

Advances, Innovations, and Prospects in High-Energy Nuclear Physics 高能核物理进展、创新与展望 CCNU, Wuhan

Qipeng Hu (胡启鹏) University of Science and Technology of China for the ATLAS collaboration Oct 20, 2024

ATLAS Highlights

Innovations

- **Dijet for studying centrality bias and nuclear break up**
- **Improved understanding of photonuclear interactions**
- **New testing ground for particle physics**

Future Perspectives

- **New track trigger in Run3**
- **Exciting heavy ion runs in 2024/2025**
- **New detector planned for Run4**

PLB 790 (2019) 108

• ATLAS has successfully controlled the single jet R_{AA} systematics to the few-percent level with 2015 data

Single inclusive jet R_{AA}

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- Widely used in constraining quenching models

Dijet asymmetry

PRC 107 (2023) 054908

R-dependence of Dijet asymmetry

• New ATLAS dijet measurements reveal the R-dependence of absolute dijet asymmetry • While JETSCAPE successfully describes the R-dependence for symmetric dijets, it fails

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- to do so for asymmetric dijets

[arXiv:2407.18796](https://arxiv.org/abs/2407.18796)

R-dependence of Dijet asymmetry — cont.

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[arXiv:2407.18796](https://arxiv.org/abs/2407.18796)

[arXiv:2407.18796](https://arxiv.org/abs/2407.18796)

Dijet: leading Dijet: sub-leading Single inclusive

 $prmalized$ x_I distributions are defined as:

-1

 $\bar{\bar{p}}$

1

Dijet quenching ATL-PHYS-PUB-2022-020 Jets are reconstructed using the anti-:^C algorithm [25] with radius parameters ' = 0*.*2*,* 0*.*3*,* 0*.*4*,* 0*.*5 and 0.6. AA *R*100 150 200 250 300 [GeV] T *p* 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 pair AA *R*Data leading jet LBT leading jet JETSCAPE leading jet Data subleading jet LBT subleading jet JETSCAPE subleading jet = 5.02 TeV NN s -1 *ATLAS pp* 255 pb -1 0-10% Pb+Pb 1.72 nb *R* = 0.2 jets *^t* anti-*k* **Leading jet** *p***^T Subleading jet** *p***^T** *x* **cut** ^J dijet yields 100 150 200 250 300 [GeV] T,1 *p* [−]⁹ 10 [−]⁸ 10 [−]⁷ 10 [−]⁶ 10 −5]10 [mb GeV T,1 dp evt N 〉AA T 〈*R* = 0.6 *R* = 0.5 *R* = 0.4 *R* = 0.3 *R* = 0.2 jets *^t ATLAS* anti-*k* Leading jet = 5.02 TeV NN s -1 0-10% Pb+Pb 1.72 nb (a) 100 150 200 250 300 [GeV] T,2 *p* [−]¹⁰ 10 [−]⁹ 10 [−]⁸ 10 [−]⁷ 10 [−]⁶ 10 −5 -1]10 [mb GeV T,2 dp pair dN evt N 〉AA T 〈1*R* = 0.6 *R* = 0.5 *R* = 0.4 *R* = 0.3 *R* = 0.2 jets *^t ATLAS* anti-*k* Subleading jet = 5.02 TeV NN s -1 0-10% Pb+Pb 1.72 nb (b) 1 #pair d#pair dG^J *,* (8) with a normalization that was used in previous dijet measurements [20–23]. The absolutely normalized G^J distributions allow a direct comparison between the dijet rates measured in Pb+Pb and ? ? collisions. This comparison is quantified by the ratio: AA ⌘ 1 ^h)AAi#AA evt d#AA pair dG^J , ¹ ! ? ? d#? ? pair dG^J ! *.* (9) Finally, the absolutely normalized G^J distributions can be integrated over the measurement range of 0.32 *<* G^J *<* 1.0 (and the corresponding ranges in ?T,1 and ?T,2) to construct the absolutely normalized dijet yields in Pb+Pb collisions: 1 ^h)AAi#AA evt π ?T,1 ⁰*.*32⇥?T,1 d2#AA pair d?T,1d?T,2 d?T,2 (10) and the dijet cross sections in ? ? collisions: 1 ! ? ? ^π ?T,1 ⁰*.*32⇥?T,1 d2#? ? pair d?T,1d?T,2 d?T,2*.* (11) The ATLAS detector [24] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near-4c coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner-detector system is immersed in a 2 T axial magnetic field and provides charged-particle tracking in |[| *<* 2*.*5. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, with the first hit typically being in the insertable Similarly, the *dijet-yield-normalized* G^J distributions are defined as: 1 #pair d#pair dG^J *,* (8) with a normalization that was used in previous dijet measurements [20–23]. The absolutely normalized G^J distributions allow a direct comparison between the dijet rates measured in Pb+Pb and ? ? collisions. This comparison is quantified by the ratio: AA ⌘ 1 ^h)AAi#AA evt d#AA pair dG^J , ¹ ! ? ? d#? ? pair dG^J ! *.* (9) Finally, the absolutely normalized G^J distributions can be integrated over the measurement range of 0.32 *<* G^J *<* 1.0 (and the corresponding ranges in ?T,1 and ?T,2) to construct the absolutely normalized 1 ^h)AAi#AA evt π ?T,1 ⁰*.*32⇥?T,1 d2#AA pair d?T,1d?T,2 d?T,2 (10) and the dijet cross sections in ? ? collisions: 1 ! ? ? ^π ?T,1 ⁰*.*32⇥?T,1 d2#? ? pair d?T,1d?T,2 d?T,2*.* (11) The analysis is conducted independently for each of the jet radius values. In each case, the leading dijets are constructed from the two highest-?^T jets in the event and are required to have the two jets the selection criteria described above: and subleading jet ?^T can be defined as: 'pair AA (?T,1) = and 'pair AA (?T,2) = 0.6 0.7 0.8 0.9 pair AA *RATLAS R* = 0.2 jets *^t* anti-*k* Leading Subleading

∟ອ -1 — 10 \blacktriangleright . −5 $\overline{}$ — 10 $\overline{}$ $B_1 \cap \overline{B_1}$ $\cap \overline{B_2}$ $\cap \overline{B_3}$. It is followed by the silicon microstrip tracker (SCT), which is followed by the silicon microstrip tracker (SCT), which is followed by the silicon microstrip tracker (SCT), whic where \mathbb{R} and \mathbb{R} and \mathbb{R} and \mathbb{R} and \mathbb{R} ϵ are defined the same way as in Eq. (1), ϵ is the integrated luminosity of the integrated luminosi 4.

 $\frac{1}{50}$ and subleading jet $R_{\rm AA}^{\rm pair}$ are probing different population Creating term of the differential information to improve modeling nd subleading jet $R^{\rm pair}_{\rm AA}$ are p
ante useful differential inform events, usef Ø ?T,2/0*.*³² d2# ? ? lifferential information to improve modelin pair AA *R* Λ _A *R* = 0.6 jets *^t* anti-*k* na a Subleading

<u>pair</u>

^d?T,1d?T,2 ^d?T,1

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 $\overline{1}$

R-dependence of dijet quenching

[arXiv:2407.18796](https://arxiv.org/abs/2407.18796)

• Smaller R dijets are more suppressed in both regions, bigger difference in leading jet projection

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- LBT and JETSCAPE cannot describe the data

Jet substructure

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[PRL 131 \(2023\) 172301](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.172301) [PRC 107 \(2023\) 054909](https://journals.aps.org/prc/abstract/10.1103/PhysRevC.107.054909)

only loosing energy by induced radiation as a single par-

energy.

From the antenna to the jet. The dynamics of a

QCD jet in vacuum is described in terms of the scales

of the problem. The initial hardness, given by the initial hardness, given by the jet μ

izing the degree of momentum broadening in the trans-• Color decoherence can be study via hard splitting angle dependence of jet quenching

med South and the first jet splitting defines the first jet splitting defines the first jet splitting defines
The first jet splitting defines the first jet splitting defines the first jet splitting defines the first jet ting opening angles between hard split the possible scenarios, depicted in Fig. 1, is the possible in Fig. 1, is $\frac{1}{2}$ • Two measurements extracting opening angles between hard splittings in jets at complementing values

FIG. 1. A sample jet event resolved with *R*med = 0*.*1 (left Casalderrey-Solana et al. the hardest resolution of the 1904 and 257 one, while the pink histogram denotes soft fragments. PLB 725 (2013) 357

- \mathbf{t} will be shown below, for typical LHC kinematics \mathbf{t} the is color decoherence can reconstructed jet with cone parameter *R* accommodates
- only one resolved charge which contains the leading co stitutus carrying nearly all of the total jet transverse stranger in the total jet transverse stranger in the total jet transverse stranger in the total jet transvers

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opening angle \mathcal{A} = \mathcal{A} =

Jet substructure — cont.

 $1.5₁$

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• Decoherence angular scale (**0.1 ~ 0.2**) observed in both de-clustered groomed jets and re-

clustered large-R jets: significant larger energy loss above the scale

[PRL 131 \(2023\) 172301](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.172301) [PRC 107 \(2023\) 054909](https://journals.aps.org/prc/abstract/10.1103/PhysRevC.107.054909)

• Jet energy loss is most directly correlated with the jet substructure not jet p_T

Jet substructure — cont.

• At $p_T > 100$ GeV, $R = 0.4$ jets are slightly more suppressed than $R = 0.2$ jets, consistency

- between ATLAS and CMS
- Tension between ATLAS and ALICE at low p_T

R-dependence of inclusive jet RA A

and = *^h* jet in (a) *p* + *p* and (b) 0-10% Pb+Pb col-

lisions at p*s*NN = 5*.*02 TeV, with the same kinematics as in

line is the 2-Gaussian fit using Eq. (2).

Analysis selections Jet-induced diffusion wake

 \mathbb{R} such a set \mathbb{R}

relatively in the soft hadrons (*p***T** \sim No significant *p*^T = 1-2 GeV/*c* range (blue) in *p* + *p* (dashed) and 0-10% **Factor (1)** TeV. The significant diffusion wake within the present uncertainties. \mathbb{R} such that \mathbb{R} sion wake within the present uncertainties.

<u>Internal in the state of the sta</u> • No significant diffusion wake within the present uncertainties.

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and= *h*jet in (a)*p*+ *p*and (b) 0-10% Pb+Pb col-

lisions atp*s*NN = 5*.*02 TeV, with the same kinematics as inFig.1.

[arXiv:2408.08599](https://arxiv.org/abs/2408.08599)

• Central value indicates ~0.5% depletion ~ **0.5 particle per unit** reduction due to wake;

Jet-induced diffusion wake - Cont.

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- $x_{J\gamma}$
- \sqrt{N} γ Tjot darripor doritanto 20% magnituritation γ • γ +jet sampel contains ~ 20% fragmentation
	- No obvious inconsistency with CMS Z+jet results

Little parade float by my daughter at age of 3, after seeing Disney Parade

Innovation emerges through dedication and perseverance

- Enlarge the impact of delivering physics
- Open doors for more sophisticated studies

 $+0.8 < y^* < +1.2$ p. Faev] $+0.3 < y^* < +0.8$ p. [GeV] $\mathbf{\alpha}^{\circ}$ $\frac{\sigma}{\tau}$ $+0.3 < y^* < +0.8$

Jet in p+Pb

PLB 748 (2015) 392

+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

[PRL 132 \(2024\) 102301](https://link.aps.org/doi/10.1103/PhysRevLett.132.102301)

Dijet in p+Pb \sim correspond to the proton-going (Pb-going) direction. The beam configuration results of \sim the center-of-mass by +0.465 units in the proton-going direction relative to the laboratory frame.

• *R*_{CP}(x _p) is qualitatively described by the color fluctuations: smaller than average interaction

-3 0 -3 1 2 3 \lesssim 4

Qipeng Hu (USTC) \sim)*,* (3)

 $\lim_{n \to \infty}$ a slight overlap in Ω in Ω Tall α , Db data; combined over (HeC), $\frac{1.2}{\sqrt{2}}$ correspondence to 10 ion part black completed over the superior of \mathbb{E} \sim discribution in the reconstruction and analysis of \sim \sim \sim \sim \sim and performed meticulous jet calibration for The diversion was made to Dijet events in 8.16 TeV p+Pb data: combined over 20 jet triggers to maximize the kinematic coverage, improved precision

$$
p_{\text{T,Avg}} = \frac{p_{\text{T,1}} + p_{\text{T,2}}}{2}
$$
, $y_{\text{b}} = \frac{y_{1}^{\text{c.m.}} + y_{2}^{\text{c.m.}}}{2}$, and $y^* = \frac{|y_{1}^{\text{c.m.}} - y_{2}^{\text{c.m.}}|}{2}$

- Striking log-linear dependence of jet *R*_{CP} on *x*_p
	- strength at larg $\overline{2}$ $\frac{1}{2}$ strength at large x_p p

[ATLAS-CONF-2024-013](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2024-013/)

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UE vs. nuclear break-ups in p+Pb **X** 33. 5455

• Correlation between UE energy and break-up neutrons becomes weaker with increasing *x*^p • Scaling of UE energy and break-up neutrons at low ZDC energy, fluctuation of break-ups when UE

• Offer a new approach to exploring hard-scattering biases in UE based centrality classifications and

-
- energy saturated
- biases in modeling nuclear break-ups

UE vs. nuclear break-ups in p+Pb - Cont.

[ATLAS-CONF-2024-013](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2024-013/)

Photonuclear jets

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ATLAS DRAFT

Qipeng Hu (USTC) Gibeng Hu (USTC) :::: ::::::: P 8 Direct and Resolved Mc samples provide the two contributions provided the signal, and the signal, and the α bottom and the contract of ::::: panel:::::: shows the

is derived from a fitted combination of MC simulation and *pp* data.

[arXiv:2409.11060](https://arxiv.org/abs/2409.11060)

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- **nCTEQ**15 WZ+SIH
- **nNNPDF**3.0
- **EPPS**21
- **TUJU**21
- nCTEQ results typically agree best. At higher H_T , the data typically agree well with TUJU
- nNNPDF overpredicts the cross sections at high H_T and x_A

Ratio between measured precise 3D cross-sections and predictions with different nPDF fits, while uncertainties of the photon flux not included:

Photonuclear jets - constrain nPDF effects

, (5)

Qipeng Hu (USTC) Events used in the measurement were recorded during stable running conditions of the LHC and meet w_1

Top pair in p+Pb

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[arXiv:2405.05078](https://arxiv.org/abs/2405.05078)

• First calibration and use p-flow jets with NN b-tagger in ATLAS heavy ion data • The $t\bar{t}$ cross section is measured to be $\sigma_{t\bar{t}} = 58.1 \pm 2.0^{+4.8}_{-4.4}$ nb

• Extrapolated $R_{\sf p+Pb}$ is consistent with unity; nNNPDF overestimates of $t\bar{t}$ $R_{\sf p+Pb}$

Nuclear modification of parton distribution function

τ anomalous magnetic moment via *γγ* → *ττ*

those observed at LEP (DELPHI)

[PRL 131 \(2023\) 151802](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.151802)

Magnetic monopoles via *γγ* → *MM*¯

[arXiv:2408.11035](https://arxiv.org/abs/2408.11035)

• 3 events in SR, consistent with background estimate (4 ± 4)

- using Run3 heavy ion data
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-

• Better limits compared to dedicated MoEDAL experiment (Nature 602 (2022) 63), achieve up to x8 improvement at masses below 120 GeV

The ATLAS ITk for Run 4: the new all-Si tracker

Run3 new L1 track trigger

meripang Hau (Wand-) apidity region, but fail to describe the data at $y \approx 0$. In each neutron measurements from ALICE [13] over a new *y* region. None of the models describe the co For the case of no neutron selection (AnAn), the data follow the trend of the forward-rapid bined results over the full rapidity range. The color dipole models agree with the measure multiplicity class, the LTA predictions tend to be lower than the CMS results, particularly for **TRT triggered UPC event with two tracks**

Jeune G.

Heavy ion operations in 2024 and beyond

- 2024 target: pp reference $>$ 300 pb -1 , Pb+Pb $>$ 1.5 nb -1
- If Run 3 gets extended, possible to collect 6 nb-1 Pb+Pb data by the end of Run 3

LHC 2024 schedule as of September 18

Phase-II ATLAS

An upgraded ATLAS (> 2030s)

- **High-granularity, high-coverage tracker (2.5 → 4.0)**
- **New ZDC (same as CMS Phase-II ZDC)**
- **High-granularity timing detector**
- Replaced muon chambers
- New and upgraded forward and luminosity detector
- Improved trigger, high-performance software & computing, deeply embedded machine learning

- Advancement in several jet measurements:
	- Unveal physics phenomenon color coherence
	- 6. Challenged jet quenching models differential dijet R_{AA}

Innovations

Summary

Future Perspectives

- New track trigger and exciting data taking in 2024/2025/2026
- New sub-detectors and various upgrades for HL-LHC
- Collaborative efforts across experiments to address open questions, such as the R-dependence of p_T jets ...
- Well-studied measurements p+Pb dijet, photonuclear jets paved the way for more sophisticated future studies
- Combining of heavy ion data with general SM studies strengthens collaboration with the broader particle physics community

Advances