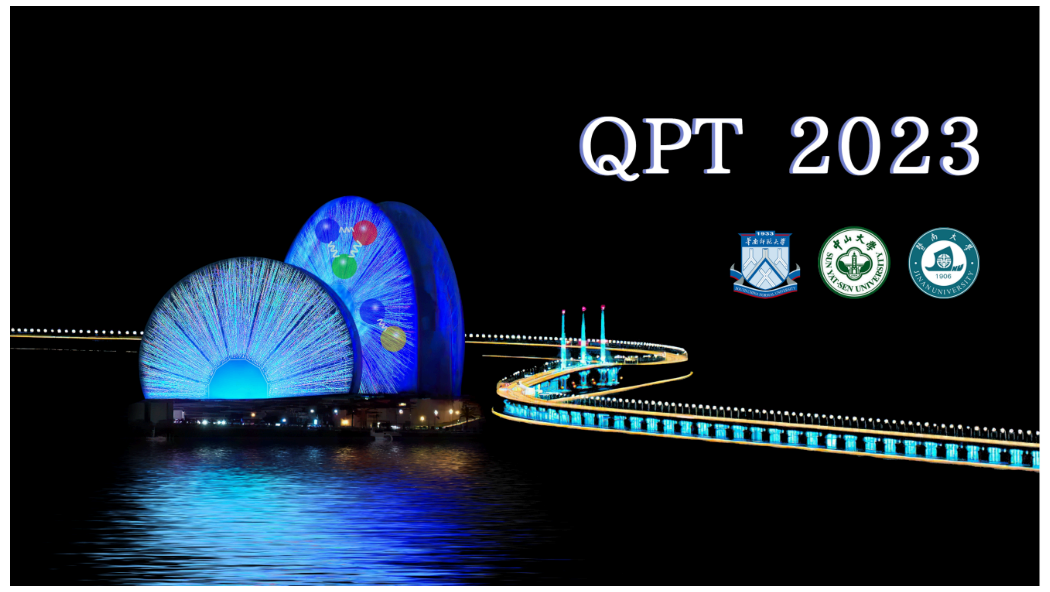


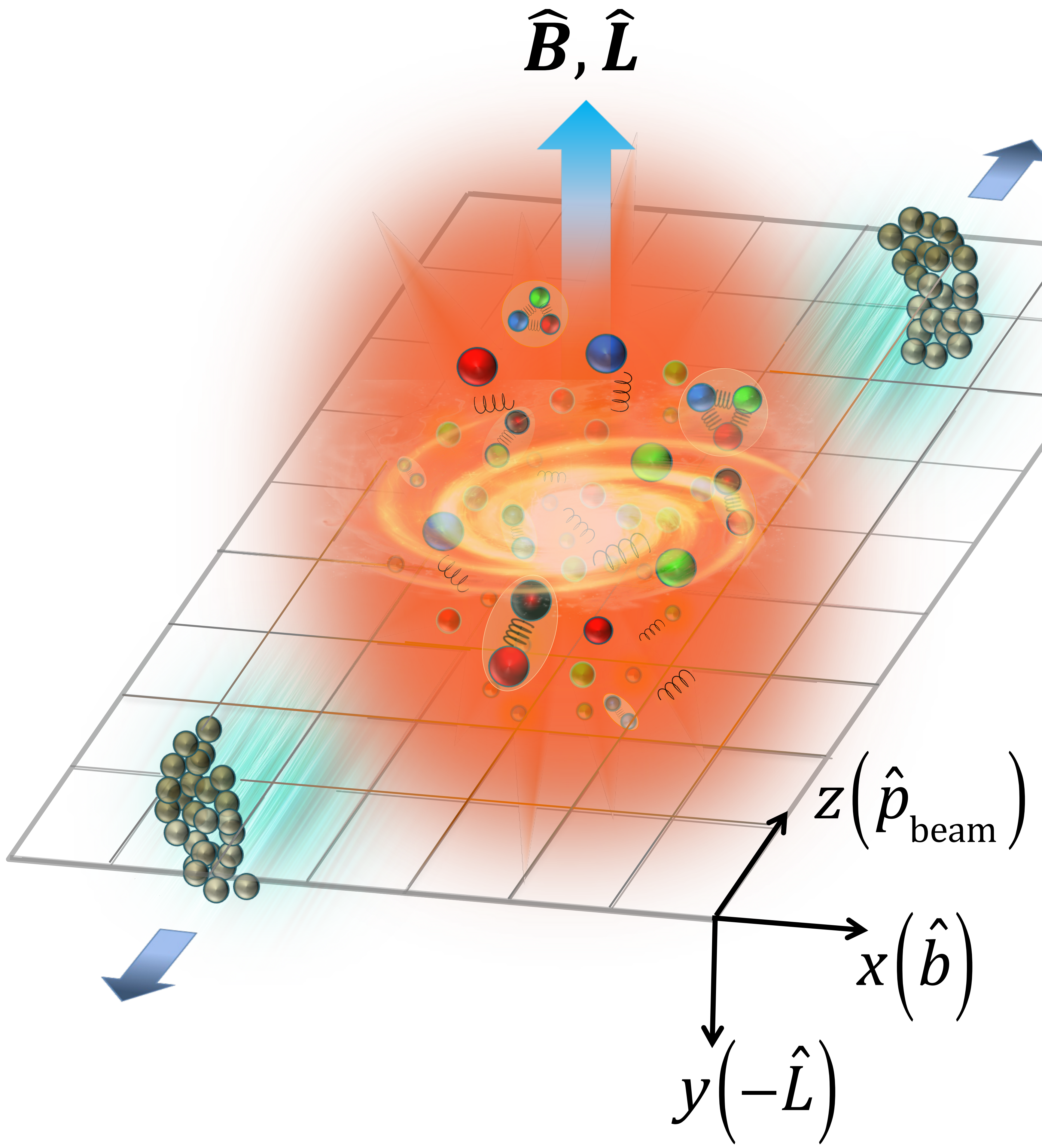
Spin Polarization in Heavy Ion Collisions

– Experimental Progress

Xu Sun

Institute of Modern Physics, Chinese Academy of Sciences

Introduction to Global Spin Polarization



- Non-central HICs have large **angular momentum and magnetic field**
- OAM ($\sim 10^4\hbar$) can polarize quarks due to "spin-orbit" interaction
- B field ($\sim 10^{18}$ Gauss) can also polarize quarks => can induce opposite spin polarization for particles and anti-particles due to opposite sign of magnetic moment
- Observerbals:
  - Λ-hyperon ($J^p = 1/2^+$) global spin polarization
  - Vector meson ($J^P = 1^-$) global spin alignment
- Provide the unique opportunity to probe the spin degrees of freedom of the QGP

How Everything Started…

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

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]
[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*
[2]*Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 25 October 2004; published 14 March 2005)

Produced partons have a large local relative orbital angular momentum along the direction opposite to the reaction plane in the early stage of noncentral heavy-ion collisions. Parton scattering is shown to polarize quarks along the same direction due to spin-orbital coupling. Such global quark polarization will lead to many observable consequences, such as left-right asymmetry of hadron spectra and global transverse polarization of thermal photons, dileptons, and hadrons. Hadrons from the decay of polarized resonances will have an azimuthal asymmetry similar to the elliptic flow. Global hyperon polarization is studied within different hadronization scenarios and can be easily tested.

DOI: 10.1103/PhysRevLett.94.102301 PACS numbers: 25.75.Nq, 13.88.+e, 12.38.Mh

Spin alignment of vector mesons in non-central $A + A$ collisions

Zuo-Tang Liang [a], Xin-Nian Wang [a,b]
[a] *Department of Physics, Shandong University, Jinan, Shandong 250100, China*
[b] *Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Received 13 December 2004; received in revised form 21 August 2005; accepted 15 September 2005
Available online 3 October 2005
Editor: J.-P. Blaizot

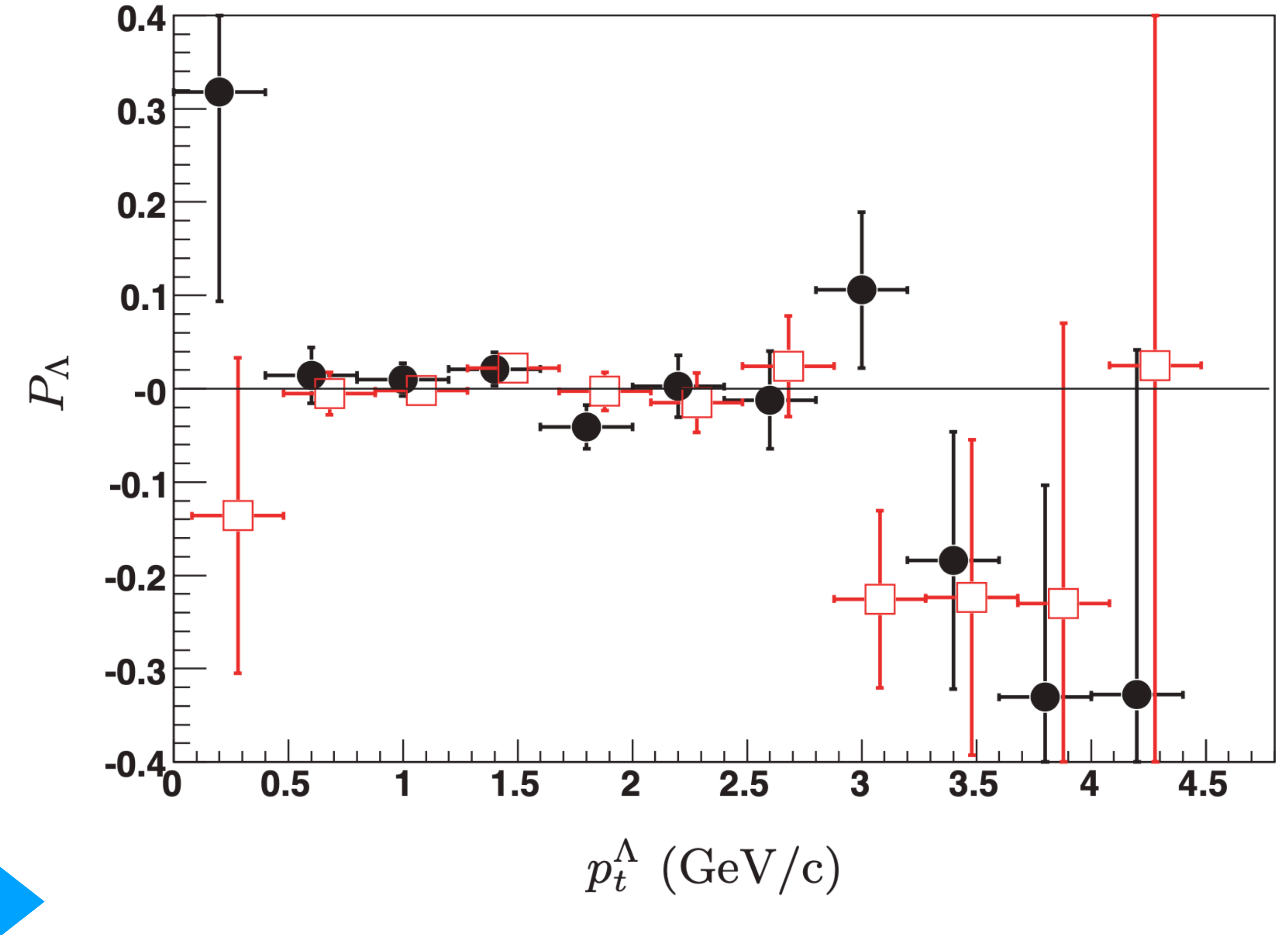
Abstract

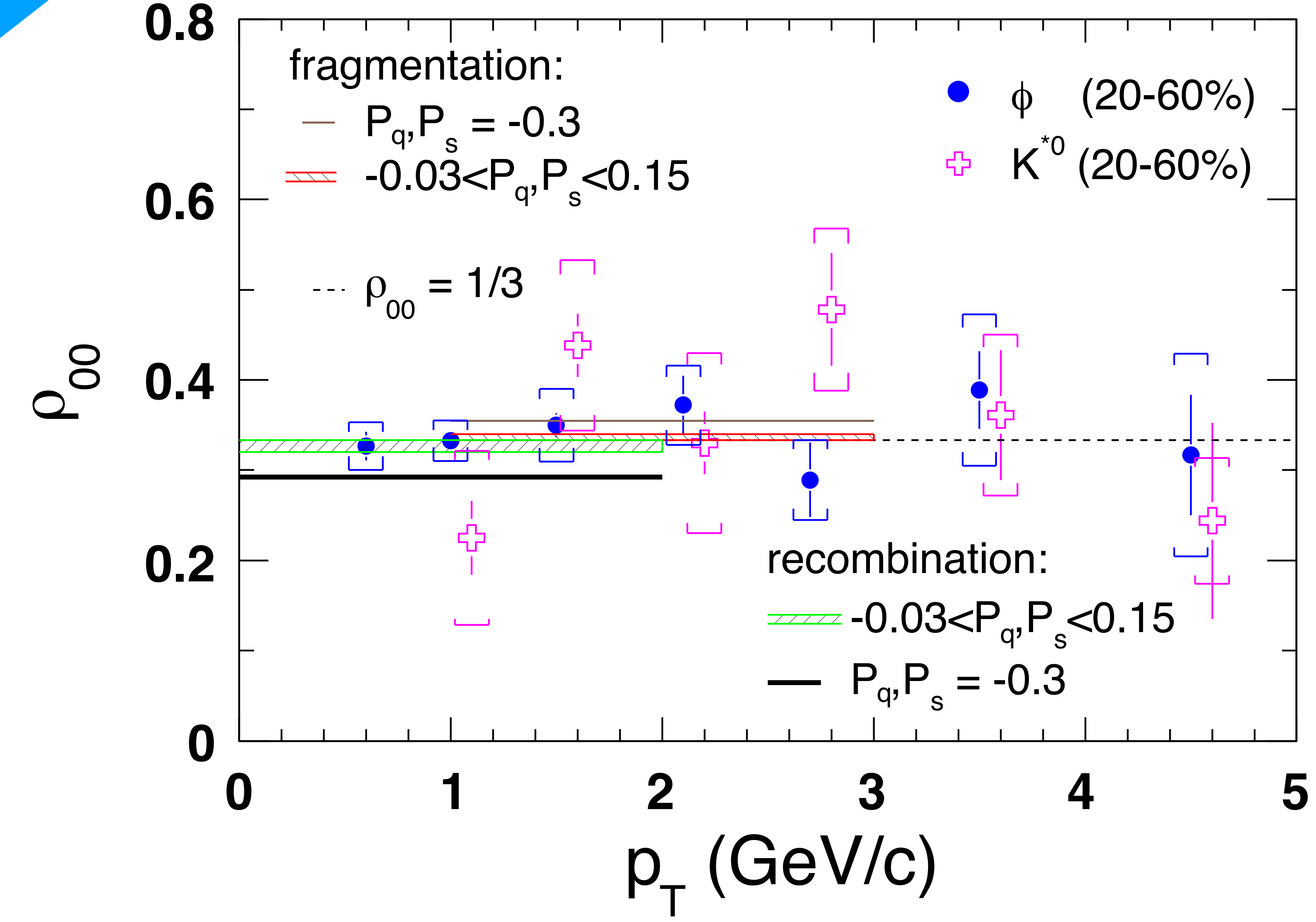
We discuss the consequence of global polarization of the produced quarks in non-central heavy-ion collisions on the spin alignment of vector mesons. We show that the alignment is quite different for different hadronization scenarios. These results can be tested directly by measuring the vector mesons' alignment through angular distributions of the decay products with respect to the reaction plane. Such angular distributions will give rise to azimuthal anisotropy v_2 of the decay products in the collision frame. Constraints provided by the data on the azimuthal anisotropy of hadron spectra at RHIC points to a quark recombination scenario of hadronization.

PACS: 25.75.-q; 13.88.+e; 12.38.Mh; 25.75.Nq

1st Attempt

STAR, PRC 76, 024915 (2007)

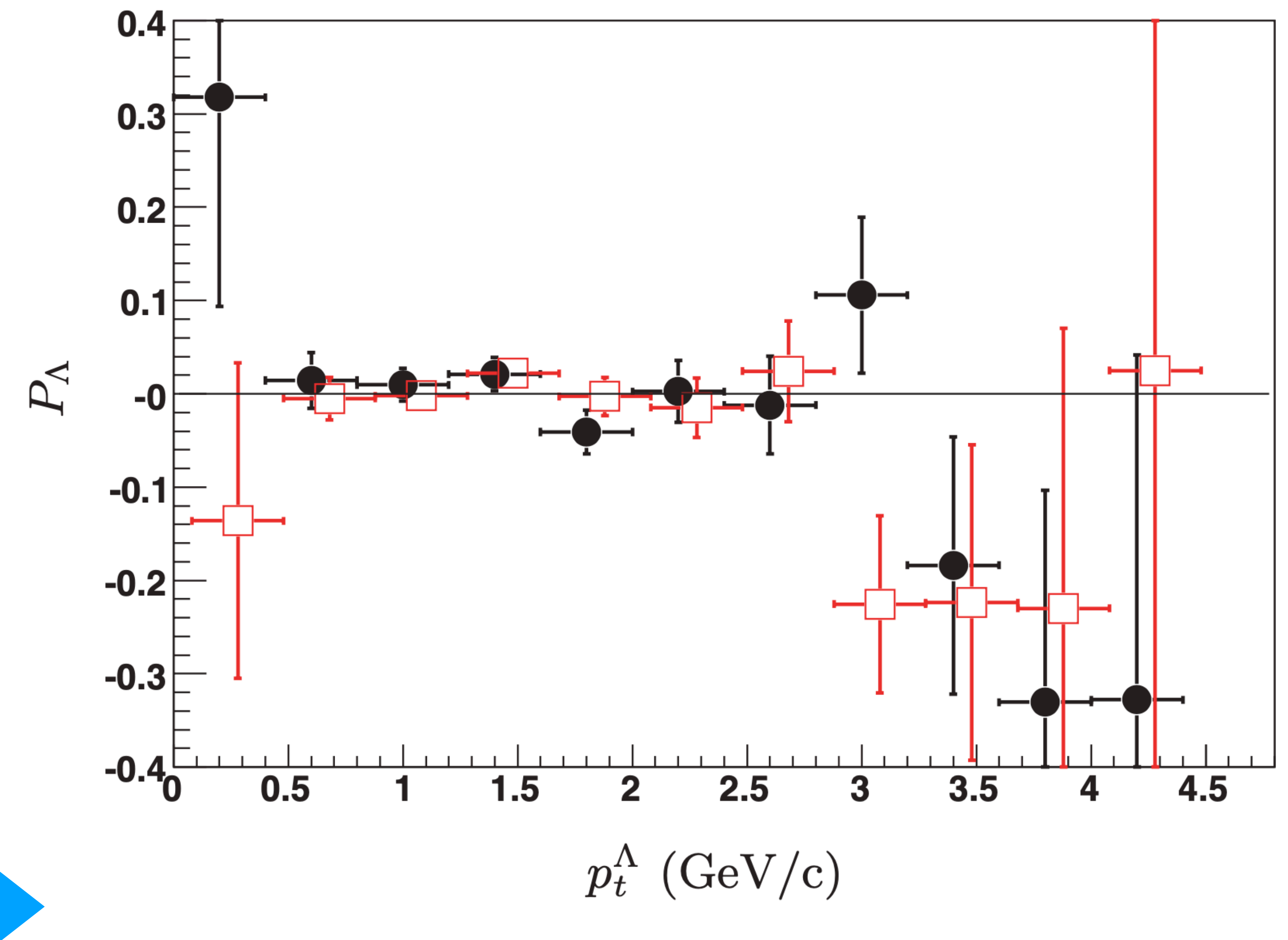




STAR, PRC 77, 061902(R) (2008)

How Everything Started…

STAR, PRC 76, 024915 (2007)



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

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]

[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*

[2]*Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

(Received 25 October 2004; published 14 March 2005)

Produced partons have a large local relative orbital angular momentum along the direction opposite to the reaction plane in the early stage of noncentral heavy-ion collisions. Parton scattering is shown to polarize quarks along the same direction due to spin-orbital coupling. Such global quark polarization will lead to many observable consequences, such as left-right asymmetry of hadron spectra and global transverse polarization of thermal photons, dileptons, and hadrons. Hadrons from the decay of polarized resonances will have an azimuthal asymmetry similar to the elliptic flow. Global hyperon polarization is studied within different hadronization scenarios and can be easily tested.

DOI: 10.1103/PhysRevLett.94.102301 PACS numbers: 25.75.Nq, 13.88.+e, 12.38.Mh

1st Attempt

Spin alignment of vector mesons in non-central $A + A$ collisions

Zuo-Tang Liang [a], Xin-Nian Wang [a,b]

[a] *Department of Physics, Shandong University, Jinan, Shandong 250100, China*

[b] *Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Received 13 December 2004; received in revised form 21 August 2005; accepted 15 September 2005

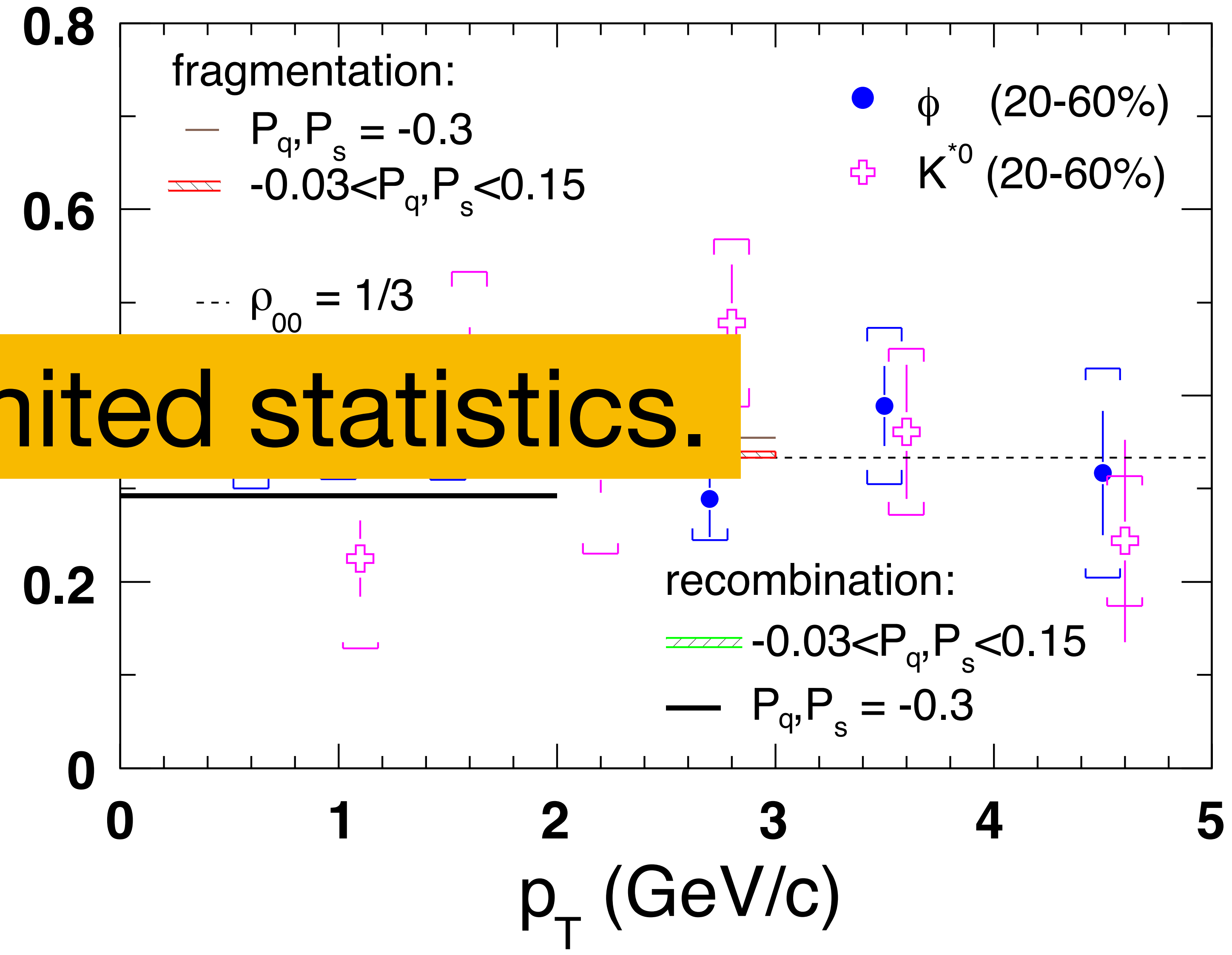
Available online 3 October 2005

No significant results reported, due to limited statistics.

Abstract

We discuss the consequence of global polarization of the produced quarks in non-central heavy-ion collisions on the spin alignment of vector mesons. We show that the alignment is quite different for different hadronization scenarios. These results can be tested directly by measuring the vector mesons' alignment through angular distributions of the decay products with respect to the reaction plane. Such angular distributions will give rise to azimuthal anisotropy v_2 of the decay products in the collision frame. Constraints provided by the data on the azimuthal anisotropy of hadron spectra at RHIC points to a quark recombination scenario of hadronization.

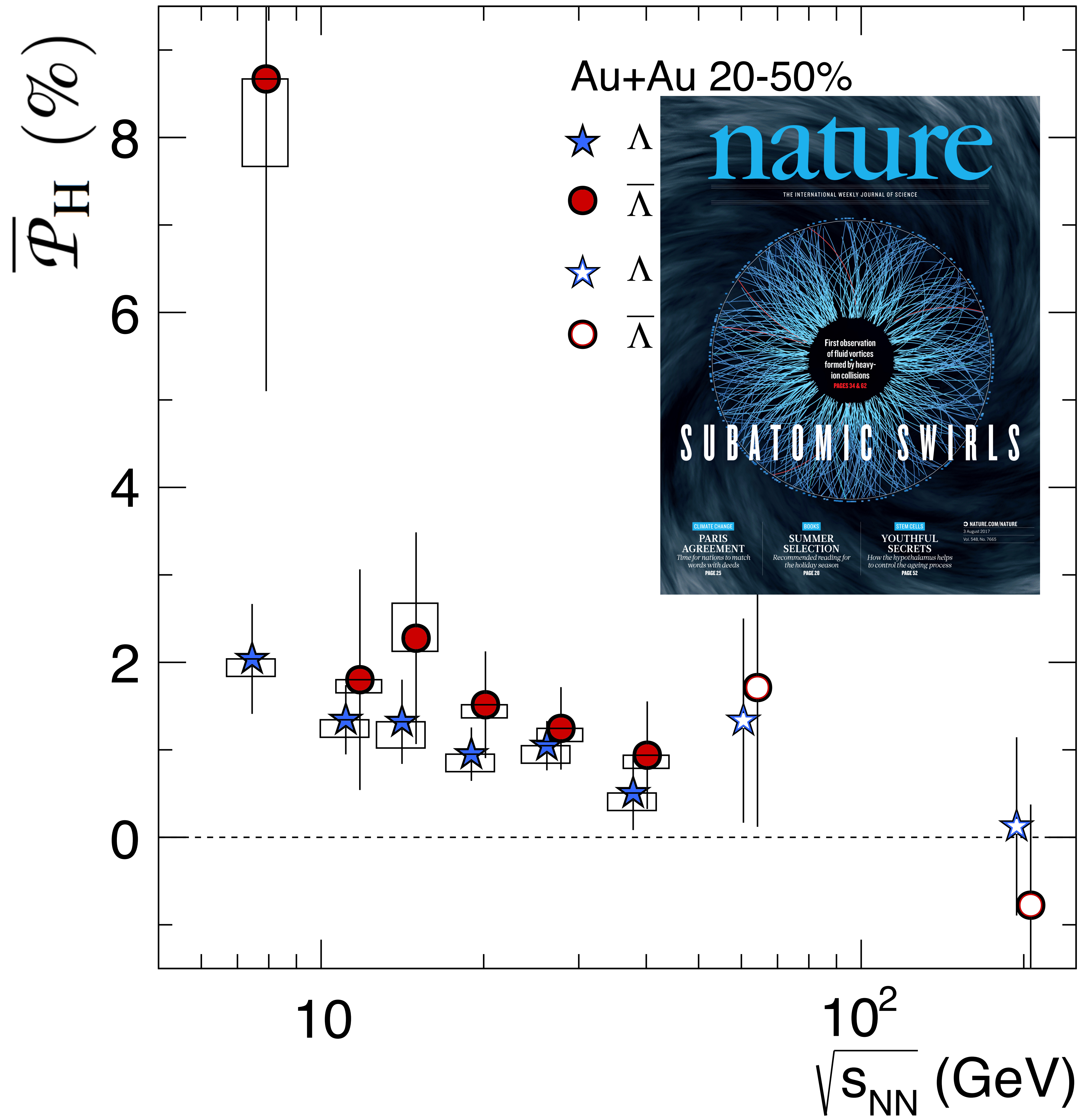
PACS: 25.75.-q; 13.88.+e; 12.38.Mh; 25.75.Nq



STAR, PRC 77, 061902(R) (2008)

Λ Global Polarization

STAR, Nature 548, 62 (2017)



Parity-violating weak decay of hyperons ("self-analyzing")

$$\Lambda(uds) \rightarrow p + \pi^-$$

Daughter baryon is preferentially emitted in the direction of hyperon's spin (opposite for anti-particle)

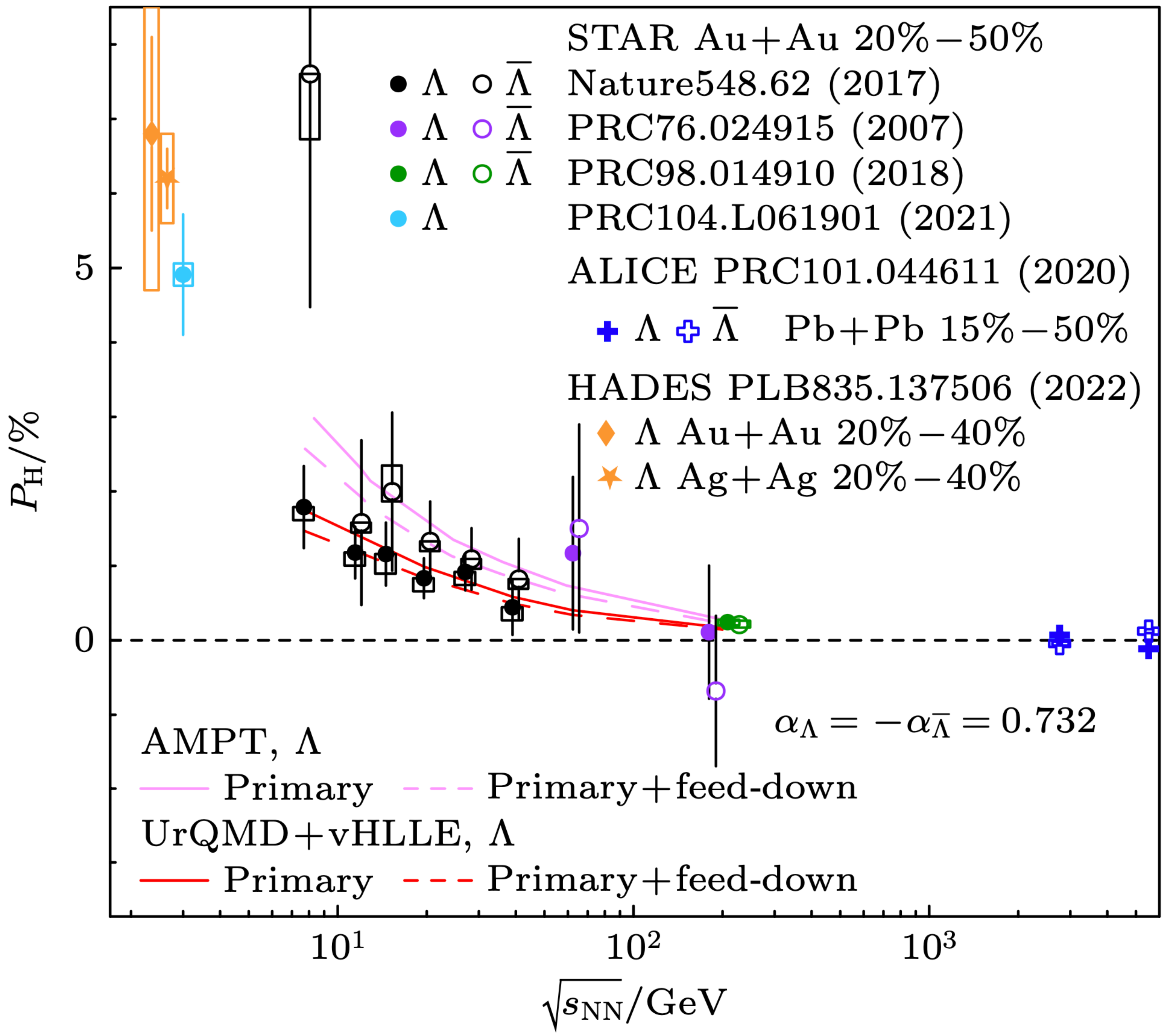
$$\frac{dN}{dcos\theta*} \sim 1 + \alpha_H P_H cos\theta*$$

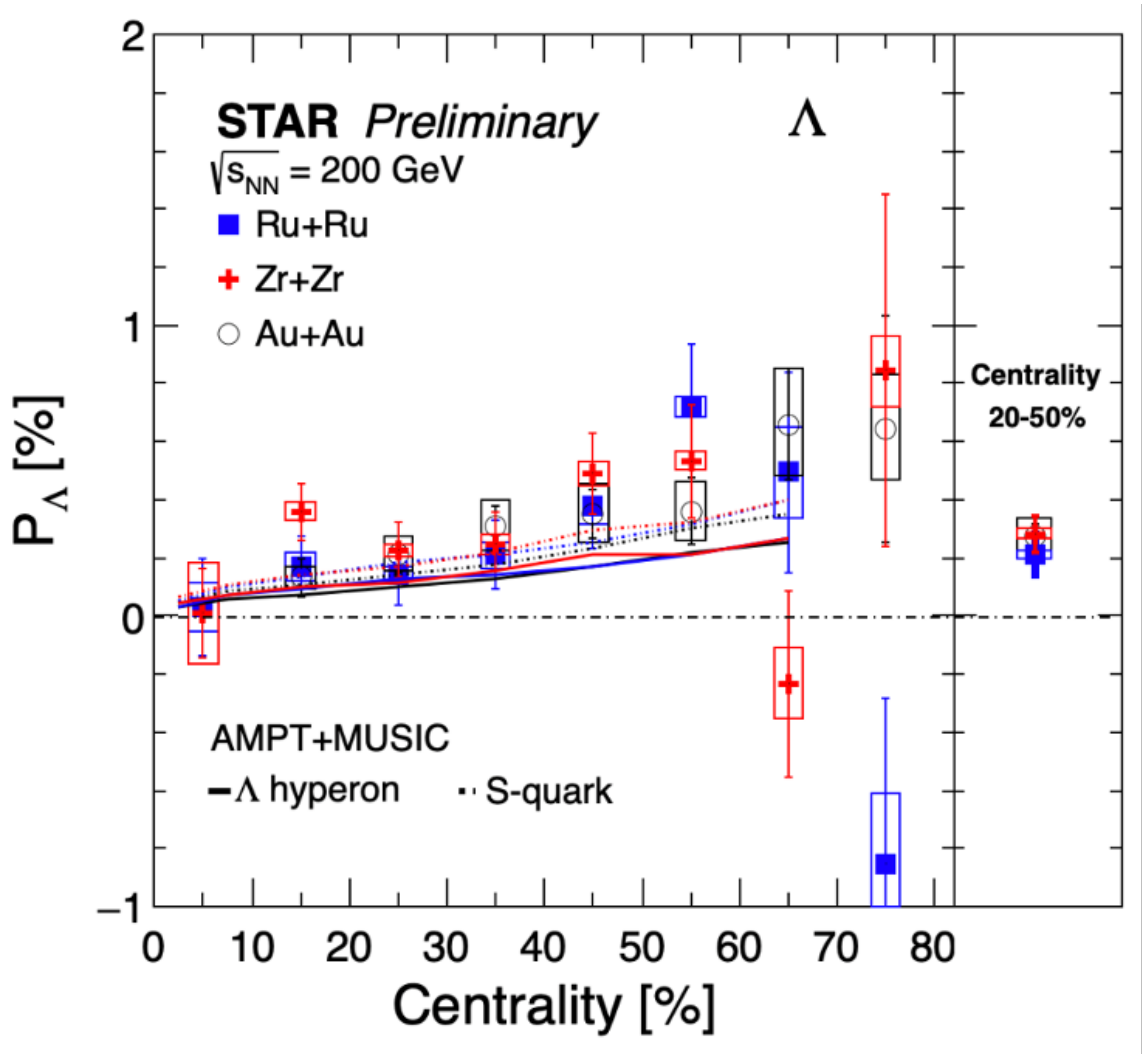
$$\omega = k_B T(P_\Lambda + P_{\bar{\Lambda}})/\hbar \sim 10^{22} s^{-1}$$

Most Vortical Fluid!

Λ Global Polarization

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

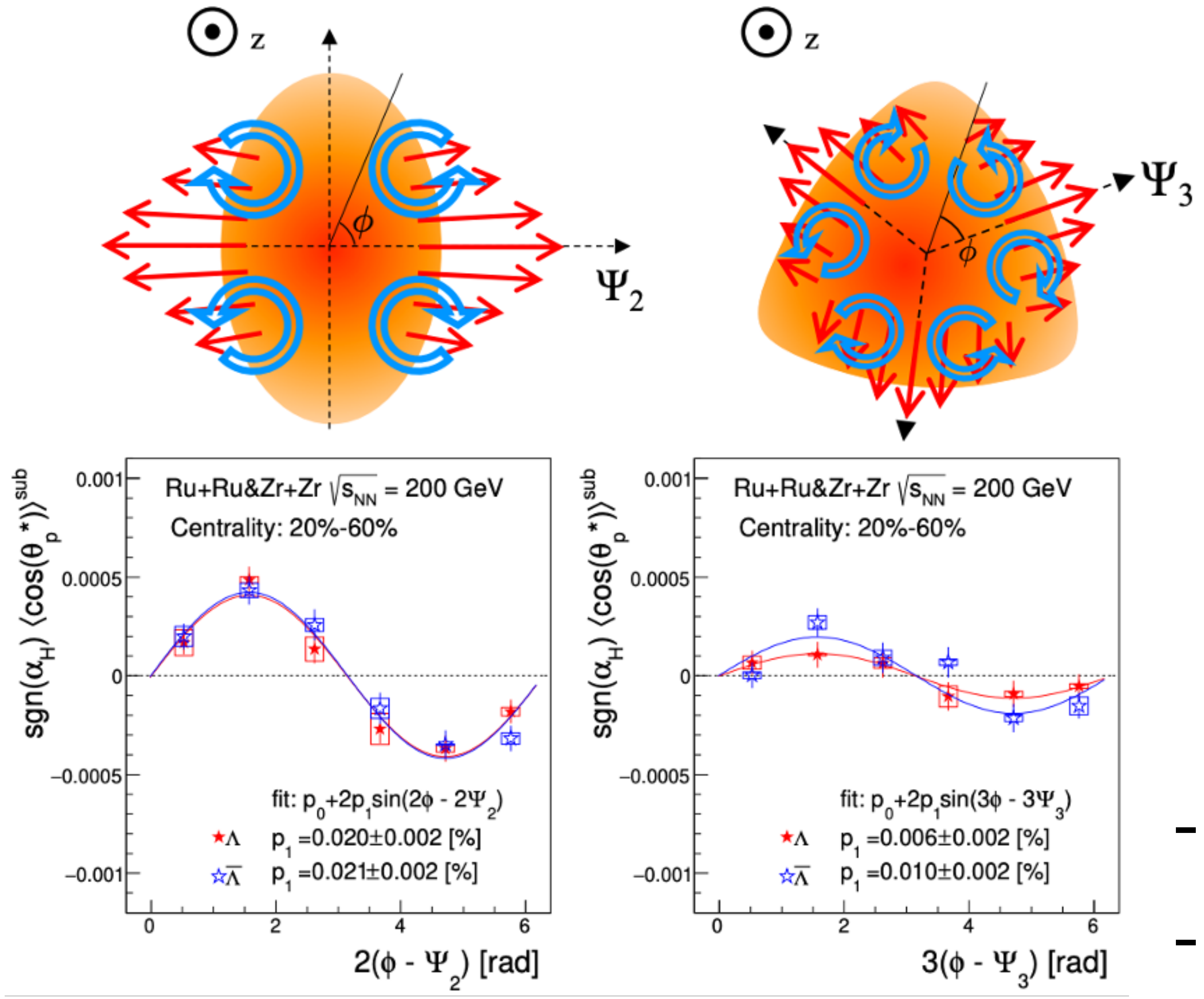




X. Gou for STAR, QPT 2023, Sun 15:20

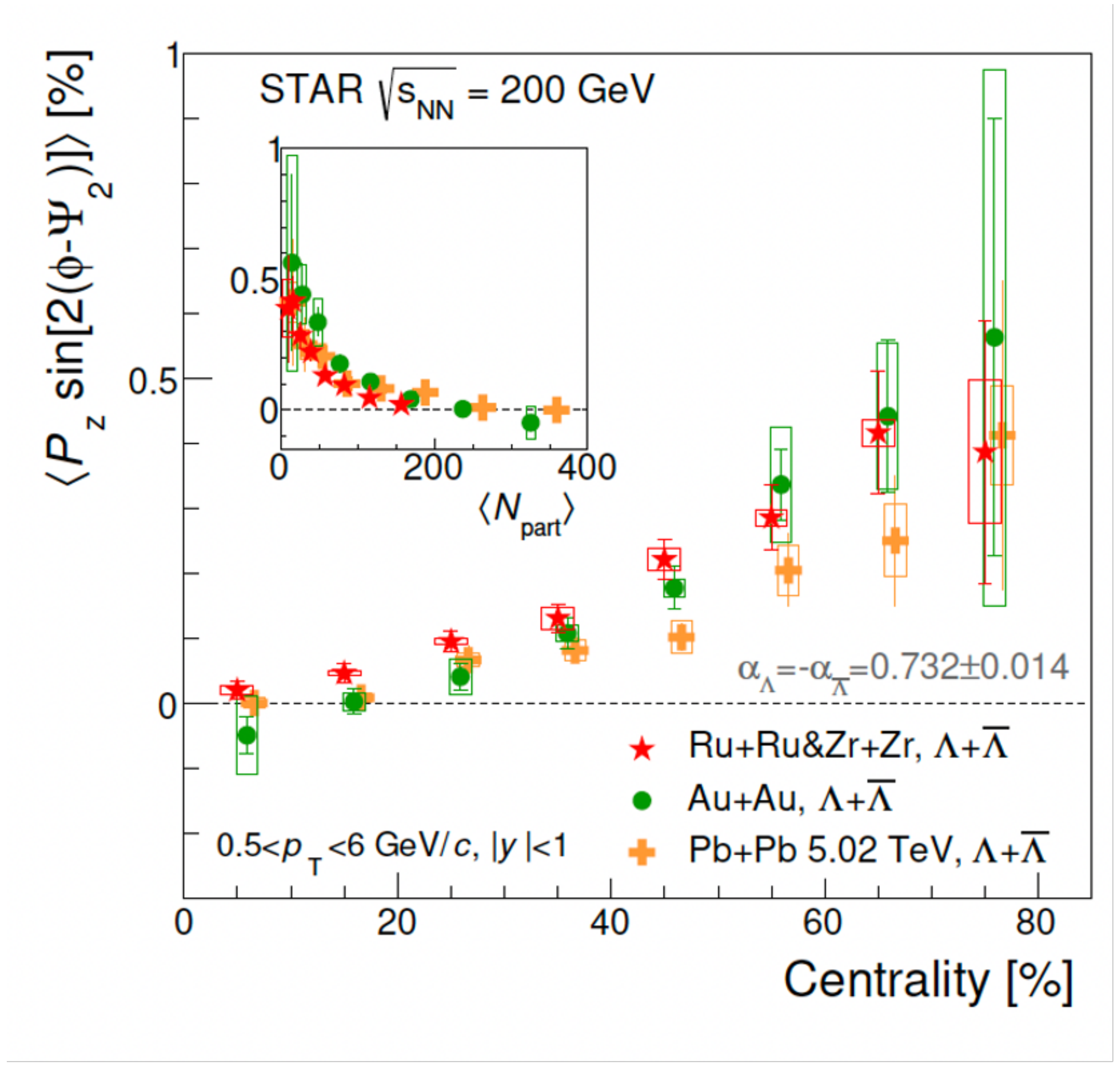
- Significant global polarization of Λ and $\bar{\Lambda}$ observed at RHIC FXT and HADES
- Global polarization of Λ and $\bar{\Lambda}$ are consistent in isobar and Au+Au collision systems

Λ Local Polarization



X. Gou for STAR, QPT 2023, Sun 15:20

STAR, PRL 131 (2023) 202301



- Significant local polarization w.r.t 2nd & 3rd-order event plane observed in isobar collisions
- Energy dependence is not obvious between 200 GeV Au+Au and 5.02 TeV Pb+Pb collisions

Spin Hall Effect

Spin Hall Effect in Condensed matter: $P \propto \pm p \times E$

Electric filed (E) → Spin-Orbit Interaction → Spin splitting in opposite directions

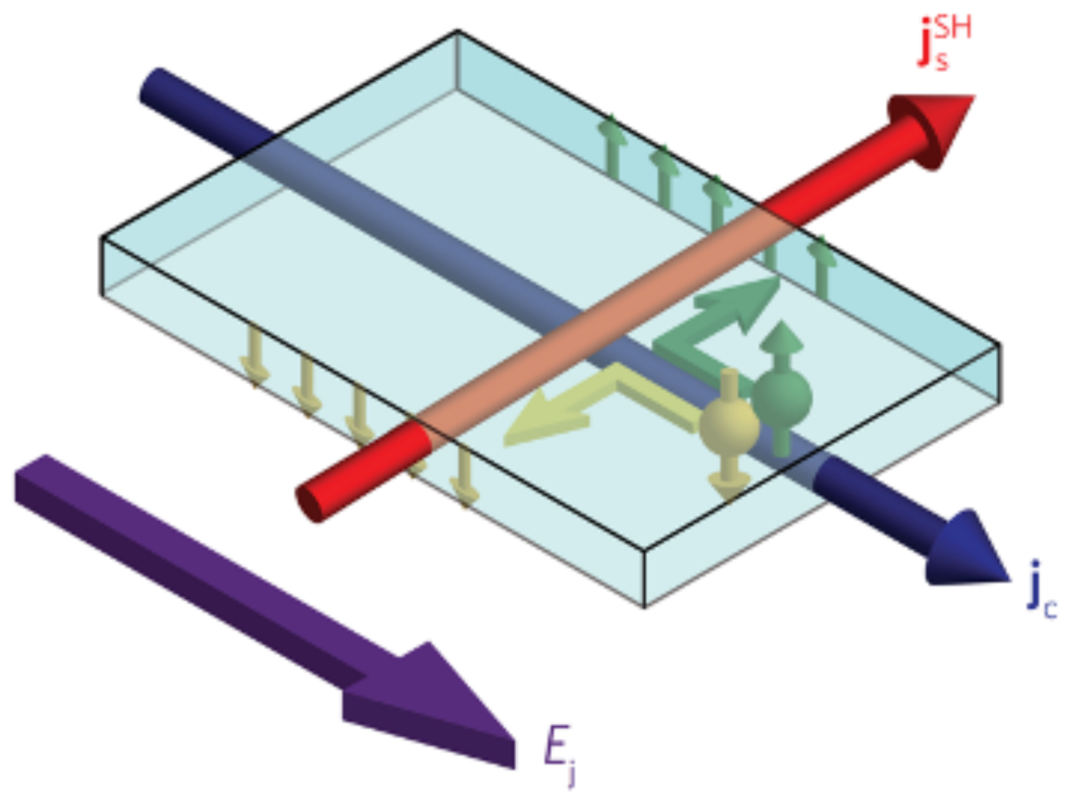
Spin Hall Effect in hot QCD matter: $P \propto \pm p \times \nabla \mu_B$

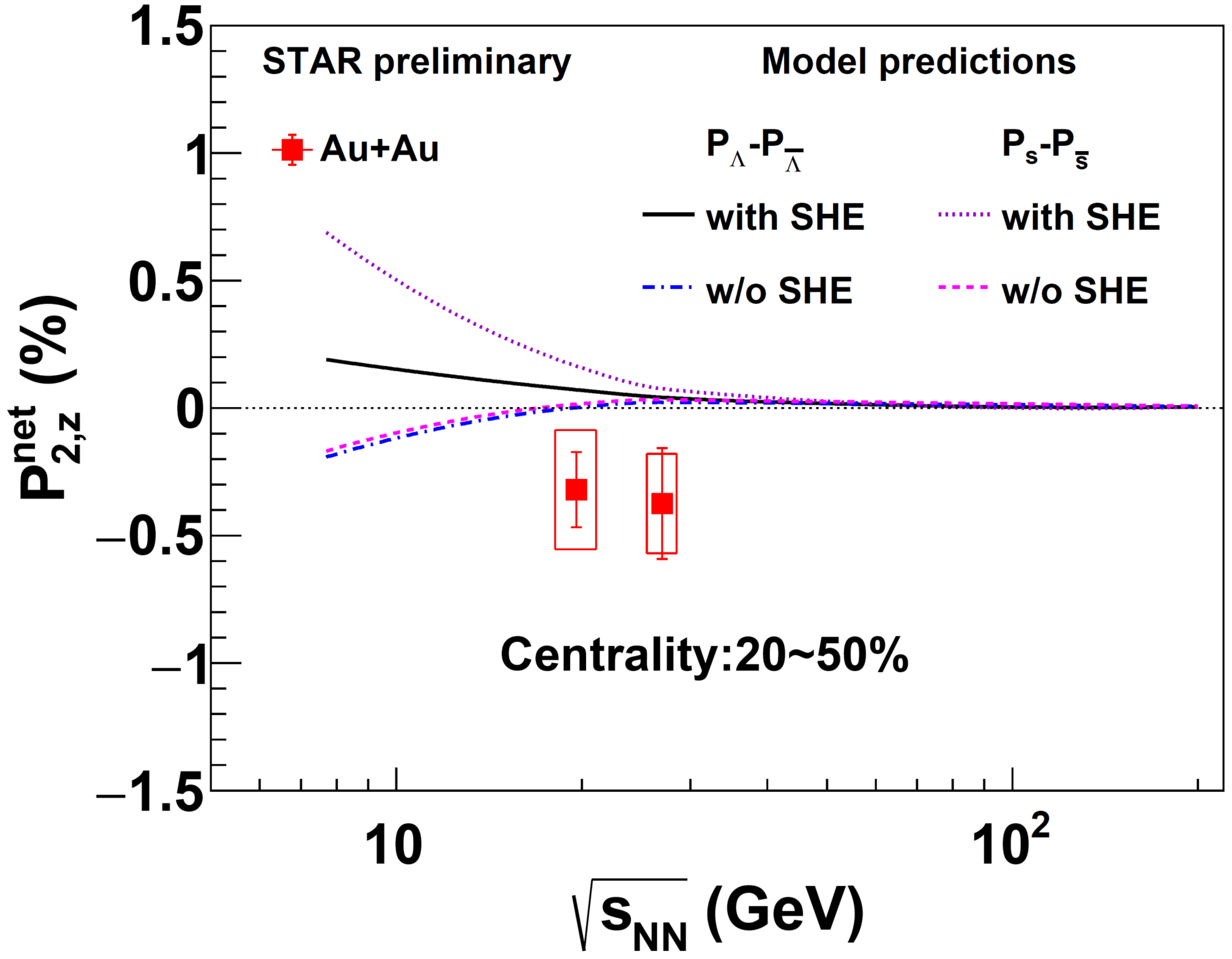
Baryon density gradient ($\nabla \mu_B$) → Spin-Orbit Interaction → Spin splitting between Λ & $\bar{\Lambda}$ local spin polarization

$$P^{net}_{2,z} = \left\langle P^{net}_{Z}(\phi) sin2\phi \right\rangle \qquad P^{net}_{z}(\phi) = P^{\Lambda}_{Z}(\phi) - P^{\bar{\Lambda}}_{Z}(\phi)$$

S. Y.F. Liu and Y. Yin PRD 104 054043 (2021)
S. Ryu, V. Jupic and C.Shen PRC 104 054908 (2021)
X-Y Wu, C. Yi, G-Y Qin and S. Pu PRC 105 064909 (2022)
B.Fu, L-G Pang, H. Song and Y. Yin arXiv 2201.12970 (2022)
Q. Hu for STAR, Chirality 2023, Beijing.

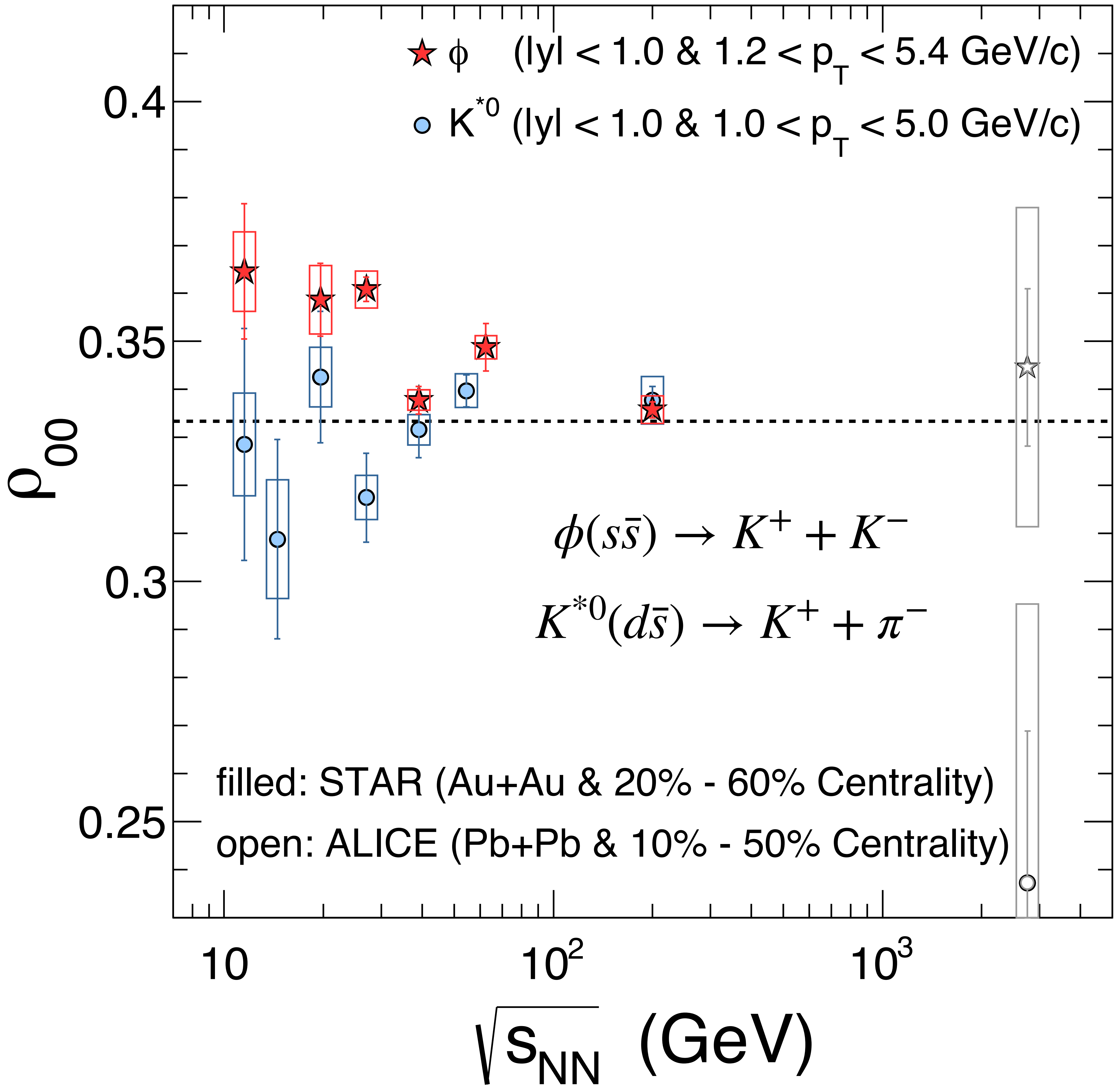
Possible detection at BESII energies!

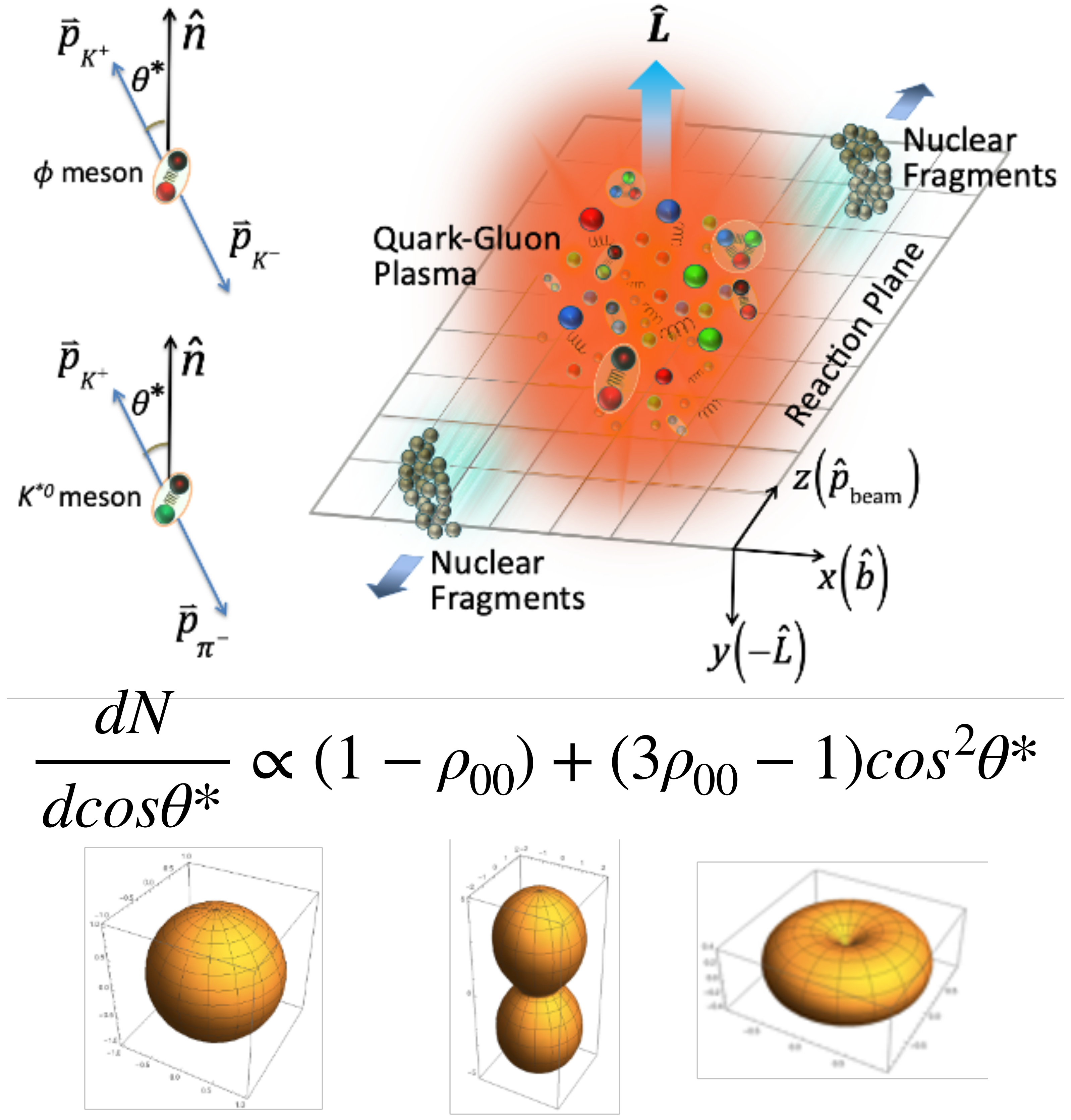




Global Spin Alignment at STAR

STAR, Nature 614, 233-248 (2023)





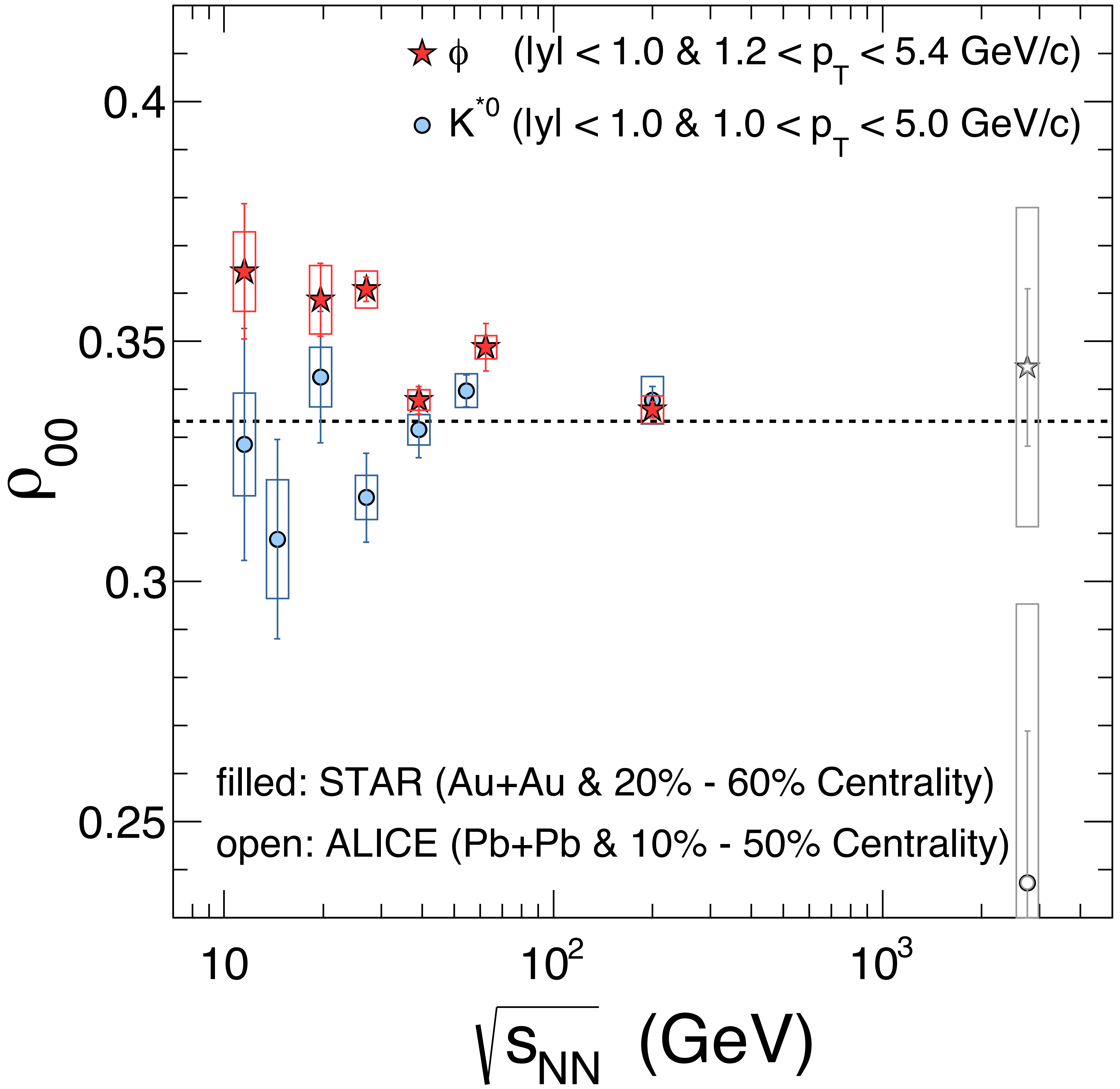
$$\frac{dN}{dcos\theta^*} \propto (1-\rho_{00}) + (3\rho_{00}-1)cos^2\theta^*$$

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

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

Global Spin Alignment at STAR

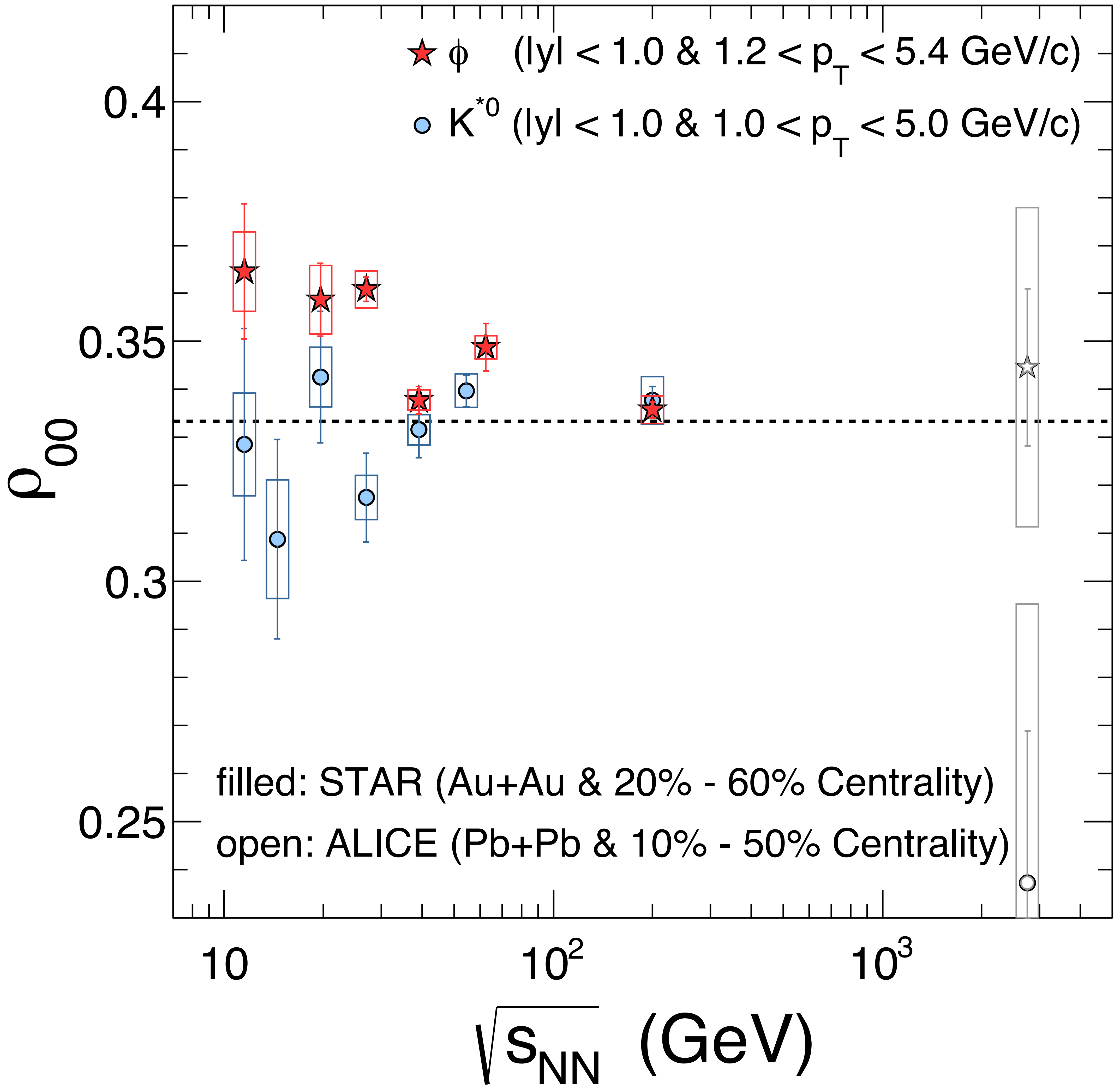
STAR, Nature 614, 233-248 (2023)



1. Liang et., al., Phys. Lett. B 629, (2005);
   Yang et., al., Phys. Rev. C 97, 034917 (2018);
   Xia et., al., Phys. Lett. B 817, 136325 (2021);
   Beccattini et., al., Phys. Rev. C 88, 034905 (2013)
2. Sheng et., al., Phys. Rev. D 101, 096005 (2020);
   Yang et., al., Phys. Rev. C 97, 034917 (2018)
3. Liang et., al., Phys. Lett. B 629, (2005)
4. Xia et., al., Phys. Lett. B 817, 136325 (2021);
   Gao, Phys. Rev. D 104, 076016 (2021)
5. Muller et., al., Phys. Rev. D 105, L011901 (2022)
6. Sheng et., al., Phys. Rev. D 101, 096005 (2020);
   Phys. Rev. D 102, 056013 (2020);
   Phys Rev. Lett. 131, 042304 (2023); arXiv:2206.05868 (2022)
7. A. Kumar, B. Muller and D.-L Yang, PRD 108 016020 (2023)

Global Spin Alignment at STAR

STAR, Nature 614, 233-248 (2023)

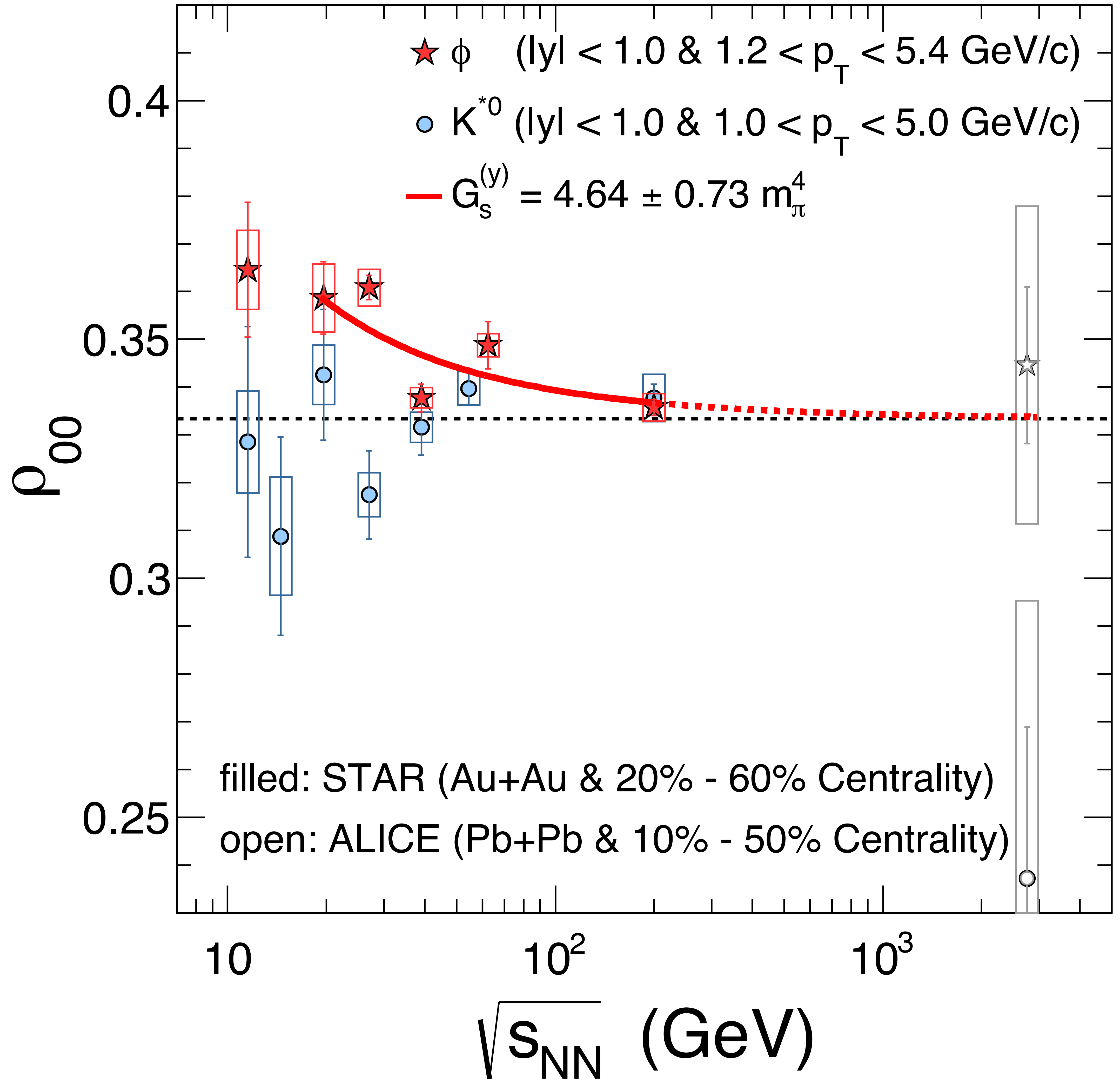


$$\rho_{00}(\phi) = \frac{1}{3} + C_\Lambda + C_\epsilon + C_E + C_F + C_L + C_A + C_\phi + C_g$$

Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: E-comp. of Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
c_F: Fragmentation[3]	> or, < 1/3 (~ 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

Global Spin Alignment at STAR

STAR, Nature 614, 233-248 (2023)

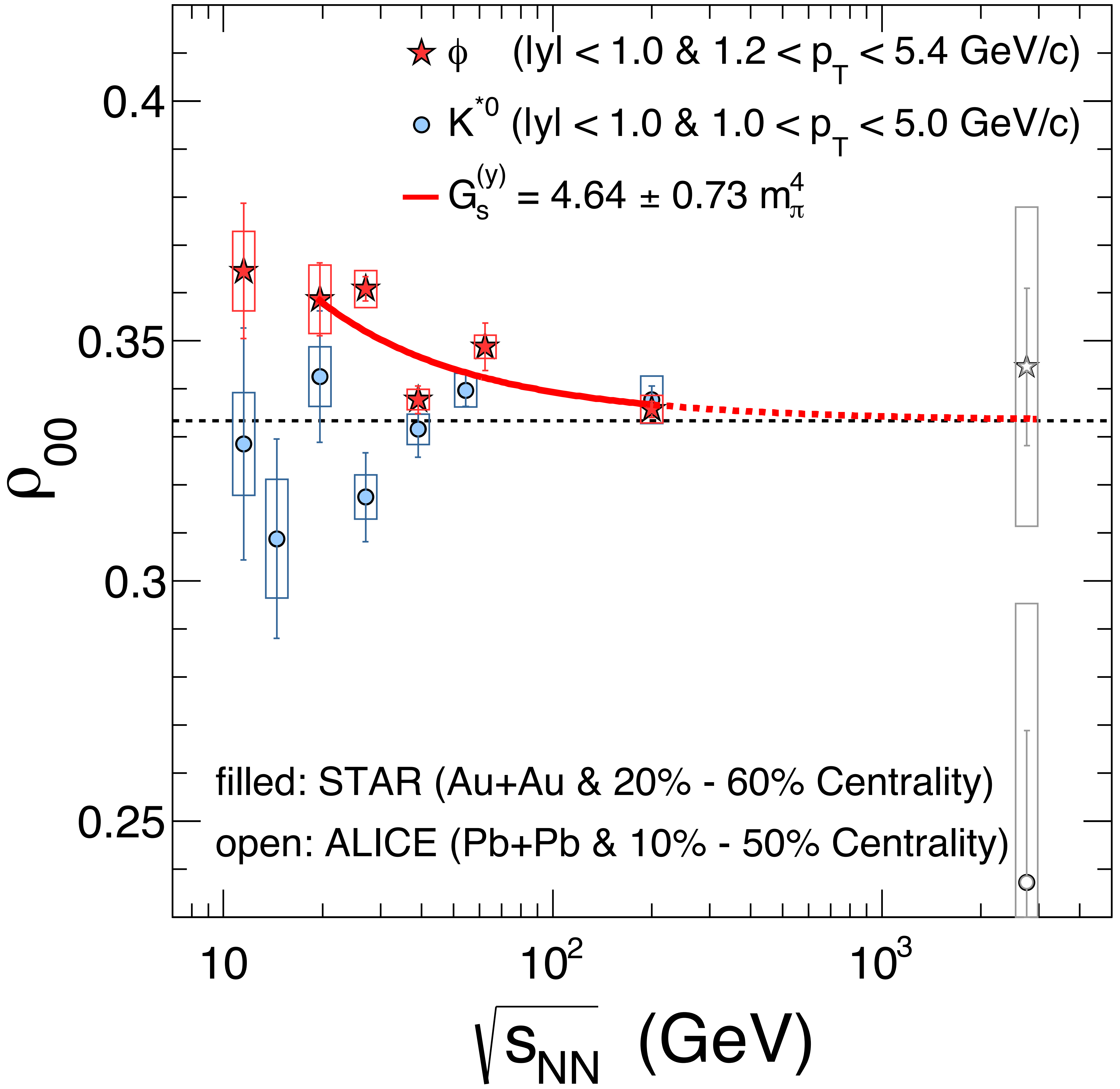


$$\rho_{00}(\phi) = \frac{1}{3} + C_\Lambda + C_\epsilon + C_E + C_F + C_L + C_A + C_\phi + C_g$$

Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: E-comp. of Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
c_F: Fragmentation[3]	> or, < 1/3 (~ 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

Global Spin Alignment at STAR

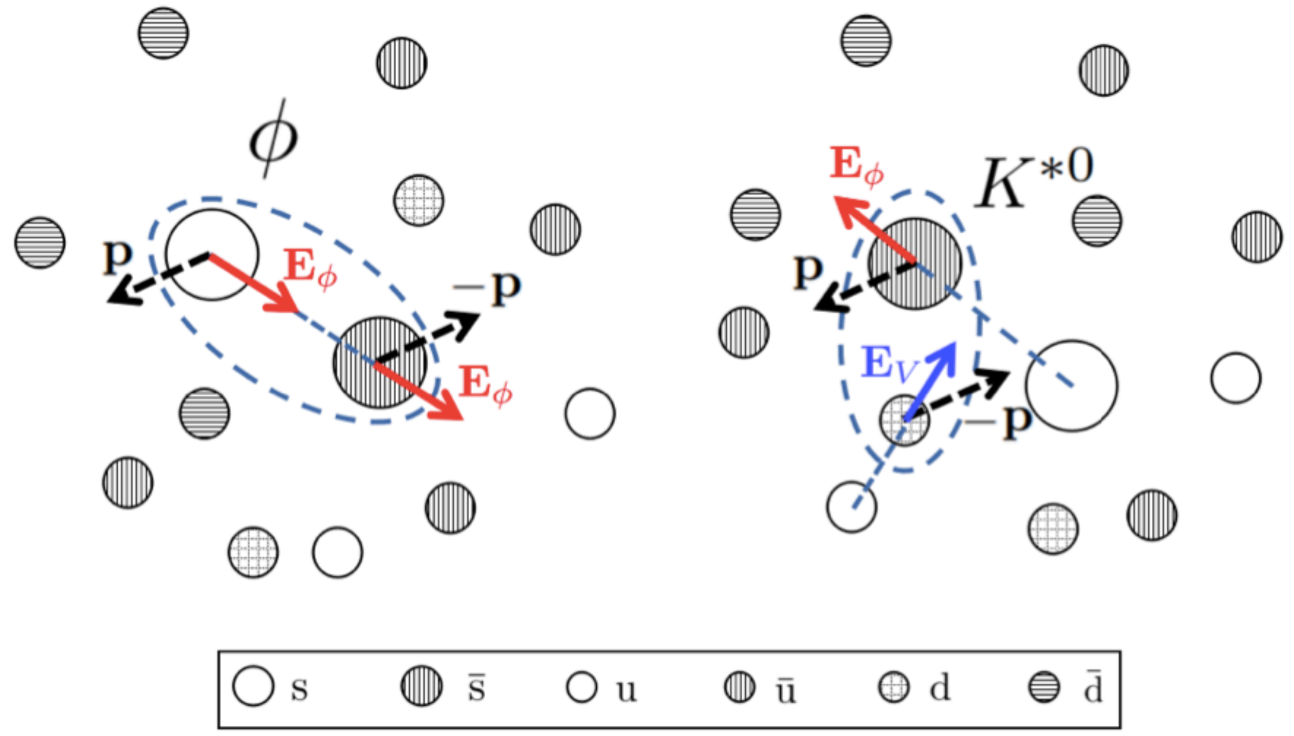
STAR, Nature 614, 233-248 (2023)



What do we learn?

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

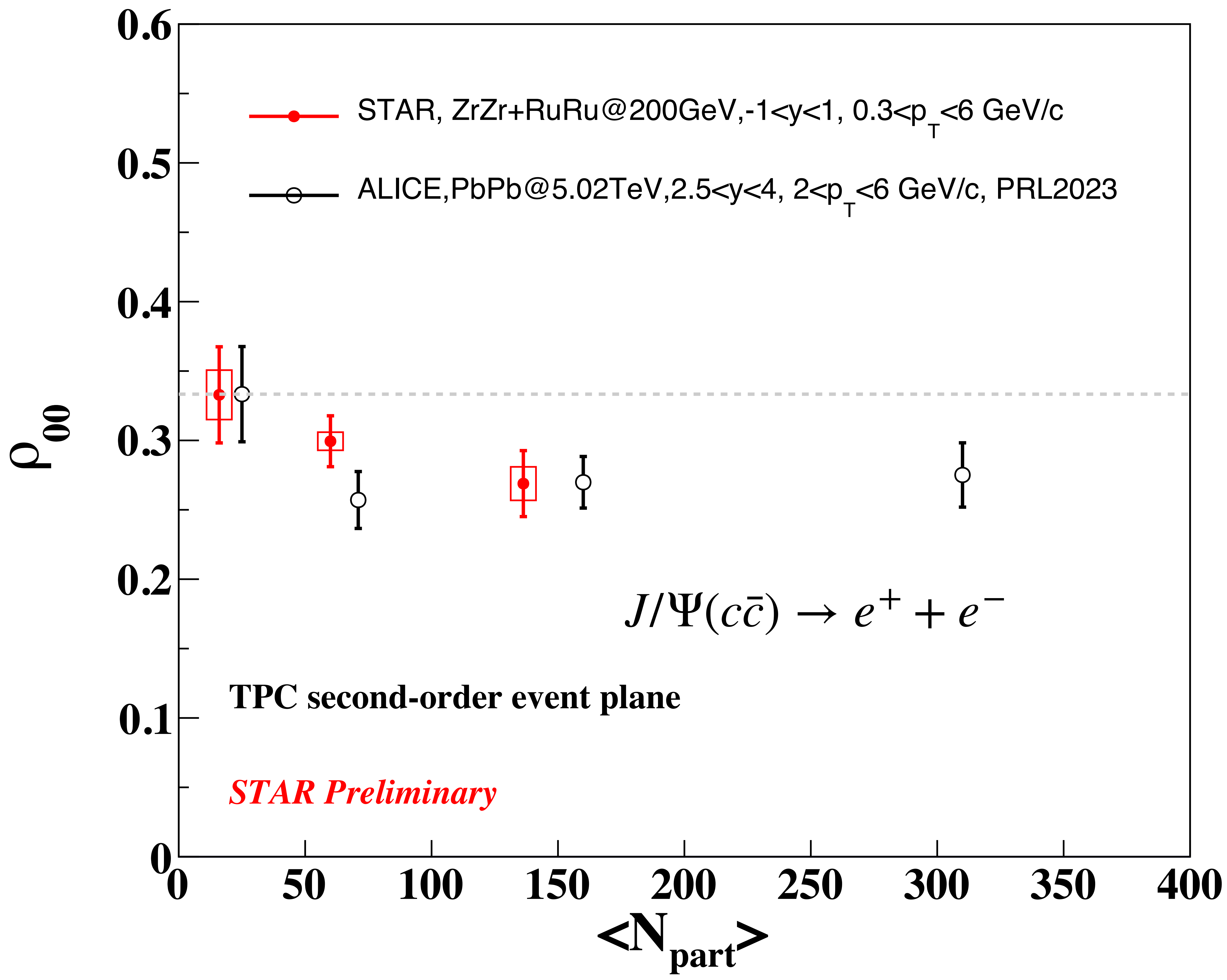
$$< P_q P_{\bar{q}} > \neq \left\langle P_q \right\rangle \left\langle P_{\bar{q}} \right\rangle$$



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

For new development of K mesons: S, Pu, QPT 2023, Sun 14:00

What about J/Psi?



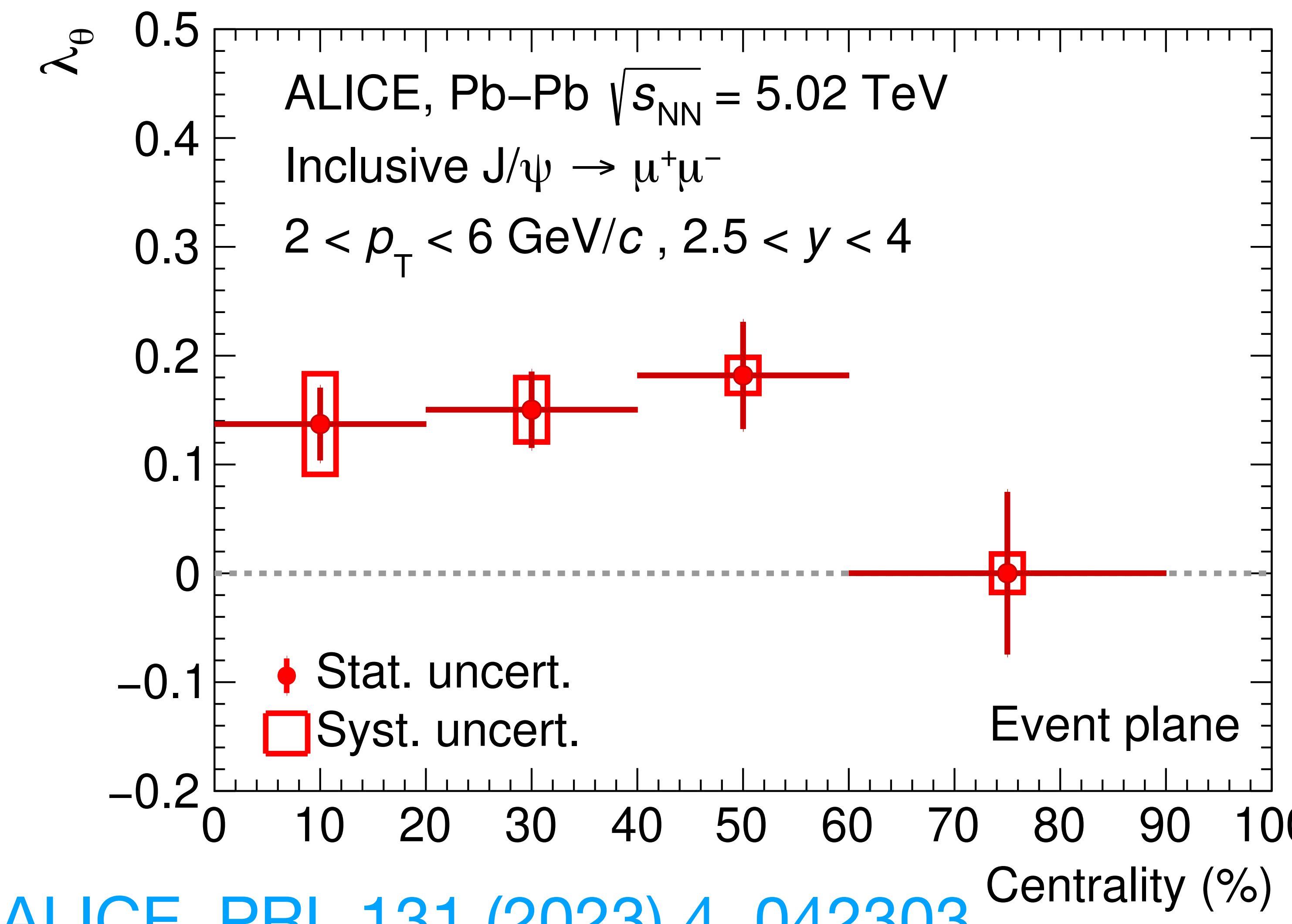
Q. Yang for STAR, QPT 2023, Sun 15:00

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

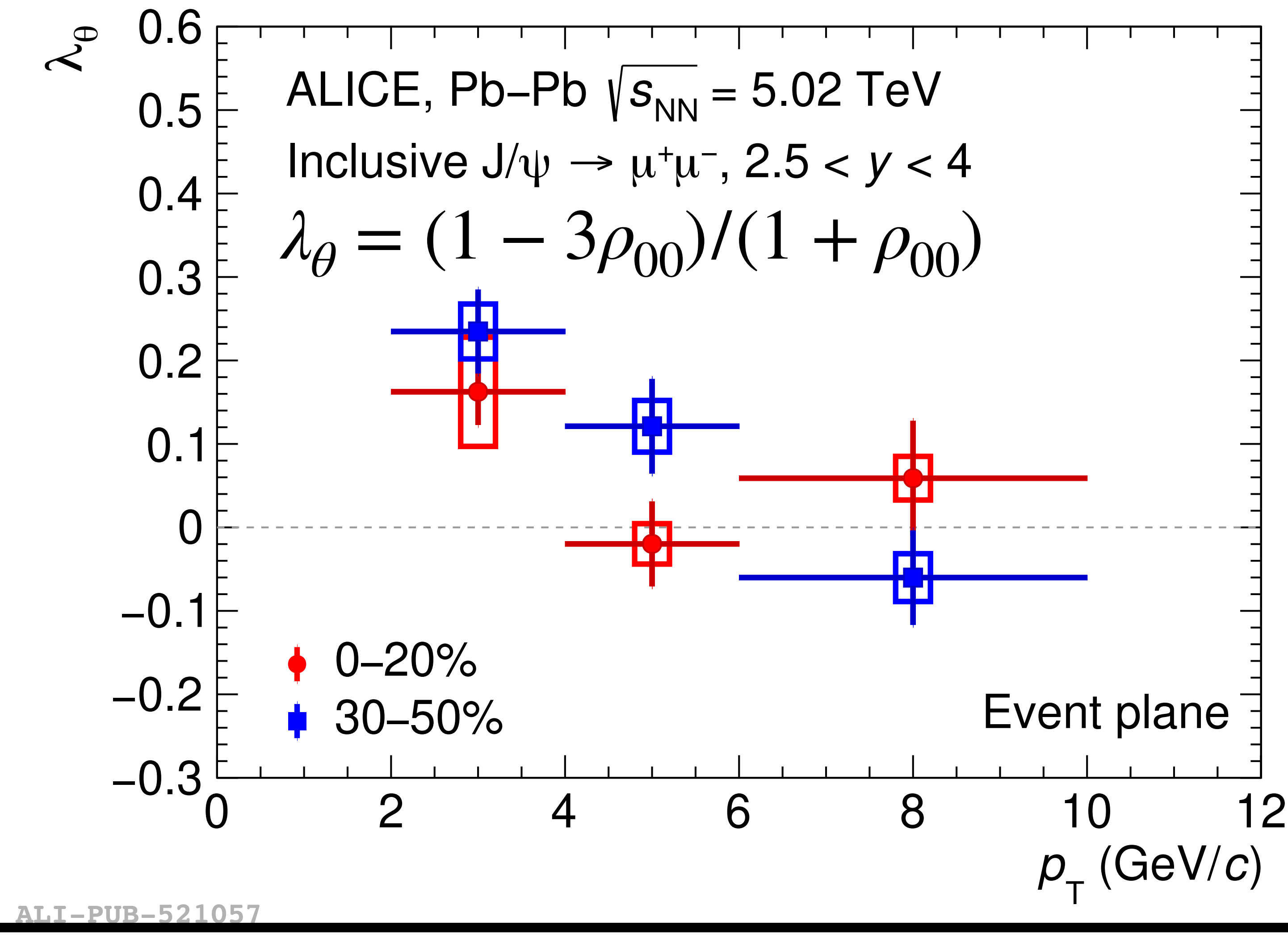
- Naive expectation from fluctuating strong force field : ρ_{00} > 1/3 at midrapidity
- Forward J/Ψ ρ_{00} at LHC and midrapidity J/Ψ ρ_{00} at RHIC, both < 1/3
- The ρ_{00} at RHIC energy is comparable to LHC results, despite of very different coalescence effect contribution

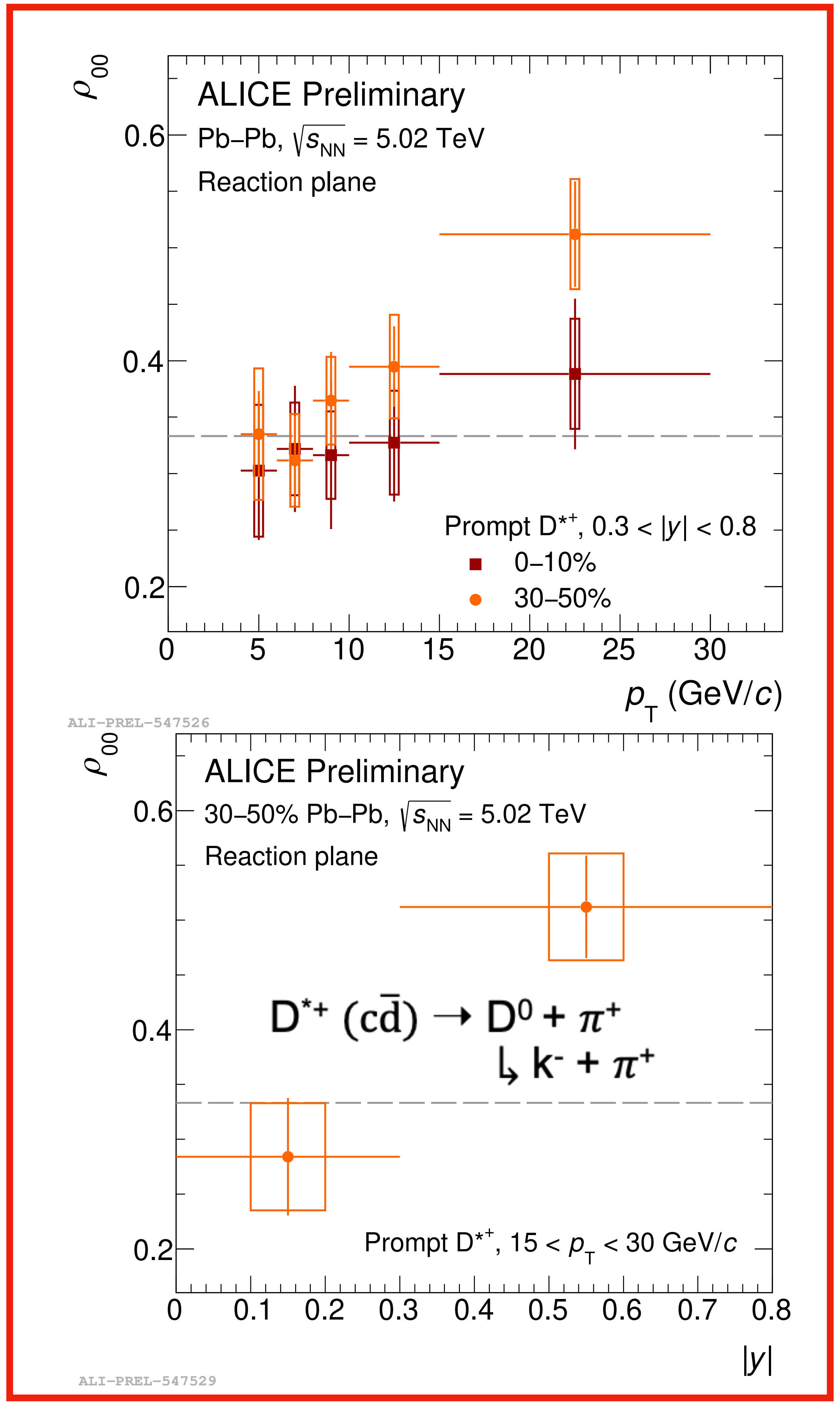
How do we understand J/Ψ ρ_{00}?

Global Spin Alignment at ALICE



ALICE, PRL 131 (2023) 4, 042303





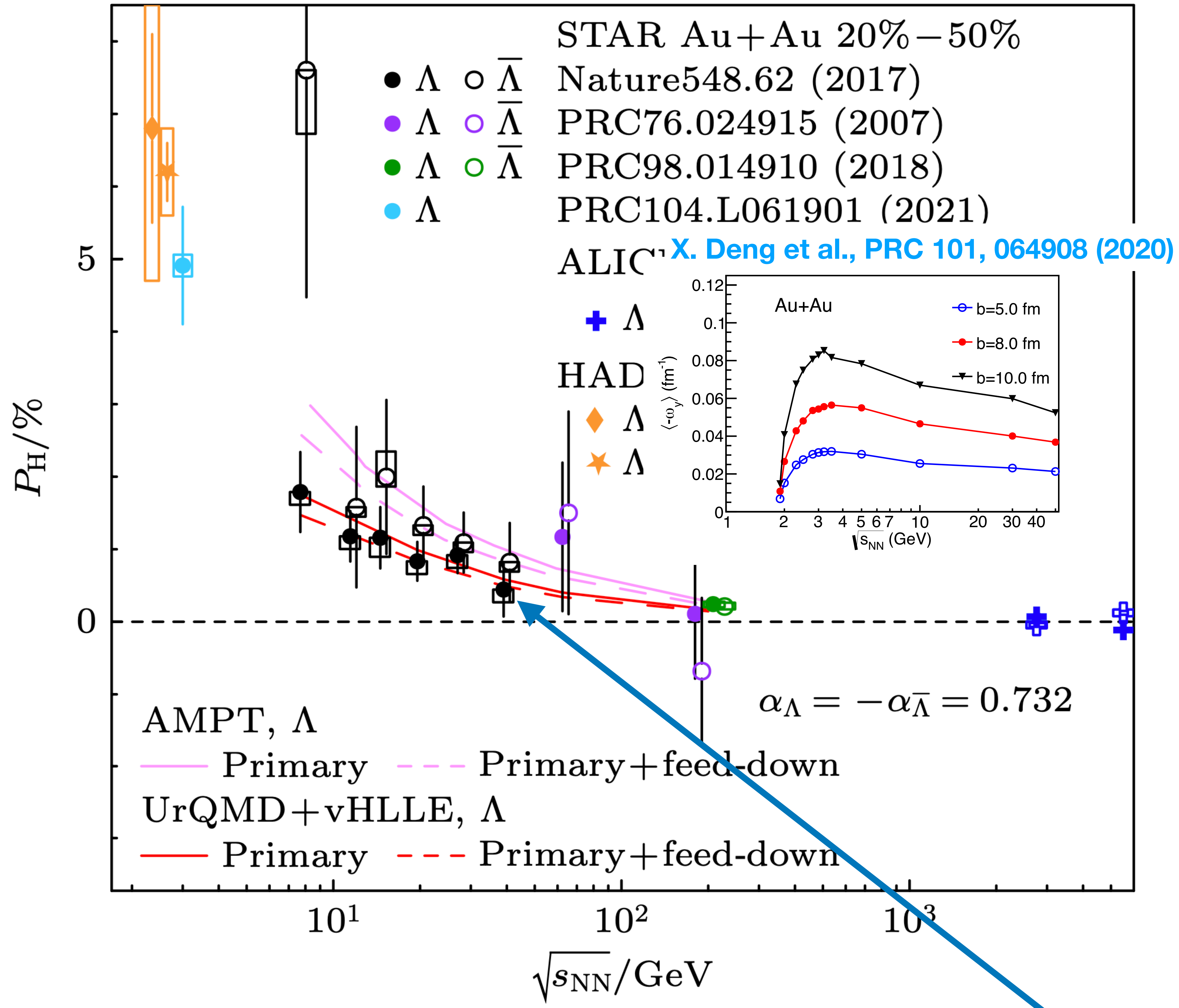
- Significant polarization (~**3.5**σ) observed in semicentral collisions (40-60%) in 2 < p_T < 6 GeV/c
- The significance of the polarization reaches ~**3.9**σ at low p_T (2 < p_T < 4 GeV/c) in 30-50%

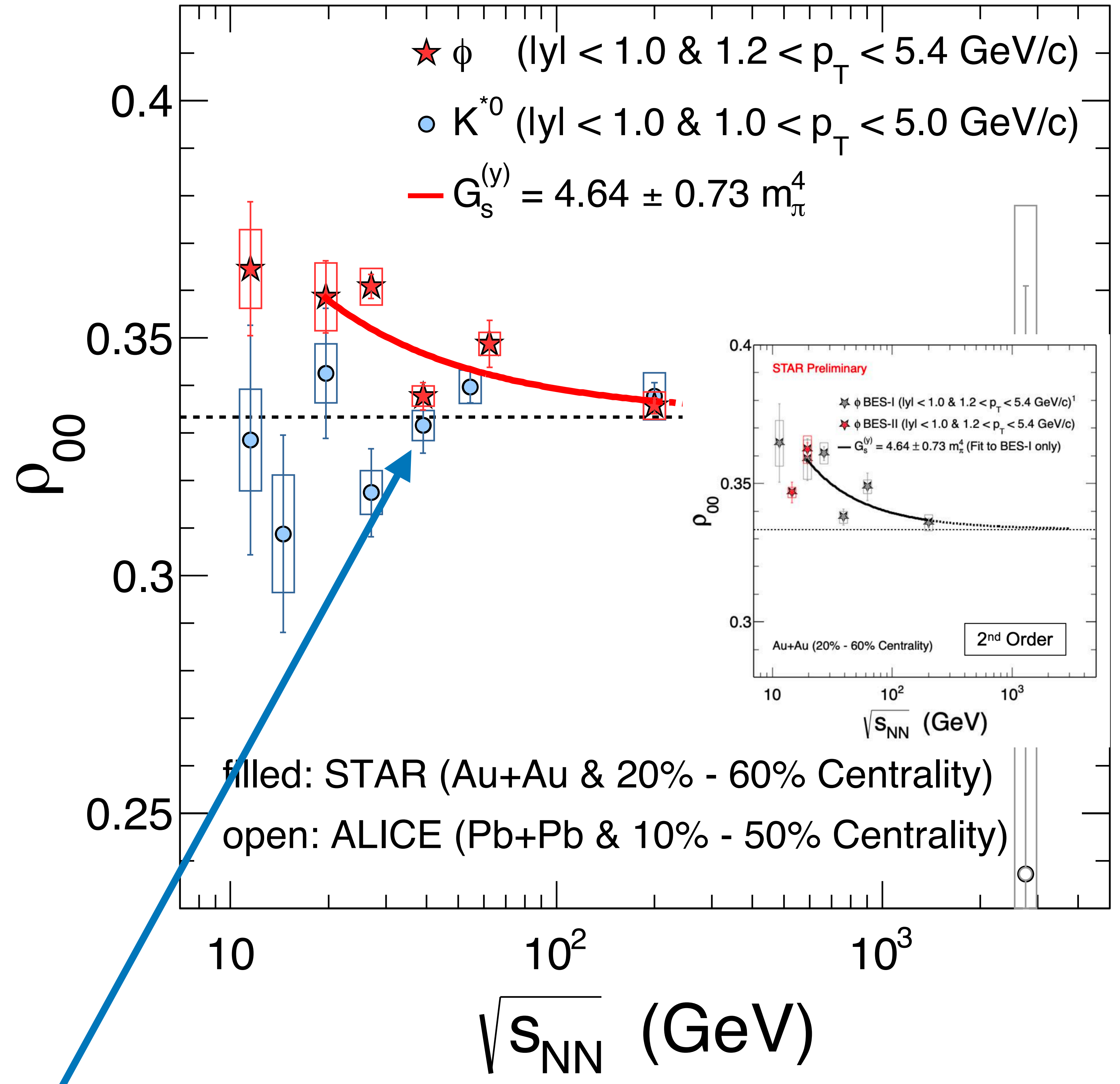
- 0-10% : ρ_{00} compatible with 1/3, 30-50%: ρ_{00} > 1/3 at high p_T
- Significant deviation at larger rapidity than at midrapidity

Theory guidance needed!

X. Bai for ALICE, QPT 2023, Sun 14:20

Puzzle?

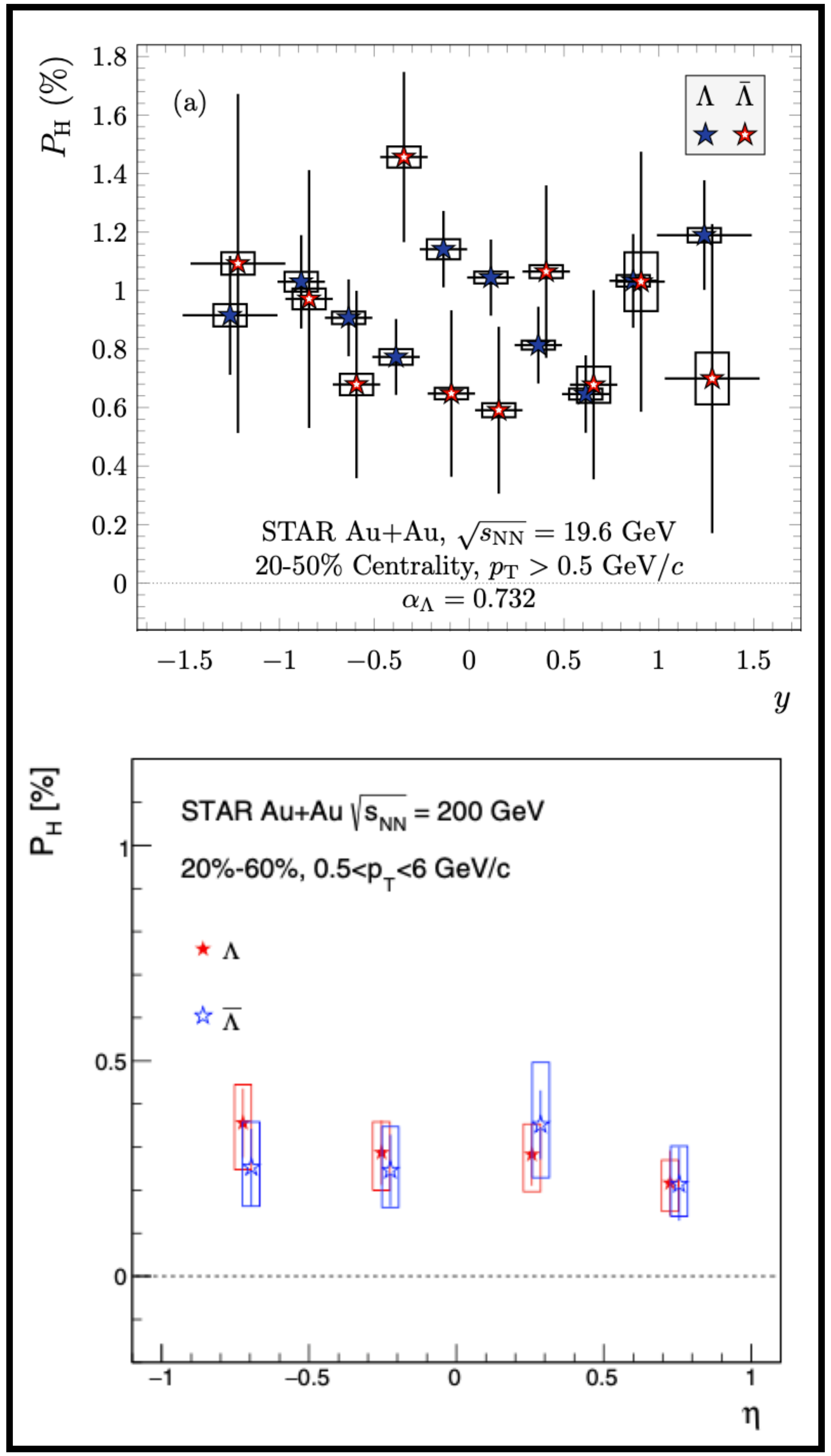


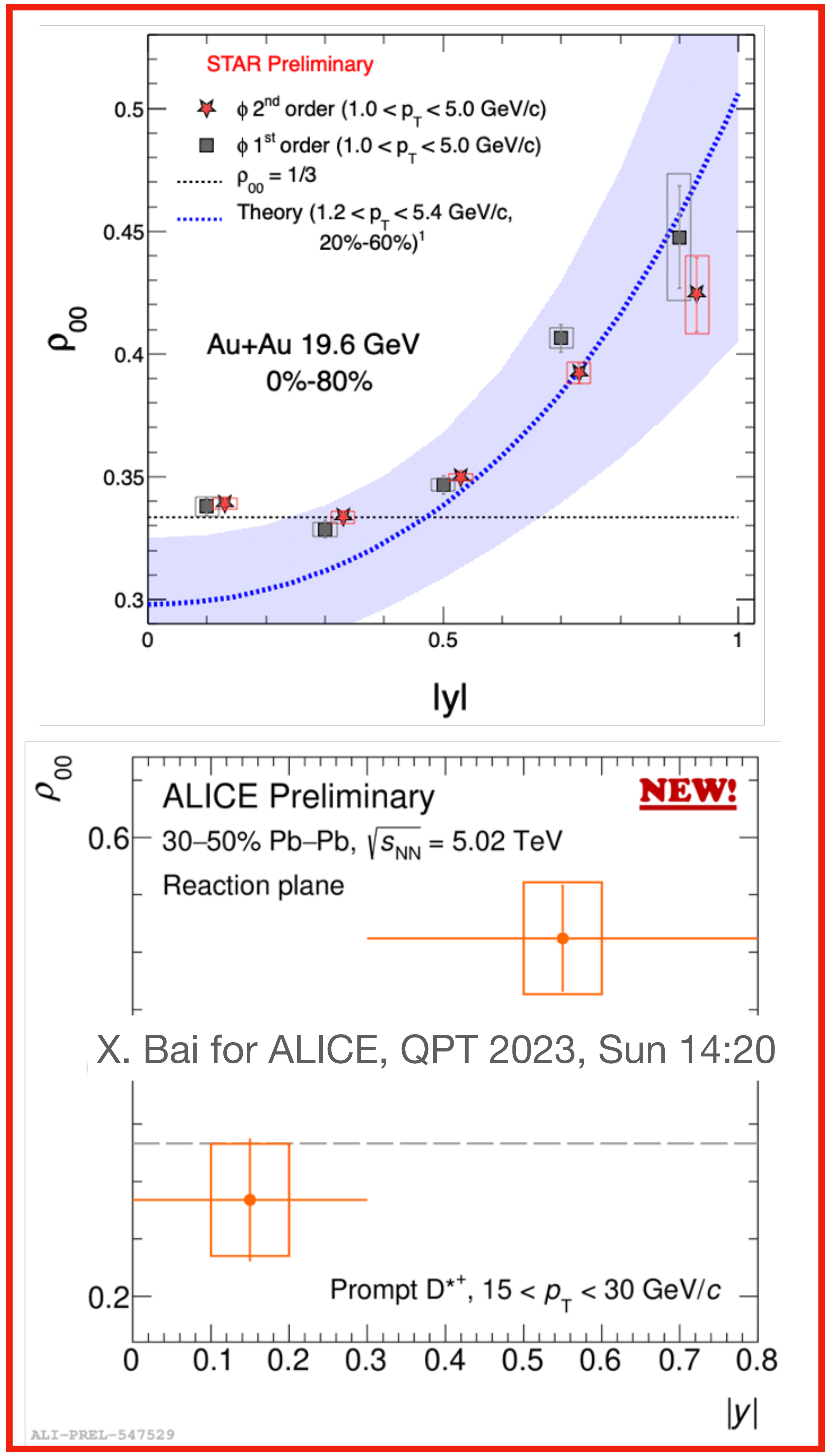


At 39 GeV both P_H and $\Delta\rho_{00}$ are ~ 0 within 1σ

Where will P_H and ρ_{00} turn down?

Puzzle?



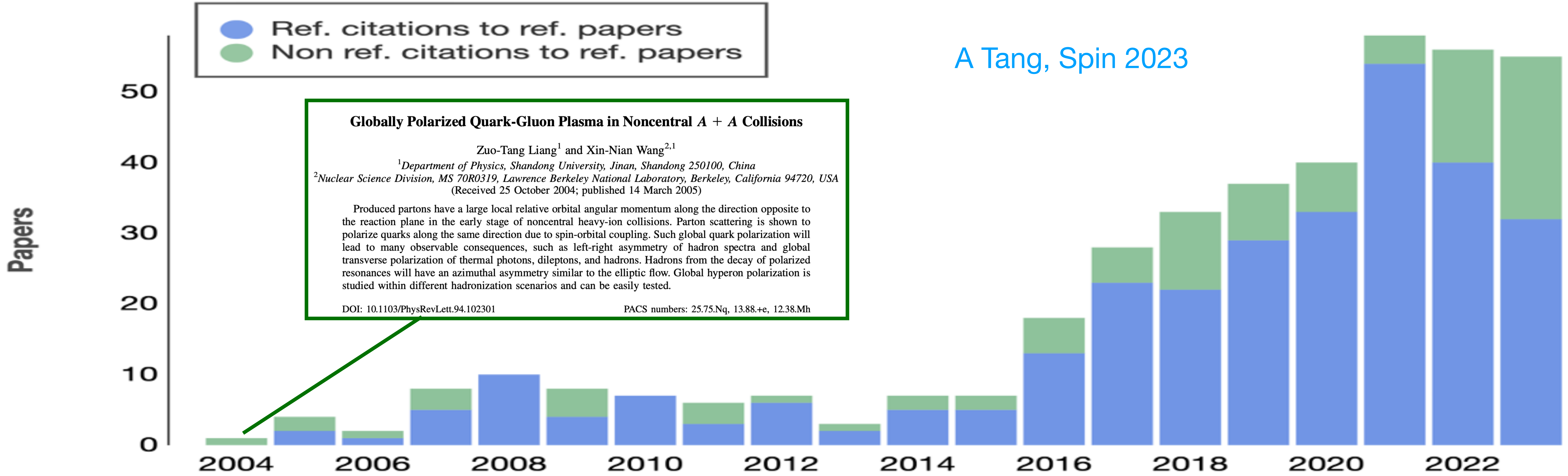


G. Wilks for STAR, Spin 2023
Theory curve : X.L. Sheng, et al., arXiv:2308.14038
S, Pu, QPT 2023, Sun 14:00

- P_H: NO rapidity dependence
- ρ_{00}: Strong rapidity dependence at both RHIC and LHC

Theory guidance needed!

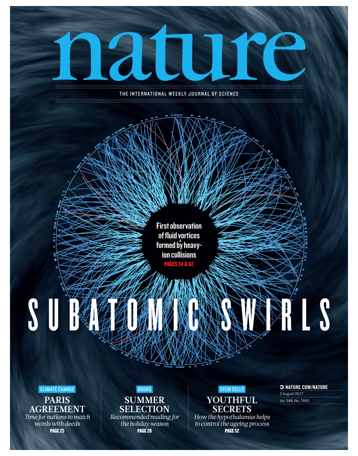
How Did We Get Here?



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

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

1st significant signal of P_Λ
STAR, Nature 548 62 (2017)



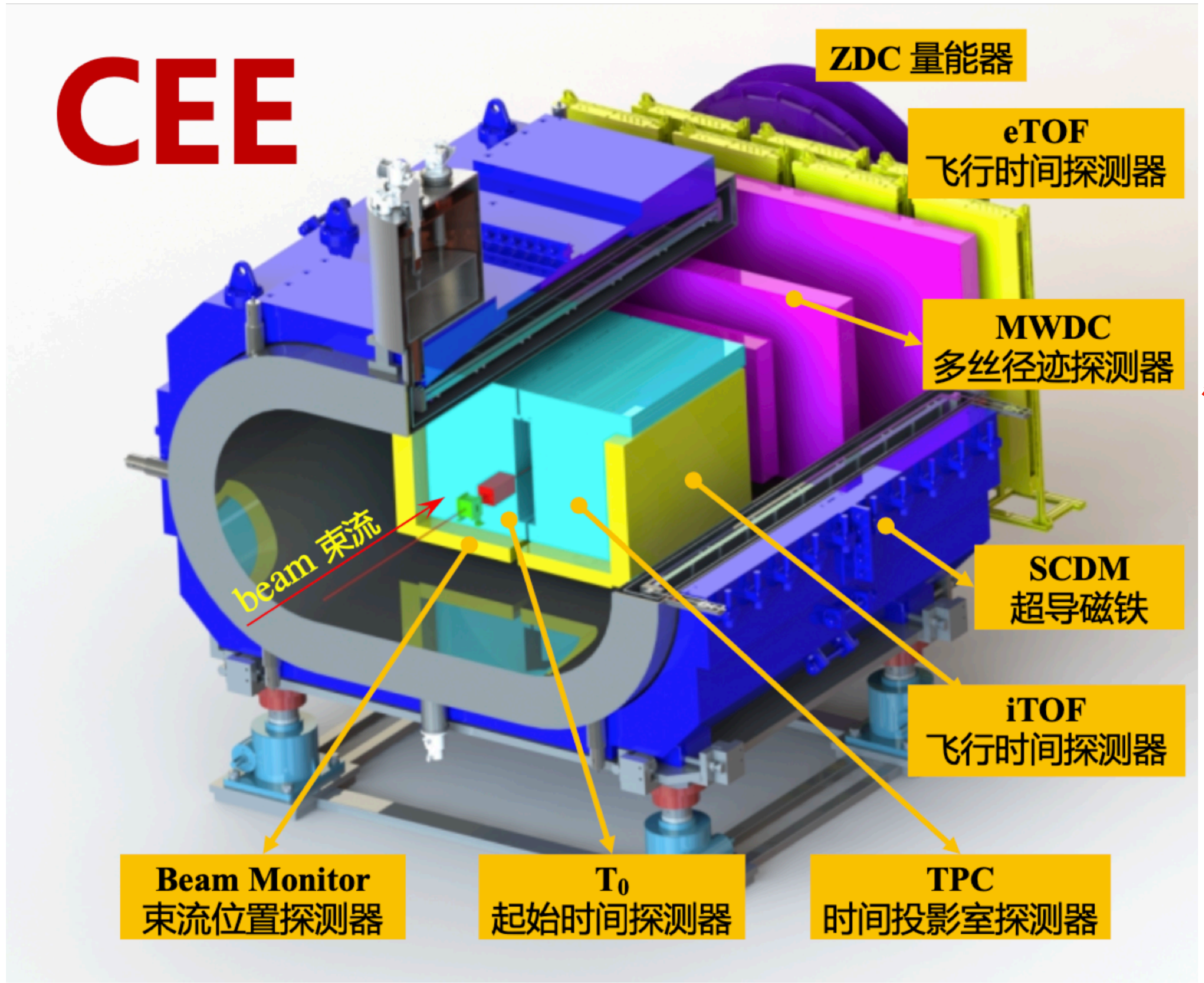
ALICE,
HADES …

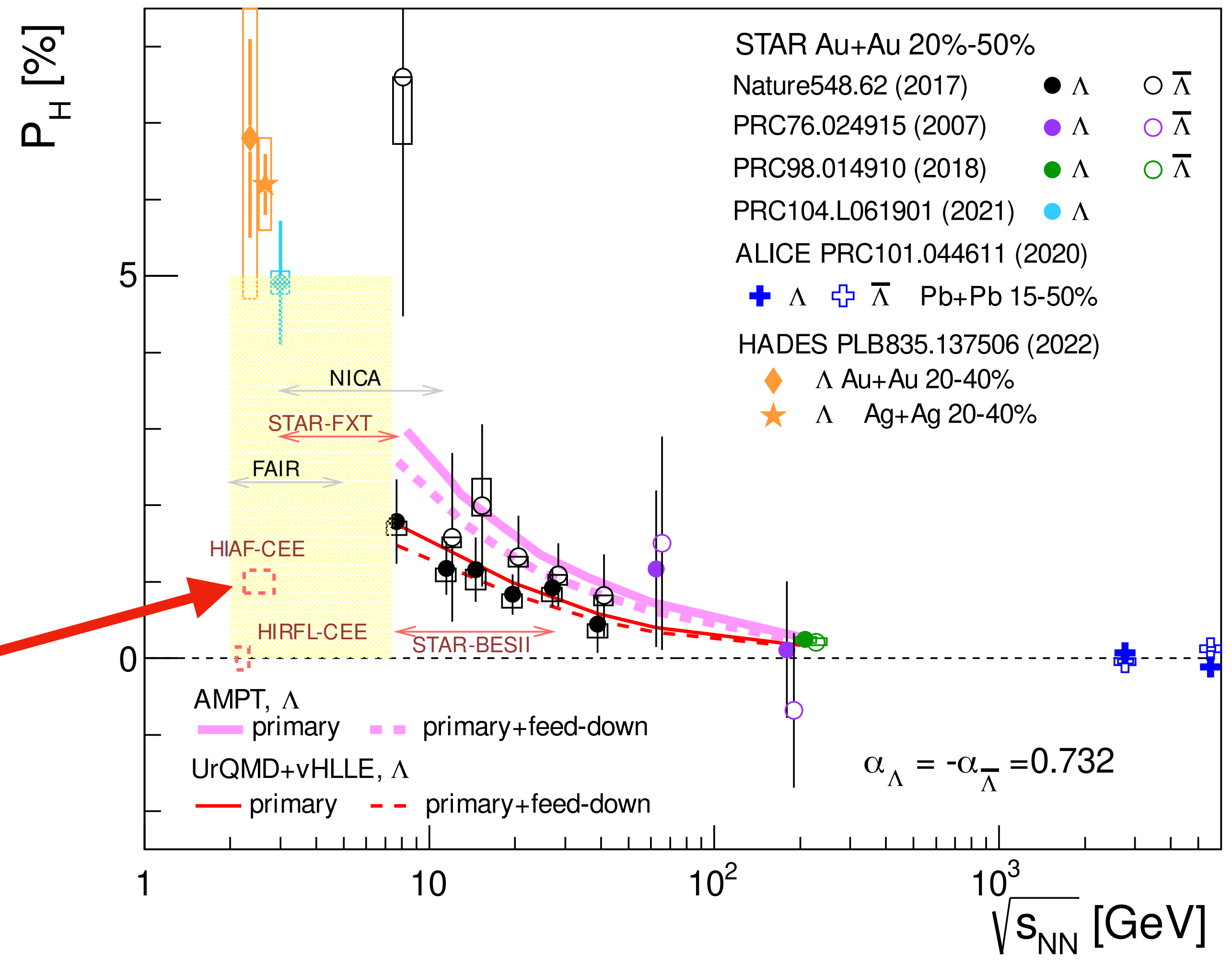
ALICE PRC 101(4)044611
HADES EPJ Web Conf. 259 11016 …

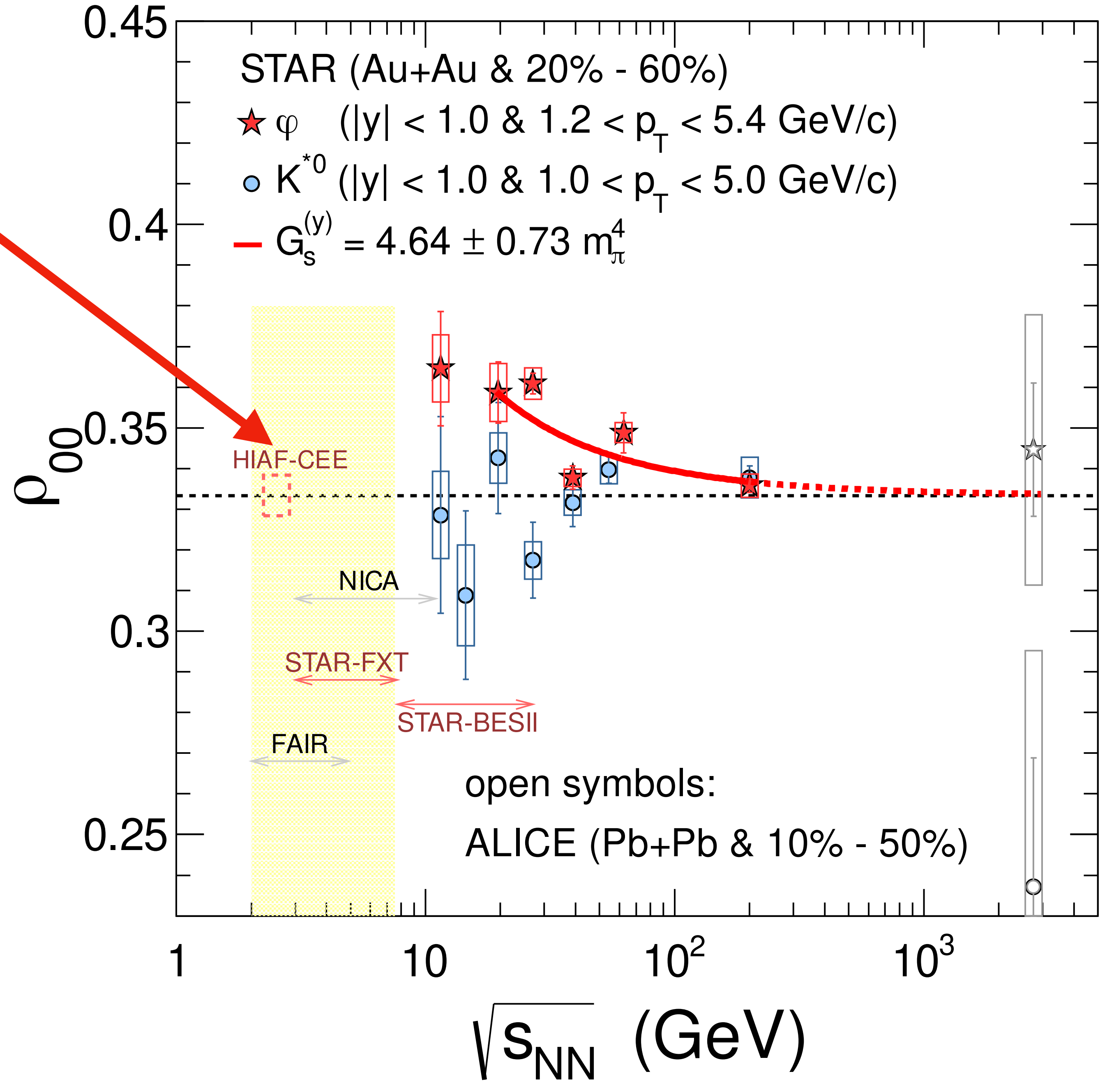
Significant signal of ρ_{00}
STAR, Nature 614 244 (2023)

Not mentioned : many theory and phenomenological studies between 2004-2022

Future Measurement in High Baryon Density Region







- CEE is under construction and will start taking data @ HIRFL in 2024
- HIAF is under construction and will start delivering beam in 2025

Summary

- Spin in heavy ion collisions is an emerging and promising field of study that probes the fascinating behavior of particles' global spin feature under extreme conditions.

- Observed the most vortical fluid known in the world, as well as tantalizing clues of a strongly fluctuating strong force field.

- Theory guidance needed: to understand alignment of ρ, K^*, ϕ, J/Ψ …

Thanks for your attention!

Backups

Experimental Observables: Global Spin Polarization

Λ-hyperon (J = 1/2⁺):

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

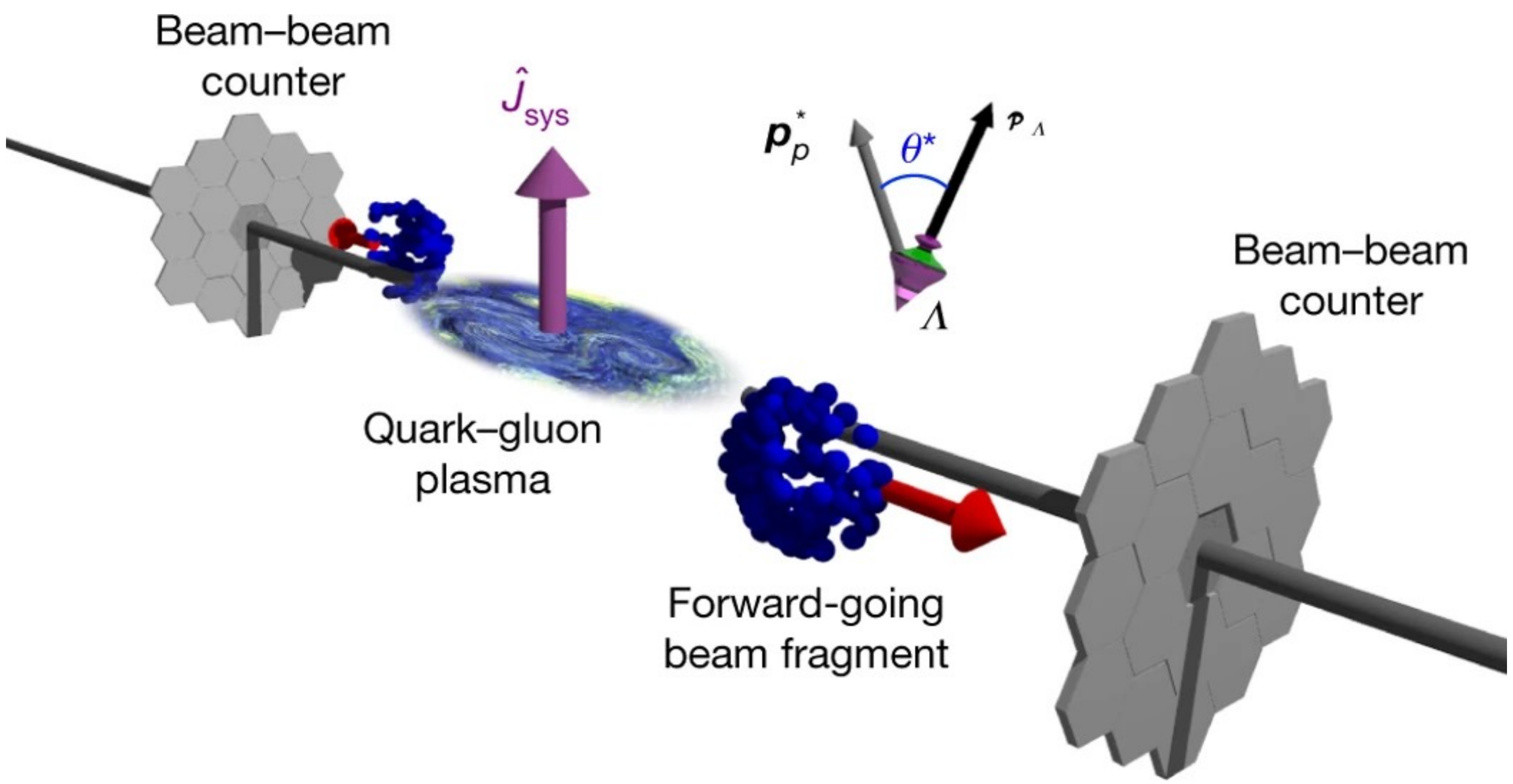
$$\frac{dN}{dcos\theta*} \sim 1 + \alpha_H P_H cos\theta*$$

P_H: Hyperon polarization

α_H: Hyperon decay parameter

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

STAR, Nature 548, 62 (2017)



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

Experimental Observables: Global Spin Alignment

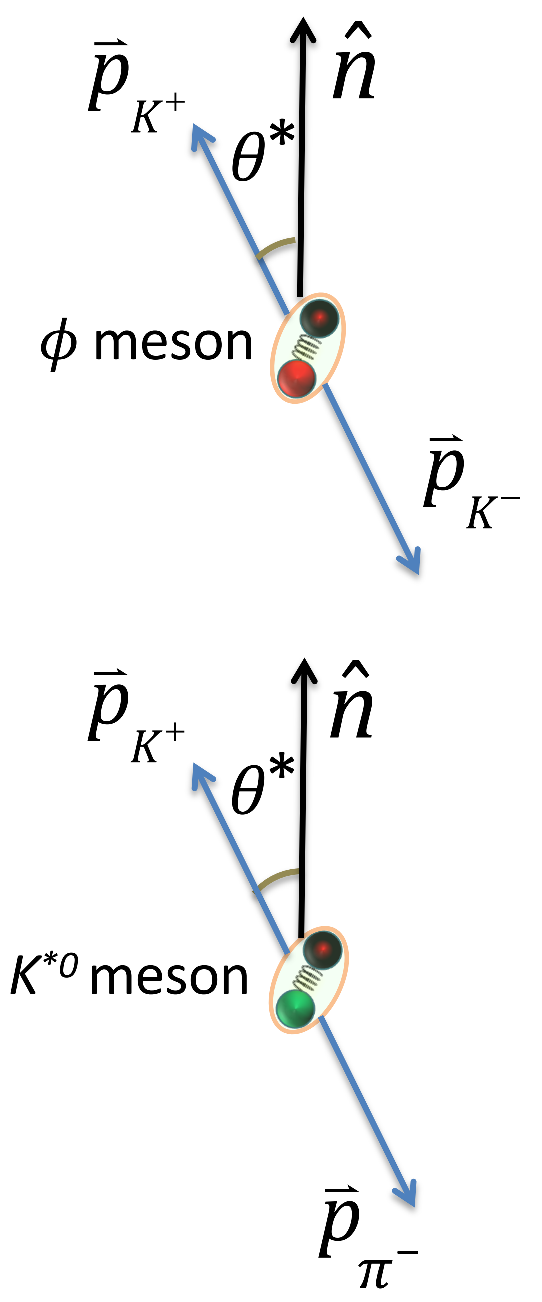
ϕ-mesons (J = 1⁻):

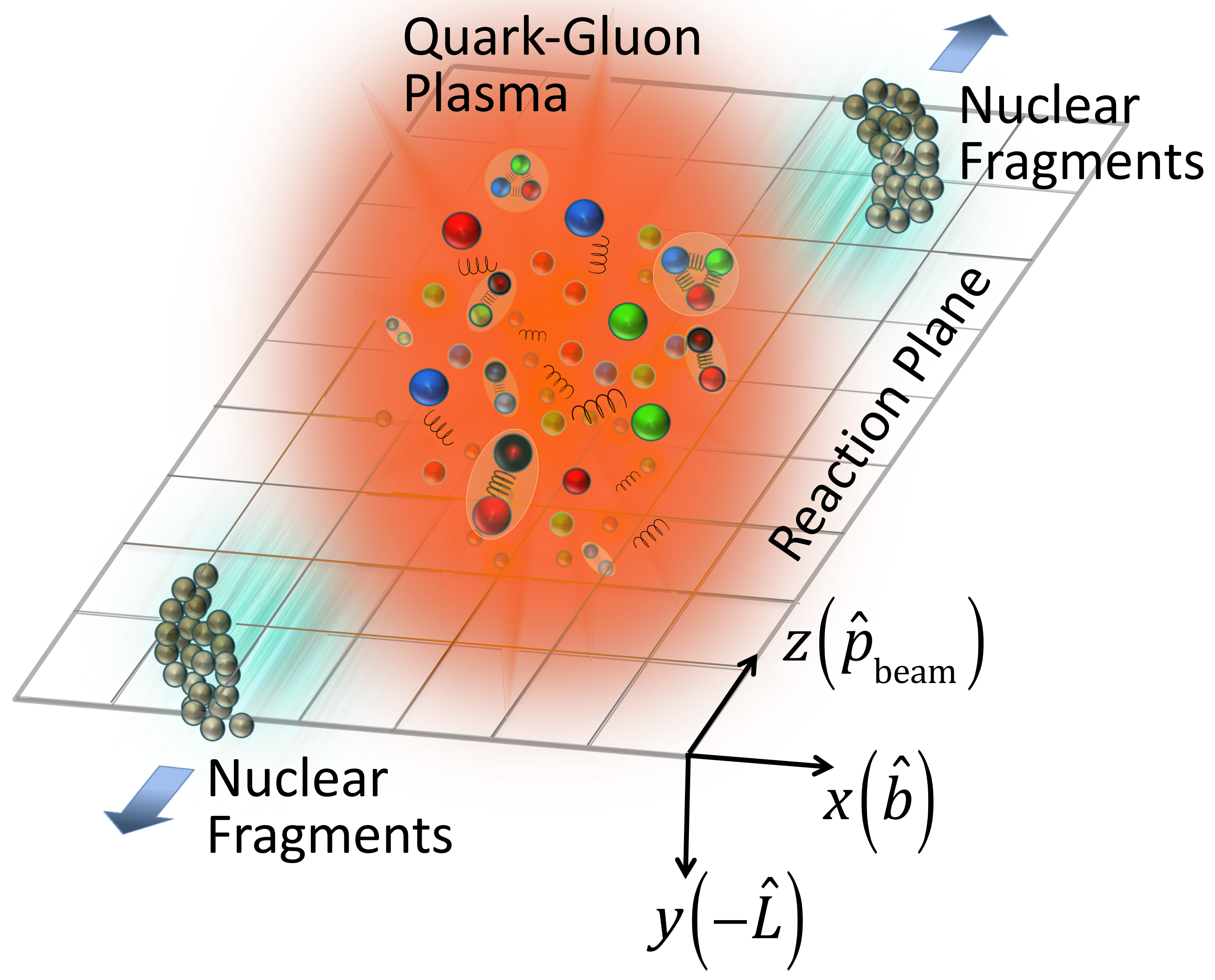
1. Cannot measure polarization sign
2. Do not need reaction plane direction — use 2nd order event plane
3. Some mesons, like ϕ, are expected to originate predominantly from primordial production => less decay contributions if compared to hyperons, more sensitive to early dynamics
4. new physics?

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

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

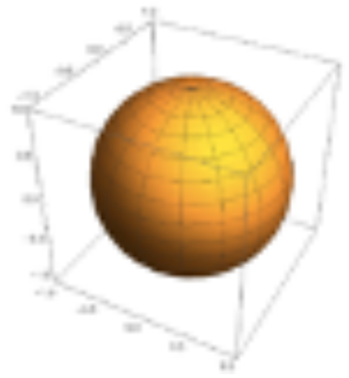
$\rho_{00} \neq 1/3$ → **spin alignment**



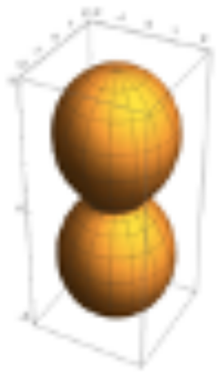


θ* is the angle between decay daughter and polarization direction in mother particle rest frame

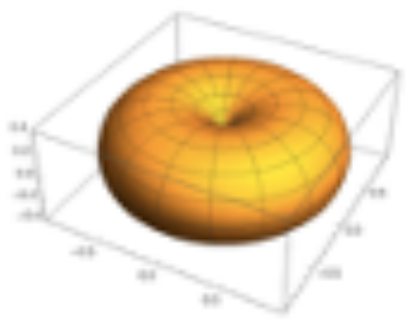
$\rho_{00} = 1/3$



$\rho_{00} > 1/3$



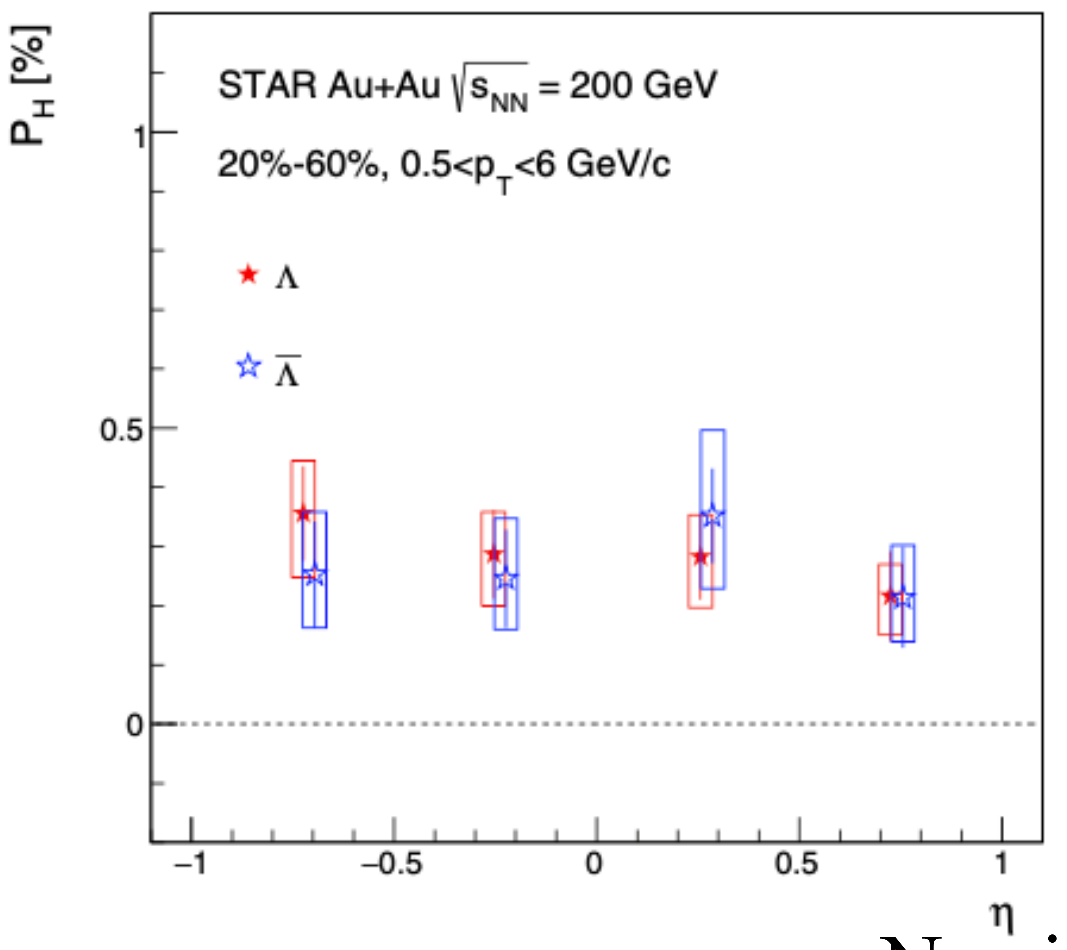
$\rho_{00} < 1/3$

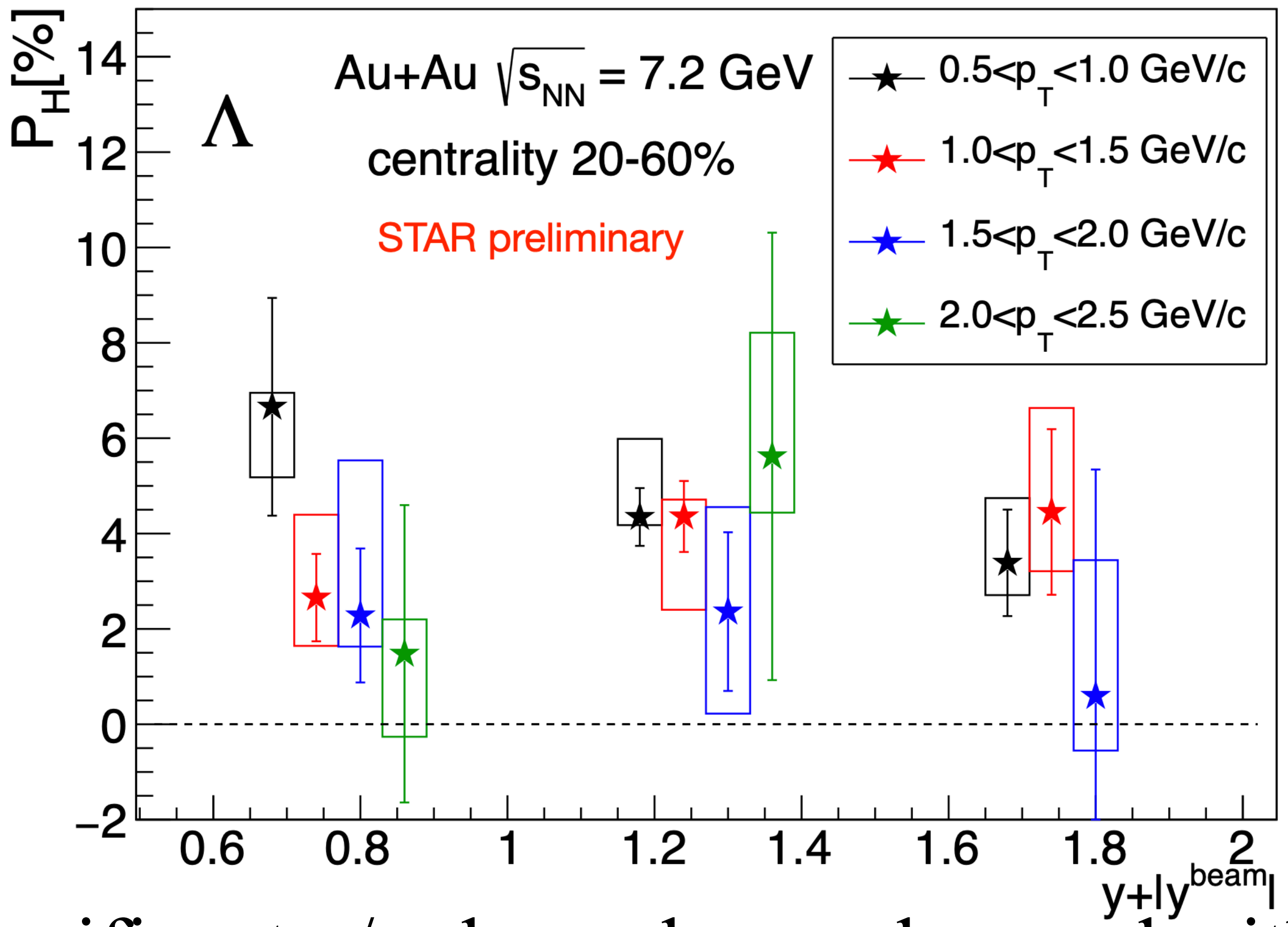


η Dependence of P_Λ

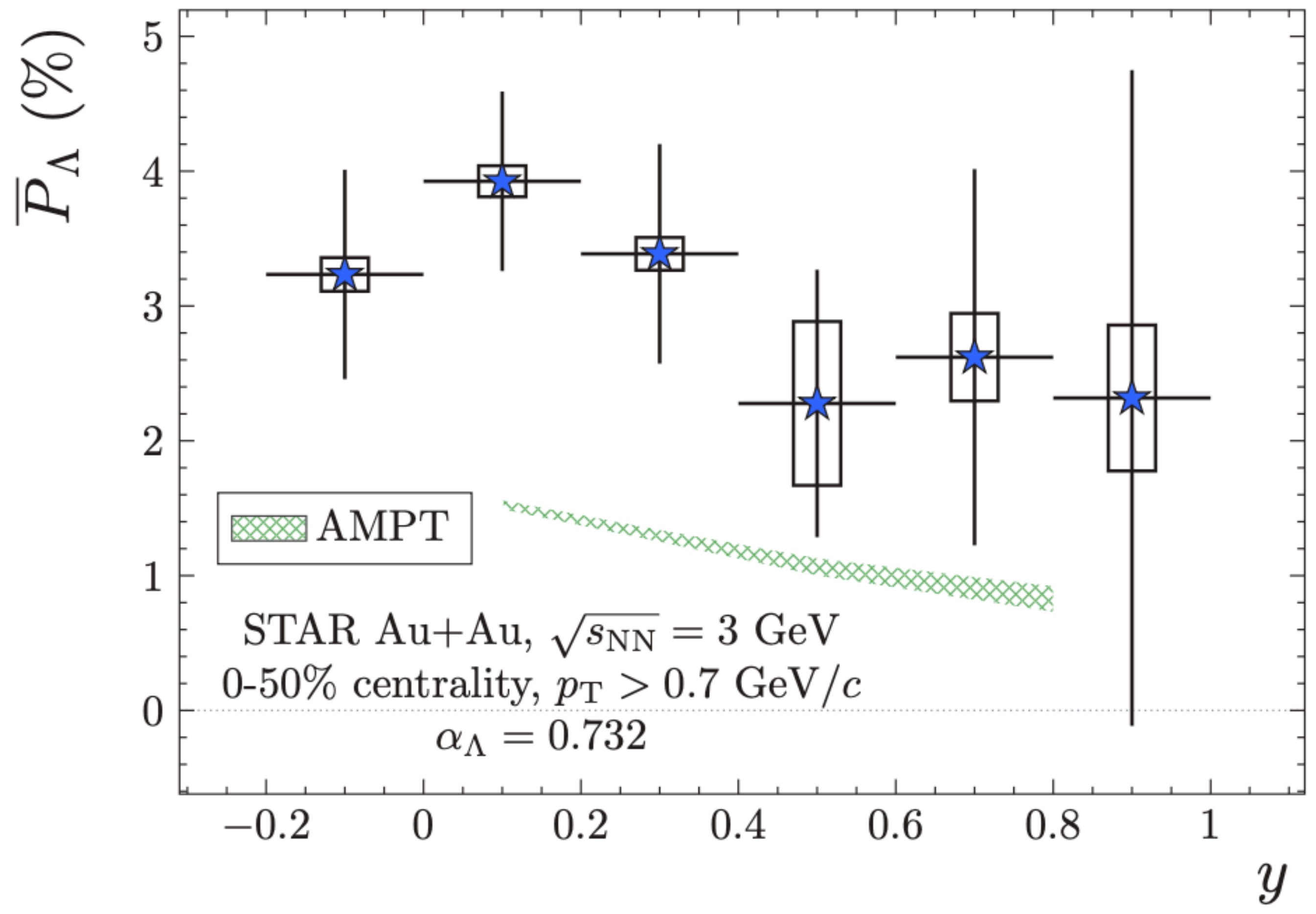
Data

Phys. Rev. C 98, 014910 (2018)





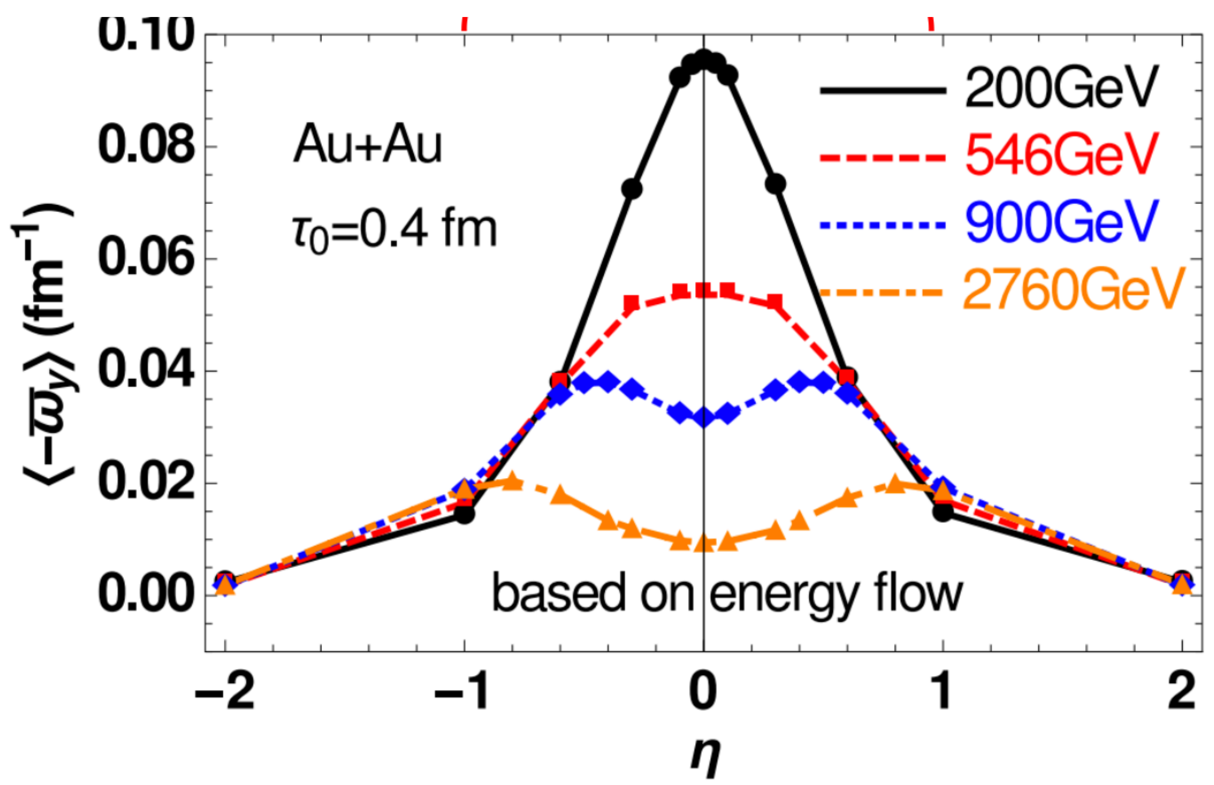
Phys. Rev. C 104, L061901 (2021)



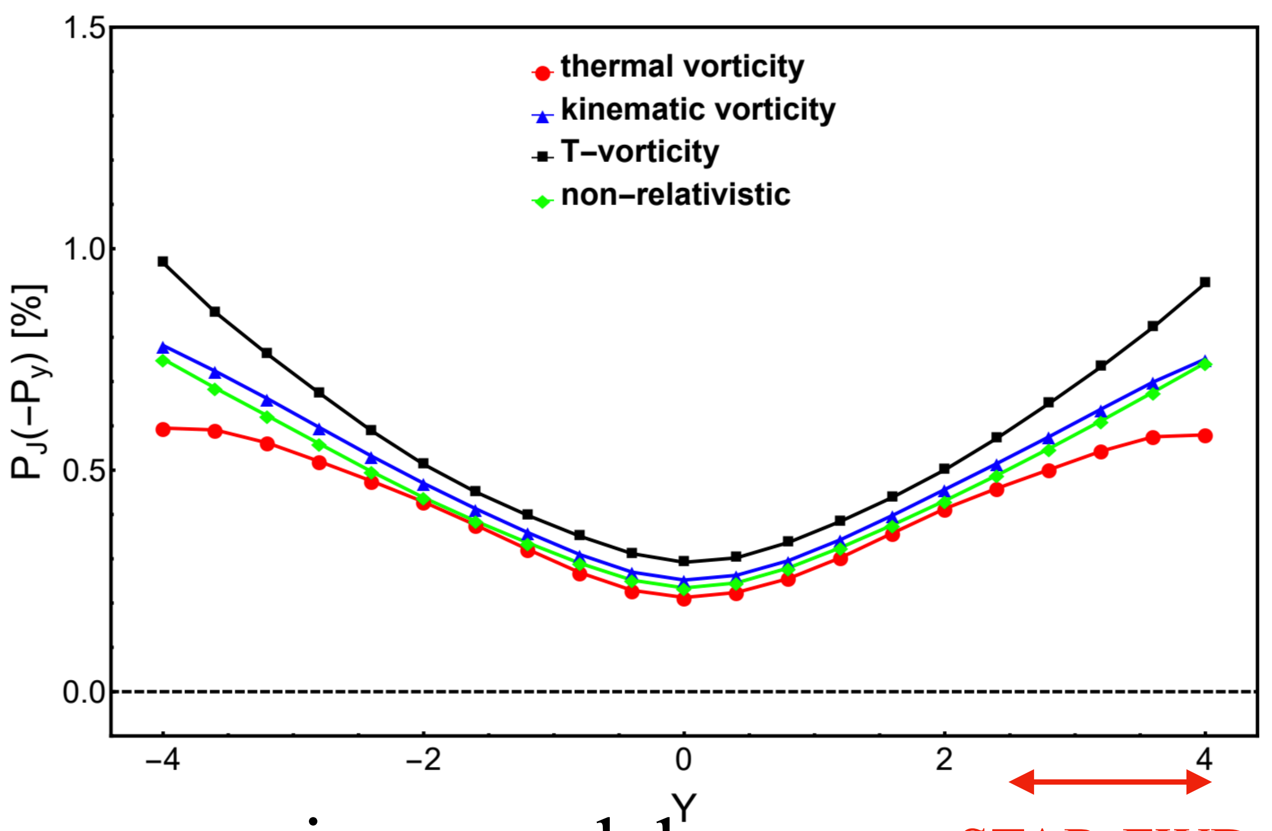
No significant y/η dependence observed within acceptance

Model

Phys Rev C 93, 064907 (2016)



Phys Rev Research 1, 033058 (2019)

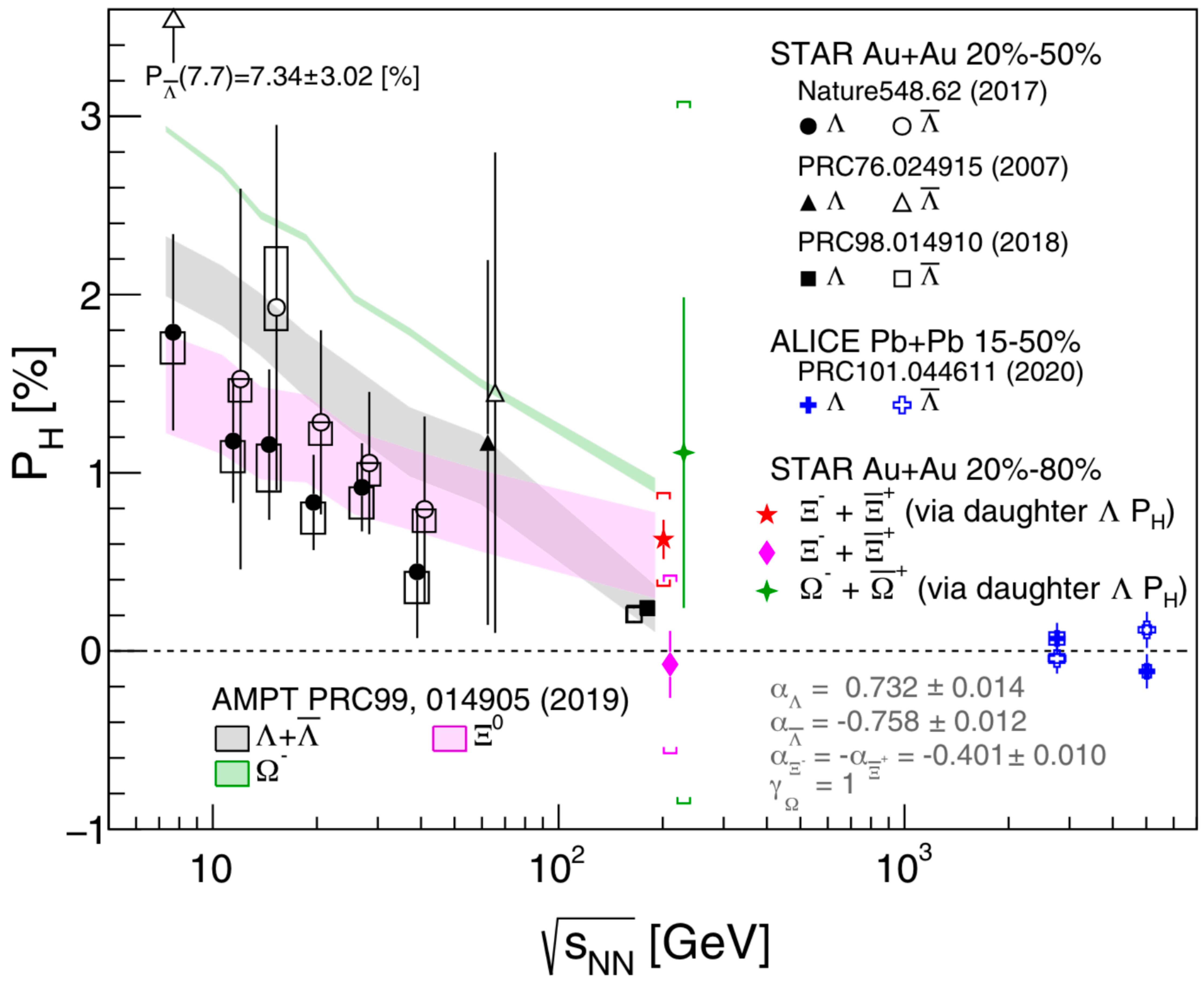


STAR-FWD

Rapidity dependence of P_Λ is different among various models

First Measurement of $P_{\Xi,\Omega}$

STAR, PRL 126. 162301 (2021)



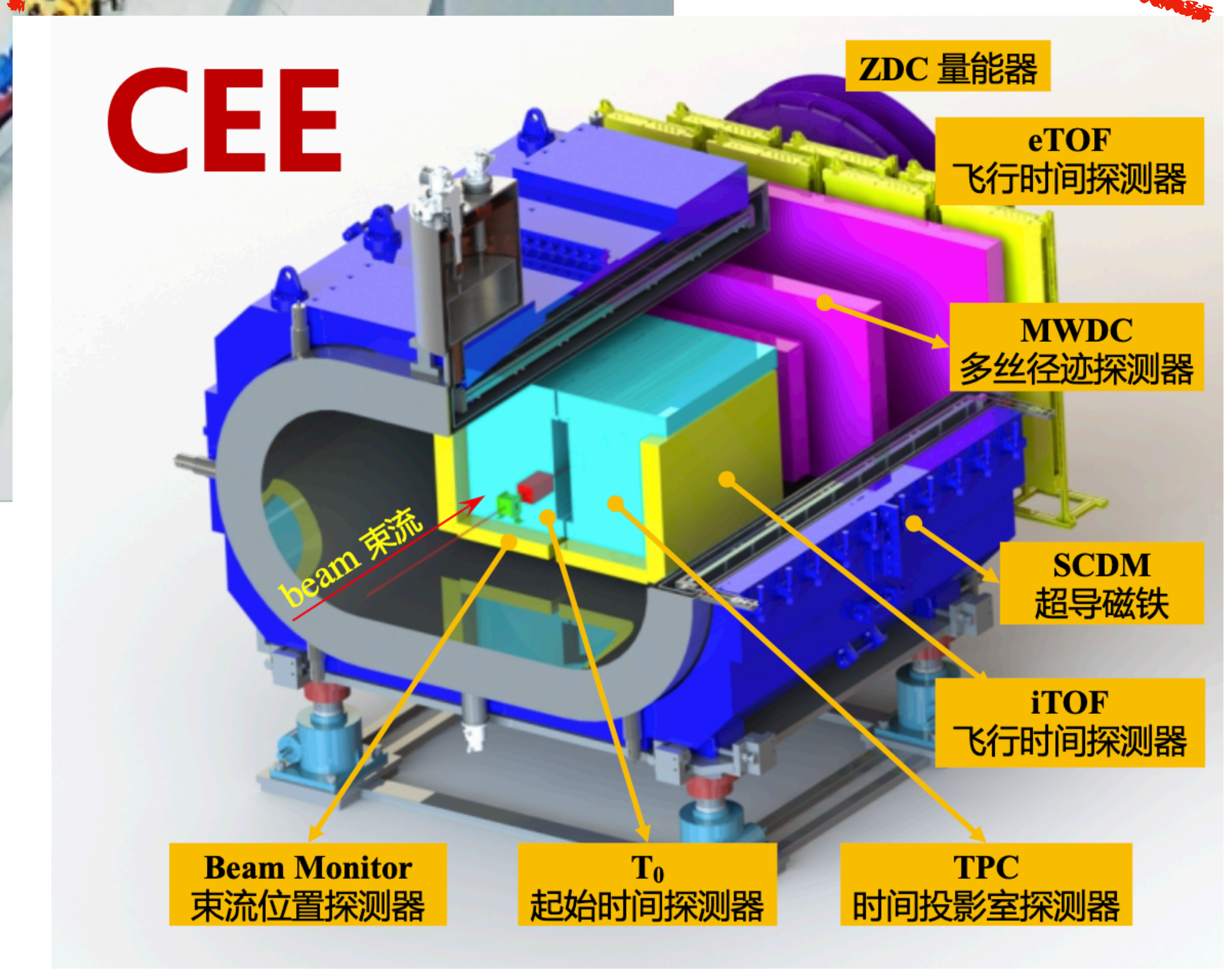
	Mass (GeV/c²)	Spin	μ_N
Λ (uds)	1.115683	1/2	0.613
Ξ (dss)	1.32171	1/2	-0.6501
Ω (sss)	1.67245	3/2	-2.02

- $P_\Lambda = 0.24 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})\,\%$
- $P_\Xi = 0.47 \pm 0.10(\text{stat.}) \pm 0.23(\text{syst.})\,\%$
- $P_\Omega = 1.11 \pm 0.87(\text{stat.}) \pm 1.97(\text{syst.})\,\%$

- Non-zero polarization for $P_{\Xi,\Omega}$
- $P_{\Xi,\Omega}$ follows global trend of P_Λ

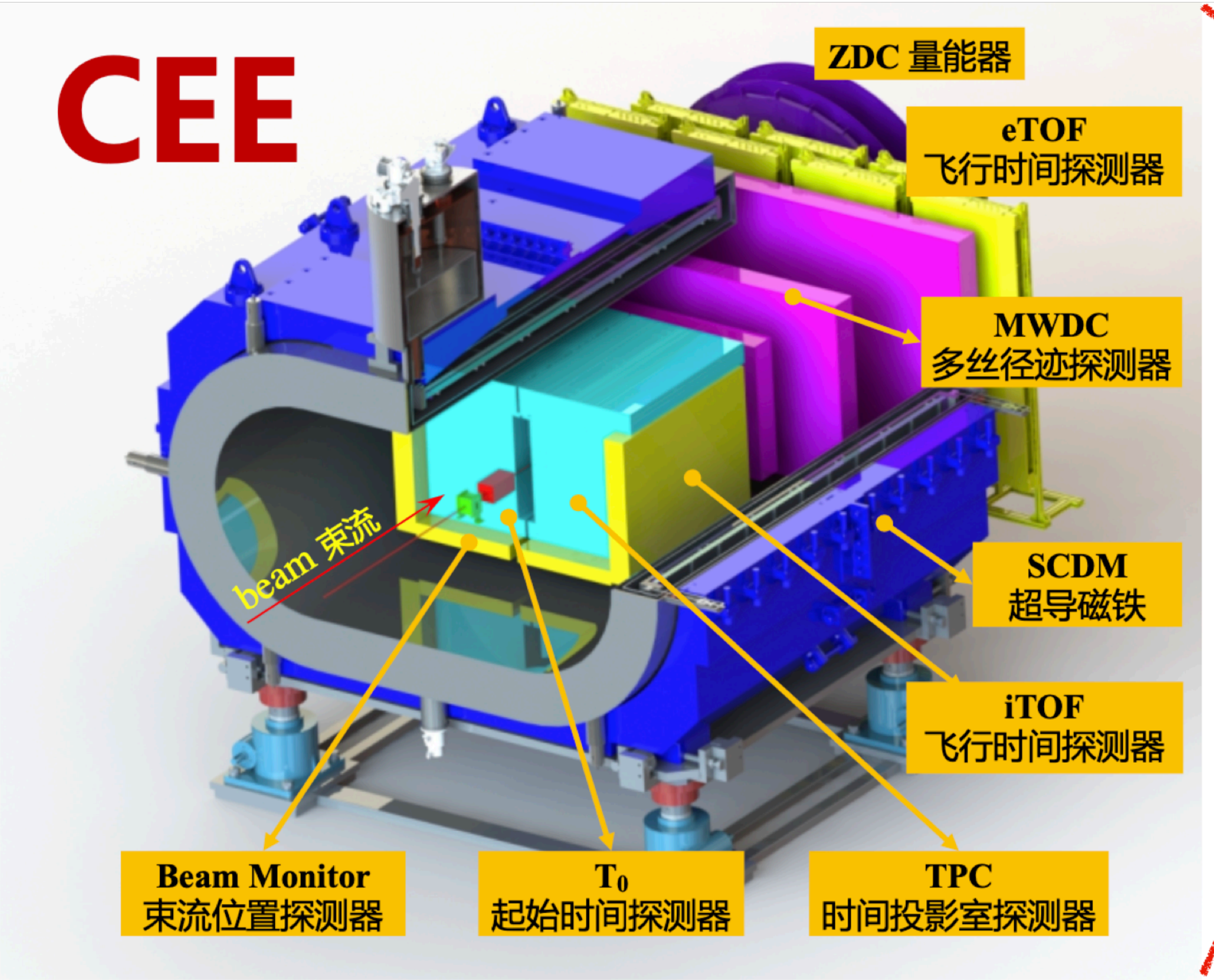
New $P_{\Xi,\Omega}$ measurements confirm the global nature of spin polarization

Feature Measurement @ HIRFL-CEE



- CEE is under construction and will start taking data @ HIRFL in 2024
- 0.5 GeV/u ($\sqrt{s_{NN}}$ = 2.11 GeV) U beam => flow, fluctuations, spectra etc.

Feature Measurement @ HIAF-CEE



- HIAF is under construction and will start delivering beam in 2025
- 0.8-9.1 GeV/u U beam => global polarization

	E_k (GeV/u)	$\sqrt{s_{NN}}$ (GeV)
HIAF U Beam	0.8-2.45	2.24-2.85
HIAF-U U Beam	2.95-9.1	3.01-4.54
HIAF p Beam	<9.3	<4.58