



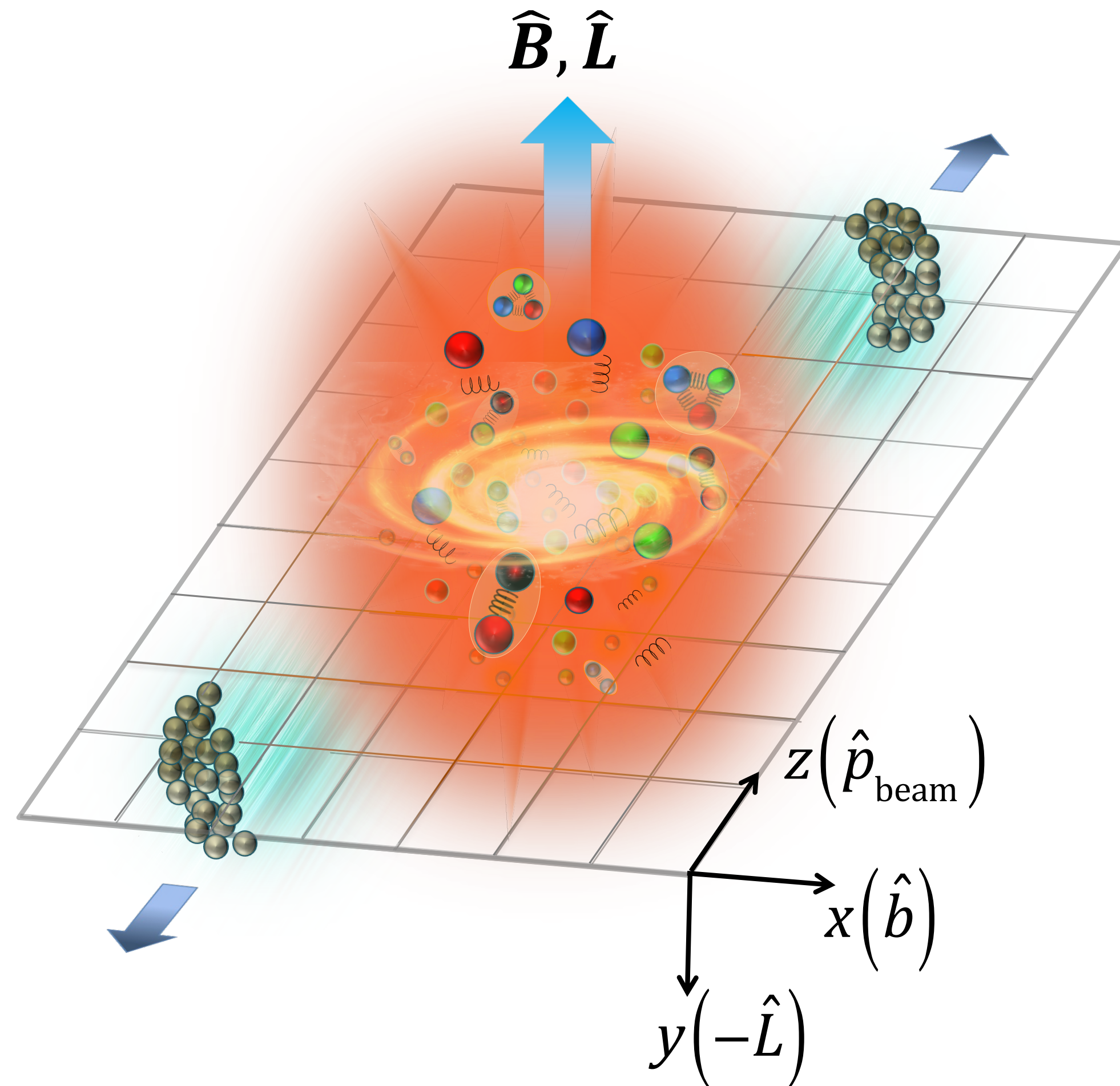
Global Spin Polarization and Alignment in Heavy-ion Collisions

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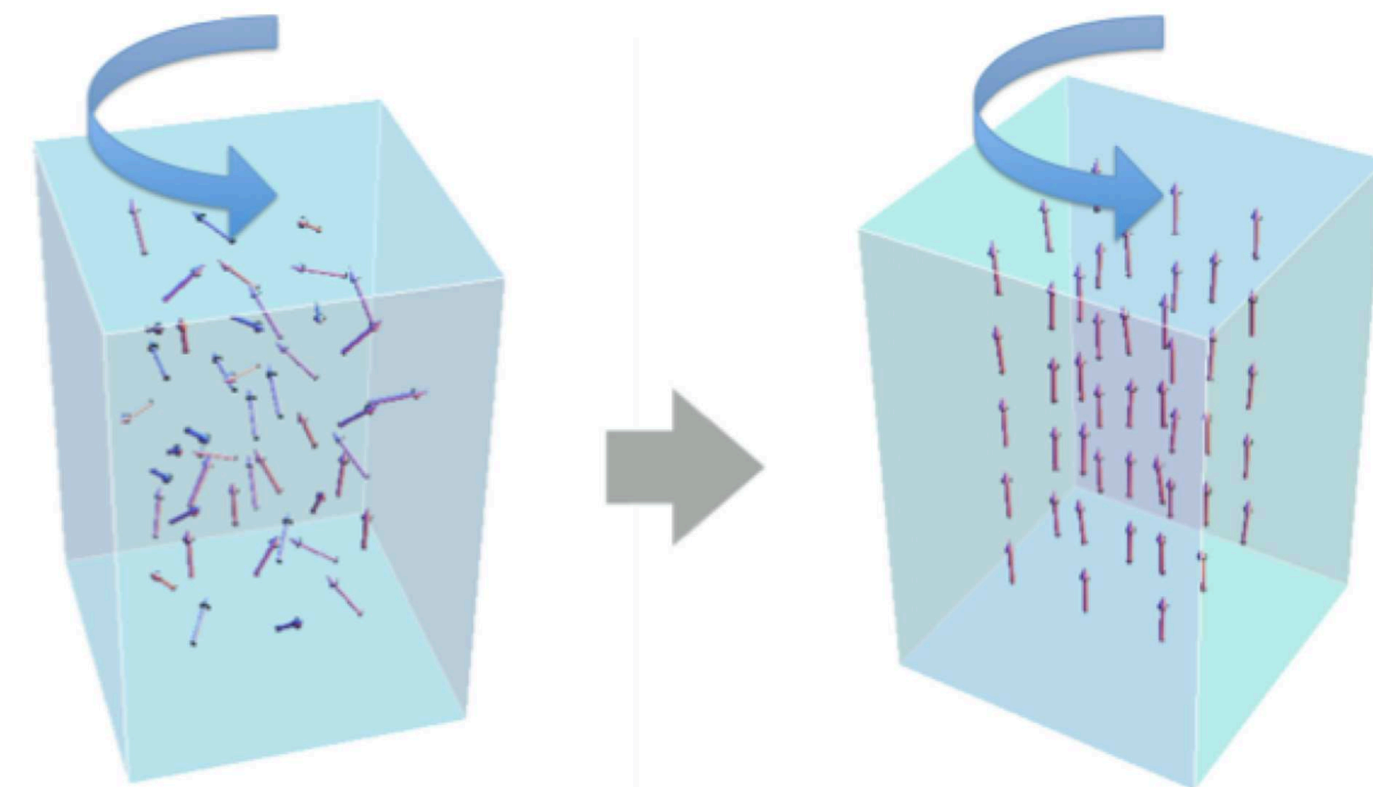
Spin-Orbital coupling in heavy-ion collisions

Liang, Wang Phys. Rev. Lett. **94**, 102301(2005); Phys. Lett. B **629**, 20 (2005)



- Non-central HICs have large initial **Orbit Angular Momentum (OAM)** and **magnetic field**
- OAM ($\sim 10^4 \hbar$) can polarize quarks due to “spin-orbit” interaction
- Observables:
 - Λ -hyperon ($J^P = 1/2^+$) global spin polarization
 - Vector meson ($J^P = 1^-$) global spin alignment

Barnett effect



Rotation $\rightarrow$ Polarization

Hyperon global spin polarization

Λ -hyperon ($J = 1/2^+$):

- Reveal polarization by preferentially emitting daughter proton in spin direction
- Polarization sign is measurable
- Need reaction plane direction
 - use 1st order event plane

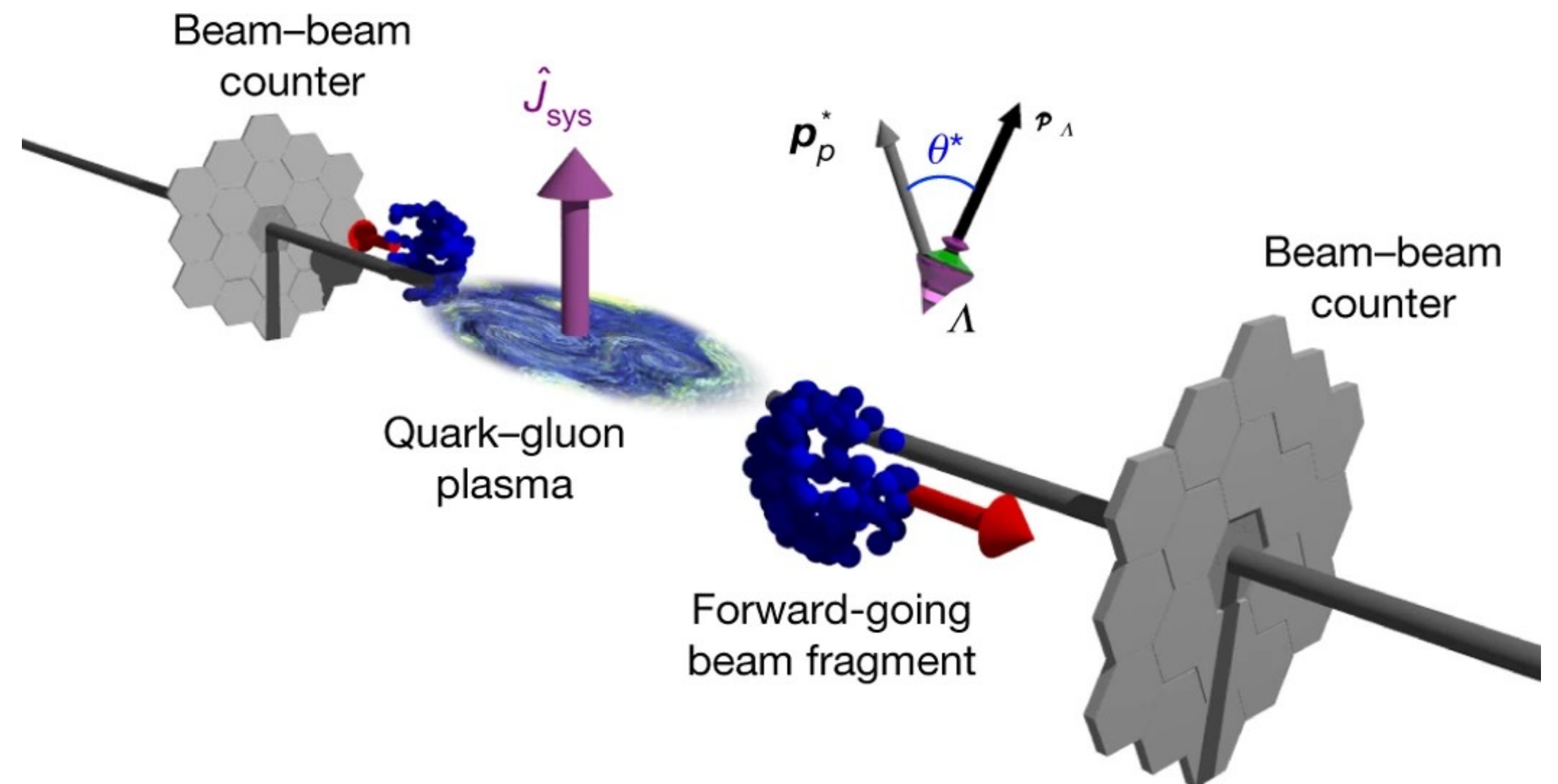
$$\frac{dN}{d\cos\theta^*} \sim 1 + \alpha_H P_H \cos\theta^*$$

P_H : Hyperon polarization

α_H : Hyperon decay parameter

$$\bar{P}_\Lambda = \frac{8}{\pi\alpha_\Lambda} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\text{Res}(\Psi_1)}$$

STAR, Nature 548, 62 (2017)



θ^* is the angle between decay daughter and polarization direction in mother particle rest frame

Vector meson spin alignment

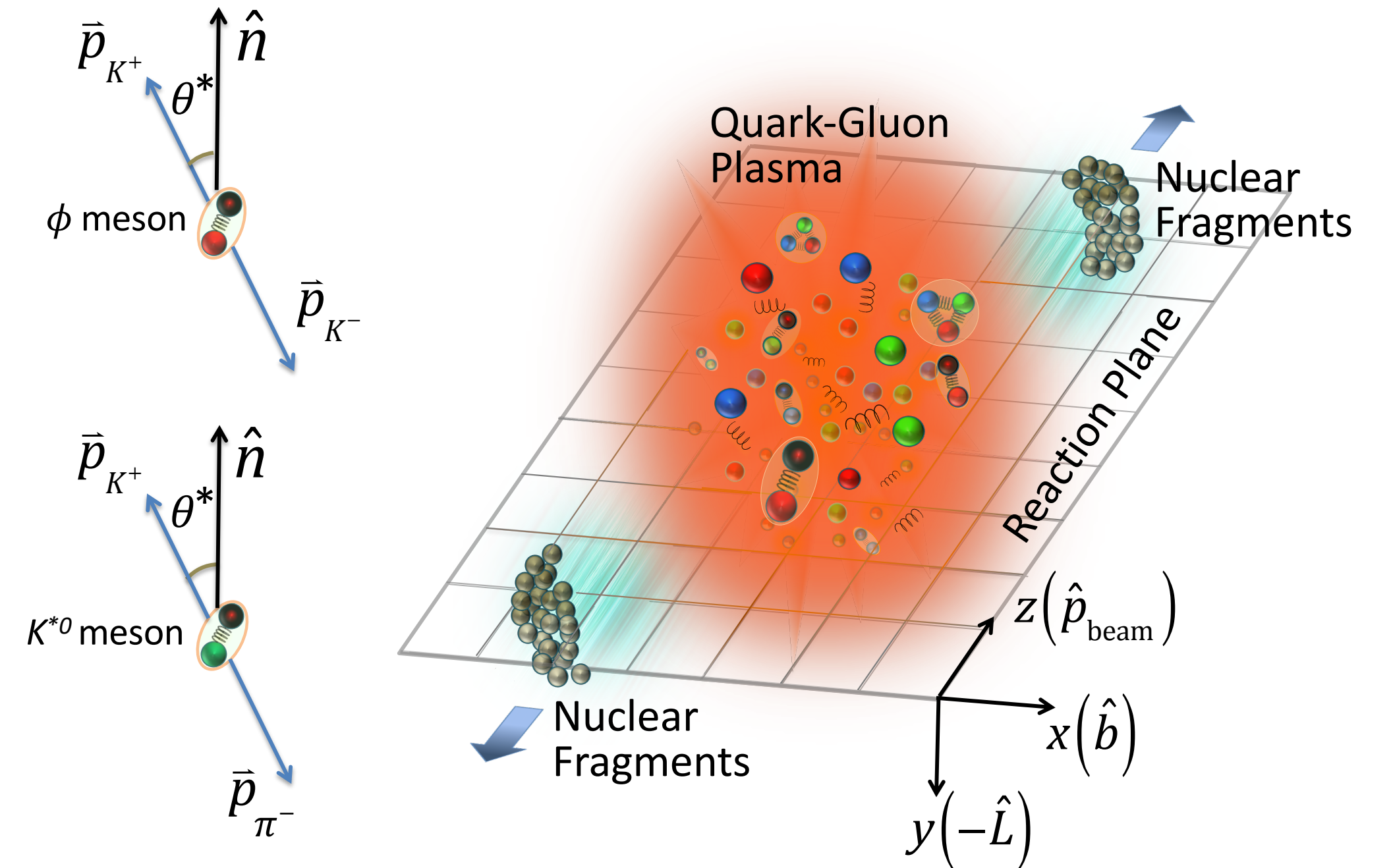
ϕ -mesons ($J = 1^-$):

- Cannot measure polarization sign
- Do not need reaction plane direction — use 2nd order event plane
- Some mesons, like ϕ , are expected to originate predominantly from primordial production => less decay contributions if compared to hyperons, more sensitive to early dynamics
- new physics?

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

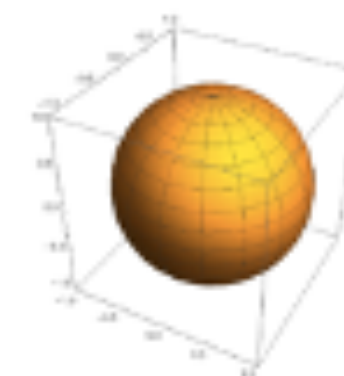
$\rho_{00} = 1/3$ $\longrightarrow$ No spin alignment

$\rho_{00} \neq 1/3$ $\longrightarrow$ spin alignment

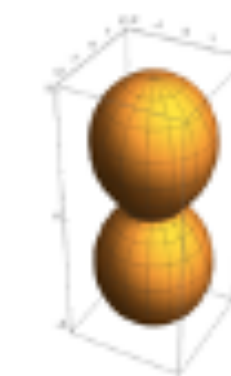


θ^* is the angle between decay daughter and polarization direction in mother particle rest frame

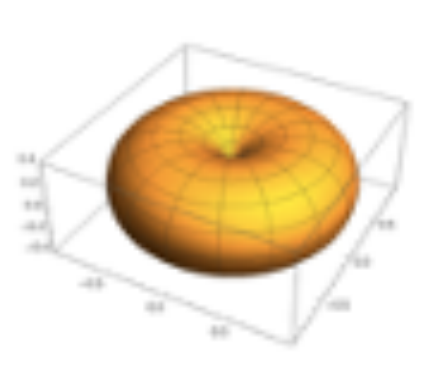
$\rho_{00} = 1/3$



$\rho_{00} > 1/3$



$\rho_{00} < 1/3$

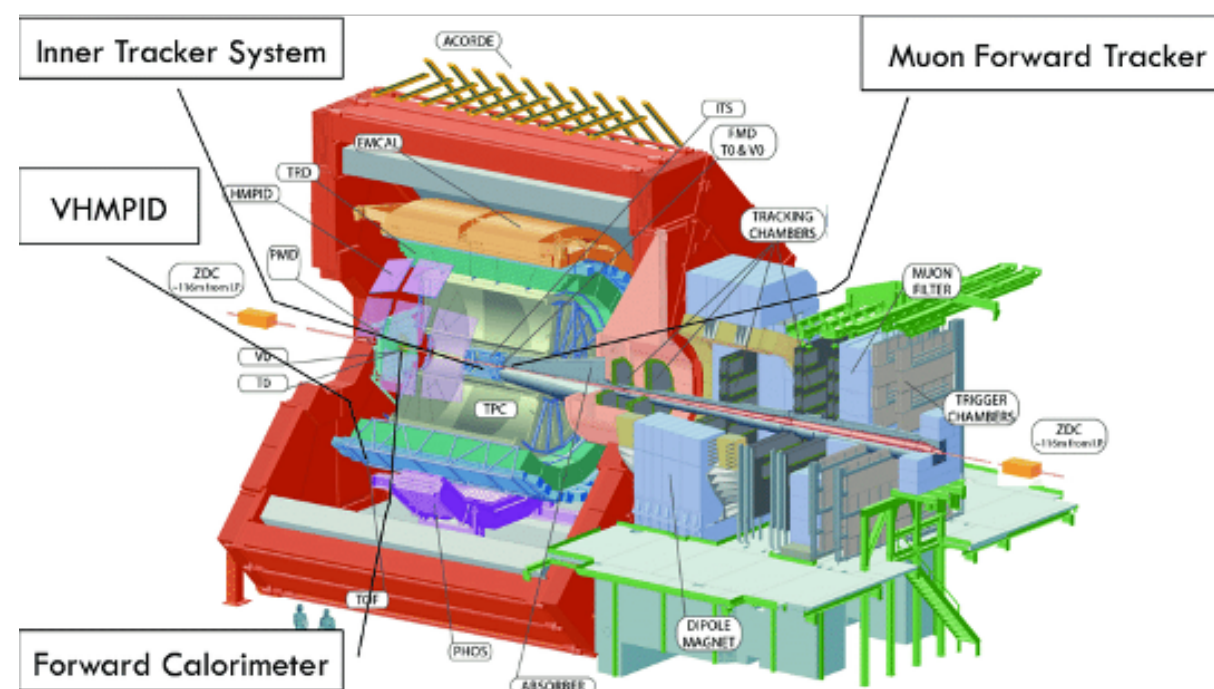


Relativistic Heavy Ion Collisions Experiments

$$\sqrt{s_{NN}} \sim \text{few } 1000 \text{ GeV}$$

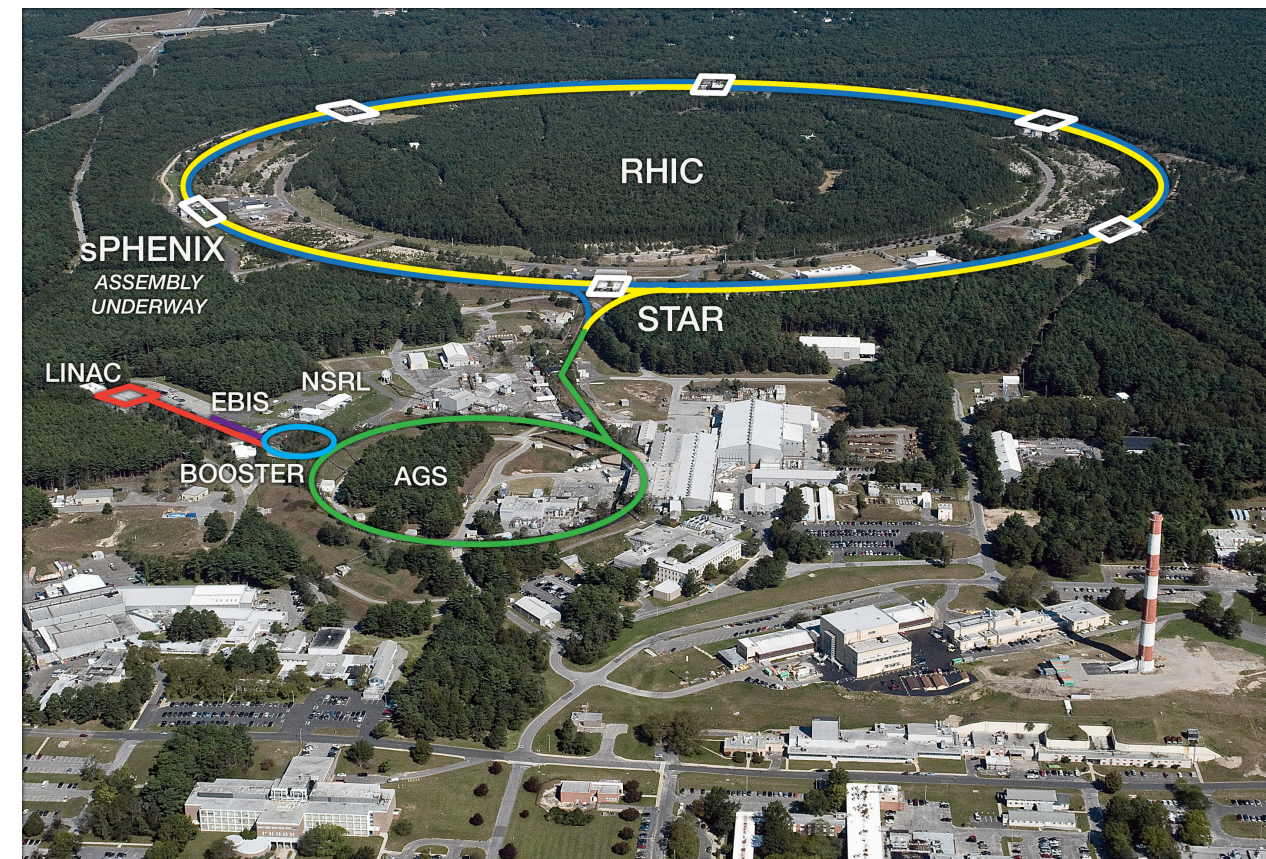


Large Hadron Collider—LHC
Circumference 27 km

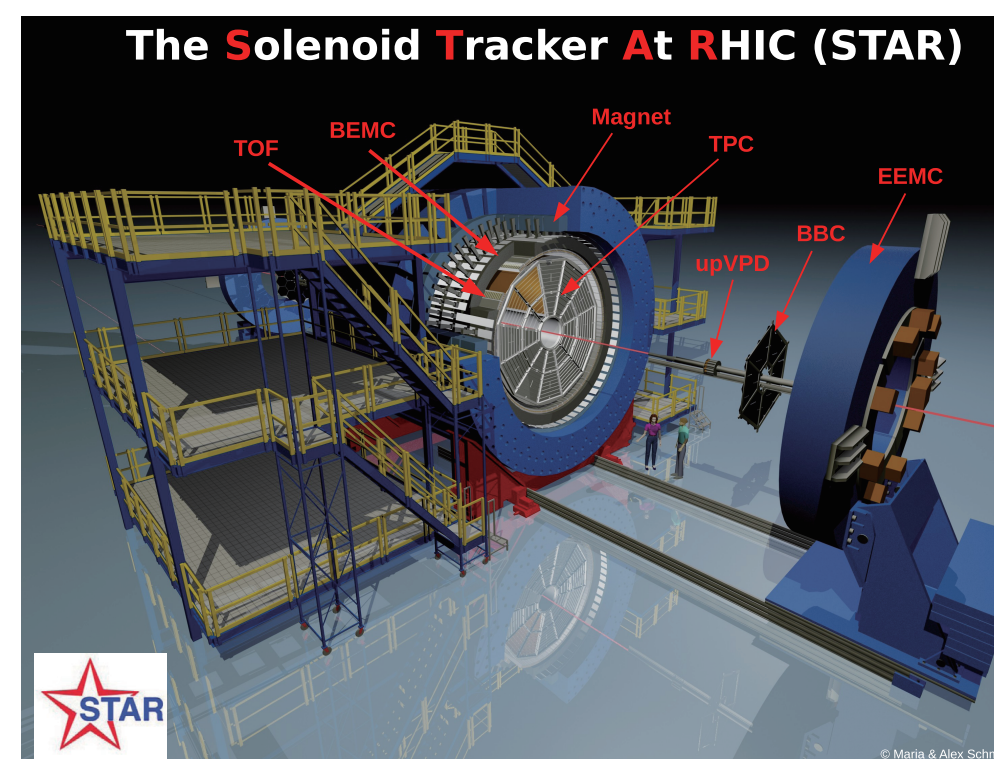


Workshop of Hyperon-Nucleon Spectrometer Physics

$$\sqrt{s_{NN}} \sim 3 - 200 \text{ GeV}$$

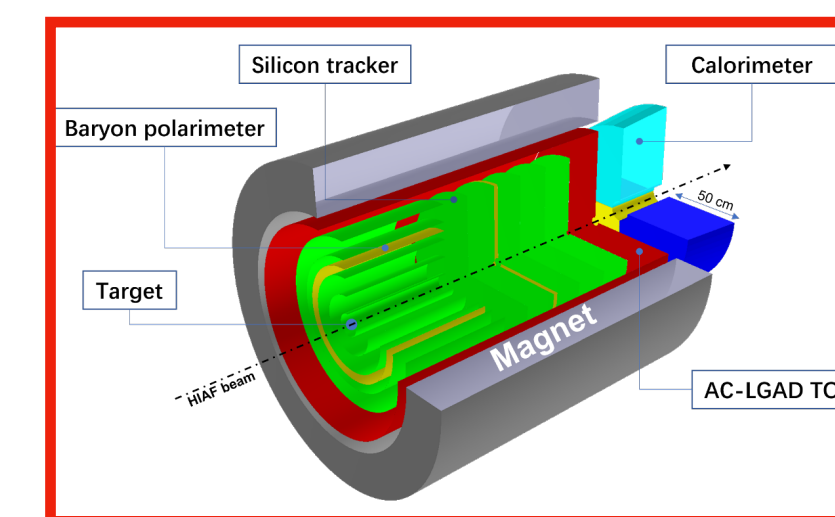


Relativistic Heavy Ion Collider—RHIC
Circumference 3.8 km

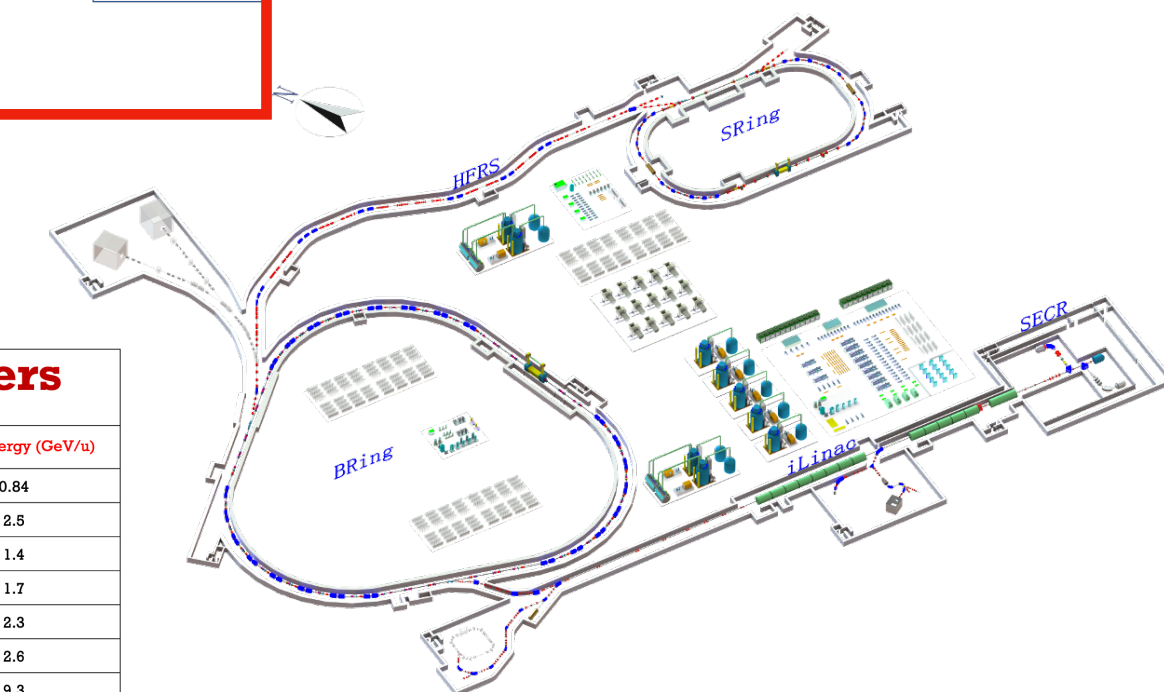


Tianjin, Aug 14-17, 2026

$$\sqrt{s_{NN}} \sim \text{few GeV}$$

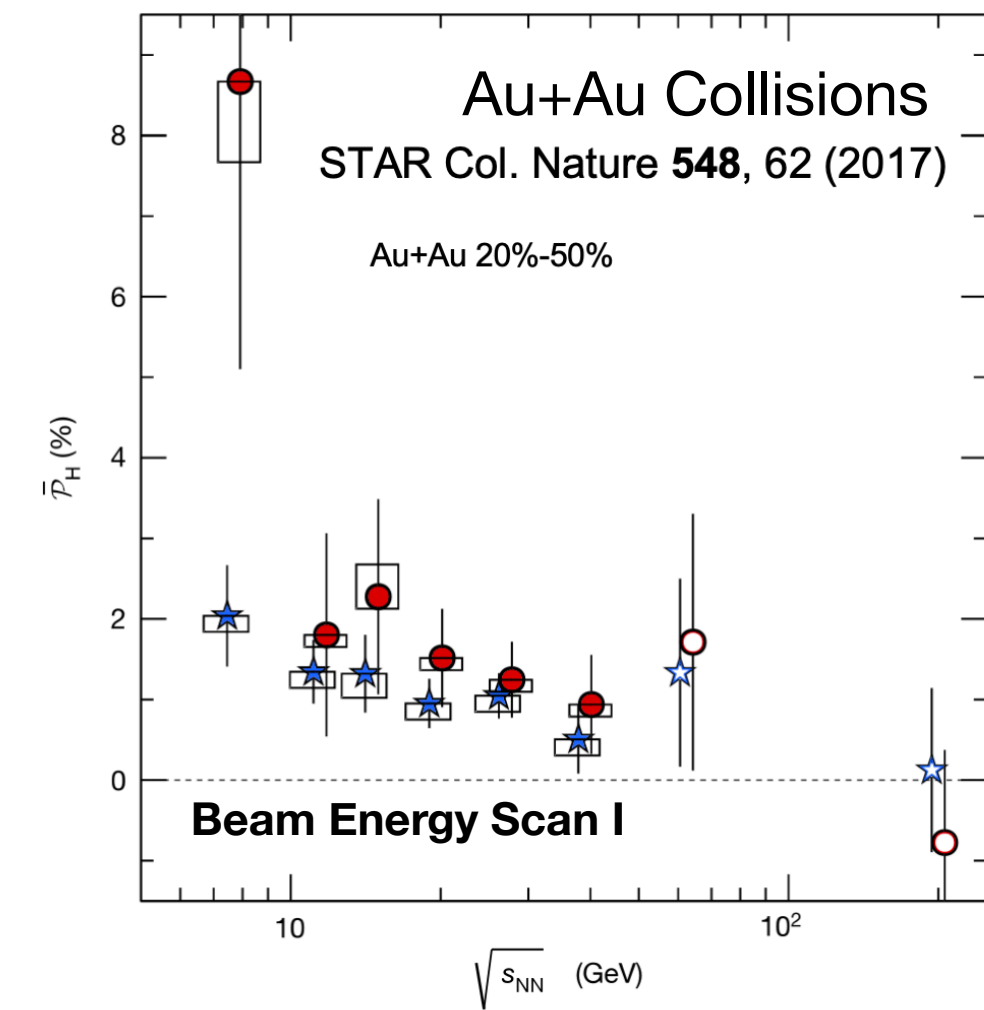
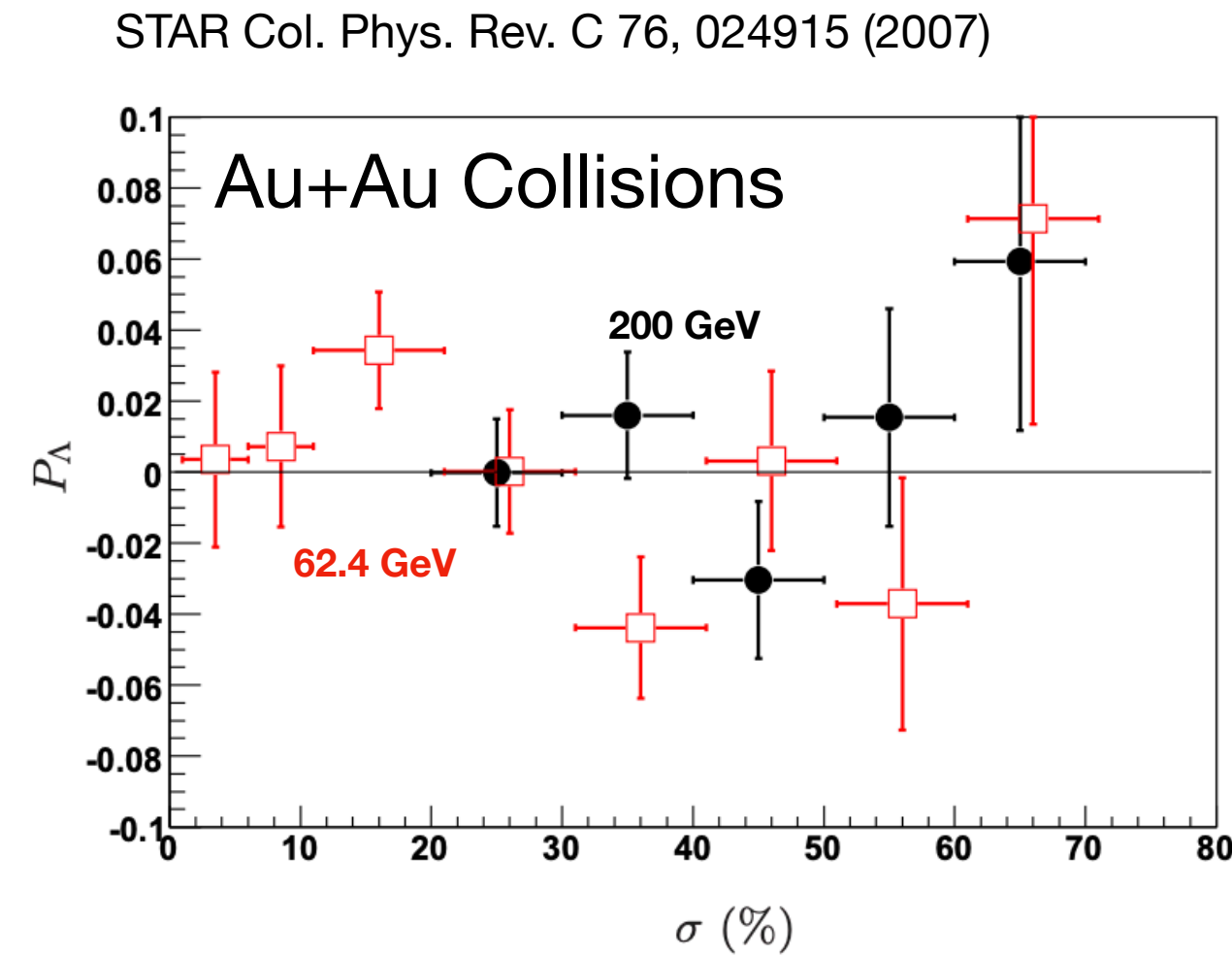
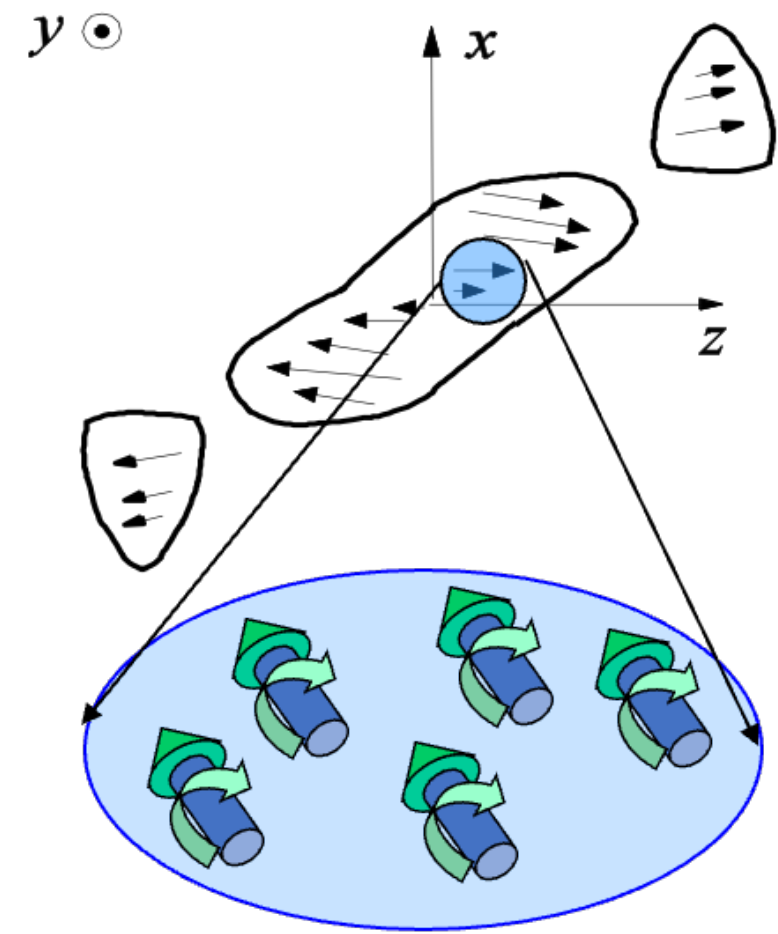


HIAF beam parameters		
Ion	Intensity (pps)	Kinetic Energy (GeV/u)
$^{238}\text{U}^{38+}$	2.0×10^{11}	0.84
$^{238}\text{U}^{26+}$	5.0×10^{10}	2.5
$^{136}\text{Xe}^{22+}$	3.8×10^{11}	1.4
$^{78}\text{Kr}^{19+}$	5.0×10^{11}	1.7
$^{40}\text{Ar}^{12+}$	7.0×10^{11}	2.3
$^{16}\text{O}^{8+}$	8.0×10^{11}	2.6
p	5.0×10^{12}	9.3



Global polarization of Λ

Liang, Wang Phys. Rev. Lett. **94**, 102301



2005

2007

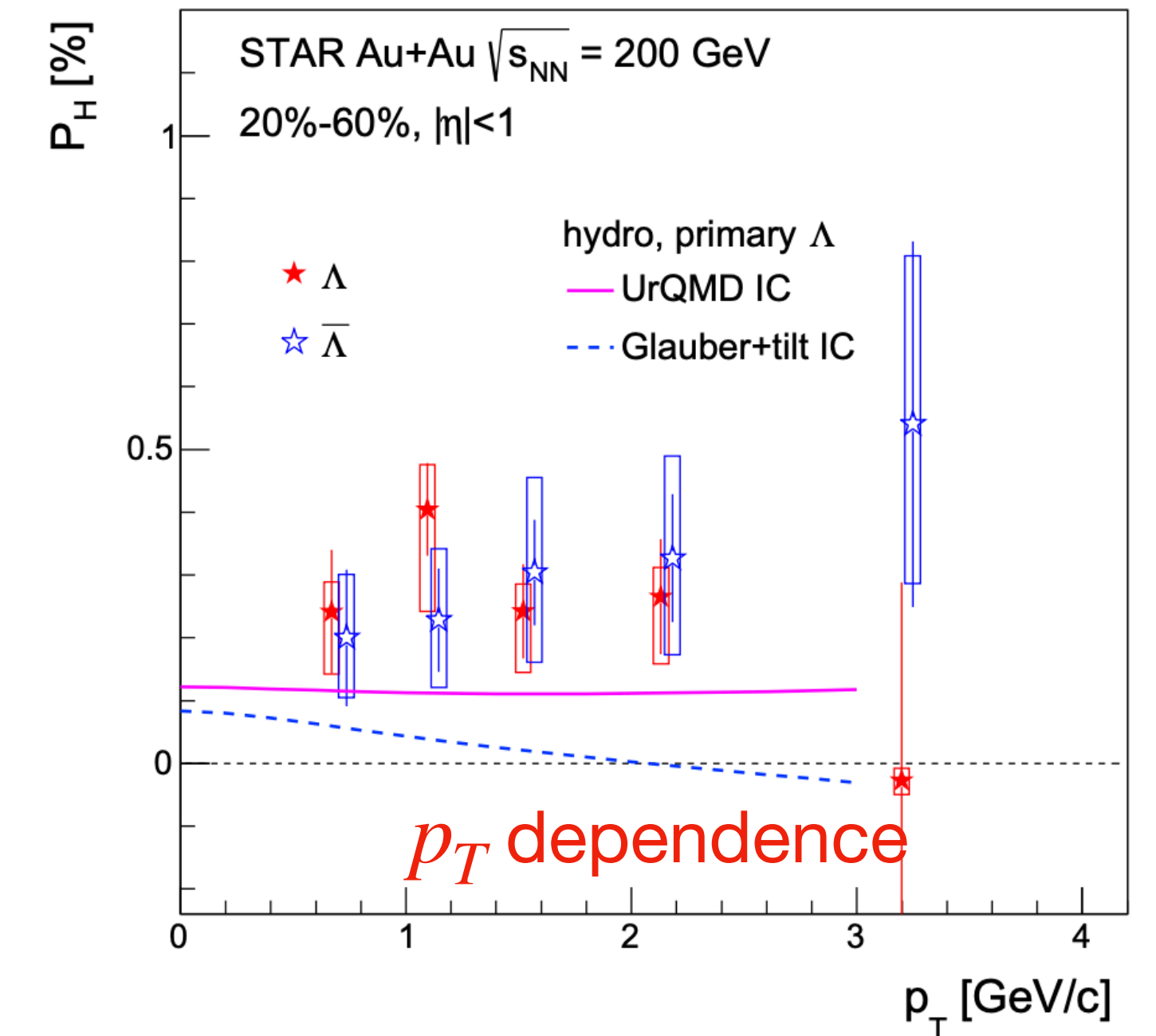
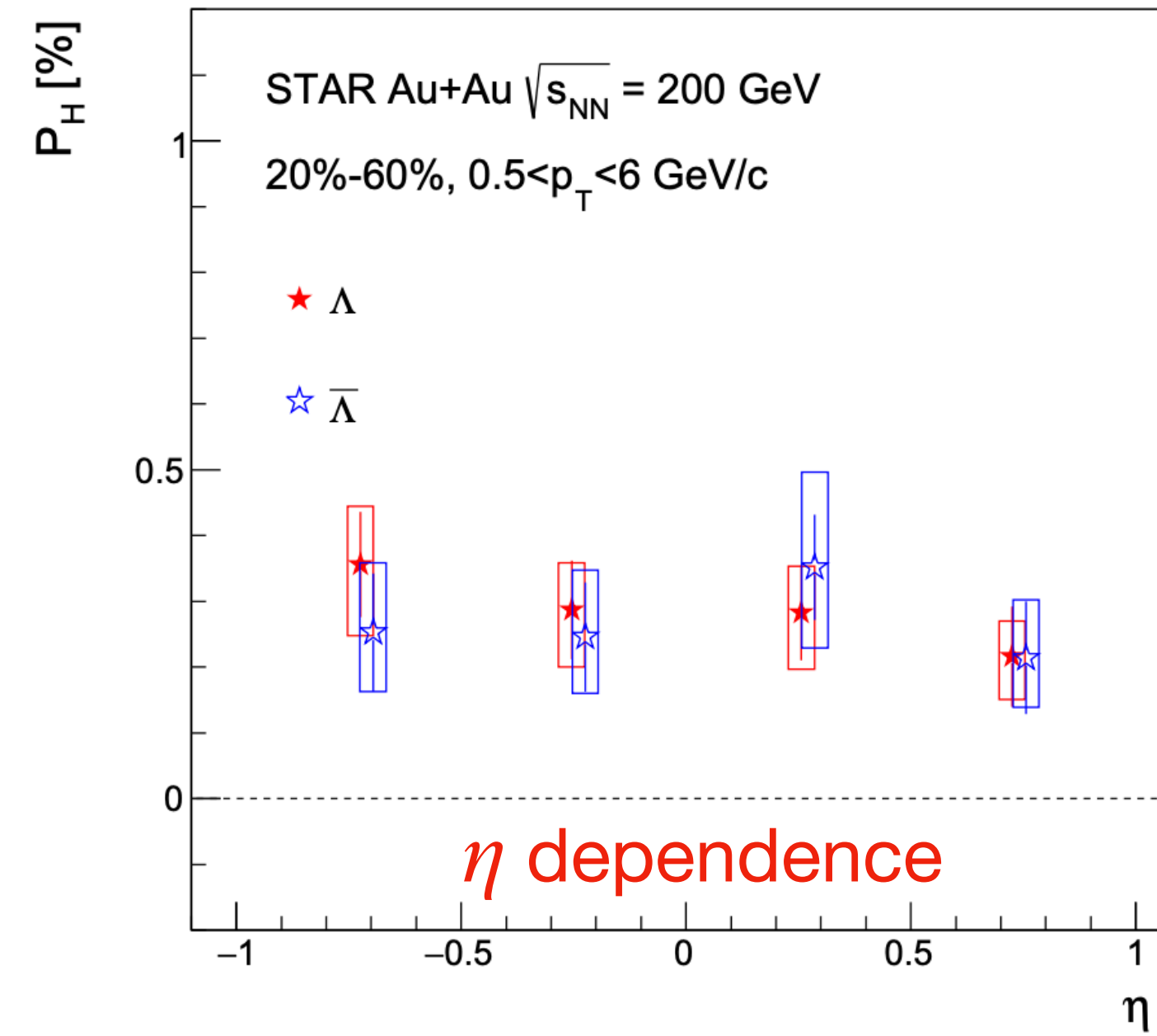
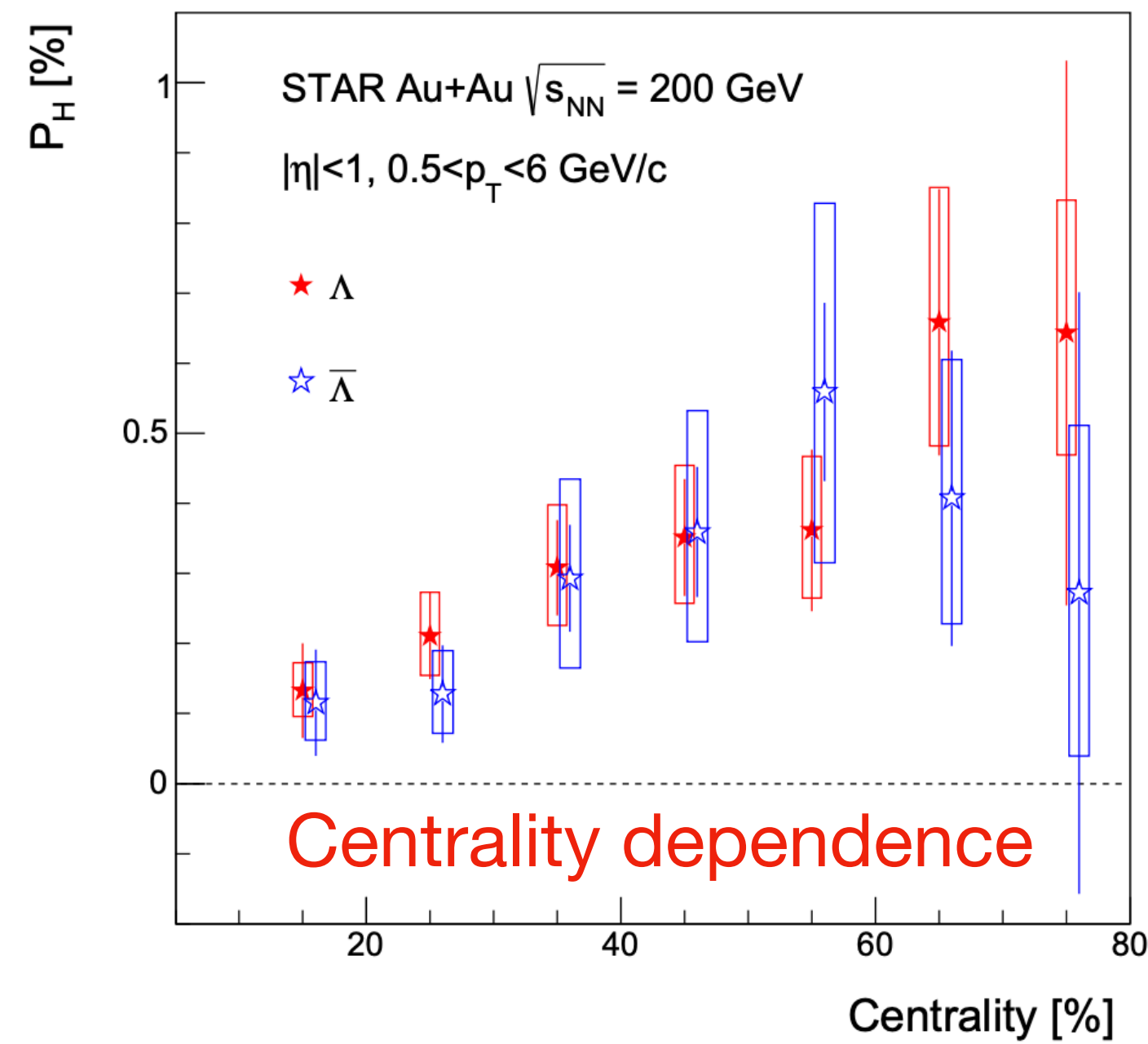
2017

- First signal of Lambda global polarization was observed in the STAR Beam Energy Scan phase I.
- The quark gluon plasma with a vorticity of $(9 \pm 1) \times 10^{21} \text{ s}^{-1}$ - most vortical fluid in nature.

$$\omega \approx k_B T (\bar{P}_{\Lambda'} + \bar{P}_{\bar{\Lambda}'}) / \hbar$$

Differential measurements of Λ P_H

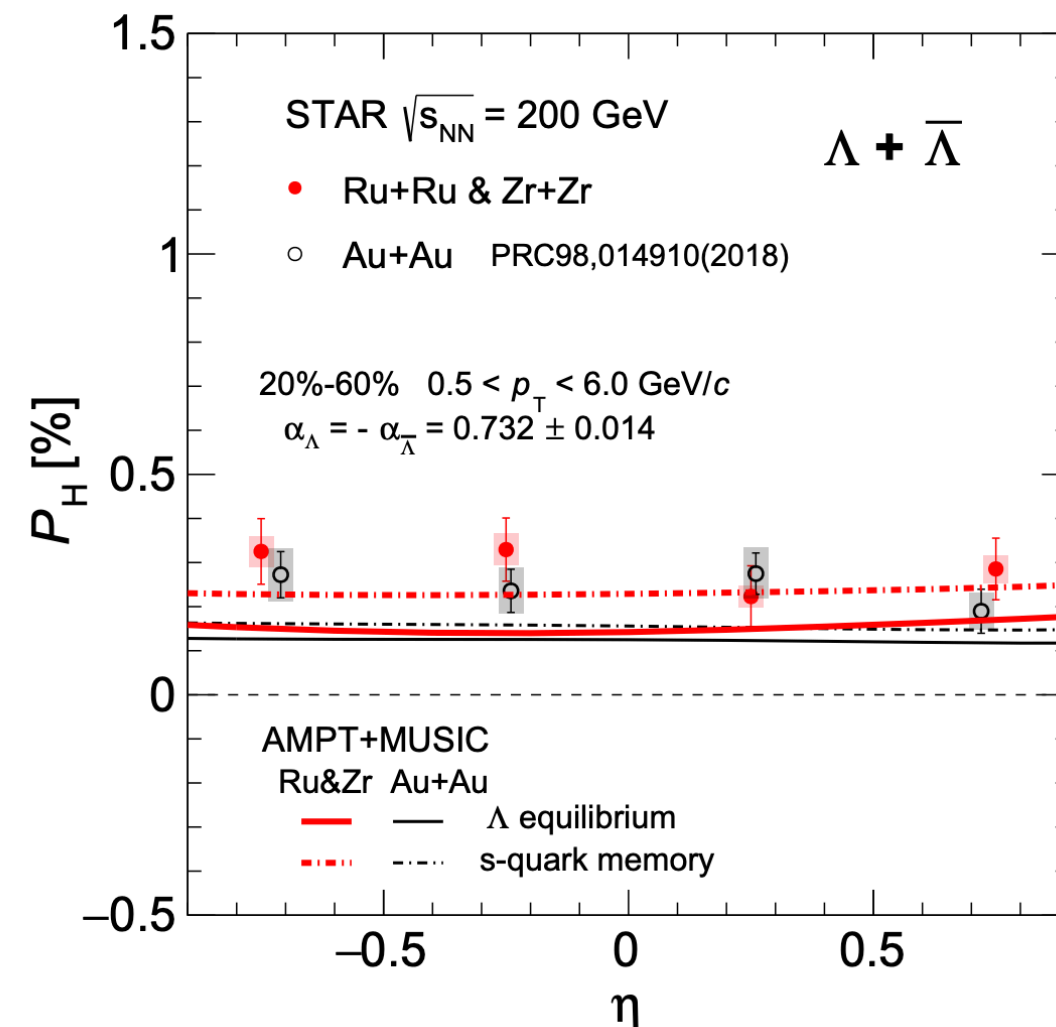
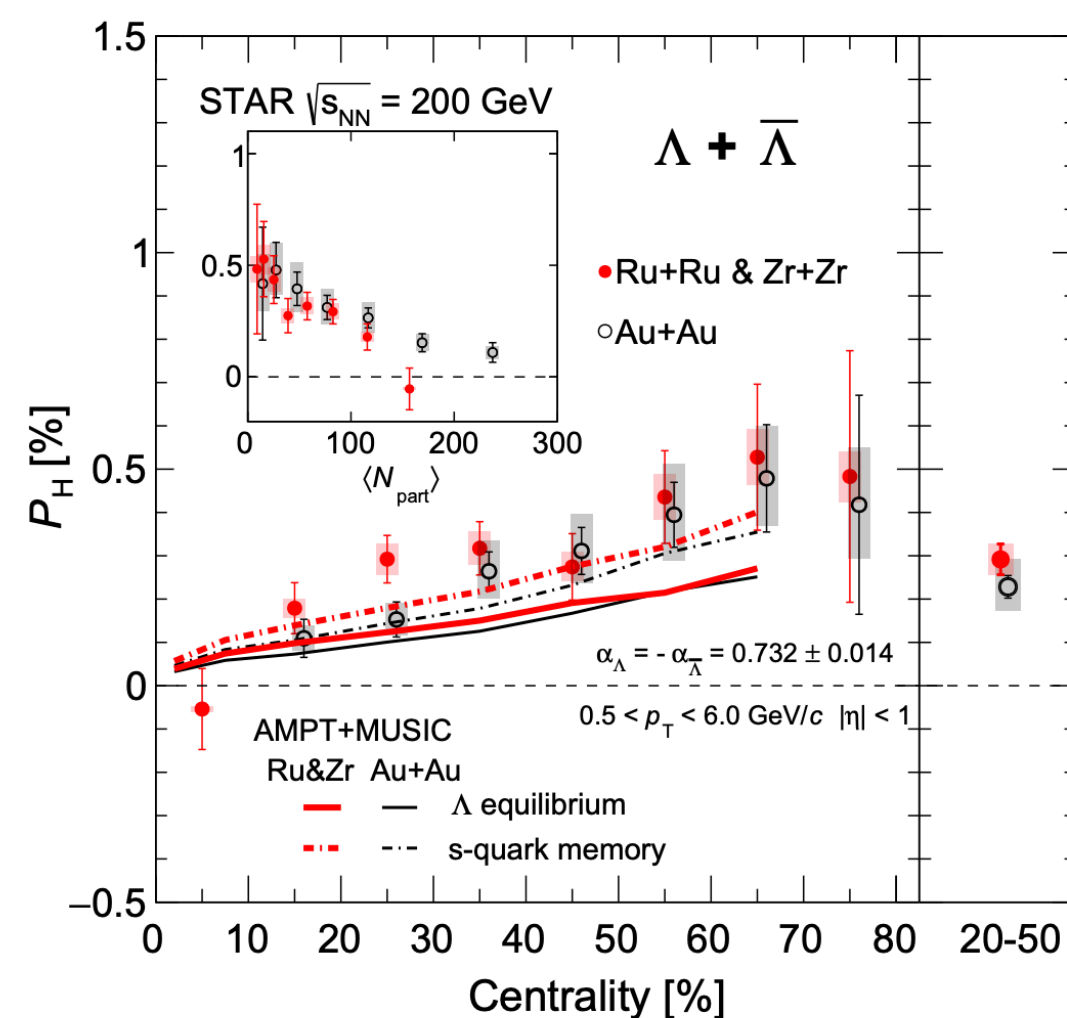
STAR, Phys.Rev.C 98 (2018) 014910



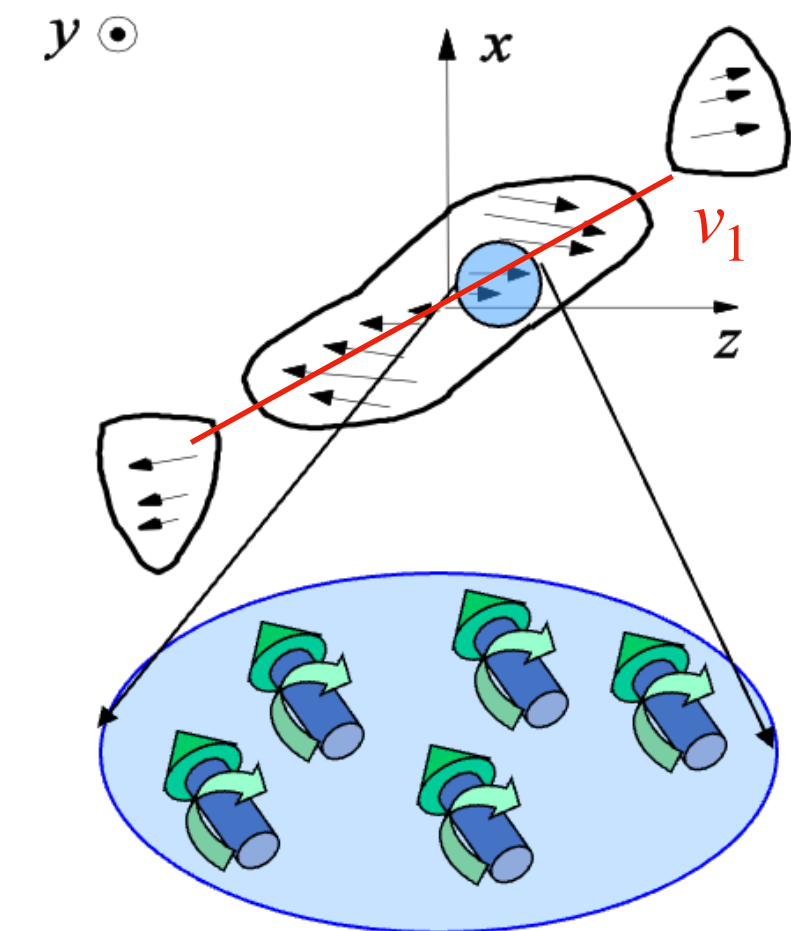
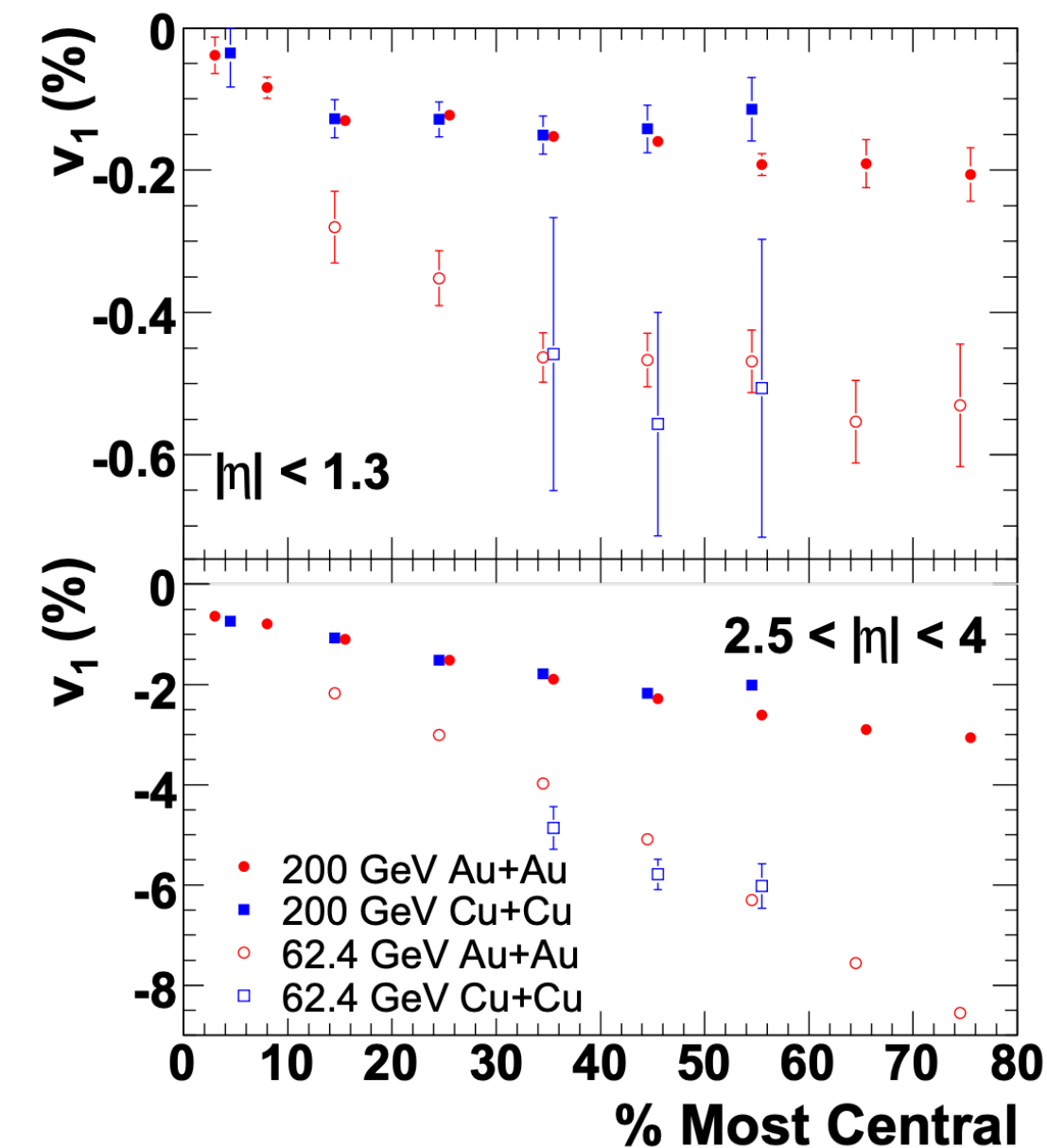
- With more data collected in run10+11+14 Au+Au 200 GeV, a significant signal was observed.
- Obvious centrality dependence, weak dependence on η and p_T .

System size independence

STAR, Phys. Lett. B **870** (2025) 139891



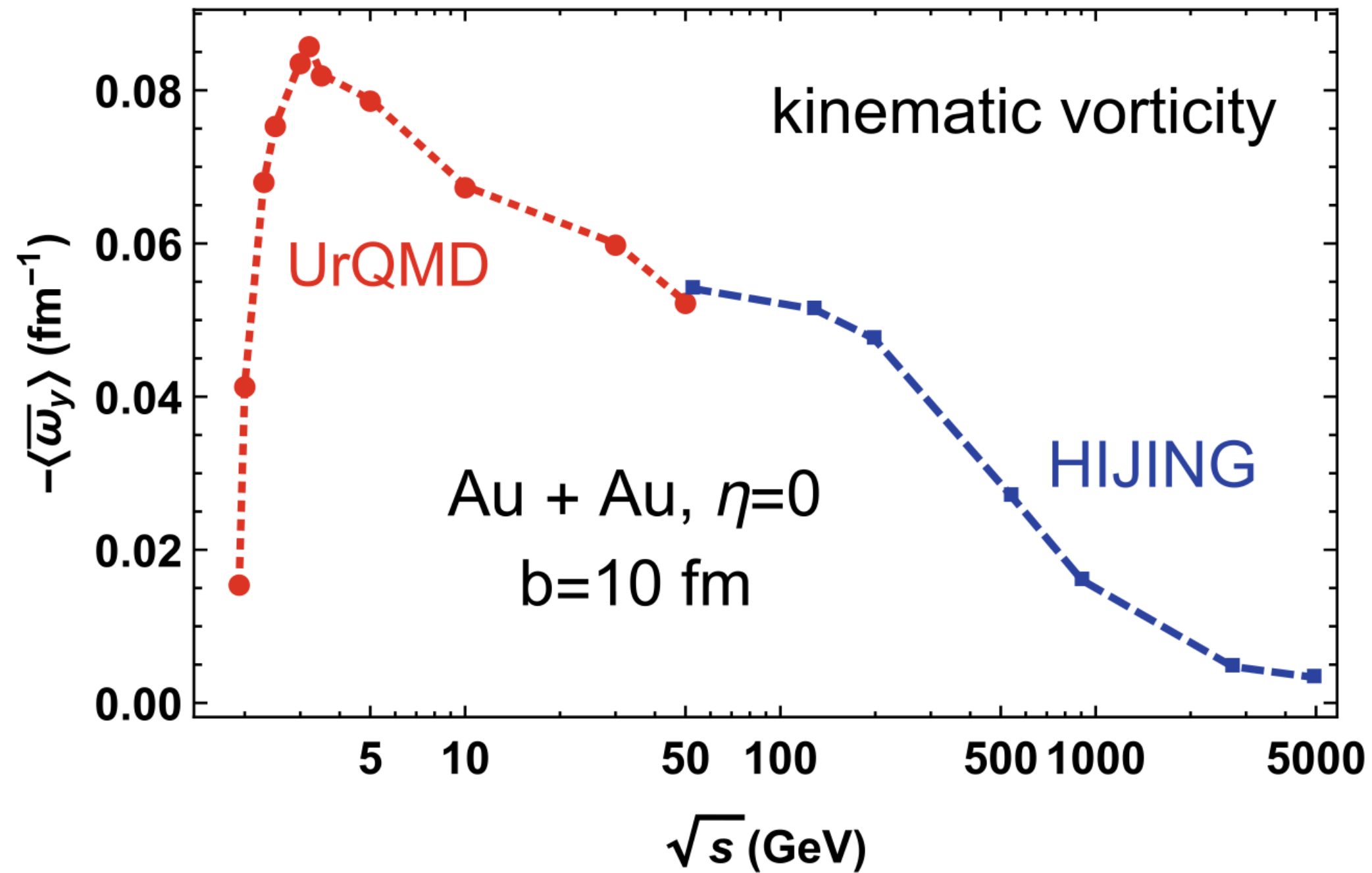
STAR, Phys. Rev. Lett. **101** (2008) 252301



- System size independence?
- Both polarization and directed flow show system size independence.

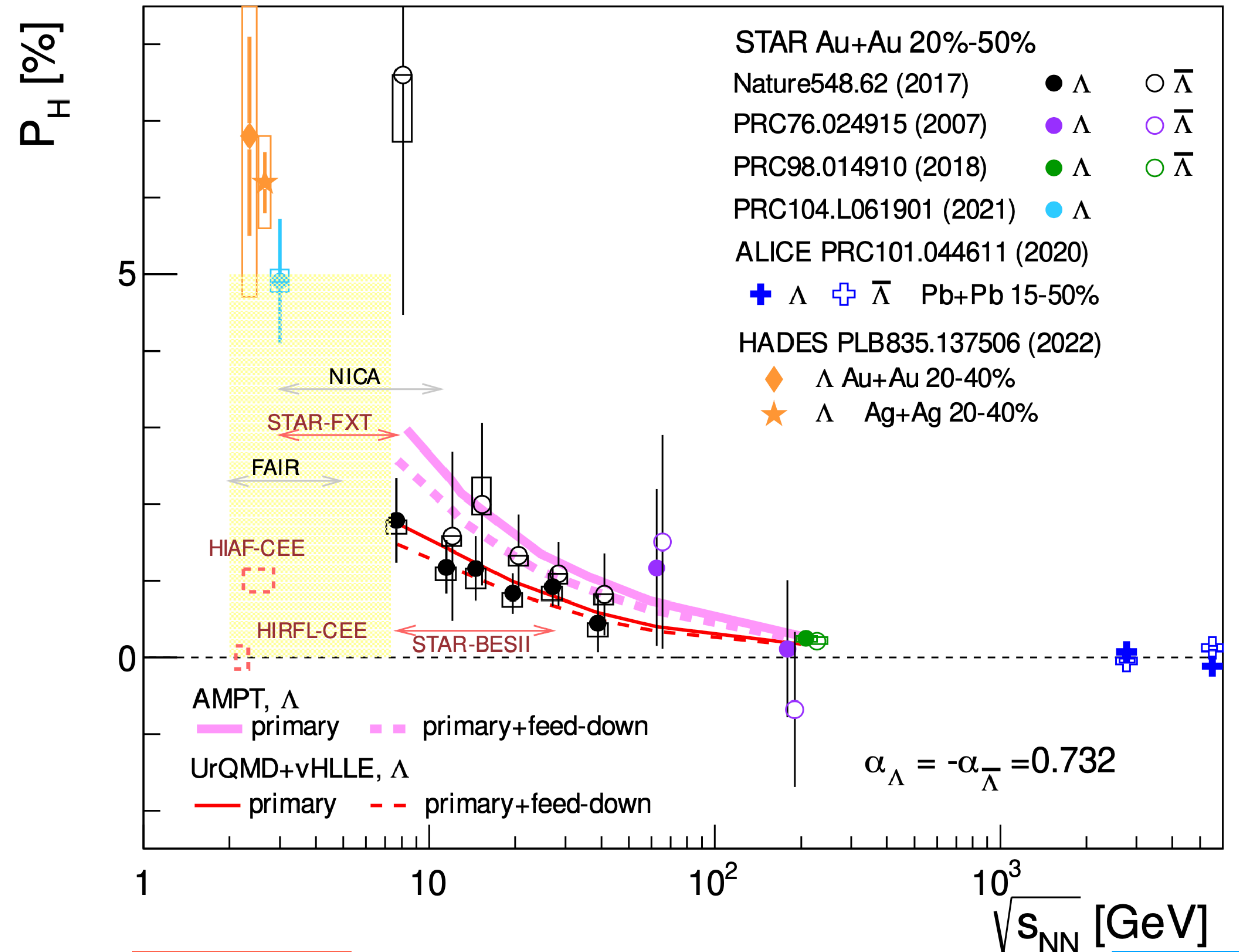
Beam energy dependence

Deng et al., PRC 101, 064908 (2020)
Guo et al., PRC 104, L041902 (2021)...



- Hadronic dominant matter retains more vorticity (?)
- Where do we observe the highest polarization?
- Expected $P_\Lambda \sim 0$ at $\sqrt{s_{NN}} \sim 2m_N$

Acta Phys. Sin. Vol. 72, No. 7(2023) 072401

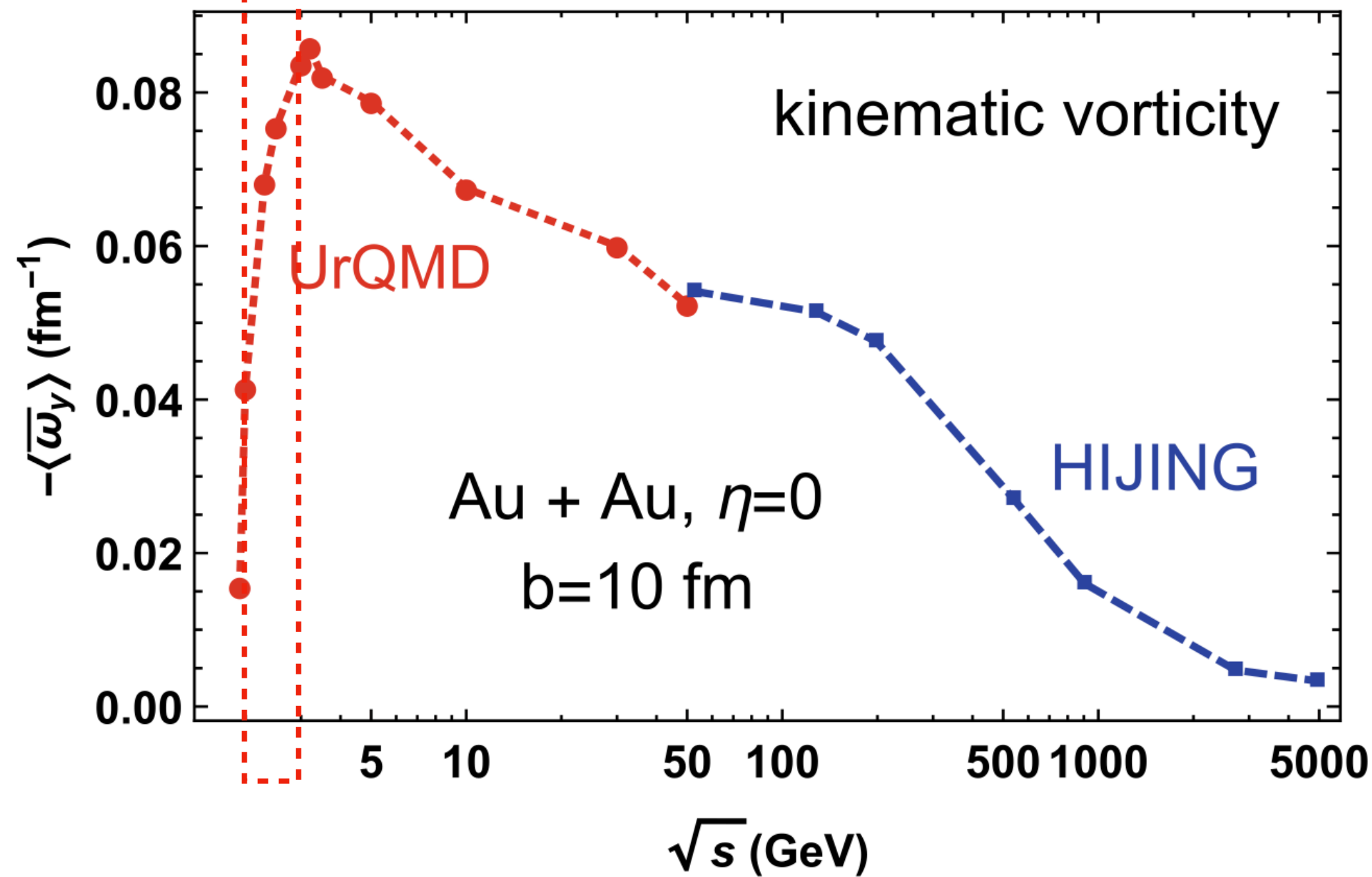


Hadronic
dominant

Partonic
dominant

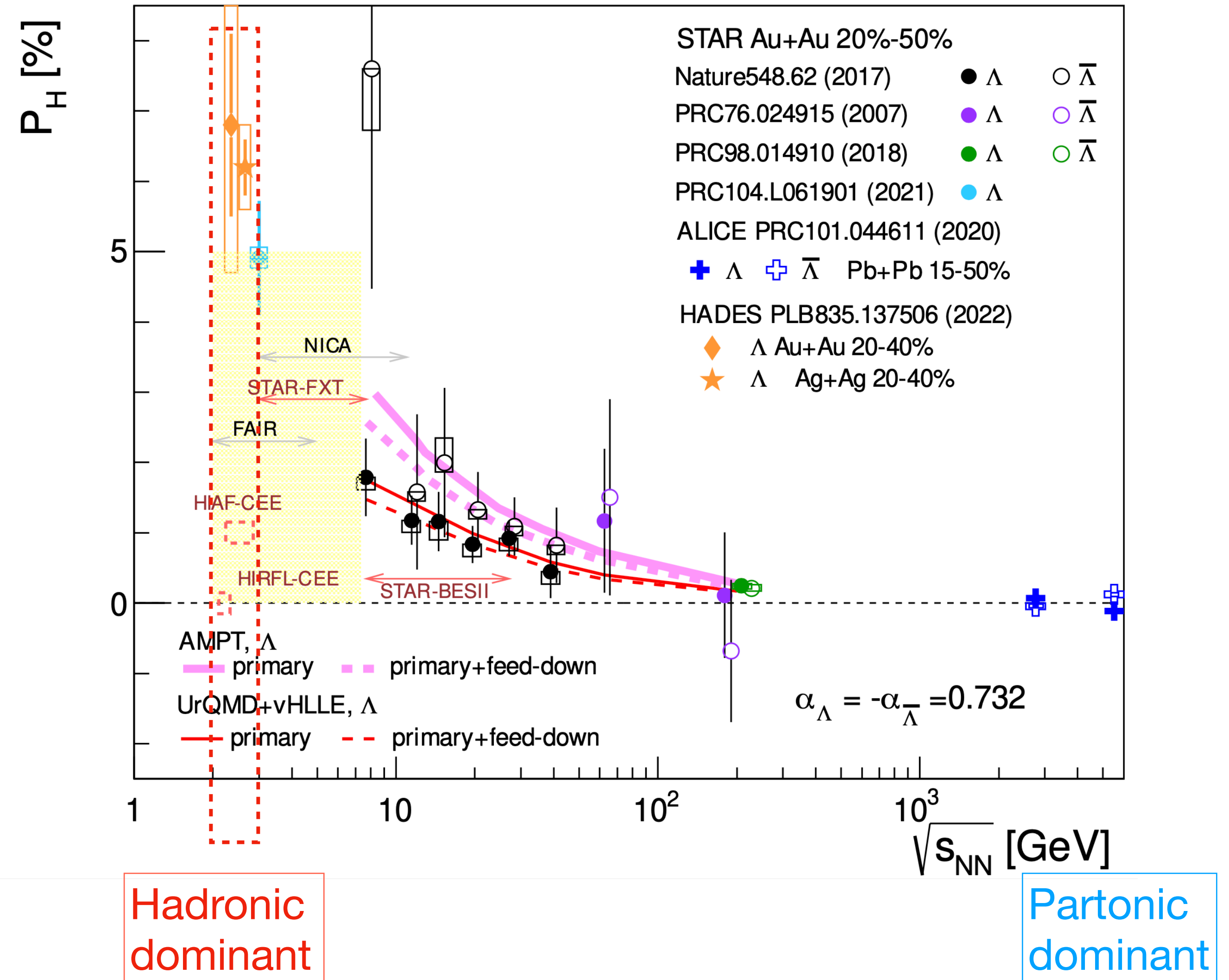
Beam energy dependence

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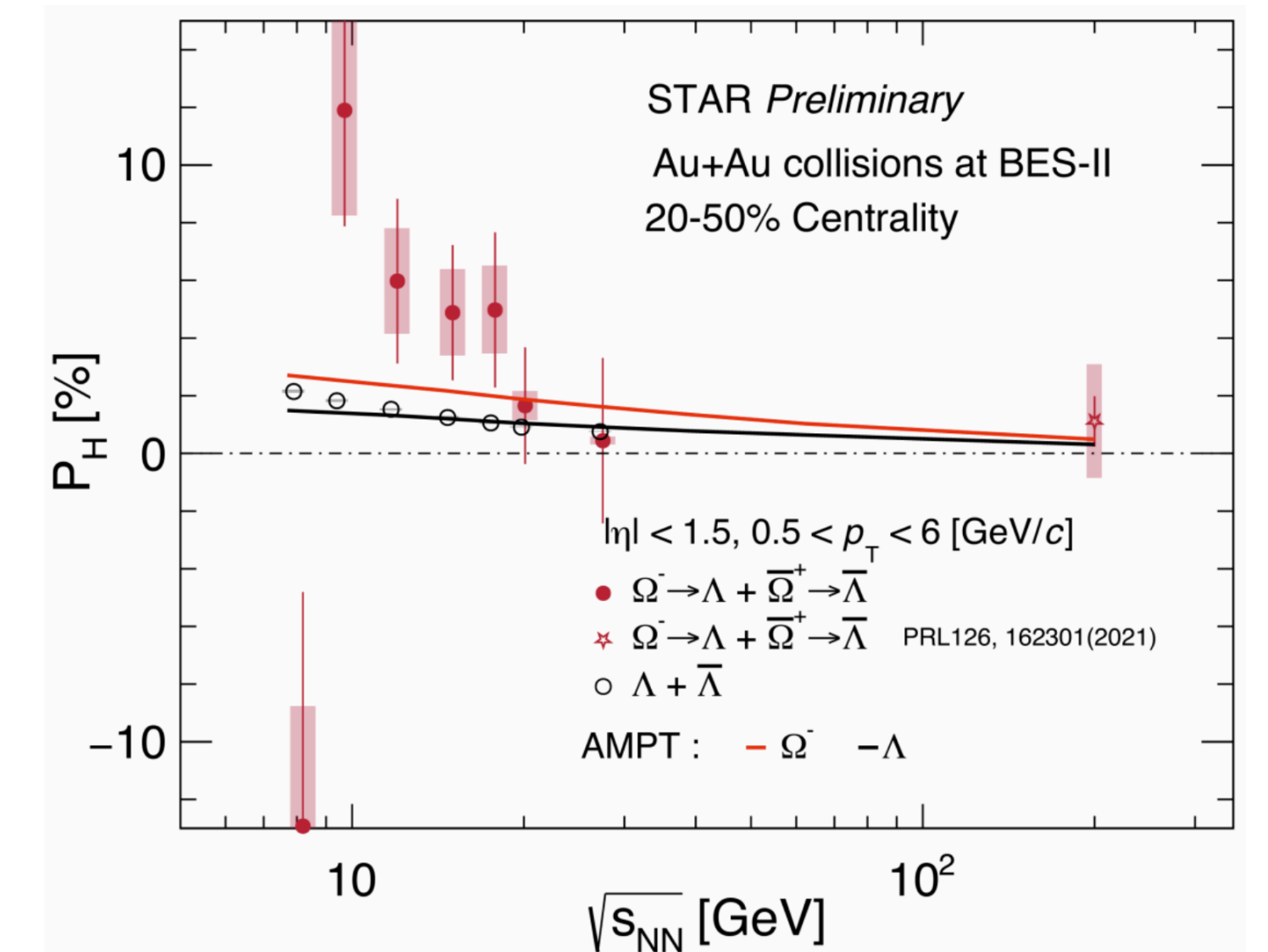
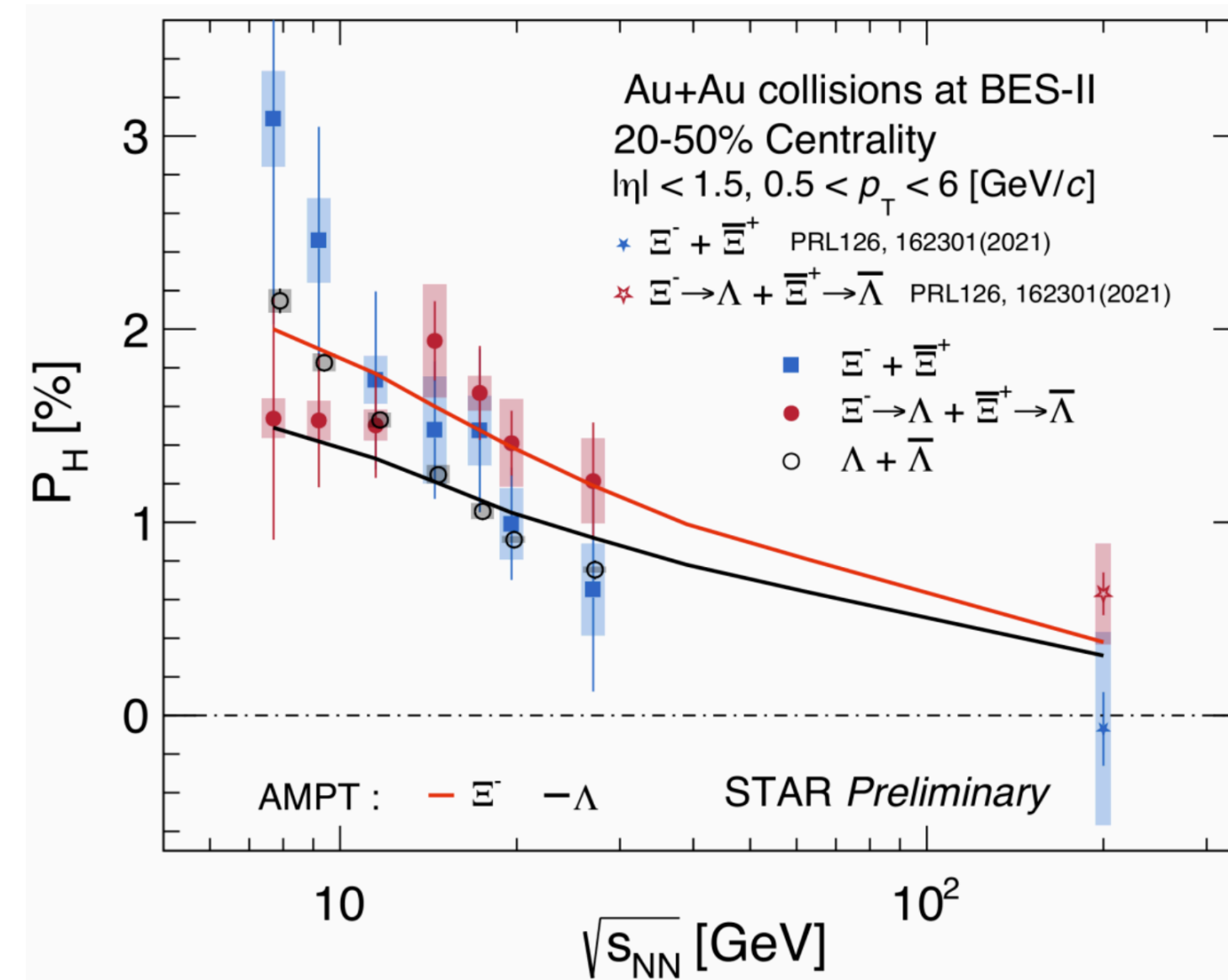
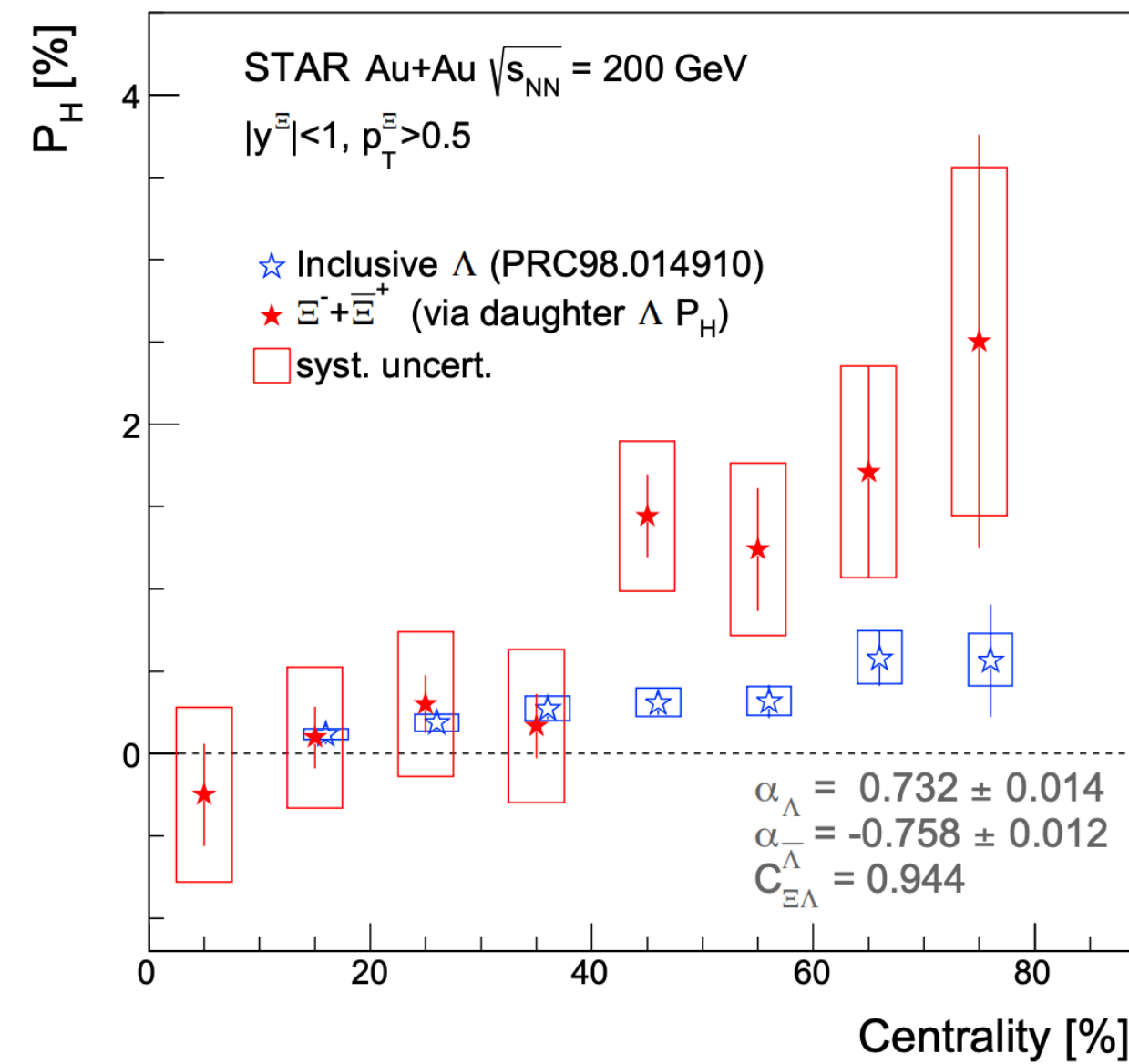
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- Where do we observe the highest polarization?
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Acta Phys. Sin. Vol. 72, No. 7(2023) 072401



Global polarization of Ξ and Ω

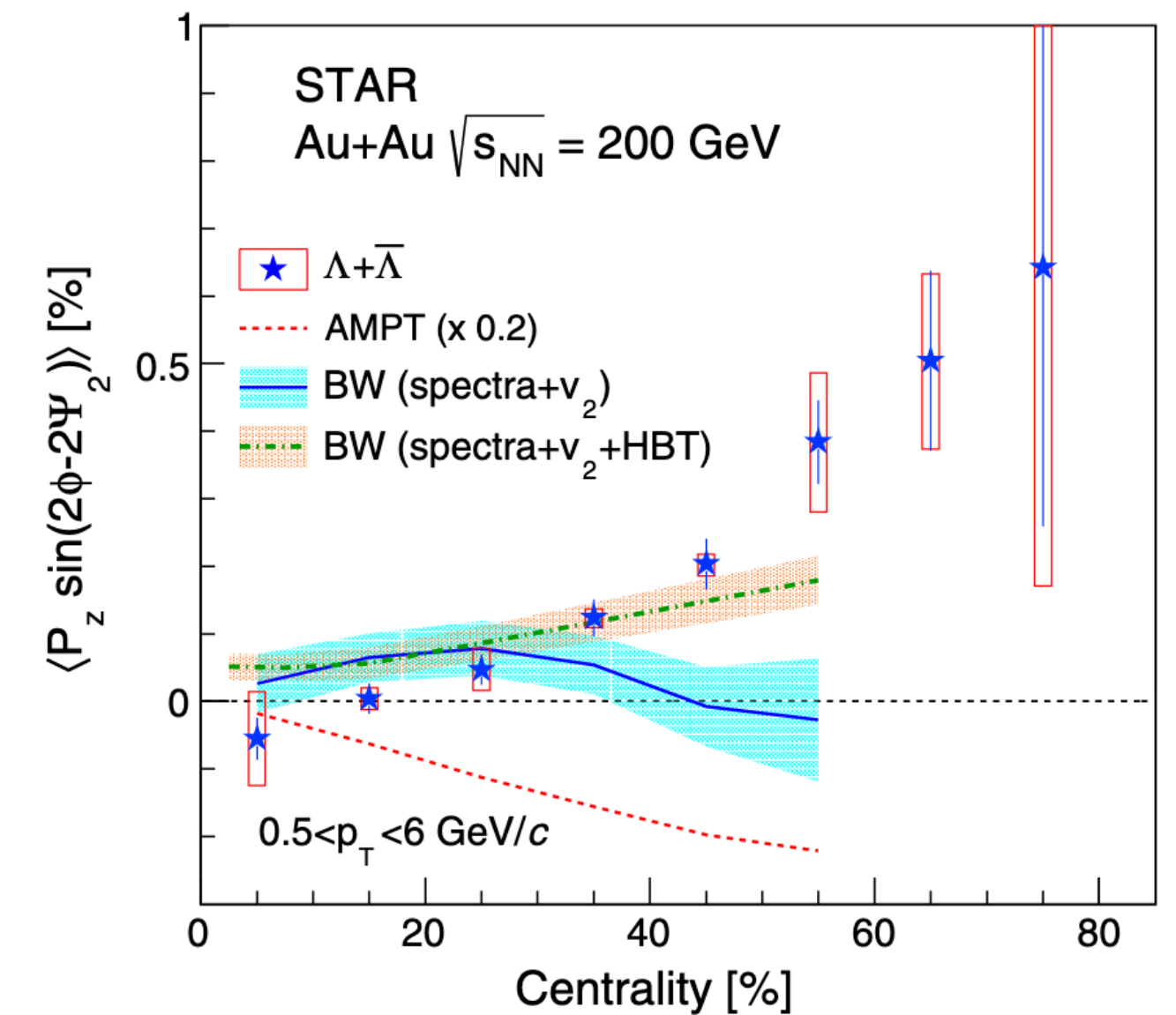
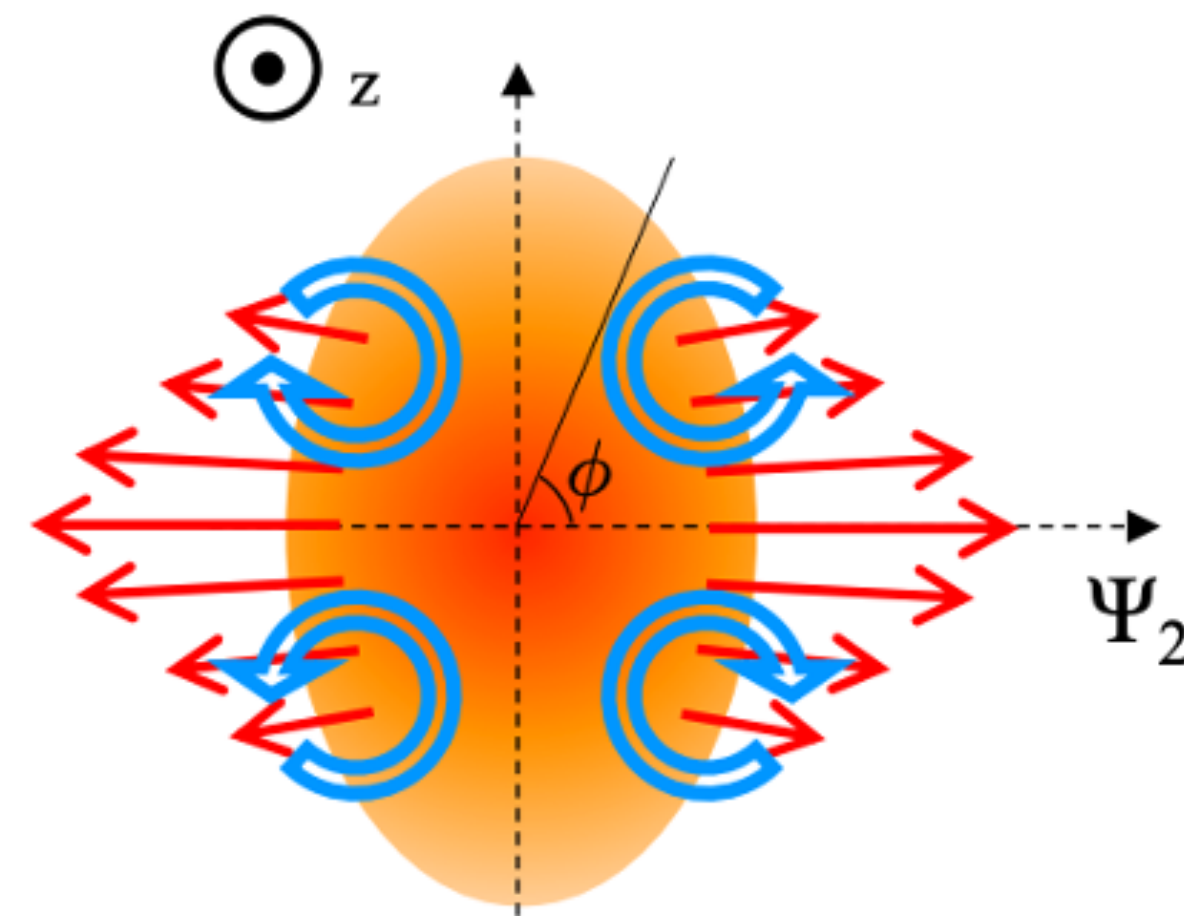
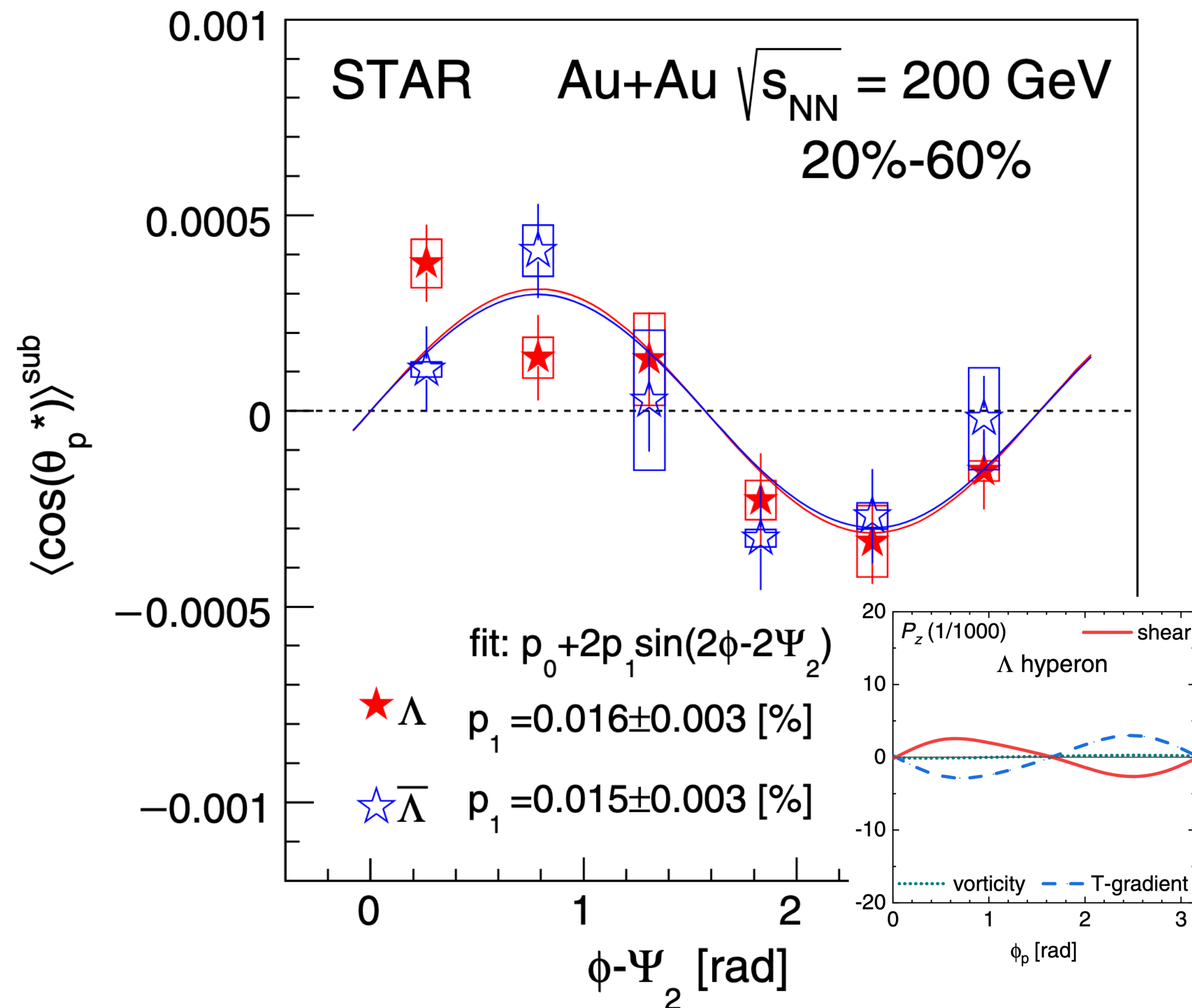
STAR, Phys. Rev. Lett. **126** (2021) 162301



- Ξ results are consistent with Λ .
- Ω appears to be larger than Λ .

Local vortices and azimuthal-angle-dependent polarization

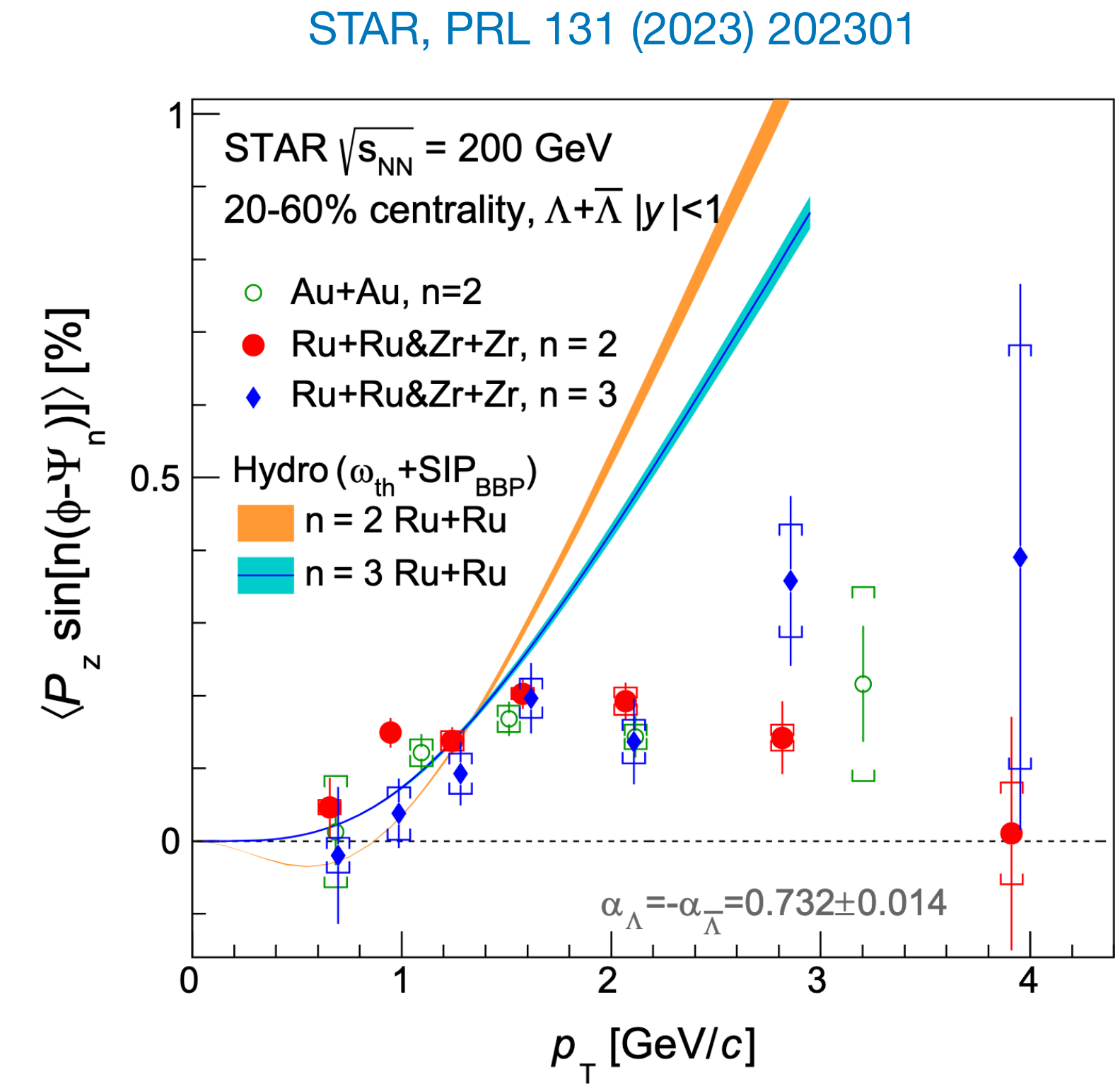
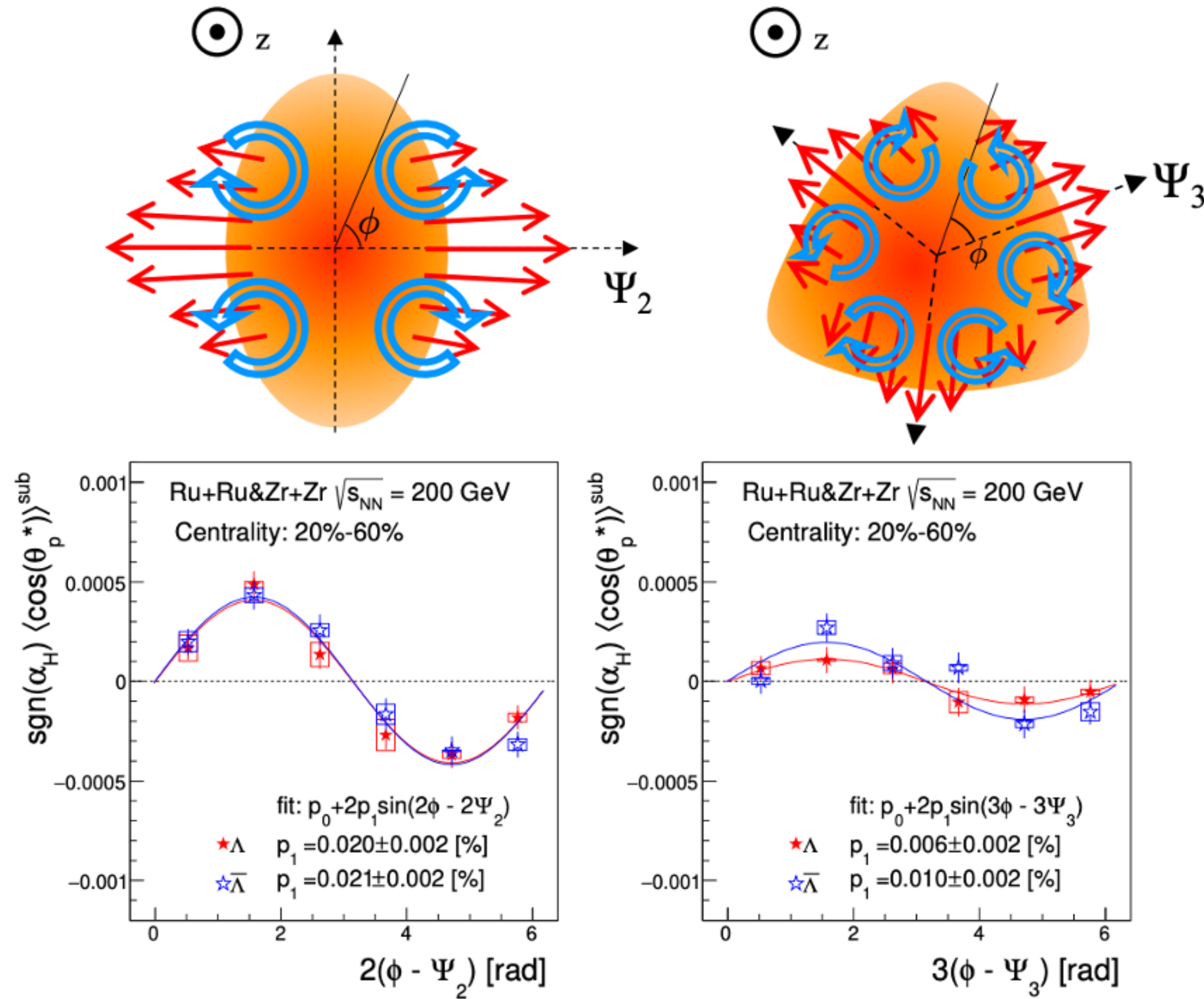
STAR, PRL 123, 132301 (2019)



- First observation of longitudinal polarization P_z w.r.t. Ψ_2
- Shear Induced Polarization (SIP) could capture the trends
- $P_{2,z}$ shows significant centrality dependence, expected from elliptic flow

Fu et al., PRL 127, 142301 (2021)

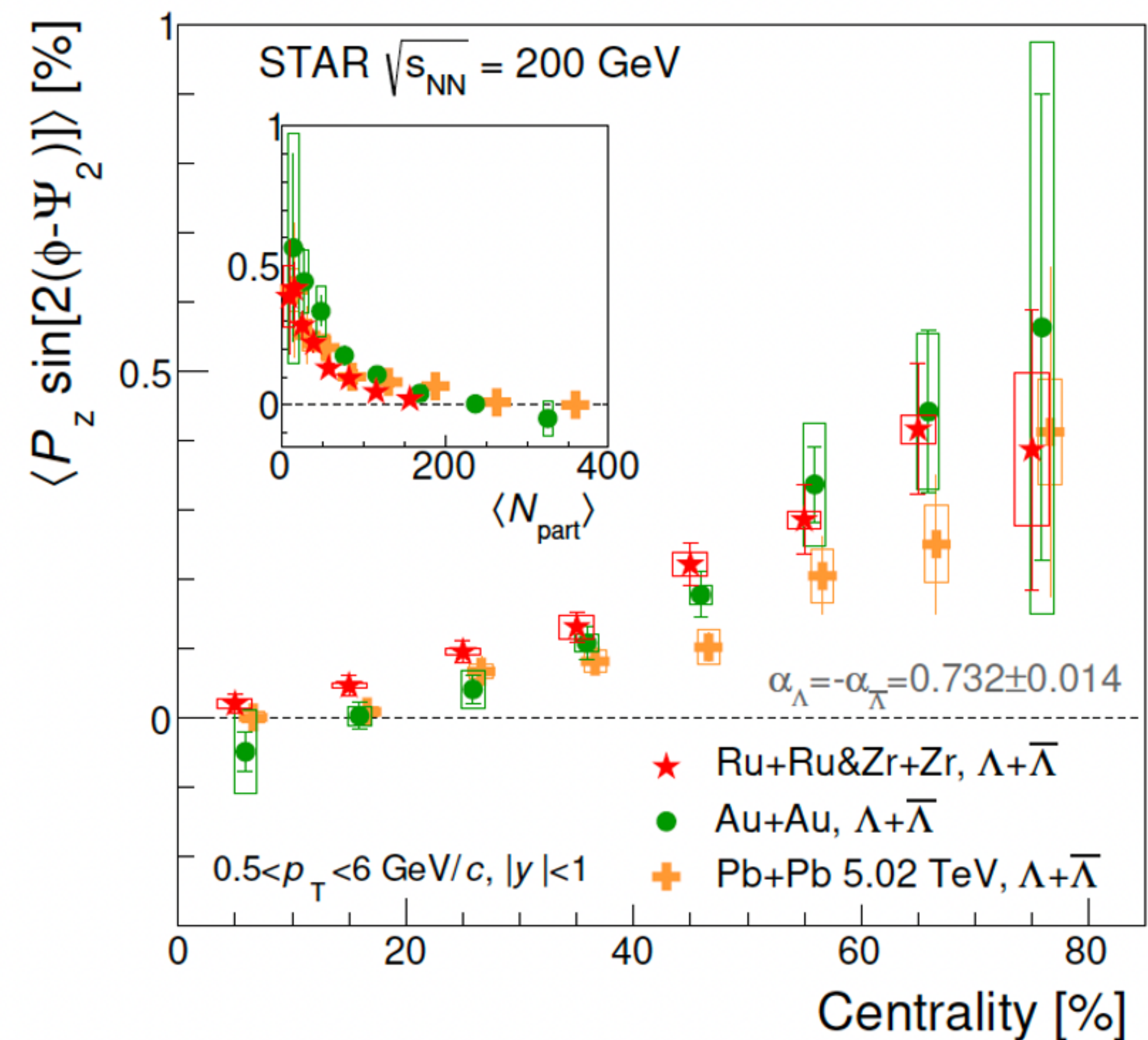
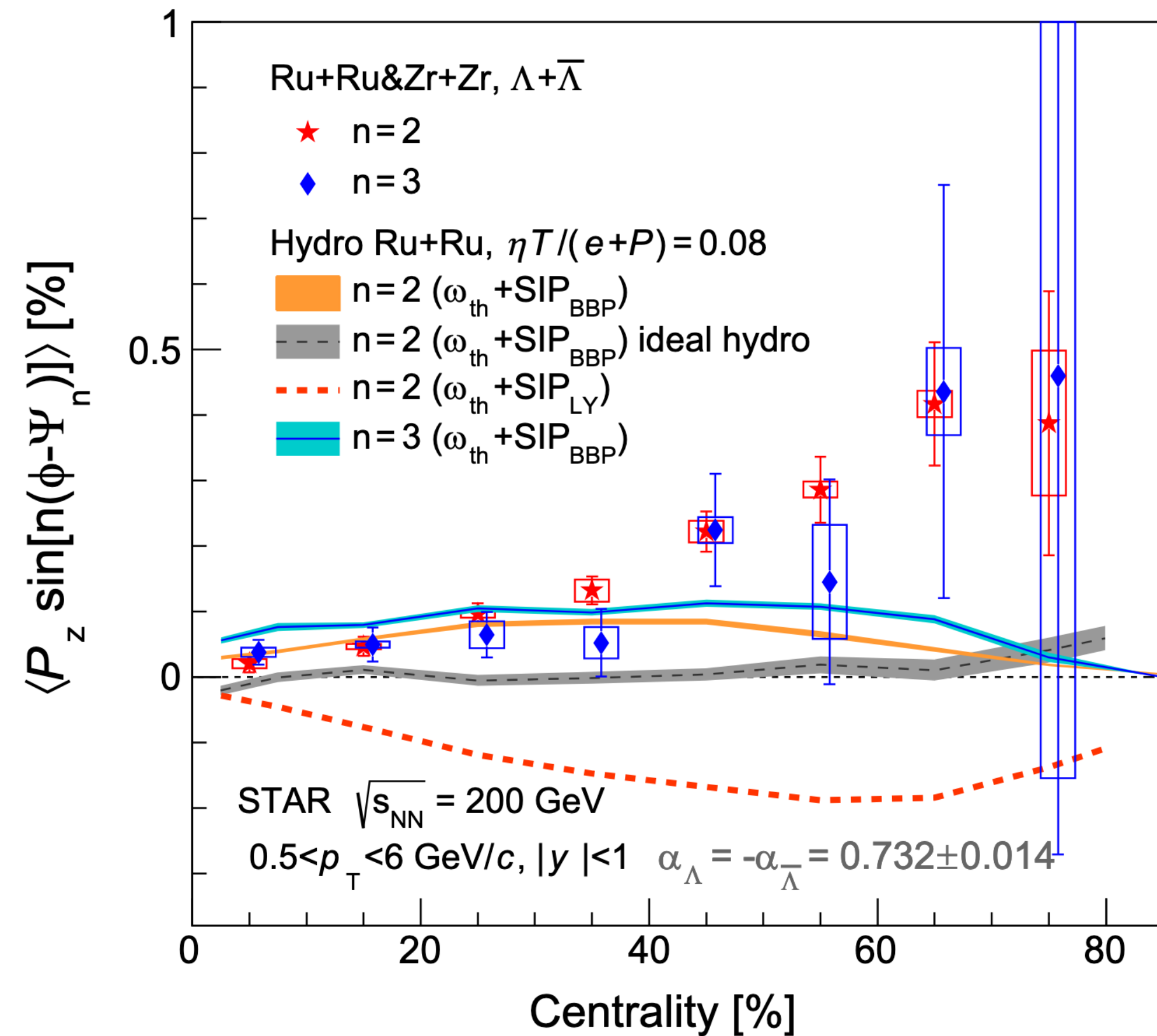
Local vortices and azimuthal-angle-dependent polarization



- Significant local polarization w.r.t 2nd & 3rd-order event plane observed in isobar collisions
- Observed p_T dependence similar to that of elliptic and triangular flow
- No obvious system size dependence

Local vortices and azimuthal-angle-dependent polarization

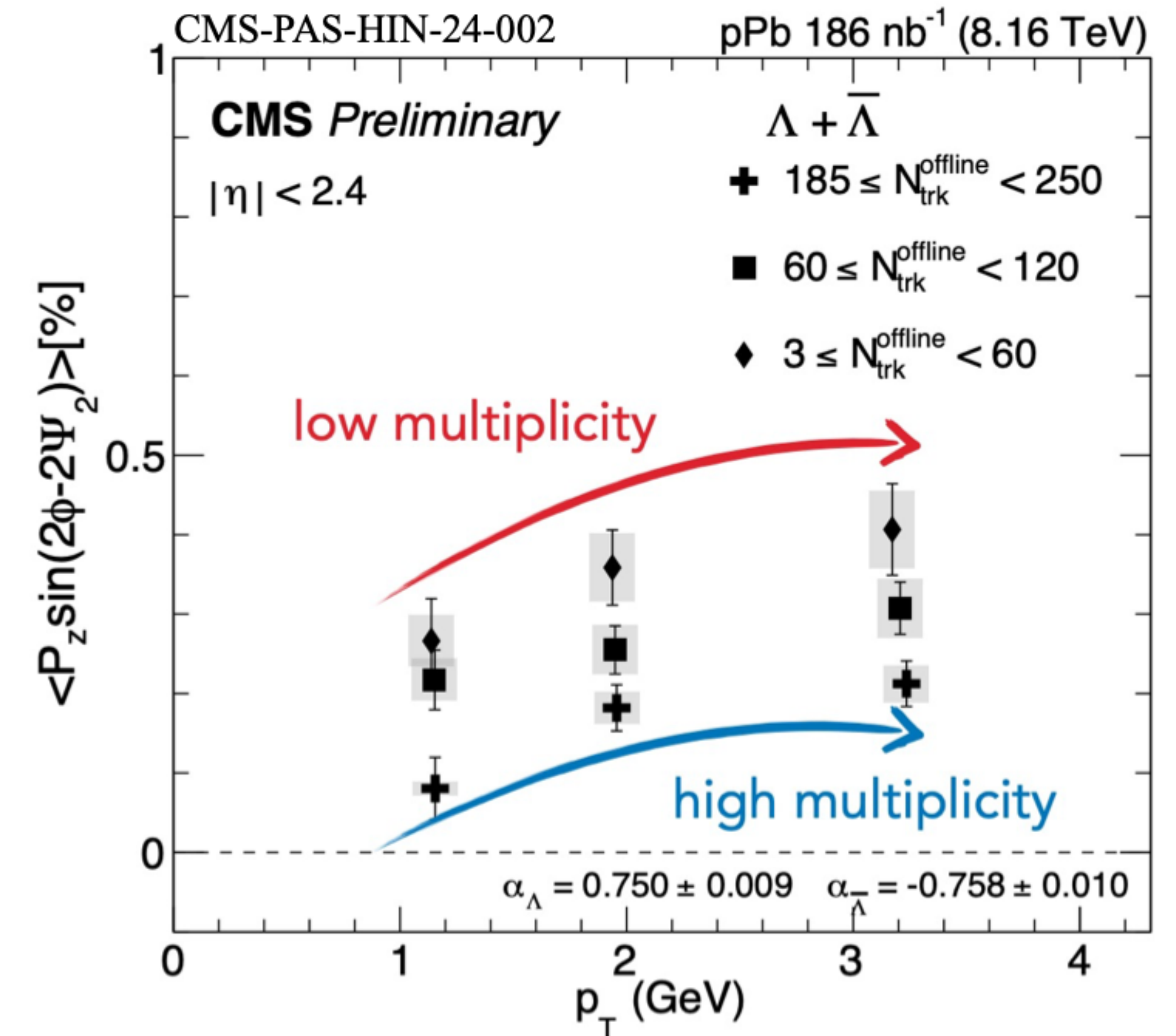
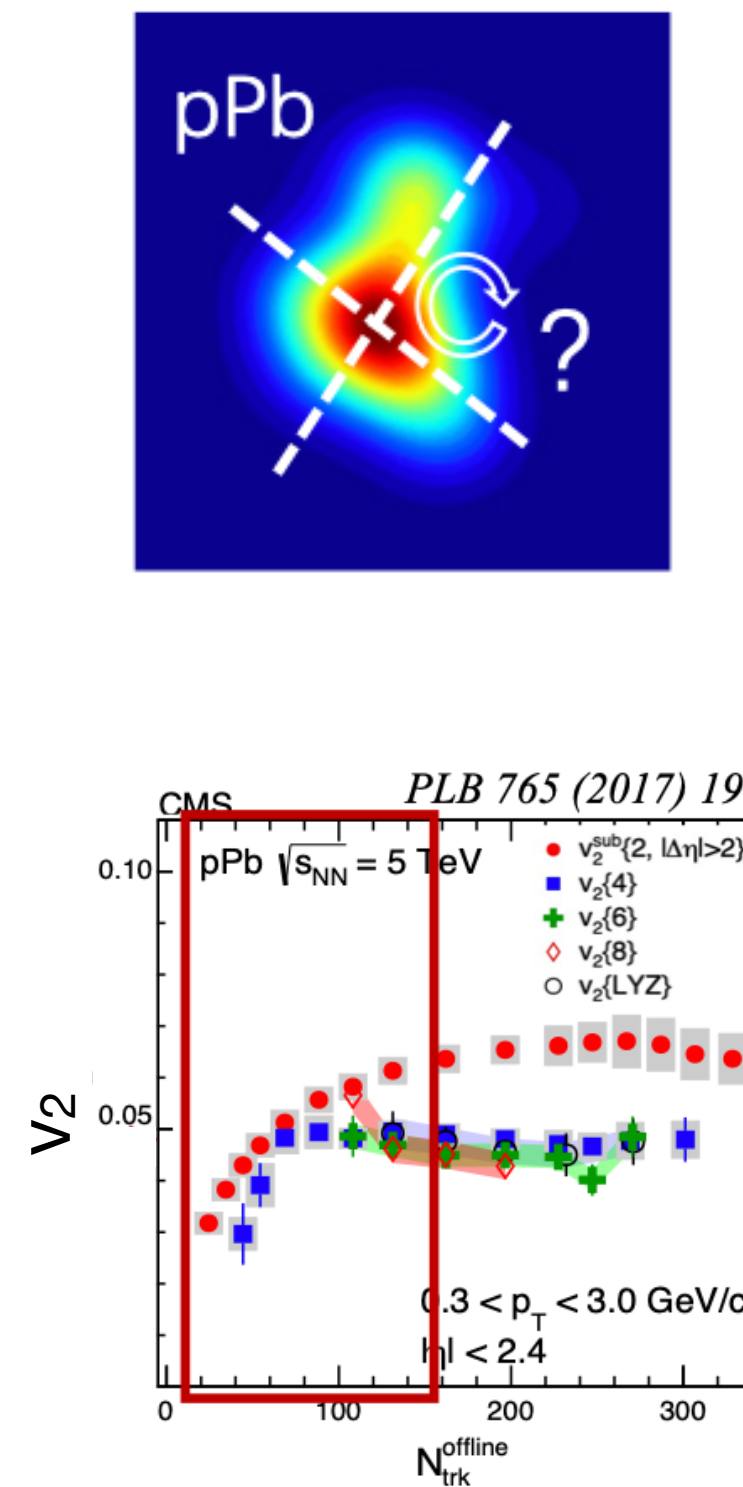
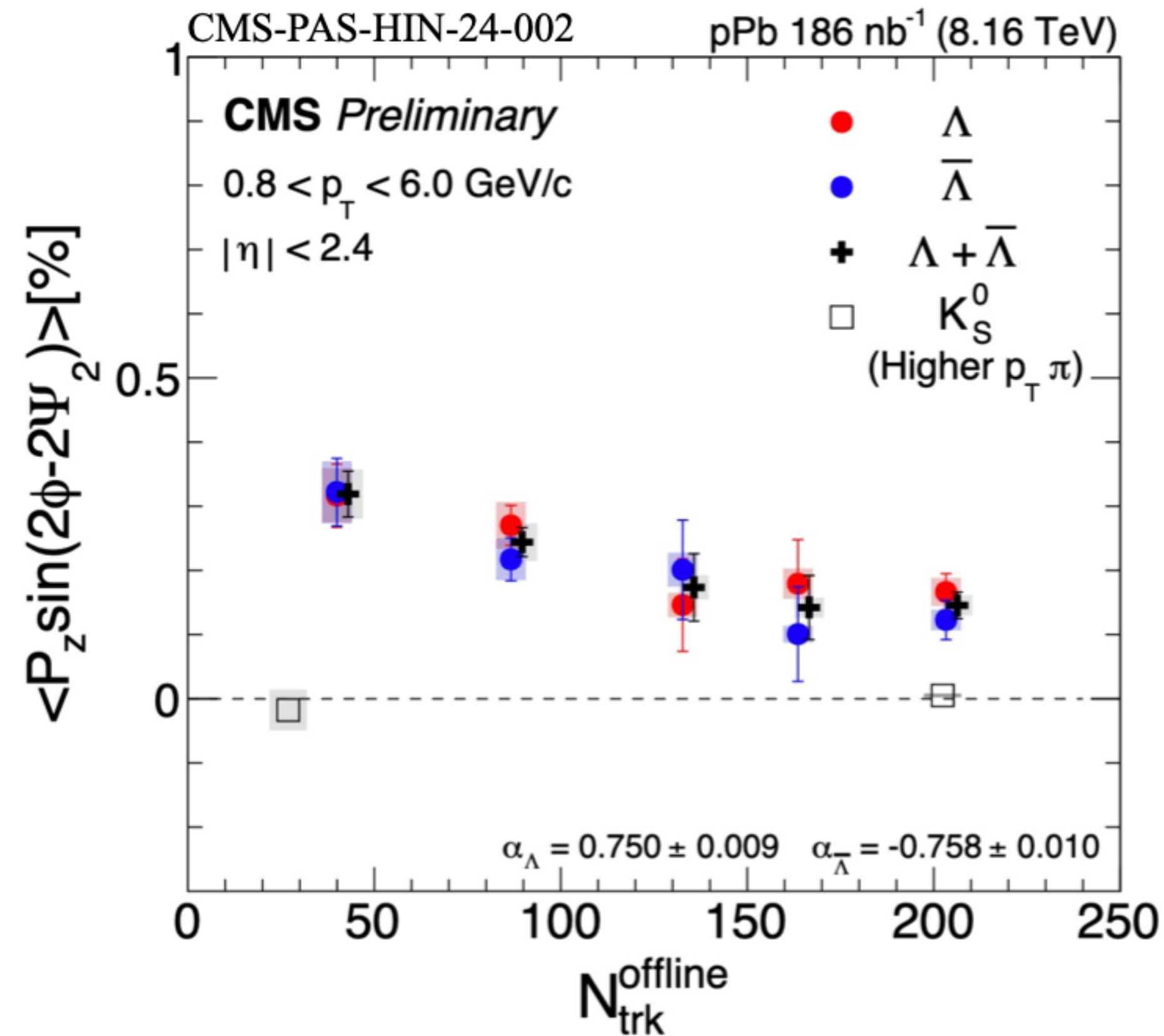
STAR, PRL 131 (2023) 202301



- Comparable local polarization w.r.t second and third order event plane
- Energy dependence is not obvious between 200 GeV Au+Au and 5.02 TeV Pb+Pb collisions

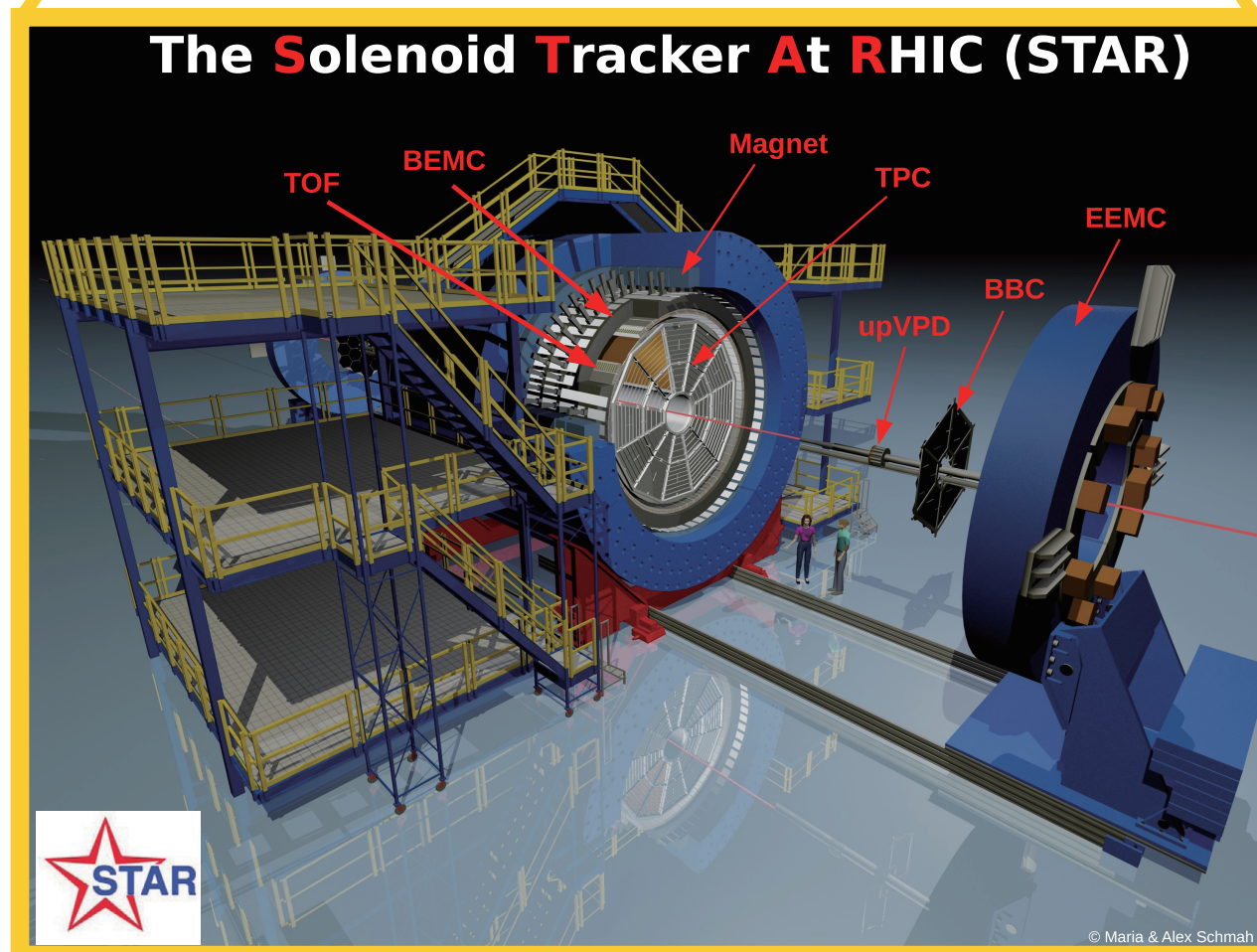
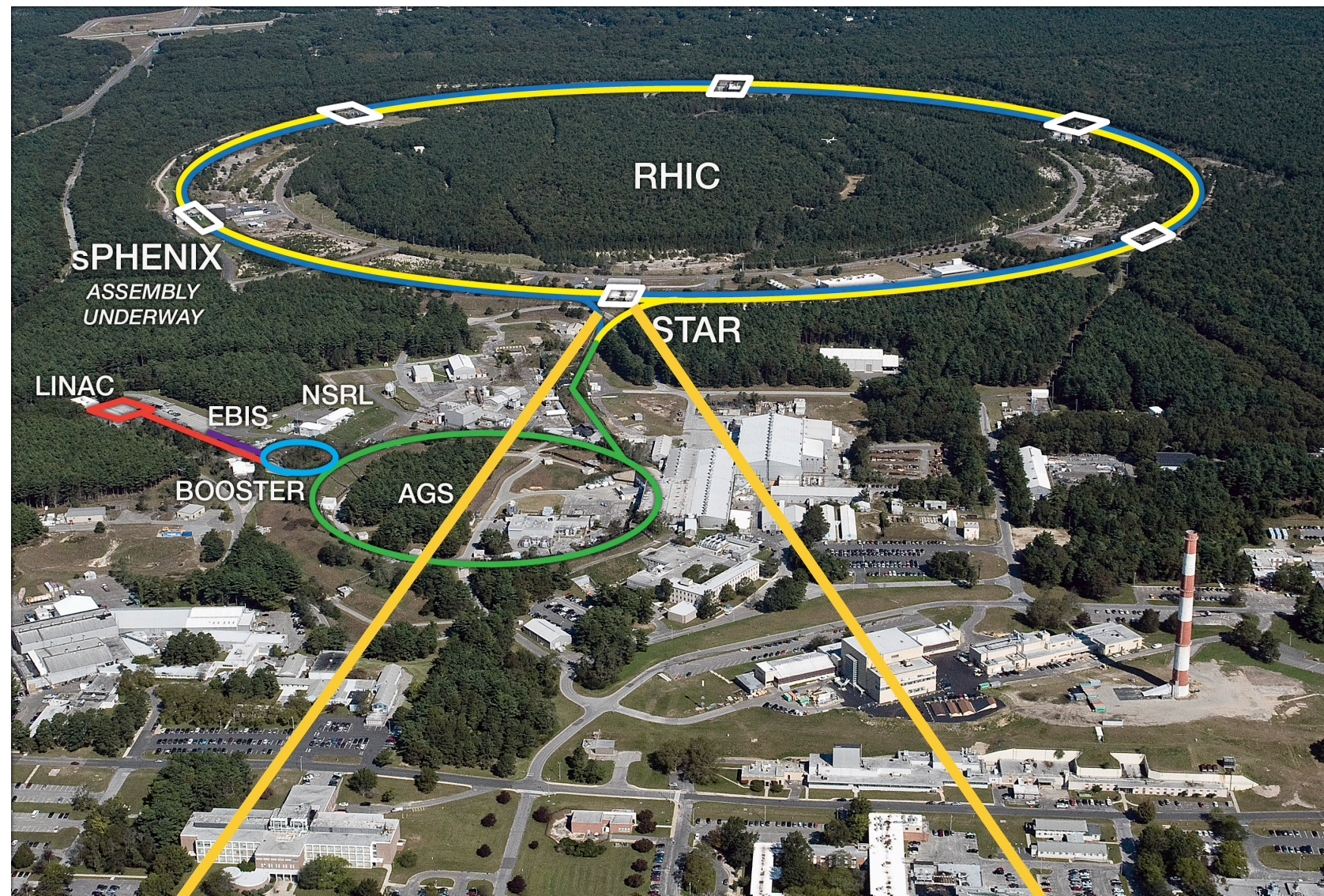
Local vortices and azimuthal-angle-dependent polarization

CMS, Phys. Rev. Lett. 135 (2025) 13, 132301

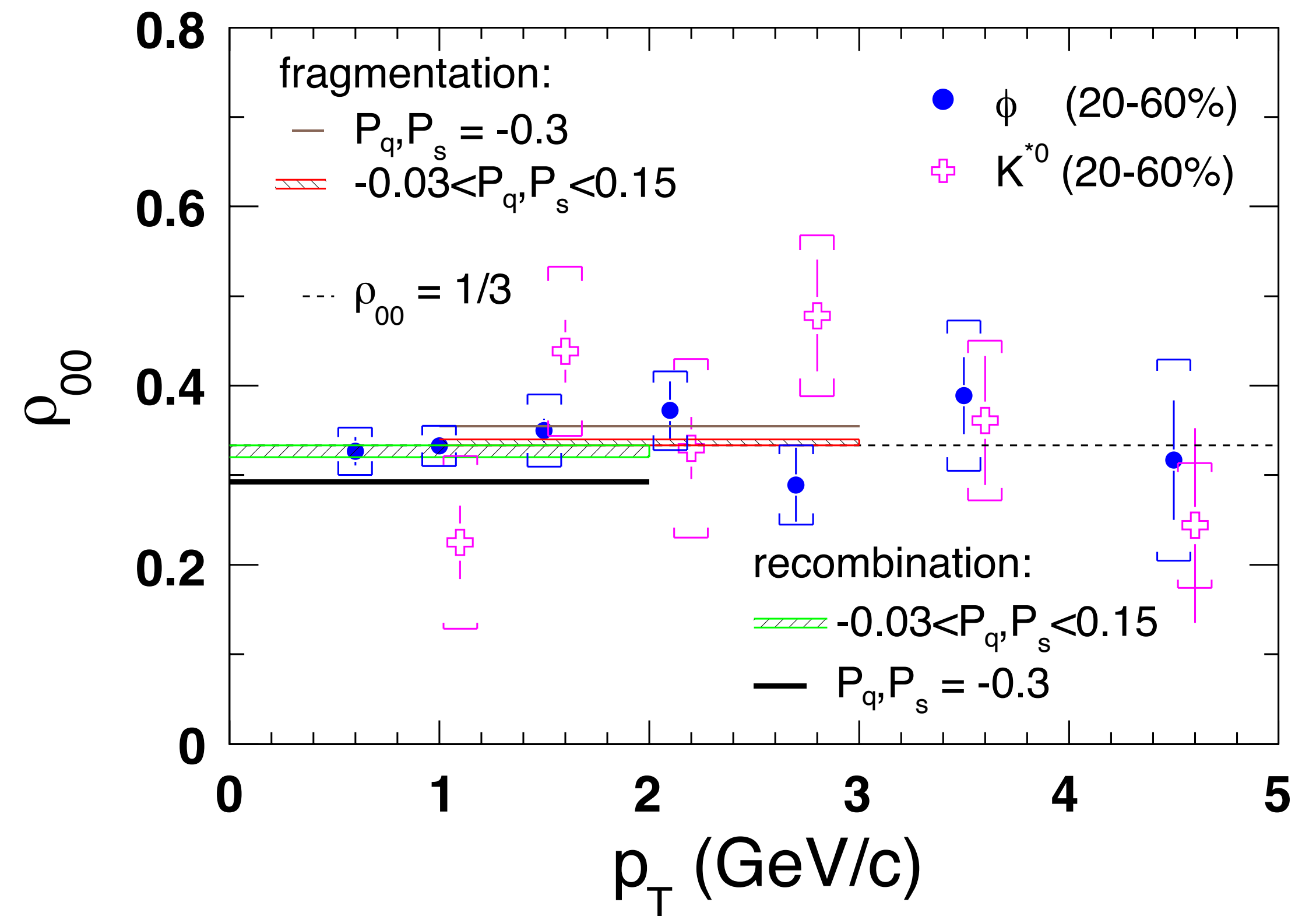


Challenge to the current theoretical implementation of spin polarization in heavy ion collisions!

Vector meson spin alignment



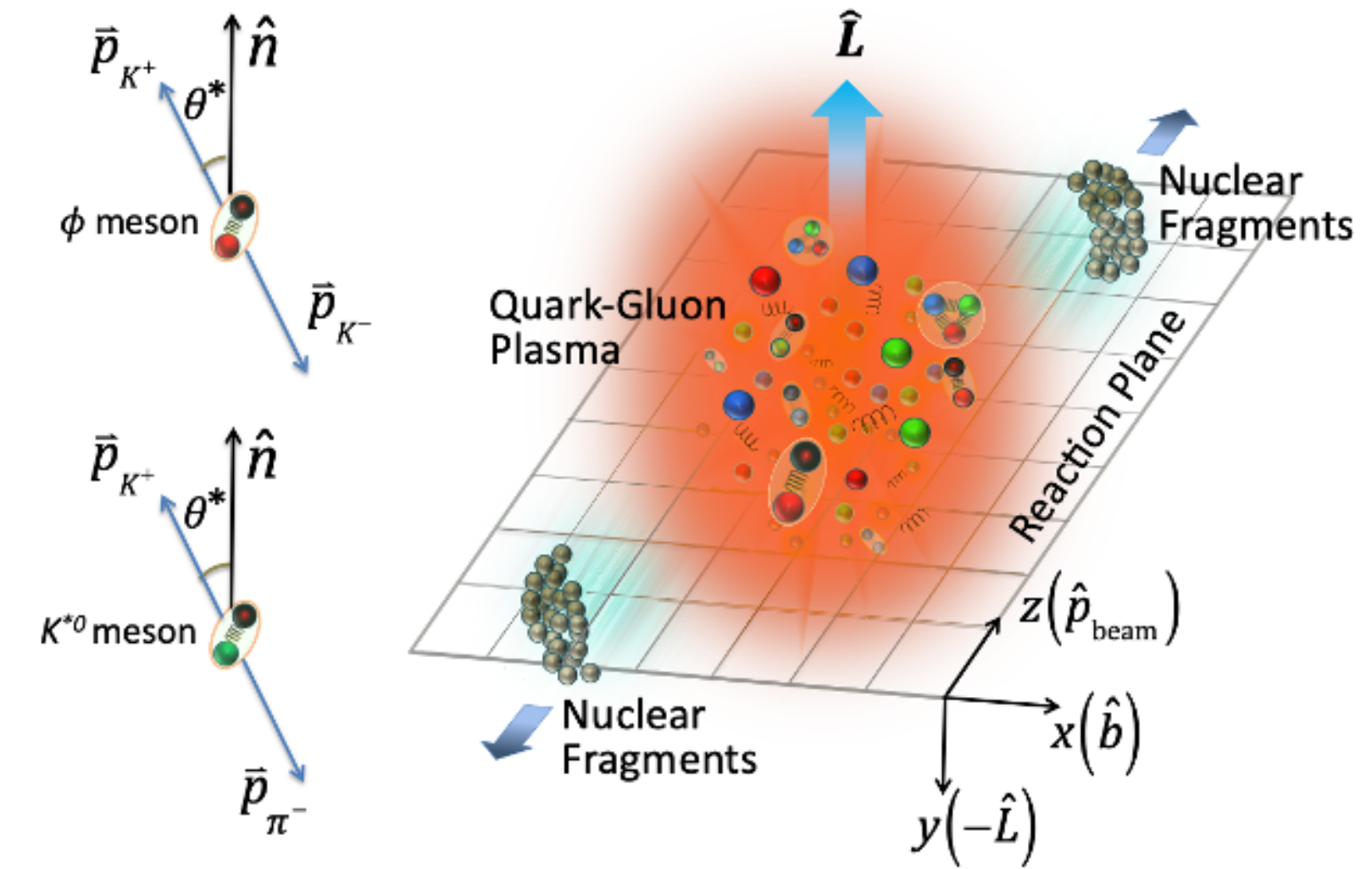
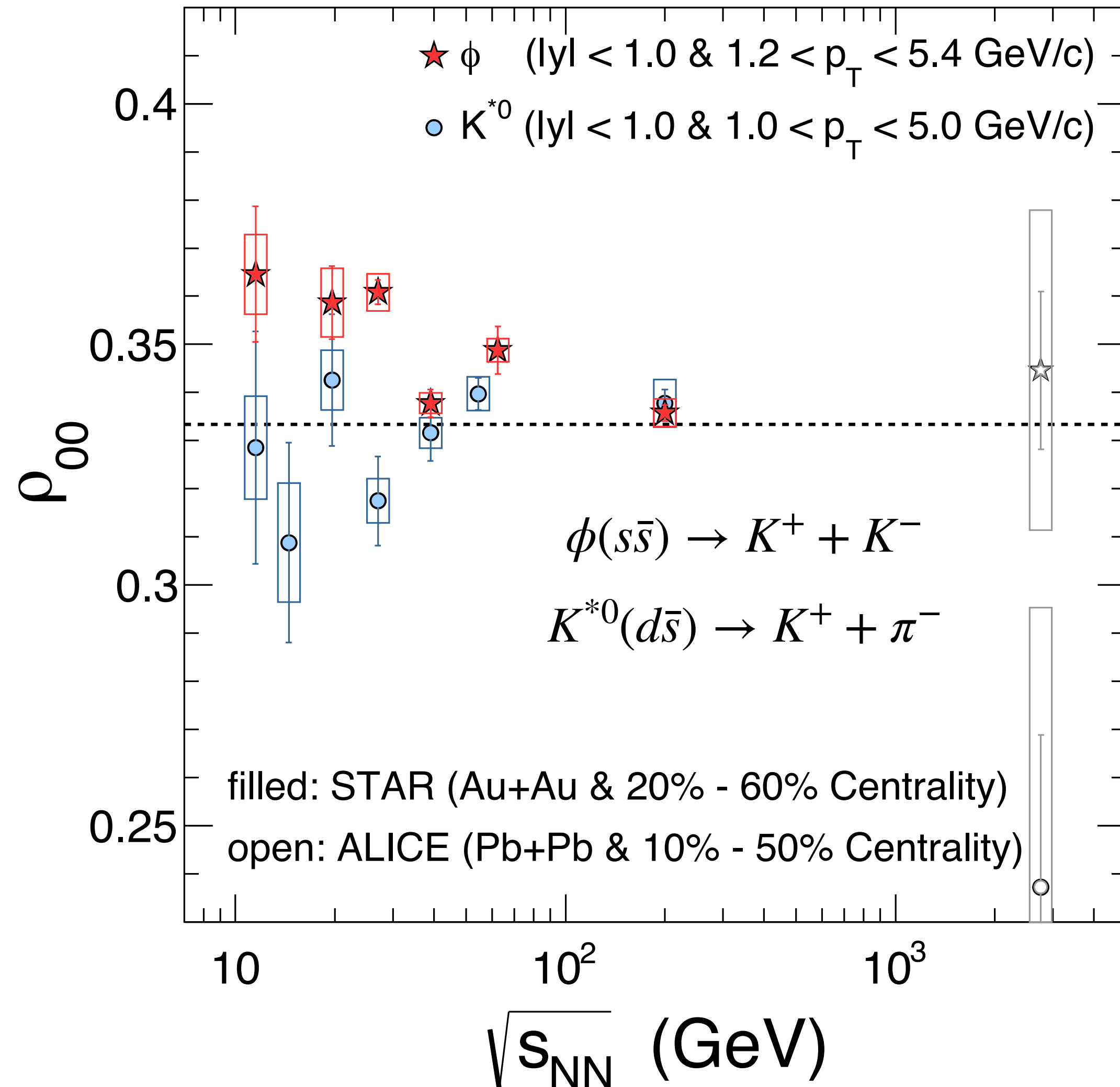
STAR, PRC 77 061902 (R) (2008)



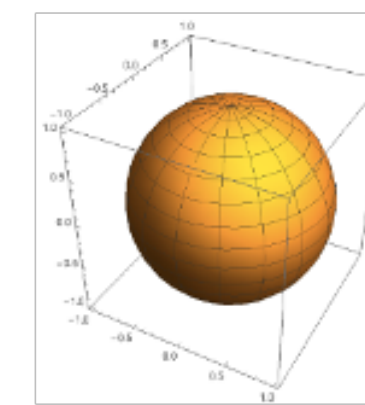
No significant results reported, due to limited statistics.

Vector meson spin alignment

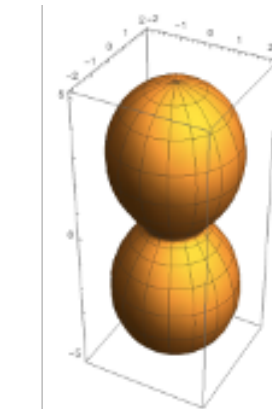
STAR, Nature 614, 233-248 (2023)



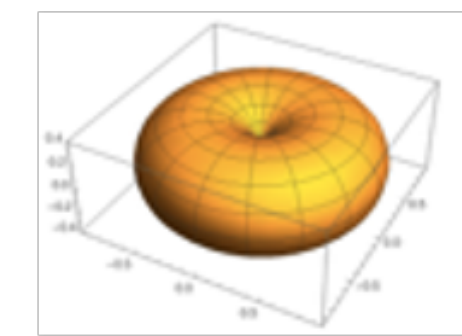
$$\frac{dN}{d\cos\theta^*} \propto (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^*$$



$$\rho_{00} = \frac{1}{3}$$



$$\rho_{00} > \frac{1}{3}$$

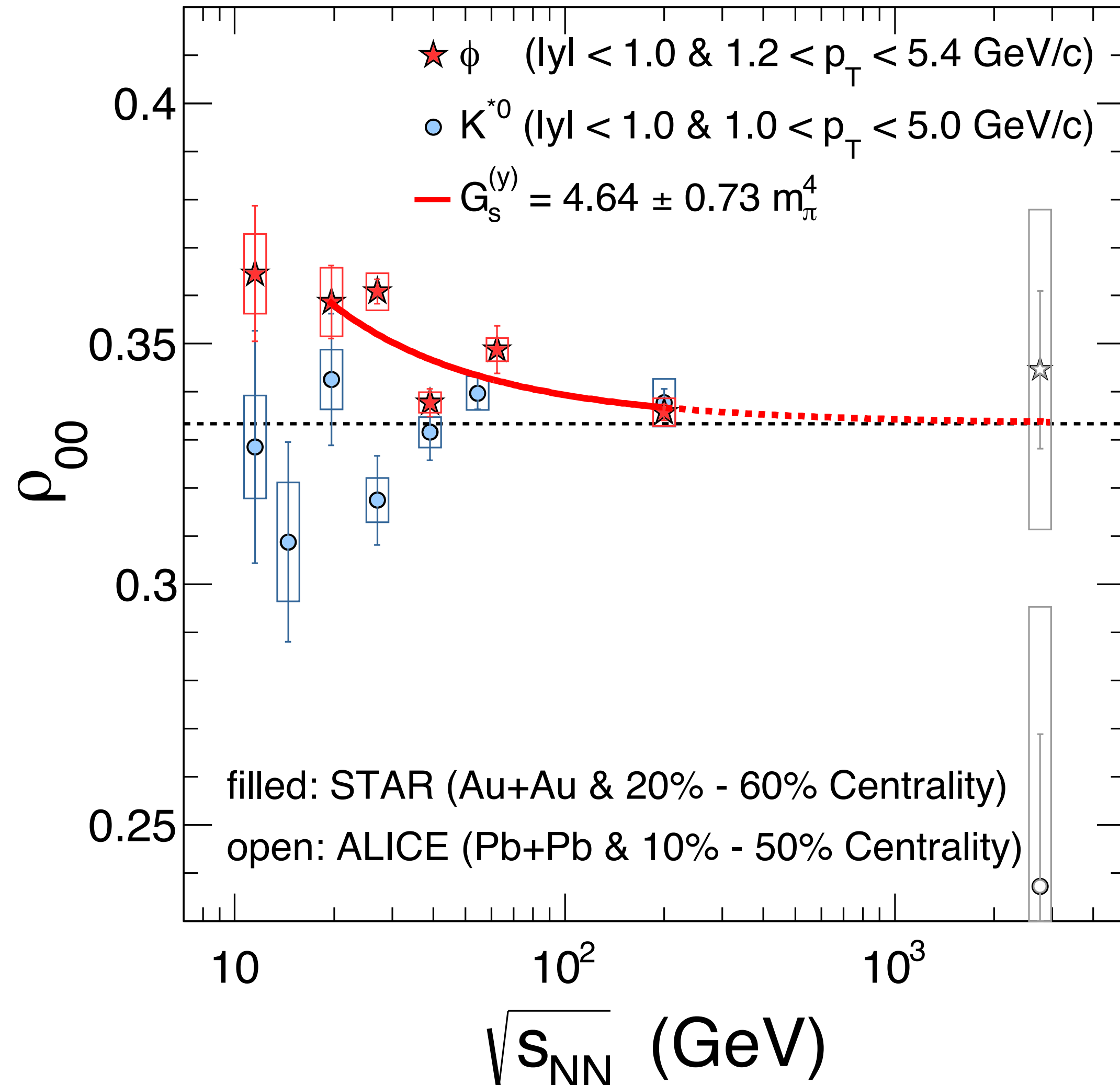


$$\rho_{00} < \frac{1}{3}$$

ϕ possesses surprisingly large global spin alignment while K^* possesses little

Vector meson spin alignment

STAR, Nature 614, 233-248 (2023)

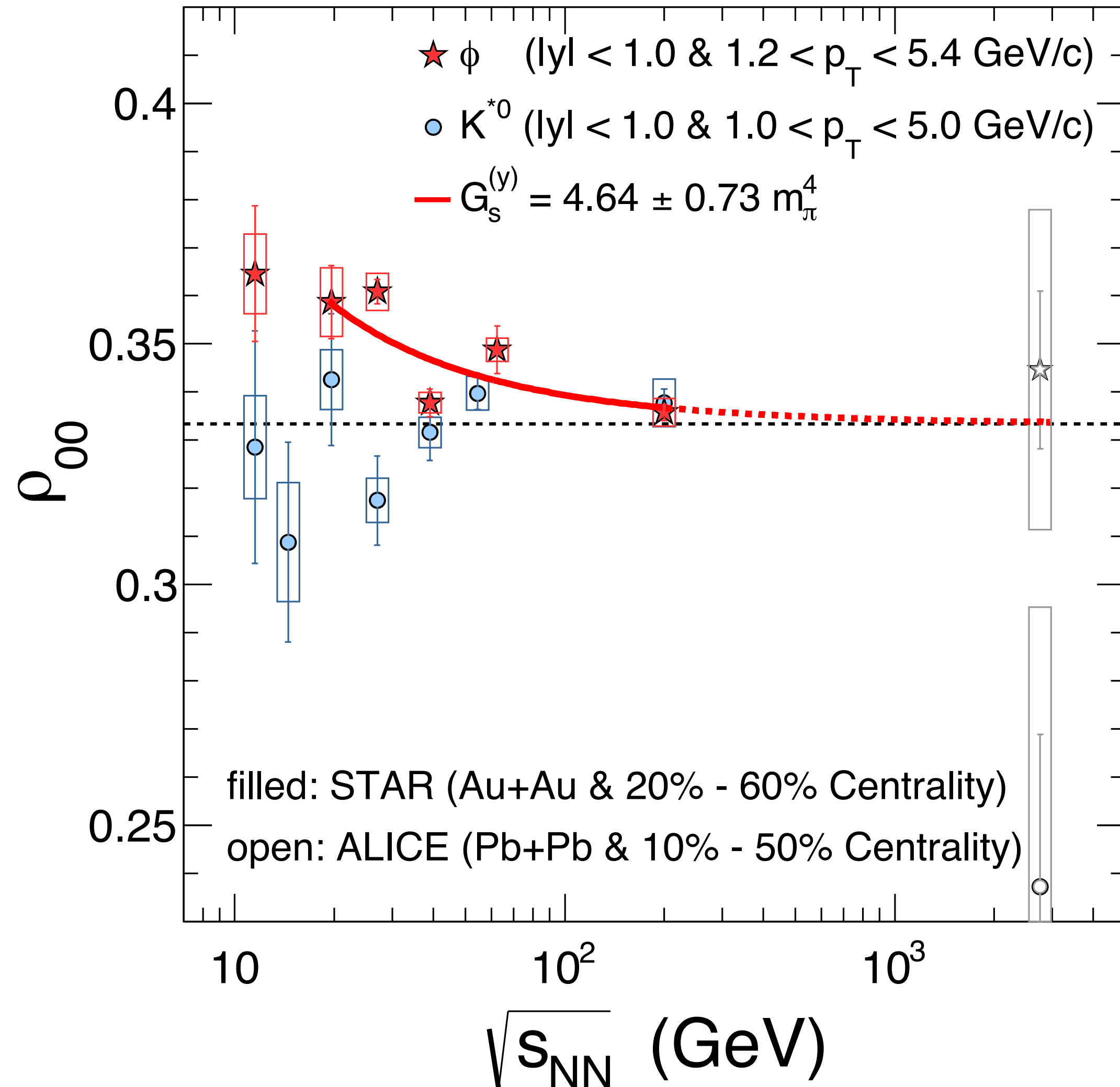


$$\rho_{00}(\phi) = \frac{1}{3} + C_\Lambda + C_\epsilon + C_E + C_F + C_L + C_A + C_\phi + C_g$$

Physics Mechanisms	(ρ_{00})
C_Λ : Quark coalescence vorticity & magnetic field ^[1]	$< 1/3$ (Negative $\sim 10^{-5}$)
C_ϵ : E-comp. of Vorticity tensor ^[1]	$< 1/3$ (Negative $\sim 10^{-4}$)
C_E : Electric field ^[2]	$> 1/3$ (Positive $\sim 10^{-5}$)
C_F : Fragmentation ^[3]	$> \text{or}, < 1/3$ ($\sim 10^{-5}$)
C_L : Local spin alignments ^[4]	$< 1/3$
C_A : Turbulent color field ^[5]	$< 1/3$
C_ϕ : Vector meson strong force field ^[6]	$> 1/3$
C_g : Glasma fields + effective potential	could be significant

Spin correlations from local field

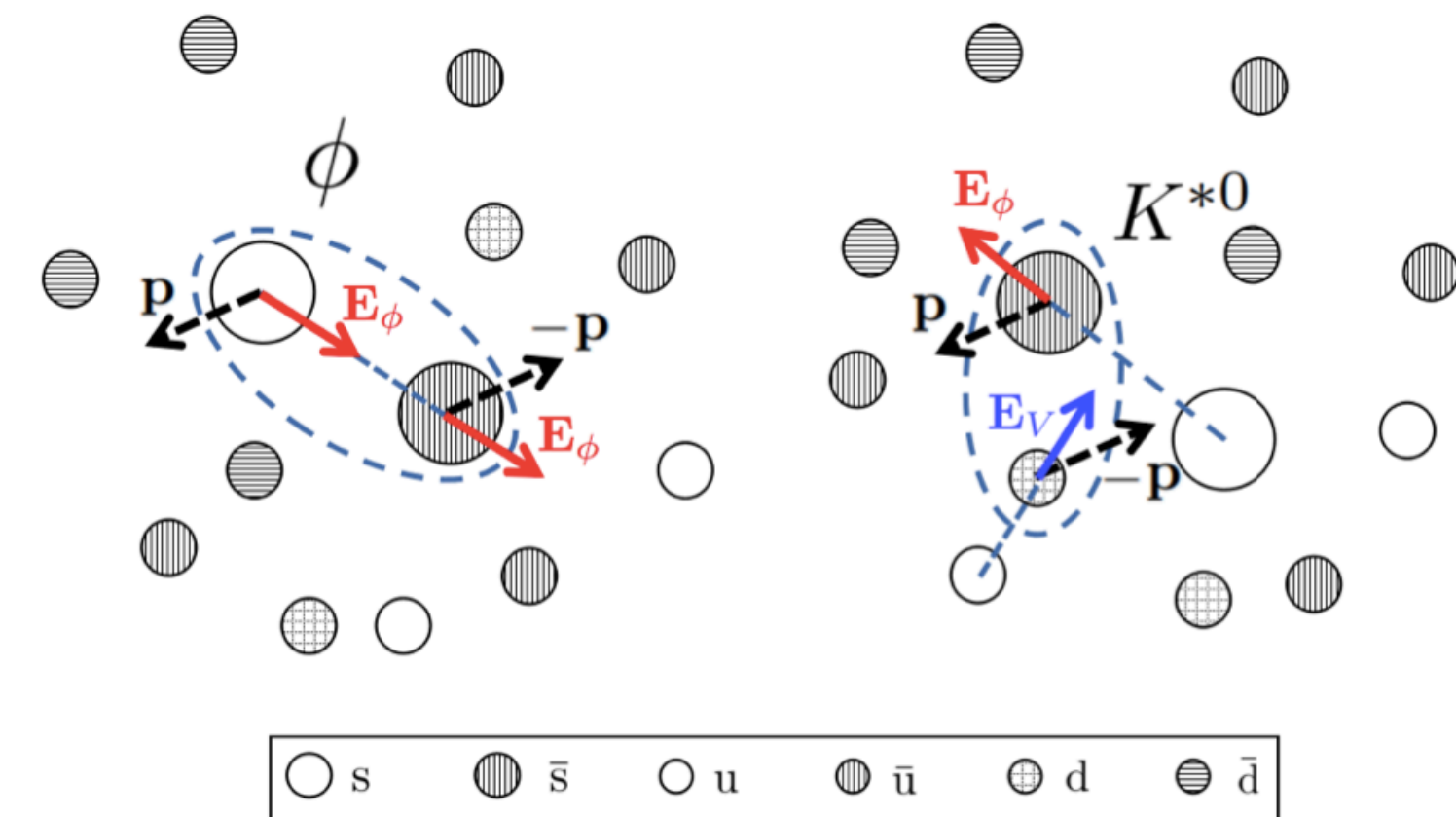
STAR, Nature 614, 233-248 (2023)



What do we learn?

$$\rho_{00}^V - \frac{1}{3} \sim \langle P_q P_{\bar{q}} \rangle \quad \rho_{00}^V - \frac{1}{3} \gg P_\Lambda^2 \approx P_q^2$$

$$\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$$



Global spin alignment measures local fluctuations, while hyperon polarization measures the mean.

Spin correlations from local field

Motivation

Relations of SDMEs to quark-antiquark spin correlations ($c_{ij}^{(q_1\bar{q}_2)}$) and quark and anti-quark polarizations (P_{q_1i} and $P_{\bar{q}_2j}$).

$$C_V = 3 + c_{xx}^{(q_1\bar{q}_2)} + c_{yy}^{(q_1\bar{q}_2)} + c_{zz}^{(q_1\bar{q}_2)} + P_{q_1x}P_{\bar{q}_2x} + P_{q_1y}P_{\bar{q}_2y} + P_{q_1z}P_{\bar{q}_2z} \quad (1)$$

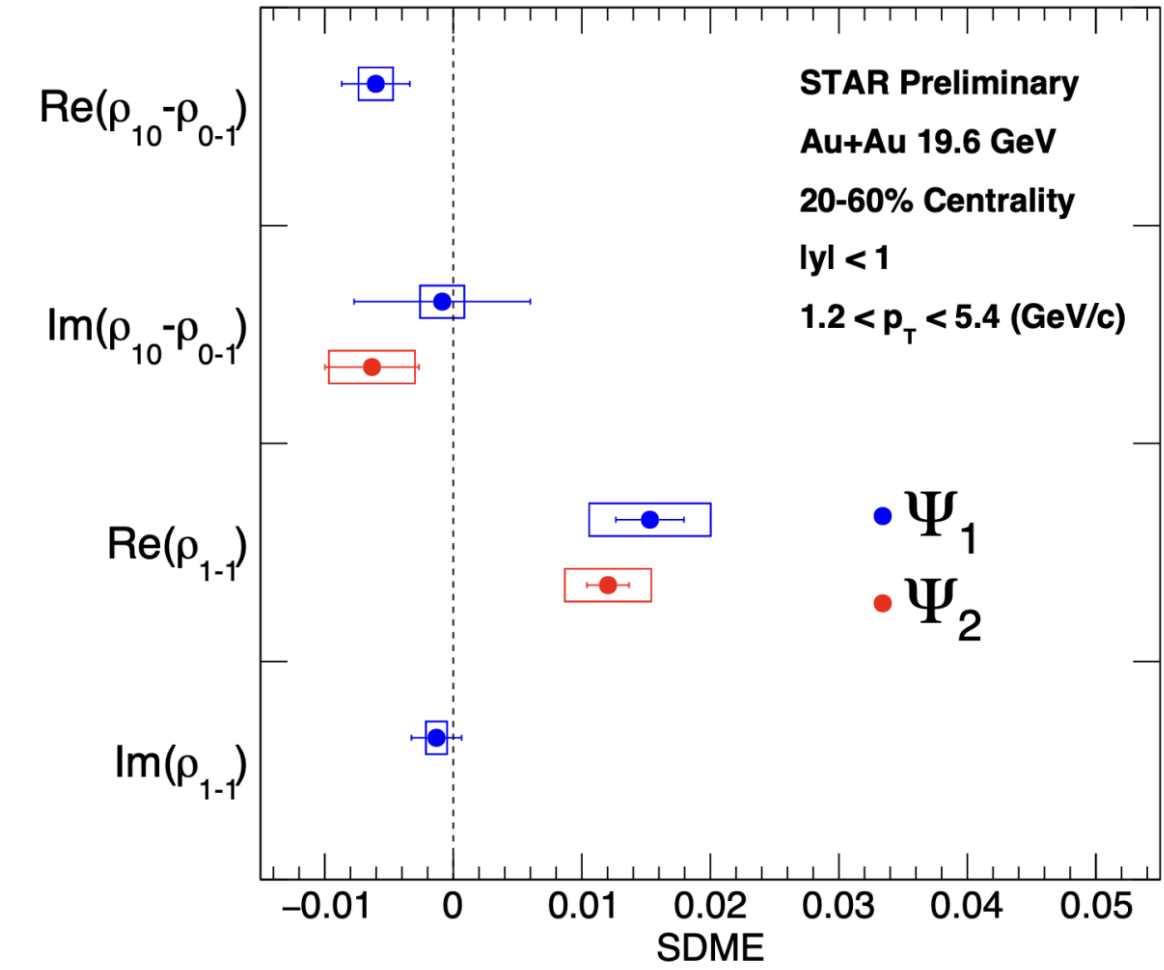
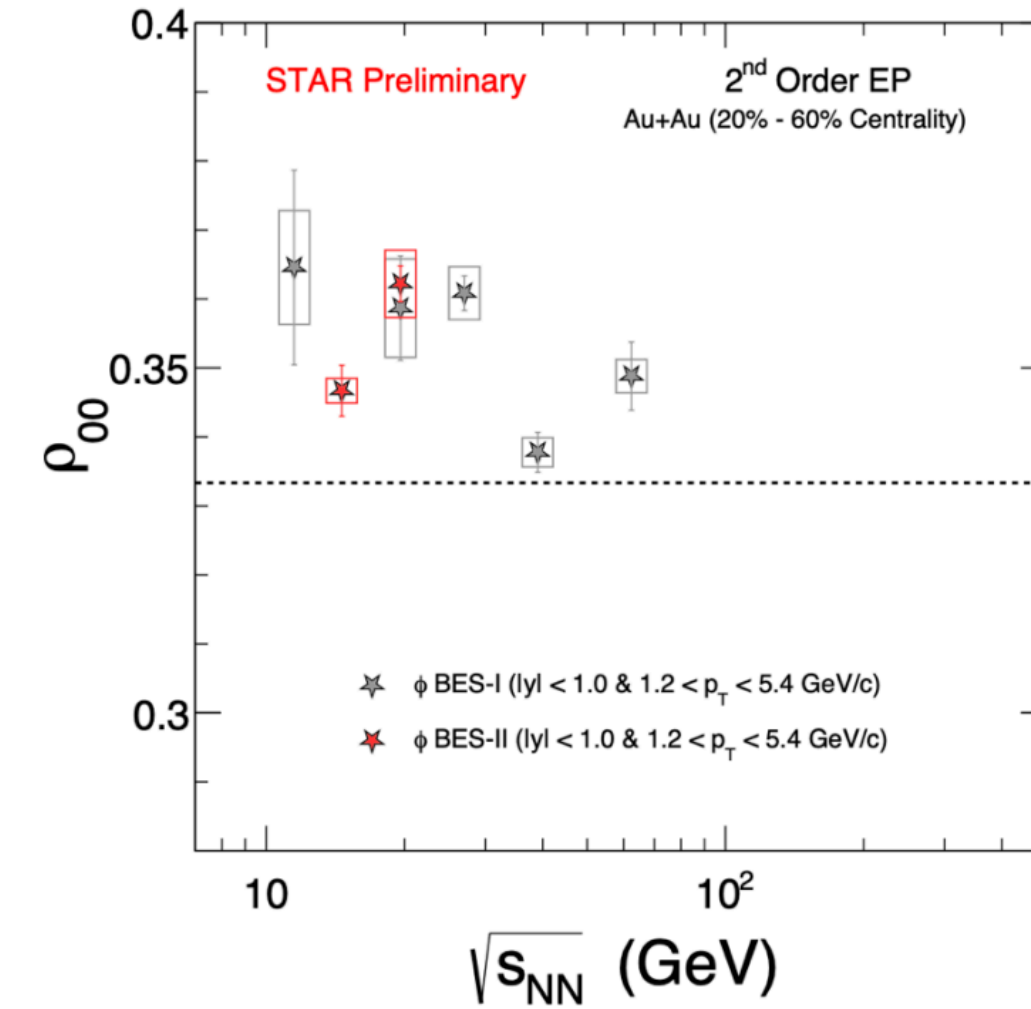
$$\rho_{00} = \frac{1}{C_V} \left[1 + c_{xx}^{(q_1\bar{q}_2)} + c_{yy}^{(q_1\bar{q}_2)} - c_{zz}^{(q_1\bar{q}_2)} + P_{q_1x}P_{\bar{q}_2x} + P_{q_1y}P_{\bar{q}_2y} - P_{q_1z}P_{\bar{q}_2z} \right] \quad (2)$$

$$\text{Re}(\rho_{10} - \rho_{0-1}) = \frac{\sqrt{2}}{C_V} \left[c_{xz}^{(q_1\bar{q}_2)} + c_{zx}^{(q_1\bar{q}_2)} + P_{q_1x}P_{\bar{q}_2z} + P_{q_1z}P_{\bar{q}_2x} \right] \quad (3)$$

$$\text{Im}(\rho_{10} - \rho_{0-1}) = -\frac{\sqrt{2}}{C_V} \left[c_{yz}^{(q_1\bar{q}_2)} + c_{zy}^{(q_1\bar{q}_2)} + P_{q_1y}P_{\bar{q}_2z} + P_{q_1z}P_{\bar{q}_2y} \right] \quad (4)$$

$$\text{Re}(\rho_{1-1}) = \frac{1}{C_V} \left[c_{xx}^{(q_1\bar{q}_2)} - c_{yy}^{(q_1\bar{q}_2)} + P_{q_1x}P_{\bar{q}_2x} - P_{q_1y}P_{\bar{q}_2y} \right] \quad (5)$$

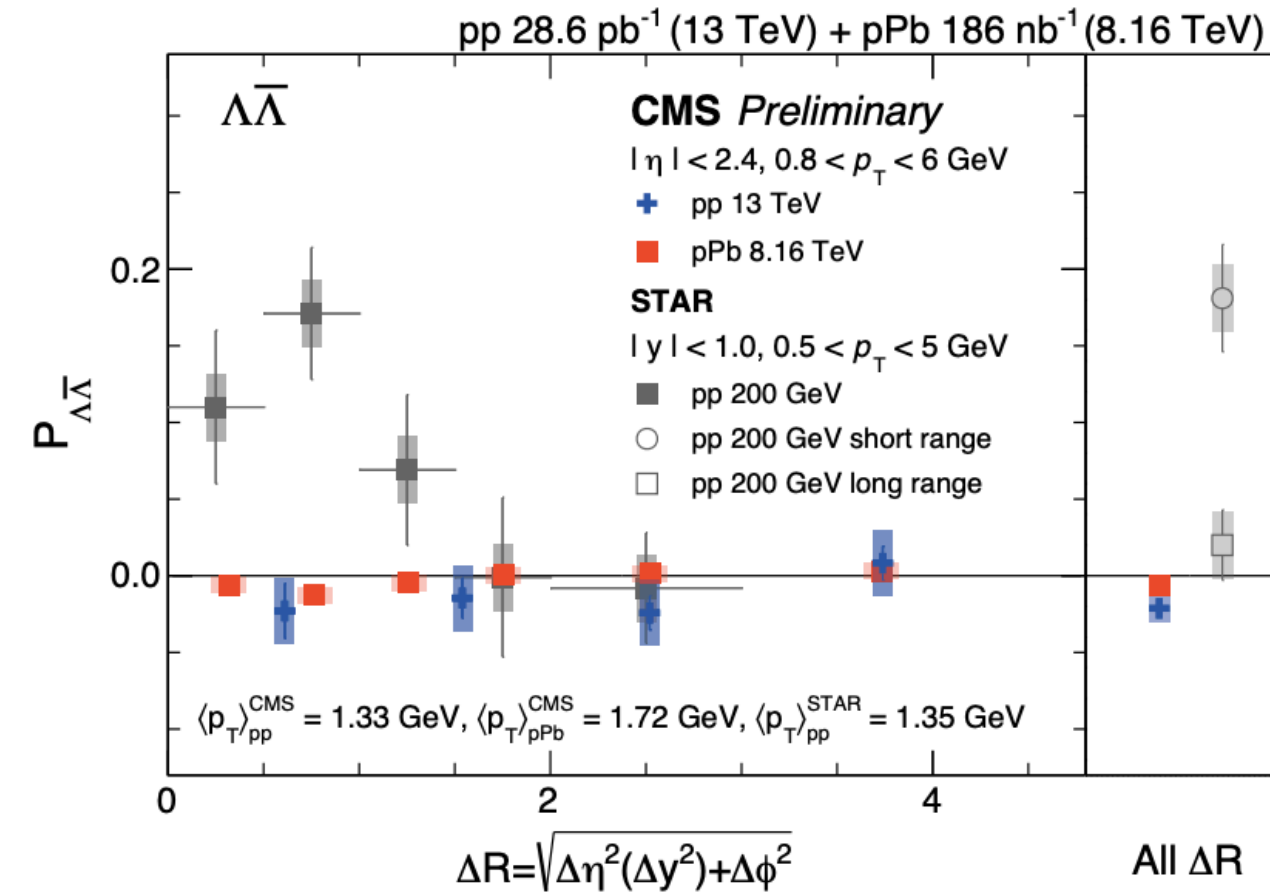
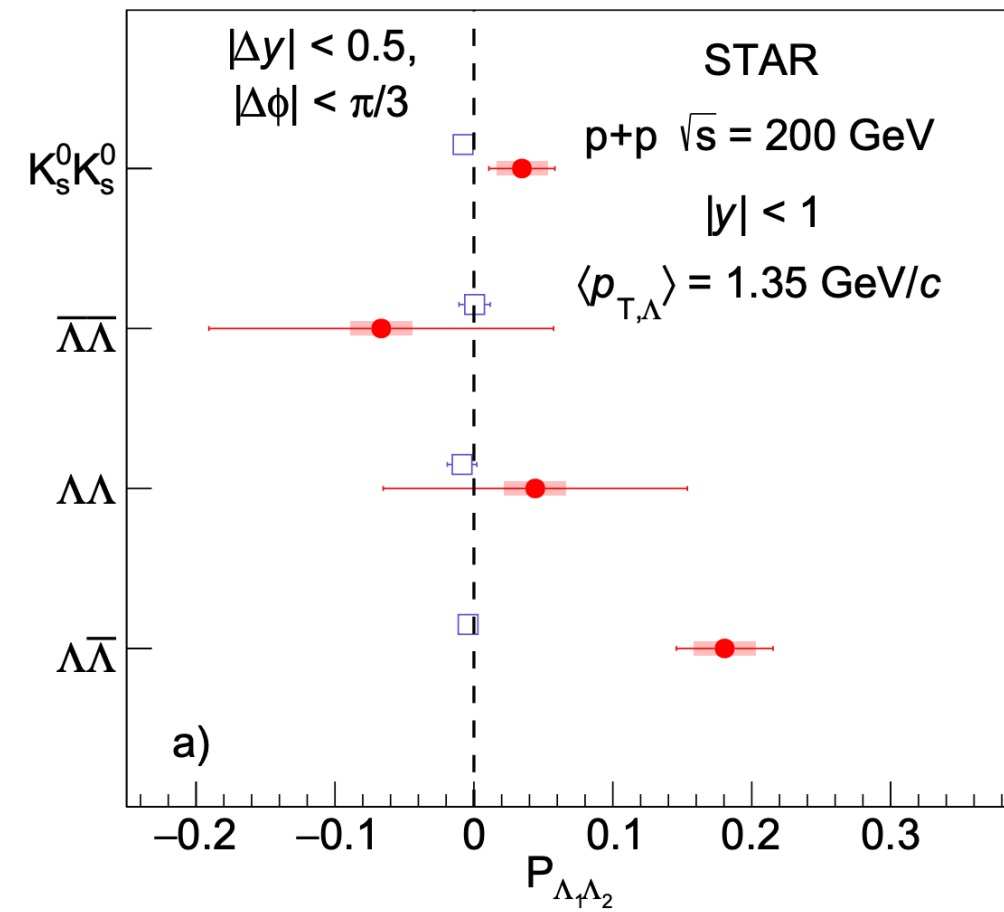
$$\text{Im}(\rho_{1-1}) = -\frac{1}{C_V} \left[c_{xy}^{(q_1\bar{q}_2)} + c_{yx}^{(q_1\bar{q}_2)} + P_{q_1x}P_{\bar{q}_2y} + P_{q_1y}P_{\bar{q}_2x} \right] \quad (6)$$



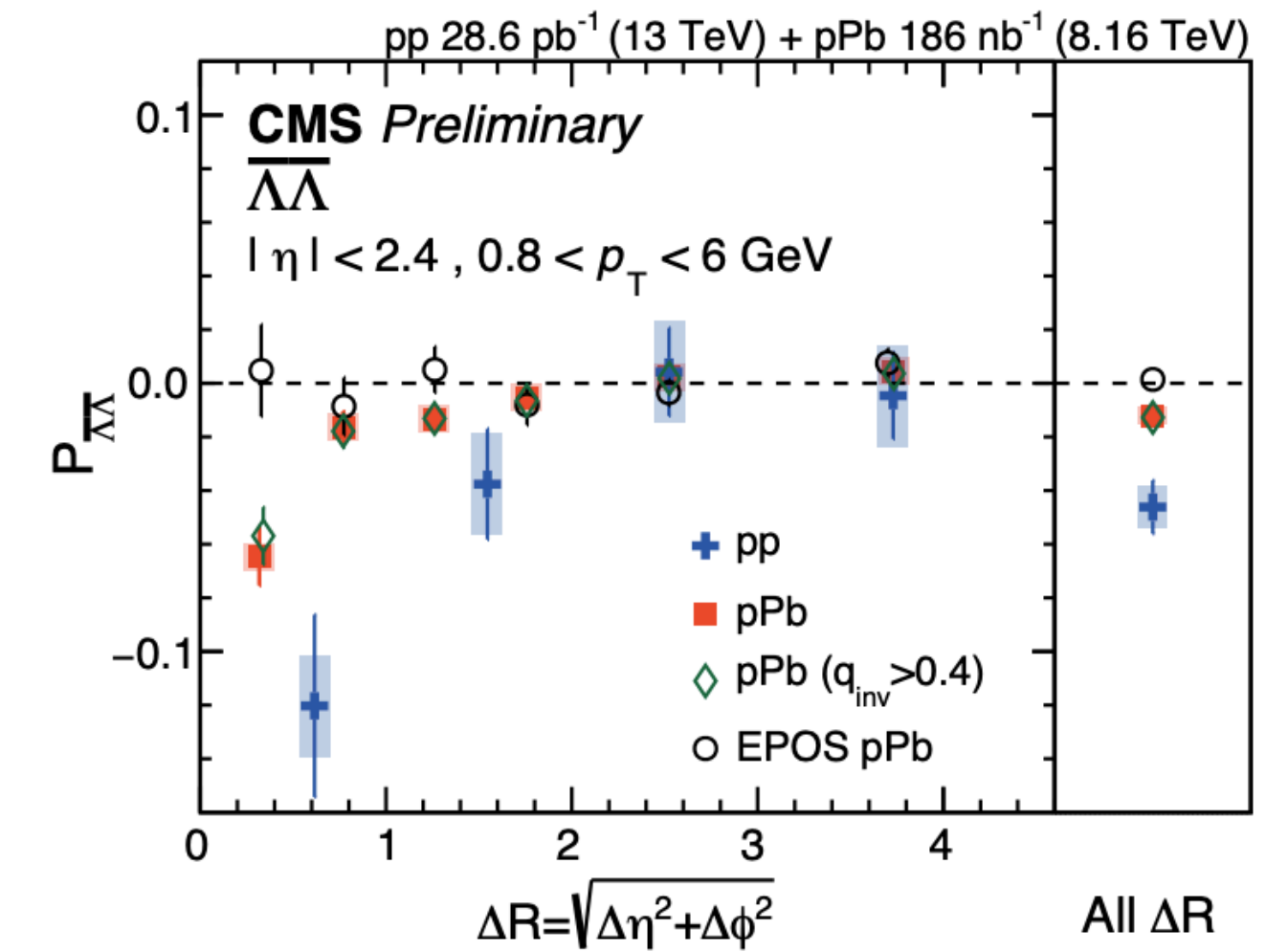
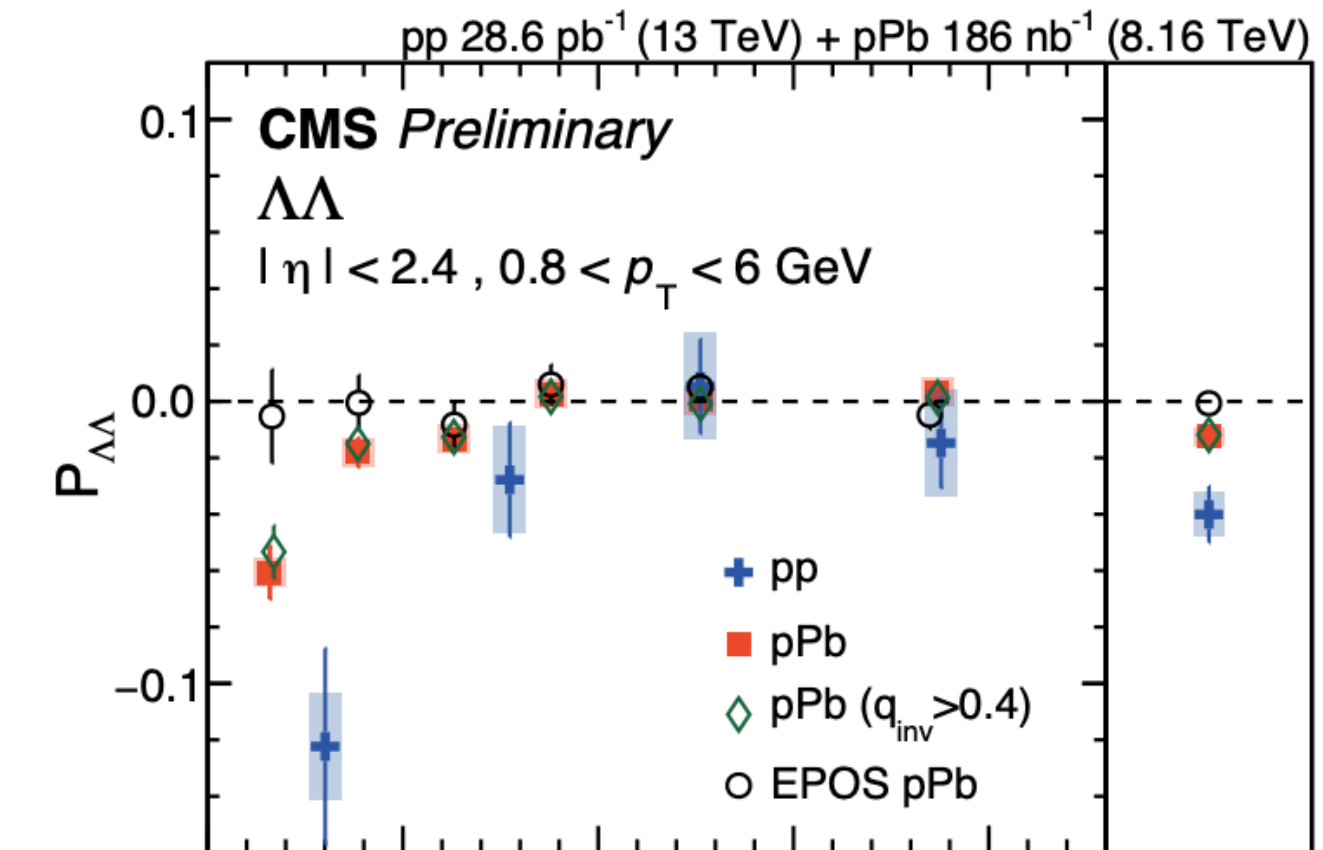
- ρ_{00} of ϕ meson in BES-II are consistent with BES-I results.
- First results show non-zero $\text{Re}(\rho_{1-1})$ in heavy-ion collisions with 3.2σ significance.

Spin correlations from local field

STAR, Nature **650** (2026) 65

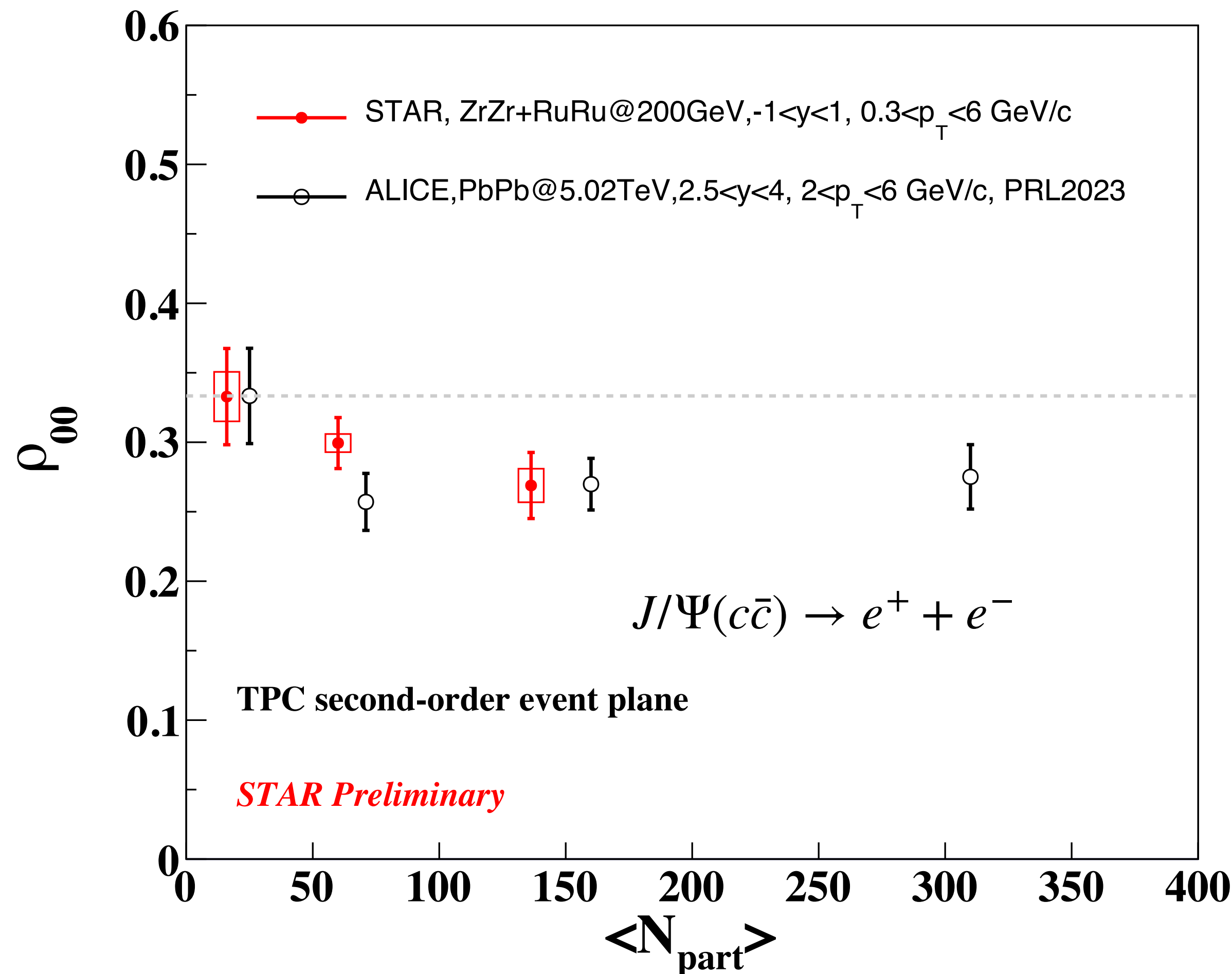


Jieke Wang DIS 2026



- Λ spin correlation has been measured in small systems.
- $p+p$ 200 GeV: $P_{OS} > 0$, $P_{SS} \approx 0$
- $p+p$ 13 TeV and $p+Pb$ 8.16 TeV: $P_{OS} \approx 0$, $P_{SS} < 0$

What about J/Psi?



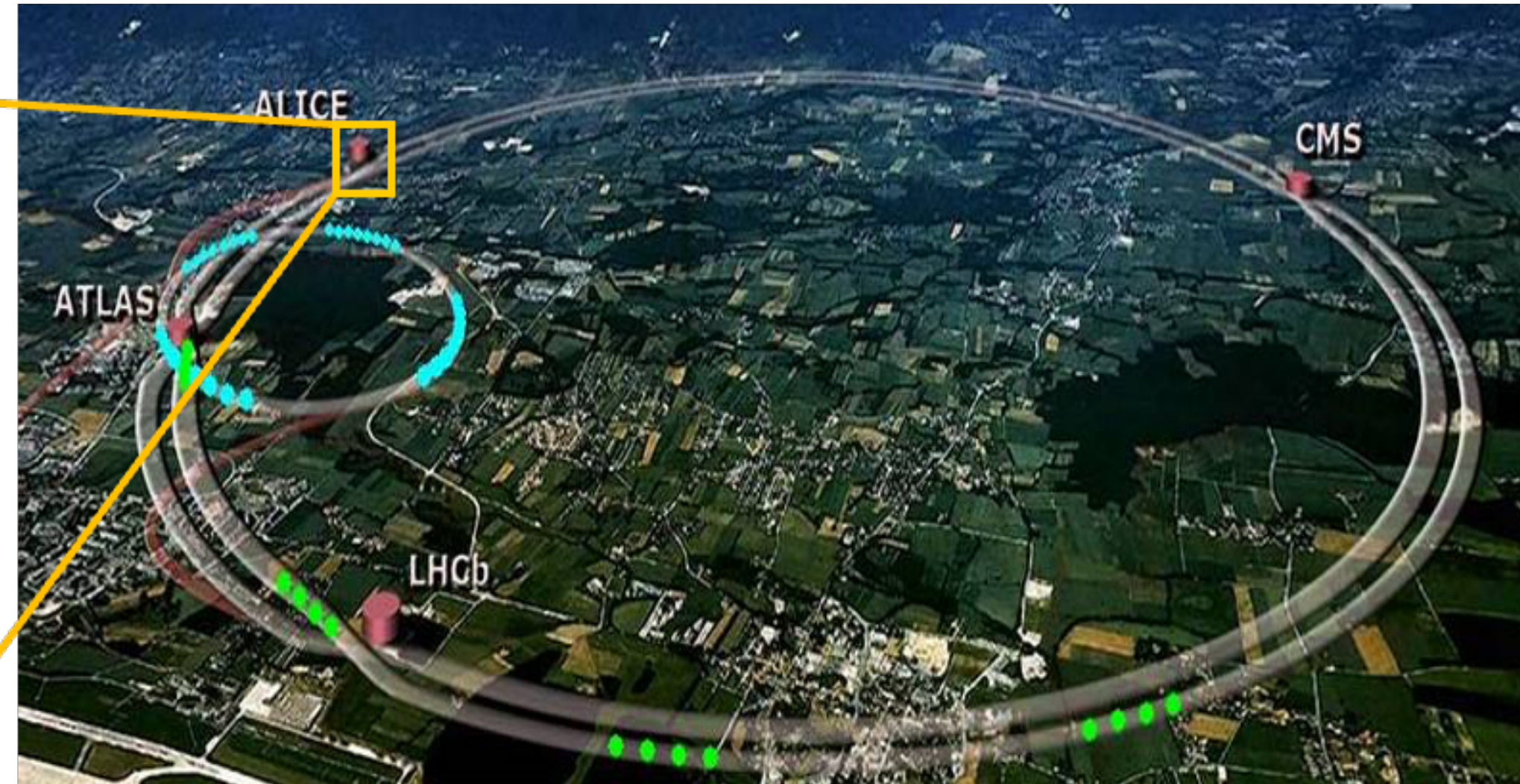
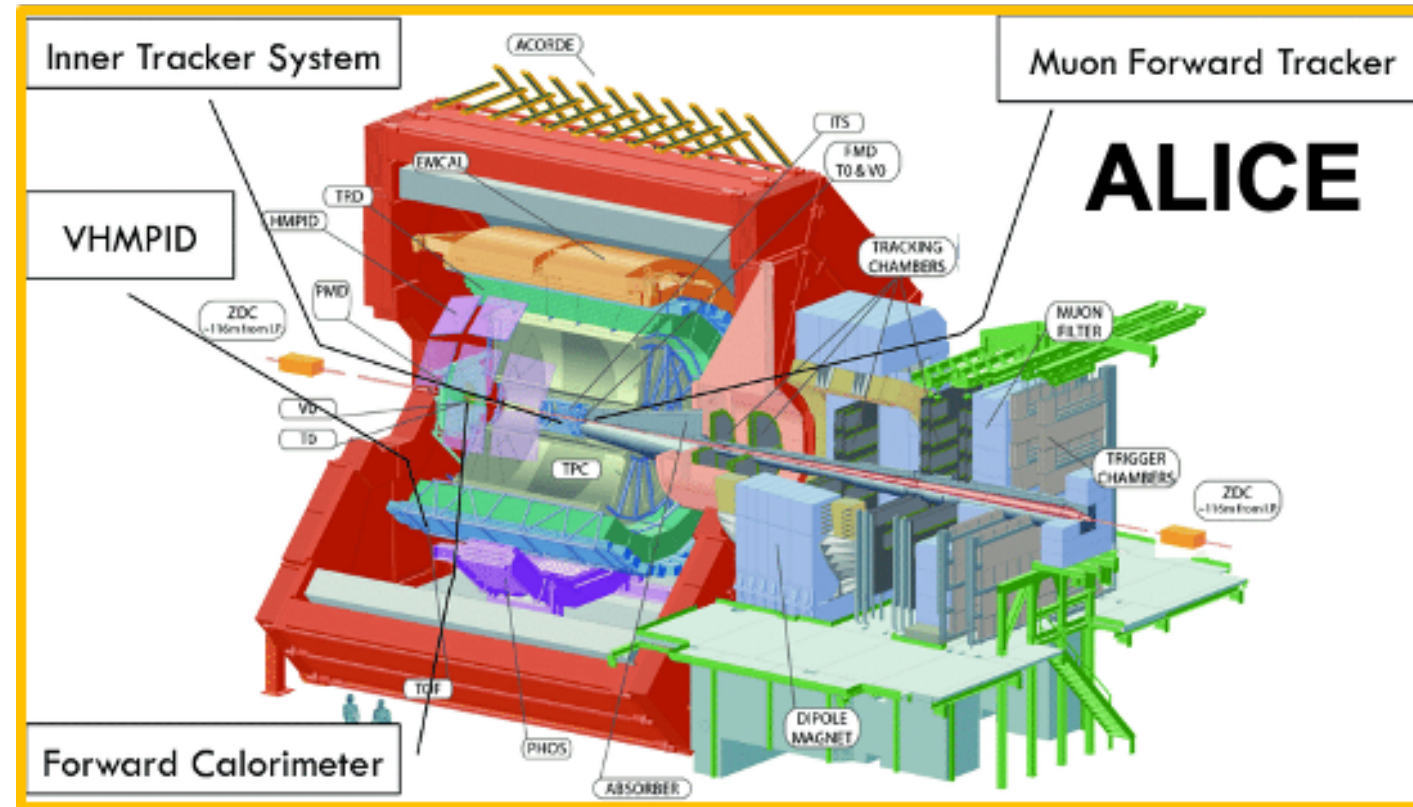
$$\frac{dN}{d\cos\theta^*} \propto (1 + \rho_{00}) + (1 - 3\rho_{00})\cos^2\theta^*$$

- Naive expectation from fluctuating strong force field : $\rho_{00} > 1/3$ at midrapidity
- Forward J/Ψ ρ_{00} at LHC and midrapidity J/Ψ ρ_{00} at RHIC, both $< 1/3$
- The ρ_{00} at RHIC energy is comparable to LHC results, despite of very different coalescence effect contribution

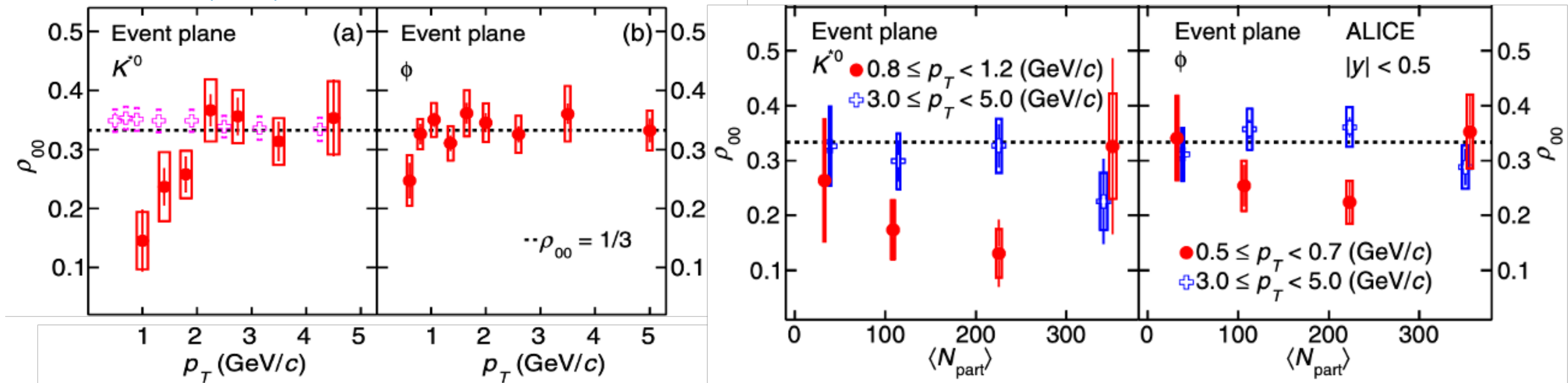
How do we understand J/Ψ ρ_{00} ?

Q. Yang @ QPT 2023

Global Spin Alignment at ALICE

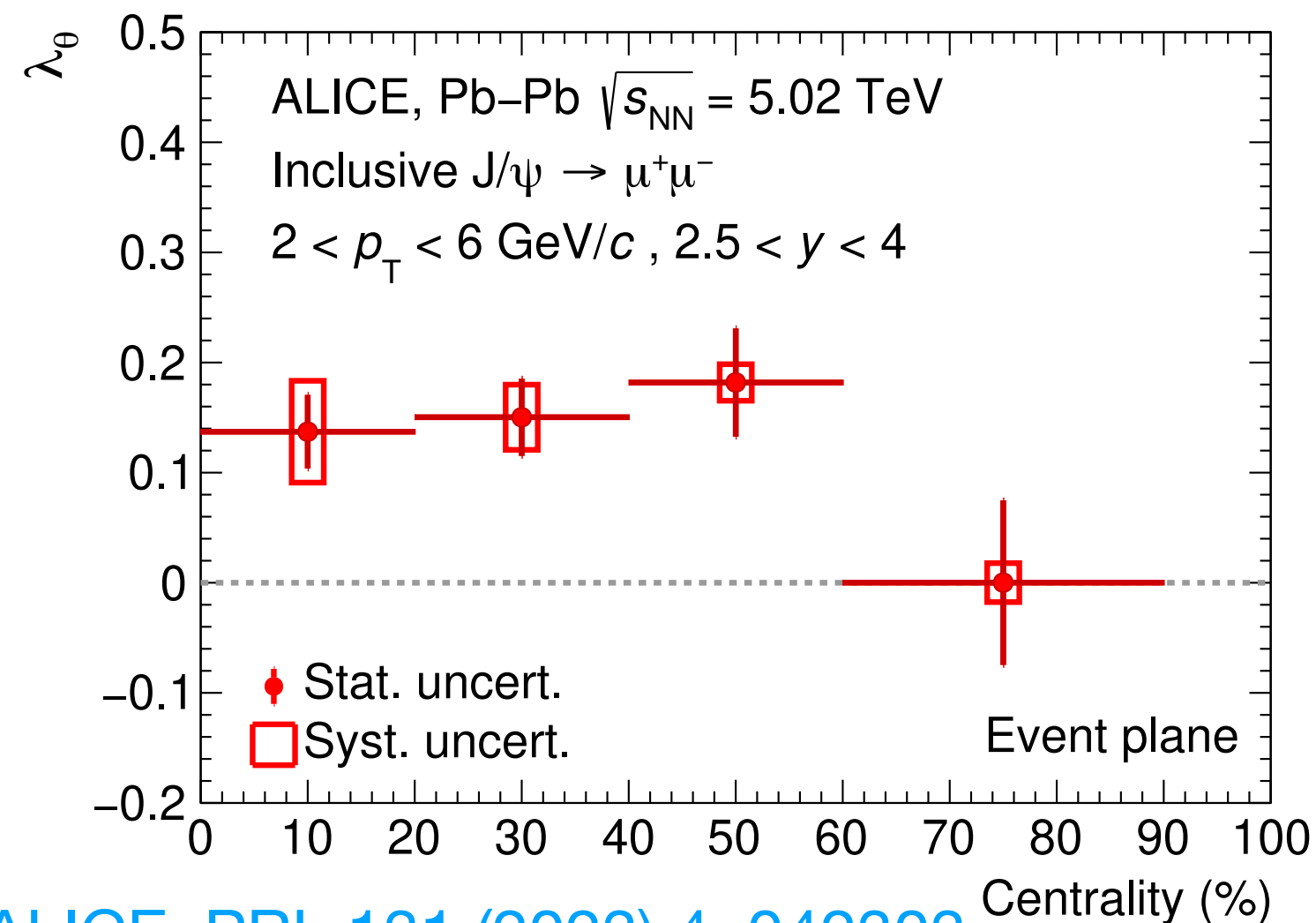


ALICE, PRL 125 012301 (2020)

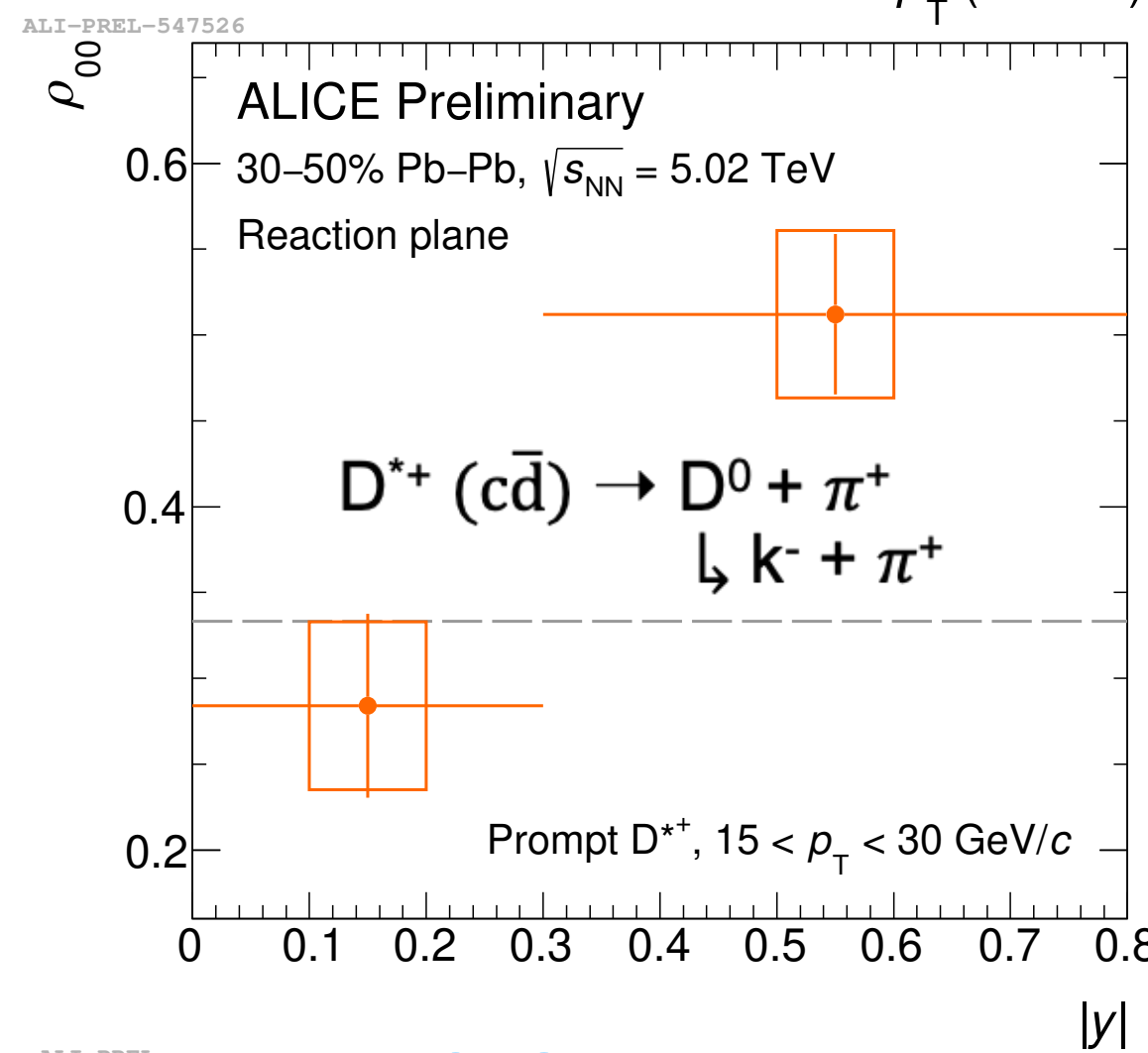
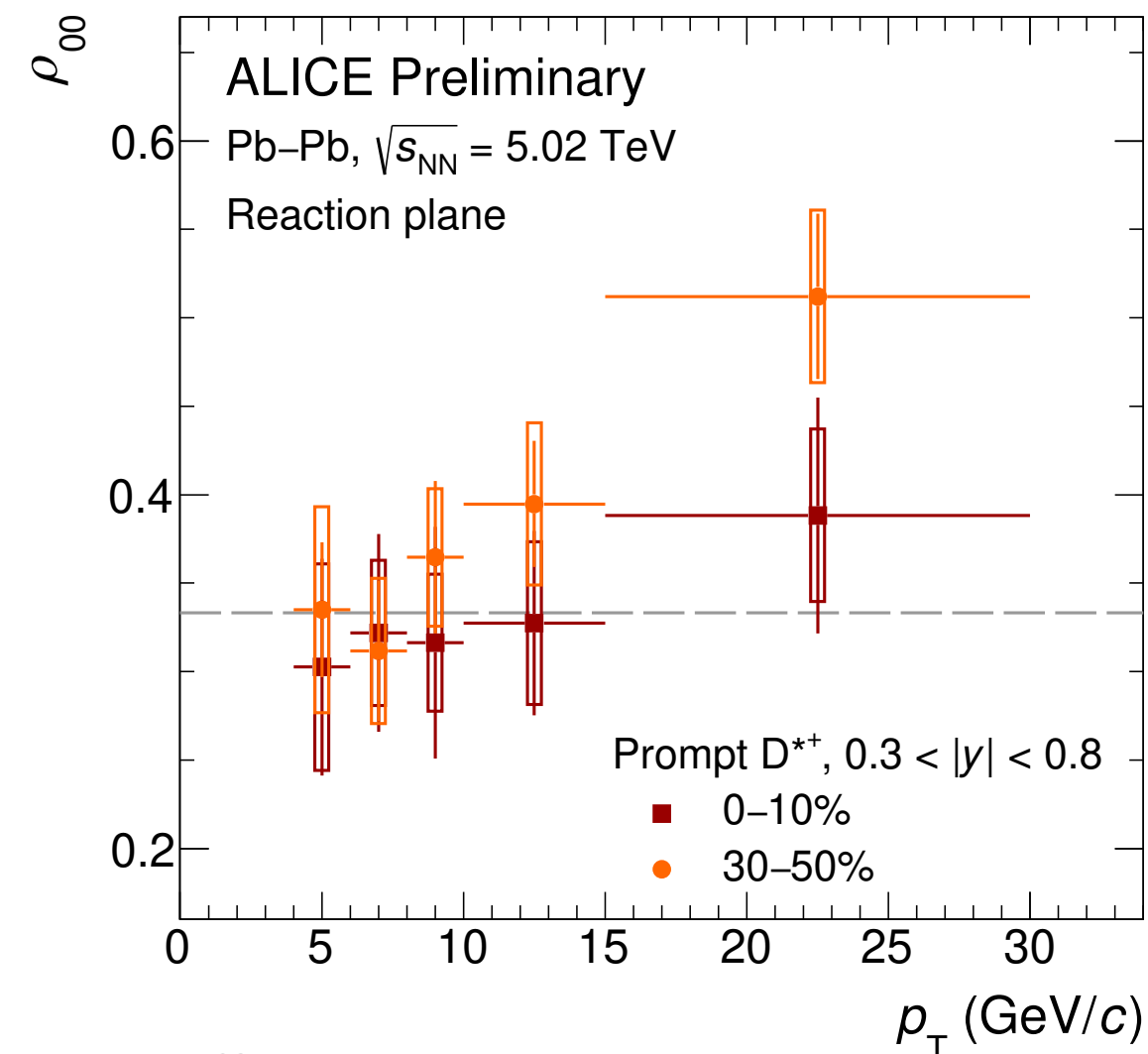
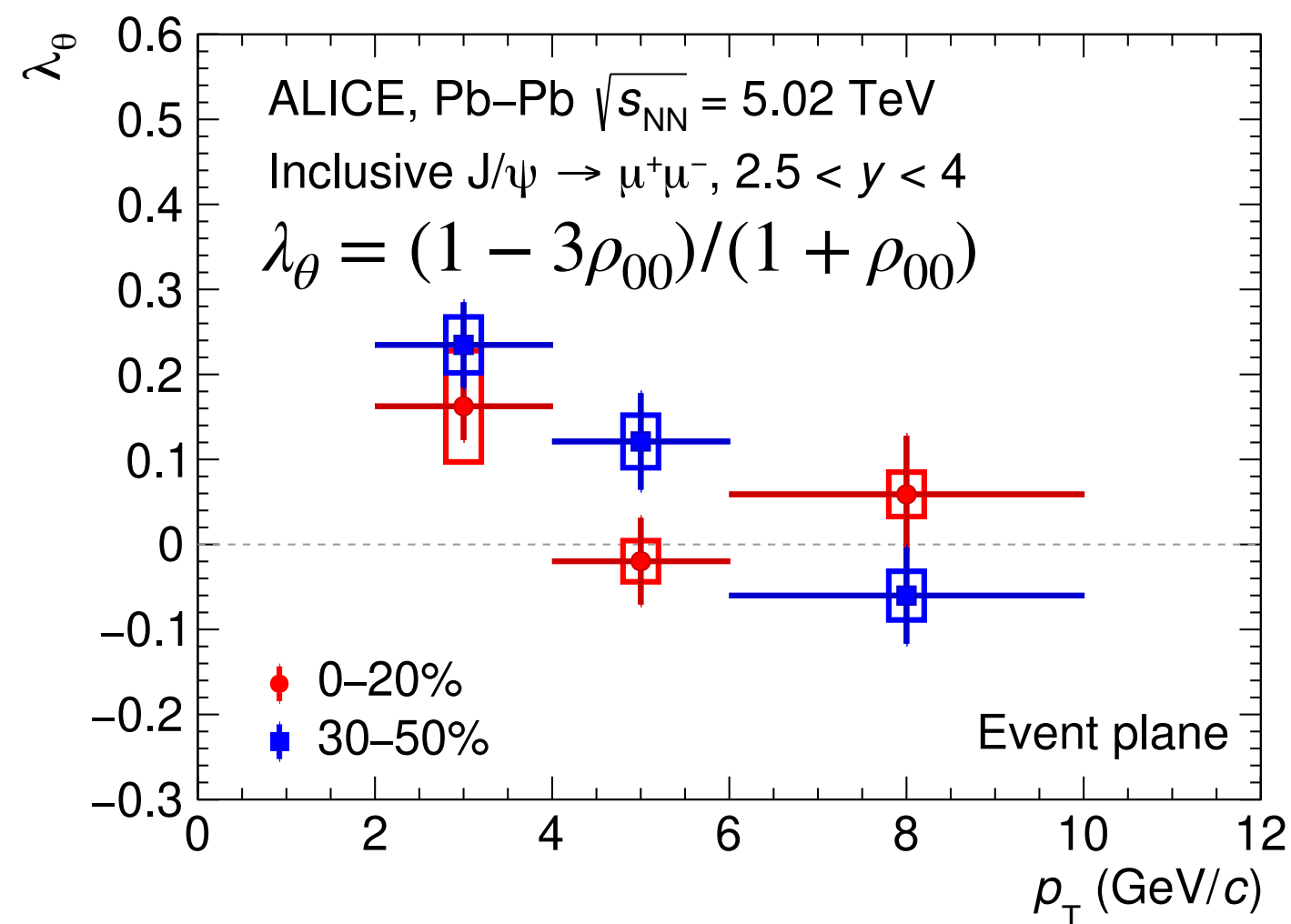


Evidence of Spin-Orbital Angular Momentum interaction

Global Spin Alignment at ALICE



ALICE, PRL 131 (2023) 4, 042303



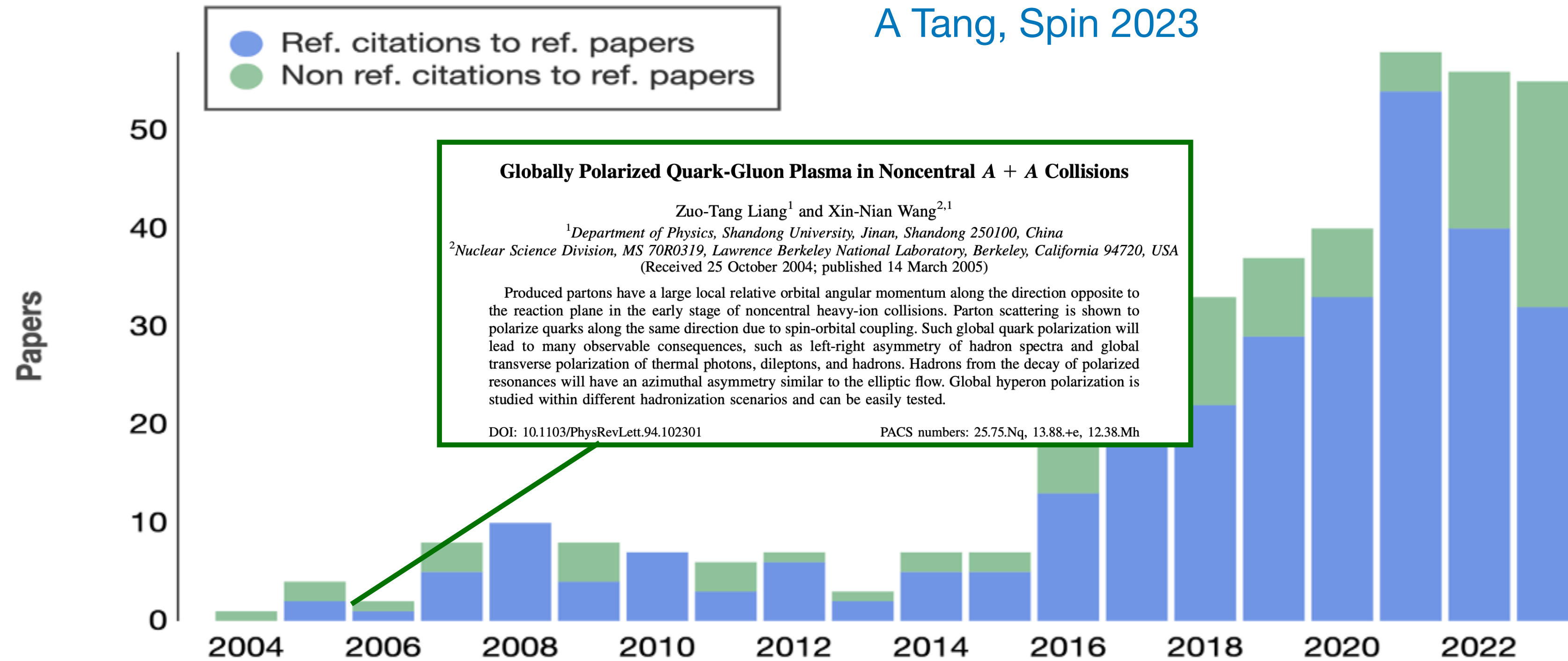
X. Bai @ QPT 2023

- Significant polarization ($\sim 3.5\sigma$) observed in semicentral collisions (40-60%) in $2 < p_T < 6$ GeV/c
- The significance of the polarization reaches $\sim 3.9\sigma$ at low p_T ($2 < p_T < 4$ GeV/c) in 30-50%
- 0-10% : ρ_{00} compatible with $1/3$,
30-50%: $\rho_{00} > 1/3$ at high p_T
- Significant deviation at larger rapidity than at midrapidity

Theory guidance needed!

How Did We Get Here?

A Tang, Spin 2023



Contribution of Chinese facilities at high baryon density?

↑ Z-T Liang and X-N Wang
PRL 94 102301 (2005)

↑ 1st experimental attempt
STAR, PRC 76 024915 (2007)

↑ ALICE, HADES ...

↑ 1st significant signal of P_{Λ}
STAR, Nature 548 62 (2017)

↑ ALICE PRC 101(4)044611
HADES EPJ Web Conf. 259 11016 ...

↑ Significant signal of ρ_{00}
STAR, Nature 614 244 (2023)



Not mentioned : many theory and phenomenological studies between 2004-2026

Workshop of Hyperon-Nucleon Spectrometer Physics

Tianjin, Aug 14-17, 2026

Summary

- Spin polarization opens a new avenue to investigate heavy-ion collisions
- Global hyperon polarization is observed with the order of a few percent. It represents a measure of the average value of the global quark polarization in the system
- Global vector meson spin alignment is observed with a surprisingly large pattern for ϕ -meson. It represents a local fluctuation/correlation between quark and anti-quark polarization
- Measurements of Λ spin correlations in different systems and energies are on-going, rich physics to be explored