Workshop on Probing Hadron Structure at the EIC, 2024

Collectivity in e+A Collisions ?

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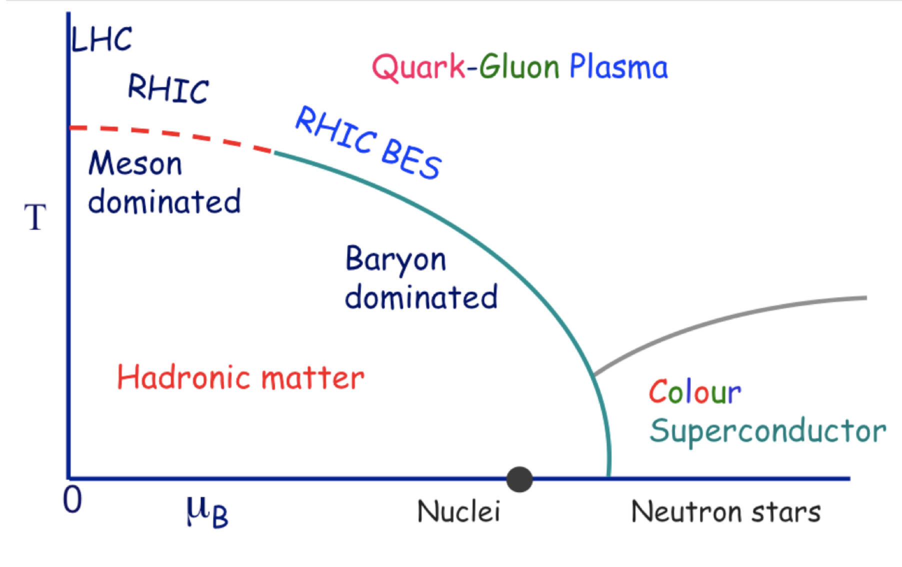
ICTS Bengaluru, 07/02/2024

Introduction

Goal:

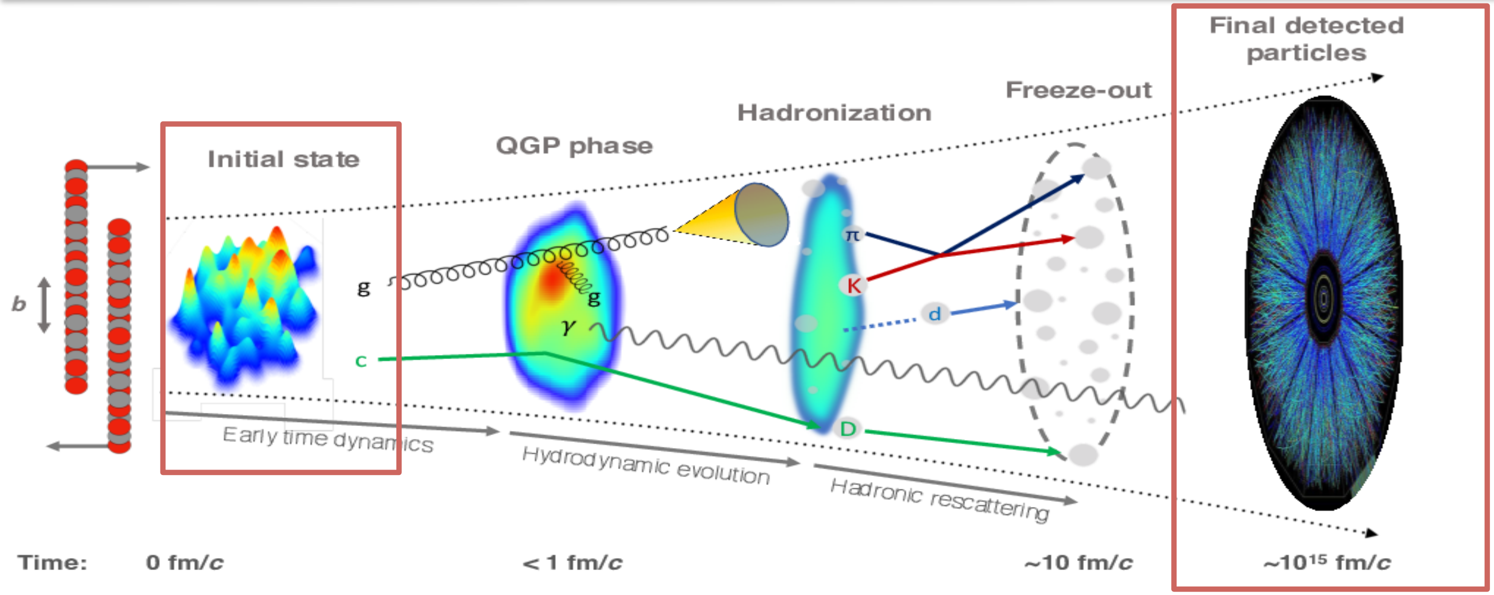
- Heavy-ion collisions aims to study the properties of hot QCD matter
- Collective flow plays an important role in probing the medium



In this talk, I will discuss :

- The present of understanding regarding collective flow and initial conditions in heavy-ion collisions.
- The importance of EIC in understanding the origin of collectivity.
  - ◆ Probing the Color Glass Condensate
  - ◆ Searching "Ridge" in Small System

Evolution of Heavy-ion Collision

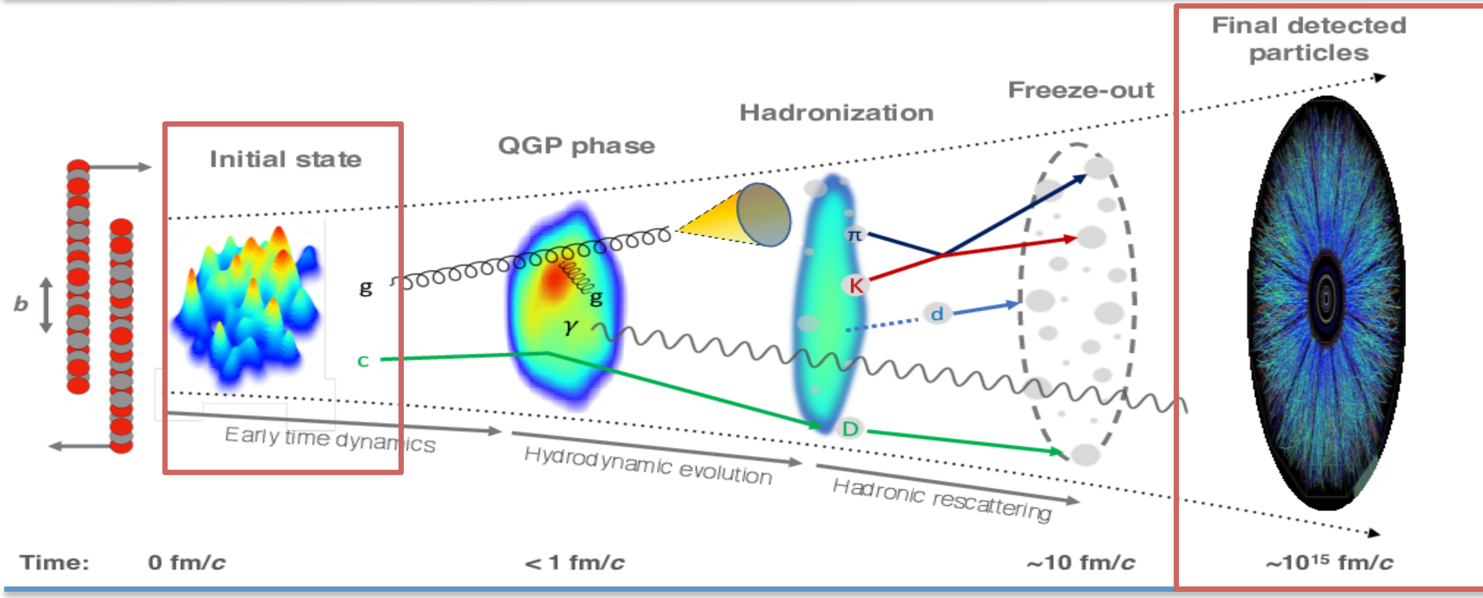


A+A

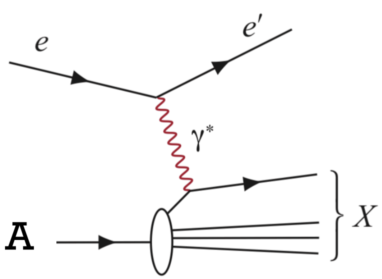
Final state observables depend on the initial state

Image Credit: Hot QCD White Paper

Evolution of Heavy-ion Collision



A+A



Initial state

CGC ?

Hadronic scattering ?

Particle detection

Time

High multiplicity e+A collision

Signature of QGP: Collectivity

Citations ~1500

PHYSICAL REVIEW D VOLUME 46, NUMBER 1 1 JULY 1992

Anisotropy as a signature of transverse collective flow

Jean-Yves Ollitrault
Service de Physique Théorique, Centre d'Études de Saclay, F-91191 Gif-sur-Yvette CEDEX, France
(Received 19 February 1992)

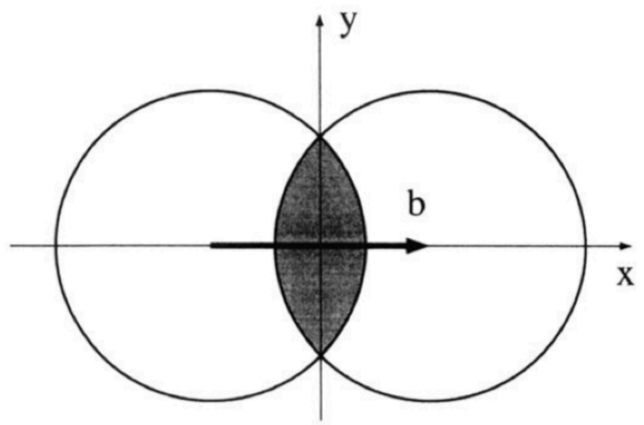
We show that anisotropies in transverse-momentum distributions provide an unambiguous signature of transverse collective flow in ultrarelativistic nucleus-nucleus collisions. We define a measure of the anisotropy from experimental observables. The anisotropy coming from collective effects is estimated quantitatively using a hydrodynamical model, and compared to the anisotropy originating from finite multiplicity fluctuations. We conclude that collective behavior could be seen in Pb-Pb collisions if a few hundred particle momenta were measured in a central event.

The large collective flow is considered to be evidence for almost perfect liquid behavior of the Quark Gluon Plasma produced in the collisions.

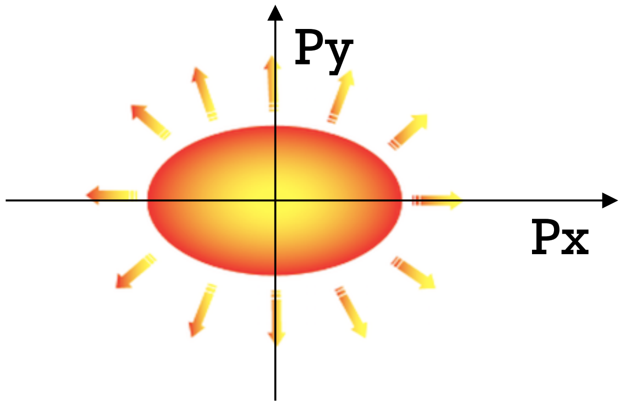
Collectivity/Flow

Spatial Anisotropy

Momentum Anisotropy



$$\frac{\partial P}{\partial X} > \frac{\partial P}{\partial Y}$$



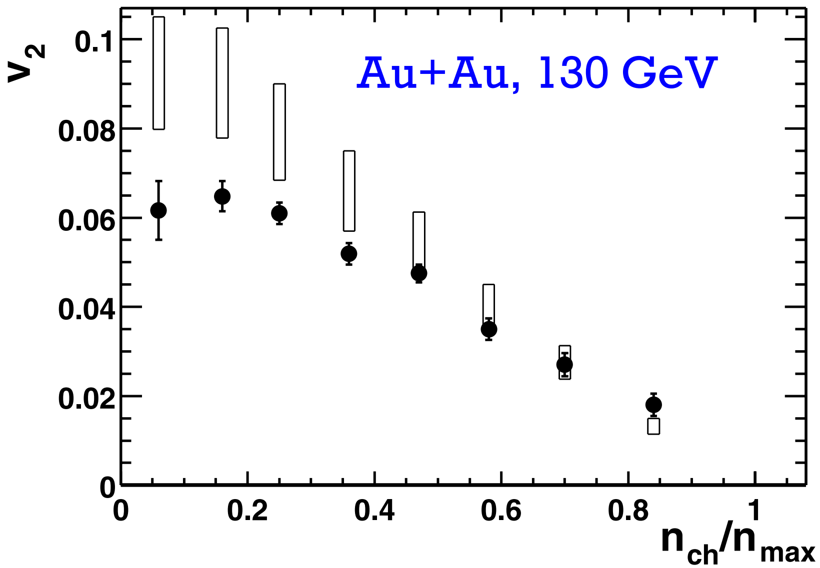
- Interaction among particles give rise to pressure (P)
- Pressure transform spatial anisotropy to momentum anisotropy

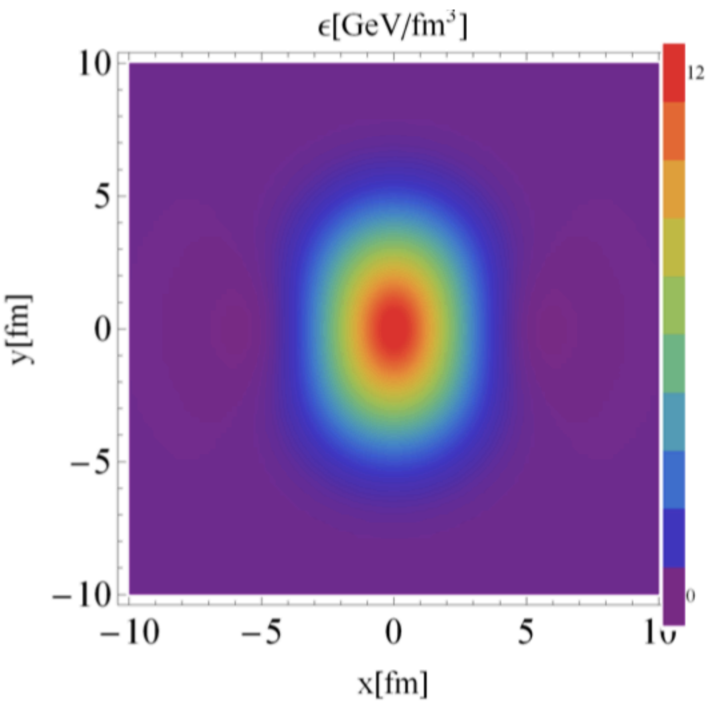
Momentum anisotropy is a measure of collectivity

J-Y Ollitrault, PRD 46, 229 (1992)

Elliptic Flow at RHIC

First RHIC result vs Hydro Calculation





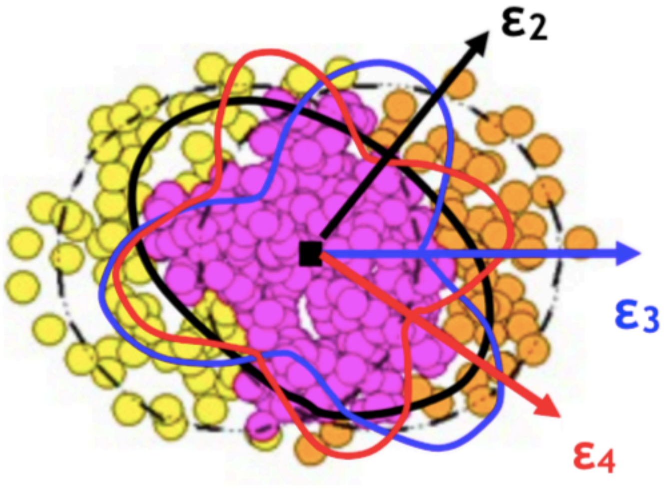
Quantitative agreement with hydrodynamic model predictions with smooth initial condition

STAR: PRL 86, 402 (2001)

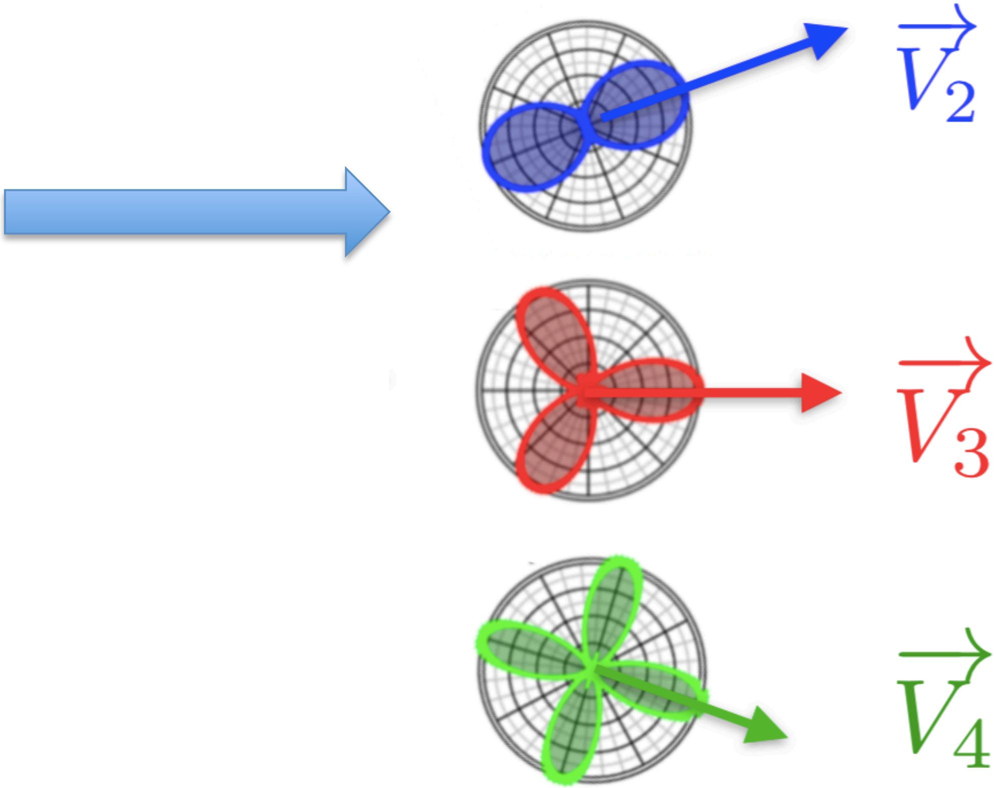
P.Huovinen, et al. PLB 503,58 (2001)

Higher Order Flow

Spatial Anisotropy



Momentum Anisotropy



$$\frac{dN}{d\phi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos\{n(\phi)\}$$

v_1, - directed flow
v_2, - elliptic flow
v_3, - triangular flow
etc.

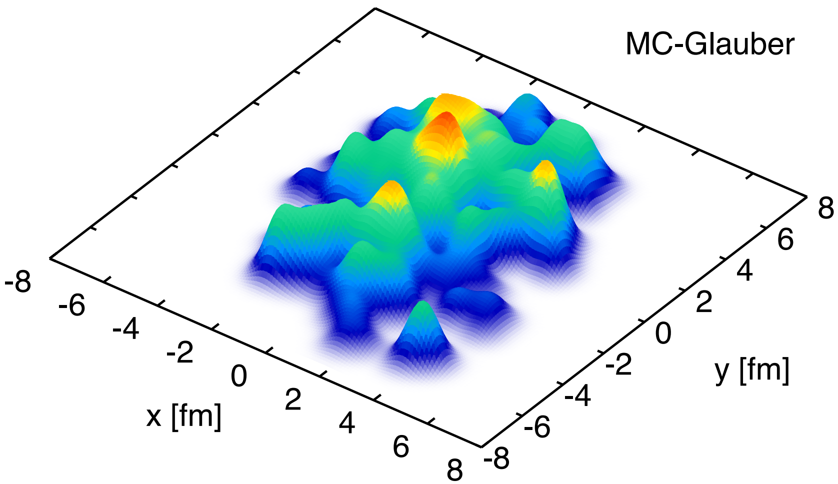
Event-by-Event fluctuation in initial state is needed to generate odd harmonics

J-Y Ollitrault, PRD 46, 229 (1992)

B. Alver and G. Roland, PRC **81**, 054905 (2010).

Commonly used Initial State

MC-Glauber:



- Uncorrelated nucleons randomly distributed in transverse plane
- Interaction probabilities between nuclei depend on

(a) Relative distance between two nuclei

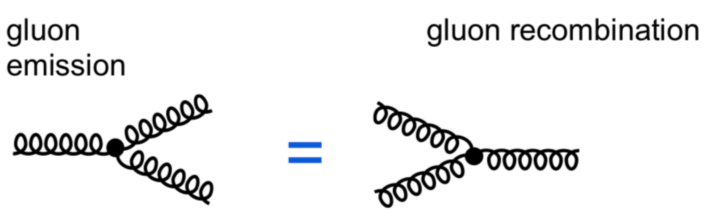
(b) The measured nucleon-nucleon inelastic cross section.

C. Gale, et al., IJMPA, 28, 1340011 (2013) M. L. Miller et al. ARNPS 57, 205 (2007).

Commonly used Initial State

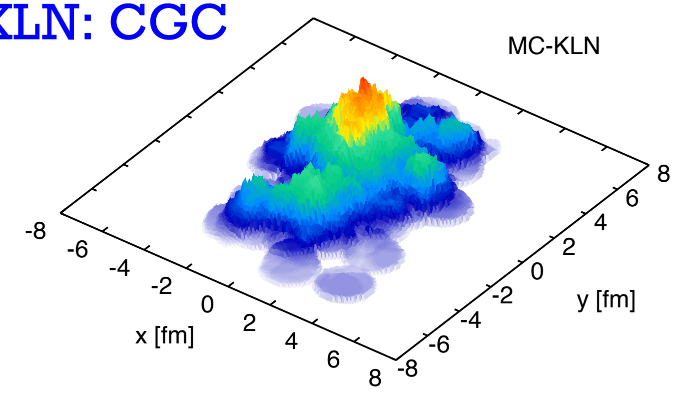
CGC based Initial Condition

At high energies, gluon saturation is predicted when gluon recombination balances gluon splitting, producing a new state of matter, known as color-glass condensate :

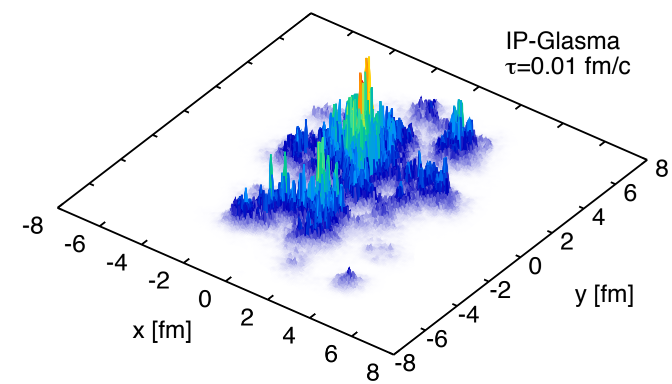


Dynamical equilibrium of gluon density

MC-KLN: CGC



IP-Glasma: CGC + Color fluctuation



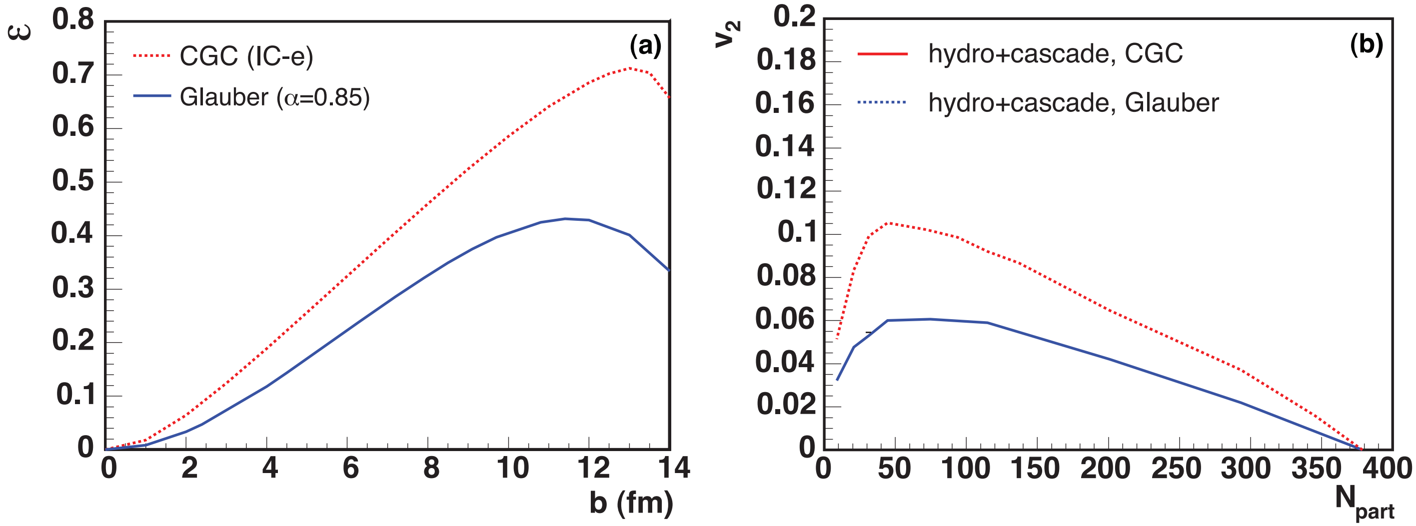
C. Gale, et al., IJMPA, 28, 1340011 (2013)

D. Kharzeev, et al. PLB 507, 121 (2001)

B. Schenke, et al. PRL 108, 252301 (2012)

Azimuthal Anisotropy as a Probe

Sensitive to Initial State , Glauber vs CGC

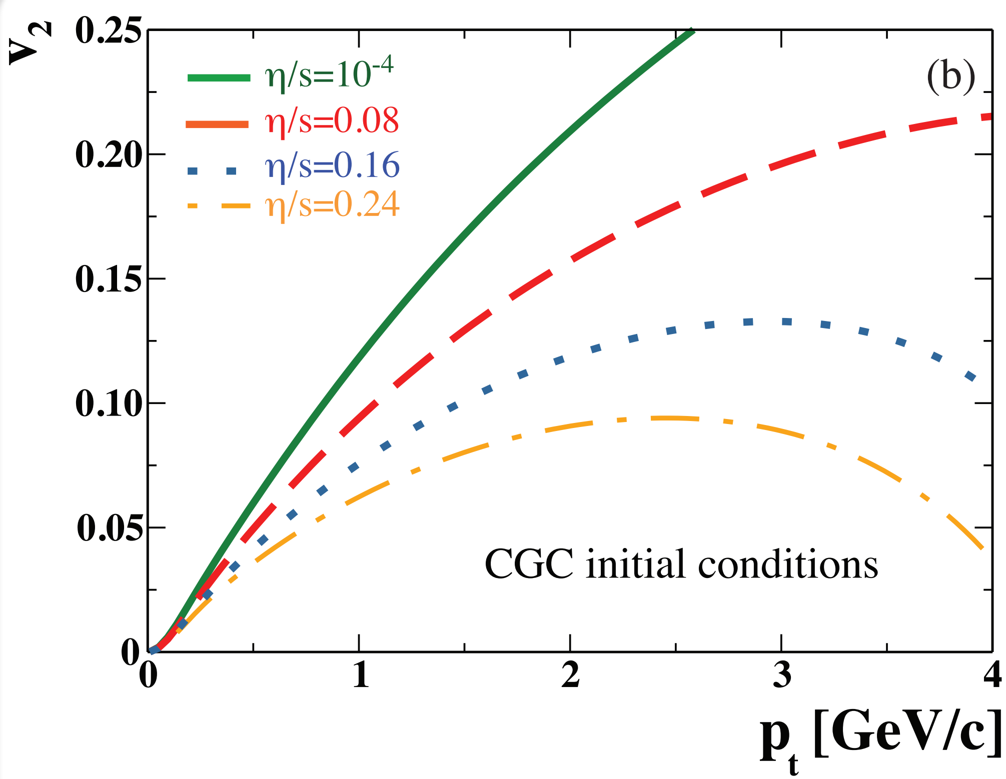


CGC initial condition give higher spatial anisotropy than Glauber

M. Luzum, et al. PRC 78, 034915 (2008).

Azimuthal Anisotropy as a Probe

Sensitive to Transport Properties of Medium



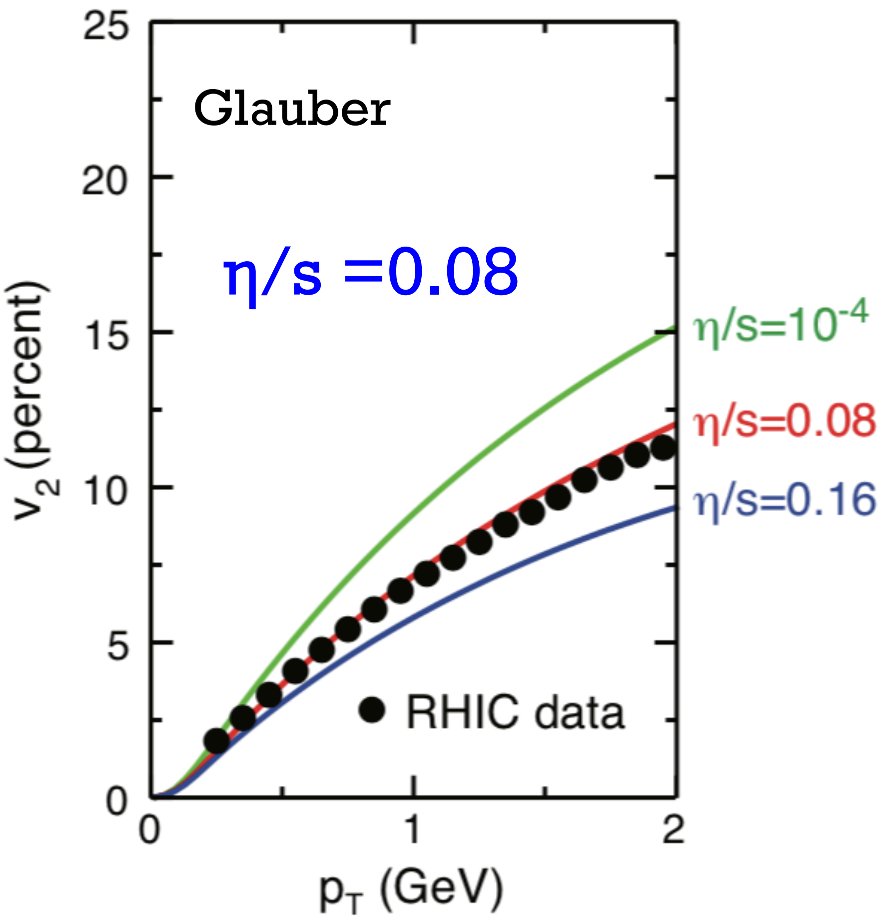
Dissipative effects like viscosity reduce elliptic flow.

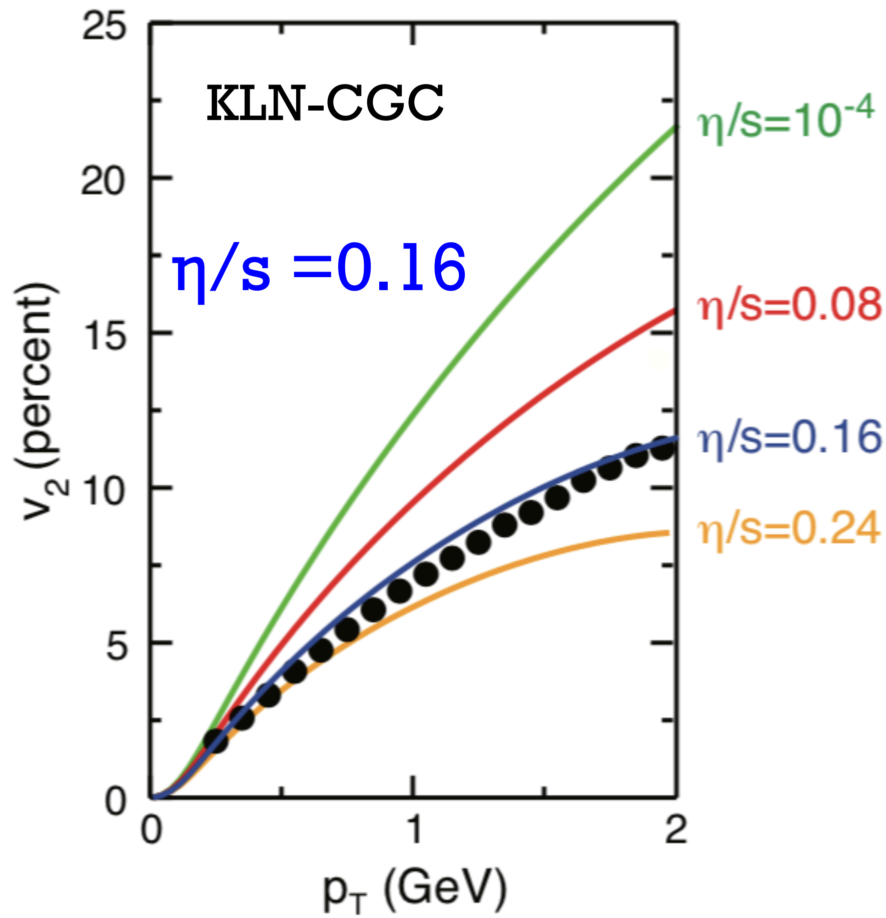
Anisotropic flow parameter (v_2) has been extensively used to extract viscous properties of QGP.

η/s : viscosity over the entropy density

M. Luzum, et al. PRC 78, 034915 (2008).

Comparison: Hydro vs Data



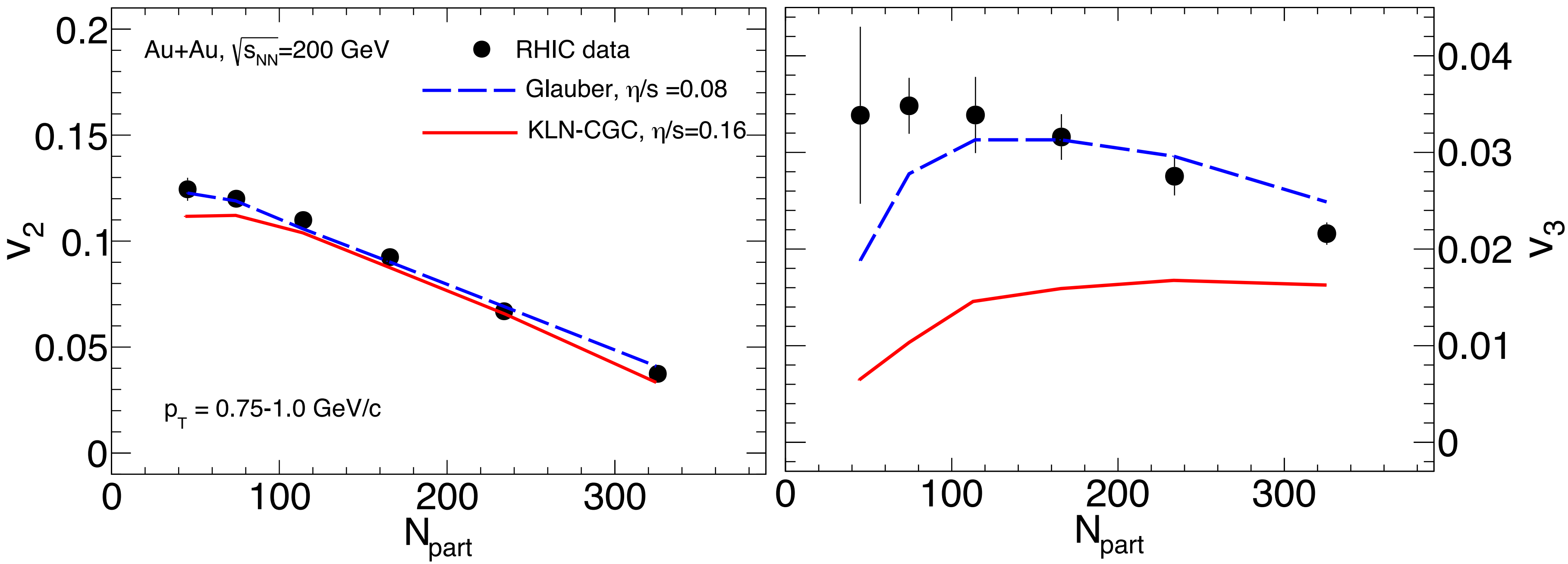


- Extracted η/s of medium depends on the choice of initial condition.

Initial eccentricity is more in CGC, hence required high viscosity to explain the data

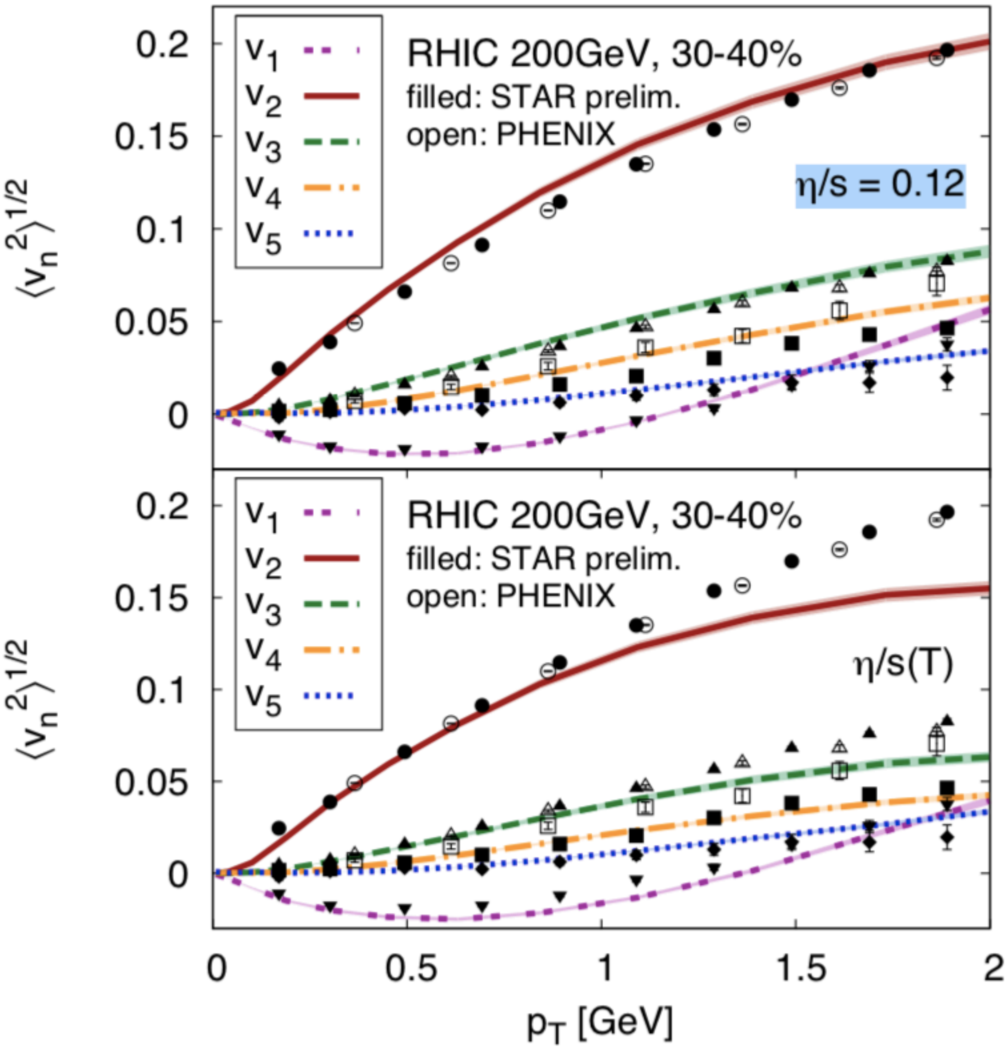
Comparison: Hydro vs Data

2nd and 3rd order flow harmonics



- CGC-KLN model under-predicts v_3

IP-Glasma +Hydro Model



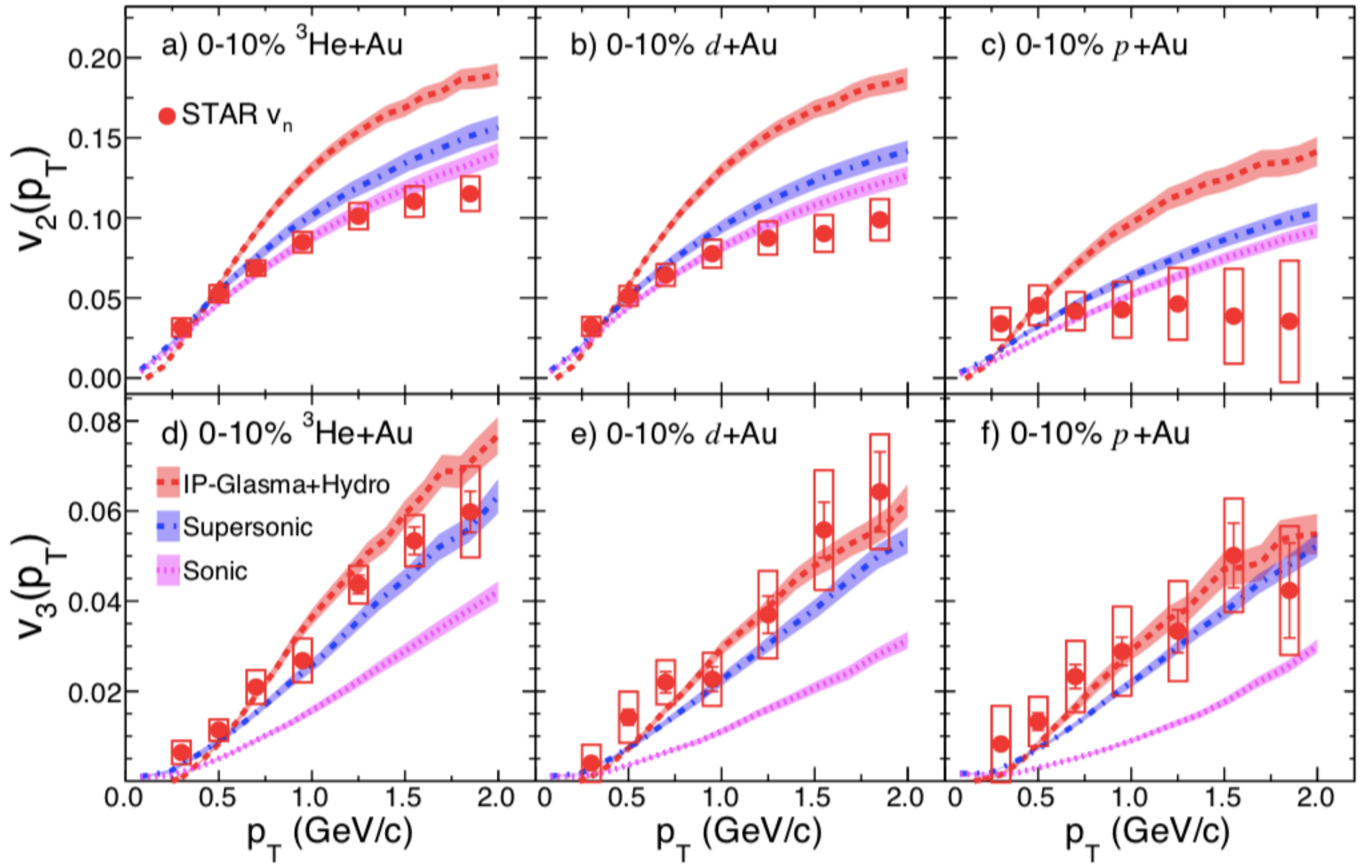
Glasma (IP-Glasma) model:

- Impact Parameter dependent Saturation Model
- Event-by-event geometric fluctuations in nucleon positions
- Intrinsic sub-nucleon scale color charge fluctuations

Explain all vn coefficient with $\eta/s = 0.12$ or $\eta/s(T)$

C. Gale et al, PRL **110**, 012302, (2013)

Collectivity in Small System



New challenges

Deeper understanding of the nucleus structure at high energy is necessary.

IP-Glasma +Hydro : Explains v_3 but fails to explain v_2

Sonic (IS : Glauber) : Explains v_2 but fails to explain v_3

Supersonic (IS : Glauber +Pre-flow phase) : Explains v_3 but overestimate v_2

STAR: arXiv: 2312.07464

Probing CGC using EIC

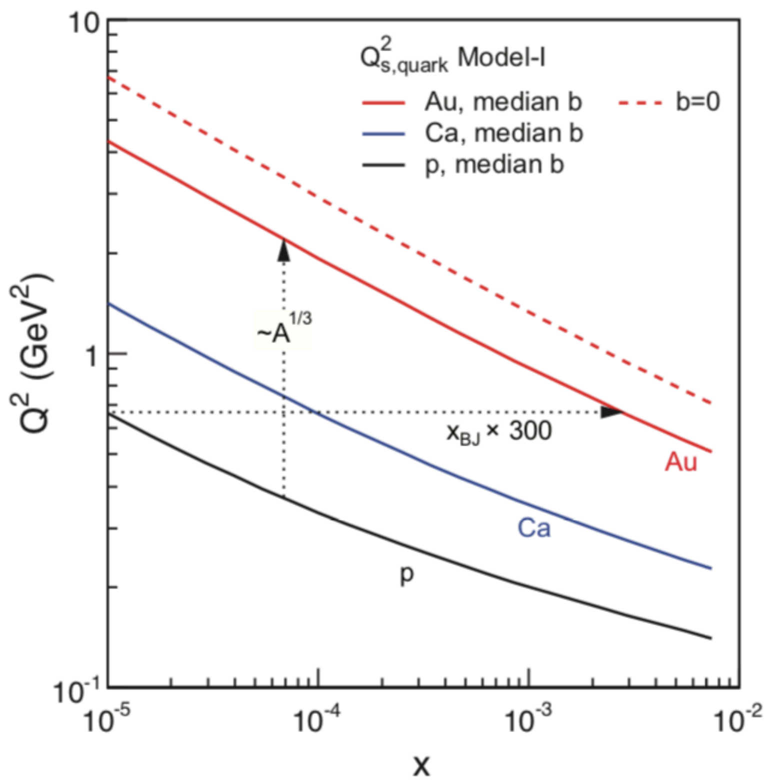
What is the nature of dense gluon matter (CGC)?

Parton densities cannot be calculated using perturbative QCD. However, one can study variation of parton density by external probe, virtual photon

Gluon Saturation Scale:

$$Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}$$

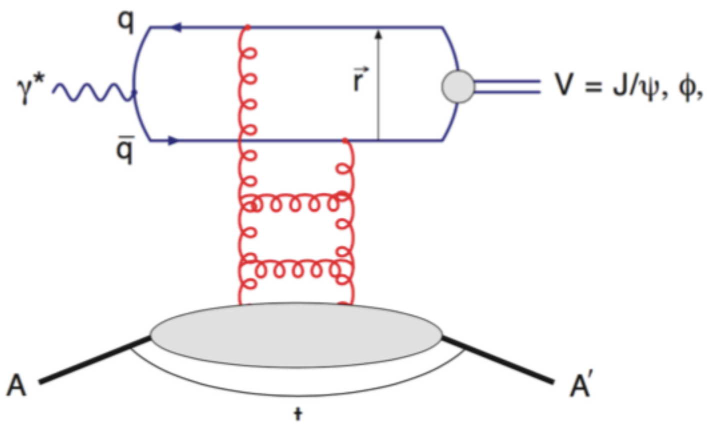
- Study the saturation regime in e+A at significantly lower energy than would be possible in e+p

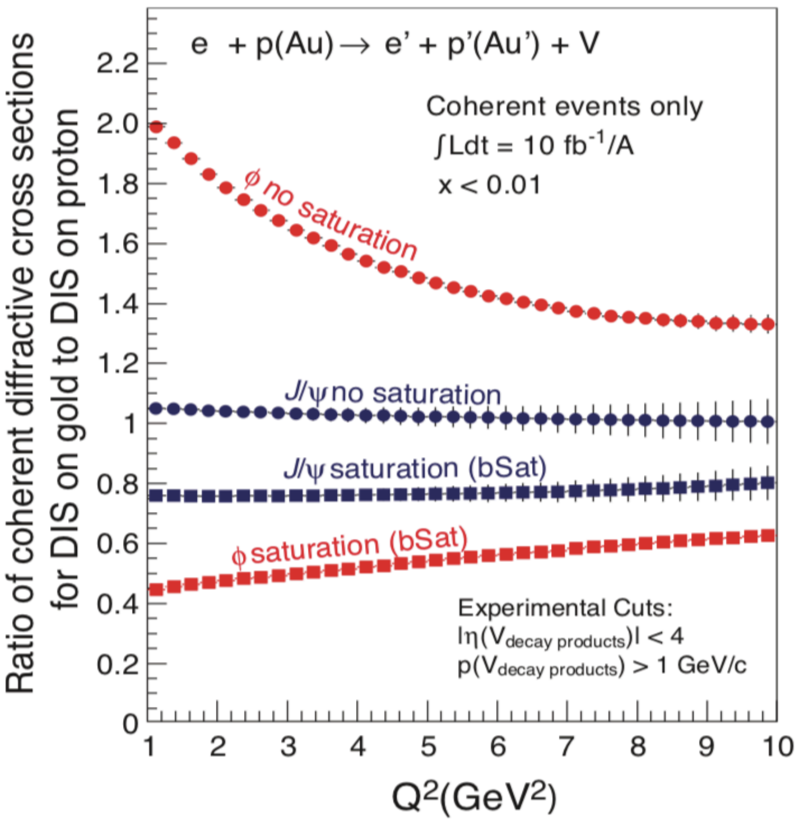


A. Accardi et. al, EPJA **52**, 268 (2016).

Probing CGC using EIC

Observable : Exclusive Vector Meson Production





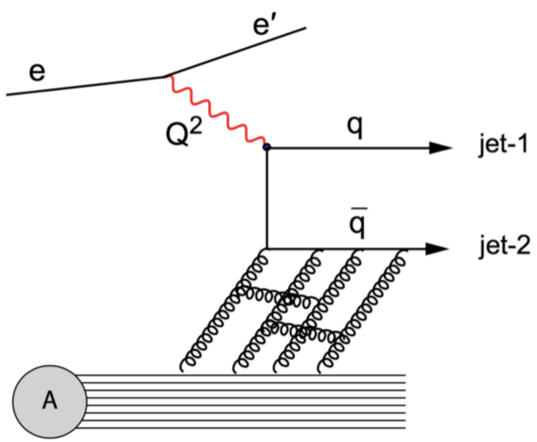
Gluon saturation based model predicted suppression of vector meson production in e + A relative to e + p collisions at the EIC.

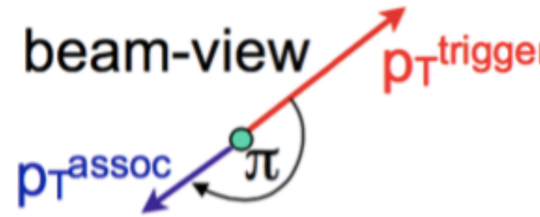
Requirement: Detection of all particles (with PID) in the event with high precision is essential

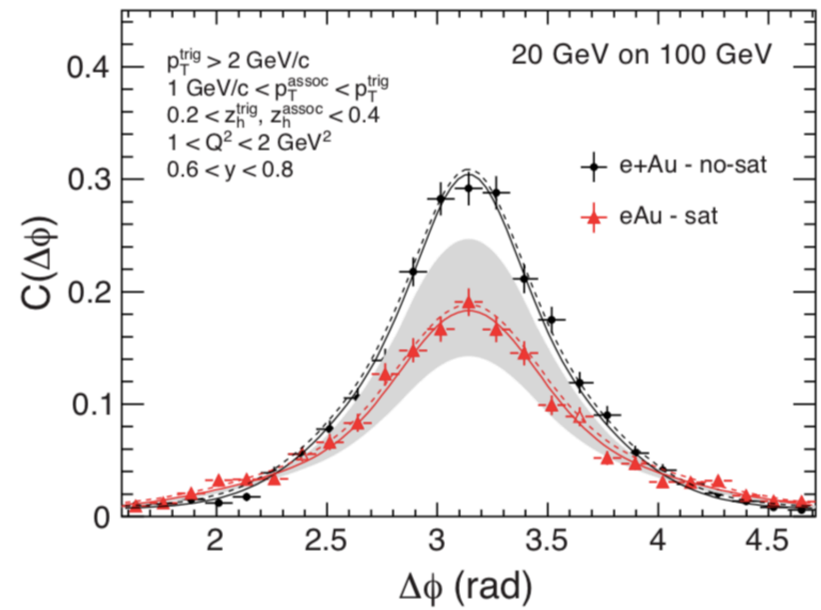
A. Accardi et. al, EPJA **52**, 268 (2016).

Probing CGC using EIC

Observable : Di-hadron Correlation







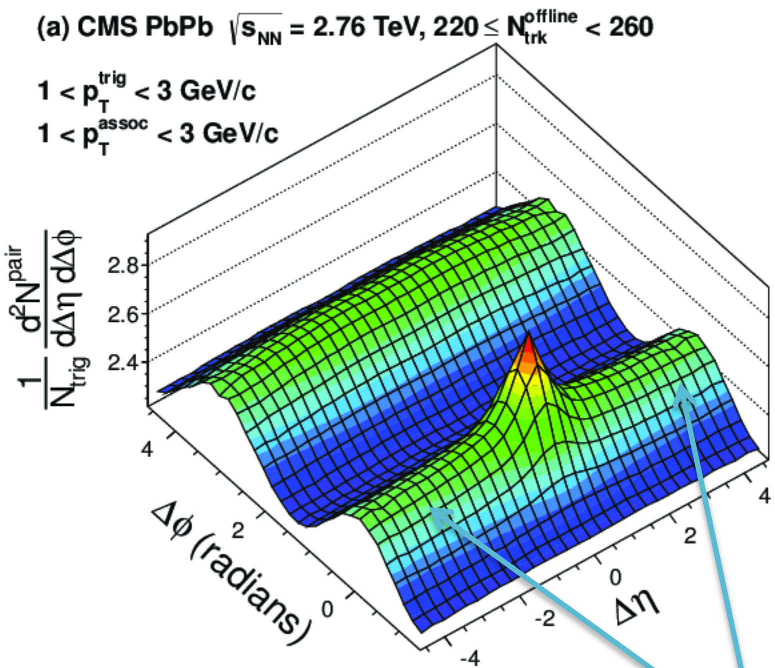
Suppression of back-to-back hadron directly probes the gluon distributions in nuclei.

Requirement: Tracking detector with full azimuth and wide rapidity coverage is preferable

A. Accardi et. al, EPJA **52**, 268 (2016).

Searching “Ridge” in Small System

Two-particle Correlation



Correlation due to :

- Momentum conservation (ΔΦ=π)
- Local charge conservation (ΔΦ~small, Δη~small)
- Collectivity

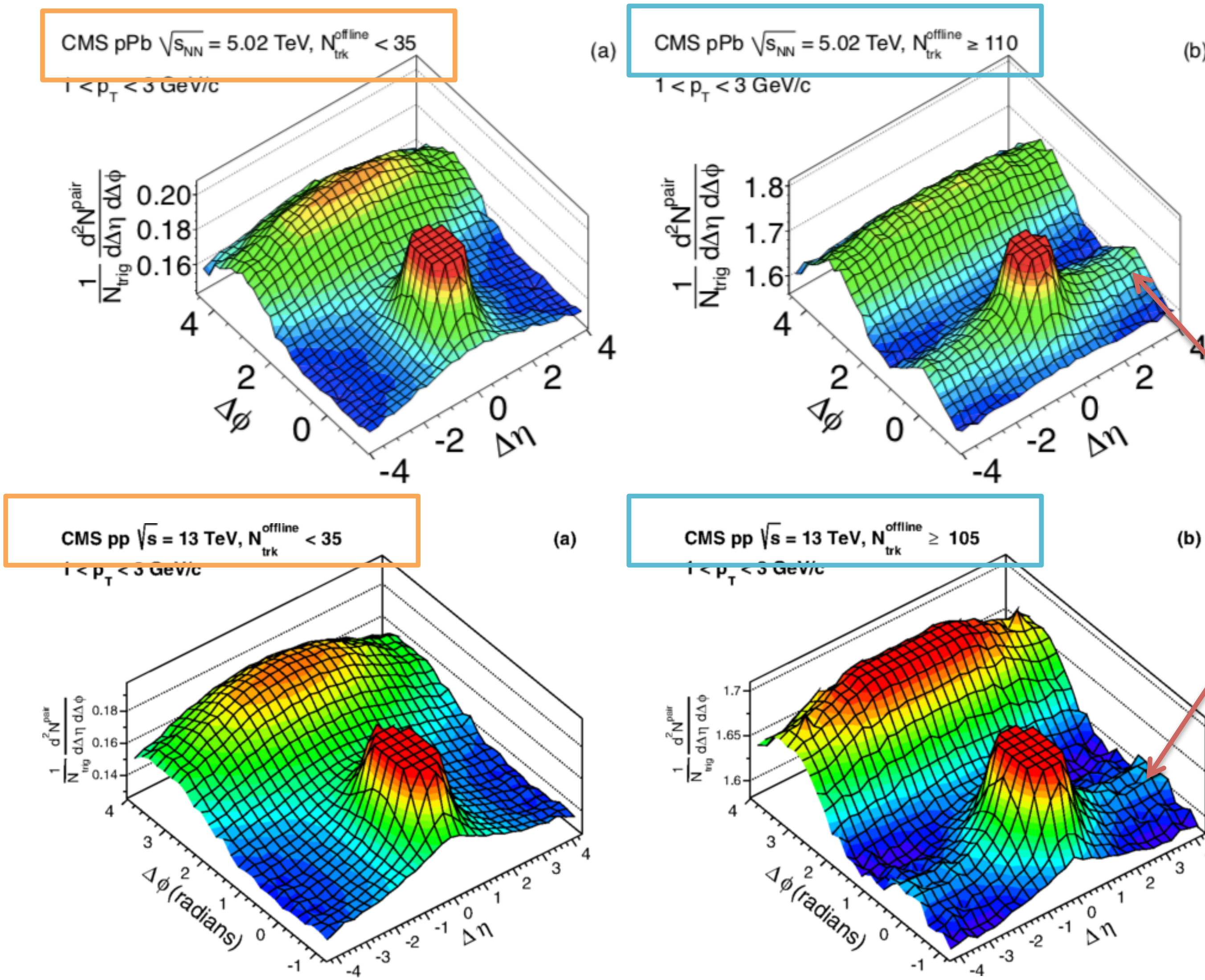
Long-range pseudorapidity separation (Δη) correlations at small azimuthal difference (Δϕ), called the ridge – a signature of collectivity.

Can we observe ridge in e+A collision ?

CMS : JHEP 7 (2011) 76

STAR :PRL 95, 152301 (2005)

Ridge in p+Pb and p+p



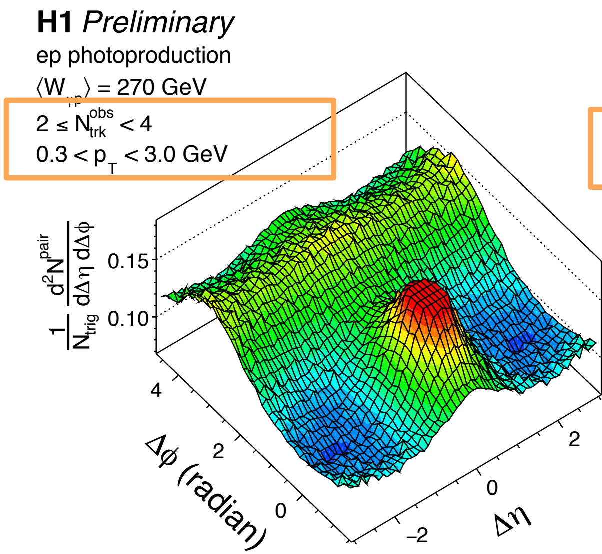
p+Pb

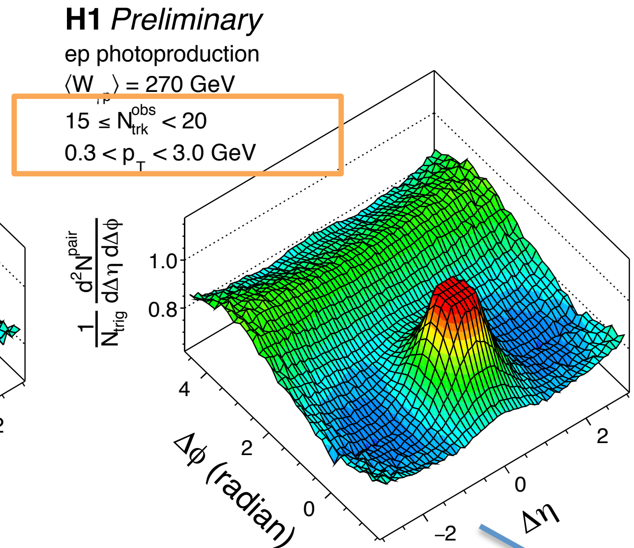
Ridge in high-multiplicity p+Pb and p+p collision

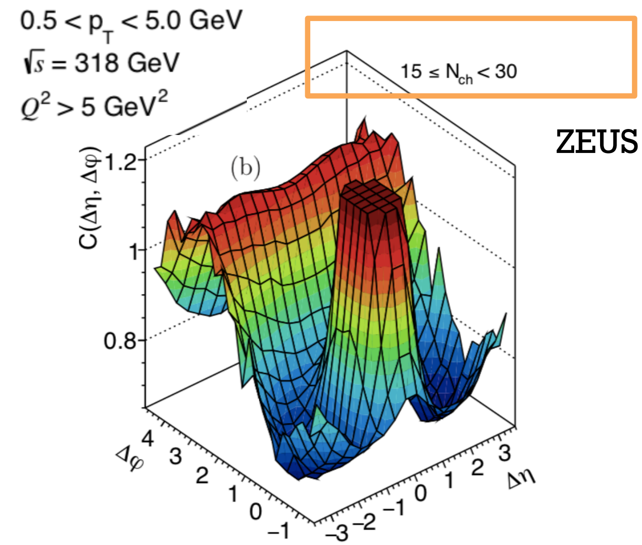
p+p

CMS: JHEP09(2010)091 CMS: PLB 718 (2013) 795

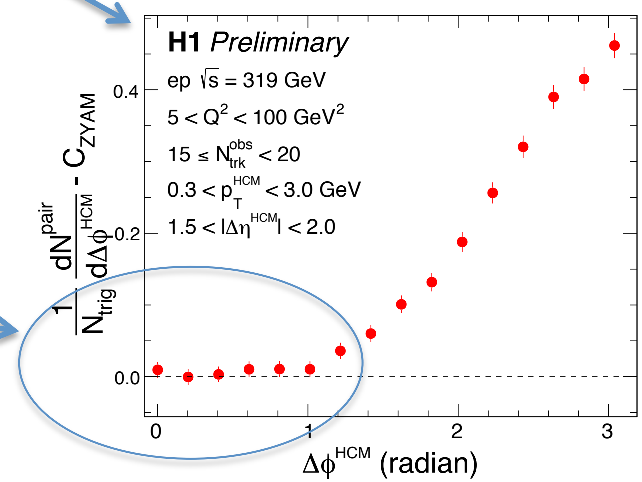
Ridge in e+p ?







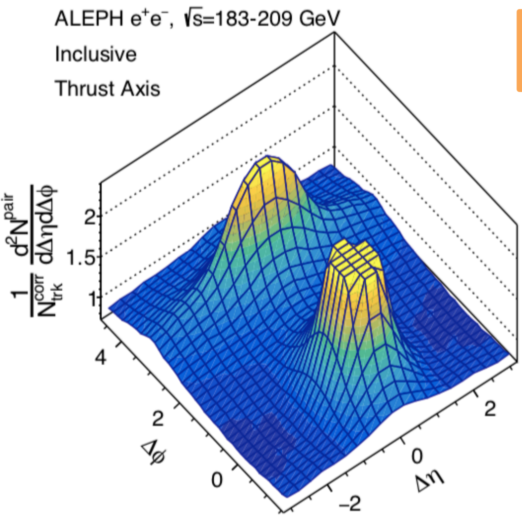
ZEUS: JHEP 04 (2020) 070

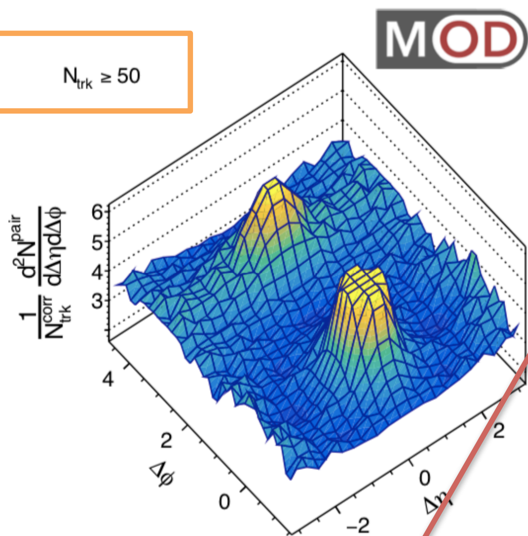


No near-side long-range correlation e+p collisions with multiplicity < 30

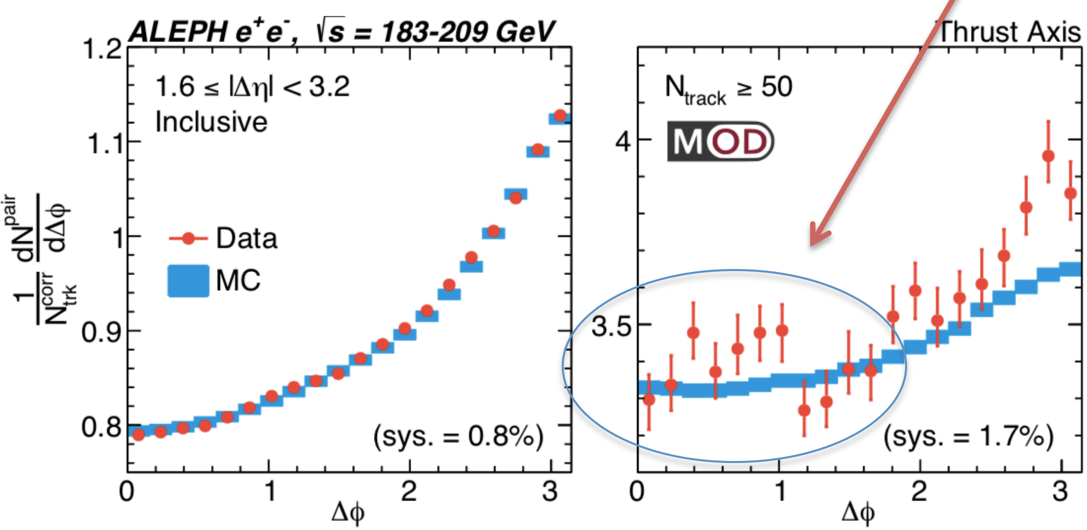
https://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-20-033.long.html

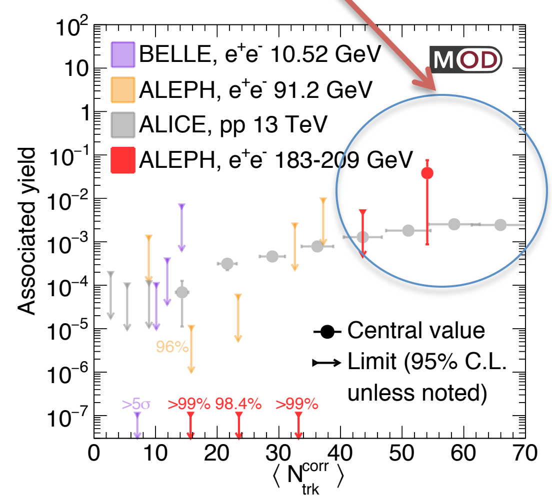
Ridge in $e^+ + e^-$?





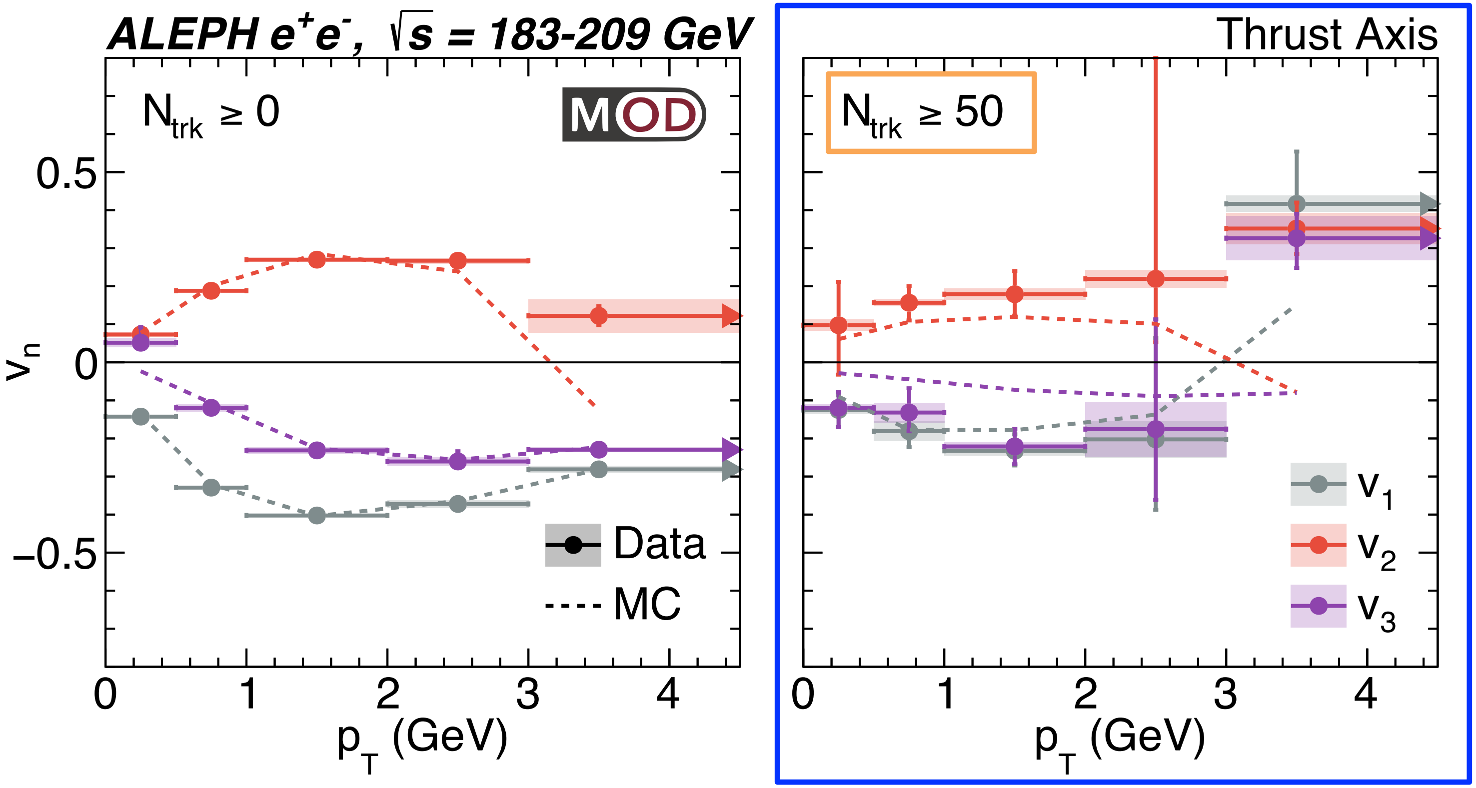
Long-range near-side excess when multiplicity >50





ALEPH: arXiv:2312.05084

Flow in $e^+ + e^-$?



Magnitudes of v_2 and v_3 in data are larger than those in the Monte Carlo reference when multiplicity > 50

ALEPH: arXiv:2312.05084

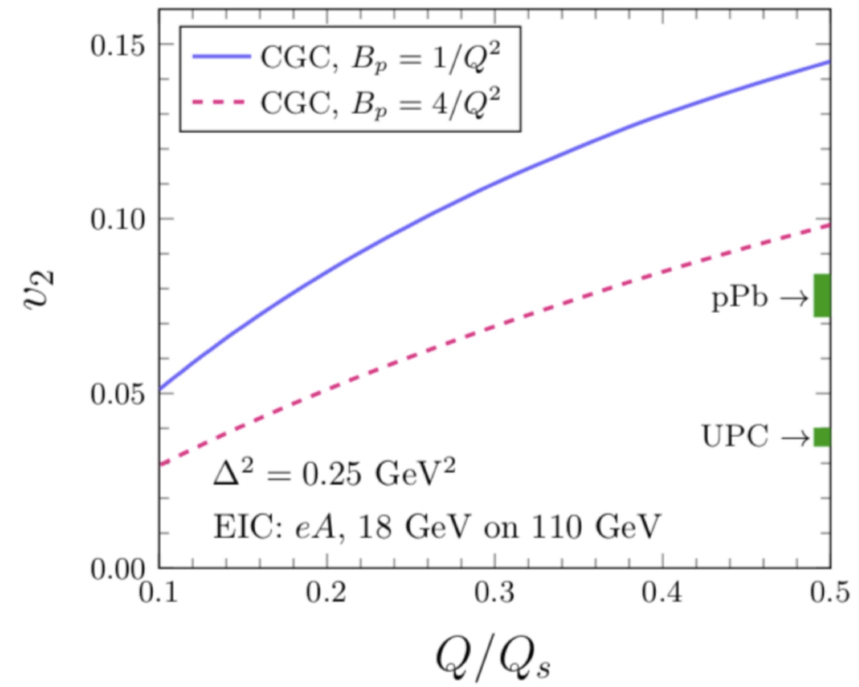
Collectivity in e+A ?

- EIC will have very high luminosity ~10^{33-34} $cm^{-2}s^{-1}$

- High multiplicity events at EIC will offer an opportunity to study the collective behavior.

- CGC based model predicts sizable v_2 in e+A collisions

- System size dependence of collectivity can be studied by varying photon virtuality



Yu Shi, et al. PRD 103, 054017 (2021)

Summary

- Azimuthal anisotropy provides insight into both the initial conditions and transport properties of the QGP medium.
- Models employing viscous hydrodynamics ($\eta/s \sim 0.1$) and incorporating sub-nucleonic fluctuations in the initial state successfully account for data observed in heavy-ion collisions.
- The existing model is inadequate in capturing flow harmonics in small collision systems.
- Sign of collectivity in high multiplicity p+p and e+e- collision.

EIC will play crucial role in understanding origin of collectivity.

Thank You

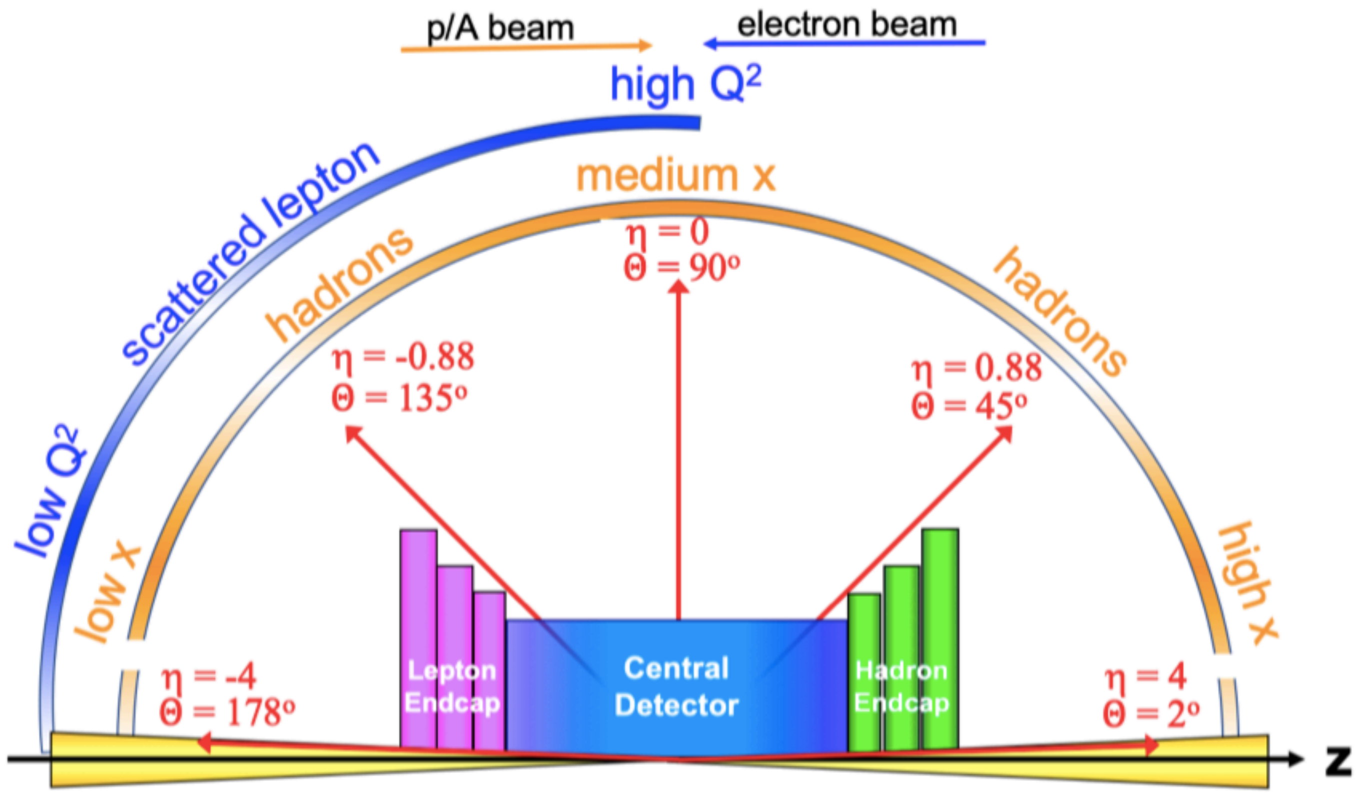


Figure 2.18: A schematics showing how hadrons and the scattered lepton for different $x - Q^2$ are distributed over the detector rapidity coverage.

Ref: https://indico.bnl.gov/event/9913/contributions/43303/attachments/31409/49584/EIC_Detector_CDR_111720.pdf