High Multiplicity eA Collisions: Azimuthal Anisotropy

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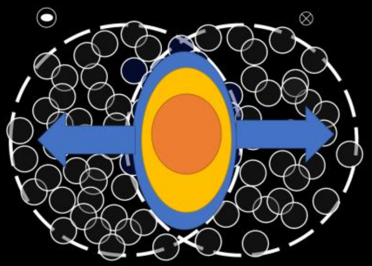
ATLAS EXPERIMENT

sPHENIX

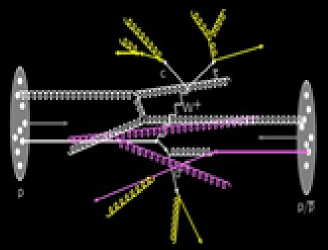
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

1ST INTERNATIONAL WORKSHOP ON A 2ND DETECTOR FOR THE EIC

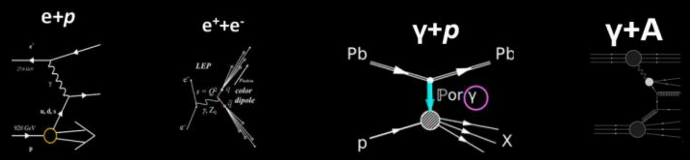
Overview



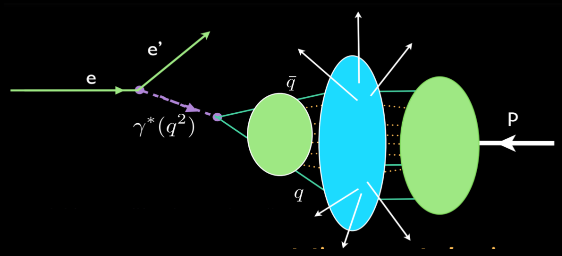
1. What is azimuthal anisotropy



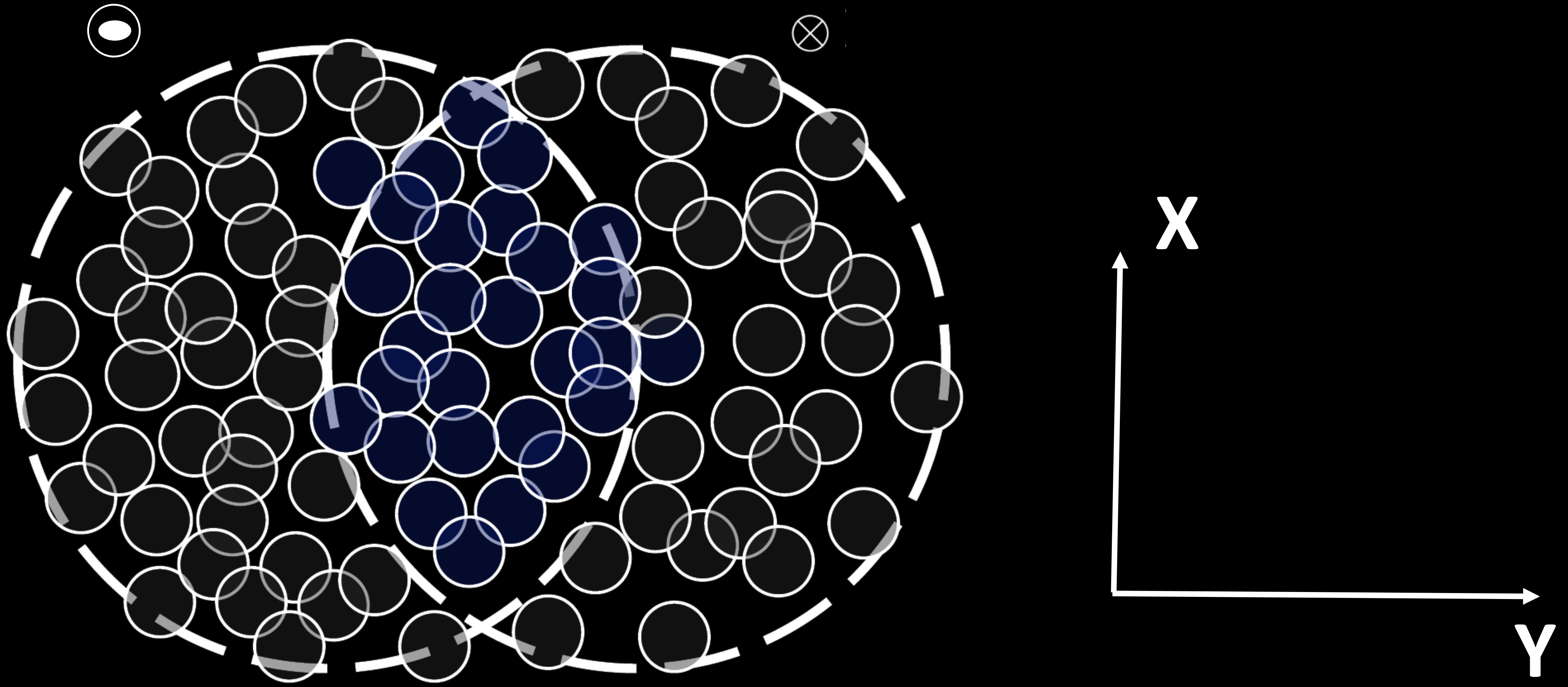
2. Where it has been observed

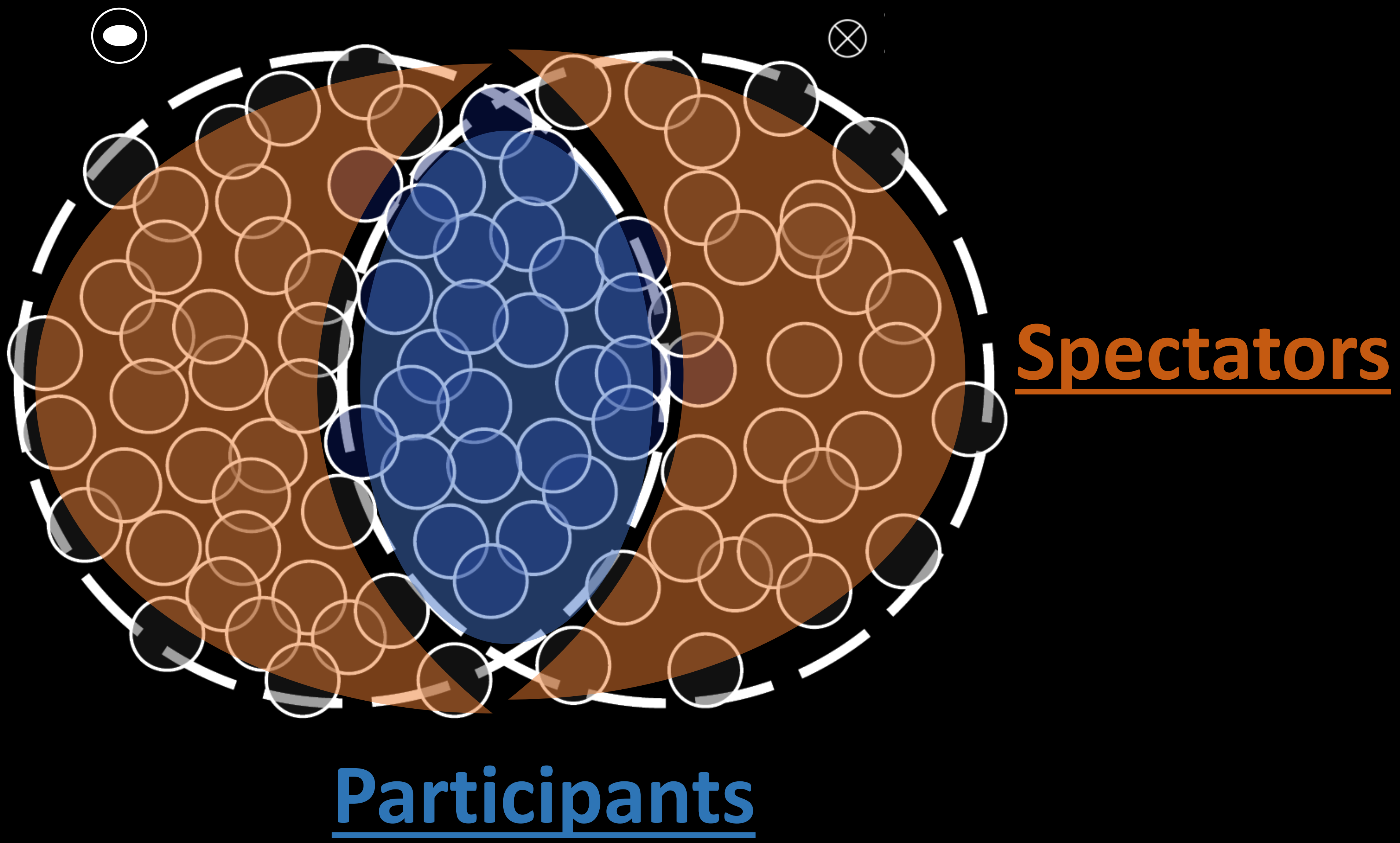


3. Recent measurements relevant for the EIC



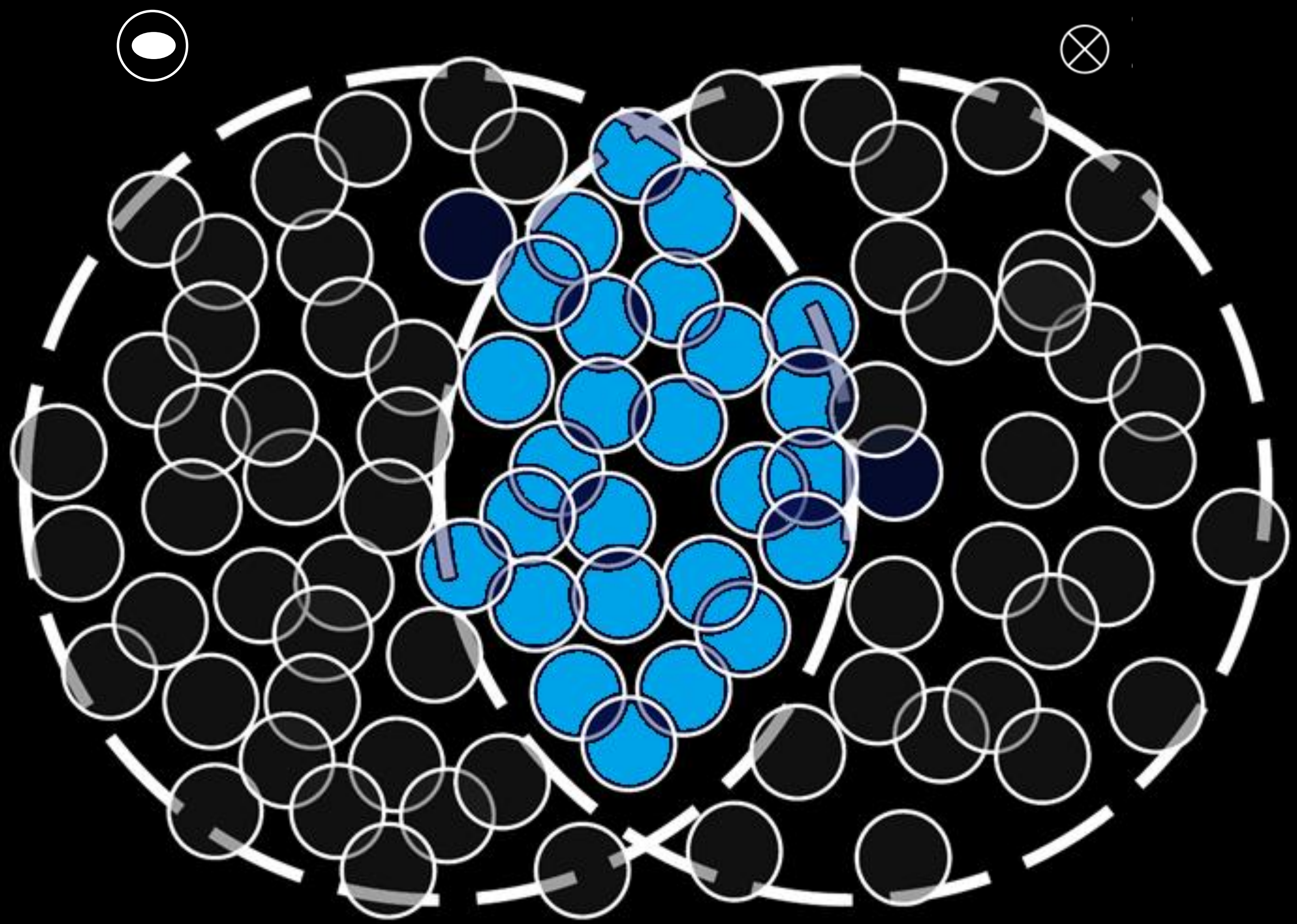
4. Perspectives for azimuthal anisotropy at the EIC

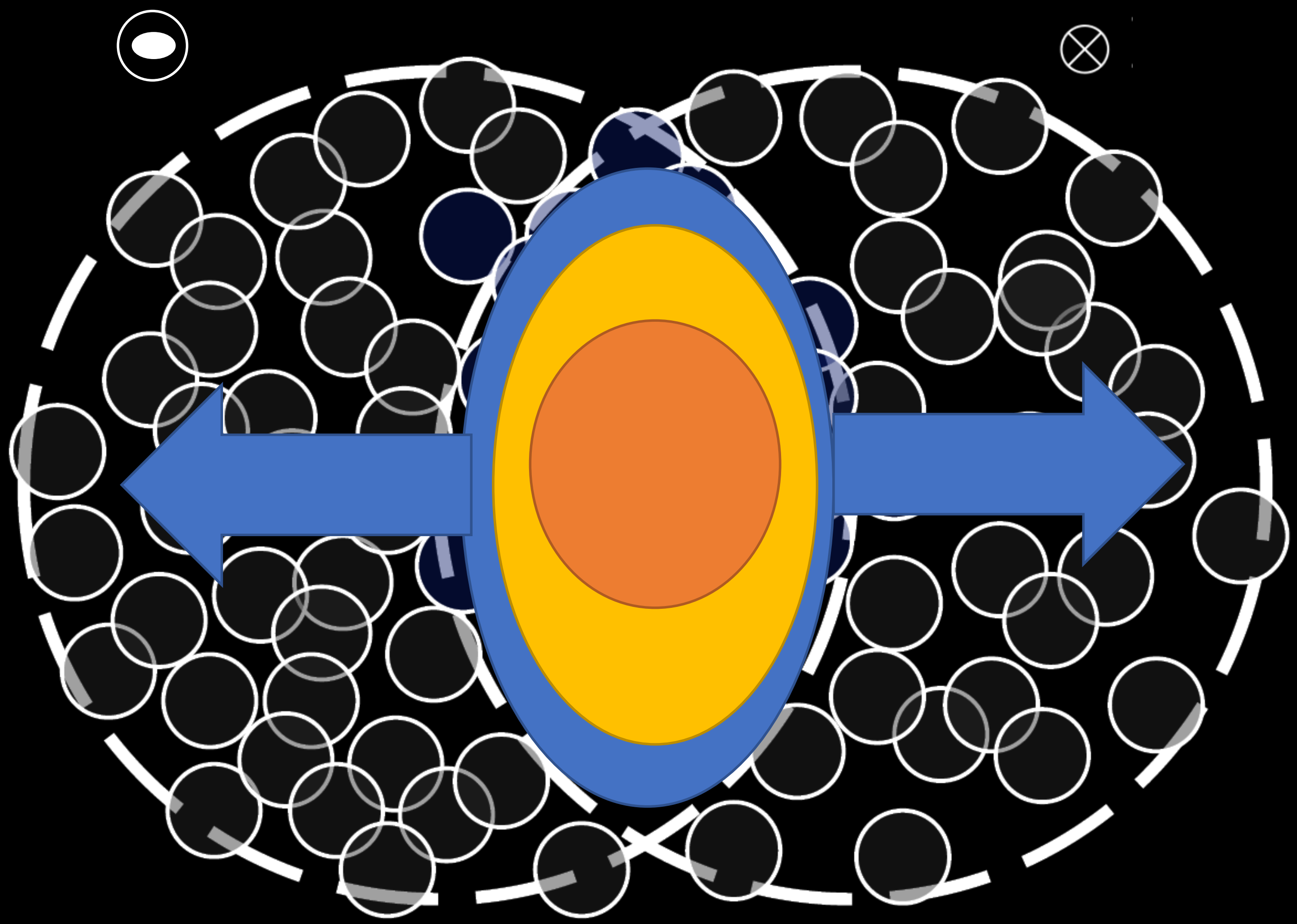

X
Y



Spectators
Participants

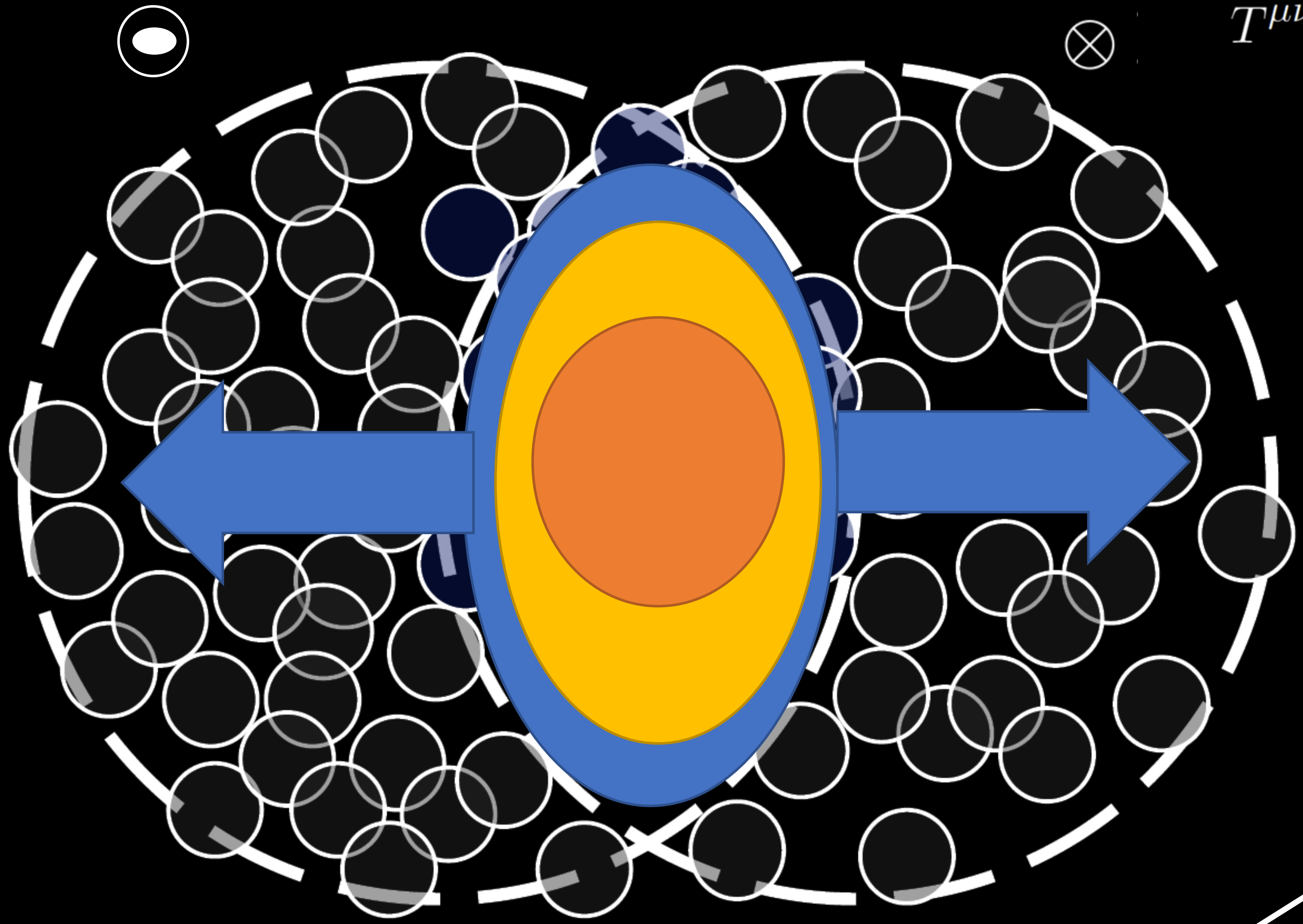
Initial state





Viscous Hydrodynamics

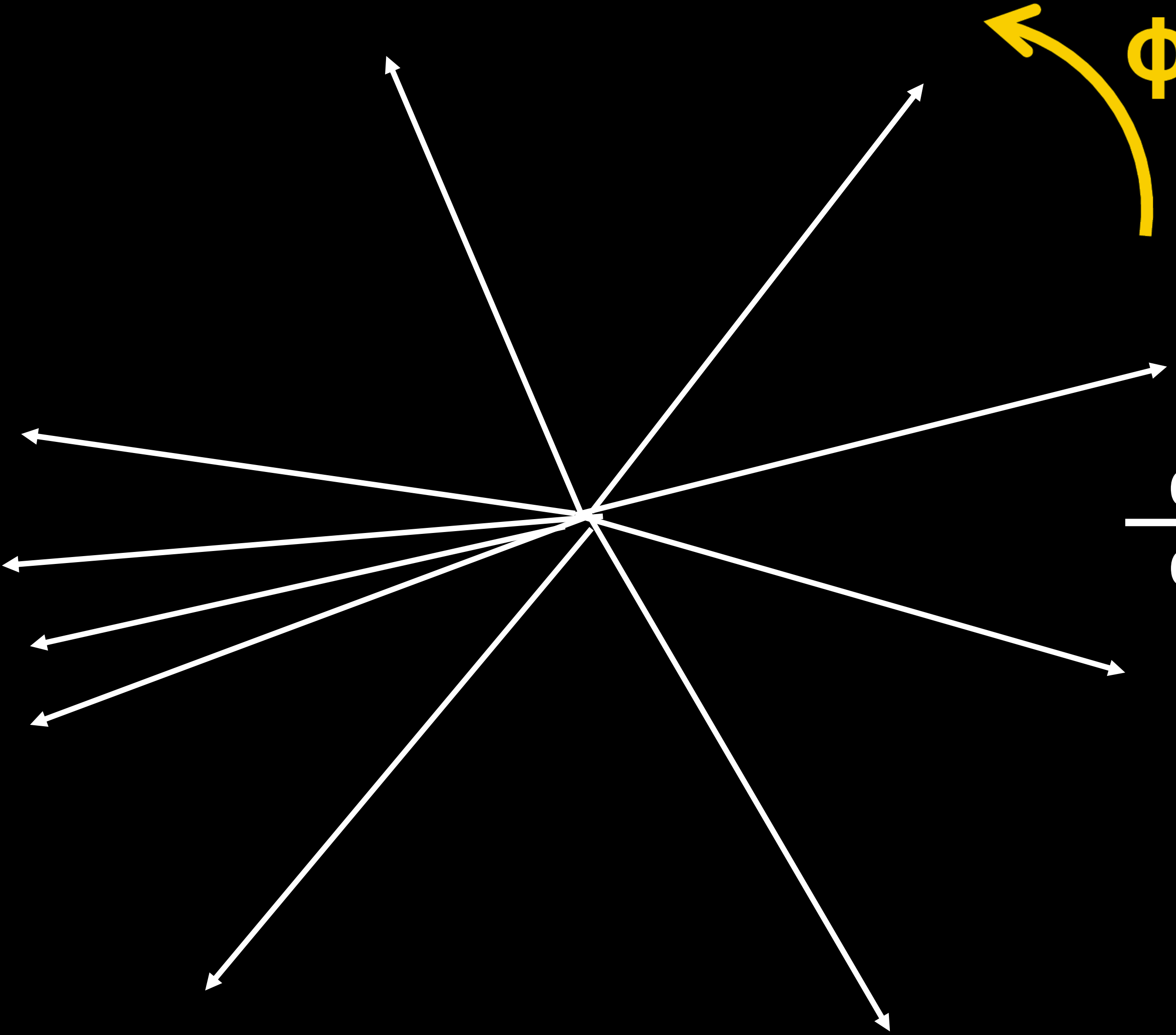
$$T^{\mu\nu} = \underbrace{\epsilon u^\mu u^\nu + P[\epsilon]\Delta^{\mu\nu}}_{\text{Ideal Hydro}} \underbrace{- \eta[\epsilon]\sigma^{\mu\nu} - \zeta[\epsilon]\Delta^{\mu\nu}\nabla^\perp_\lambda u^\lambda}_{\text{Viscous Hydro}}$$



Equation of state $P[\epsilon]$

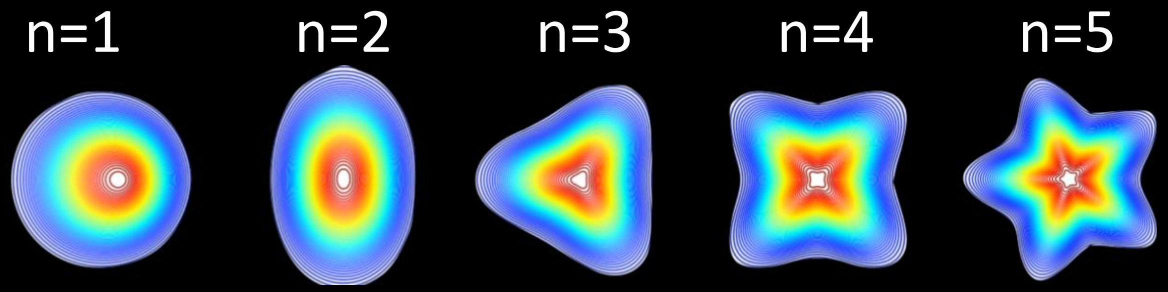
transport coefficients $\eta[\epsilon]\ \zeta[\epsilon]$.

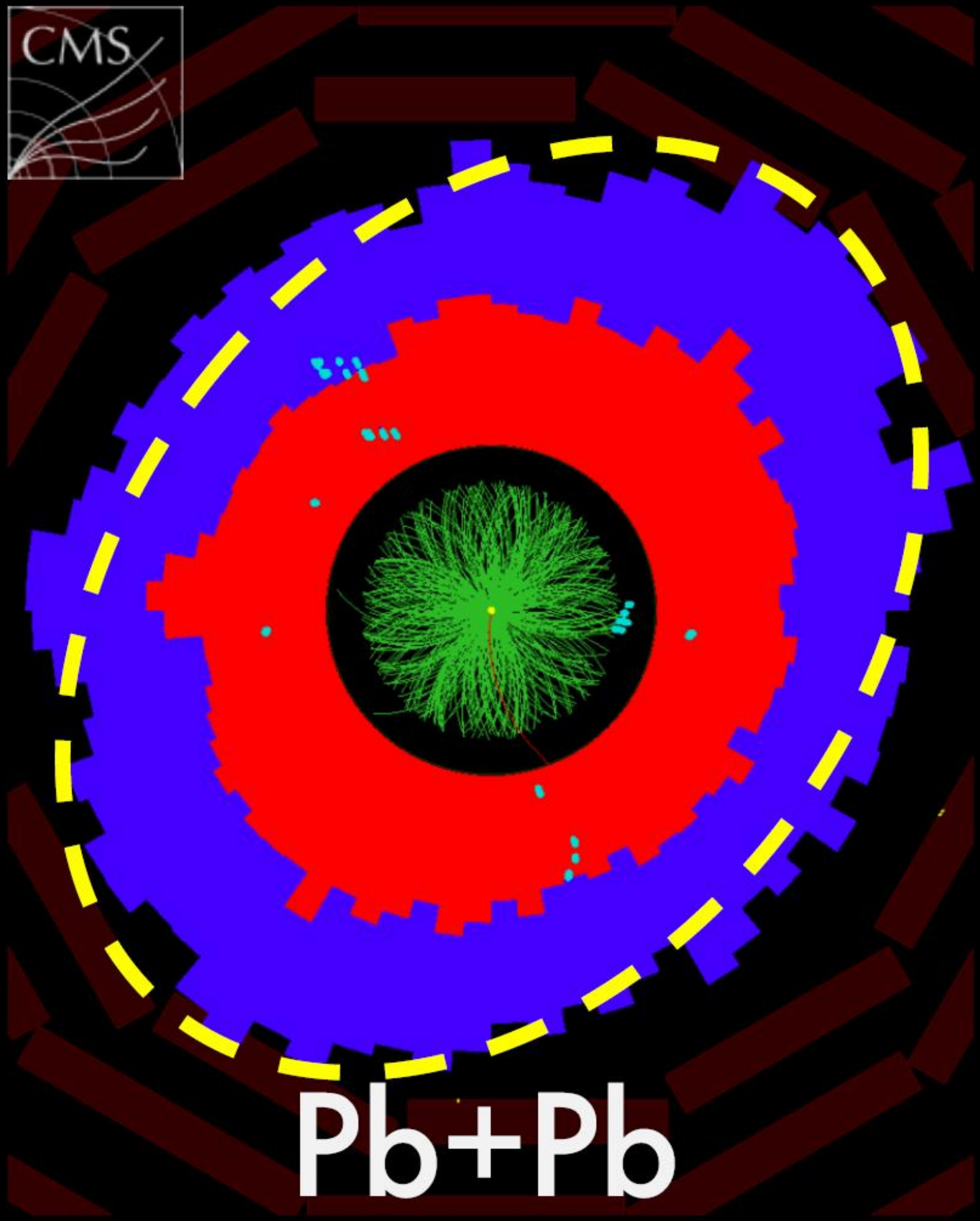
Initial state → **Hydro** → Momentum anisotropy



Azimuthal anisotropy

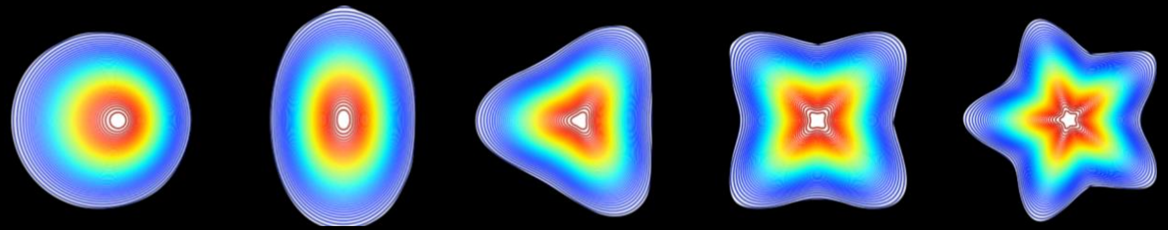
$$\frac{dN}{d\phi} \alpha \; 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + \ldots$$





Single-particle azimuthal anisotropy

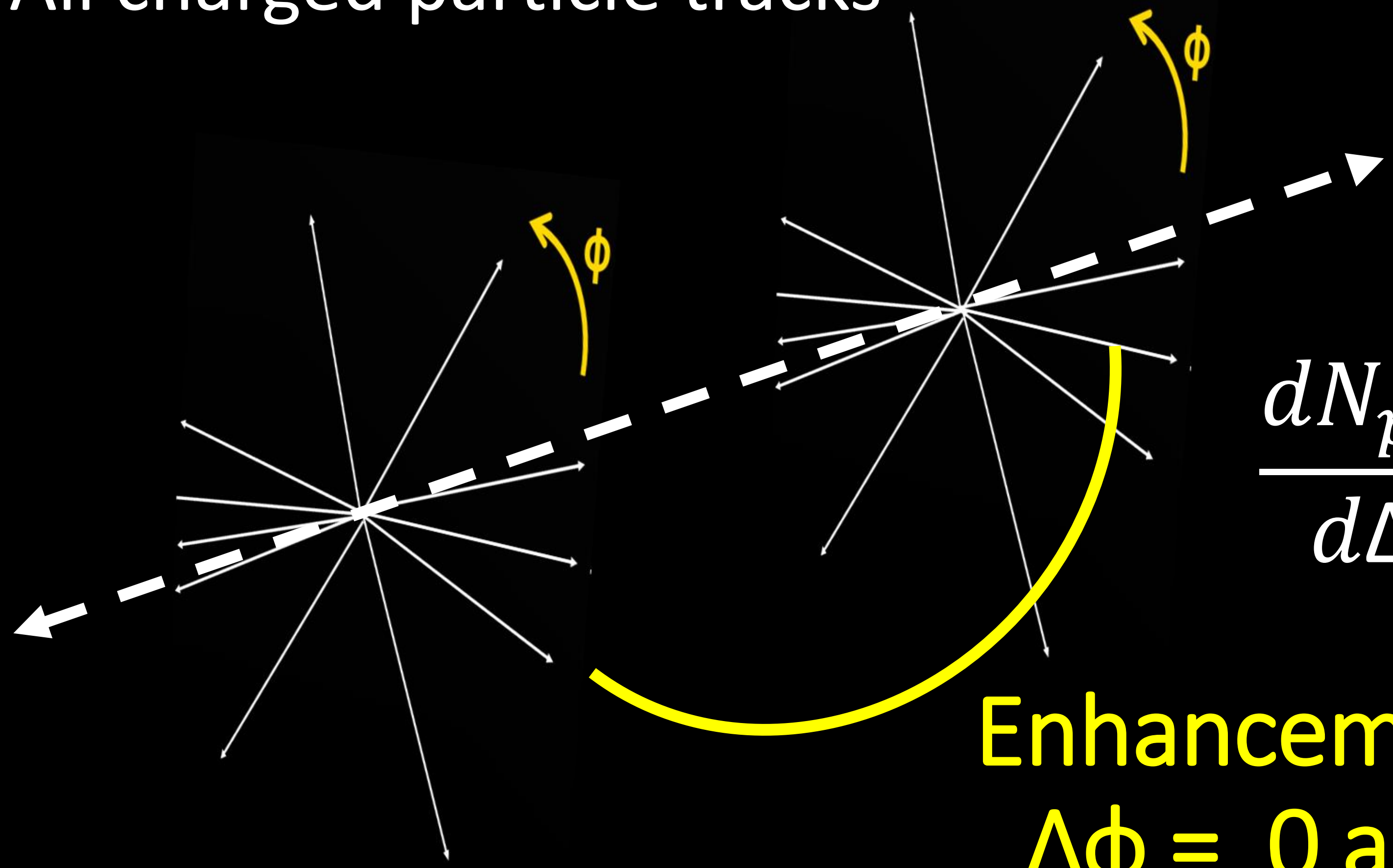
$$\frac{dN}{d\phi} \propto 1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + 2v_3\cos(3\phi) + \ldots$$



Two-particle correlation

For the purposes of this talk

All charged particle tracks



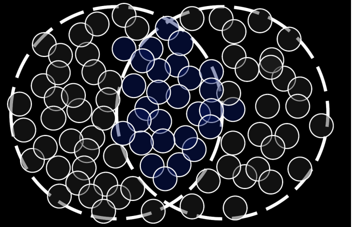
rapidity

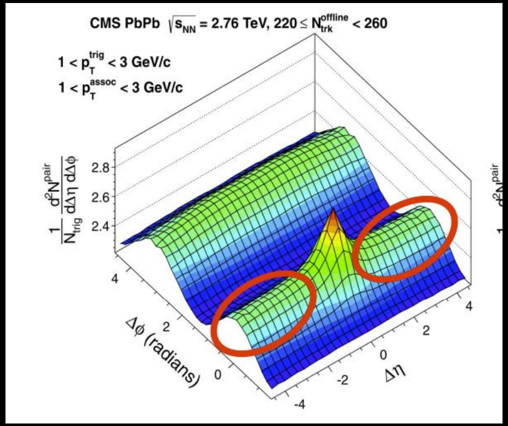
$$\frac{dN_{pair}}{d\Delta\phi} \;\alpha\; 1 + 2v_{2,2}\cos(2\Delta\phi) + \,..$$

Enhancement at
$\Delta\phi = 0$ and π

System size

Pb+Pb



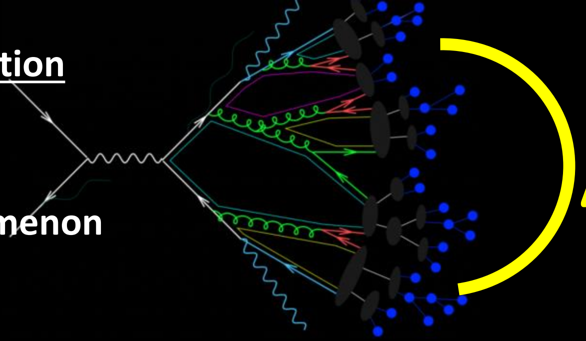


Momentum conservation

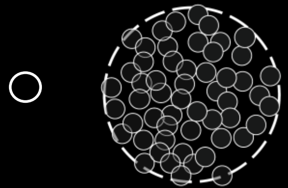
Jets & particle decays

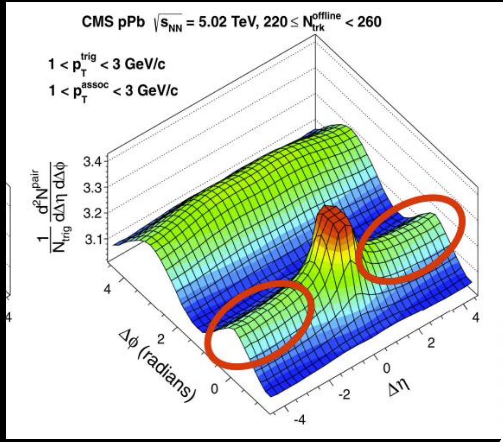
Termed "nonflow"

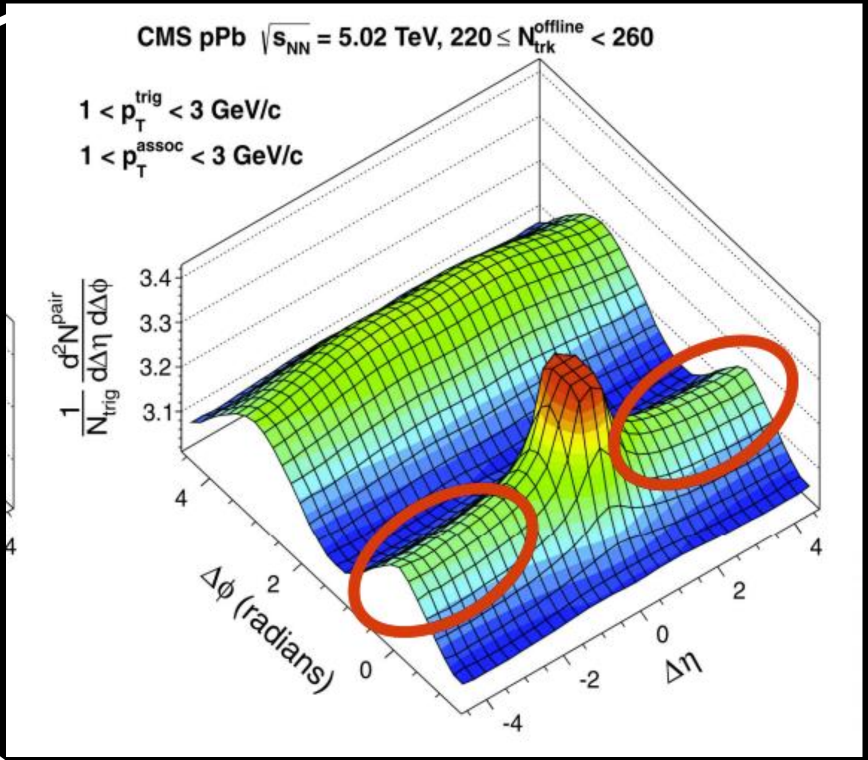
Not collective phenomenon



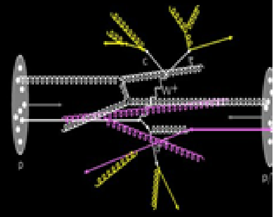
p+Pb

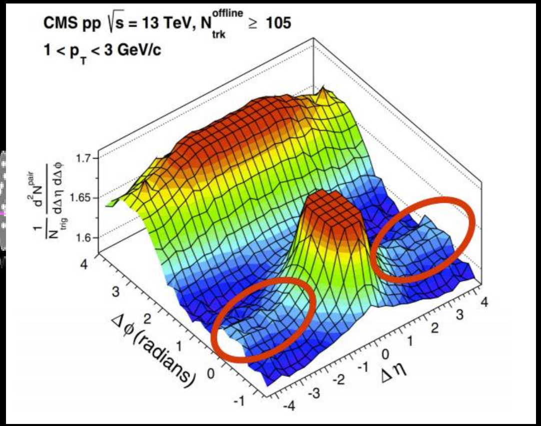


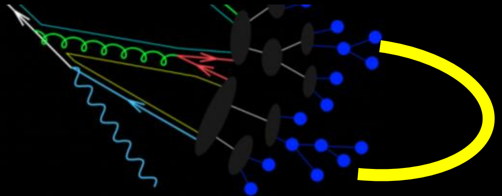




pp



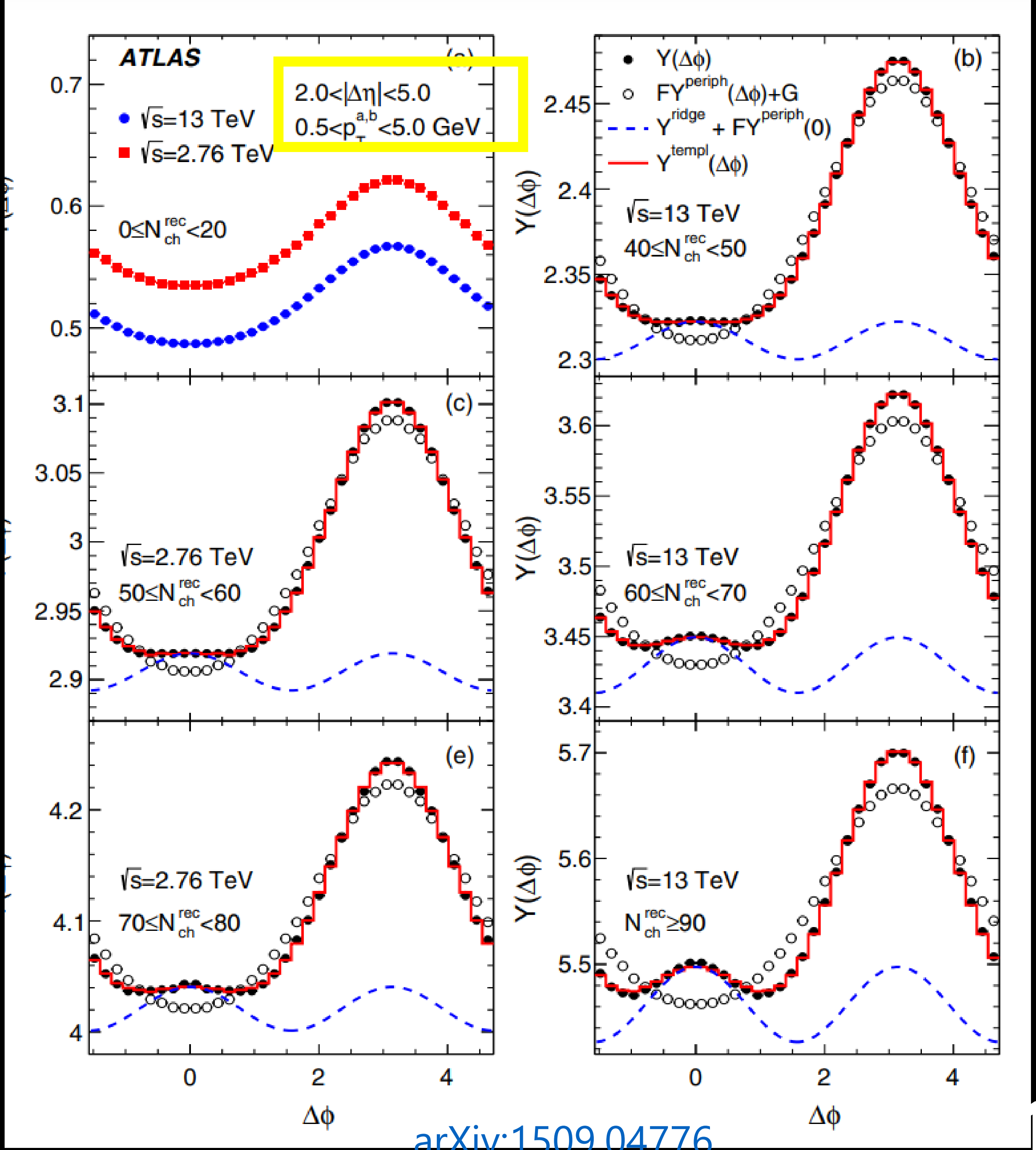




pp azimuthal anisotropy

- **13 TeV *pp* collision correlations at different N_{ch} (black markers)**
- "Near-side ridge" ($\Delta\phi=0$) clearly visible in in $N_{ch}>90$
- Near-side ridge NOT visible for $N_{ch} < 60$.
- Near-side ridge does not actually change % modulation with increasing N_{ch}
- **nonflow background decreases with growing N_{ch}**

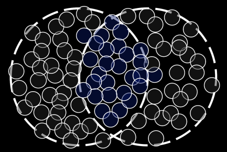
Multiplicity/acceptance is key for observing flow-like correlations

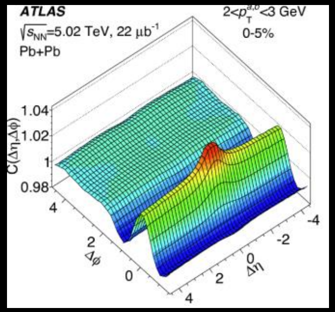


arXiv:1509.04776

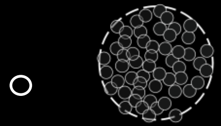
System size

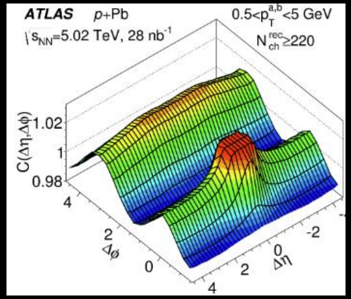
Pb+Pb



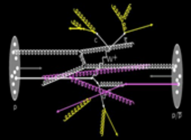


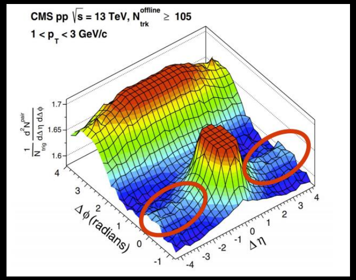
p+Pb





pp

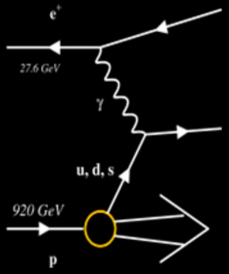




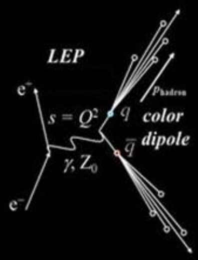
What are the minimal condition for collectivity?

Many new searches in other small systems

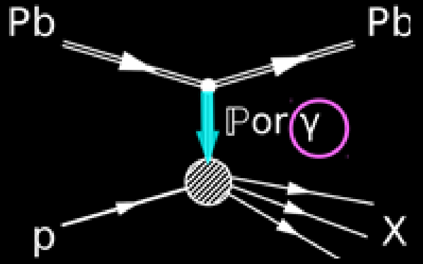
e+*p*



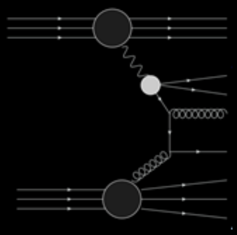
e⁺+e⁻



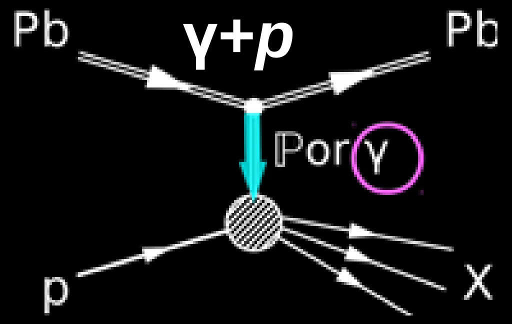
γ+*p*



γ+A

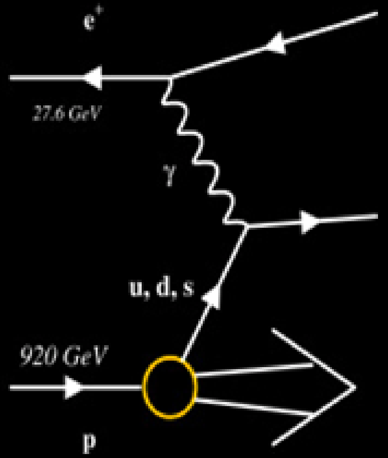


Recent measurements relevant for the EIC

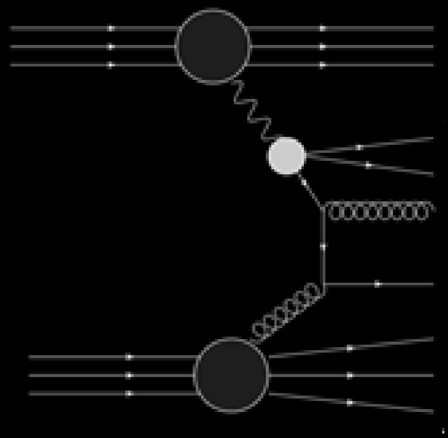


Today

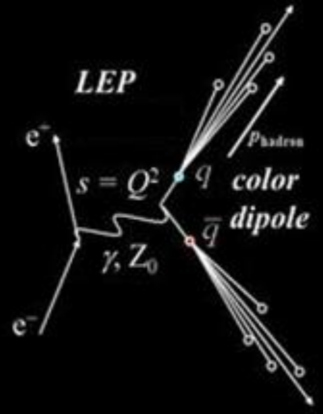
e+p



γ+A



e+e-



γ+p collectivity
arXiv:2204.13486

H1 experiment

Preliminary

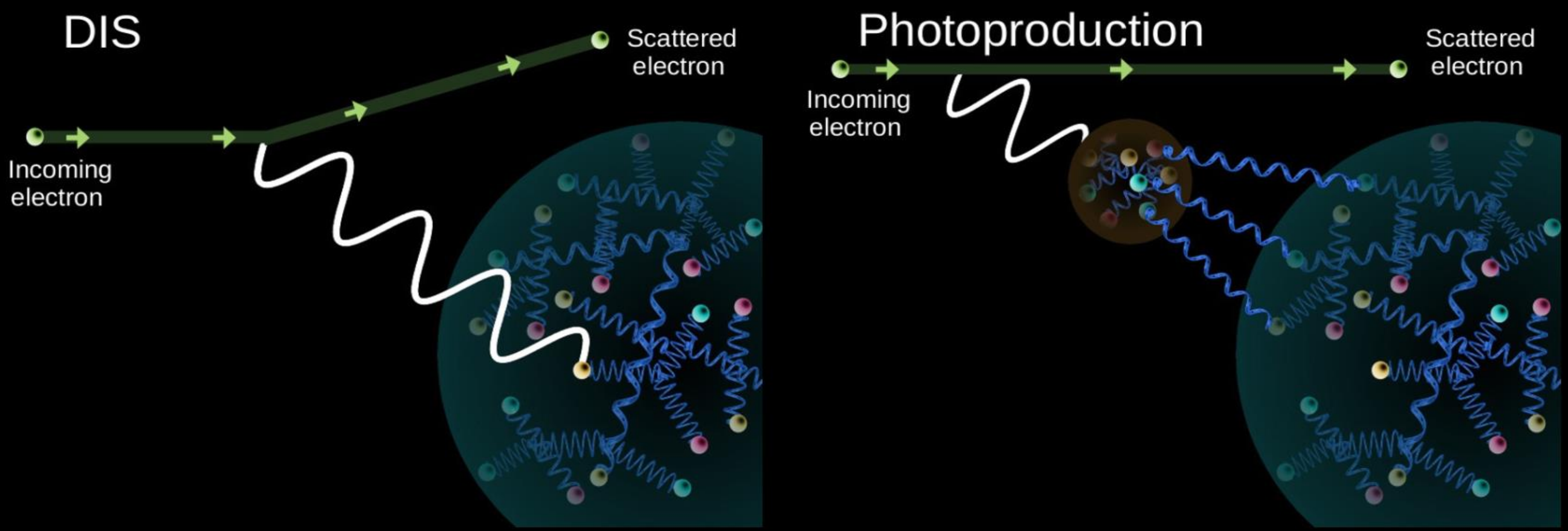
arXiv:2106.12377

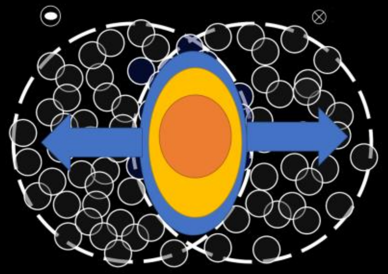
γ+A collectivity
arXiv:2101.10771

ICHEP22 talk

QM22 talk

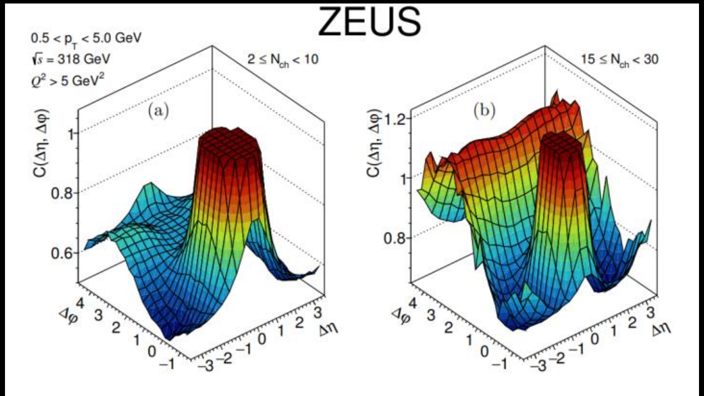
Azimuthal anisotropy in e-p collisions

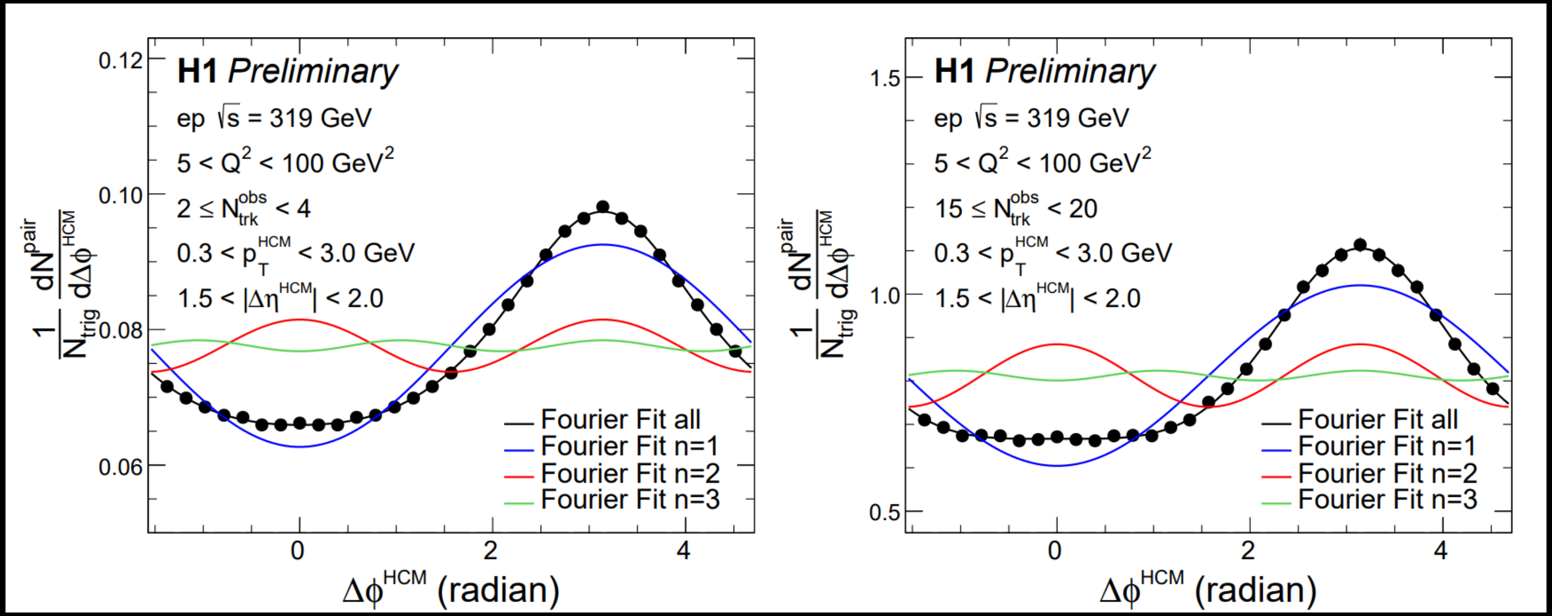




- We have observed azimuthal anisotropy in systems where a non-perfectly-circular energy deposit has been created with some transverse extent
- DIS: Point-like interaction region would suggest little geometry or final-state interactions
- Photoproduction: photon mostly fluctuates to a vector meson and interacts hadronically with the target. This provides an energy deposit with a transverse extent and possible elliptic geometry.

ep correlations



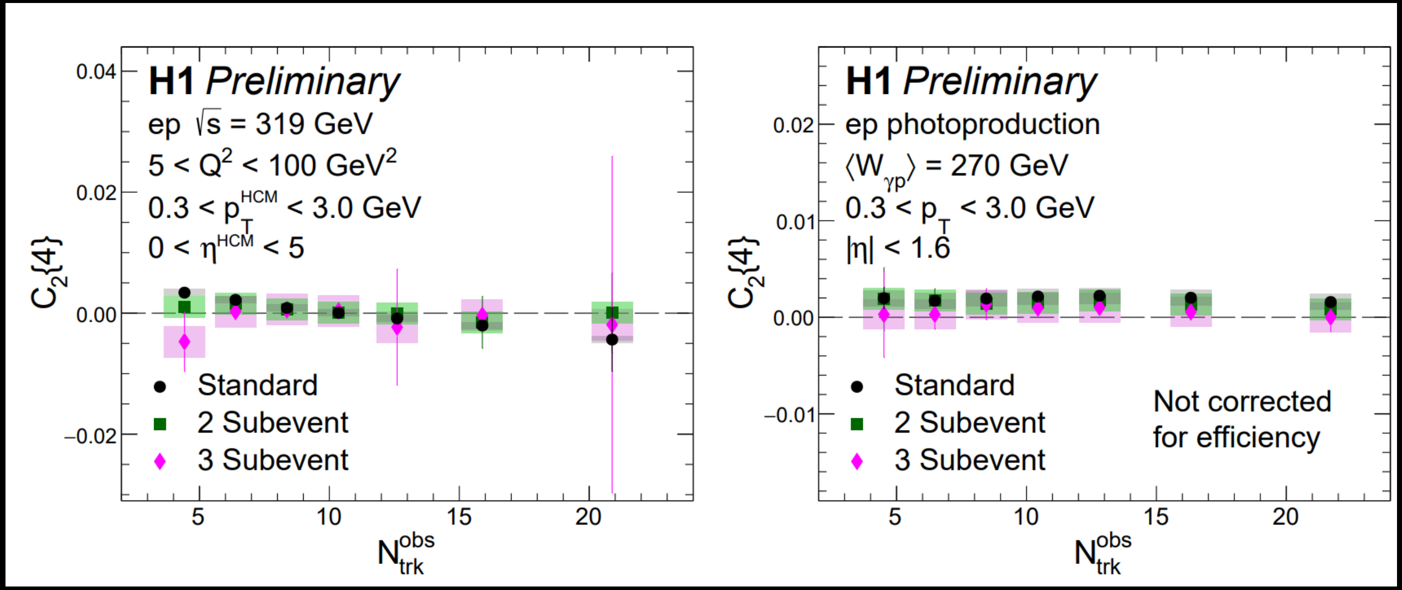


- DIS selection on Q^2
- No near-side ridge but given the low multiplicity one would not expect collective effects to be visually apparent.
- Neither H1 or ZEUS in either photoproduction or DIS see signs of collectivity

Multi-particle correlations with H1

Multi-particle correlations

- Collective dynamics are thought to impact all the particles in the event
- Non-flow background: correlations only a few particles
- Because of the above two items, 4,6,8,10 (!) particle correlations have been conducted in small systems.
- More subevents further reduces background but decreases acceptance



- In hadron-hadron collisions, the non-flow background has a positive $C_2\{4\}$ and the collective signature is negative $C_2\{4\}$
- No signs of collectivity, but more multiplicity reach and stats would be extremely helpful
- Once again, given cumulant results in pp collisions, we wouldn't necessarily expect the background to be adequately suppress at low N_{ch}

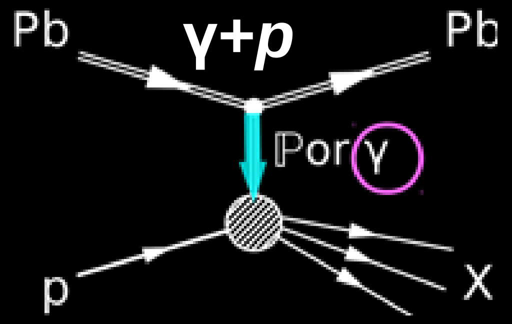
Recent measurements relevant for the EIC

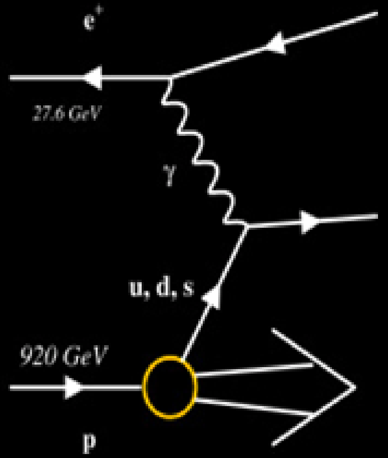
Today

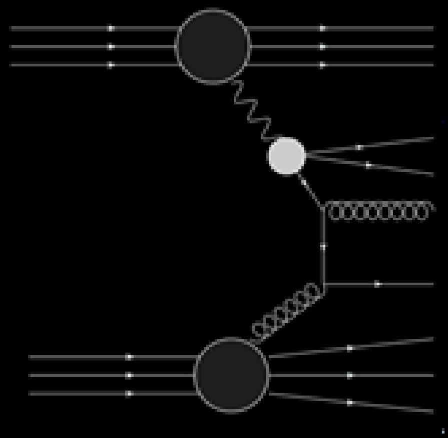
e+*p*

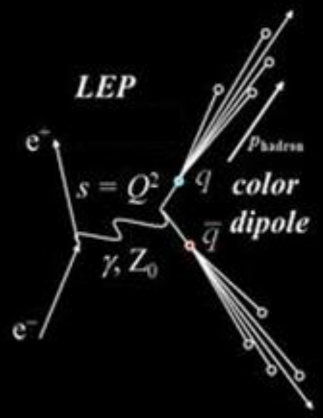
γ+A

e⁺+e⁻









CMS

γ+*p* collectivity
arXiv:2204.13486

H1 experiment

ZEUS

Preliminary

arXiv:2106.12377

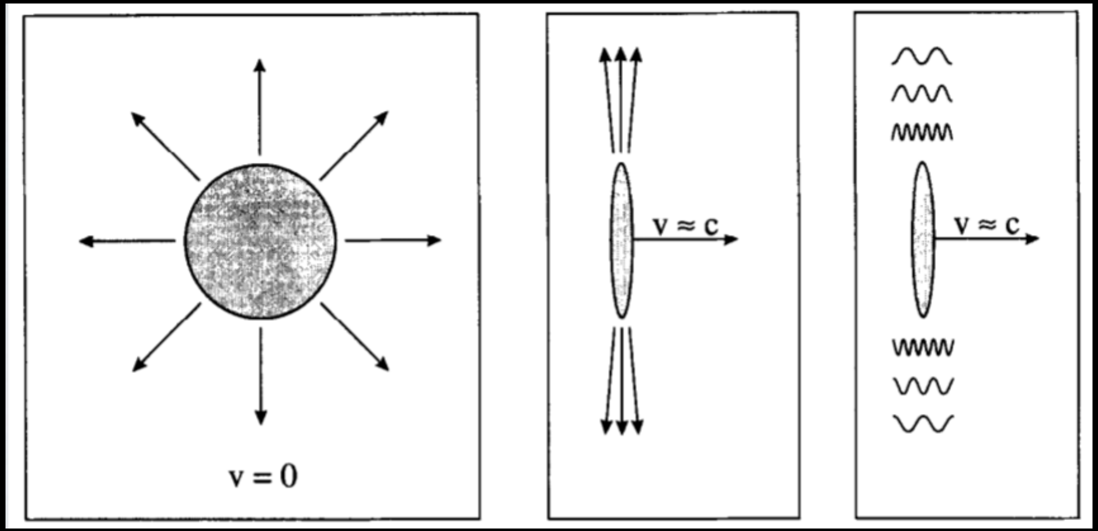
ATLAS EXPERIMENT

γ+A collectivity
arXiv:2101.10771

ICHEP22 talk

QM22 talk

Ultra-peripheral collisions at the LHC

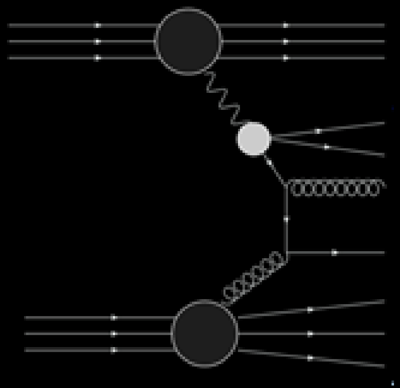


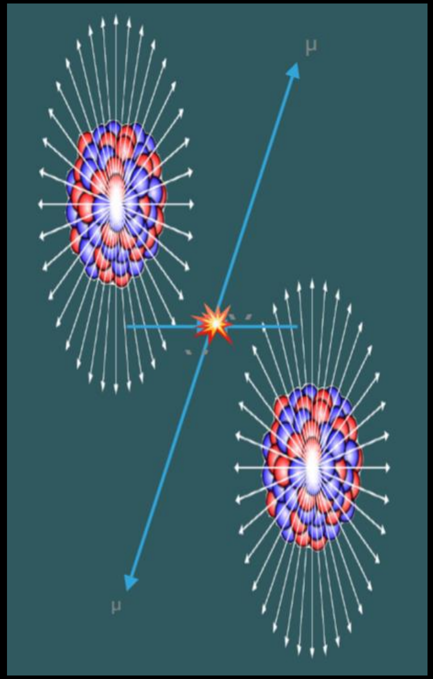
Coulomb fields of moving charges can be treated as an equivalent flux of quasi-real photons (Q^2=0) which are boosted to high energies.

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

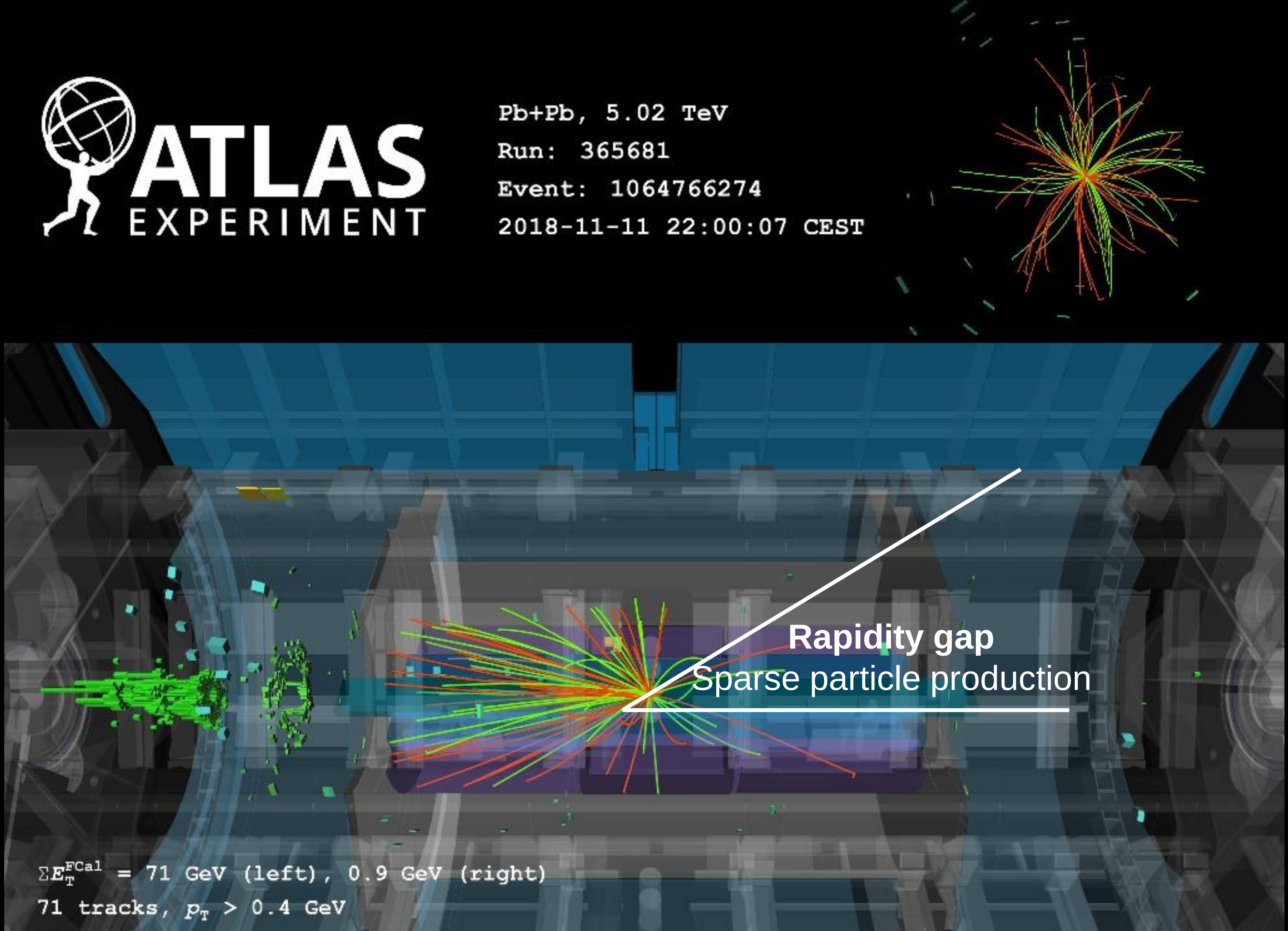
When $b > 2R_A$ two categories of interactions

- 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



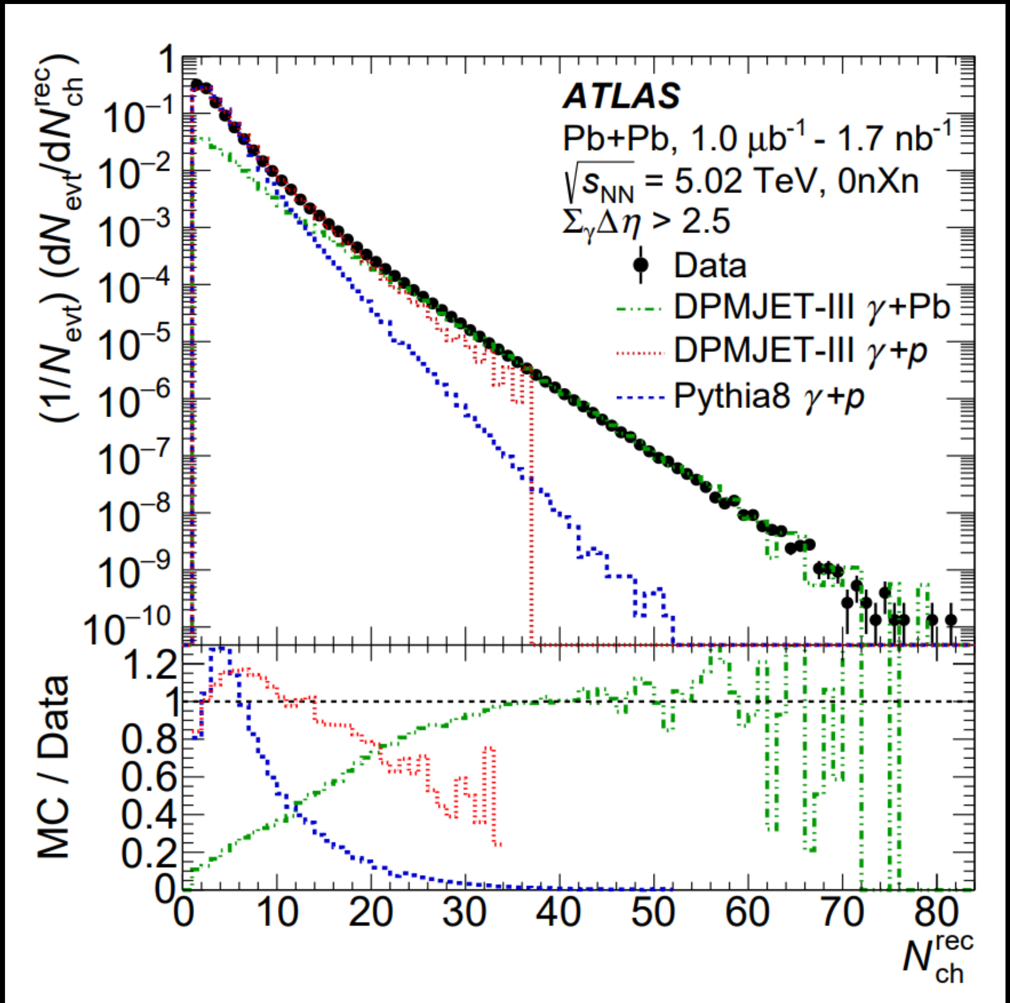


Pb
going
direction



photon
going
direction

Multiplicity in photonuclear collisions at the LHC



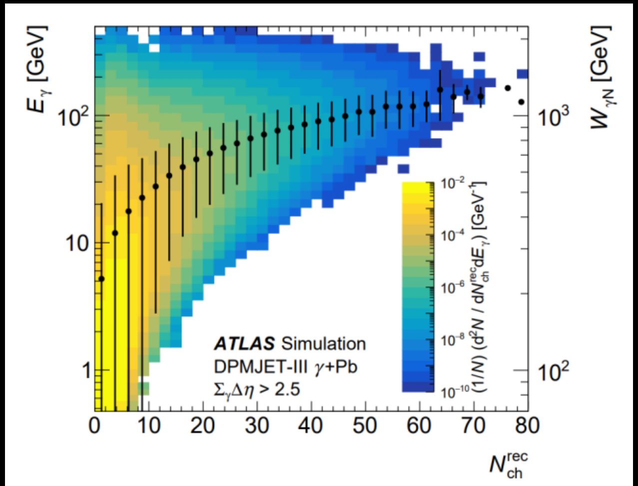
Large number of final state particles for photon induced collisions

Multi-nucleon interaction in the Pb target

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

Much greater observed Nch is possible if the detector acceptance was centered around the collision frame

Selecting the highest energy collisions →

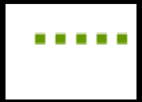


$|\eta|<2.5$, $p_T>400$ MeV

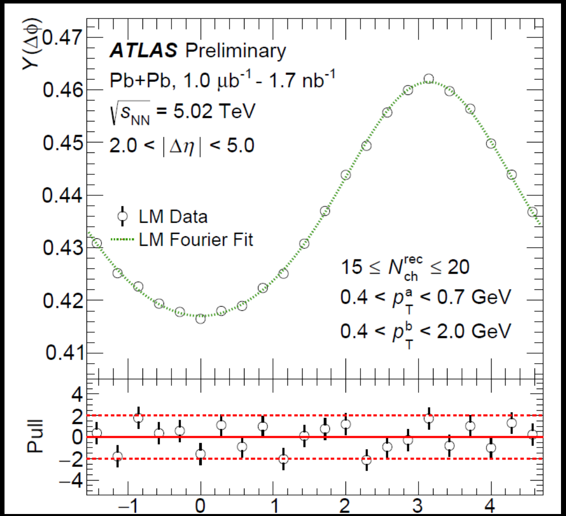
arXiv:2101.10771

Template fit in photonuclear

High-multiplicity (HM) correlation data



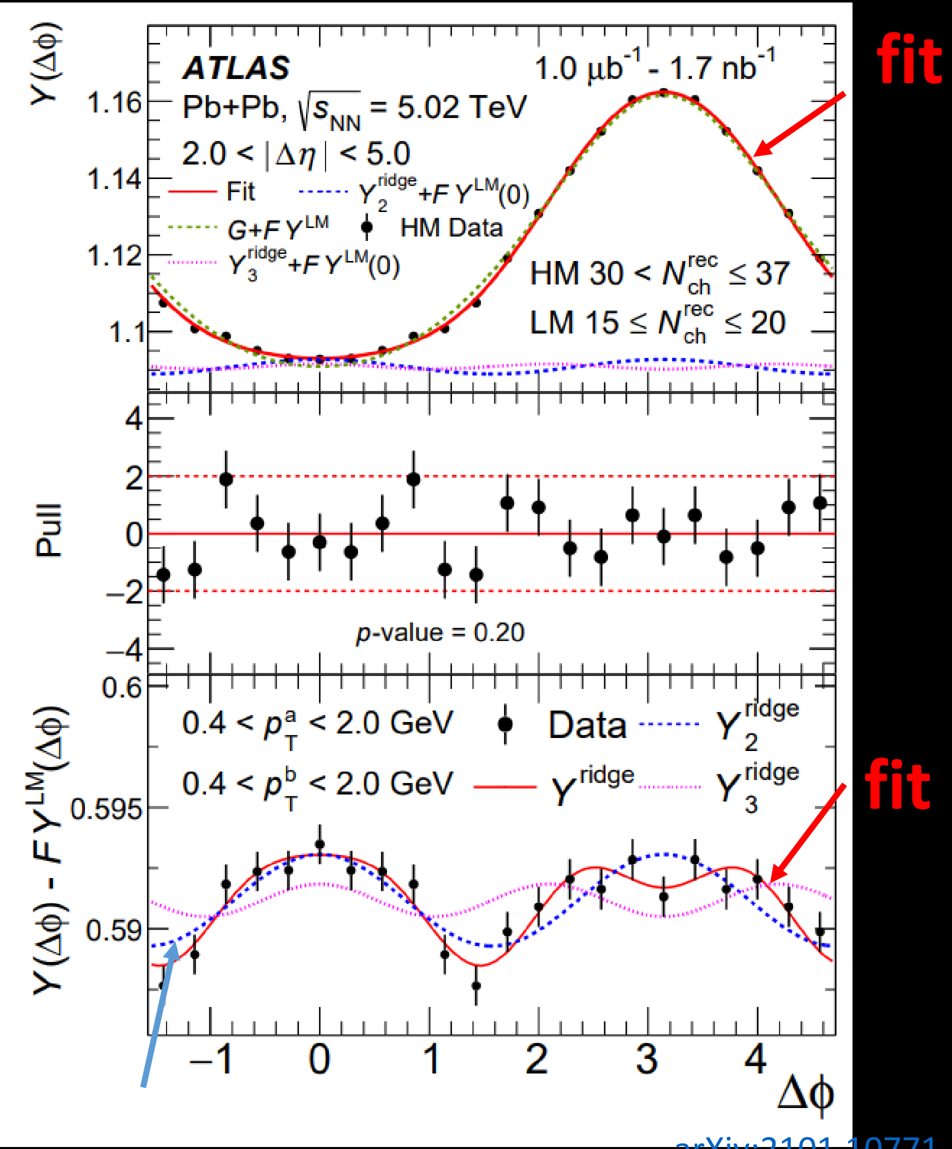
Low multiplicity (LM)
template for jet/non-flow correlation



<u>Nonflow subtraction</u>

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

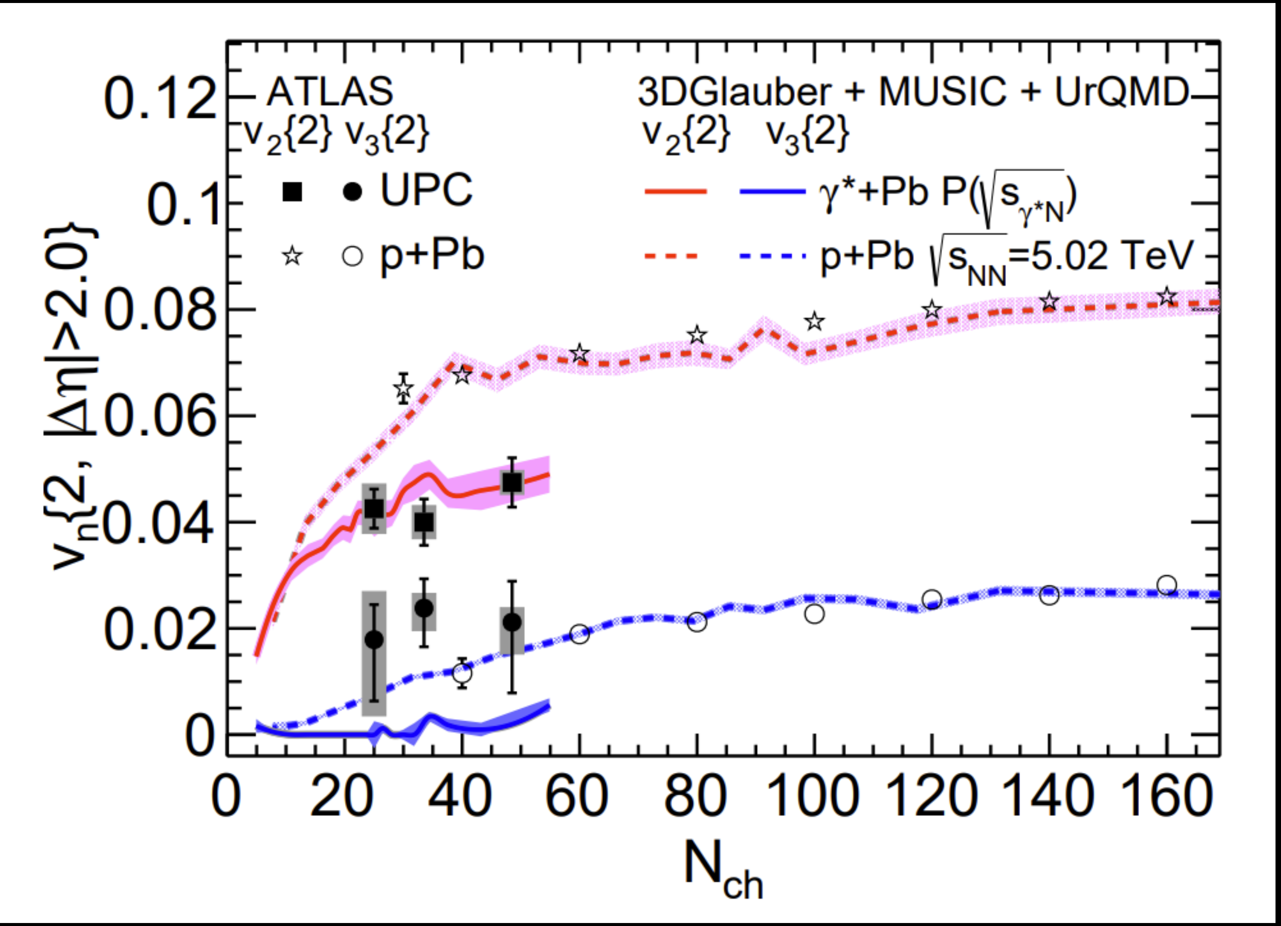
$$Y^{HM}(\Delta\phi) = FY^{LM}(\Delta\phi) + G\left\{1 + 2\sum_{n=2}^{3} v_{n,n}\cos(n\Delta\phi)\right\}$$



arXiv:2101.10771

After nonflow subtraction clear cos(2Δϕ) modulation

New γ+Pb theory comparisons



New comparison to 3DGlauber + MUSIC +UrQMD

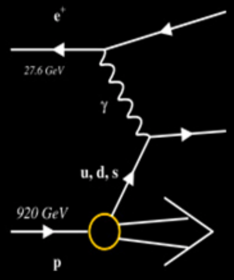
Quantitatively reproduces both *p*+Pb and γ+Pb simultaneously

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

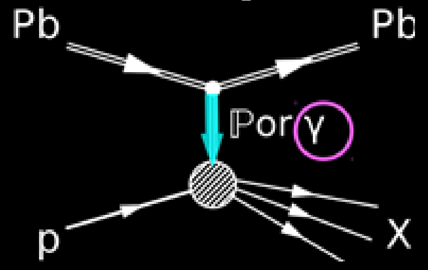
arXiv:2203.06094 arXiv:2101.10771

Why photonuclear

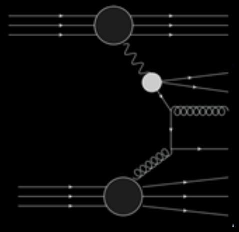
e+*p*



γ+*p*



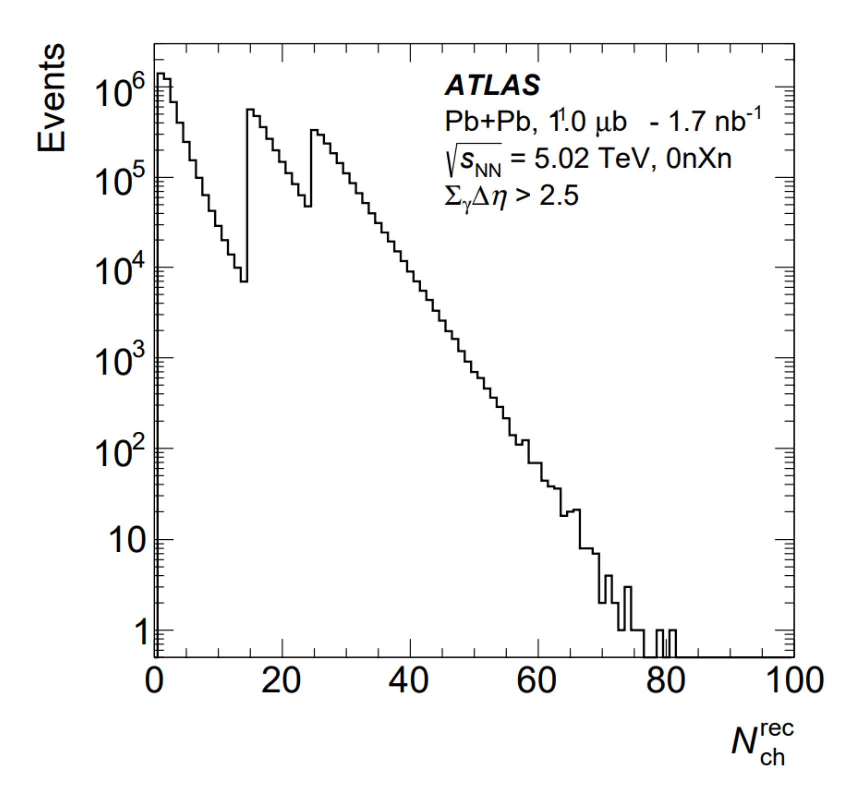
γ+A



Definitive signatures of collective behavior was found in photonuclear collisions at the LHC. What is the difference with these other systems where no signatures were observed but the underlying collective mechanism exists!

Large amount of high-multiplicity data

- Template fit was applied to remove non-flow
  - The underlying assumptions in this method may not be justified in *ep* - more studies!
  - Requires multiplicity range
- ATLAS employed an intricate triggering scheme
- Important for EIC: high-multiplicity software trigger and low-level event activity trigger is essential
- Less important for EIC: Rapidity gaps and Zero-Degree Calorimeter triggers objects as well
  - LHC experiments have to reject PbPb background



arXiv:2101.10771

Large number of high multiplicity events is key

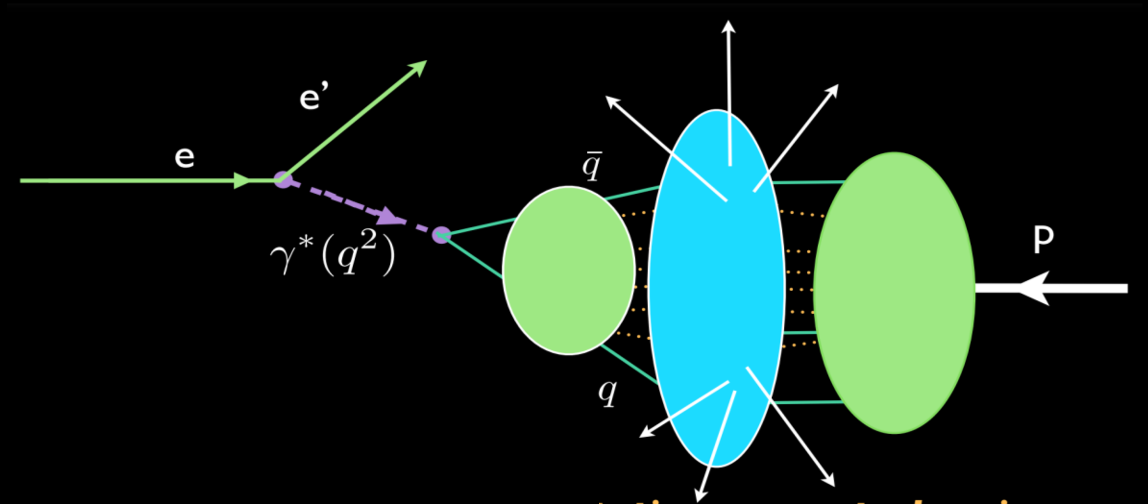
EIC and HERA azimuthal anisotropy

- Given the results in photonuclear collisions at the LHC, it seems natural to suspect that there is detectible azimuthal anisotropy at HERA and EIC.
  - Resolved photon-hadron collisions dominate the photoproduction cross section
  - To a certain extent the decrease in beam energy does not strongly impact the development of azimuthal anisotropy
  - Multi-nucleon scattering can drastically enhance collective effect when comparing ep and eA.

- Recent and future experimental data analysis techniques will help in the extraction of collective signatures in the more challenging low-multiplicity environment.

Intermediate Q^2 region

- Thinking of the photon as a color dipole with probe size of 1/Q, would it be possible “tune” the size of the initial energy deposit in a way not achievable up to this point.
- This intermediate Q^2 region of say 0-5 GeV^2 is interesting for many reasons.
- Leading model vary in the scale size of energy deposition fluctuations in a hadron collision, ranging from the proton size to CGC calculations of about half a nucleon size. Heavy ions collision are not sensitive to the difference.



Summary

- Azimuthal anisotropy is an important probe of the QGP formation and properties and in small systems is highly sensitive to how energy is deposited in collisions.
- Experimental data analysis techniques are continuously being improved to make quantitative measures at low event multiplicities.
- These experimental studies are fundamentally improved by reaching higher multiplicities with large statistics and wide acceptances
- Evidence for a possible observation of collectivity at the EIC is mixed, but lots of good signs and many more studies to be done.
- Measurements of collectivity at the EIC could allow systematic control of the initial state which is not possible in any other collision system.

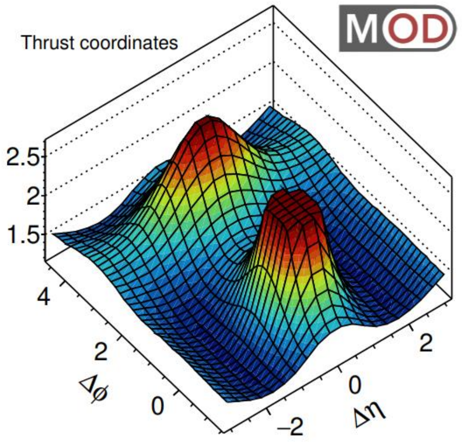
Thank you!

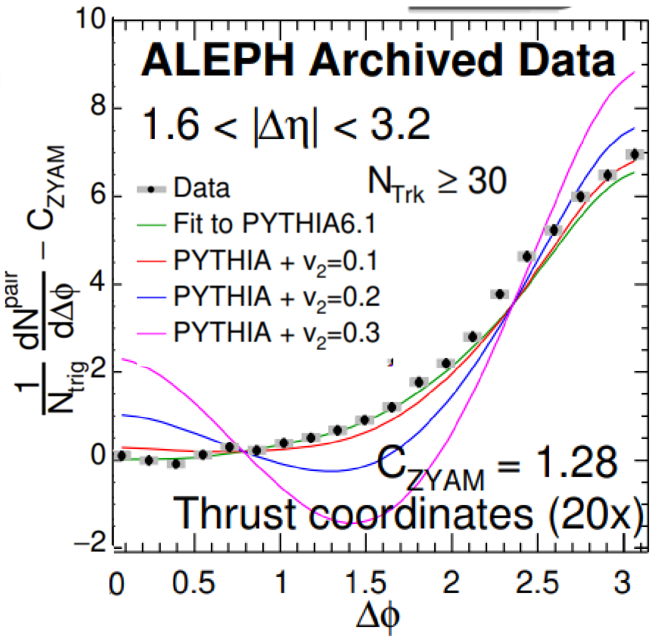
Collectivity searches in $e^{+}+e^{-}$

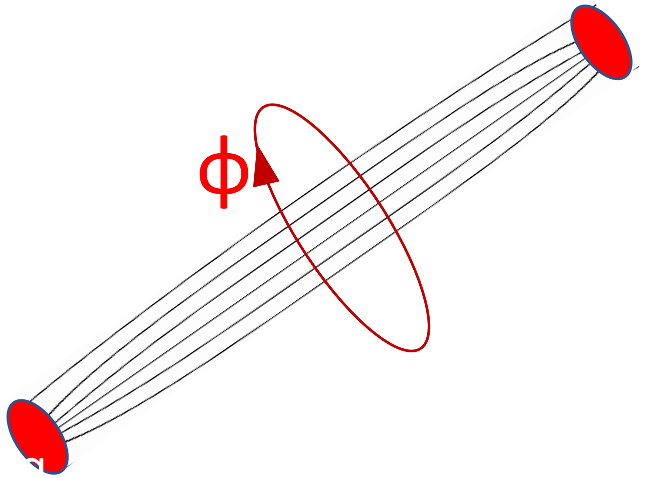
2-particle correlation in $e^{+}+e^{-}$

- Utilizes thrust coordinates
- Large amount of nonflow – could it be removed?

arXiv:1906.00489







No obvious extended (in *η*) geometry in $e^{+}+e^{-}$
Would not necessarily expect ridge even if collective effects exist