}}$ $\sum_{i=1}^{n}$ *x*targ = *p* avg ^T (*e*⌘¹ ⁺ *^e*⌘²)/ $\sqrt[k]{}$ \overline{s}

Energy production ATLAS-CONF-2015-019

- Steady decrease with increasing $p_T^{\;avg}$
- Generators have similar antycorrelation, but vary in overall magnitude

- Steady decrease with increasing $p_T^{\;avg}$
- Generators have similar antycorrelation, but vary in overall magnitude

- Anti-correlation is stronger when η^{dijet} approaches the ΣE_T measuring region
- This can be evaluated as a function of x_{targ} and x_{proj} (~ Bjorken x)

- Over a factor of two drop in ΣE_T ratio with x_{targ}
- Generators show qualitatively similar behavior

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_{ch}/dη shows:
	- Significant asymmetry in the rapidity
	- Centrality dependence of dNch/dη/(**<**Npart**>/**2) is sensitive to the model used for cenrality determination
	- Comparison to Z-bosons show intriguing similarities between p +Pb observables, and very good consistency with N_{part} and N_{coll} scaling
- Presented a measurement of correlation of the underlying event in the backwards region with hard scattering kinematic variables :
	- $\langle \Sigma E_T \rangle$ is strongly correlated with x_{targ} , but only weakly with x_{proj}
	- The results indicate that the p+Pb jet effect is not a trivial energy conservation

Thank You!

Back Up Slides

Removal of events with large η gaps

• pPb interactions produce an additional coherent and photo-nuclear component of events consistent with the excitation of the proton

- Full coverage |η| < 4.9 divided into Δη= 0.2 intervals
- Occupied interval , contains reconstructed tracks or calorimeter clusters with $p_T > 200$ MeV

• ΔηPb gap = ΣΔηPb Empty interval

• Electromagnetic or diffractive excitation of the proton typically produce ΔηPb gap>2 (fgap **=** 6%)

Glauber and Glauber-Gribov models

To model Npart distribution we used:

- standard Glauber with σ_{NN} cross section = 70±5mb
- Glauber-Gribov color fluctuation models, with $\langle \sigma_{NN} \rangle$ cross section = 70±5mb

In Glauber-Gribov model:

 σ_{tot} is considered frozen for each event

 10^{5}

parameter $Ω$ controls the amount of fluctuations

 \rightarrow GGCF ω_{σ} = 0.11 $-GGCF \omega_{\alpha} = 0.2$

 $\bigcap_{\alpha\in\mathcal{C}}$ *N*(*P* 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 Glauber *ATLAS* Simulation $p+Pb$, 1 μb ⁻¹ $\sqrt{\varepsilon_{\scriptscriptstyle{\mathrm{NN}}}}$ = 5.02 TeV $\sigma_{_{\rm NN}}$ [mb] 0 50 100 150 P_H($\sigma_{\rm NN}$) [mb 1] 0 0.01 0.02 • Ω is extracted from experimental data: 0.55 [PLB633 (2006) 245– 252, and $\frac{1}{\sigma_{tot} + \sigma_0}$ $\frac{72\frac{\sigma_{tot}}{\sigma_0 + 3}}{\Omega^2}$ 47-354
252, and $\frac{1}{\sigma_{tot} + \sigma_0}$

*N*part E Shulga The XXVth International Conference on Nucleus-Nucleus Collisions 25

0 10 20 30 40 50 60

Constructing FCal ΣΕ_Τ^{Pb} response

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

We allowed: $k(N_{part}) = k_0 + k_1 * (N_{part}-2); \quad \Theta(N_{part}) =$ $\theta_0 + \theta_1$ *(log(N_{part}-1)); In WN : $k(N_{part}) = k*N_{part}$; $\theta(N_{part}) = \theta$;

 E_T response for N_{part} was weigthed according to Glauber or Glauber-Gribov model and fitted to the data
Eshulga model and fitted to the data

FCal E_T **distribution fits**

 dN_{ext}/dE_T obtained by summing the gamma distributions over different N_{part} values weighted by $P(N_{part})$

Fits to the measured $\mathsf{E}^{\mathsf{Pb}}{}_{\mathsf{T}}$ distributions show reasonable agreement over 3 orders of magnitude in E_T distribution.

N_{part} for different Glauber models

- Standard Glauber has highest fluctuations of produced E_T per participant
- \bullet <code>E@|</code>ls<code>uber-Gribov</code> $\mathfrak{B}^{\text{def}}$ n. The fluctuation and therefore gives 28 $h: -h \rightarrow + h$

Multiplicity reconstruction methods of the same shape represent corrected distributions corresponding to d*N*ch/d⌘. Right bottom: The ratio of corrected **Multiplicity reconstruction methods** and pullity reculistique in Filmules and presention in the results are presented in \boldsymbol{v}

- Method 1 is chosen as the default result for dN_{ch}/dη
- 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_{vtx}), and η as:

• Only up to 4% difference

Z-candidates

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

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Rapidity Differential Cross-Section

CERN-PH-EP-2015-146 [arXiv:1507.06232]

p+Pb @ LHC and ATLAS

p+Pb @ LHC and ATLAS

p+Pb @ LHC and ATLAS

