

Measurement of Global Spin Polarization at RHIC

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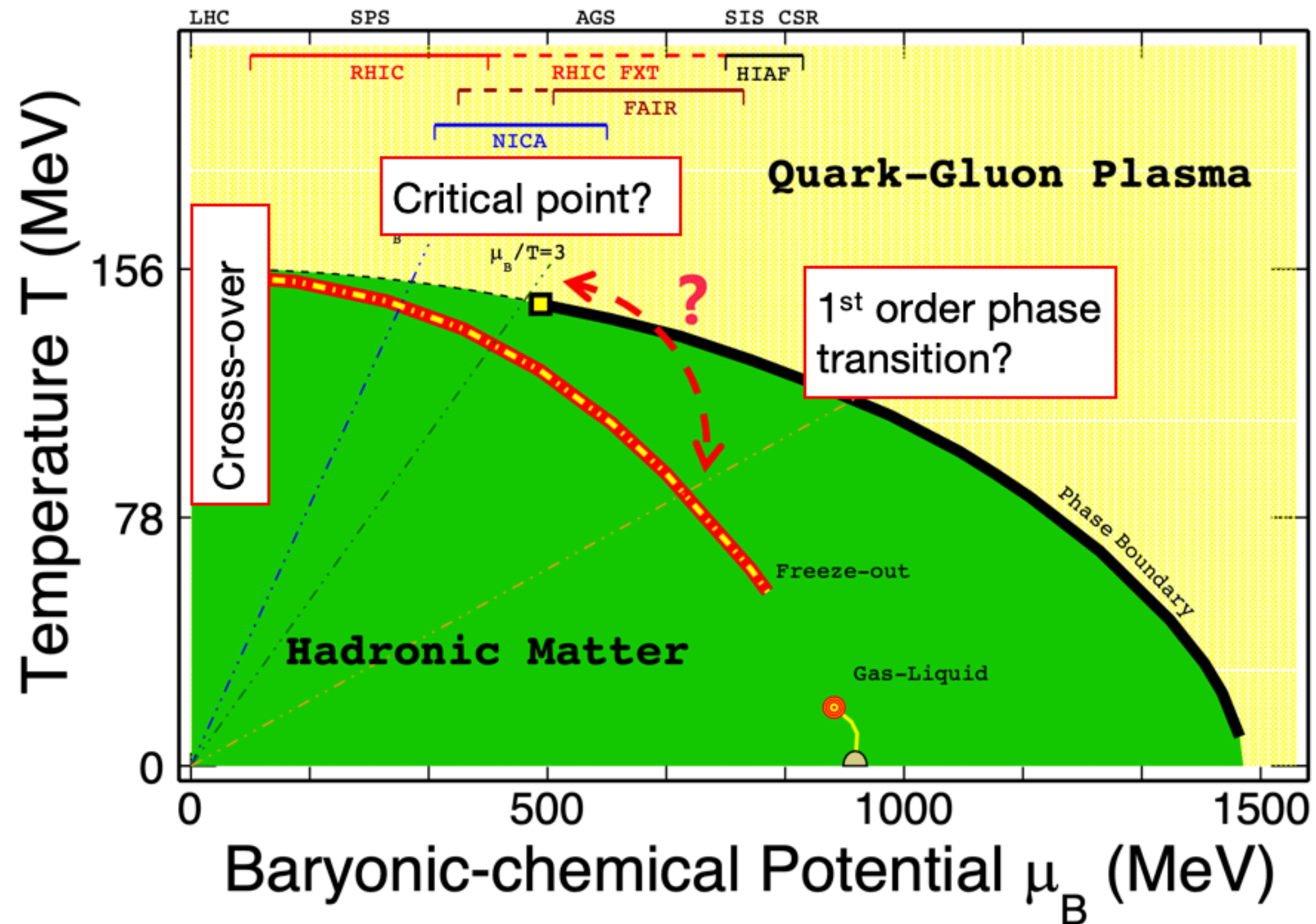


Outline

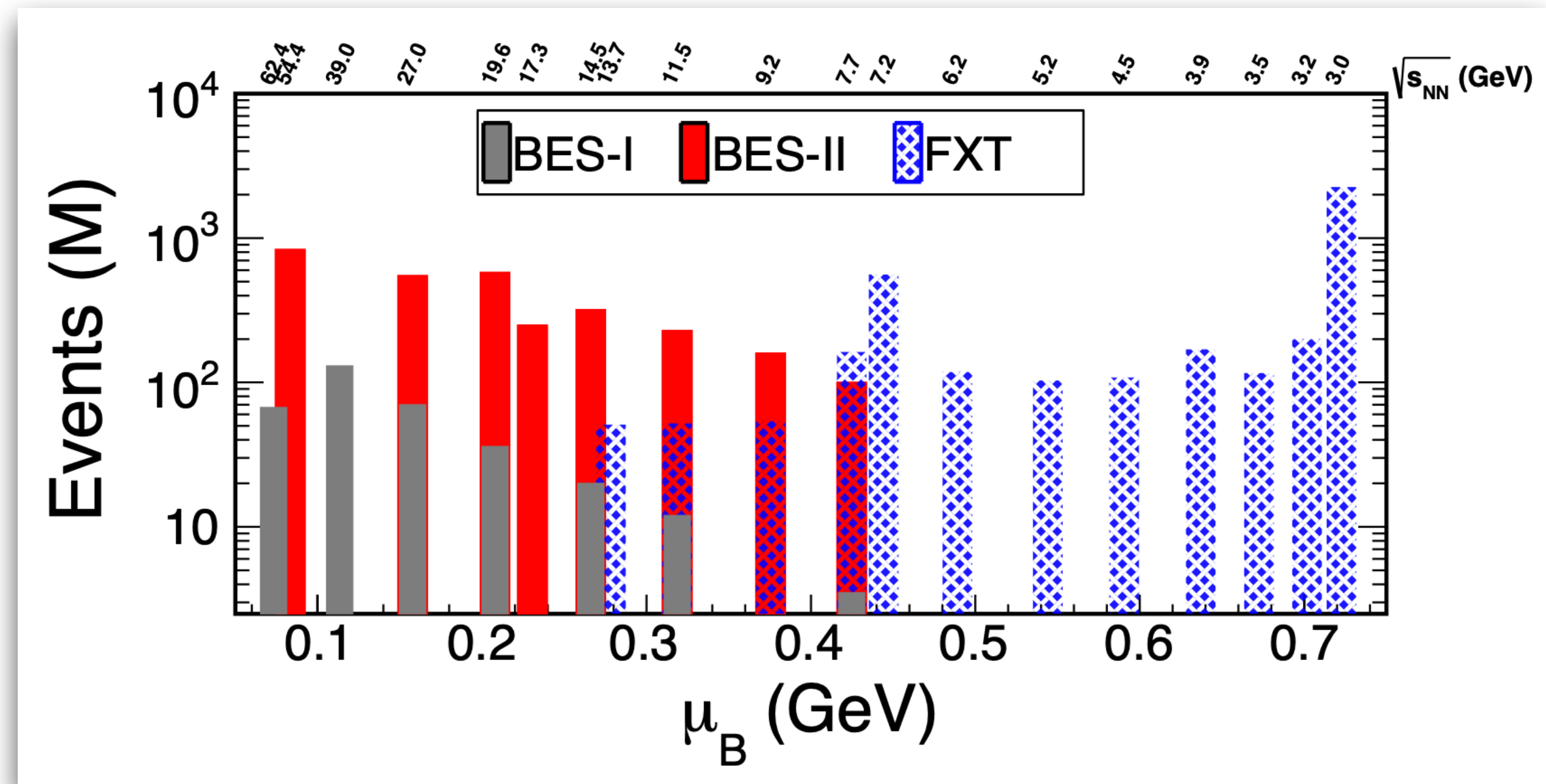
- RHIC Beam Energy Scan Program
- Experimental results:
 - Global spin polarization (Beam-energy, centrality & rapidity dependence)
 - Local spin polarization (Beam-energy, baryonic SHE)
 - Opportunities at high baryon density region
- Summary

RHIC BES program

Phase diagram of QCD



BES Program:



RHIC Beam Energy Scan (BES):

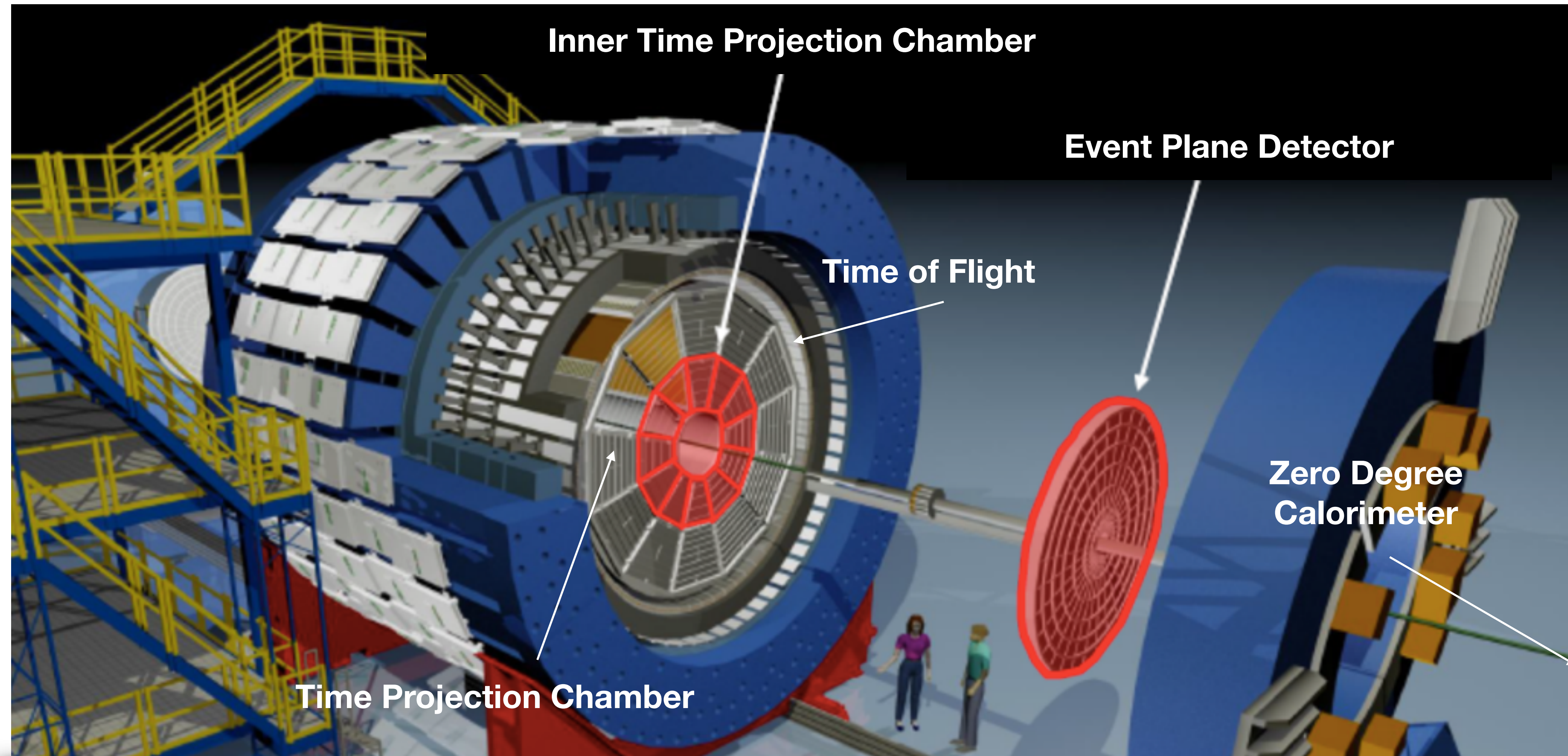
- Find signatures of Phase Transition
- QCD Critical point
- Turn-off of QGP signatures

Collider: 7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27, 39, 54.4, 62.4, 200 (GeV)
Fixed Target: 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7, 9.2, 11.5, 13.7 (GeV)

High statistics data and detector upgrade in BES-II

→ most precise data to map the QCD phase diagram

STAR Detector



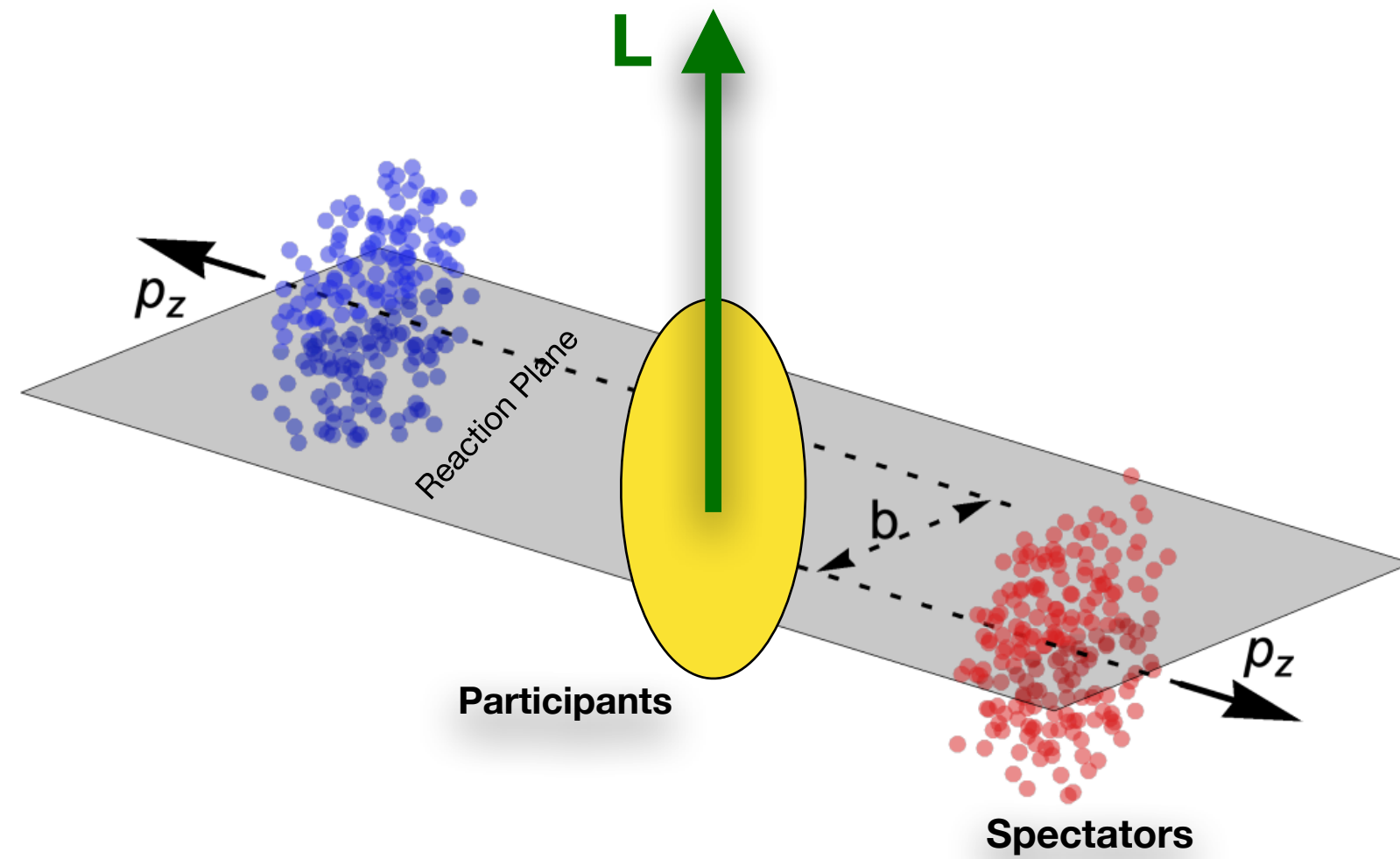
- Uniform acceptance, full azimuthal coverage, excellent PID capability
- TPC: tracking, centrality and event plane
- EPD, ZDC, BBC: event plane (polarization axis, perpendicular to event plane)
- TPC+TOF: particle identification

Motivation

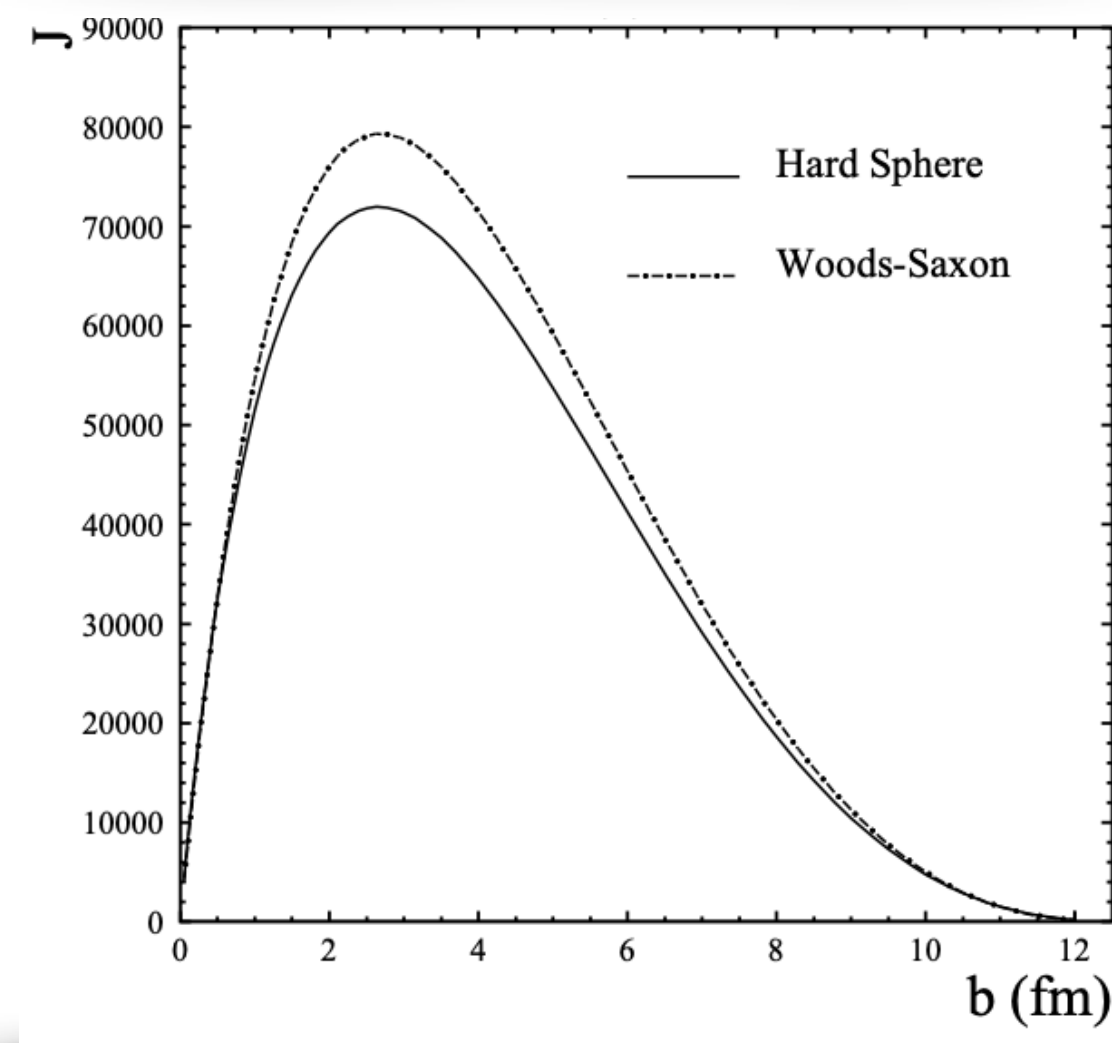
In non-central heavy-ion collisions

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

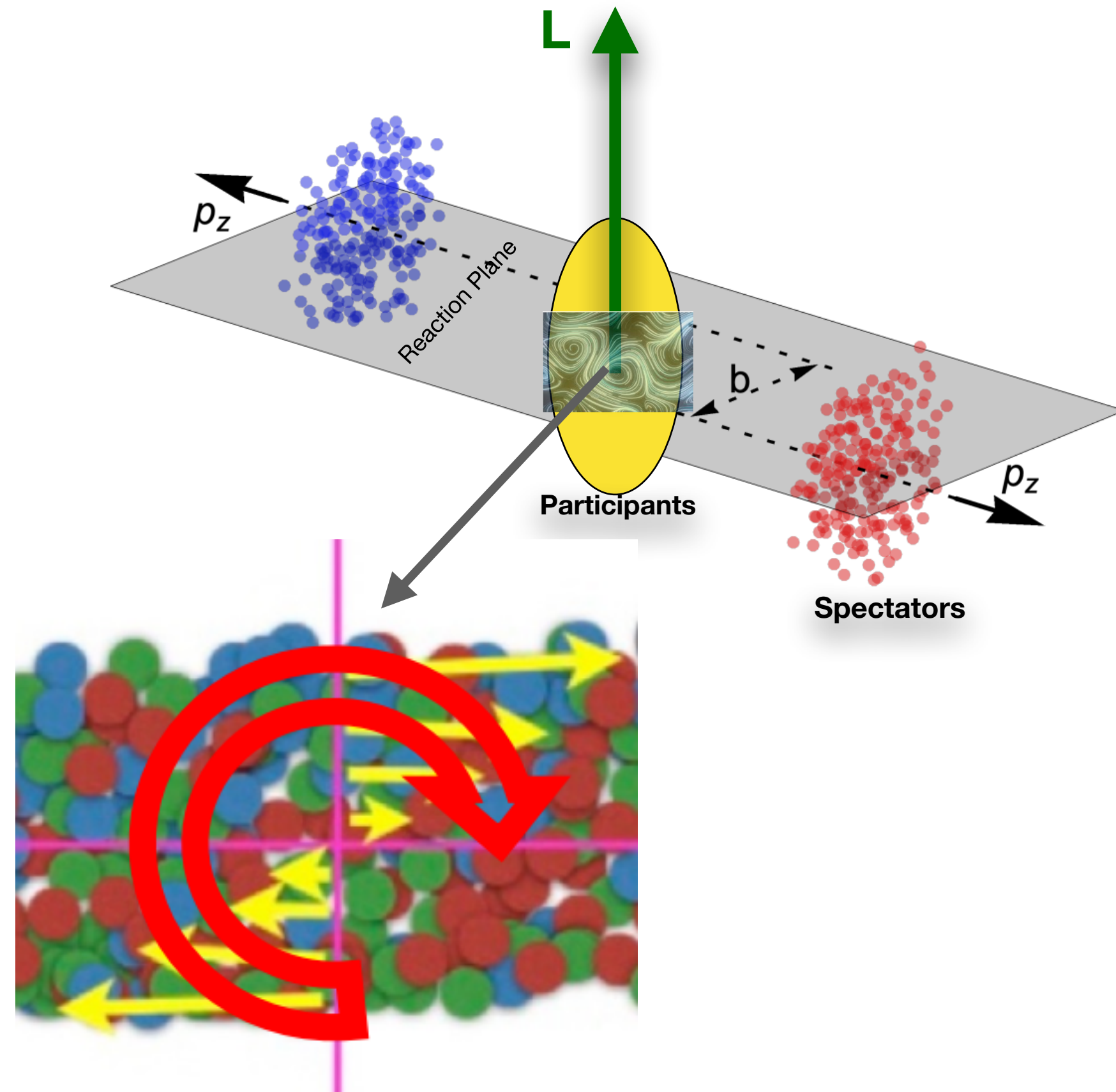
$$L = r \times p \sim bA\sqrt{s_{\text{NN}}} \sim 10^4 \hbar$$



Angular momentum



Motivation



Vorticity generation

In non-central heavy-ion collisions

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

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

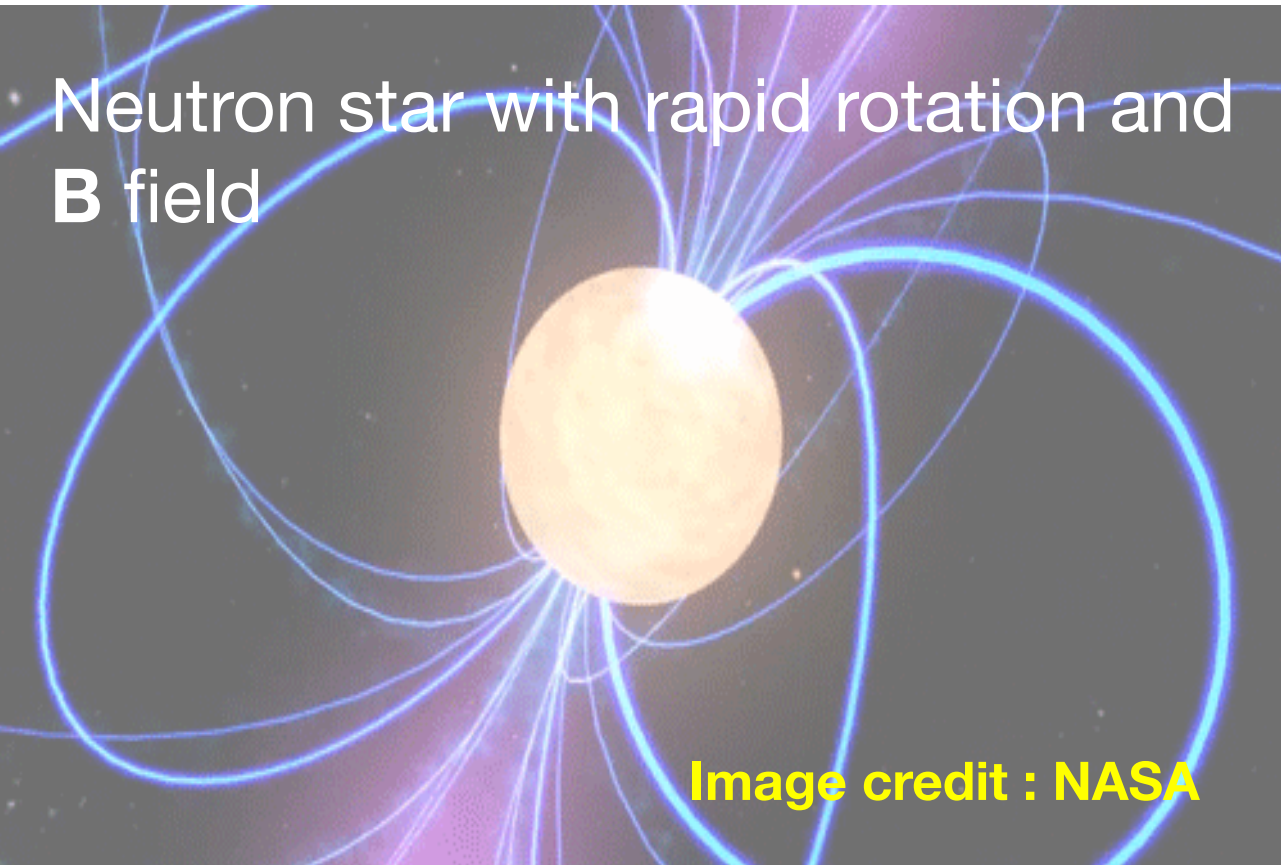
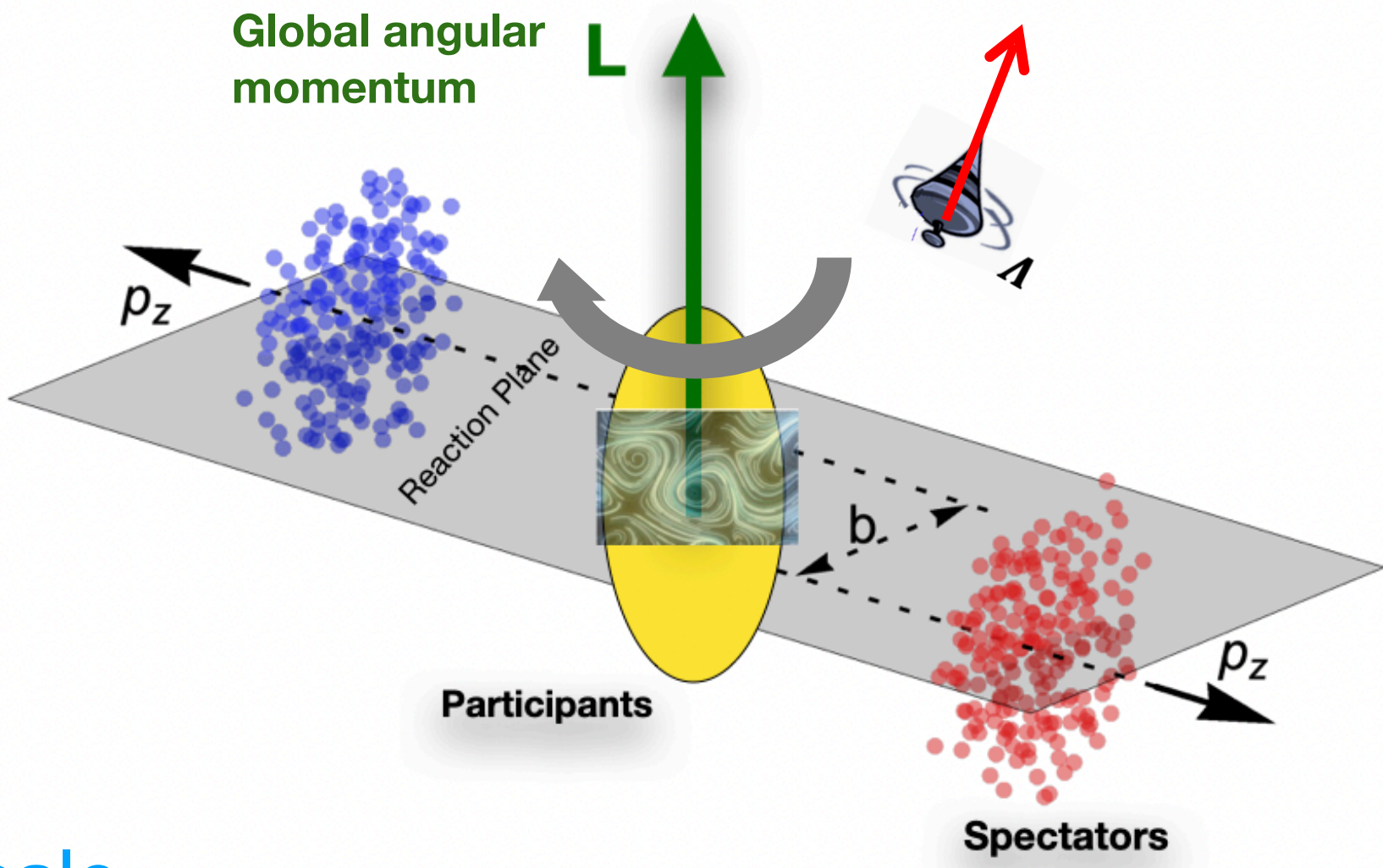
- Gradient of longitudinal flow velocity $\rightarrow$ vorticity along orbital angular momentum

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

- 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)

QCD matter under rapid global rotation



Scale



Major question:
How angular momentum distributed into the system?

Allows to study properties of the system

Vorticity	(s^{-1})
Tornado	10^{-1}
Superfluid He	150
Heavy-ion collisions	$10^7 - 10^{21}$

Heavy-ion collisions create rapidly rotating QCD matter in laboratory → controlled experiment

Measurement global spin polarization

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

$$\bullet \frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H \mathbf{P}_H^* \cdot \mathbf{p}_d^*)$$

$\mathbf{P}_H$: Hyperon polarization

α_H : Hyperon decay parameter

$\mathbf{p}_d$: Daughter momentum direction

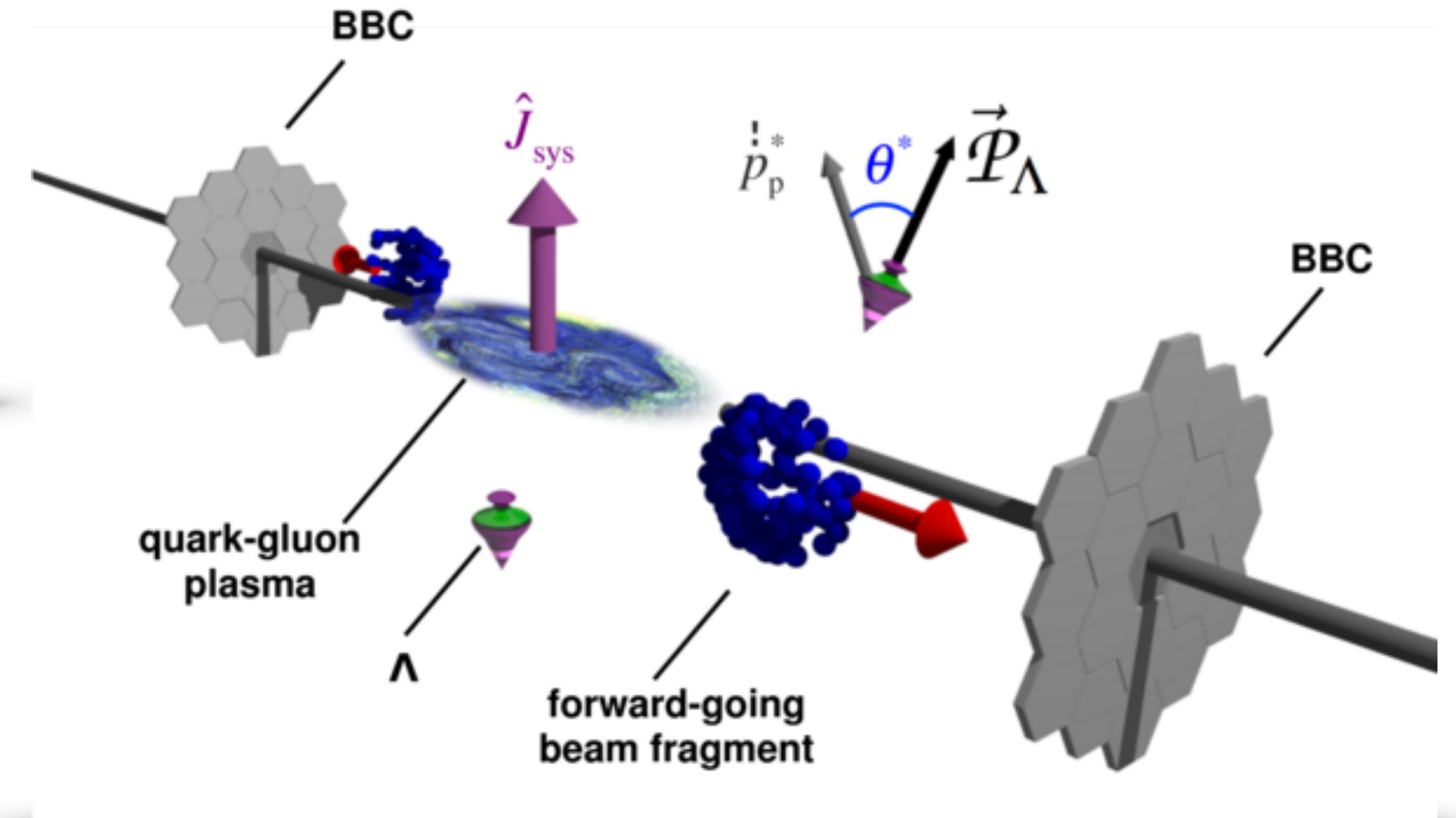
* : Measurements in parent's rest frame

Component perpendicular to reaction plane:

$$\bullet P_H = \frac{8}{\pi\alpha_H} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\text{Res}(\Psi_1)}$$

ϕ_d : Daughter azimuthal angle

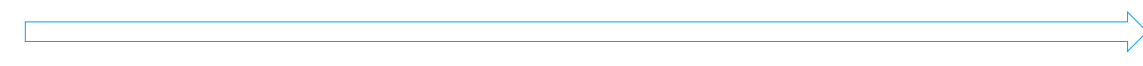
Ψ_1 : 1st order event plane



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

Observation of global polarization of Λ hyperons

First prediction in 2005



Discovery in 2017

Globally Polarized Quark-Gluon Plasma in Noncentral $A + A$ Collisions

[Zuo-Tang Liang](#)¹ and [Xin-Nian Wang](#)^{2,1}

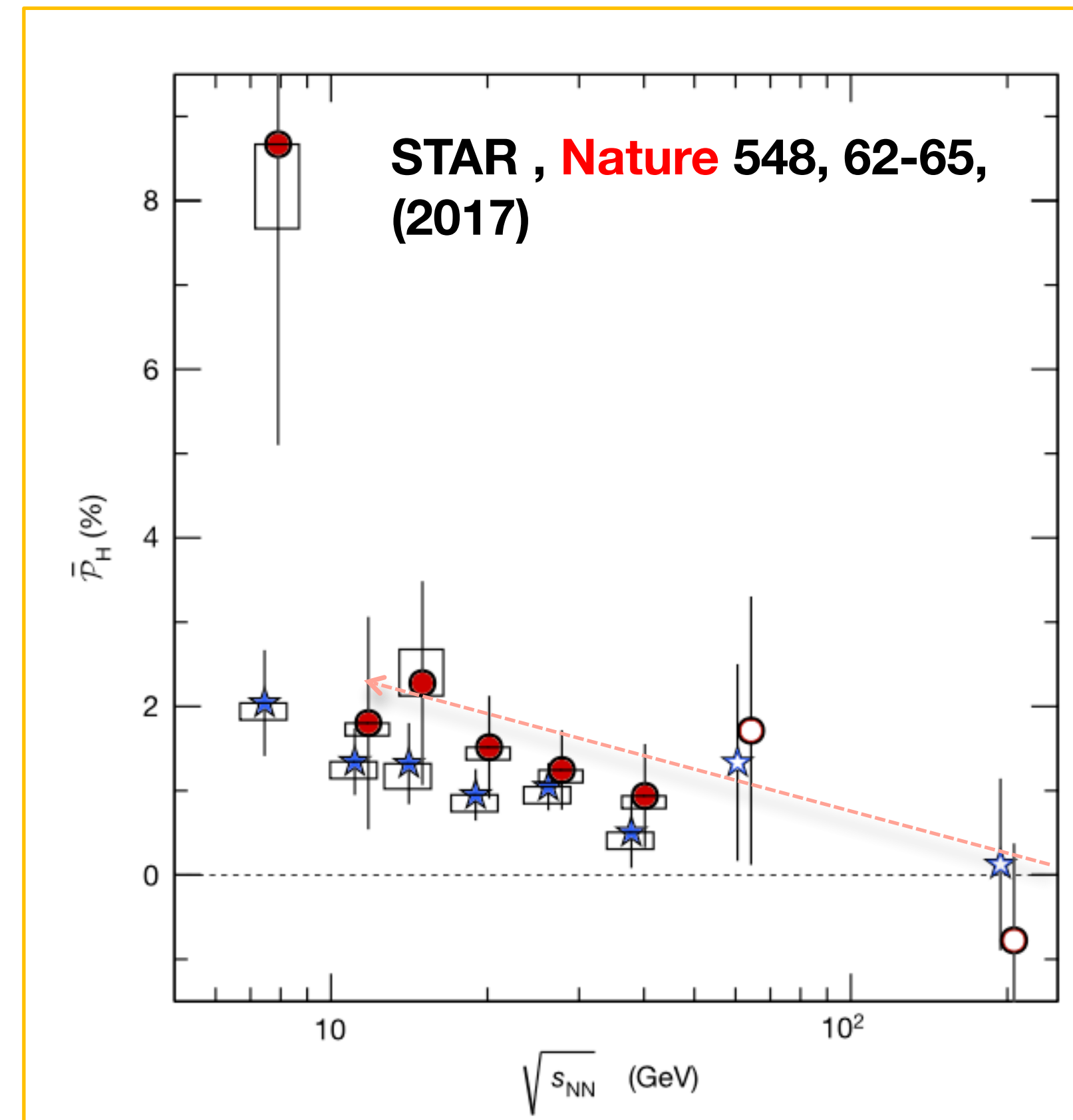
Show more

Phys. Rev. Lett. **94**, 102301 – Published 14 March, 2005 | Erratum Phys. Rev. Lett. **96**, 039901 (2006)

DOI: <https://doi.org/10.1103/PhysRevLett.94.102301>



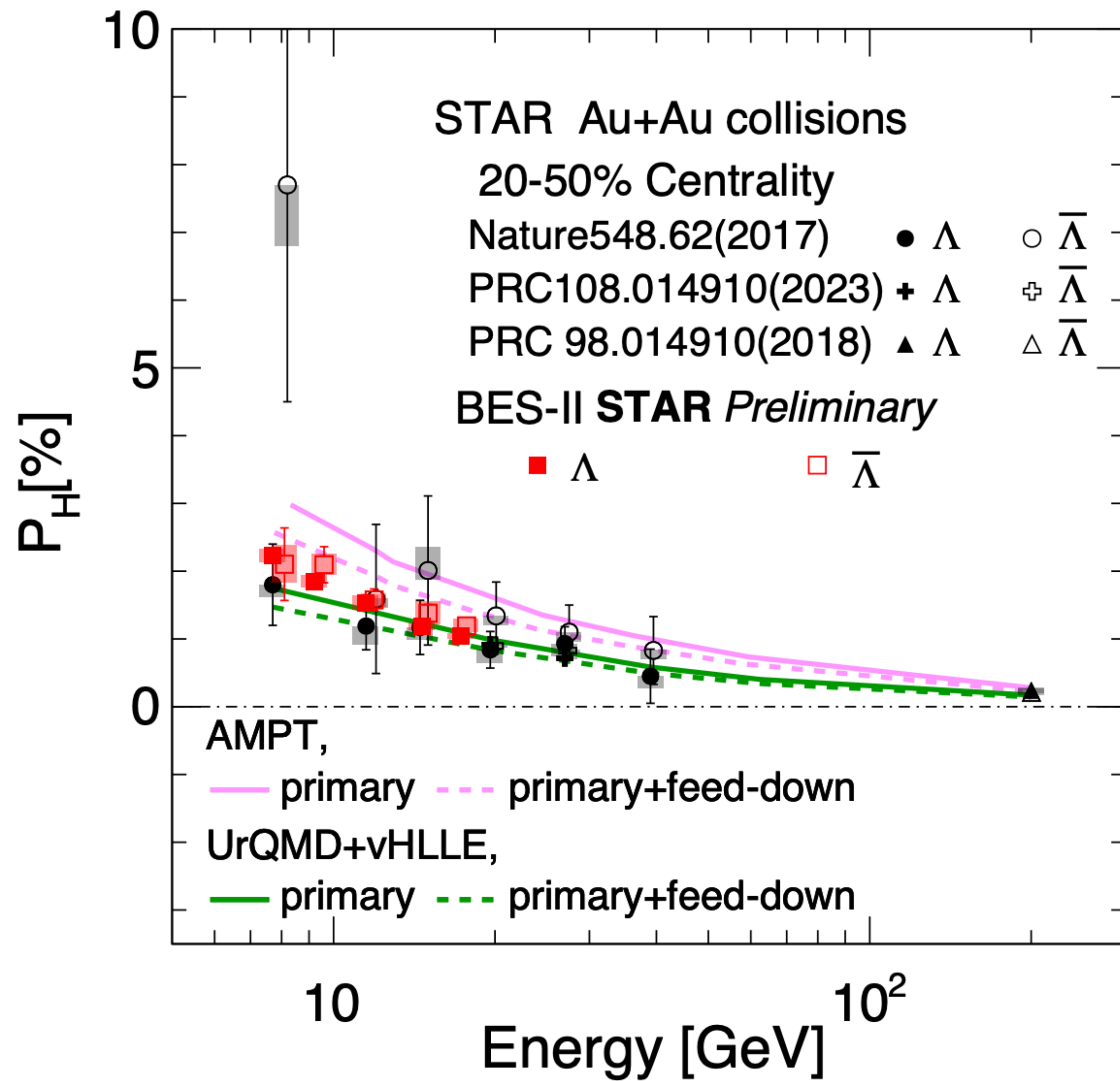
like a global rotation of QGP



- Discover the Evidence of **vorticity** ($\sim 10^{21} \text{ s}^{-1}$) in Quark Gluon Plasma
- Opened new avenue of research: probe spinning QGP matter under extreme rotation

Global polarization: beam energy dependence

Beam energy dependence of global P_Λ

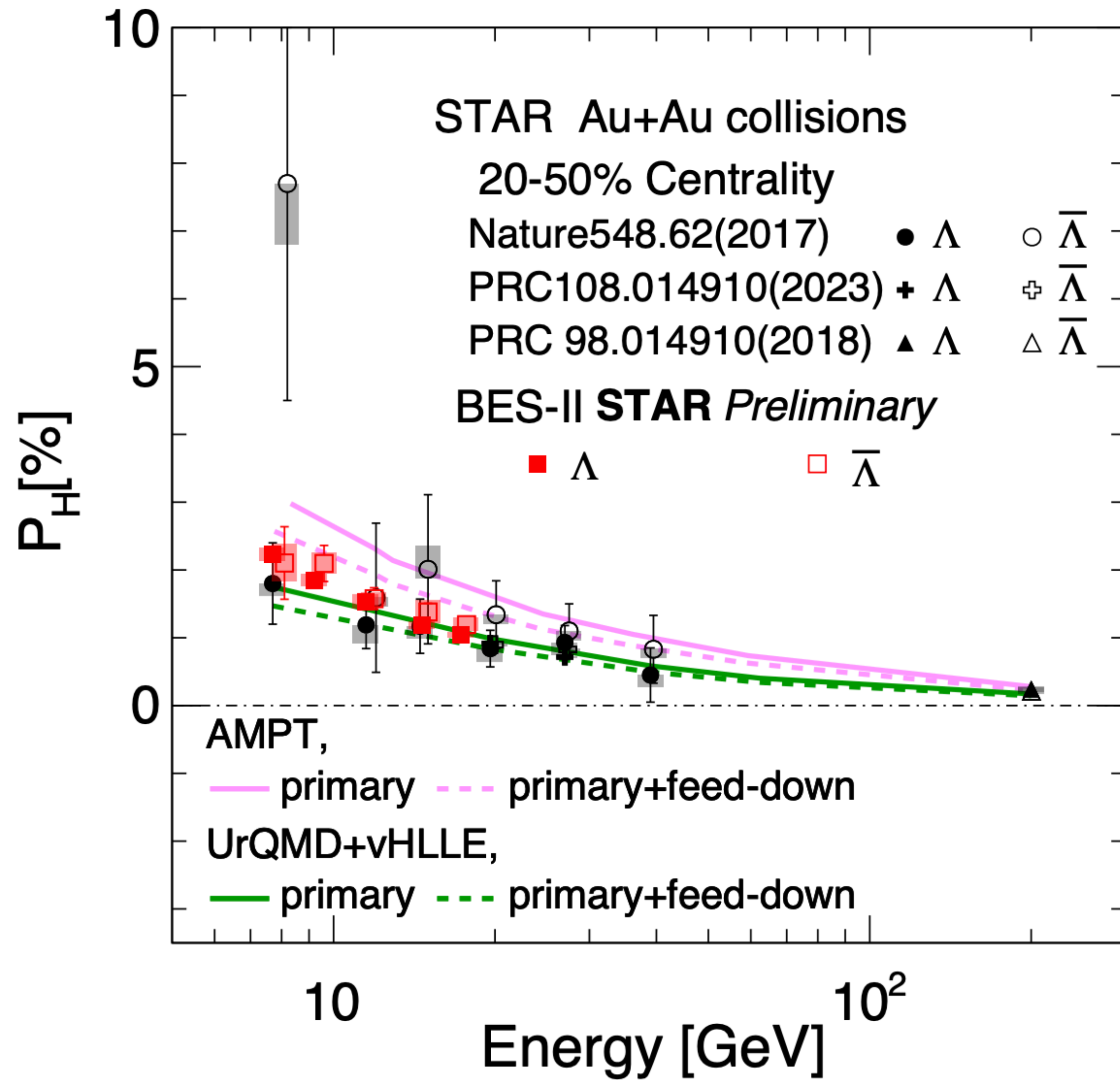


- BES-II: uncertainty reduced by a factor ~ 9
- P_Λ smooth increase with decrease in beam energy
- Models can capture the energy dependence trend

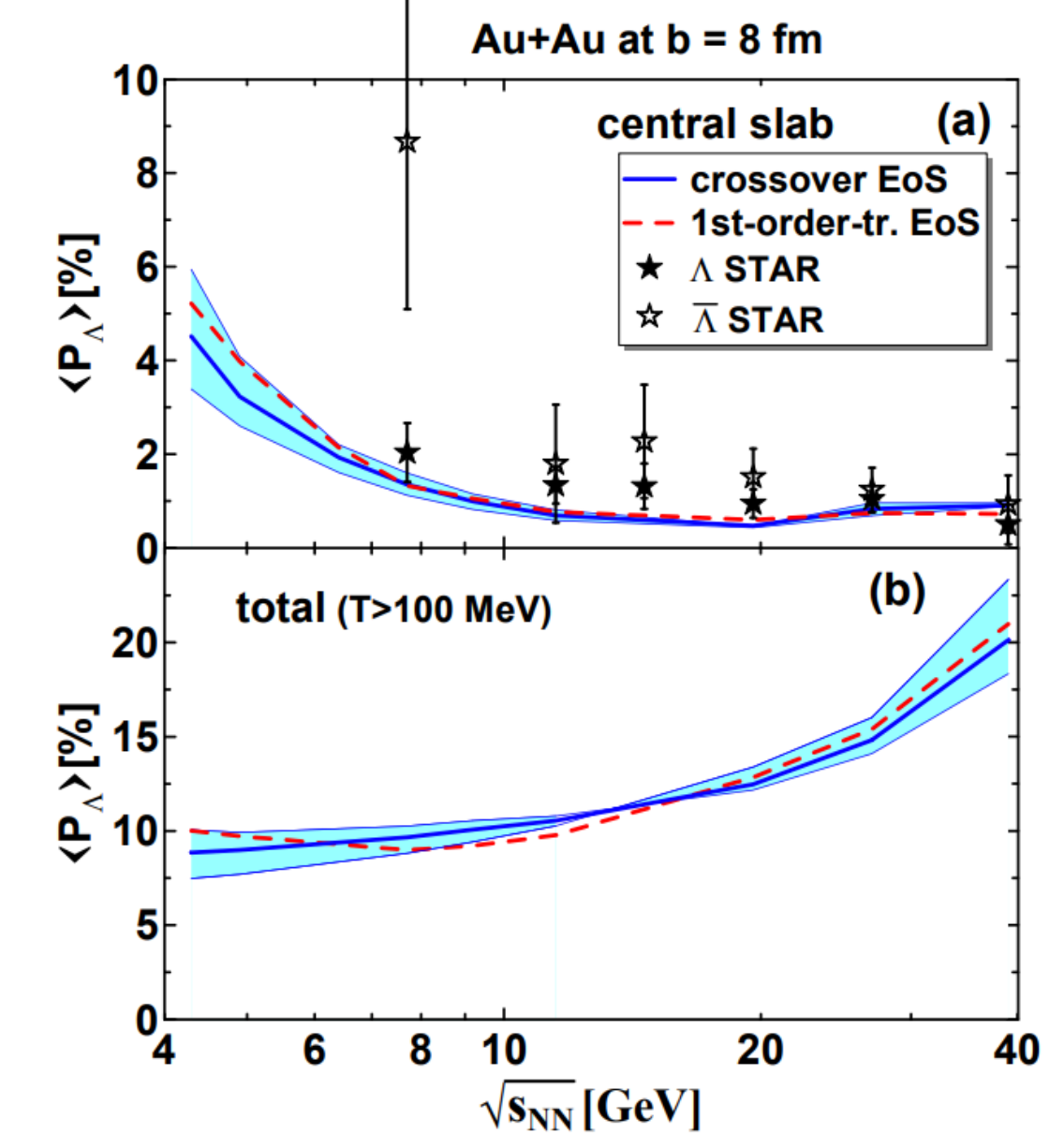
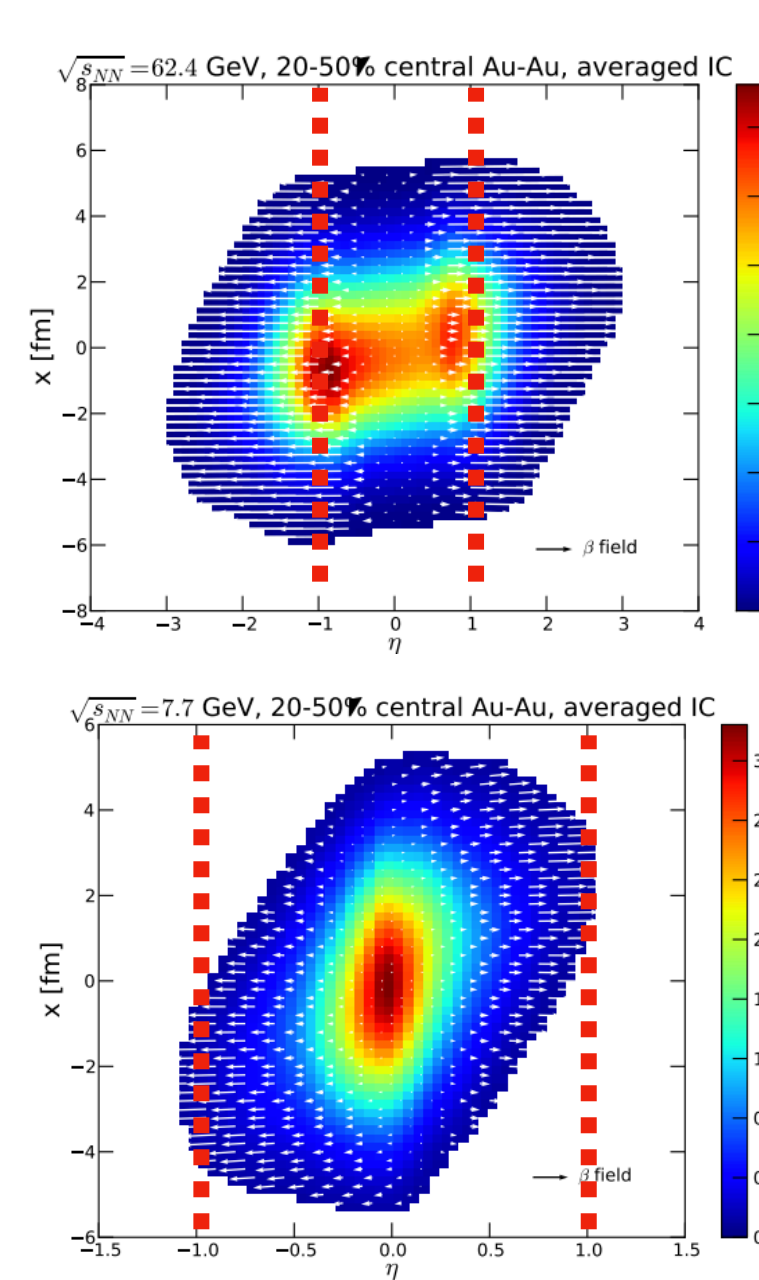
STAR:
Phys Rev C 76, 024915 (2007)
Nature 548, 62 (2017)
Phys Rev C 101, 044611 (2020)
Phys Rev C 104, 061901 (2021)

ALICE:
Phys Rev C 101, 044611 (2020)

Beam energy dependence of global P_Λ



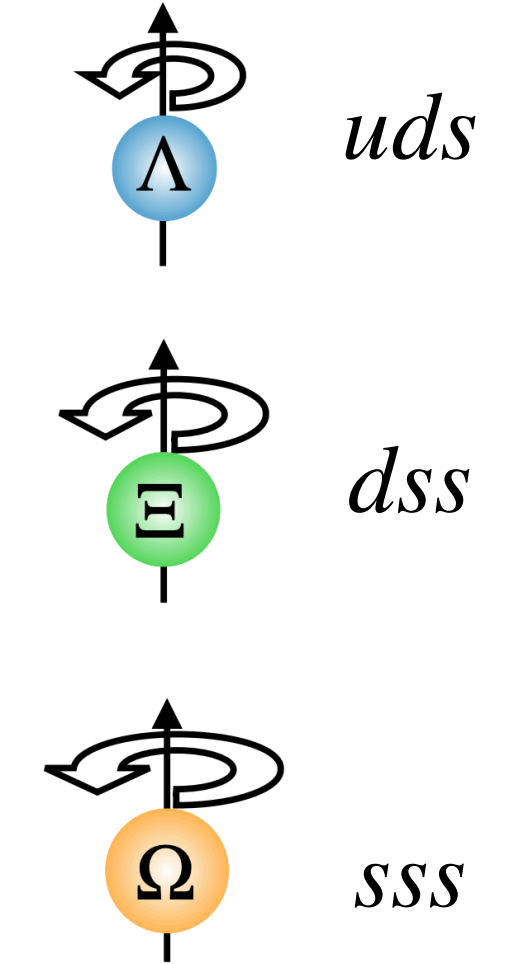
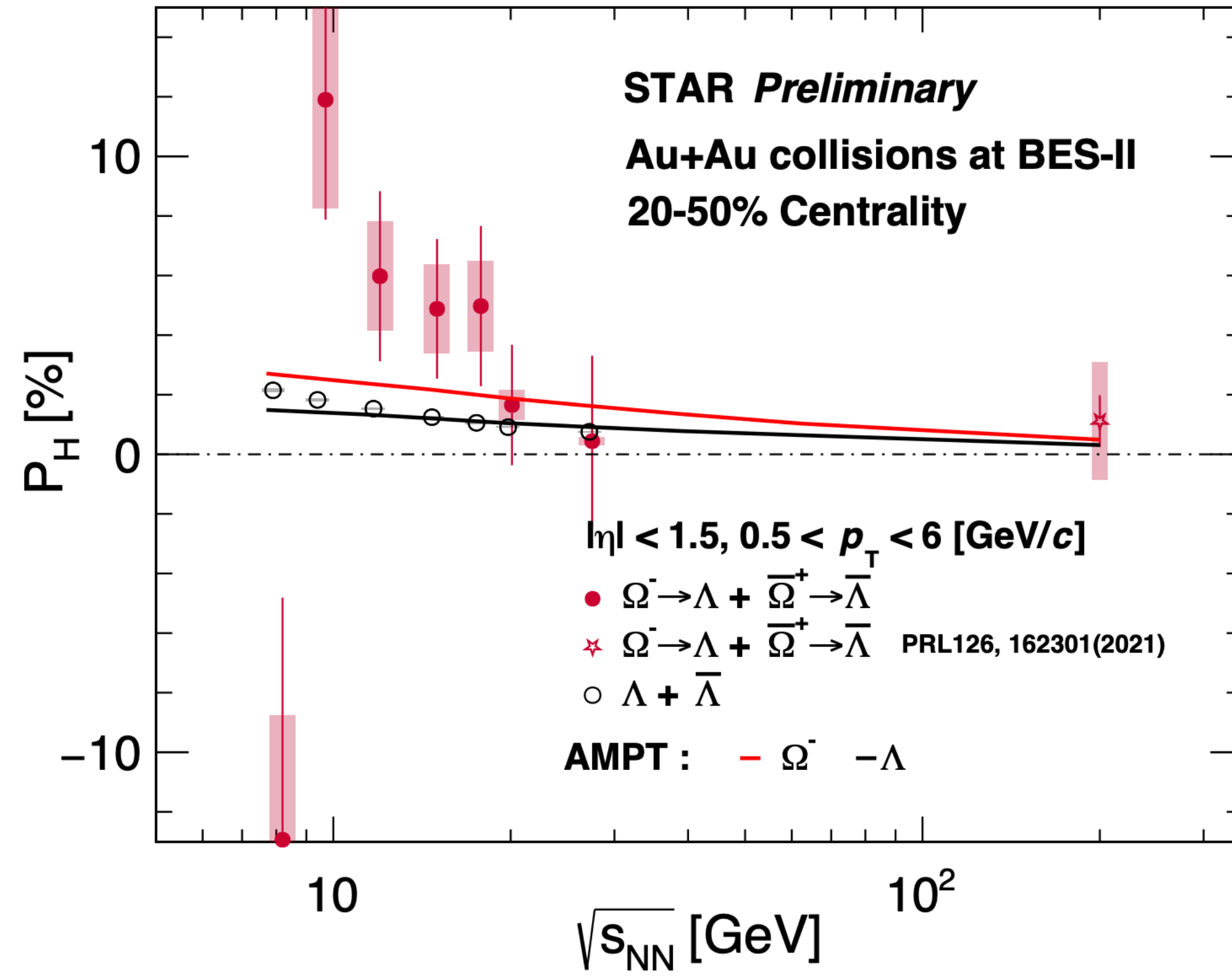
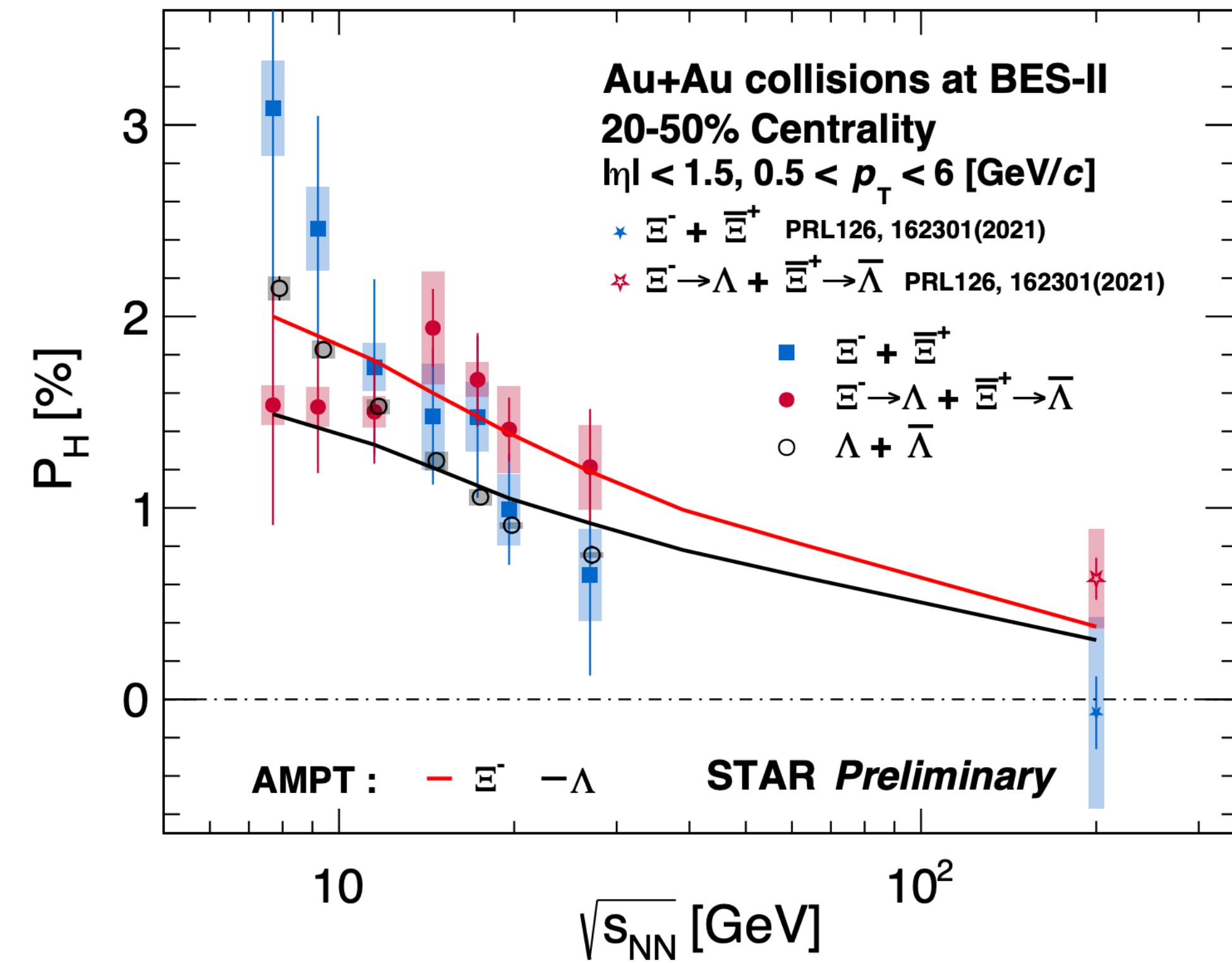
- BES-II: uncertainty reduced by a factor ~ 9
- P_Λ smooth increase with decrease in beam energy
- Models can capture the energy dependence trend



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)

- High precision in data can differentiate models

Beam energy dependence of global $P_{\Lambda, \Xi, \Omega}$



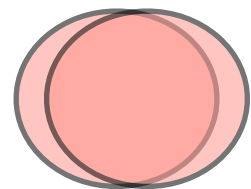
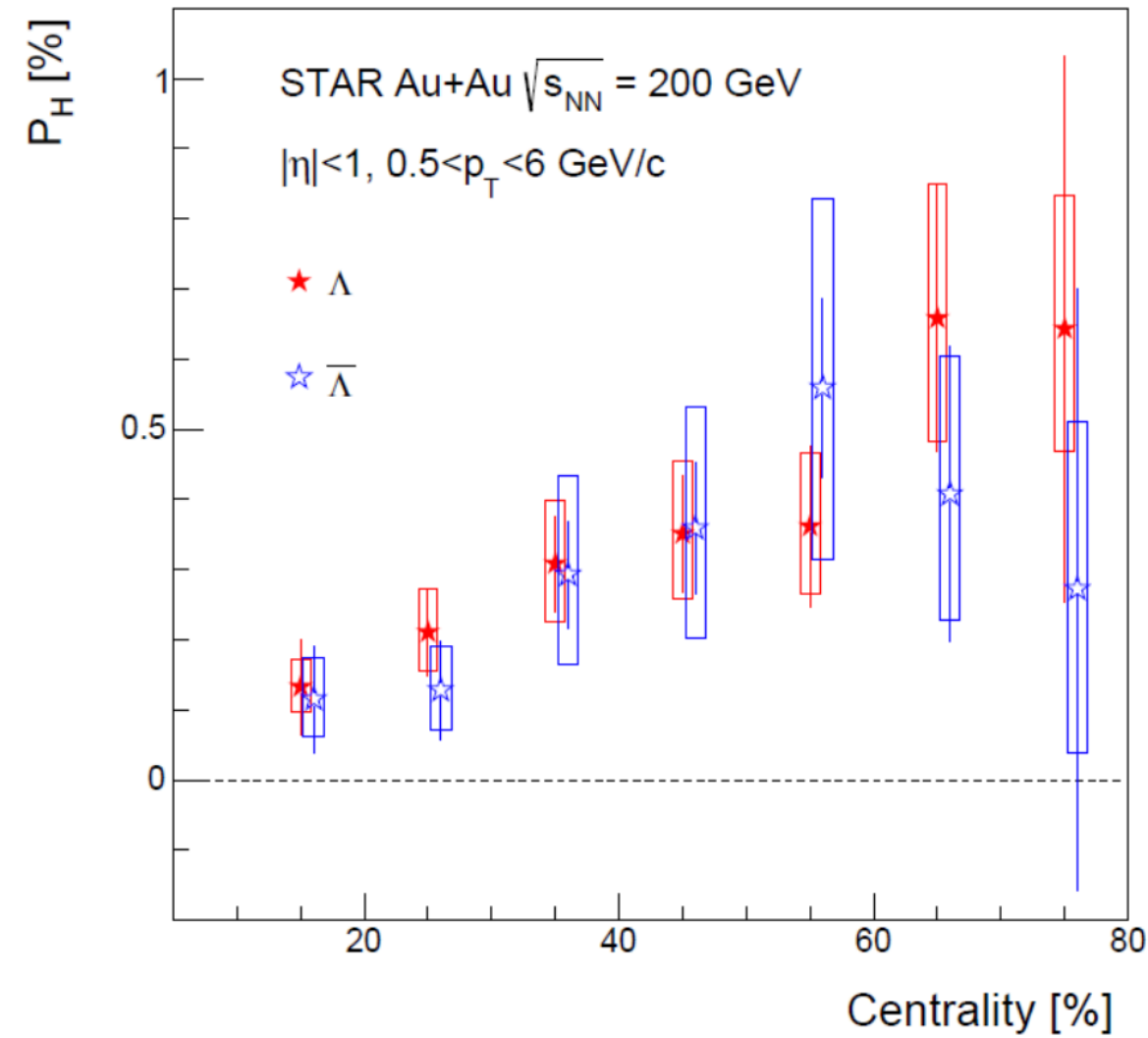
- Expectation:
- $P_{\Lambda} < P_{\Xi} < P_{\Omega}$

- BES-II: First measurements of Ξ and Ω , follow energy dependent trend
- $P_{\Lambda} \sim P_{\Xi} \sim P_{\Omega}$: precision not sufficient to distinguish ordering

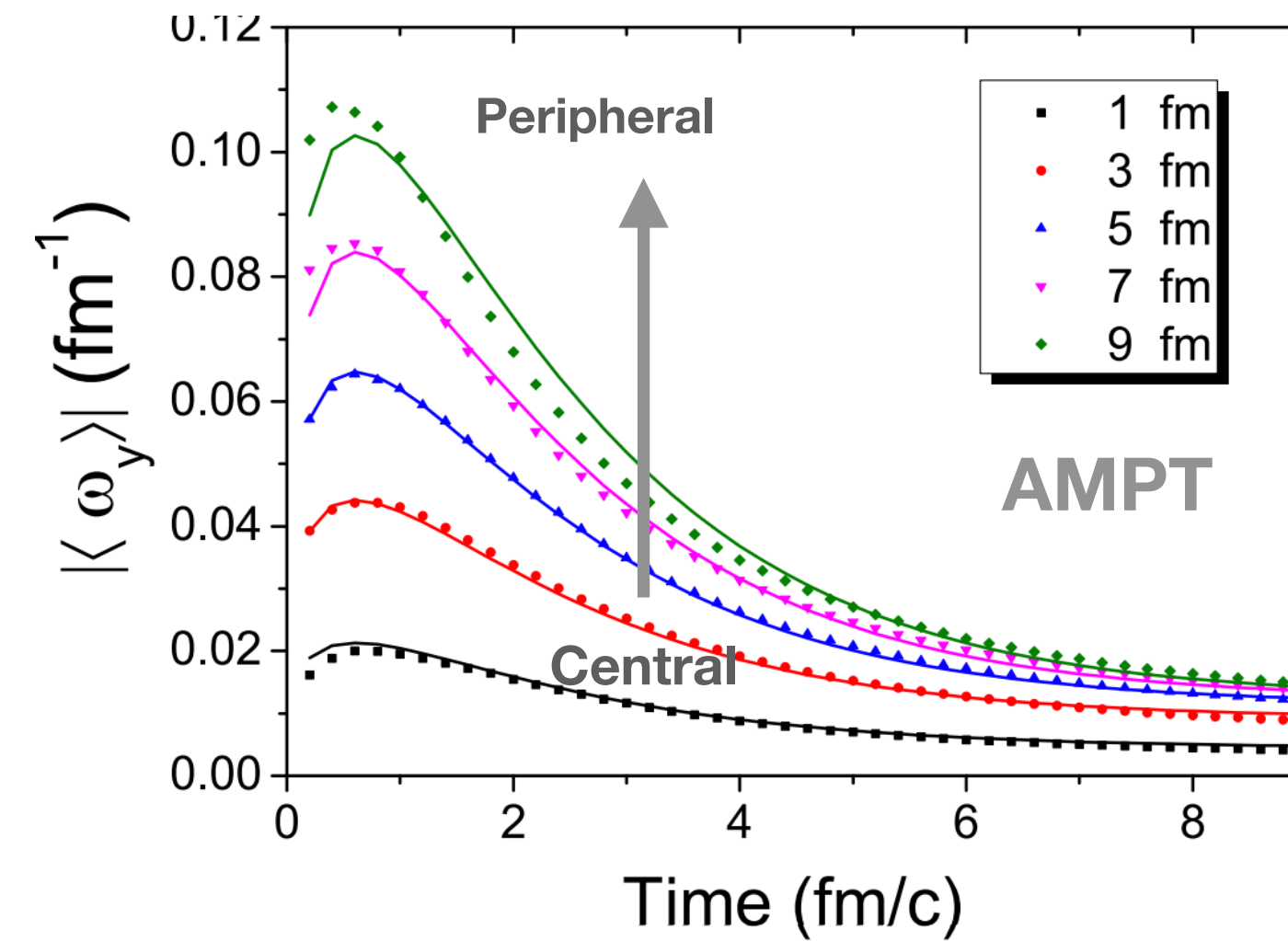
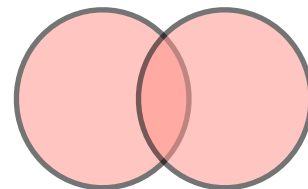
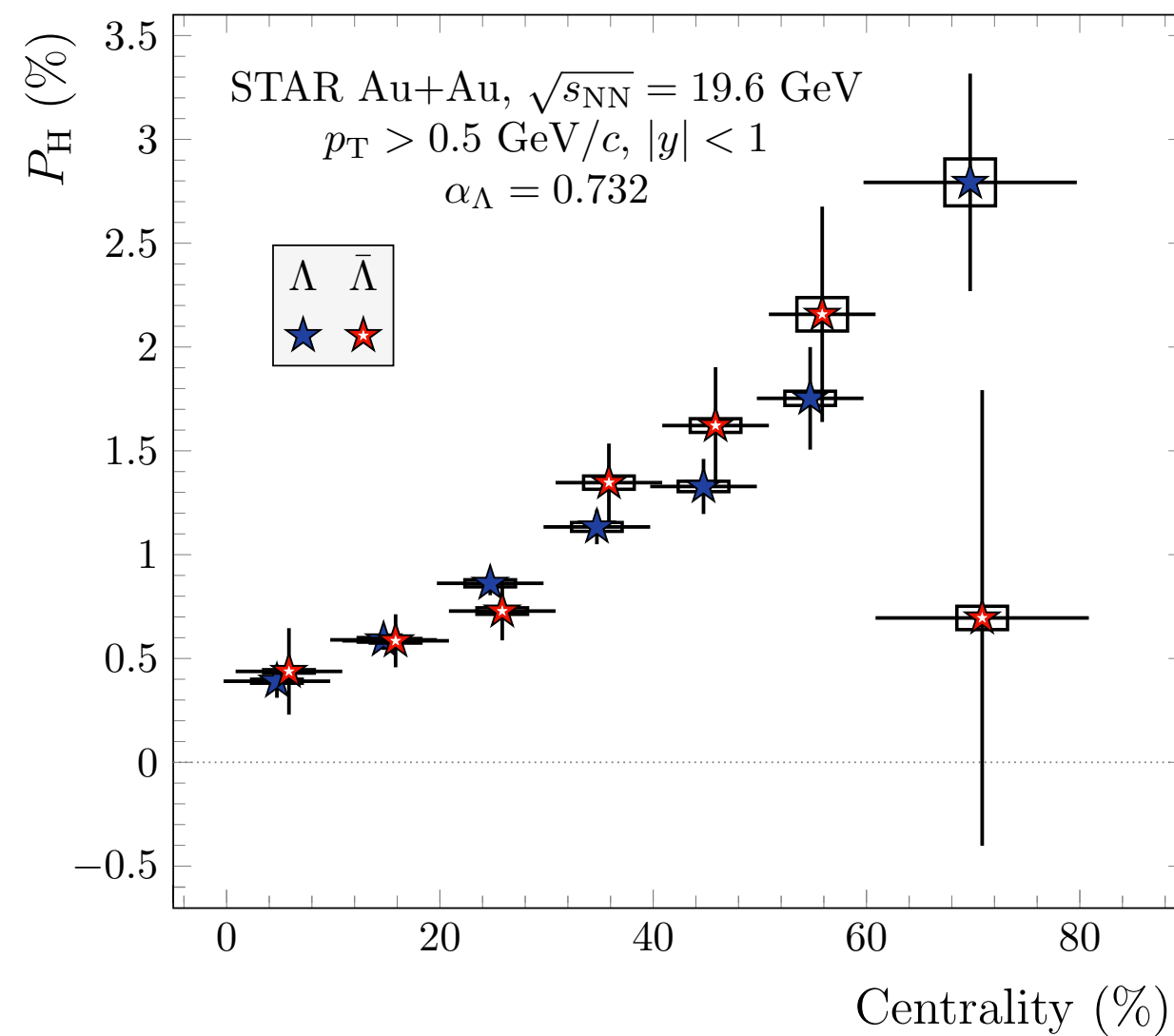
Global polarization: differential measurements (centrality and rapidity dependence)

P_Λ : centrality dependence

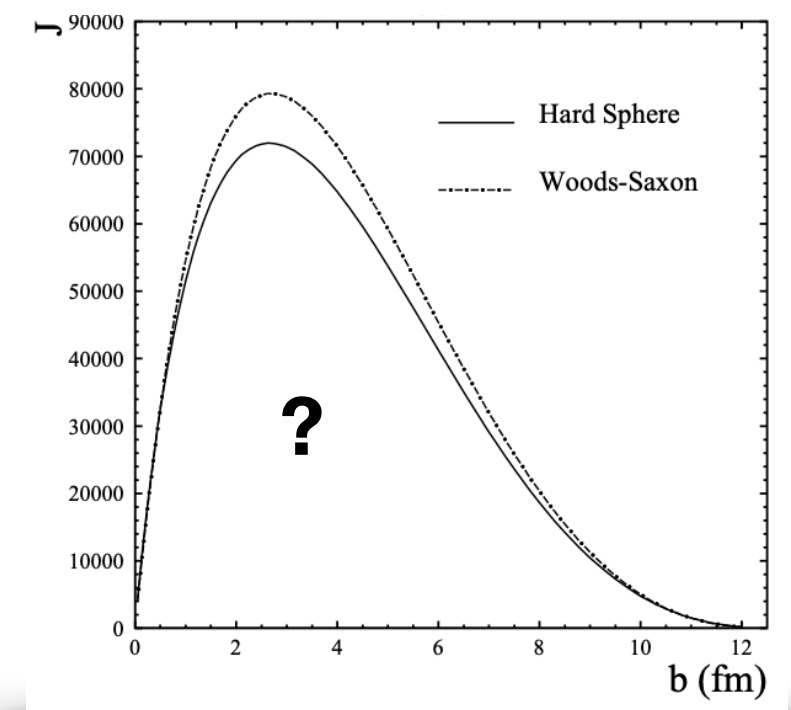
$$\sqrt{s_{NN}} = 200 \text{ GeV}$$



$$\sqrt{s_{NN}} = 19.6 \text{ GeV}$$



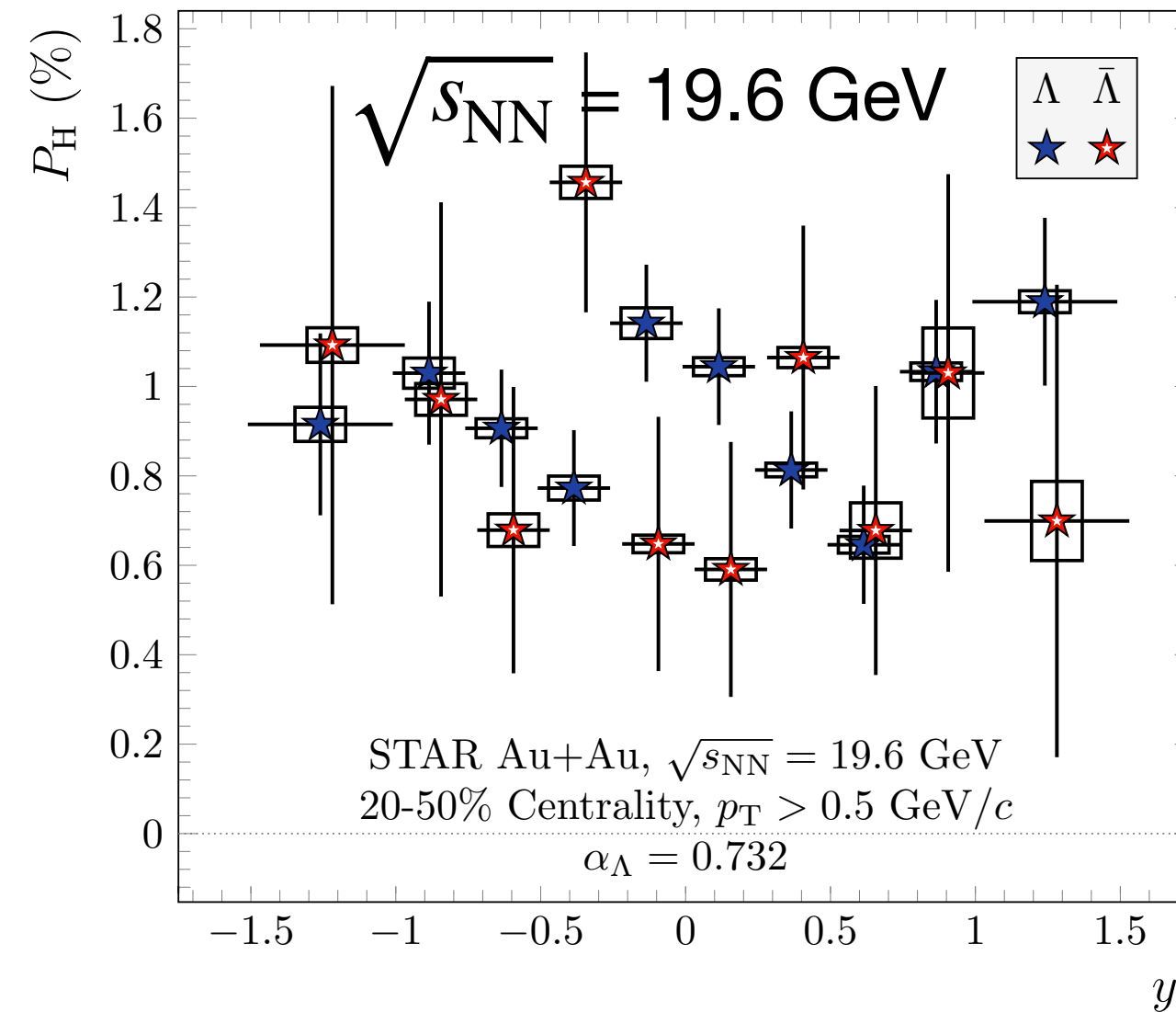
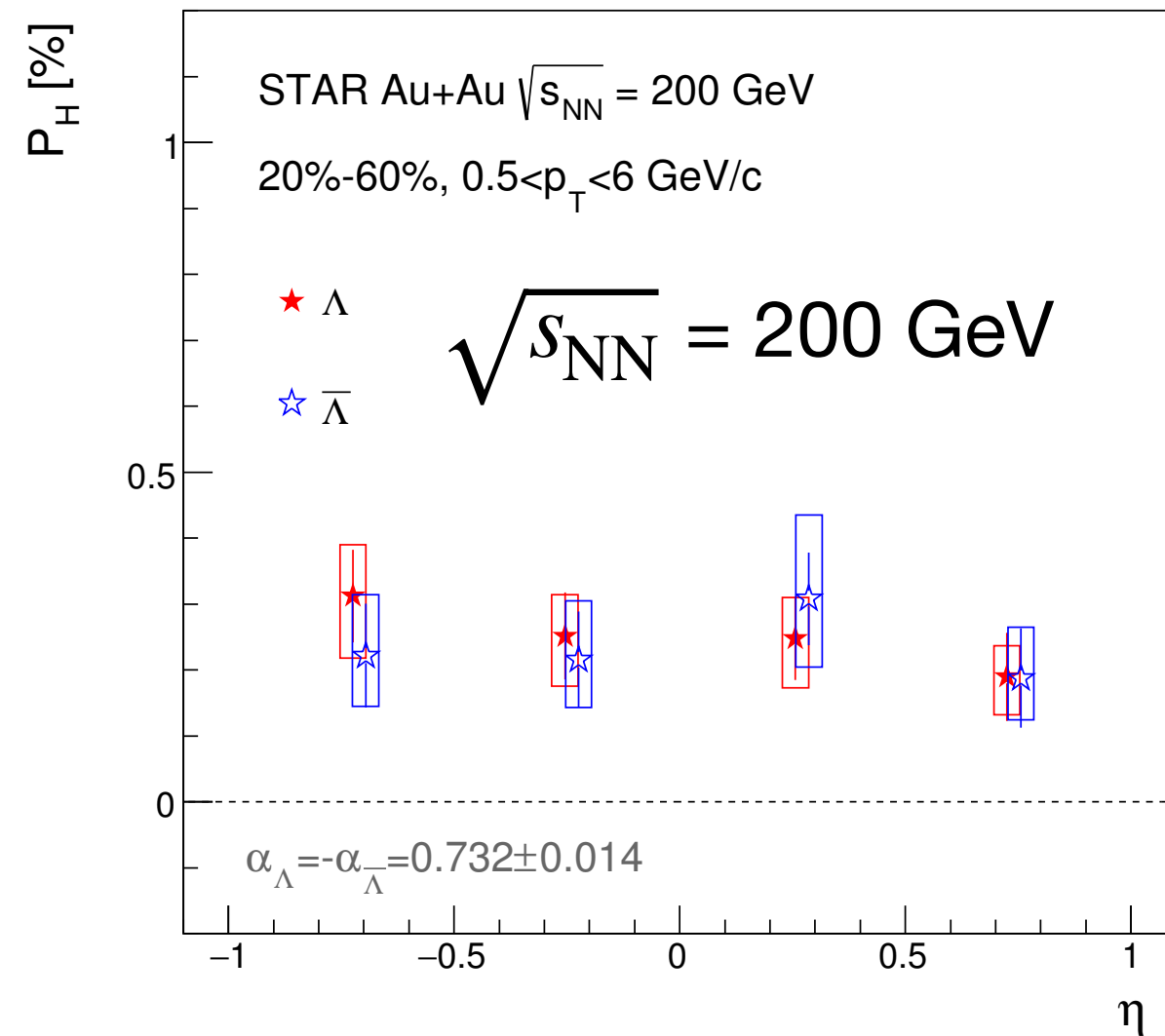
Jiang et al,
 Phys Rev C 94, 044910 (2016)



- P_Λ increases from central to peripheral collisions
- Similar pattern followed across beam energies
- Trend consistent with expectation from vorticity

Is there a saturation? No drop in polarization expected from angular momentum?

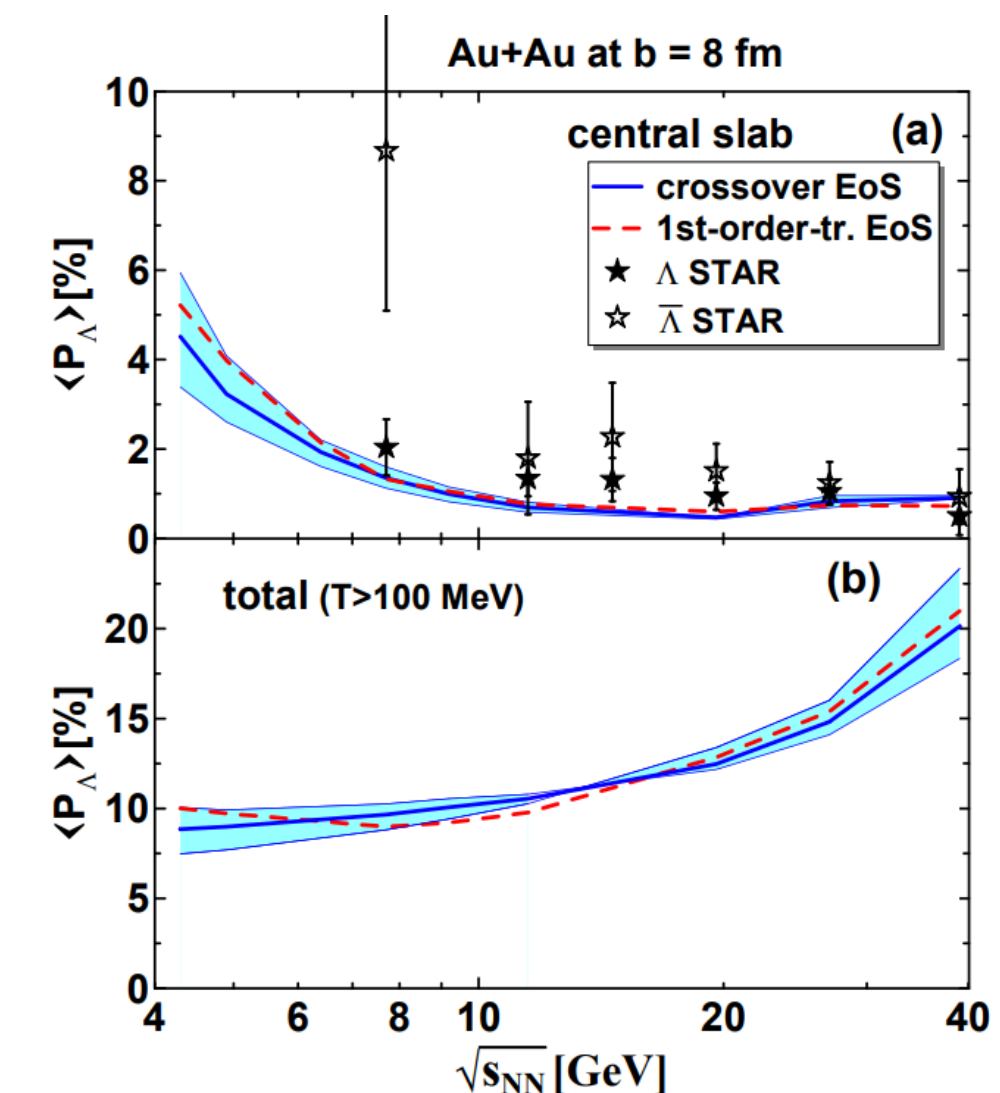
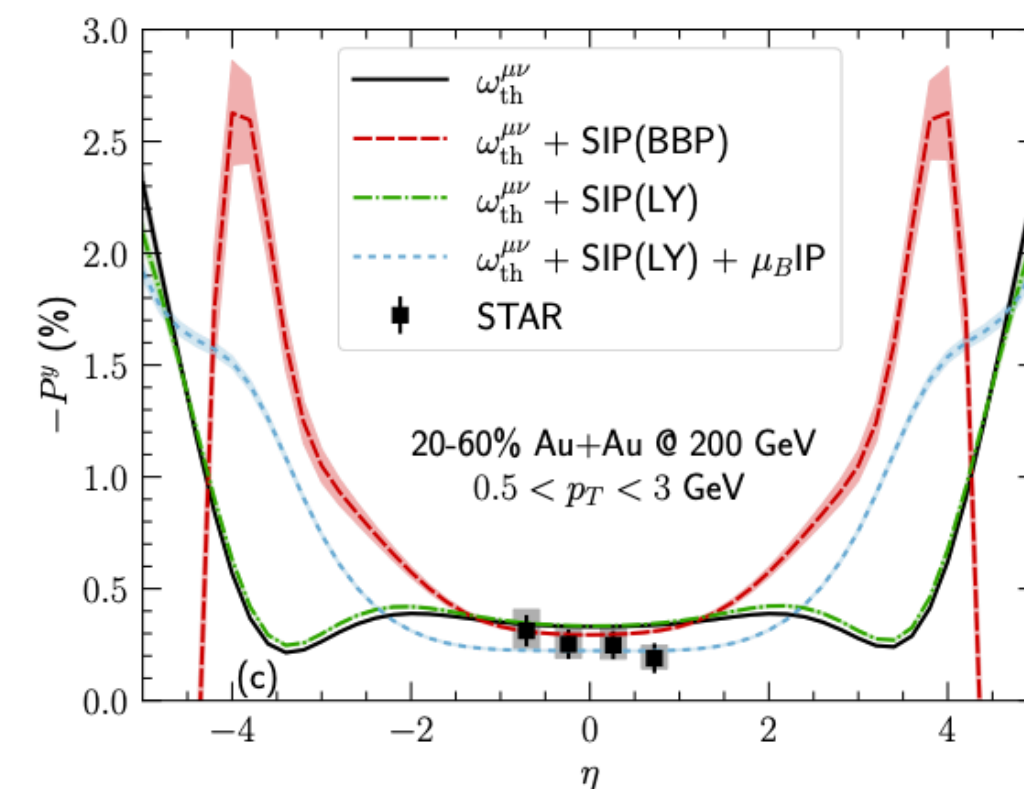
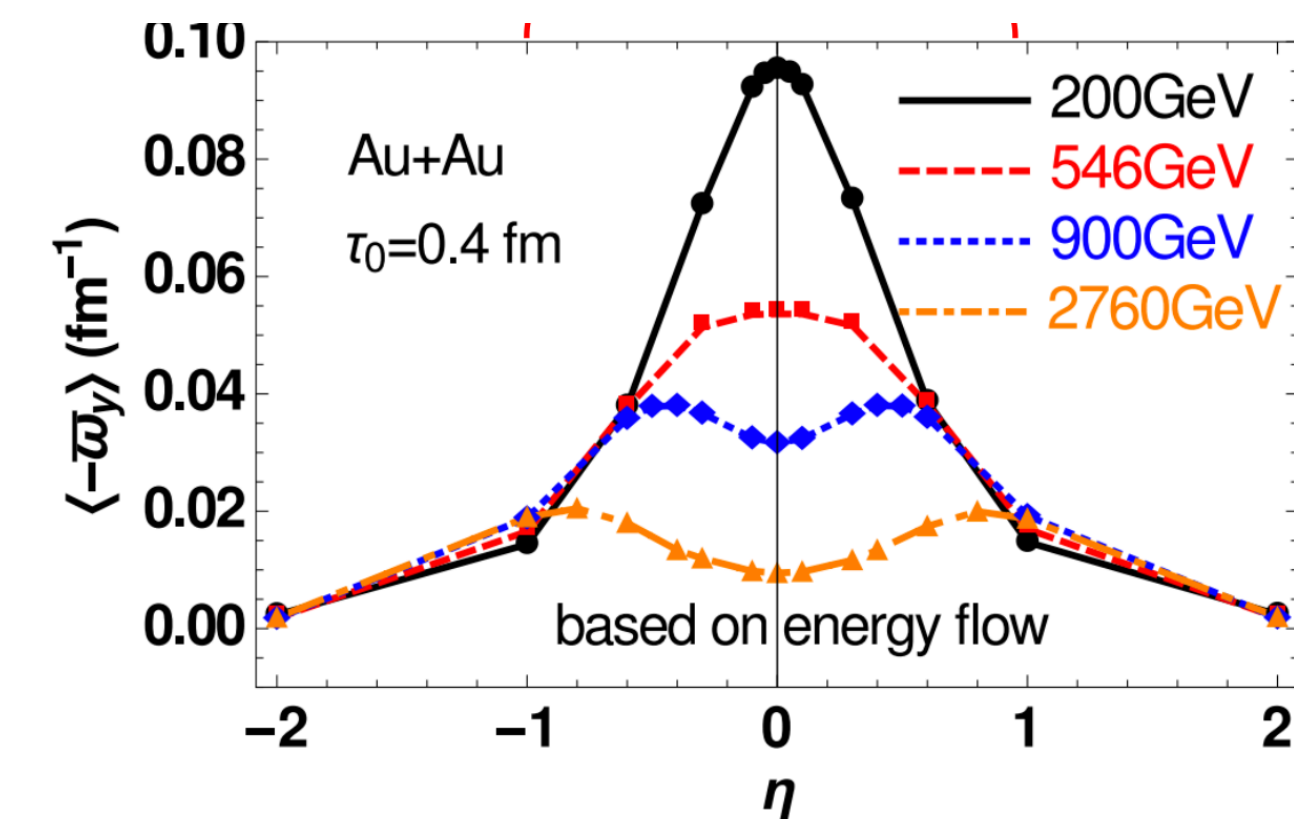
P_Λ : rapidity dependence



- No significant rapidity dependence observed within measured acceptance

Deng and Huang, Phys Rev C 93, 064907 (2016)
Wu et al, Phys Rev Research 1, 033058 (2019)
Alzhrani et. al., Phys Rev C 106, 014905 (2022)

- Rapidity dependence of P_Λ is different among various models



Major question: How angular momentum is distributed into the system, correlation with baryon stopping?

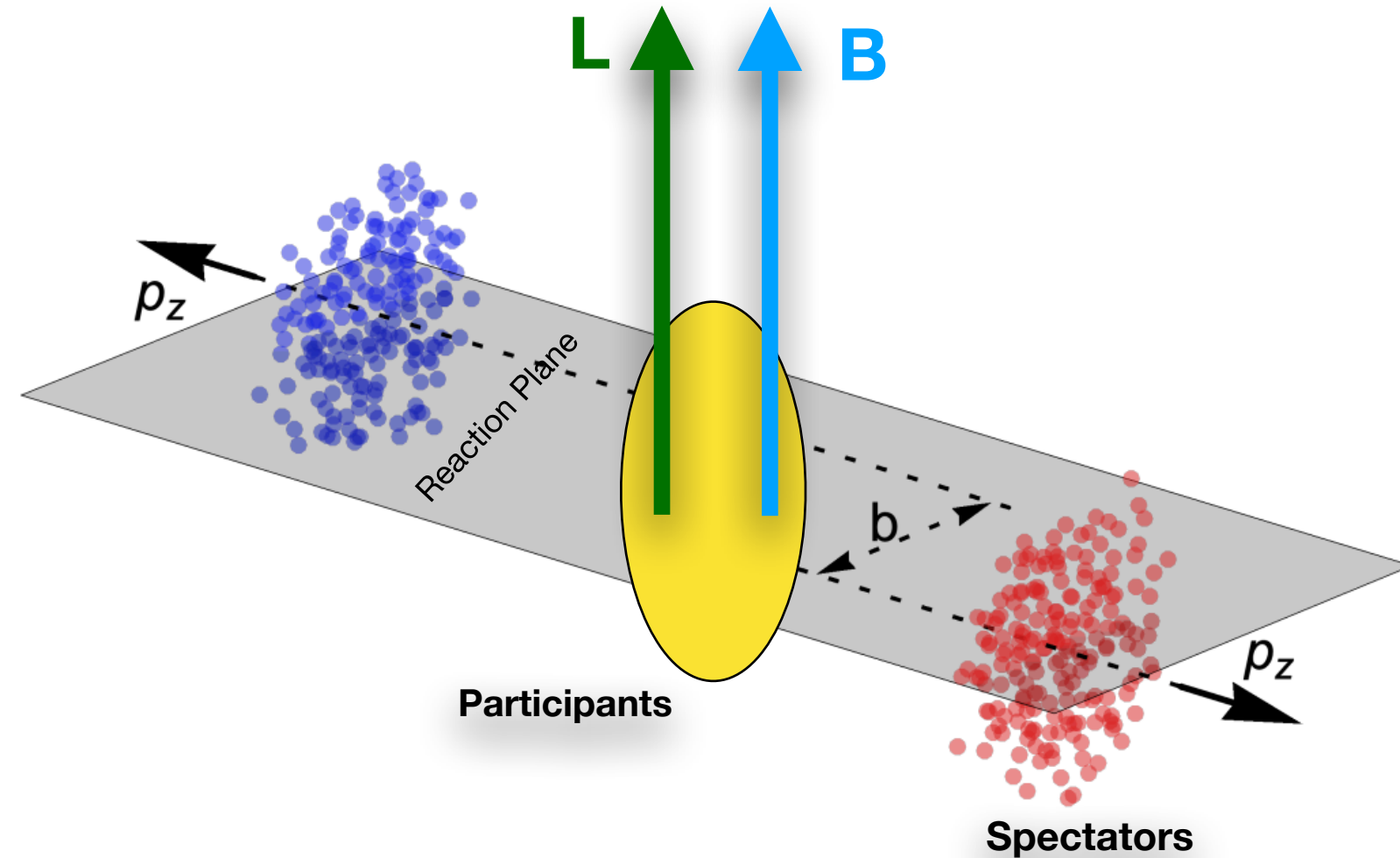
Differences in global spin polarization P_{Λ} and $P_{\bar{\Lambda}}$

Possible constraint on B field by P_Λ

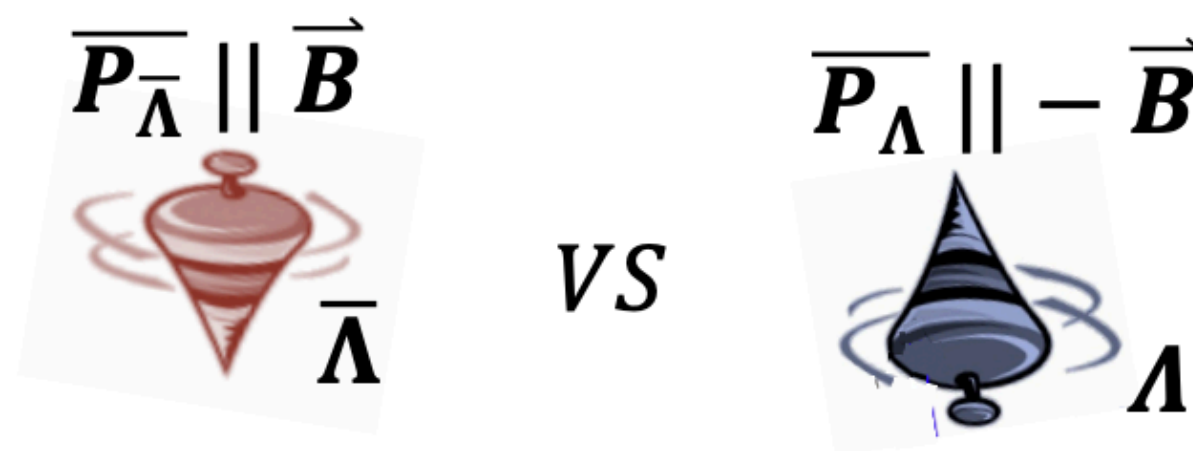
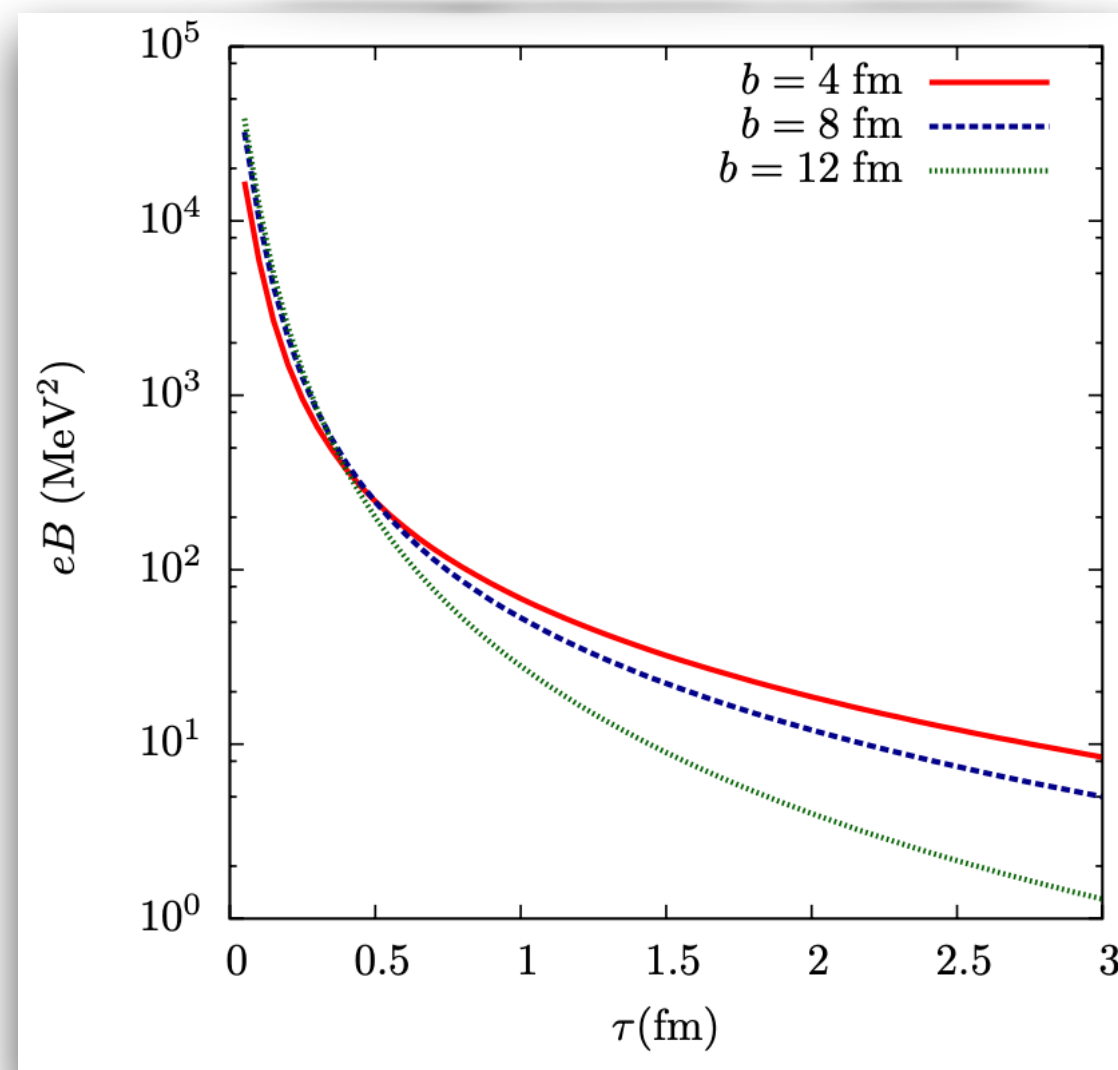
In non-central heavy-ion collisions

- **Initial strong magnetic field ($\mathbf{B}$)** is expected

$$eB \sim m_\pi^2 \sim 10^{18} \text{ Gauss}$$
- Such strong $\mathbf{B}$ field can also polarize quarks. Can induce different spin polarization for quarks and anti-quarks with different magnetic moments



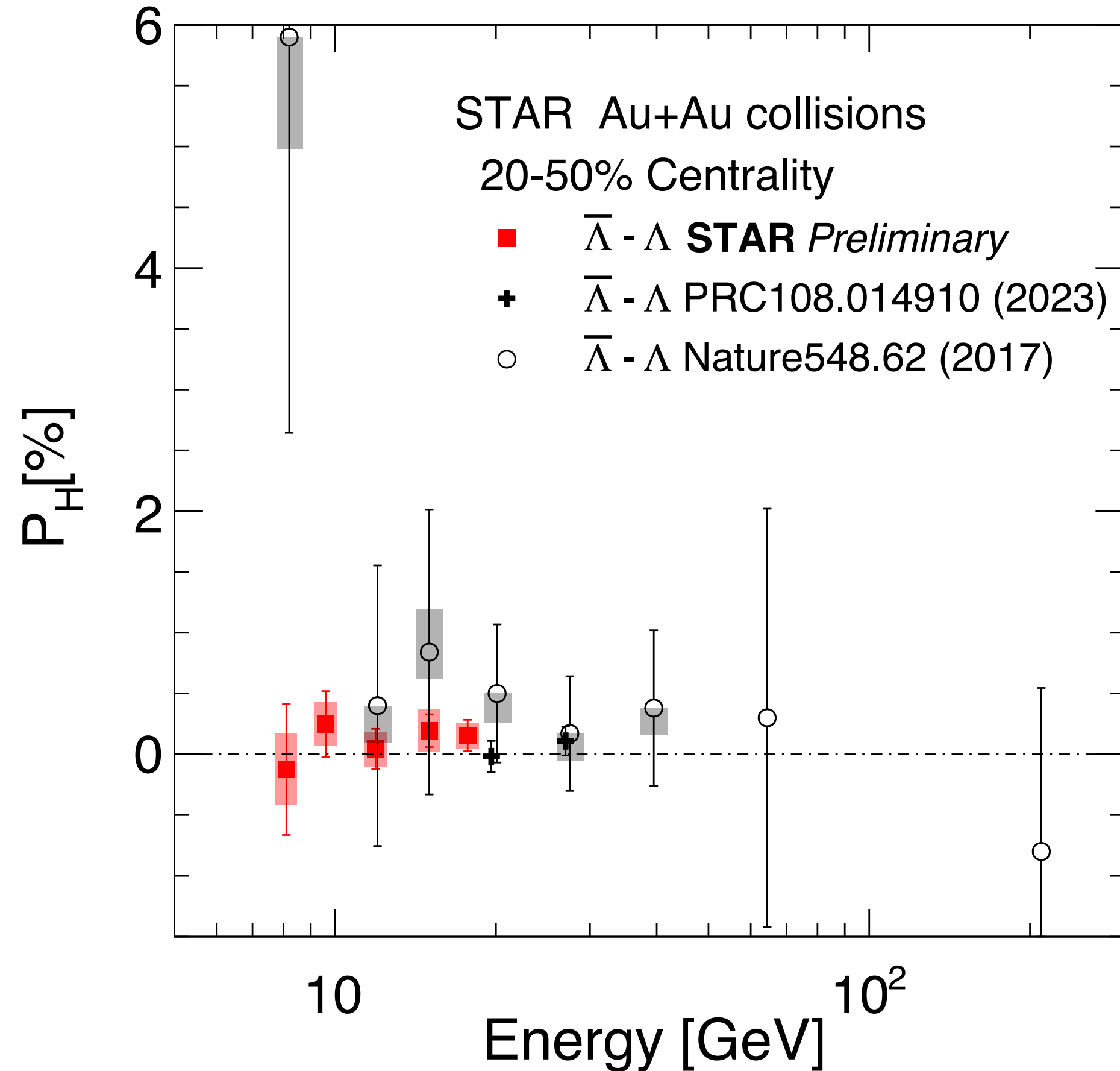
Magnetic Field



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

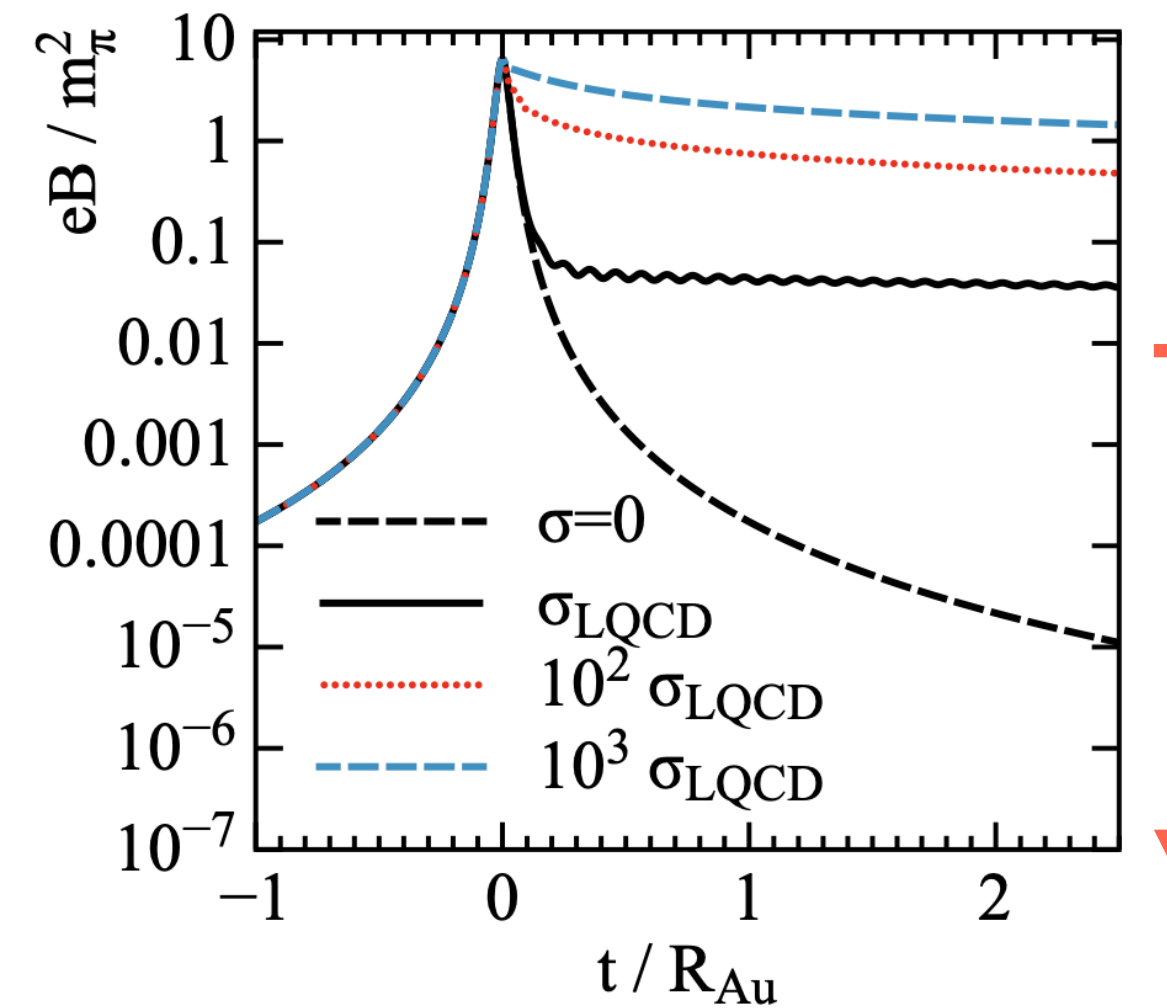
Possible constraint on B field by P_Λ

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)

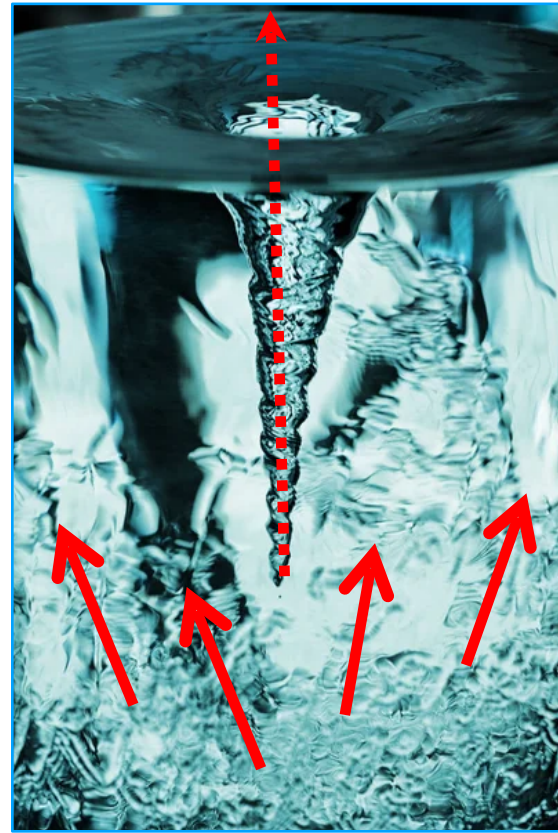
Scenarios can cause Λ and anti- Λ polarization difference:

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

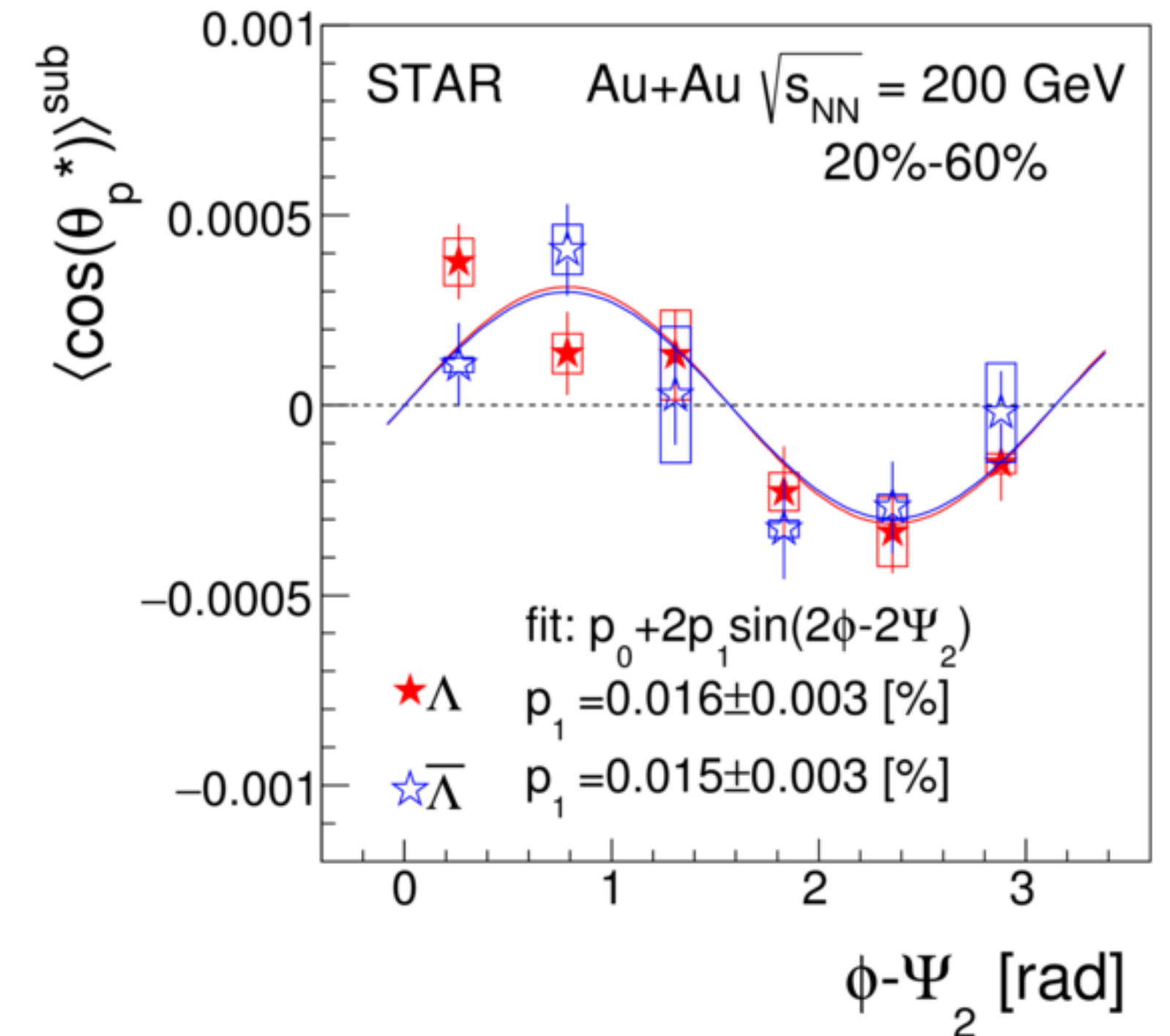
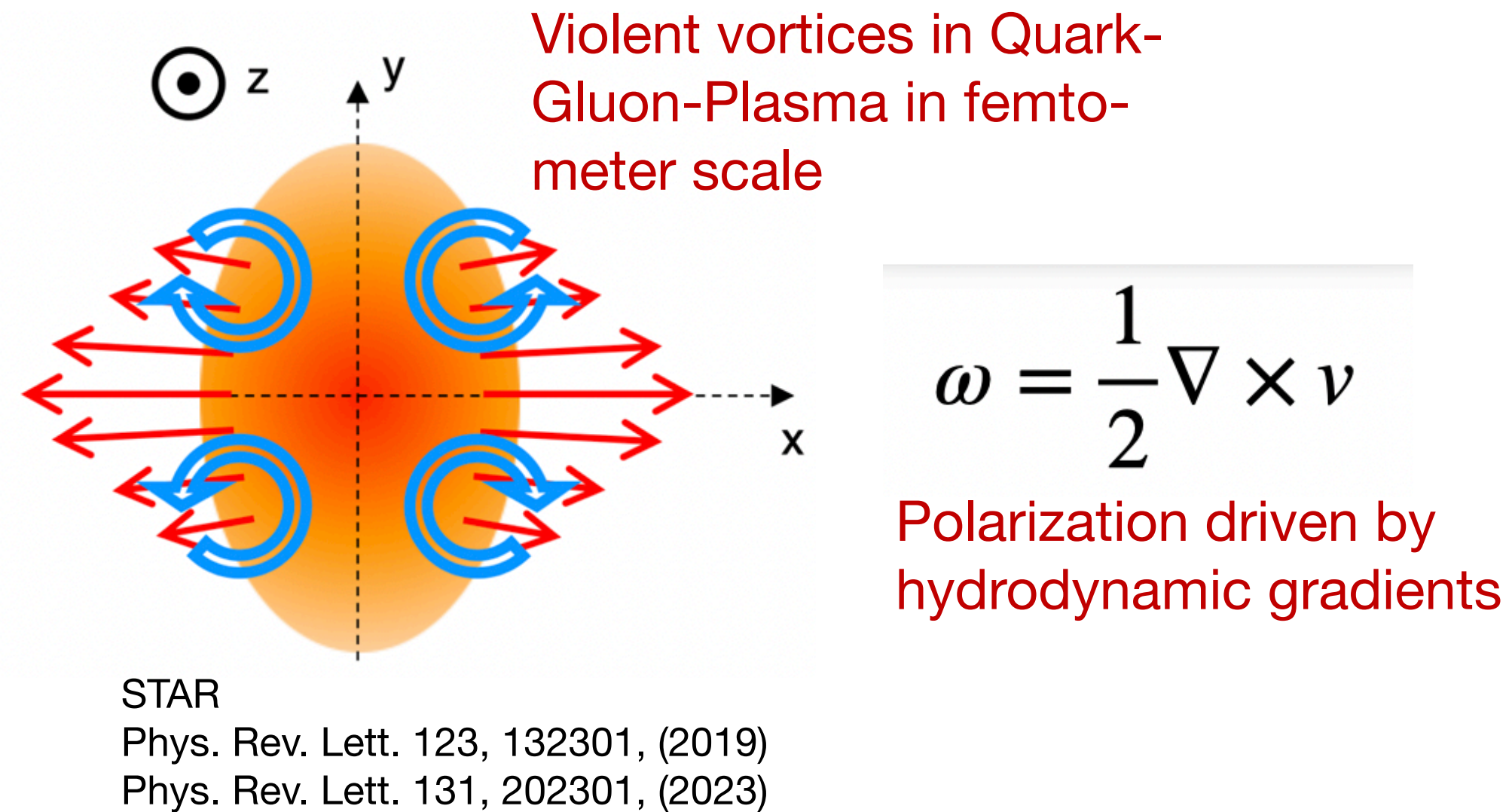
- No difference between Λ , $\bar{\Lambda}$ is observed with BES-II data
- Results set an upper-limit on late stage magnetic-field ($B \leq 10^{13} T$)

Local polarization: beam energy dependence

Local vortices via helicity polarization of Λ



More refine structures of vortices



Local vortices within QGP $\rightarrow$ azimuthal angle dependence of Λ polarization (most challenging for theory)

Contributions = Thermal vorticity + Kinematic vorticity + Shear effect + Baryon density gradient (**bSHE**)

Baryonic Spin Hall effect (SHE)

Condensed matter

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

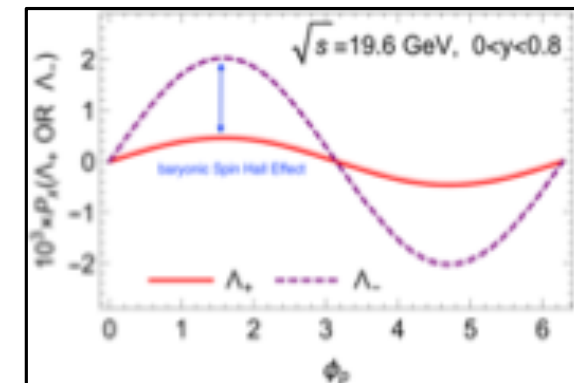
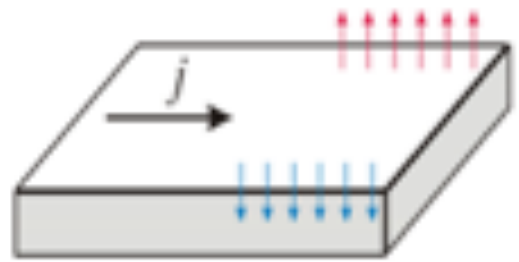
splitting in spin on opposite boundaries

Heavy Ion Collisions

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

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

“spin-orbit”

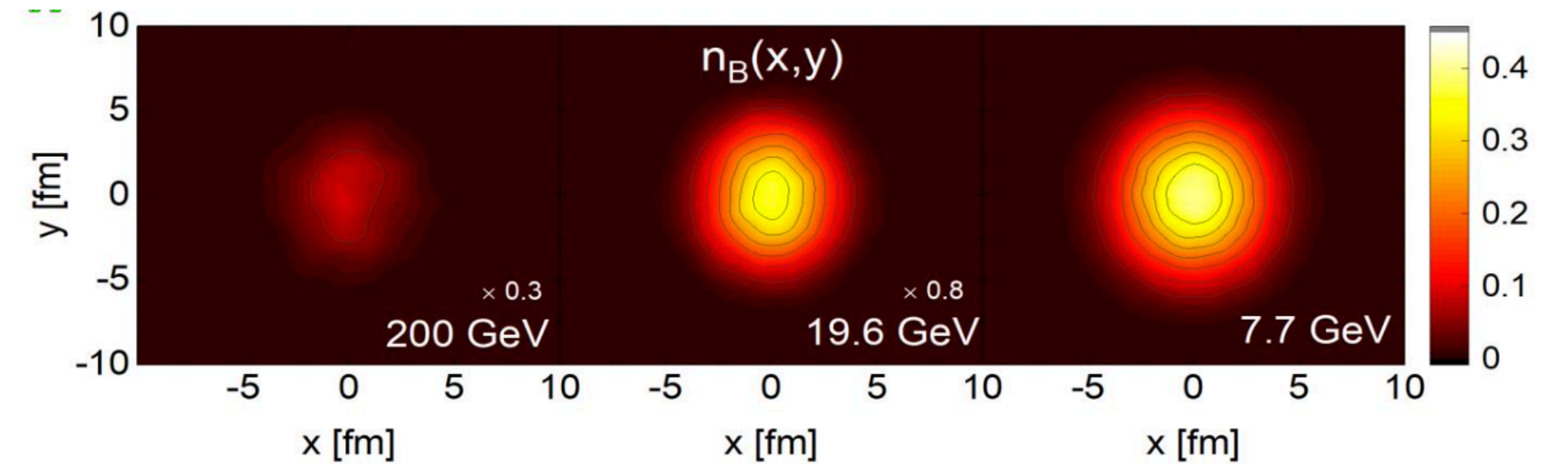


Predicted Spin Hall type effect driven by gradient of baryonic density ($\nabla \mu_B$)

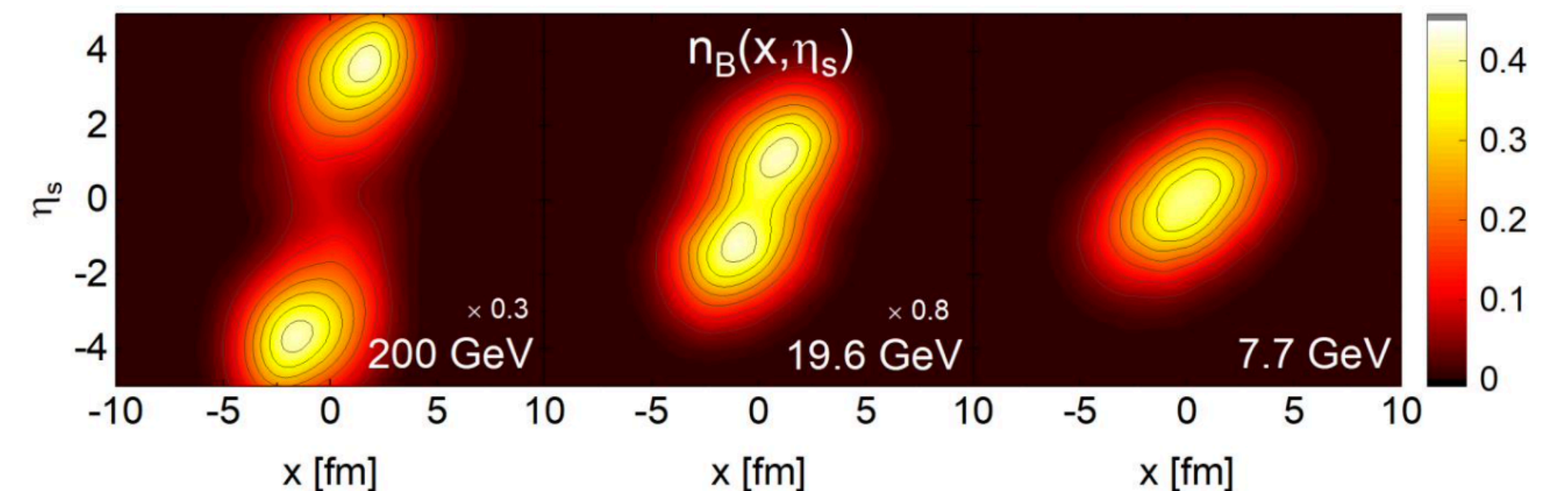
Polarization $\sim$ vorticity $\oplus \nabla T \oplus$ Shear $\oplus \nabla \mu_B$

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

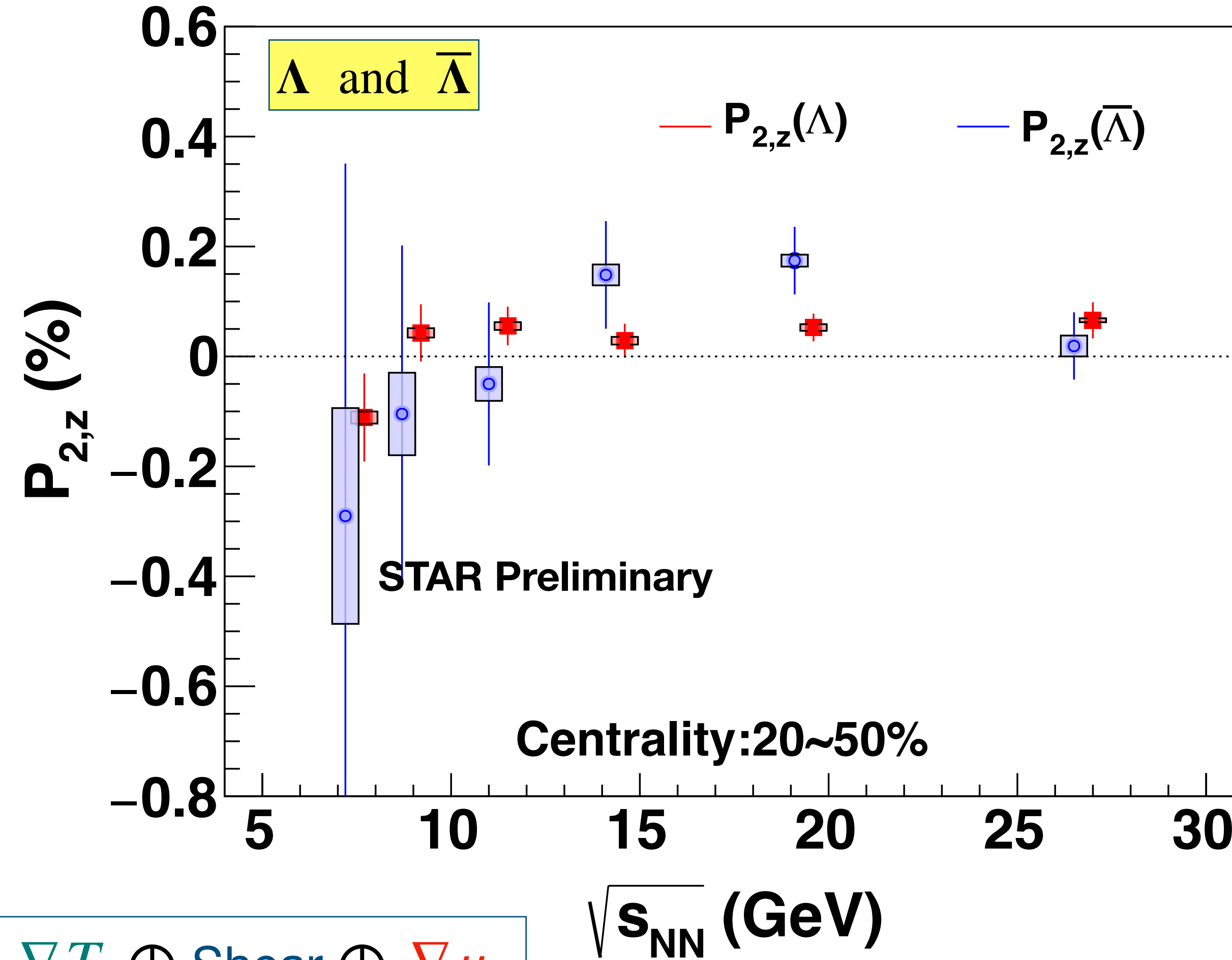
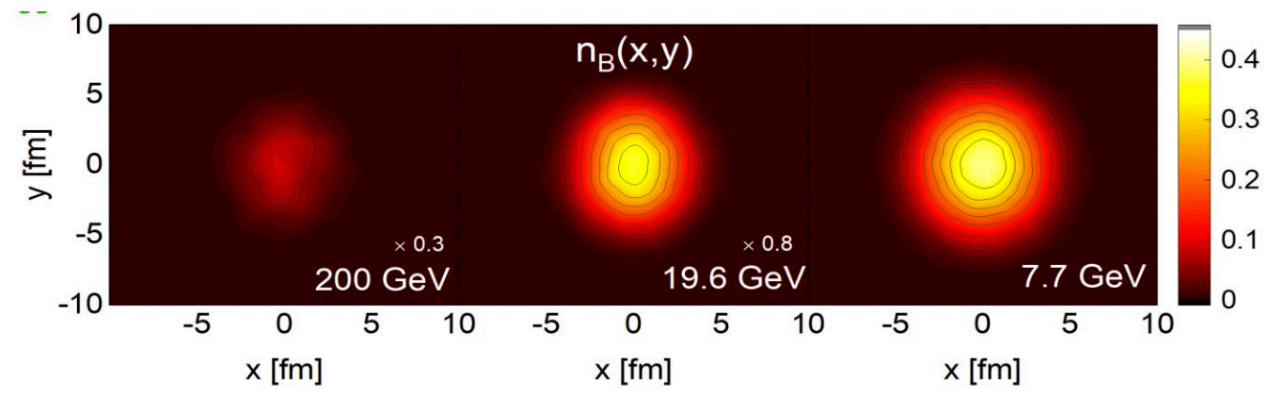
Transverse-plane (x, y)



Longitudinal-plane (x, η)



Baryonic Spin Hall effect (bSHE)



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

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

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

Kinematics:

$0.5 < p_T < 5.0$ GeV/c

$|y| < 1.0$ for 27 GeV

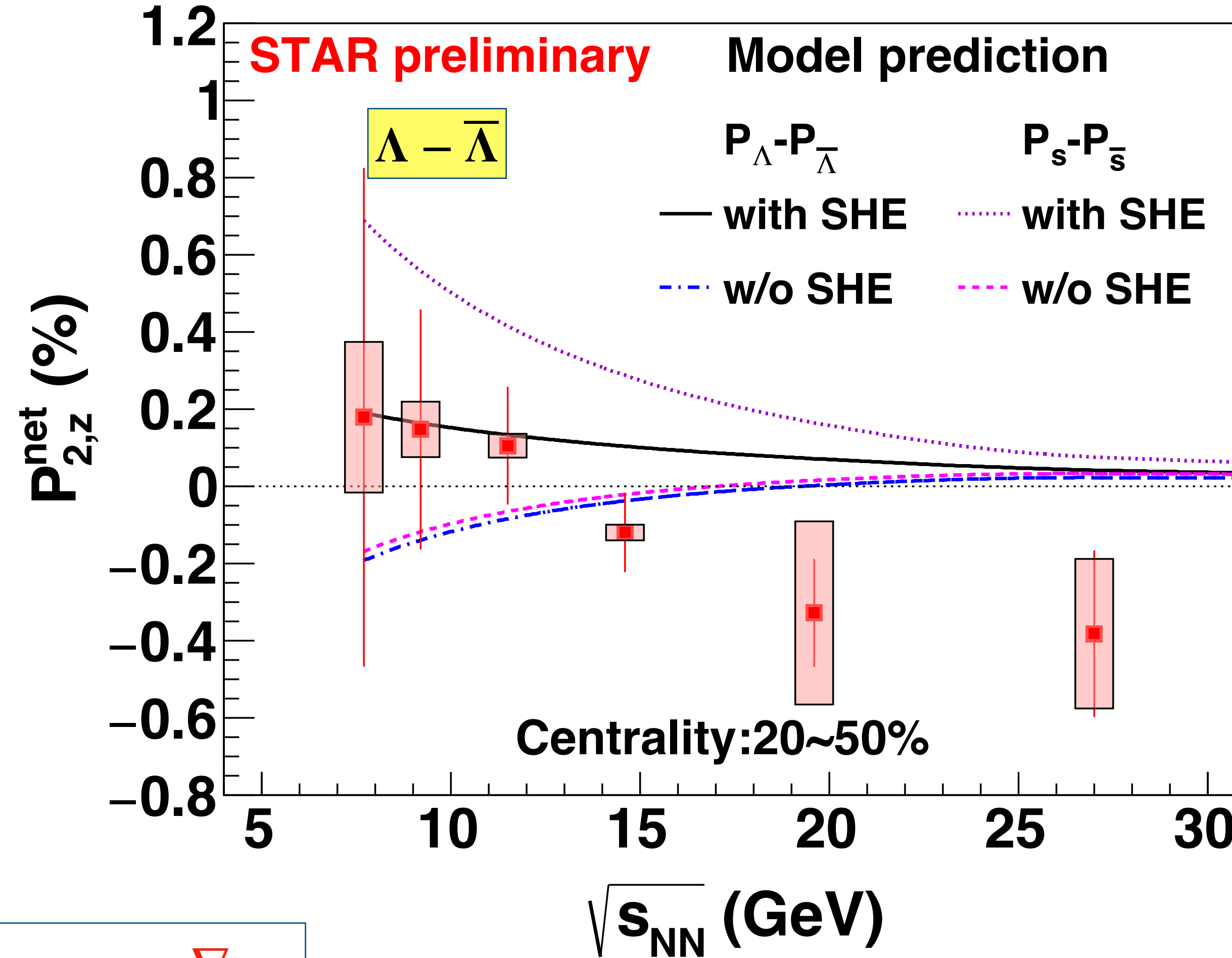
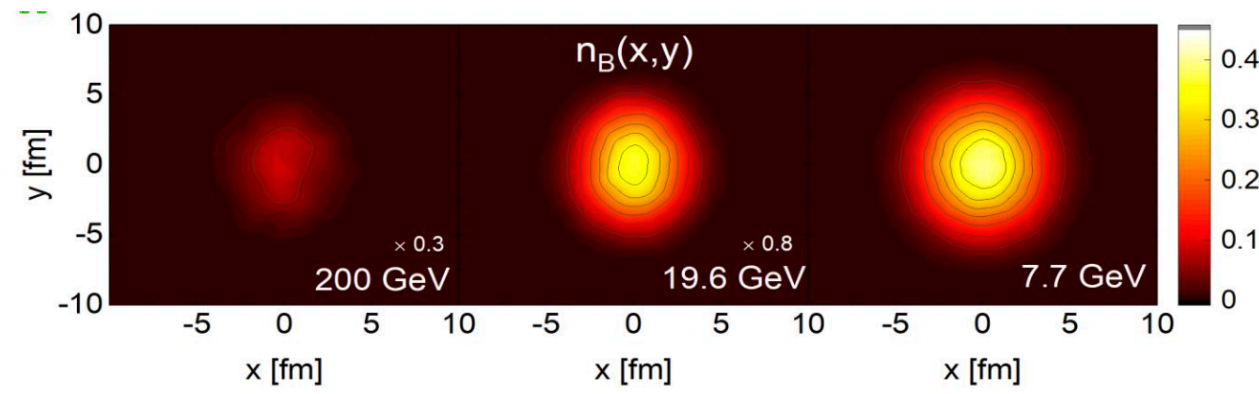
$|y| < 1.5$ for other energies

Qiang Hu, SQM 2024 (STAR)

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

- $P_{2,z}$: non-zero, no strong energy dependence, (hints of sign change at lower energies ?)

Baryonic Spin Hall effect (bSHE)



Polarization difference $\sim \nabla \mu_B$

- Not sufficient precision at BES energies

$$P_{2,z}^{\text{net}} = P_{2,z}^{\Lambda} - P_{2,z}^{\bar{\Lambda}}$$

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

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

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

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

Kinematics:

$0.5 < p_T < 5.0 \text{ GeV}/c$

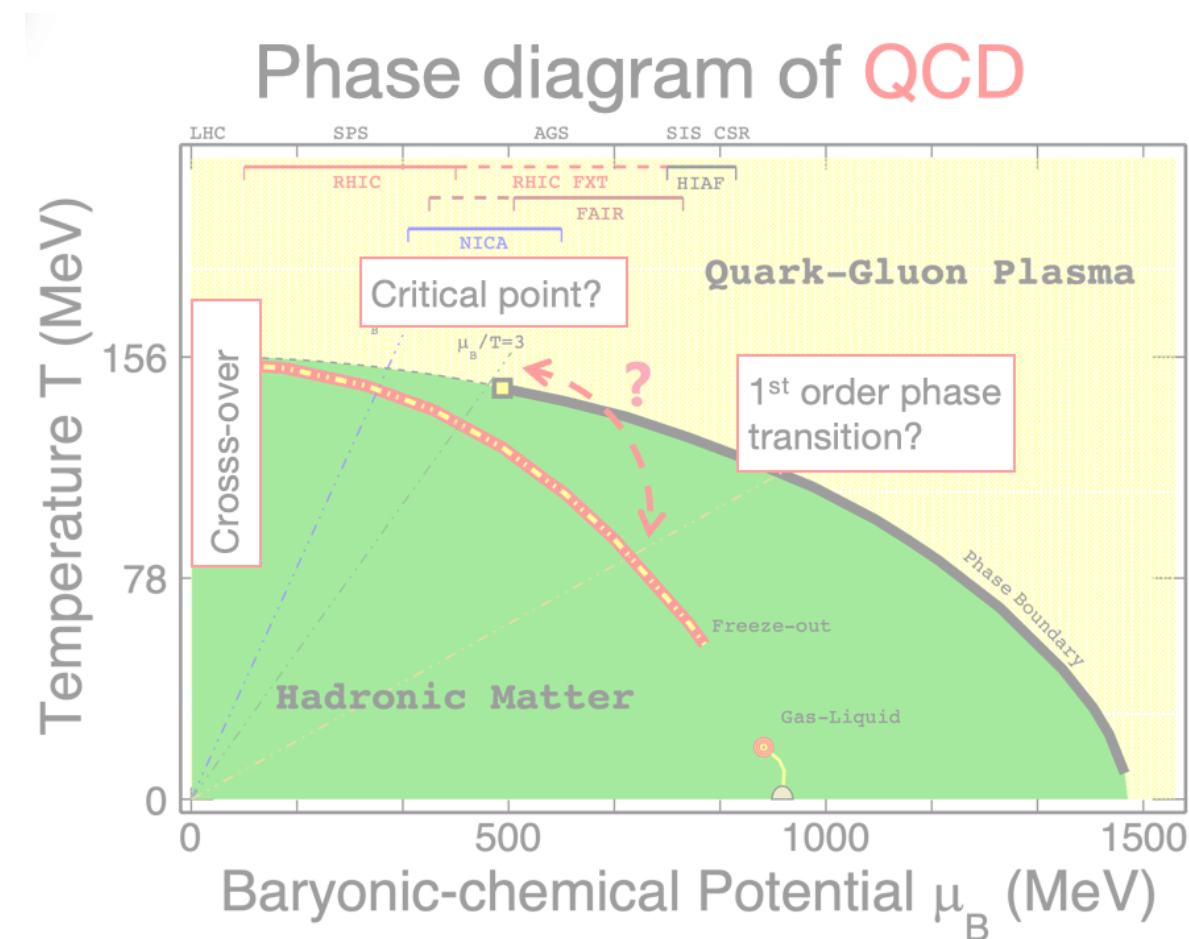
$|y| < 1.0$ for 27 GeV

$|y| < 1.5$ for other energies

Qiang Hu, SQM 2024 (STAR)

Future opportunities

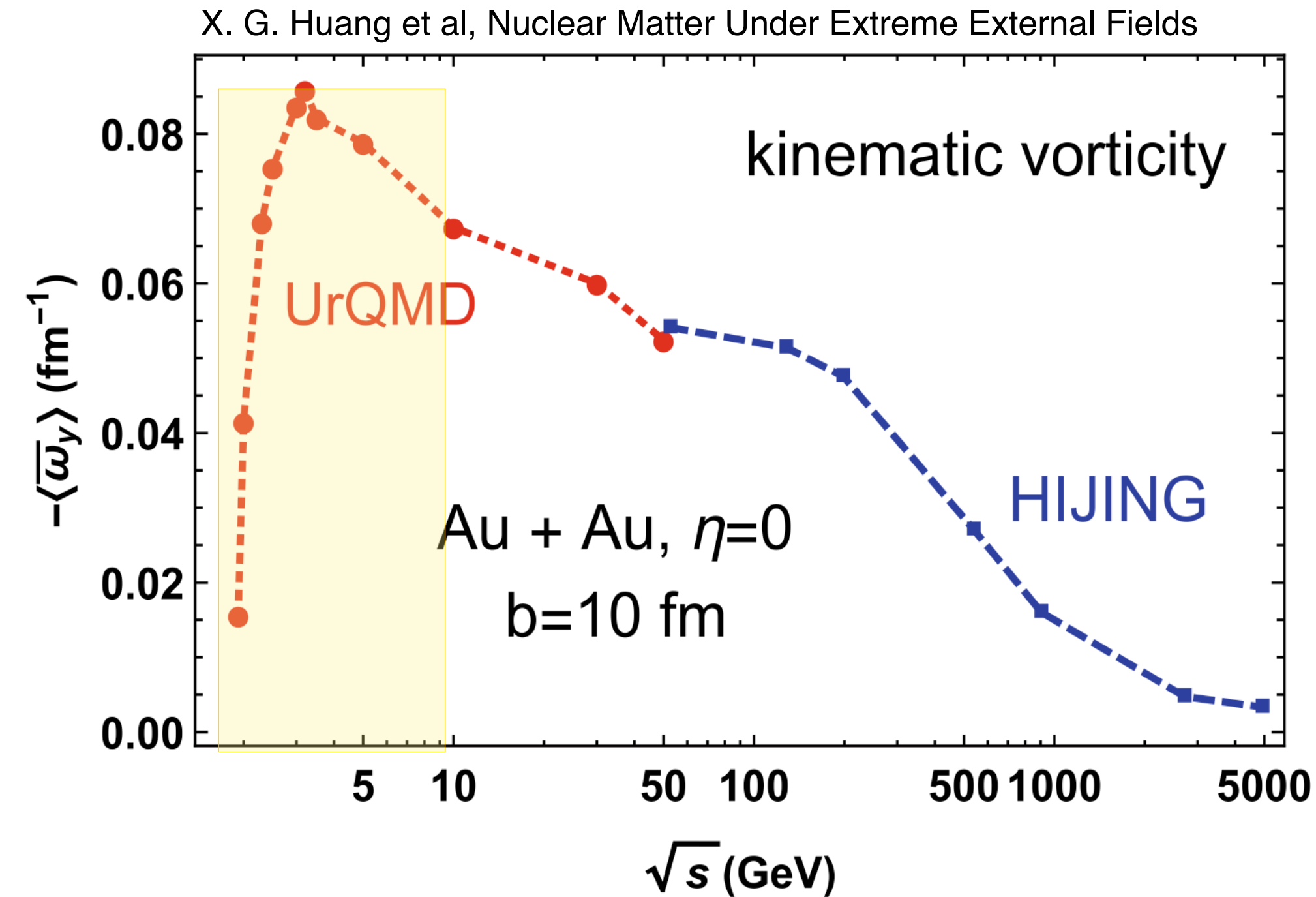
Global polarization at high baryon density region



Global spin polarization of Λ at high baryon density



- Beam energy dependence of angular momentum interactions
 - Can induce *non-monotonicity* and affects *QCD-EoS*



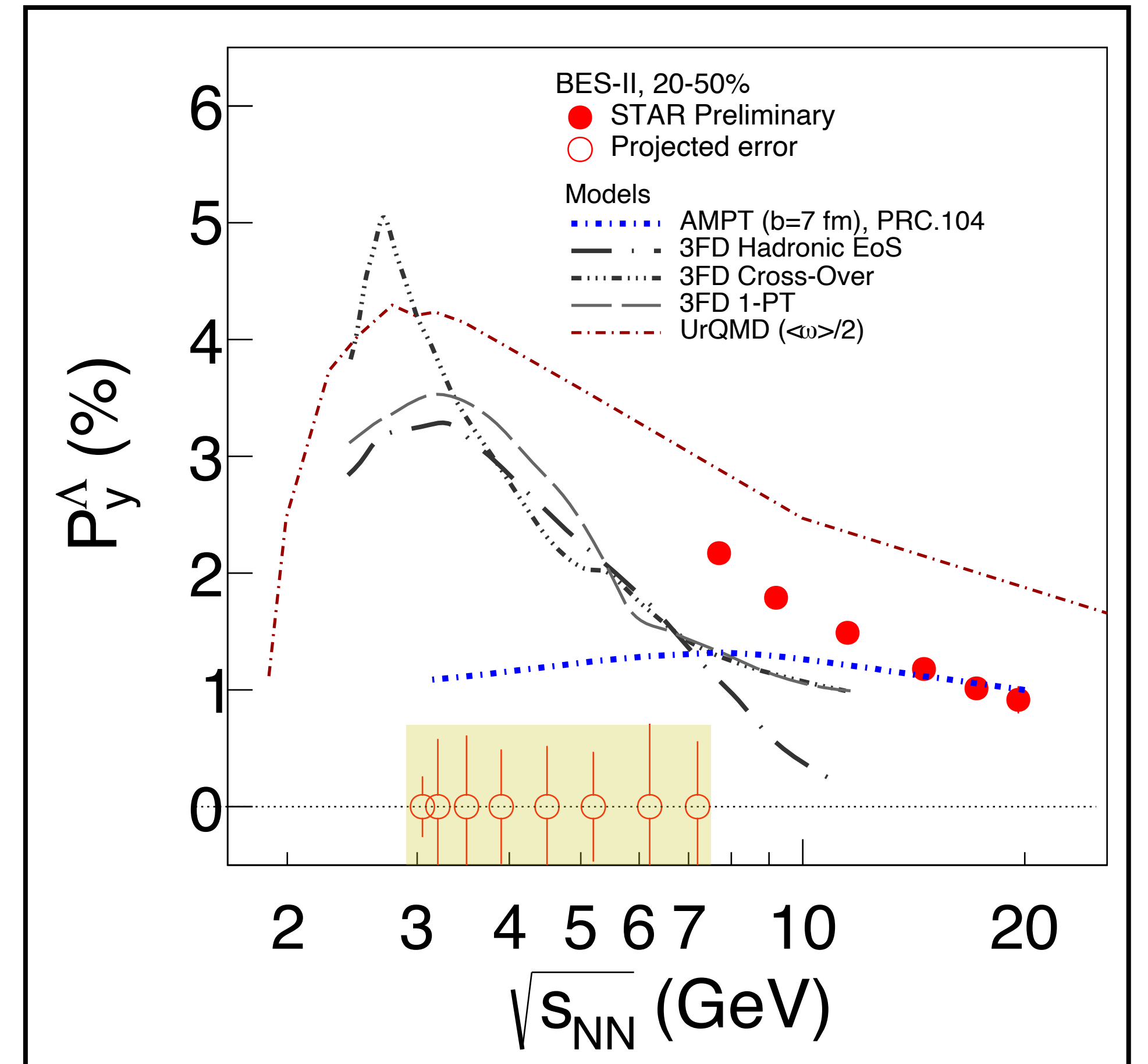
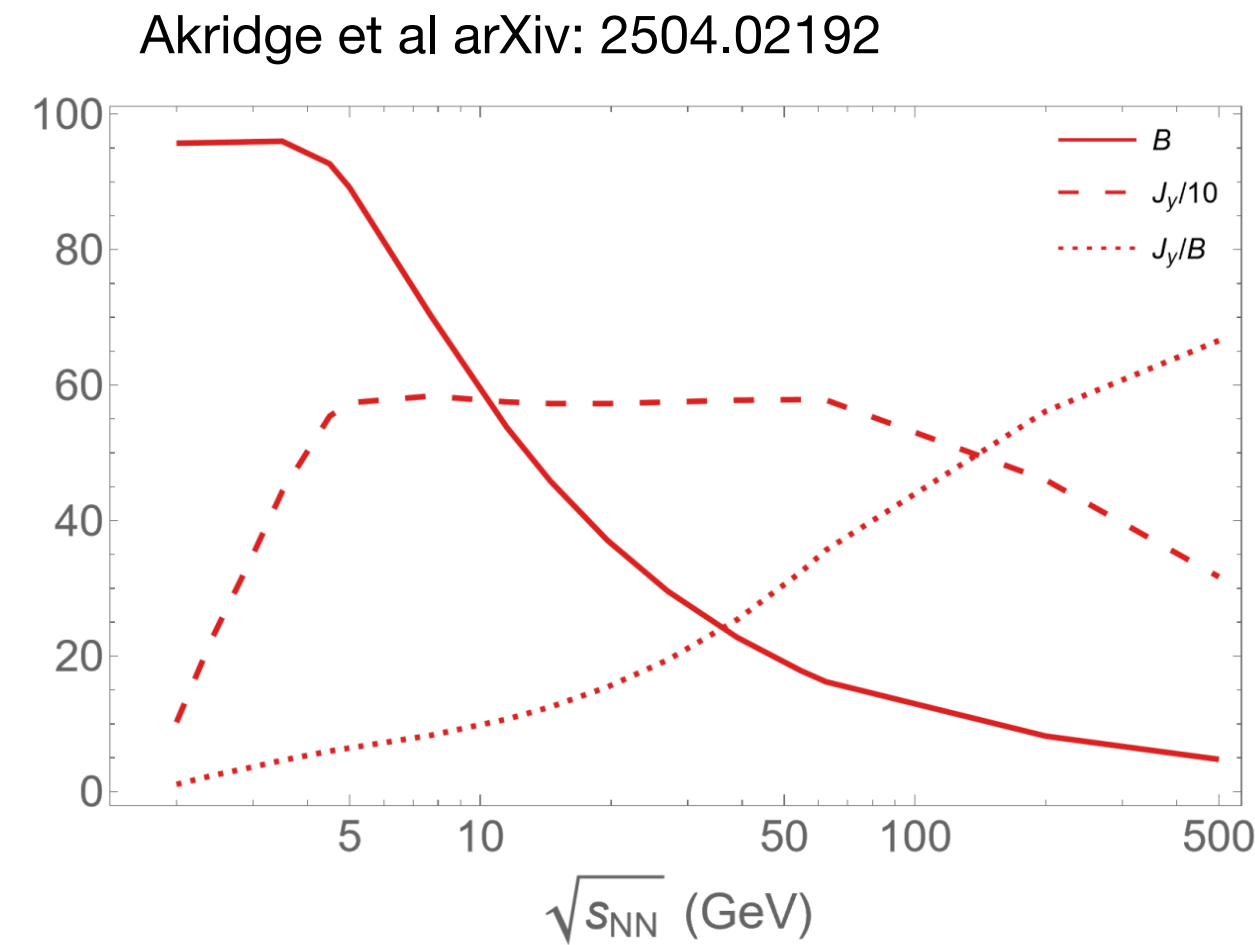
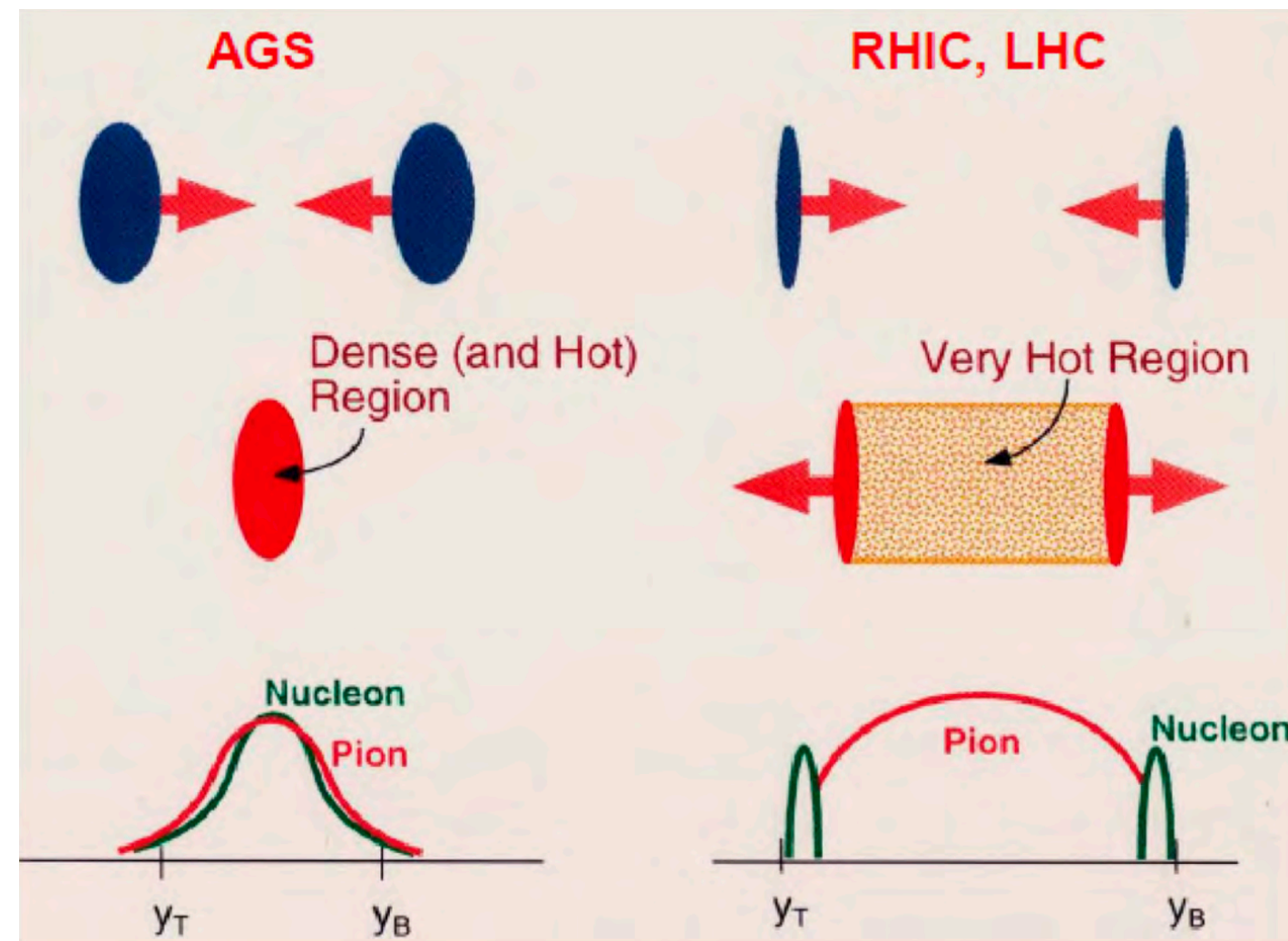
$$L \sim \frac{1}{2} Ab \sqrt{s} \sqrt{1 - (2M/\sqrt{s})^2}$$

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

Faster/Slower rotation induces anisotropic stresses and redistributes matter internally
 → **Equation of State (EoS)**

• *Is there a non-monotonic pattern in global polarization?*

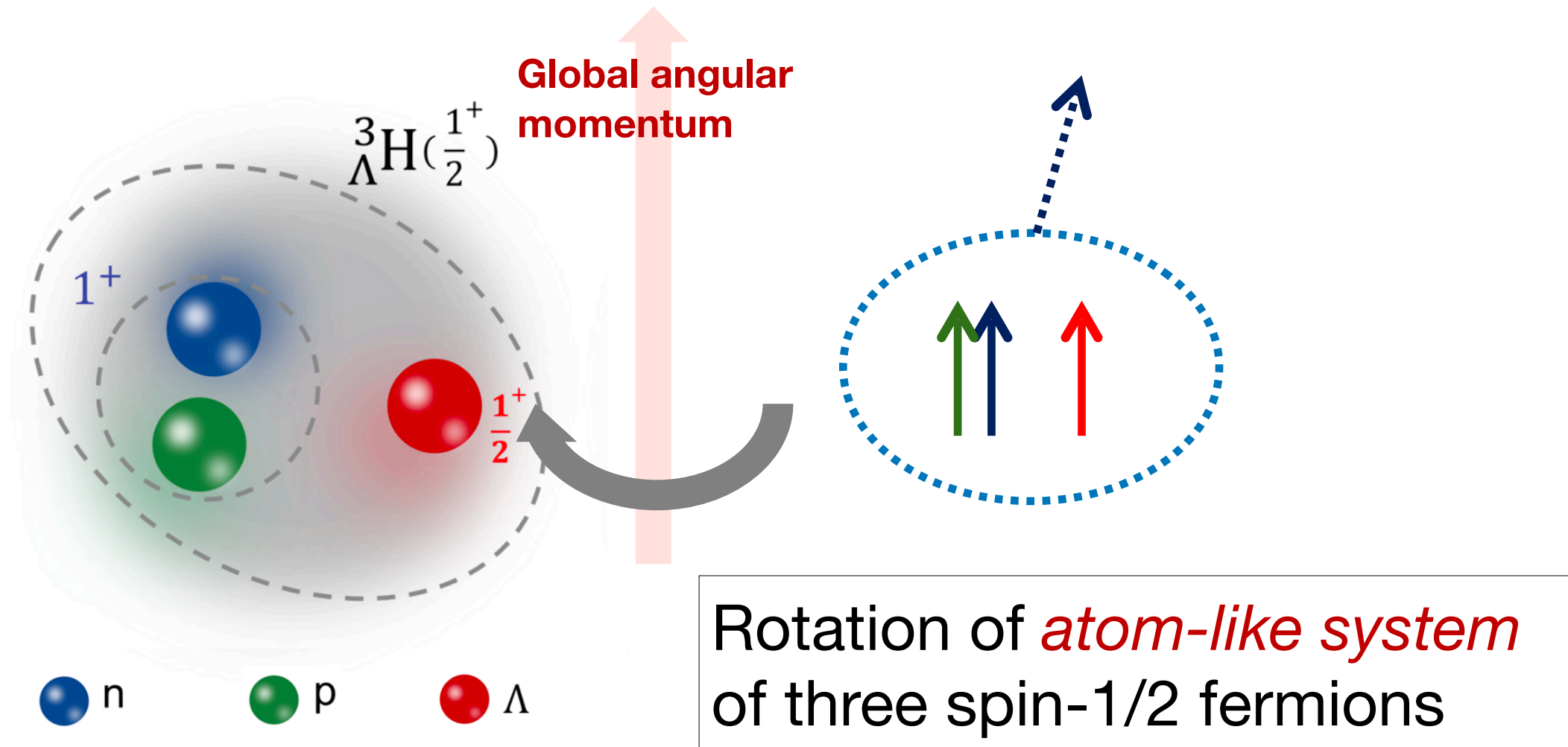
Global spin polarization of Λ at high baryon density



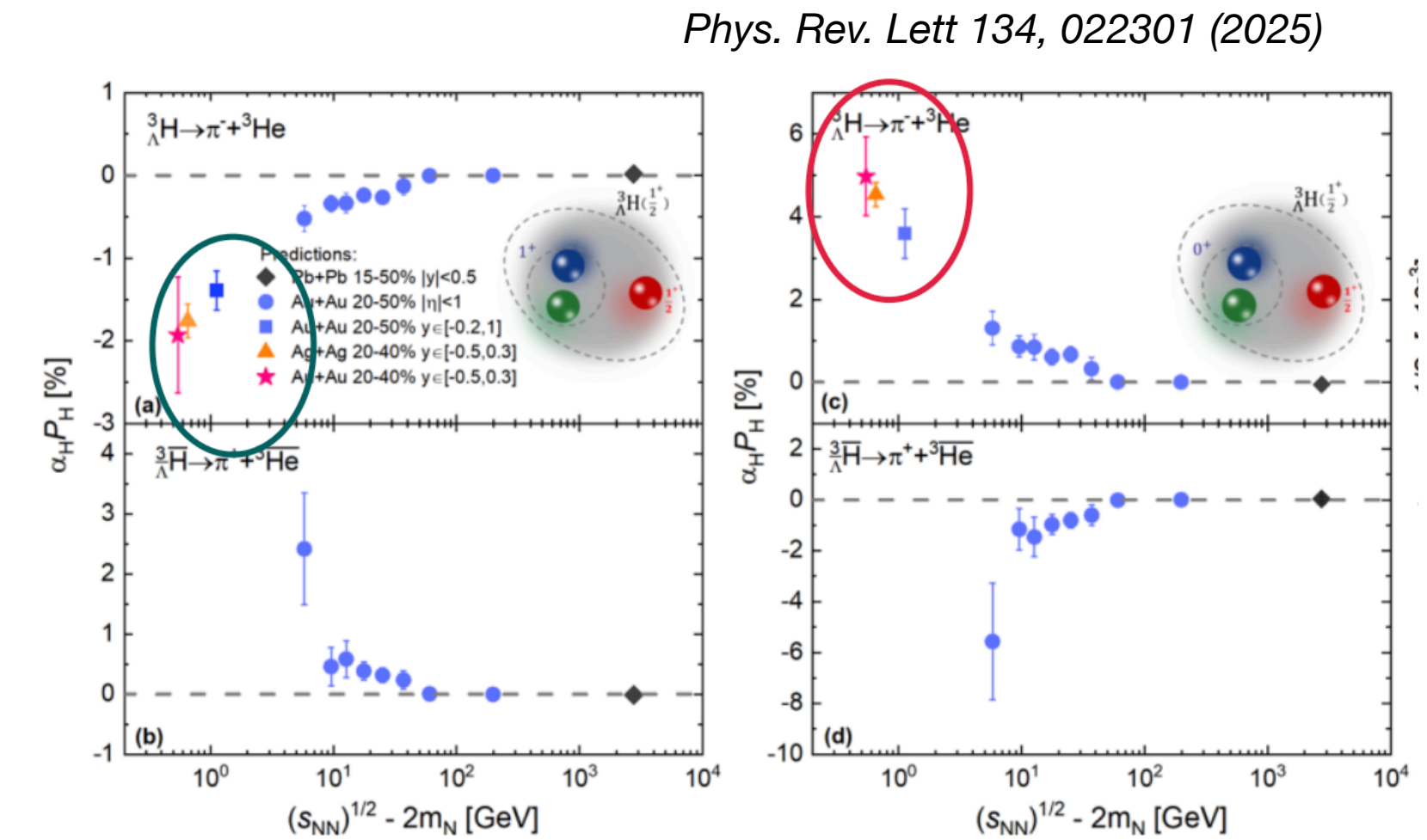
- *Is there a non-monotonic pattern in global polarization?*
- *Interplay between angular momentum and baryon stopping?*
- *Partonic versus Hadronic dominant medium carrying vorticity?*
- *Dependence on QCD EoS with spin degrees of freedom*

- Measurement of P_Λ using STAR fixed-target data is underway
- Unlike higher beam energy, 3 GeV acceptance can reach mid and target rapidity region

Global spin polarization of hyper-triton ${}^3_{\Lambda}\text{H}$ (pn Λ)

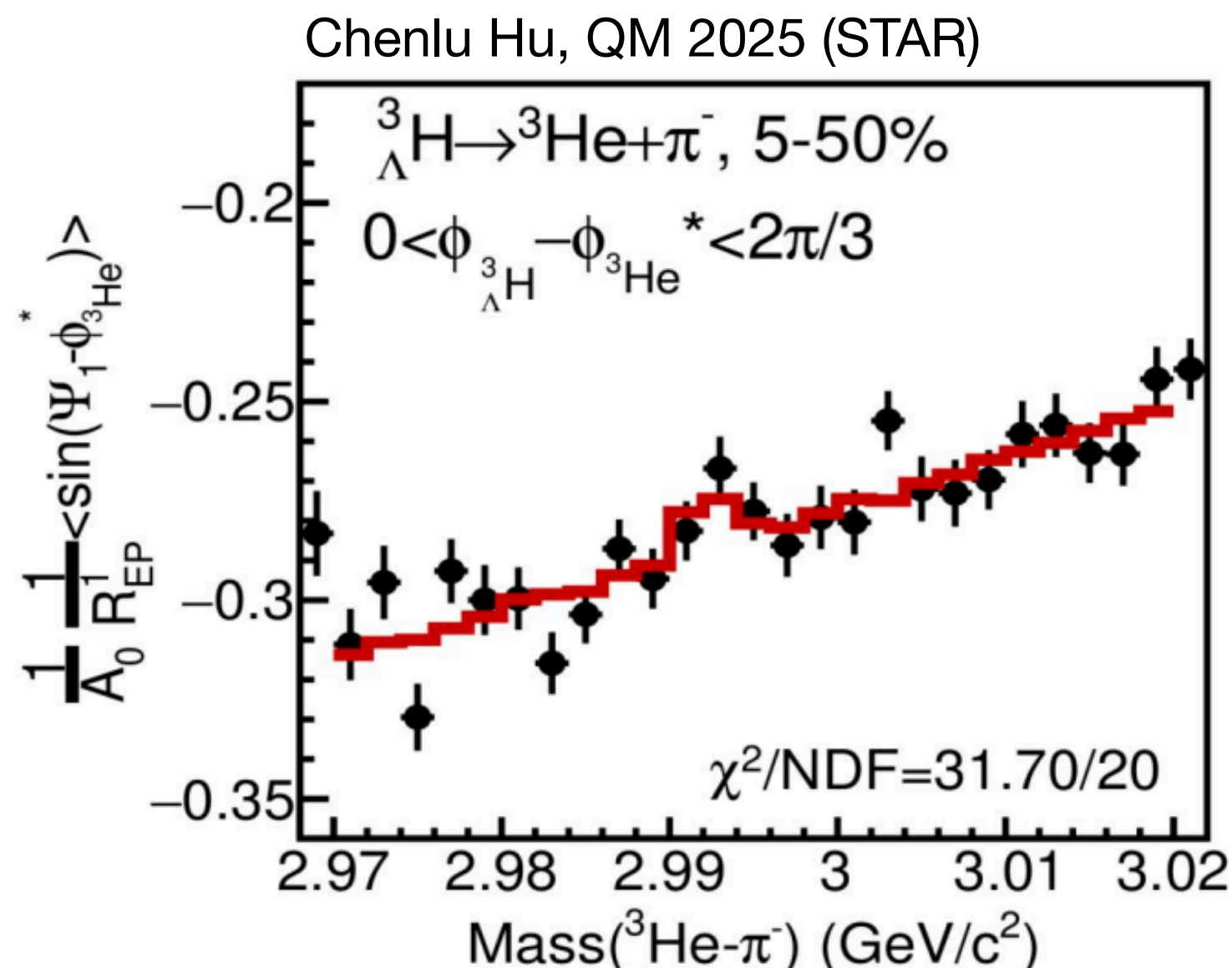


- Unique loosely bound “*pn Λ* ” system under global rotation
- Abundant ${}^3_{\Lambda}\text{H}$ Production at FXT region



- Sign of ${}^3_{\Lambda}\text{H}$ polarization relative to Λ
- What is spin structure of hyper-triton?
singlet or triplet?*

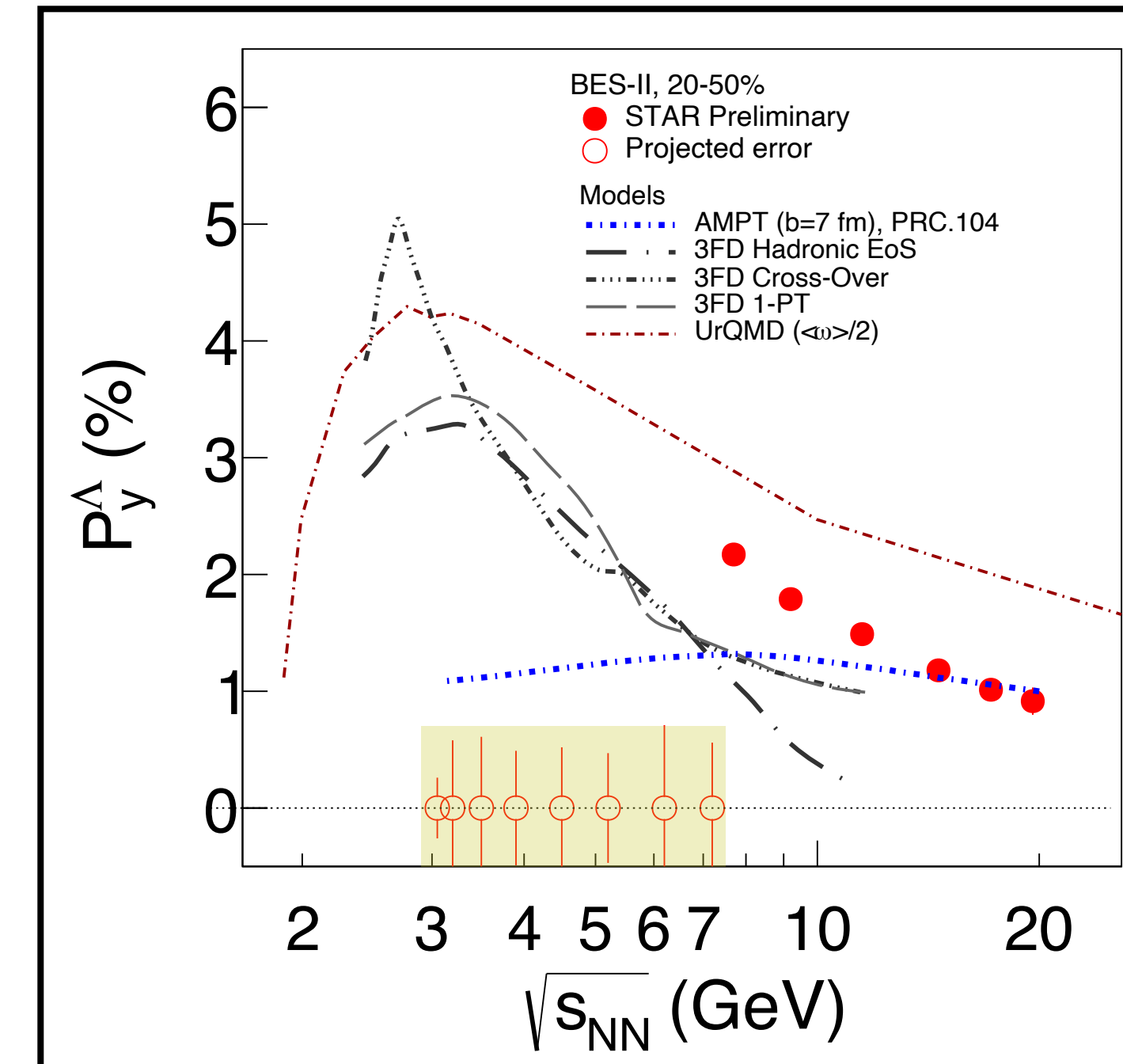
Next Talk: Kaijia Sun



- Measurement using STAR fixed-target data is underway

Summary

- Global spin polarization of hyperons (P_y)
 - monotonic beam energy dependence for Λ ,
 - $P_\Lambda \sim P_\Xi \sim P_\Omega$ follow same energy dependence
 - clear centrality dependence at all beam energies
 - no strong rapidity dependence within acceptance
 - No difference between Λ and $\bar{\Lambda}$
- Local spin polarization of hyperons
 - In-plane ($P_{2,z}$) positive magnitude
 - Baryonic Spin Hall effect: ($P_{2,z,z}^{\Lambda-\bar{\Lambda}}$) hints of sign change, no precision



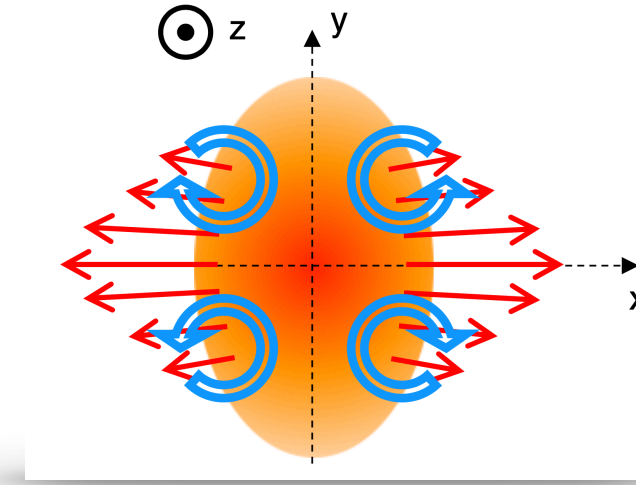
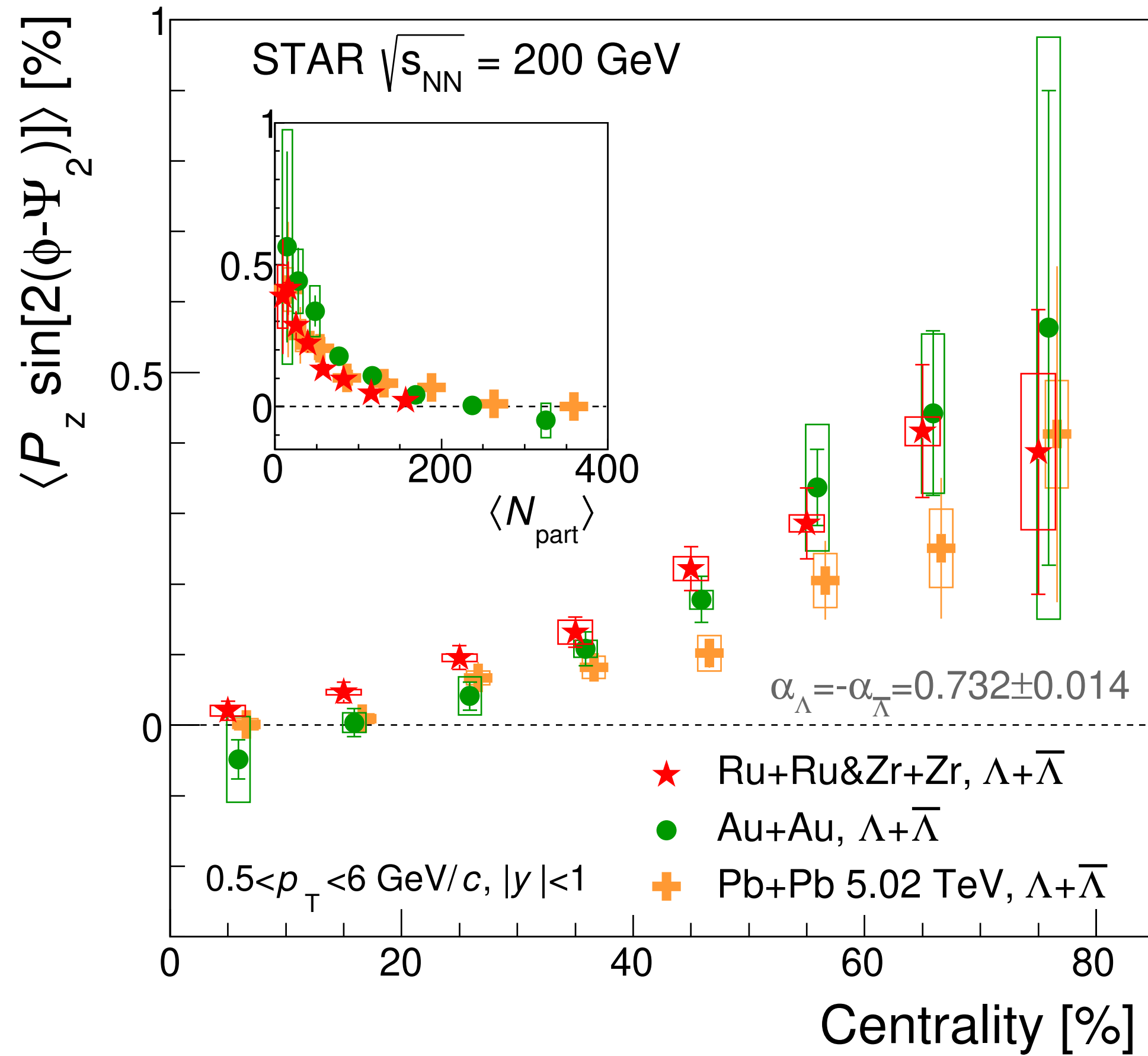
- Measurement at high baryon density are essential to address important questions:
- Expected non-monotonic pattern induced by angular momentum?
- Correlation with baryon stopping?
- QCD EoS?



Thank you for your attention!

Many Thanks to STAR colleagues!

Local spin polarization of hyperons

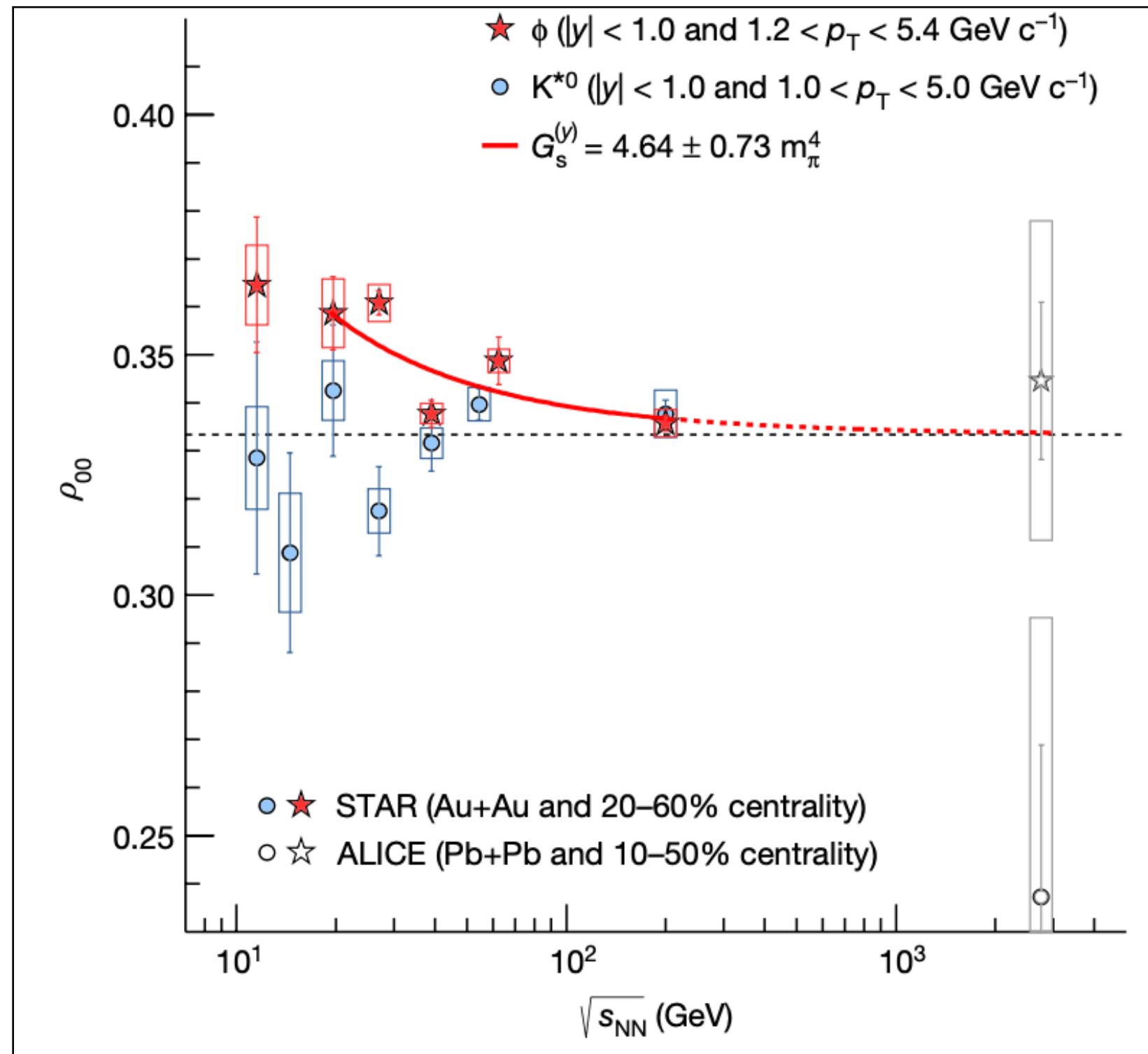


- $P_{2,z}$ shows significant centrality dependence, expected from elliptic flow

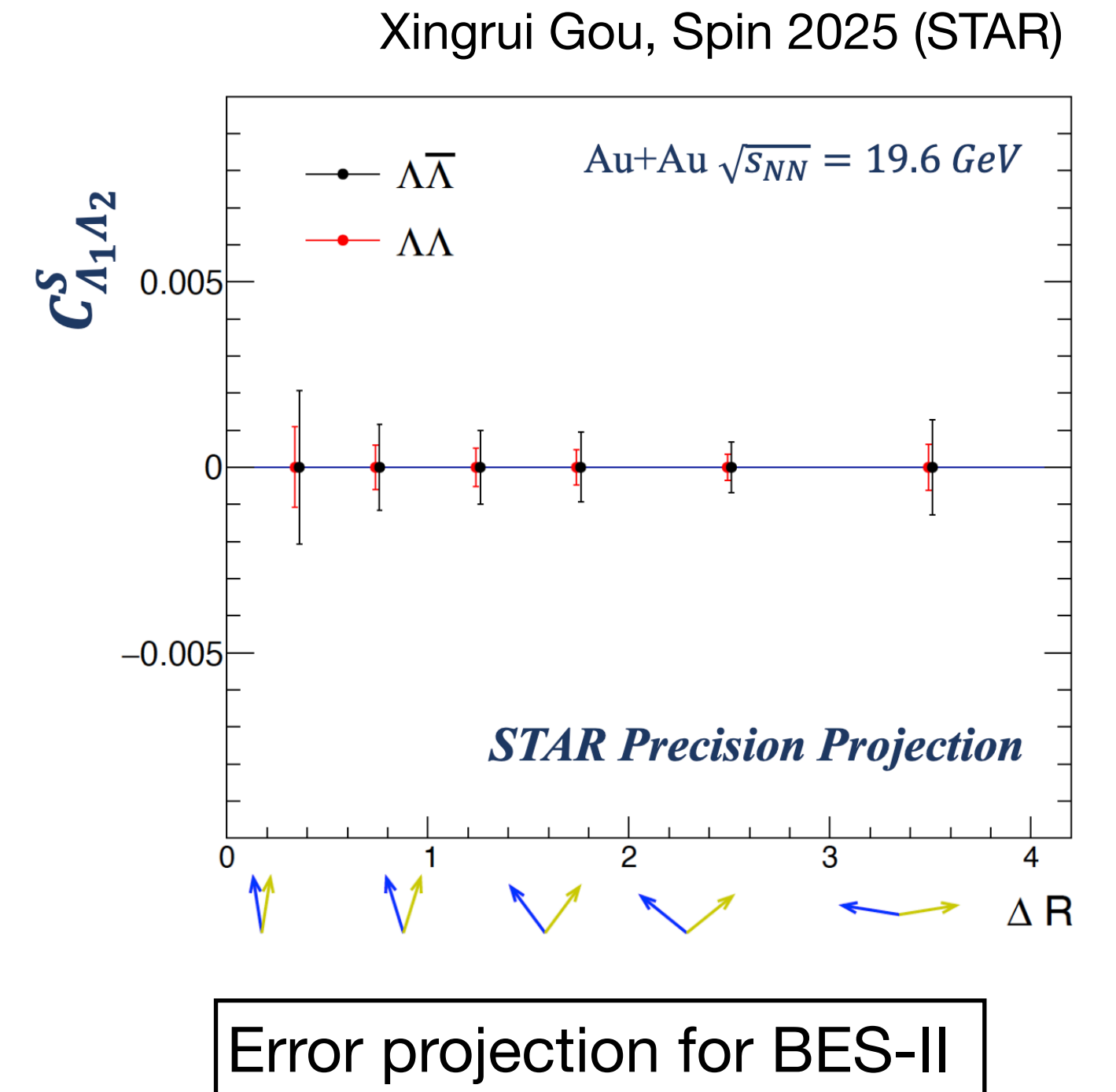
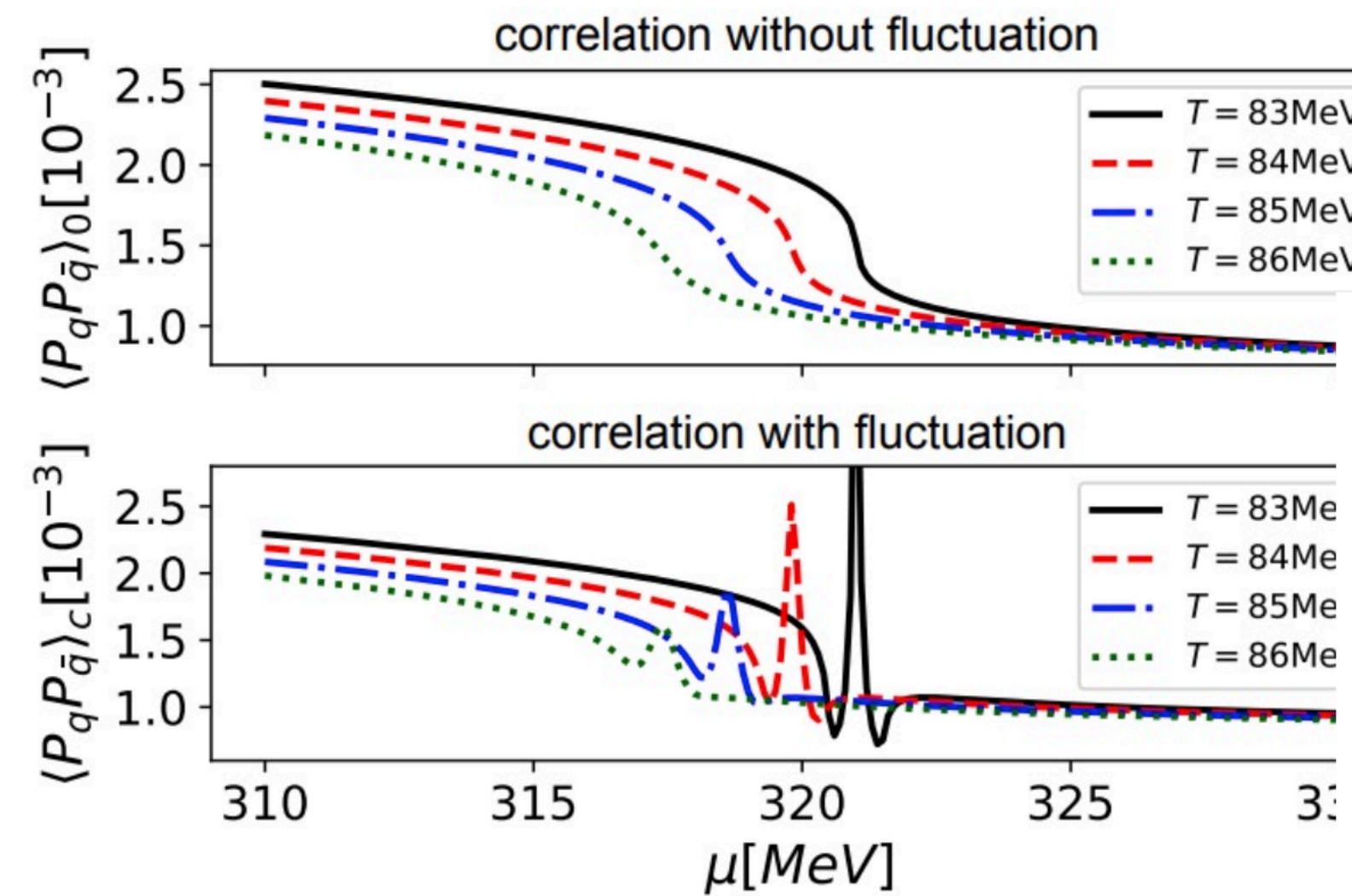
STAR: Phys Rev Lett 131, 202301 (2023)

Spin-spin correlations in BES

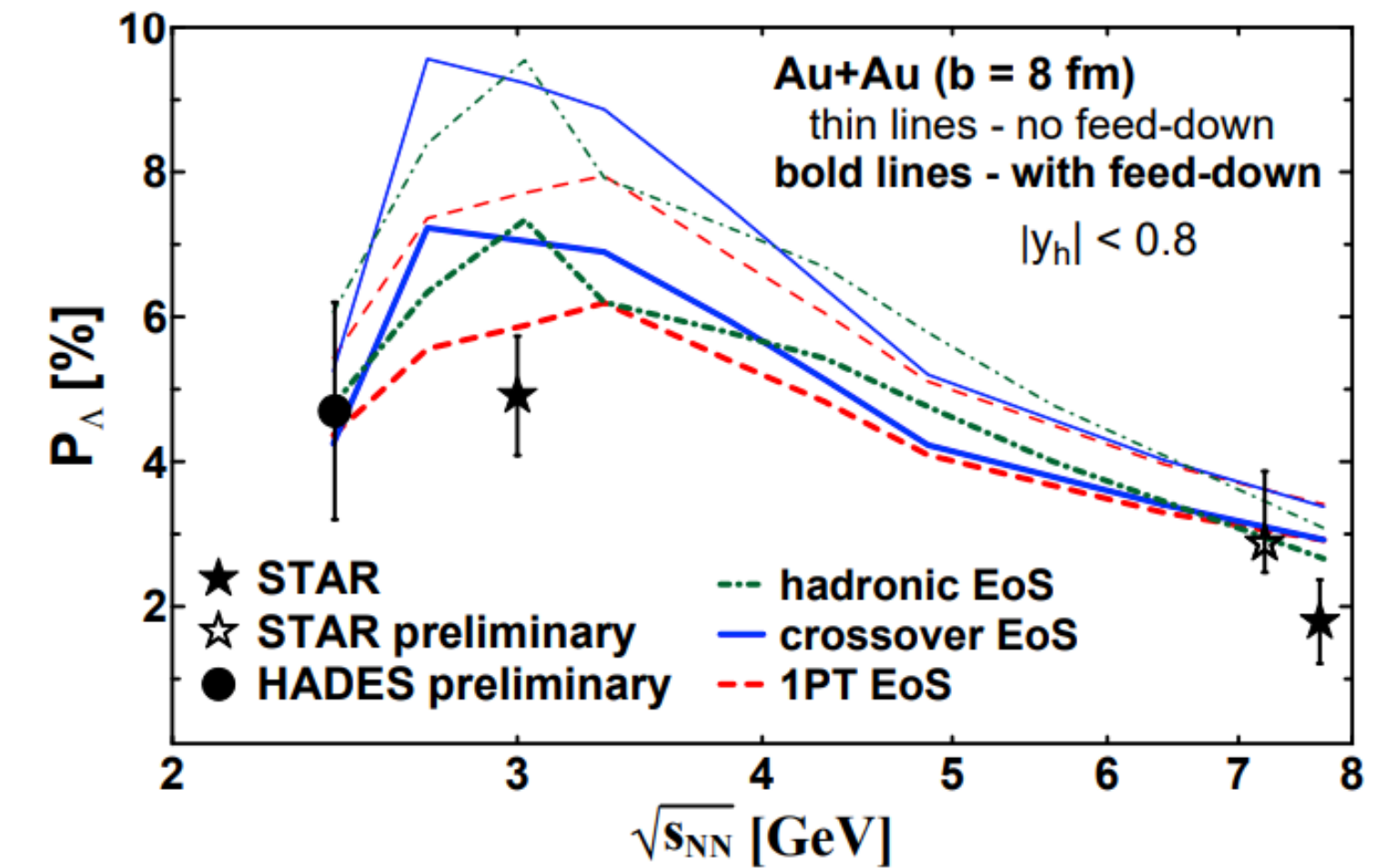
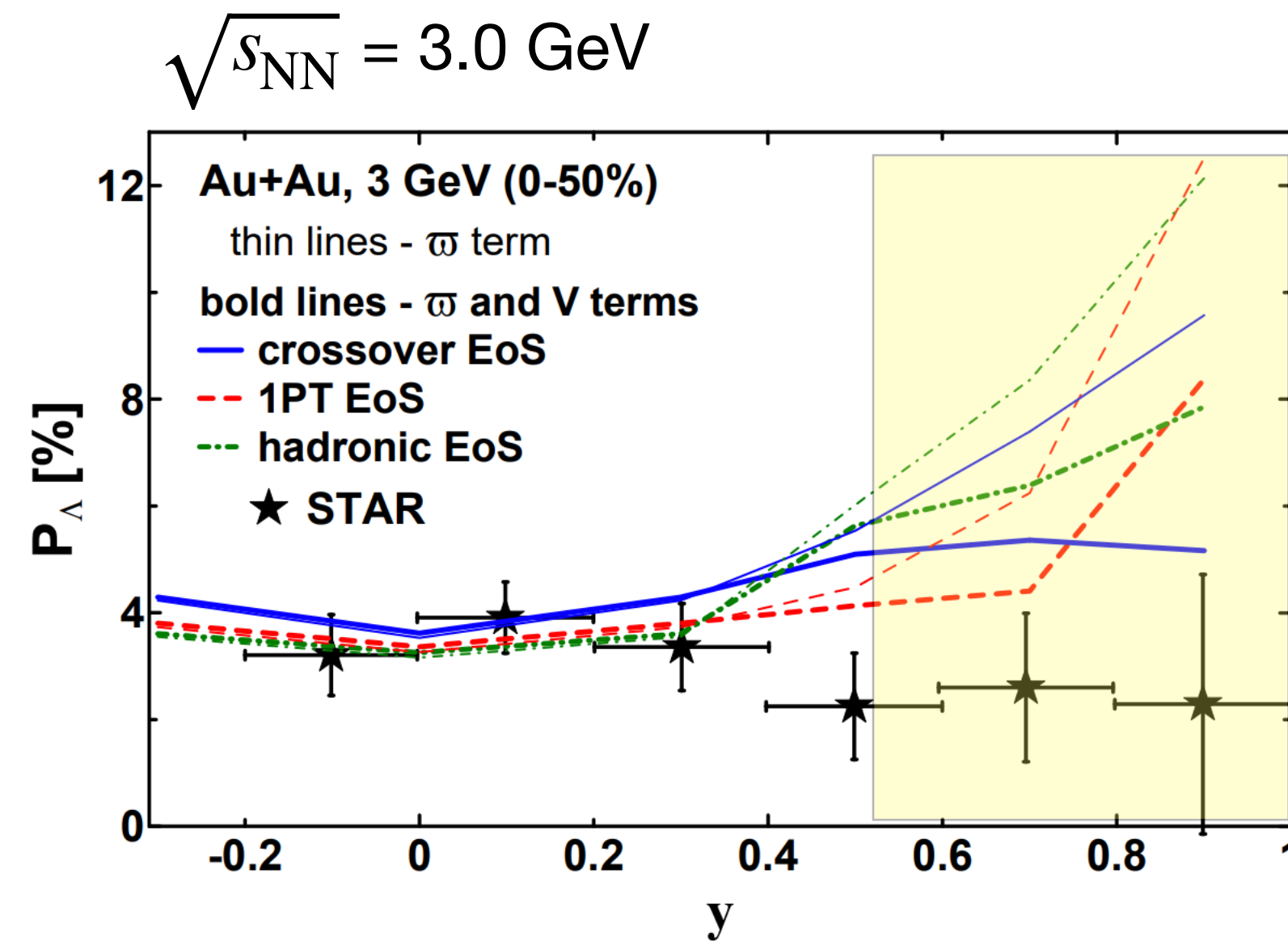
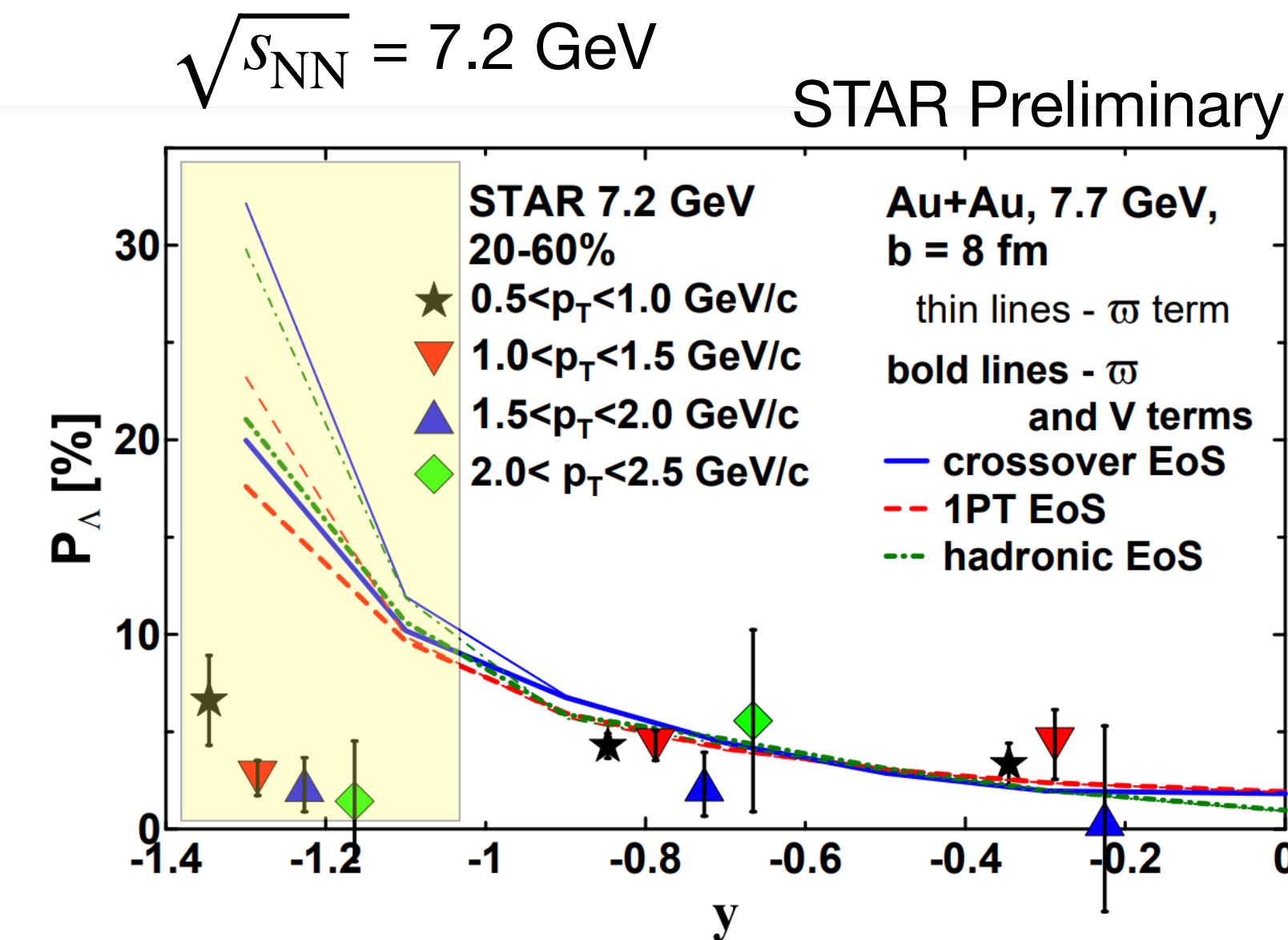
Article | Published: 18 January 2023
Pattern of global spin alignment of ϕ and K^*0 mesons in heavy-ion collisions
 STAR Collaboration
Nature 614, 244–248 (2023) | [Cite this article](#)



- Signal larger than expectation from P_Λ
- Role of spin fluctuation



P_Λ : rapidity dependence with models

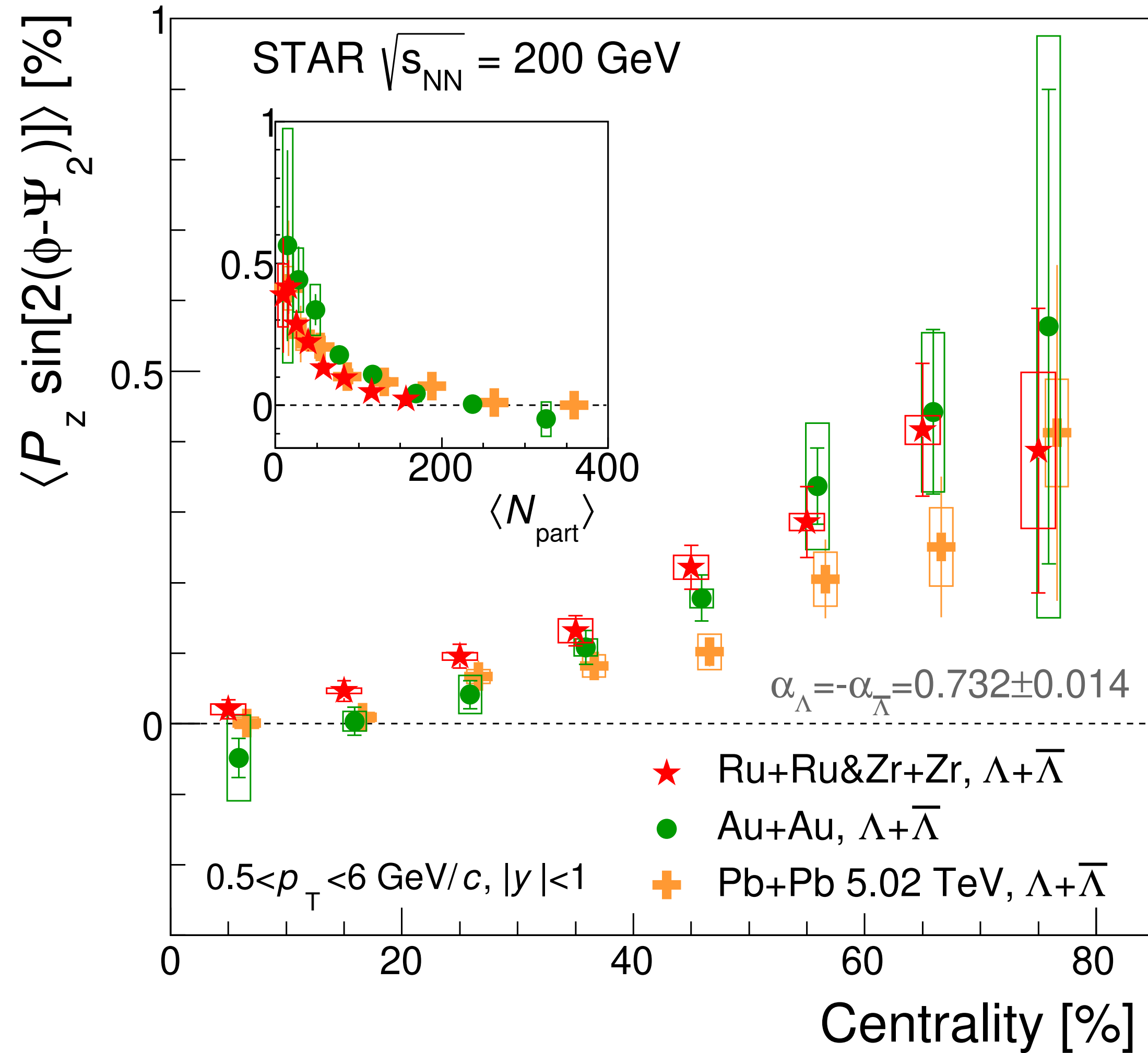


Ivanov et. al., Phys Rev C 105, 034915 (2022)

- 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

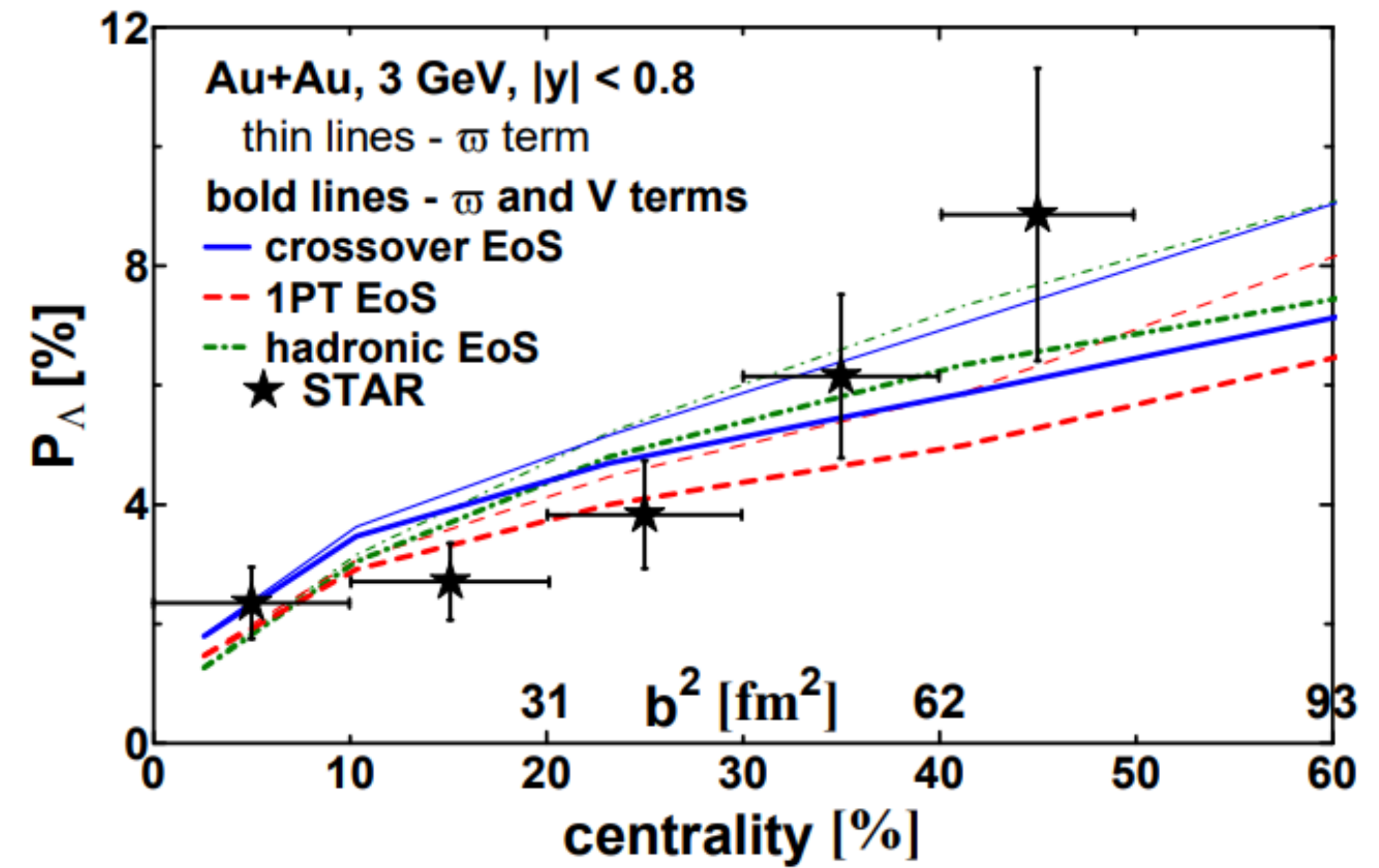
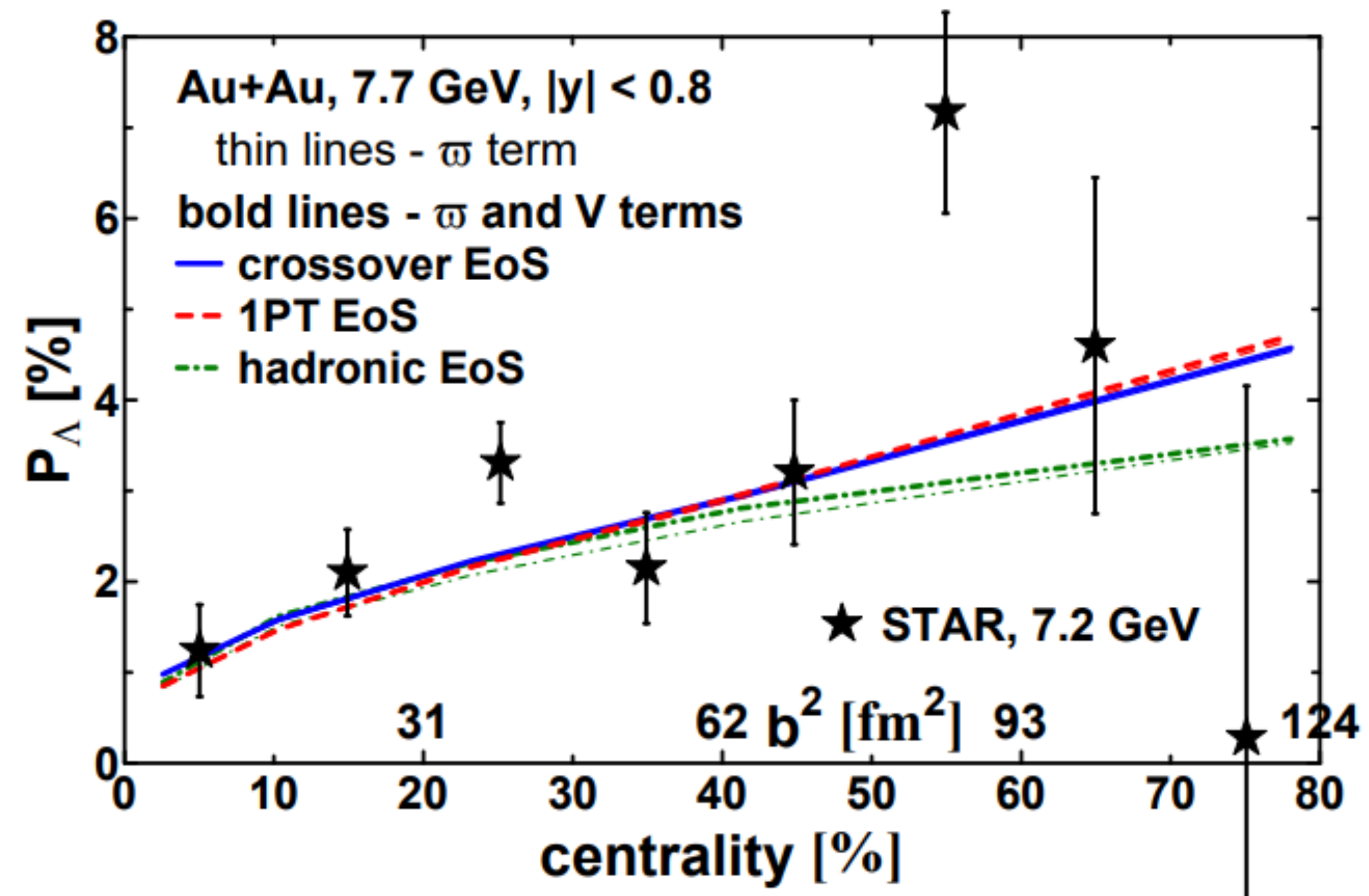
Local (P_z) spin polarization of hyperons



- Clear centrality dependence of P_z
- At mid-central collisions
Zr+Zr, Ru+Ru $>$ Au+Au $\sim$ 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)

P_Λ : centrality dependence with 3FD model



Baryonic Spin Hall effect (SHE)

Condensed matter

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

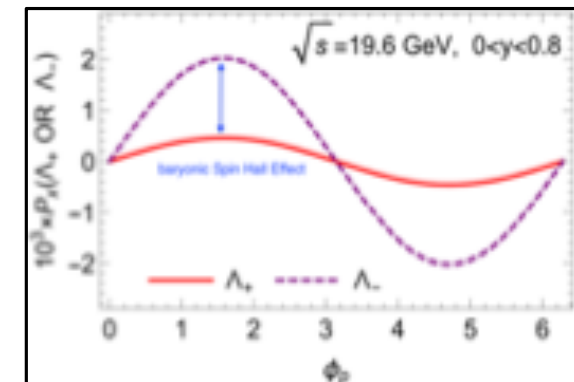
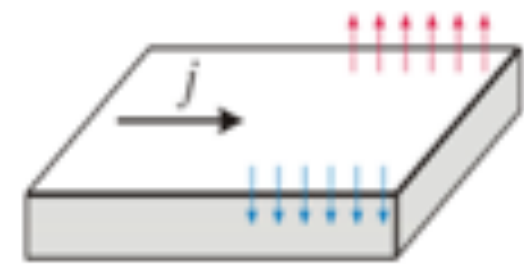
splitting in spin on opposite boundaries

Heavy Ion Collisions

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

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

“spin-orbit”



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

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

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

How do we visualize?

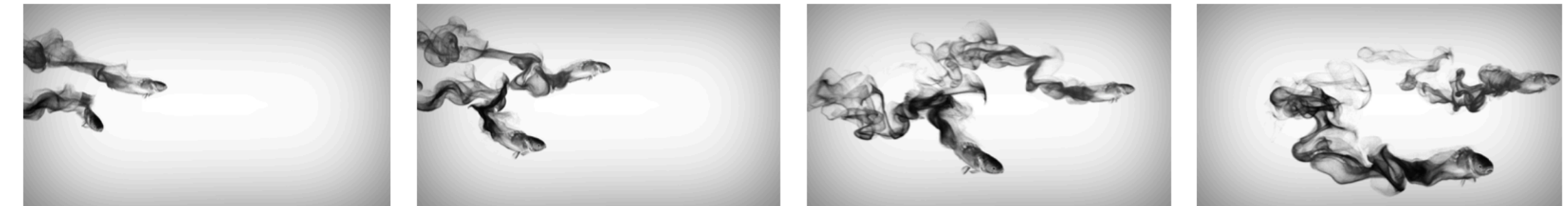


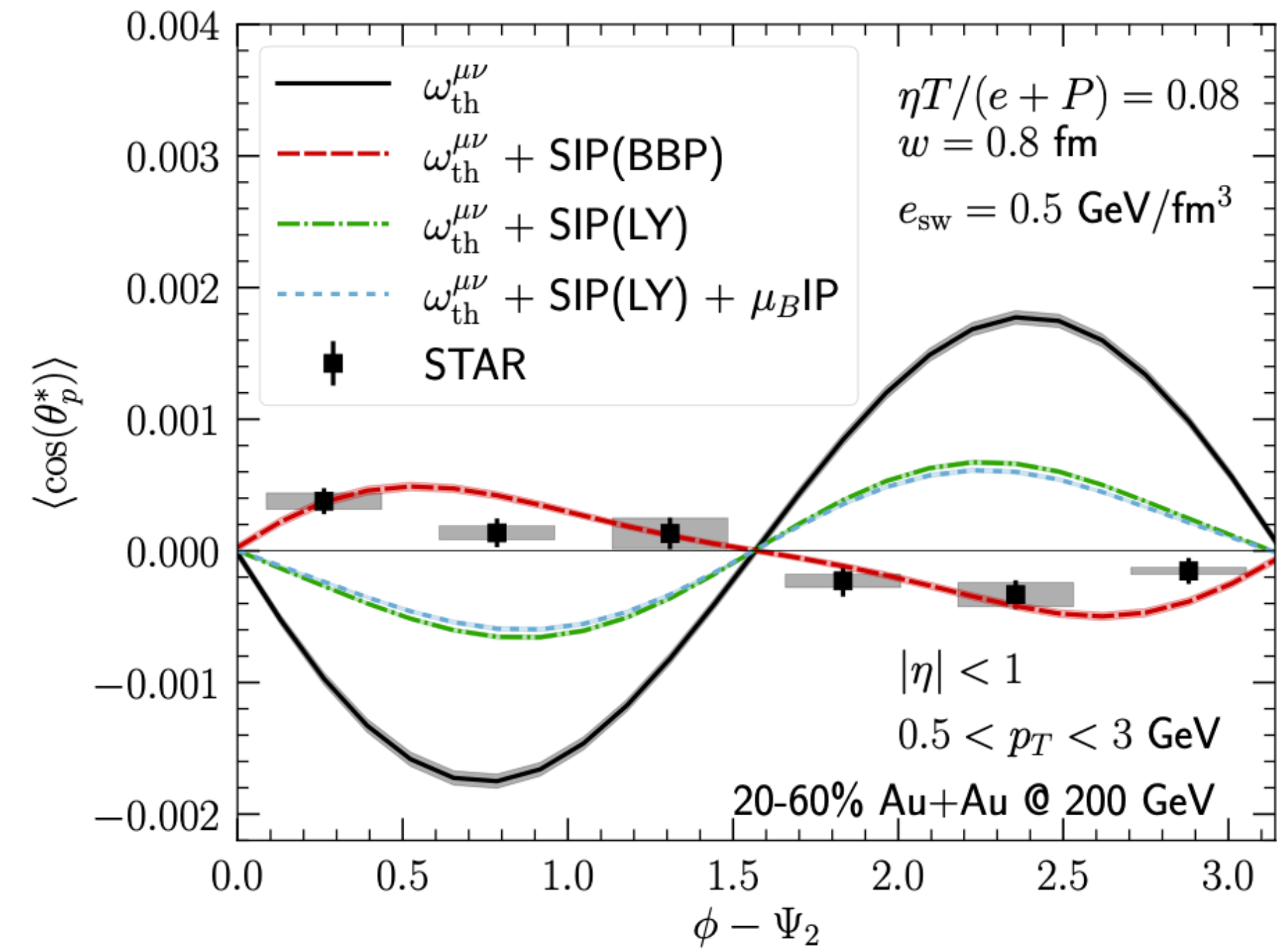
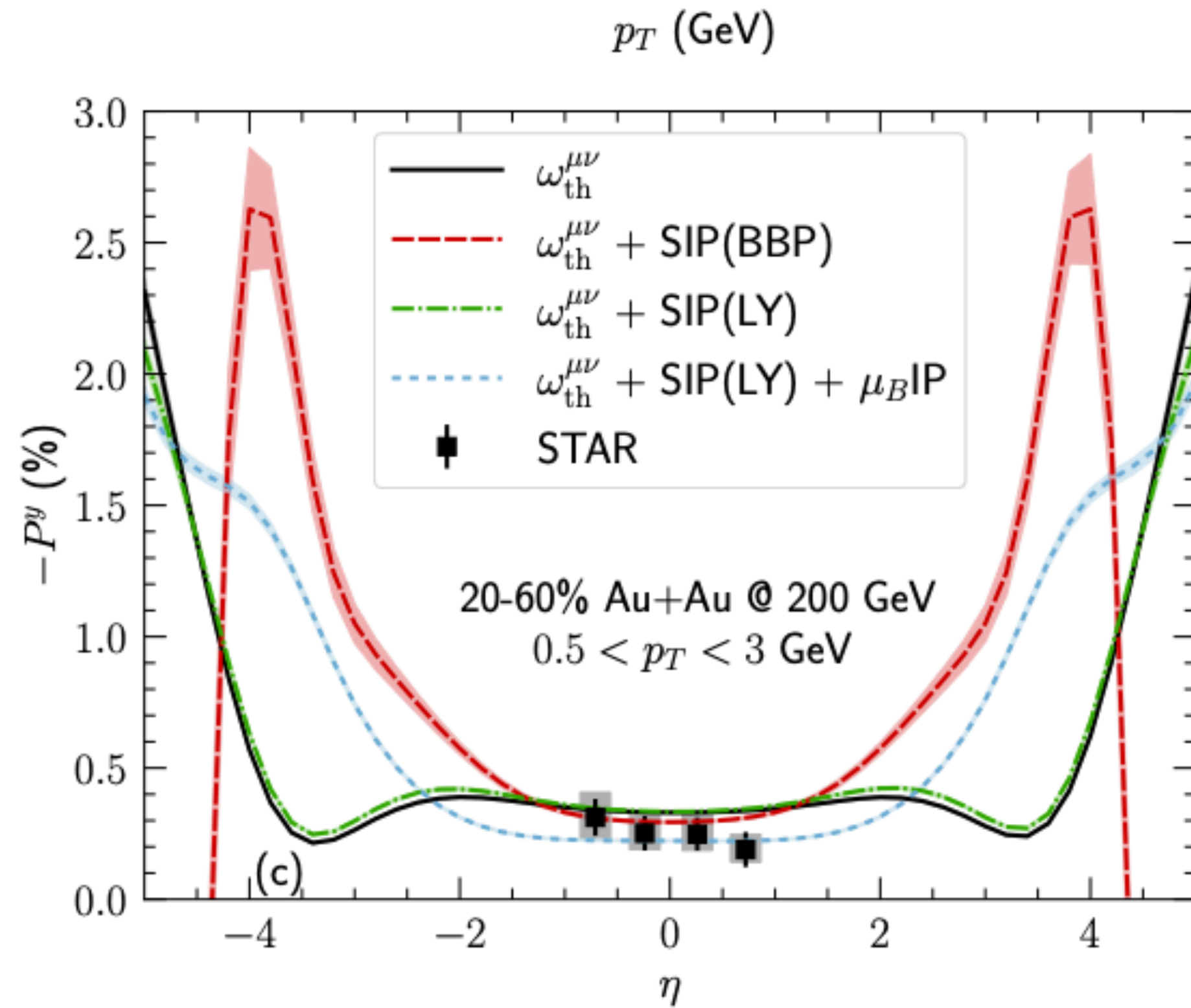
Figure 1: An example of ink-made fish animation created with our method. Two fish are swimming in water freely, and the fishtails swing in high speed. Ink flows emit from the fishtails at the same time, then the attractive dynamic ink diffusion effects can be observed.

<https://doi.org/10.1145/2087756.20877>

Naive picture

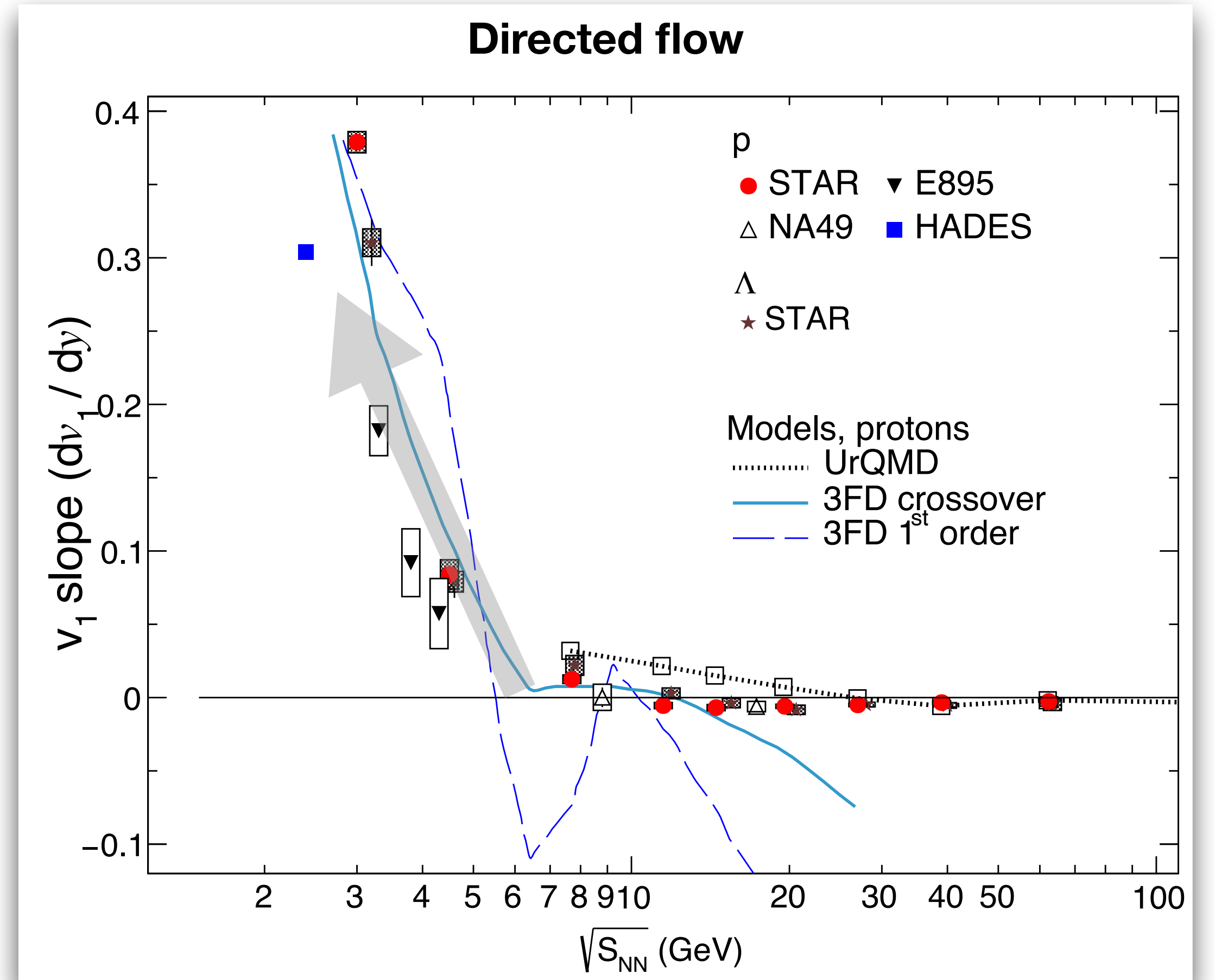
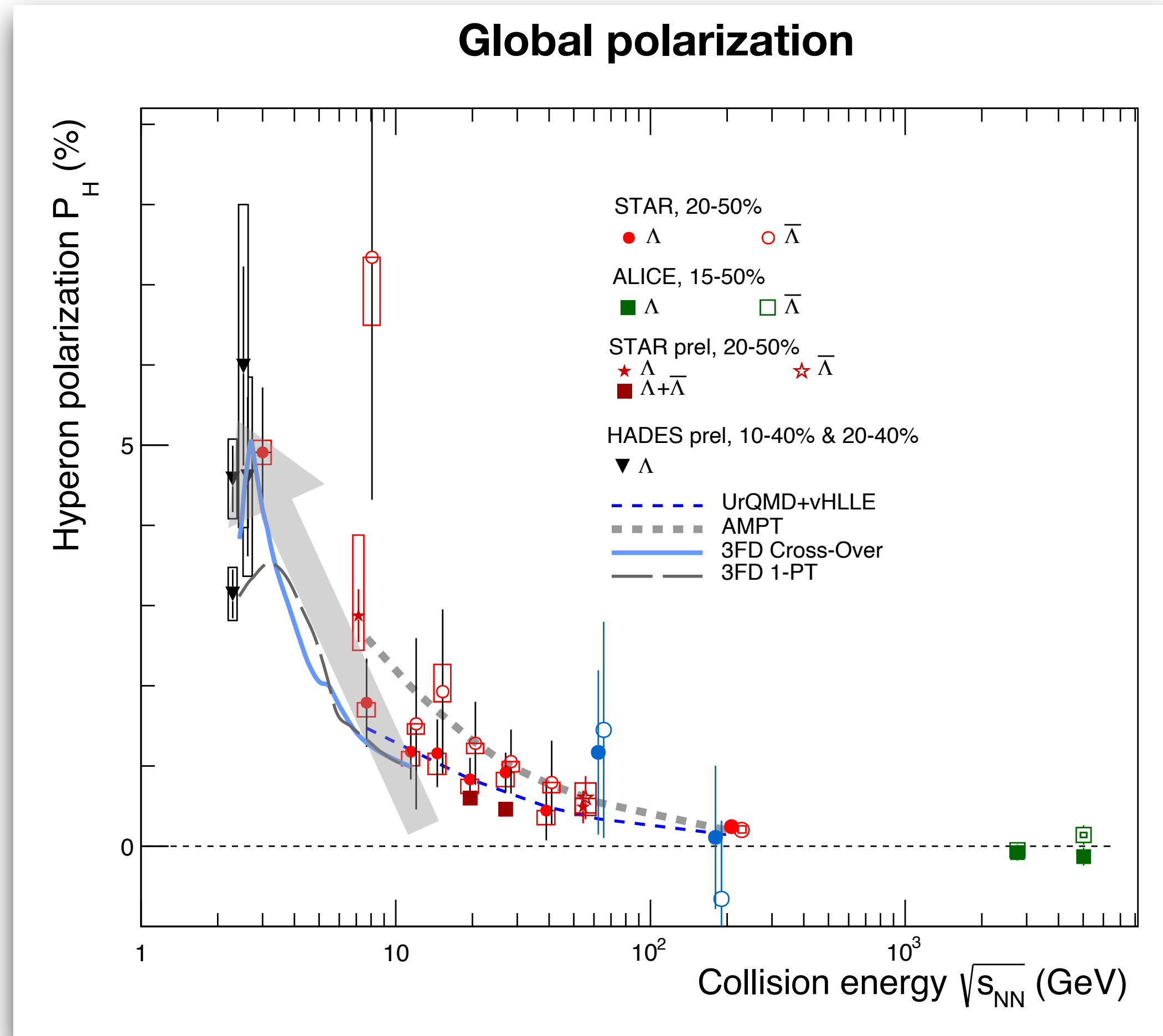
- Consider **ink** as baryons in the medium
- Ink (baryon) density is changing $\rightarrow$ (baryon) chemical potential gradient ($\nabla \mu_B$)
- Heavy-ion collisions (much complicated) $\rightarrow$ adding ink (baryon) into expanding swirling water $\rightarrow$ baryonic Spin Hall effect
- How the ink (baryon) density changing in transverse and longitudinal plane?

Local spin polarization



Alzhrani et. al., Phys Rev C 106, 014905 (2022)

Beam energy dependence of global P_Λ



- Similar rising pattern in polarization and directed flow at low energy
- Some models can capture such rising trend in both P_H and v_1