Recent highlights on measurement of bulk properties from RHIC

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STAR

U.S. DEPARTMENT OF ENERGY | Office of Science

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IMP

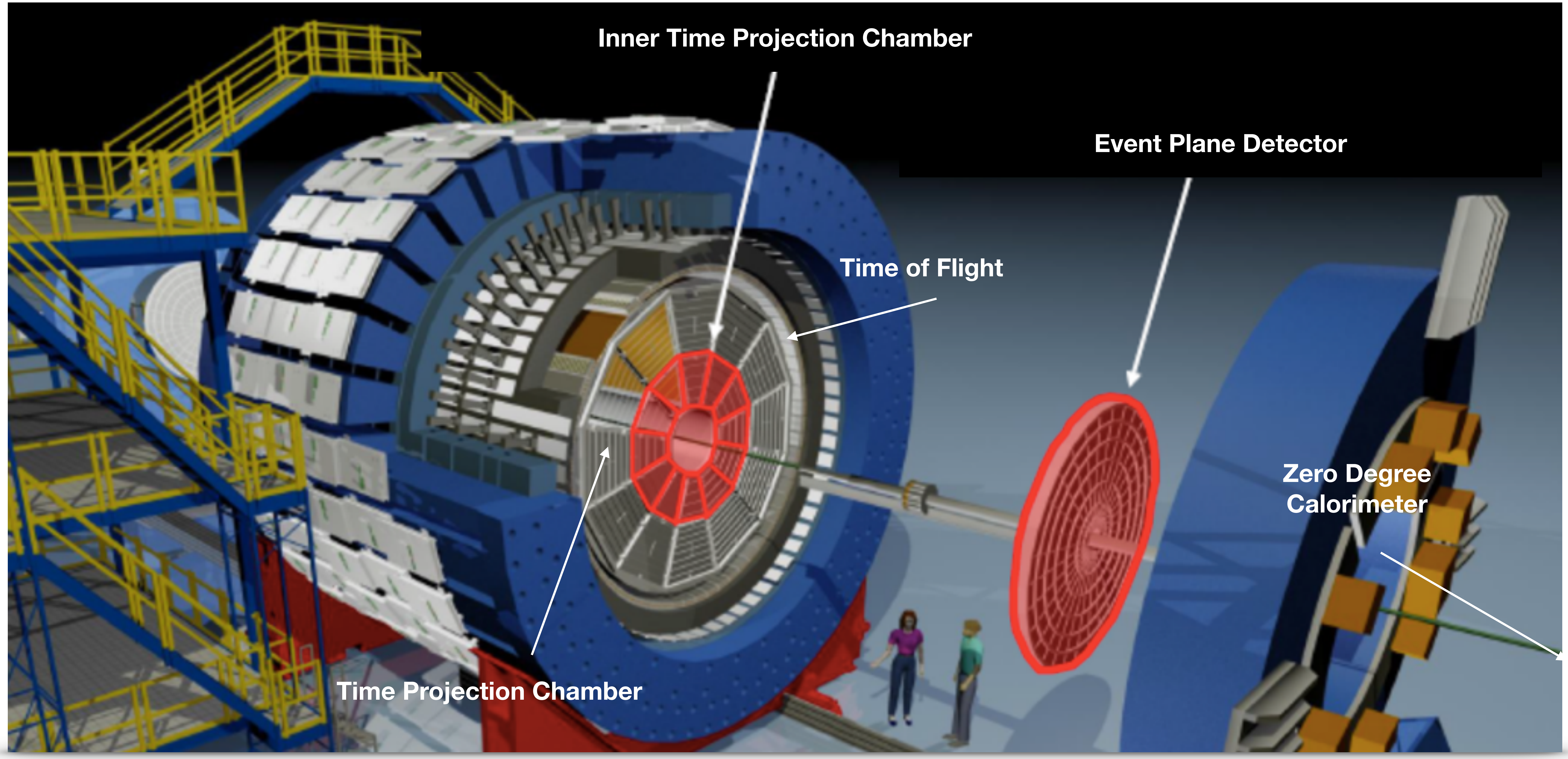
Outline

- Motivation
- Overview of bulk properties from STAR at RHIC

1. **Collective flow** (directed, elliptic and triangular flow)
2. **Flow-fluctuation** (flow decorrelation, flow-momentum correlations)
3. **Spin dynamics:** (spin polarization, alignment)

- Summary

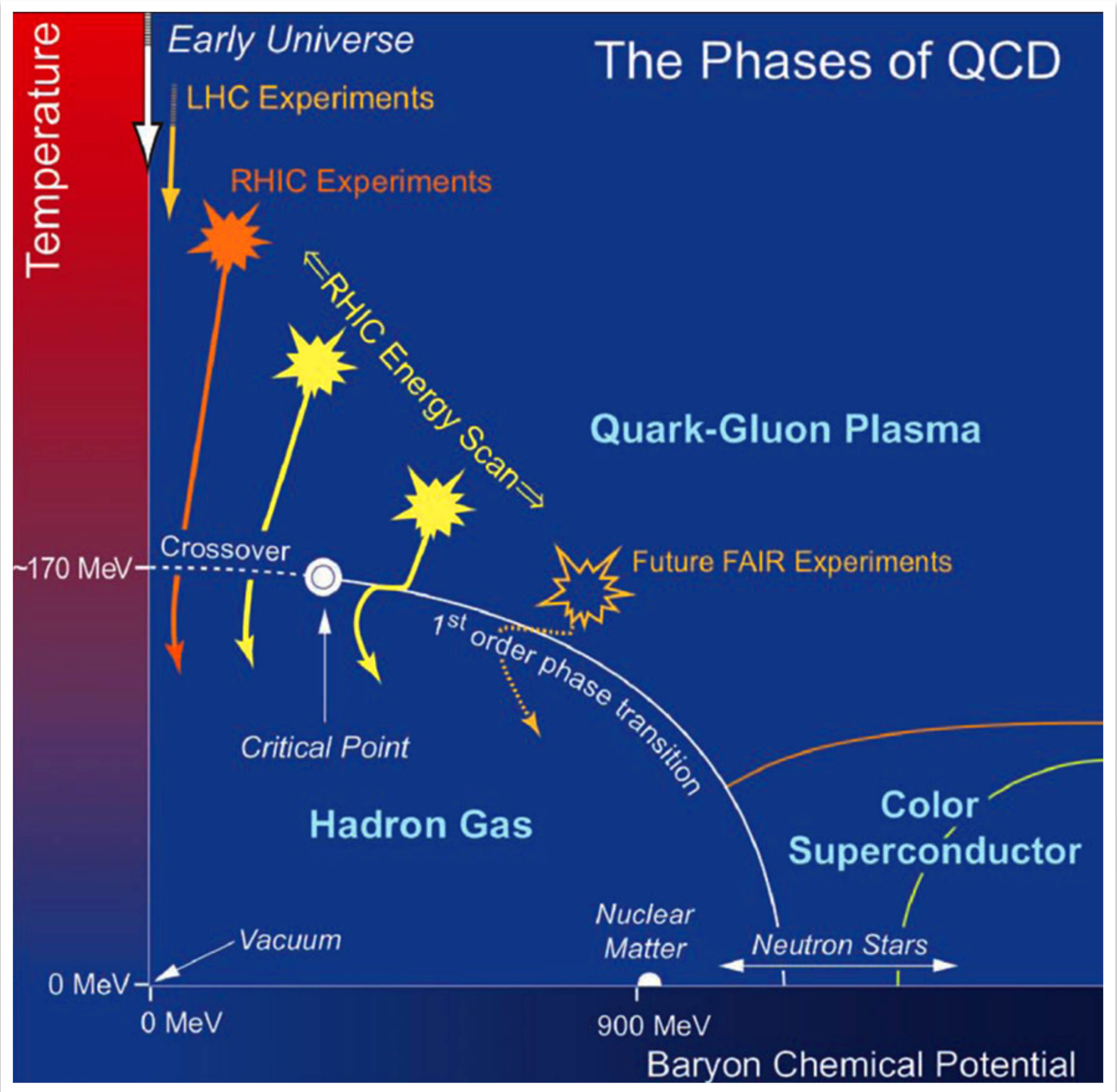
STAR detector



- Uniform acceptance, full azimuthal coverage, excellent PID capability
- **TPC (iTPC)**: tracking, centrality and event plane
- **EPD, ZDC, BBC**: event plane
- **TPC+TOF**: particle identification

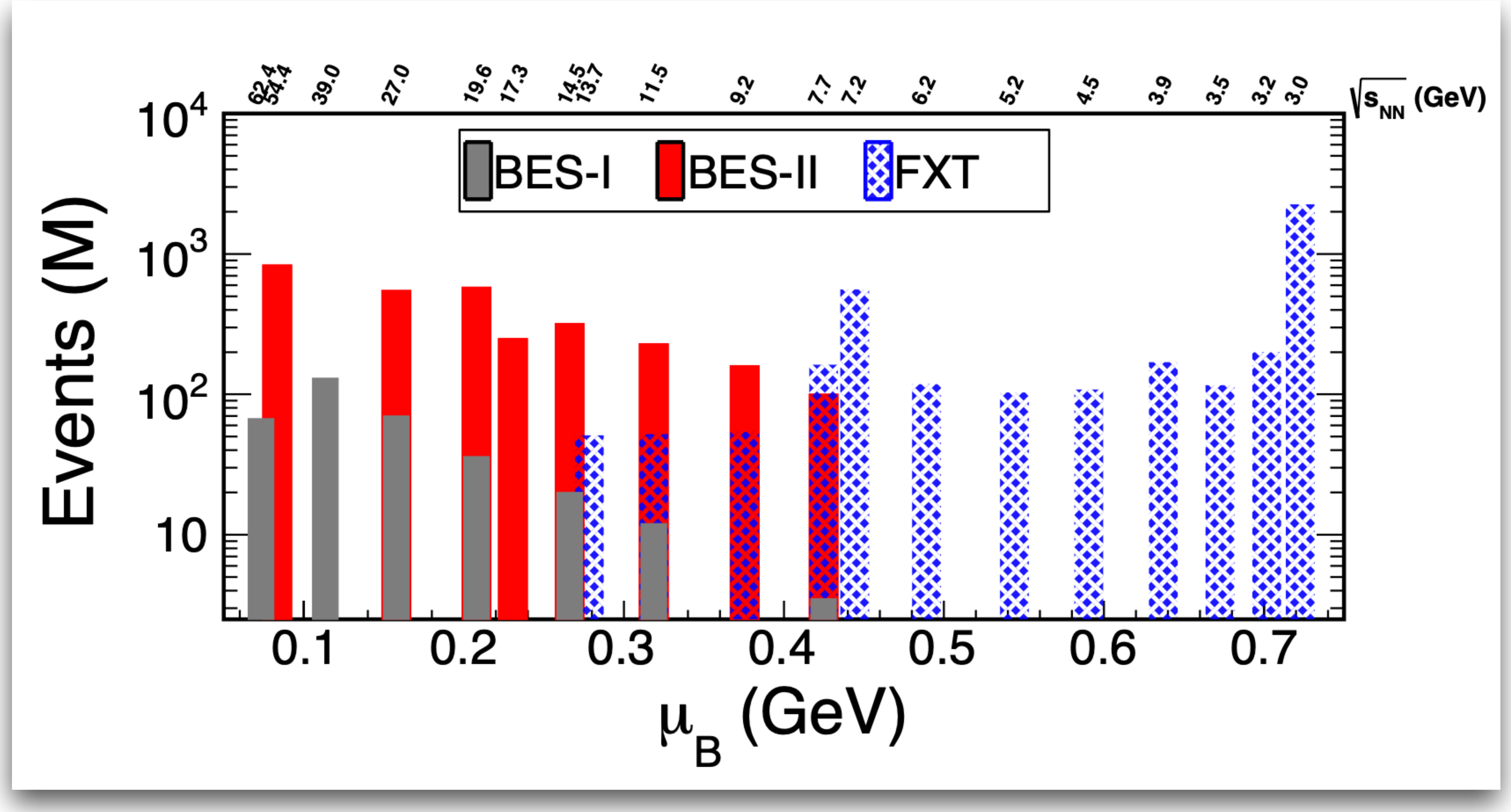
Motivation

Conjectured QCD Phase diagram



Explore QCD Phase diagram by varying beam energy, proxy for baryon chemical potential (μ_B)

BES Program:

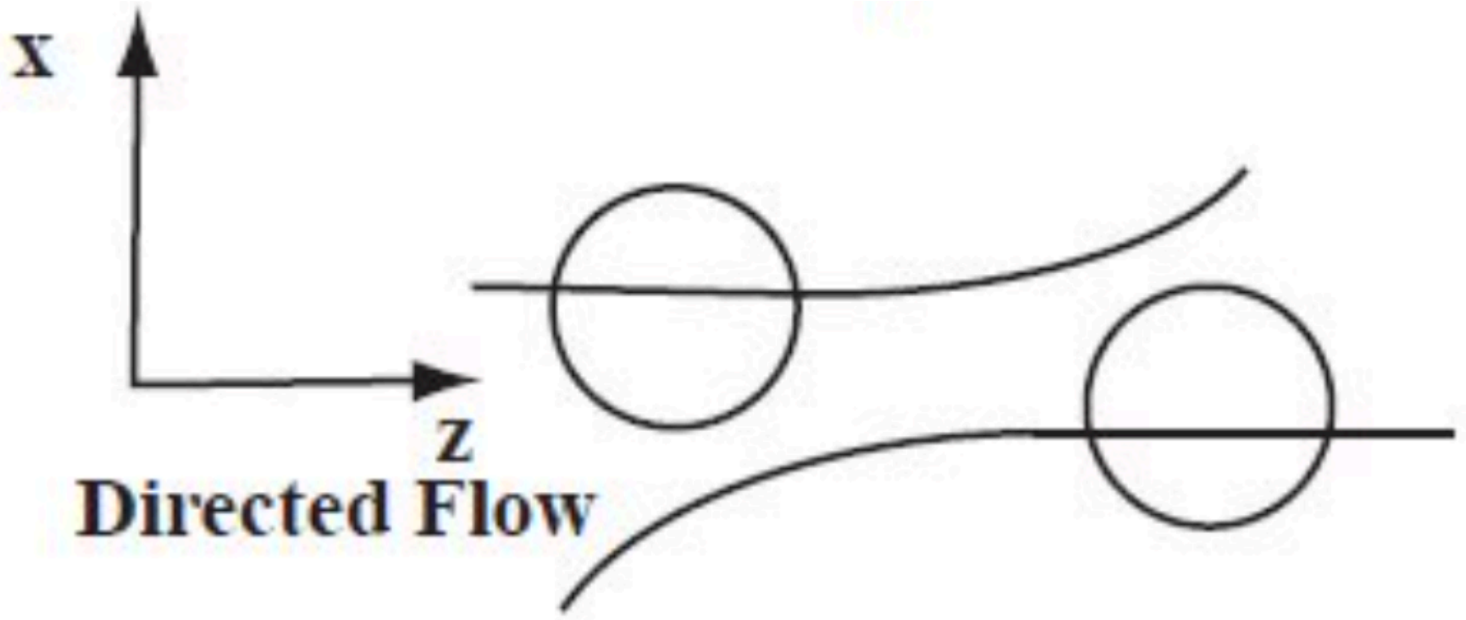


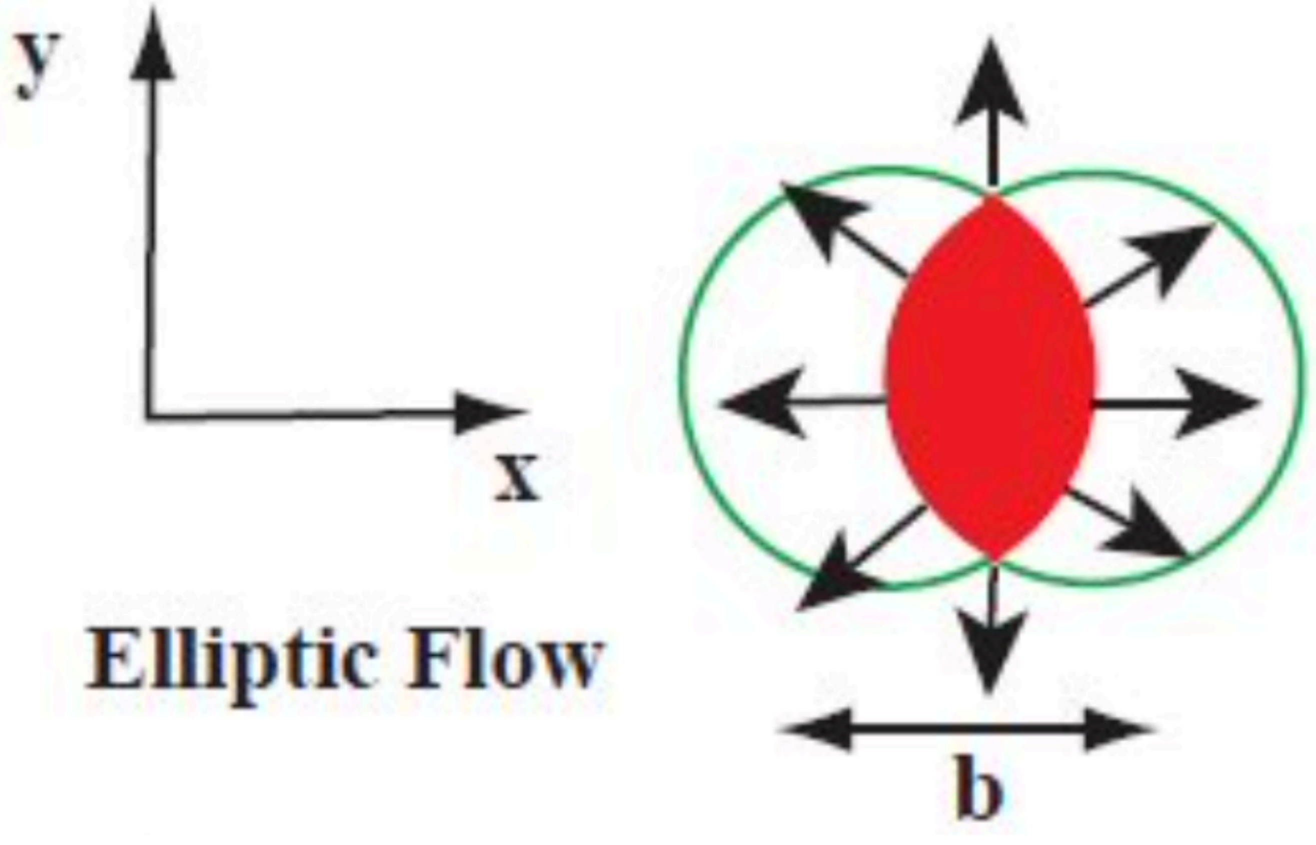
BES-II upgrades: **iTPC, EPD, eTOF**

High statistics data and detector upgrade in BES-II enhances the capability of various measurements with excellent precision

Collective flow

Collective flow





A. Poskanzer el. al. arXiv: 0809.2949

- Collective flow can be measured from the Fourier expansion

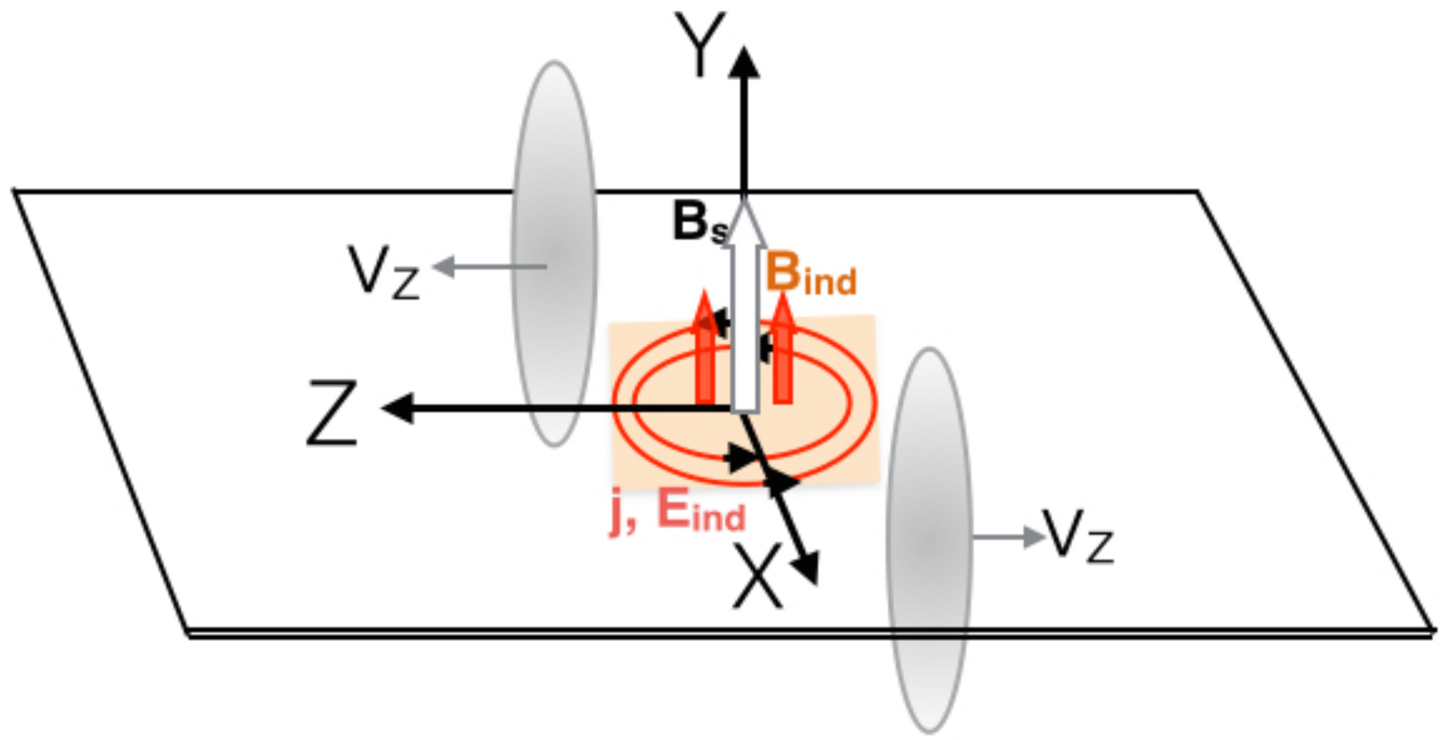
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum 2v_n \cos n(\phi - \Psi_n^{EP})\right)$$

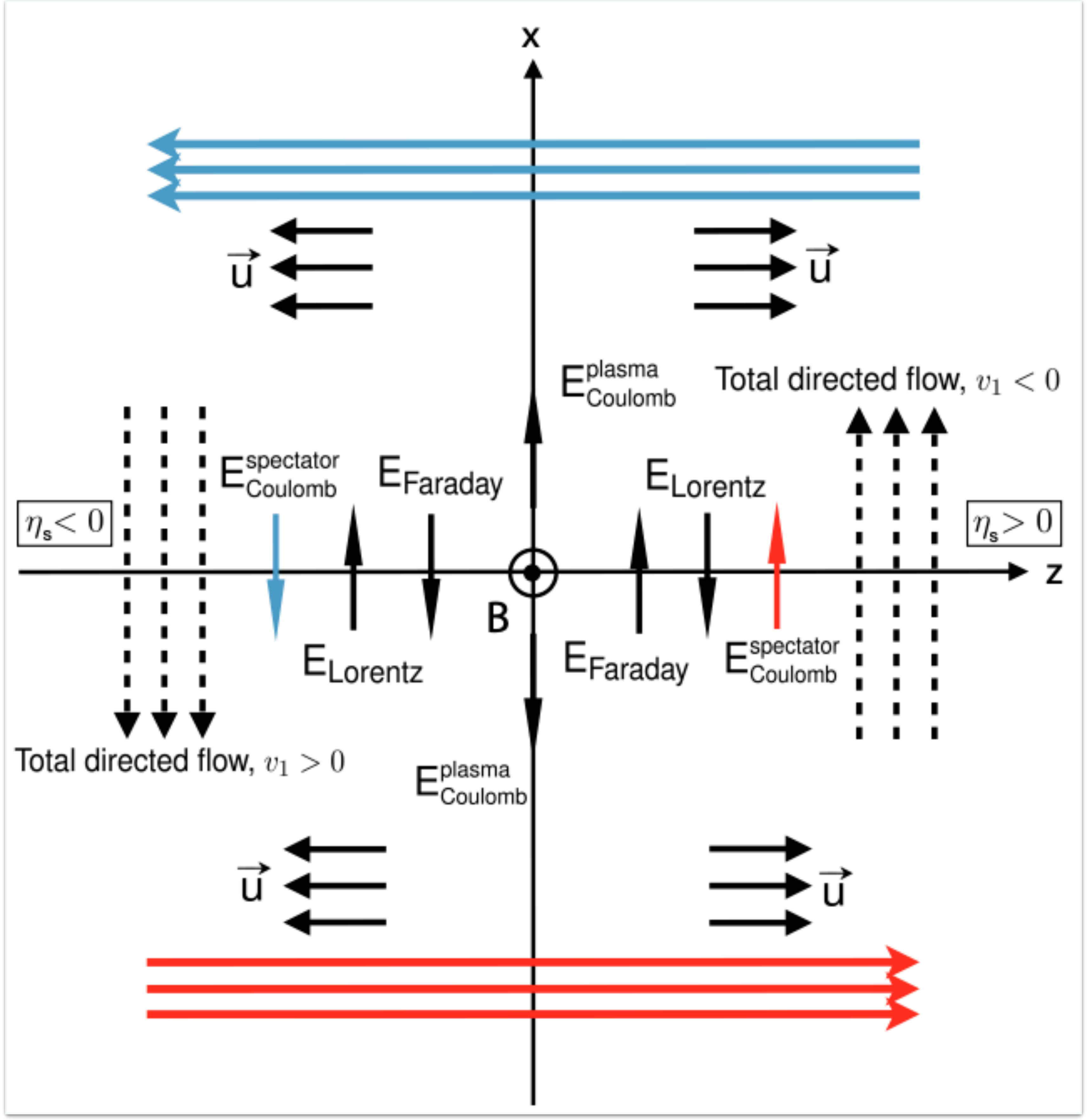
- v_1 : Directed flow
- v_2 : Elliptic flow
- v_3 : Triangular flow

$$v_n = \langle \cos n(\phi - \Psi_n^{EP})\rangle / \Psi_{Resolution}$$

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

Directed flow from initial strong electromagnetic field





- The moving spectators can produce an enormously large **B** field (eB ~10^{18} G)
- It can *induce following competitive effects* in rapidity-odd v_1

- **Hall effect:**

  Lorentz force exerts a sideways push on charged particles

  In opposite directions at opposite rapidity
- **Faraday effect:**

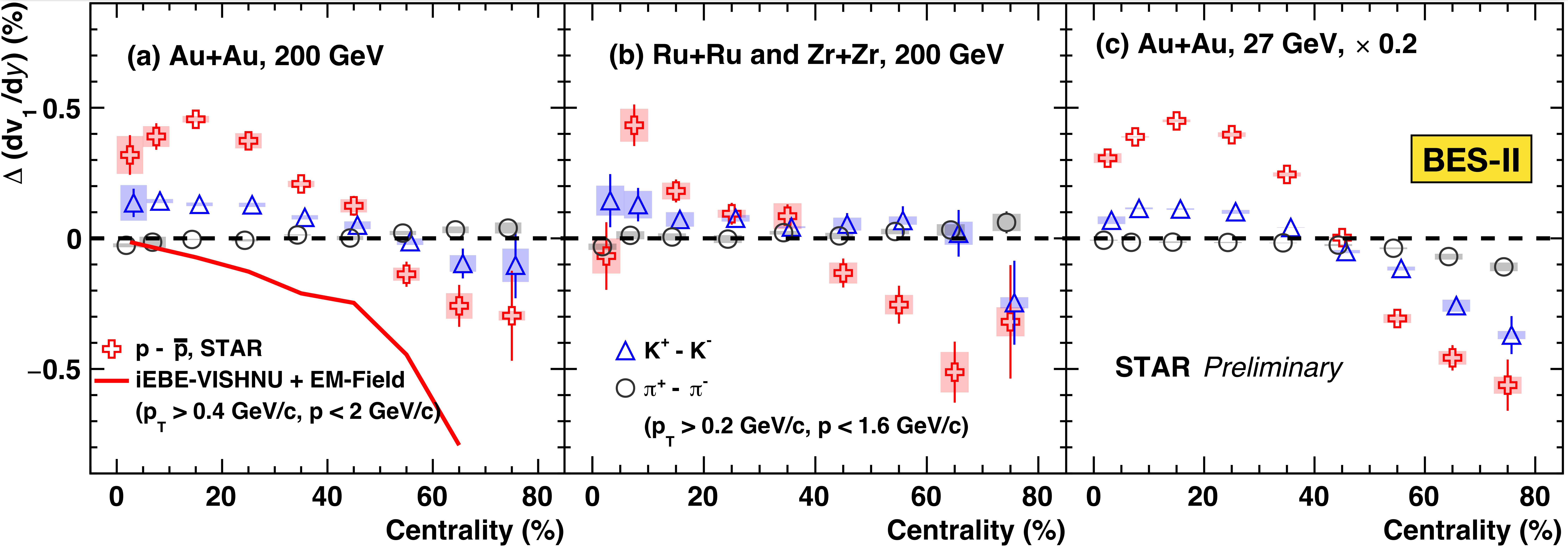
  Rapid decay of **B** field induces Faraday current to generate large **E** field

  Induced Faraday current will oppose the drift due to **B** field
- **Coulomb effect:**

  Coulomb field of the charged spectators

U. Gursoy el. al. Phys. Rev. C 98, 055201 (2018); Phys. Rev. C 89, 054905 (2014)

Charge dependent directed flow

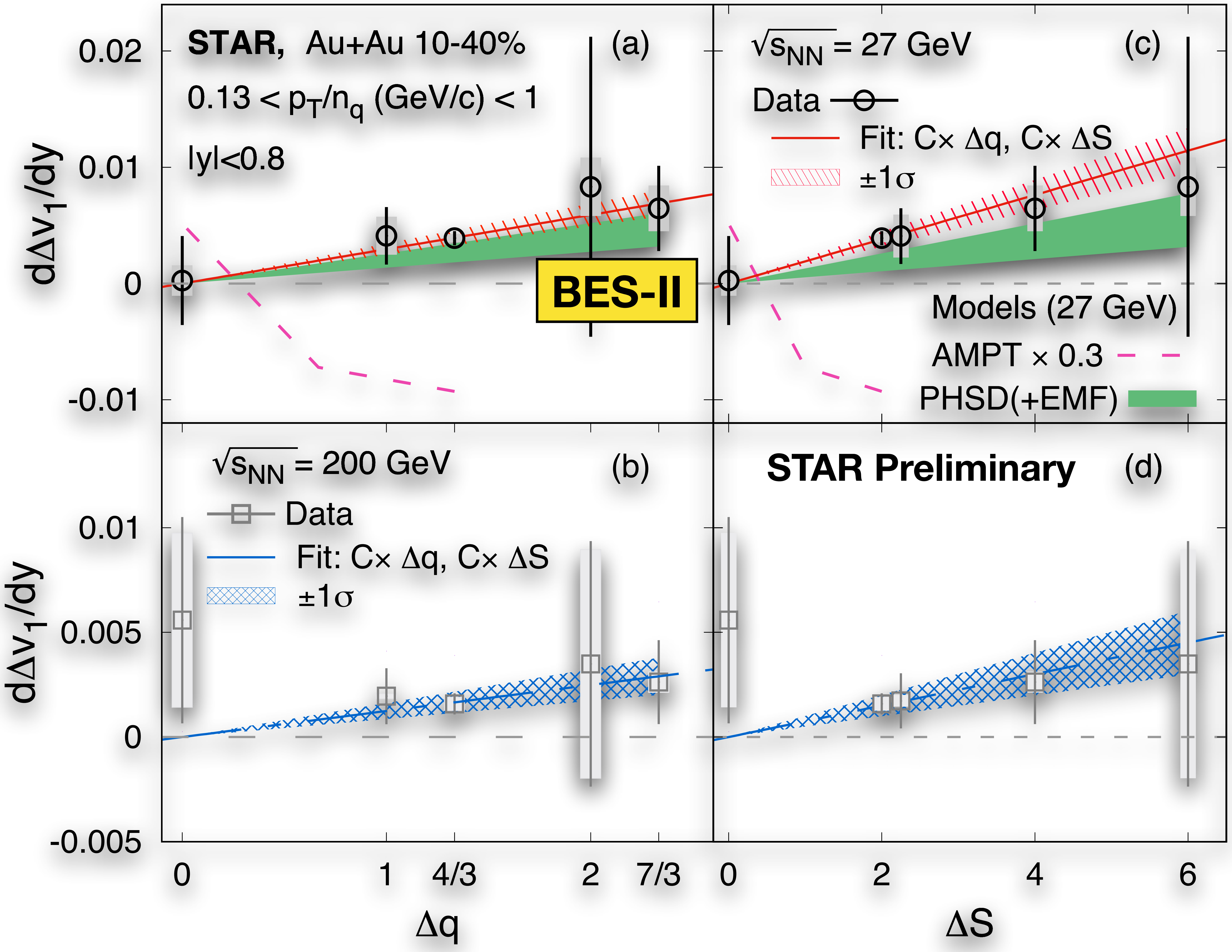


Among p and $\bar{p}$

- in (mid) central collisions: **positive v_1-slope difference** (Transported quark effect)
- in peripheral collisions: **negative v_1-slope difference (> 5σ)**, which increases with decrease in beam energy (Could be due to the dominance of Faraday+Coulomb effect)

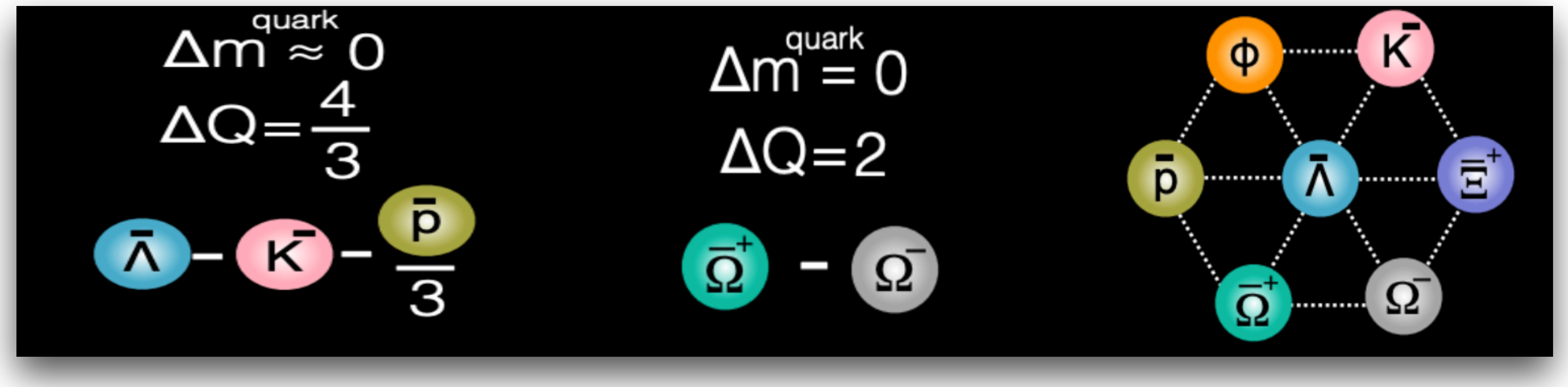
Indication of *EM* field driven effects in HIC

Charge dependent directed flow



Indication of *EM* field driven effects in HIC

v_1 splitting measured using combination of *transported-quark-free* hadrons

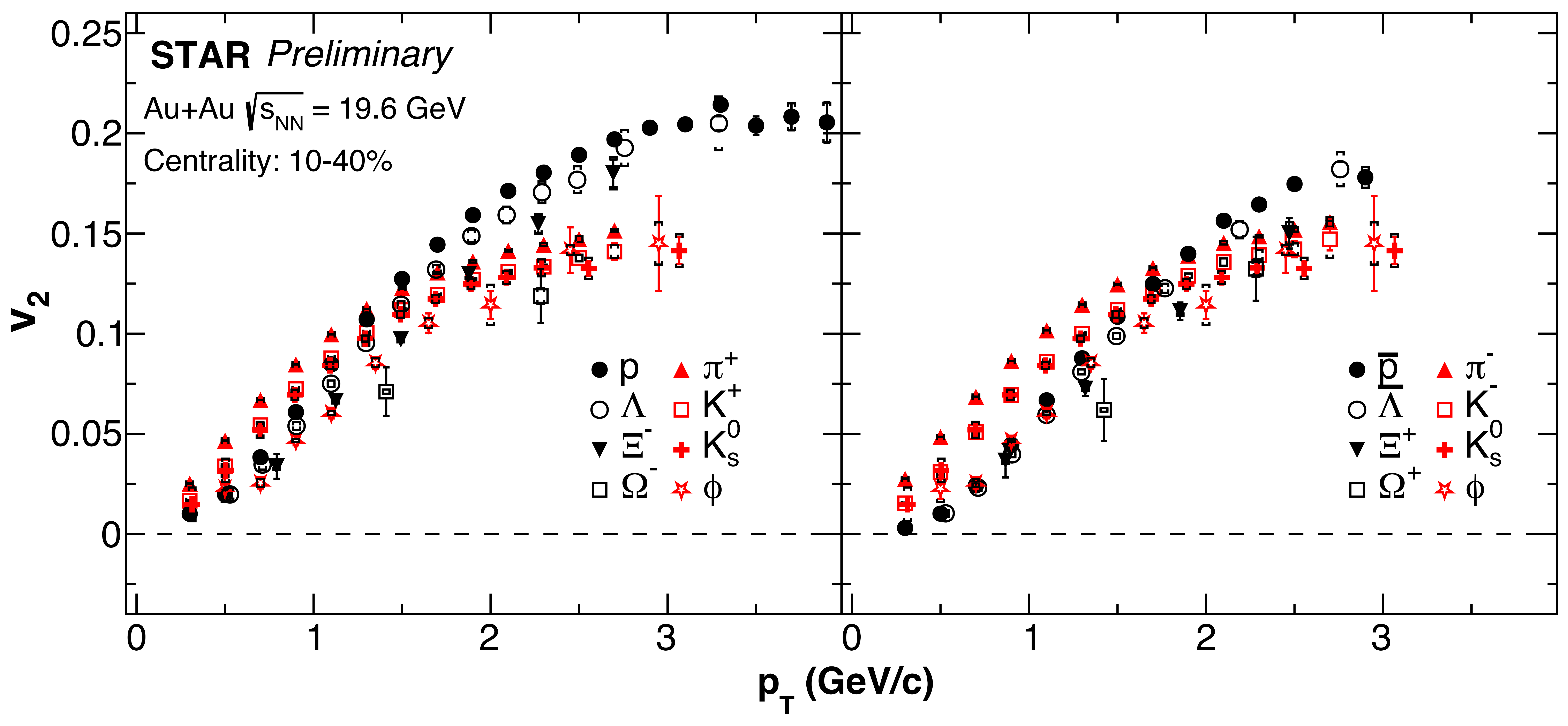


- **v_1-slope difference** observed as function of charge difference (Δq) and strangeness difference (ΔS)
- **Larger v_1-slope difference** at 27 GeV than 200 GeV

See Poster (08/02):
Ashik Ikbal (STAR)

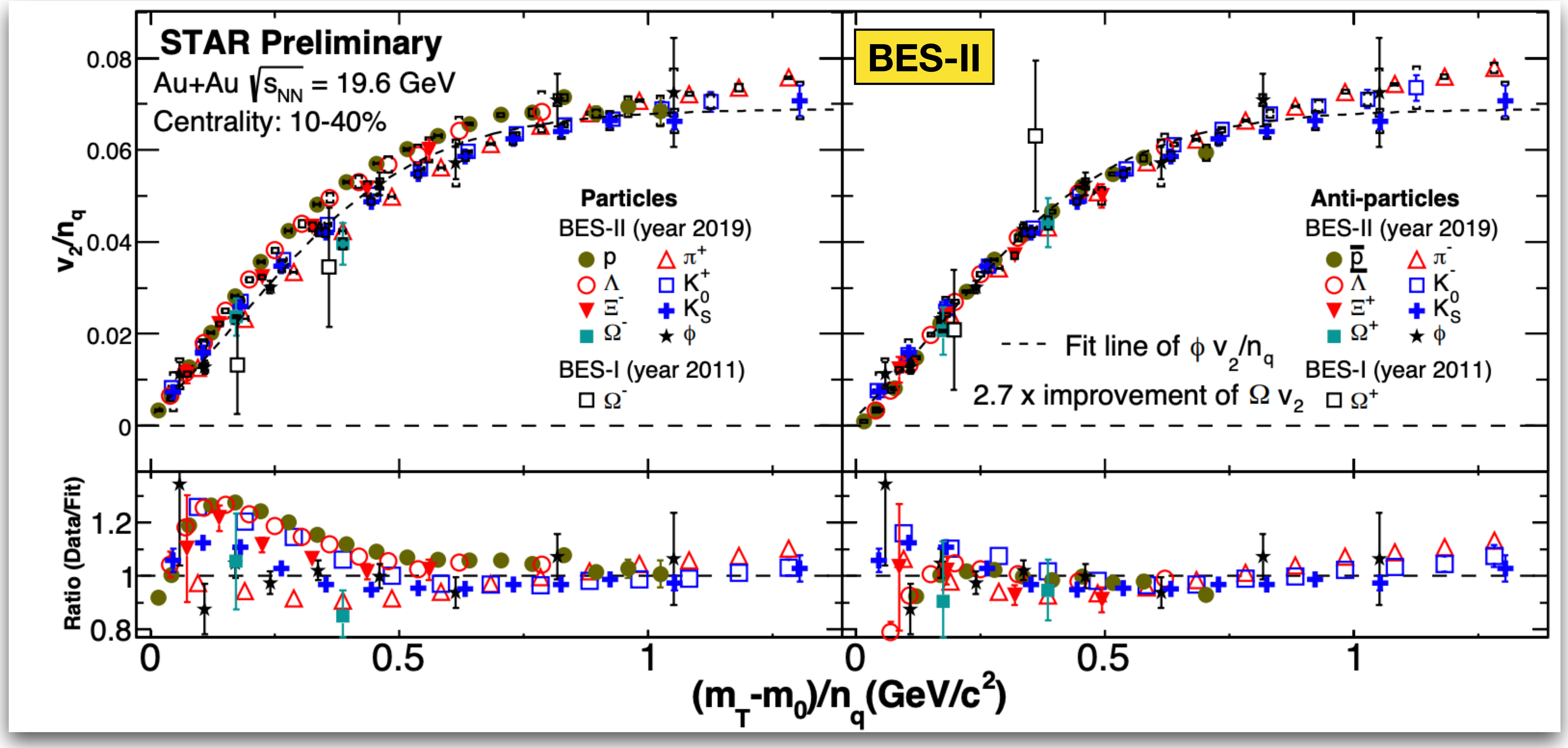
Elliptic flow (v_2) of identified particles

BES-II



- At low p_T: **mass ordering** in v_2
- At intermediate p_T: v_2 shows **baryons vs. mesons** ordering

NCQ scaling of v_2



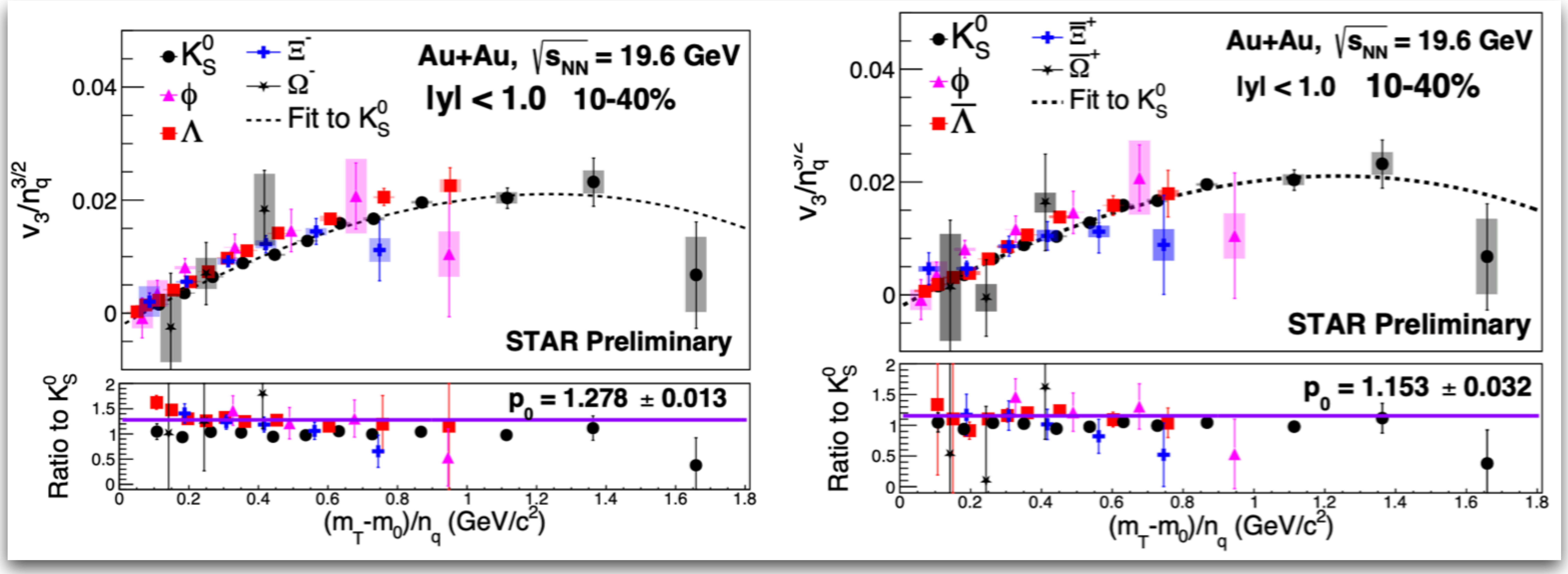
- **NCQ scaling** of v_2 holds ~ 20% for particles; ~ 15% for anti-particles
- ϕ mesons follow an approximate NCQ scaling

See Poster (08/02): Prabhupada Dixit (STAR)

Indication of *partonic* collectivity

NCQ scaling of v_3

BES-II

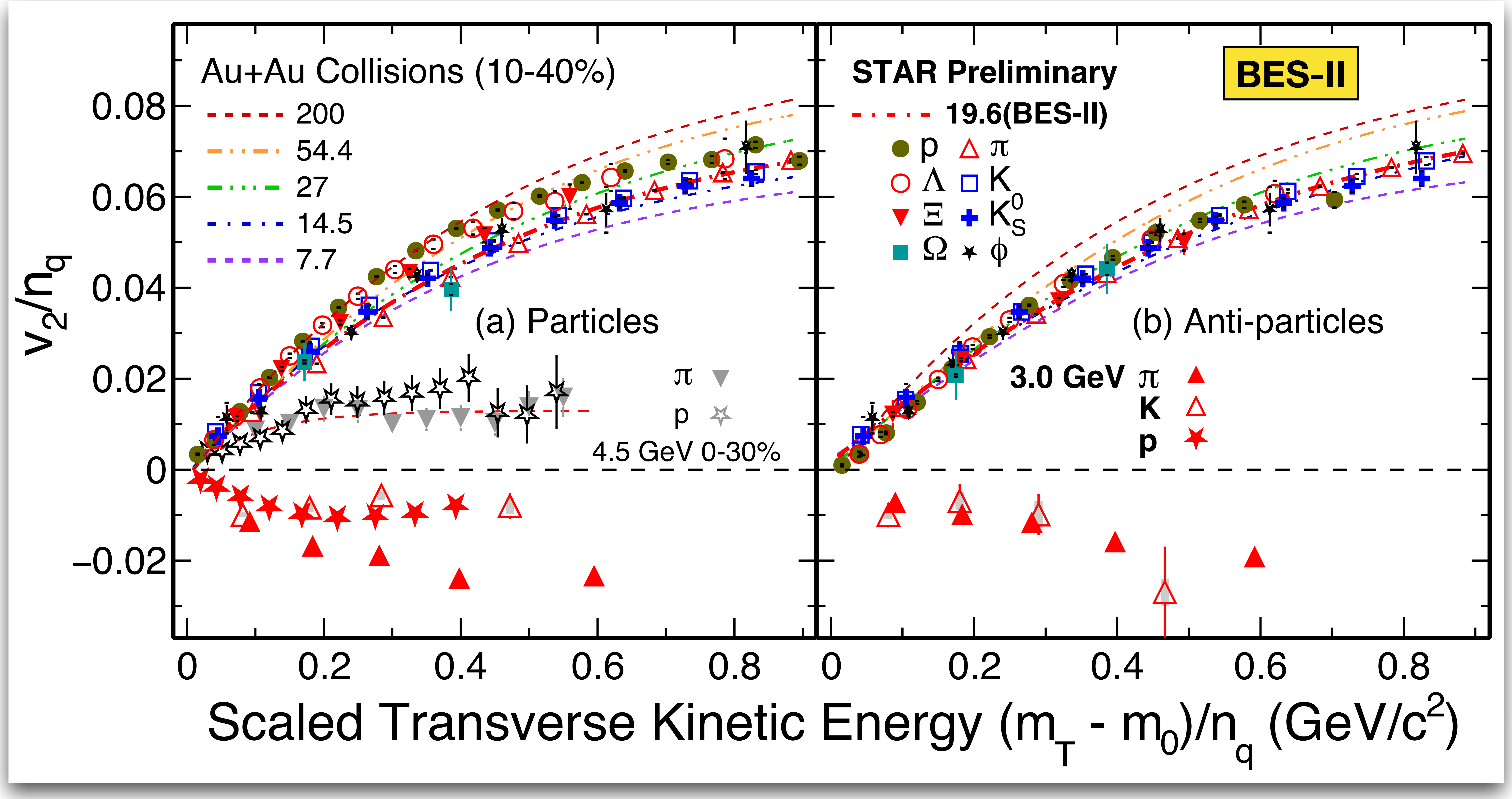


- **NCQ scaling** for v_3 holds ~ 30% for particles; ~ 15% for anti-particles

Indication of *partonic* collectivity

See Poster (08/02):
Prabhupada Dixit
(STAR)

Breaking of NCQ scaling of v_2



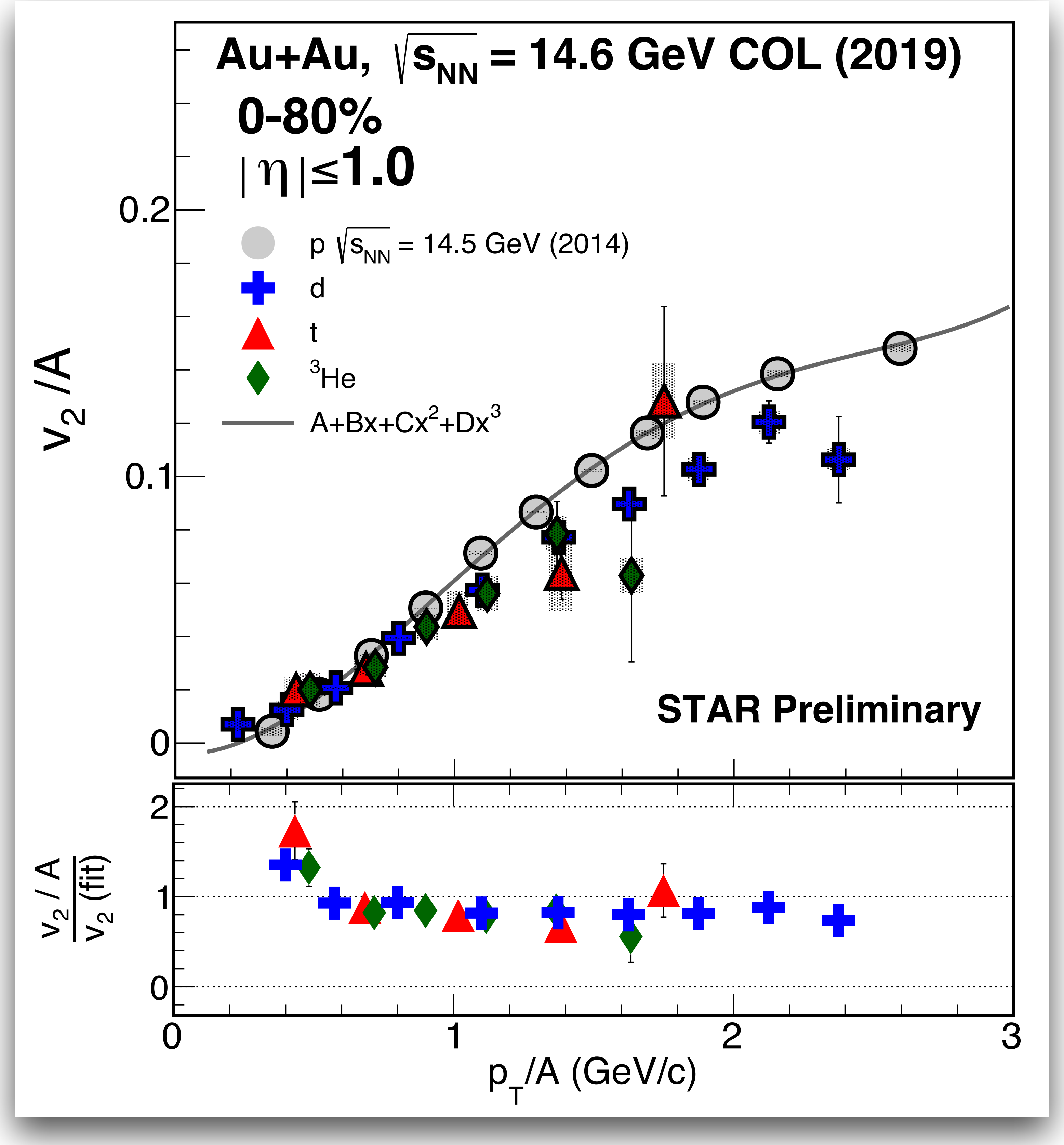
- **NCQ scaling for v_2 breaks** at 3 GeV

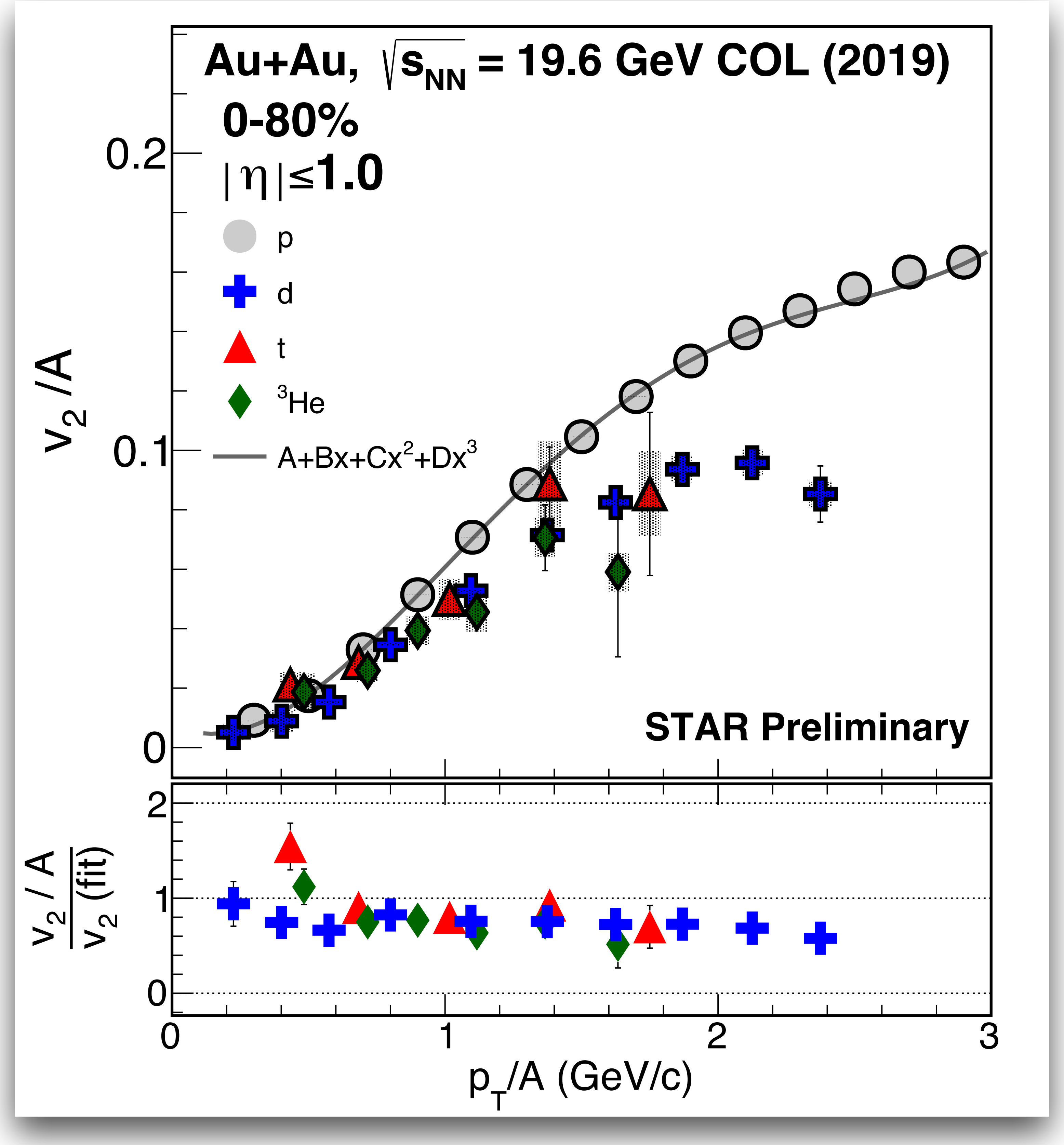
Indication of *disappearance* of partonic collectivity

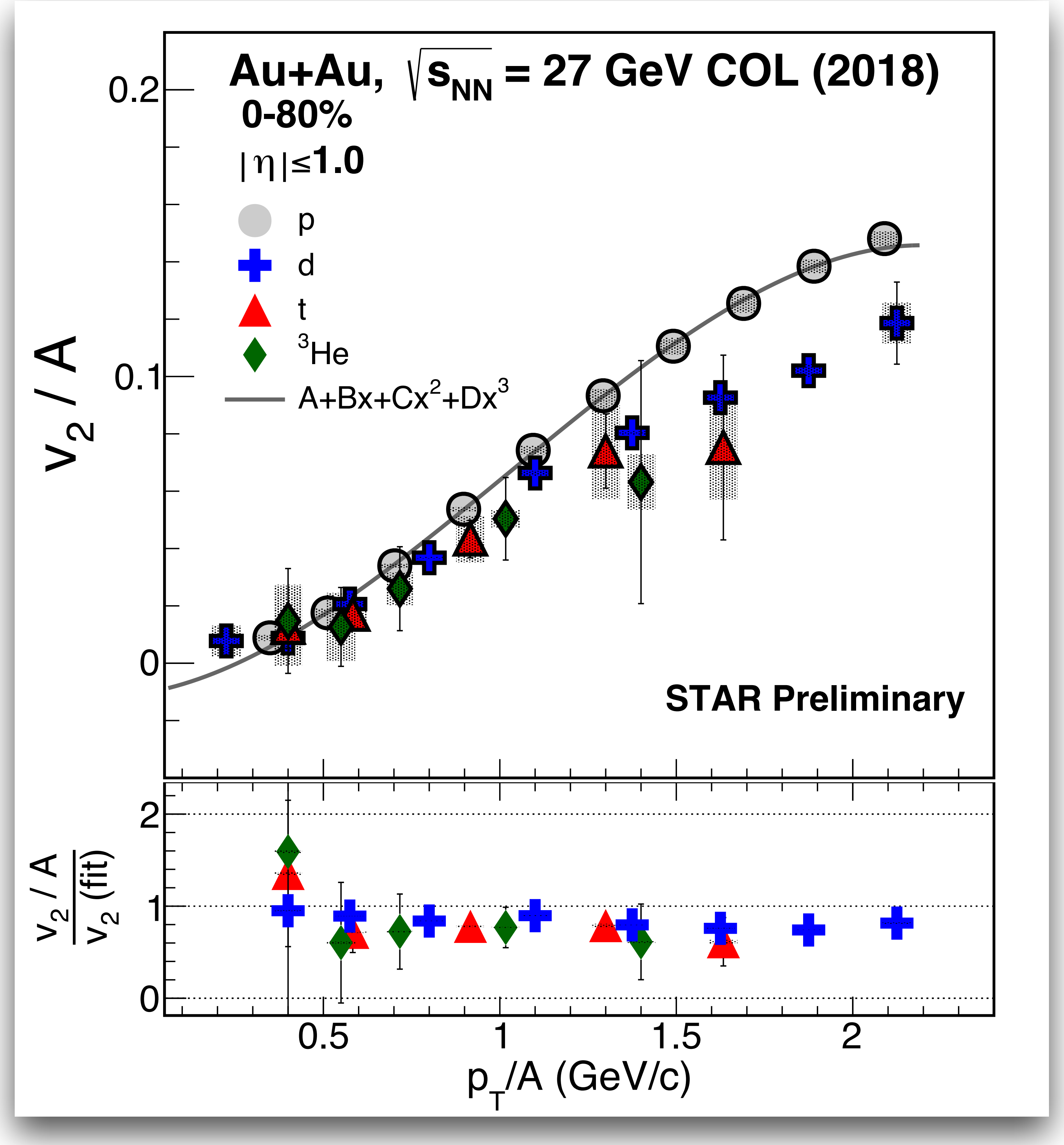
STAR: Phys. Lett. B 827, 137003, (2021)

Elliptic flow (v_2) of light nuclei

BES-II







- Light nuclei v_2 obey mass number scaling at ~ 30% level

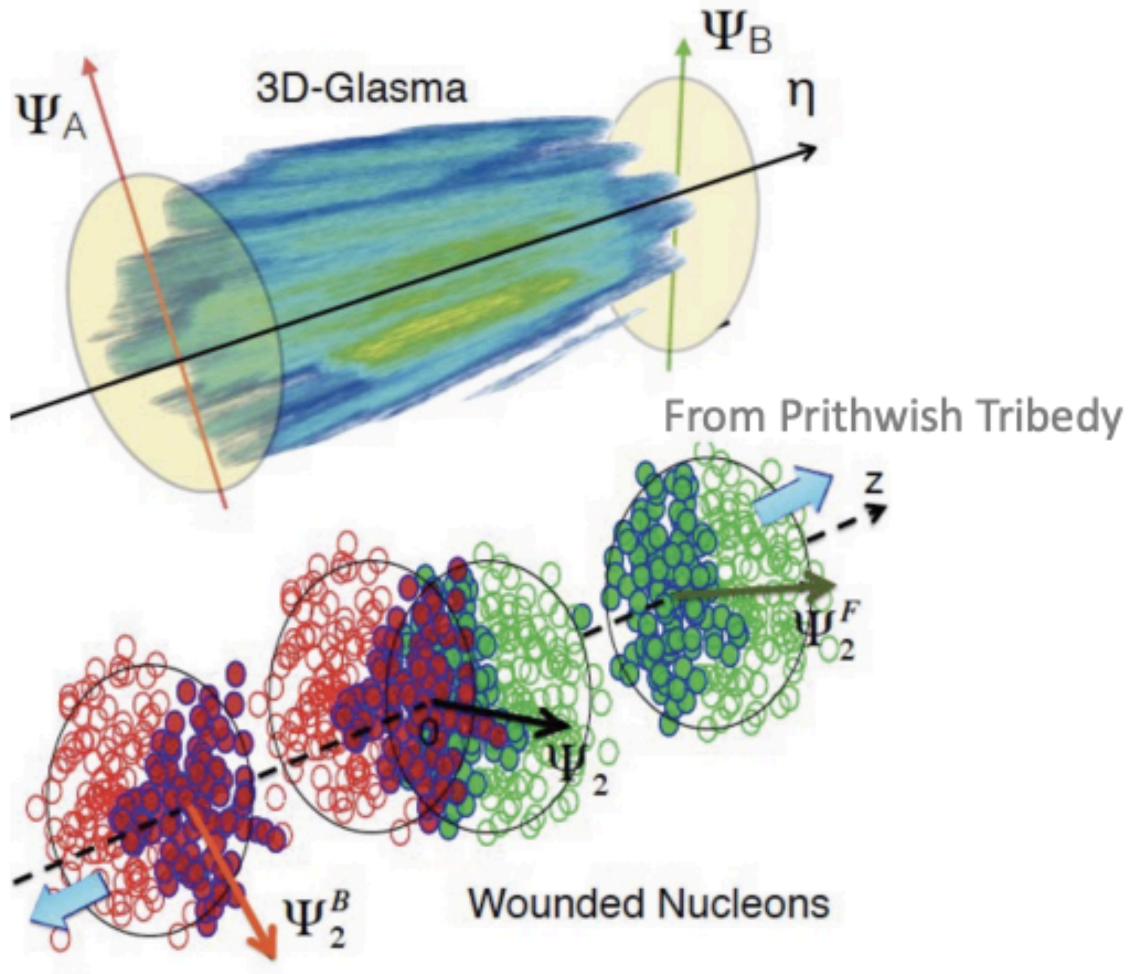
Role of *coalescence mechanism* in light nuclei formation

See Talk (10/02):
Rishabh Sharma (STAR)

Flow fluctuation

Longitudinal flow decorrelation

BES-II



From Prithwish Tribedy

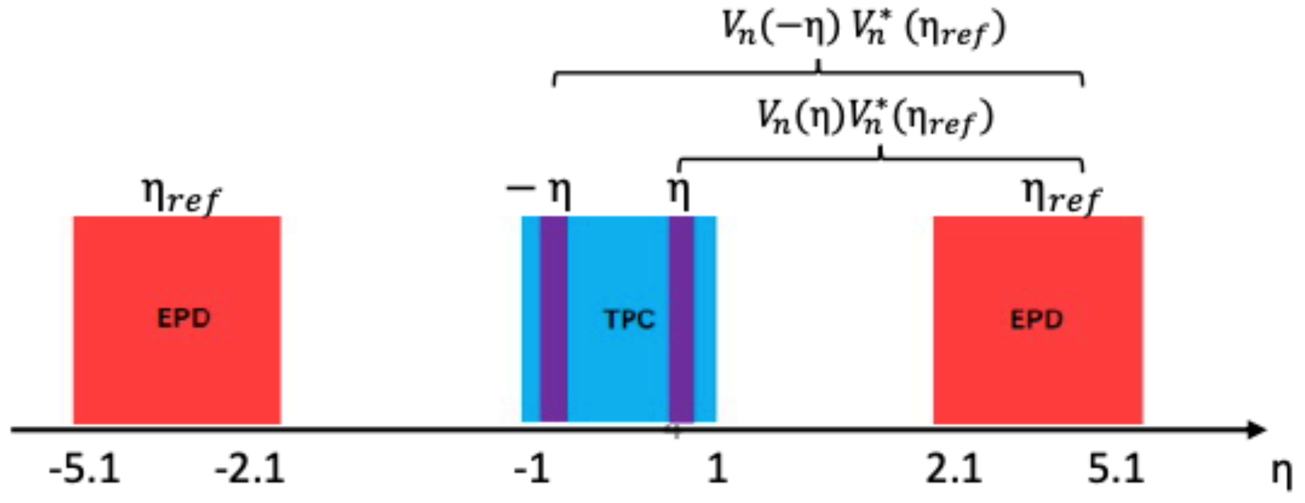
From Wei Li

Observable

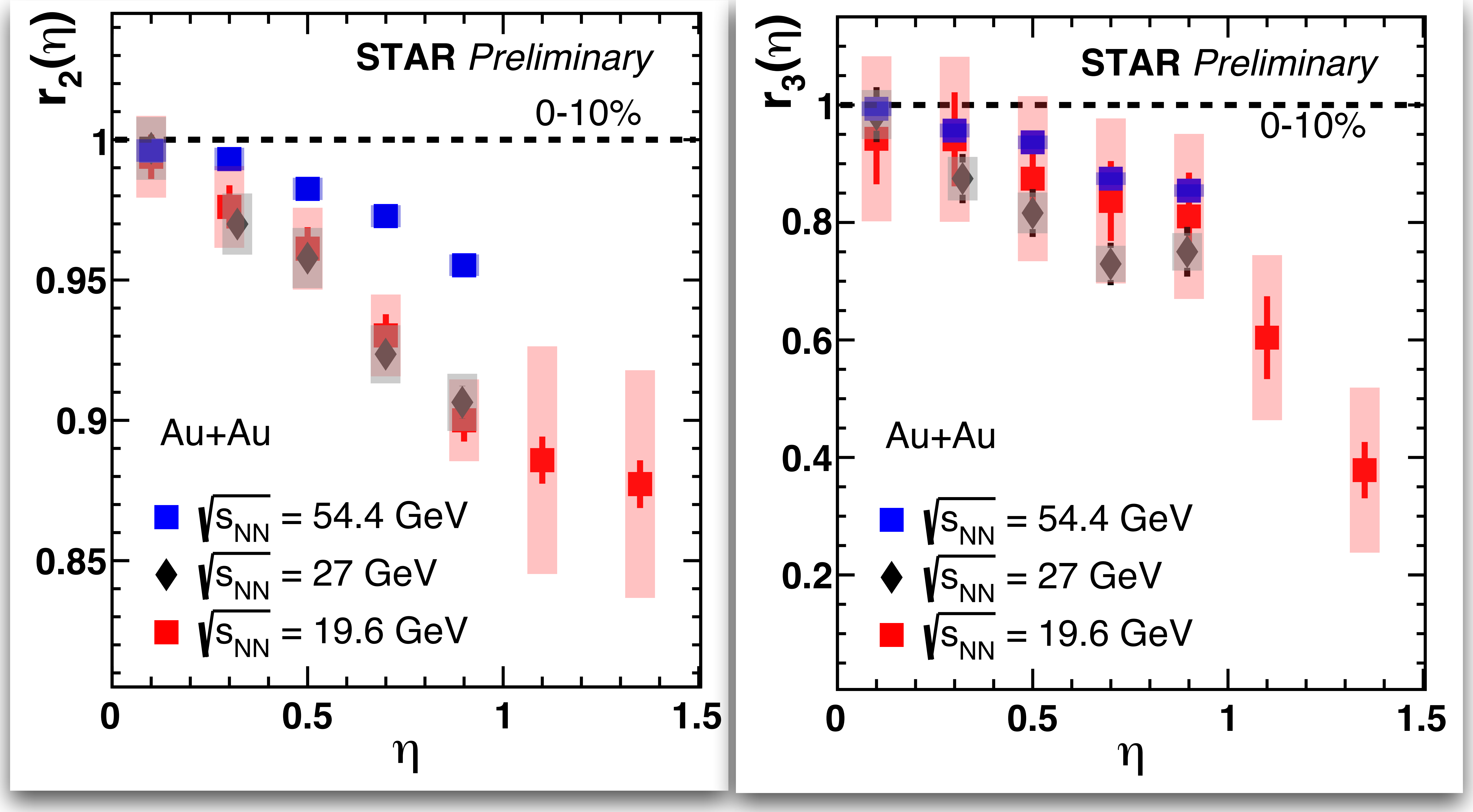
$$r_n(-\eta,\eta) = \frac{V_{n\Delta}(-\eta,\eta_{ref})}{V_{n\Delta}(\eta,\eta_{ref})}$$

$$= \frac{\langle v_n(-\eta)v_n(\eta_{ref})\cos\{n[\Psi_n(-\eta)-\Psi_n(\eta_{ref})]\}\rangle}{\langle v_n(\eta)v_n(\eta_{ref})\cos\{n[\Psi_n(\eta)-\Psi_n(\eta_{ref})]\}\rangle}$$

✓ The $r_n(-\eta,\eta)$ measures decorrelation between −η and η



✓ The large η gap can avoid short-range correlation

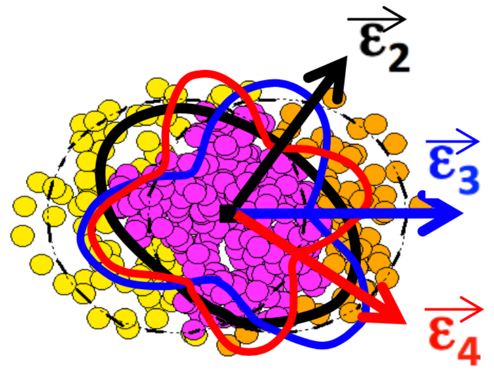


- Larger flow de-correlation at lower beam energies
- Can constrain initial state fluctuations, transverse & longitudinal dynamics

Ratios of v_2, v_3 and $\langle p_T \rangle$-variances in isobar collisions

Initial Shape

$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} \equiv -\frac{\langle r^n e^{in\phi}\rangle}{\langle r^n\rangle}$$

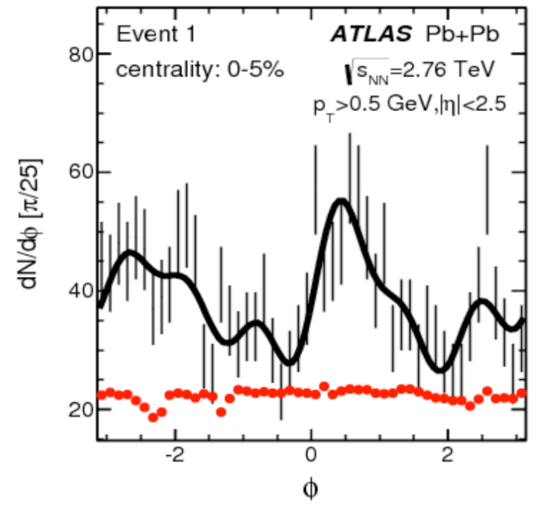


Hydro response

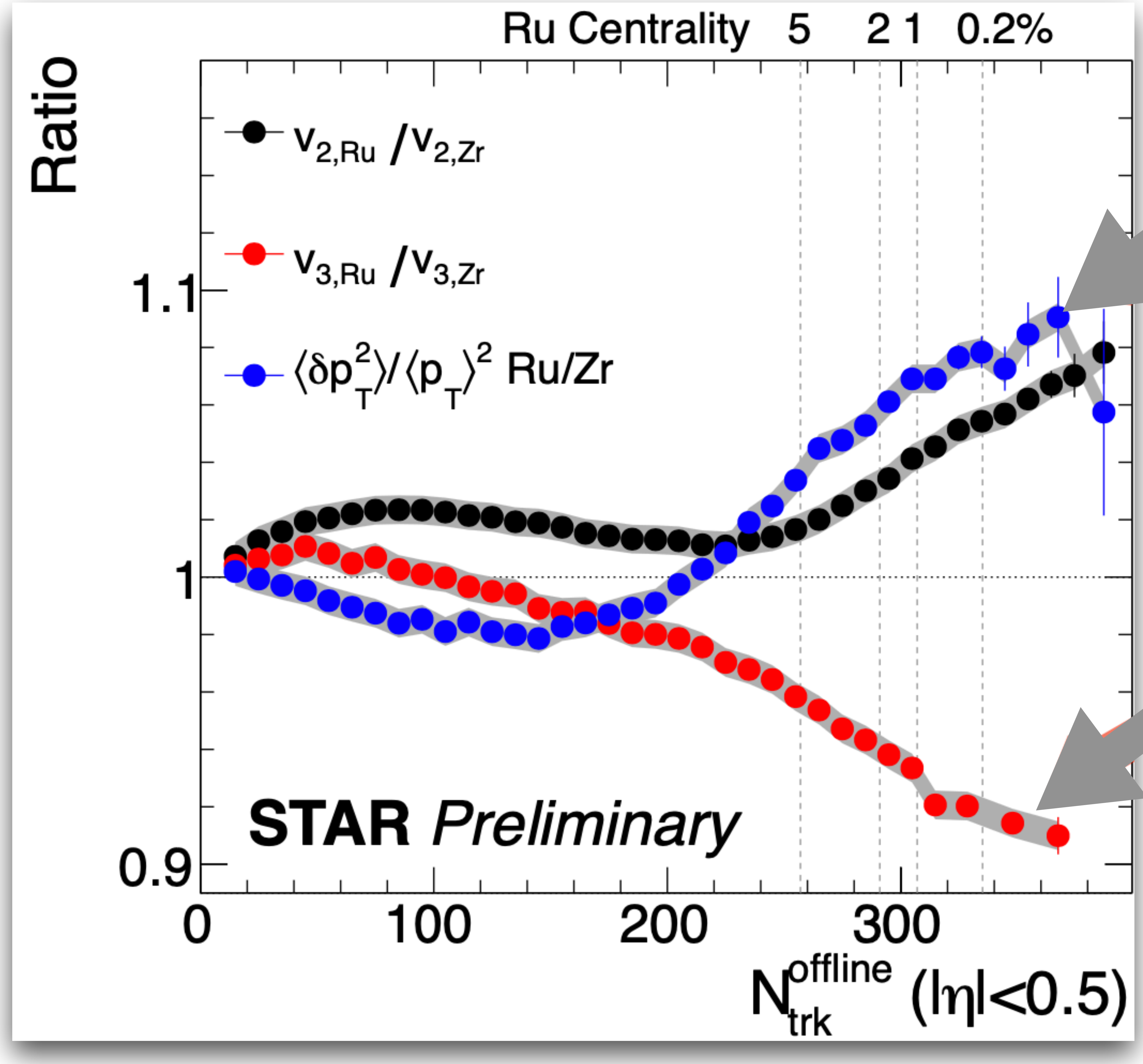
$$\epsilon_n \rightarrow v_n$$

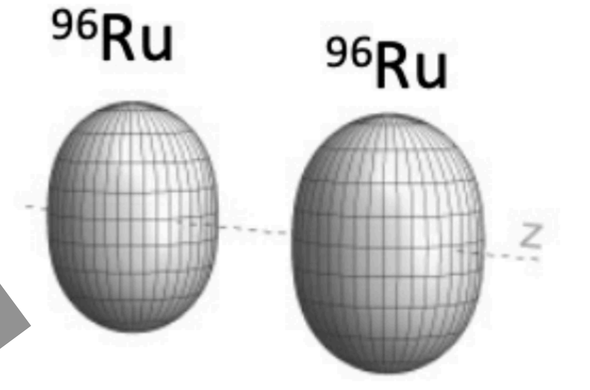
Harmonic flow

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

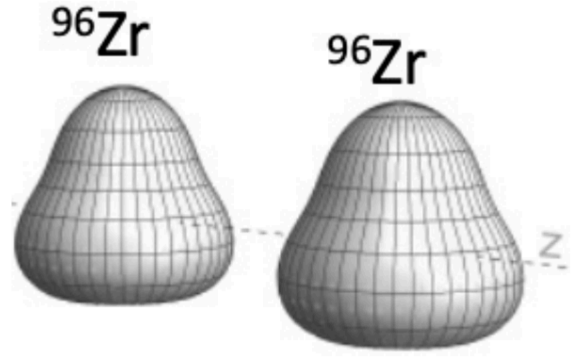


Can probe shape and size fluctuations via v_2, v_3, $\langle p_T \rangle$ variances





$\beta_2(Ru) > \beta_2(Zr)$



$\beta_3(Zr) > \beta_3(Ru)$

- Can constrain nuclear deformation parameters
- Estimate from AMPT: $\beta_{2,Ru} \sim 0.16 \pm 0.02$, $\beta_{3,Zr} \sim 0.20 \pm 0.02$

C. Zhang el. al., Phys. Rev. Lett. 128, 022301 (2022)

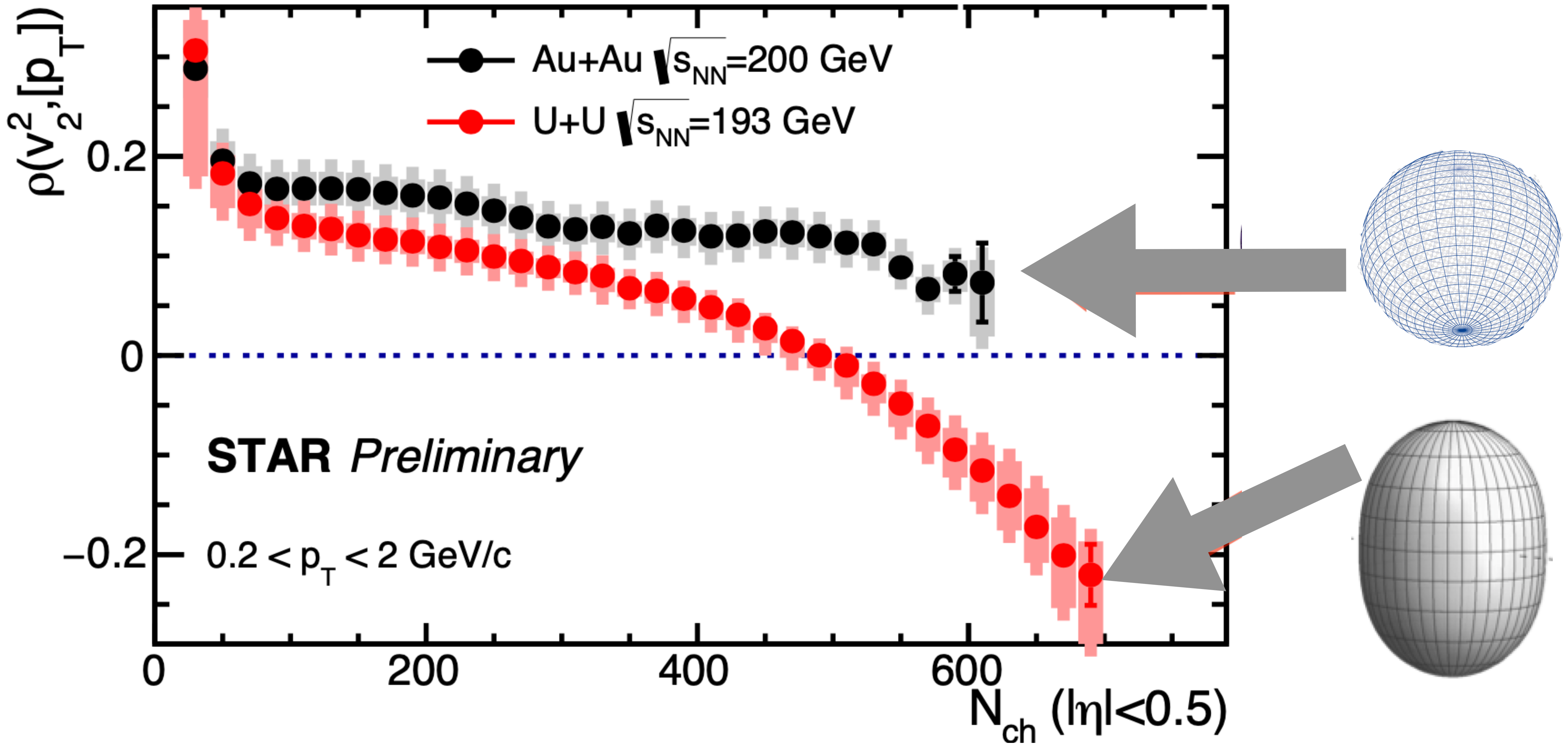
Flow momentum correlation

Pearson coefficients

Correlation between flow harmonics and transverse momentum

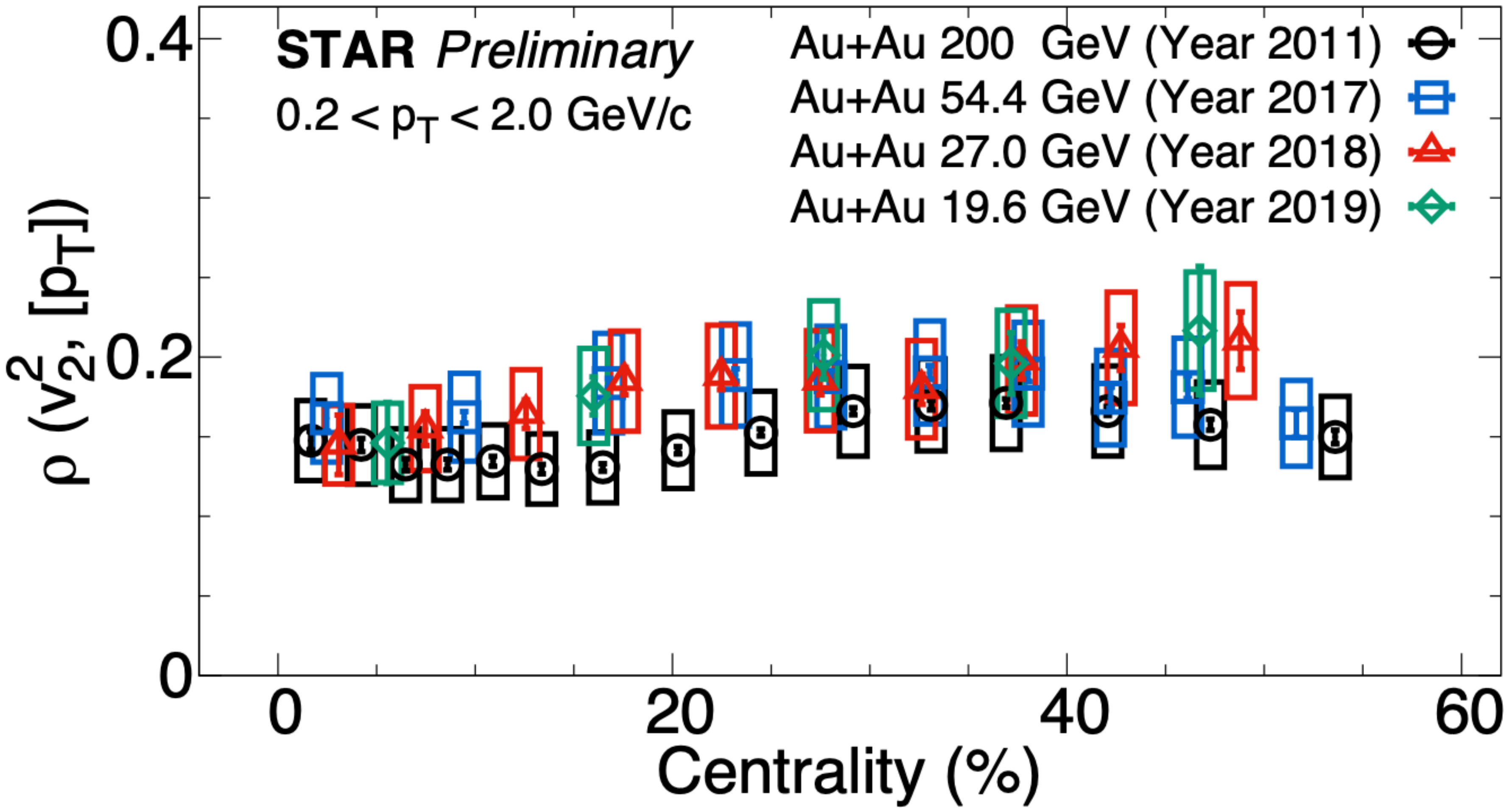
$$\rho(\mathrm{v}_\mathrm{n}^2, [\mathrm{p}_\mathrm{T}]) = \frac{\mathrm{cov}\,(\mathrm{v}_\mathrm{n}^2, [\mathrm{p}_\mathrm{T}])}{\mathrm{Var}(\mathrm{v}_\mathrm{n}^2)_\mathrm{dyn}\,\langle \delta \mathrm{p}_\mathrm{T} \delta \mathrm{p}_\mathrm{T} \rangle}$$

Can probe shape and size fluctuations, nuclear deformations



Estimate based on data and IP-Glasma + Hydro model comparison:

$\beta_{2,U} \sim 0.28 \pm 0.03$

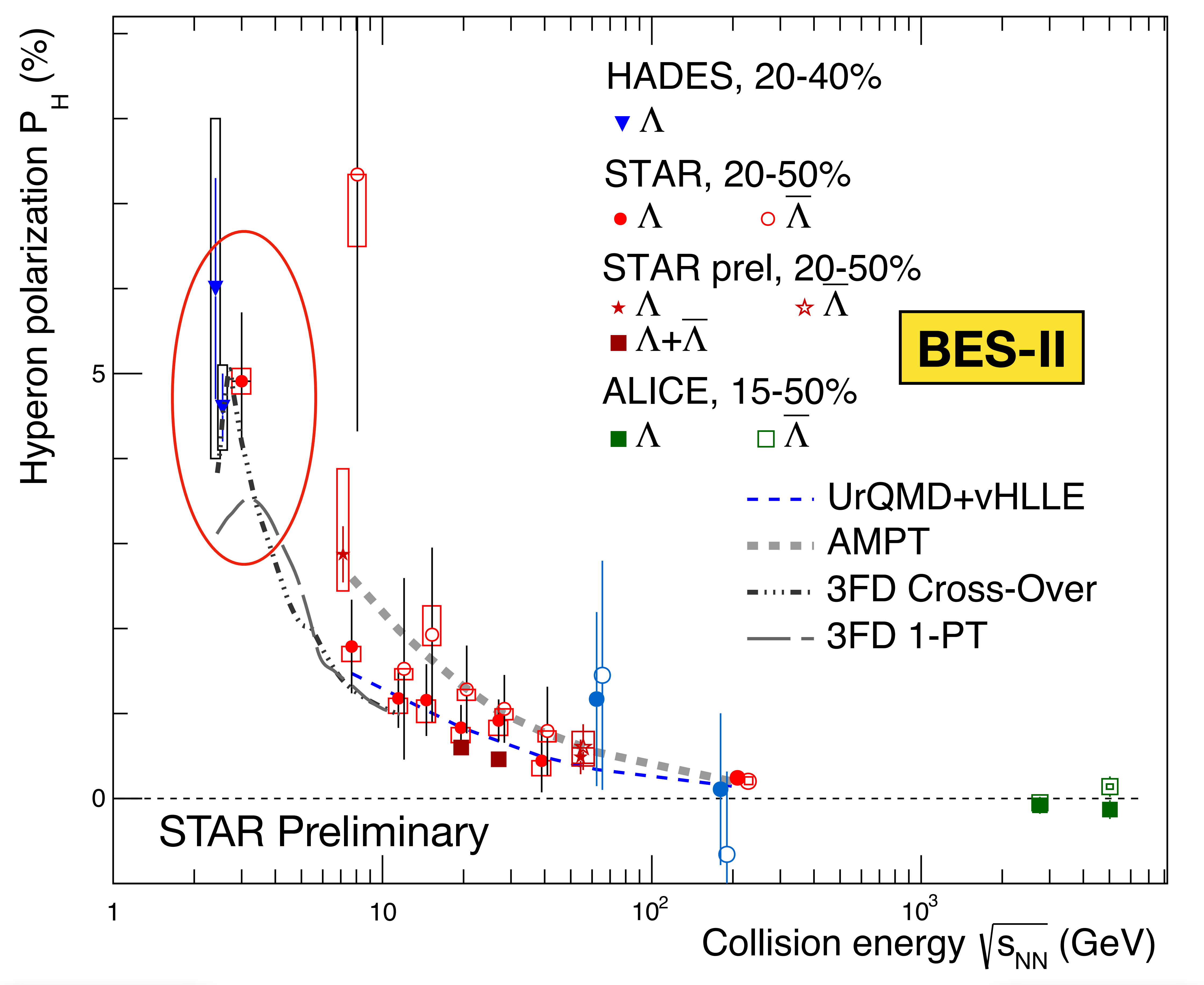


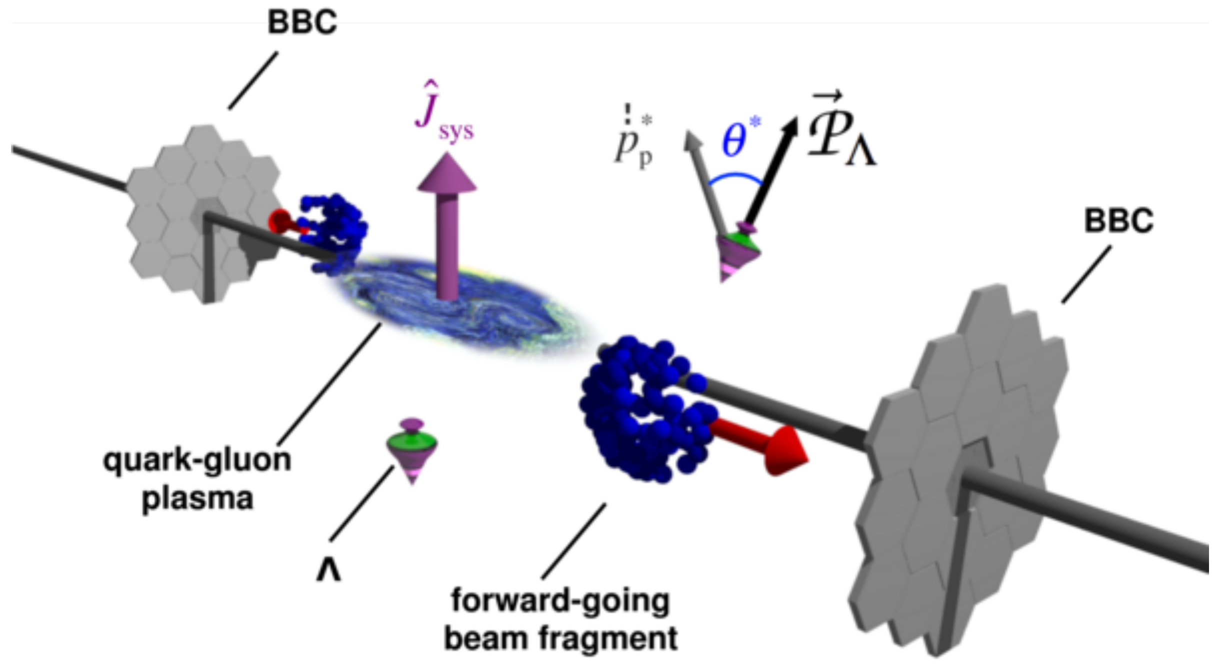
P. Bozek, Phys. Rev. C 93, 044908 (2016)
B. Schenke et. al., Phys. Rev. C 102, 034905 (2020)
G. Giacalone et. al., Phys. Rev. Lett. 128, 042301 (2022)

- Can constrain **nuclear shape and size**
- Sensitive to hydrodynamic evolution

Spin dynamics

Global spin polarization of Λ





$$P_\Lambda = \frac{8}{\pi \alpha_\Lambda} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

- Global Λ polarization increases monotonically with decreasing beam energy

Does the hadronic dominant matter retain more vorticity (?)

Where do we observe highest polarization?

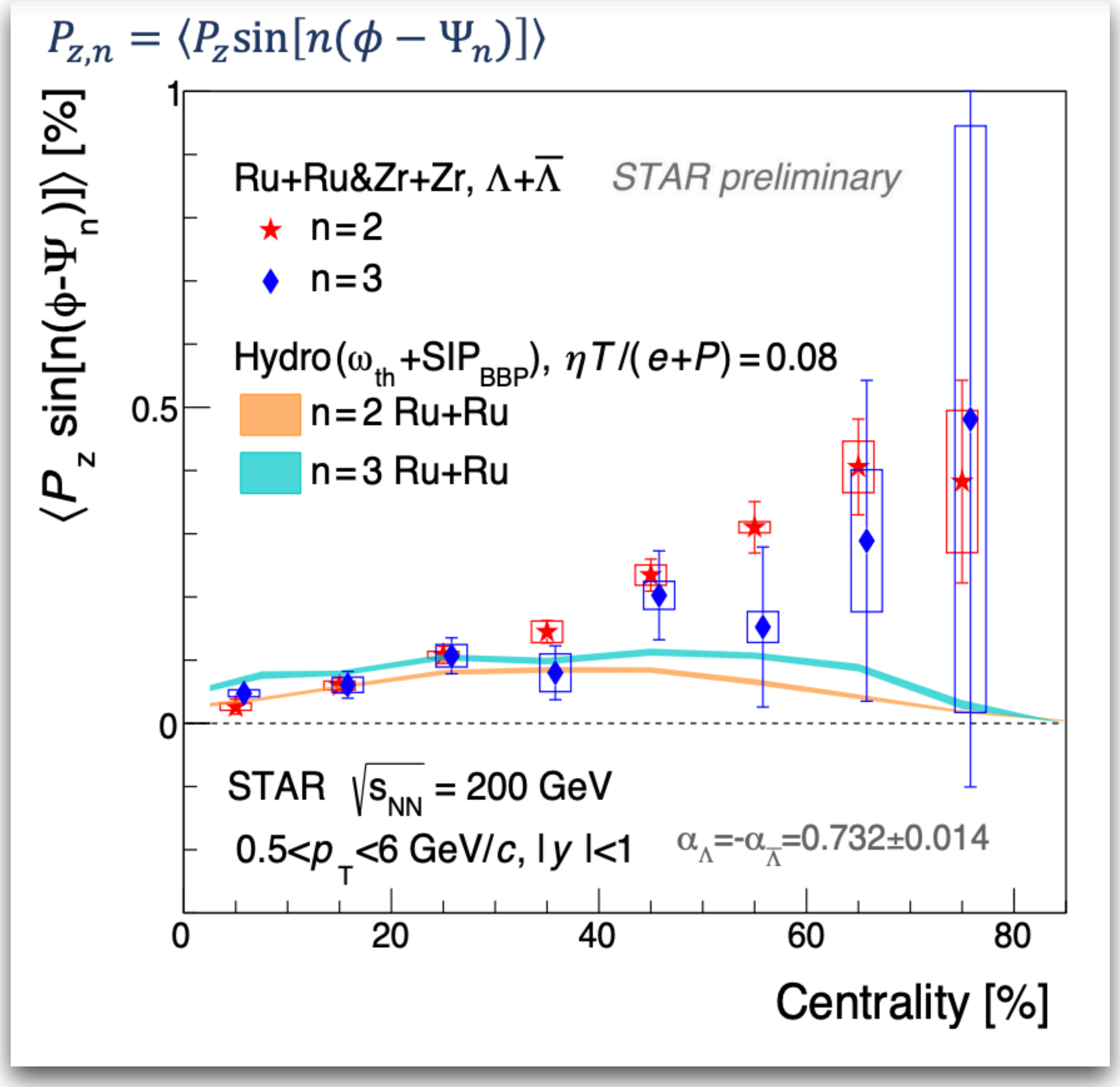
Hadronic dominant

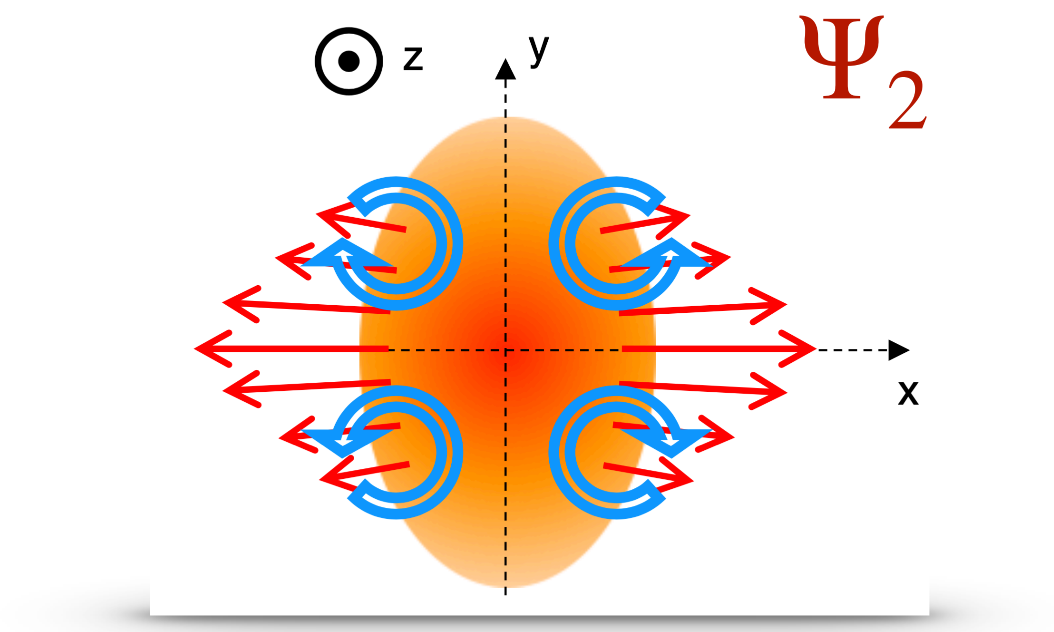
Partonic dominant

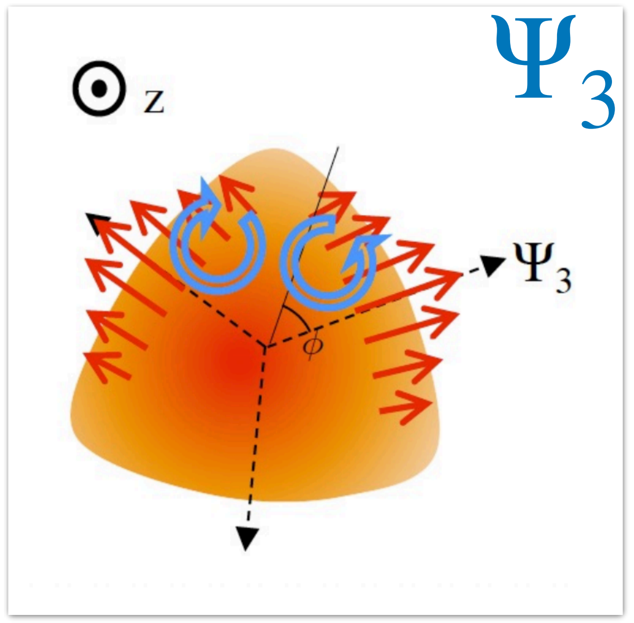
Expected, $P_\Lambda \sim 0$ at $\sqrt{s_{NN}} \sim 2m_N$

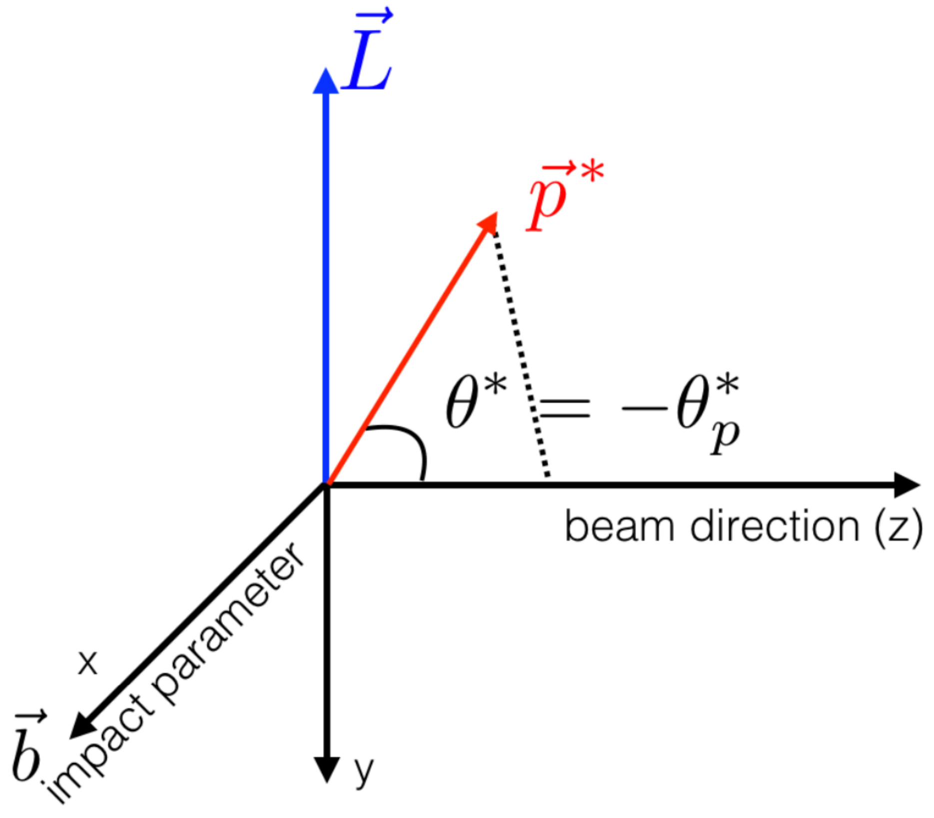
STAR: Phys. Rev. C 76, 024915 (2007); Nature 548, 62 (2017); Phys. Rev. C 101, 044611 (2020); Phys. Rev. C 104, 061901 (2021)
ALICE: Phys. Rev. C 101, 044611 (2020); HADES: Phys. Lett. B 137506 (2022)

Local spin polarization of Λ









$$P_z = \frac{3}{\alpha_H}\langle \cos\theta^*_{\mathrm{p}} \rangle$$

- *Complex vortical structures* emerged with respect to second and third order event planes

$P_z(\Psi_3) \sim P_z(\Psi_2)$

STAR: Phys. Rev. Lett. 123, 132301 (2019)
F. Becattini et. al., Phys. Rev. Lett. 120, 012302 (2018)

Baryonic Spin Hall effect (SHE)

Condensed matter

$$\mathrm{s} \propto \pm\, \mathrm{p} \times \mathrm{E}$$

Heavy Ion Collisions

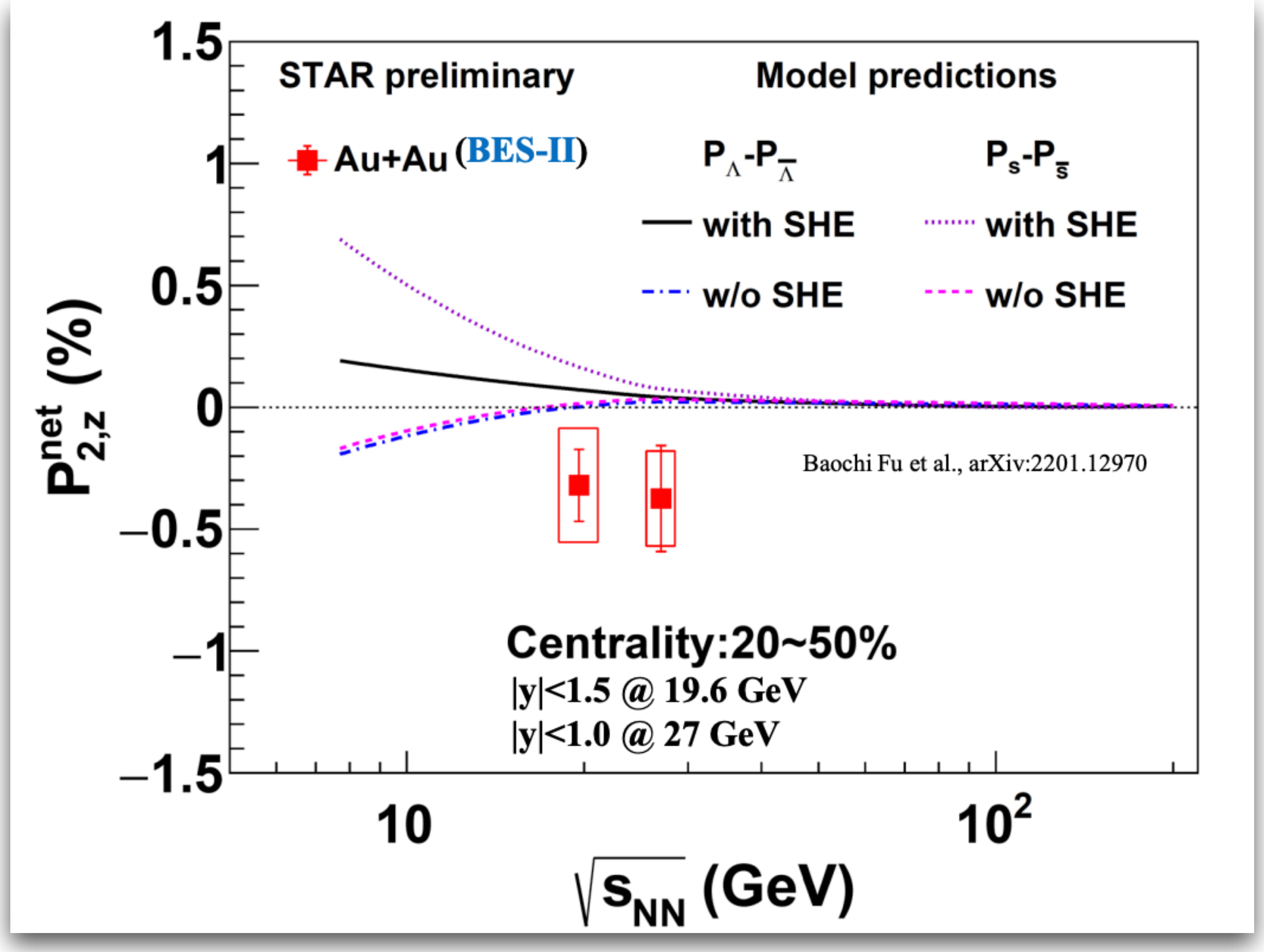
$$\mathrm{s} \propto \pm\, \mathrm{p} \times \nabla \mu_\mathrm{B}$$

Predicted Spin Hall type effect driven by gradient of baryonic density ($\nabla \mu_B$)

Can be accessed by splitting in local polarization of Λ and $\overline{\Lambda}$: $\mathrm{P}_\mathrm{z}^{\Lambda} - \mathrm{P}_\mathrm{z}^{\overline{\Lambda}}$

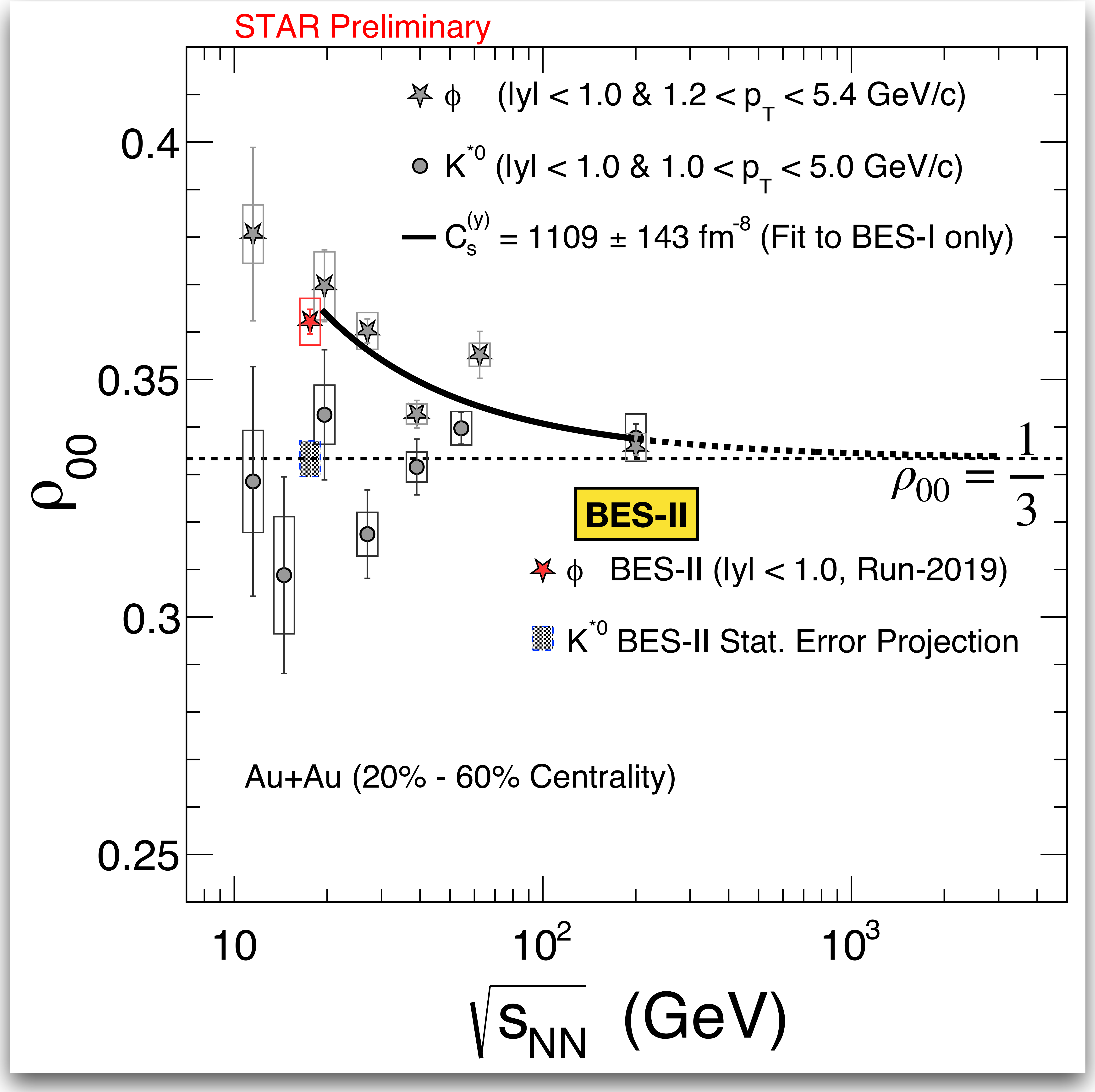
Fu et., al., arXiv: 2201.12970

Polarization ~ vorticity $\bigoplus$ ∇T $\bigoplus$ Shear $\bigoplus$ $\nabla \mu_B$



$\mathrm{P}_\mathrm{z}^{\Lambda} - \mathrm{P}_\mathrm{z}^{\overline{\Lambda}}$ ~< 0 : No indication of baryonic SHE

Global spin alignment (ρ_{00}) of ϕ and K^{*0}



STAR: **Nature**, 614, 244-248, (2023)
https://www.nature.com/articles/s41586-022-05557-5

$$\frac{dN}{d\cos\theta^*} = N_0\left((1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right)$$

- Surprisingly, ϕ ρ_{00} >> 1/3 but K^{*0} ρ_{00} ~ 1/3
- Can not be explained by *conventional* polarization mechanisms
- ϕ meson results can be accommodated by a model invoking a strong force field of vector meson

$$\rho_{00}(\phi) \approx \frac{1}{3} + \overbrace{c_\Lambda + c_\epsilon + c_E}^{\sim 10^{-4}-10^{-5}} + c_\phi$$

Sheng el. al., Phys Rev D 101, 096005 (2020)
Sheng el. al., Phys Rev D 102, 056013 (2020)

Summary

- **Collective motion:** Precision flow measurement from BES-II is ongoing; Charge dependent v_1 results indicate EM induced effects; Probing partonic collectivity using NCQ scaling of v_n

- **Flow fluctuation:** new decorrelation and flow-momentum correlation measurements provide new constraints on nuclear shape and size fluctuations; Provide constraints on initial state and hydrodynamic models

- **Spin polarization:** Complex vortical patterns emerged for Λ; Surprising (and puzzling) signal of spin alignment of vector mesons

Thank you for your attention