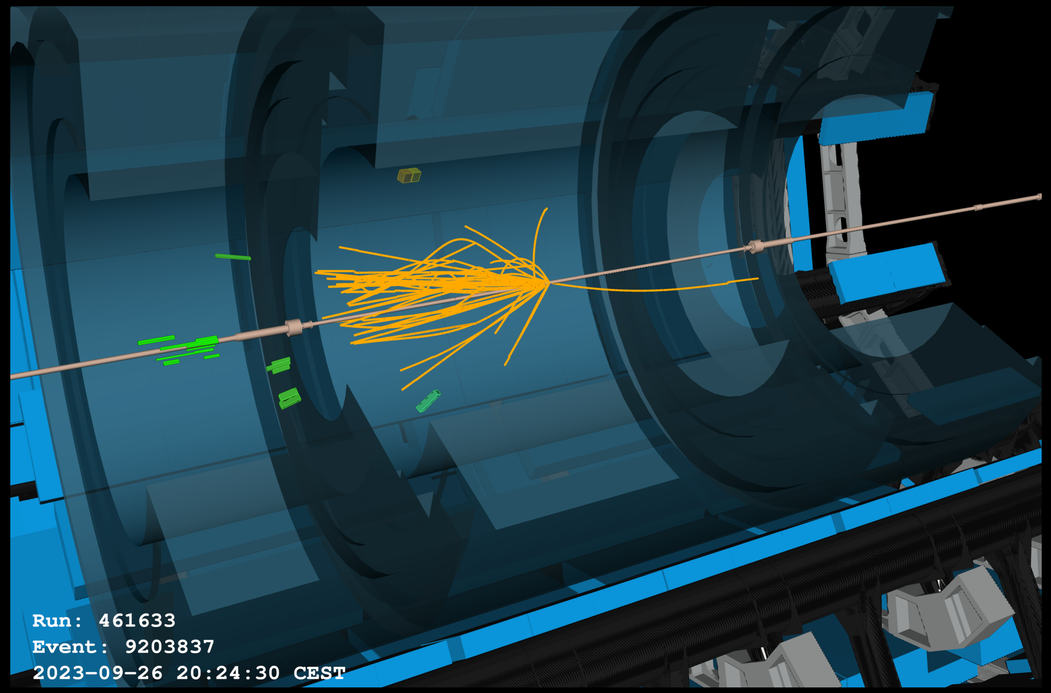
ATLAS studies and plans in photon-induced Pb+Pb and proton-nucleus collisions at the LHC



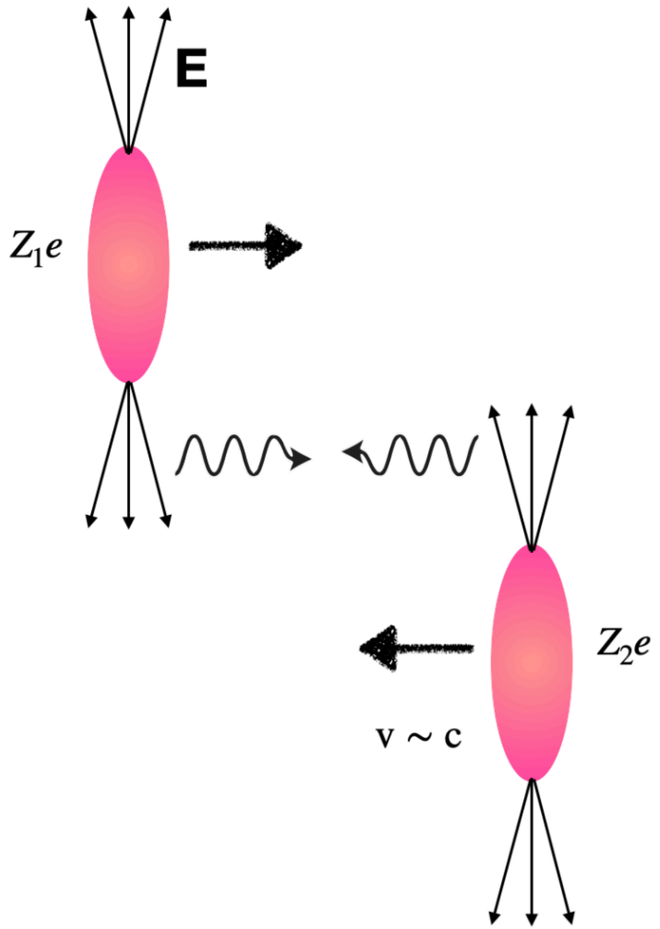
Physics with high-luminosity proton-nucleus collisions at the LHC - Workshop

Sruthy Jyothi Das for the ATLAS Collaboration

5 July 2024, CERN

ATLAS HISTORY : Photon induced Pb+Pb

Ultra-Peripheral collisions (UPCs)



Coulomb fields of moving charges, equivalent
to a flux of quasi-real high-energy photons

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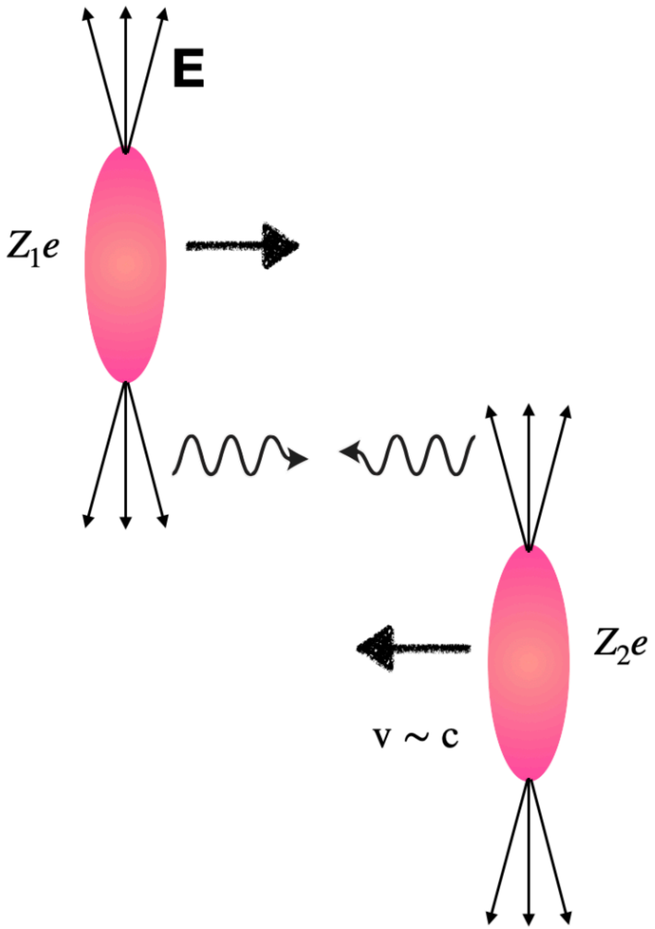
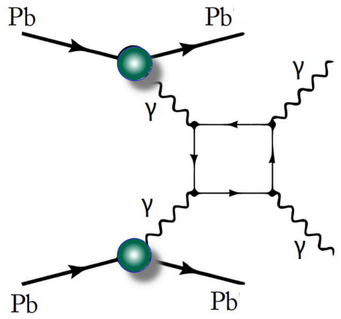


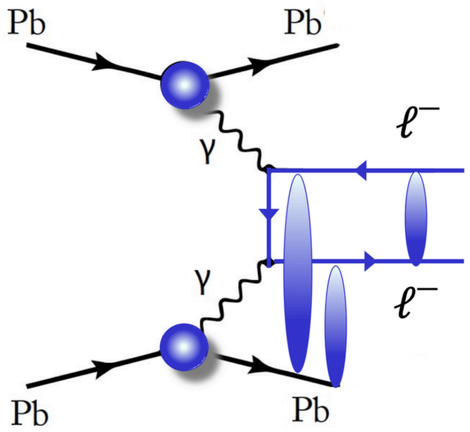
I. Electromagnetic process (Two-photon interactions)



Nature Phys. 13 (2017) 852

Phys. Rev. Lett. 123 (2019) 052001

JHEP 03 (2021) 243



- $\gamma\gamma \rightarrow \mu\mu$

Phys. Rev. Lett. 121 (2018) 212301

Phys. Rev. C 104 (2021) 024906

Phys. Rev. C 107 (2023) 054907

- $\gamma\gamma \rightarrow \tau\tau$

Phys. Rev. Lett. 131 (2023) 151802

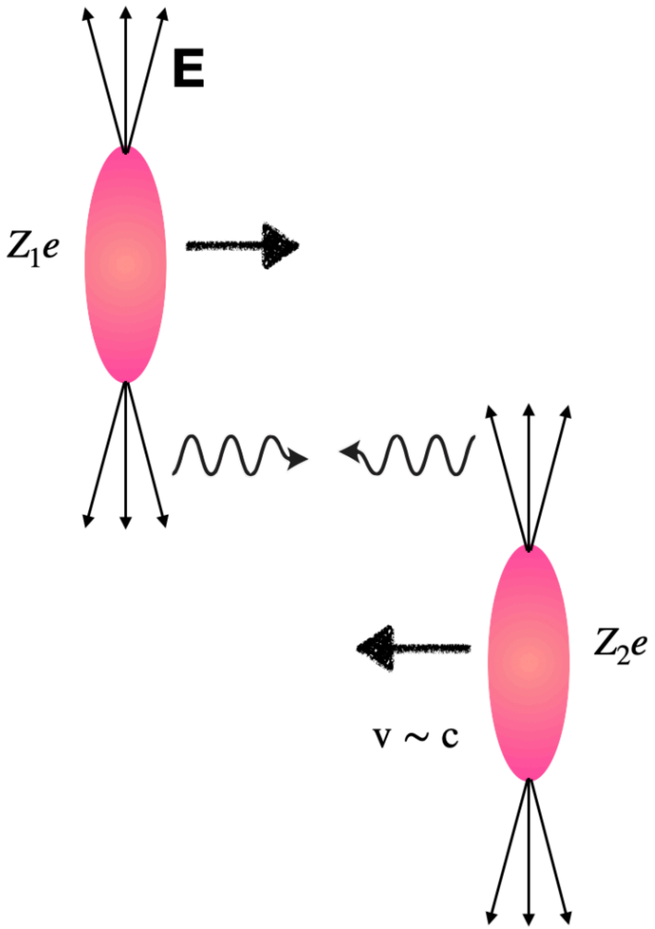
- $\gamma\gamma \rightarrow ee$

JHEP 06 (2023) 182

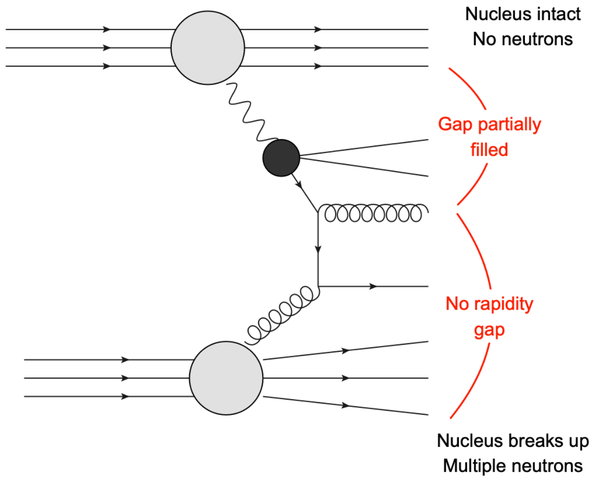
Heavy ion collisions provide clean environment for study of QED & BSM processes

ATLAS HISTORY : Photon induced Pb+Pb

Ultra-Peripheral collisions (UPCs)



II. Photon-hadron interactions (One-photon interactions)



- $\gamma + A \rightarrow A^* + V$
- $\gamma + A \rightarrow X$

Photonuclear two-particle correlation:

Phys. Rev. C. 104 (2021) 014903

Photonuclear charged-hadron yield:

ATLAS-CONF-2023-059

Photonuclear di-jets:

ATLAS-CONF-2022-021

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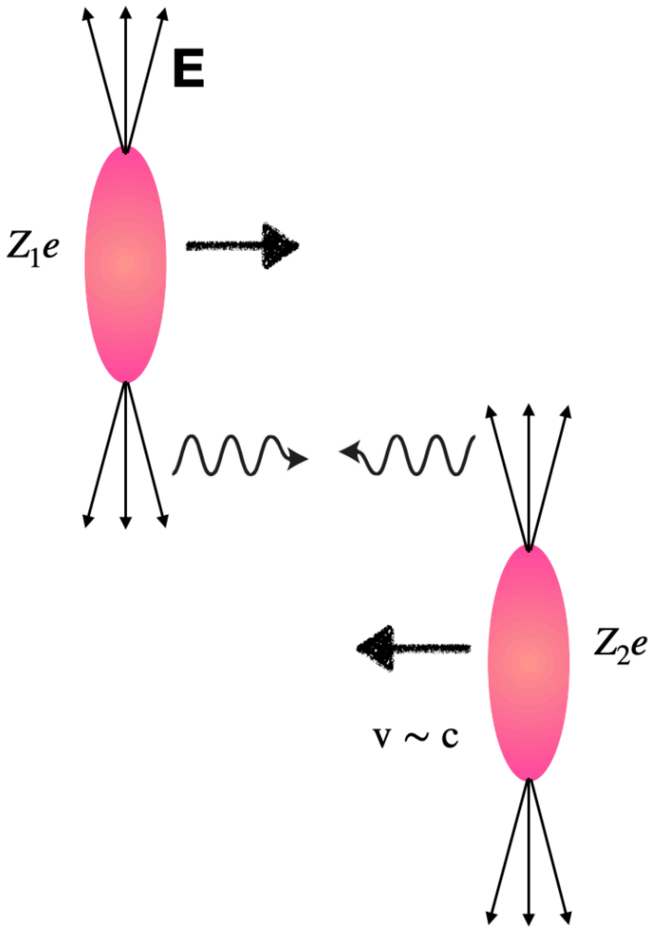
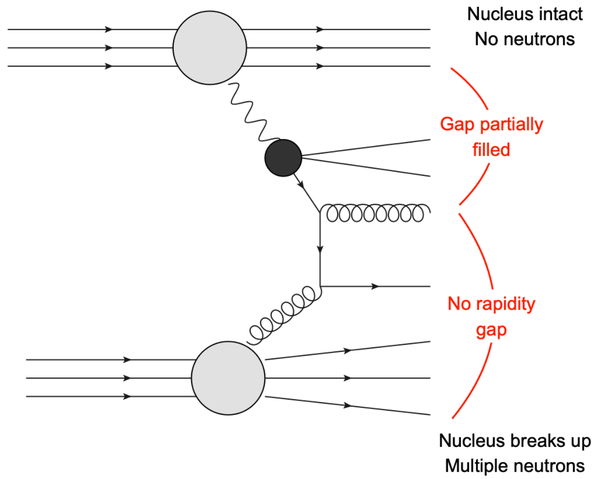




Focus of this talk

Photonuclear two-particle correlation:

Phys. Rev. C. 104 (2021) 014903

Photonuclear charged-hadron yield:

ATLAS-CONF-2023-059

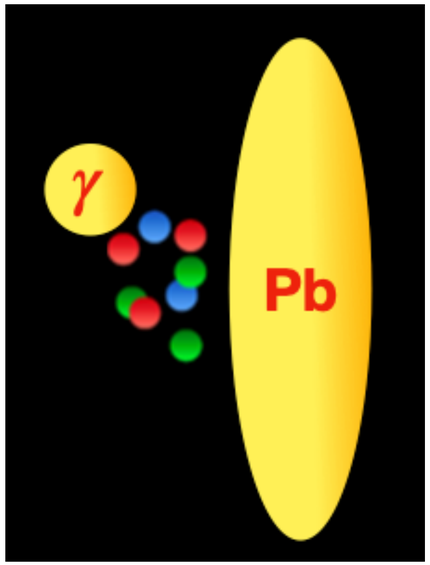
Photonuclear di-jets:

ATLAS-CONF-2022-021

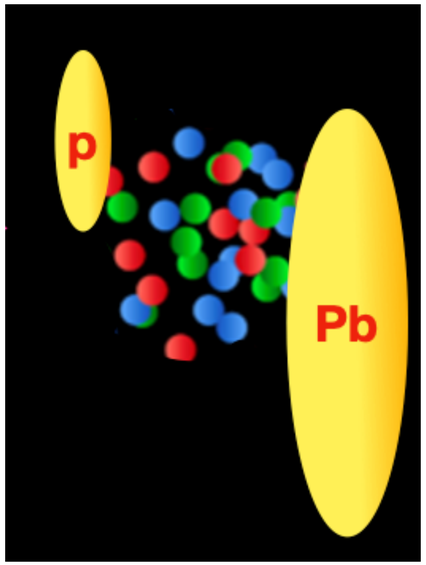
Photonuclear processes provide insights into Quark-Gluon Plasma medium properties

Overview

This talk will focus on “small system and Quark-Gluon Plasma (QGP) observables”



comparison



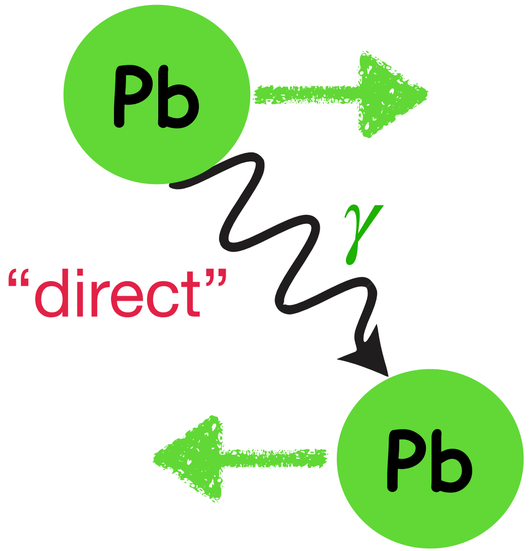
and

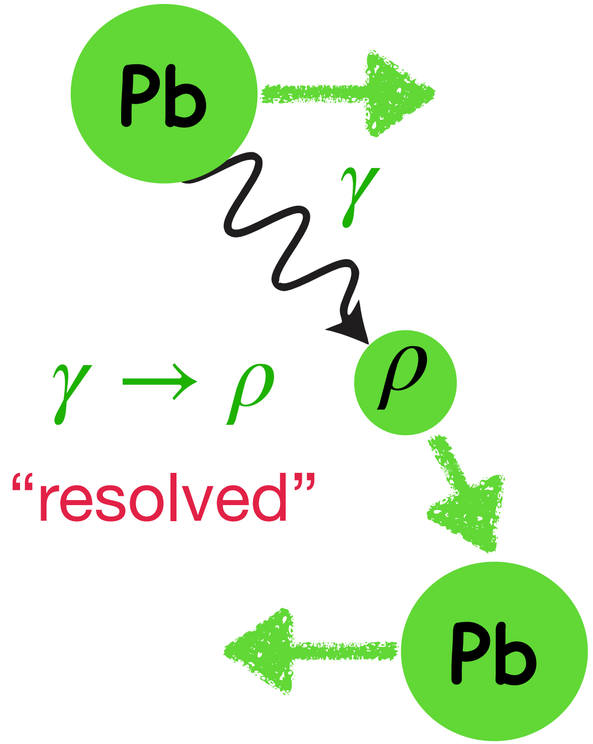
Run-3/4 plans for γ+Pb and γ+p

Photonuclear interactions

When two nuclei miss each other, EM field of one nucleus (photon) breaks up the other nucleus →Ultra Peripheral Collisions (UPC)

More specifically, photonuclear collisions.





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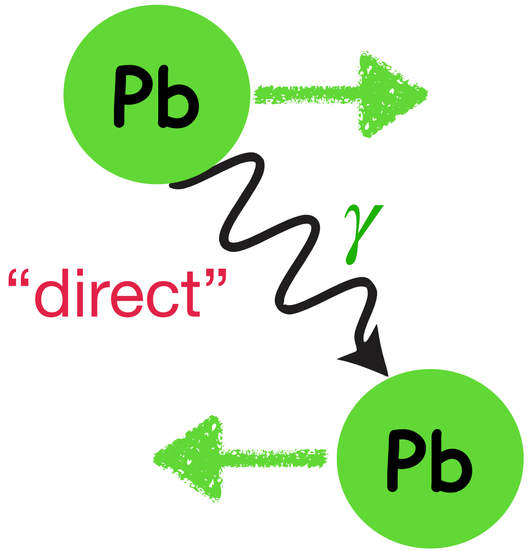
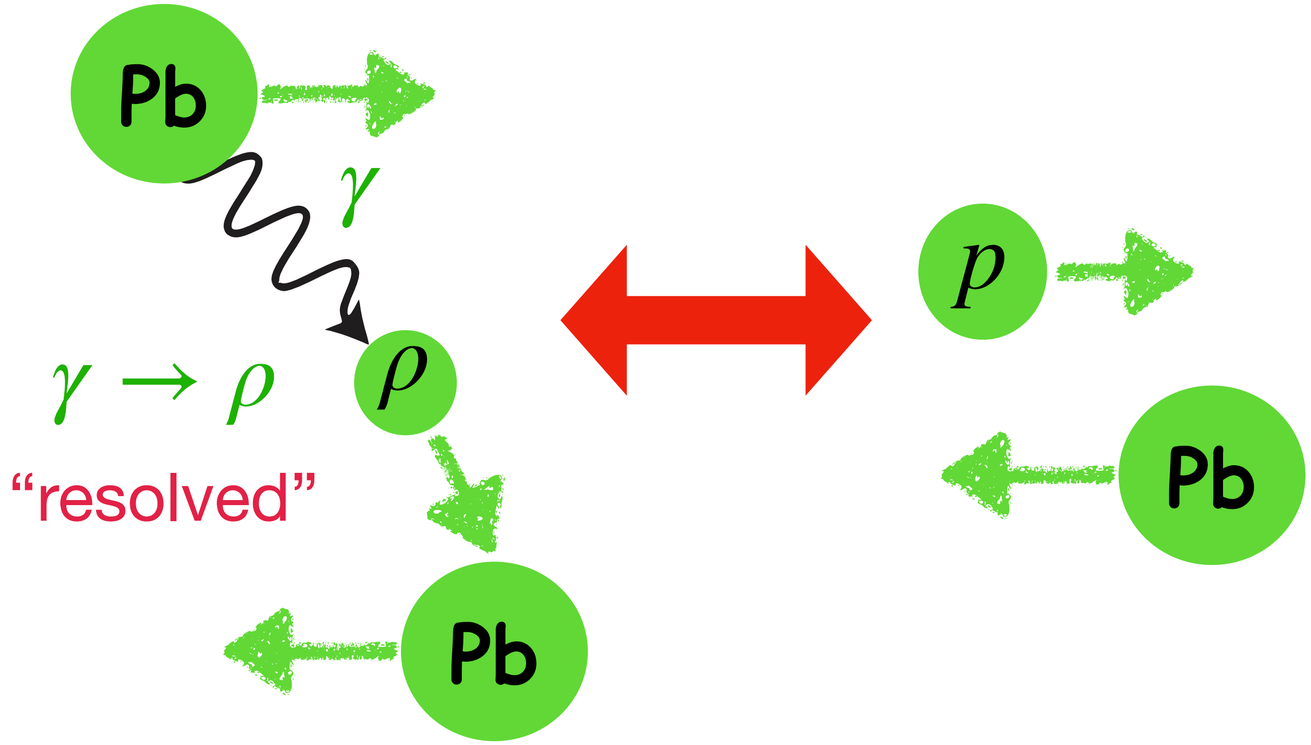
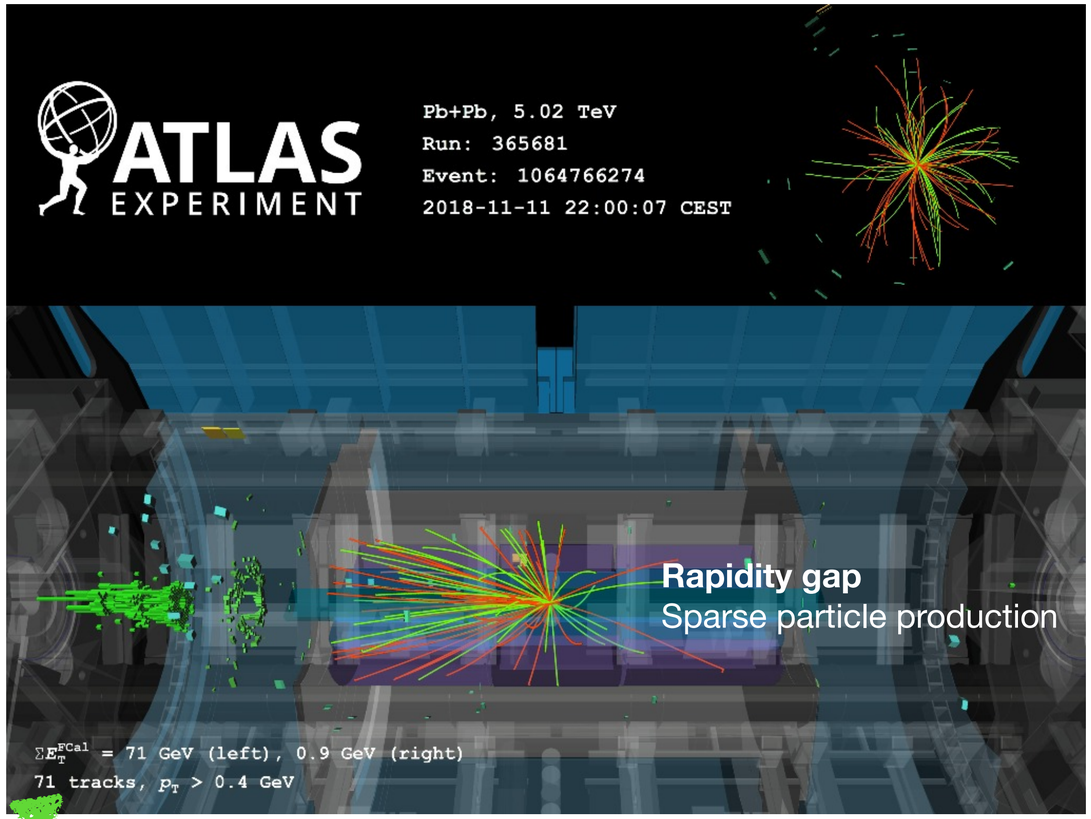


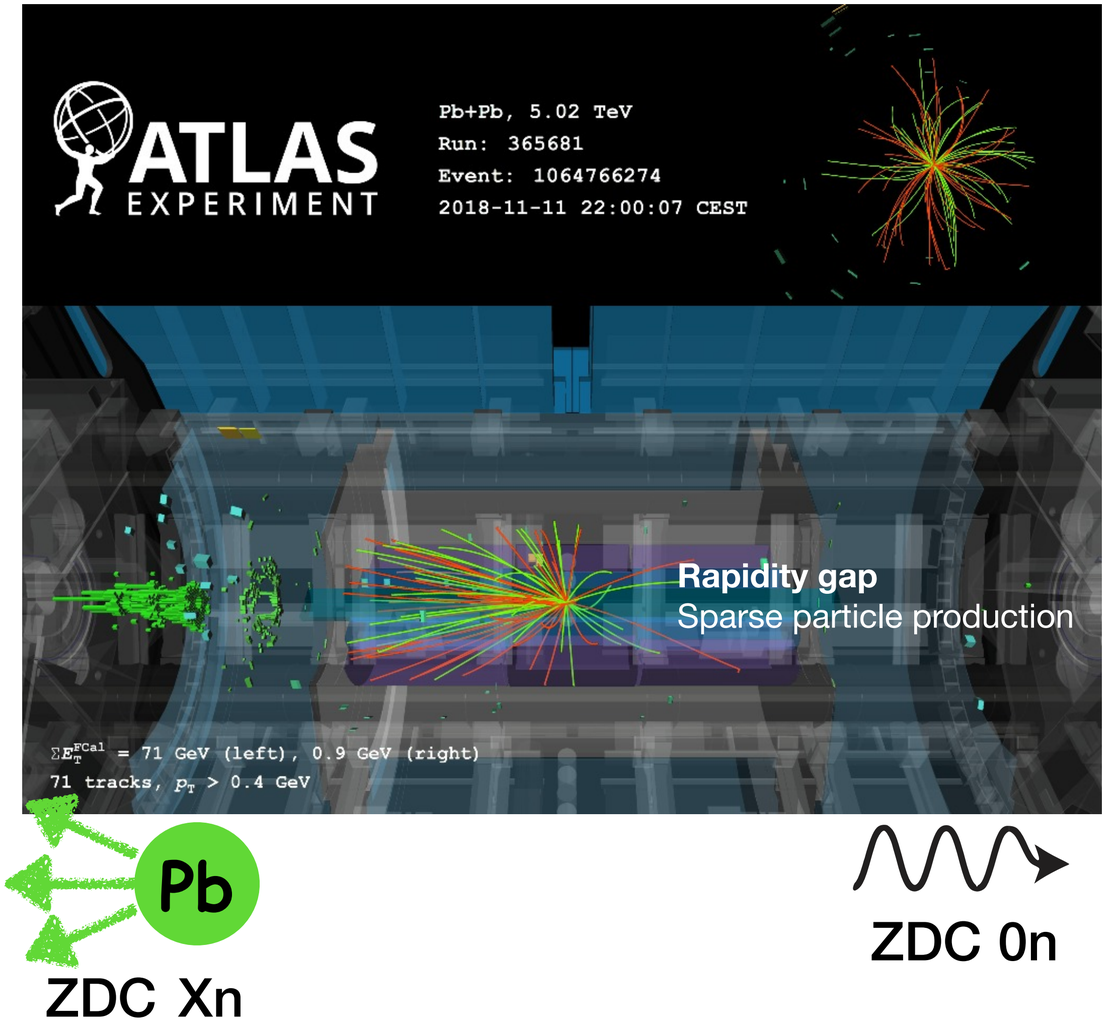


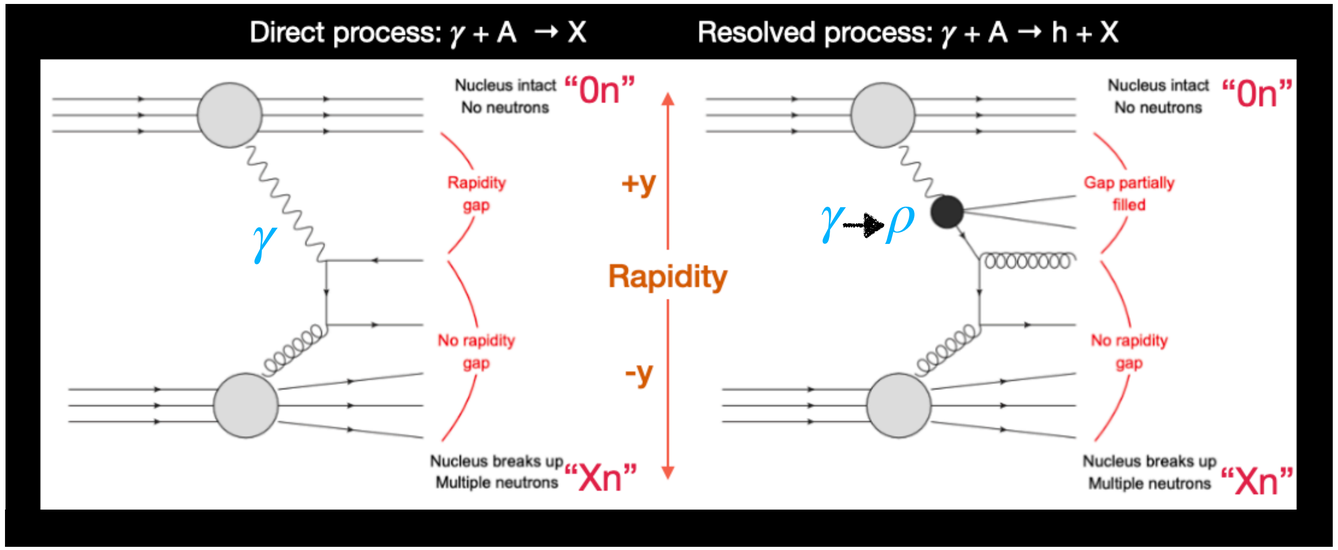
How do γ+Pb and p+Pb compare?

Photonuclear event selection



Photonuclear event selection



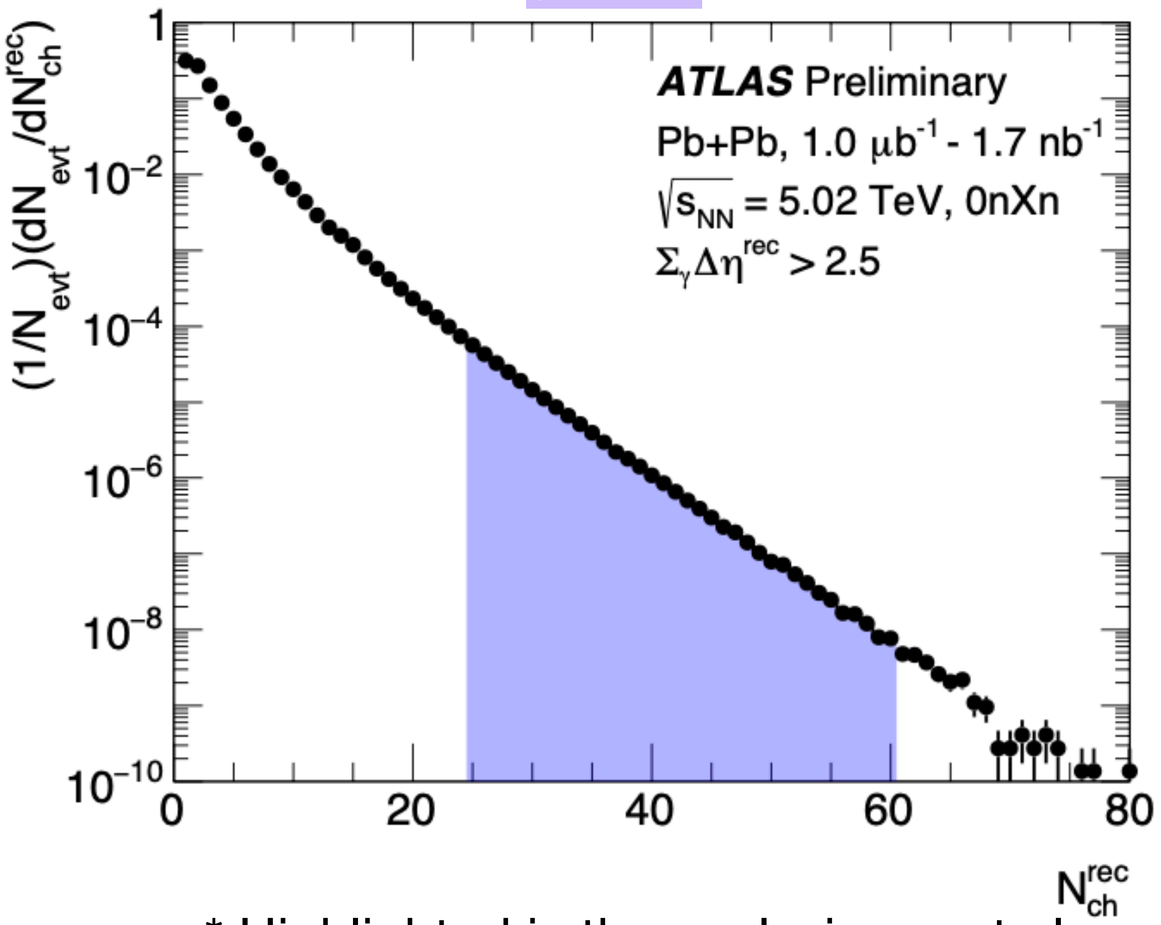


Single sided nuclear breakup "0nXn" &

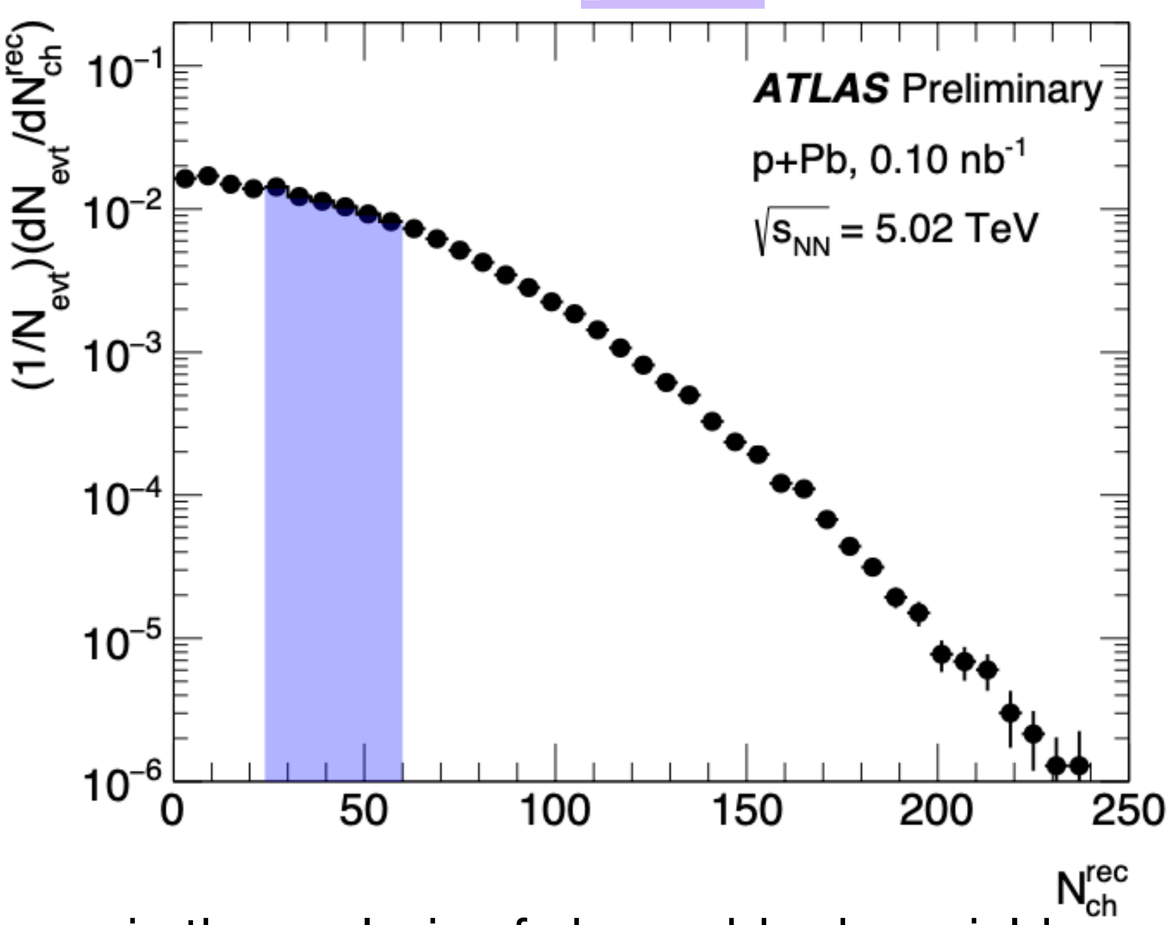
Rapidity gap $\Sigma_\gamma \Delta\eta^{\mathrm{rec}} > 2.5$

Multiplicity selection

γ+Pb



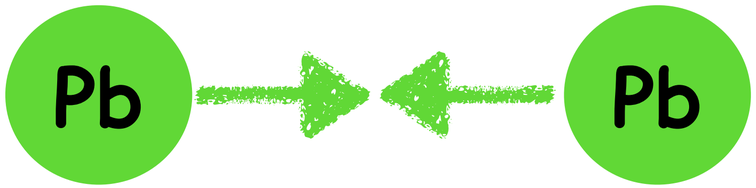
p+Pb



* Highlighted is the analysis event class chosen in the analysis of charged-hadron yield

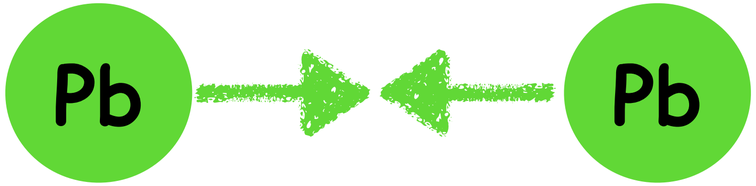
ATLAS-CONF-2023-059

Collectivity in heavy-ion collisions



A tiny drop of QGP is created in heavy-ion collisions and it expands like a fluid.

Collectivity in heavy-ion collisions



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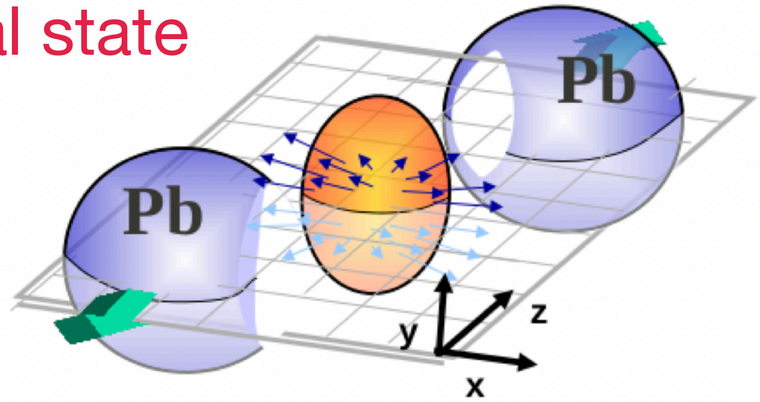

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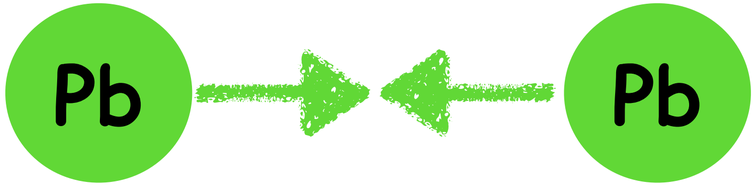

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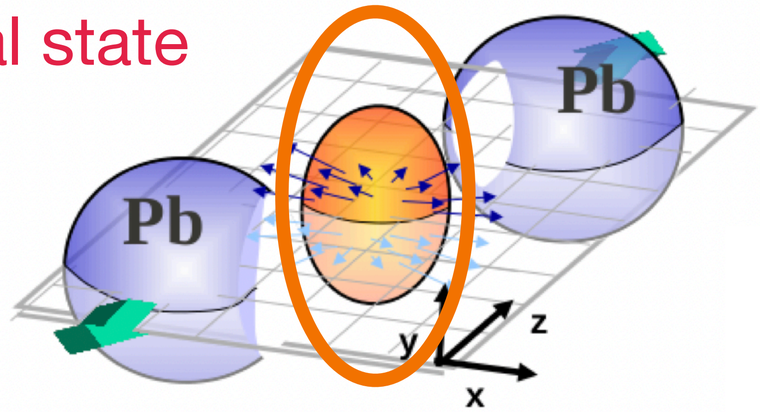

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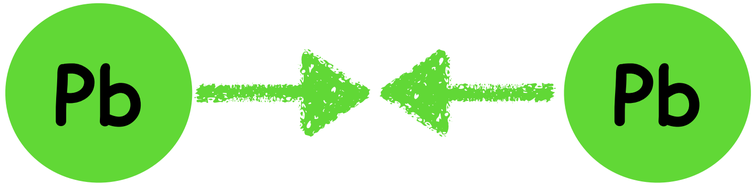

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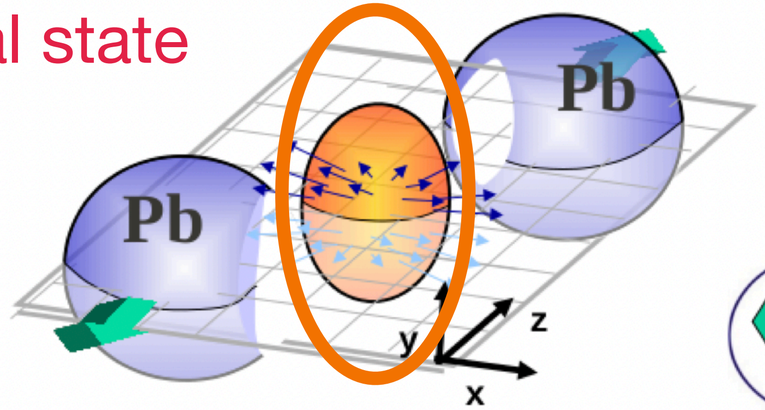
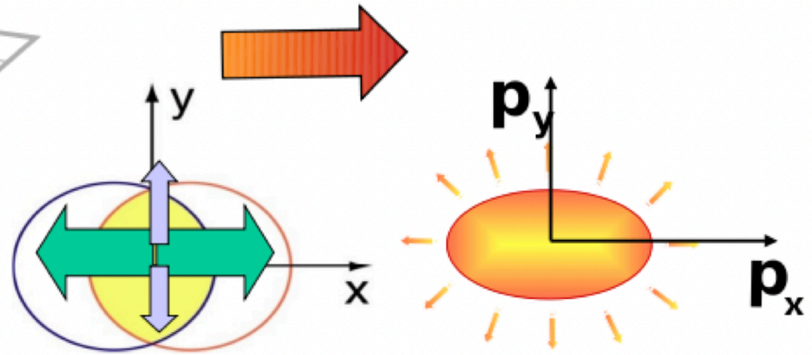


Final state



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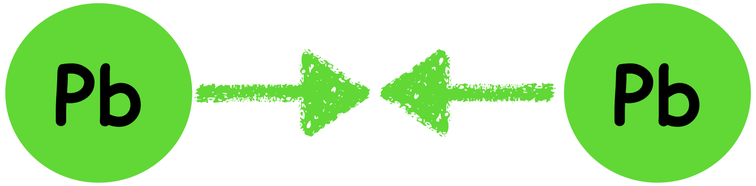

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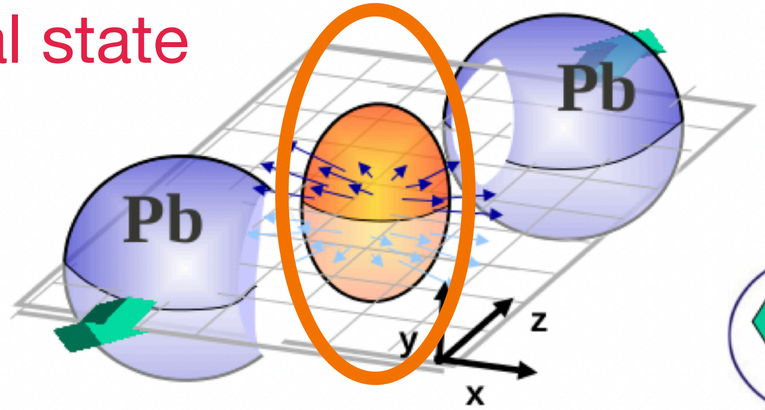
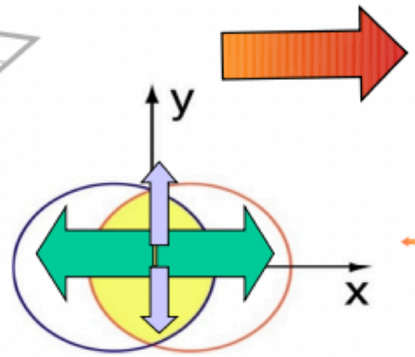
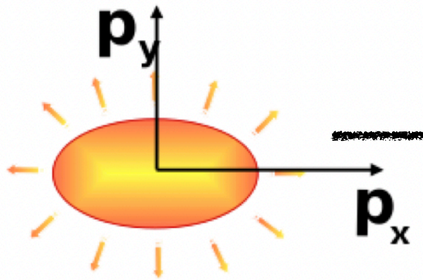
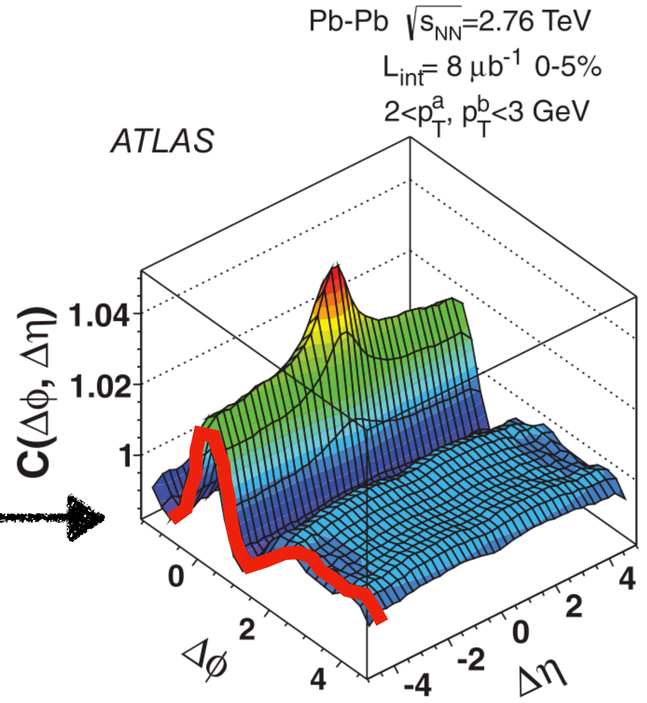




Final state





Phys. Rev. C 86 (2012) 014907

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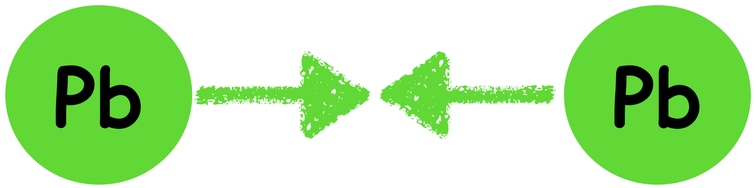

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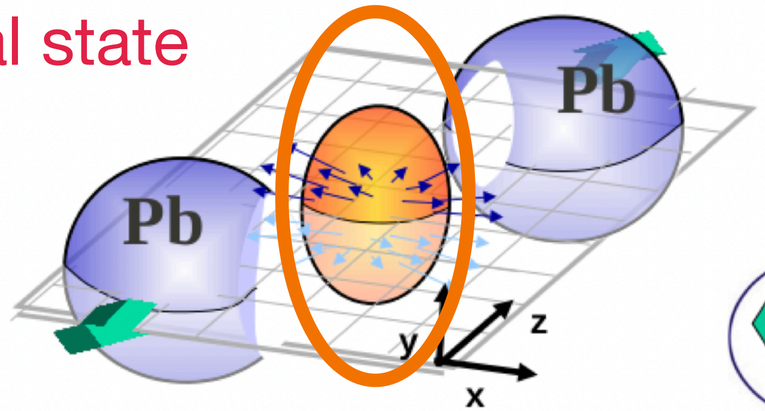

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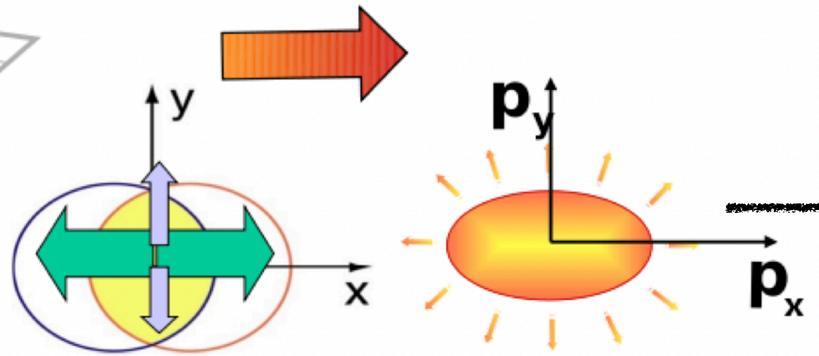
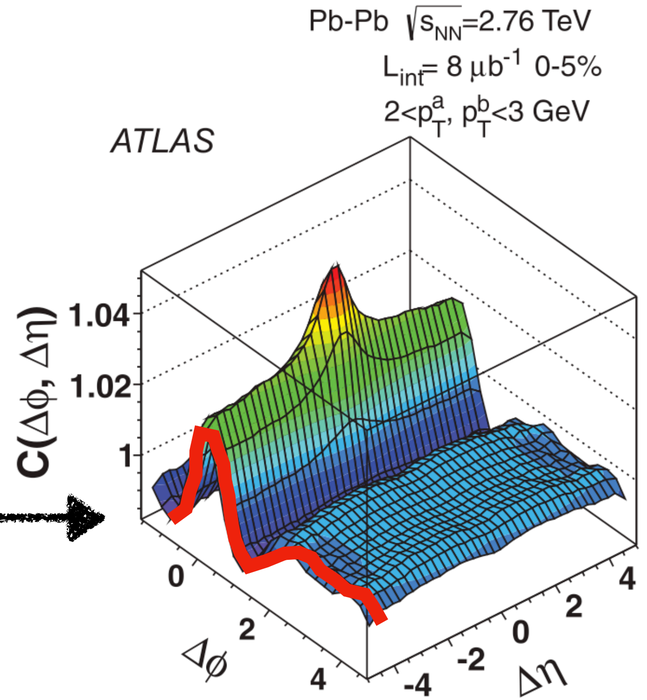
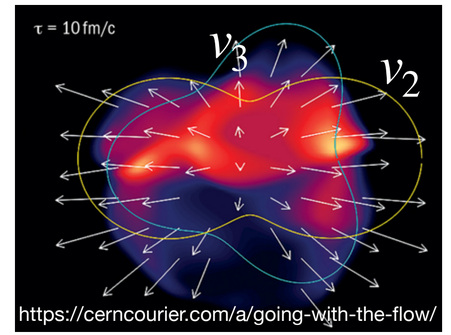




Phys. Rev. C 86 (2012) 014907

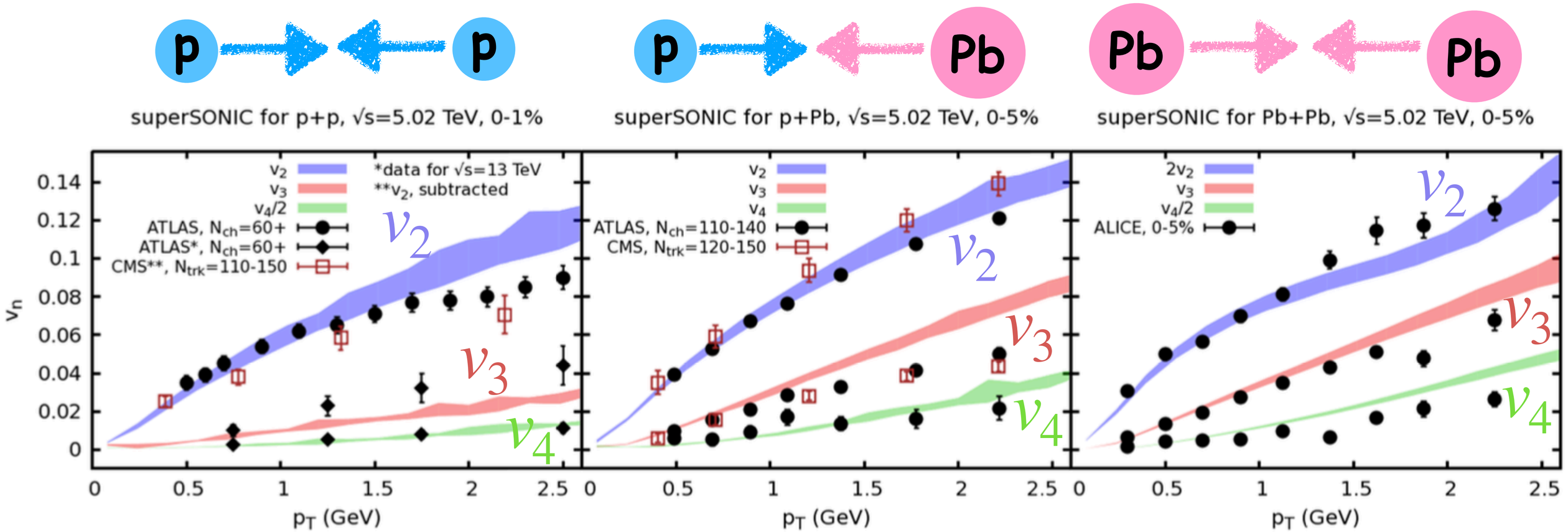
Spatial anisotropy in the initial state energy density translates into momentum anisotropy in the final state → v_2 (*Flow*)

Initial state fluctuations → v_3, v_4 …



https://cerncourier.com/a/going-with-the-flow/

Can we observe flow in small systems like *pp*, *p*Pb?



Theory: *Physics Letters B 774 (2017) 351–356*

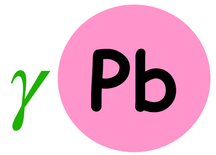
ATLAS: *Physical Review C 90 (2014) 044906*

Hydrodynamic models can successfully describe v_2, v_3, v_4

in systems of wide size ranges: *pp*, *p*Pb and Pb+Pb!

Do photonuclear events create QGP droplets?

Two-particle azimuthal correlations in photonuclear ultraperipheral Pb+Pb collisions at 5.02 TeV with ATLAS



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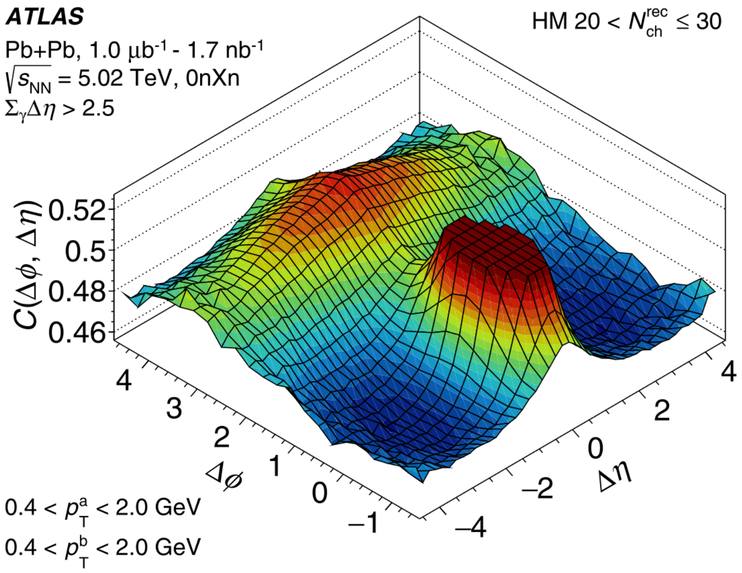
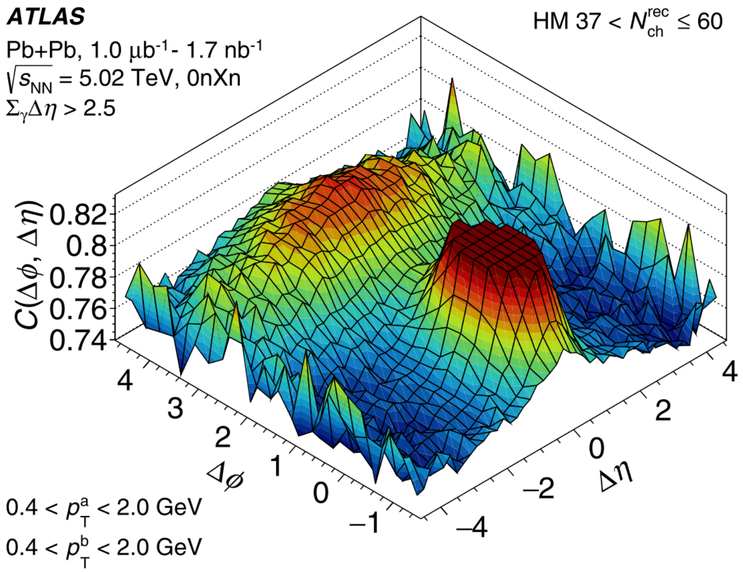
(ATLAS Collaboration)

(Received 27 January 2021; accepted 17 June 2021; published 12 July 2021)





Physical Review C 104 (2021) 014903

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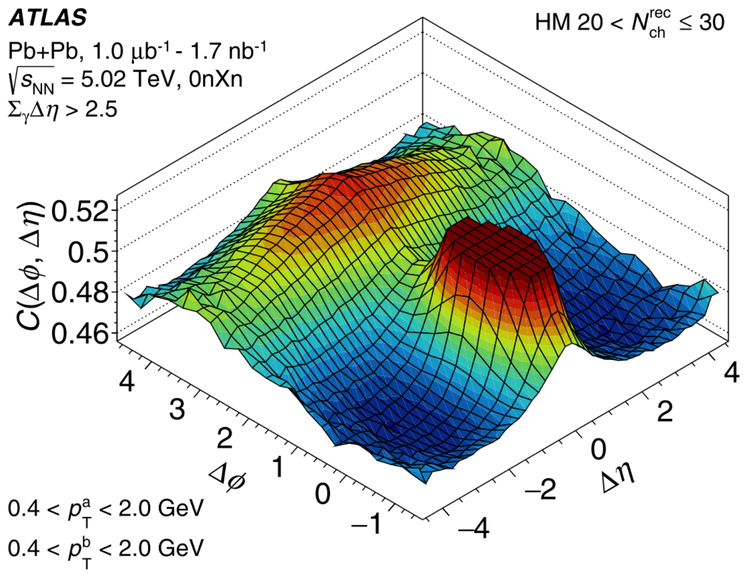
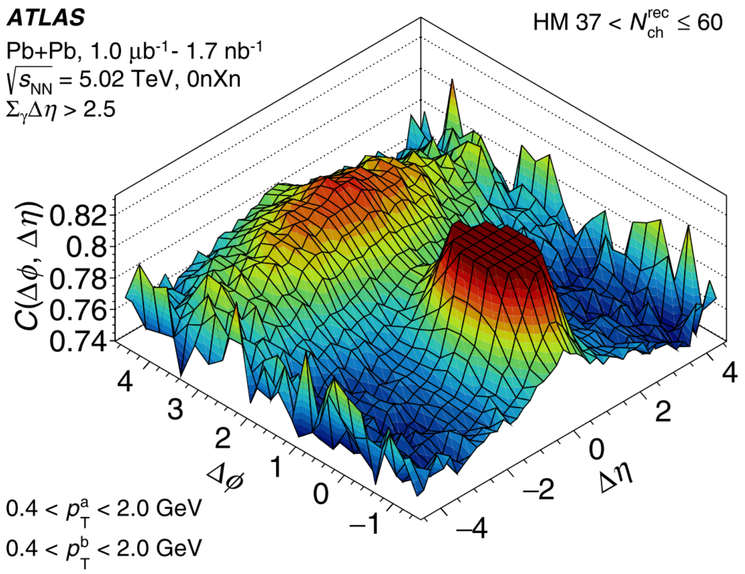
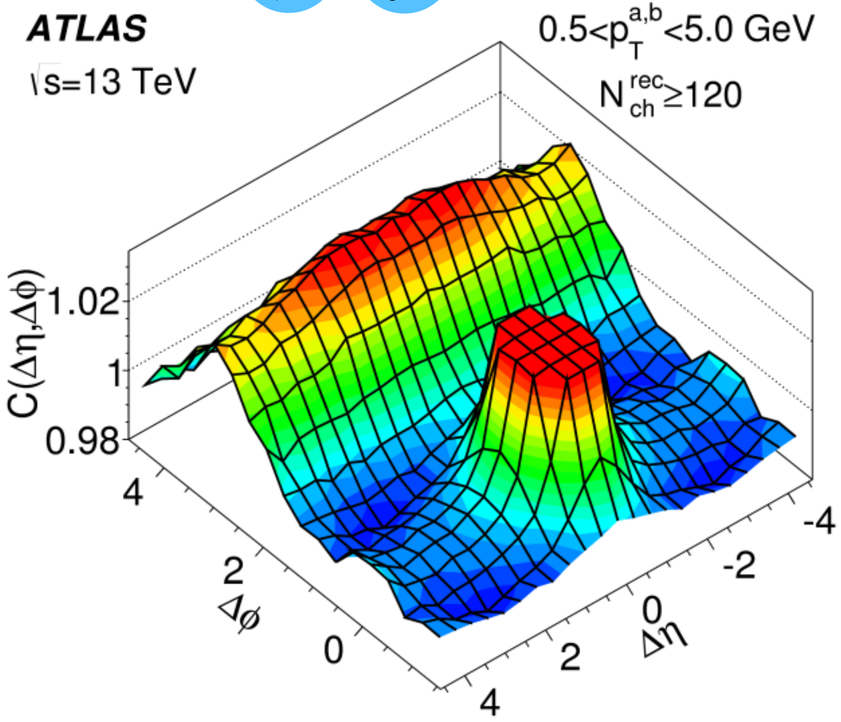




Physical Review C 104 (2021) 014903

p p



Phys. Rev. Lett. 116 (2016) 172301

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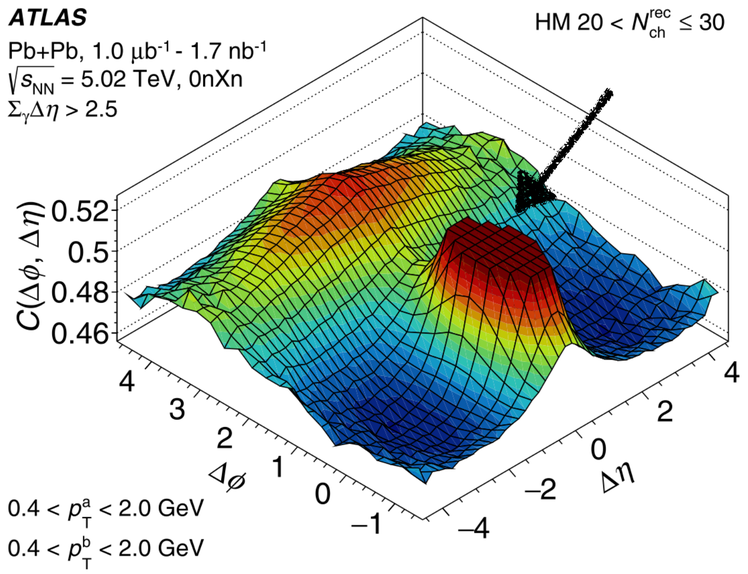

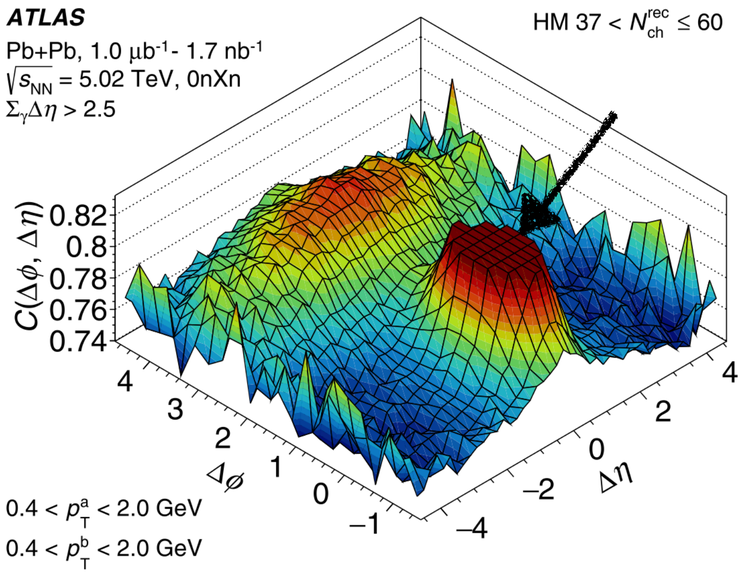

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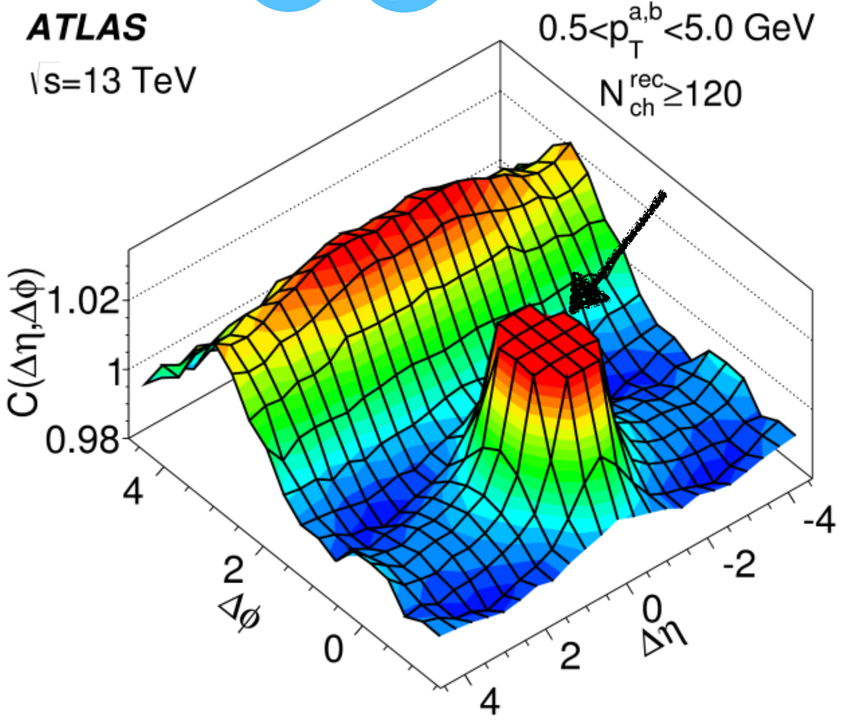

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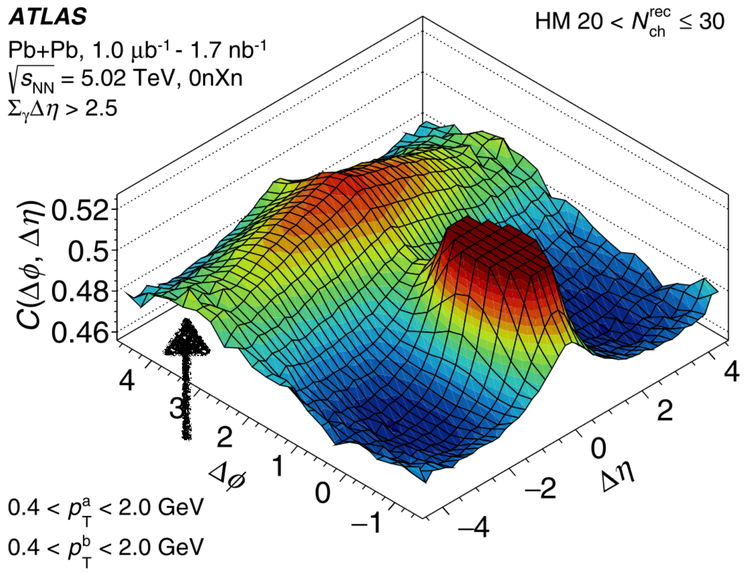
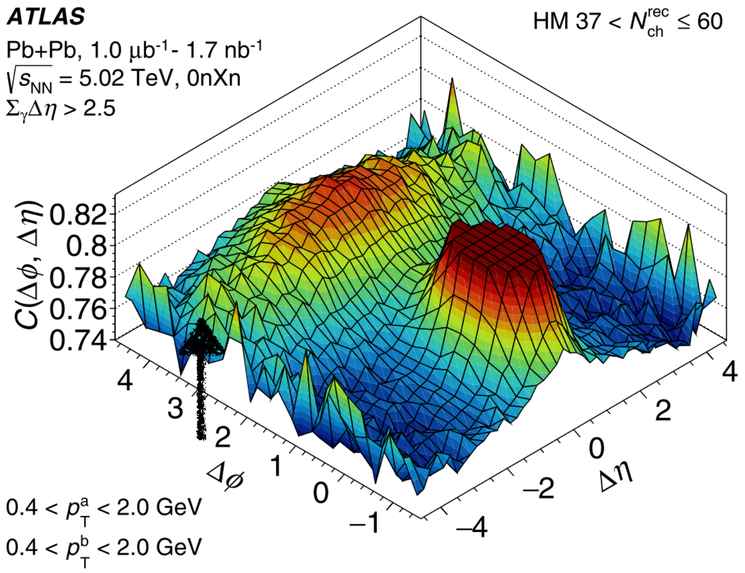
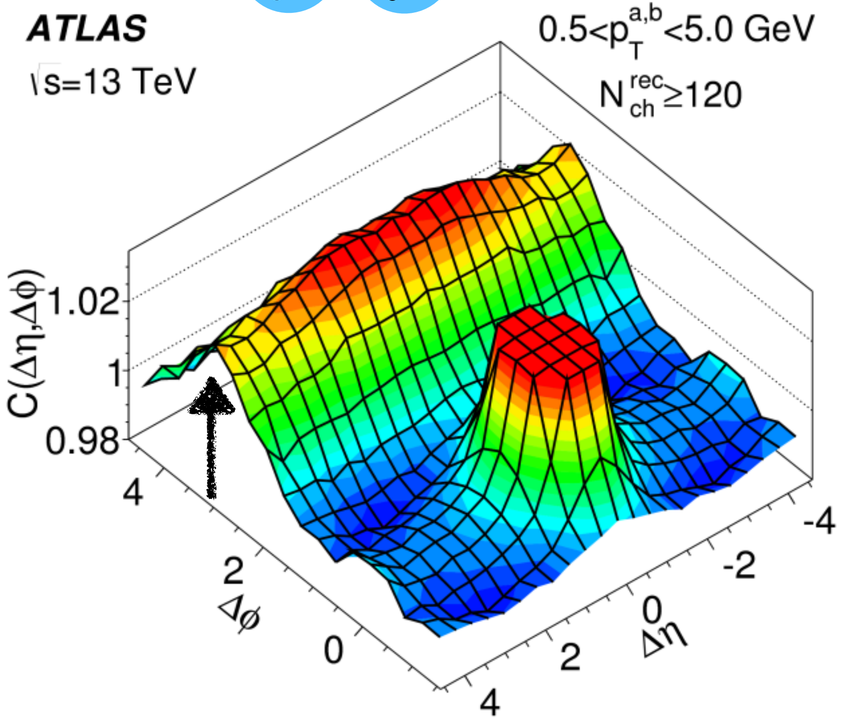




Physical Review C 104 (2021) 014903

p p



Phys. Rev. Lett. 116 (2016) 172301

Two-dimensional correlation functions in γ+Pb have features similar to those observed in *pp* collisions

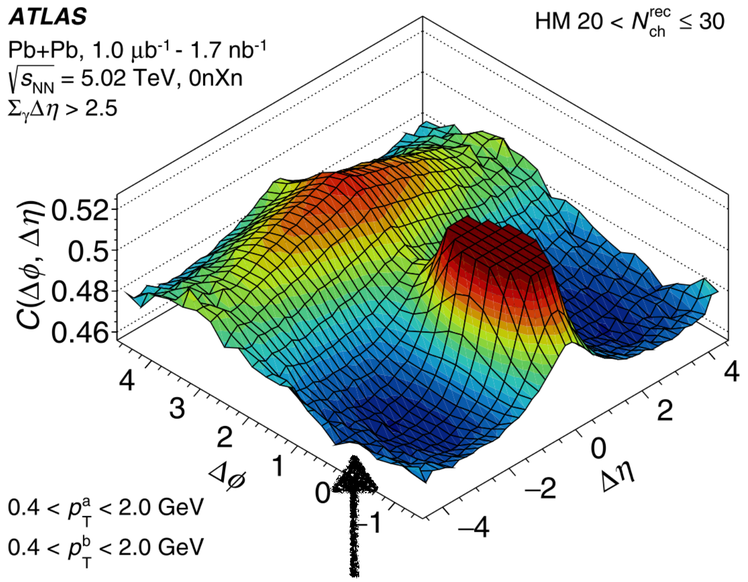
Do photonuclear events create QGP droplets?

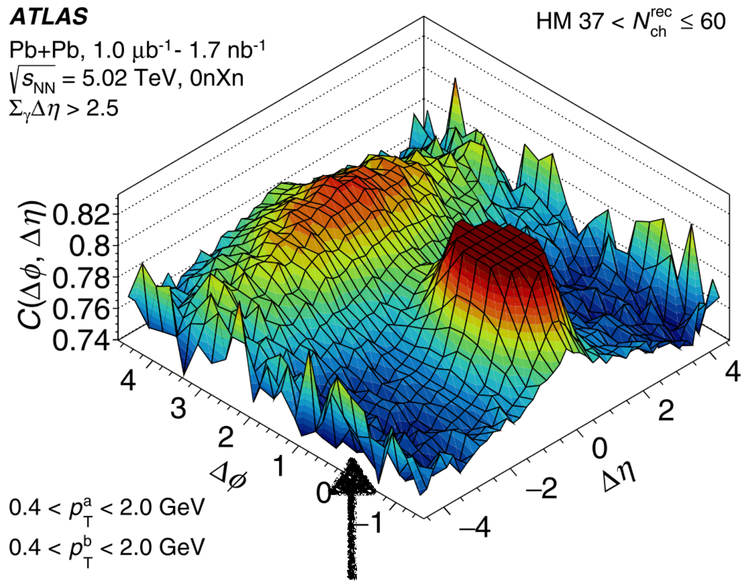
Two-particle azimuthal correlations in photonuclear ultraperipheral Pb+Pb collisions at 5.02 TeV with ATLAS

γ Pb

G. Aad *et al.**
(ATLAS Collaboration)

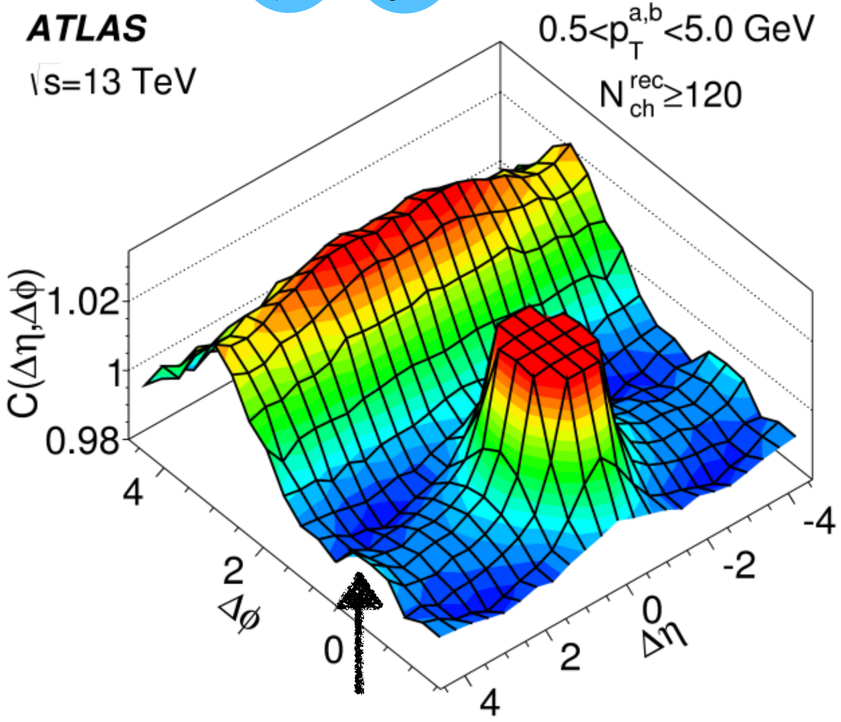
(Received 27 January 2021; accepted 17 June 2021; published 12 July 2021)





Physical Review C 104 (2021) 014903

p p



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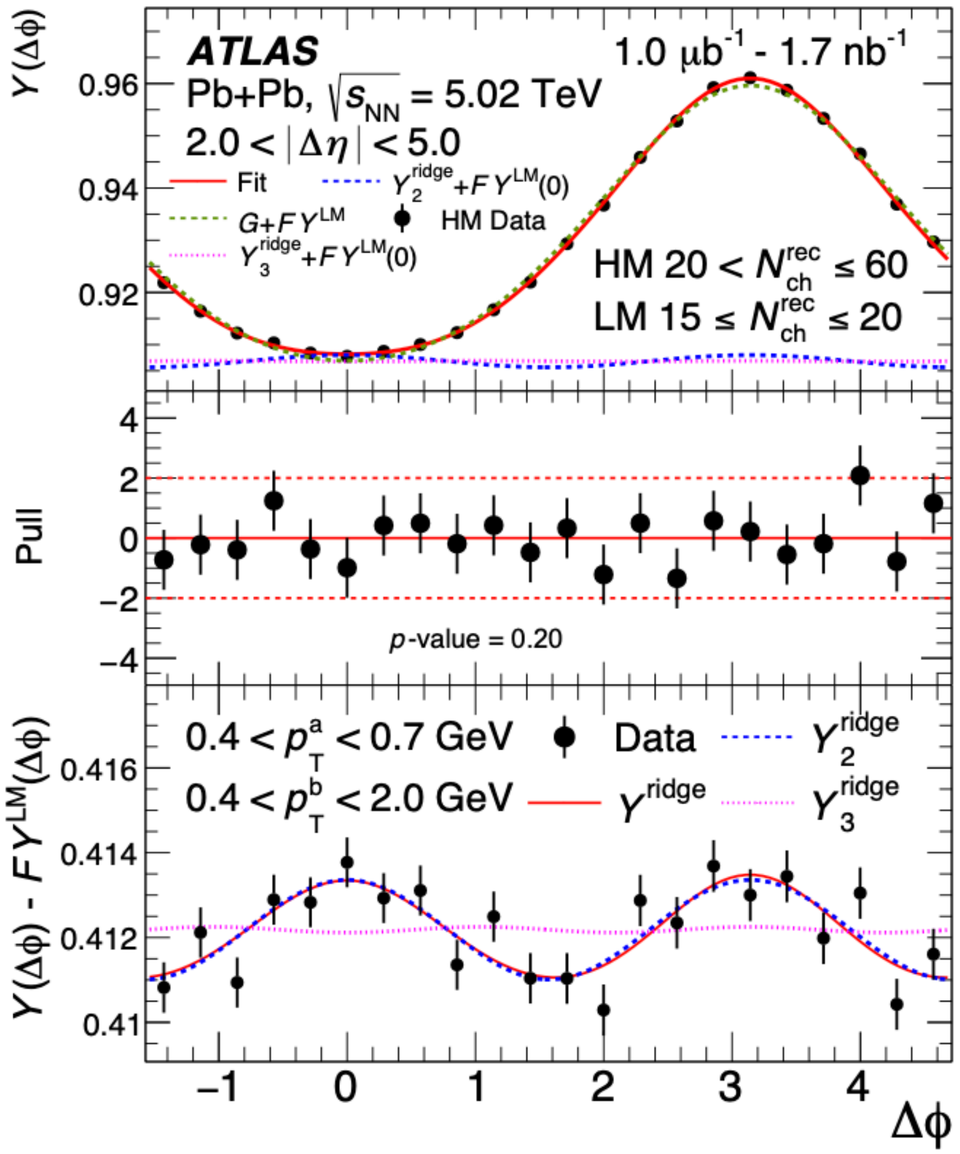
Do photonuclear events create QGP droplets? - Elliptic flow



Phys. Rev. C. 104 (2021) 014903

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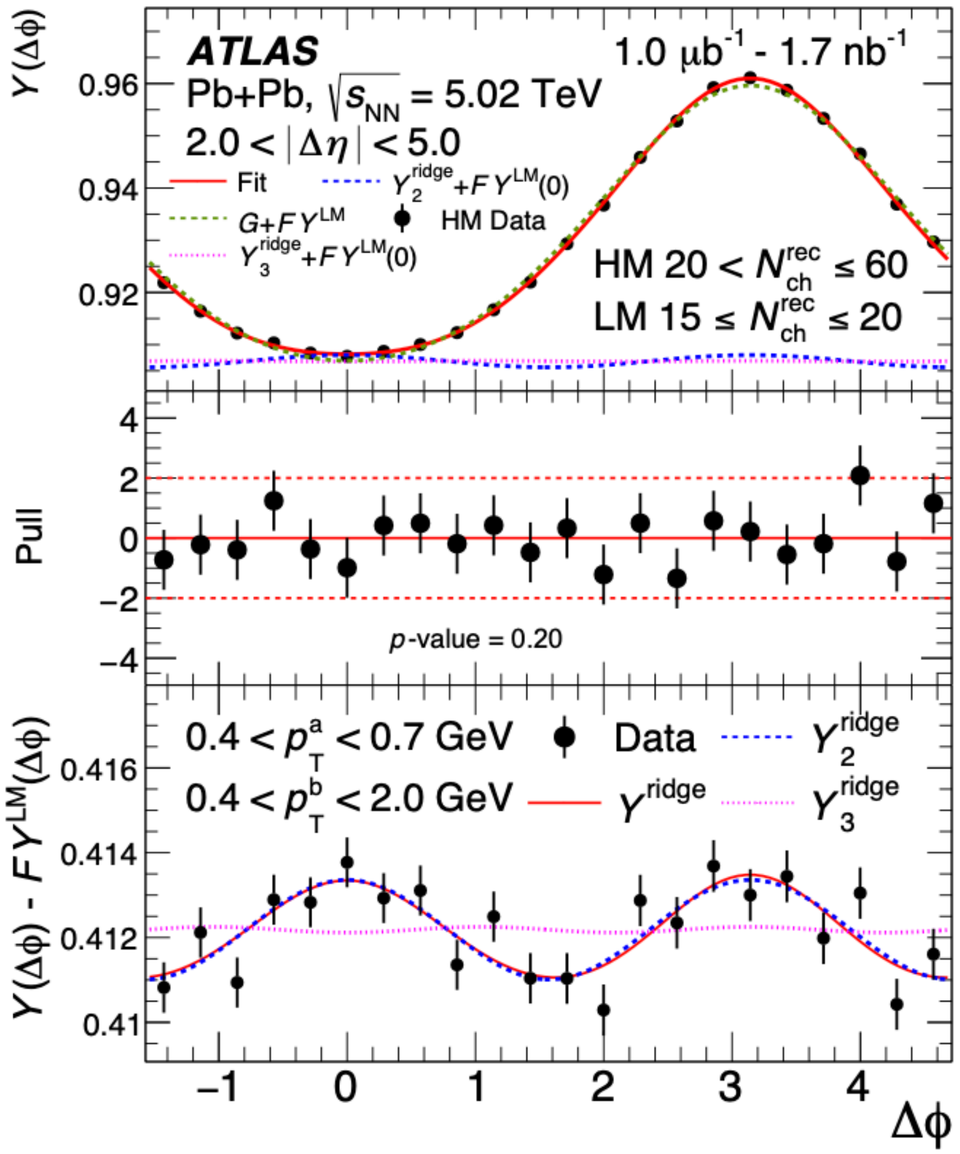

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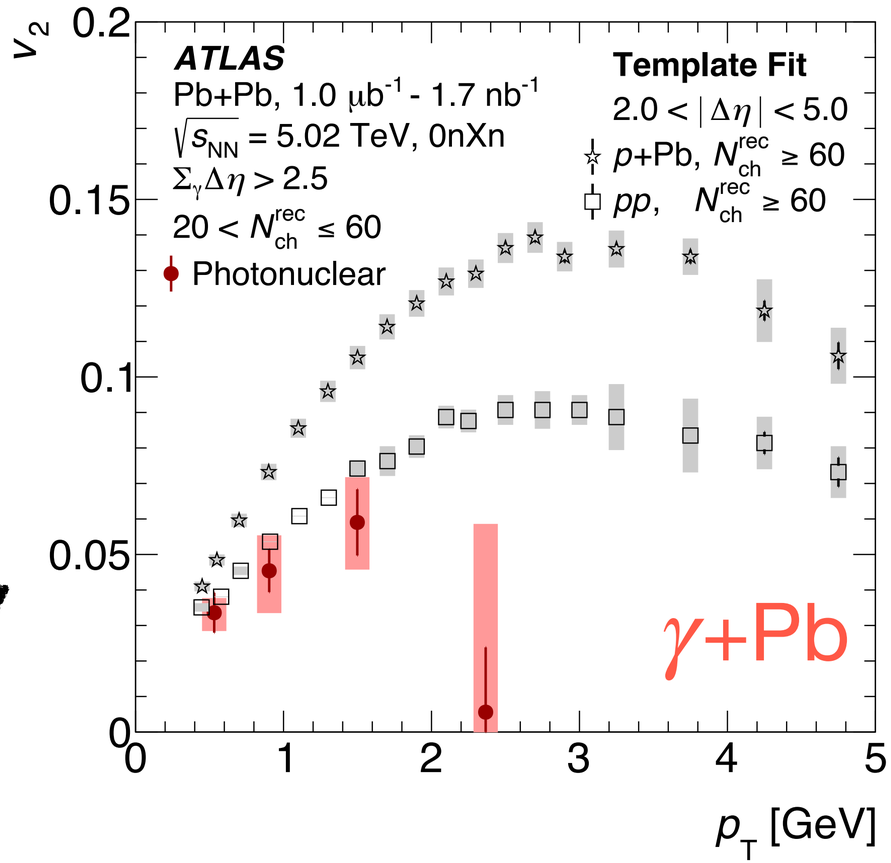
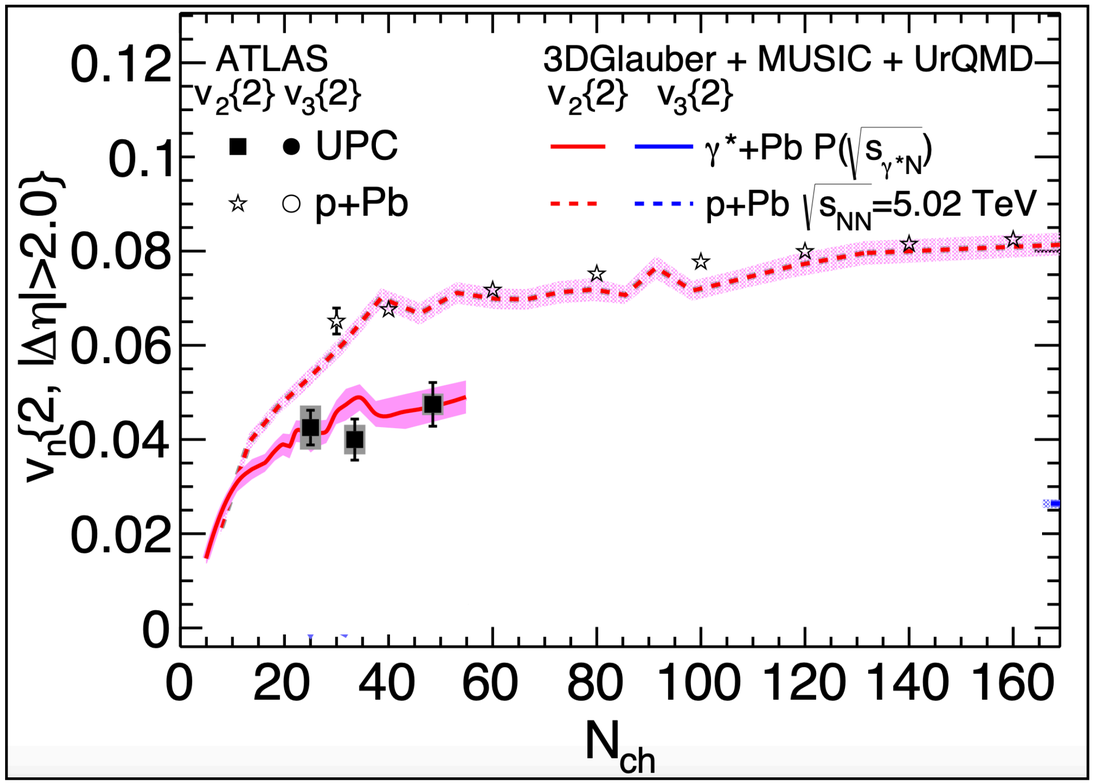


Collective flow (v_2) found by ATLAS in photo-nuclear collisions!

Motivation to look for more QGP-like signals!

Do photonuclear events create QGP droplets? - Radial flow

Phys. Rev. Lett. 129 (2022) 252302 Wenbin Zhao, Chun Shen, and Björn Schenke



3+1D hydrodynamics

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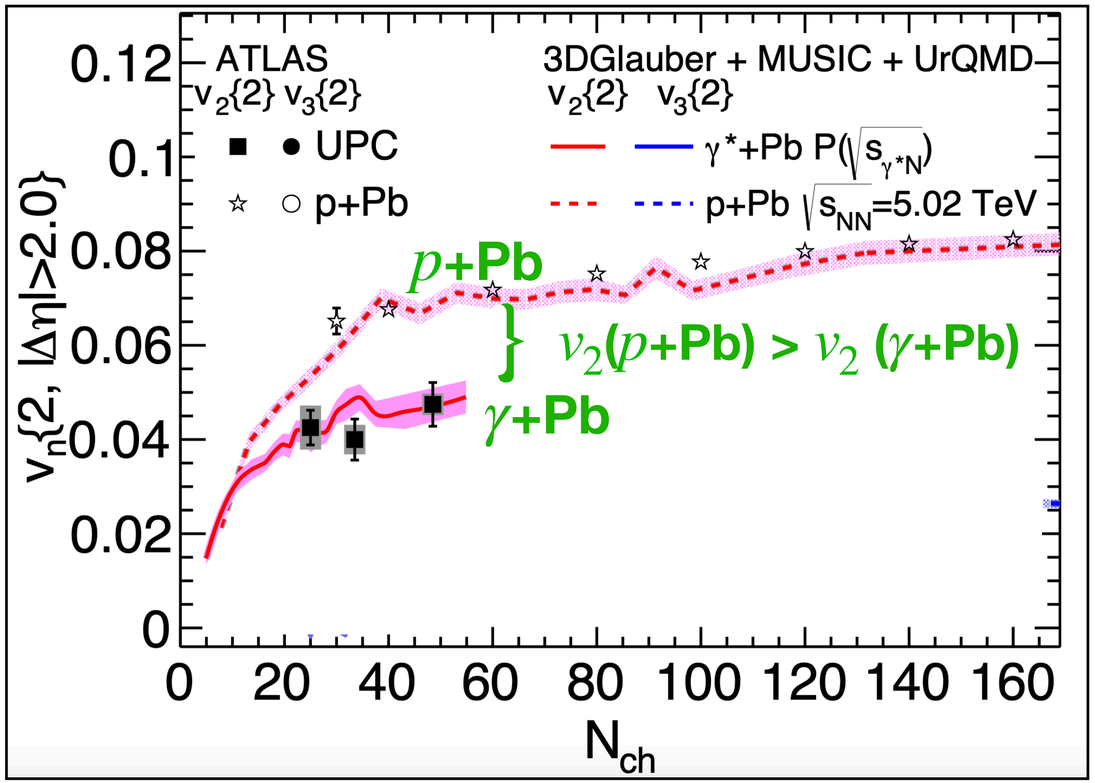
Phys. Rev. Lett. 129 (2022) 252302 Wenbin Zhao, Chun Shen, and Björn Schenke



3+1D hydrodynamics suggests

elliptic flow hierarchy between γ+Pb and p+Pb

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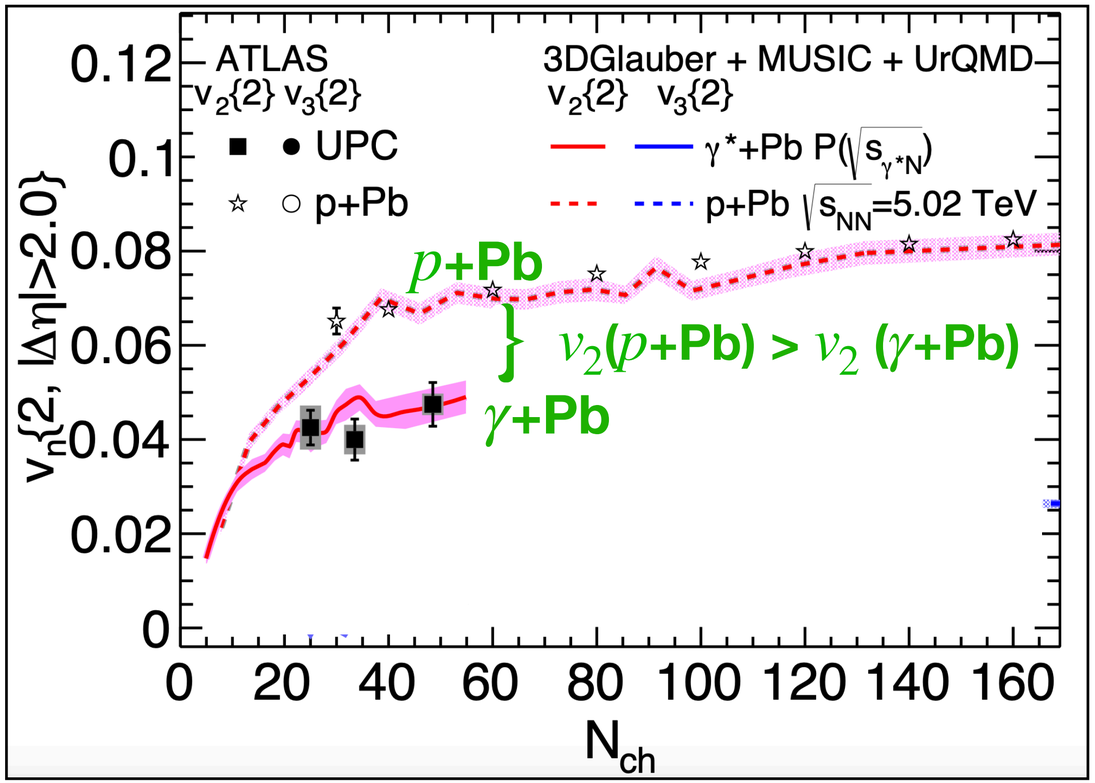

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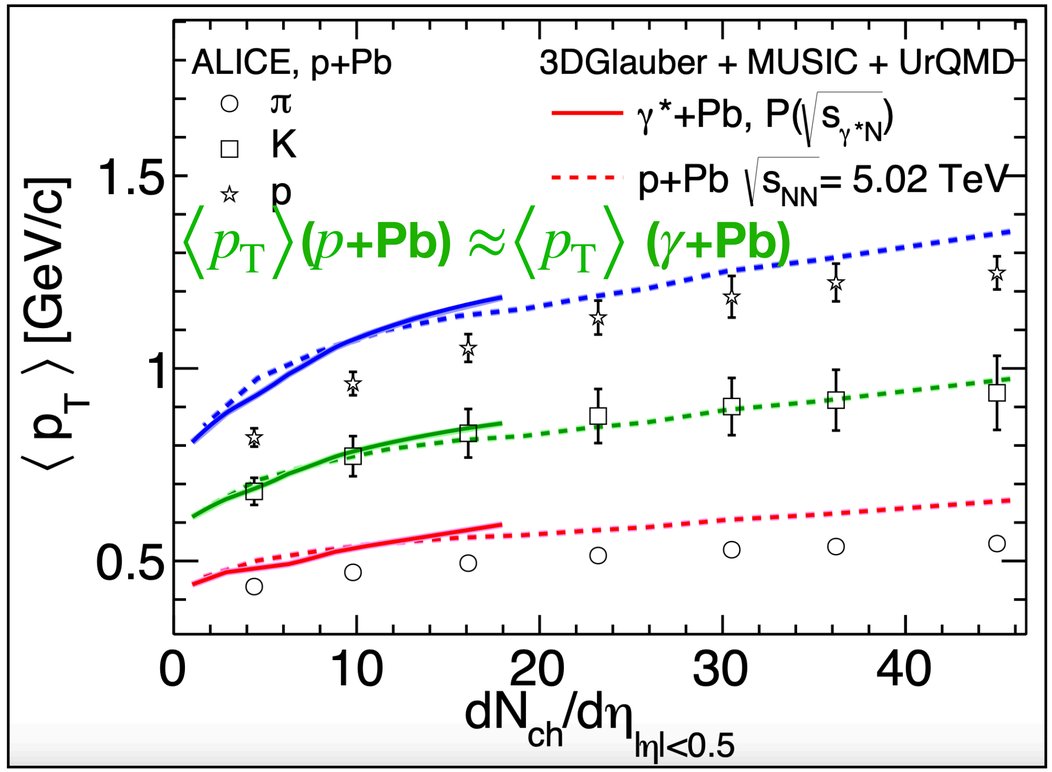
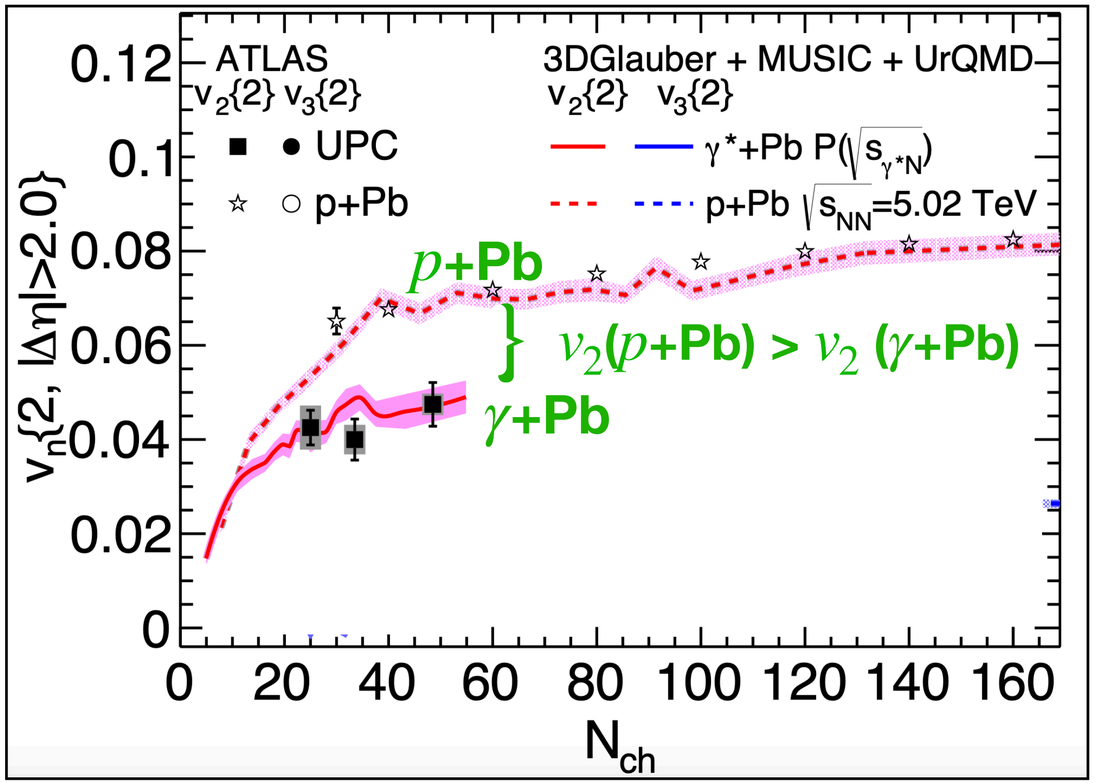


Prediction is that both systems should have same radial flow, therefore the same $\langle p_T \rangle$

Do photonuclear events create QGP droplets? - Radial flow



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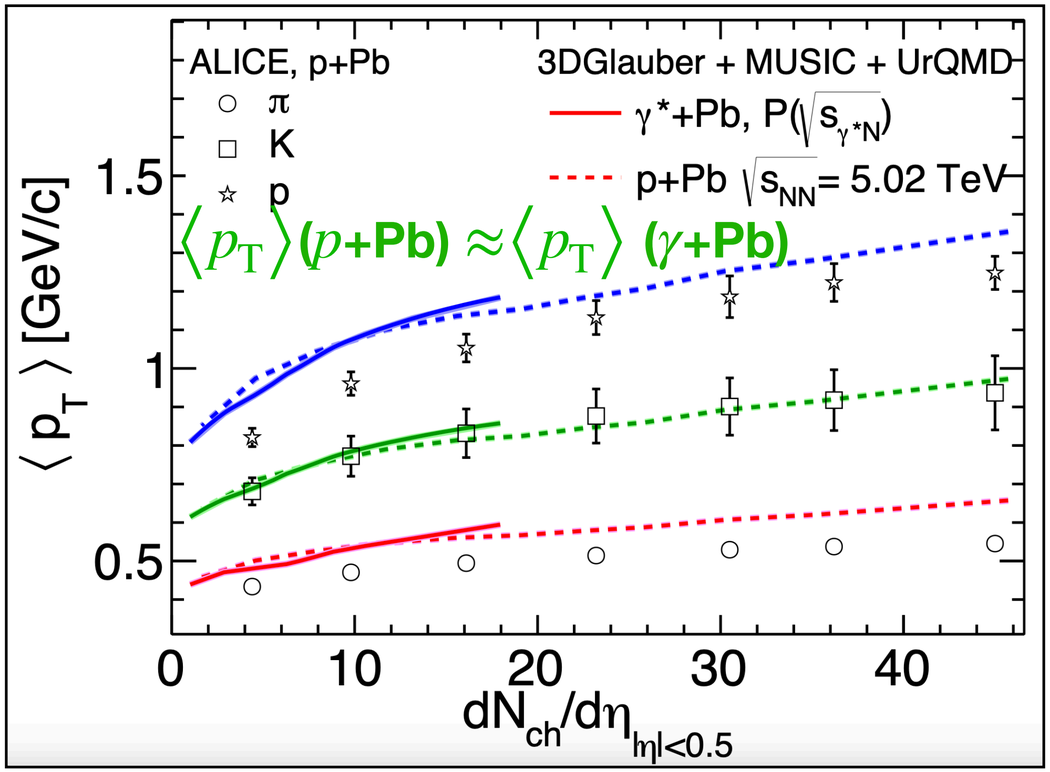


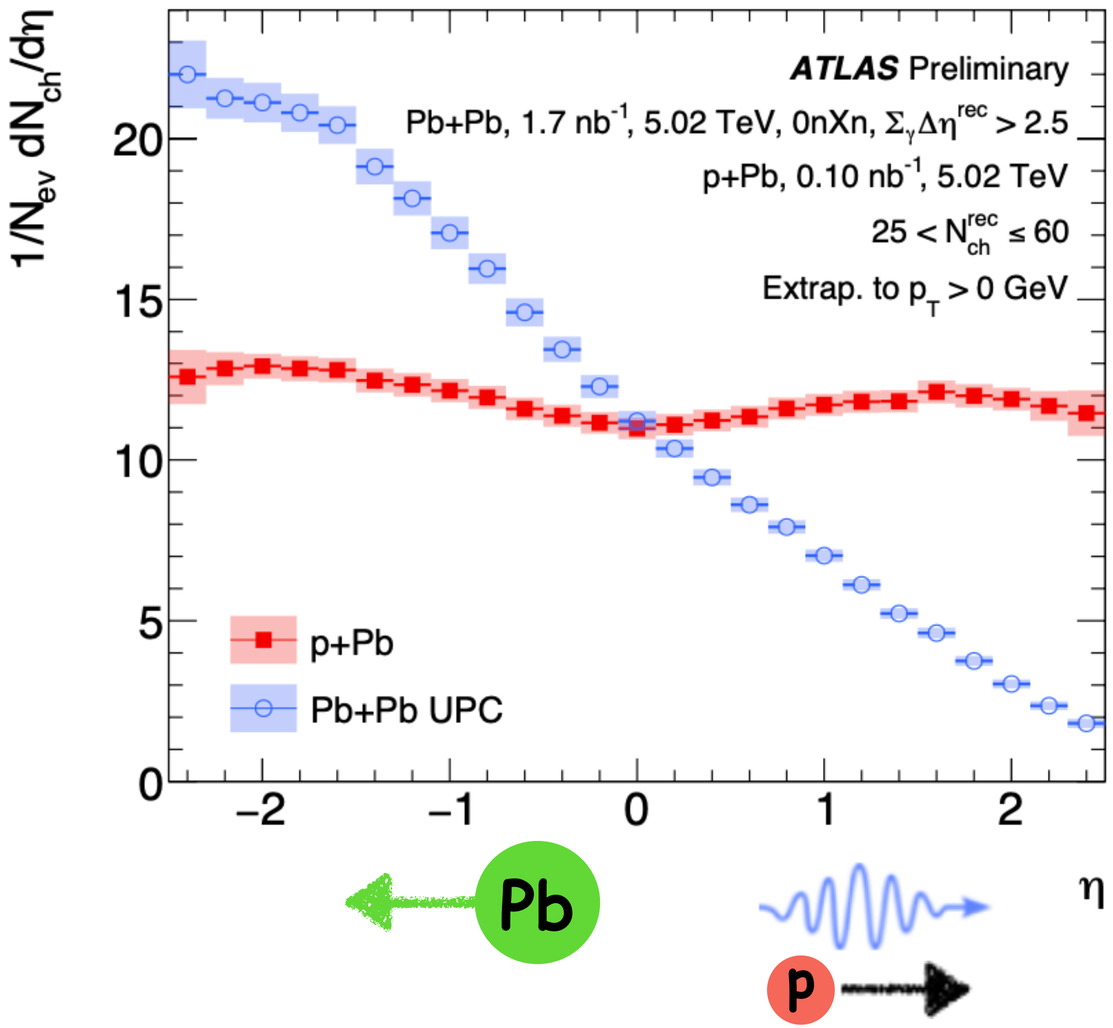
Prediction is that both systems should have same radial flow, therefore the same $\langle p_T \rangle$

Relevant observables: $\langle p_T \rangle$ of charged hadrons

ATLAS-CONF-2023-059

Yield comparison: γ+Pb vs p+Pb

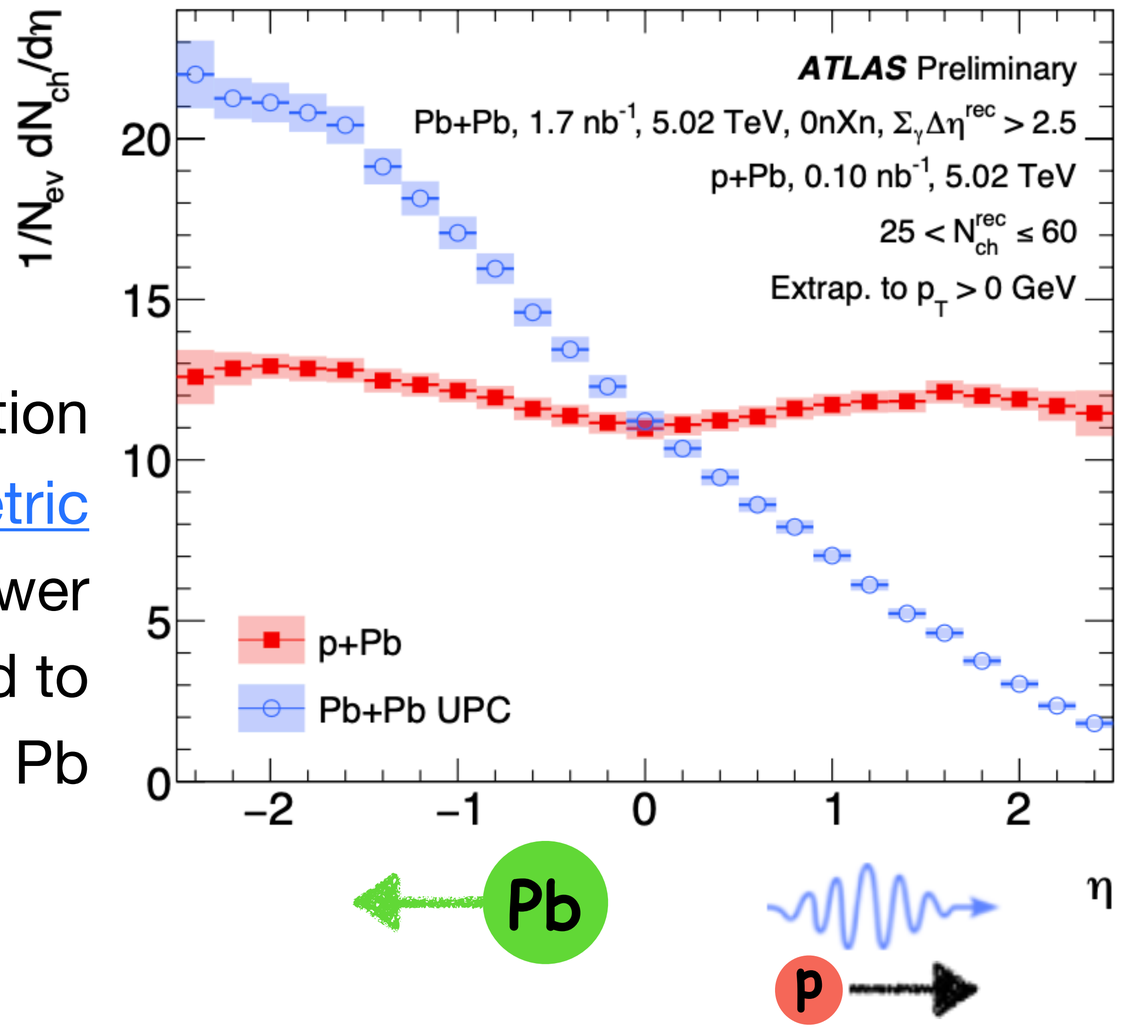
ATLAS-CONF-2023-059



Yield comparison: γ+Pb vs p+Pb

ATLAS-CONF-2023-059

γ+Pb distribution
is highly asymmetric
Photon energy lower
compared to
energy per nucleon in Pb



p+Pb distribution
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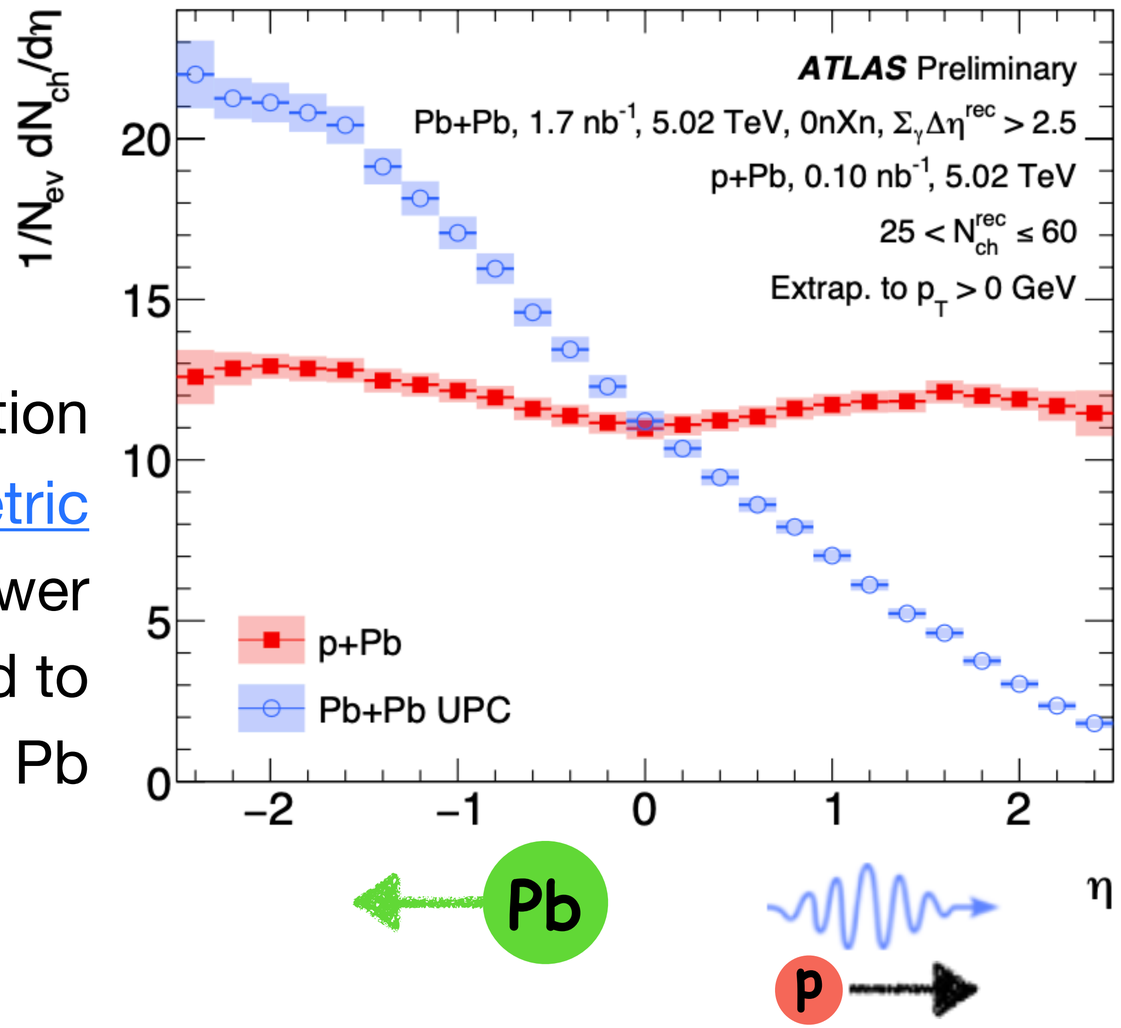

p+Pb distribution
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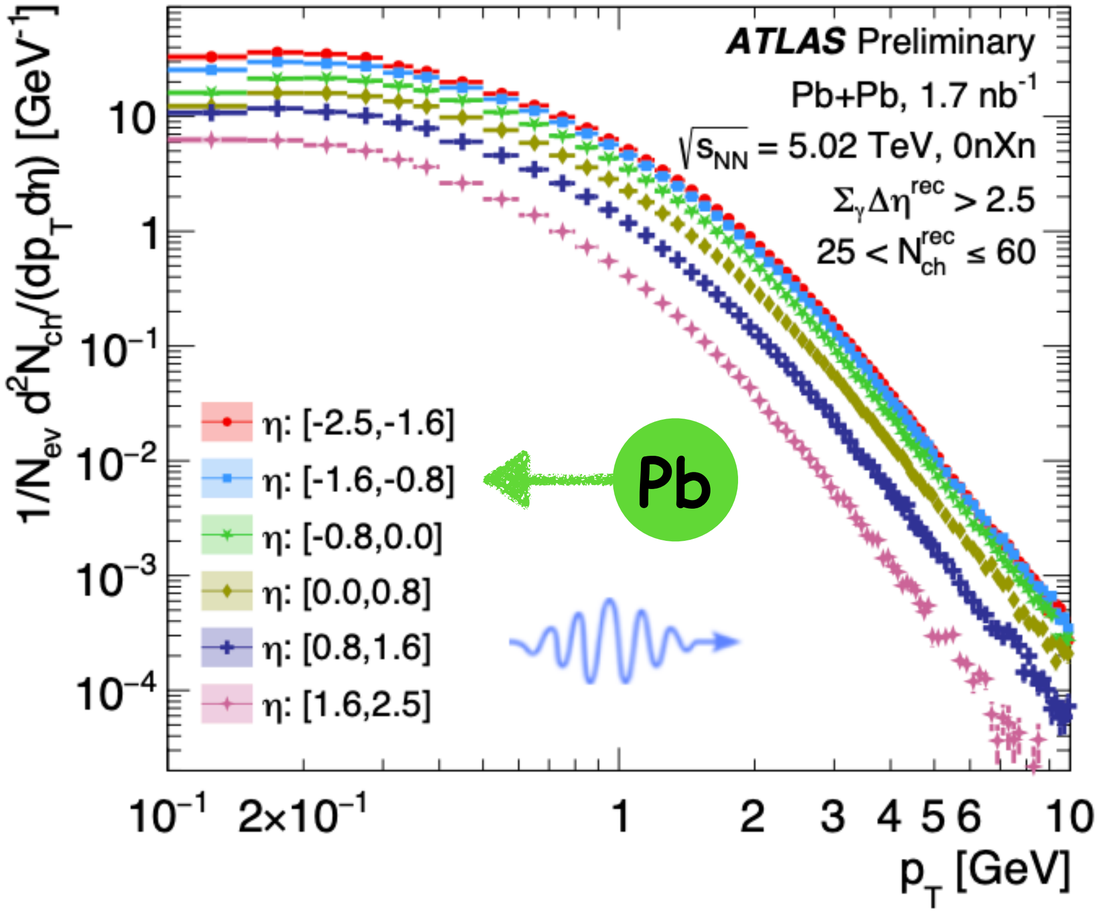
Given the extreme asymmetry, it is important to study γ+Pb properties in different η regions separately!

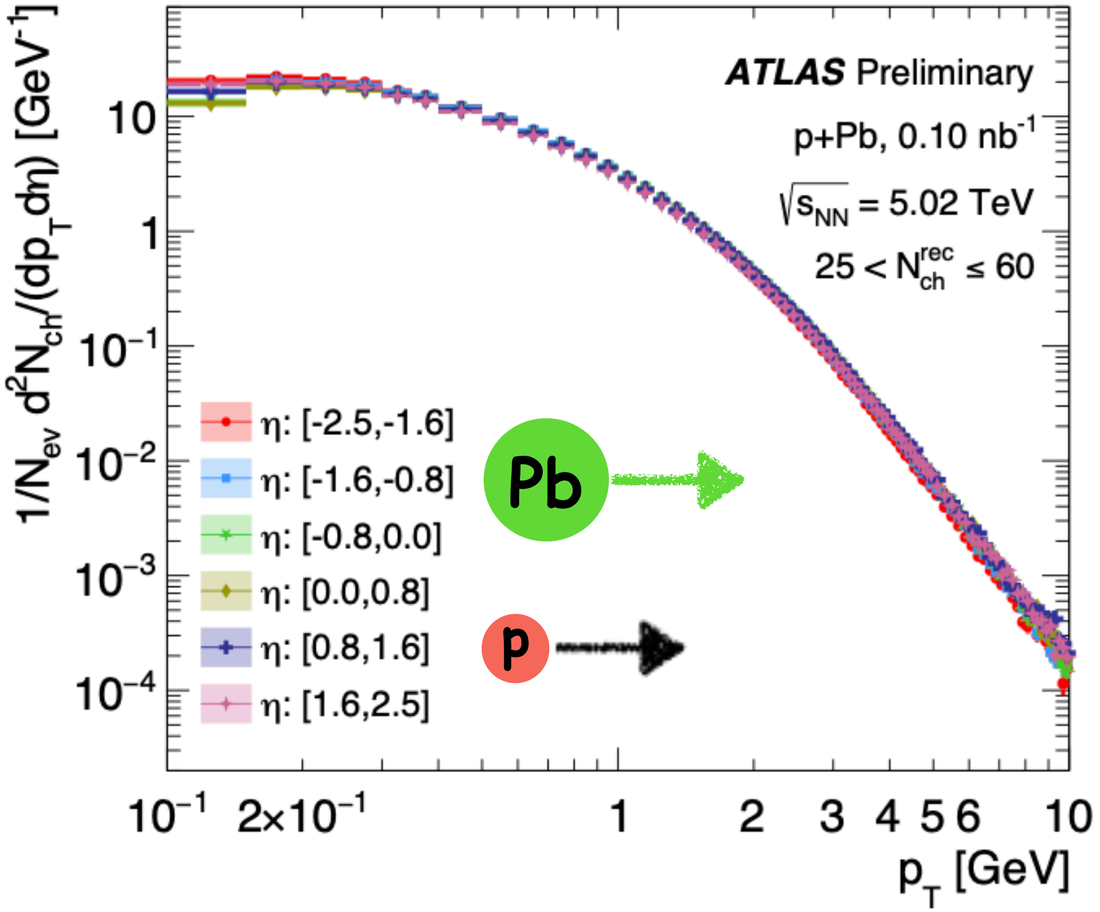
Yield comparison: γ+Pb vs p+Pb

ATLAS-CONF-2023-059

γ+Pb



p+Pb

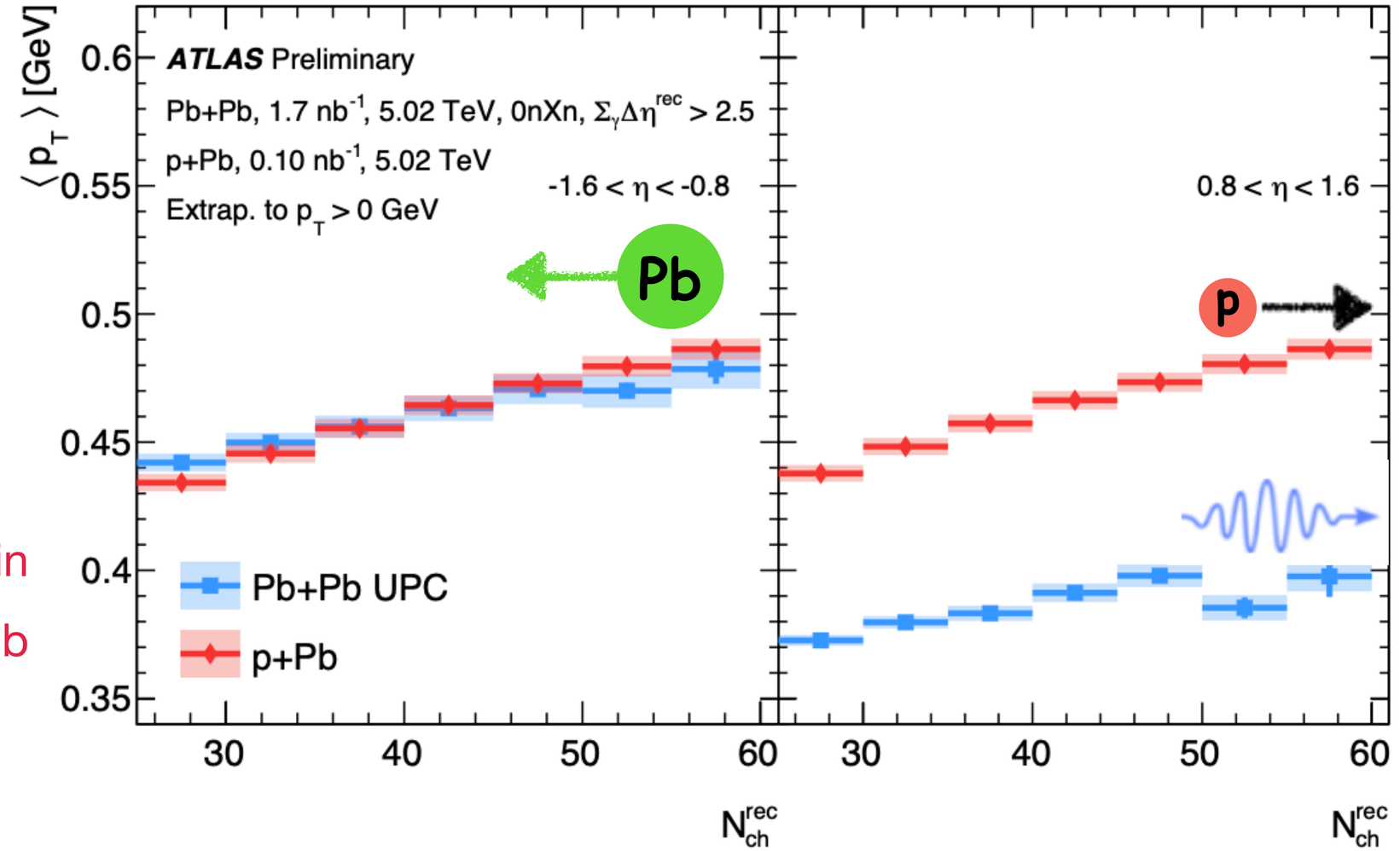


Similarly falling momentum distributions. Further quantified via $\langle p_T \rangle$

ATLAS-CONF-2023-059

$\langle p_{\mathrm{T}} \rangle$ comparison: γ+Pb vs p+Pb

$\langle p_{\mathrm{T}} \rangle$ similar in γ+Pb and p+Pb



$\langle p_{\mathrm{T}} \rangle$ lower in γ+Pb than p+Pb

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ATLAS-CONF-2023-059

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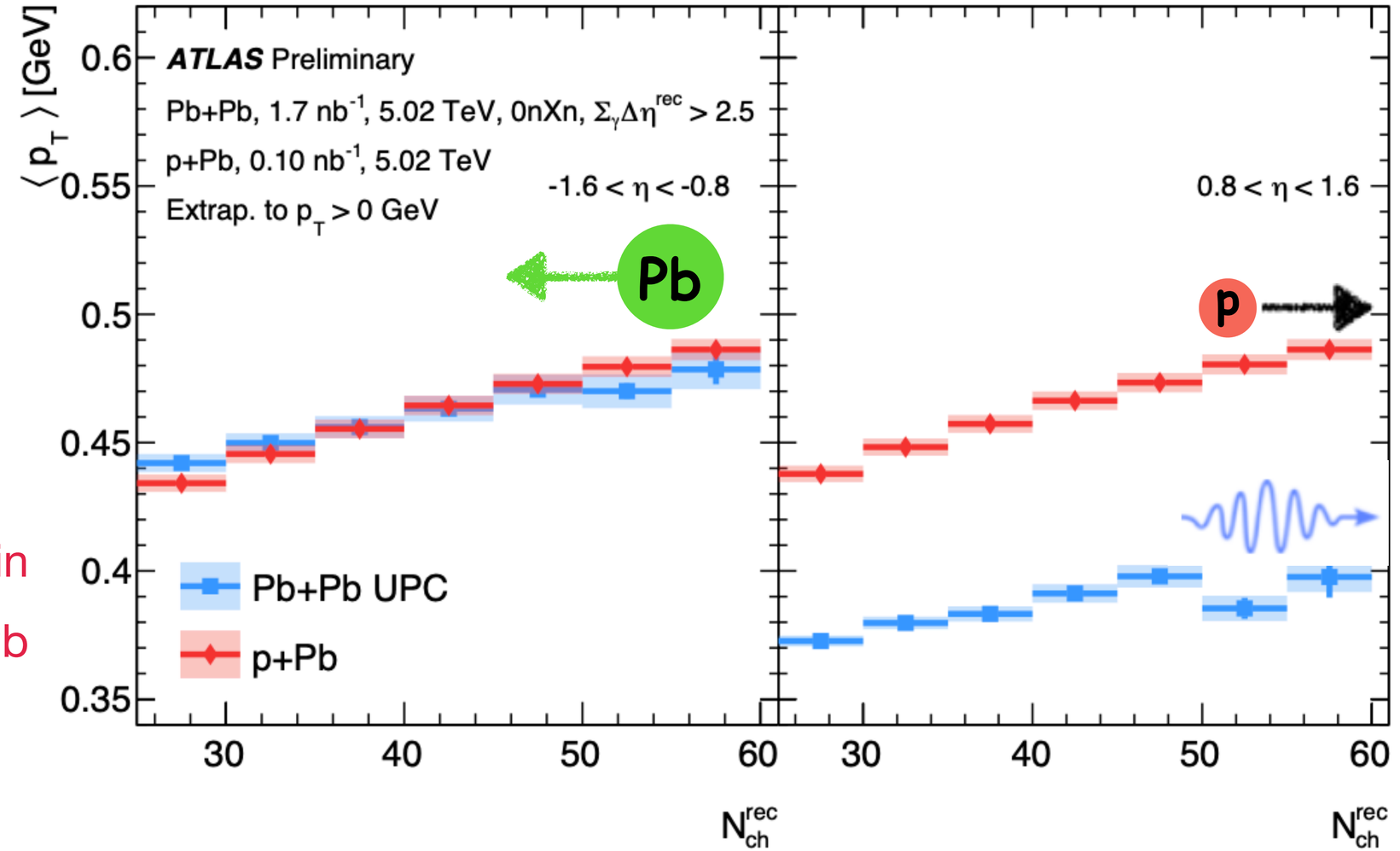
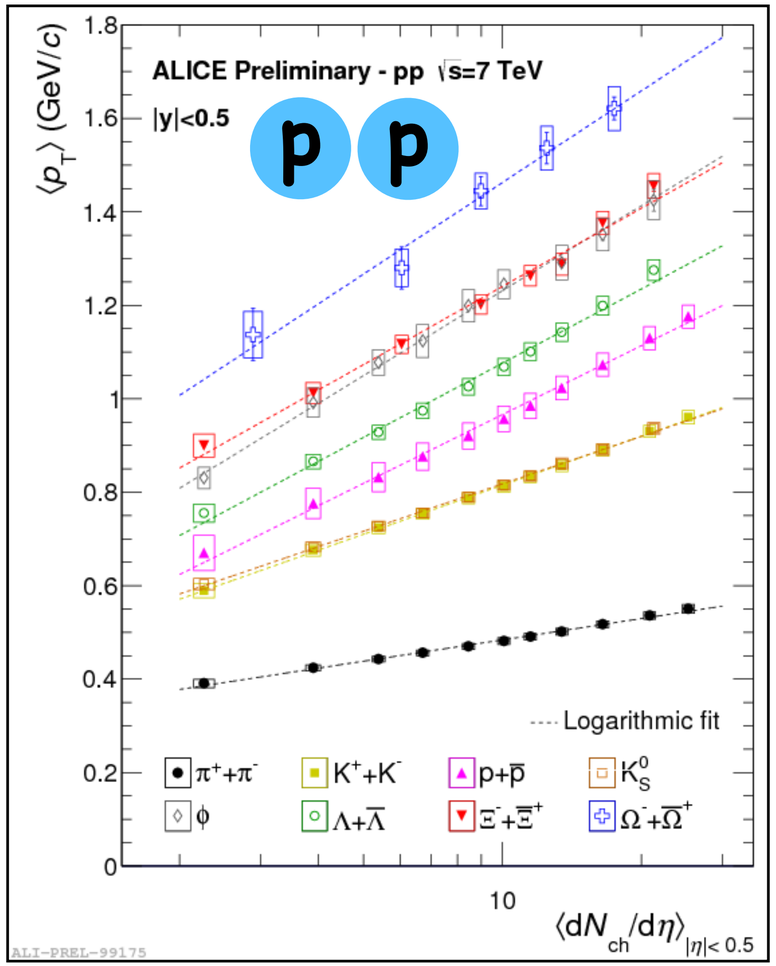


$\langle p_{\mathrm{T}} \rangle$ lower in γ+Pb than p+Pb

Theory (3+1D hydrodynamics) predicts both γ+Pb and p+Pb should have same radial flow, therefore same $\langle p_{\mathrm{T}} \rangle$ (in backward rapidity). Phys. Rev. Lett. 129 (2022) 252302 Wenbin Zhao, Chun Shen, and Björn Schenke

K_S^0, Λ and Ξ^- are more sensitive to radial flow (ongoing work)

Other QGP signatures

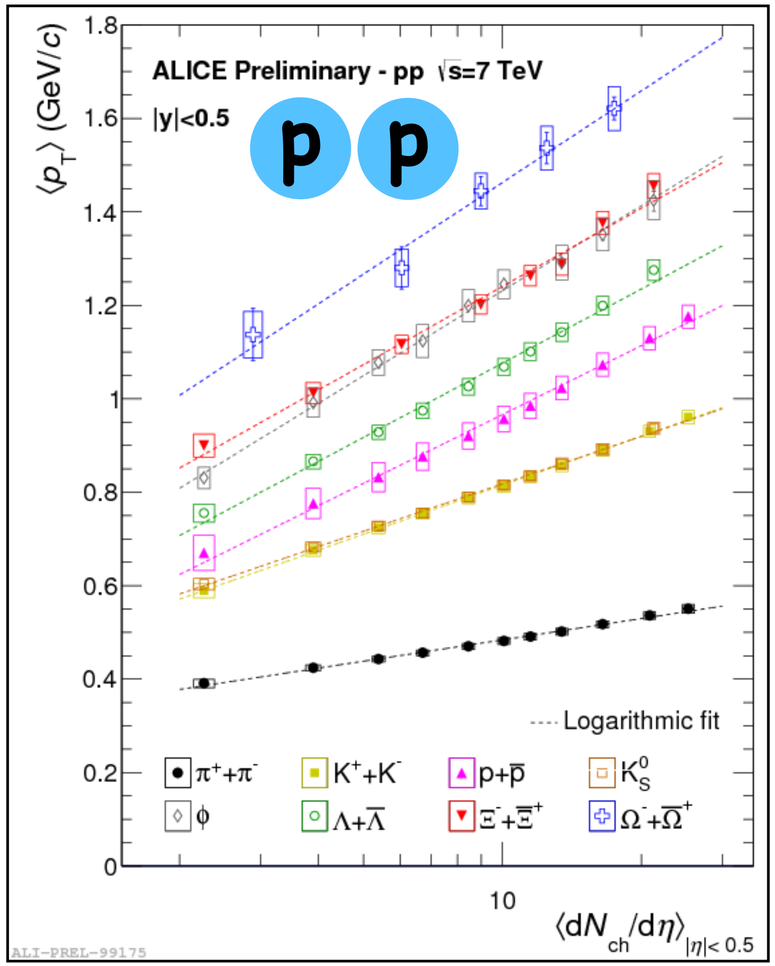


$\langle p_{\mathrm{T}} \rangle$ is sensitive to radial flow -

is a QGP-like signal

Nuclear Physics A 956 (2016) 777-780

Other QGP signatures



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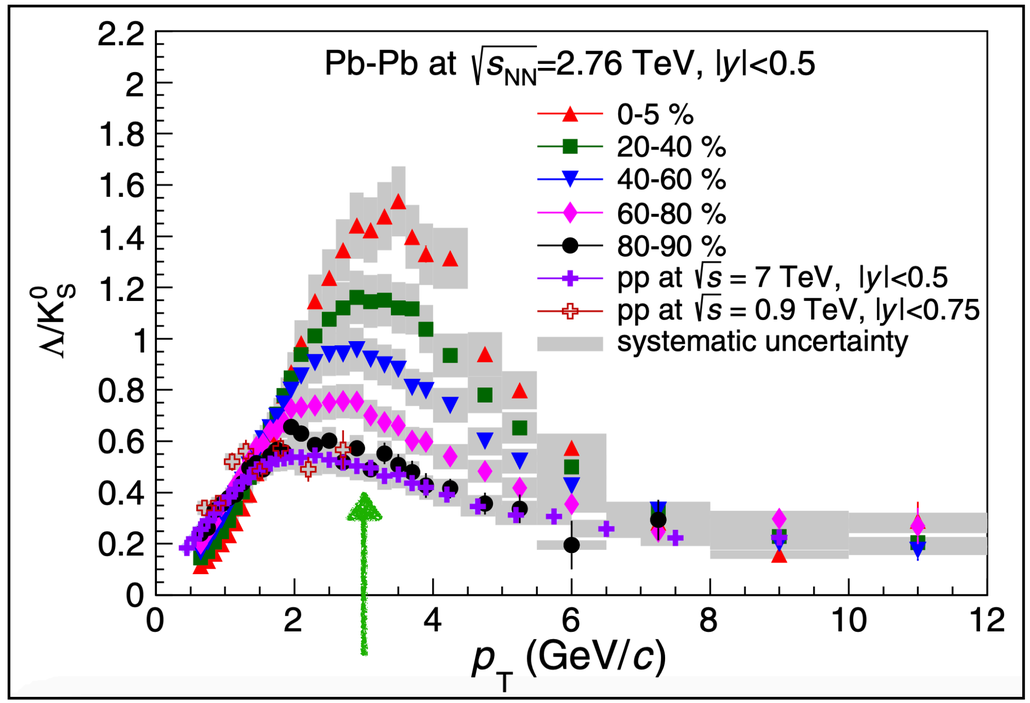
p p Pb Pb

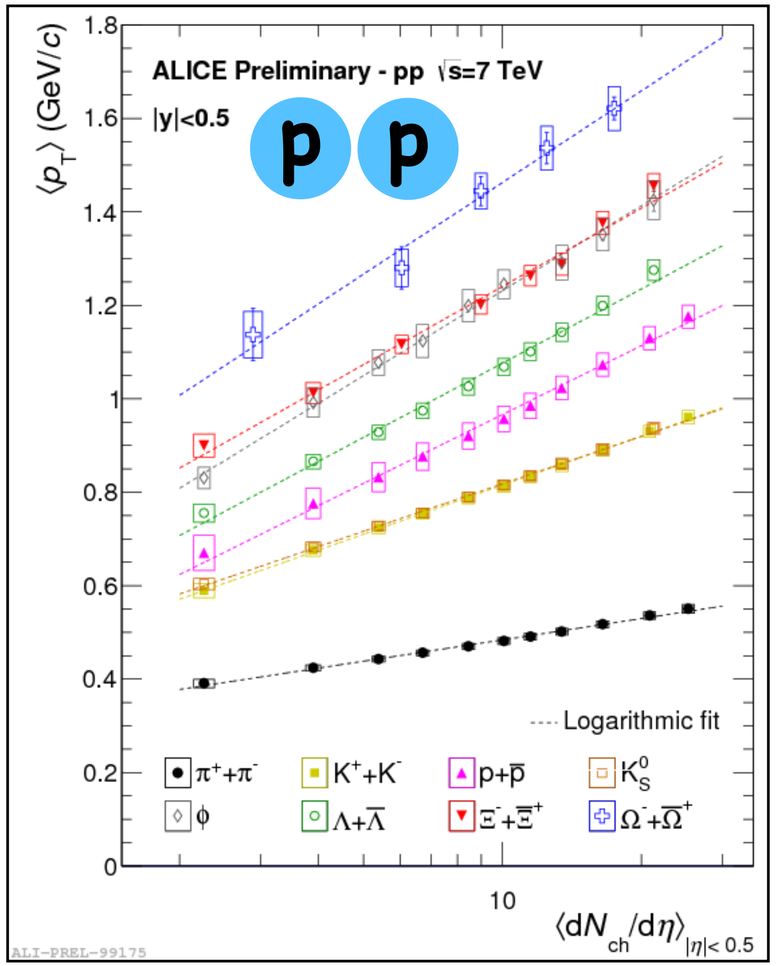


Baryon Anomaly

Enhanced baryon-to-meson ratio observed at intermediate p_T, is a QGP-like signal.

Phys. Rev. Lett. 111 (2013) 222301

Other QGP signatures



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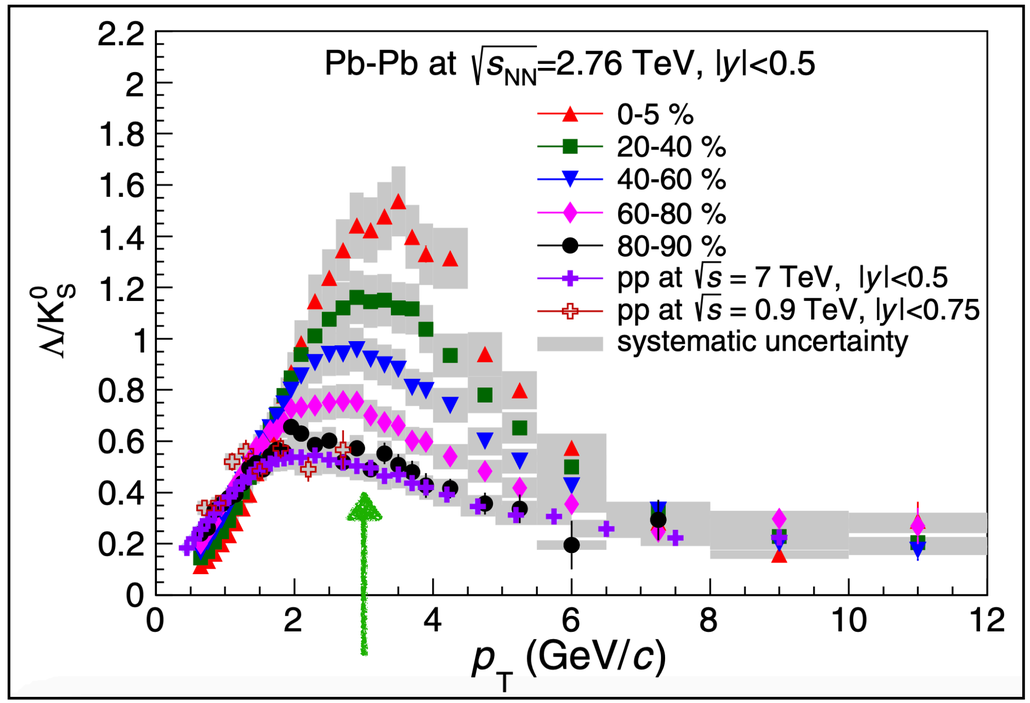

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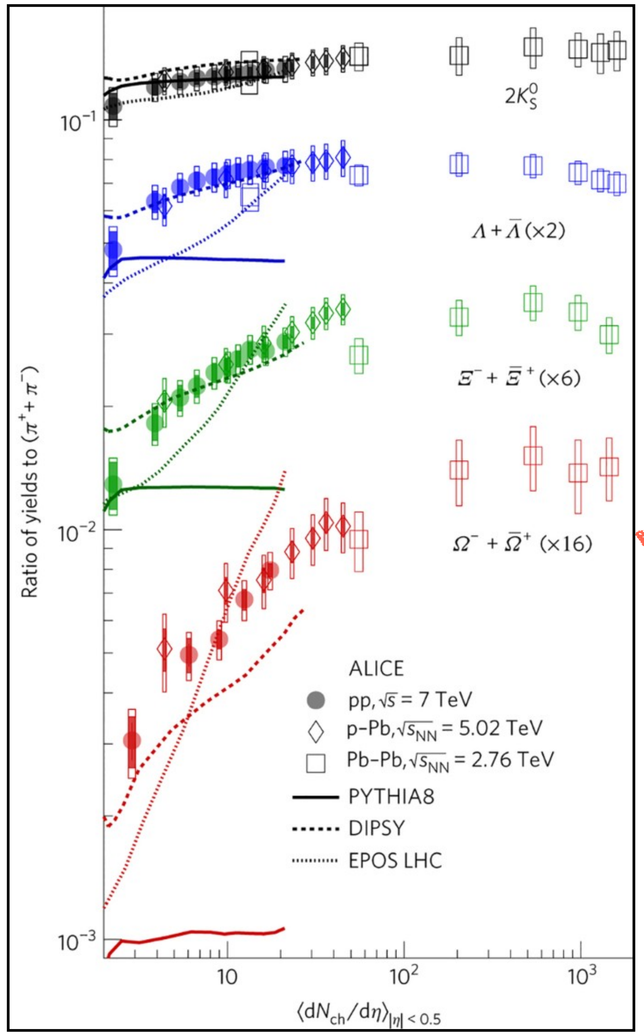


Strangeness enhancement is a signature of QGP.

Nature Physics 13 (2017) 535-539

Other QGP signatures

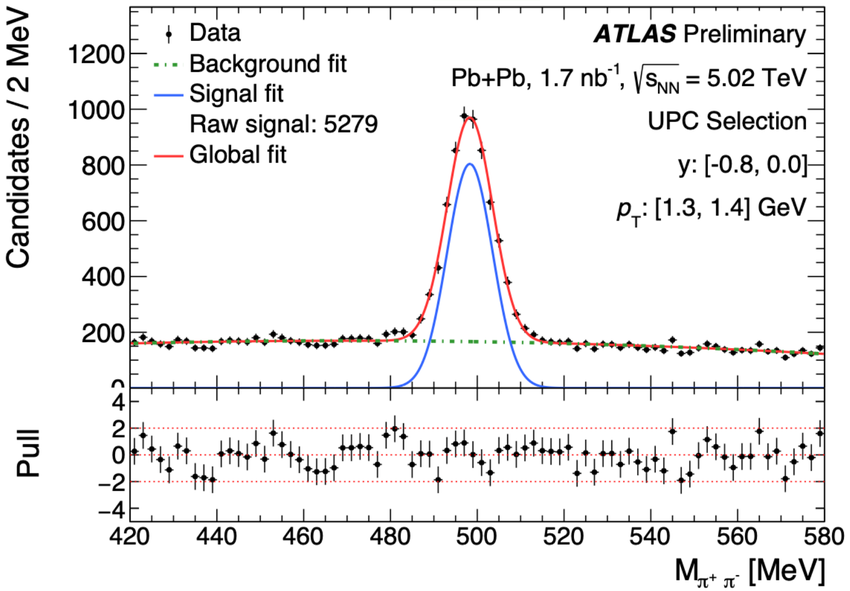
ATLAS-CONF-2023-059

The yield measurements are being extended to particles such as

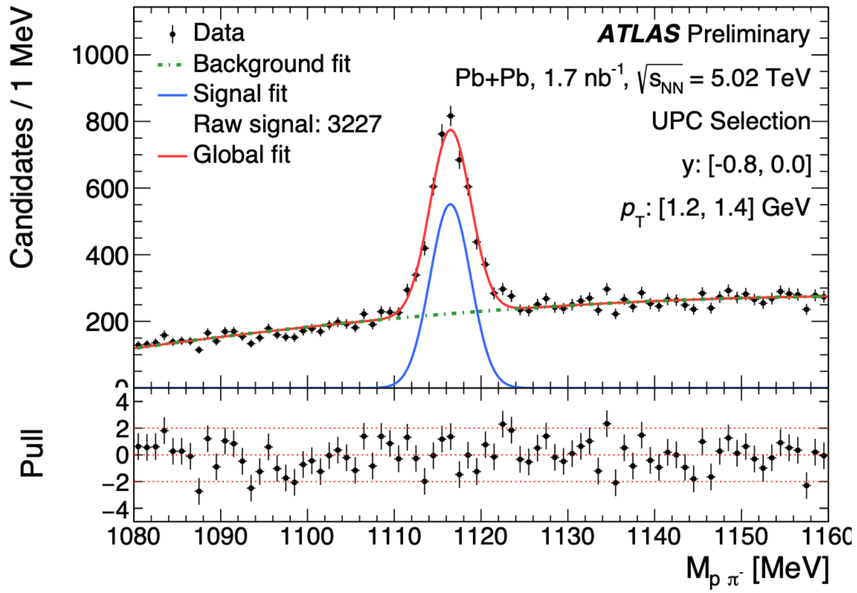
K^0_S, Λ and Ξ^- — in search of more QGP-like signals —

strangeness enhancement, baryon anomaly, radial flow etc.

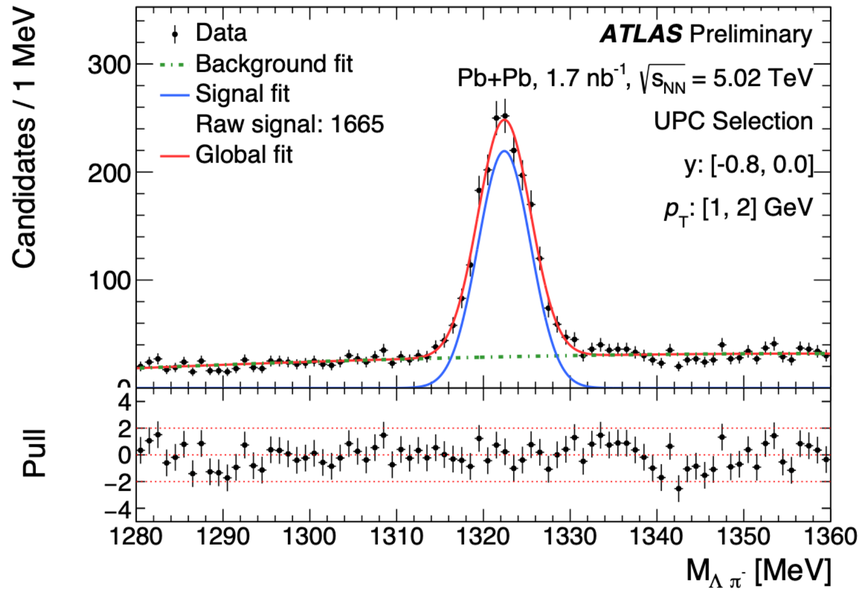
K^0_S



Λ

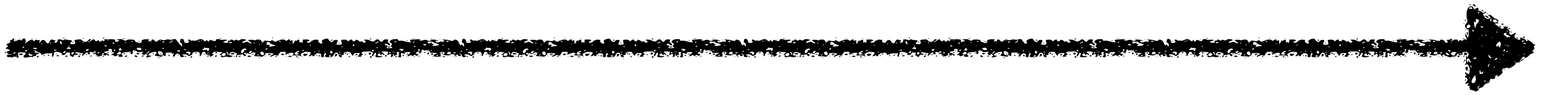


Ξ^-



QGP signatures across all system-size

✅ : QGP-like signal present



smaller system-size

QGP-like signals	Pb Pb	p Pb	p p	γ Pb	γ p
1. Collective flow v_2	✅	✅	✅	✅	❌
2. Radial flow $\langle p_{\mathrm{T}} \rangle$	✅	✅	✅	Charged hadrons ✅ Identified particles ❓	
3. Strangeness enhancement	✅	✅	✅	❓	
4. Baryon anomaly	✅	✅	✅	❓	

QGP signatures across all system-size

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QGP-like signals	Pb Pb	p Pb	p p	γ Pb	γ p
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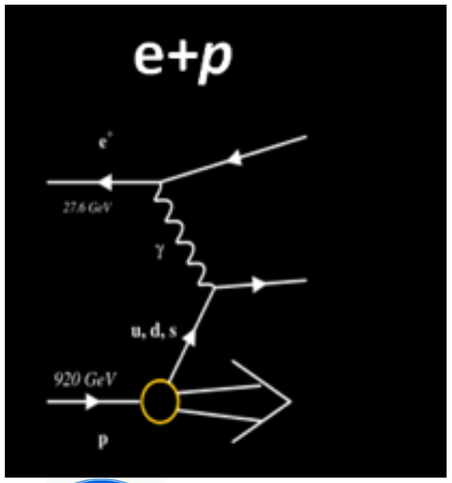
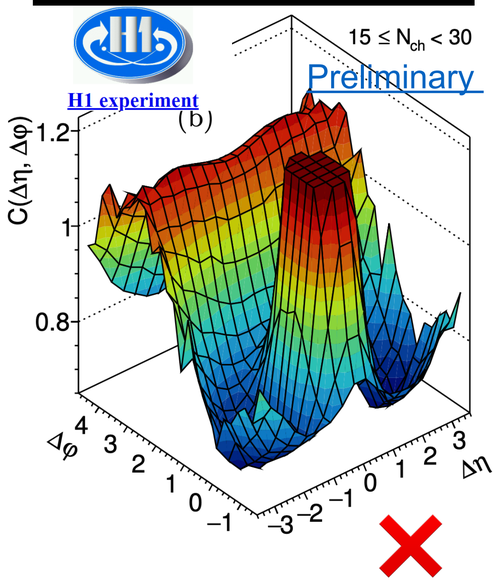
2. Radial flow $\langle p_{\mathrm{T}} \rangle$	✅	✅	✅	Charged hadrons ✅ Identified particles STAY TUNED	
3. Strangeness enhancement	✅	✅	✅	STAY TUNED	
4. Baryon anomaly	✅	✅	✅	STAY TUNED	

What are the minimal conditions for collectivity?

Many new searches in other small systems





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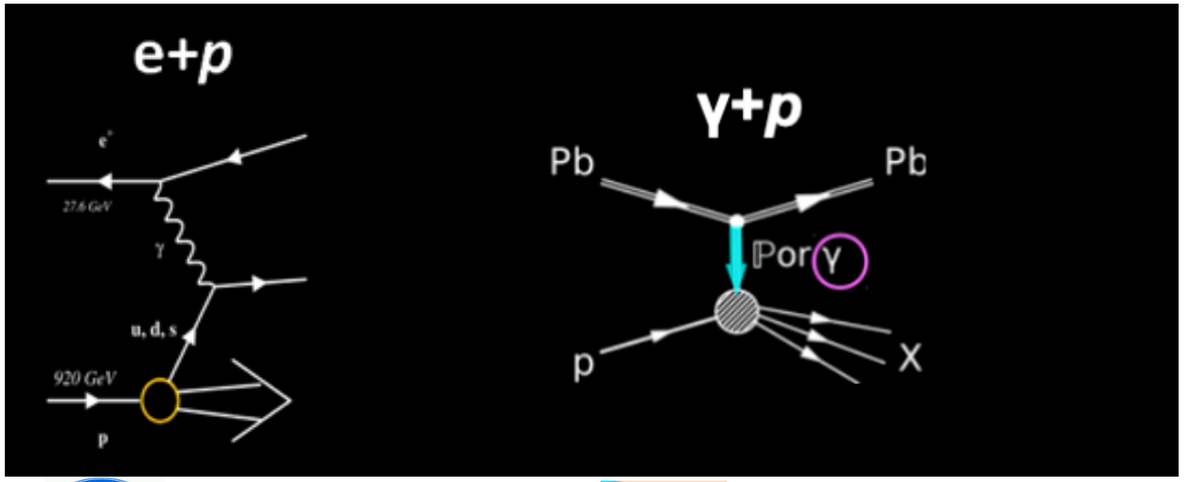
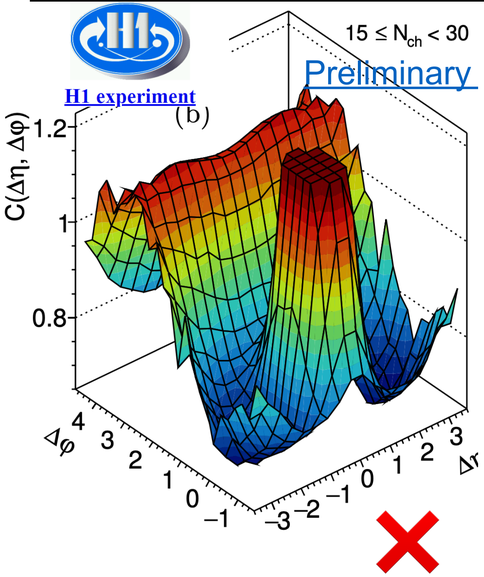
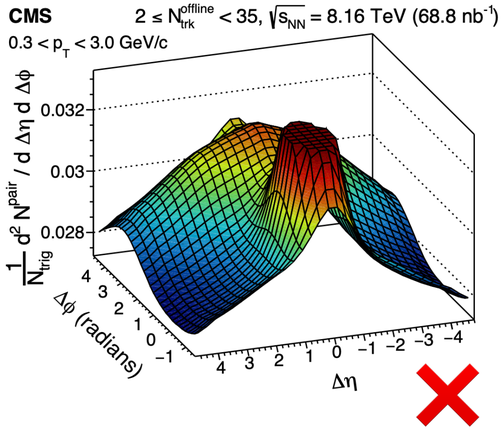


H1 experiment



γ+p collectivity

arXiv:2204.13486



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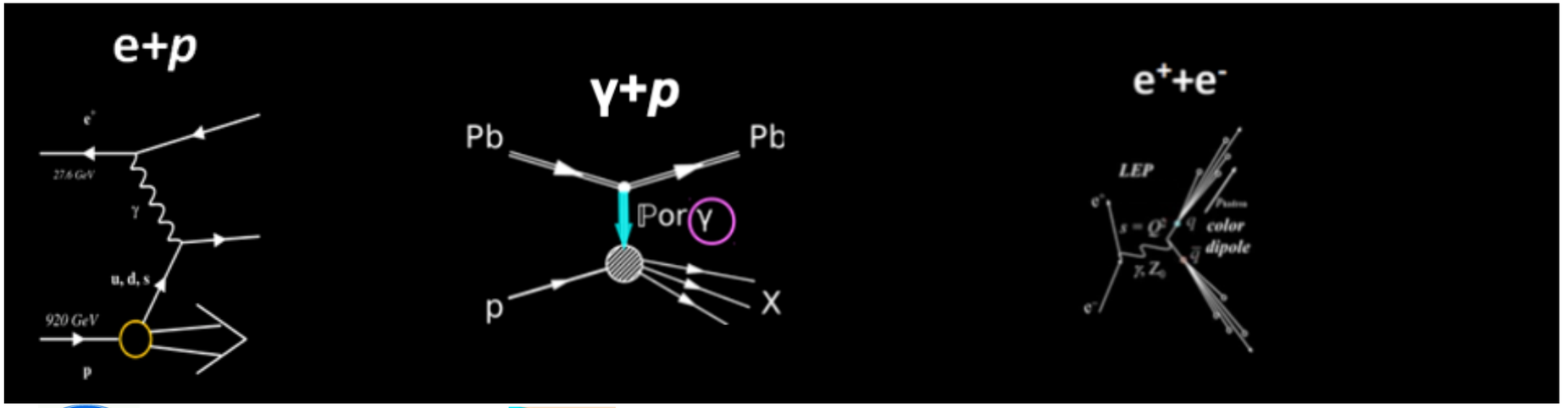
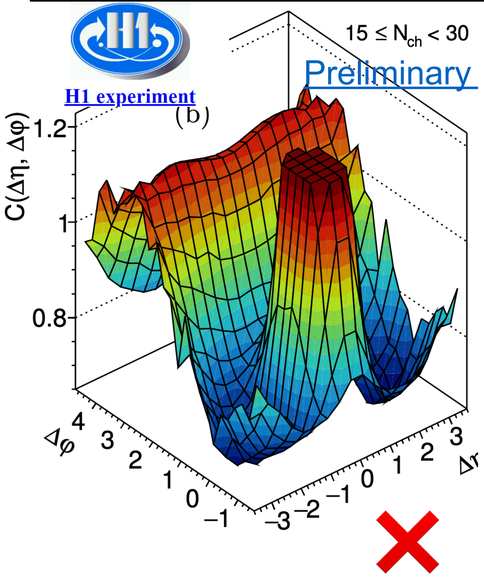


H1 experiment

Preliminary



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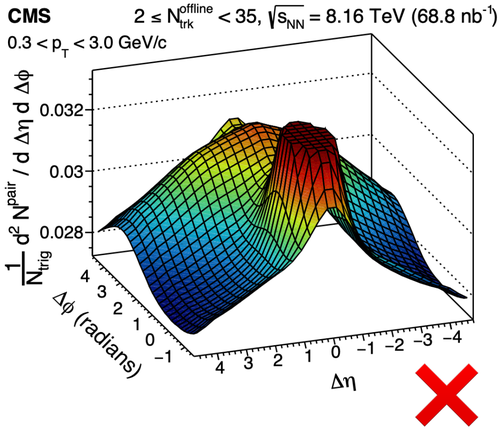
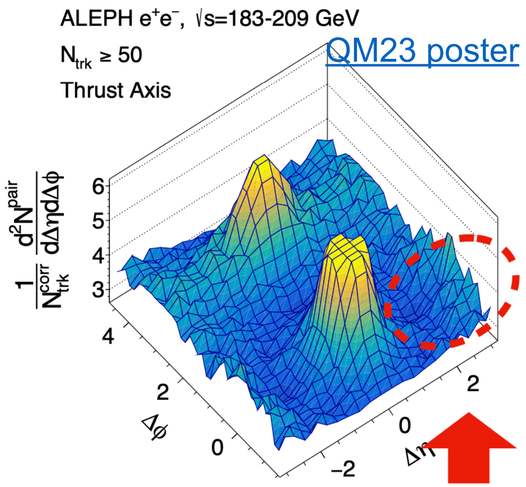


High mult. e^+e^-

QM23 poster



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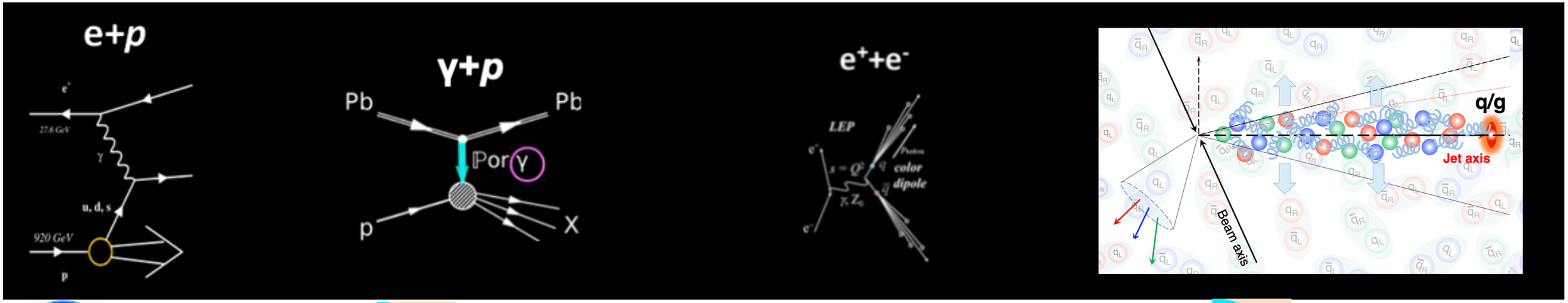

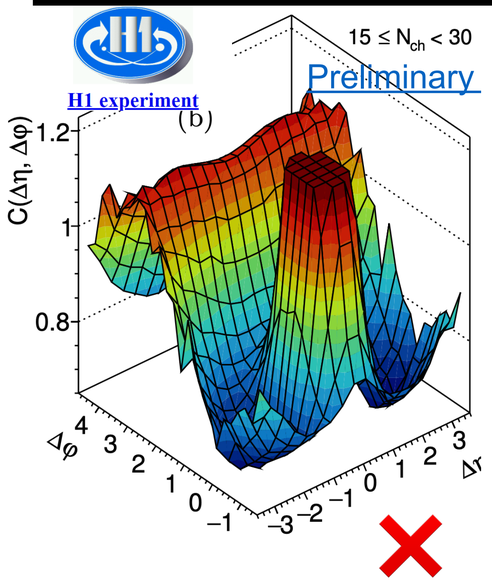

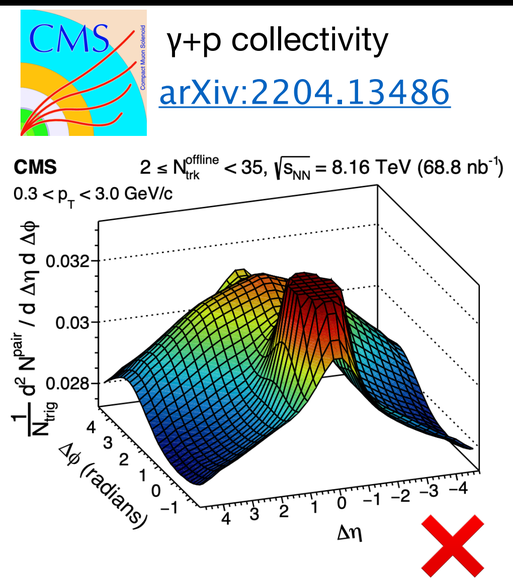

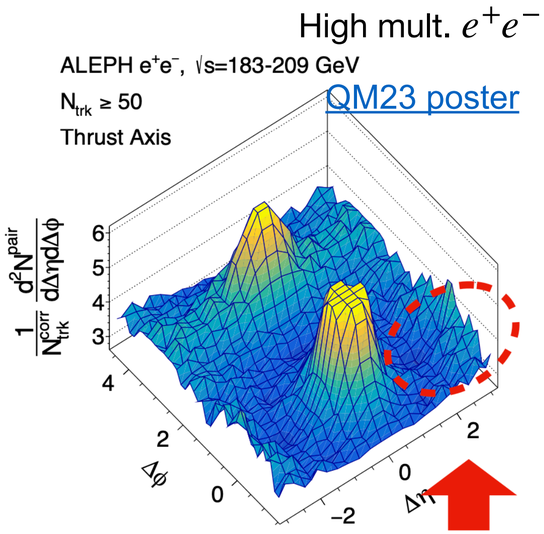

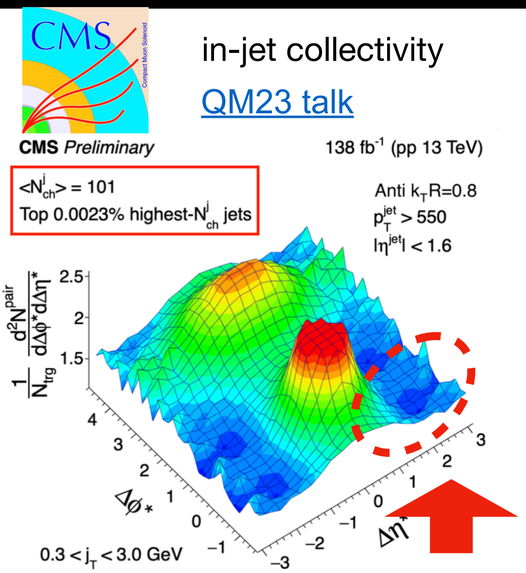

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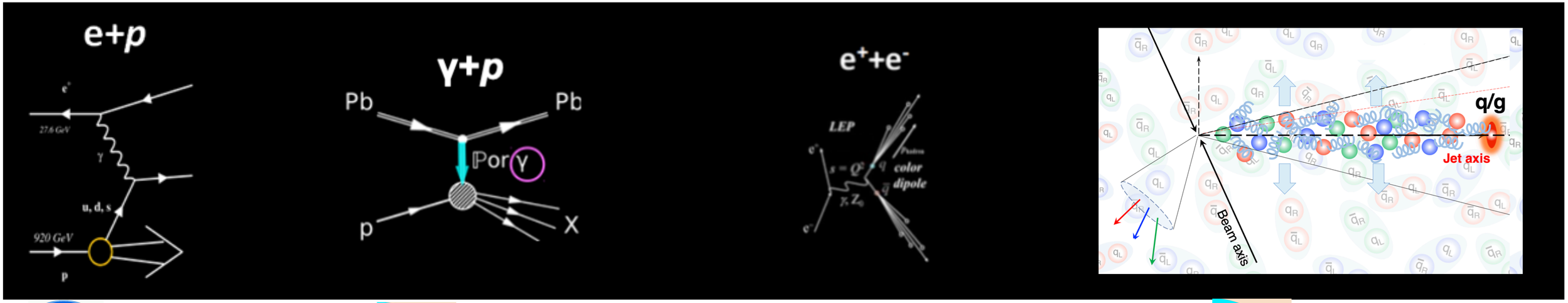


H1 experiment

15 ≤ N_{ch} < 30

Preliminary

γ+p collectivity

arXiv:2204.13486

High mult. e^+e^-

ALEPH e^+e^-, √s=183-209 GeV

N_{trk} ≥ 50

QM23 poster

in-jet collectivity

QM23 talk

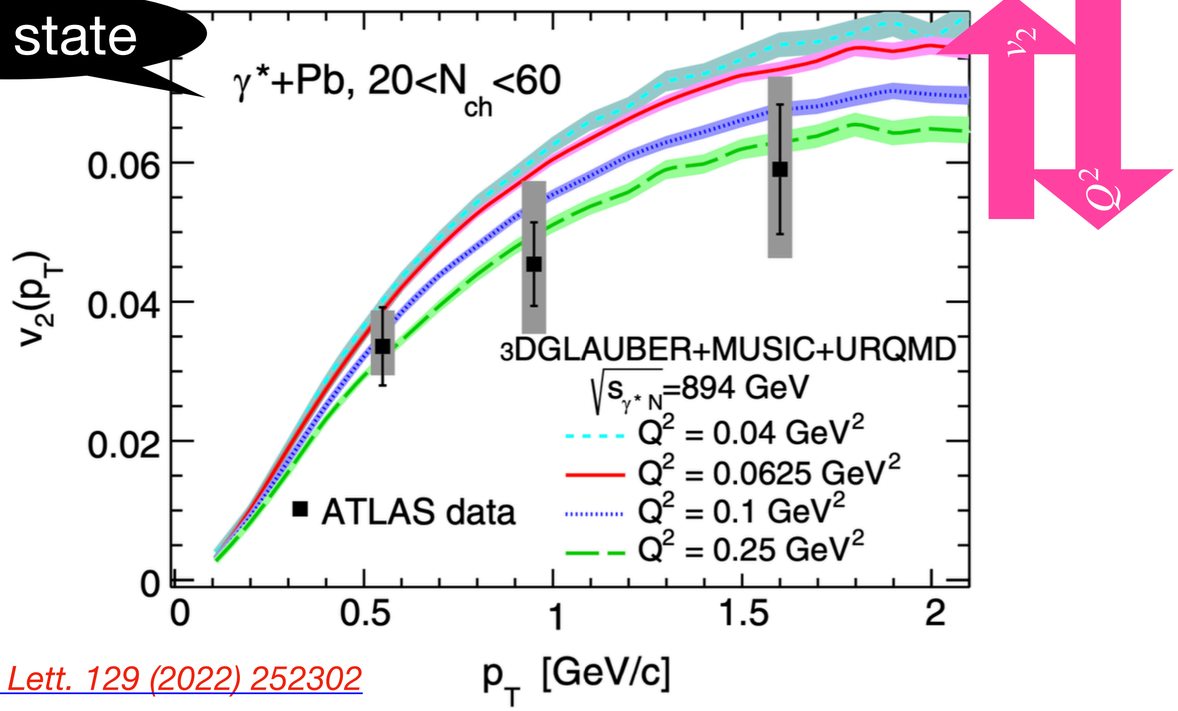
Motivates Run 3/4 γ+p and γ+Pb collectivity measurements!

Connects HERA and future EIC physics

γA close connections to EIC

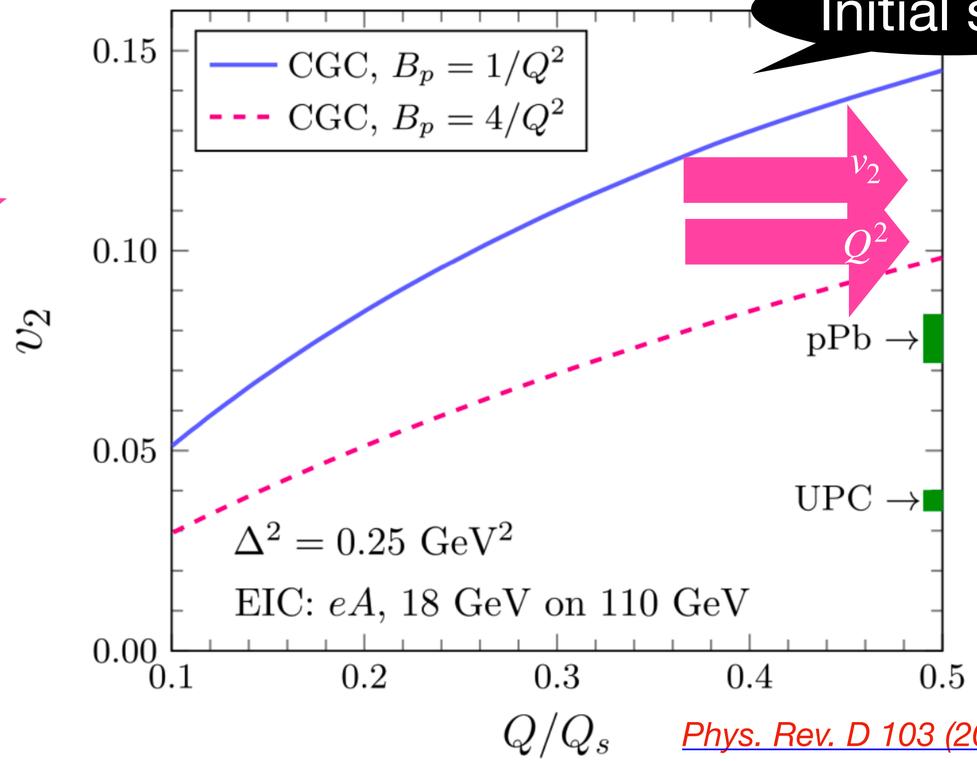
Electron-Ion Collider physics has close connections to UPC physics, allows precise measurement of the energy and virtuality of the colliding photon.

Final state



Phys. Rev. Lett. 129 (2022) 252302

Initial state

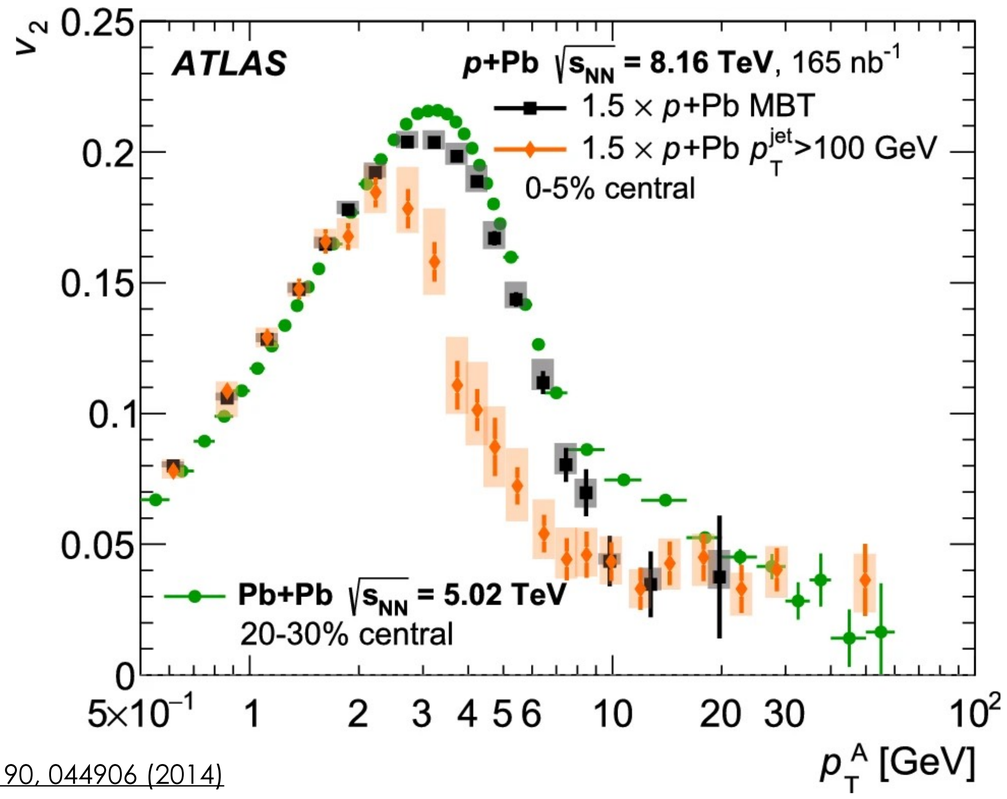


Phys. Rev. D 103 (2021) 054017

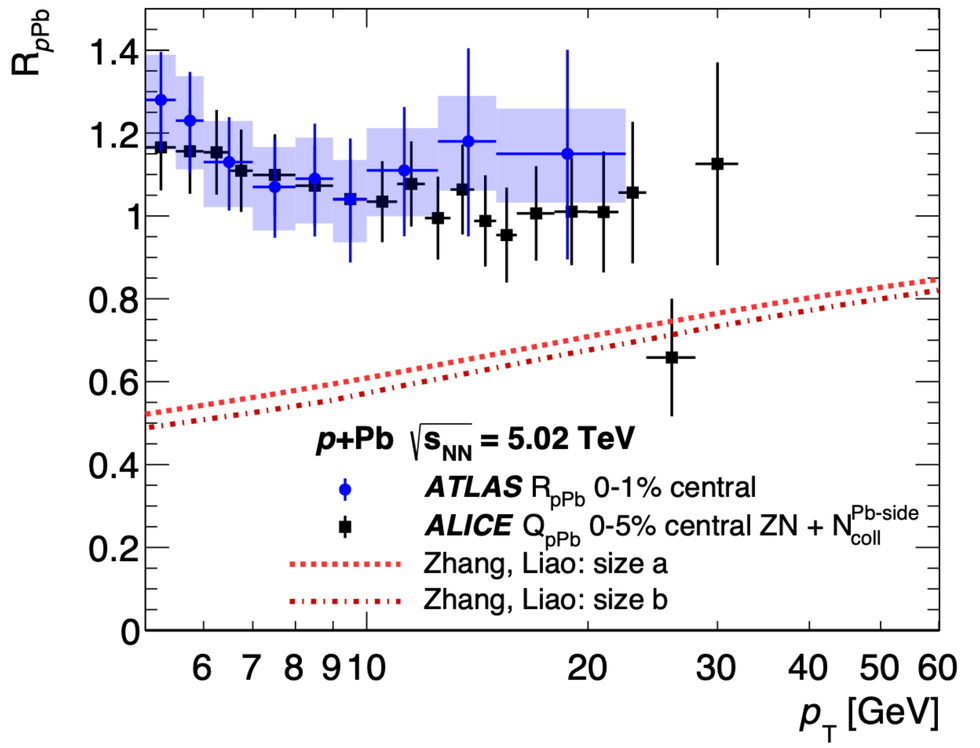
Predictions by hydrodynamic model and CGC, in **opposite directions**

EIC can be a "tie-breaker" between the initial-state and final-state models!

High p_{T} puzzle: flow but no energy loss !?



PHYSICAL REVIEW C 90, 044906 (2014)



At low p_{T}, v_2 is interpreted as flow. At high p_{T}, v_2 in $p + \mathrm{Pb}$ could result from jet-quenching.

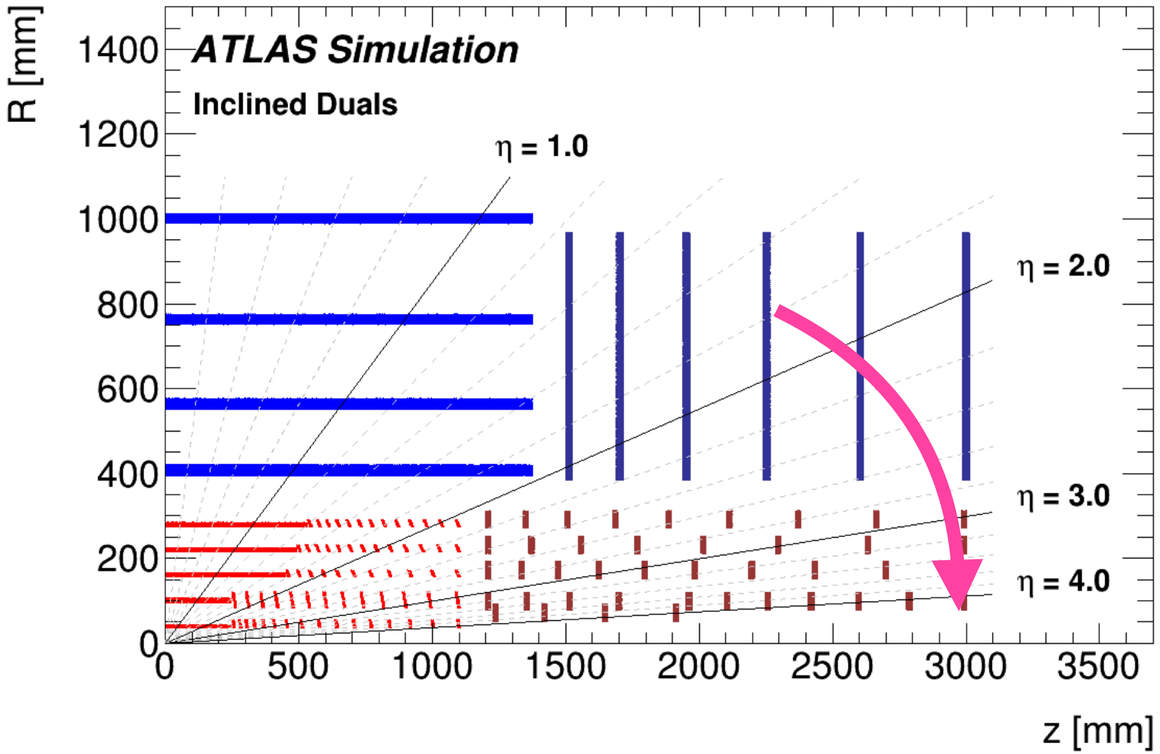
Previous ATLAS measurements shows that jet quenching is not observed in $p\mathrm{Pb}$.

Run-3 $p + \mathrm{O}$ collisions with a different geometry, but similar size could help understand this better!

arXiv:1802.06804

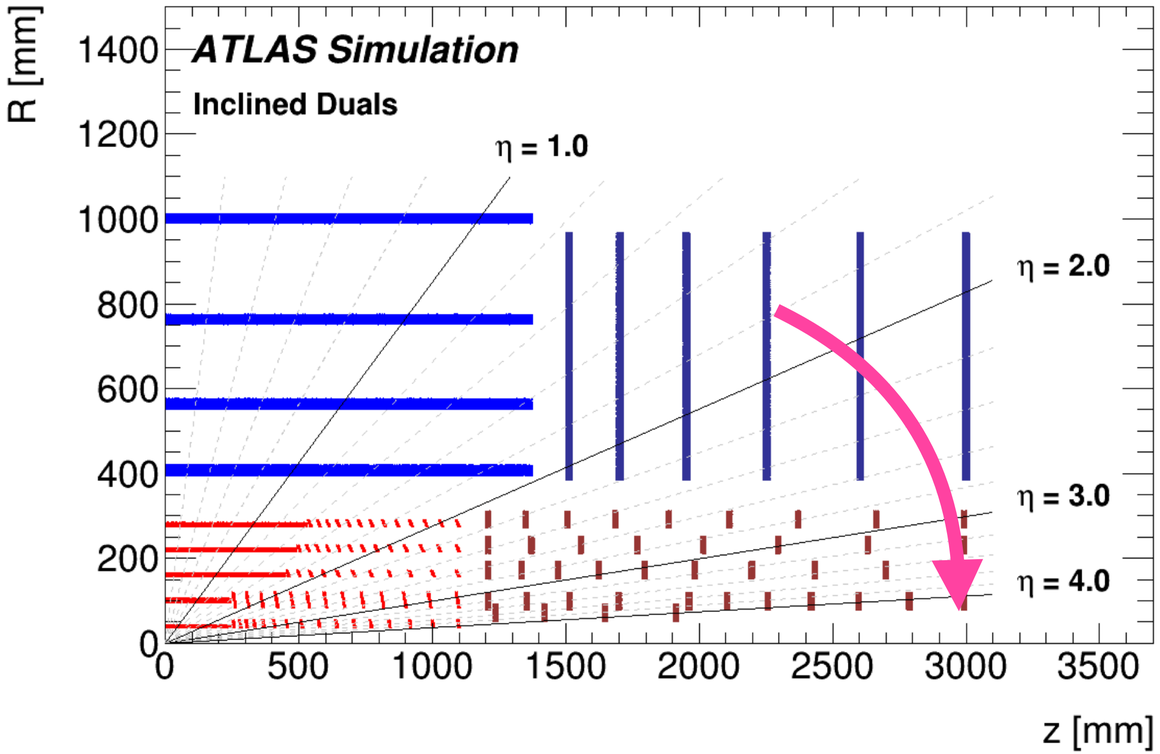
Run-4 extended rapidity: big win for flow!

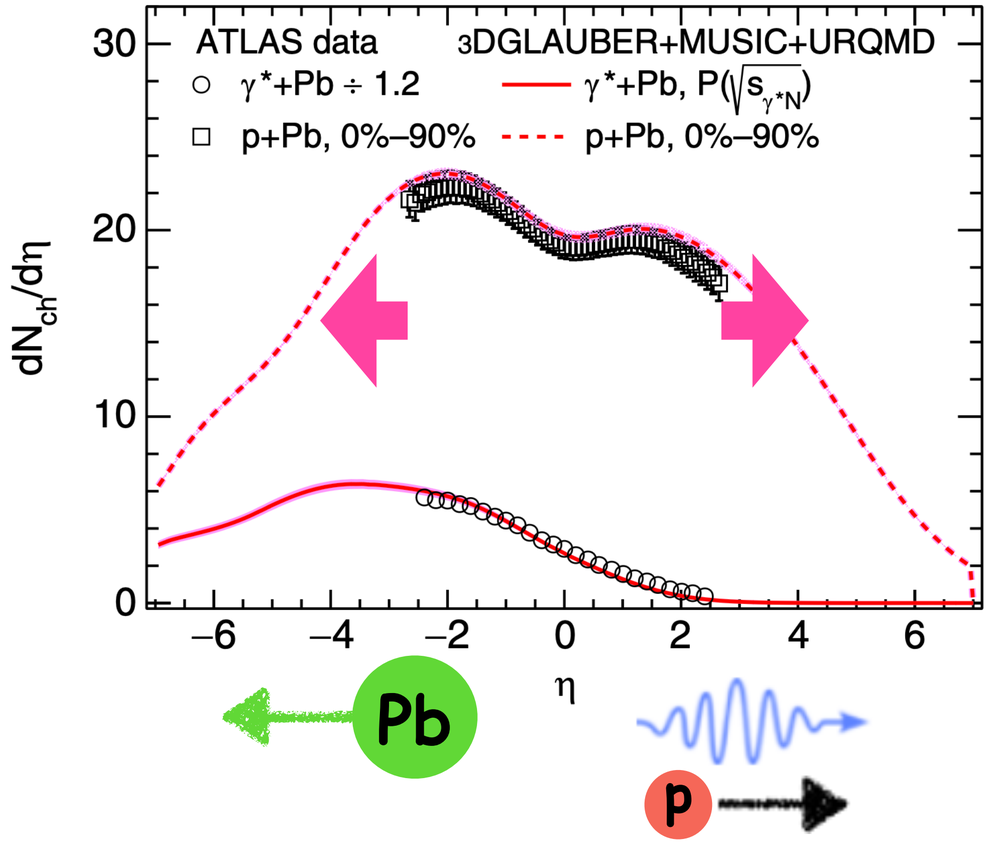
ATLAS Run-4, major tracking upgrades: $|\eta| < 4.0$



Run-4 extended rapidity: big win for flow!

ATLAS Run-4, major tracking upgrades: $|\eta| < 4.0$

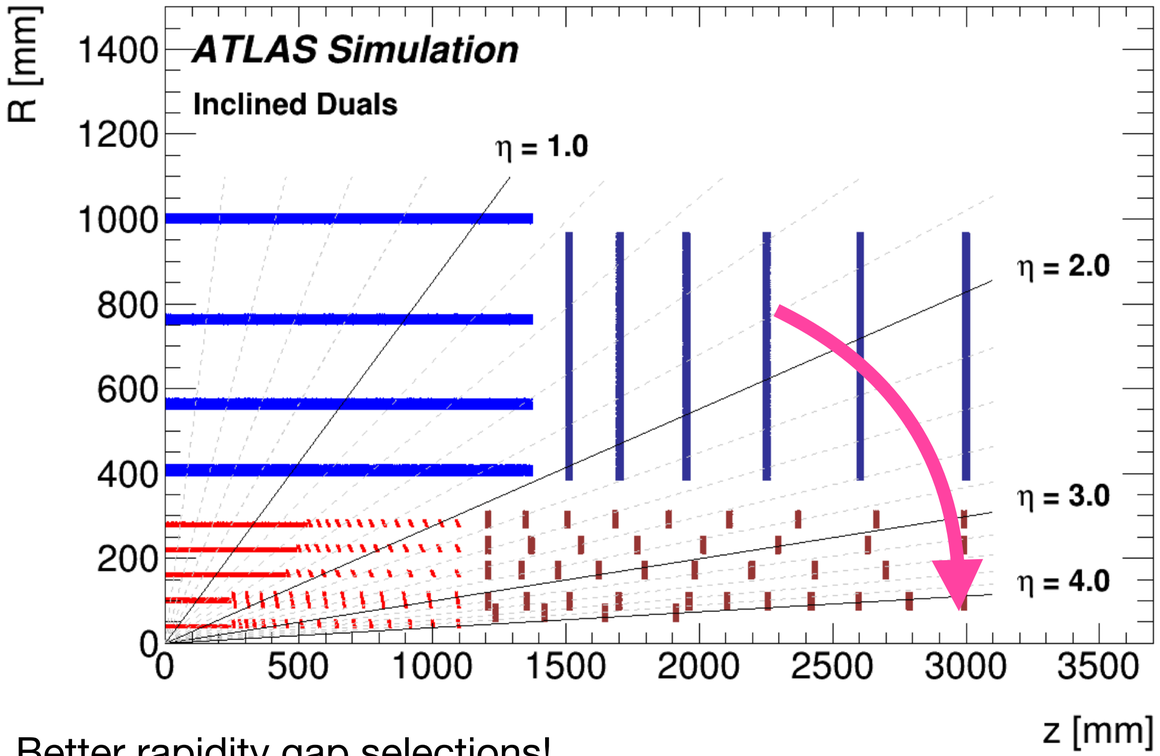


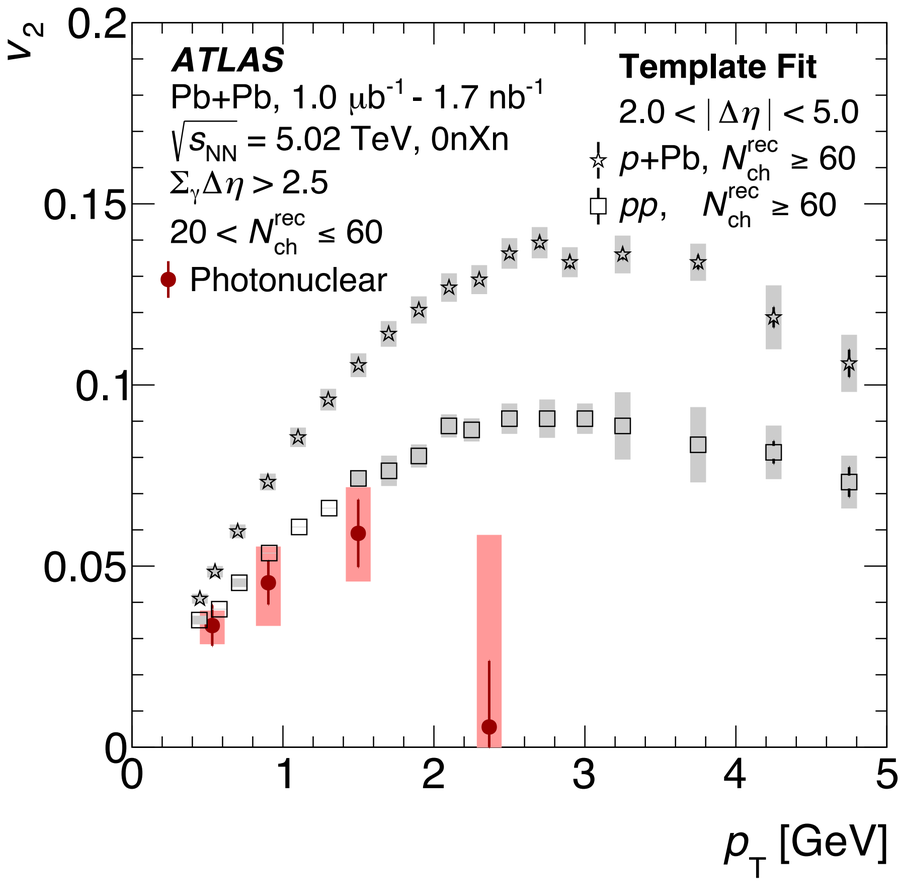


Exciting opportunities for UPC yield measurements to forward rapidity and with better gap selections!

Run-4 extended rapidity: big win for flow!

ATLAS Run-4, major tracking upgrades: $|\eta| < 4.0$



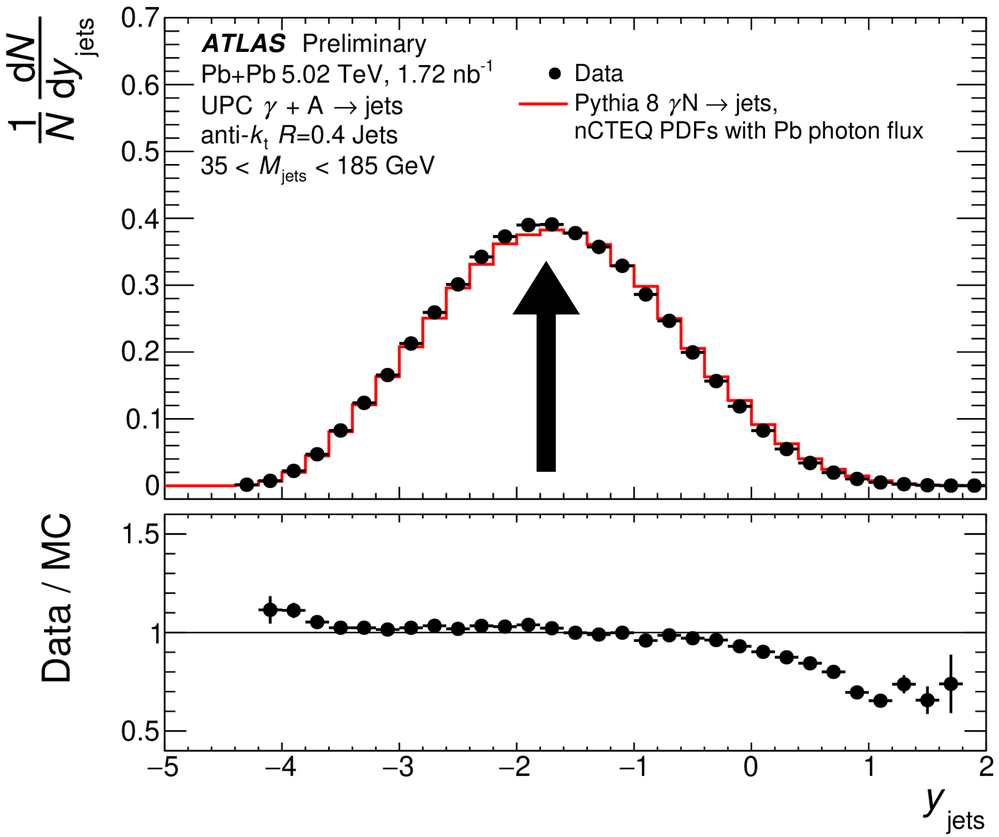


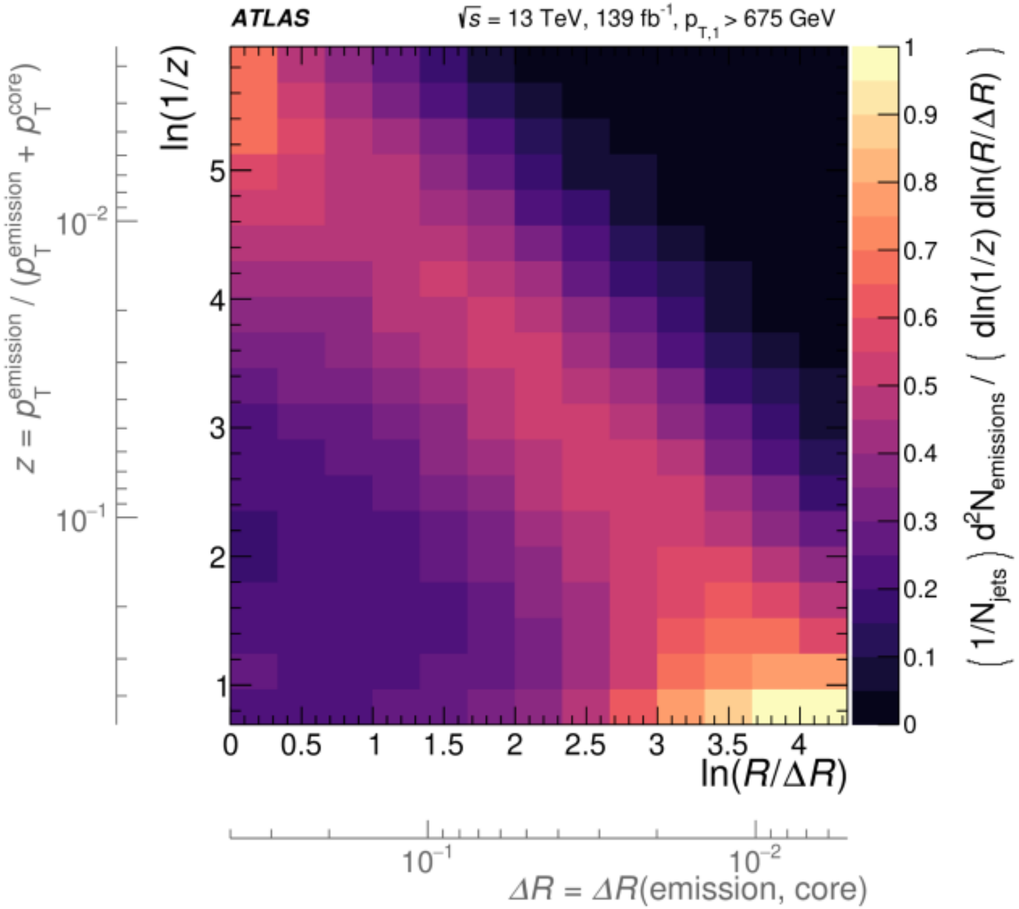
- Better rapidity gap selections!
- Extended tracker acceptance allows additional statistics!
- Better separations between the particles entering correlations!
- Test applicability of hydrodynamics with statistically significant measurement of higher order flow harmonics (v_4)

Exciting opportunities for UPC flow measurements!

Run-4 extended rapidity: jet substructure

ATLAS-CONF-2022-021

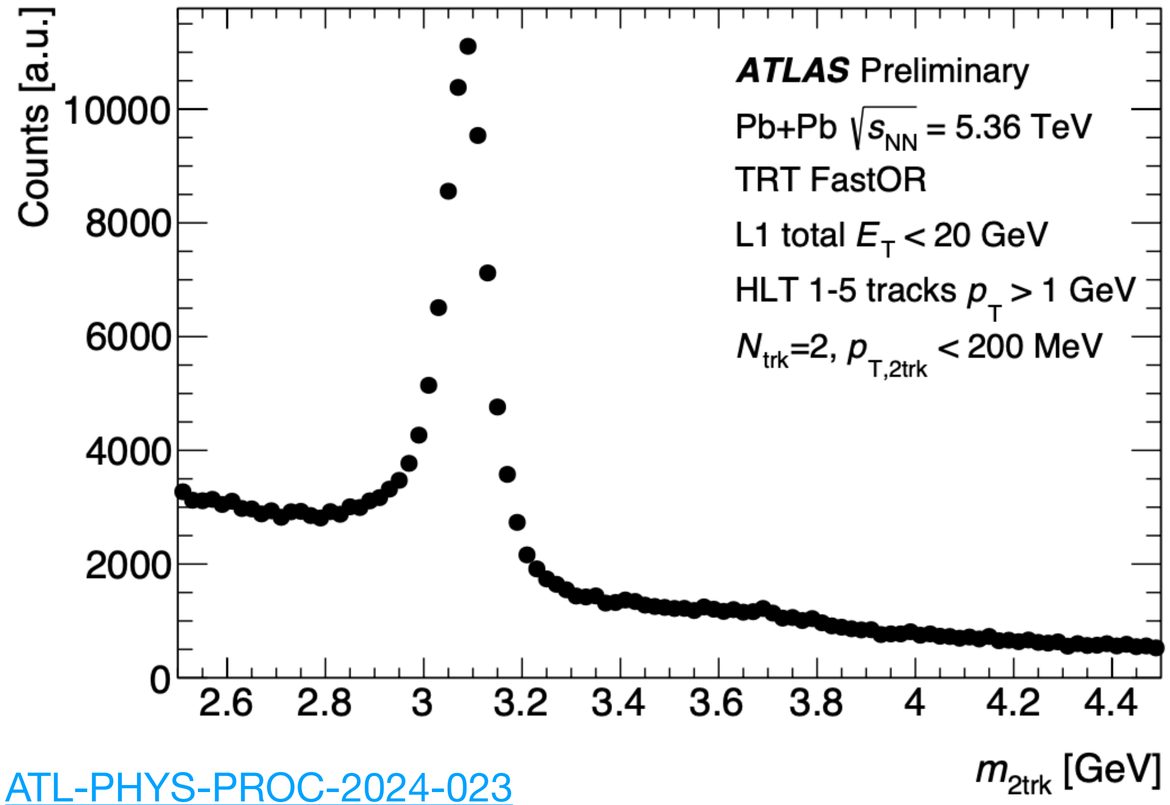




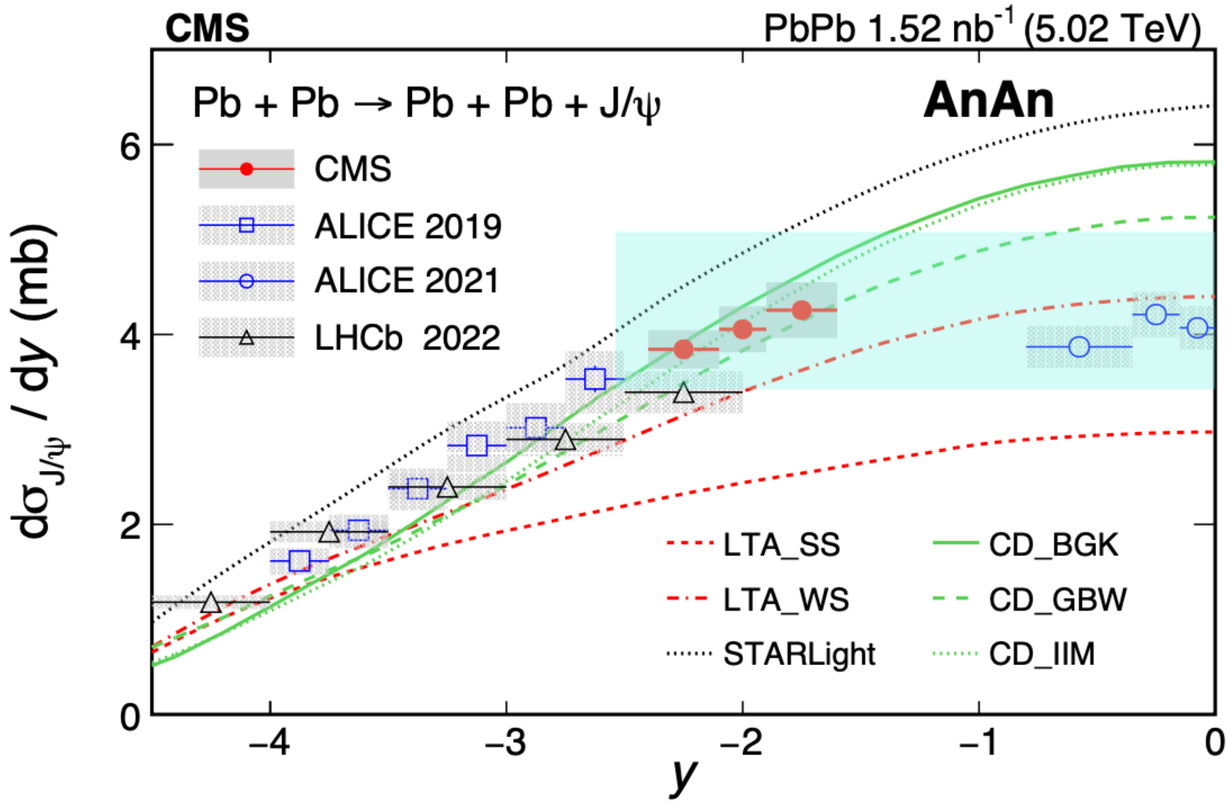
Exciting opportunities for UPC jet measurements with Run-4 extended tracker rapidity coverage!

See talk by R. Longo on July 4th

Improved TRT trigger



ATL-PHYS-PROC-2024-023



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Run-3 Improved TRT trigger lets us accumulate large samples of exclusive J/ψ using full acceptance of our tracker!

Summary

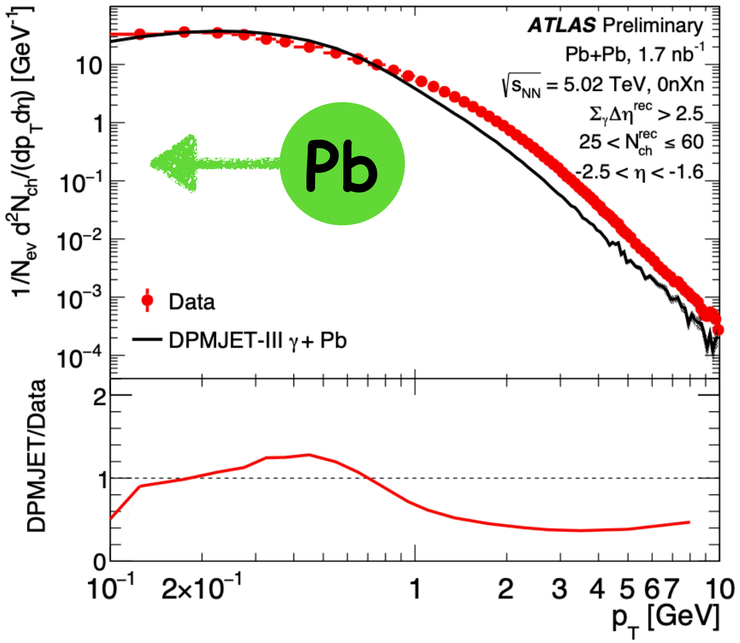
- Lots of interesting results in the comparison of γ+Pb and p+Pb in Run 2! More to come!
- Run 3/4 γ+p and γ+Pb collectivity measurements connect HERA and future EIC physics!
- Opportunities for flow measurements with p+O in Run 3!
- Exciting opportunities with extended tracker rapidity coverage up to $|\eta| < 4.0$ in Run 4!

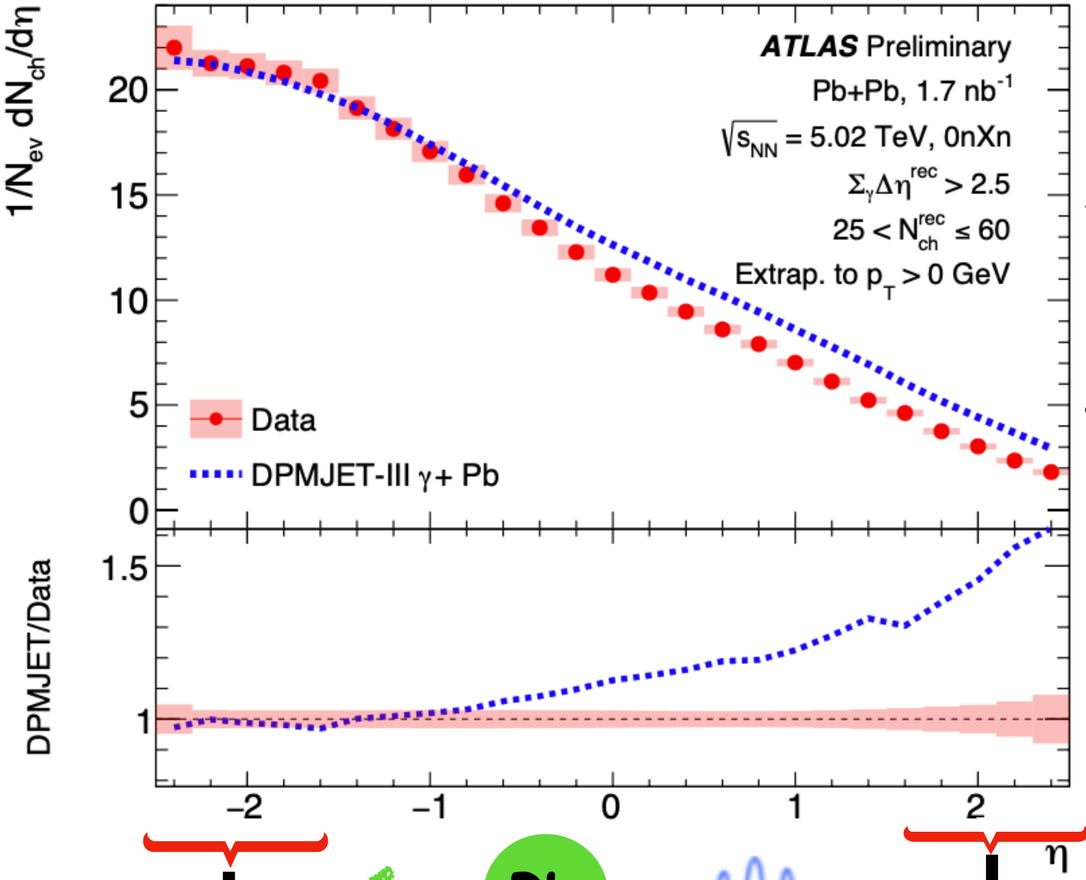
Thank you for your attention!

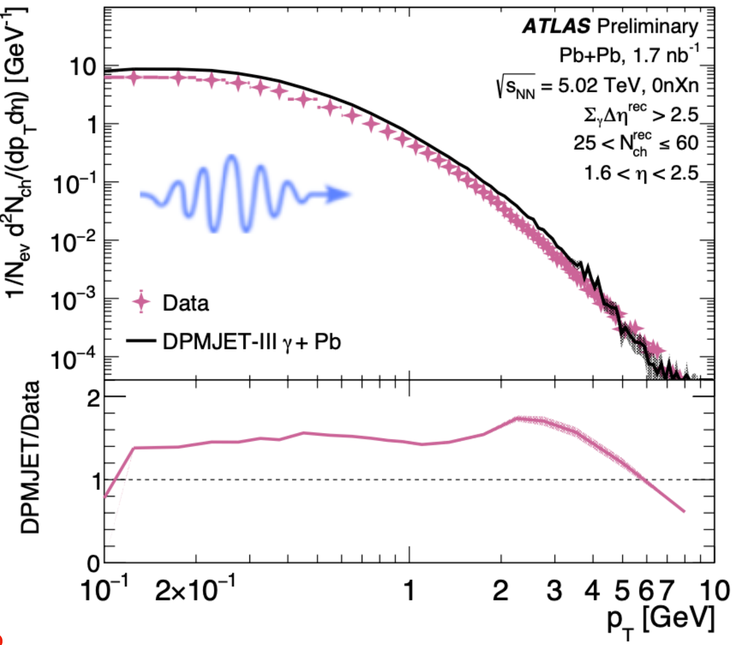
Back up

DPMJET-III comparison

ATLAS-CONF-2023-059







Pb

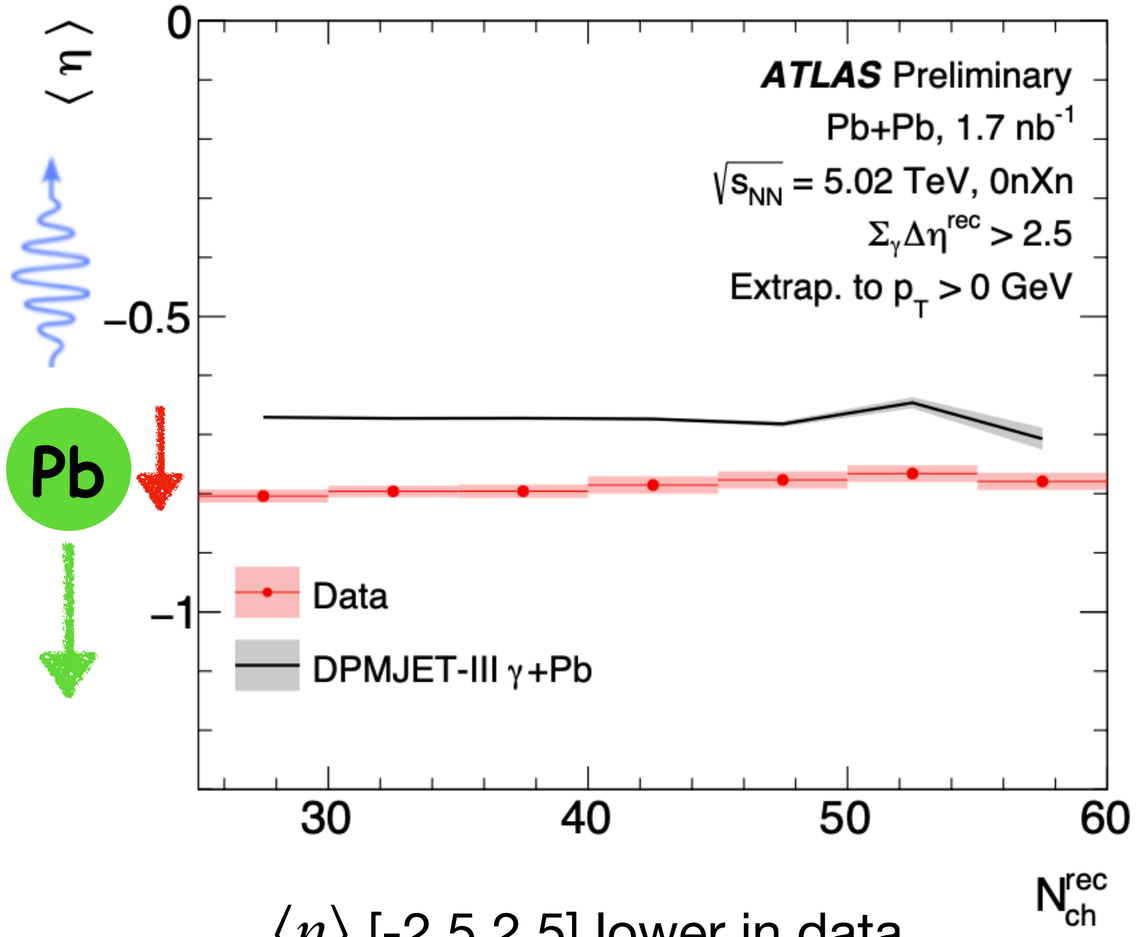
Pb

DPMJET agrees at backward rapidity

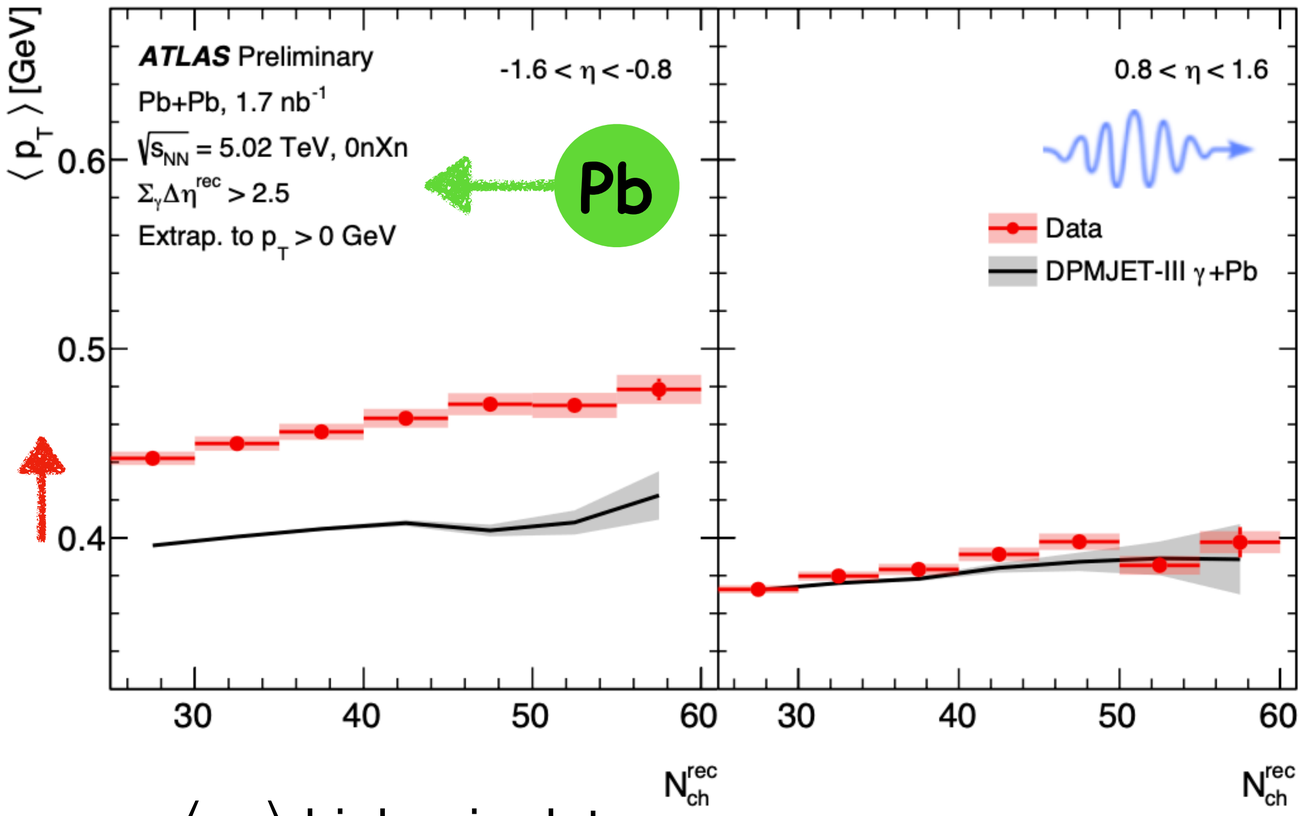
DPMJET over-predicts at forward rapidity

DPMJET-III comparison

ATLAS-CONF-2023-059



$\langle \eta \rangle$ [-2.5,2.5] lower in data

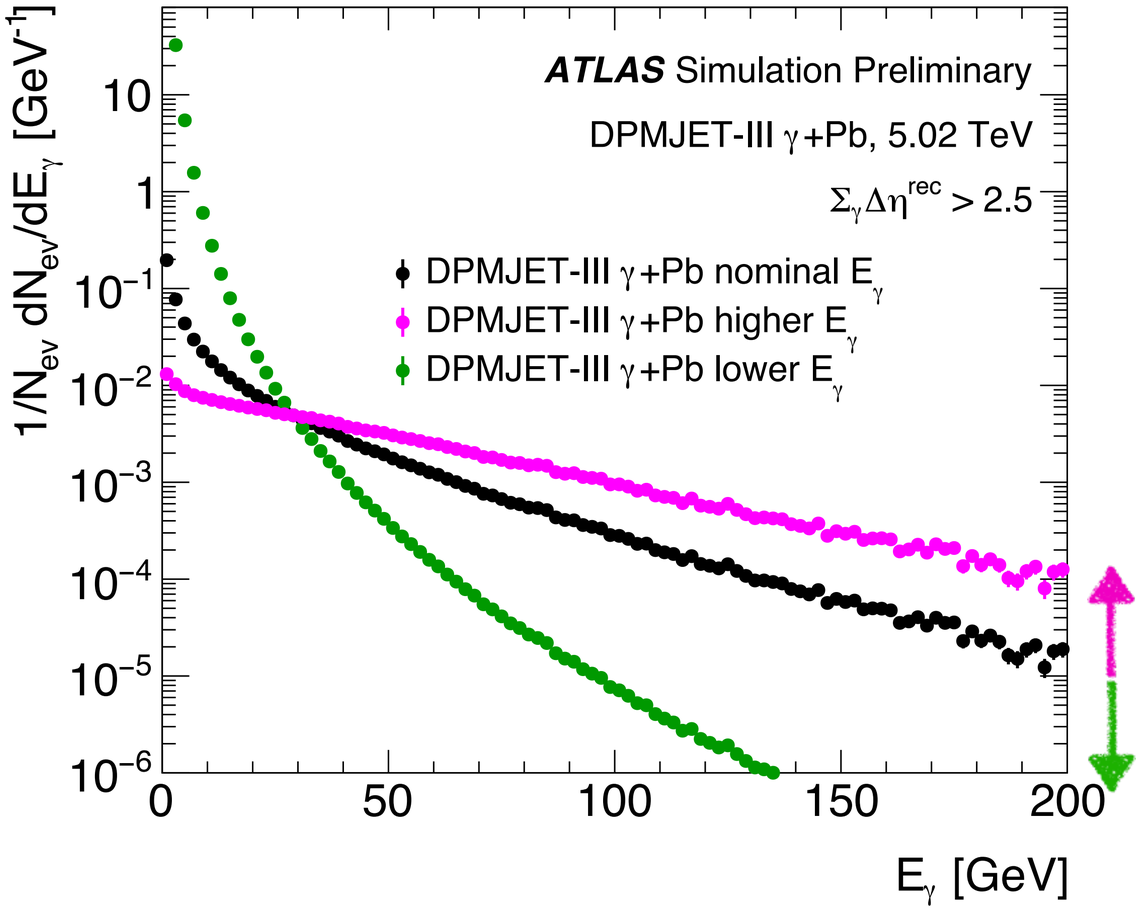


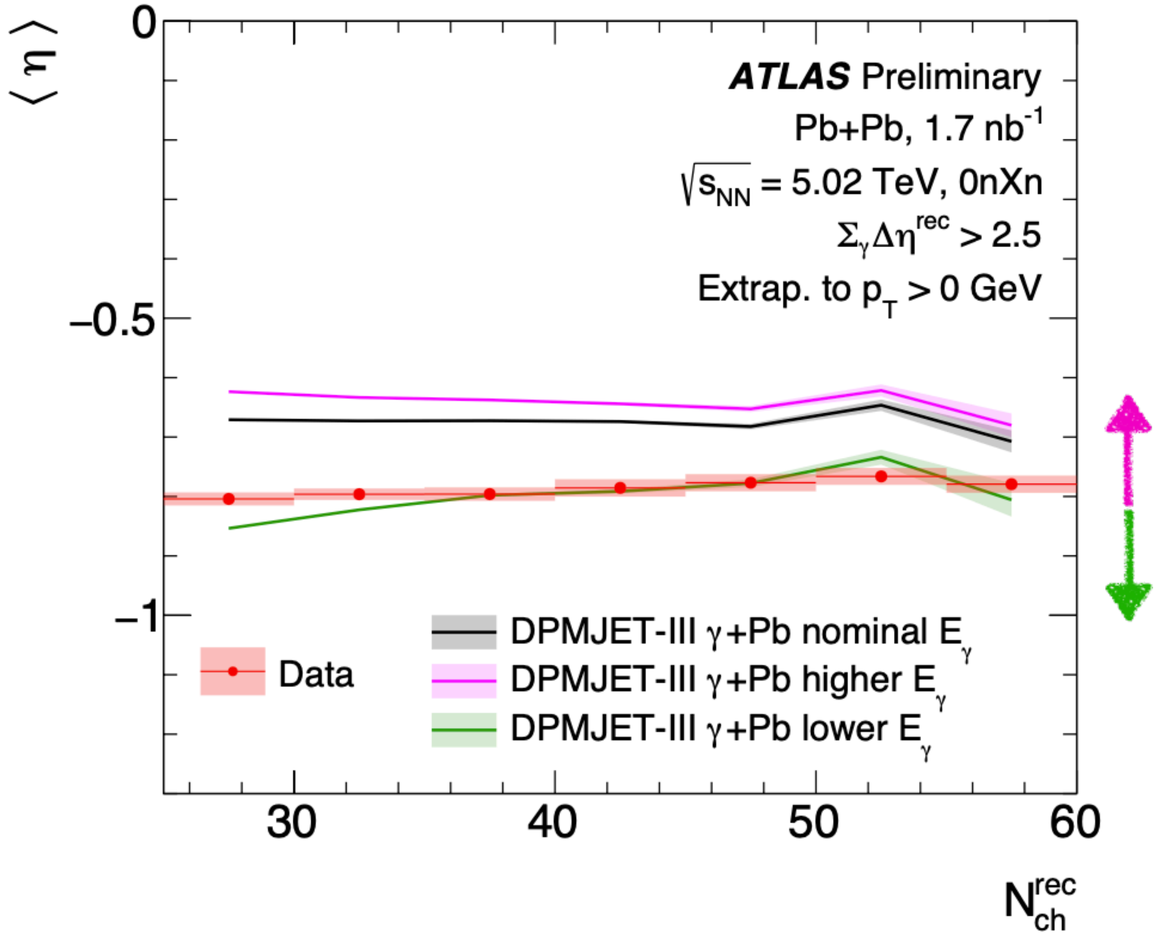
$\langle p_{\mathrm{T}} \rangle$ higher in data

Radial flow?

ATLAS-CONF-2023-059

Study of photon energy and particle production





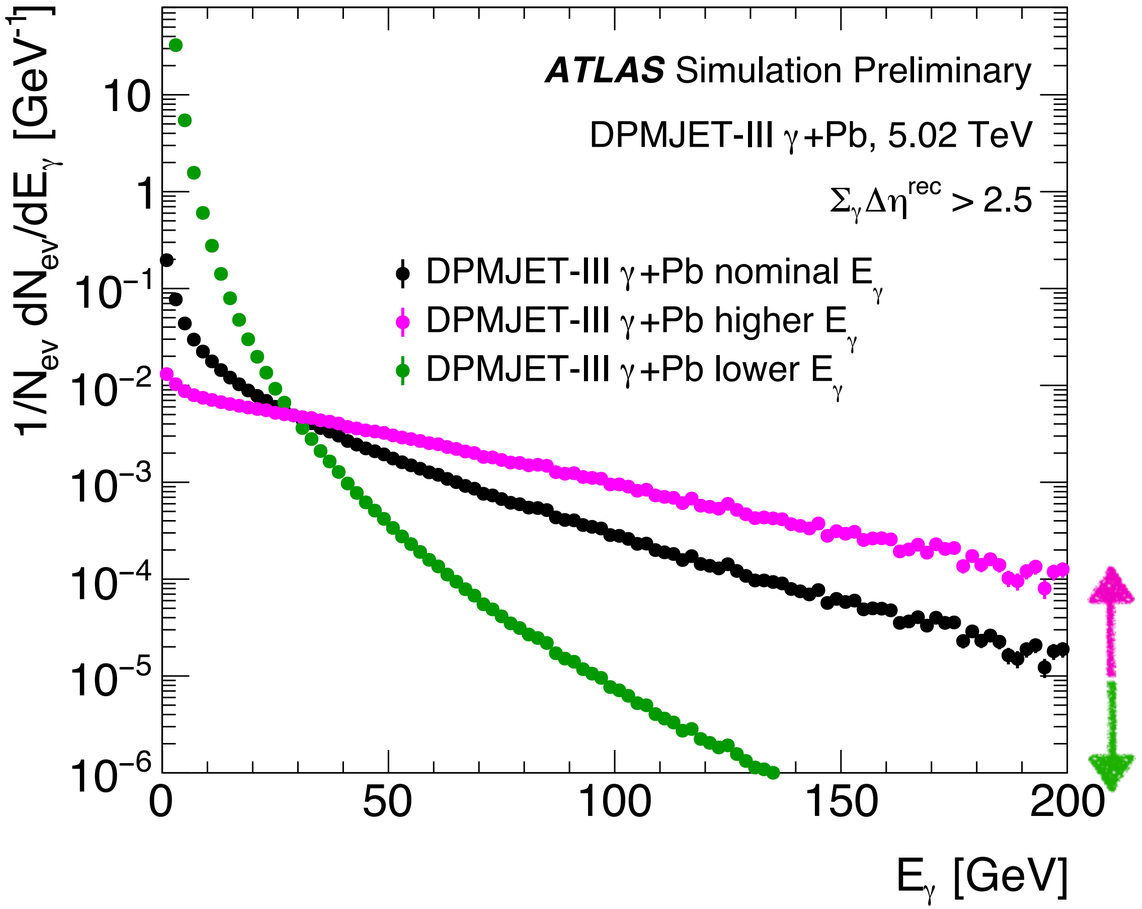
Arbitrarily re-weigh photon energy distribution to relatively allow:

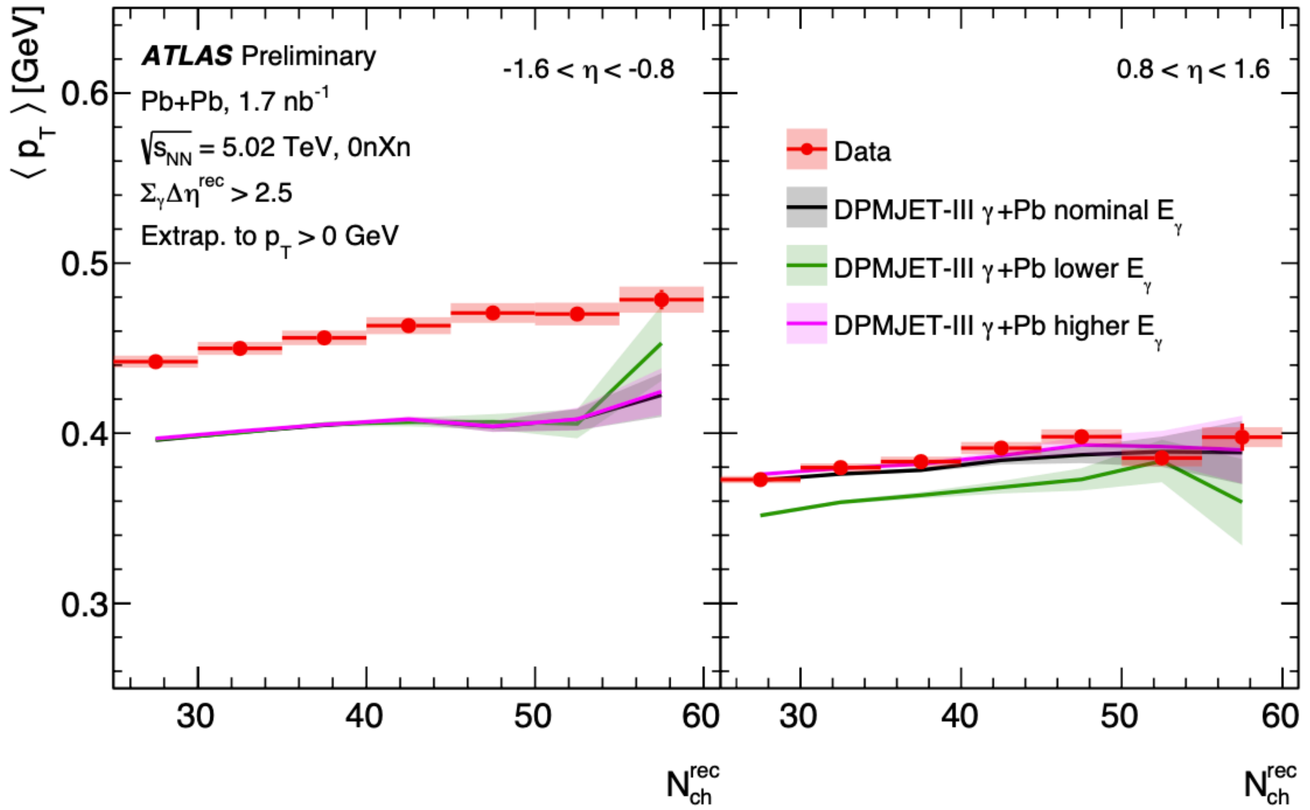
1) more high-energy photons
2) more low-energy photons.

$\langle\eta\rangle$ is matched with "low-energy photon" re-weighting

ATLAS-CONF-2023-059

Study of photon energy and particle production





Arbitrarily re-weigh photon energy distribution to relatively allow:

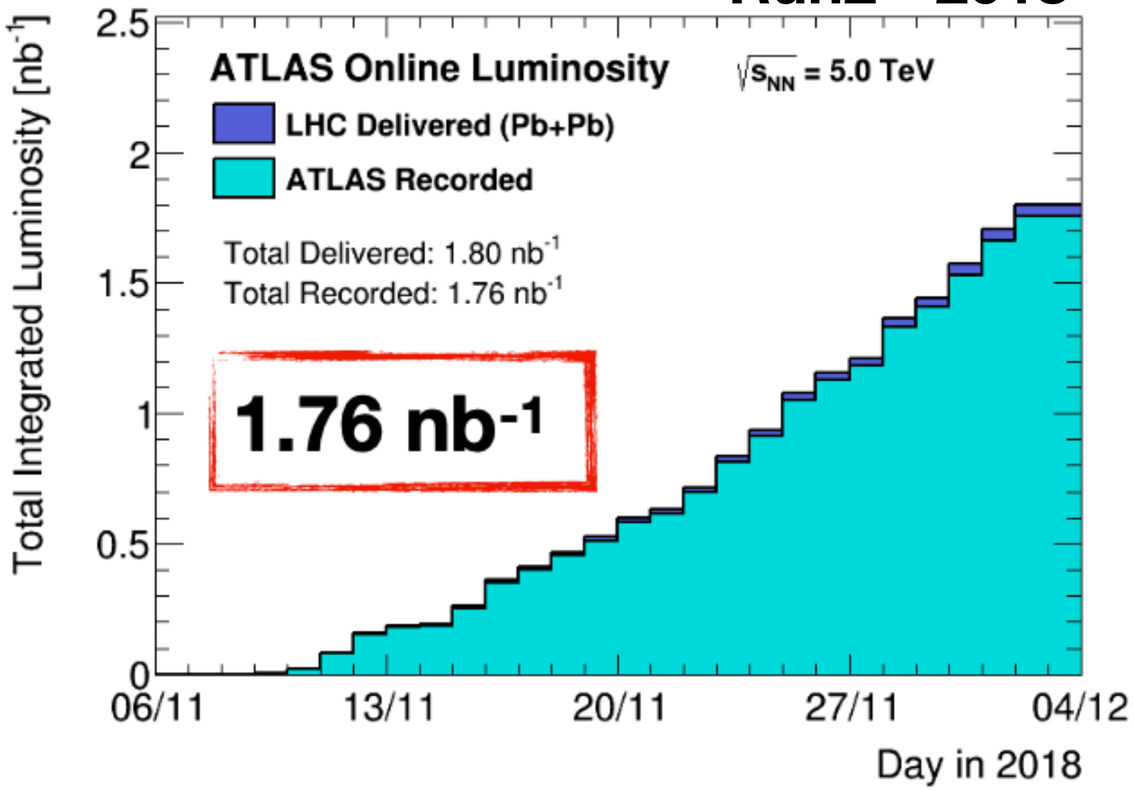
1) more high-energy photons
2) more low-energy photons.

$\langle \eta \rangle$ is matched with "low-energy photon" re-weighting

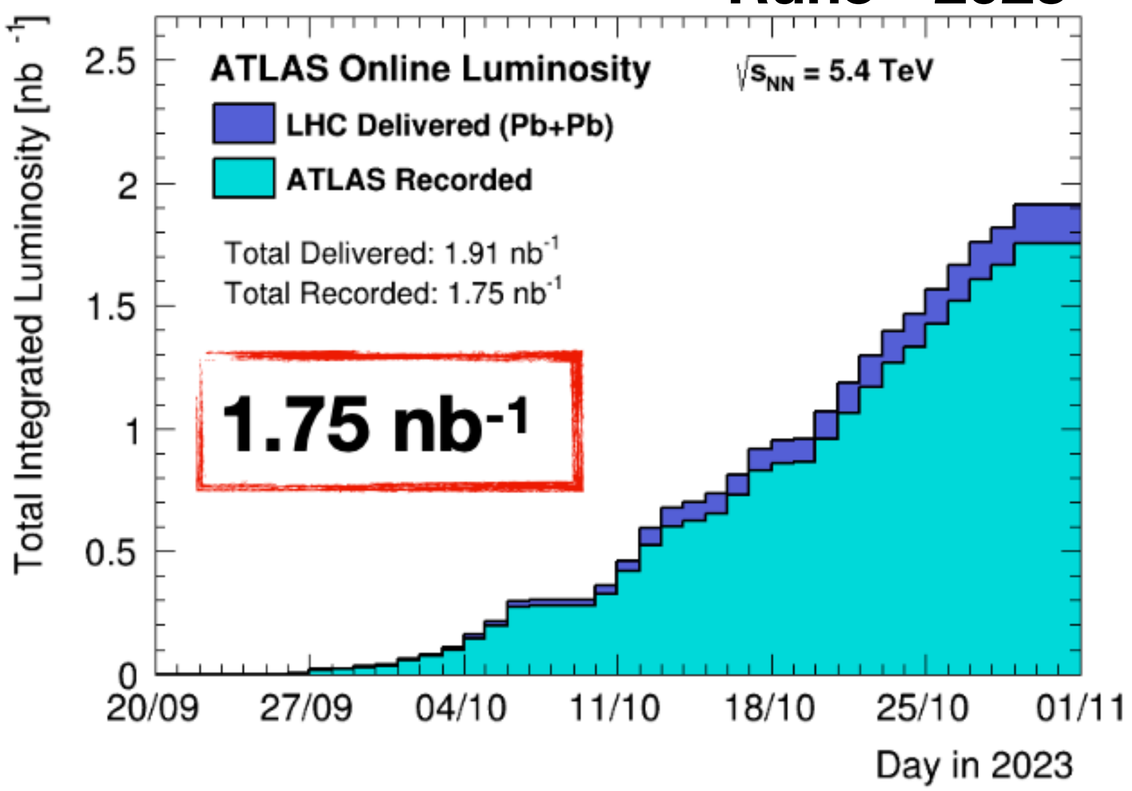
$\langle p_T \rangle$ couldn't be matched in all η regions simultaneously

Run-4 extended rapidity

Run2 - 2018



Run3 - 2023



- For most measurements, we at least need 2023+2024 data to be an improvement w/ respect to Run2
  - Except for UPC physics —> Significant improvements in ZDC and Trigger

Run 3/4 γ+Pb

- UPC collisions are excellent QED, BSM, and even QCD laboratories
  - Clean way to look for BSM particles; gravitons, axion-like, monopoles etc
  - Constraints on tau g-2 with precision comparable to LEP
  - Possibility to do precision QCD measurements - like fragmentation and hadronization in γγ -> qqbar

- Interesting opportunities to explore in photo-nuclear collisions
  - Collective phenomena in small collision system
    - ➡ Extended pesudorapidity $|\eta| < 4.0$ in Run4 will be particularly beneficial
  - Potential to constrain nuclear PDFs with di-jets, exclusive vector mesons

Run 3/4 γ+Pb

- Improve existing measurements with statistics, new ZDC, and TRT trigger

  - UPC ridge-v2, UPC Jets-v2, tau g-2, LbL
  - TRT trigger
    - ➡ Improve di-electron measurement —> bkg for light-by-light
    - ➡ Improve Taus measurement
    - ➡ Charmonia (J/Ψ,Ψ(2S)) in UPC
  - Current monopole measurement only 2015 data, no trigger in 2018
    → increase in statistic x100+ with 2023 data due to dedicated trigger