"Insights" on baryon dynamics from recent measurements on directed flow and polarization

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Outline

- Motivation
- Experimental results:

1. *Directed flow* of identified particles (baryons)

   (Probe baryon dynamics and strong electromagnetic field)

3. *Spin polarization* of hyperons (baryons)

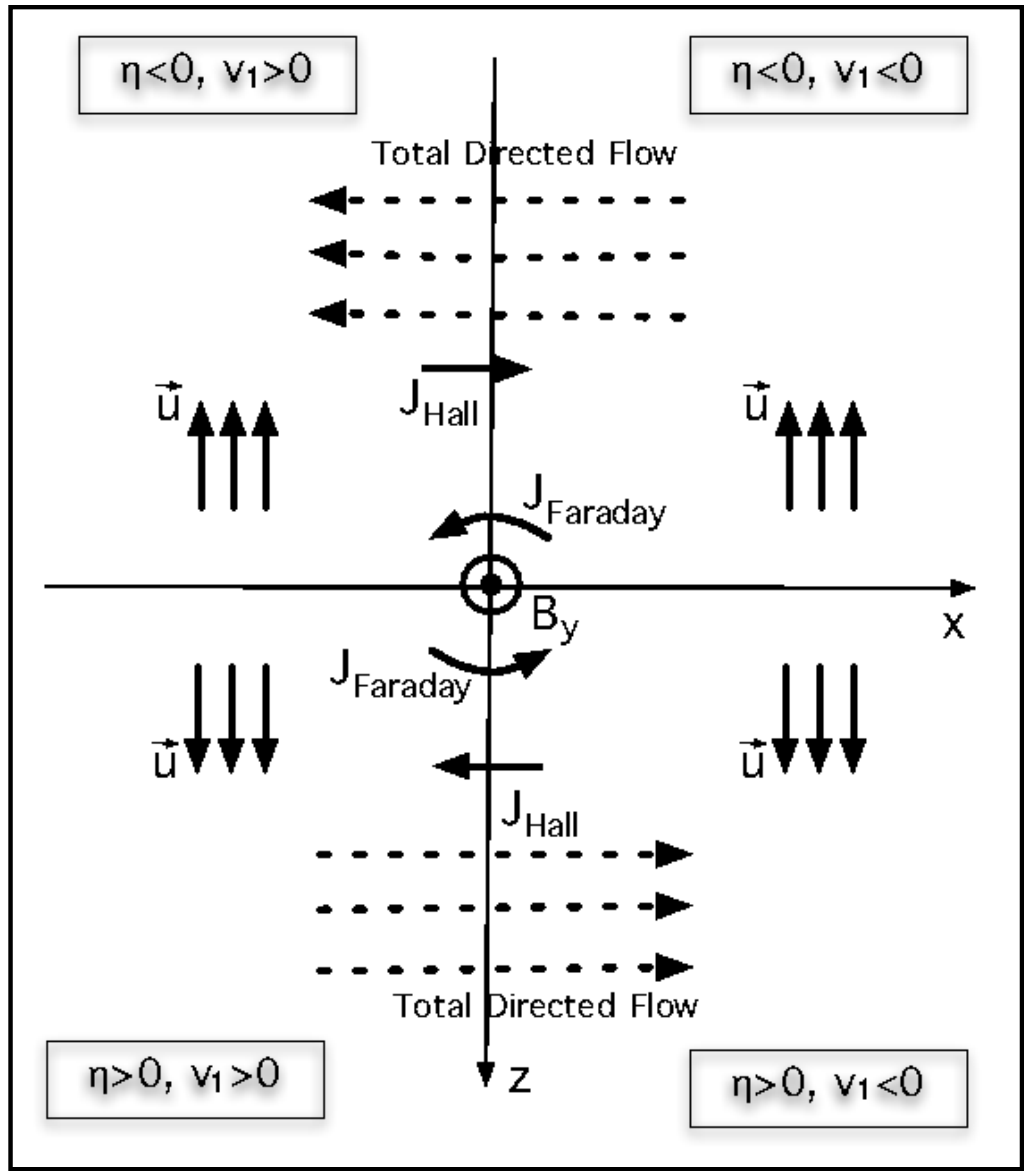
   (Probe baryonic Spin Hall effect bSHE)

- Summary

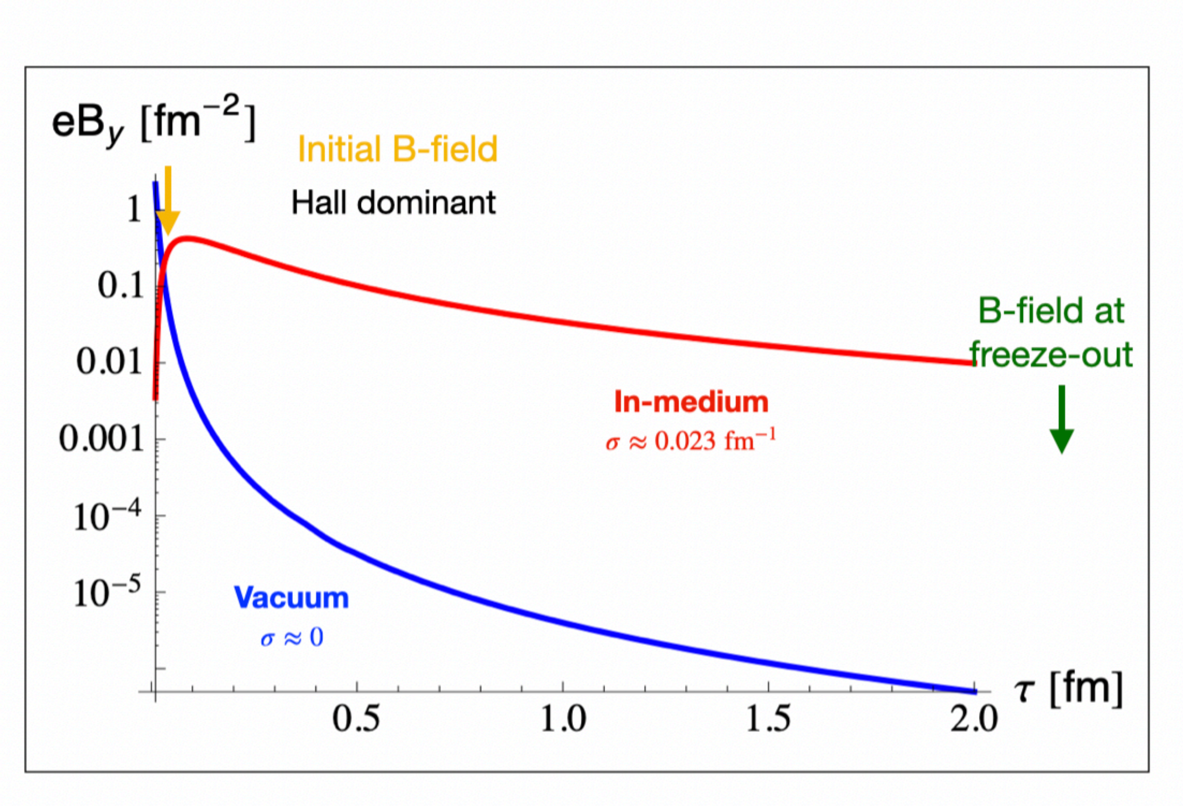
Gursoy et al, Phys Rev C 89, 054905 (2014)

Motivation

Directed flow $v_1 \sim \langle \cos(\phi - \Psi_R) \rangle$



- The moving spectators can produce enormously large **B** field (eB ~10^{18} G)
- There could be three competitive effects
- Hall effect: $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$
  Lorentz force exerts a sideways push on charged particles
  In opposite directions for opposite particles
  (along -ve X-direction in +ve rapidity and vice-versa)
- Faraday effect: $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
  Time dependent **B** field generates a large **E** field
  Induced Faraday current will oppose the drift due to **B** field
- Coulomb effect:
  Coulomb field of the charged spectators



- **Imprints of EM field effects**
- Hall: positive Δv_1
- Faraday: negative Δv_1
- Coulomb: negative Δv_1

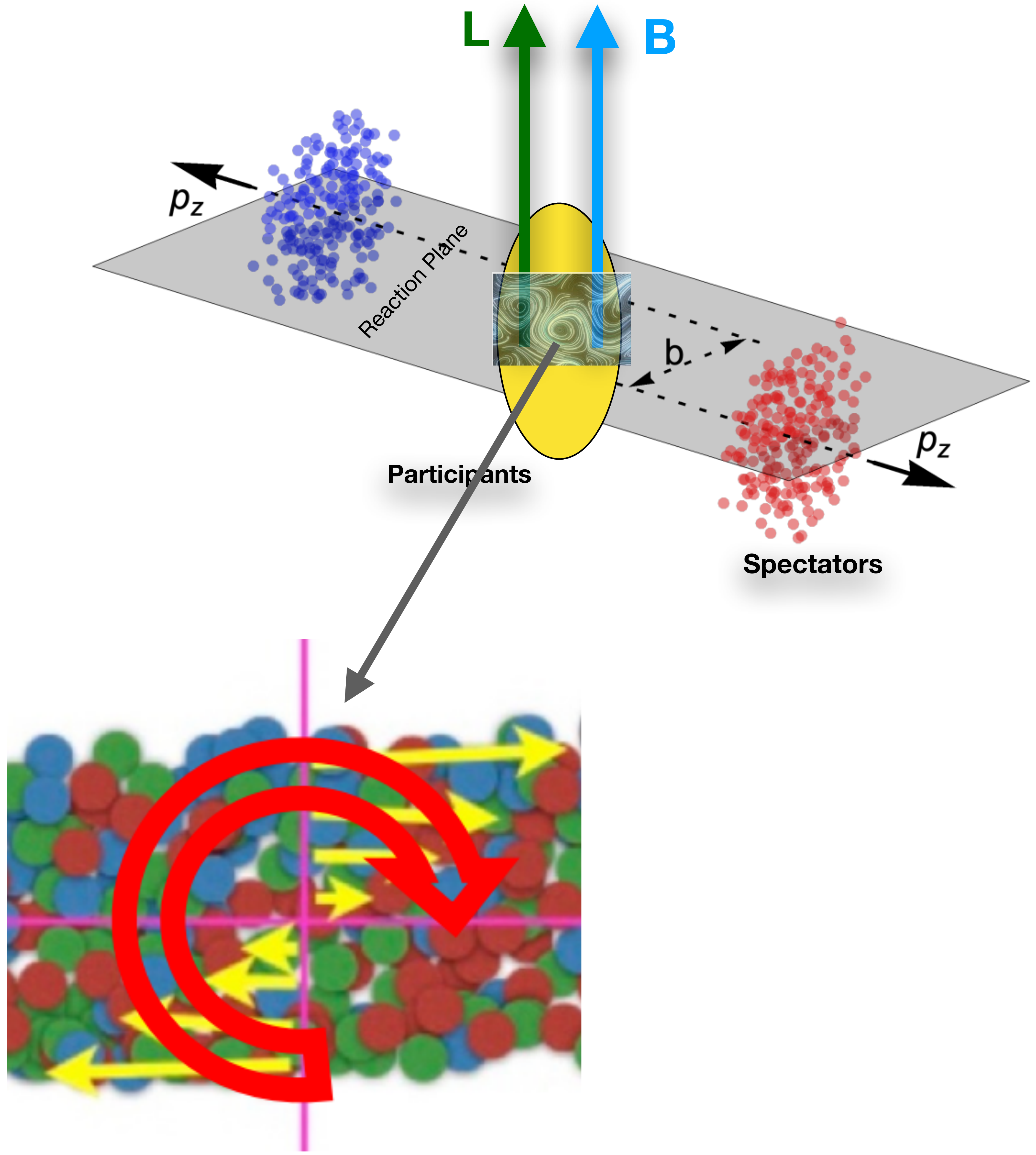
- Δv_1 sensitive to *QGP conductivity (σ)*

Observable

$$\Delta v_1 \sim v_1(h^+) - v_1(h^-)$$

- **Non-EM field effects**
- Transport: $\Delta v_1^{\dagger} \neq 0$
- ....

Motivation



Vorticity generation

In non-central heavy-ion collisions

- A **large orbital angular momentum** (OAM) imparted into the system

$$L = r \times p \sim bA\sqrt{s_{NN}} \sim 10^4\ \hbar$$

- Gradient of longitudinal flow velocity → vorticity along orbital angular momentum

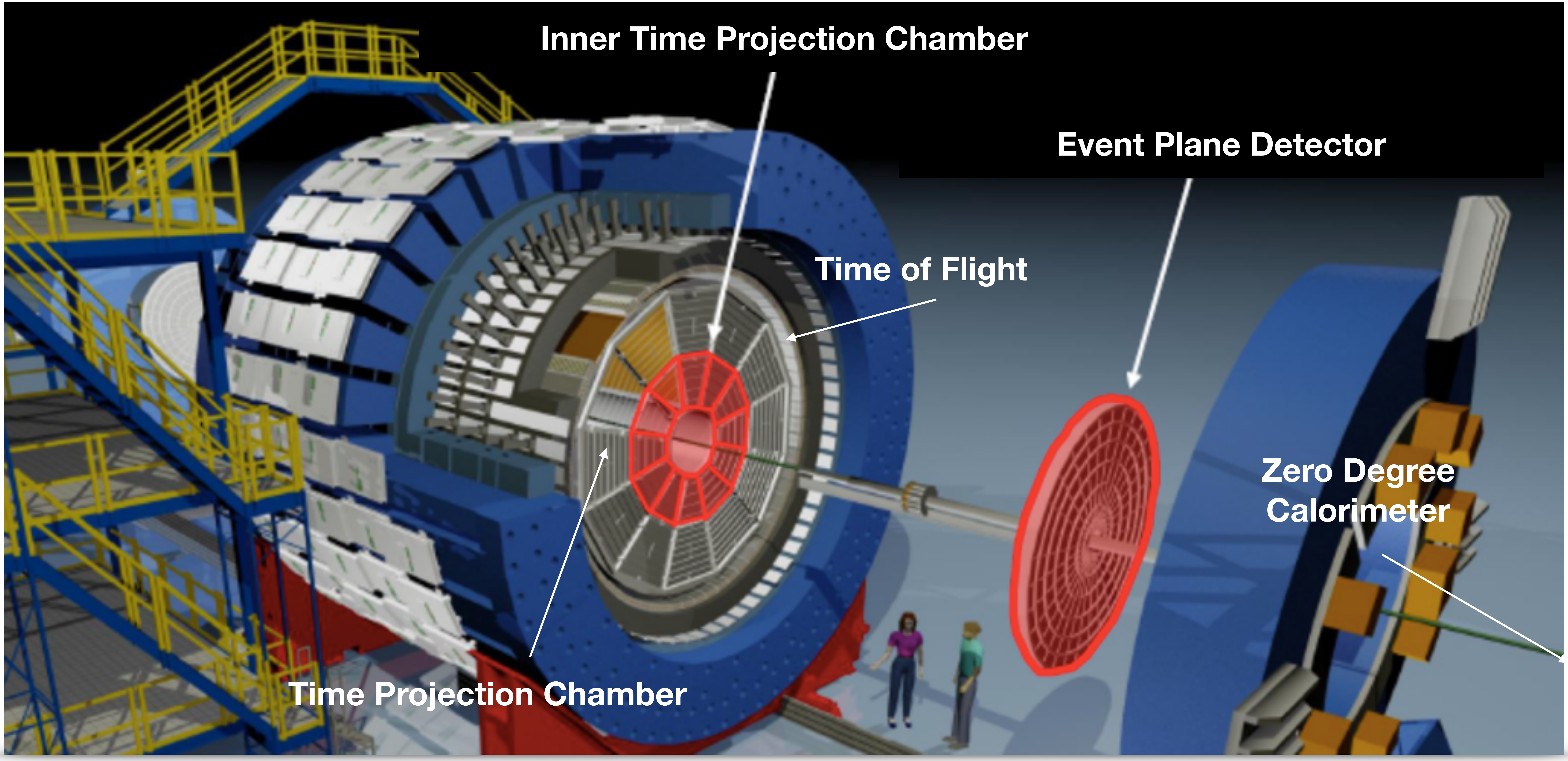
$$\omega = \frac{1}{2}\nabla \times v \qquad \omega_y = \frac{1}{2}(\nabla \times v)_y \approx \frac{1}{2}\frac{dv_z}{dy}$$

- Polarize quarks and anti-quarks due to “spin-orbit” interaction.

Liang et. al., Phys Rev Lett B 94, 102301 (2005)
Jiang et al, Phys Rev C 94, 044910 (2016)

Polarization are sensitive to various gradients of the medium

STAR Detector

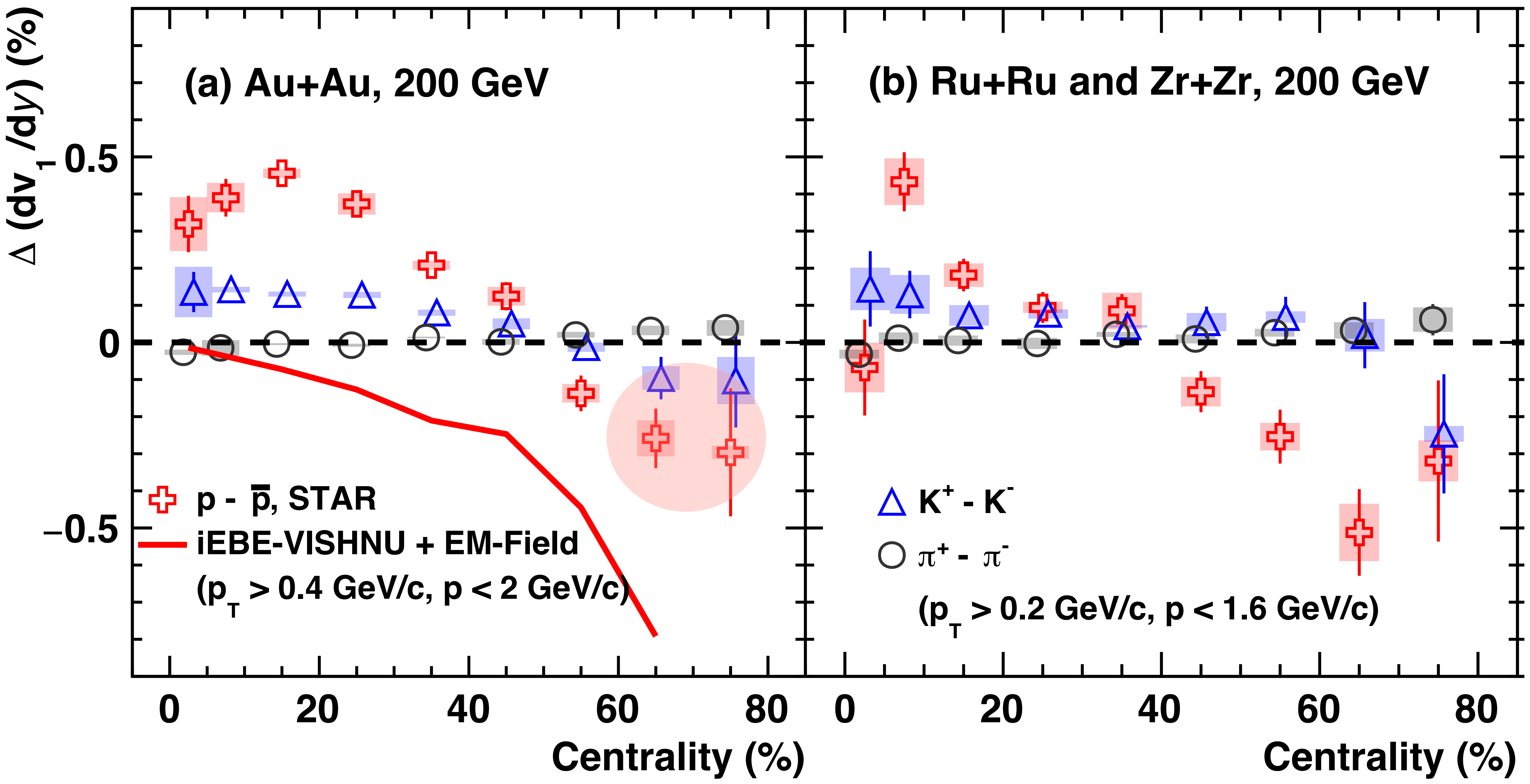


- Uniform acceptance, full azimuthal coverage, excellent PID capability
- TPC: tracking, centrality and event plane
- EPD, ZDC, BBC: event plane (polarization axis, perpendicular to event plane)
- TPC+TOF: particle identification

Directed flow of identified particles

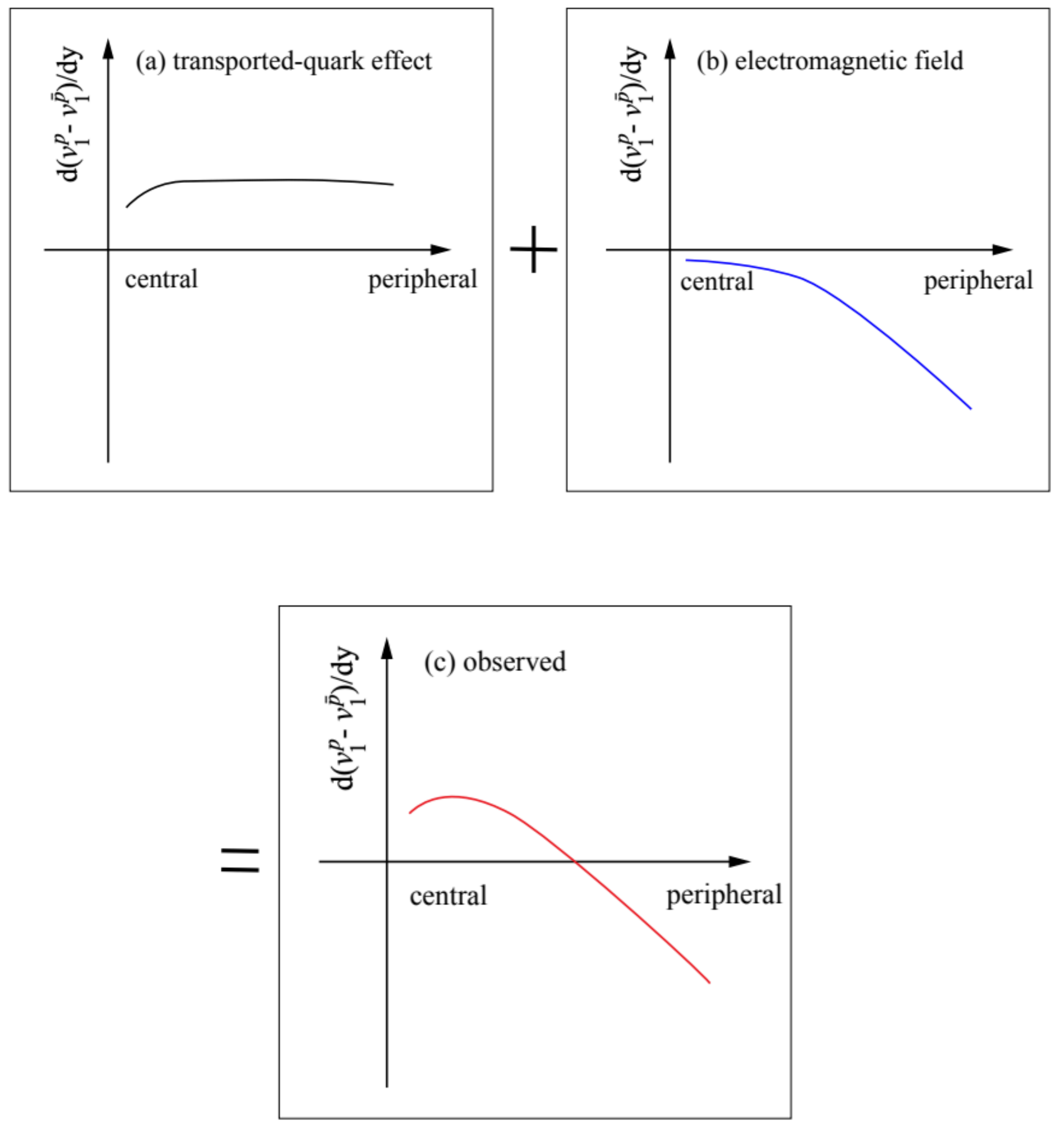
Charge dependent directed flow

Observation $\Delta v_1 : h^+ - h^-$



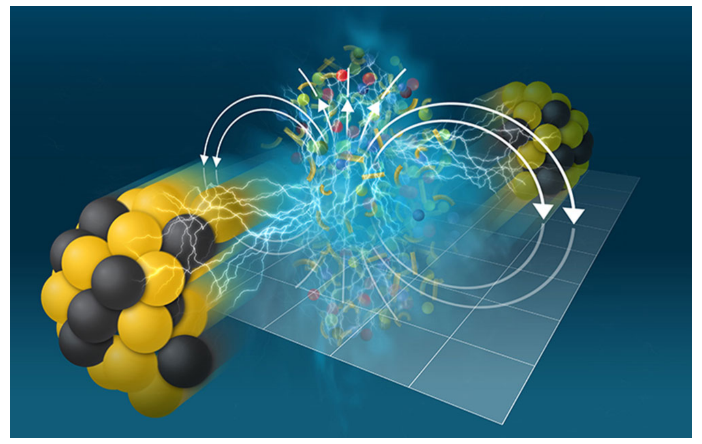
STAR, Phys Rev X 14, 011028 (2024)

Expectation



- For protons and kaons: sign change in Δv_1 in peripheral collisions
  (Negative Δv_1 consistent with Faraday+Coulomb dominates over Hall effect)
- For pions: Δv_1 ~ 0 (large uncertainty)

Results featured in APS Phys



FOCUS

Colossal Magnetic Field Detected in Nuclear Matter

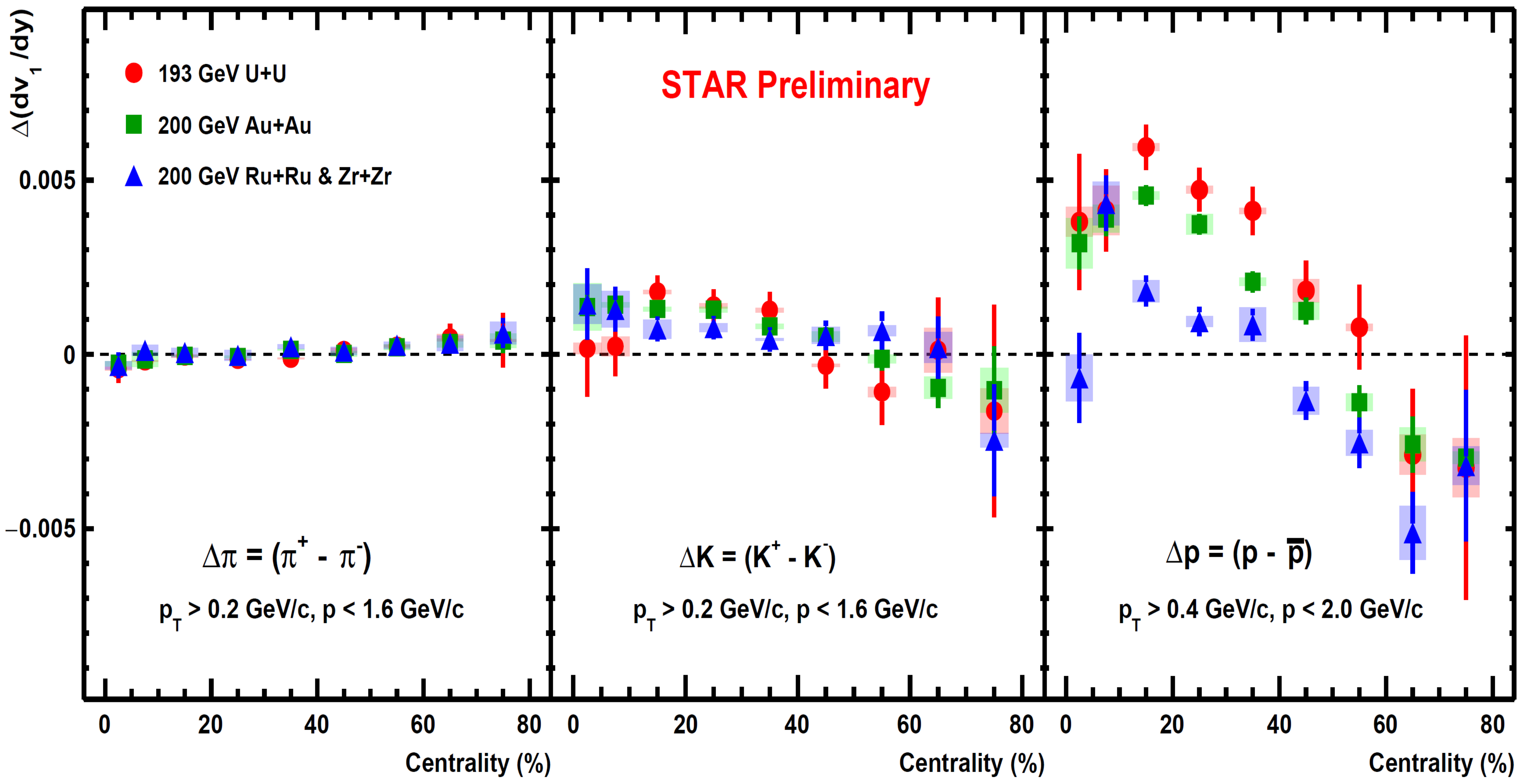
February 23, 2024 • *Physics* 17, 31

Collisions of heavy ions briefly produced a magnetic field 10^{18} times stronger than Earth's, and it left observable effects.

Strongest possible pulse of an electromagnetic field in a laboratory setting during heavy-ion collisions

Charge dependent directed flow: system size dependence

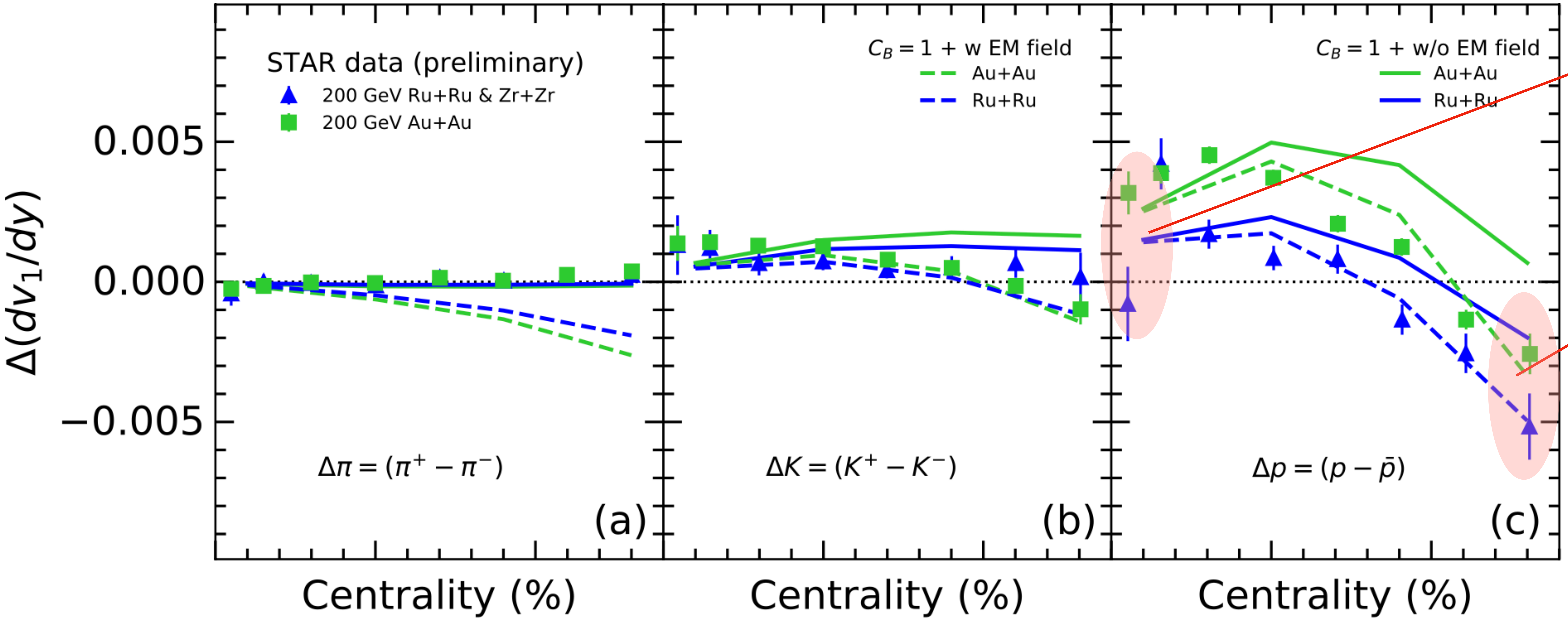
Observation $\Delta v_1 : h^+ - h^-$



- pion's/kaon's Δv_1: no obvious system size dependence across centrality
- proton's Δv_1: system size dependence across centrality

in different systems several factors to be considered:
- strength and lifetime of EM-field
- QGP lifetime and conductivity
- transport
- …

Charge dependent directed flow: with hydro + EM



Splitting in most-central collisions
Can be related to baryon transport

Proton splitting in mid-central and peripheral collisions can be interplay between baryon transport and electro-magnetic field

Parida et al, 2305.08806

- <u>For proton's</u>
- **Baryon transport + EM field** *with QGP conductivity* $\sigma \sim 0.023$ fm^{-1} required to capture *system size dependence* across centrality

- Central: baryon transport
- Peripheral: EM-field

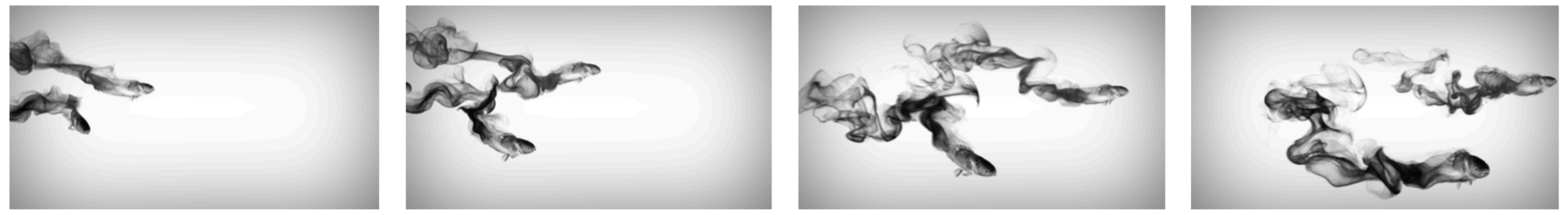


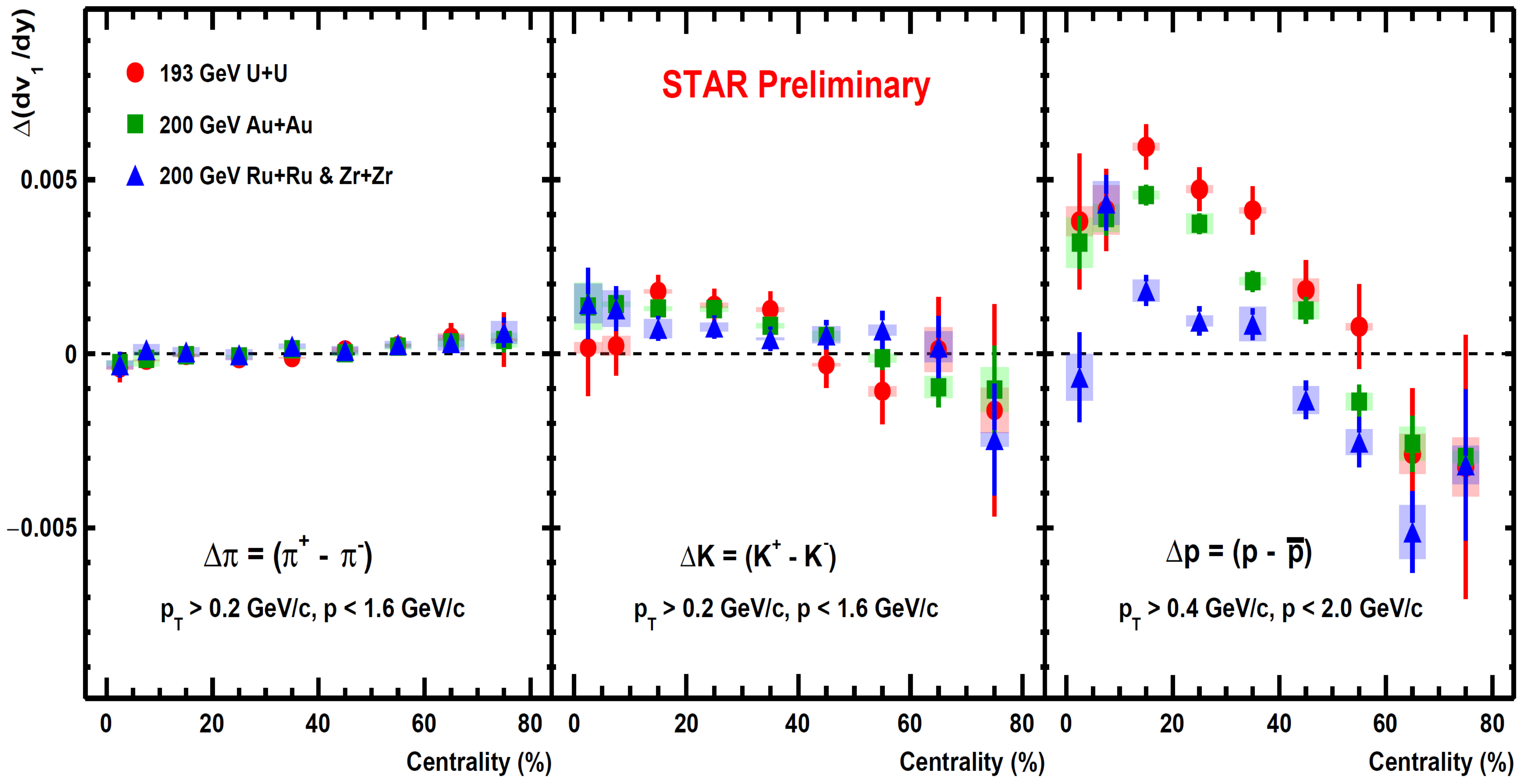
Figure 1: *An example of ink-made fish animation created with our method. Two fish are swimming in water freely, and the fishtails swing in high speed. Ink flows emit from the fishtails at the same time, then the attractive dynamic ink diffusion effects can be observed.*

https://doi.org/10.1145/2087756.20877

- In HIC, **Ink** (baryon) density is changing → $(\nabla\mu_B)$
- How the ink (baryon) density changing in transverse and longitudinal plane?

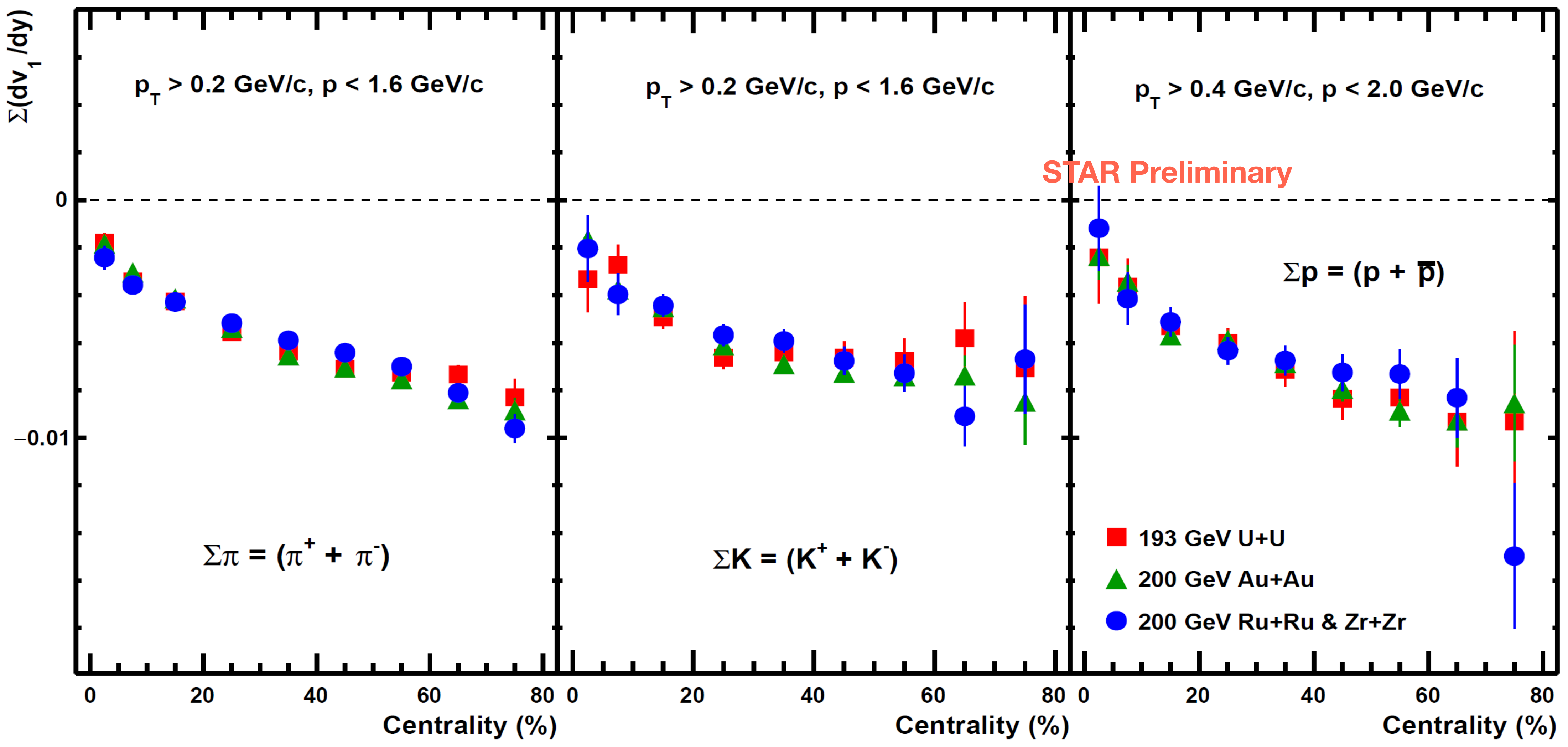
Next Talk by Tribhuban Parida

Charge dependent directed flow: system-size dependence



Net-baryon + EM

- **Difference** Δv_1: $h^+ - h^-$
- pions & kaons: U+U ~ Au+Au ~ Isobar
- protons: U+U < Au+Au < Isobar



NO effect from Net-baryon + EM

- **Sum** Σv_1 : $h^+ + h^-$
- pions & kaons: U+U ~ Au+Au ~ Isobar
- protons: U+U ~ Au+Au ~ Isobar

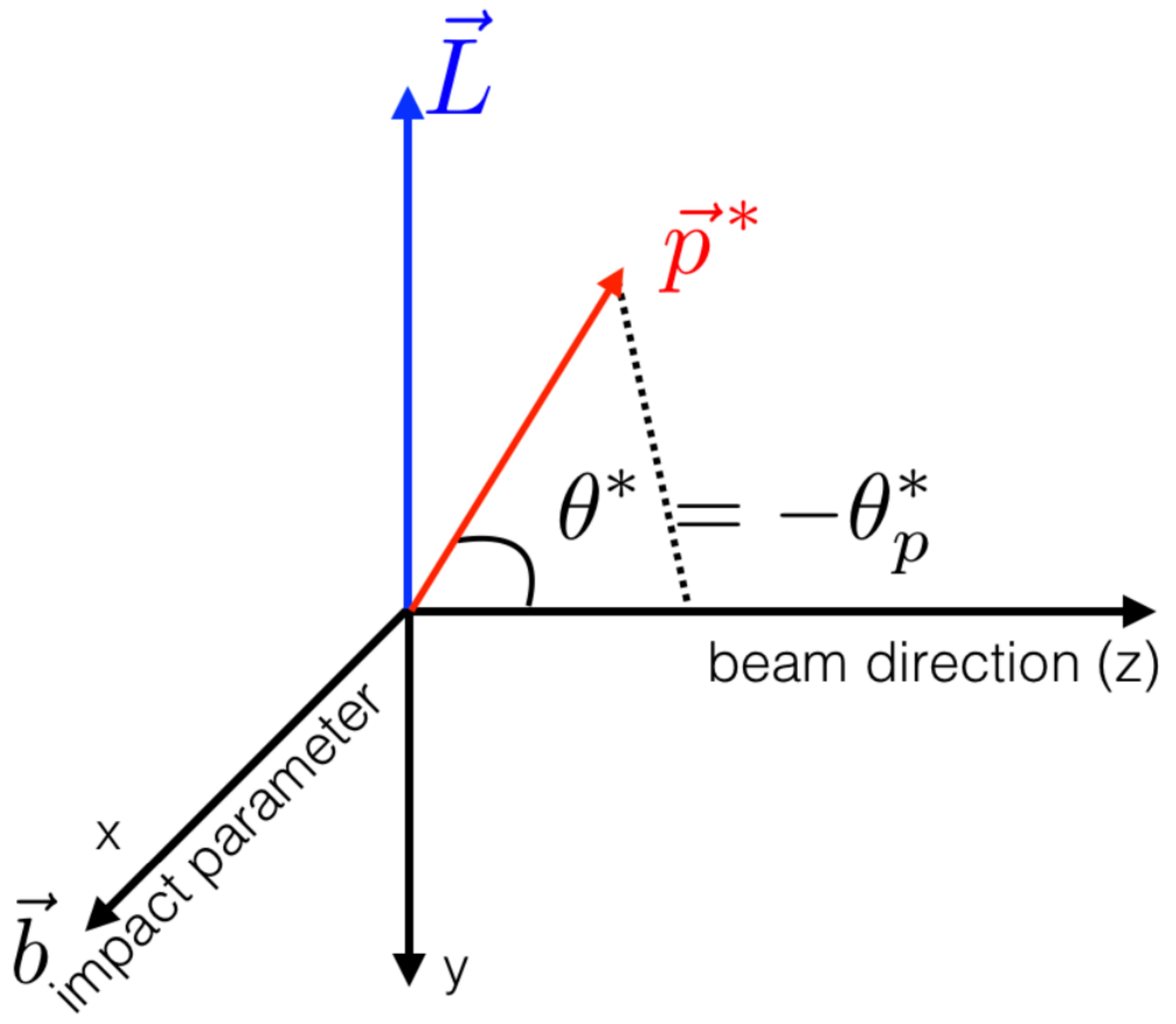
Baryon transport + EM-field → can capture this trend

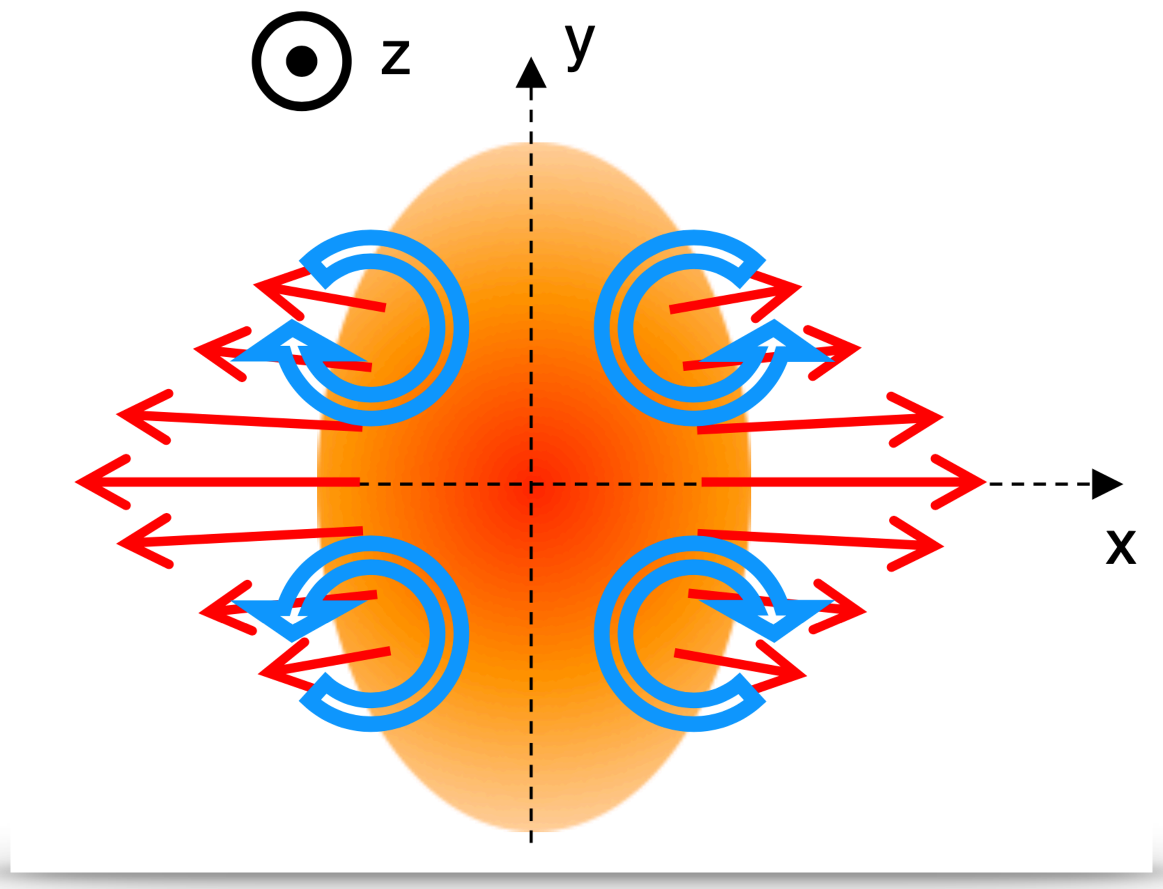
Farhan Taseer, SQM 2024 (STAR)

Next Talk by Tribhuban Parida

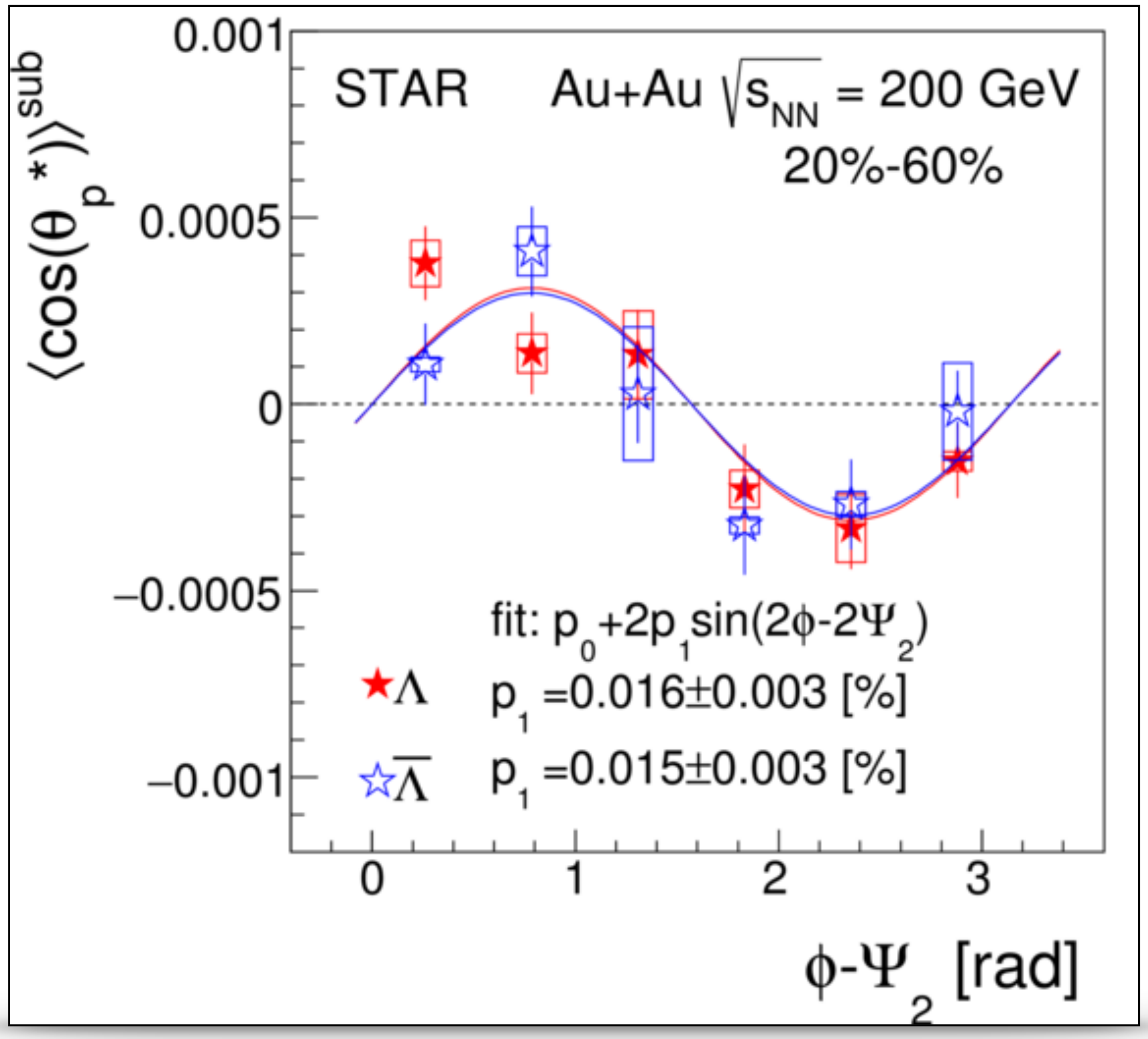
Local spin polarization of hyperons

Measurement of local spin polarization of hyperons





$$\omega = \frac{1}{2}\nabla \times v$$



STAR: Phys Rev Lett 123, 132301 (2019)

Longitudinal polarization

- Elliptic flow is expected to generate a longitudinal component of polarization (P_z)
- $P_z = \frac{3}{\alpha_H}\langle\cos\theta_p^*\rangle$
- Local polarization is expected to be sensitive to space and time variation of vorticity and convolute with flow driven space-momentum correlation

Becattini, Karpenko, Phys Rev Lett 120, 012302 (2018)

STAR: Phys Rev Lett 123, 132301 (2019)

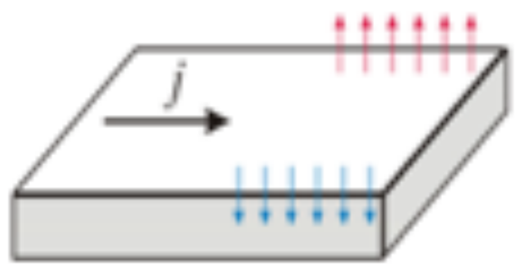
Baryonic Spin Hall effect (bSHE)

$$\omega = \frac{1}{2}\nabla \times v$$

Condensed matter

$$s \propto \pm p \times E$$

splitting in spin on opposite boundaries

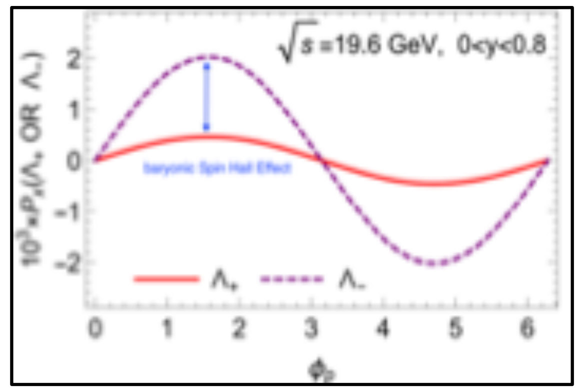


Heavy Ion Collisions

$$s \propto \pm p \times \nabla \mu_B$$

splitting in local polarization of Λ and $\overline{\Lambda}$: $P_z^{\Lambda} - P_z^{\overline{\Lambda}}$

"spin-orbit"

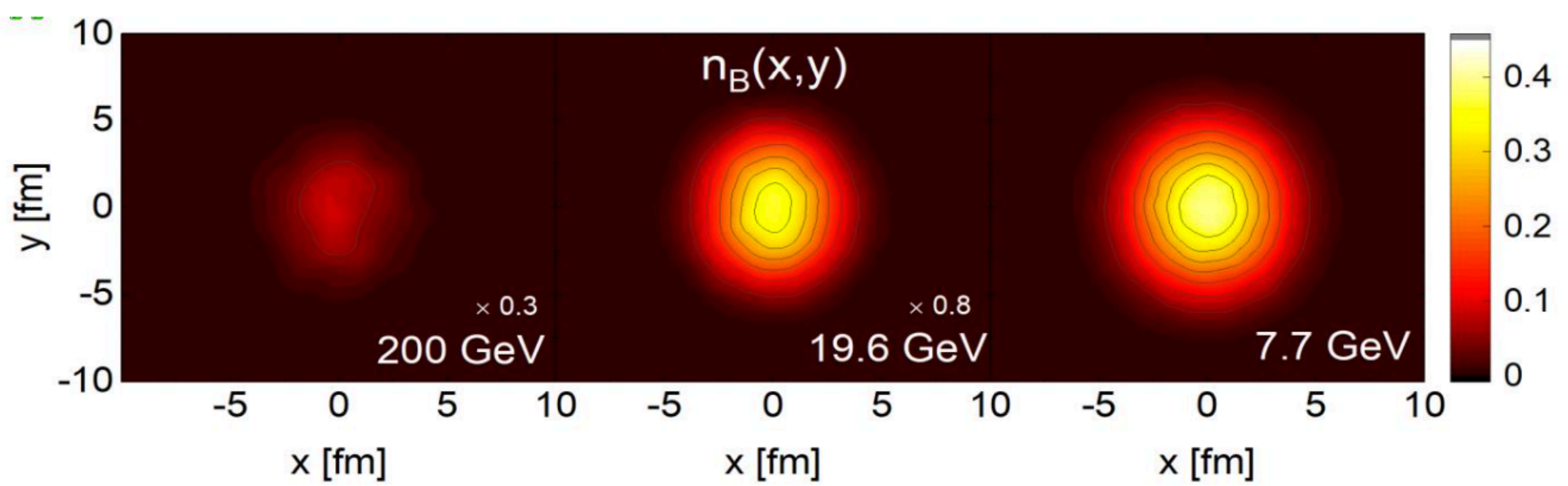


Predicted Spin Hall type effect driven by gradient of baryonic density ($\nabla \mu_B$)

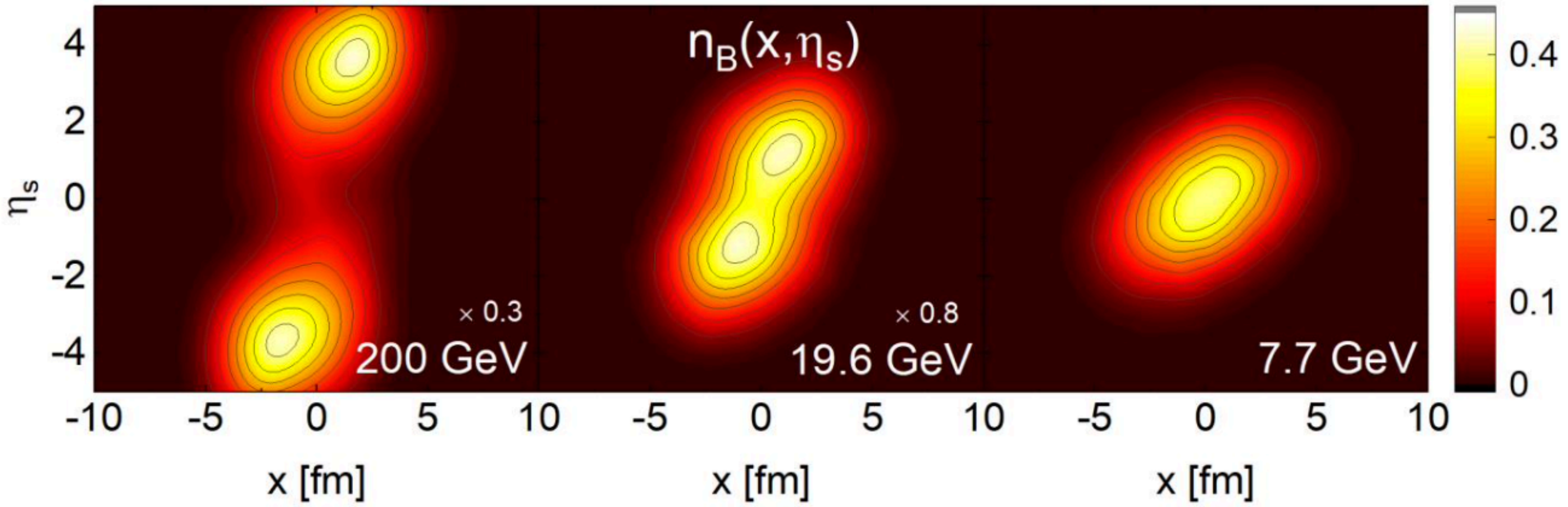
Polarization $\sim$ ∇T $\oplus$ Shear $\oplus$ $\nabla \mu_B$

Fu et., al., Phys Rev Lett 127, 142301 (2021)
Liu and Yin, Phys Rev D 104, 054043 (2021)

Transverse-plane (x, y)



Longitudinal-plane (x, η)



How do we visualize bSHE?

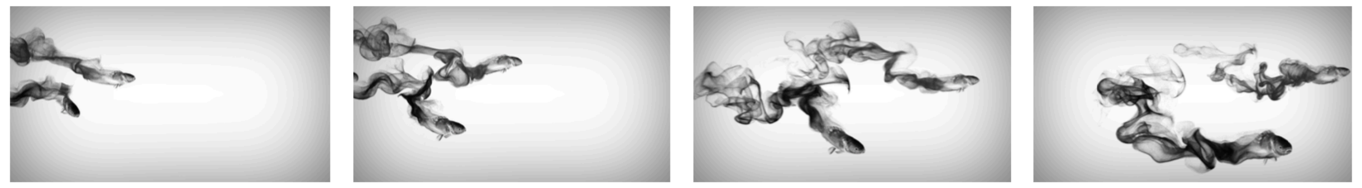


Figure 1: *An example of ink-made fish animation created with our method. Two fish are swimming in water freely, and the fishtails swing in high speed. Ink flows emit from the fishtails at the same time, then the attractive dynamic ink diffusion effects can be observed.*

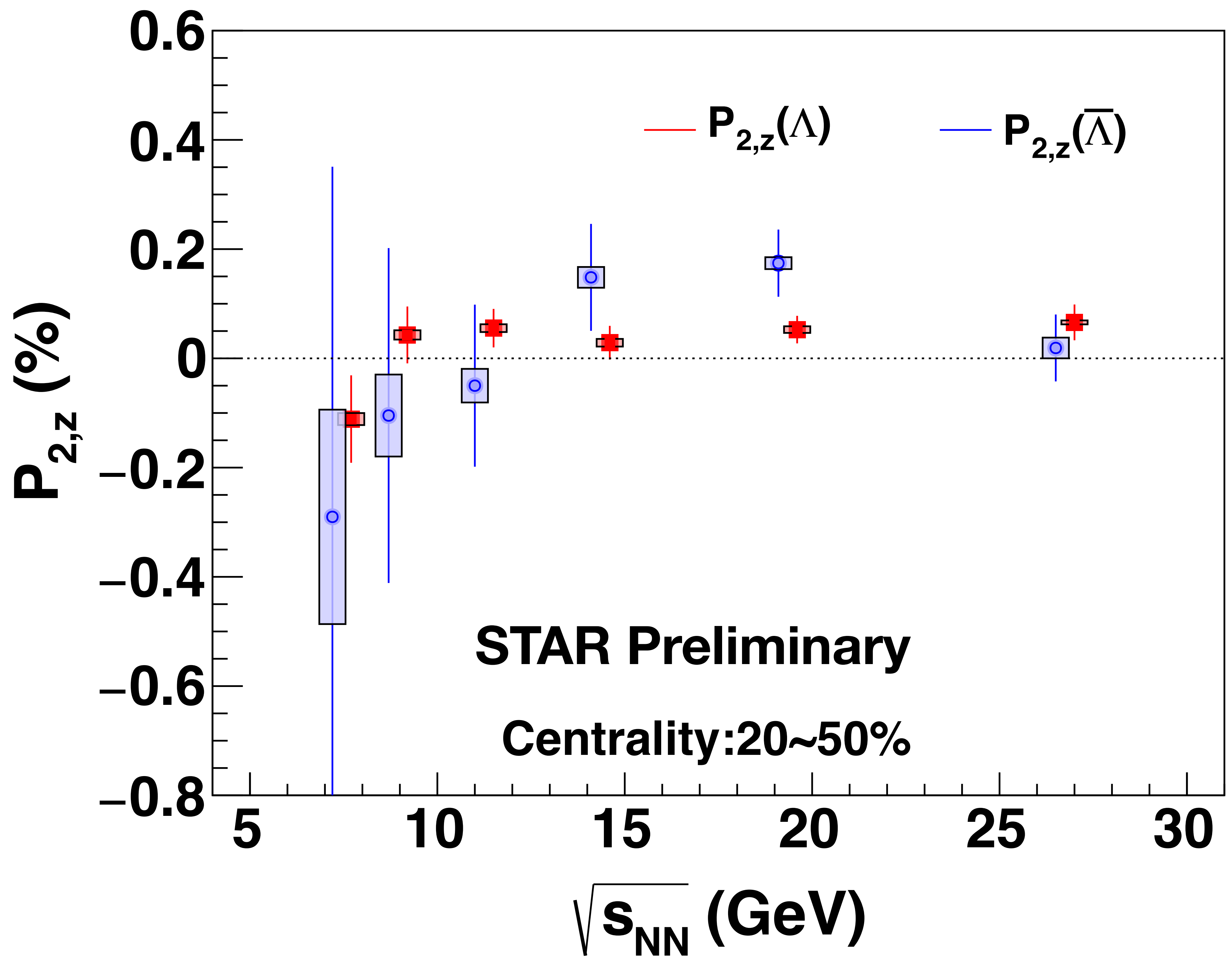
- In HIC, **Ink** (baryon) density is changing → ($\nabla \mu_B$)
- How the ink (baryon) density changing in transverse and longitudinal plane?

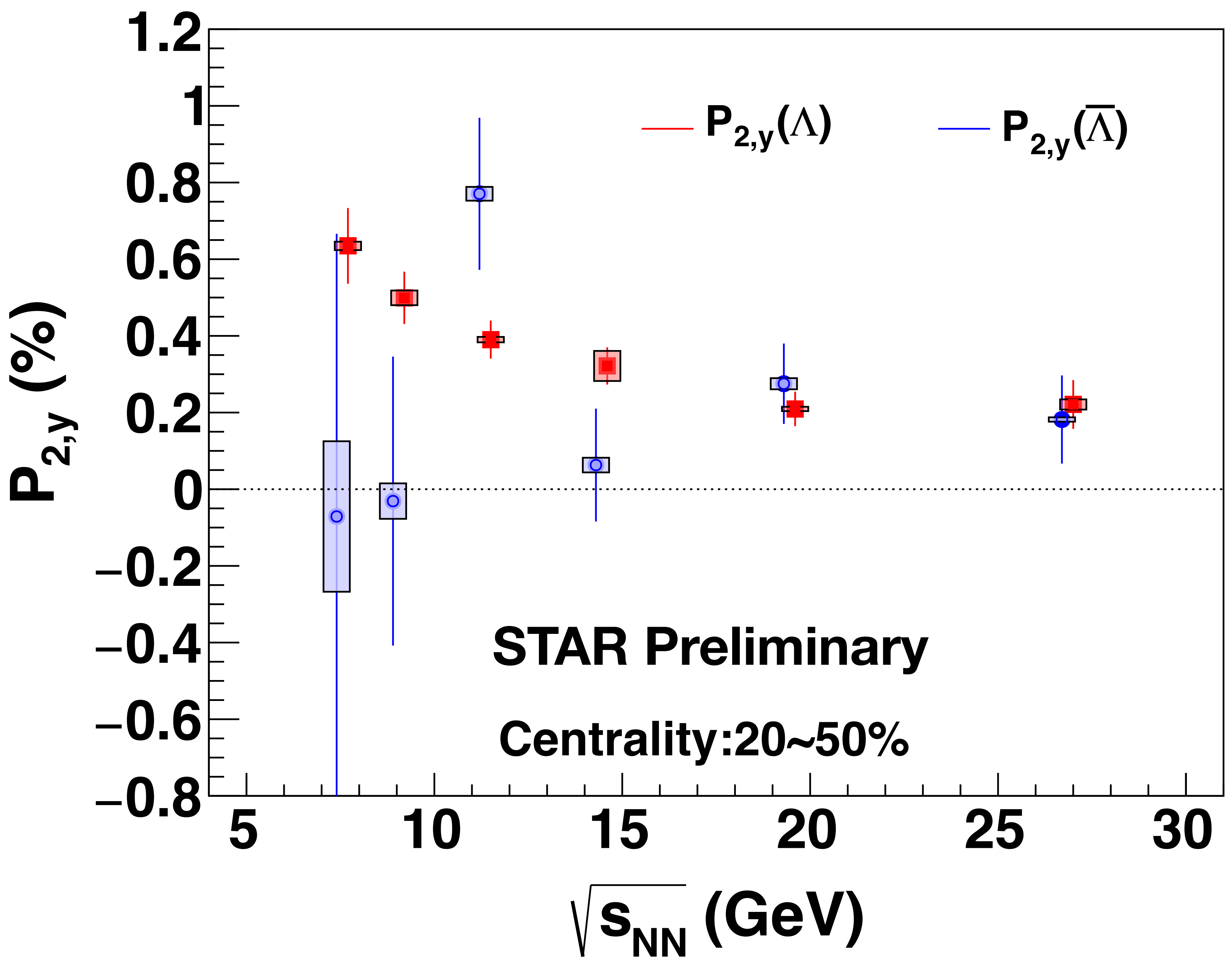
Baryonic Spin Hall effect (bSHE)

Observable $P_{2,z} = \langle P_z \sin(2\Delta\phi) \rangle$

Λ and $\bar{\Lambda}$

$P_{2,y} = -\langle P_y \cos(2\Delta\phi) \rangle$





$$P_y = \frac{8}{\pi \alpha_\Lambda R_{EP}} \langle \sin(\Psi_1 - \phi_p^*) \rangle$$

$$P_z = \frac{3}{\alpha_H} \frac{\langle \cos \theta_p^* \rangle}{\langle (\cos \theta_p^*)^2 \rangle}$$

Kinematics:
$0.5 < p_T < 5.0$ GeV/c
$|y| < 1.0$ for 27 GeV
$|y| < 1.5$ for other energies

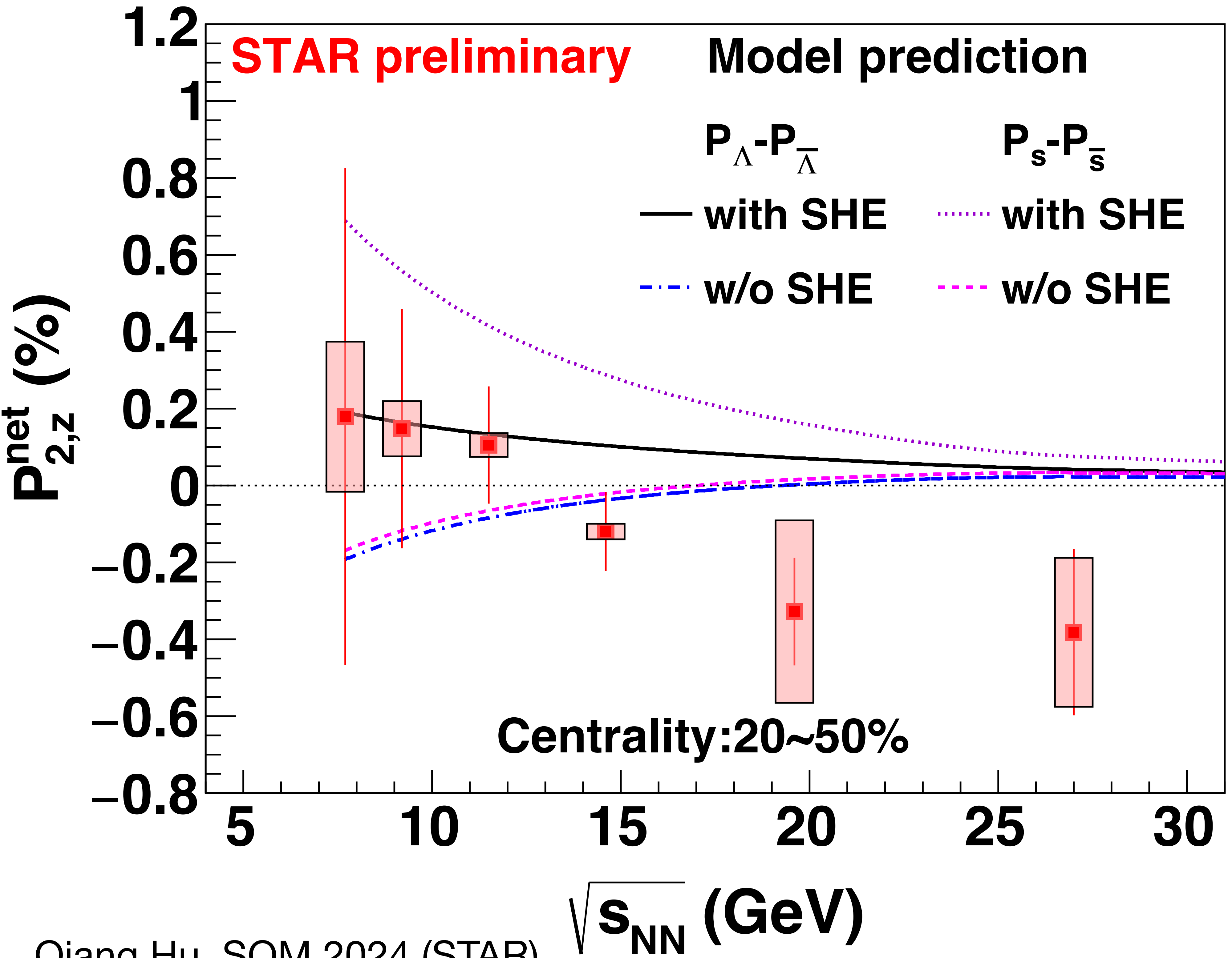
Qiang Hu, SQM 2024 (STAR)

- $P_{2,z}$: non-zero, no strong energy dependence, (hints of sign change at lower energies ?)
- $P_{2,y}$: first observation of monotonic energy dependence (better significance for Λ)

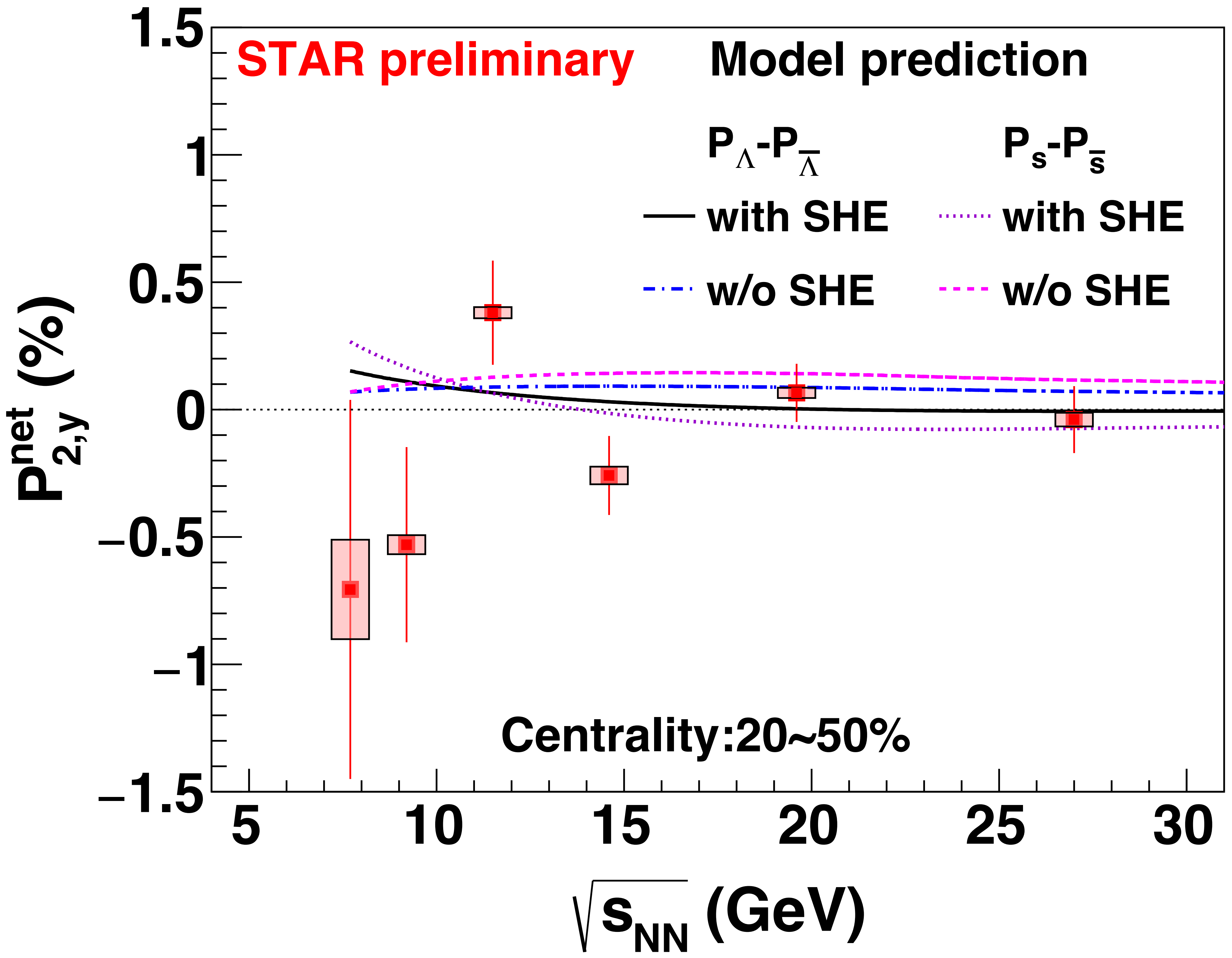
Baryonic Spin Hall effect (SHE)

$\Lambda - \overline{\Lambda}$

$P^{net}_{2,z} = P^{\Lambda}_{2,z} - P^{\overline{\Lambda}}_{2,z}$



$P^{net}_{2,y} = P^{\Lambda}_{2,y} - P^{\overline{\Lambda}}_{2,y}$



Qiang Hu, SQM 2024 (STAR)

$$P_y = \frac{8}{\pi \alpha_\Lambda R_{EP}} \langle \sin(\Psi_1 - \phi_p^*) \rangle$$

$$P_{2,y} = -\langle P_y \cos(2\Delta\phi) \rangle$$

$$P_z = \frac{3}{\alpha_H} \frac{\langle \cos\theta_p^* \rangle}{\langle (\cos\theta_p^*)^2 \rangle}$$

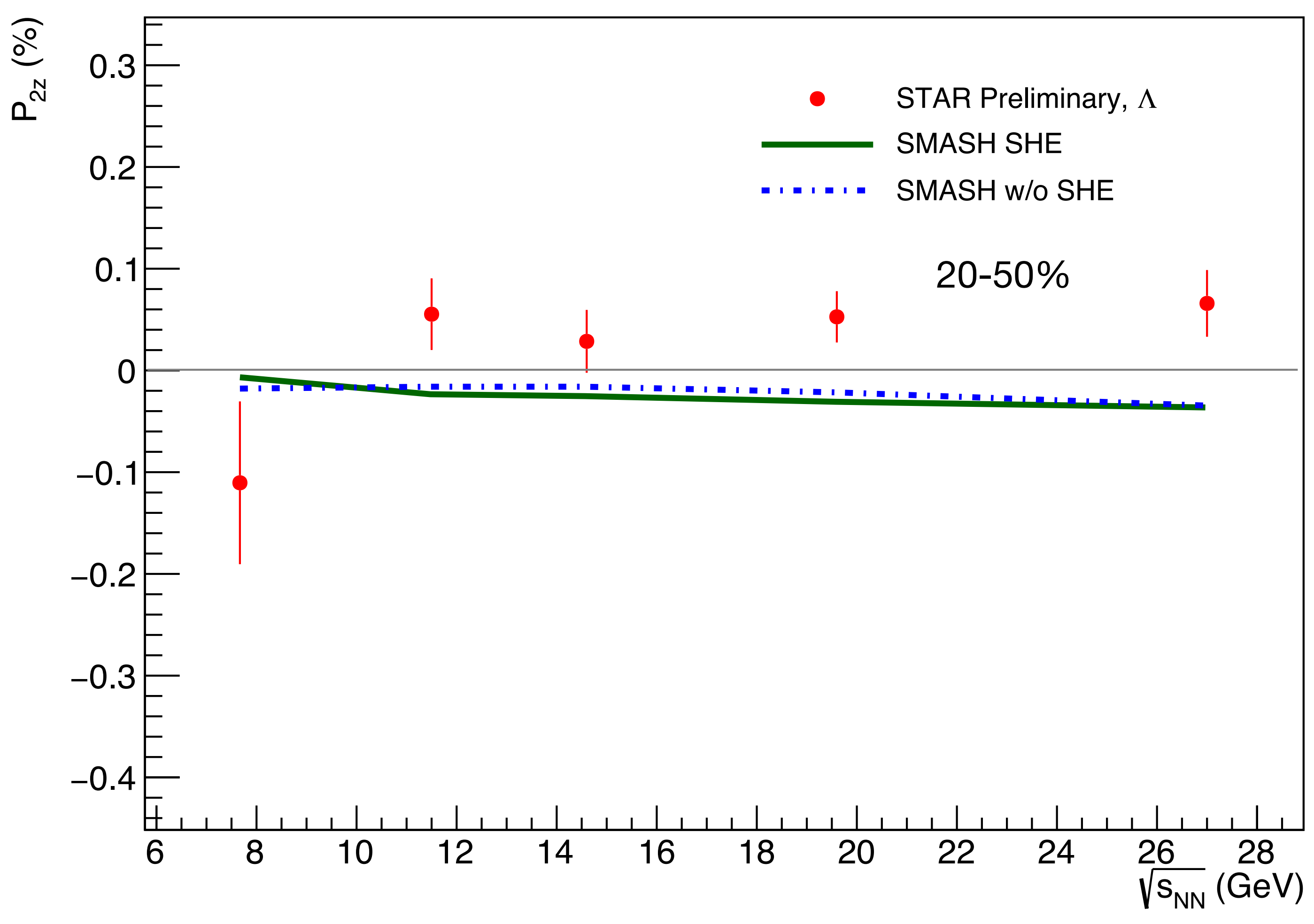
$$P_{2,z} = \langle P_z \sin(2\Delta\phi) \rangle$$

Kinematics:
$0.5 < p_T < 5.0$ GeV/c
$|y| < 1.0$ for 27 GeV
$|y| < 1.5$ for other energies

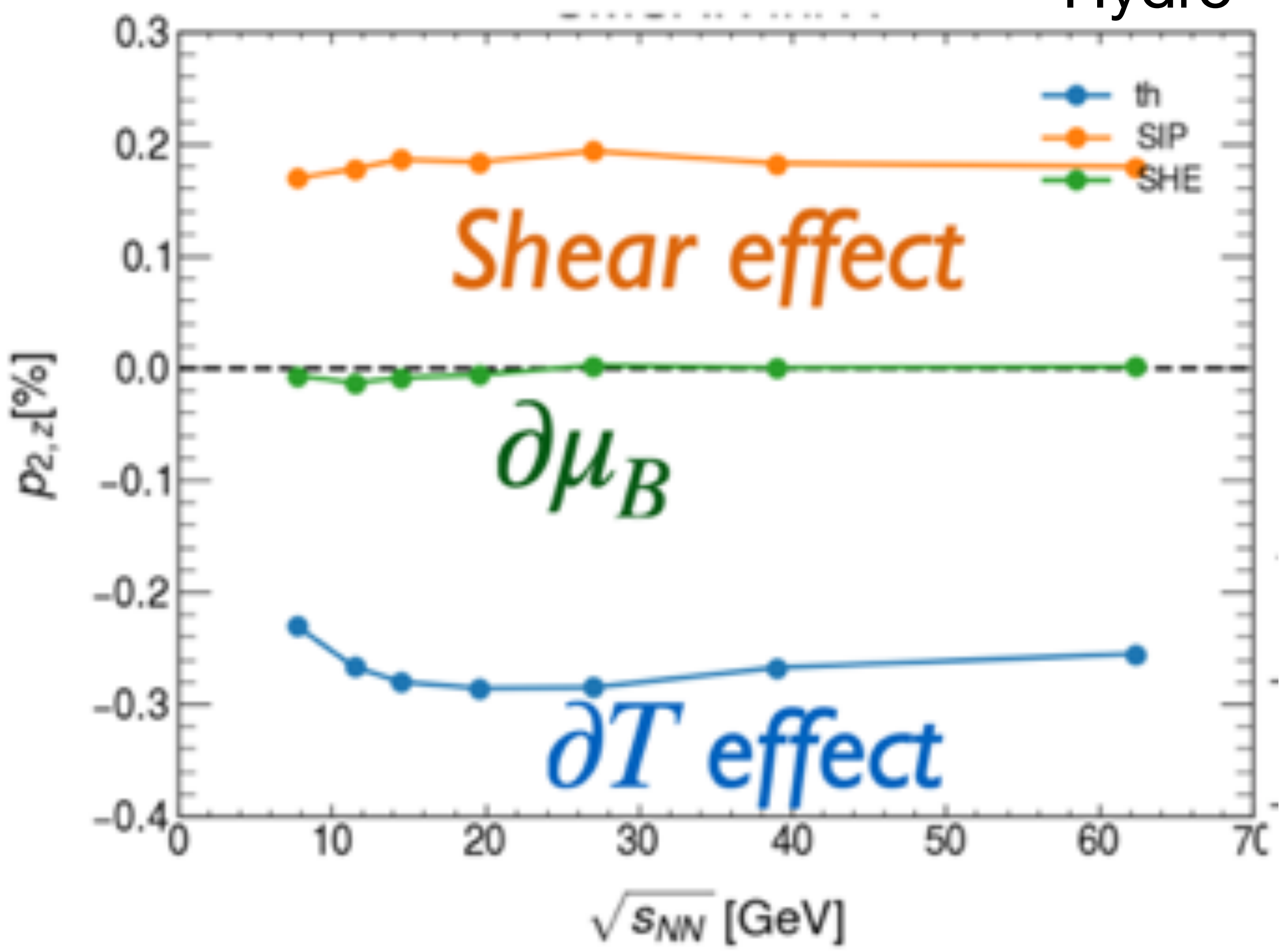
- Not sufficient precision for $(\Lambda - \overline{\Lambda})$ at BES energies
- Non-trivial pattern, hints of sign change at lower energies (?)

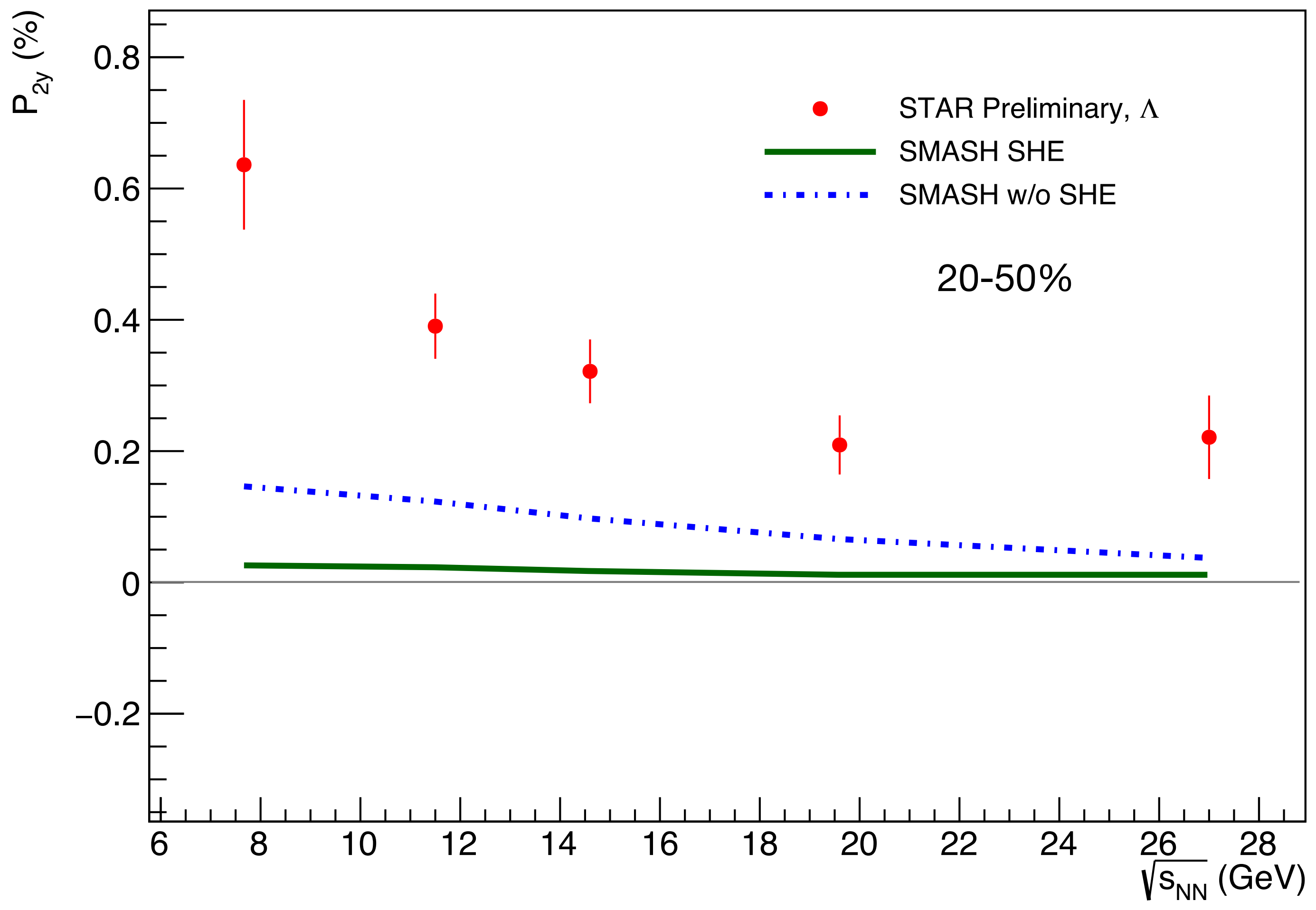
Baryonic Spin Hall effect (bSHE) with hydro model

Λ

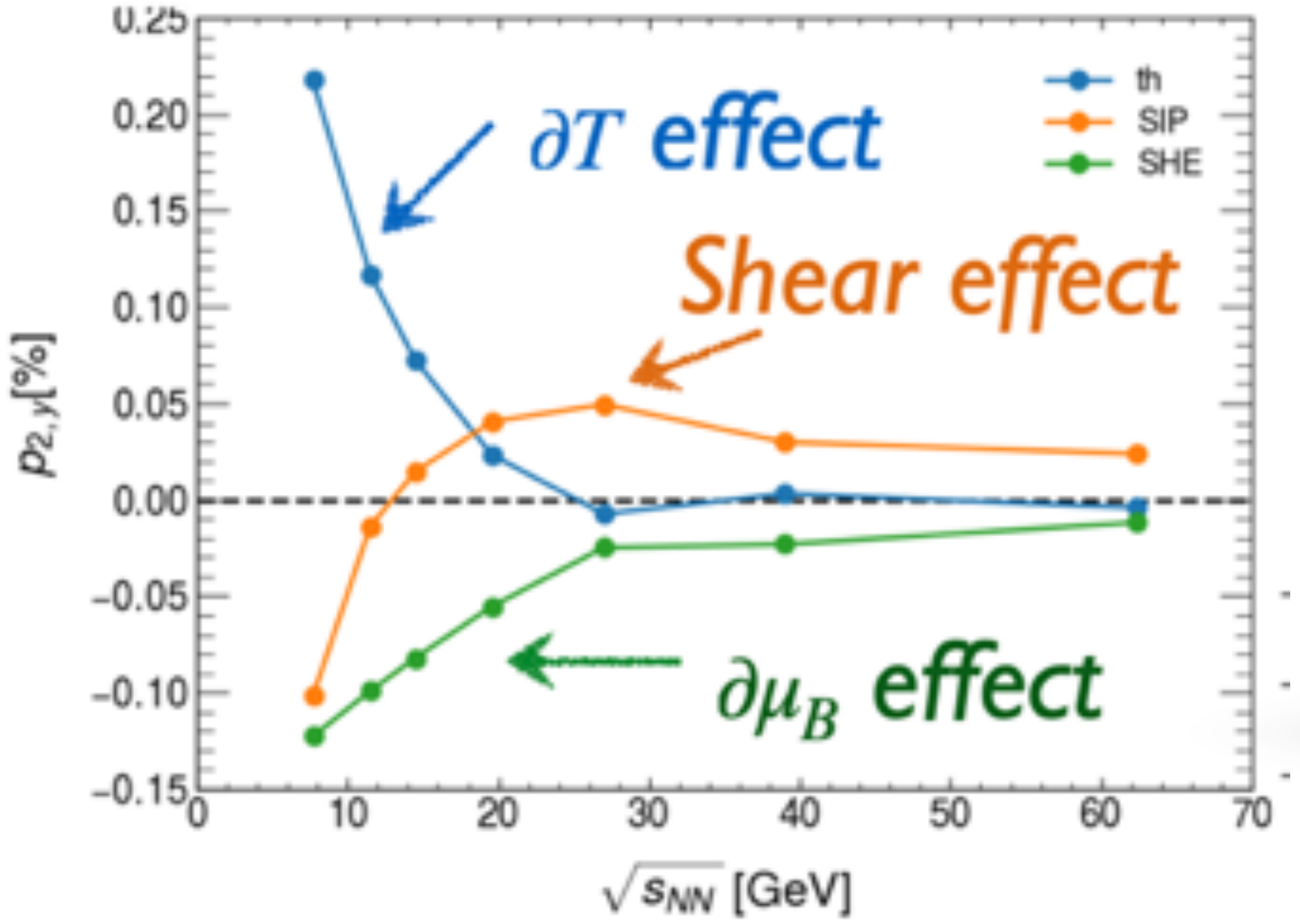


Hydro





Hydro



Decompose local polarization (naive model)

- $P_{2,z} = C_1 \times \text{SIP} \oplus C_2 \times \nabla T \oplus C_3 \times \nabla \mu_{B-\text{trans}}$

- Data: $P_{2,z}$ small magnitude but positive
- Model: $\delta\mu_{B-\text{trans}}$ negligible,

- $P_{2,y} = C_1 \times \text{SIP} \oplus C_2 \times \nabla T \oplus C_3 \times \nabla \mu_{B-\text{long}}$

- Data: $P_{2,z}$ large magnitude and monotonic
- Model: $\delta\mu_{B-\text{long}}$ non-negligible

- A simultaneous model fit with global and local polarization data → help understand the energy dependence pattern and the expected *non-trivial contribution from* $\nabla \mu_B$

C_1, C_2 and C_3 can naively considered as medium response to Shear, Thermal gradient and chemical potential (unknowns)

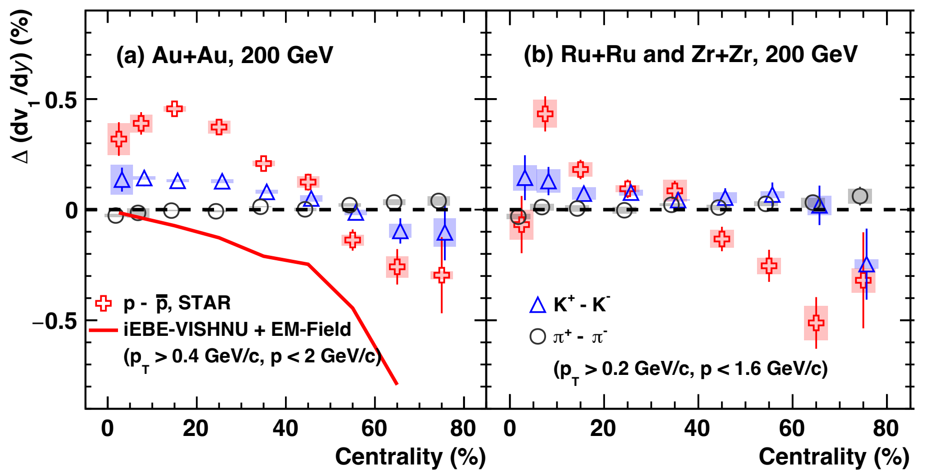
Yi Yin, RHIC AGS 2024
Hydro: Xiang Wu et al (private. comm.), Phys Rev C 105 6, 064909 (2022)

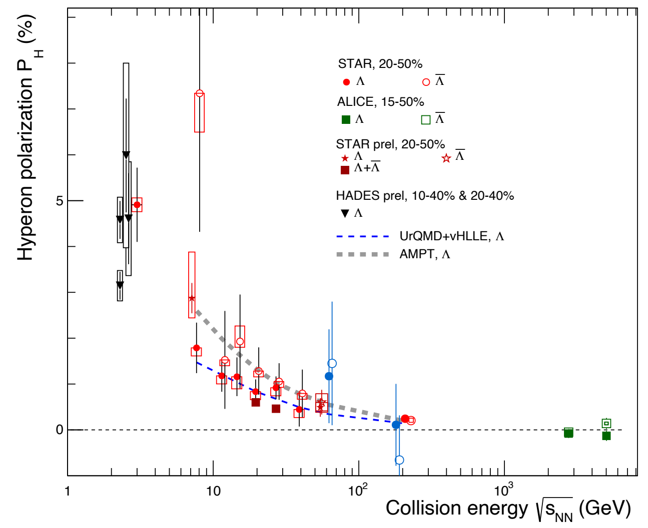
Summary

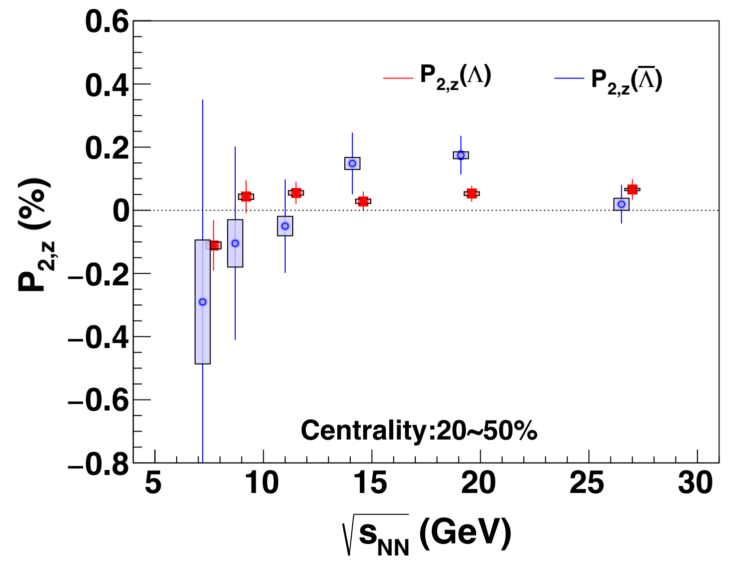
- <u>Directed flow (v_1)</u>
  - Sign change in Δv_1 in peripheral collisions
  - $v_1(p - \bar{p})$: system size dependence; $v_1(p + \bar{p})$: no dependence
  - Interplay of baryon transport and electromagnetic field with conducting QGP

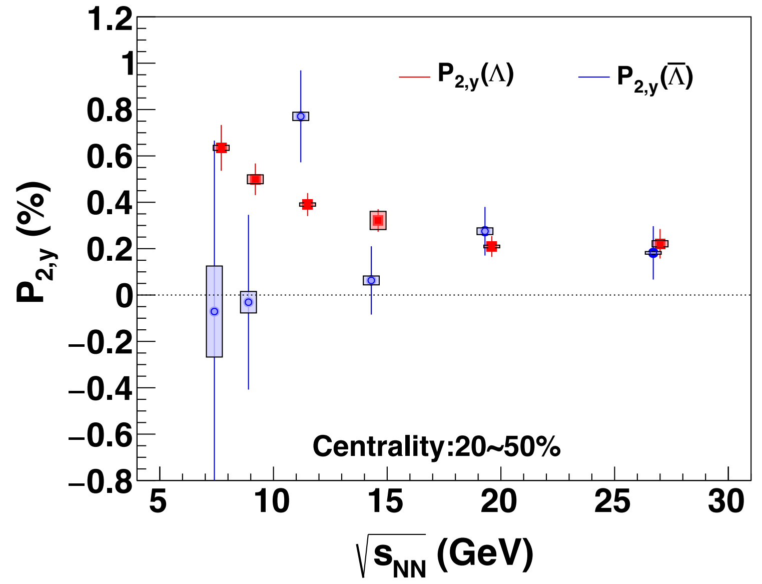
- <u>Global spin polarization (P_y)</u>
  - P_y monotonic beam energy dependence
  - Correlation between the net-baryon and angular momentum deposition

- <u>Local spin polarization ($P_{2,z,y}$)</u>
  - In-plane ($P_{2,z}$) positive magnitude; Out-of-plane ($P_{2,y}$) monotonic energy dependence
  - Signal of novel baryon density ($\nabla \mu_B$) driven polarization (baryonic SHE)







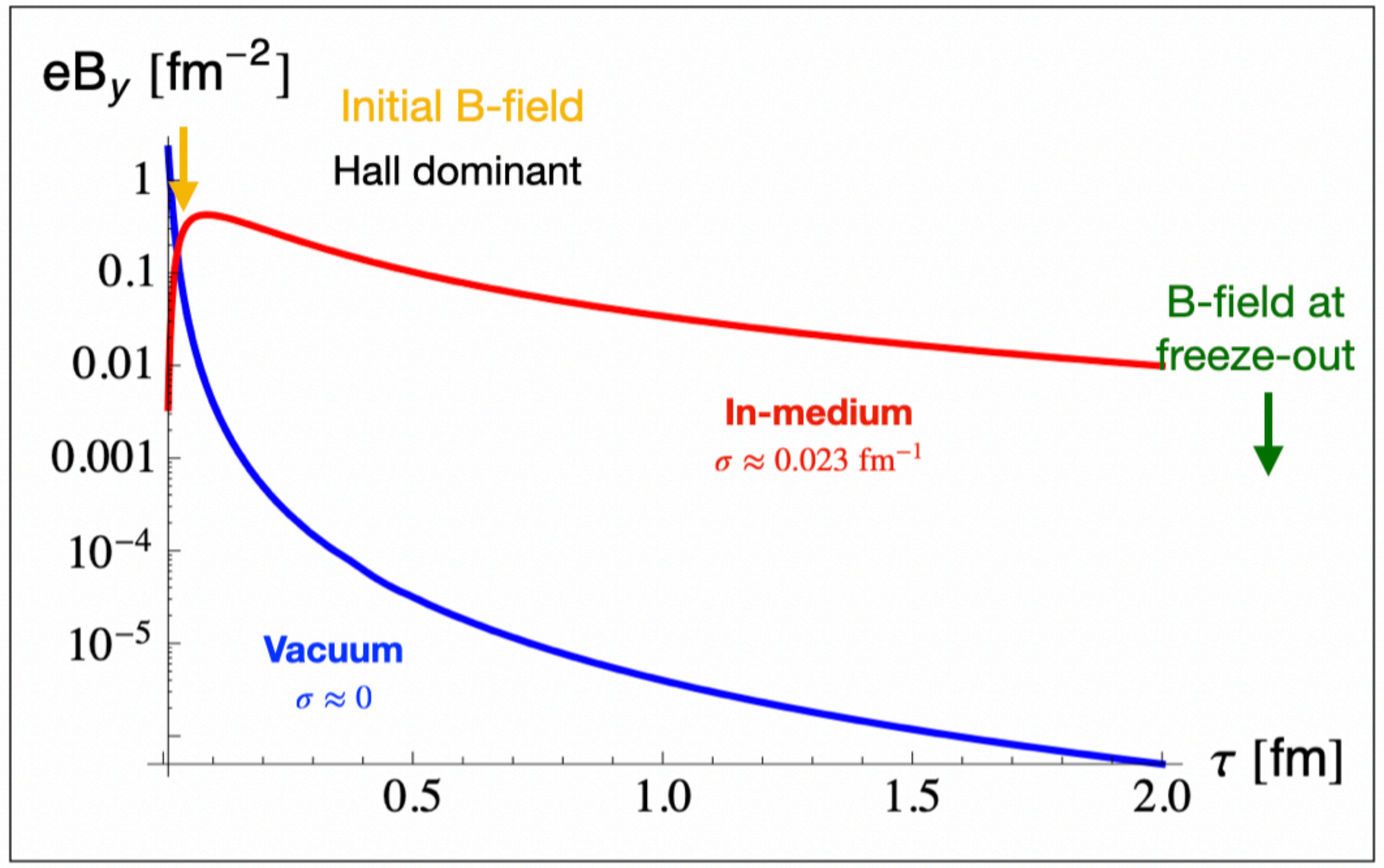


Thank you for your attention

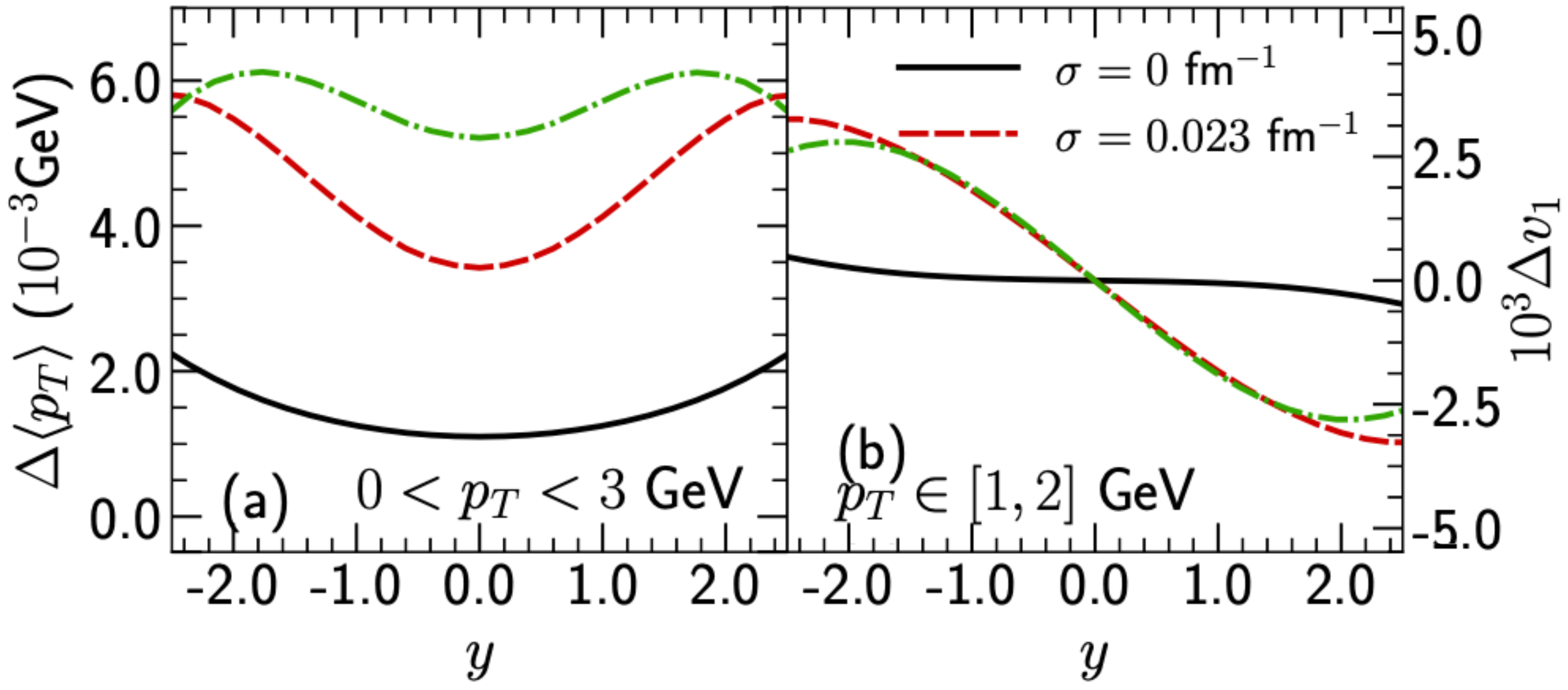
Many thanks to STAR and theory colleagues for discussions

Motivation

Magnetic Field



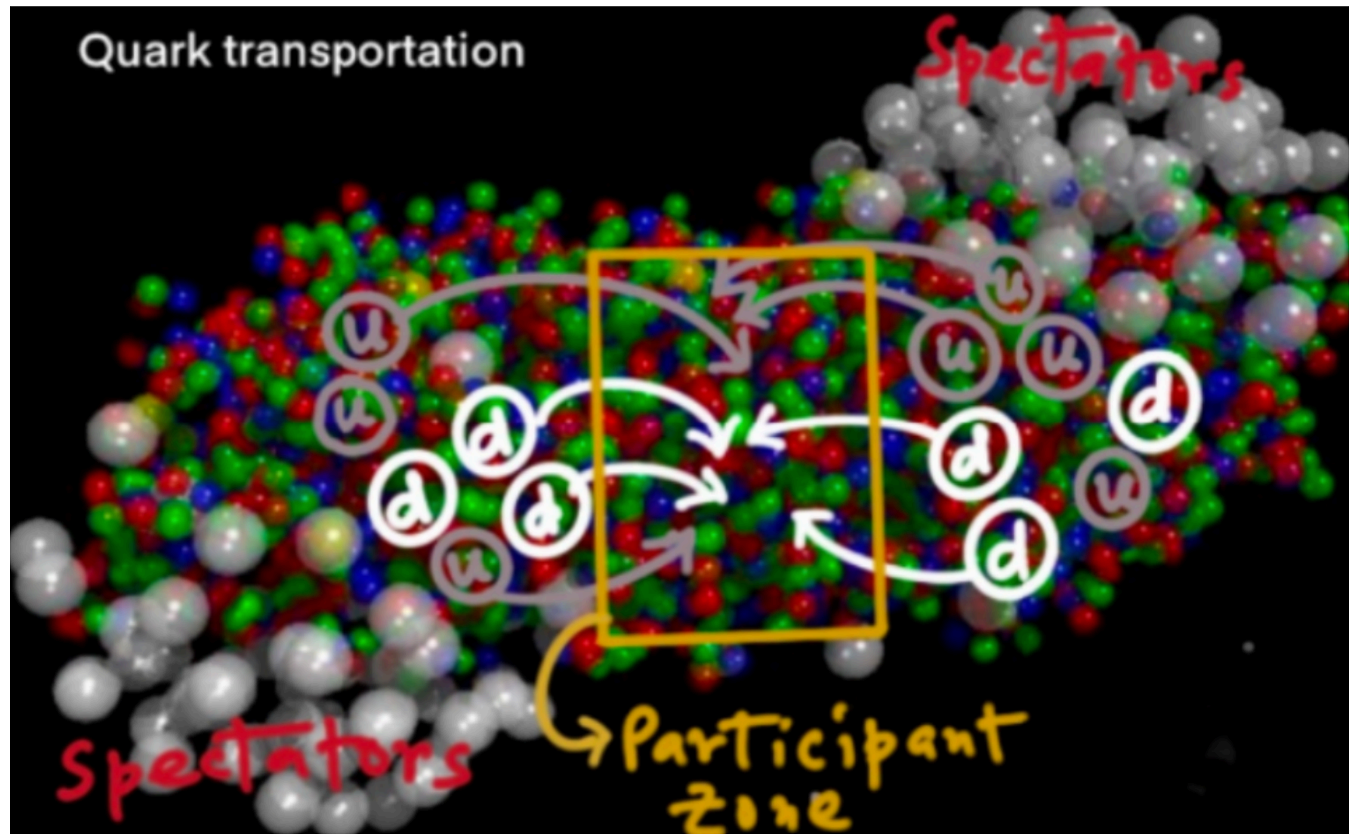
Observable $\Delta v_1 \sim v_1(h^+) - v_1(h^-)$



- Δv_1 sensitive to QGP conductivity (σ)

- **Non-EM field effects**
- Transport: $\Delta v_1^\dagger \neq 0$
- ....

Transported quark effect: $\Delta v_1 \neq 0$



$p : uud$ $\quad \bar{p} : \bar{u}\bar{u}\bar{d}$ $\quad \frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} > 0$

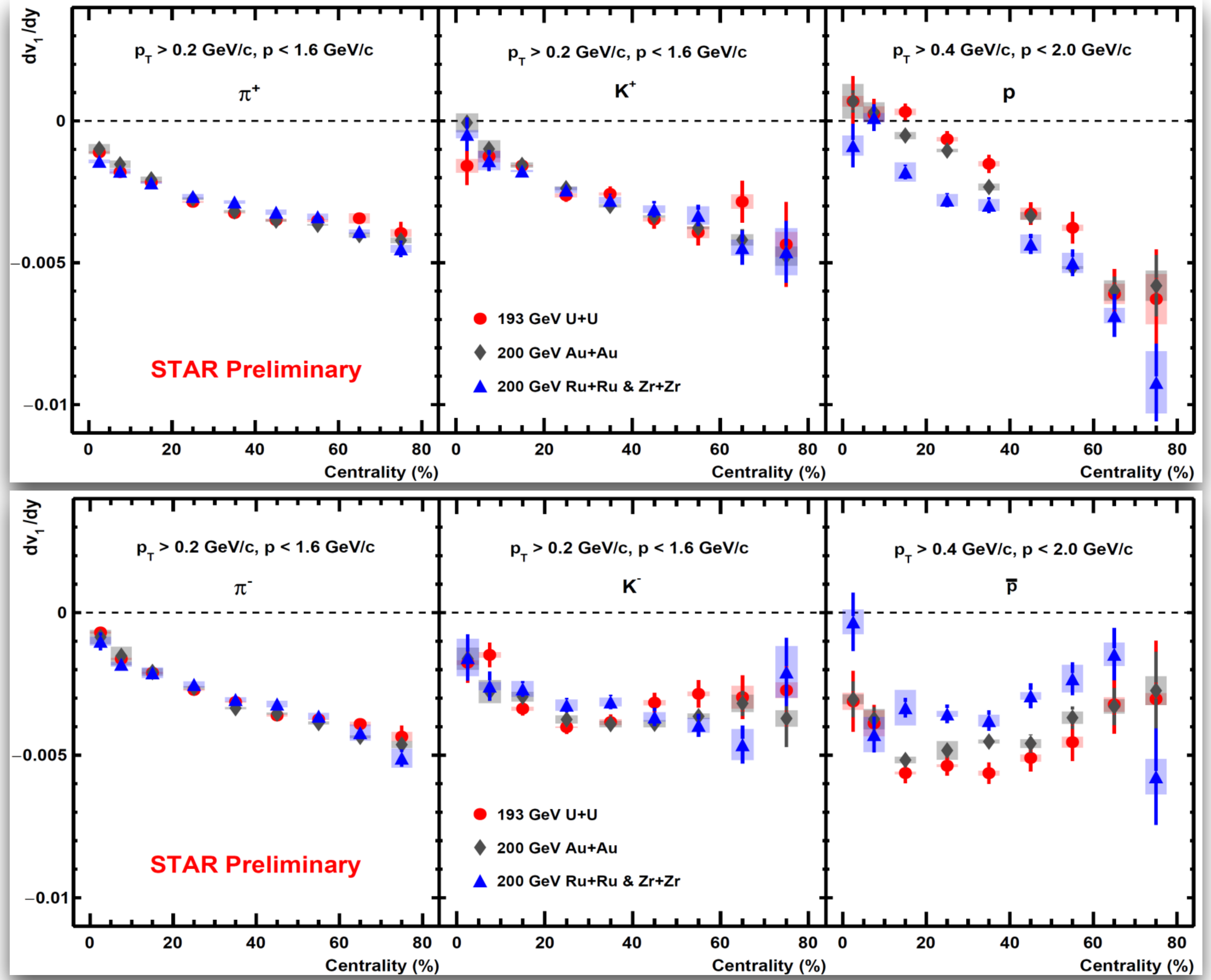
$K^+ : u\bar{s}$ $\quad K^- : \bar{u}s$ $\quad \frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} > 0$

$\pi^+ : u\bar{d}$ $\quad \pi^- : \bar{u}d$ $\quad \frac{dv_1^+}{dy} - \frac{dv_1^-}{dy} < 0$

(#d>#u, Au neutron rich)

"*u*" and "*d*" quarks transported from incoming nuclei towards mid-rapidity

Charge dependent directed flow: system size dependence

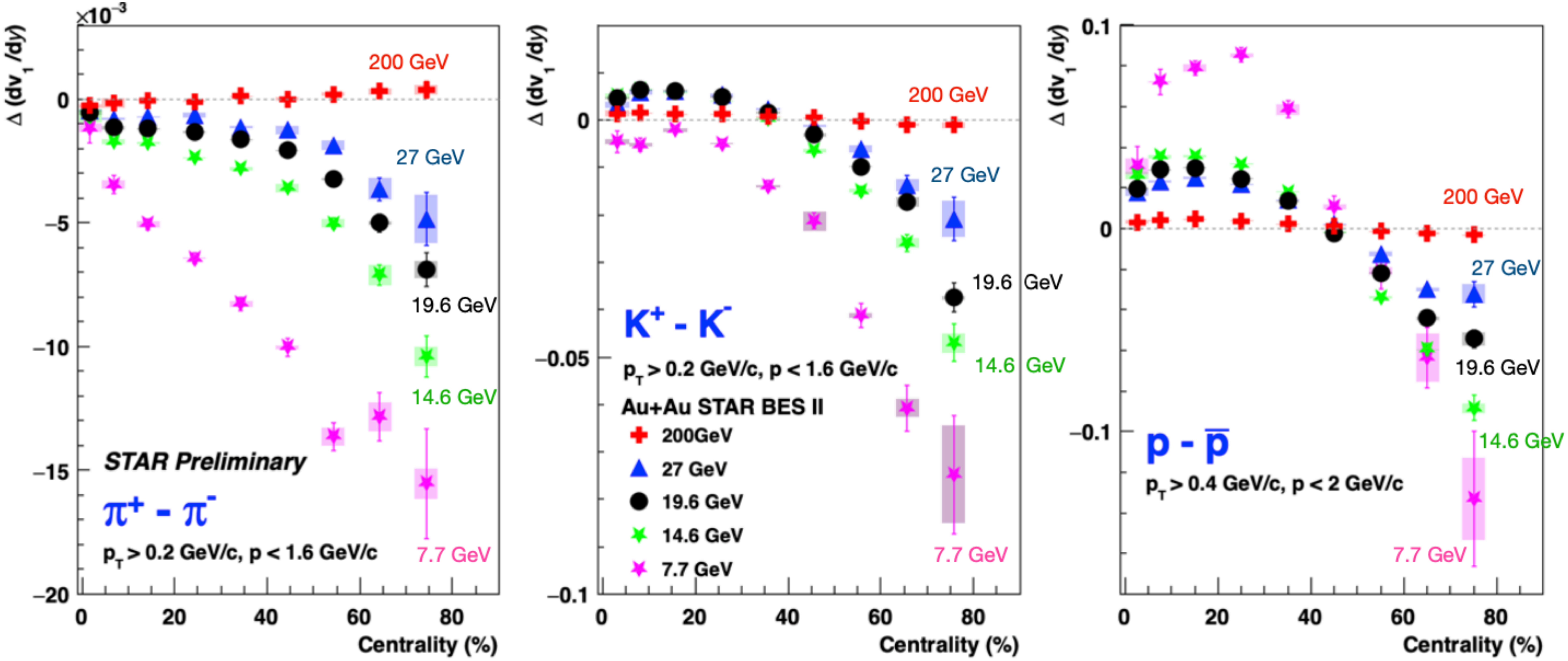


Farhan Taseer, SQM 2024 (STAR)

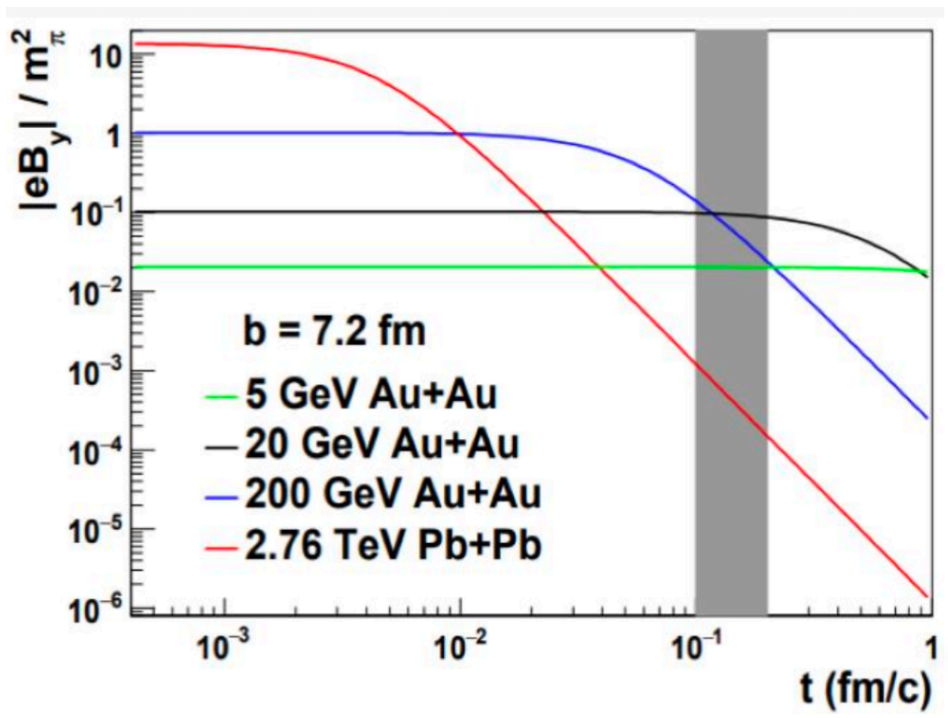
- pions & kaons: U+U ~ Au+Au ~ Isobar
- protons: U+U < Au+Au < Isobar
- anti-protons: U+U > Au+Au > Isobar

Charge dependent directed flow: energy dependence

pions **kaons** **protons**



- In peripheral, negative Δv_1 increases with decreasing beam energy



With decreasing energy:

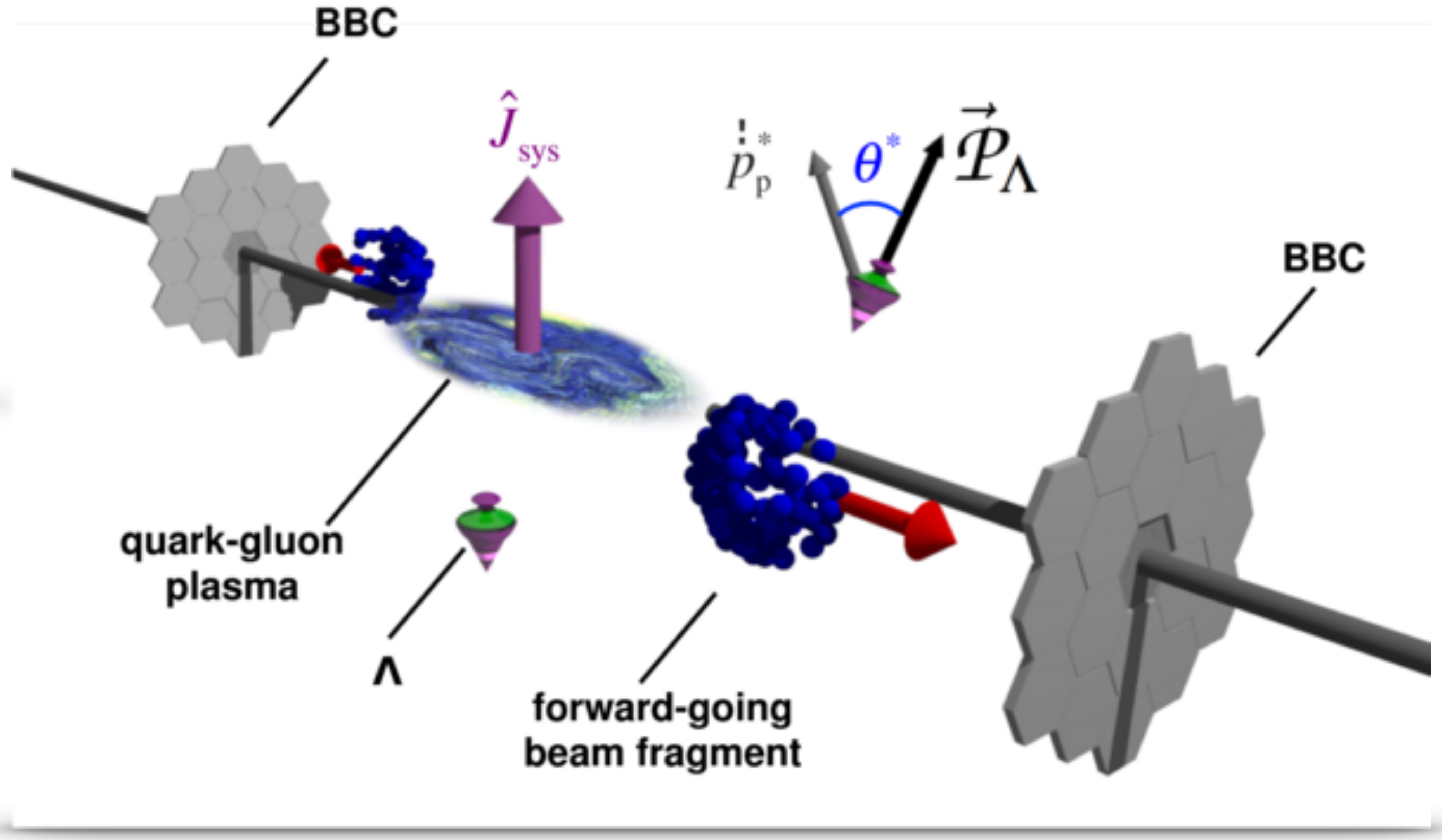
- Nuclear passage time is large and B-field lifetime could be longer
- Lifetime of fireball could be shorter

Measurement global spin polarization

Global polarization is measured from the angular distributions using parity violating weak decay of hyperons ("self-analyzing"):

- $\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}^*_{\mathbf{H}} \cdot \mathbf{p}^*_{\mathbf{d}})$

$\mathbf{P}_{\mathbf{H}}$: Hyperon polarization
α_H : Hyperon decay parameter
$\mathbf{p}_{\mathbf{d}}$: Daughter momentum direction
$*$: Measurements in parent's rest frame



Component perpendicular to reaction plane:

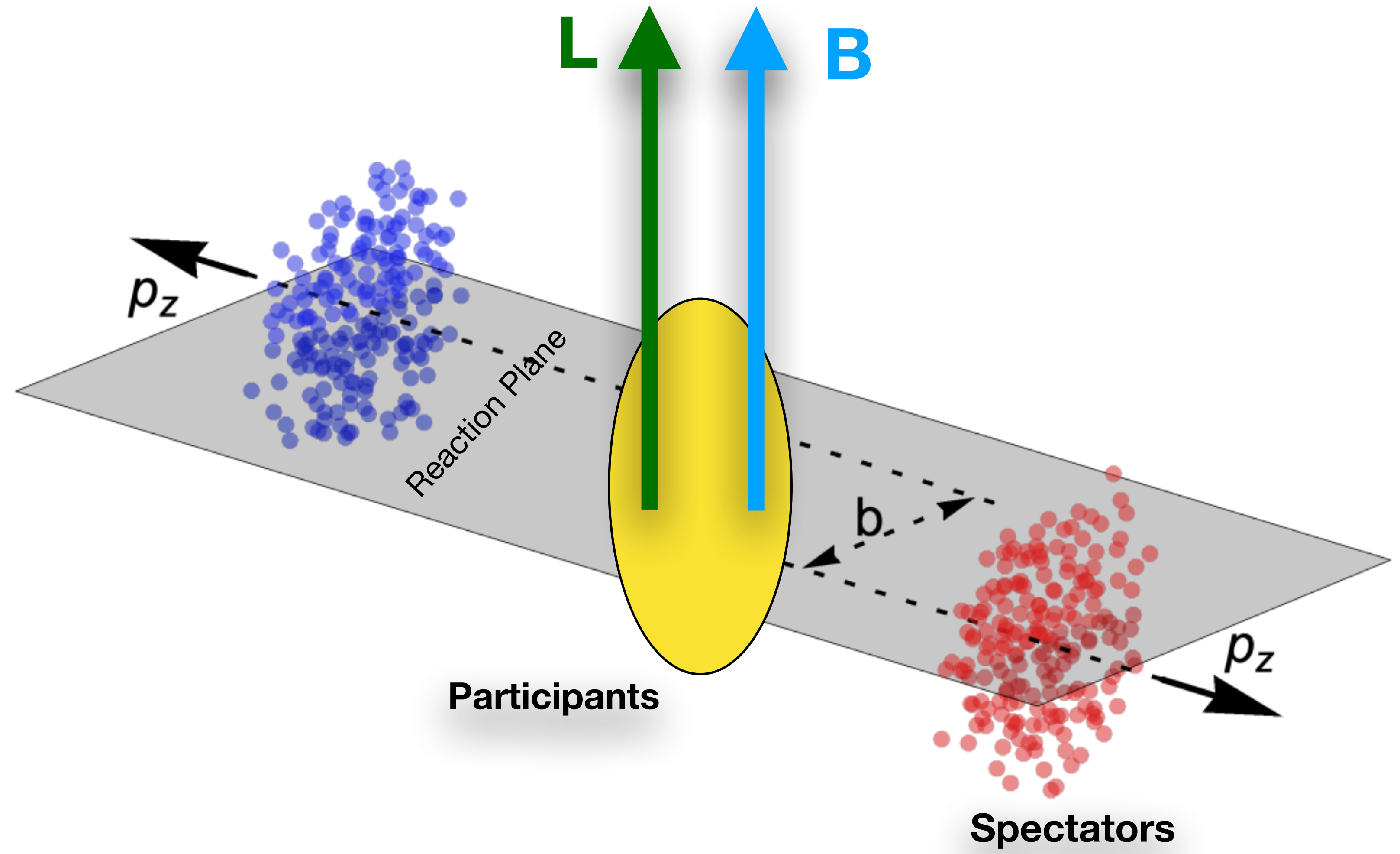
- $P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi^*_d) \rangle}{\mathrm{Res}(\Psi_1)}$

Schiling et. al., Nucl Phys B 15, 397 (1970)
(STAR Collaboration) Phys Rev C 76, 024915 (2007)

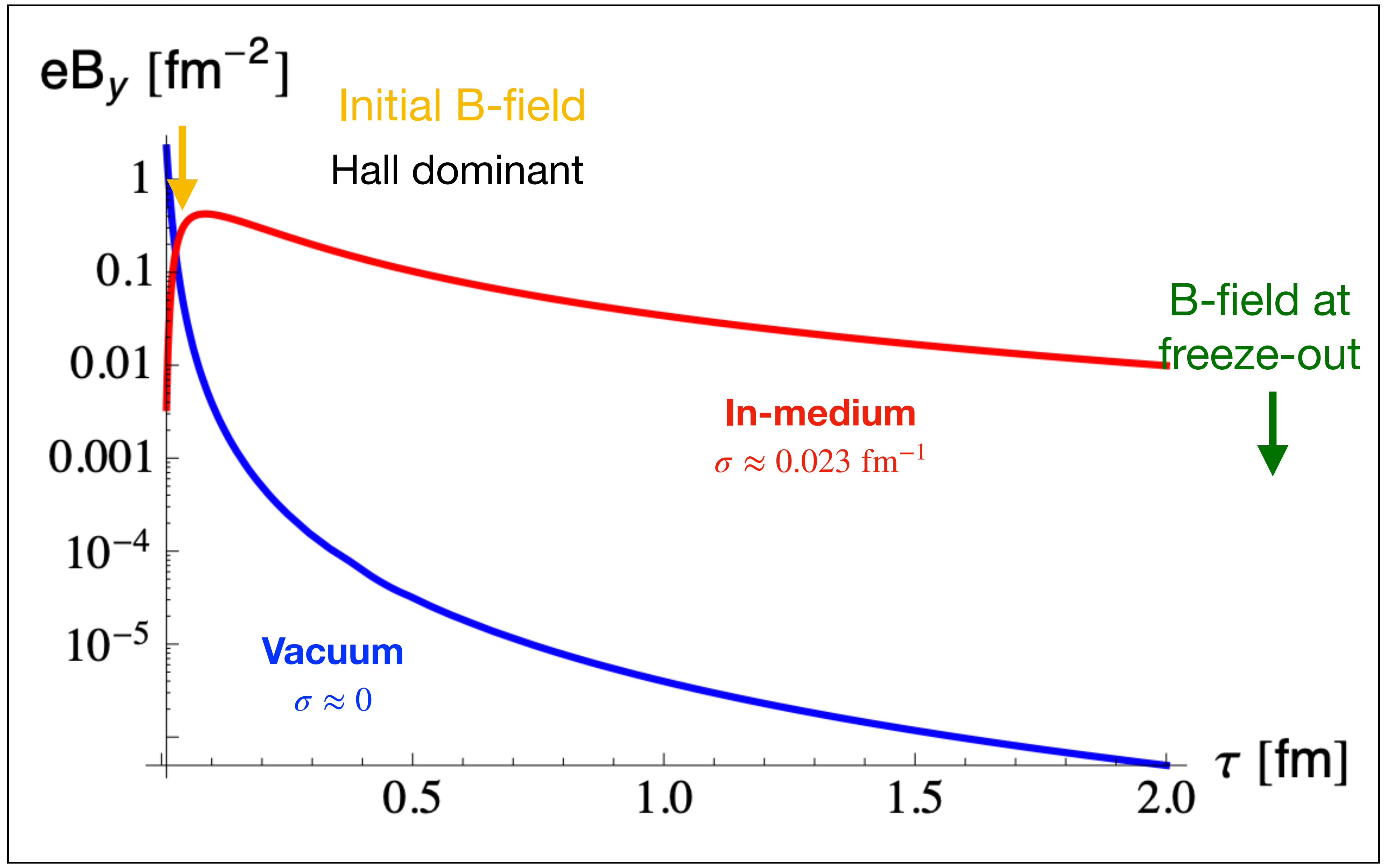
ϕ_d : Daughter azimuthal angle
Ψ_1: 1st order event plane

Spin polarization of hyperons (baryons)

Motivation



Magnetic Field



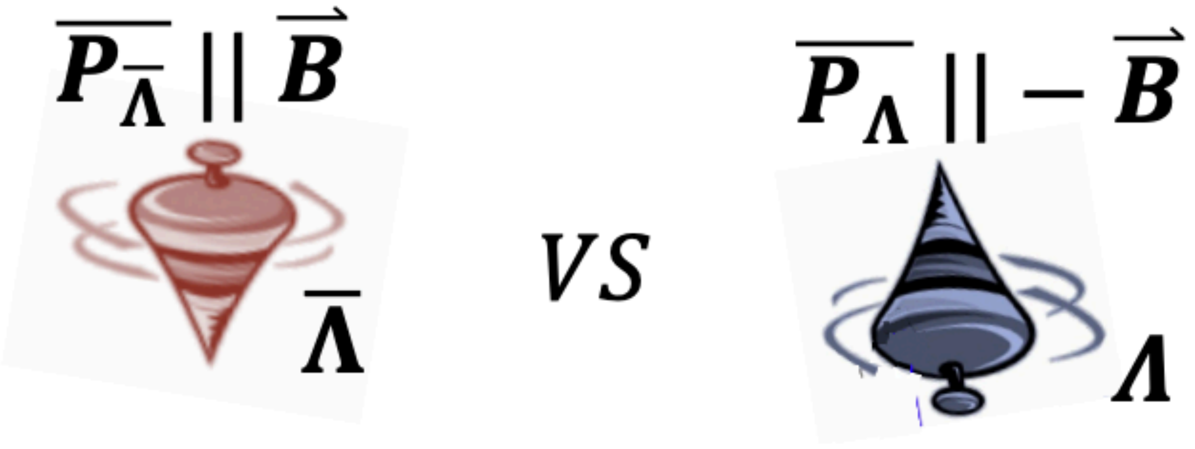
In non-central heavy-ion collisions

- **Initial strong magnetic field** (**B**) is expected

$$eB \sim m_\pi^2 \sim 10^{18}\ \text{Gauss}$$

- Such strong **B** field can also polarize quarks. Can induce different spin polarization for quarks and anti-quarks with different magnetic moments

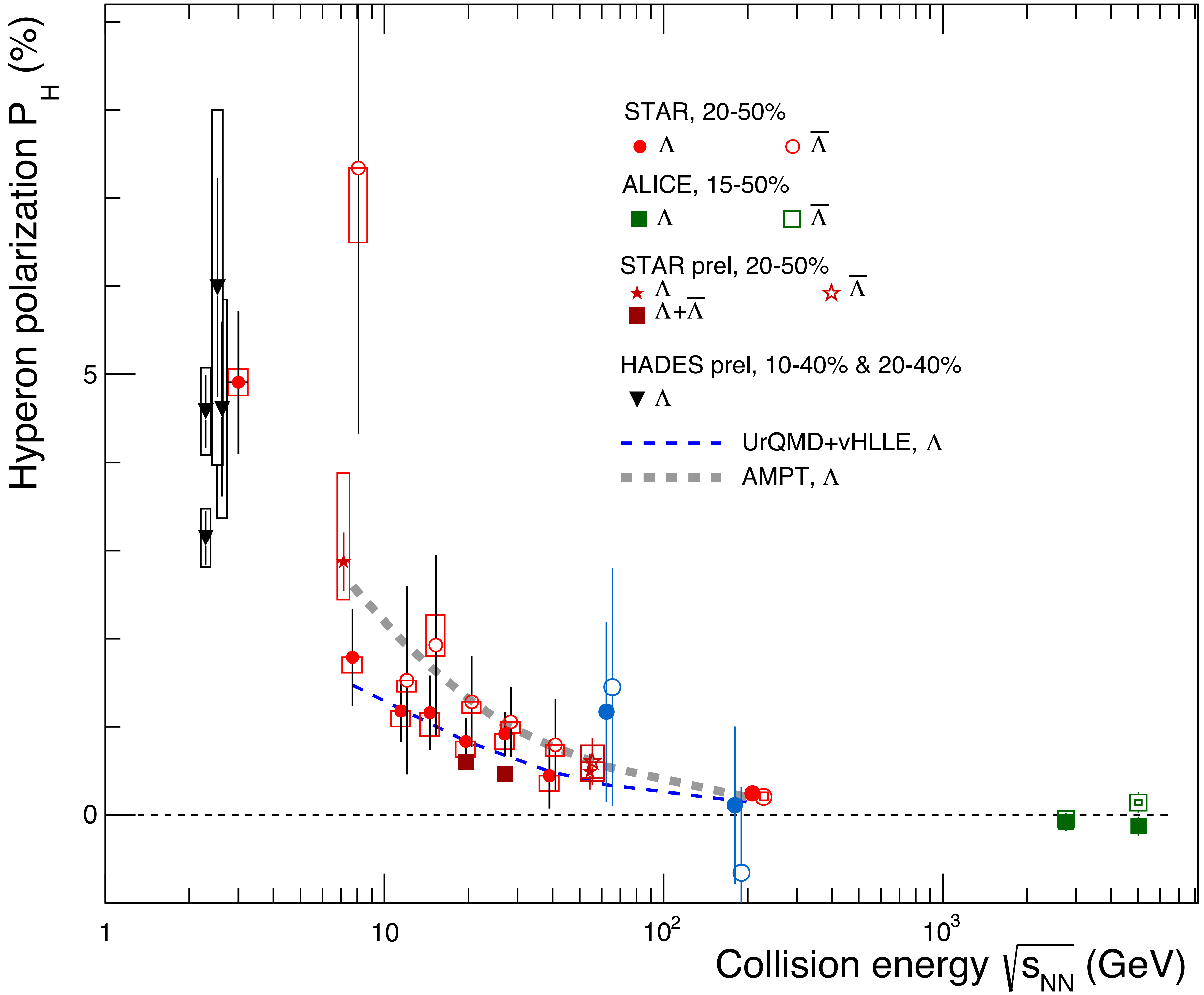
- **Imprints of EM field effects**
- $(P_\Lambda - P_{\bar{\Lambda}}) \approx \dfrac{2\mu_\Lambda B}{T}$



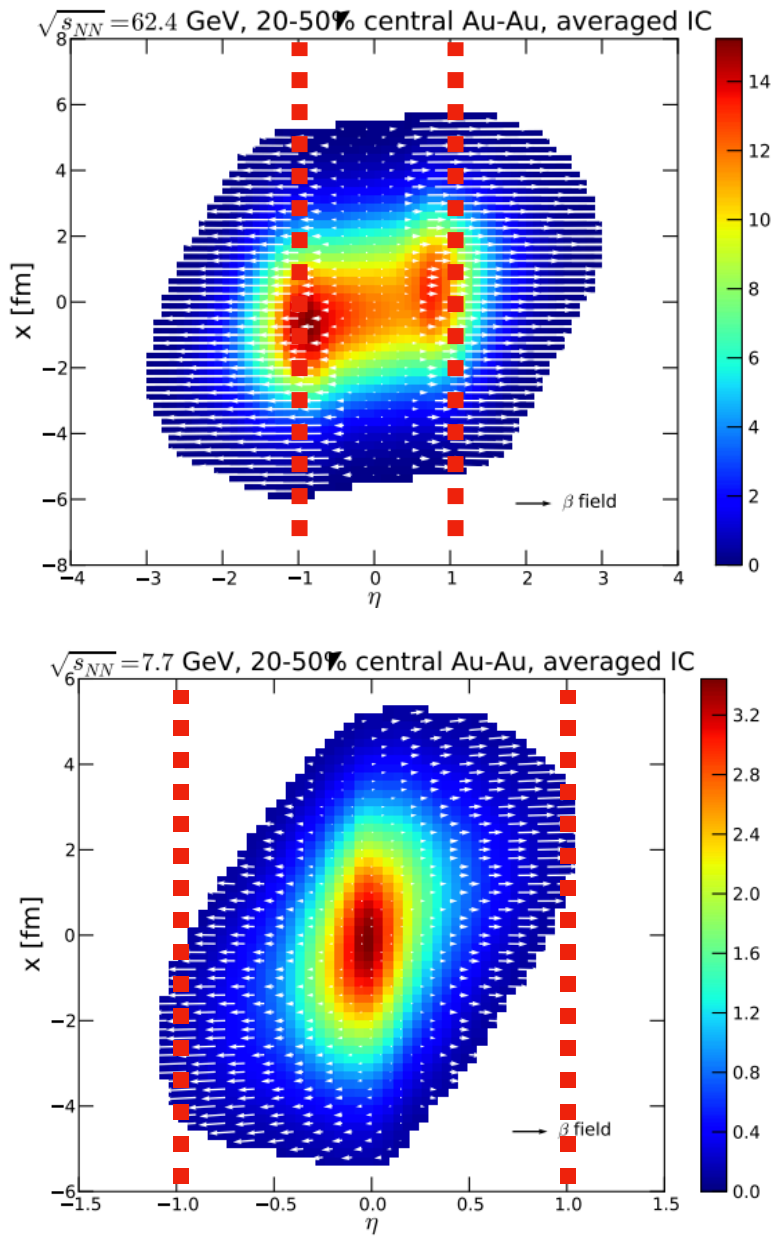
$$(P_\Lambda - P_{\bar{\Lambda}}) \approx \frac{2\mu_\Lambda B}{T}$$

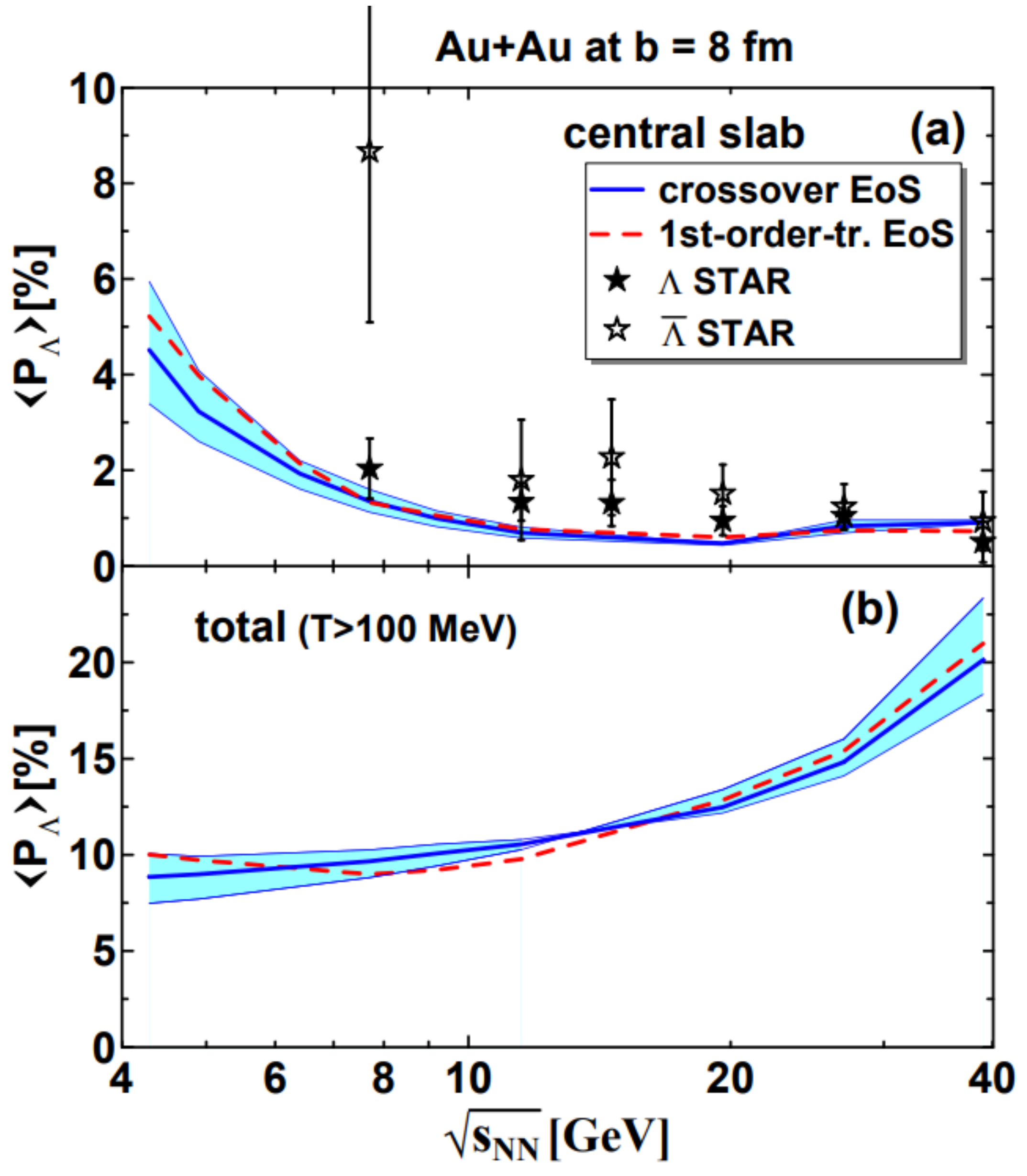
Kharzeev, Nucl Phys A803, 227 (2008)

Beam energy dependence of global $\mathbf{P}_\Lambda$



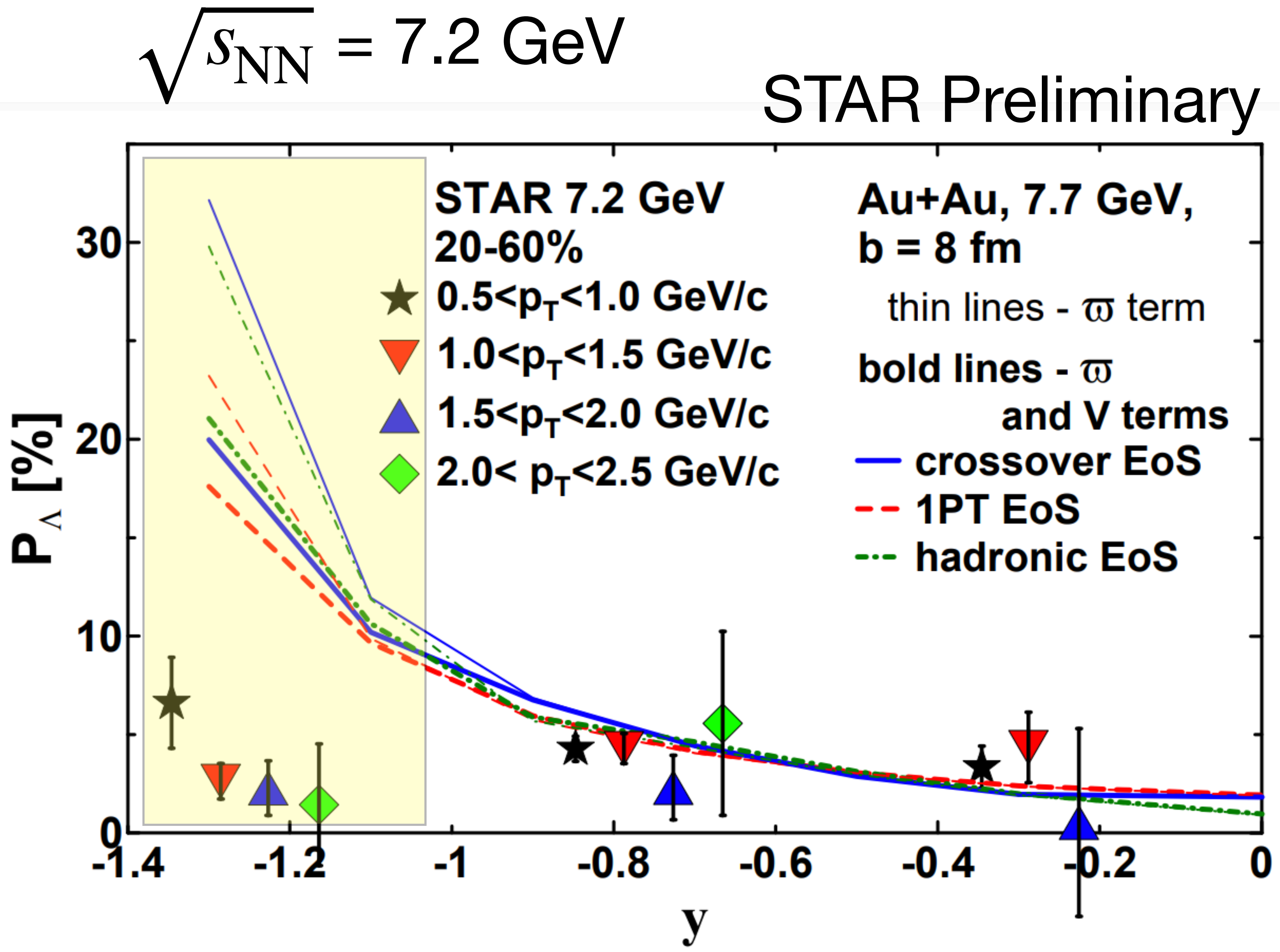
- P_Λ follows increasing trend from 5.02 TeV down to 2.4 GeV
- Models can capture the energy dependence trend

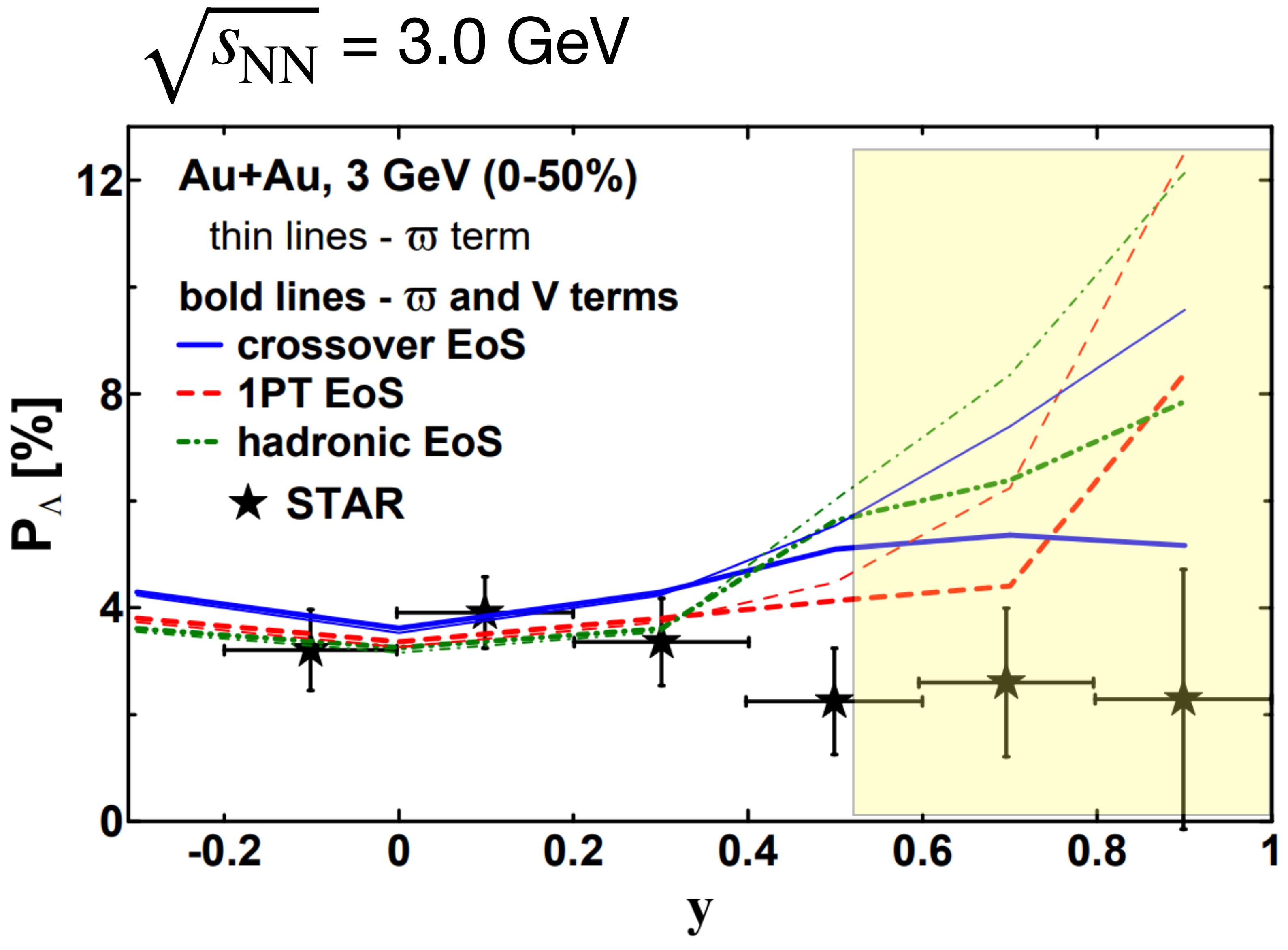


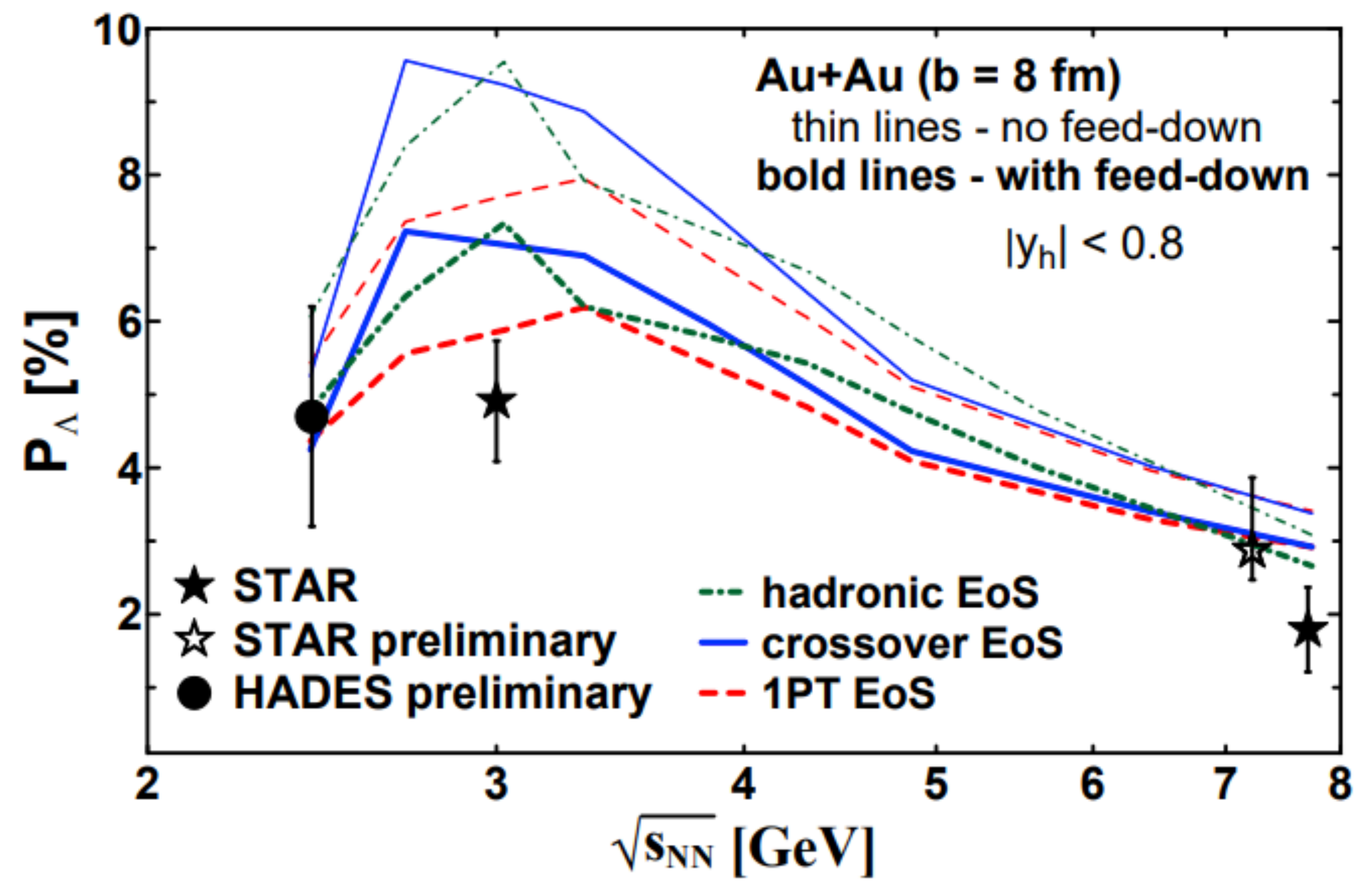


Karpenko et. al., Eur Phys J C 77, 213 (2017)
Ivanov et. al., Phys Rev C 100, 014908 (2019)
Ivanov et. al., Phys Rev C 102, 024916 (2020)

P_Λ: rapidity dependence with models







Ivanov et. al., Phys Rev C 105, 034915 (2022)

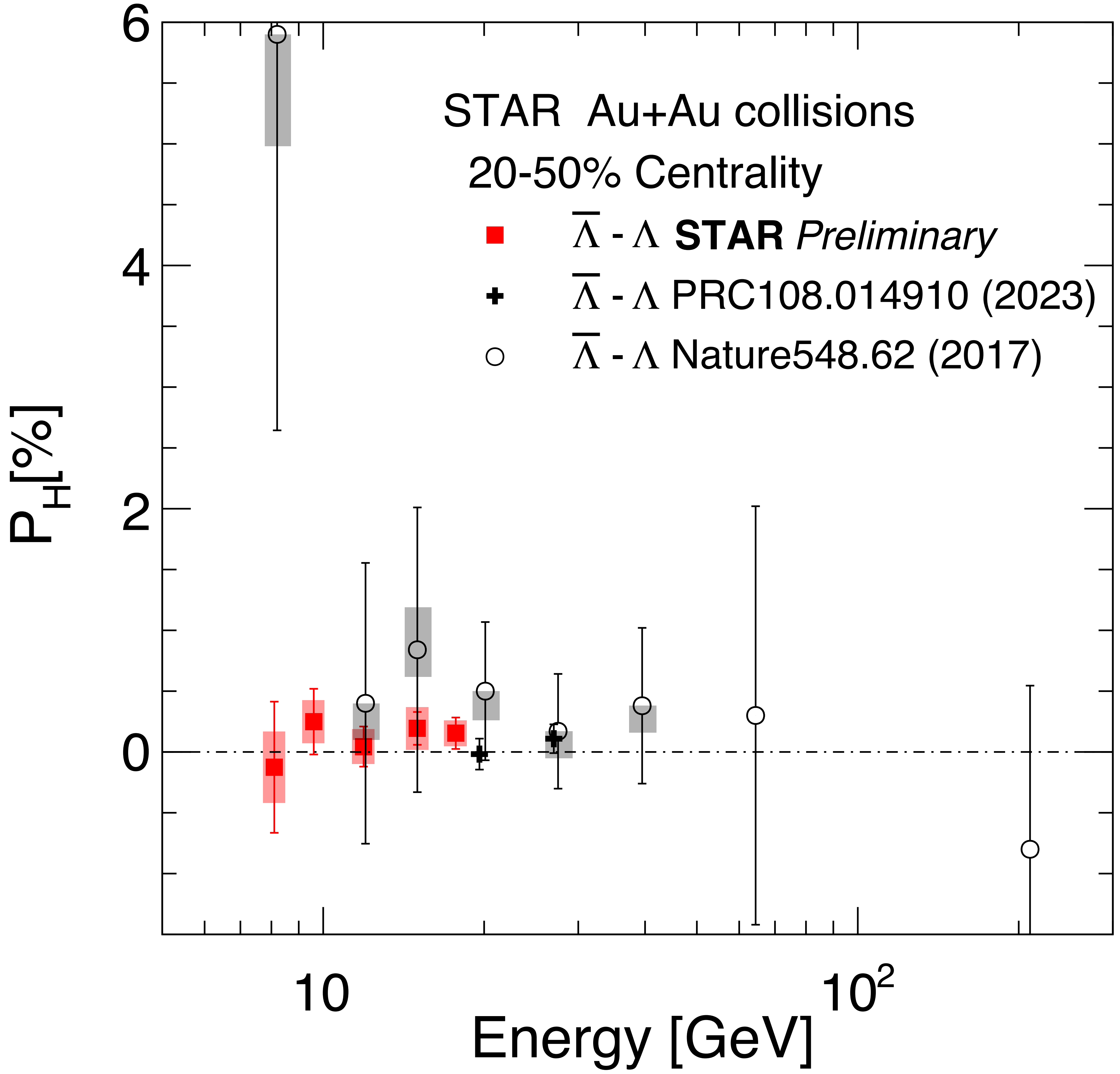
- Challenge for present models to explain rapidity dependence of P_Λ , while they can largely capture its energy dependence at mid-rapidity
- Needed proper modeling of amount of angular momentum deposition along rapidity

The correlation between net-baryon and angular momentum needed to be understood

J Liao, Chirality workshop 2024, Beijing

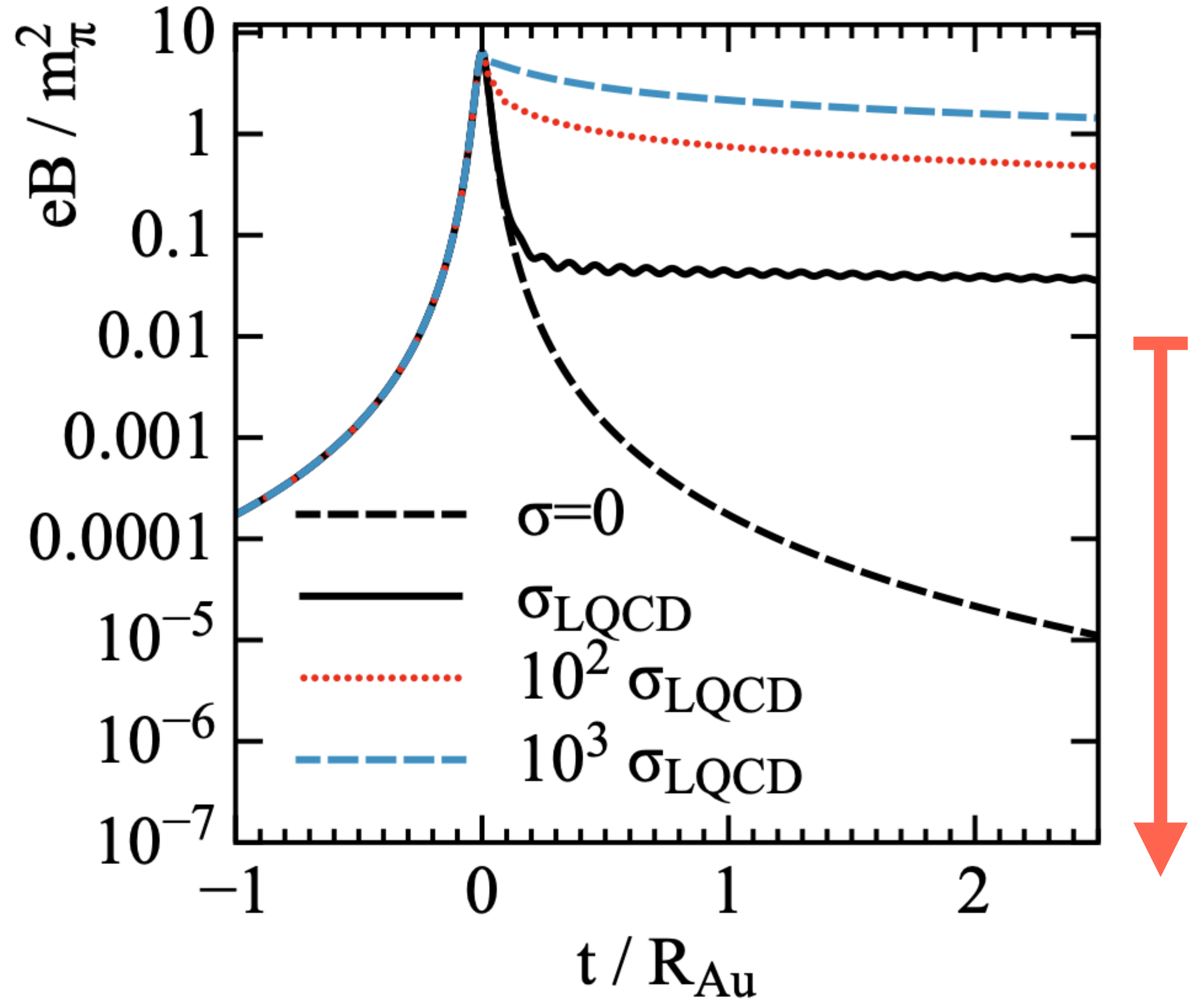
Possible constraint on B field by P_Λ

STAR BES-II



- Magnetic field

$$B \approx \frac{T}{2\mu_\Lambda}(P_\Lambda - P_{\bar{\Lambda}})$$



McLerran and Skokov, Nucl Phys A 929, 184 (2014)

Scenarios can cause Λ and anti-Λ polarization difference:

- Different freeze out for particles and anti-particles
- Different response to mesonic field generated by baryonic current
- …..

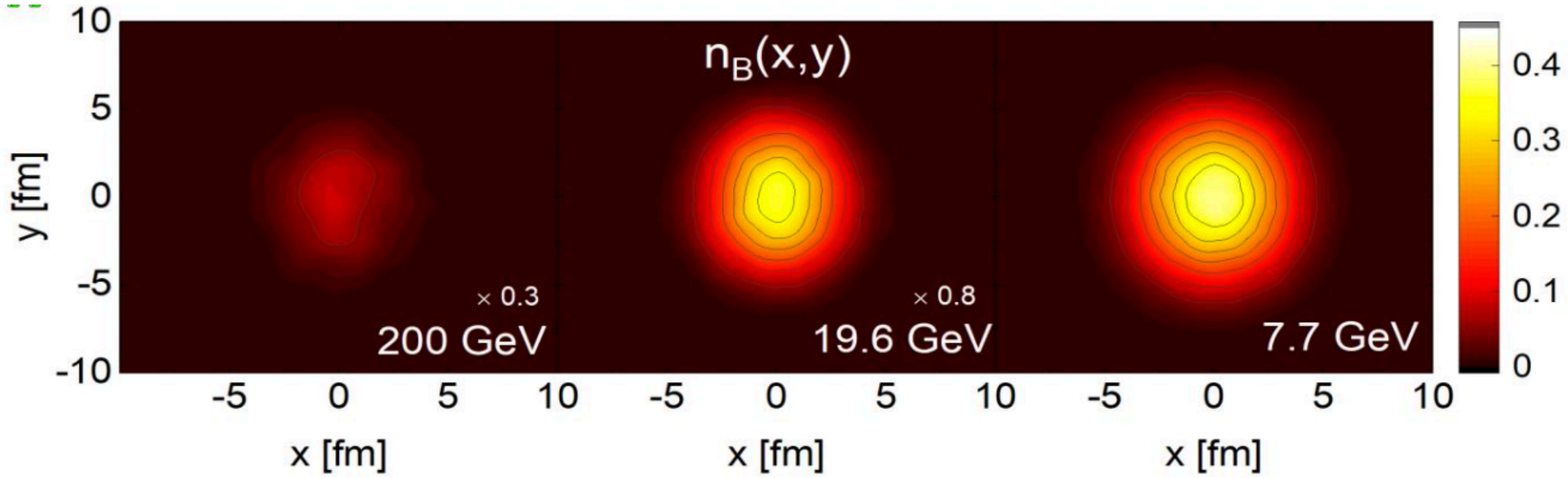
- No difference between Λ, $\bar{\Lambda}$ is observed with BES-II data
- Results set an upper-limit on late stage magnetic-field ($B \leq 10^{13}\ T$)

Baryonic Spin Hall effect (bSHE)

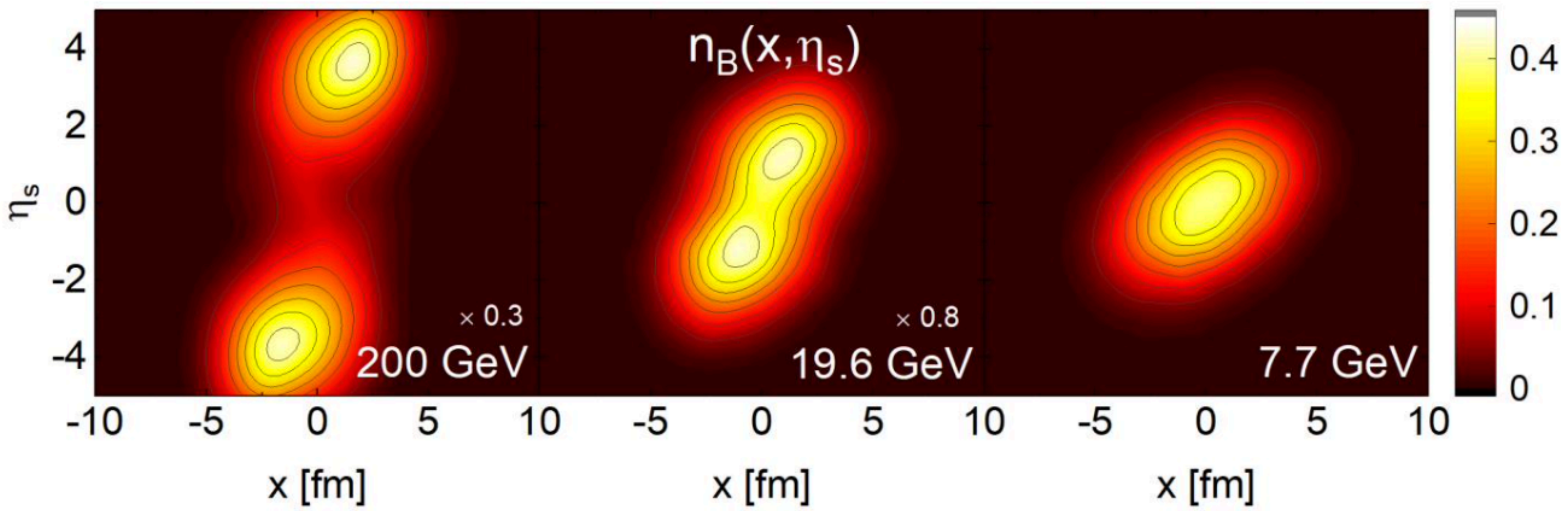
$$\omega = \frac{1}{2}\nabla \times v$$

Baryon density profile

Transverse-plane (x, y)



Longitudinal-plane (x, η)



Fu et., al., arXiv: 2201.12970

Decompose local polarization (naive model)

In-plane polarization

- $P_{2,z} = \langle P_z \sin(2\Delta\phi)\rangle$
- $P_{2,z} = C_1 \times \mathrm{SIP} \oplus C_2 \times \nabla T \oplus C_3 \times \nabla \mu_{B-\mathrm{trans}}$

Out-of-plane polarization

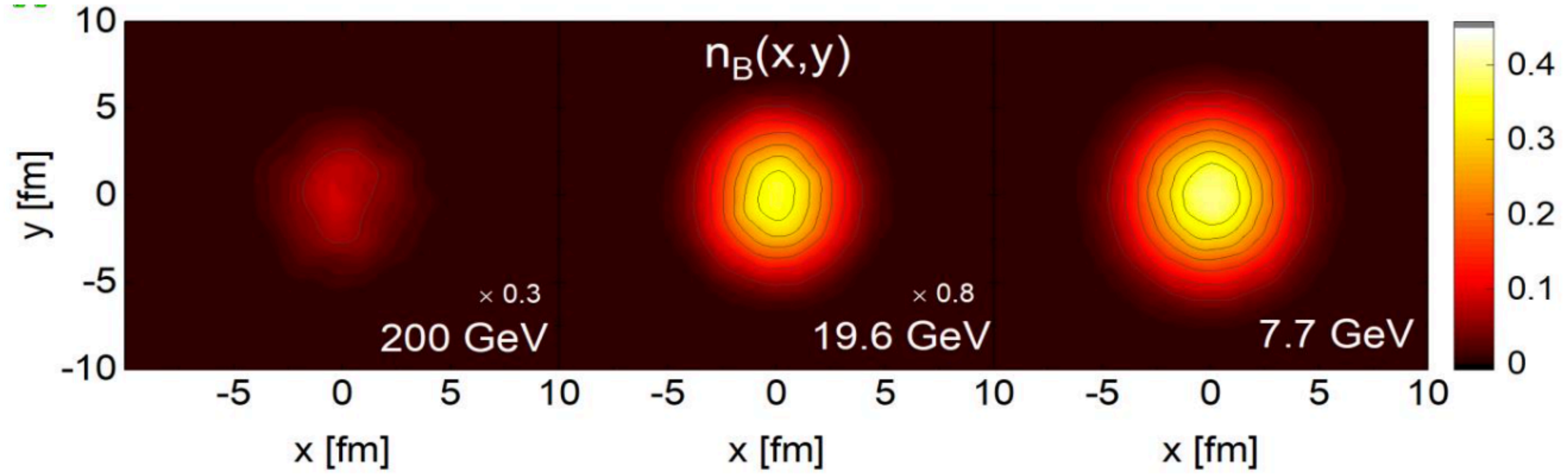
- $P_{2,y} = -\langle P_y \cos(2\Delta\phi)\rangle$
- $P_{2,y} = C_1 \times \mathrm{SIP} \oplus C_2 \times \nabla T \oplus C_3 \times \nabla \mu_{B-\mathrm{long}}$

C_1, C_2 and C_3 can naively considered as medium response to Shear, Thermal gradient and chemical potential (unknowns)

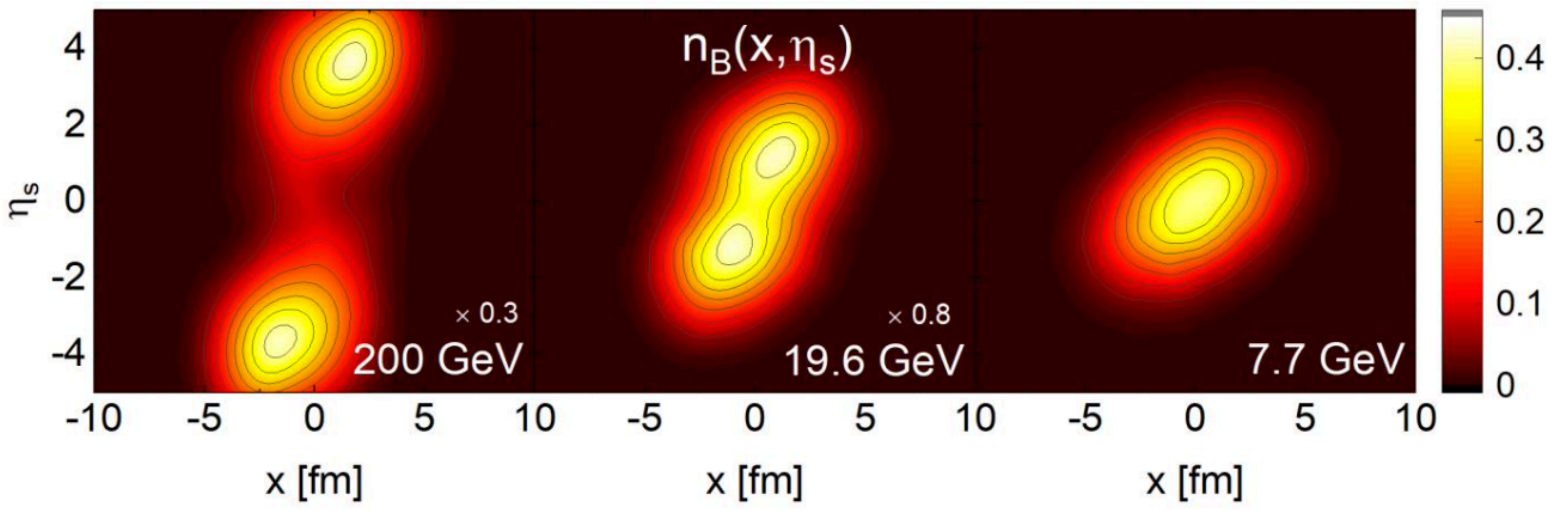
Baryonic Spin Hall effect (bSHE)

Baryon density profile

Transverse-plane (x, y)



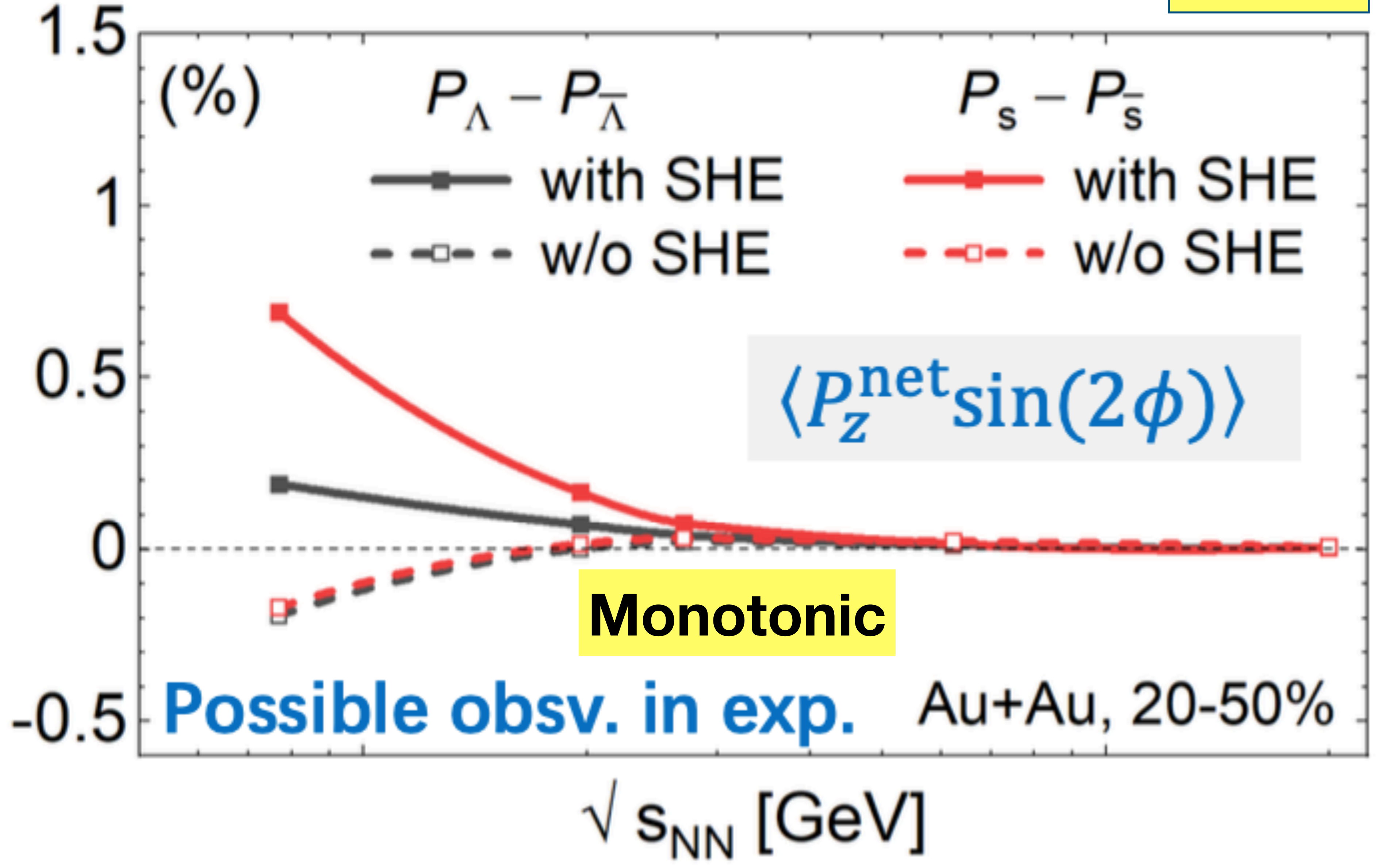
Longitudinal-plane (η, x)

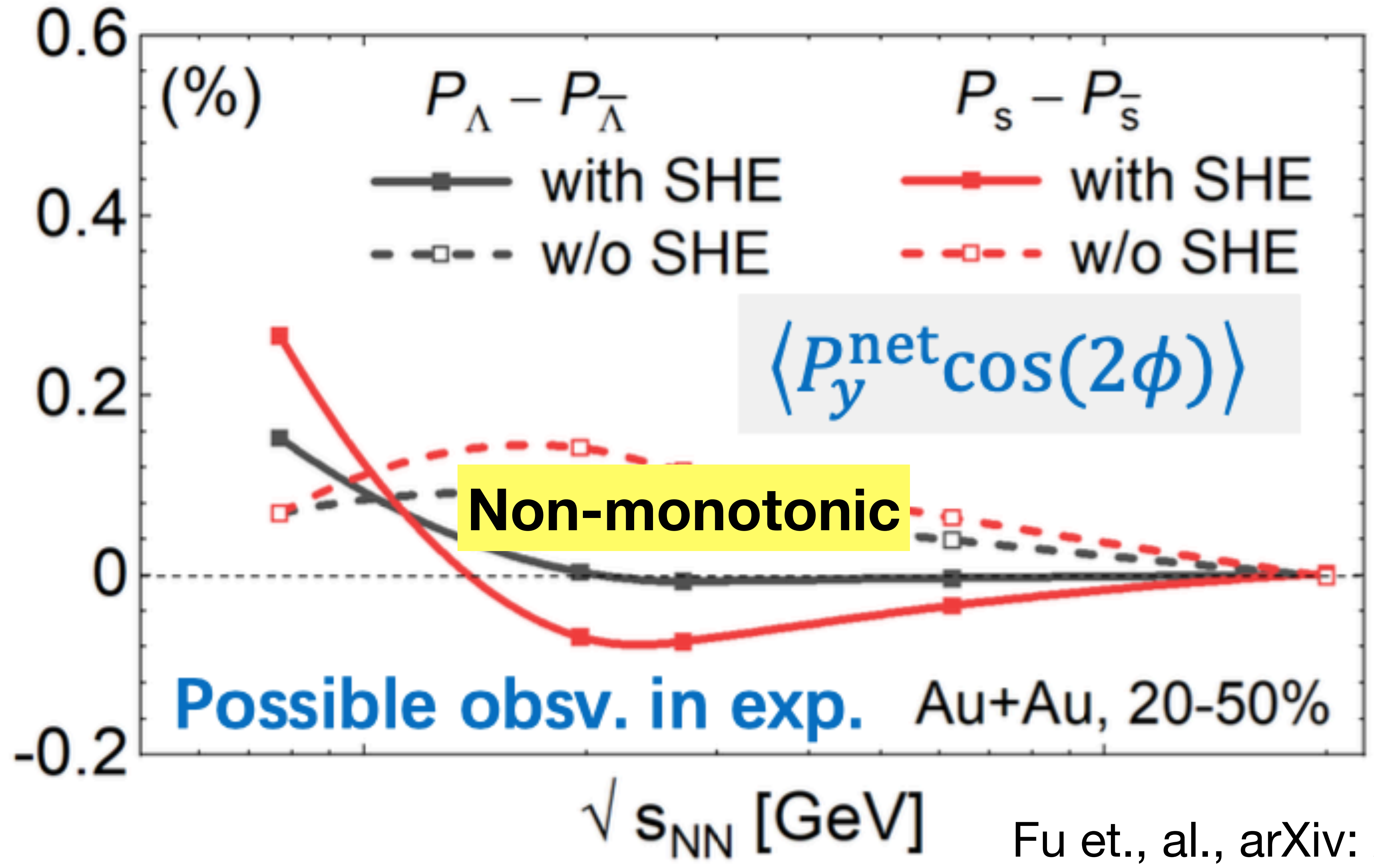


Local polarization: ($\Lambda - \overline{\Lambda}$)

- In-plane: monotonic increase
- Out-of-plane: non-monotonic increase

$\Lambda - \overline{\Lambda}$

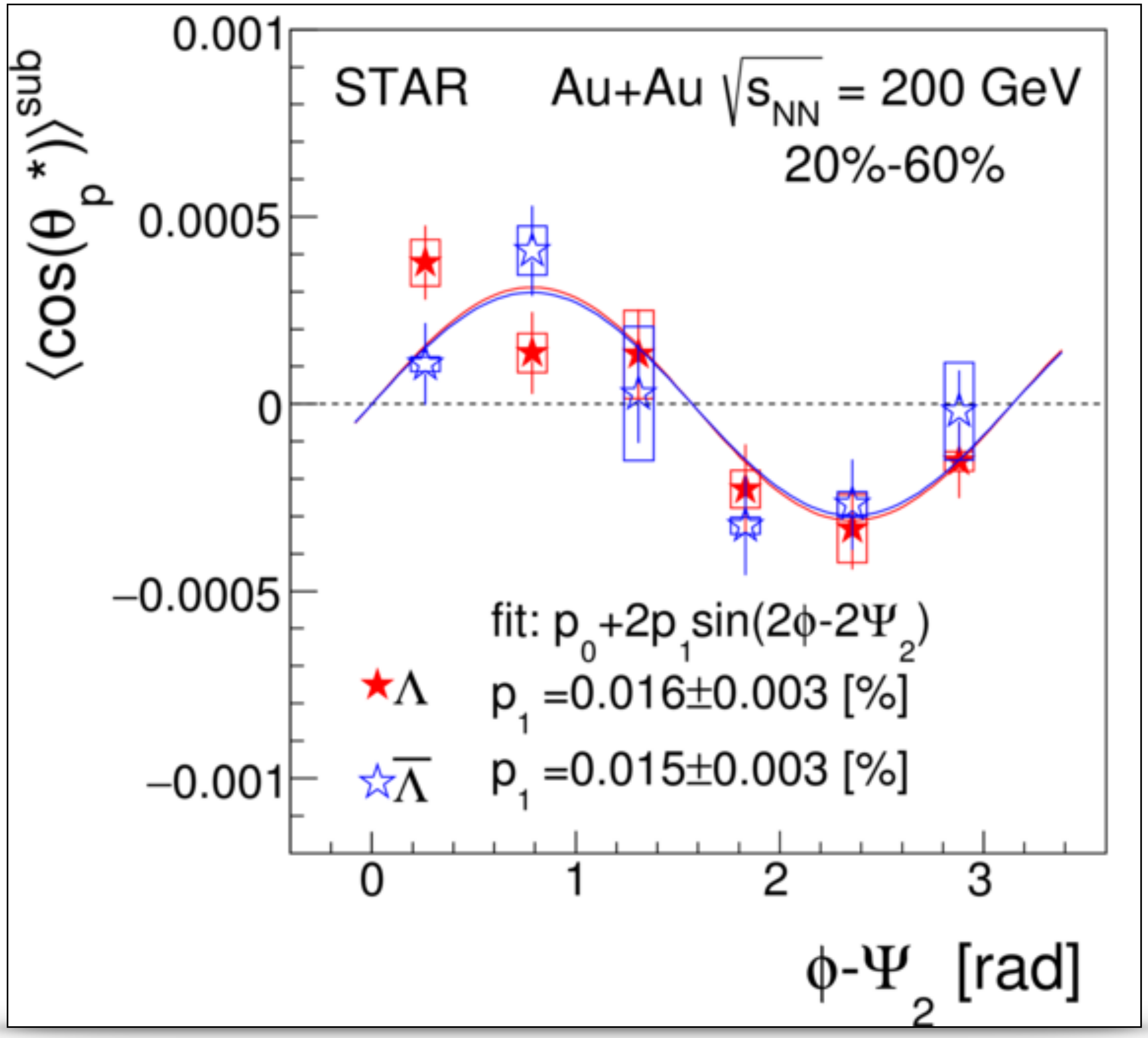




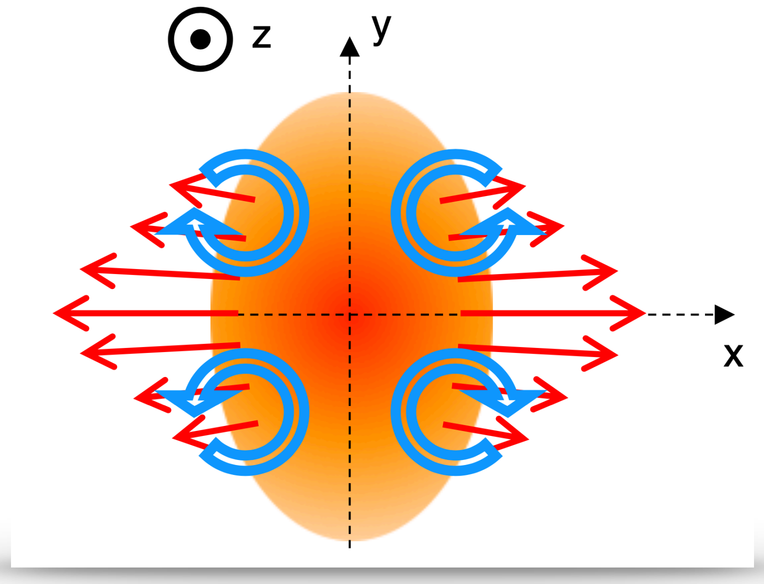
Fu et., al., arXiv: 2201.12970

Local (P_z) spin polarization of hyperons

STAR: Phys Rev Lett 123, 132301 (2019)



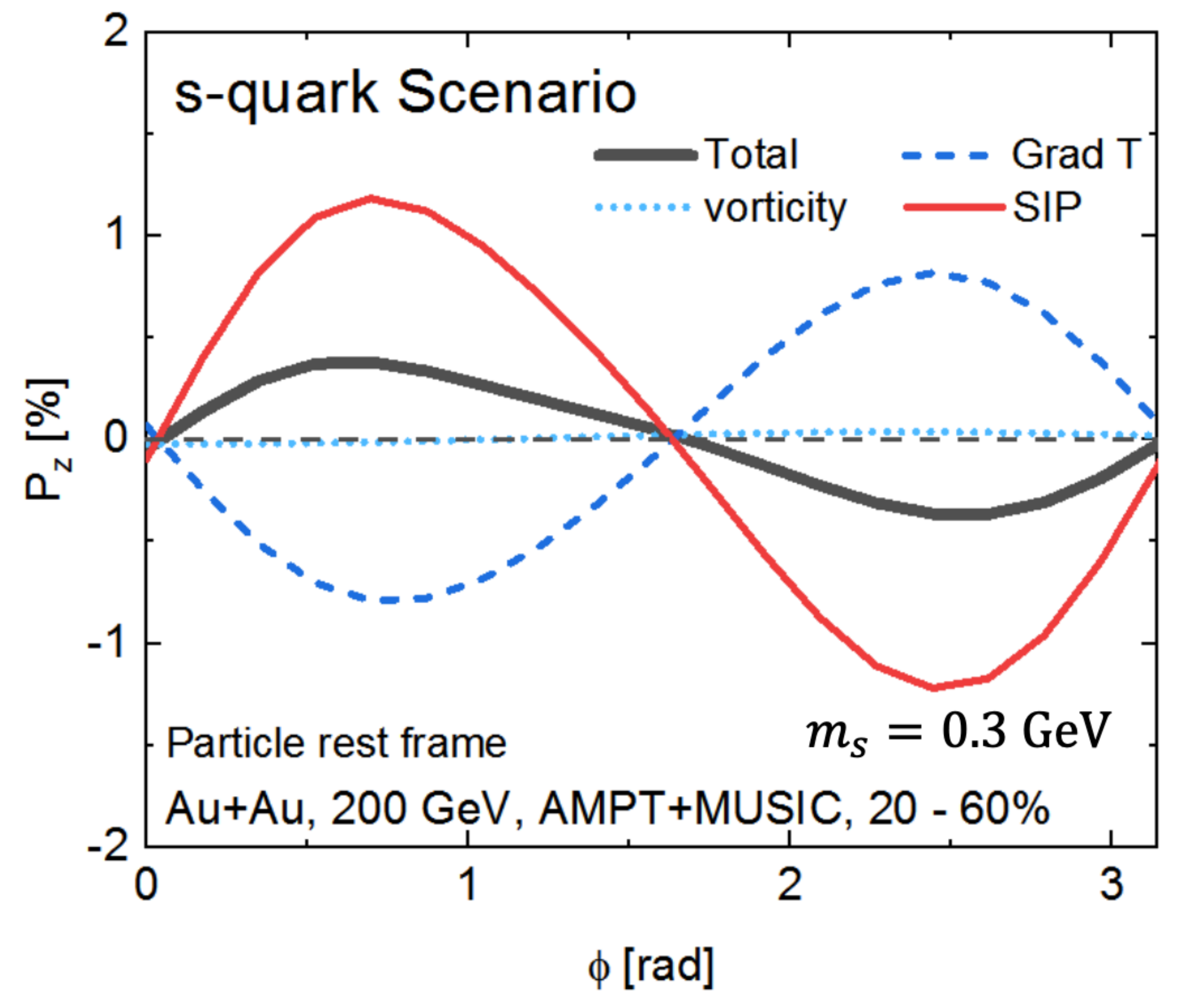
$P_{2,z}$ shows significant centrality dependence expected from elliptic flow

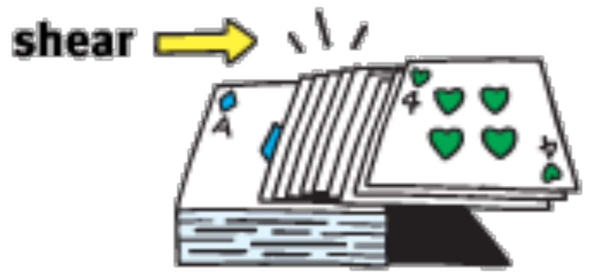


<u>One of the scenario:</u>

<u>Shear Induced Polarization (SIP)</u>

Total = vorticity ⊕ ∇T ⊕ Shear

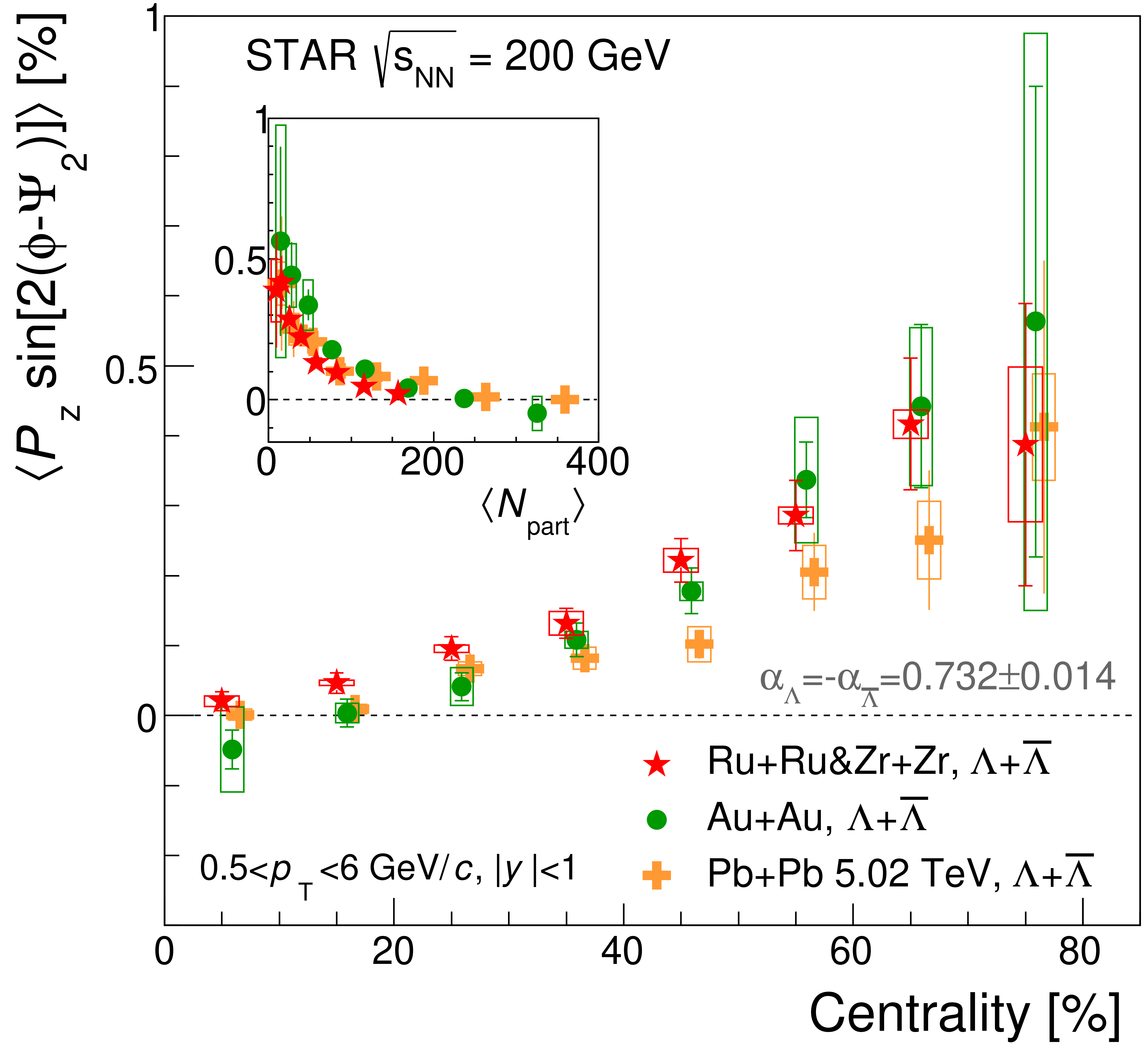




Fu et., al, Phys Rev Lett 127, 142301 (2021)

Amplitude of sine-modulation sensitive to hydrodynamic gradients

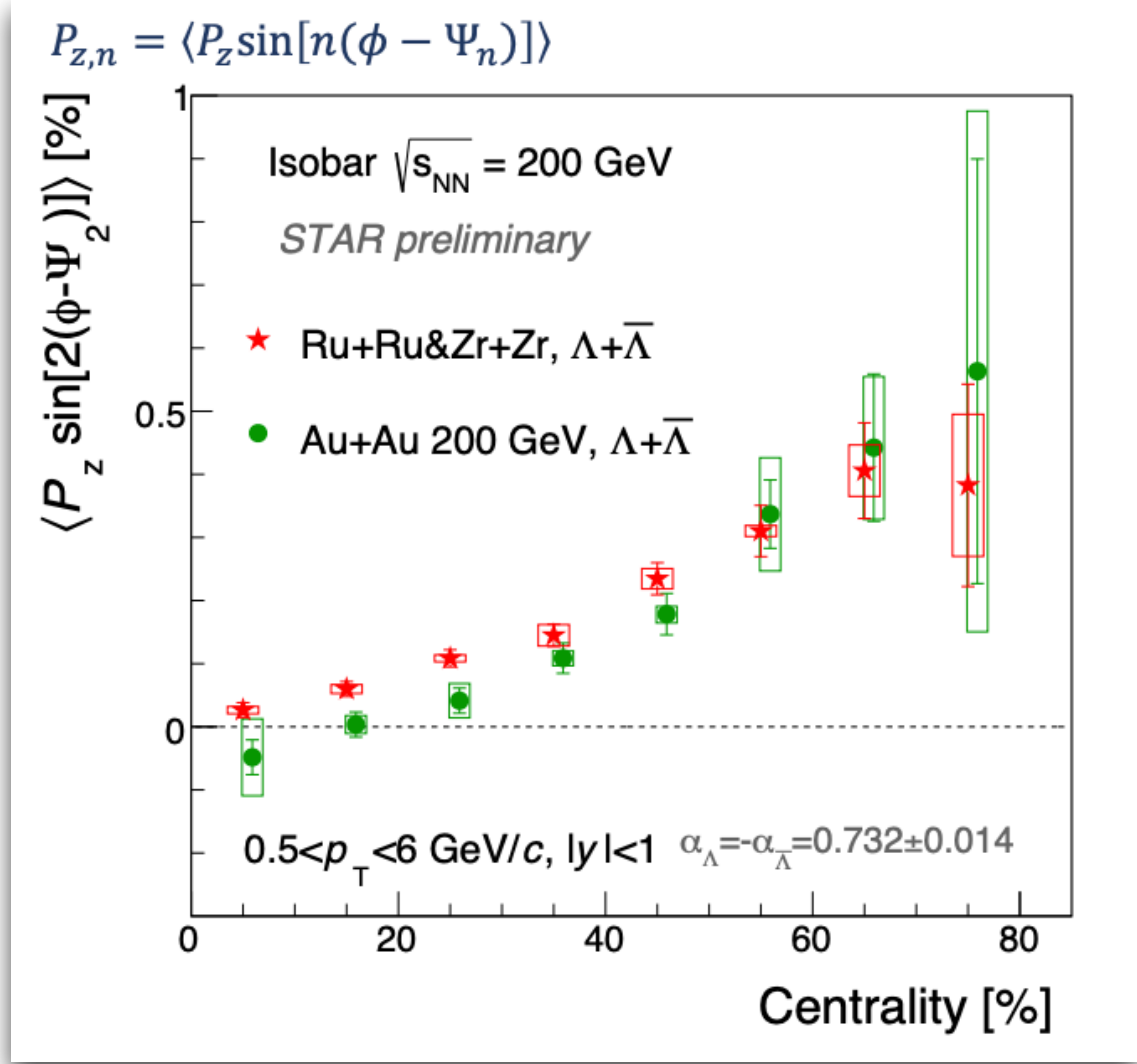
Local (P_z) spin polarization of hyperons



- Clear centrality dependence of P_z
- At mid-central collisions Zr+Zr,Ru+Ru > Au+Au ~ Pb+Pb
- Hints of system size dependence, No obvious energy dependence

STAR: Phys Rev Lett 123, 132301 (2019)
STAR: Phys Rev Lett 131, 202301 (2023)
ALICE: Phys Rev Lett 128, 172005 (2022)

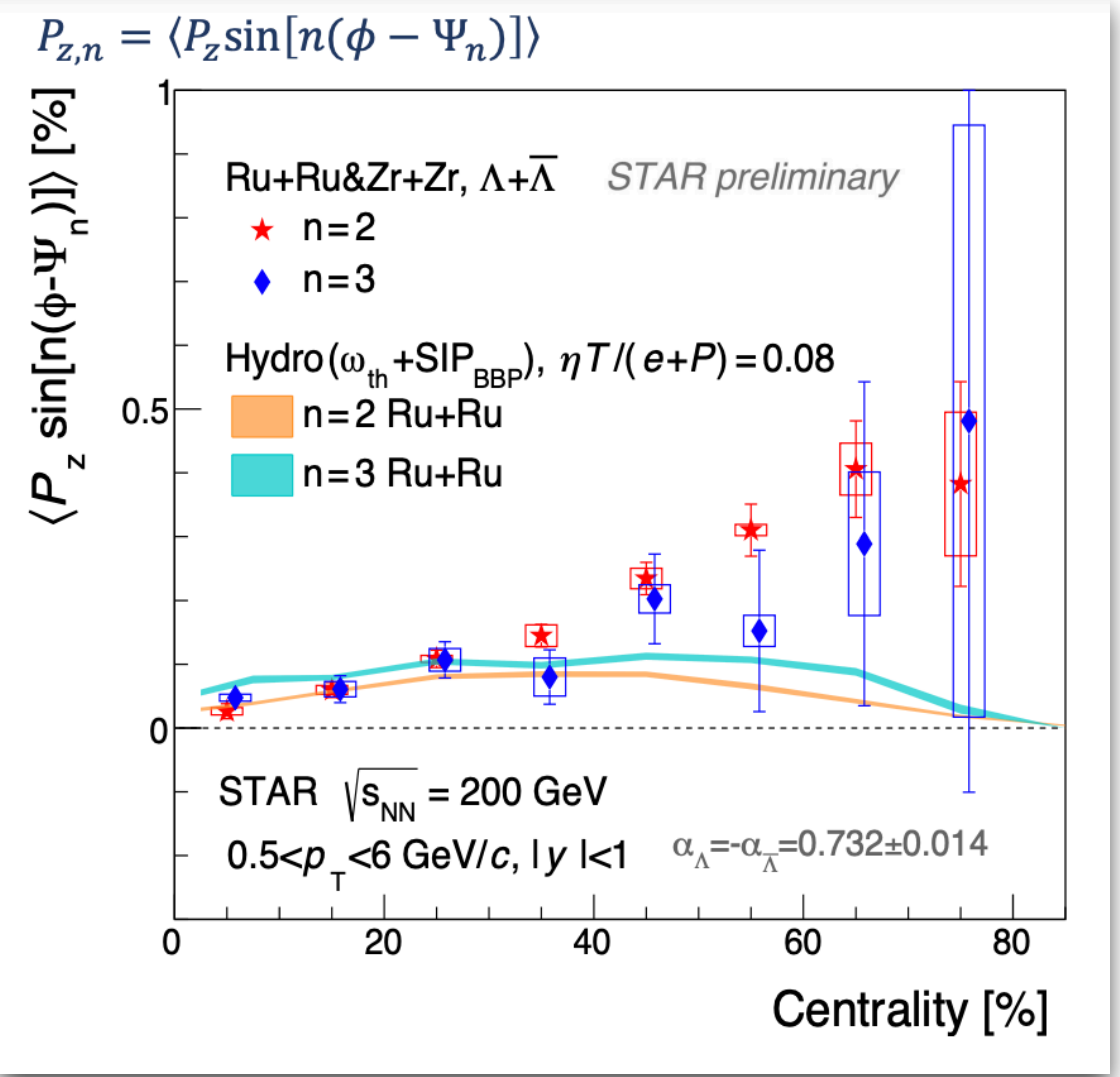
System size and energy dependence of P_z



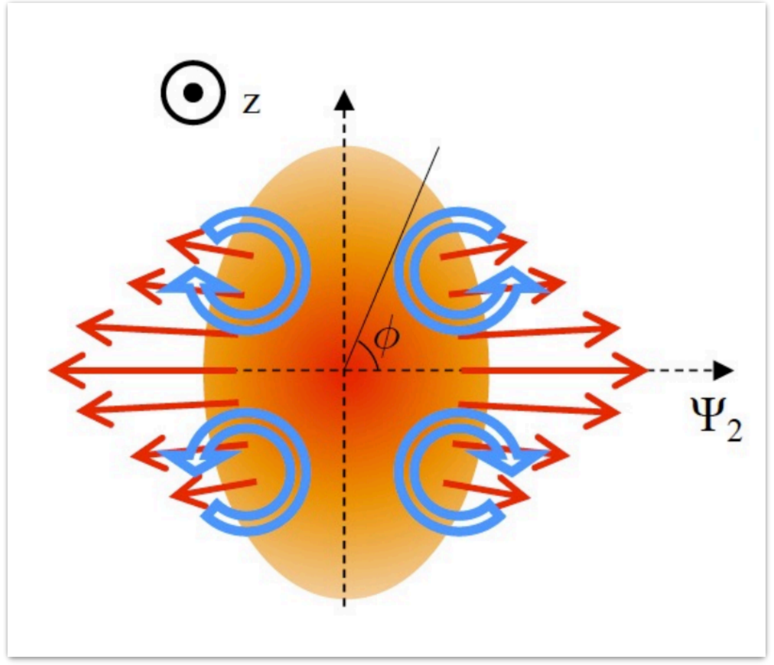
- At mid-central collisions Zr+Zr,Ru+Ru > Au+Au
- Hints of system size dependence

STAR: Phys Rev Lett 123, 132301 (2019)

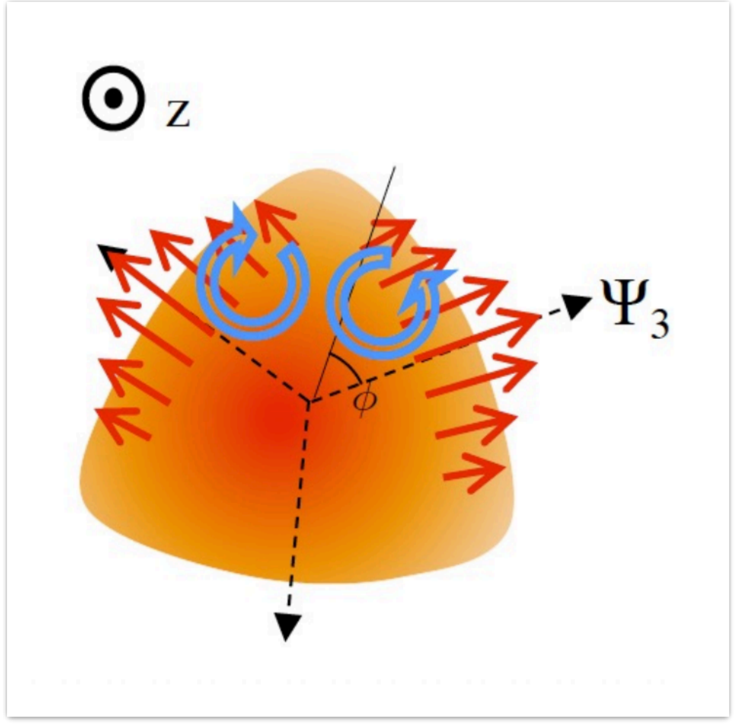
Event plane harmonic dependence of P_z



Alzhrani et. al., arXiv: 2203.15718



Vs.



- Significant local polarization wrt 3rd order event plane
  $P_z(\Psi_3) \sim P_z(\Psi_2)$
- Results can provide information on complex vortical structures; constrain on initial conditions, transport parameters …