Collective Dynamics
- An Experimental Overview

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Outline

- Introduction
- Collectivity at top RHIC and LHC energies
- Collectivity in Small Systems
- Collectivity at Low Energies
- Summary & Outlook

See Talks by: S. Singha (Tue, 15:10), Y. Sekiguchi (Wed, 09:20), J. Seo (Wed, 11:00) X. Liu (Mon, 14:15), G. Yan (Mon, 15:05), M. Nie (Tue, 17:00)

Introduction

✓ **RHIC and LHC Top Energy**

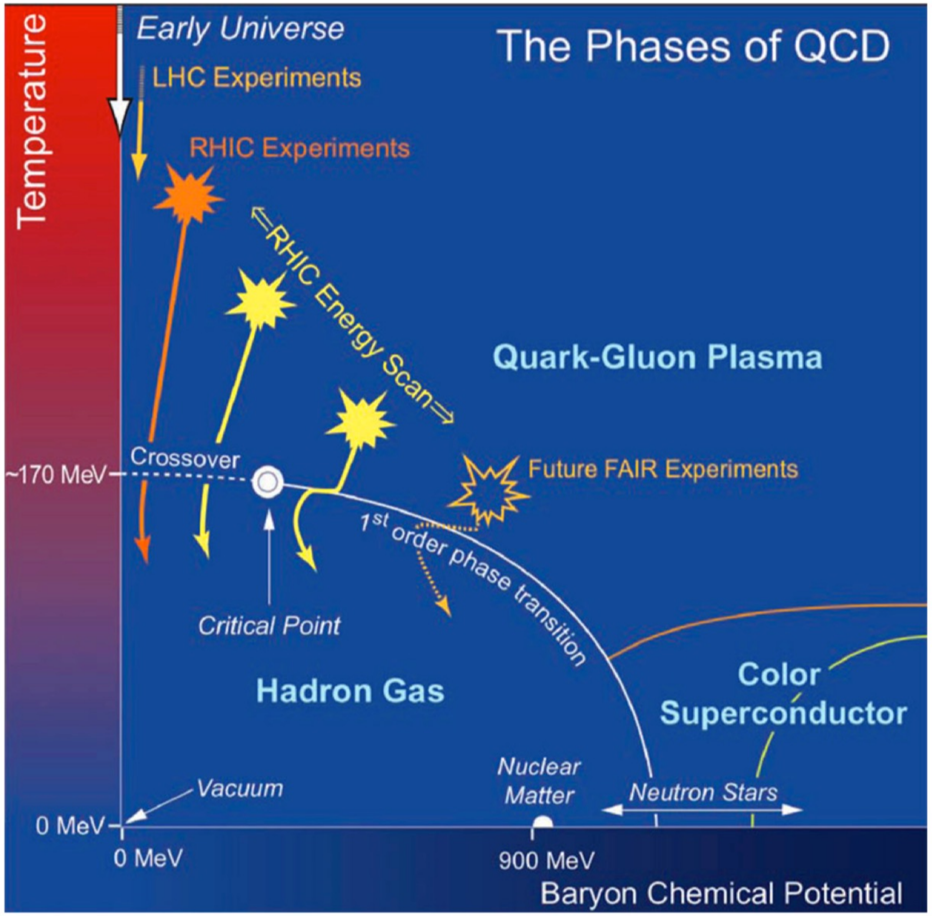
- QCD at high energy density and/or temperature
- Properties of QGP, Equation of State

✓ **Beam Energy Scan (BES) Program**

- QCD phase transition
- Search for QCD critical point
- Turn-off of QGP signatures

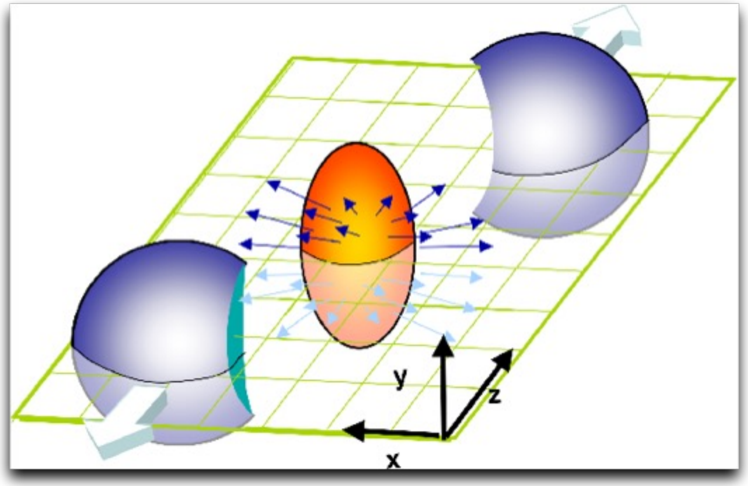
✓ **Fixed-Target Program**

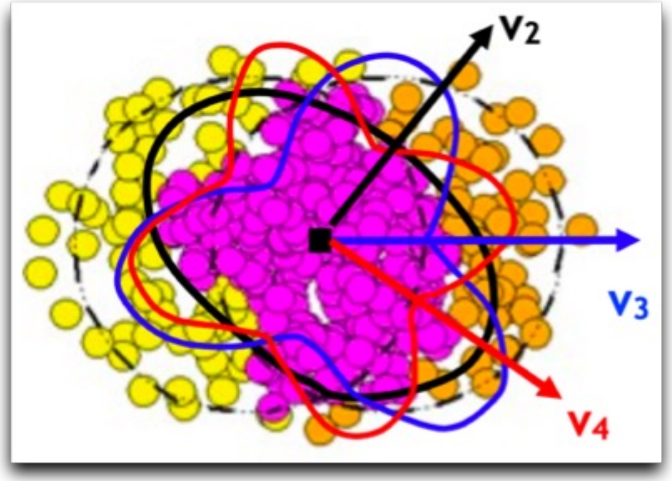
- Probe high baryon density regime ($\mu_B \sim 420$ - 720 MeV)



STAR: arXiv: 1007.2613

Collectivity





- Azimuthal anisotropy is studied by a Fourier expansion of azimuthal distribution of final-state particles:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_T, y)\cos\left(n\left(\phi - \Psi_R\right)\right)\right)$$

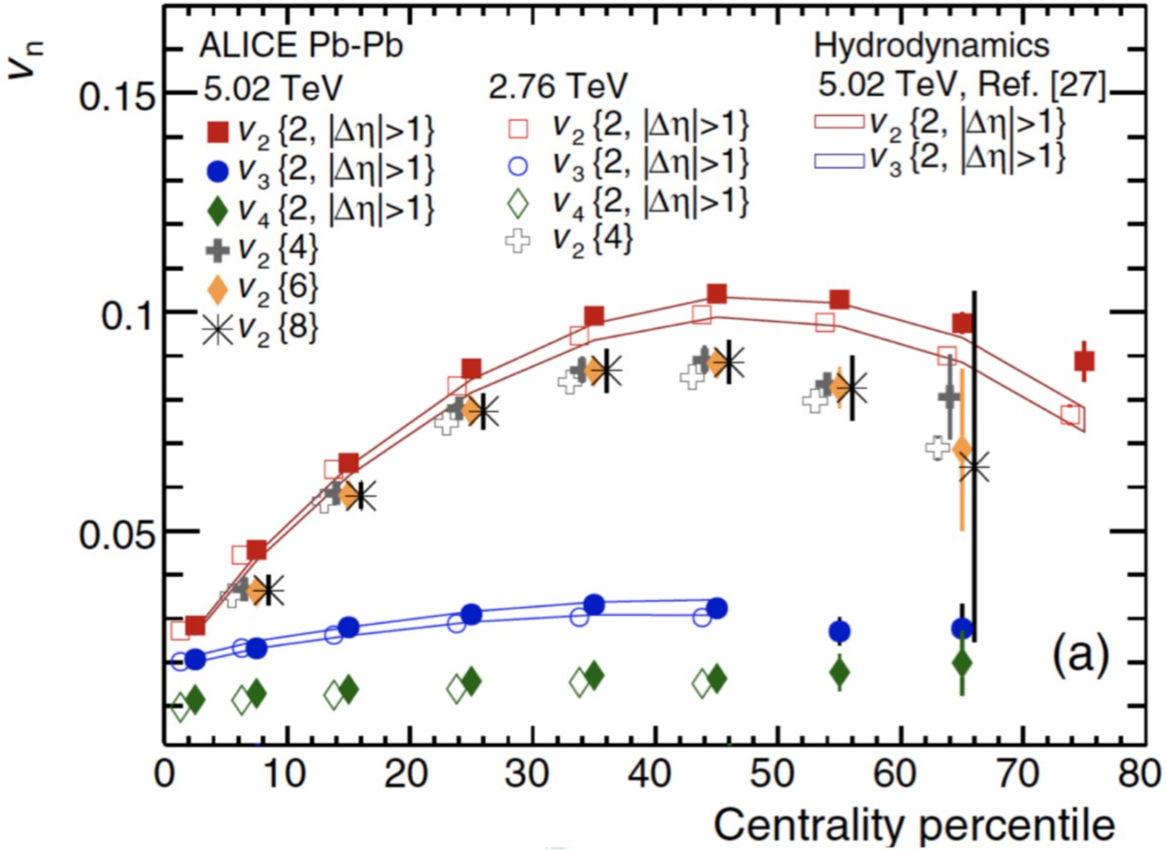
S. Voloshin, Y. Zhang, Z. Phys. C 70, 665 (1996)
A. Poskanzer et al., PRC 58, 1671 (1998)

$$v_n = \langle\cos(n(\phi - \Psi_R))\rangle, \quad \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

v_1: directed flow,
v_2: elliptic flow,
v_3: triangular flow, ...

- Flow coefficients are sensitive to the initial state and properties of the medium

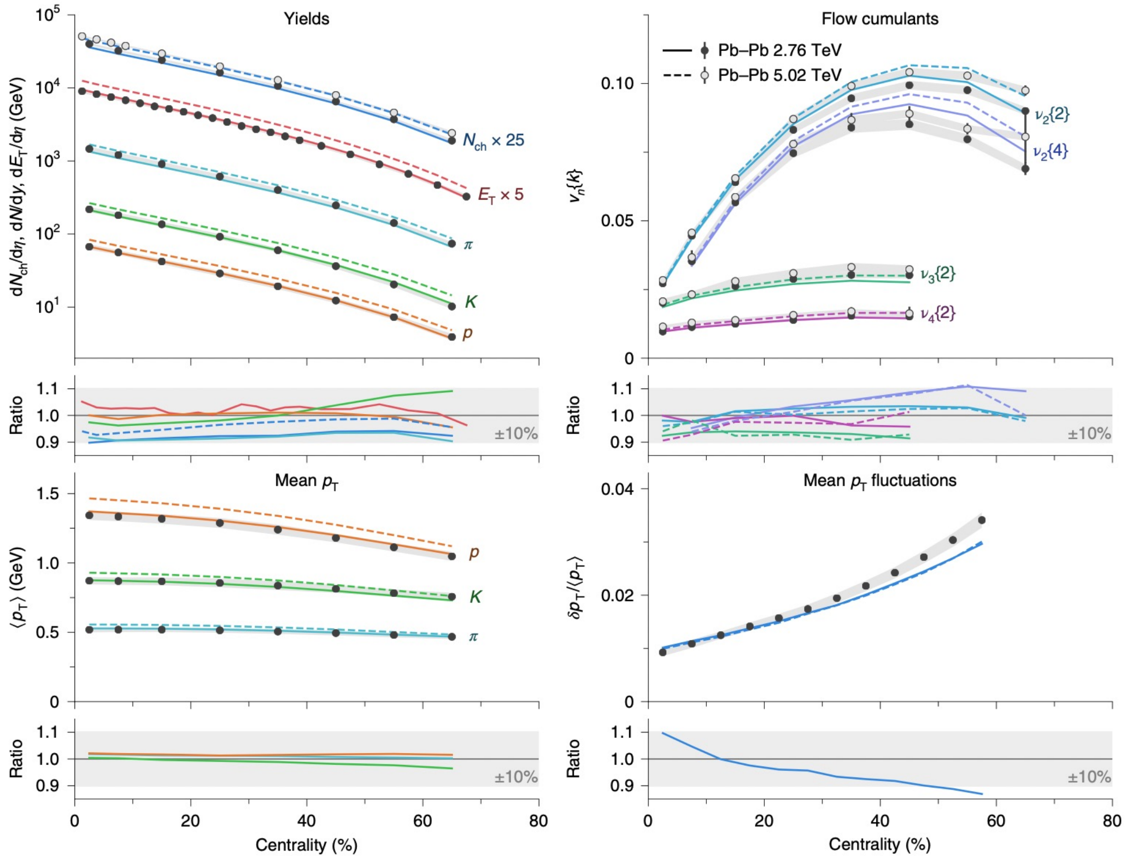
Flow of Charged Hadrons

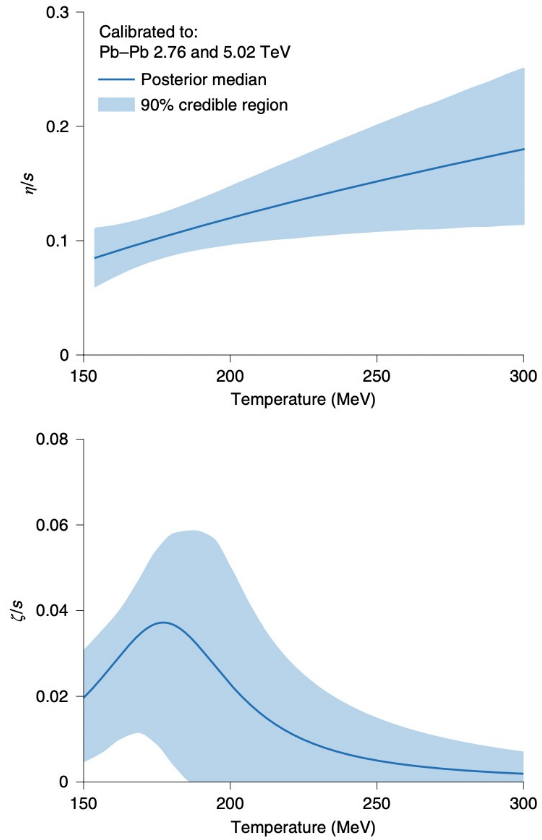


ALICE, PRL116, 132302 (2016)

- Flow coefficients v_n provide detailed information on the initial conditions and transport properties of the created medium
- Flow of charged hadrons well described by hydrodynamic models

Specific Shear and Bulk Viscosity

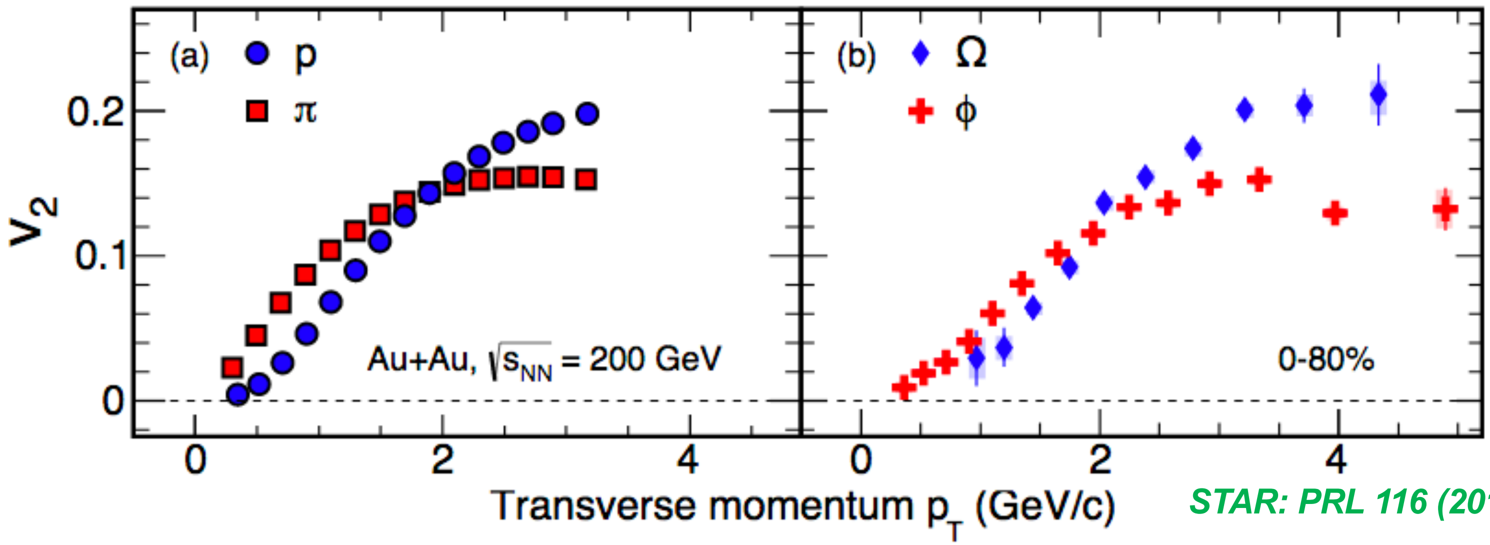




J. E. Bernhard et al, Nature Physics, 15 ,1113 (2019)

- Precise estimation of temperature dependence of the specific shear and bulk viscosity

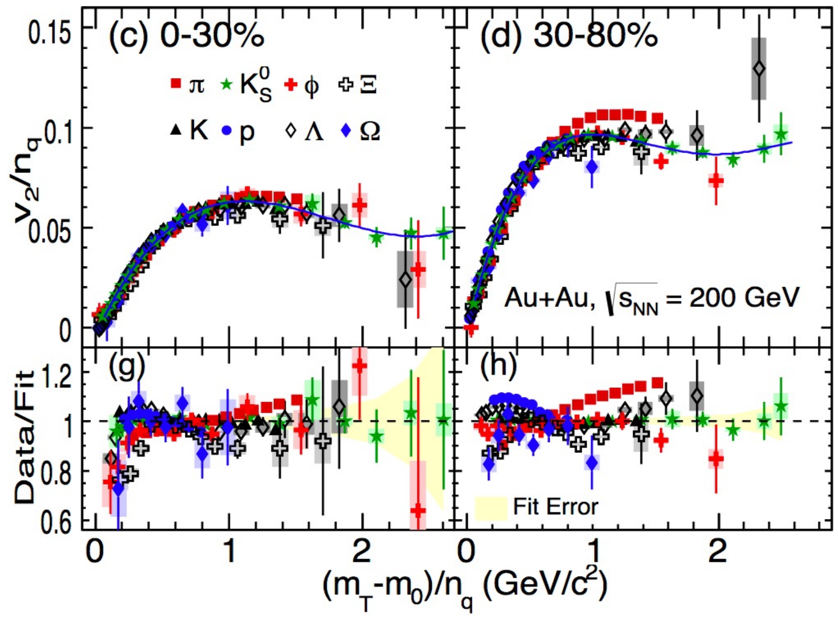
Flow of Identified Hadrons



STAR: PRL 116 (2016) 6, 062301

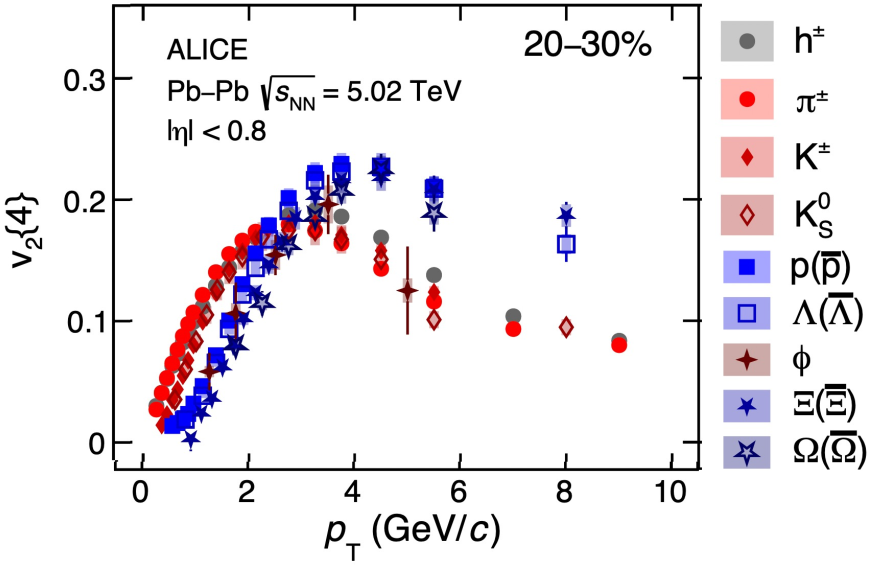
- Mass ordering of v_2 at low p_T
- Baryon-meson v_2 splitting
- Similar magnitude of v_2 between Ω and p
- Scaling of v_2 by number of constituent quarks (baryons = 3, mesons = 2) ➡ NCQ Scaling

✓ Partonic Collectivity at RHIC



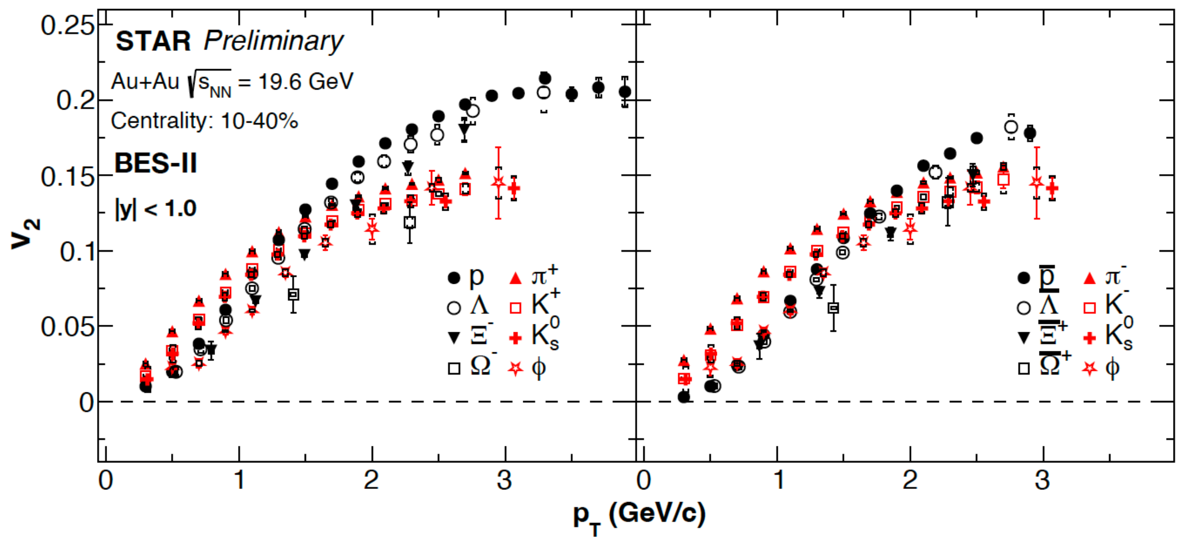
Flow of Identified Hadrons

- ✓ Partonic collectivity at LHC energies

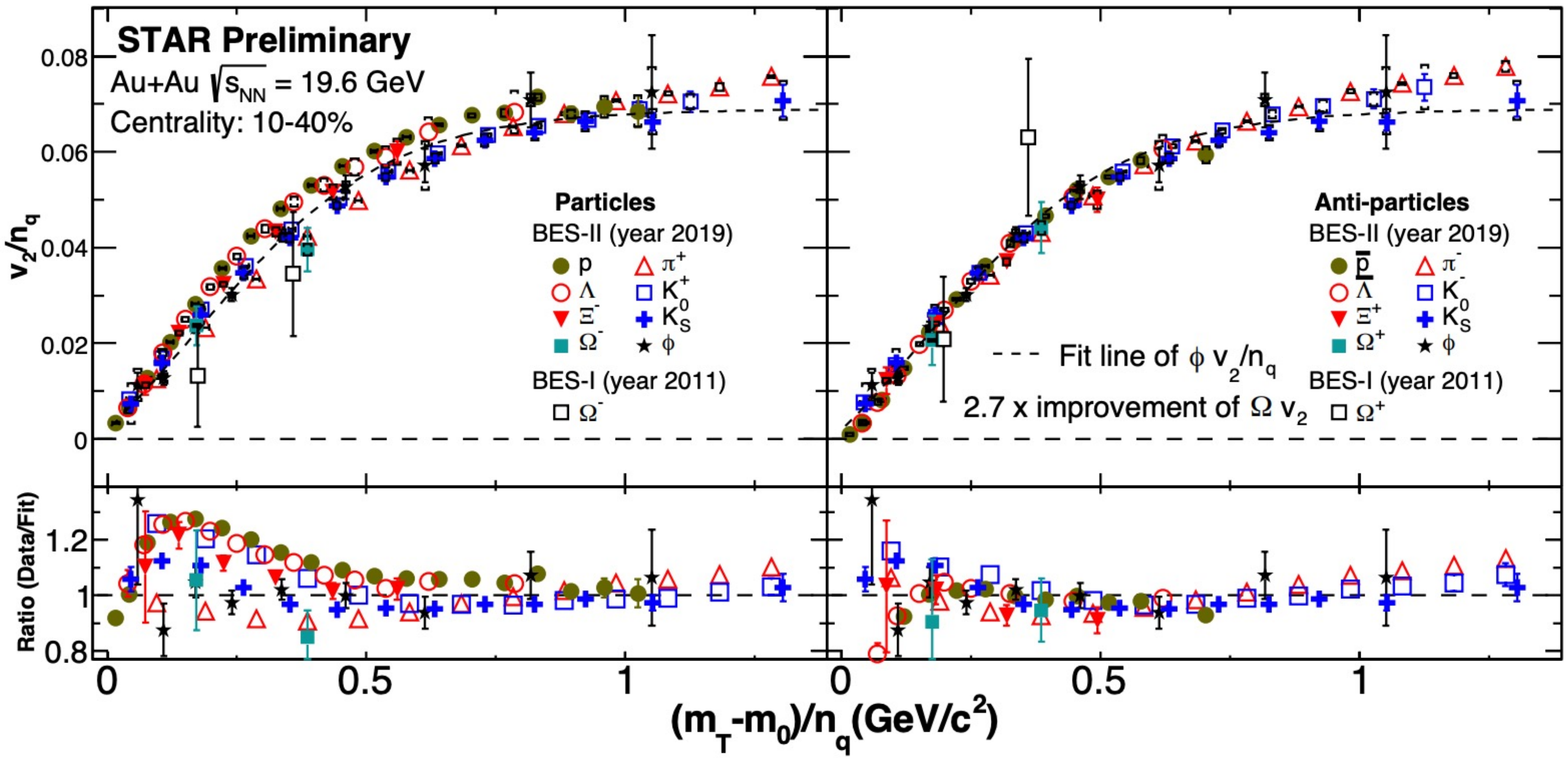


ALICE: arXiv:2206.04587

- ✓ Look for turn off signature of partonic collectivity

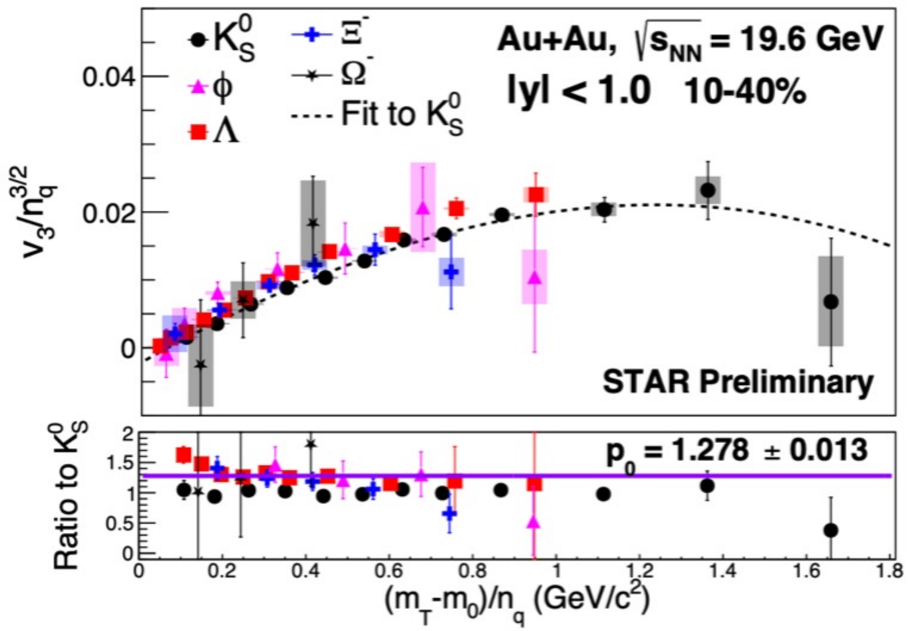


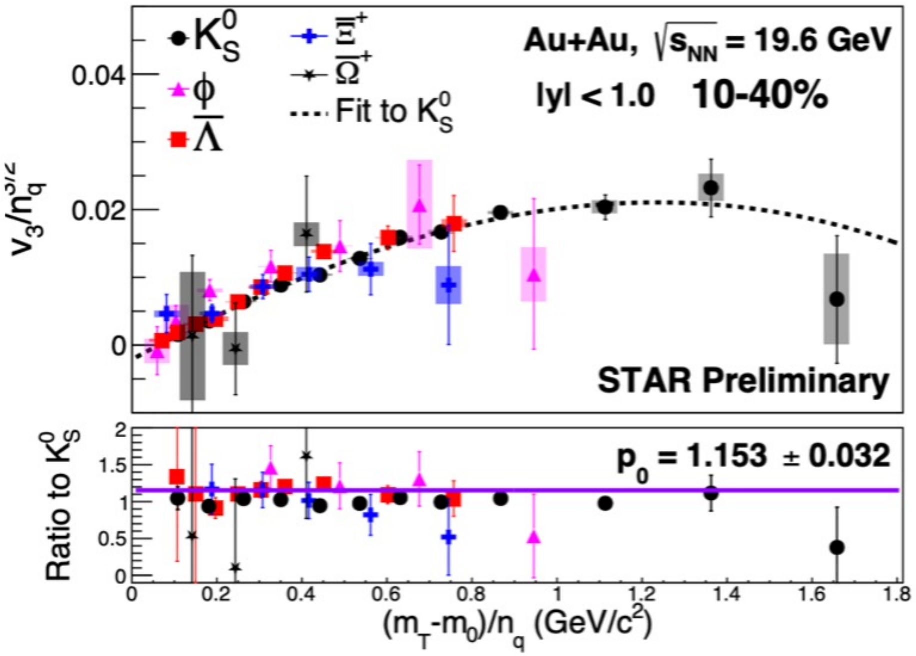
NCQ Scaling of v_2



- NCQ scaling of v_2 holds: ~ 20% for particles, ~ 15% for anti-particles
- ϕ mesons follow an approximate NCQ scaling

NCQ Scaling of v_3

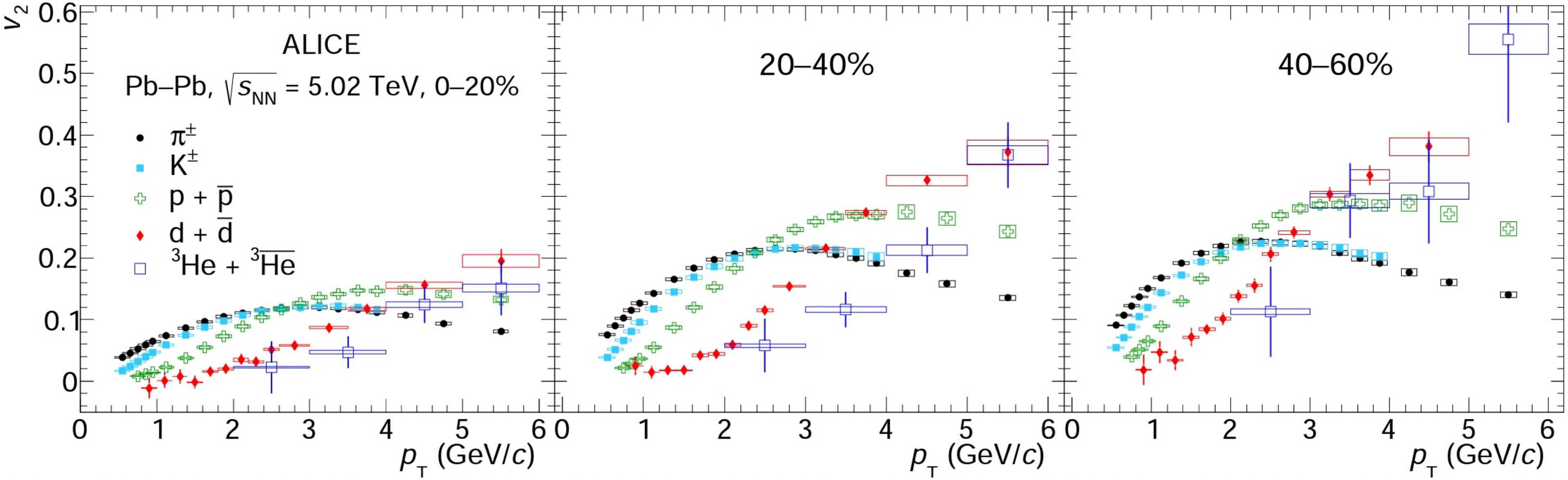




- NCQ scaling for v_3 holds: ~ 30% for particles, ~ 15% for anti-particles

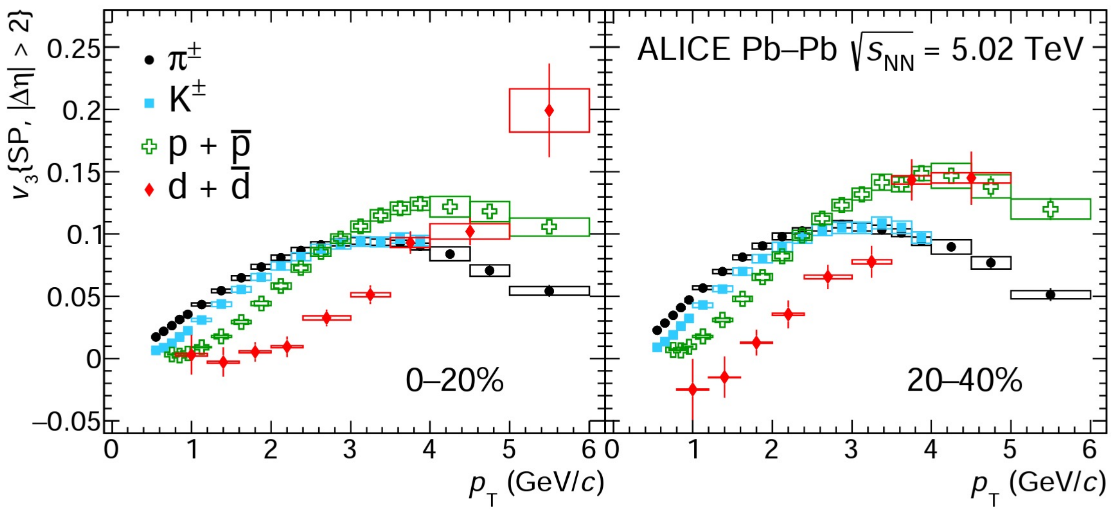
Flow of Light Nuclei

Flow of Light Nuclei

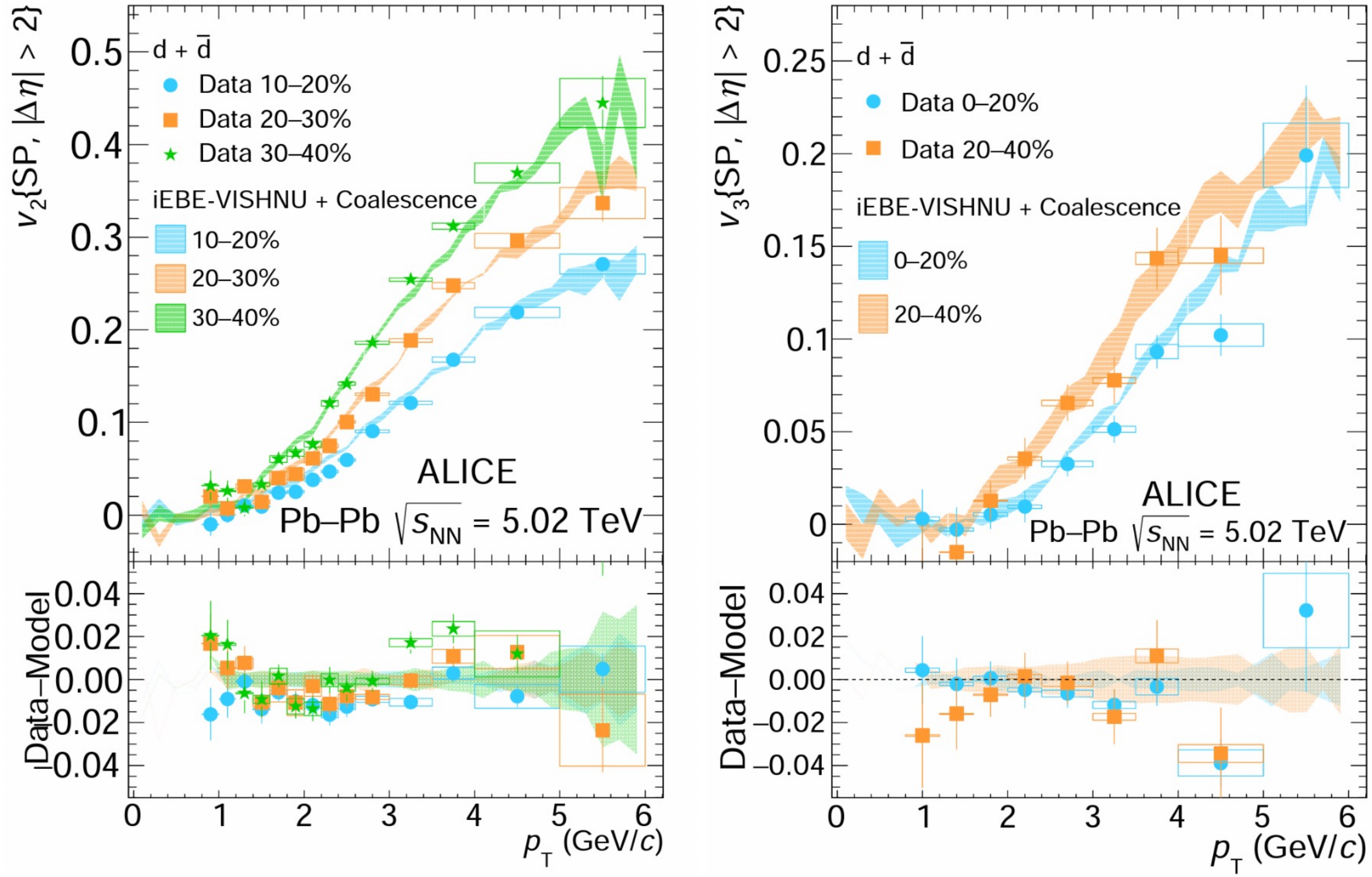


ALICE, PRC 102 (2020) 055203

- Flow of light nuclei is useful in understanding their production mechanism



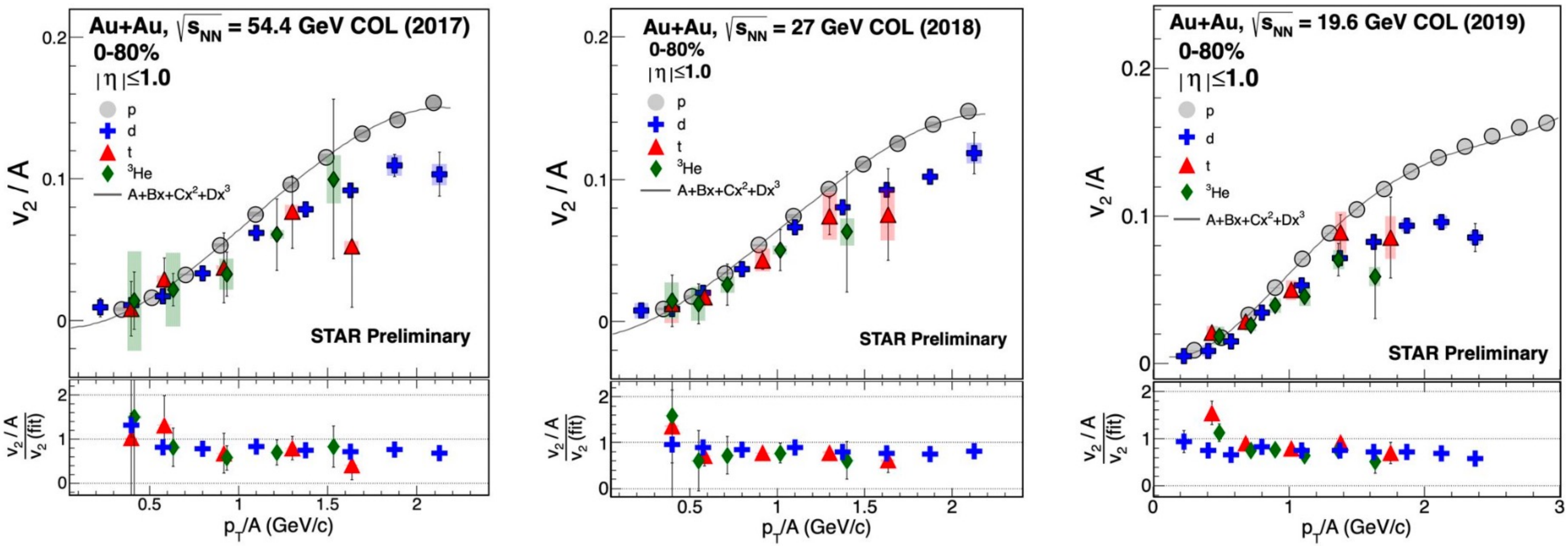
Flow of Light Nuclei



ALICE, PRC 102 (2020) 055203

- A model implementing light nuclei formation via coalescence of nucleons originating from a hydrodynamical evolution of the fireball coupled to an UrQMD simulation of the hadronic cascade describes the data reasonably well

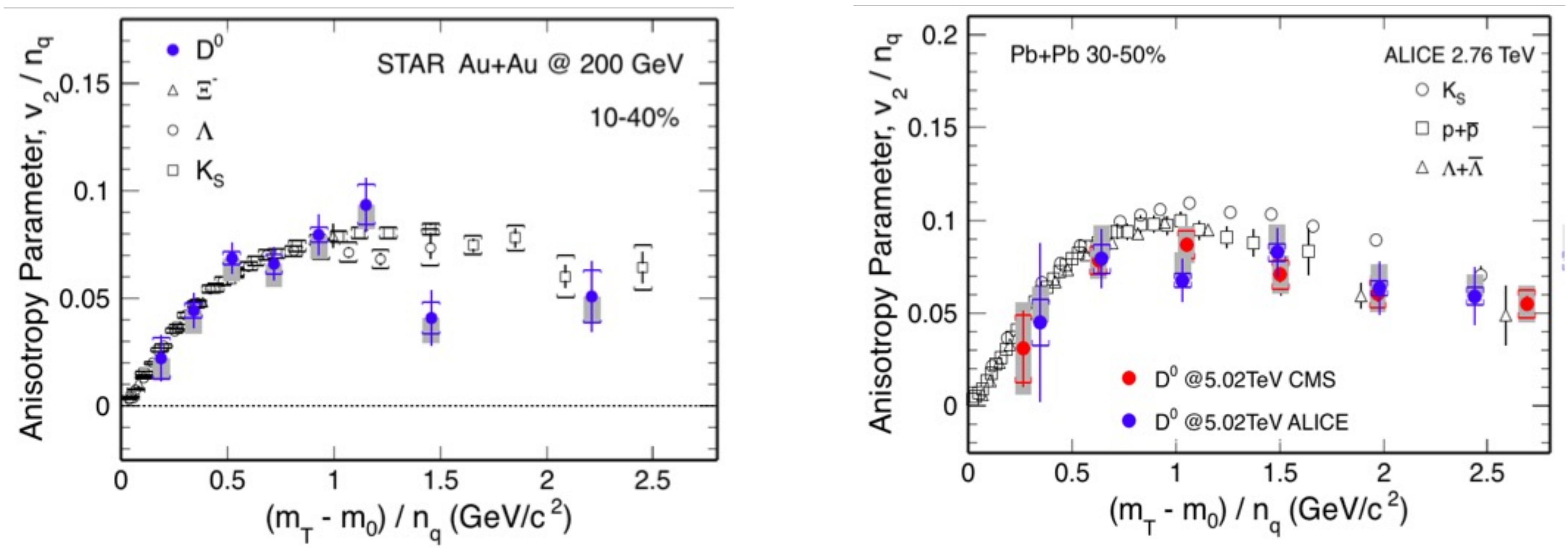
Mass Number Scaling at RHIC



- v_2 of light nuclei follows the mass number scaling within 20-30%

Flow of Heavy Flavor Hadrons

Flow of Heavy Flavor Hadrons

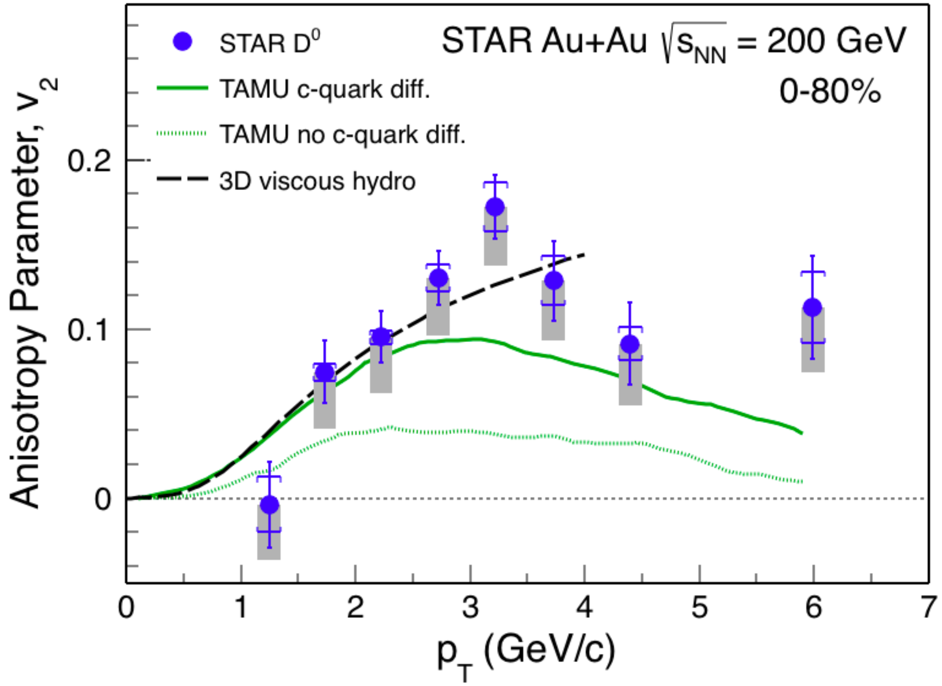


STAR, PRL 118 (2017) 212301
ALICE, PRL 120 (2018) 102301
CMS, PRL 120 (2018) 202301

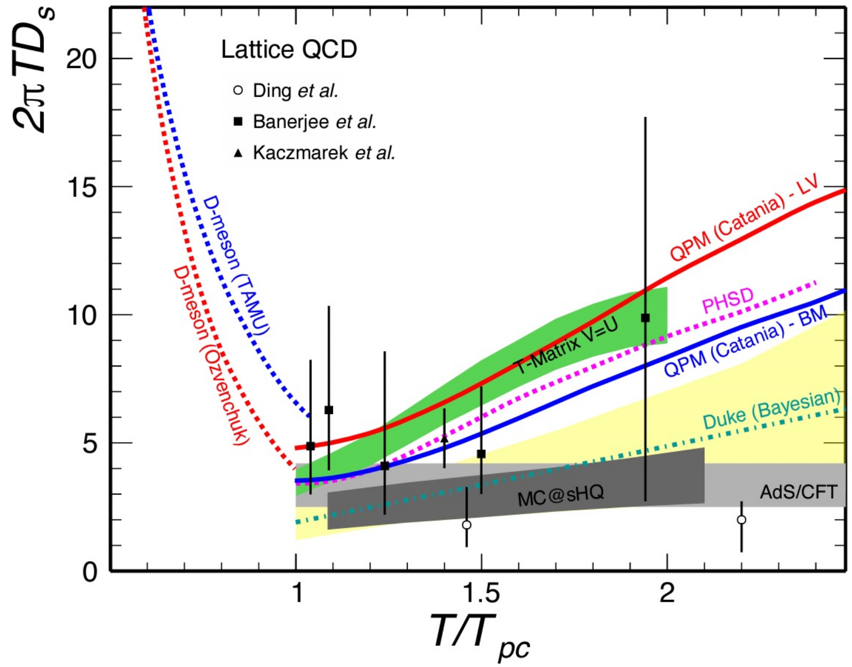
- Significant *D*-meson v_2 in Au+Au at RHIC and Pb+Pb collisions at LHC
- v_2 of D meson follows the NCQ scaling as light hadrons

✓ **Evidence of charm quarks reaching local thermal equilibrium**

Flow of Heavy Flavor Hadrons



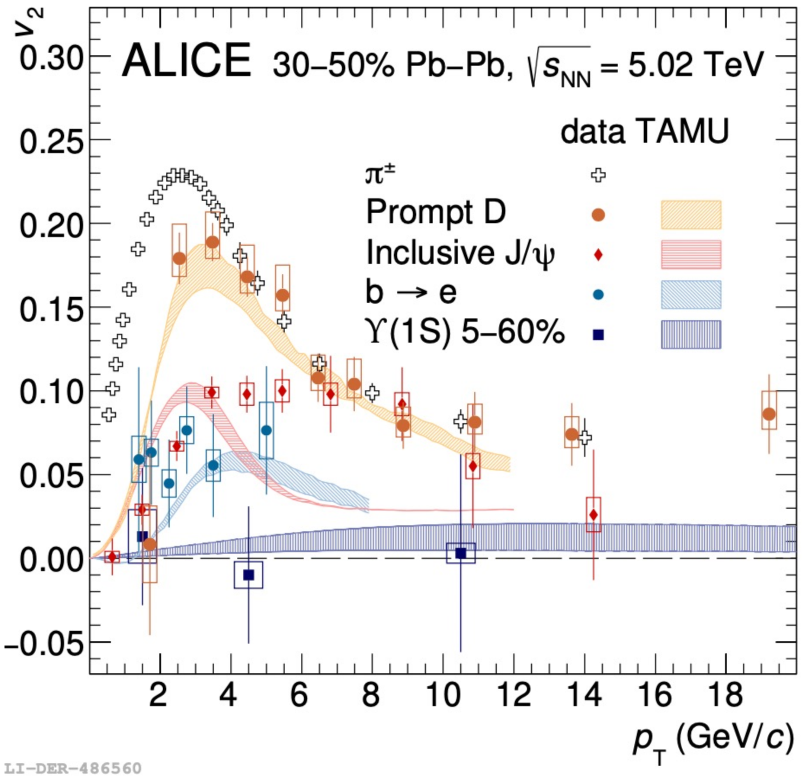
STAR, PRL 118 (2017) 212301

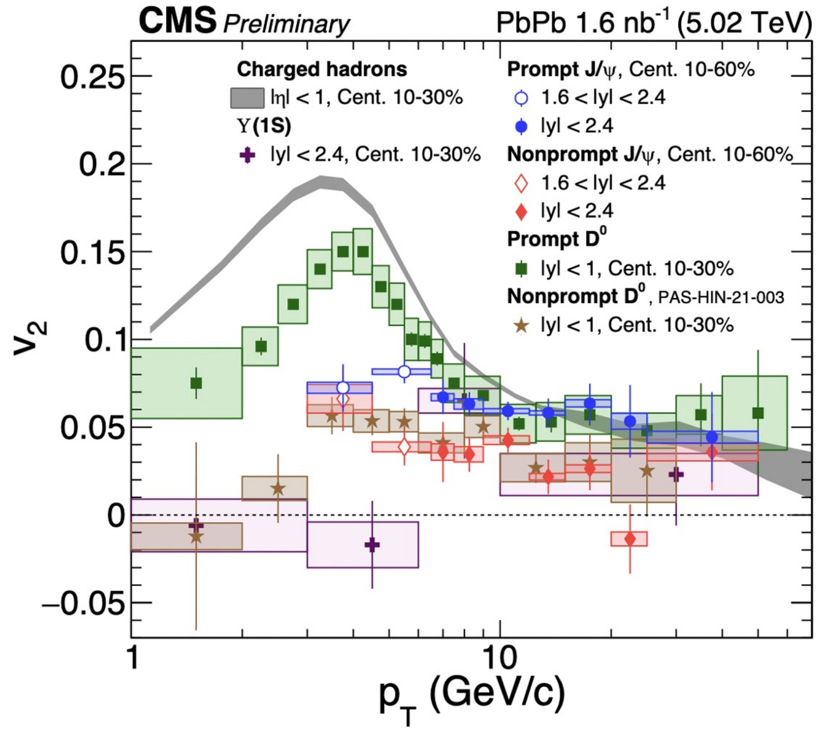


X. Dong, Y-J Lee & R. Rapp,
Ann. Rev. Nucl & Part. Sci. 69 (2019) 417

- Large D_0 v_2 ordinated from charm quark diffusion in QGP
- 3D viscous hydro consistent with D_0 v_2 data up to ~ 4 GeV/c
- Model calculations with $2\pi TD_S$ ~2 - 5, can explain measured D_0 v_2
  -- consistent with lattice calculations

Flow of Heavy Flavor Hadrons



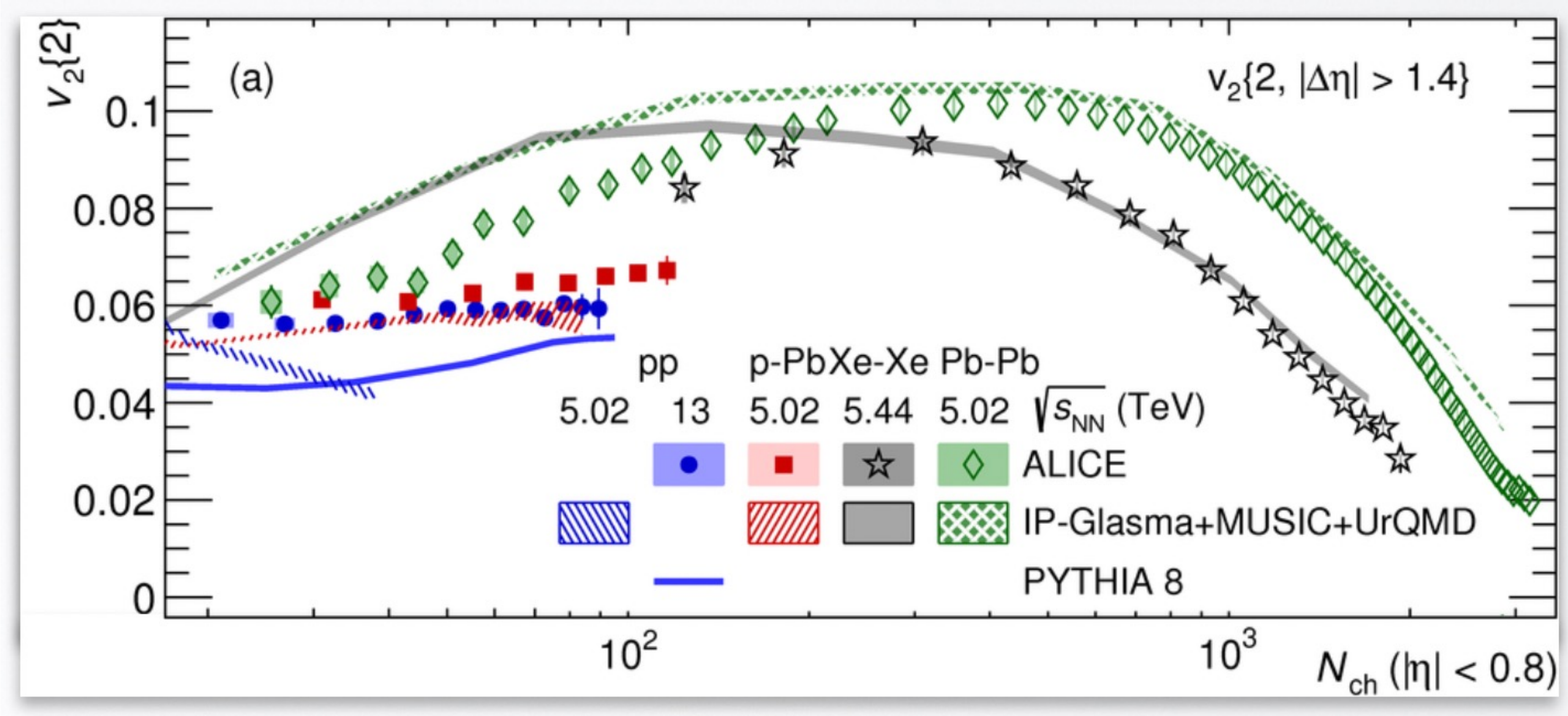


PLB 816, 136253 (2021)

- Positive v_2 of charmed hadrons observed at LHC
- Smaller v_2 of open-beauty hadrons

Collectivity in Small Collision Systems

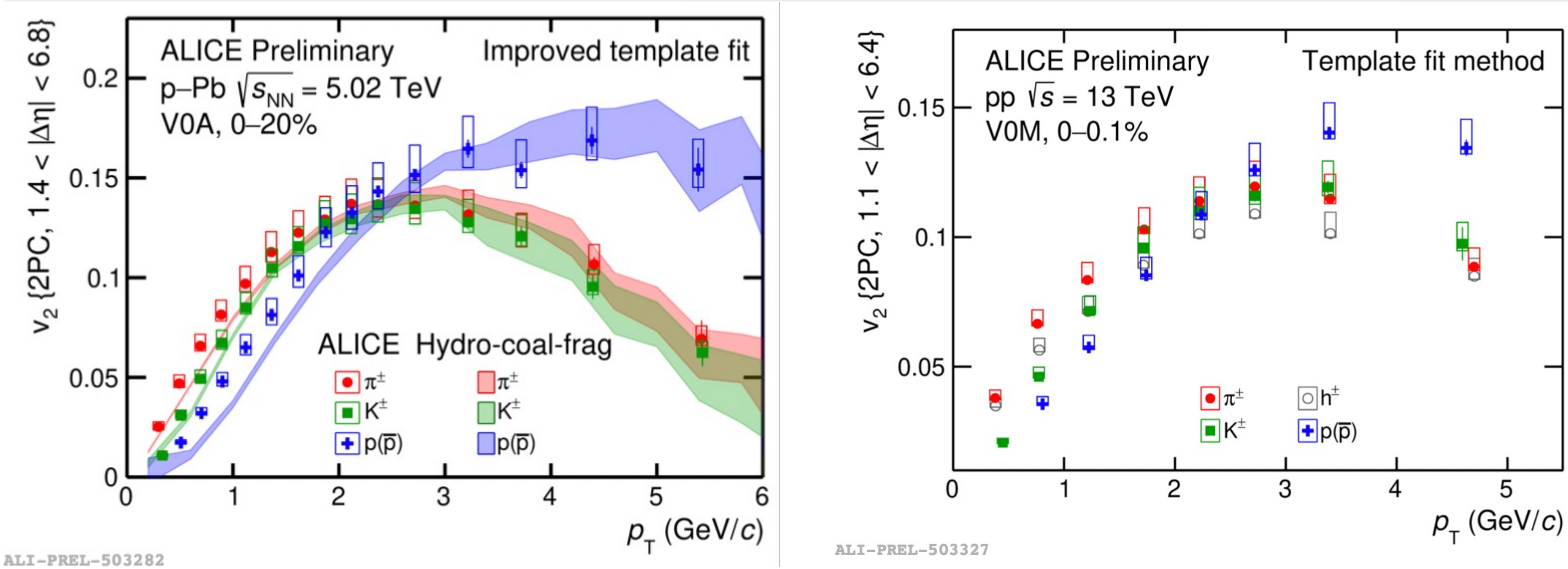
Collectivity in Small Collision Systems



ALICE, Phys. Rev. Lett. 123, 142301 (2019)

- Sizeable flow observed across all collision systems
- What is the origin of the observed collective effects in small systems?

Collectivity in p-Pb and pp Collisions

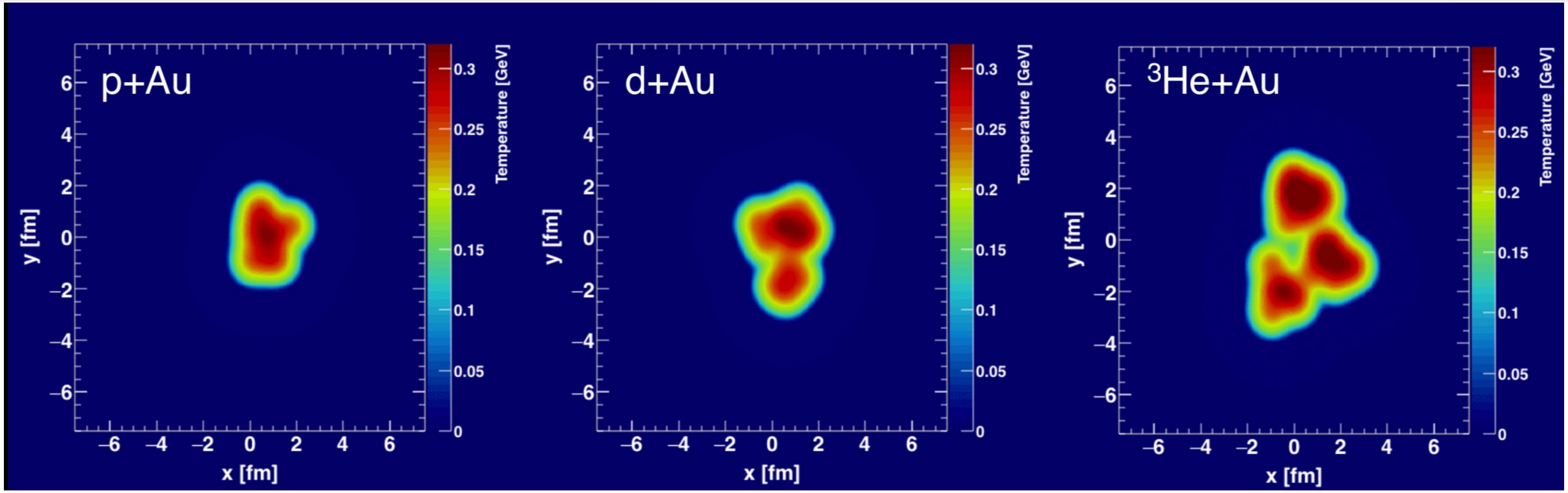


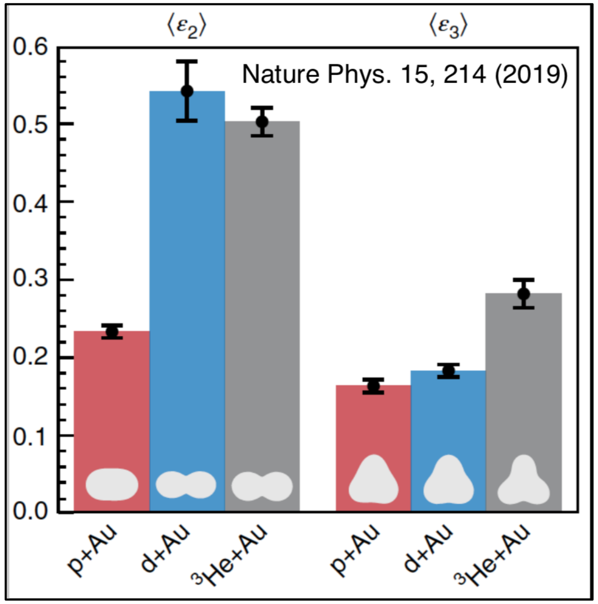
W. Zhao et al., PRL 125, 072301 (2020)

- Mass ordering is observed in both p–Pb and pp collisions at low p_T
- Baryon-meson splitting at intermediate p_T is observed in both p–Pb and pp collisions

- Models including hydrodynamics, quark coalescence and jet fragmentation describe the p-Pb data well
  ➡ observation of partonic collectivity in p–Pb collisions

Collectivity in Small Systems

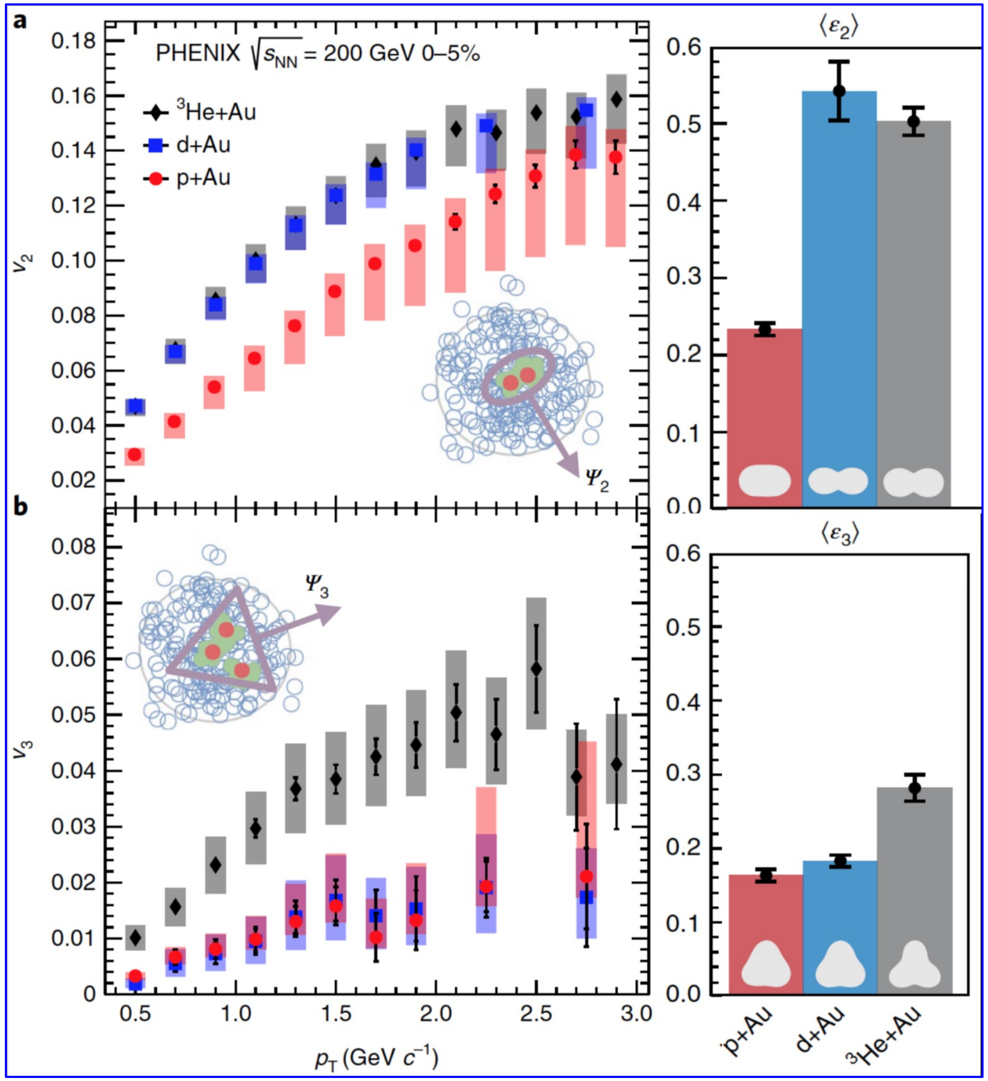




- Clearly different initial collision geometry in p/d/^{3}He+Au collisions
- Smaller <ε_2> in p+Au collisions
- Larger <ε_3> in ^{3}He+Au collisions

PHENIX, Nature Phys. 15, 214 (2019)

Collectivity in Small Systems



PHENIX, Nature Phys. 15, 214 (2019)

$$\varepsilon_2^{p+\mathrm{Au}} < \varepsilon_2^{d+\mathrm{Au}} \approx \varepsilon_2^{^3\mathrm{He+Au}}$$

⇓

$$v_2^{p+\mathrm{Au}} < v_2^{d+\mathrm{Au}} \approx v_2^{^3\mathrm{He+Au}}$$

$$\varepsilon_3^{p+\mathrm{Au}} \approx \varepsilon_3^{d+\mathrm{Au}} < \varepsilon_3^{^3\mathrm{He+Au}}$$

⇓

$$v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}} < v_3^{^3\mathrm{He+Au}}$$

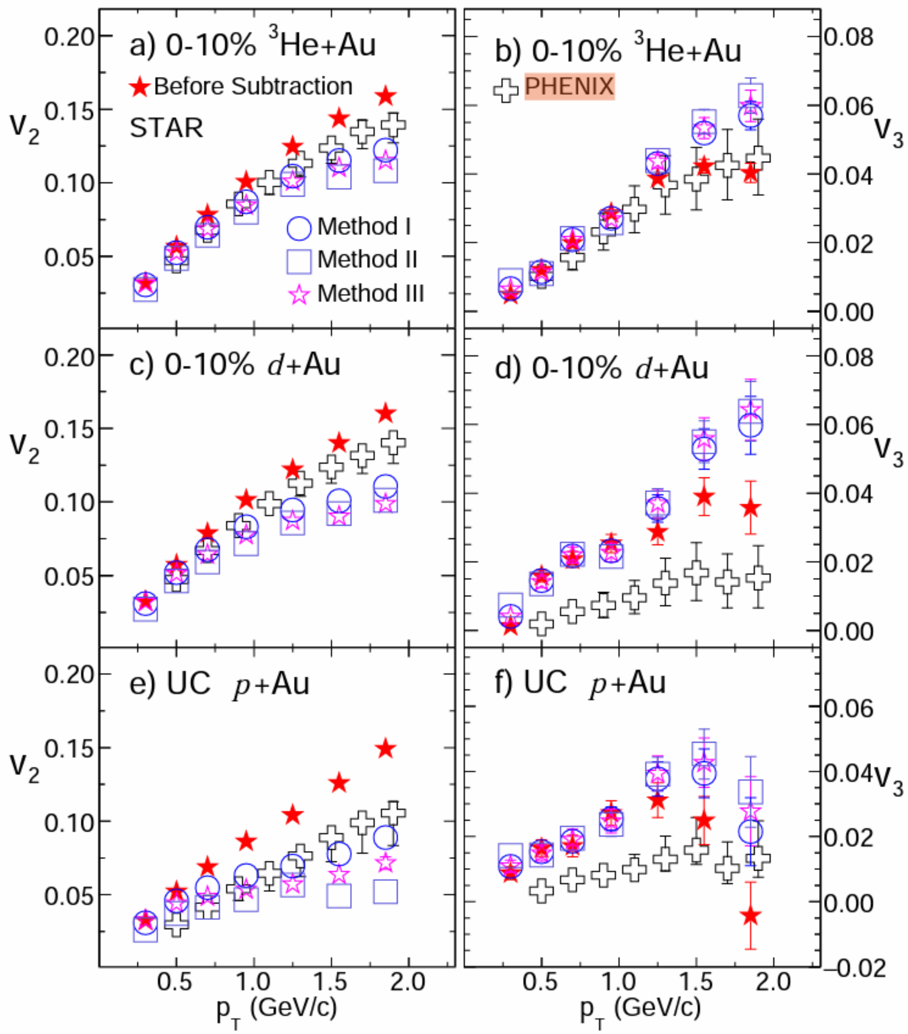
✓ **Suggests flow is geometric in origin**

Collectivity in Small Systems

- STAR measurement of v_2 is compatible with PHENIX measurement within uncertainties
- STAR v_3 measurements for p+Au and d+Au collisions are about a factor of 3 larger than those reported by PHENIX
- Model study shows that upto 50% of this v3 discrepancy could result from the larger longitudinal decorrelation possible in the PHENIX measurements.

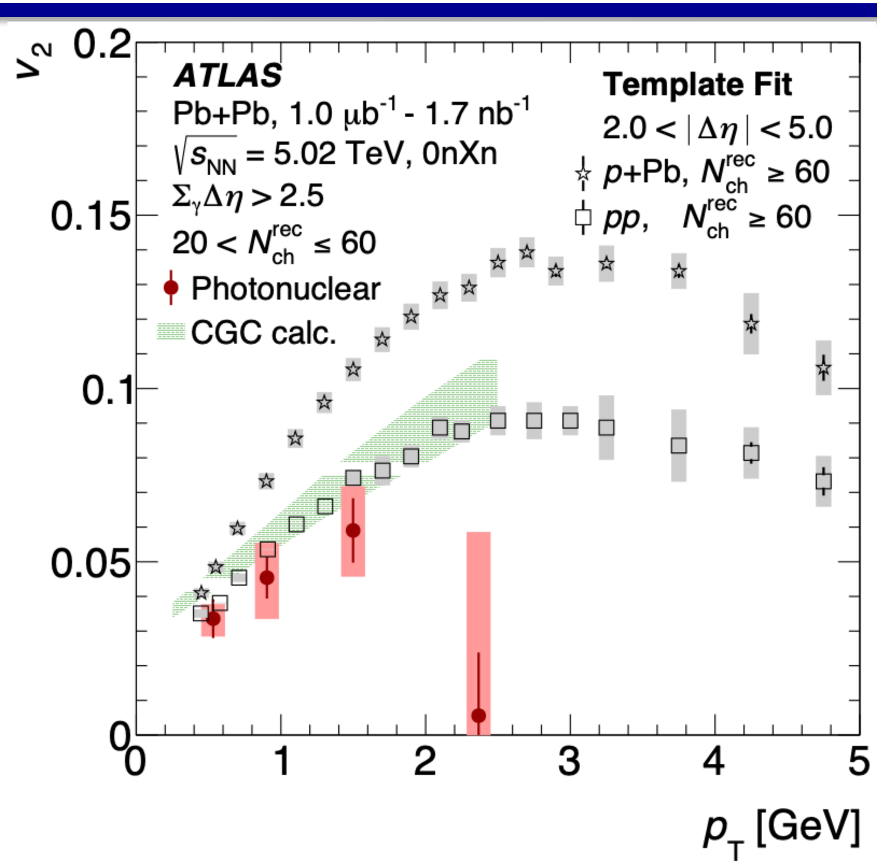
arXiv:2211.16376 [nucl-th]

- Further developments in the model calculations to include nonflow and pre-hydrodynamic flow effects could shed light on the remaining 50% differences.



STAR: arXiv:2210.11352

Collectivity in γ–Pb and γp collisions

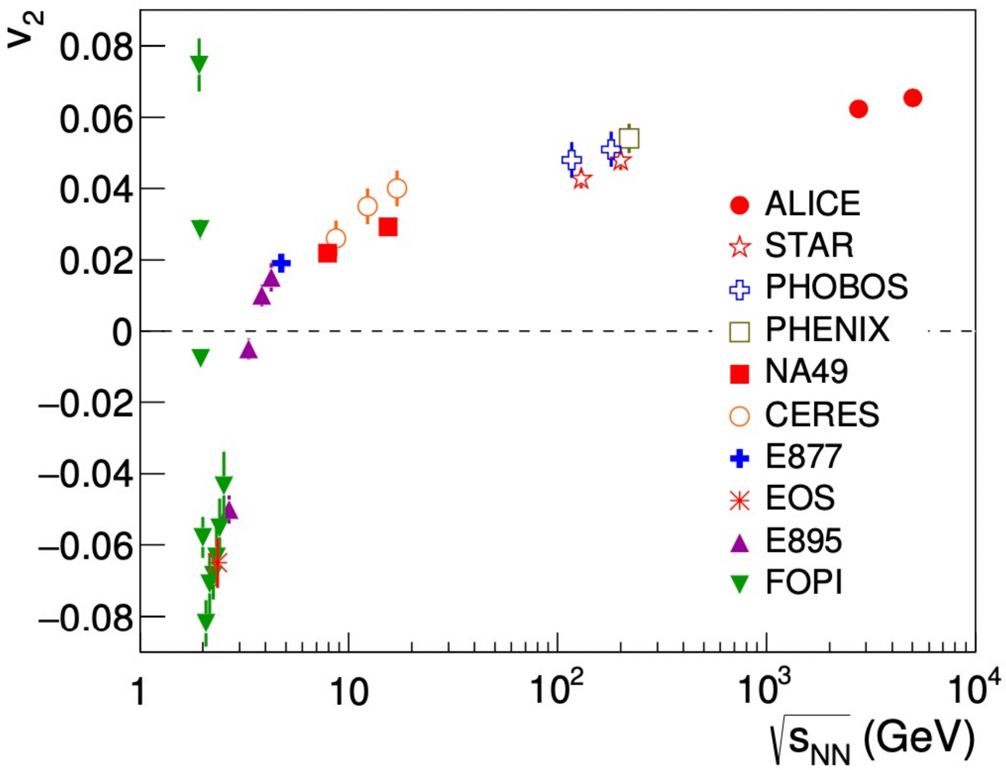


ATLAS, Phys. Rev. C. 104 (2021) 014903

- The p_T–differential v_2 for photonuclear and pp collisions is comparable within uncertainties in p_T < 2 GeV/c
- CGC calculations (initial-state effects only) is in reasonable agreement with the data

Collectivity at Low Energies

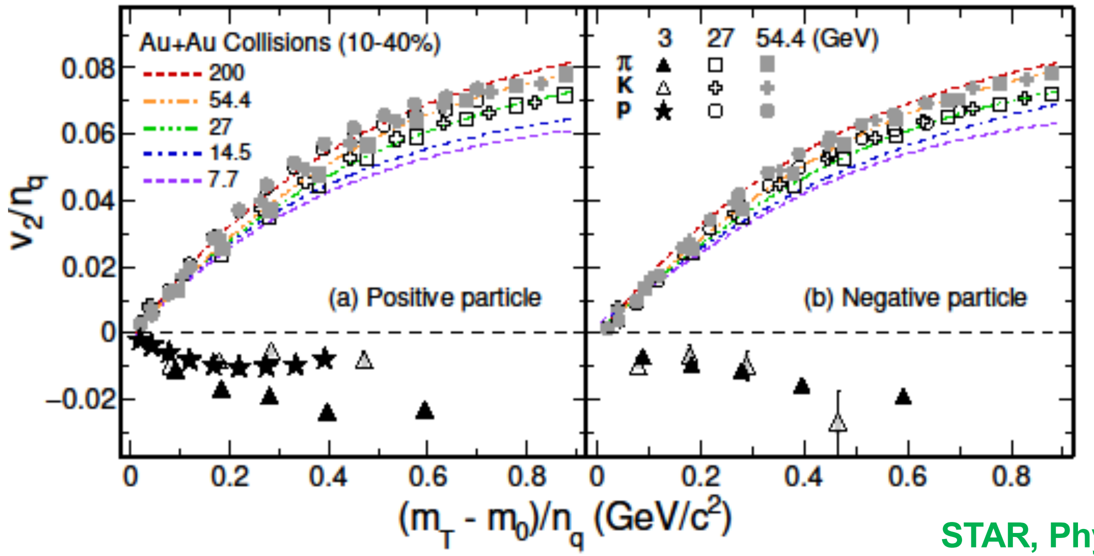
Energy Dependence of v_2



ALICE, arXiv:2211.04384

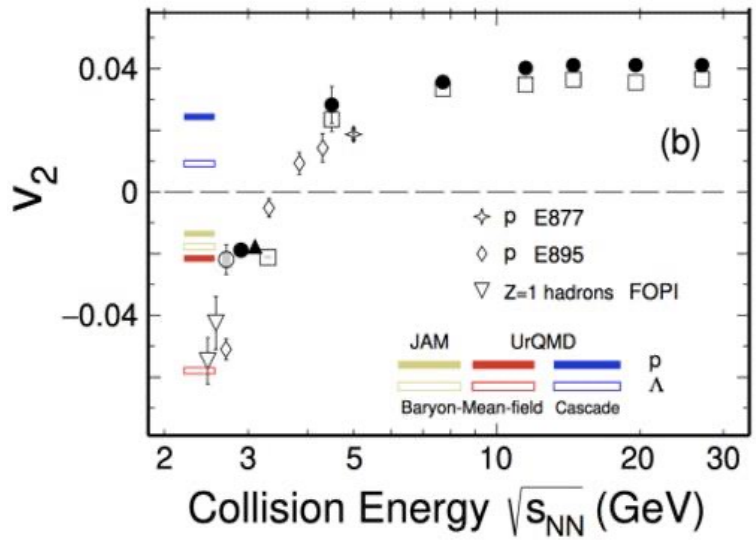
- v_2 measurements at the LHC reported by ALICE in midcentral collisions show an increase of about 30% compared to the top energy at RHIC
- Elliptic flow did not saturate at higher energies
  -- consistent with most of the hydrodynamic model predictions
- Elliptic flow becomes negative at lower energies

Collectivity at Low Energies

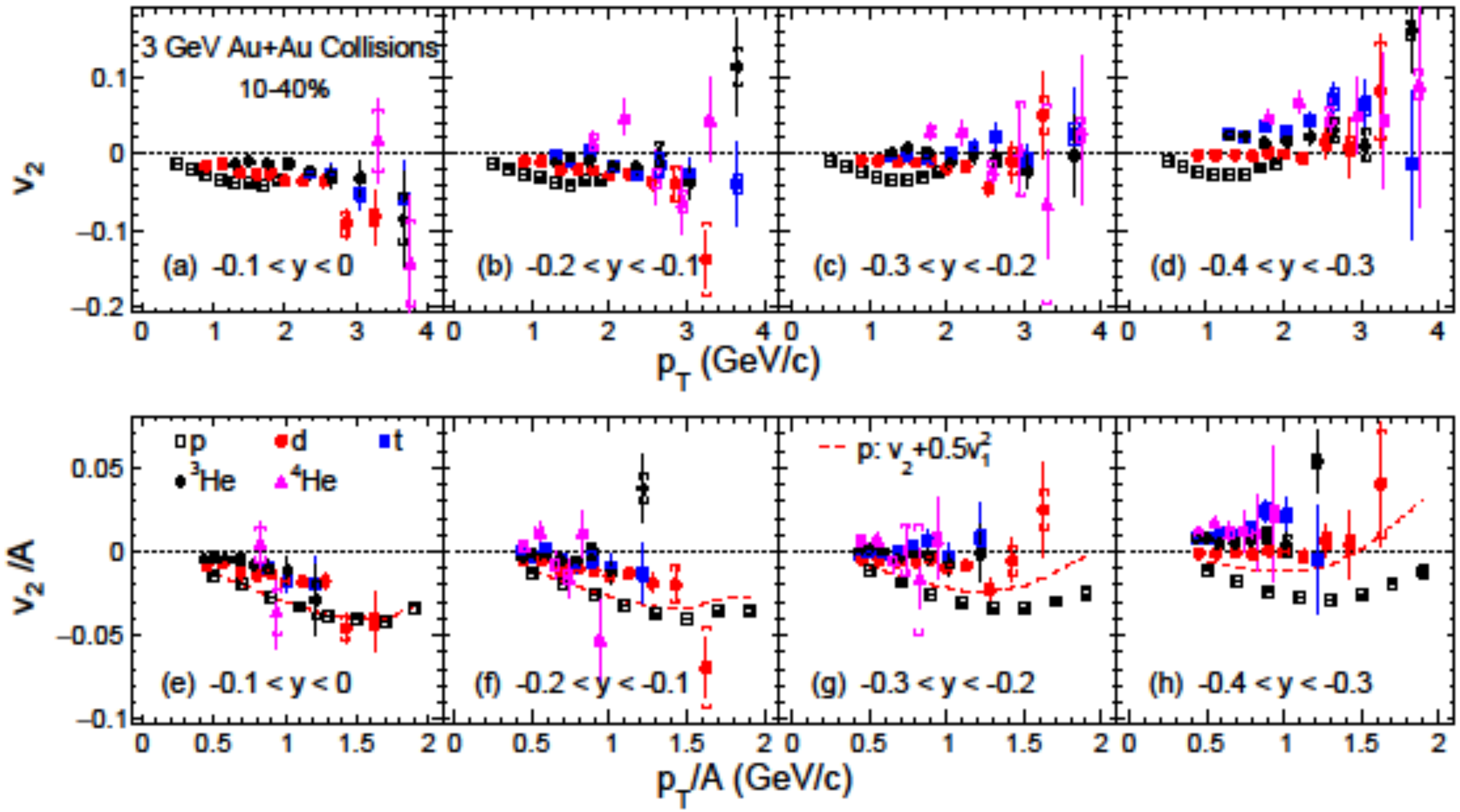


STAR, Phys. Lett. B 827 (2022) 137003

- Elliptic flow is negative in Au+Au collisions $\sqrt{s_{NN}}$ = 3 GeV
- The NCQ scaling breaks, especially for positively charged particles
  - ✓ Hadronic interaction dominated matter



Collectivity at Low Energies



STAR, Phys. Lett. B 827 (2022) 136941

- No mass number scaling is observed for light nuclei at $\sqrt{s_{NN}}$ = 3 GeV

Summary

- **Evidence of partonic collectivity at top RHIC and LHC energies**
- **Precision measurement of transport properties of the medium**
- **Observation of collectivity in small collision systems**
- **Signature of partonic collectivity seems to disappear at lower energies**

✓ Stay tuned for more exciting results from high statistics BES-II dataset and LHC Run3 with upgraded detectors

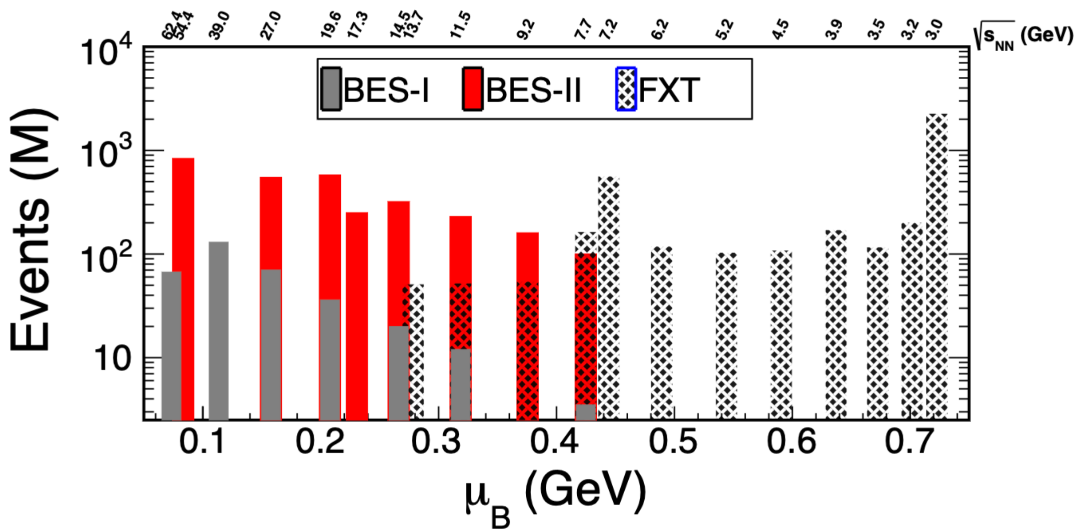
Thank You!

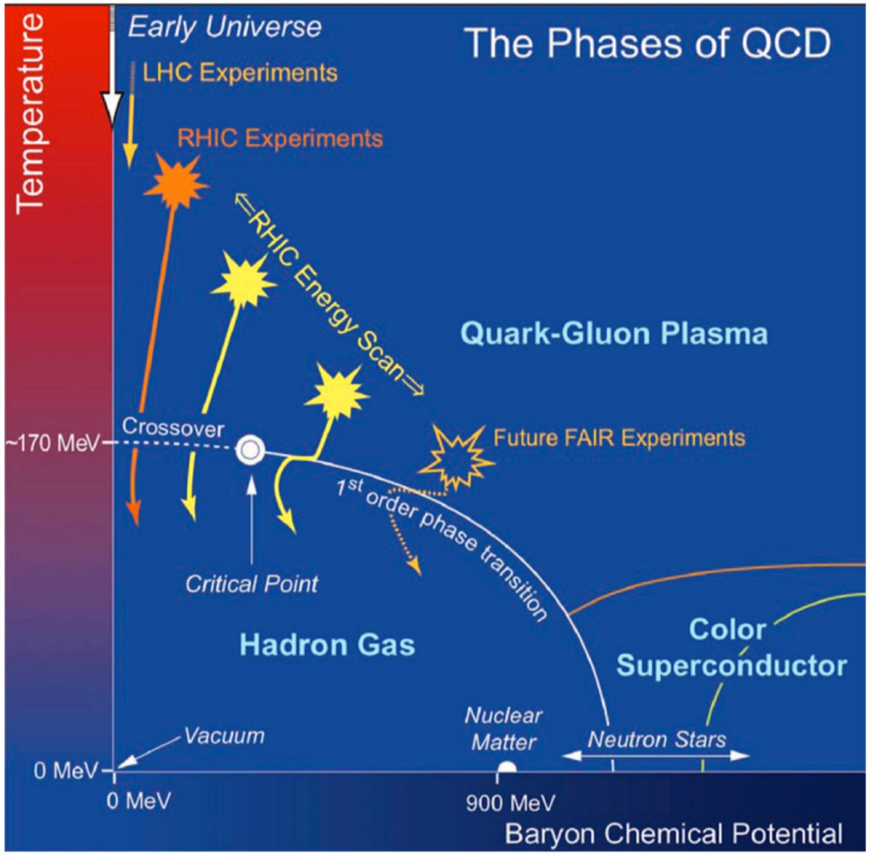
BES Program at RHIC

- RHIC provides a unique opportunity to explore the QCD phase diagram with different collision energies
  - ✓ Search for QCD critical point, 1st order phase transition, turn-off of QGP, etc.

- **BES-I** (2010 – 2011, 2014, 2017):
  $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4 GeV

- **BES-II** (2018, 2019 – 2021):
- **Collider mode:**
  $\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27 GeV
- **Fixed-Target mode:**
  $\sqrt{s_{NN}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2 7.7 GeV





STAR: arXiv: 1007.2613
BES-II white paper: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598