Measurements of collectivity in small systems with ATLAS

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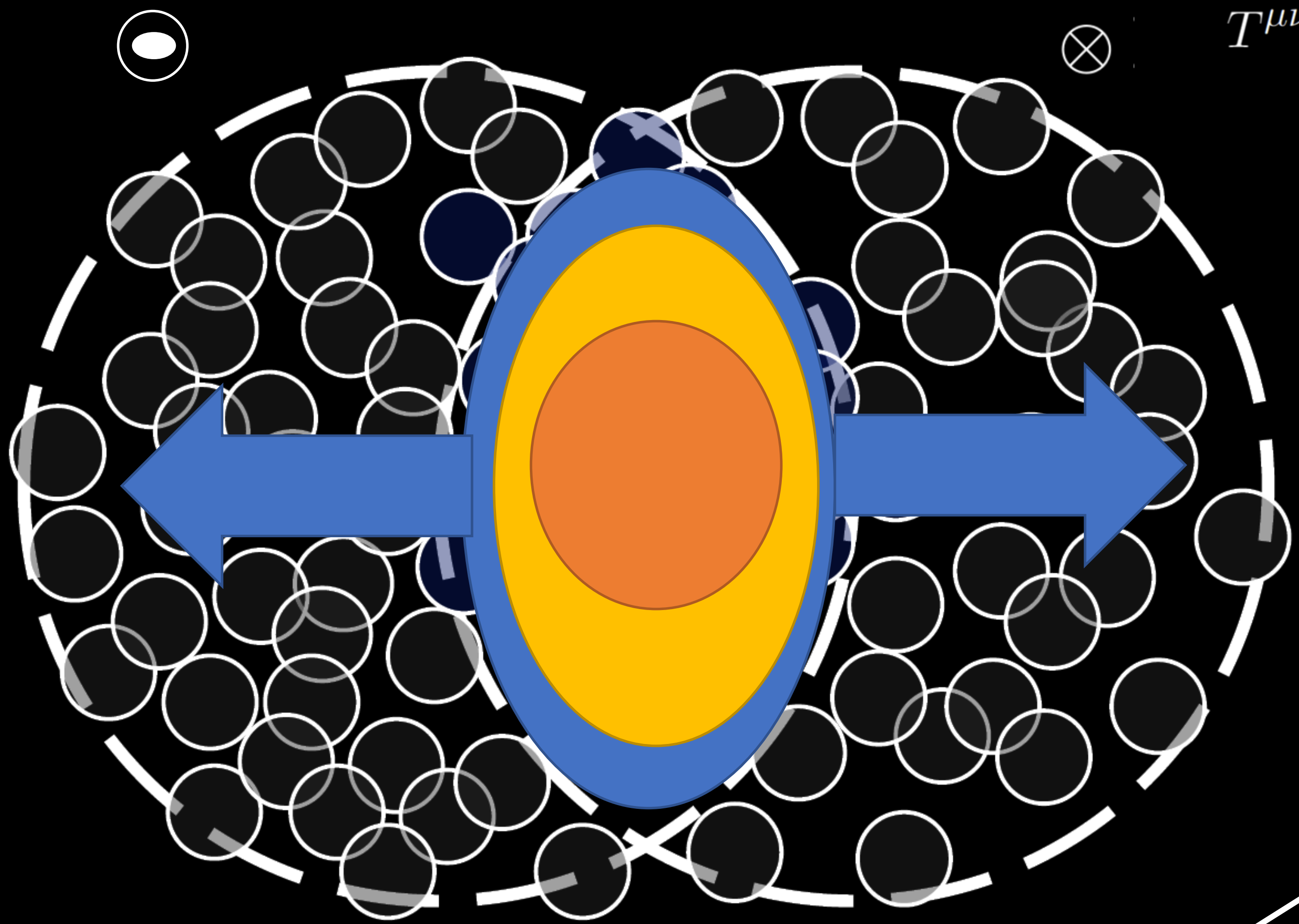
Overview

ATLAS measurements devoted to understanding the origin and initial conditions of small system collectivity

- **Basic characteristics and collectivity photonuclear collision**
- **Longitudinal flow decorrelations in *pp***
- **Jets fragment v_2**



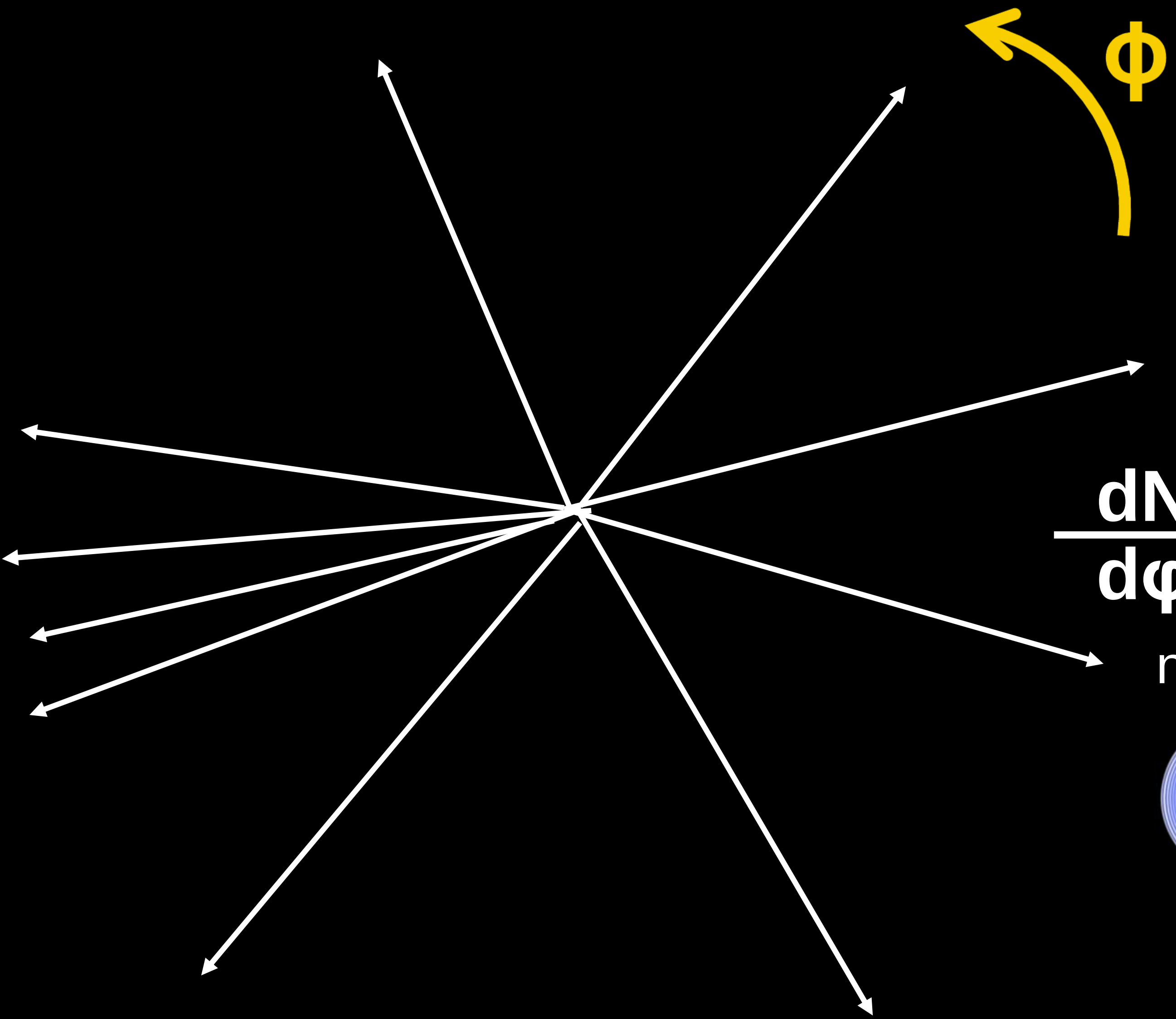
Viscous Hydrodynamics

$$T^{\mu\nu} = \underbrace{\epsilon u^\mu u^\nu + P[\epsilon]\Delta^{\mu\nu}}_{\text{Ideal Hydro}} \underbrace{- \eta[\epsilon]\sigma^{\mu\nu} - \zeta[\epsilon]\Delta^{\mu\nu}\nabla^{\perp}_{\lambda}u^{\lambda}}_{\text{Viscous Hydro}}$$

Equation of state
transport coefficients

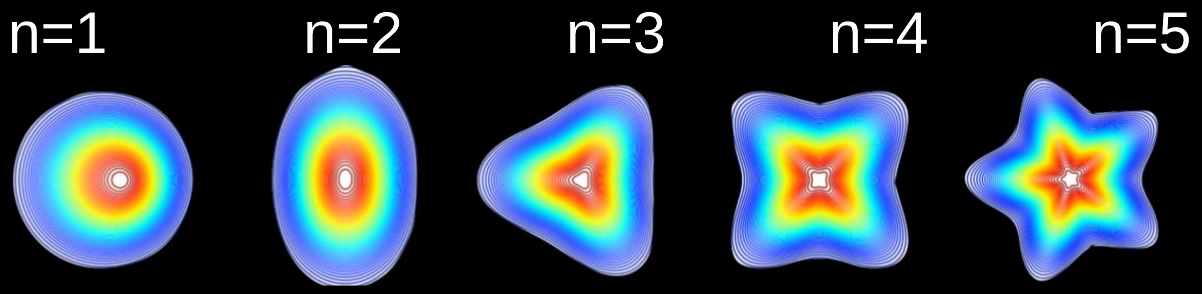
$P[\epsilon]$ $\eta[\epsilon]$ $\zeta[\epsilon]$.

Initial state → ? → **Hydro** → **Momentum anisotropy**



Azimuthal anisotropy

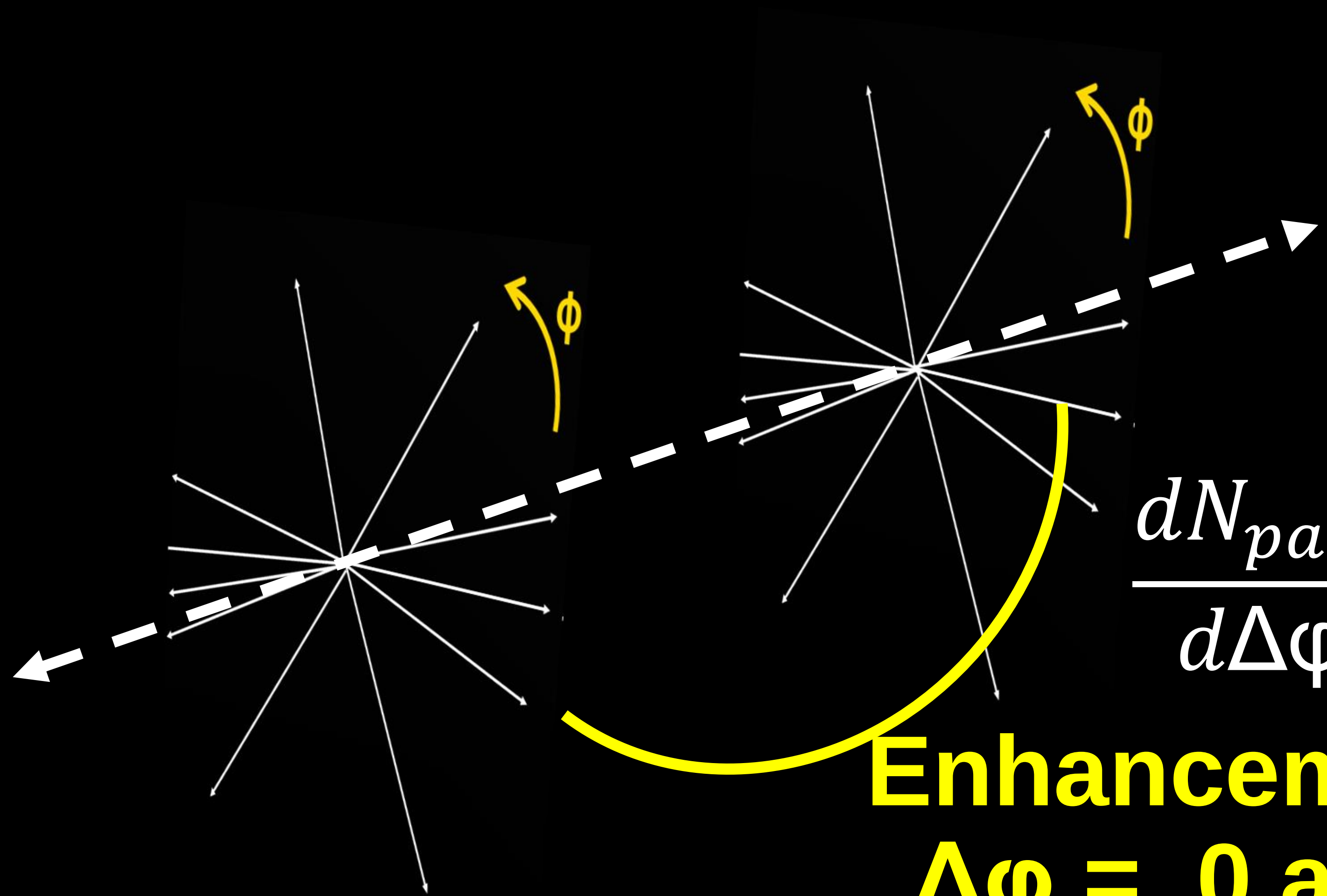
$$\frac{dN}{d\varphi} \alpha \; 1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + 2v_3\cos(3\varphi) + \ldots$$



Two-particle correlation

For the purposes of this talk

All charged particle tracks



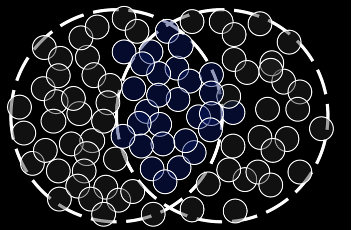
$$\frac{dN_{pair}}{d\Delta\varphi} \alpha\ 1 + 2v_{2,2}\cos(2\Delta\varphi) + .$$

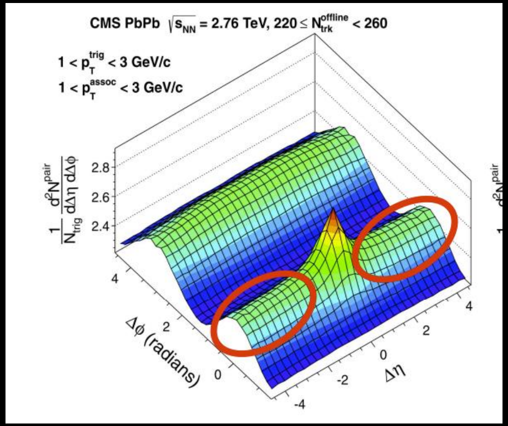
Enhancement at

Δφ = 0 and π

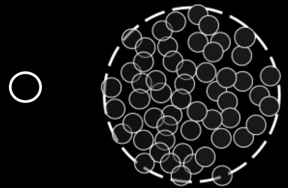
System size

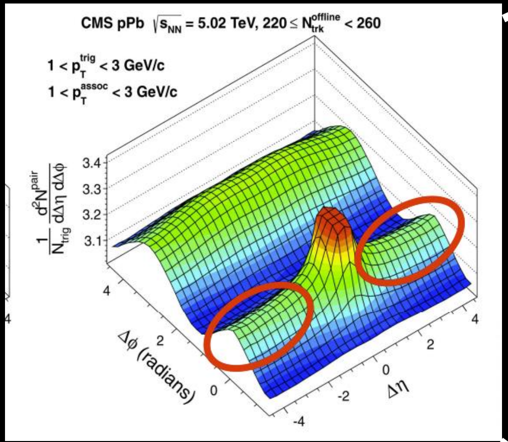
Pb+Pb



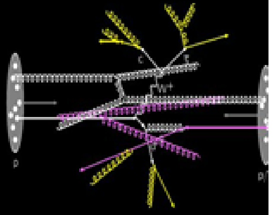


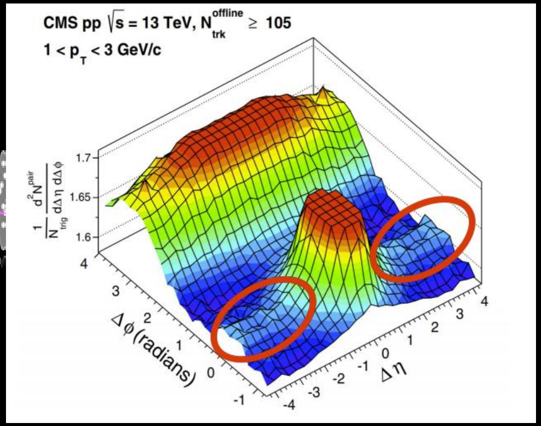
p+Pb





pp



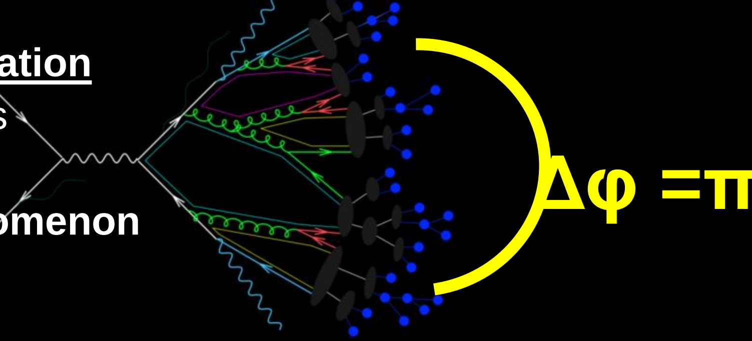


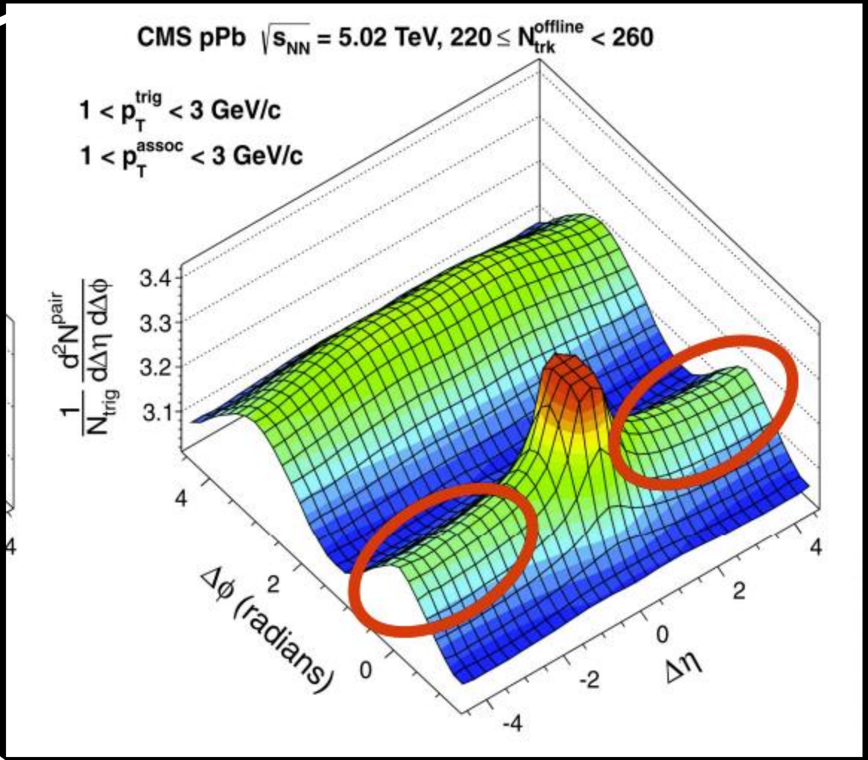
Momentum conservation

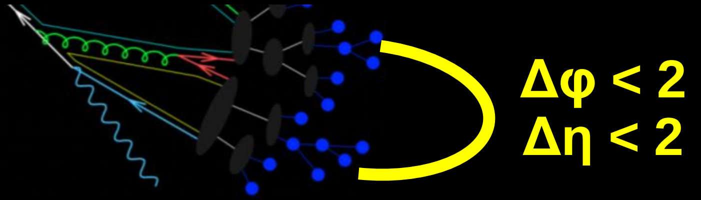
Jets & particle decays

Termed "nonflow"

Not collective phenomenon



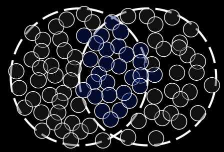


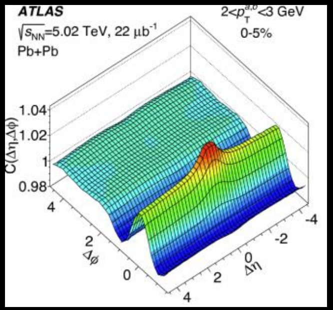


System size

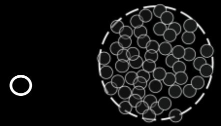
What are the minimal conditions for collectivity?
Many new searches in other small systems

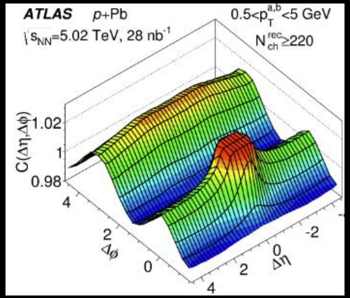
Pb+Pb



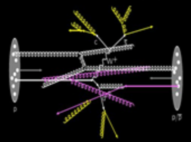


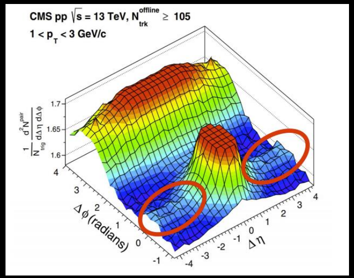
p+Pb



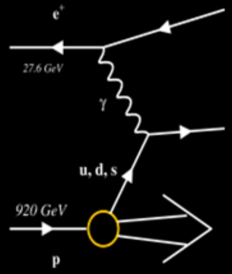


pp

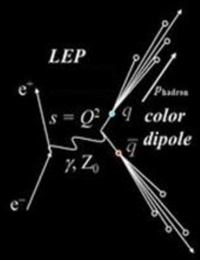




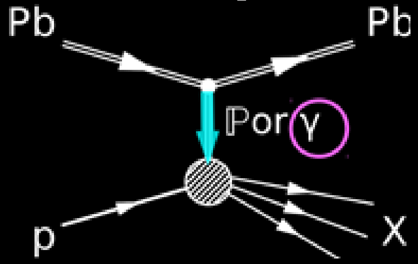
e+*p*



$e^+ + e^-$

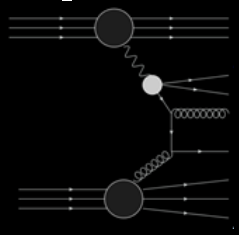


γ+*p*



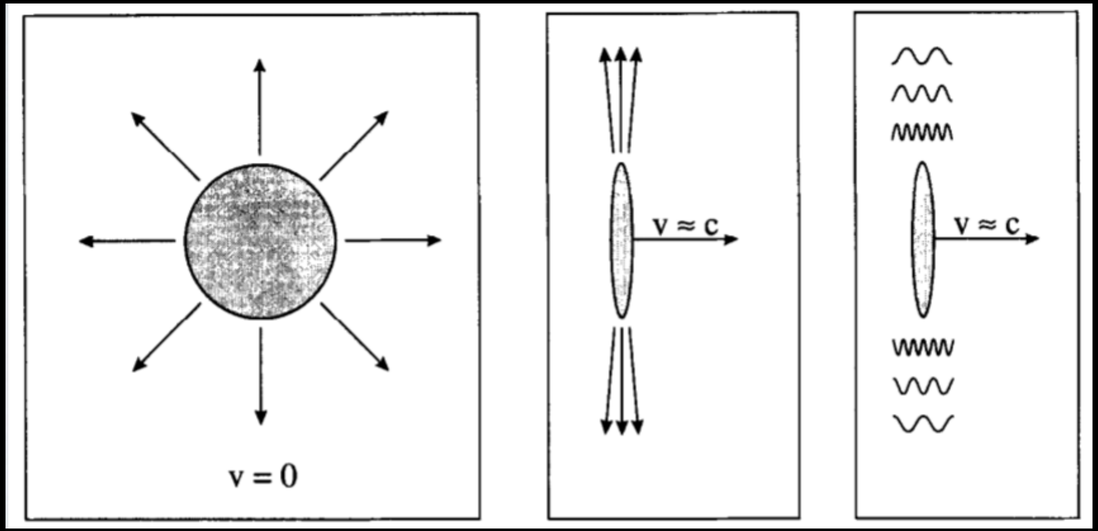
γ+A

Today



Collectivity and particle production in photonuclear collision

Ultra-peripheral collisions at the LHC

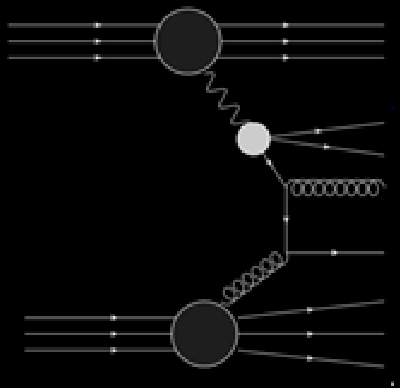


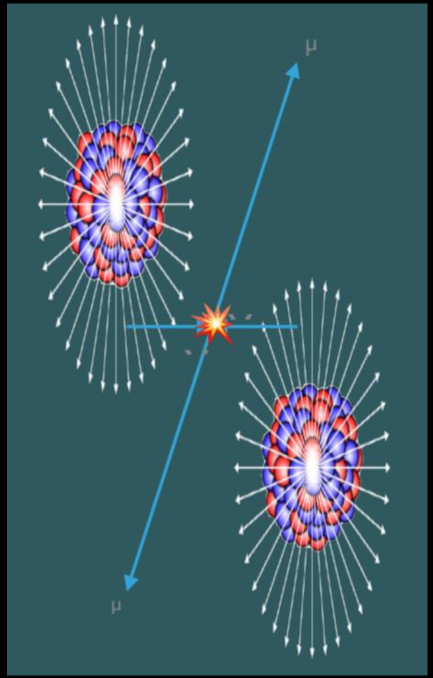
Coulomb fields of moving charges can be treated as an equivalent flux of quasi-real photons (Q^2=0) which are boosted to high energies.

Photons reach energies of 10s of GeV with a 2.5 TeV Pb beam at the LHC

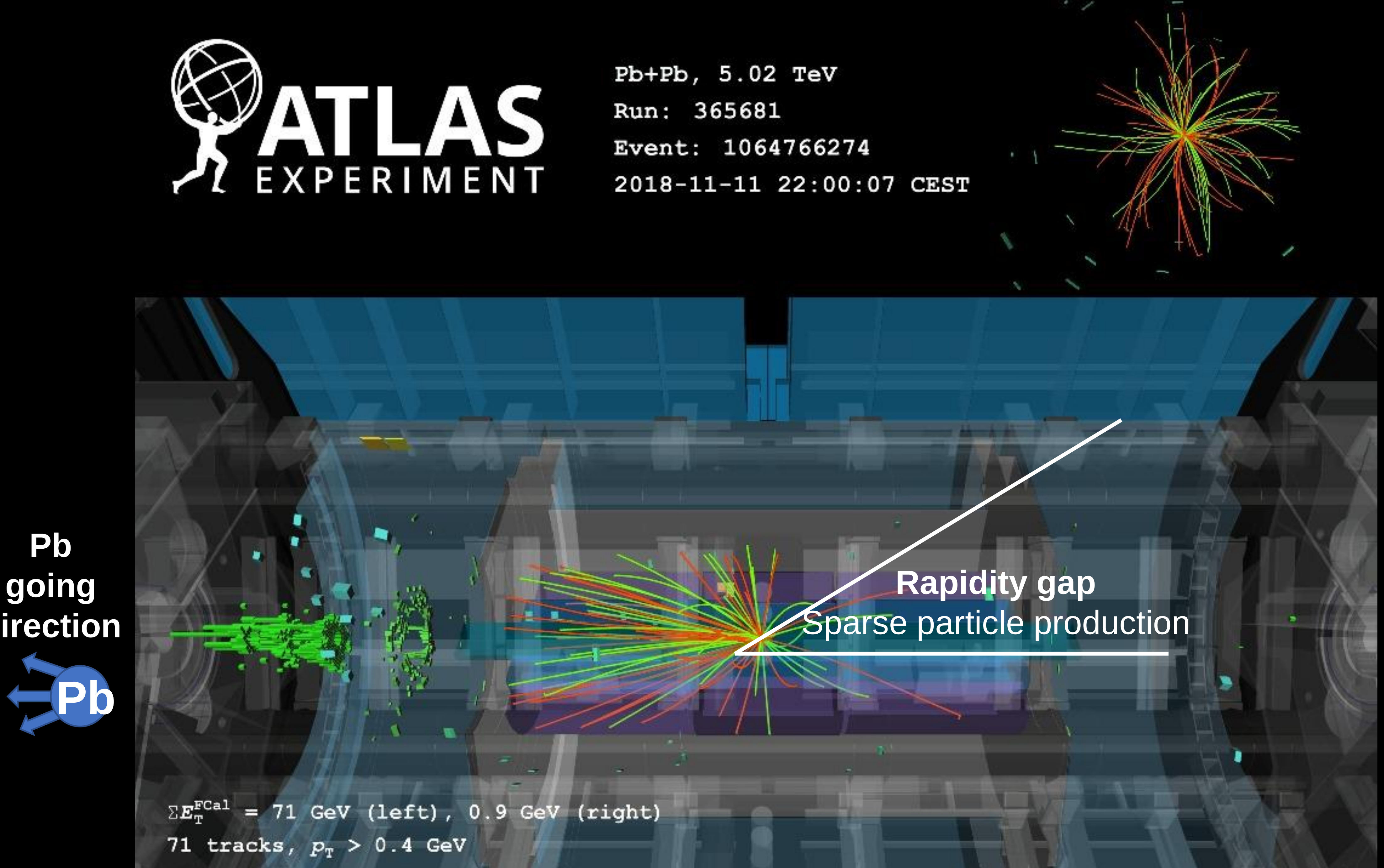
When $b > 2R_A$ two categories of interactions

- Pure EM processes
  - γγ → γγ arXiv:1904.03536 & arXiv:2008.05355
  - γγ → μμ arXiv:2011.12211
  - γγ → ττ arXiv:2204.13478
  - γγ →ee *arXiv:2207.12781*
- Photo-hadron interactions
  - γ + A → A* + V
  - γ + A → X



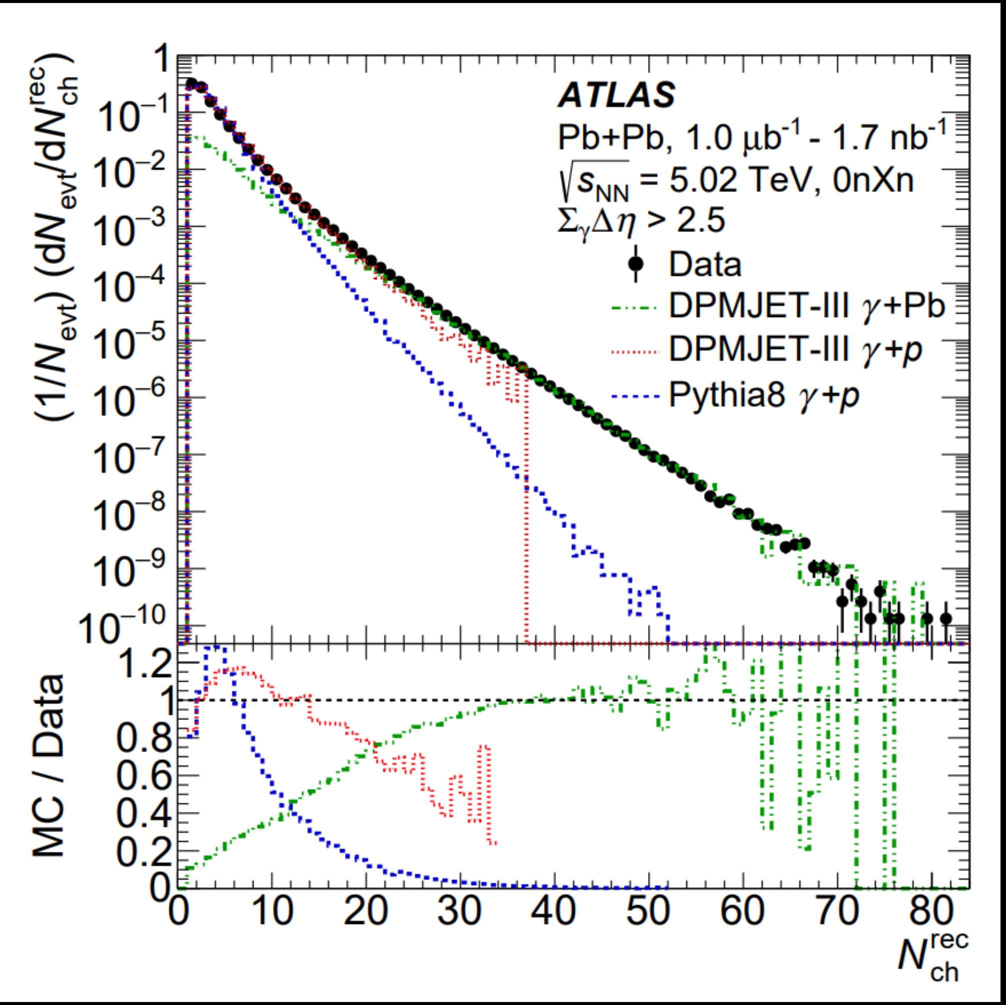


Pb going direction



photon going direction

Multiplicity in photonuclear collisions



|η|<2.5, p_T>400 MeV

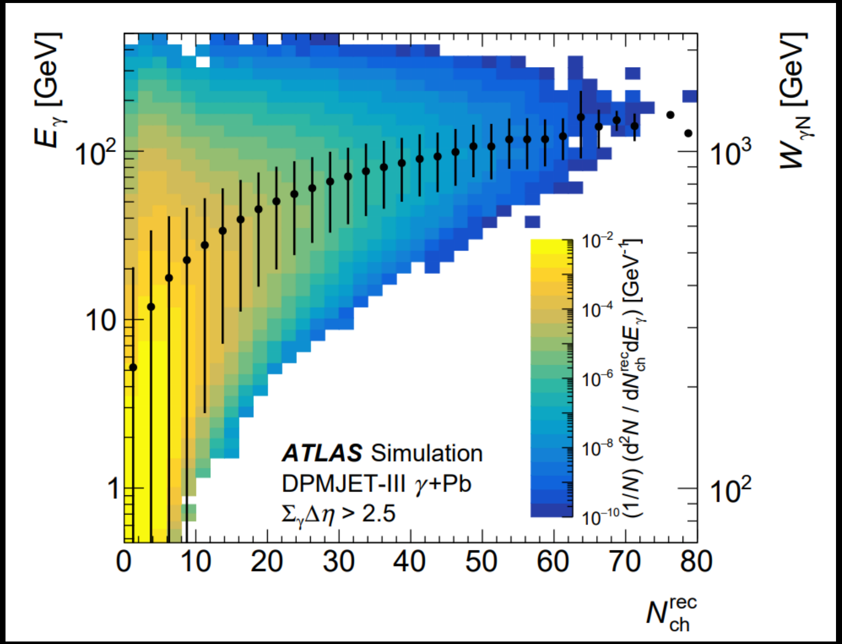
Large number of final state particles for photon induced collisions

Multi-nucleon interaction in the Pb target

Double the reach in N_{ch} in γA than in γp

Selecting the highest energy collisions →

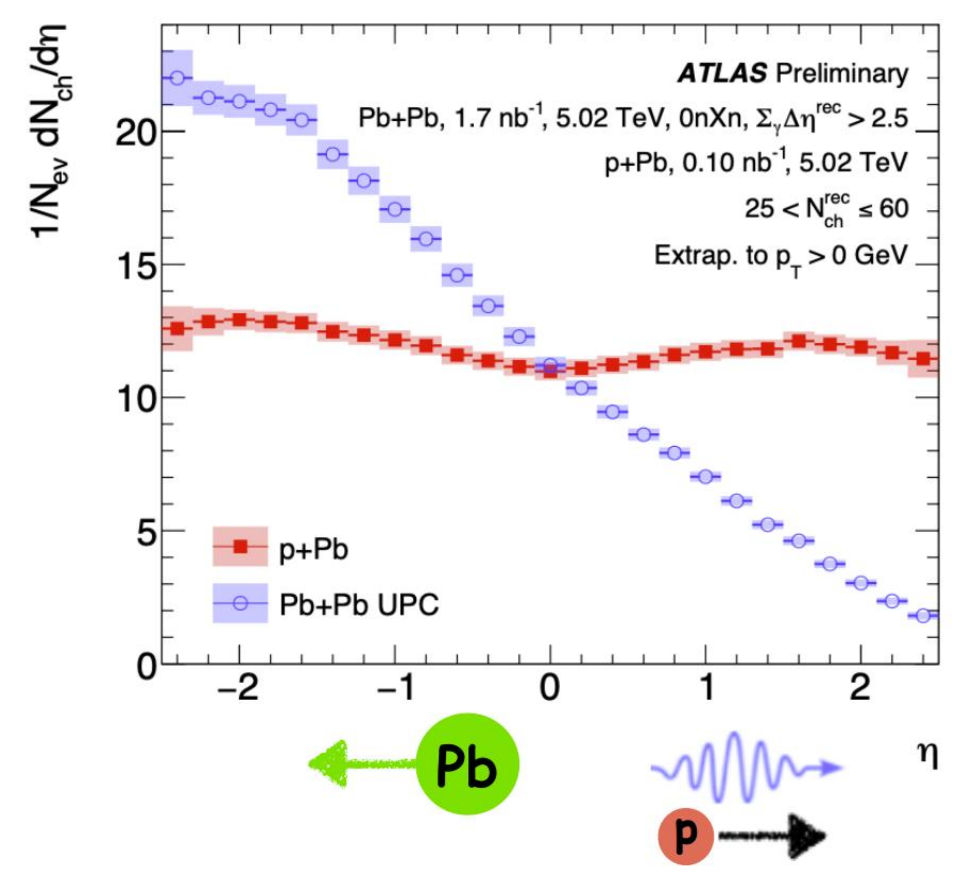
~ 1 TeV $\sqrt{s}$



arXiv:2101.10771

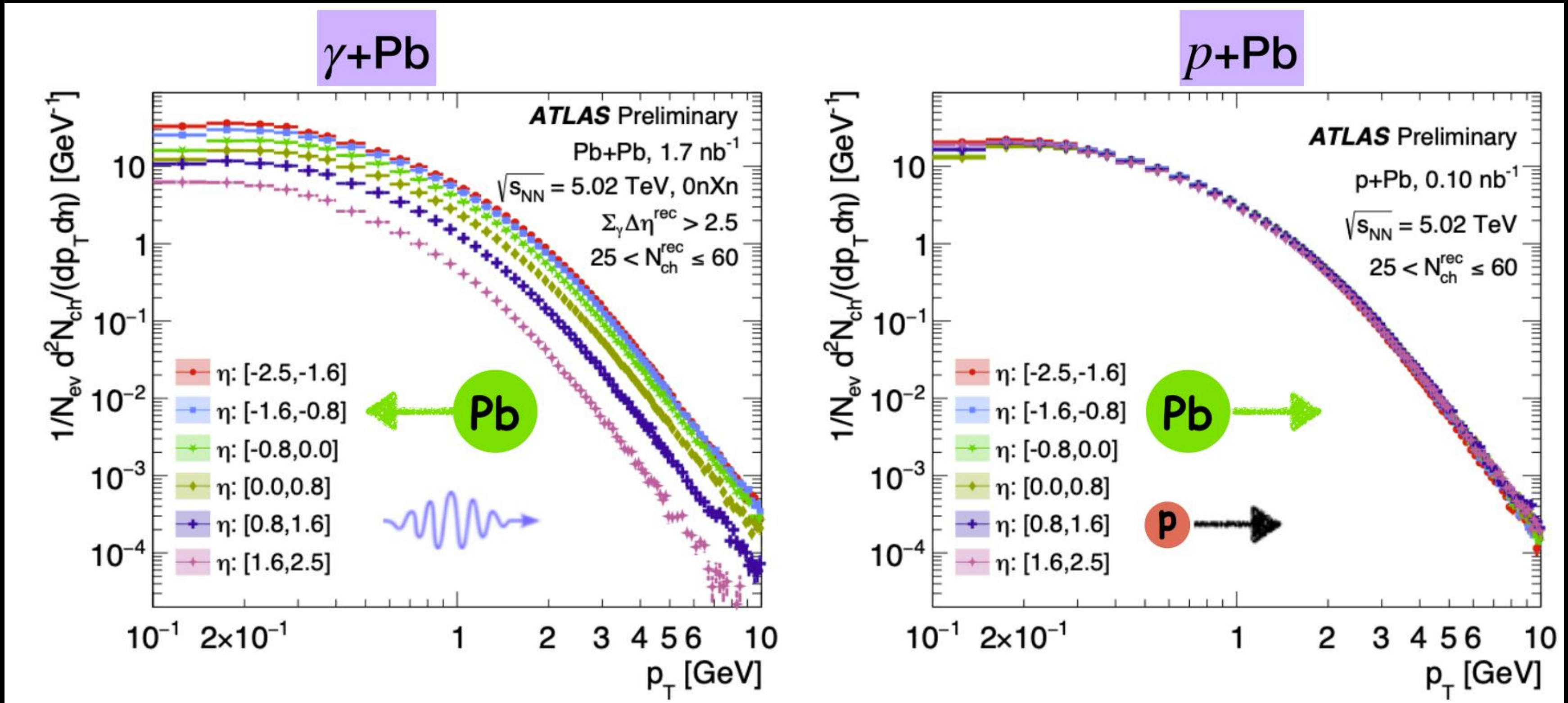
$dN_{ch}/d\eta$ is asymmetric in γPb

- γPb $dN_{ch}/d\eta$ distribution is highly asymmetric
- Compare to **low multiplicity *p*Pb**
- p+Pb distribution is nearly symmetric for selected low multiplicity events



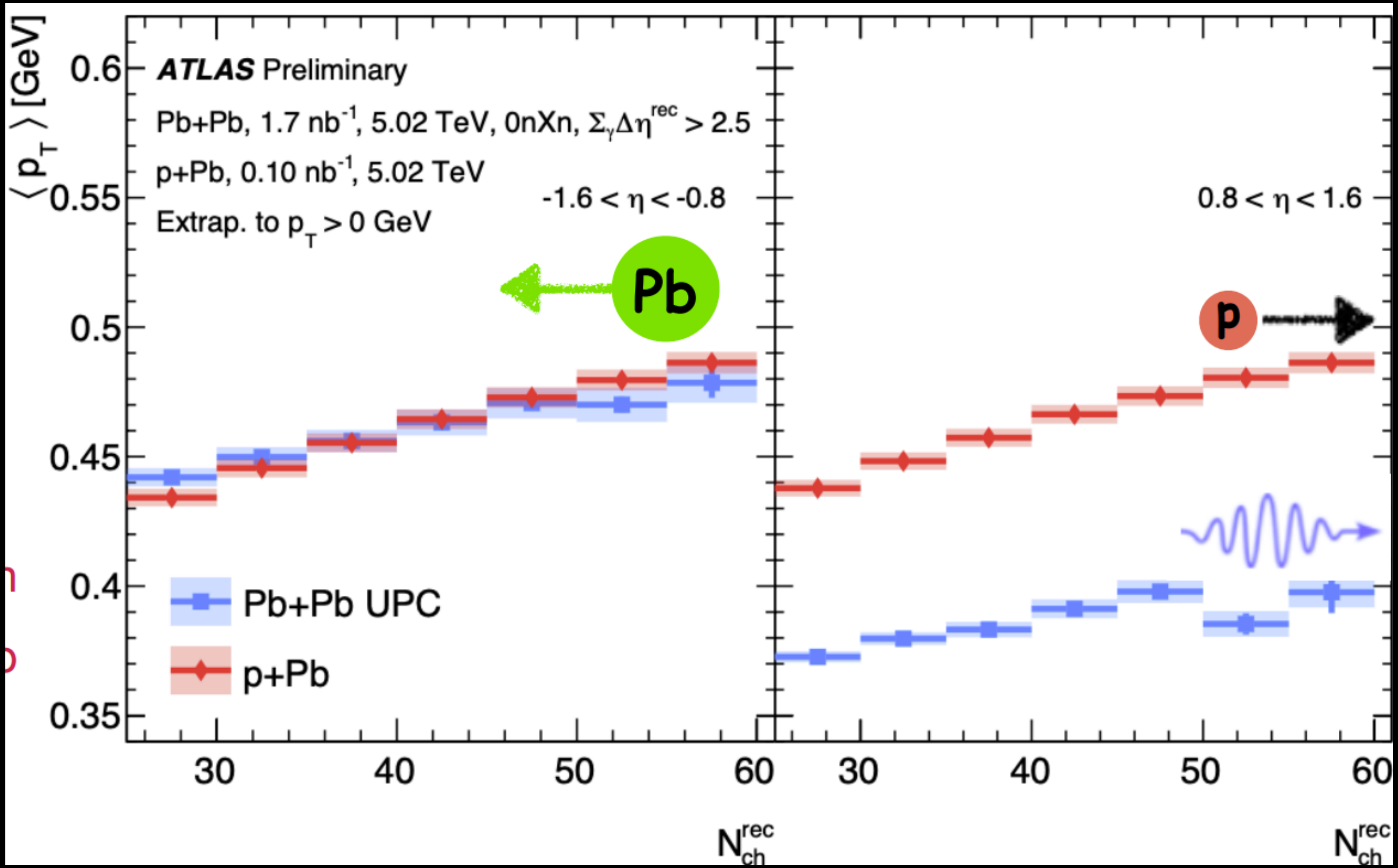
Different particle production regimes in forward/backward η

Invariant yields as a function of p_T



Similarly falling momentum distributions
Further quantified via ⟨pT⟩

$\langle p_T \rangle$ in γPb

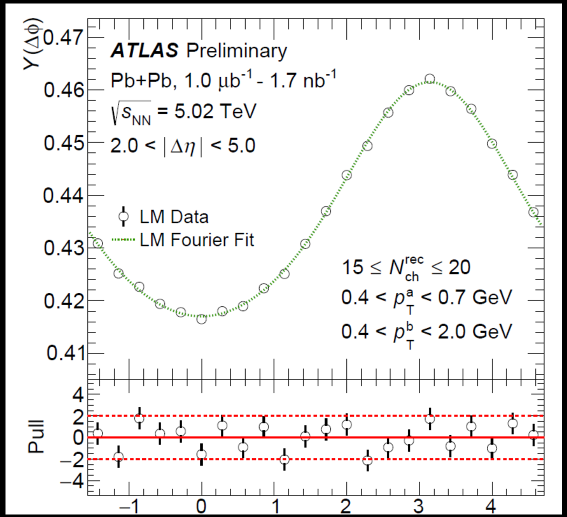


In the Pb-going direction there is a similar $\langle p_T \rangle$ as function of N_{ch} in p+Pb and γPb have perhaps a similar radial flow

Template fit in photonuclear

High-multiplicity (HM) correlation data

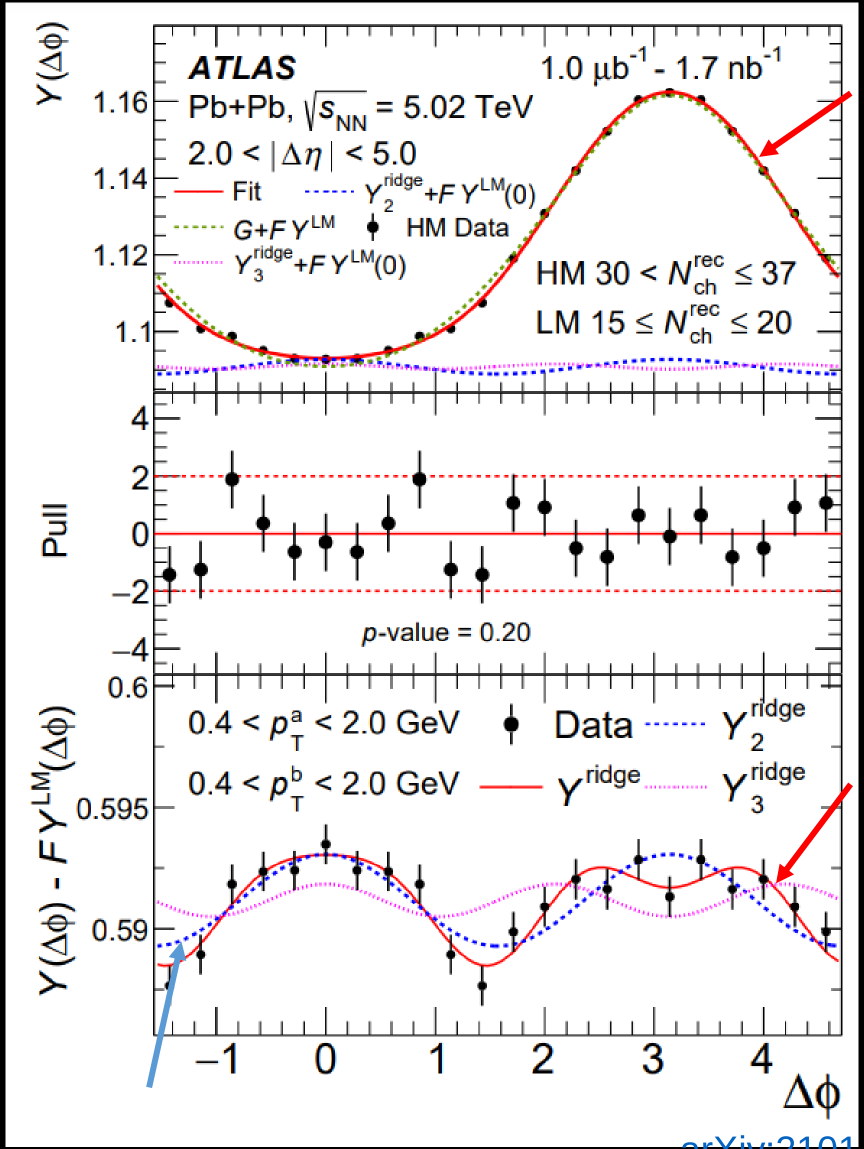
Low multiplicity (LM)
template for jet/non-flow correlation



Nonflow subtraction

- HM fit with LM data and flow coef.
- HM and LM assumed to have same flow shape
- Different LM selection leads to similar results

$$Y^{HM}(\Delta\phi) = FY^{LM}(\Delta\phi) + G\left\{1 + 2\sum_{n=2}^{3} v_{n,n}\cos(n\Delta\phi)\right\}$$



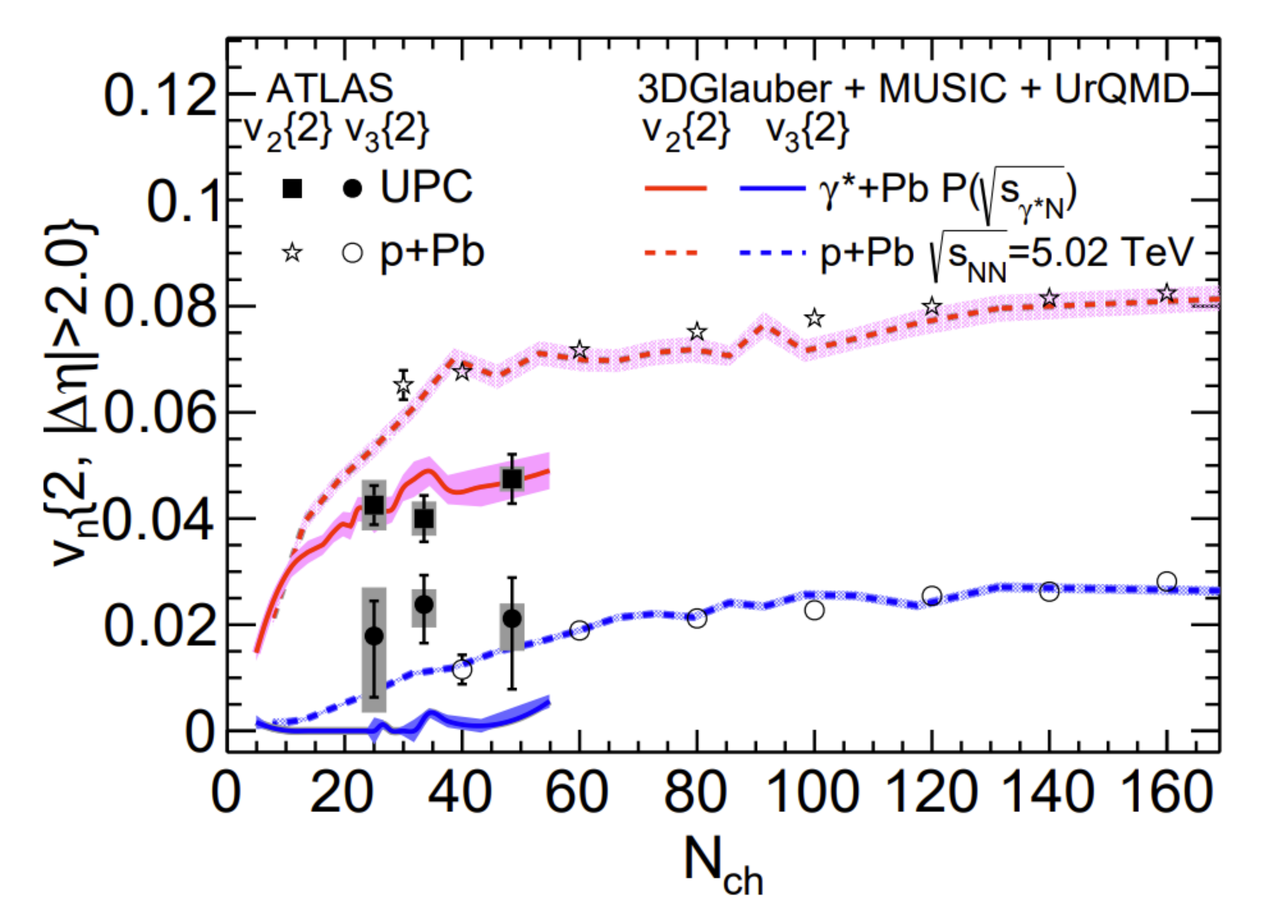
fit

fit

arXiv:2101.10771

After nonflow subtraction clear cos(2Δφ) modulation

New γ+Pb theory comparisons



Nonzero γPb v_2

comparison to
3DGlauber + MUSIC +UrQMD

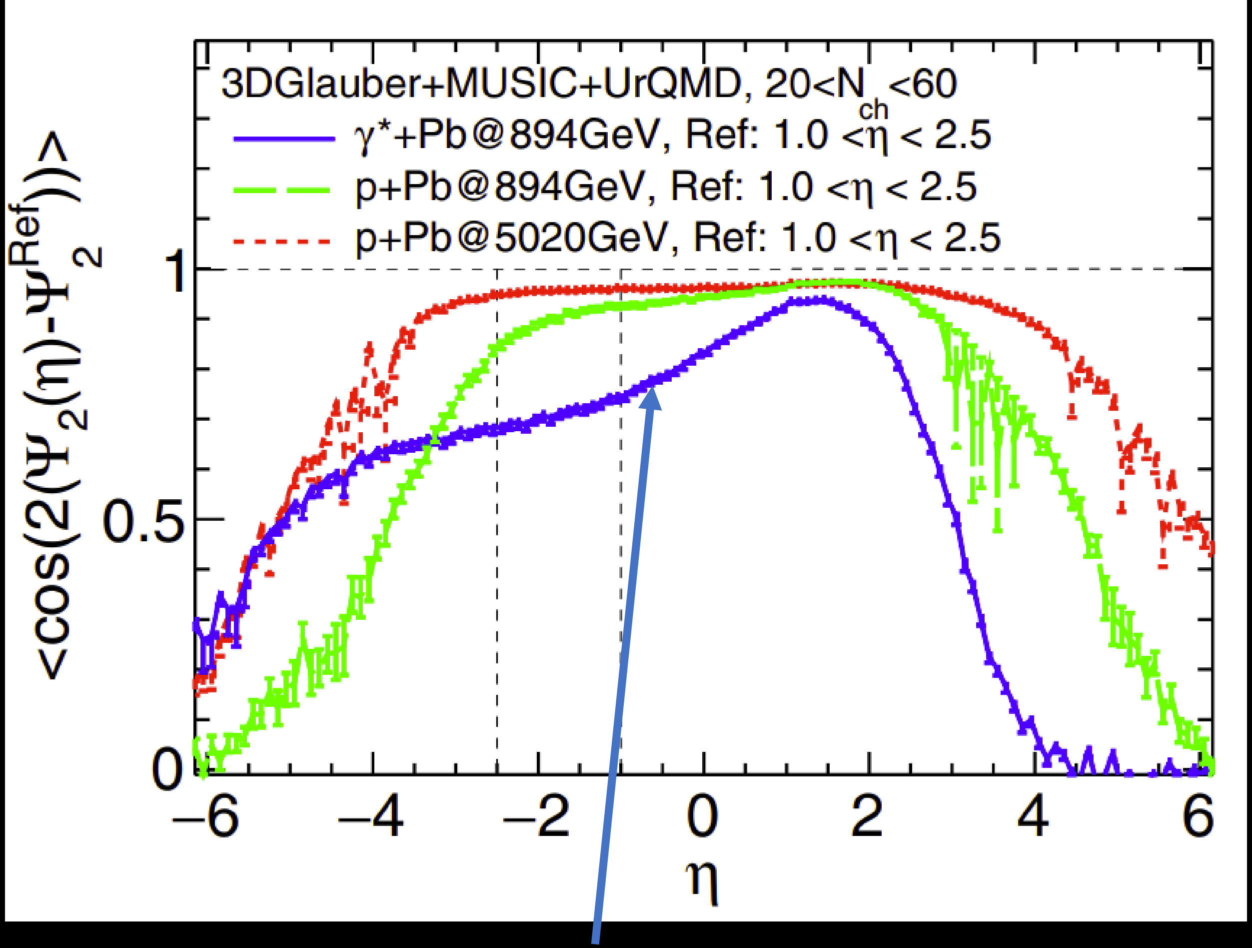
Why is
v_2 (γ *Pb) < v_2 (pPb)
Correlations performed in forward rapidity in γPb suppresses observed collectivity

arXiv:2203.06094 arXiv:2101.10771

Why is γPb v_2 smaller

EPJ Web of Conferences 276, 01002 (2023) SQM22

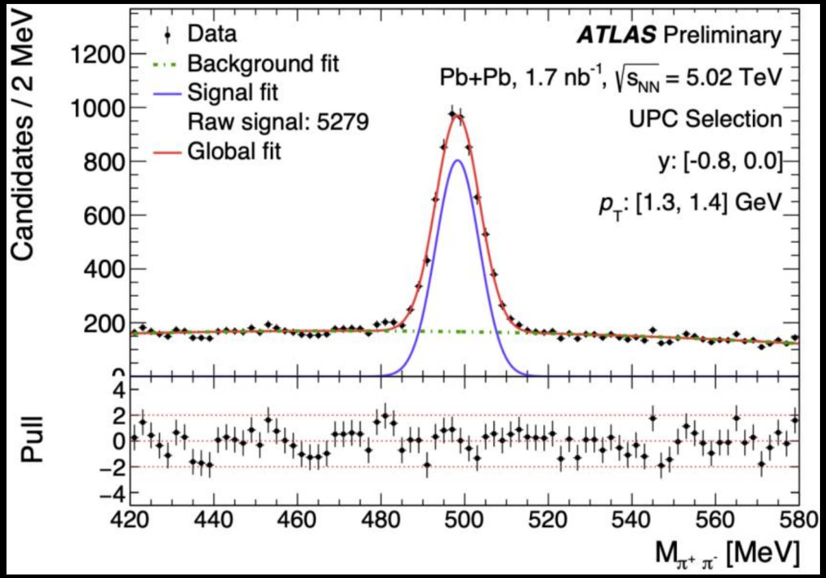
- Correlations in small systems are performed with a rapidity gap between the particles
- The event plan can fluctuate between theses rapidities and decreasing the observed v2
- This effect is larger at forward rapidities.
- Because γPb is so boosted the "forward rapidities" are probes relative to other systems with the ATLAS detector.



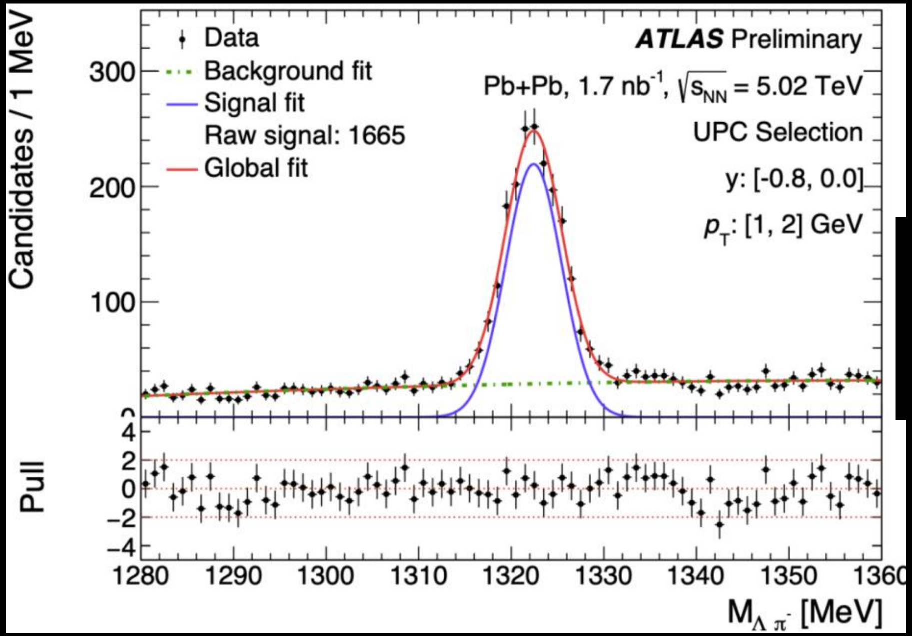
I will show measurements that reflects the slope of these lines next!

Advertisement of upcoming results

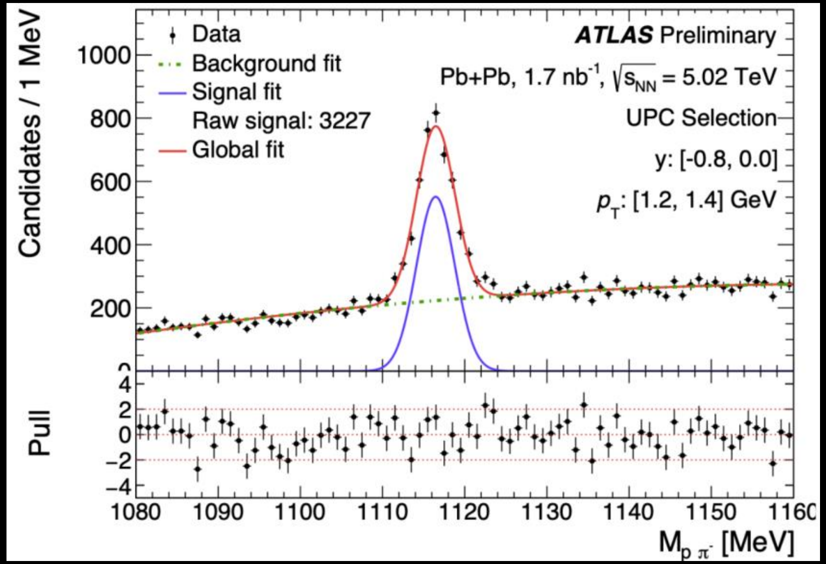
- Strangeness enhancement, baryon anomaly, baryon stopping…
- Novel incoming quantum numbers in γPb
- Performance plots of displaced vertex identified particle candidates in γPb



K_S^0



Ξ^-

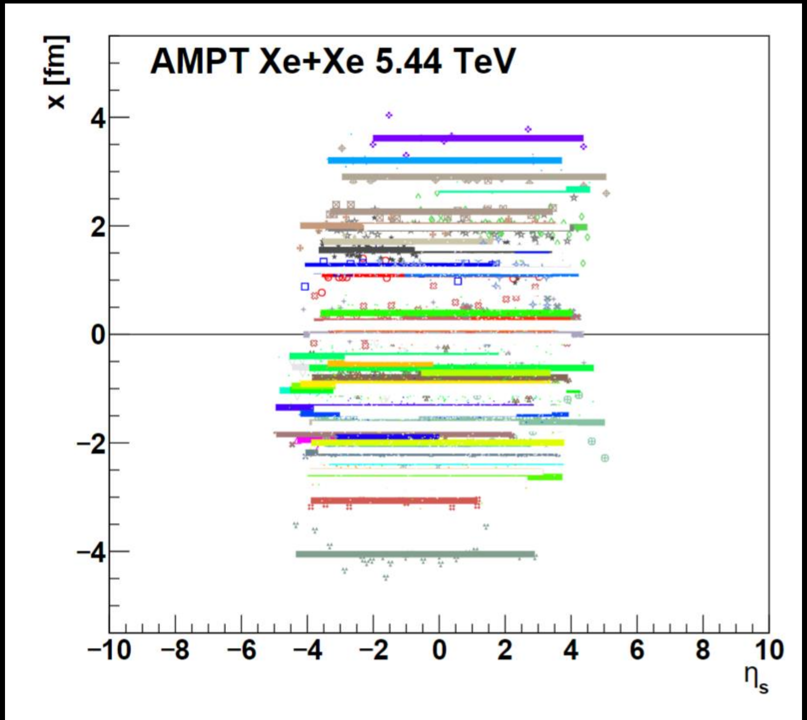


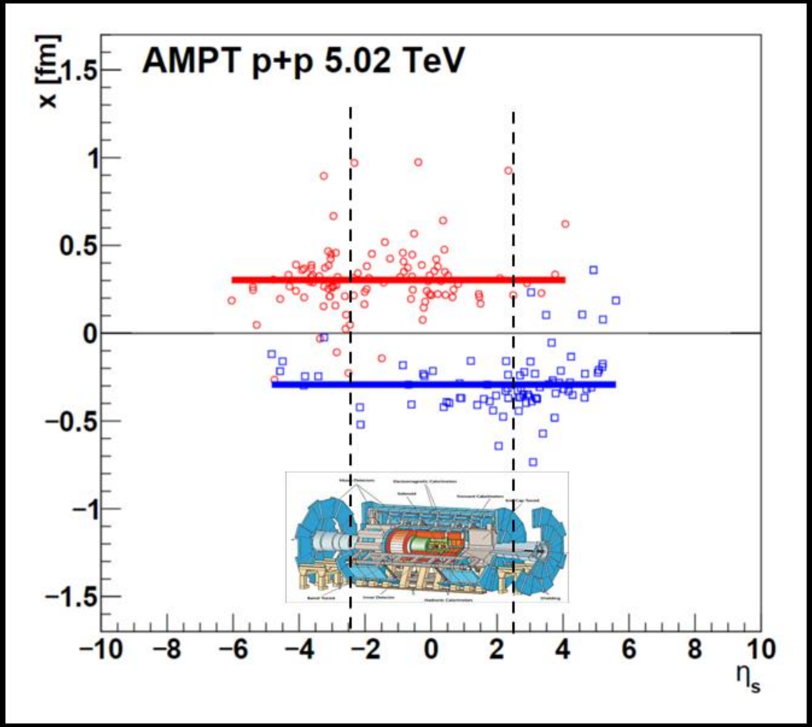
Λ

ATLAS-CONF-2023-059

New results expected this year in γPb

Flow decorrelations in small systems





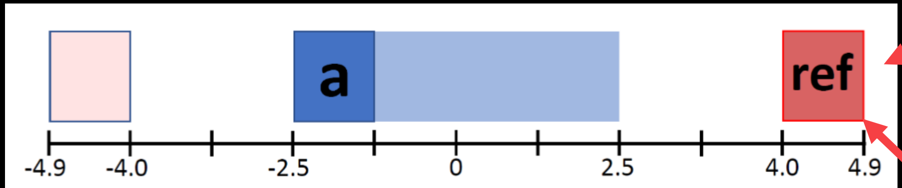
Analysis overview

Systems analyzed

***pp* 13 TeV   Xe+Xe 5.44 TeV**

Analysis steps

Step 1: Two-particle correlations between inner detector tracks and forward calorimeter



pp: calorimetric clusters

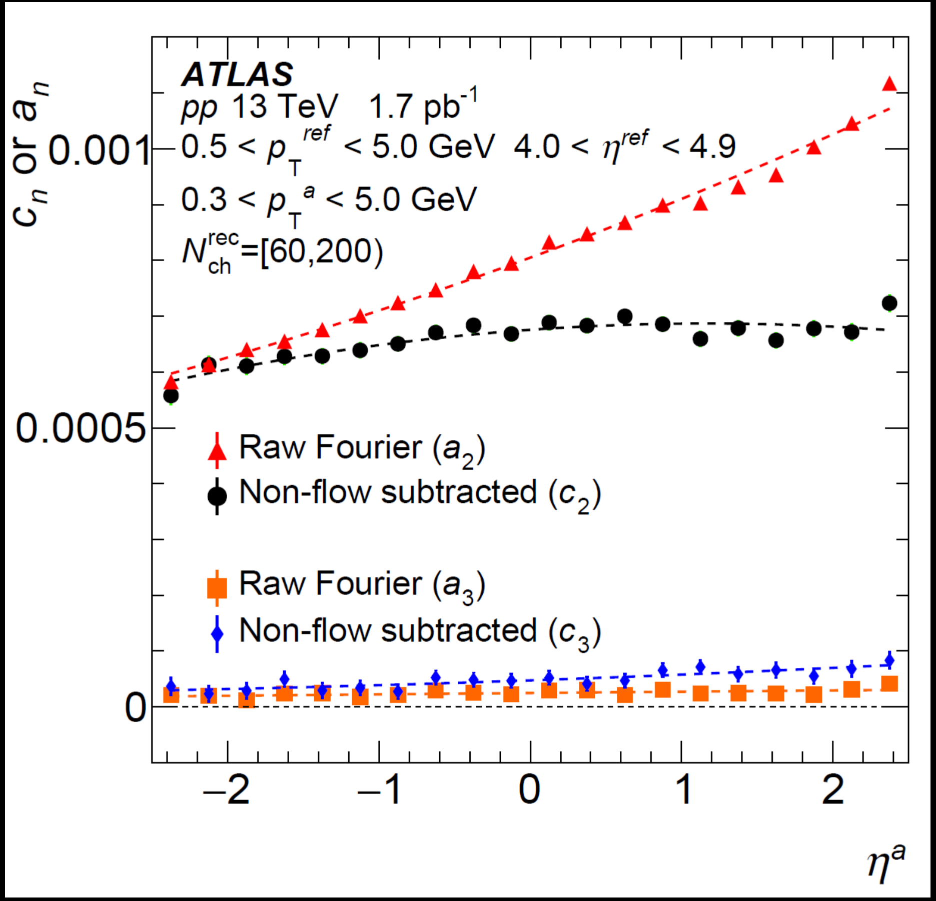
Xe+Xe: calorimetric towers

$$\Delta\phi = \underbrace{\phi^{a}}_{\eta^{a} = [-2.5,2.5]} - \underbrace{\phi^{ref}}_{\eta^{ref} = [4.0,4.9]}$$

Step 2: measure Fourier moments and perform non-flow subtraction as a function of η^{a}

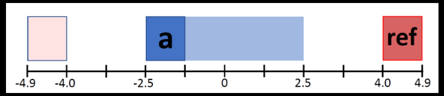
Step 3: Parametrize decorrelation via the slope of $v_{n,n}(\eta^{a})$

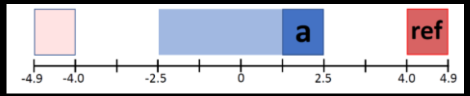
$v_{2,2}(\eta^a)$ and non-flow subtraction



Nonflow a_2 is positive

Nonflow a_3 is negative





arXiv:2308.16745

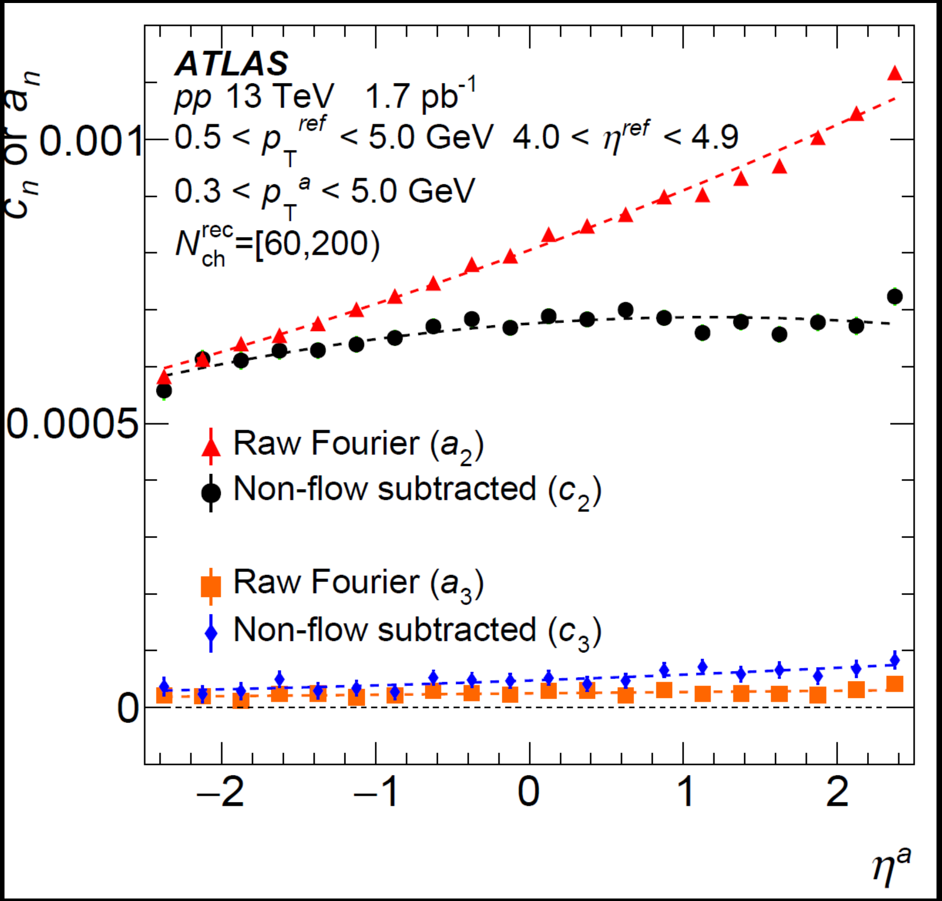
Raw Fourier a_2: large $da_2/d\eta$
Non-flow subtraction: : small $dc_2/d\eta$ with a large subtraction for small gaps and a small correction for large gaps

3rd moment has opposite hierarchy!
Raw Fourier a_3: small $da_3/d\eta$
Non-flow subtraction: : larger $dc_3/d\eta$

Nonflow is a large background for decorrelation measurements

Parametrize dependence of correlation coefficients

arXiv:2308.16745



We characterize the η^a behavior of the correlation coefficients with a fit function,

$$A(1 + F_n \times (\eta^a) + S_n \times (\eta^a)^2)$$

Decorrelation observable

- F_n is the linear fractional change in the correlation coefficient and is the parameter of interest.

Other parameters in the fit

- ***A*** is the mid-rapidity flow and is not of interest
- S_n is an η^a–even function and does not represent decorrelation and is not of interest.
- Data is described by the function well

Past observable

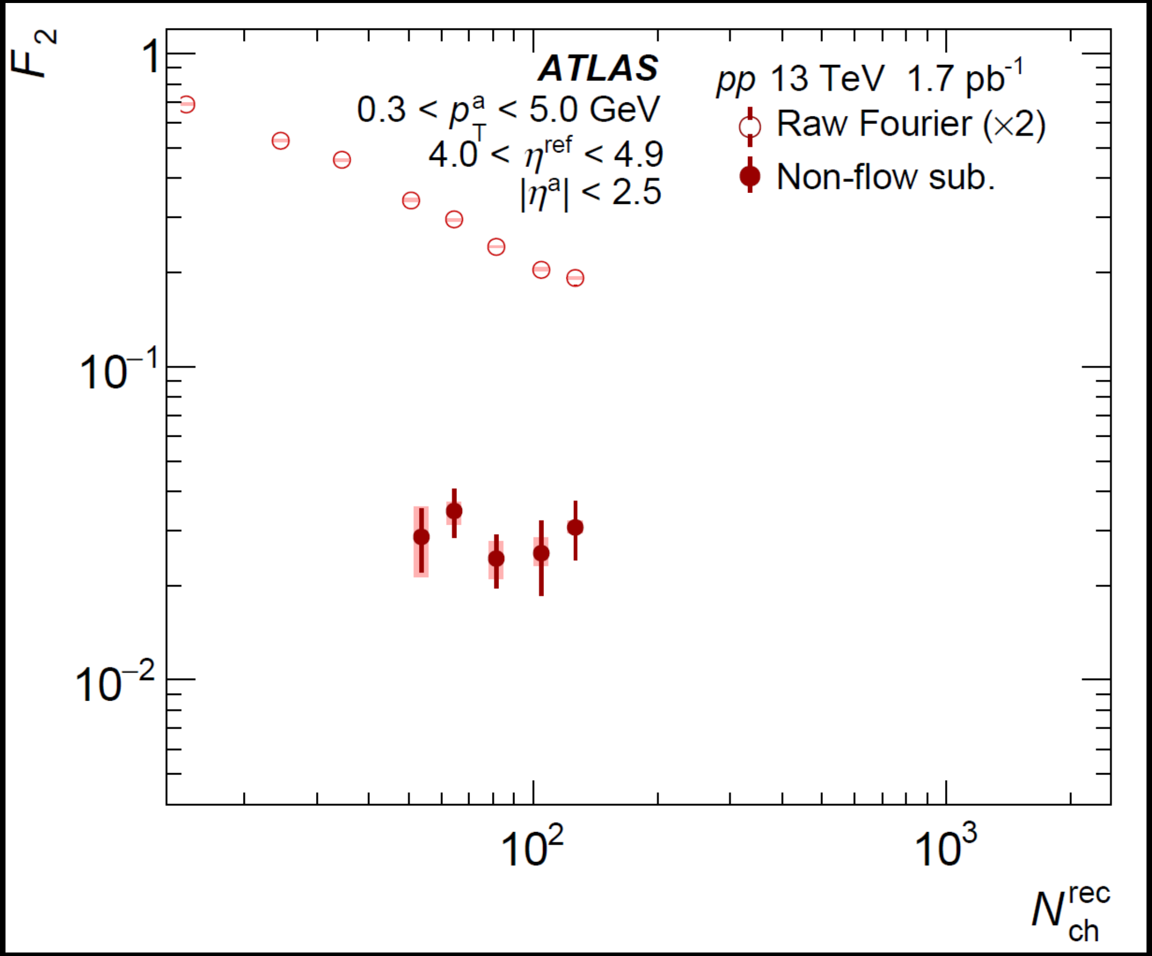
$$r_n(|\eta^a|) = \frac{c_n(-|\eta^a|)}{c_n(|\eta^a|)}$$

$$\approx 1 - 2F_n|\eta^a|$$

F_n is the fractional change in $v_{2,2}$ per a unit rapidity it characterizes longitudinal decorrelation effects well

Results in 13 TeV pp

arXiv:2308.16745



Raw Fourier (x2)

- combination of flow and nonflow
- Nonflow yields a huge fake decorrelation signal of raw F_2 = 0.09-0.4 which varies heavily with multiplicity

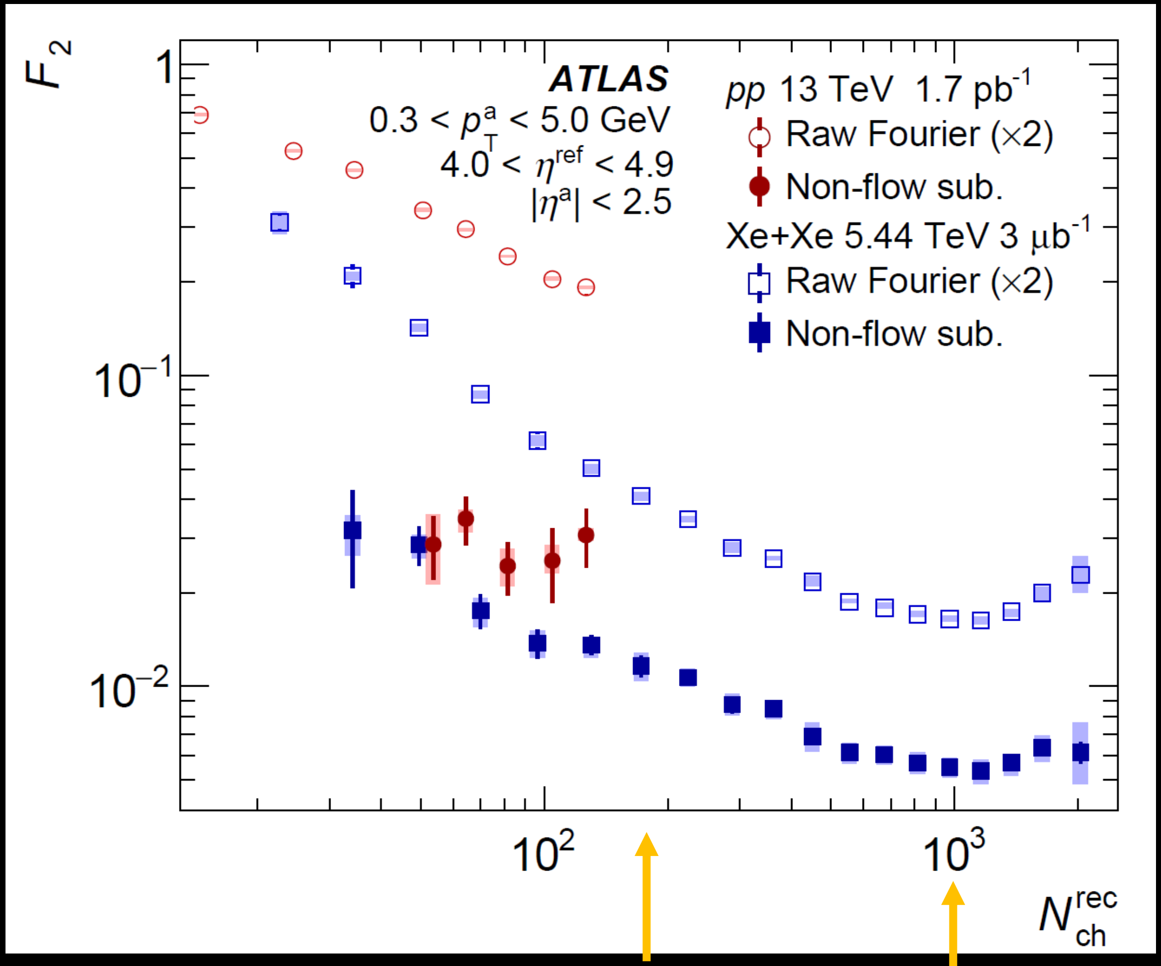
Nonflow subtracted F_2 (solid markers)

- Much smaller, F_2 = 0.02-0.03, which is multiplicity independent

Little change in longitudinal dynamics as a function of multiplicity

Results in Xe+Xe

arXiv:2308.16745



60% central

80%

Raw Fourier (x2)

- Consistent with past results in large systems from ***ATLAS*** and others for centrality > 60%

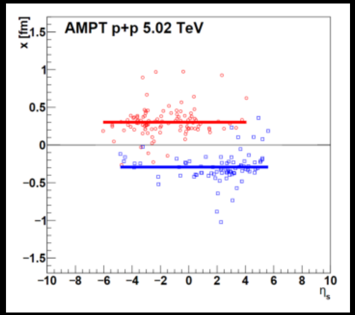
Nonflow subtracted F_2

- Nonflow subtraction removes 40-70% of raw decorrelation in peripheral.
- Decorrelation of ~0.03 observed in most peripheral ~80-90% centrality

- But we also observe 30% nonflow effect for more than 50% central
  - Template fit assumption-violating effects such as modification to nonflow shape may cause an overestimate of nonflow effects.
  - but with current available techniques is a significant background in all 2PC and event-plane measurements of decorrelation.

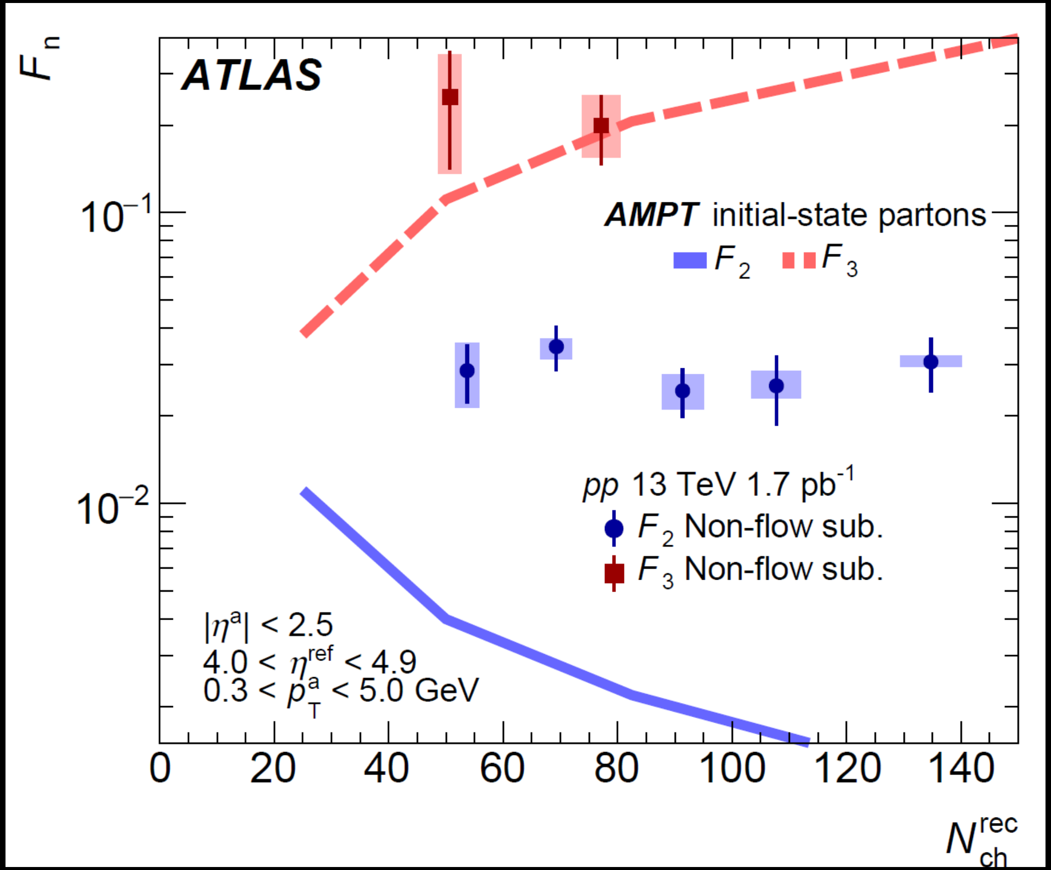
Qualitatively different behavior in the same N_{ch} range for *pp* and Xe+Xe

Comparisons to AMPT: *pp*



arXiv:2308.16745

- F_2: AMPT predicts an order of magnitude lower F_2 which is N_{ch} dependent
- Our results disfavor models with a small number of long color strings in the initial state and highlights the need for sub-nucleonic degrees of freedom.
- AMPT F_3 which is fluctuation driven agrees better with the data



Much larger F_2 in data than AMPT: disfavors a few long strings as initial state

v_2 of jet constituents

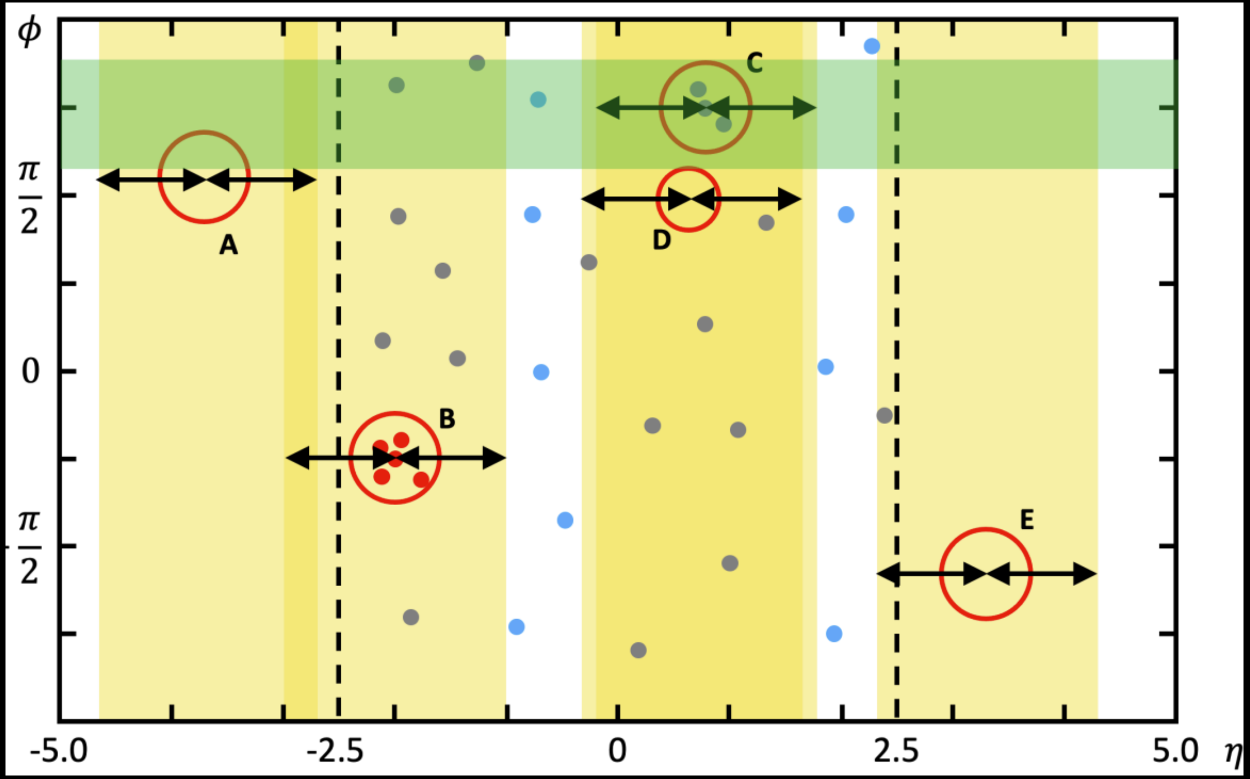
Correlation between jet particles and underlying event particles

Correlate

constituents of Jets with $p_T^G > 40$ GeV, $|\eta|<2.1$

with

underlying event particles (away from all jets)



Other details

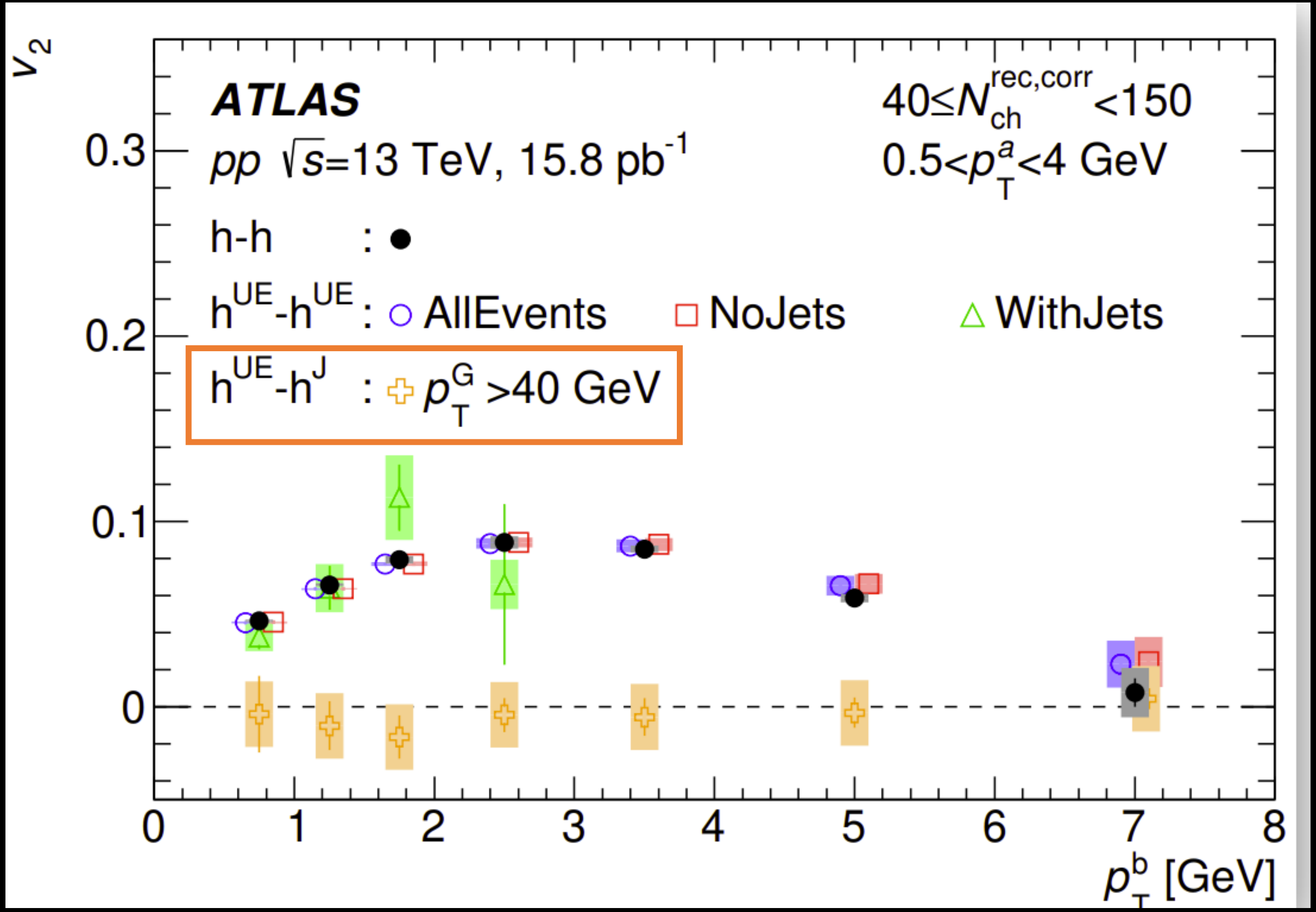
- Require balance jet with $p_T^G > 15$ GeV and $\Delta\varphi > 5\pi/6$ to reduce non-flow effects in 2PC
- Apply isolation to remove potential distortion of 2PC

v_2 of jet particles

- Jet particle v2 consistent with zero within uncertainties

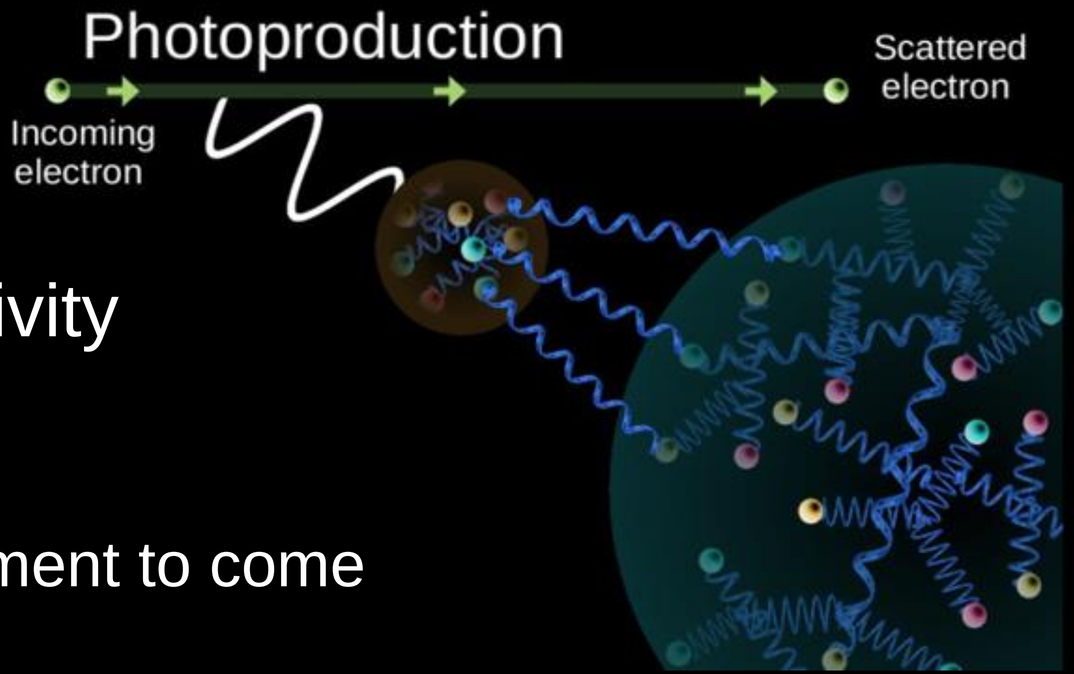
Major conclusions

- Jets do not contribute to the ridge signature in pp collisions
- Particles arising from jet even at low pT do not participate in the collective



arXiv:2303.17357

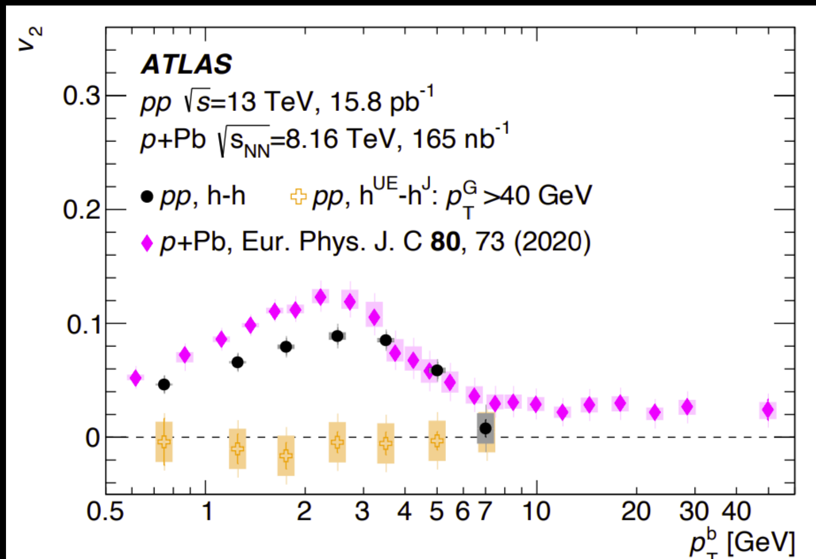
Conclusions



- γPb collisions have clear signs of collectivity
  - Non-zero v2
  - Implication for the EIC
  - Baryon anomaly and strangeness measurement to come

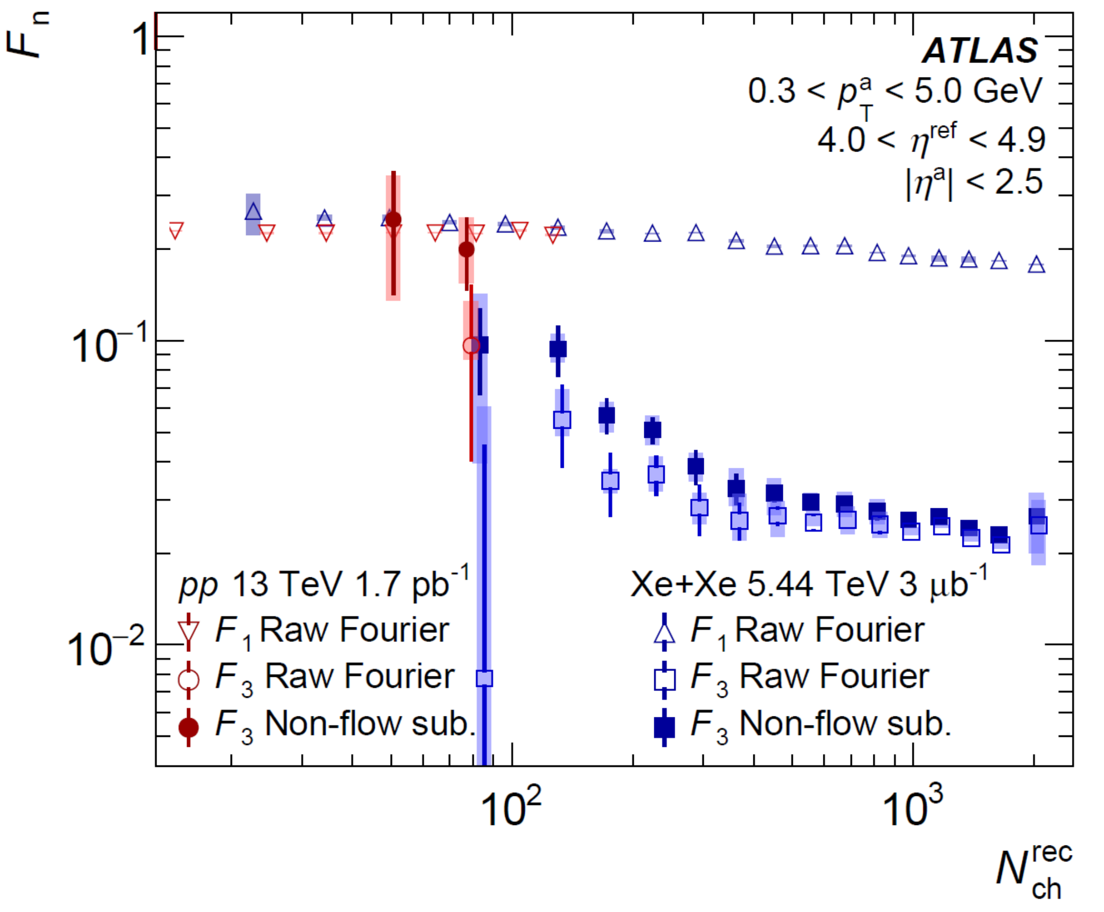
- Detailed measurements of longitudinal decorrelations
  - Nch independent F_n in pp collisions
  - Disfavors models without sub-nucleonic structure

- Jets of > 40 GeV and all their constituents do not participate in the flow
  - Extending this measurement to pPb



Other moments

arXiv:2308.16745



F_3

- similar qualitative features as 2nd
- Nonflow bias F_3 down but smaller bias because F_3 is generally larger
- Agreement between Xe+Xe within statistical uncertainties for low N_{ch}

F_1

- Completely dominated by nonflow not allowing for subtraction with current methods.
- Very little multiplicity dependence because there is little change in flow/nonflow composition

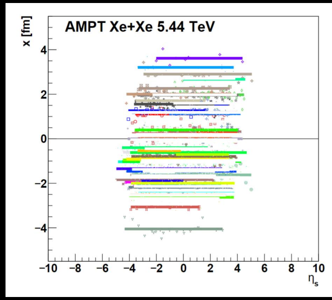
Comparisons to AMPT: Xe+Xe

- AMPT initial state geometric decorrelation F_n is shown and is calculated as follows

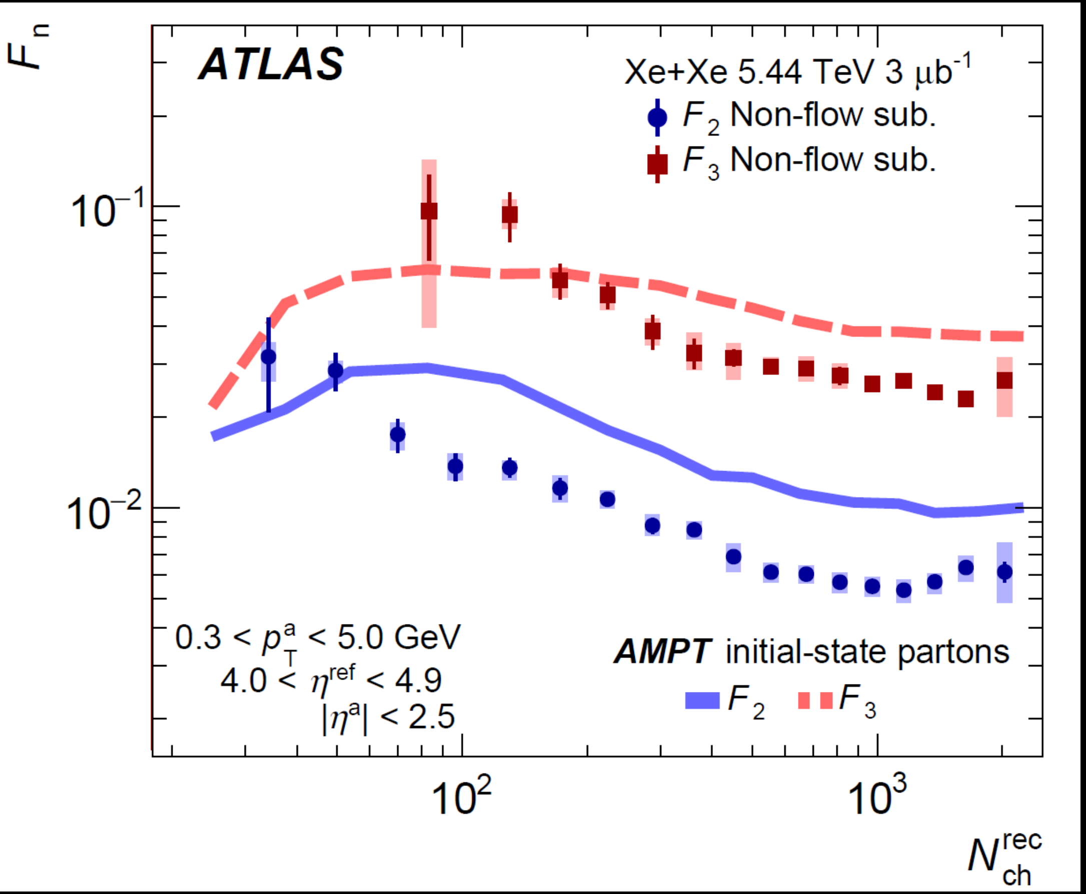
$$\overrightarrow{\varepsilon_2}(\eta^a)\cdot\overrightarrow{\varepsilon_2}(\eta^{ref}) = A(1+F_n\,\eta^a + S_n\,\eta^{a2})$$

- We observe qualitative agreement with AMPT in Xe+Xe in central and mid central collisions
  - within a factor of 2

- A qualitative change in behavior towards smaller decorrelation at low multiplicities is present in AMPT and does not appear in the data.
- This may also indicate the need for sub-nucleonic degrees of freedom.



arXiv:2308.16745



Data indicates sub-nucleonic structure is required to describe peripheral AA and pp

Underlying event bias on particle flow jets