Flow in small systems at the LHC

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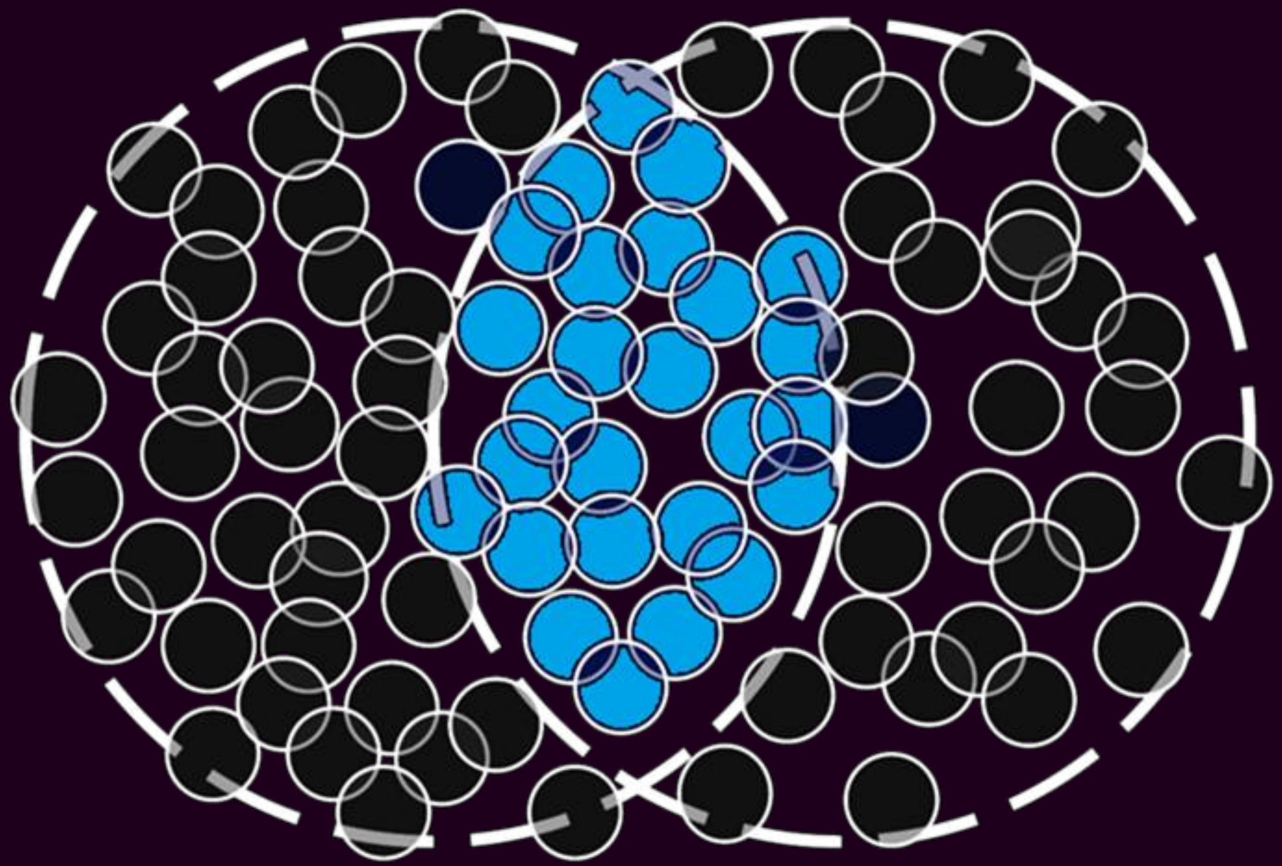
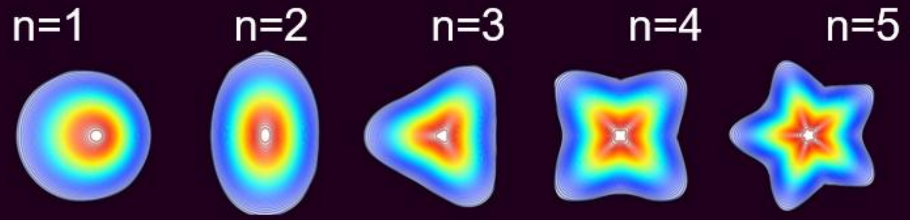
Initial state of heavy ion collisions

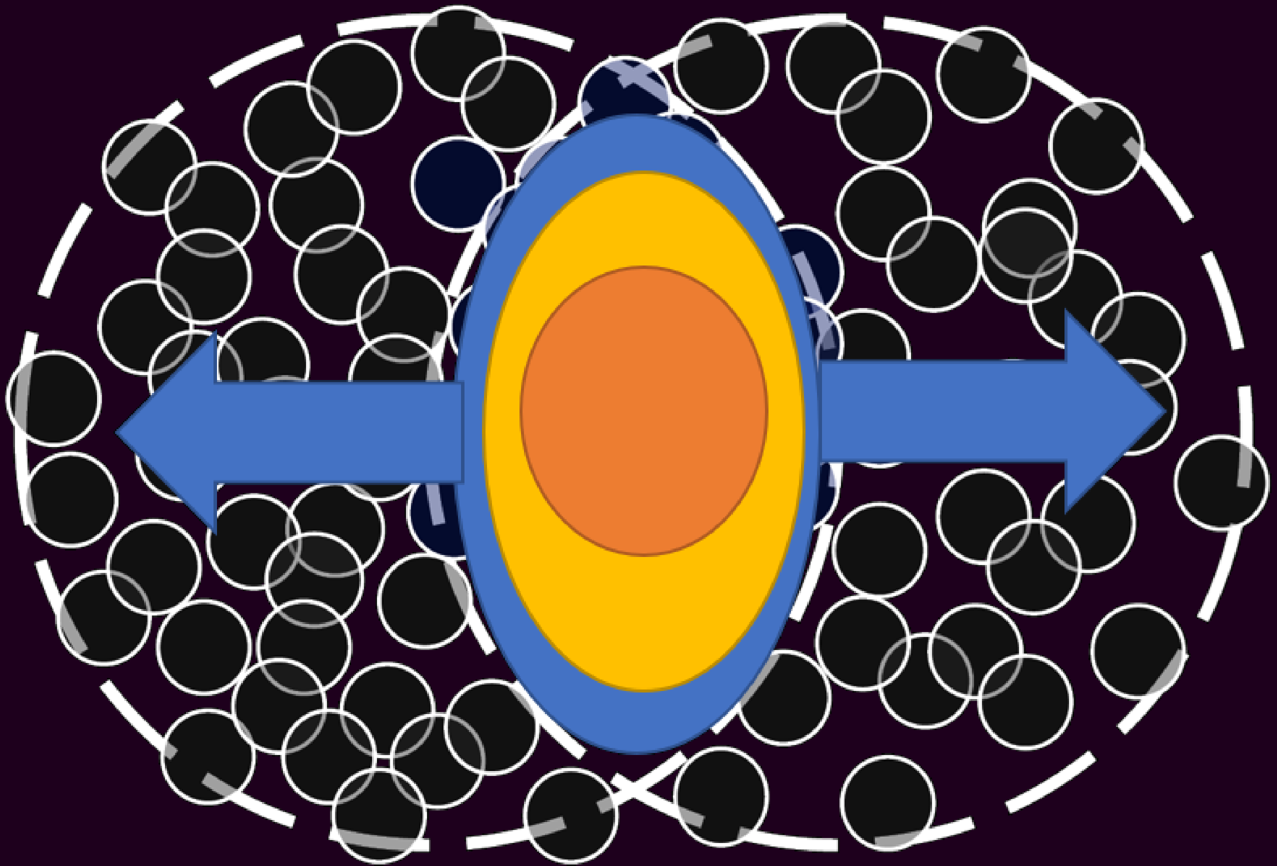


Parametrize spatial anisotropy

Geometric eccentricity

$$\varepsilon_n = \frac{\sqrt{\langle r_i^n \cos(n\varphi_i)\rangle^2 + \langle r_i^n \sin(n\varphi_i)\rangle^2}}{\langle r_i^n \rangle}$$





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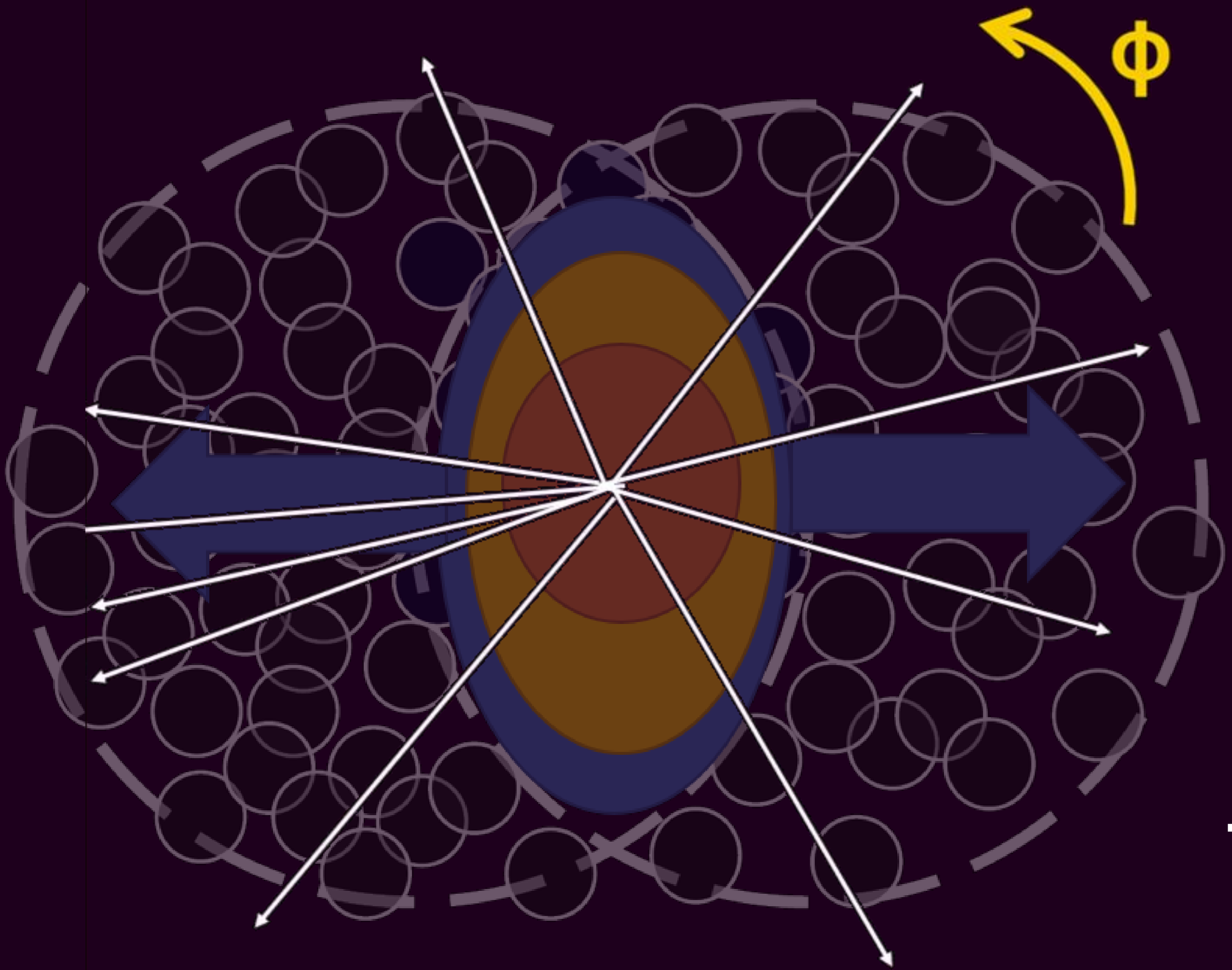
<u>Viscous Hydrodynamics</u>

$$T^{\mu\nu} = \epsilon u^\mu u^\nu + P[\epsilon]\Delta^{\mu\nu} - \eta[\epsilon]\sigma^{\mu\nu} - \zeta[\epsilon]\Delta^{\mu\nu}\nabla^\perp_\lambda u^\lambda$$

<u>Equation of state</u>
<u>transport coefficients</u> $P[\epsilon]\ \ \eta[\epsilon]\ \ \zeta[\epsilon]$.

<u>Initial state</u> → **Pre-equilibrium dynamics** → **Hydrodynamic expansion** → **<u>Momentum anisotropy</u>**



Parametrize spatial anisotropy
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Viscous Hydrodynamics

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Equation of state
transport coefficients $P[\epsilon]\ \ \eta[\epsilon]\ \ \zeta[\epsilon]$

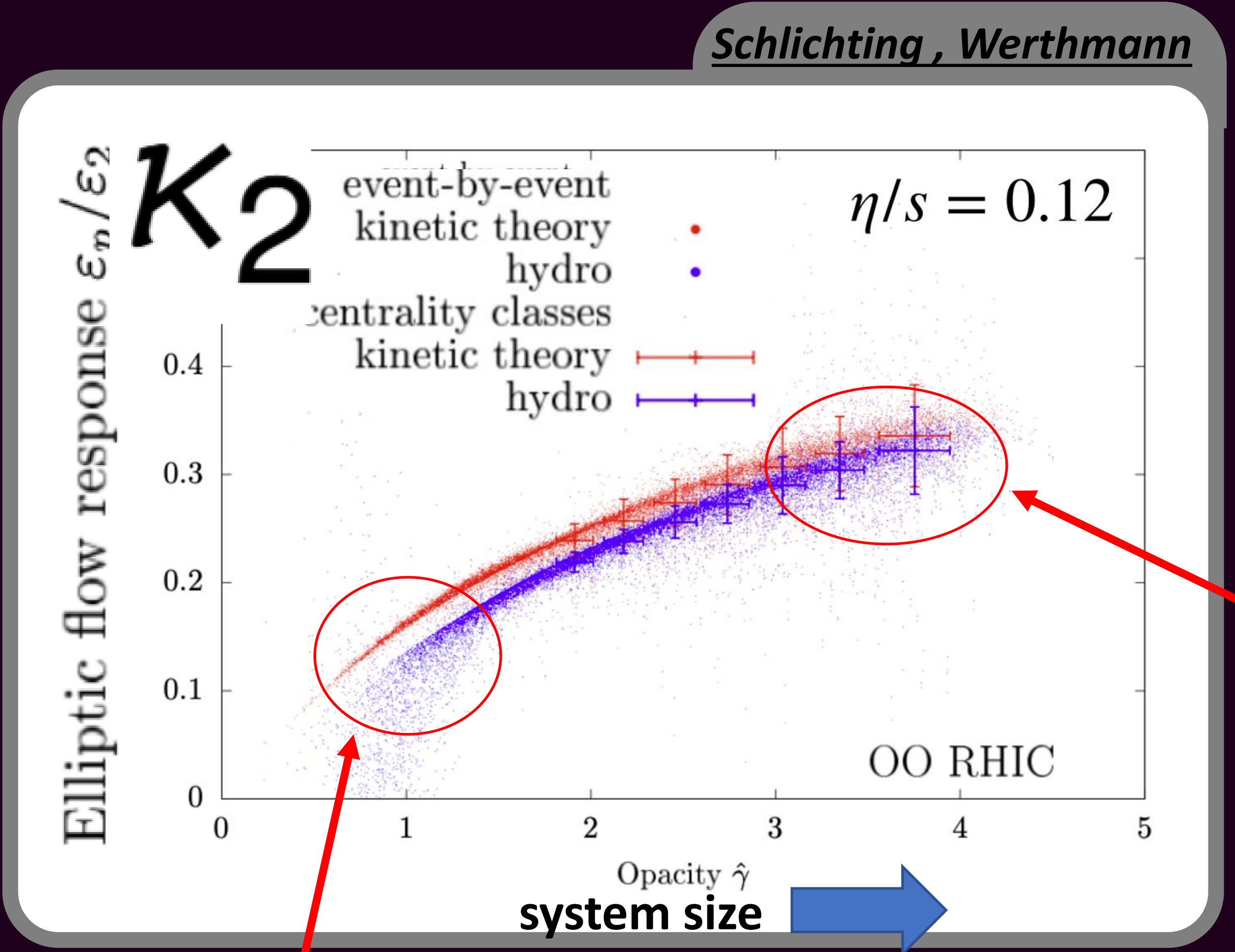
Azimuthal Momentum anisotropy

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

Initial state ε_n → **Pre-equilibrium dynamics** → **Hydrodynamic expansion** → **Momentum anisotropy** V_n

$$V_n \simeq \kappa_n \varepsilon_n$$

Break down of hydrodynamics in small systems



Azimuthal anisotropy is a response to geometry

$$v_n \simeq \kappa_n \varepsilon_n$$

Event by event calculation of kappa for **hydrodynamics** and **kinetic theory**

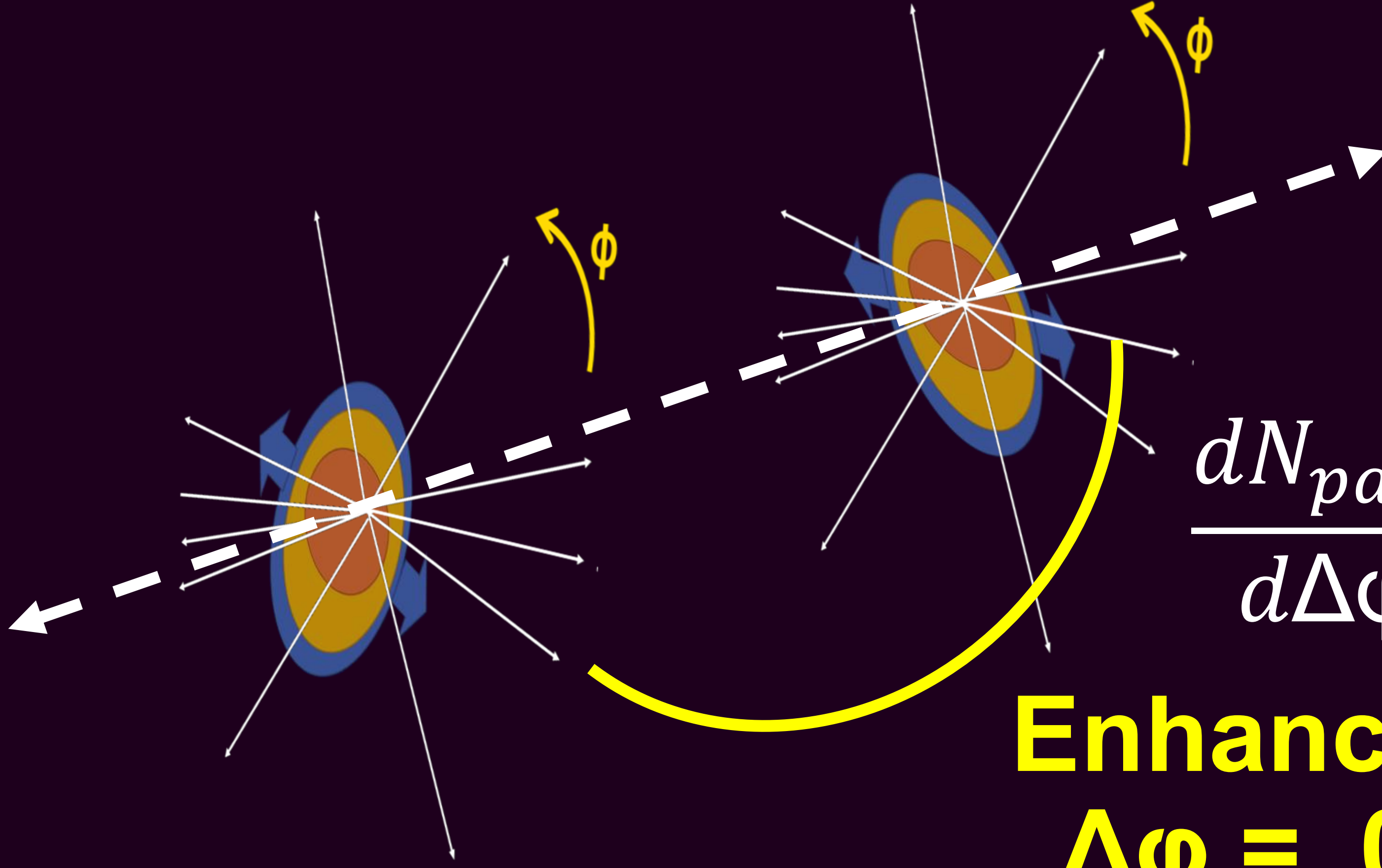
The two models converge at large system size

Break down of hydro at small system size

Explore HOT QCD

Can we gain experimental sensitivity to far-from-equilibrium dynamics

Two-particle correlations

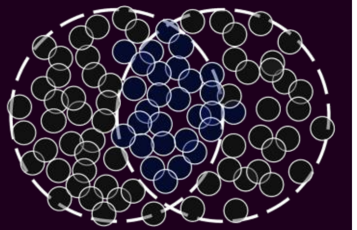


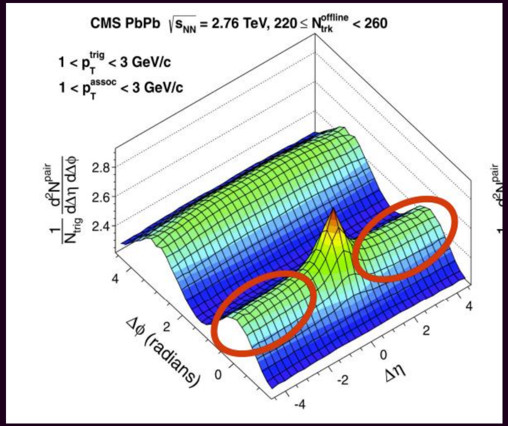
$$\frac{dN_{pair}}{d\Delta\varphi} \alpha\ 1 + 2v_{2,2}\cos(2\Delta\varphi) + .$$

Enhancement at
$\Delta\varphi$ = 0 and π

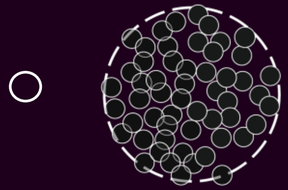
System size

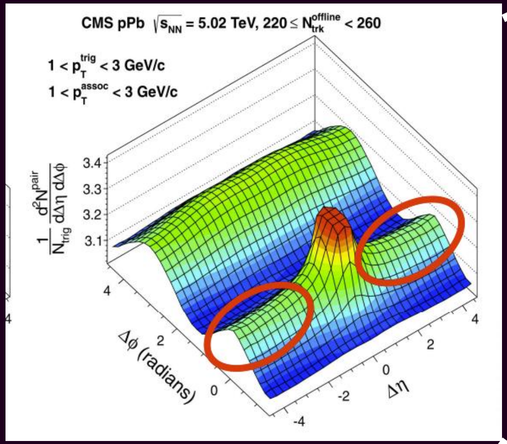
Pb+Pb



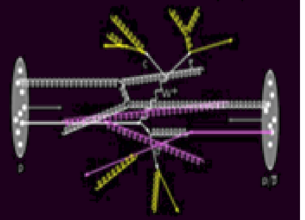


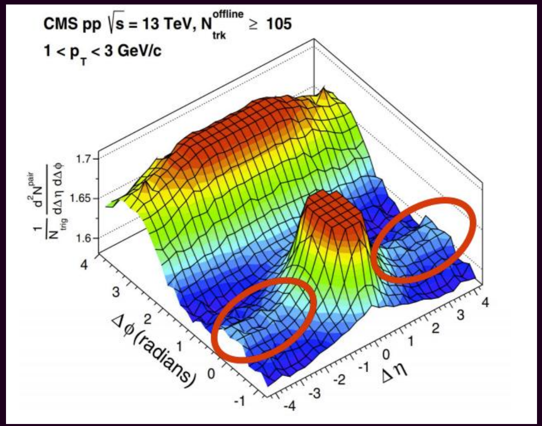
p+Pb





pp



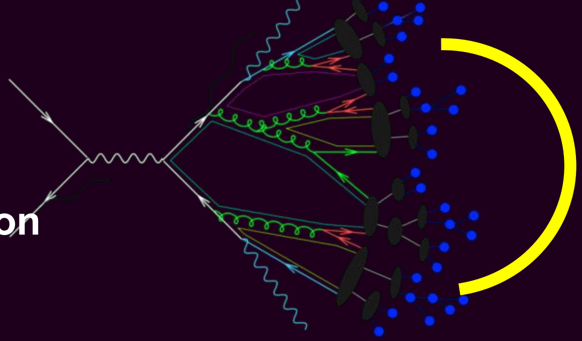


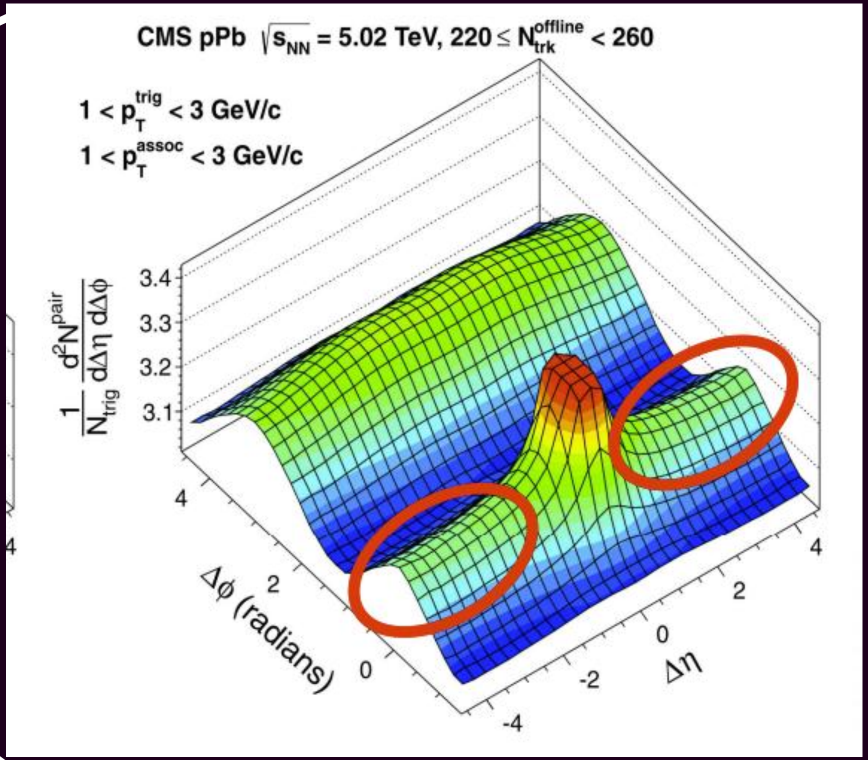
Momentum conservation

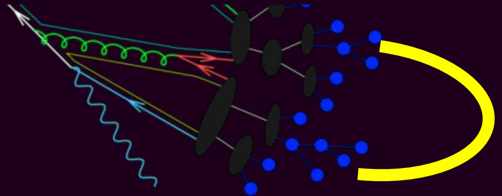
Jets & particle decays

Termed “nonflow”

Not collective phenomenon

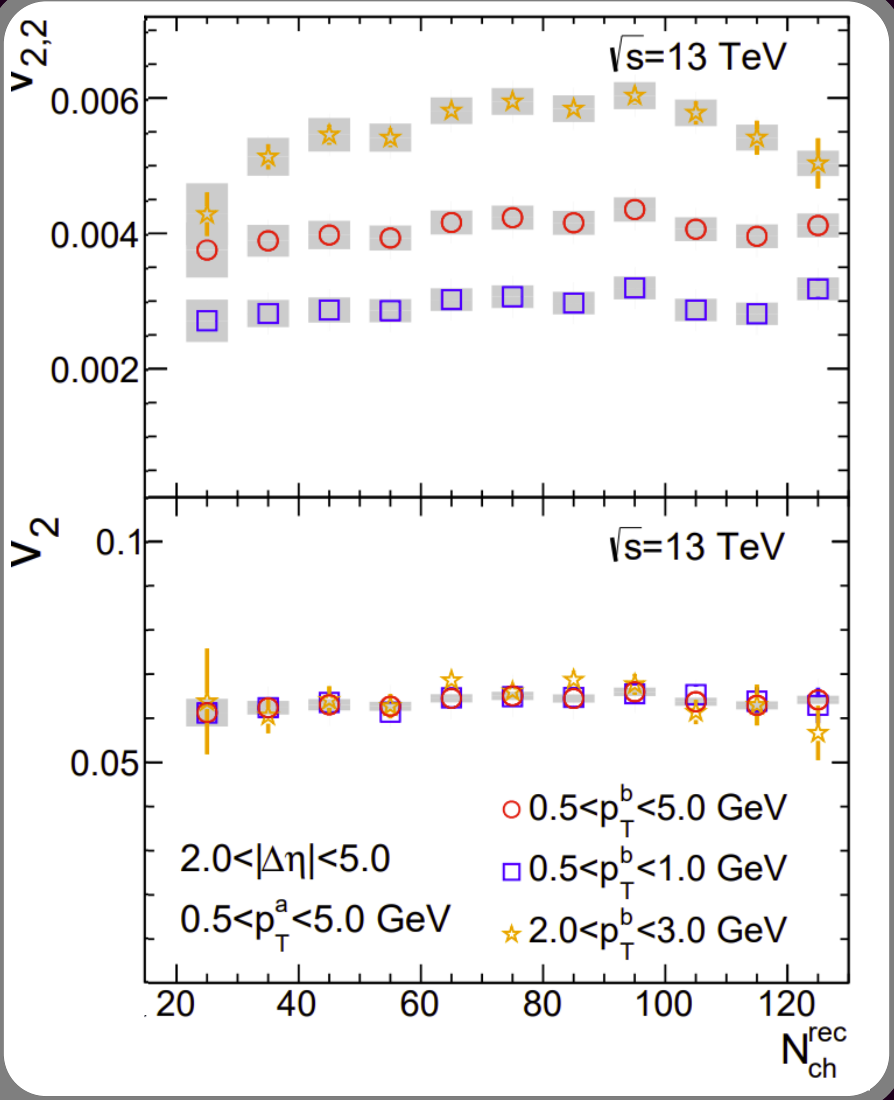






Δφ < 2
Δη < 2

First signs of collectivity in small systems



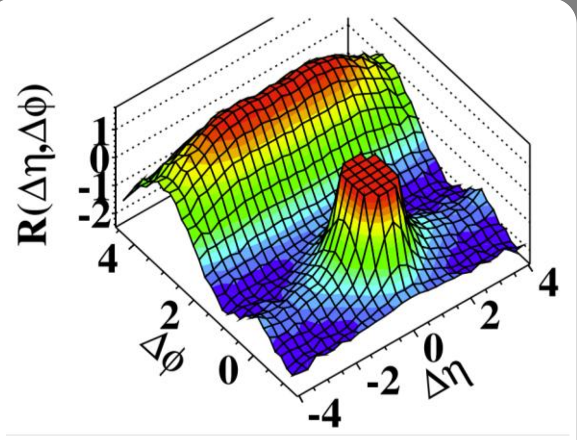
arXiv:1509.04776

CMS **ridge observation**

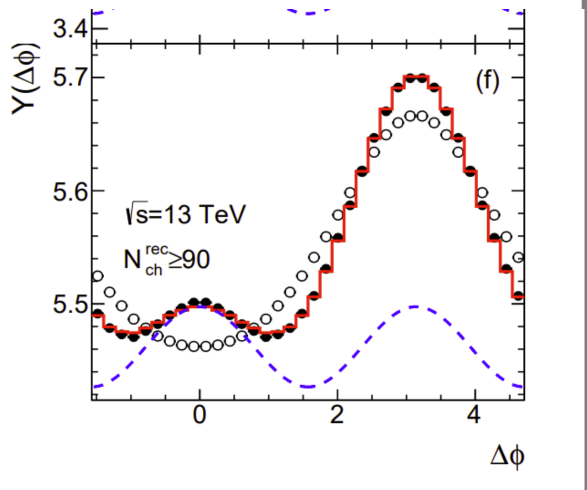
- First small systems ridge by
- Leaveraged LHC's experiments,
  - high performance software trigger
  - larger N_{ch} reach

ATLAS **measurement**

- Non-flow subtraction – first v_n
- Demonstrated factorization
  - Consistent with anisotropy generated from universal (in p_T) hydro flow vector
  - Inconsistent with CGC which has large decorrelation in p_T



arXiv:1009.4122



arXiv:1509.04776

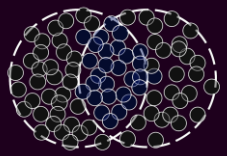
Essential questions

- Can we break hydro by pushing into a regime governed, by what, far-out-of-equilibrium hydro, kinetic theory, parton escape, etc?
- How well do we know the initial-state geometry?
- Can we remove nonflow effects in a systematic way?
- What is the role of fluctuations?
- Are there other precision tools?

What is the approach

An earnest precision-oriented march to lower and lower multiplicities and system size.

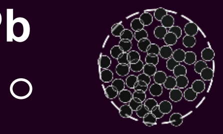
Too big?

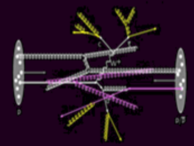
Pb+Pb 

^{16}O

+

^{16}O

p+Pb 

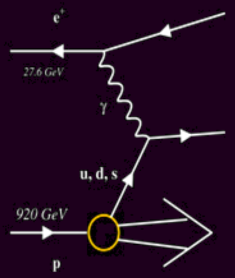
pp 

Too small?

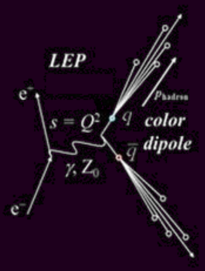
OR

A creative explosion which interrogates the assumed building blocks of collectivity by completely removing them.

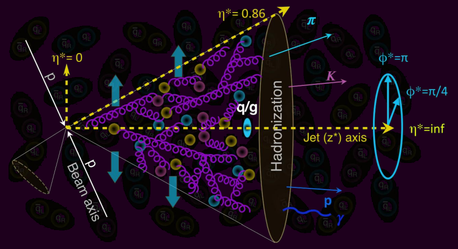
e+*p*



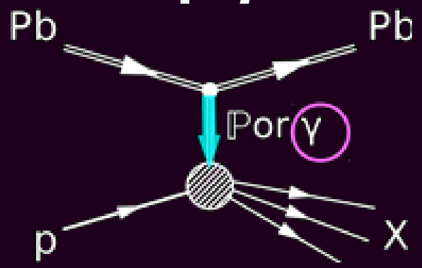
e$^+$+e$^-$



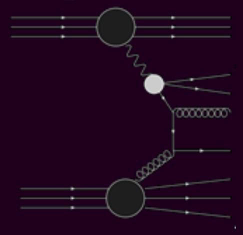
Jets



γ+*p*



γ+A



Geometry

Fluctuations

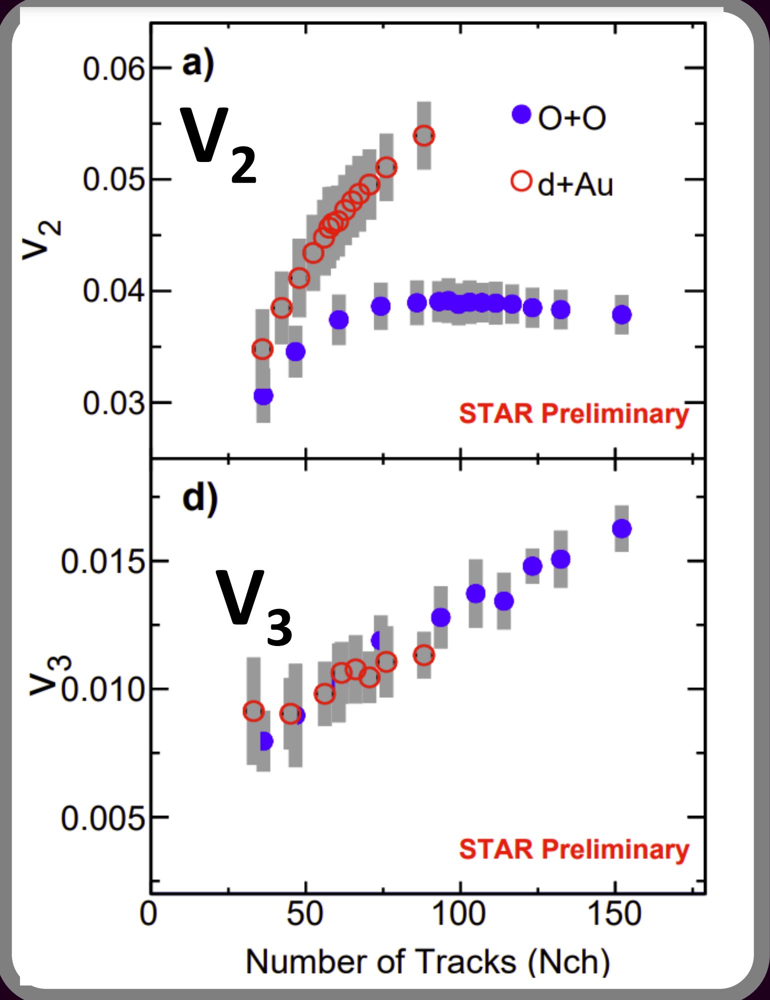
Transport

Novel small systems

Future

$^{16}O+^{16}O$ with STAR

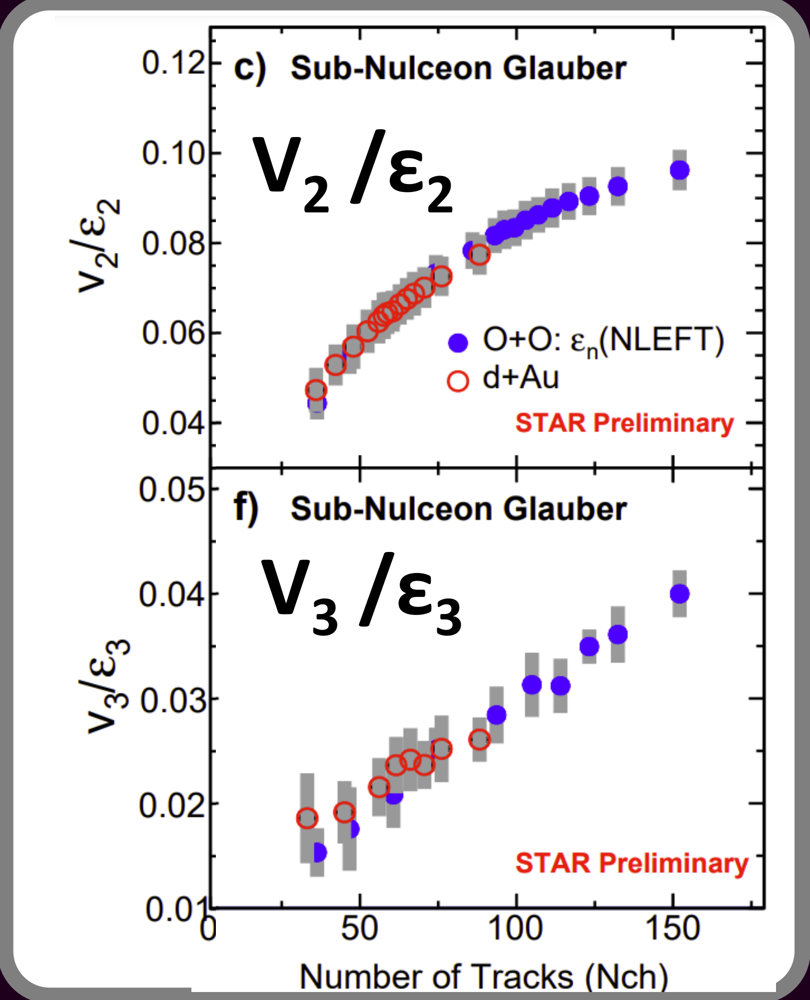
Zhengxi Yan



- v_2 and v_3 in O+O and *d*+Au with nonflow subtraction
- 20-30% difference in v_2 between O+O and d+Au

Divide by geometry

- Agreement of v_n/ε_n
- O+O ε_2 is less than a few percent sensitive to subnucleonic effects
- Larger systems transfer initial-state geometry more effectively



v_n of equally sized systems are driven by geometry

Geometry

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Longitudinal decorrelation in small systems

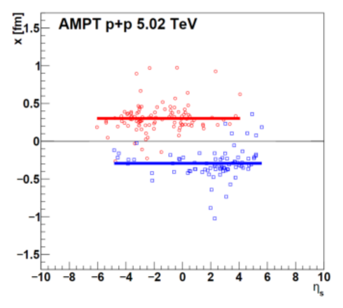
F_n is the fractional change in $v_{n,n}$ per a unit additional rapidity separation

$$v_{n,n} \propto 1 + F_n \eta_{separation}$$

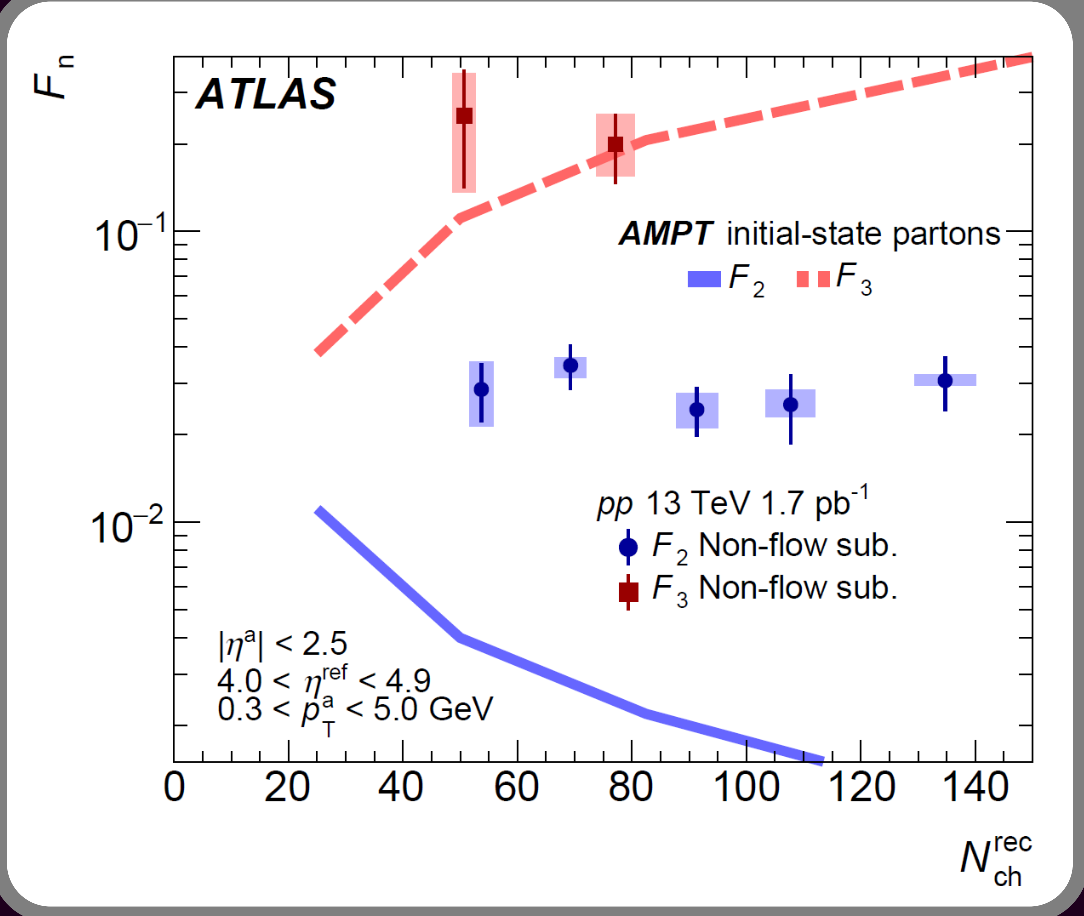
Calculated by comparing $v_{2,2}$ with |Δη| as low as |Δη| = 1.5 to as large as |Δη| = 7.4

probes the shape of the initial state

- AMPT's simple 2-string model has insufficient longitudinal fluctuations

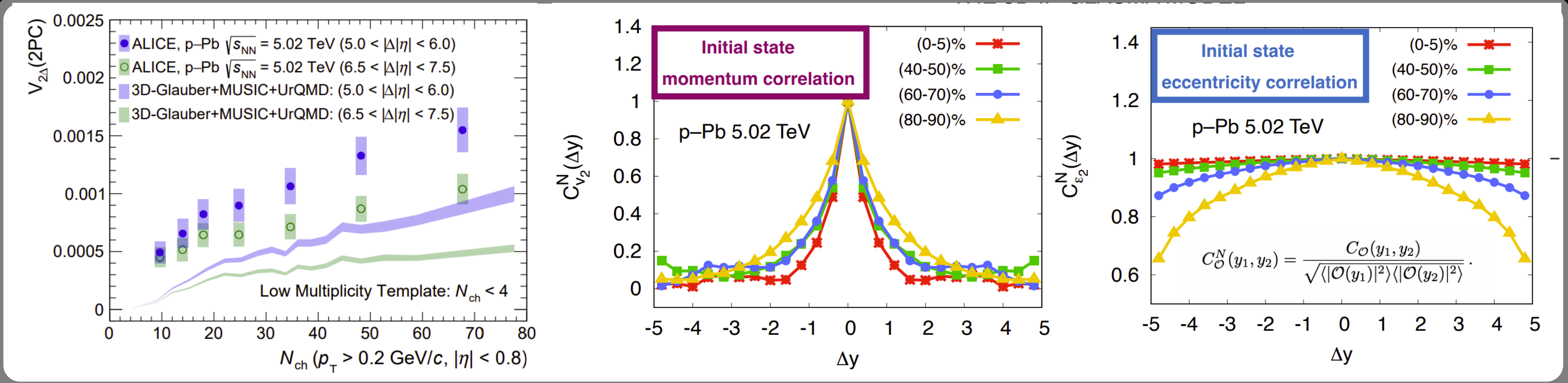


arXiv:2308.16745



Nucleon-level geometry is inadequate to describe longitudinal dynamics

How long is the long-range ridge?



arXiv:2504.02359

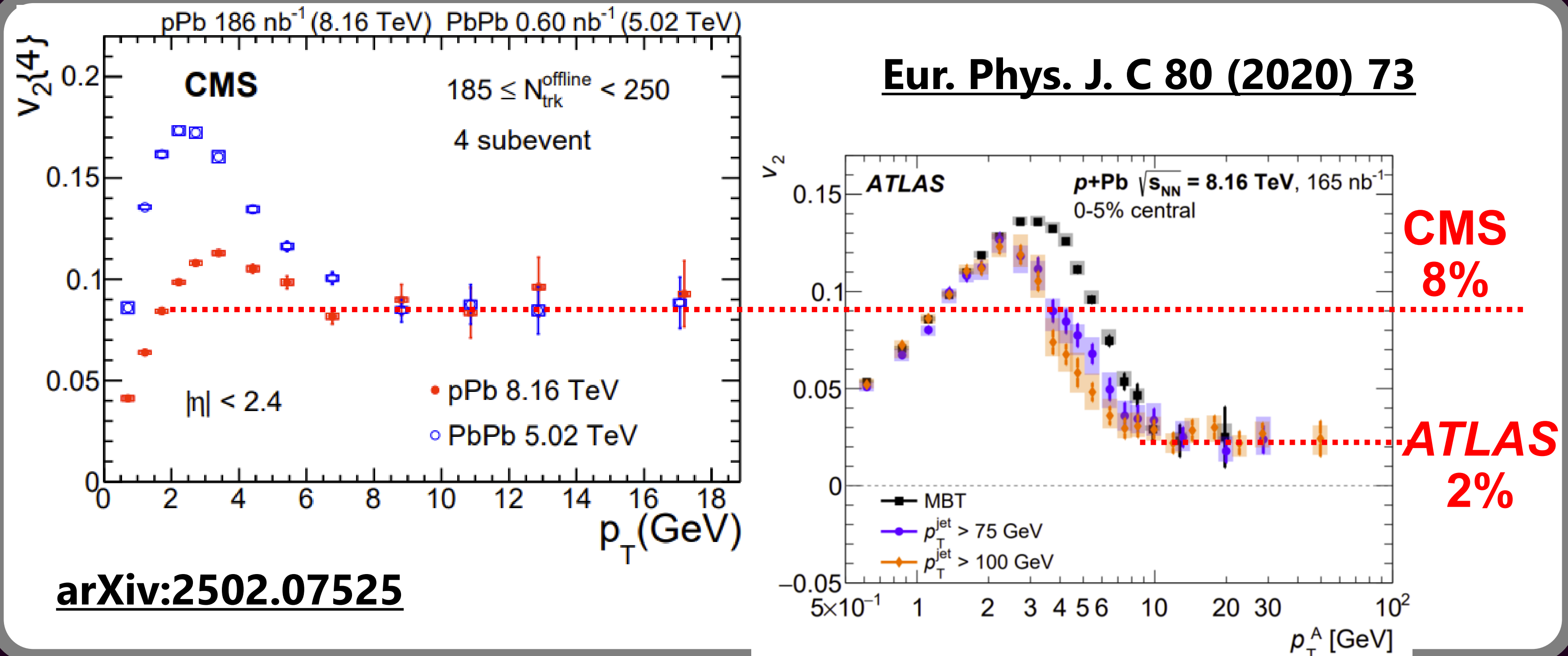
Phys. Rev. D 105, 094023

- ~ 3% v_2 for very large rapidity gap |Δη| > 7.5
- Initial-state momentum anisotropy correlations die out with |Δ*η*| >2
- Final-state effects (hydro+geometry) survive large separations in *η*

Long range correlations are driven by final state effects

Multi-particle cumulant high-pT $v2$ in pPb

- No Jet quenching in pPb R_{AA} -1 < +/- 10%
- High-p_T v_2 observed by ATLAS
- Multiparticle cumulants are less sensitive to nonflow
- Cumulants give access to fluctuations
- How $v_2\{4\}$=8% and $v_2\{2\}$=2%?



arXiv:2502.07525

Eur. Phys. J. C 80 (2020) 73

$$v_n\{4\} = -\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}}$$

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2\langle\langle 2' \rangle\rangle\langle\langle 2 \rangle\rangle$$

1 trigger particle, 3 associated particles

↑ Fluctuations?

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2$$

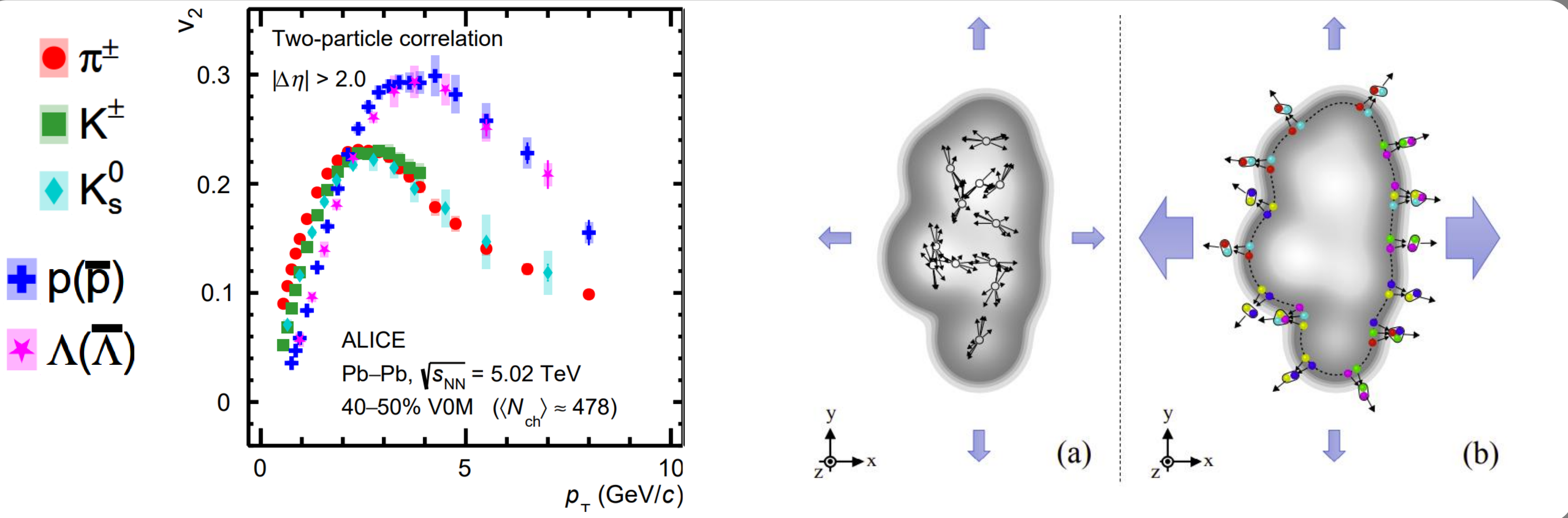
4 associated particles

↓ Fluctuations?

Geometry
Fluctuations
Transport
Novel small systems
Future

What is flowing?

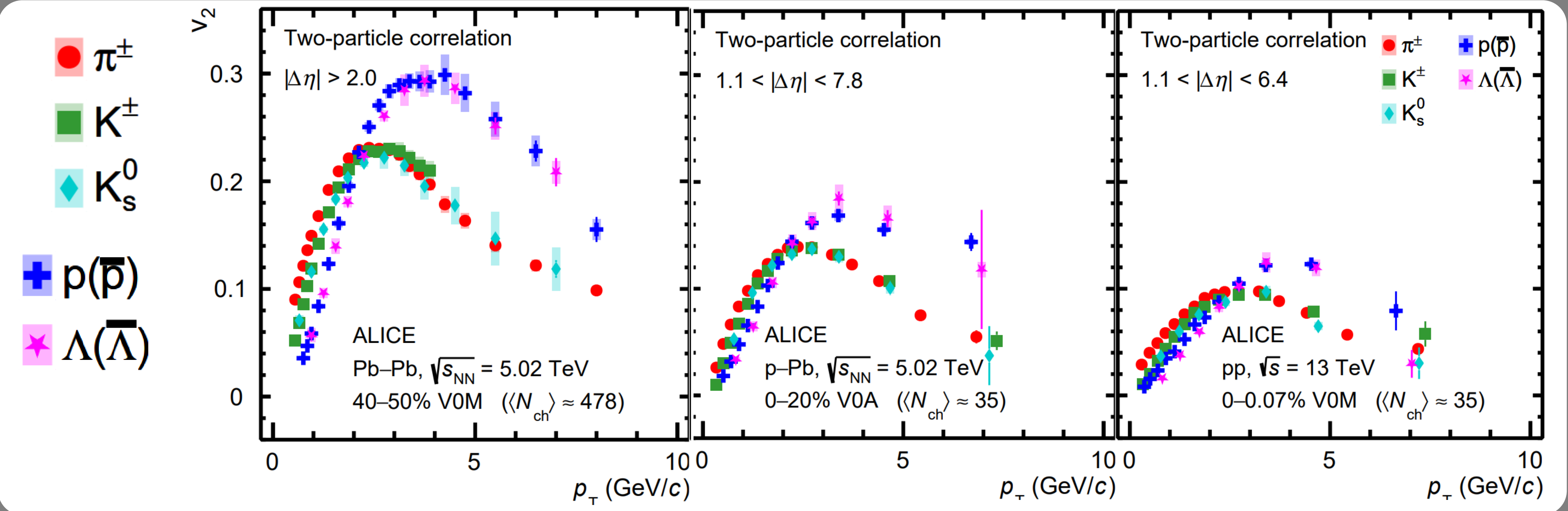
arXiv:2411.09323



- p_T **< 3 GeV**: **Mass ordering** arises from the interplay between radial expansion and anisotropic flow of the velocity field which pushes heavier particles to higher p_T
- **3 <** p_T **< 5 GeV**: **Baryon and meson grouping** arises from parton coalescence
- Non-flow subtraction with the template fit

Partonic flow in *pp*

arXiv:2411.09323

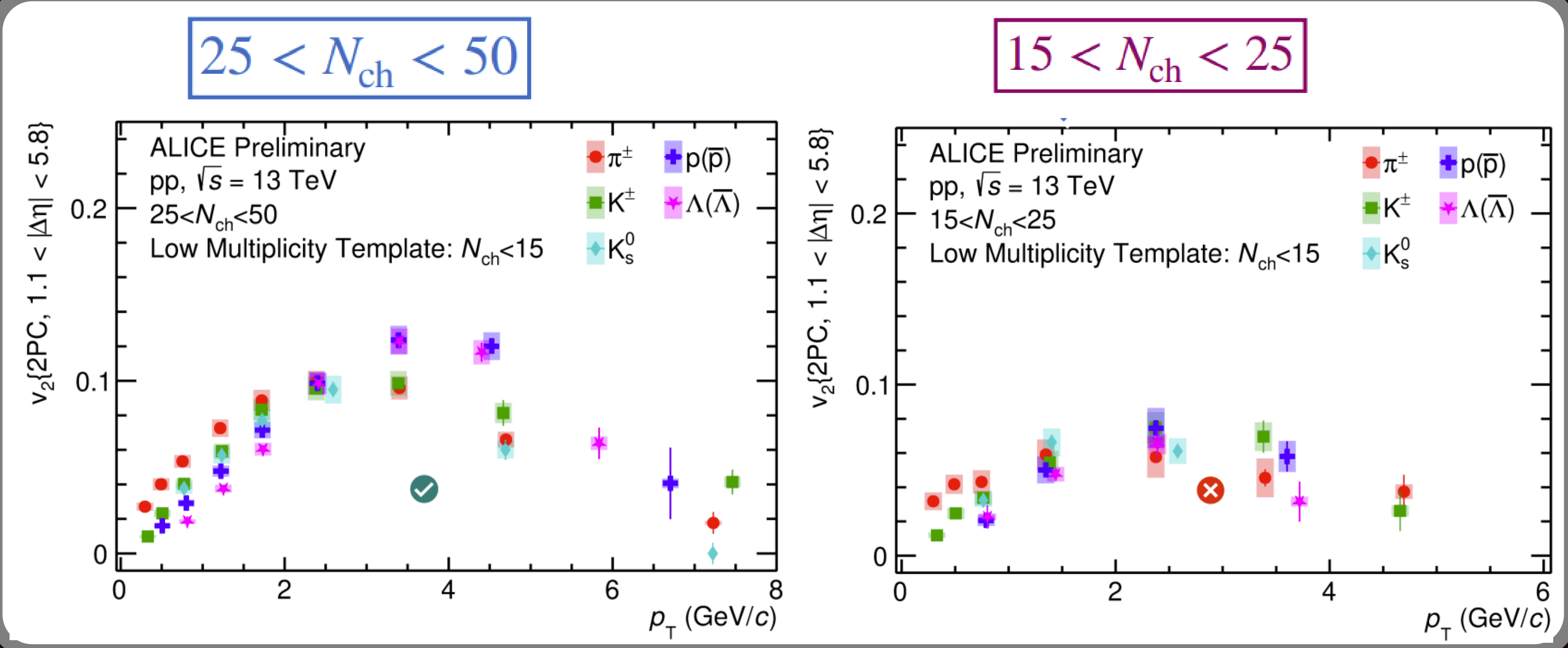


- ➢ **p_T < 3 GeV**: **Mass ordering** arises from the interplay between radial expansion and anisotropic flow of the velocity field which pushes heavier particles to higher p_T
- ➢ **3 < p_T < 5 GeV**: **Baryon and meson grouping** arises from parton coalescence
- ➢ Non-flow subtraction with the template fit

Strong evidence of a deconfined flowing parton medium in *pp* and *p*Pb

The breakdown of partonic flow?

- **Breakdown of baryon-meson grouping in low multiplicity *pp***
- Mass ordering persists
- Nonflow subtract issue are largest at high p_T and low multiplicity
- Are probes like these **less sensitive to uncertainties in initial state geometry?**



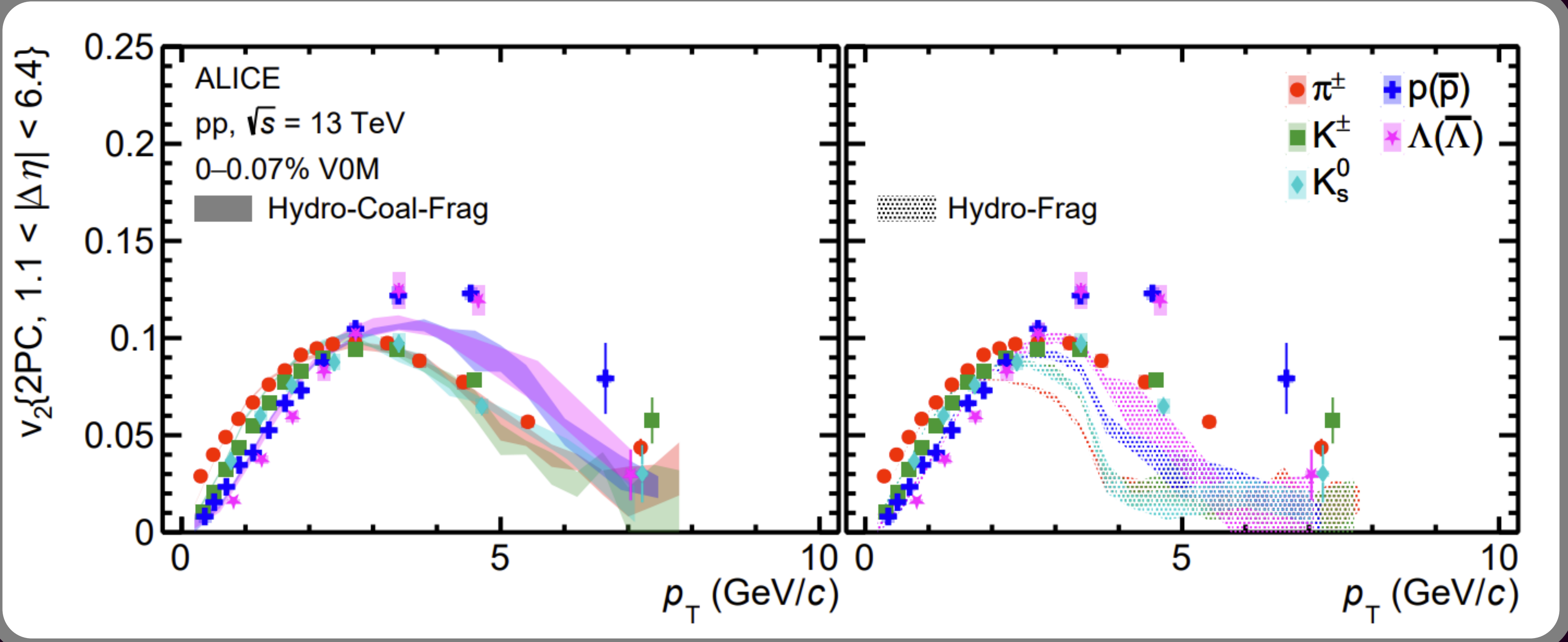
small collision systems presented either a single baryon or meson v_2, limiting the opportunity to explore potential groupings among baryons and mesons [45, 46]. Other similar measurements have not shown a clear grouping and splitting of baryon and meson v_2 at intermediate p_T in small systems, differing from similar measurements in heavy-ion collisions [24]. This difference may arise from difficulties in accounting for non-flow effects in small systems. The results presented in Fig. 2 show, for the first time,

Nonflow subtraction is imperative for precision measurements

Are there tools like this to probe the breakdown of hydro?

Partonic flow in *pp*

arXiv:2411.09323



➢Coalescence between medium quarks and fragmentation quarks is necessary for adequately describing *pp* results

Coalescence is necessary but not sufficient to reproduce baryon-meson grouping

Geometry

Fluctuations

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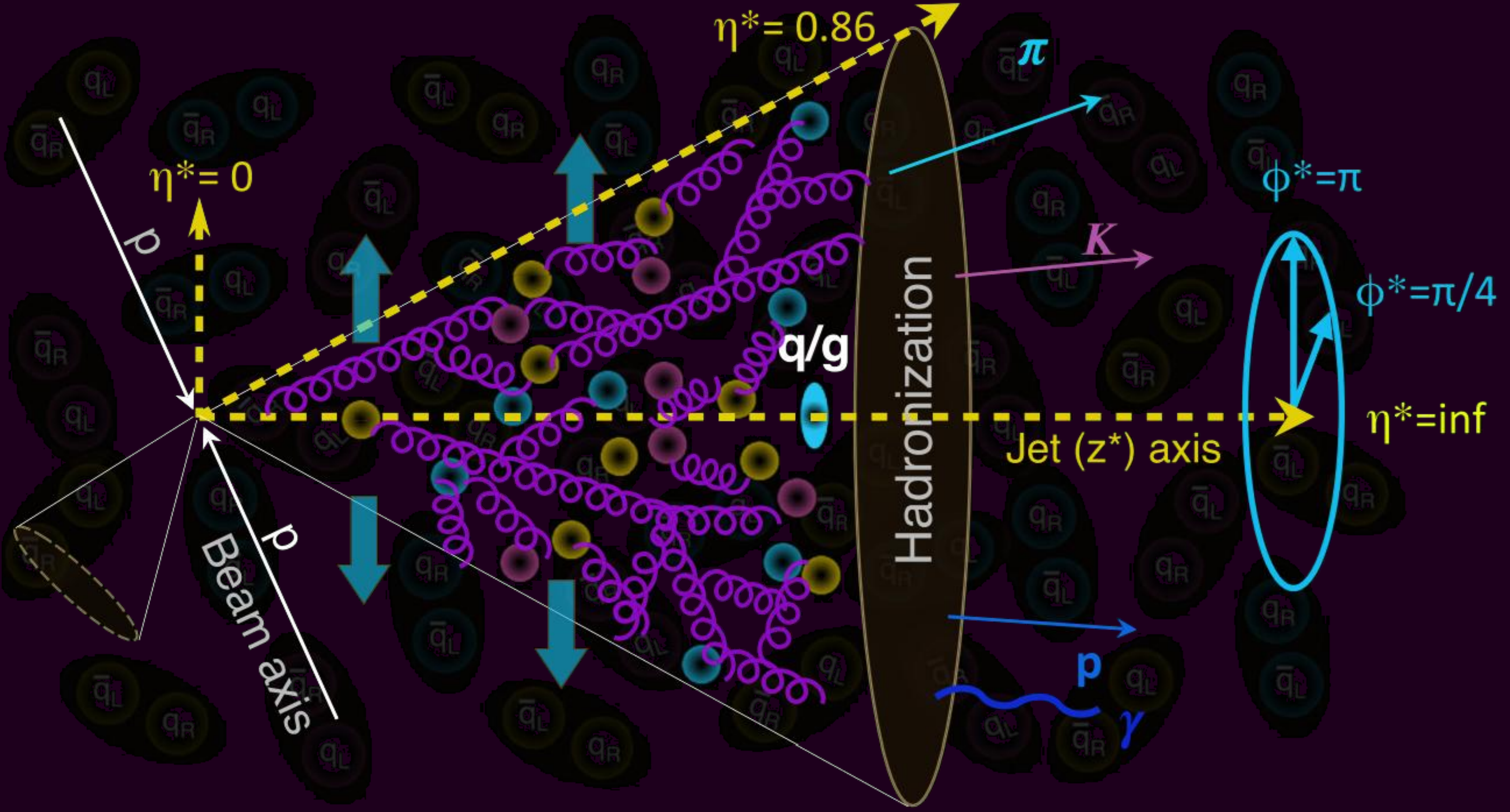
Novel small systems

Future

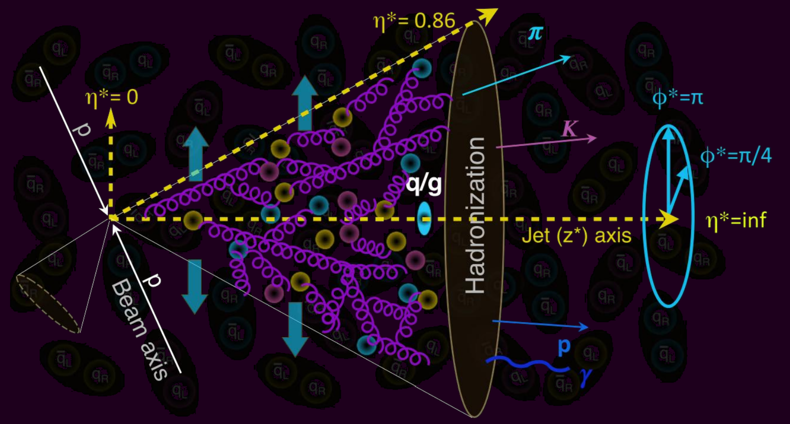
High multiplicity jet system

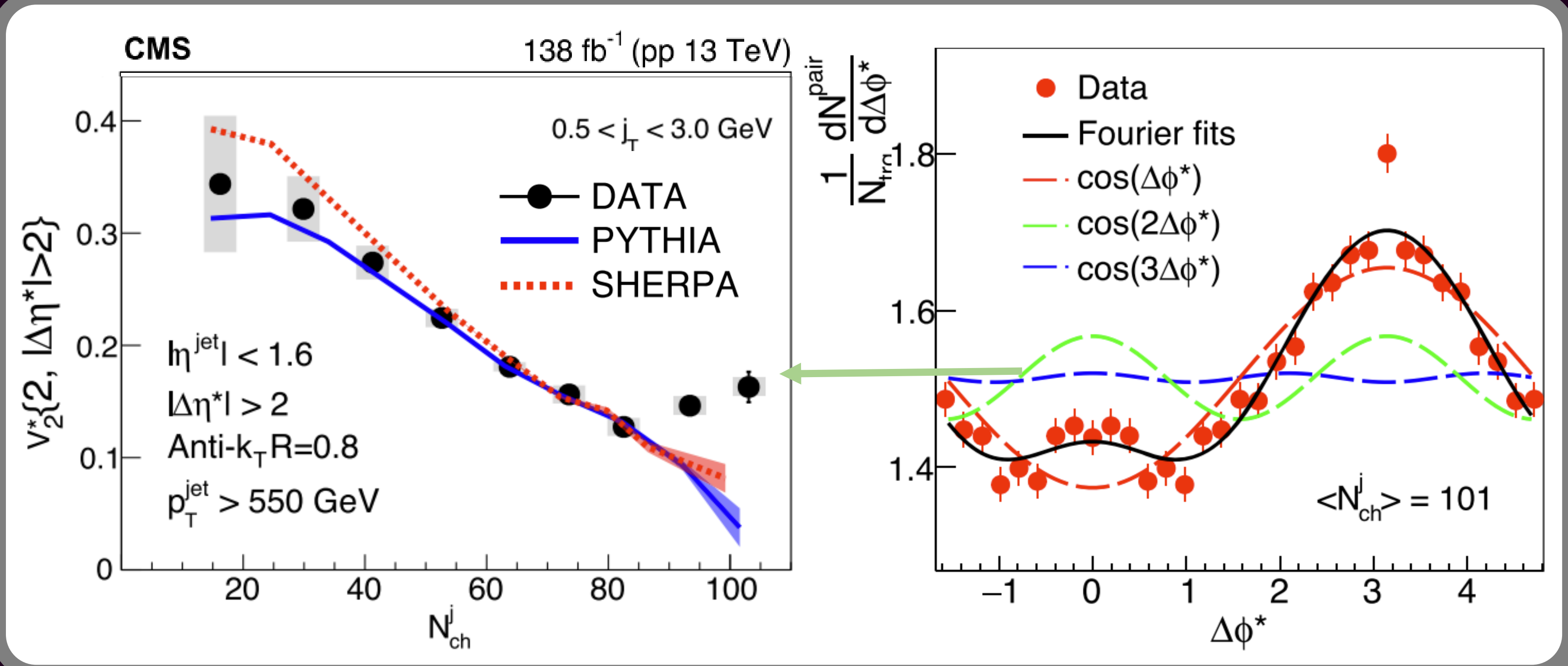


Enhanced v_2 within high-multiplicity jets

Use jet axis as beam axis

$\phi, \eta, p_T \rightarrow \phi^*, \eta^*, j_T$





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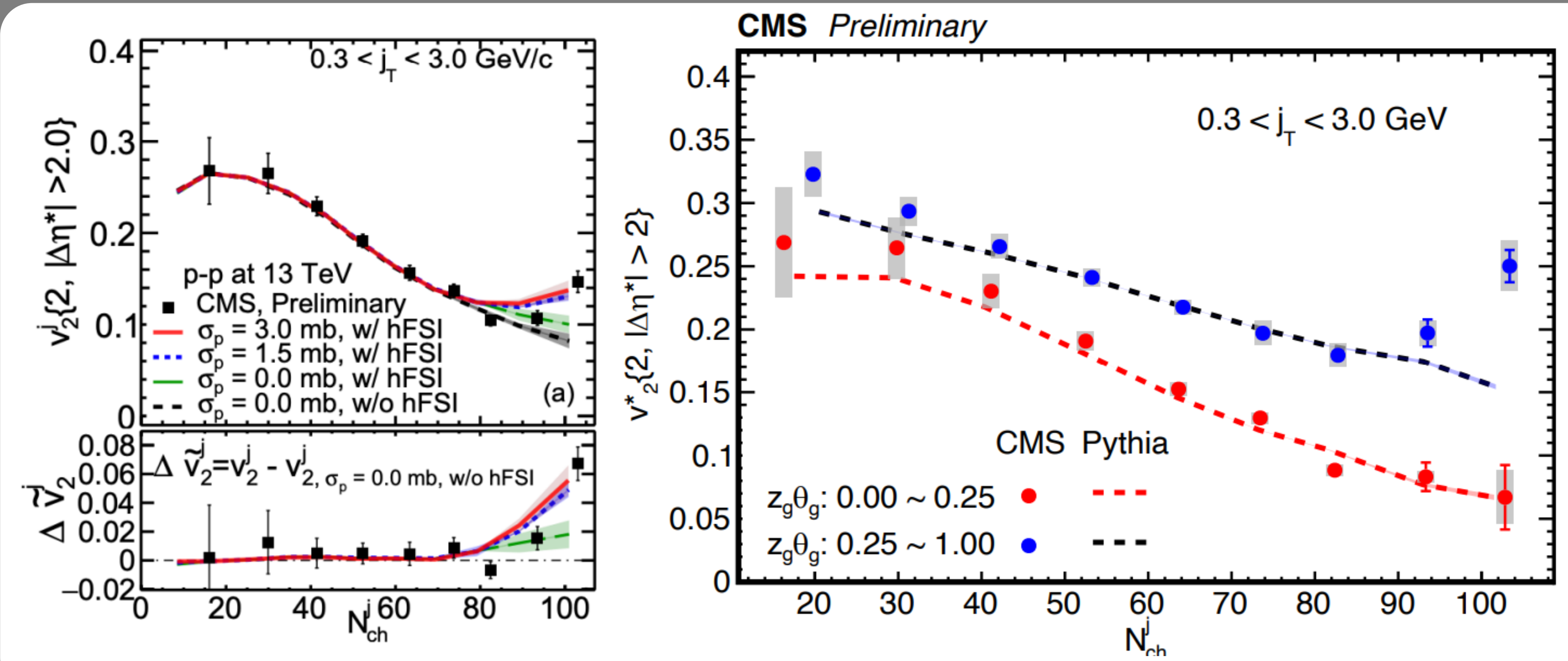
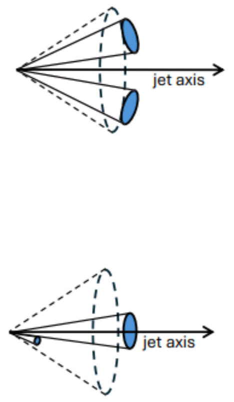
- 138 fb^{-1}: Full Run 2 statistics used
- In the highest multiplicity jets a flow-like elliptic enhancement is observed
- Measured a very large v2 = 16.29%
- **What's next**: j_T dependence, flow factorization, …?

Enhanced v_2 within high-multiplicity jets

arXiv:2401.13137

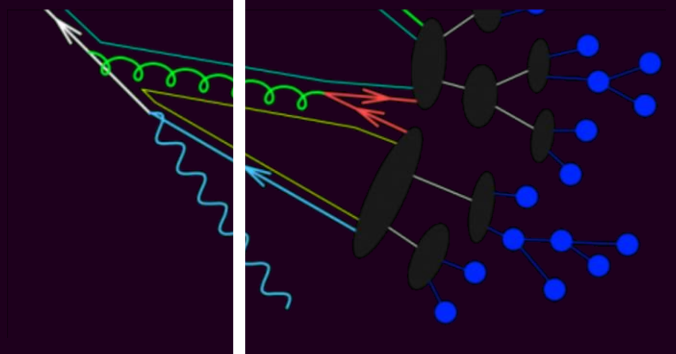
Theory comparison using PYTHIA jet shower model combine with parton re-scattering ZPC





Xiaoyu Liu

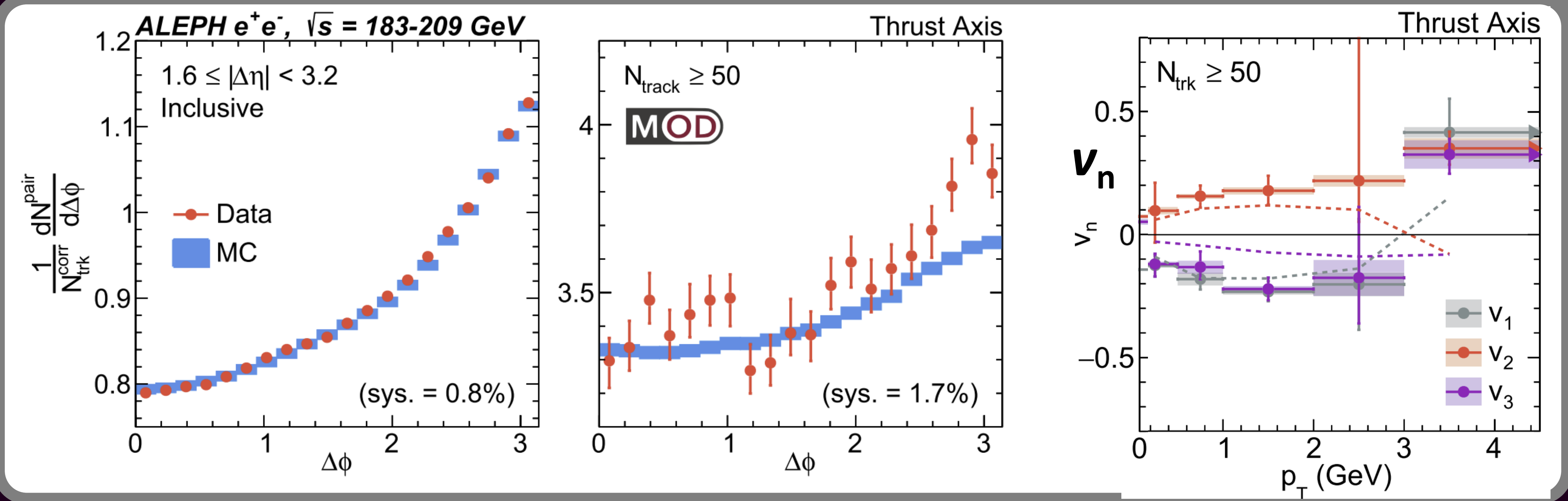
PYTHIA | AMPT-like



Does pQCD provide us a well-constrained geometry?

- New results: grouping jets in terms of substructure
- 2-prong jets show much larger collective effects

Azimuthal anisotropy in e^+e^-



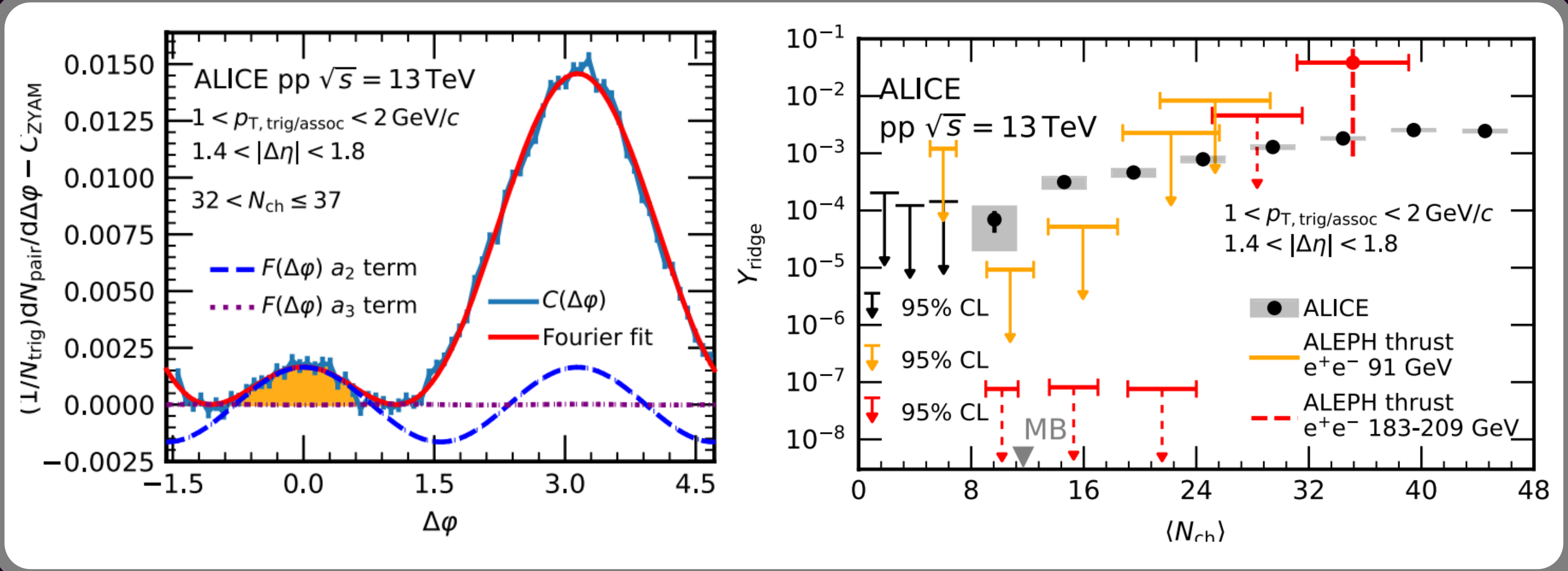
PLB 856, 138957 (2024)

- 2-particle correlation performed in the thrust axis (much like the high multiplicity jets)
- The V_n coefficients have poor data-MC agreement when pushed to the highest multiplicities
- One can interpret this as signs of other effects in data not simulated and perform nonflow subtraction
- $v_n^{flow} = v_n^{data} - v_n^{MC}$: this method yields a positive v_2 but a negative v_3 which is not interpretable in the geometry-driven interpretation

Issues with nonflow sub. make qualitative conclusions of collectivity hard

Ridge yields in the smallest systems: *pp* & e^+e^-

Extraction of **nearside per-a-trigger yields:** integral of **Orange** region



Phys. Rev. Lett. 132

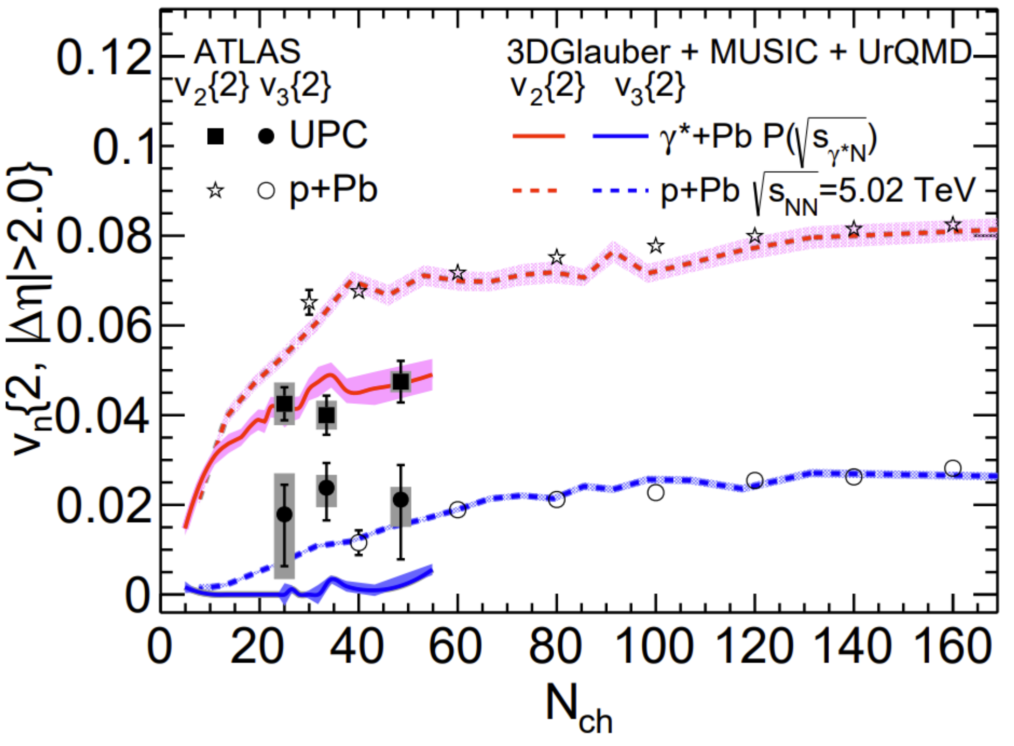
Nearside per-a-trigger yields are challenging to interpret

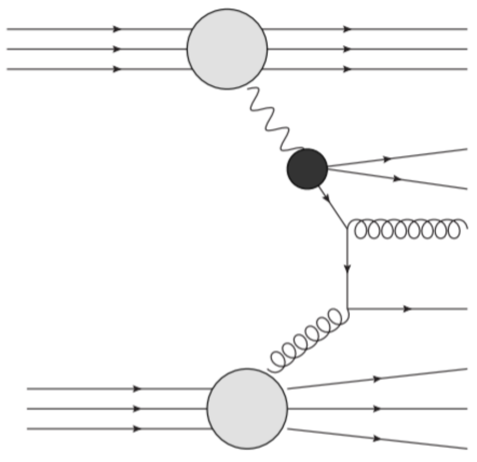
- yield depends on shape and scale of nonflow
- Per-trigger yield grows with growing N_{ch} – results don't necessarily demonstrate a increasing v_2
- have to be compared to theory with flow and nonflow

Can make direct comparisons to e^-e^+

Only quantitative statements can be made about nonflow

γ+Pb azimuthal anisotropy at the LHC





Phys. Rev. Lett. 129, 252302
Phys. Rev. C 104, 014903

γ+Pb collisions

$\langle W_{\gamma N} \rangle$ range 0.5 – 1.0 TeV

Single-sided nuclear breakup

Mostly hadronic-like collisions

Selected with rapidity gap

Observe Nonzero γPb v_2

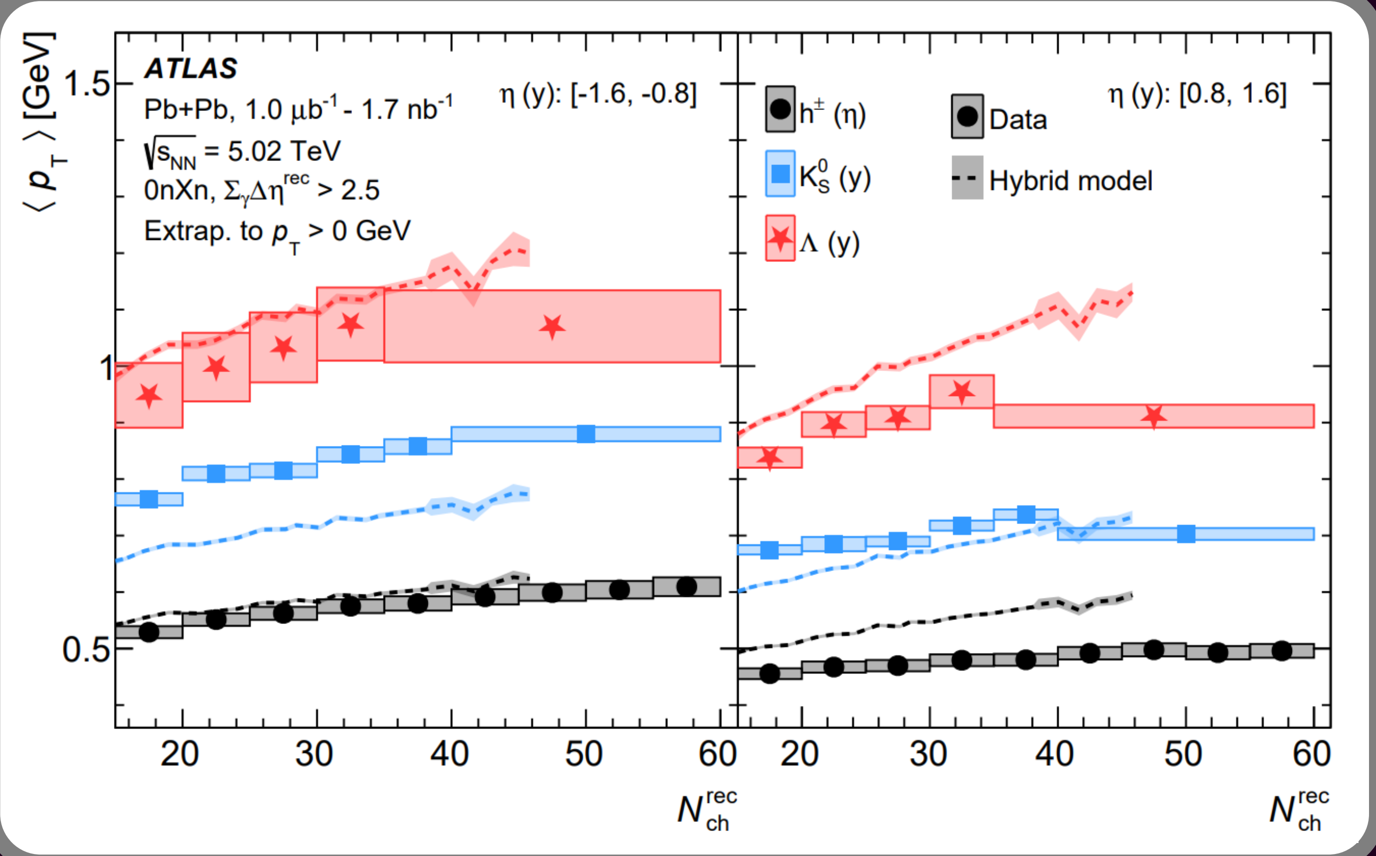
comparison to 3DGlauber + MUSIC +UrQMD

Why is v_2 (γ *+Pb) < v_2 (p+Pb)

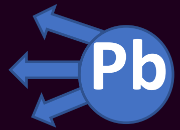
γ+Pb correlations performed at forward rapidities which suppresses observed v_2 due to enhanced longitudinal decorrelation

Identified particle <p_T> in γ+Pb

arXiv:2503.08181



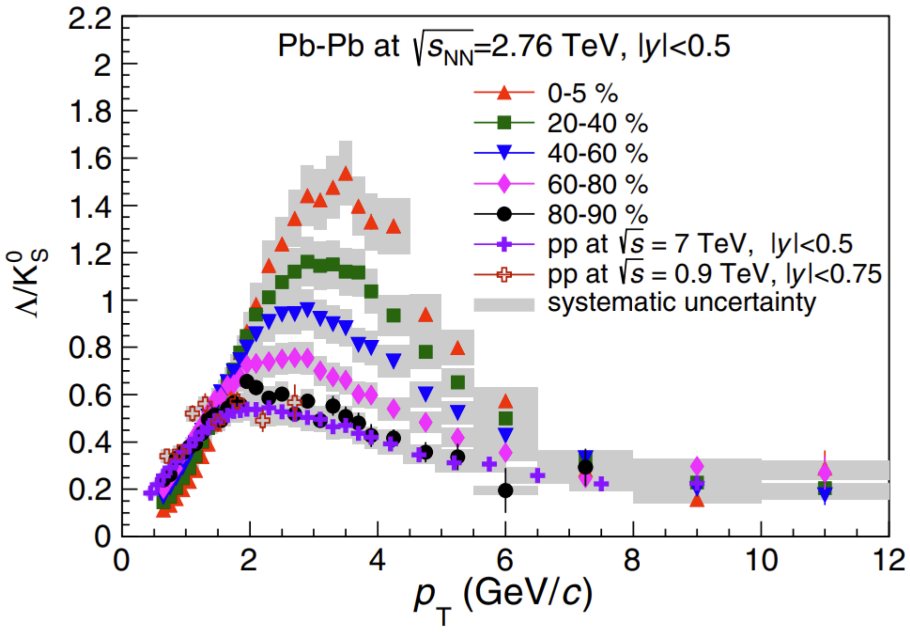
- ➢Why <p_T> with N_{ch}
  - Higher energy density achieved in higher multiplicity collisions leads to stronger radial expansion.
  - Signature of collectivity
- ➢Larger <pT> in the Pb-going direction
- ➢Qualitative agreement with the Hydro model



Behavior in data is consistent with qualitative picture of radial flow

Baryon anomaly in γA

Phys. Rev. Lett. **111**, 222301

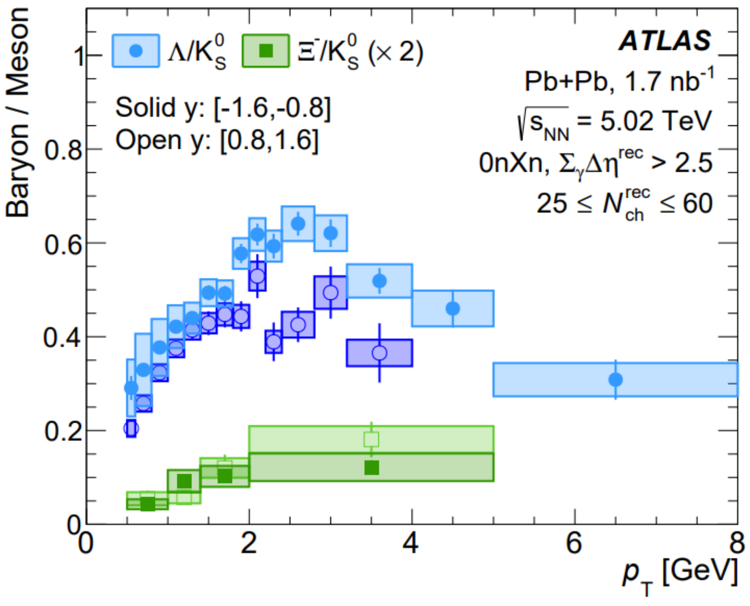


- Evidence of hadronization in a dense environment
- Observe large baryon enhancement at mid-pT in *γA,* similar to pPb
- Possibly see larger baryon enhancement in the Pb going direction

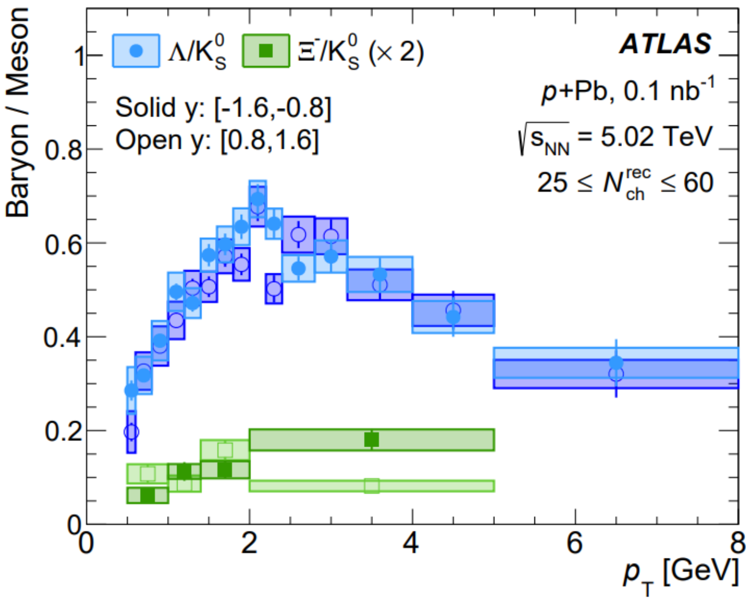
Baryon anomaly in γ+Pb

γ+Pb

arXiv:2503.08181



p+Pb



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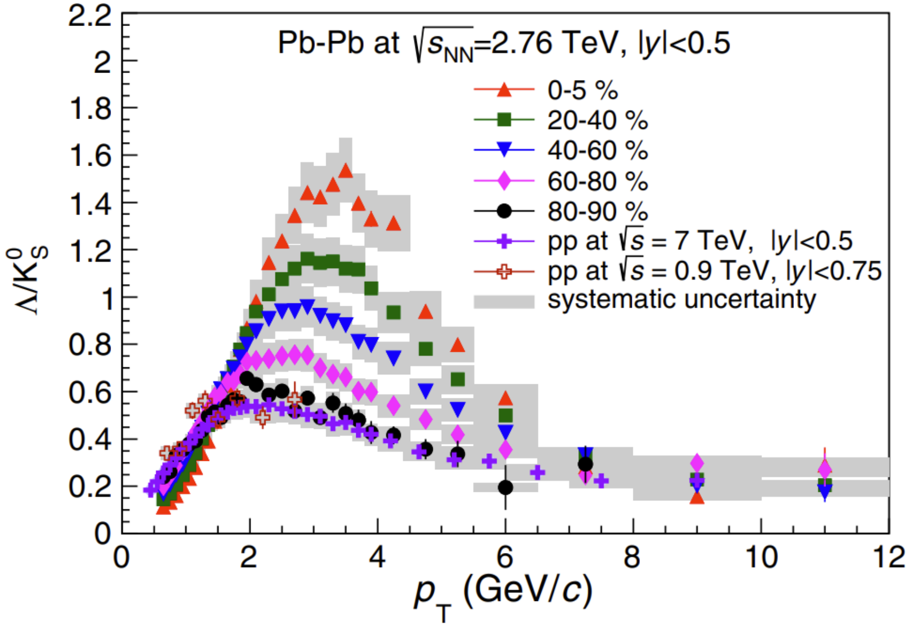


- ➢Evidence of hadronization in a dense environment
- ➢Observe large baryon enhancement at mid-pT in *γ*Pb, similar to pPb
- ➢Possibly see larger baryon enhancement in the Pb-going direction

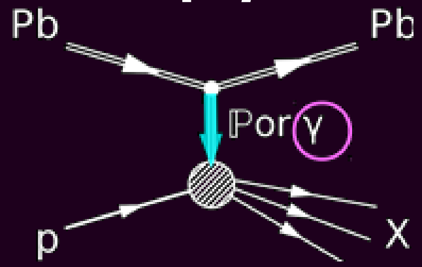
Observe large baryon enhancement at mid-pT in *γA*, similar to pPb

The smallest systems

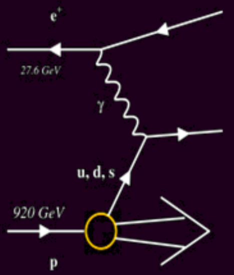
Observing the minimal criteria for QGP formation?

Uncertainty in nonflow subtraction
→ no firm conclusion

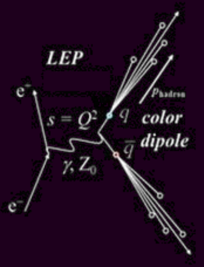
γ+*p*



e+*p*



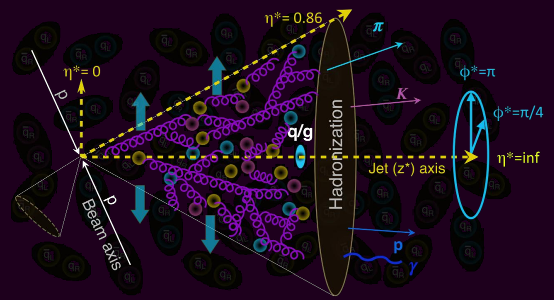
$e^+ + e^-$



Maybe?

N_{ch} threshold observed

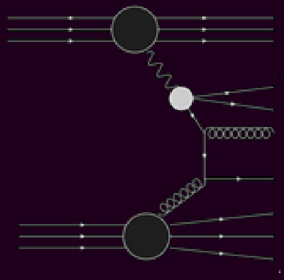
Jets



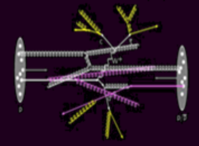
So much like previously explored systems, how is *γ*Pb unique?

1. Boast / decorrelations
2. Unique quantum numbers

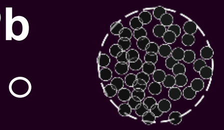
γ+A



pp



p+Pb



Geometry

Fluctuations

Transport

Novel small systems

Future

Future: LHC $^{16}O+^{16}O$ and $^{20}Ne+^{20}Ne$ runs

The plan in July

- ~2 nb^{-1} of 5.36 TeV $^{16}O+^{16}O$
- < 1 day of 5.36 TeV $^{20}Ne+^{20}Ne$

Advantages of O+O and over *p*Pb

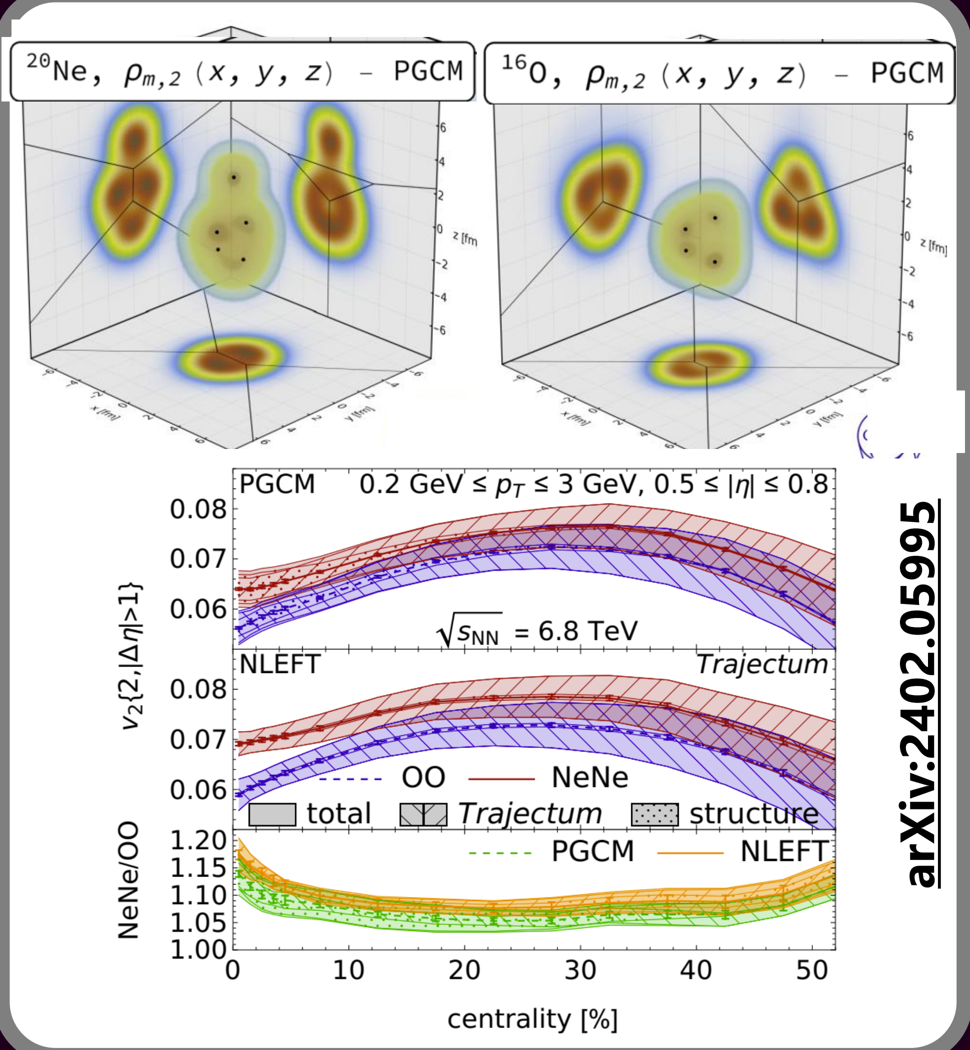
- Initial-state geometry better under control
- less sensitivity to proton substructure
- Symmetric collision system
- First identical system at RHIC and LHC

Comparisons to Ne+Ne

- We can compare 2 small systems of similar size but different initial-state geometries
- Ratios of O+O to Ne+Ne can test linear response to geometry

Density map of ^{16}O and ^{20}Ne

v_2 of OO and NeNe for geometry models PGCM (top) and NLEFT (middle)

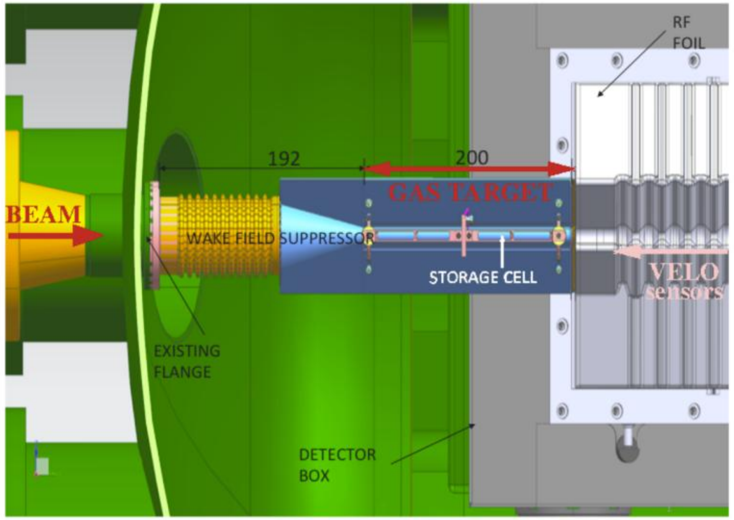


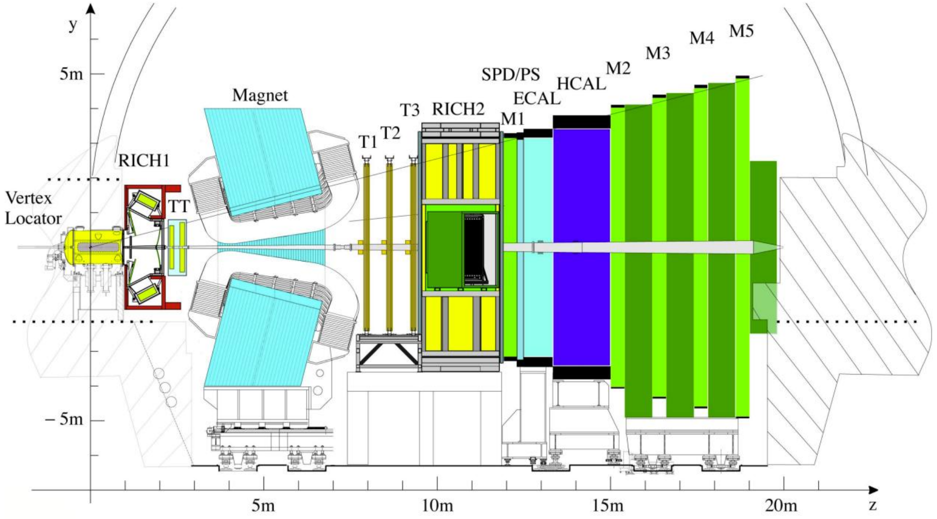
arXiv:2402.05995

Geometry better constrained → sharper test of hydrodynamics

LHCb + SMOG2

More details here





- SMOG2 provides fixed target capabilities which allows for many targets
- Could repeat the RHIC small system energy scan but at similar energies as RHIC
  - Pb+p, Pb+d, Pb+He
- Ratios of similar collisions systems at different energies can cancel initial state geometry effects and yield precision measurements of transport
- Important collective studies with the closing of RHIC

Summary

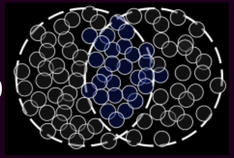
- We have learned a lot:
  - hydro qualitatively works
  - fluctuations are important
  - sub-nucleonic structure is necessary
  - Nonflow has to be systematically considered
- The findings of the field are largely qualitative
- In many small systems, the uncertainties in and the general complexity of the initial state prevents quantitative statements on the nature of collectivity in small systems and how for example it differs from large systems
- Attempts to find the smallest systems or systems with very simple initial state geometry (e.g. e+e-) do not produce enough particles to suppress uncertainties of nonflow removal
- Our tool kit is growing rapidly
- Light ion collisions maybe be a sweet spot, for our current level of understanding, because of its sensitivity to out-of-equilibrium effects, relatively small amount of nonflow, and its better constrained geometry

Backup

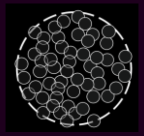
A push towards precision

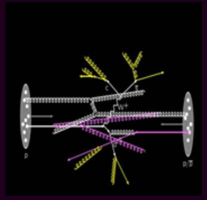
The near future lies in a regime constrained theoretical uncertainties and well understood removal of non-flow

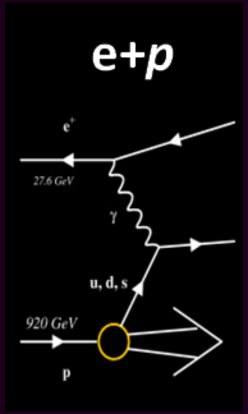
Pb+Pb

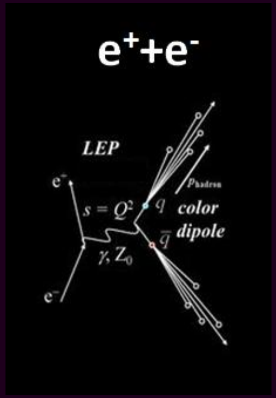


p+Pb

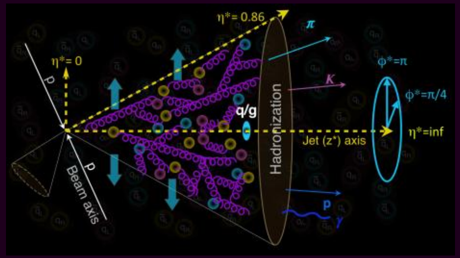




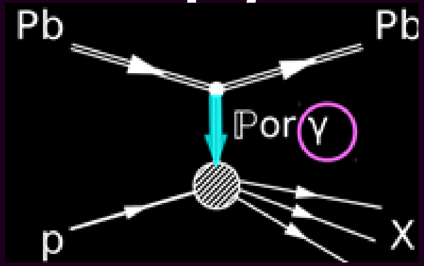




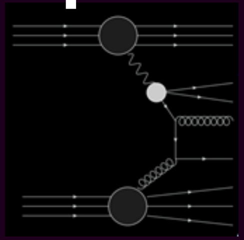
Jets



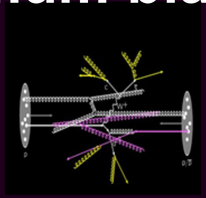
γ+p



γ+A



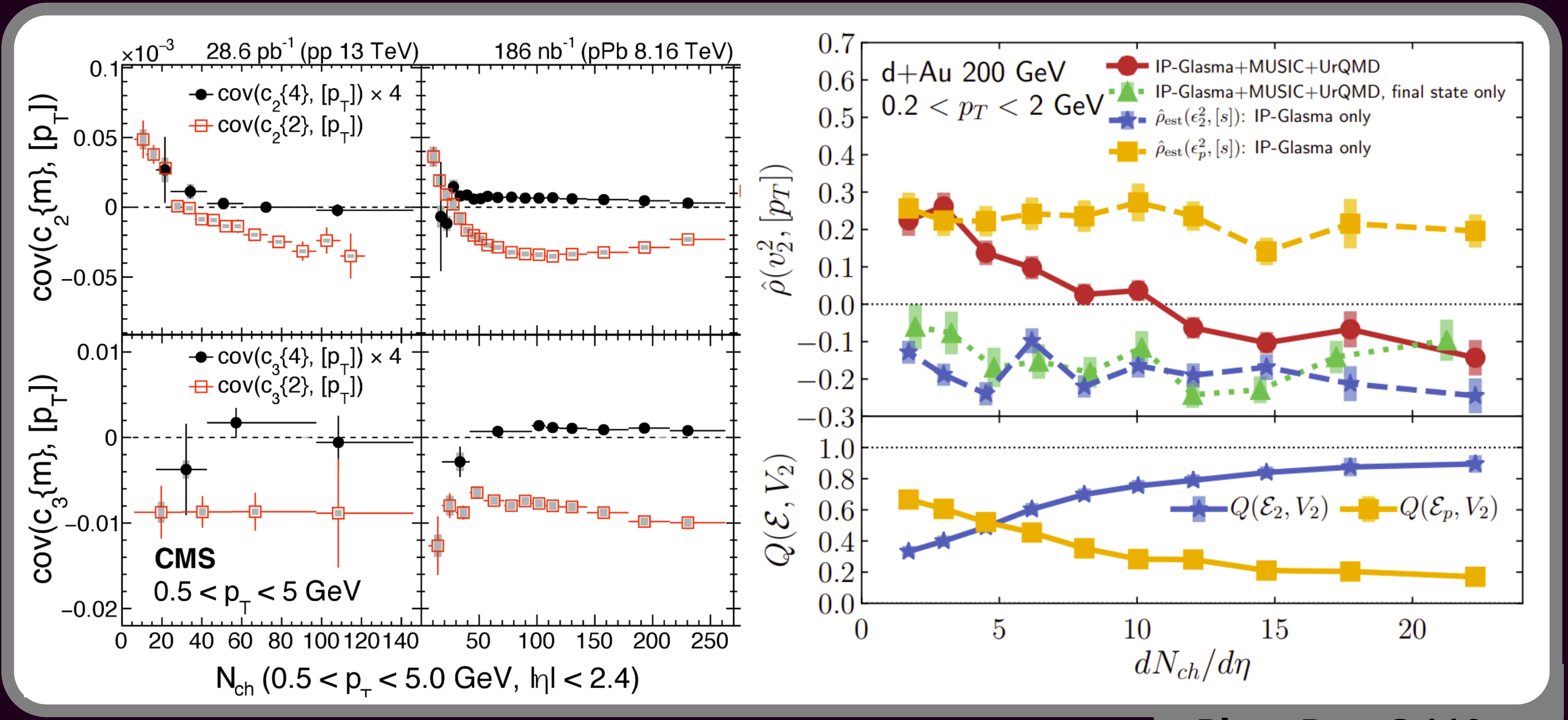
Minimum bias



Without this these will remain a disconnected set of facts

Vn-pT with CMS in small systems

$$\mathrm{cov}(c_n\{2\},[p_\mathrm{T}]) = \Re\left\langle \sum_{a,b} \exp^{in(\phi_a-\phi_b)}\left([p_\mathrm{T}] - \langle[p_\mathrm{T}]\rangle\right)\right\rangle$$



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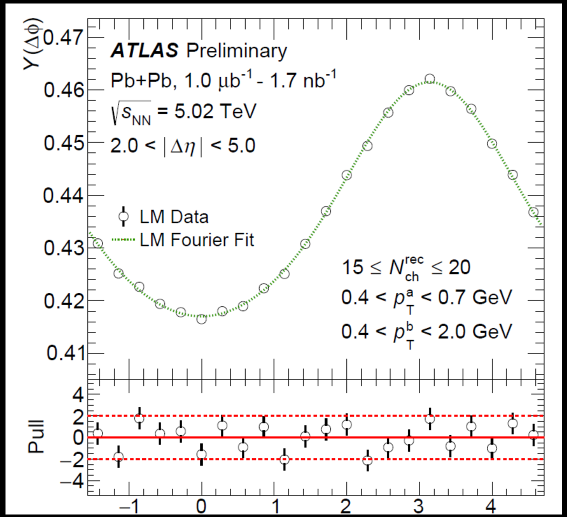
- contributions from nonflow can create sign change at low Nch
- Without subevents, it's hard to interpreted the effects from nonflow even on a qualitative level
- Vn pt arXiv:2410.04578

Template fit in photonuclear

High-multiplicity (HM) correlation data

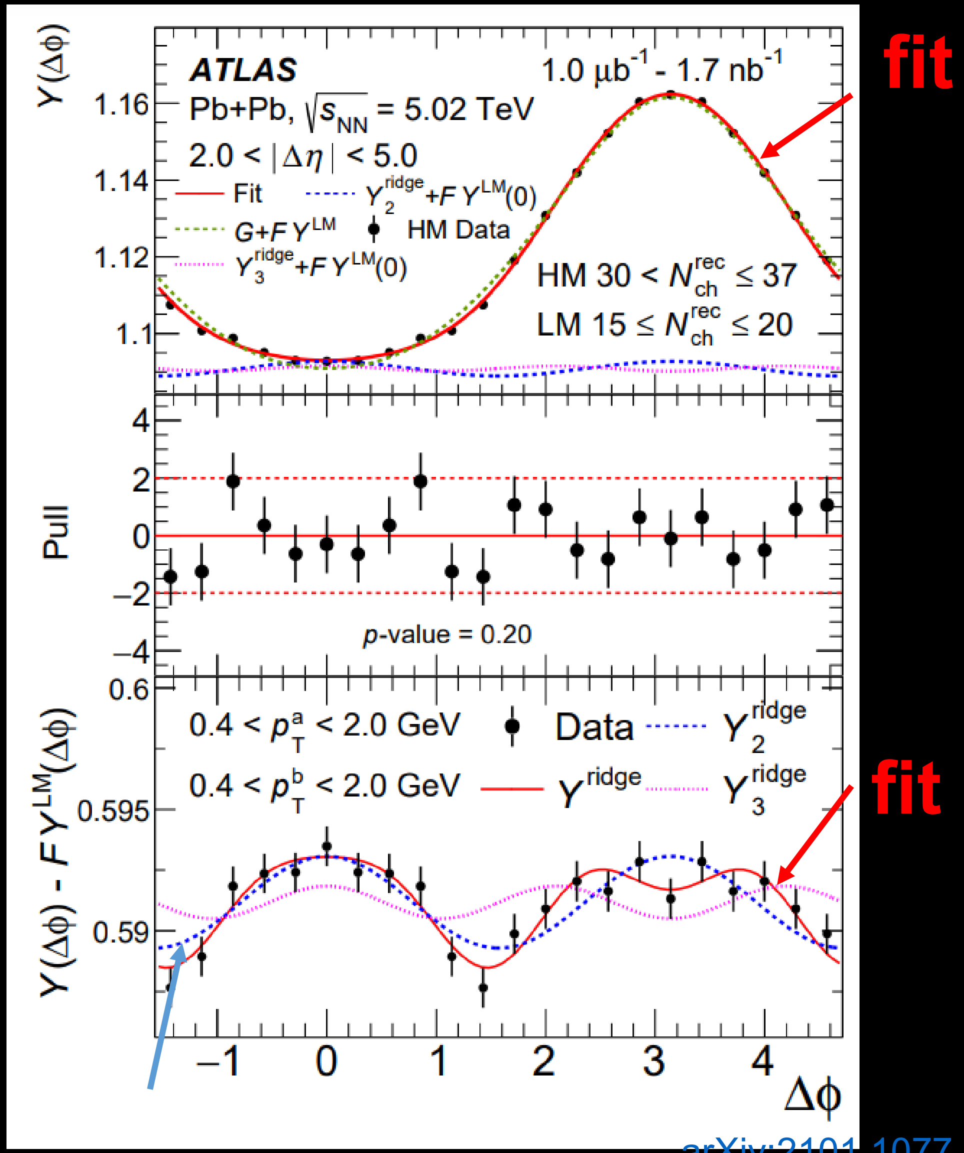
Low multiplicity (LM)
template for jet/non-flow correlation



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

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



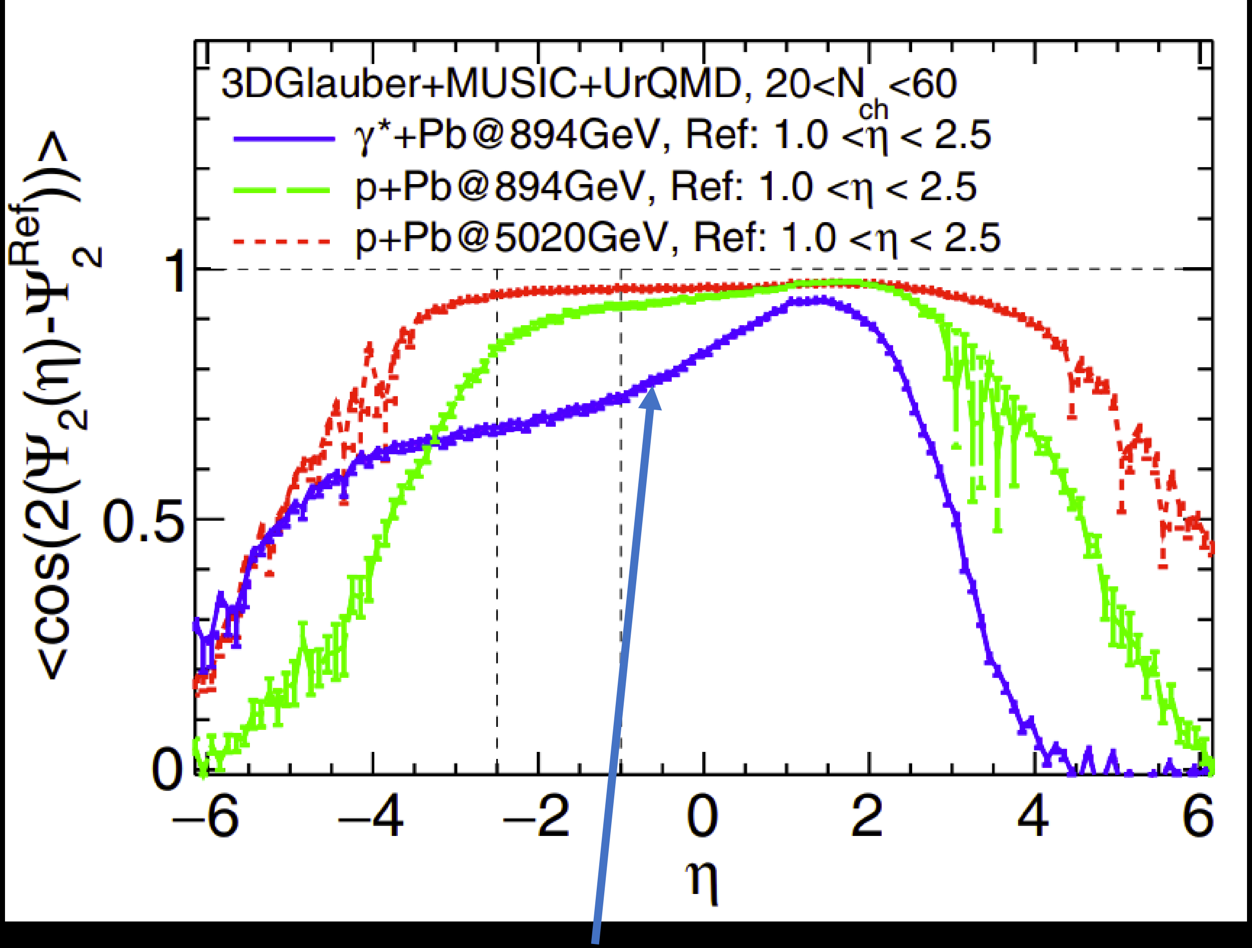
arXiv:2101.10771

After nonflow subtraction clear cos(2Δφ) modulation

Why is γPb v_2 smaller

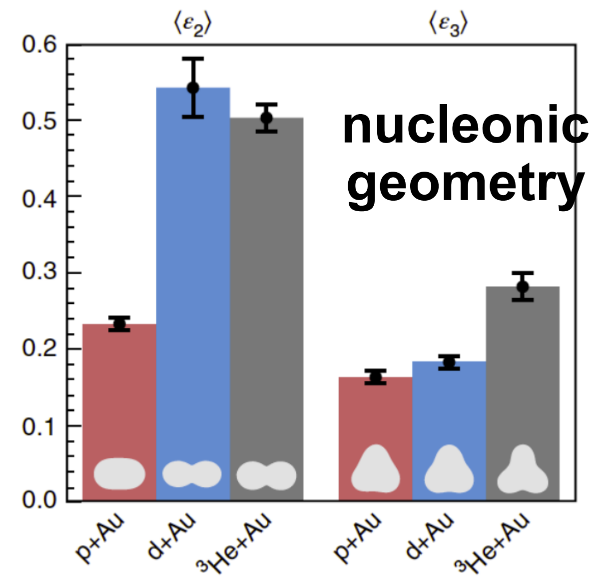
EPJ Web of Conferences 276, 01002 (2023) SQM22

- 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.

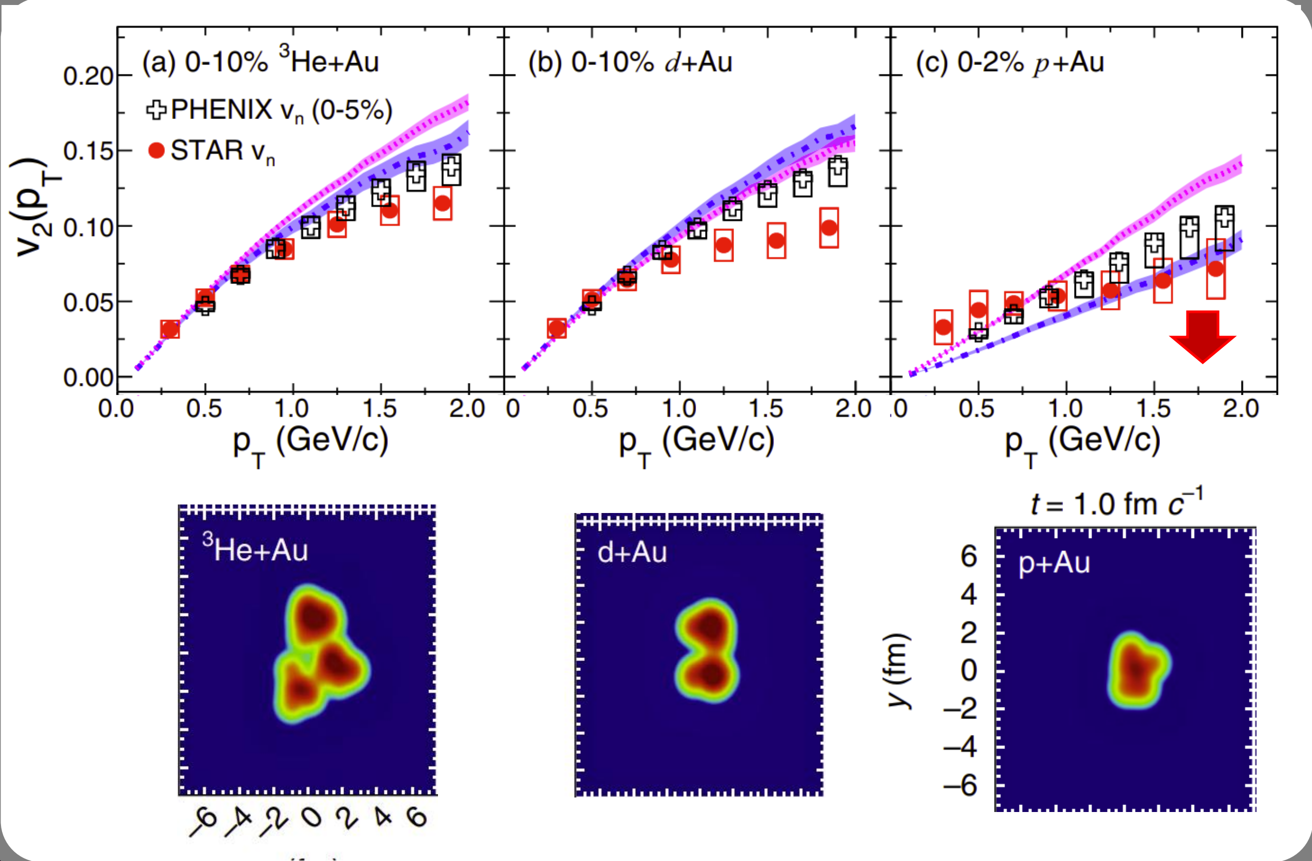


I will show measurements that reflects the slope of these lines next!

Geometry: flow in p+Au d+Au He+Au



Nature Physics 15, (2019)



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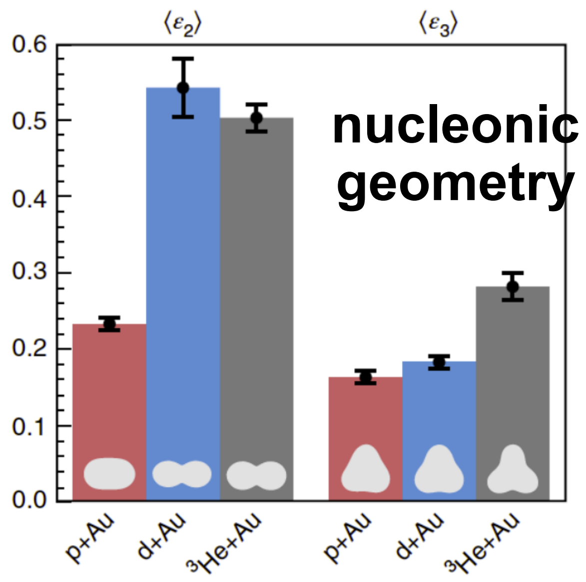
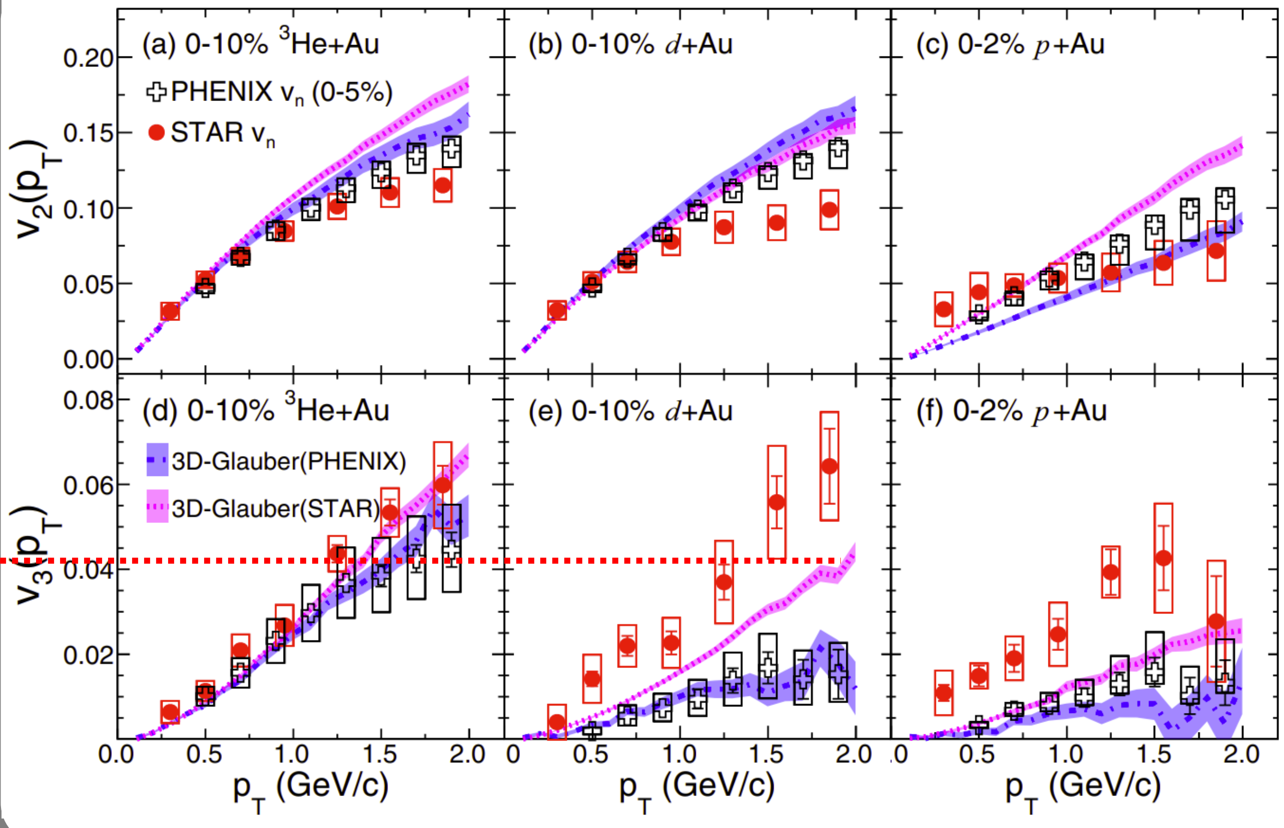
Response to geometry in small systems!

Geometry: flow in p+Au d+Au He+Au



Nature Physics 15, (2019)

Similar v_3 in STAR d+Au and ^{3}He+Au



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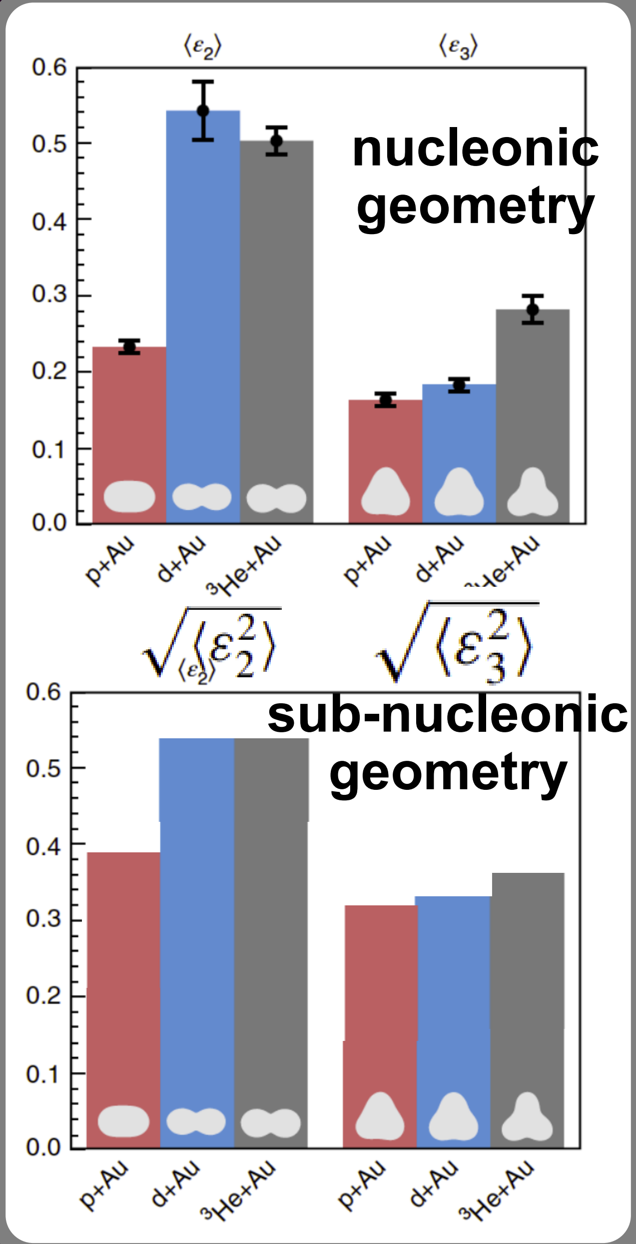

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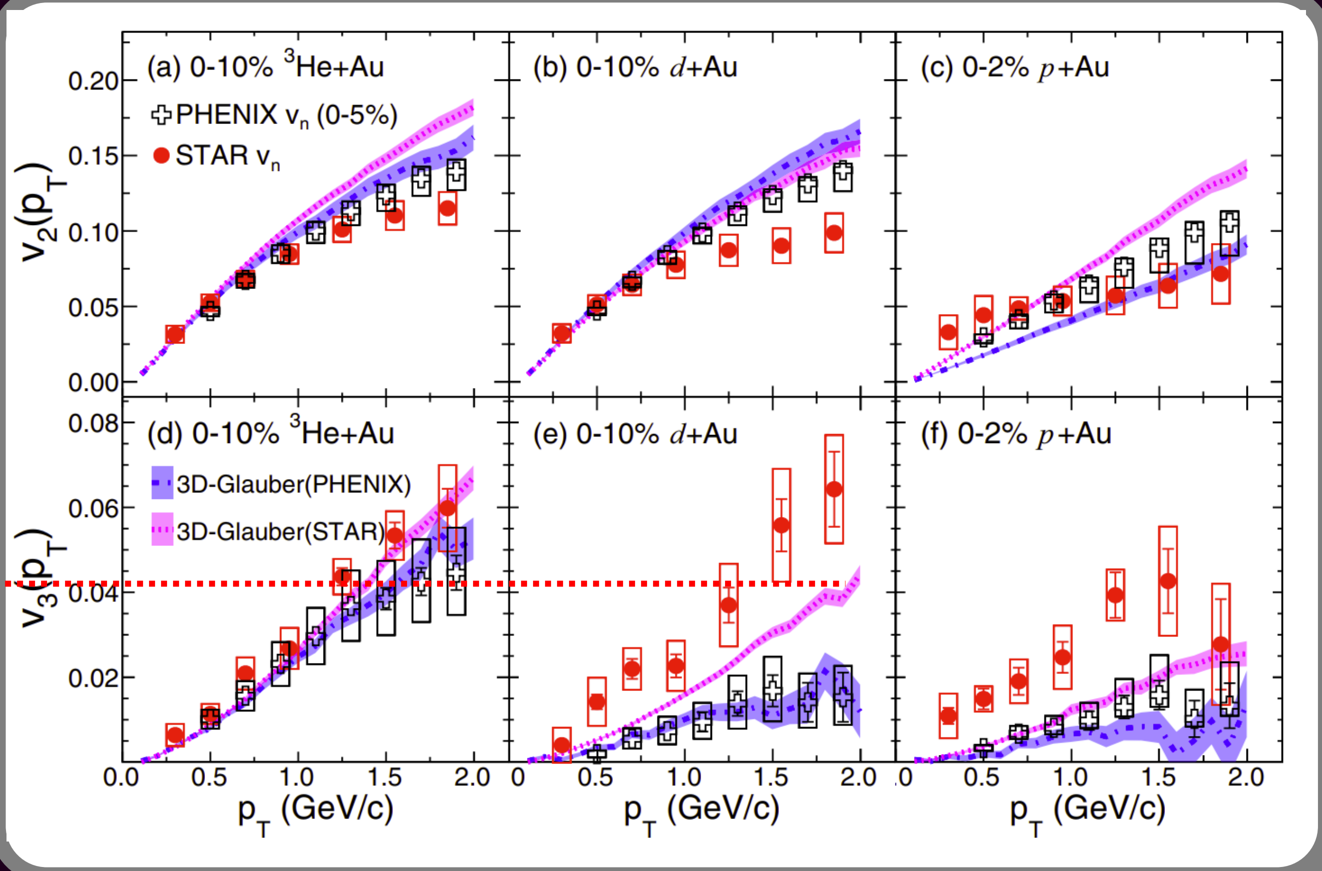

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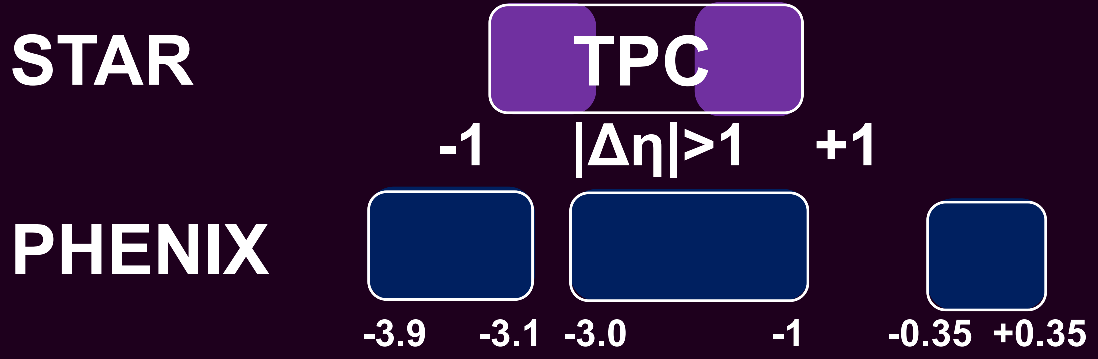
Sub-nucleonic geometry + fluctuations predicts smaller difference in geometry between *d* and ^{3}He

Precise sub-nucleonic geometry needed to describe small systems especially *p*+Au

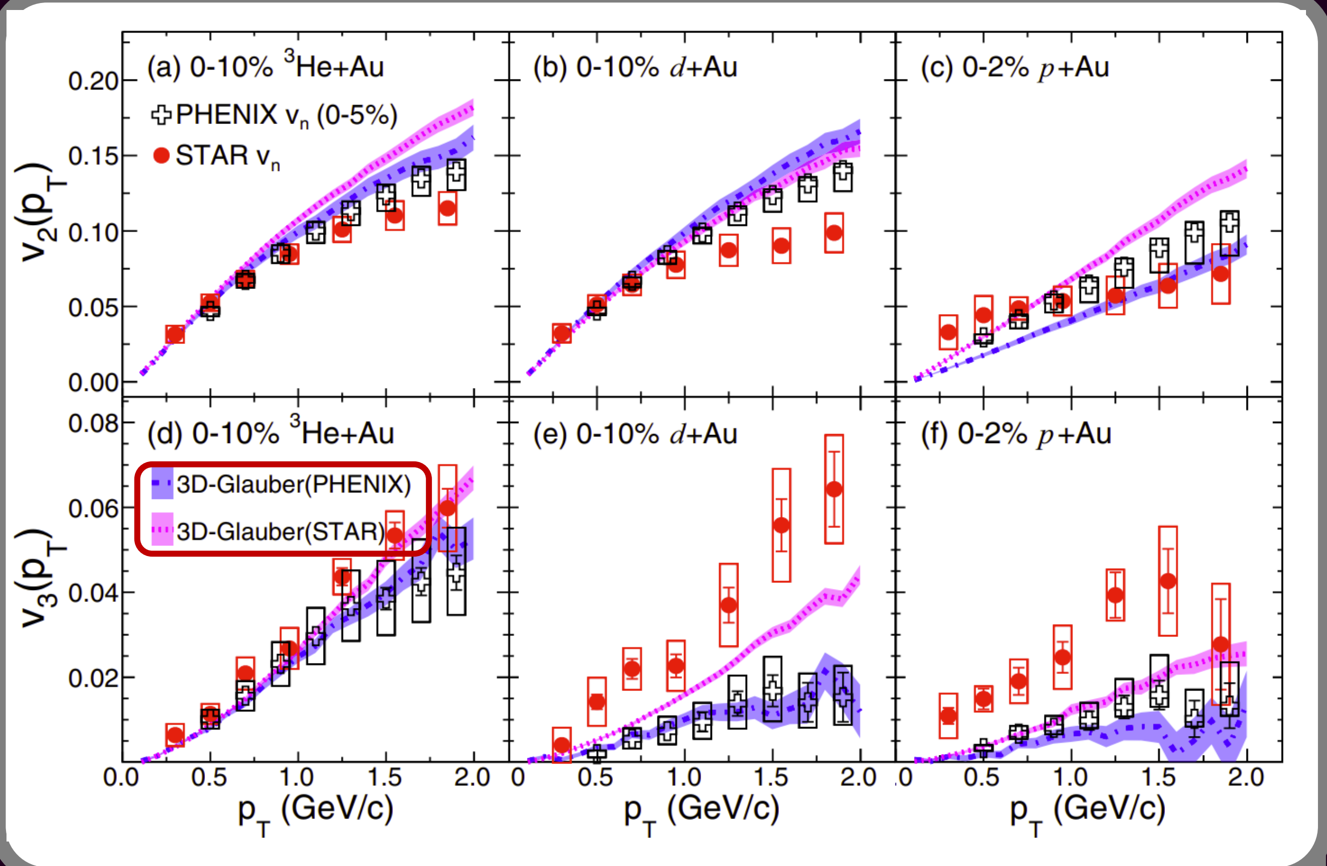
PHENIX vs. STAR: *p*+Au *d*+Au ^{3}He+Au



Larger η separation → more event plane fluctuation
PHENIX has a larger Δη gap → more fluctuations

Model: 3D sub-nucleon Glauber+MUSIC+UrQMD

Still some 20-30% discrepancies between data-model



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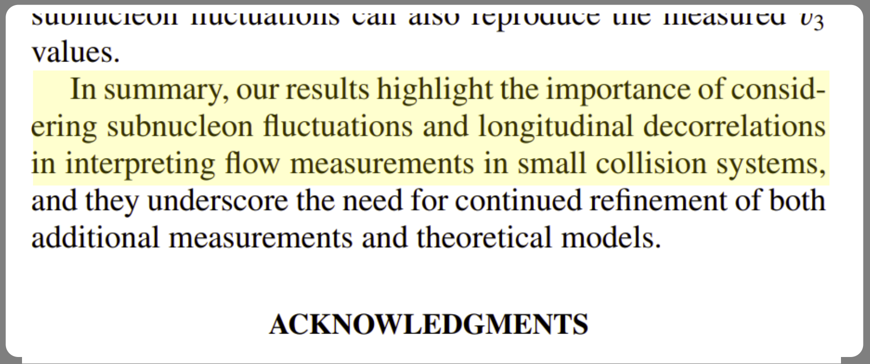

subnucleon fluctuations can also reproduce the measured v_3 values.

In summary, our results highlight the importance of considering subnucleon fluctuations and longitudinal decorrelations in interpreting flow measurements in small collision systems, and they underscore the need for continued refinement of both additional measurements and theoretical models.

ACKNOWLEDGMENTS

Longitudinal decorrelations is larger in smaller systems

Longitudinal decorrelations are important in the push to precision