Spin Polarization in Heavy Ion Collisions
– Experimental Progress

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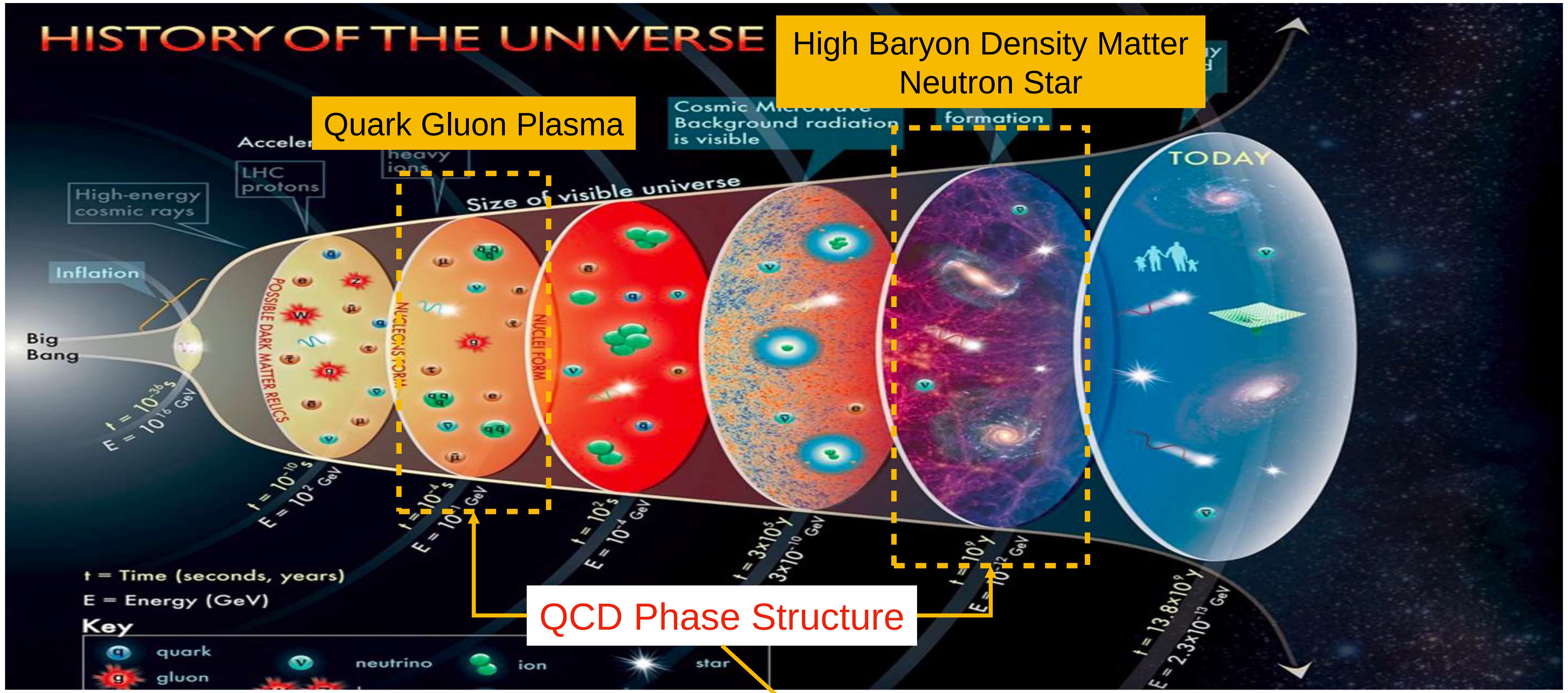
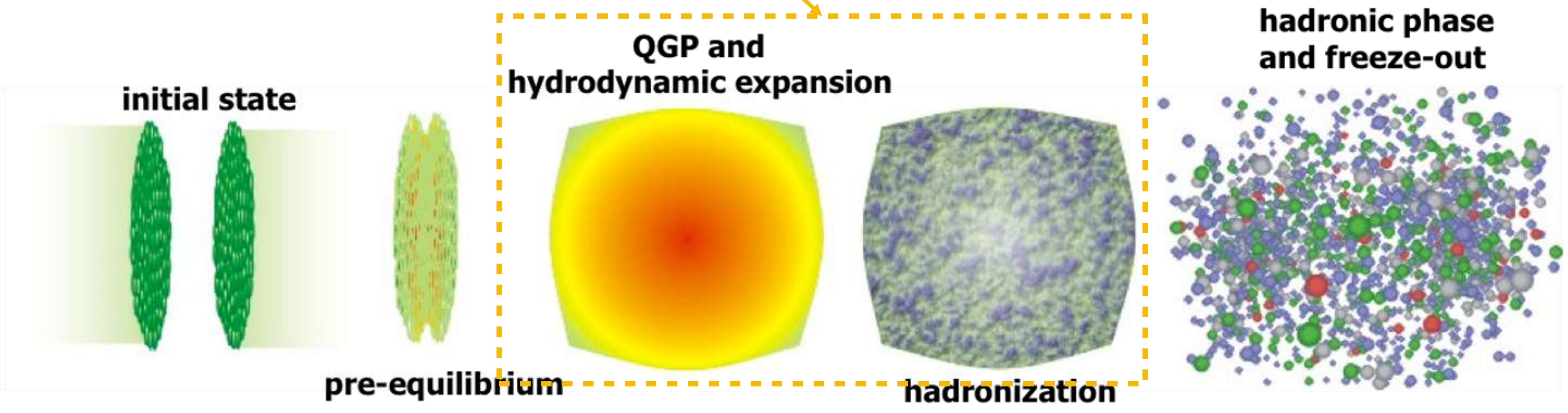
Big Bang vs. Little Bang

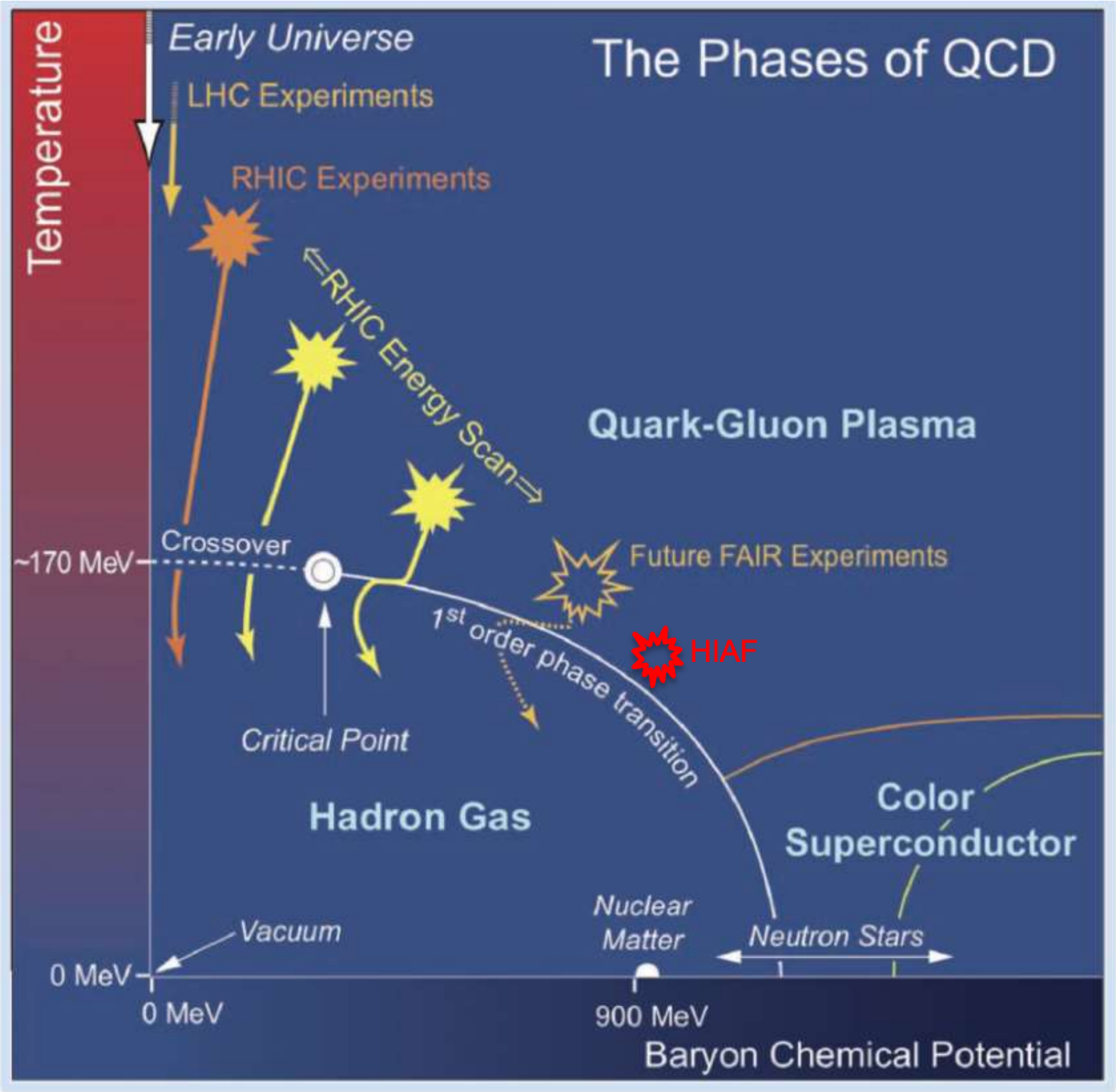
Big Bang

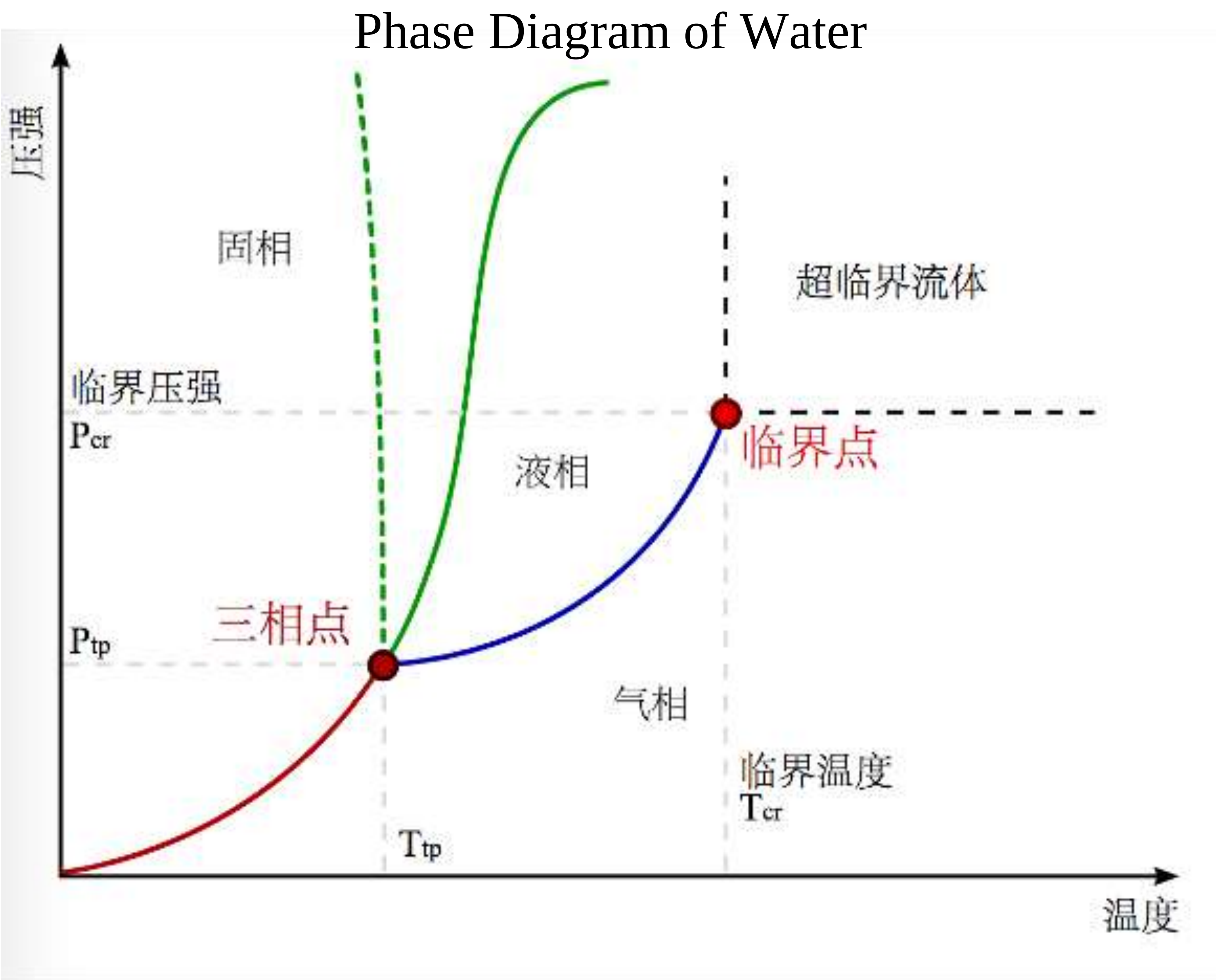


Little Bang



QCD Phase Diagram



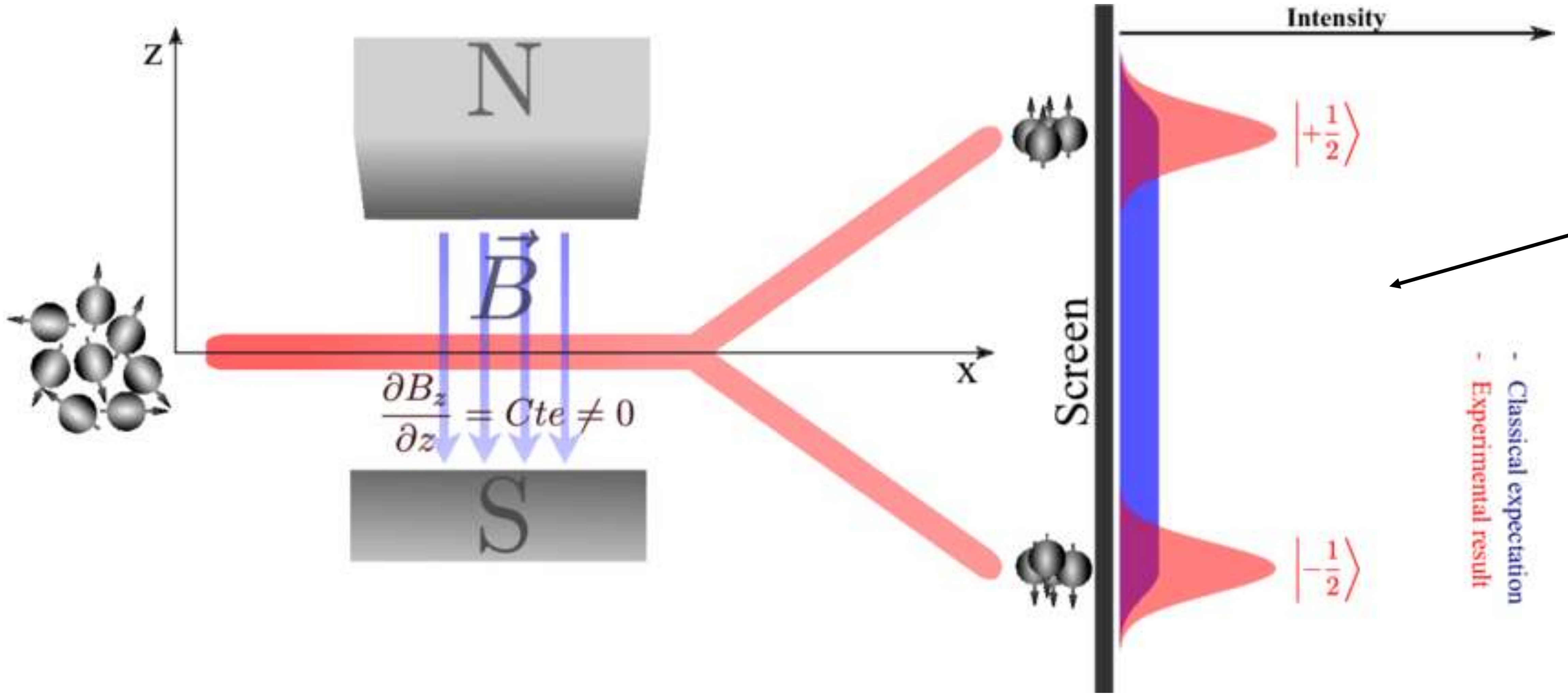


Exploring QCD phase diagram:

- Signs of 1st order phase transition => HBT, v1 analyses
- QCD critical point => Fluctuation analyses
- Signature of QGP => Collective flow & NCQ scaling
- **Vorticity => Λ-Hyperon global spin polarization & ϕ-meson global spin alignment**

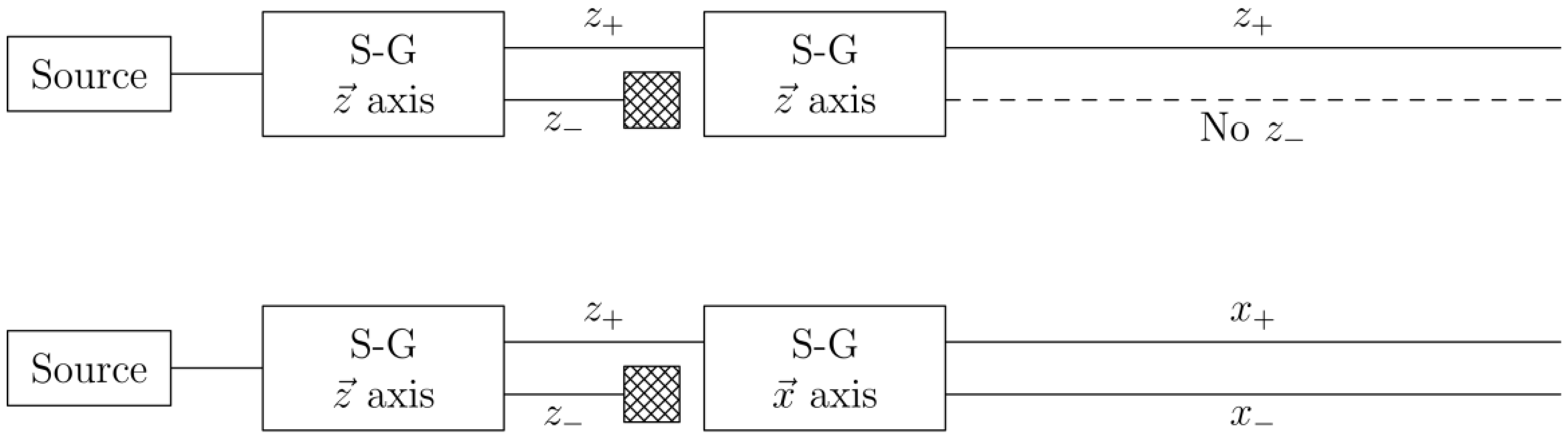
Spin Polarization

Stern–Gerlach Experiment



Unpolarized Beam

Sequential Stern–Gerlach Experiment



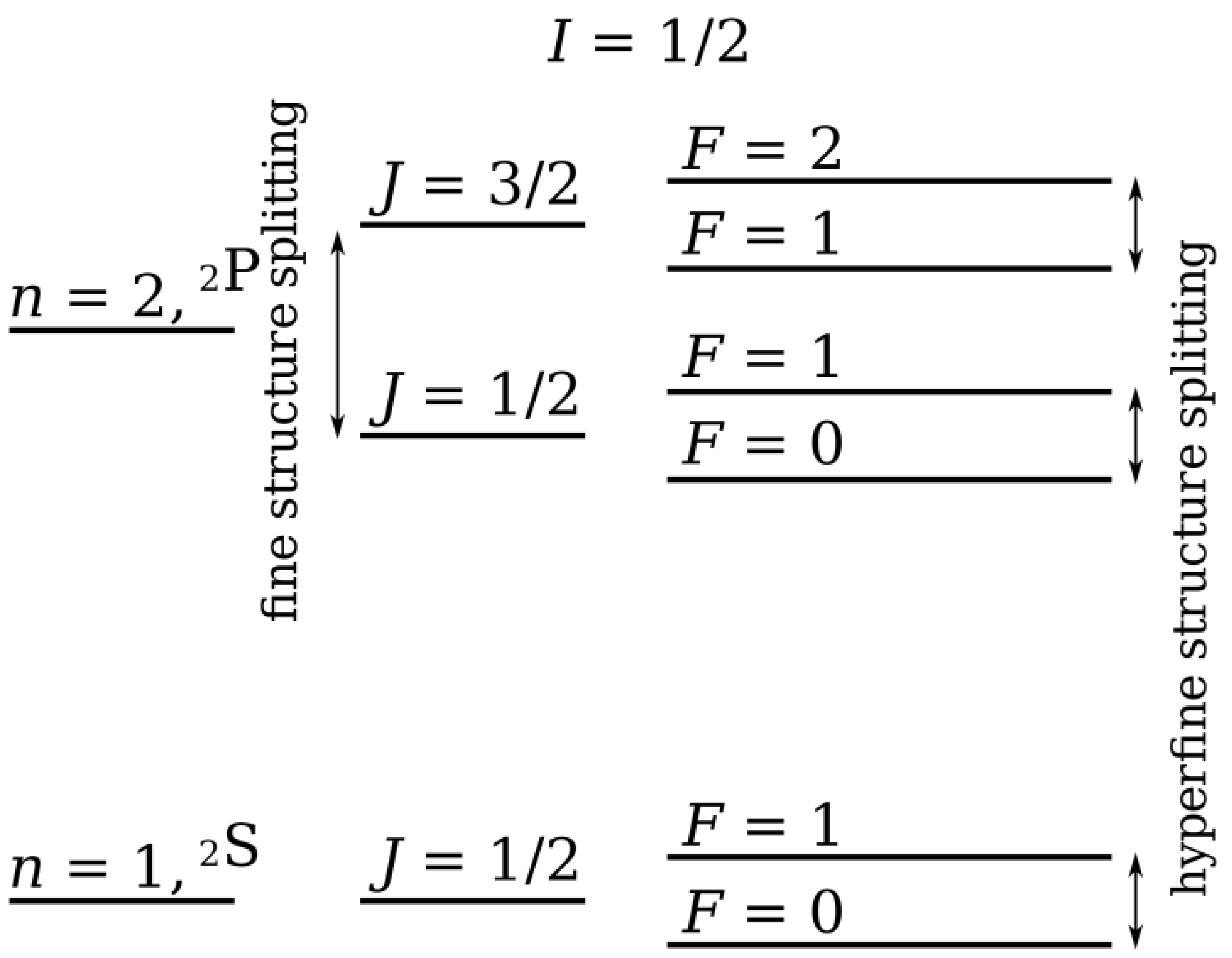
Polarized Beam

Magnetic filed could can polarize quarks by inducing opposite spin polarization for particles and anti-particles due to opposite sign of magnetic moment

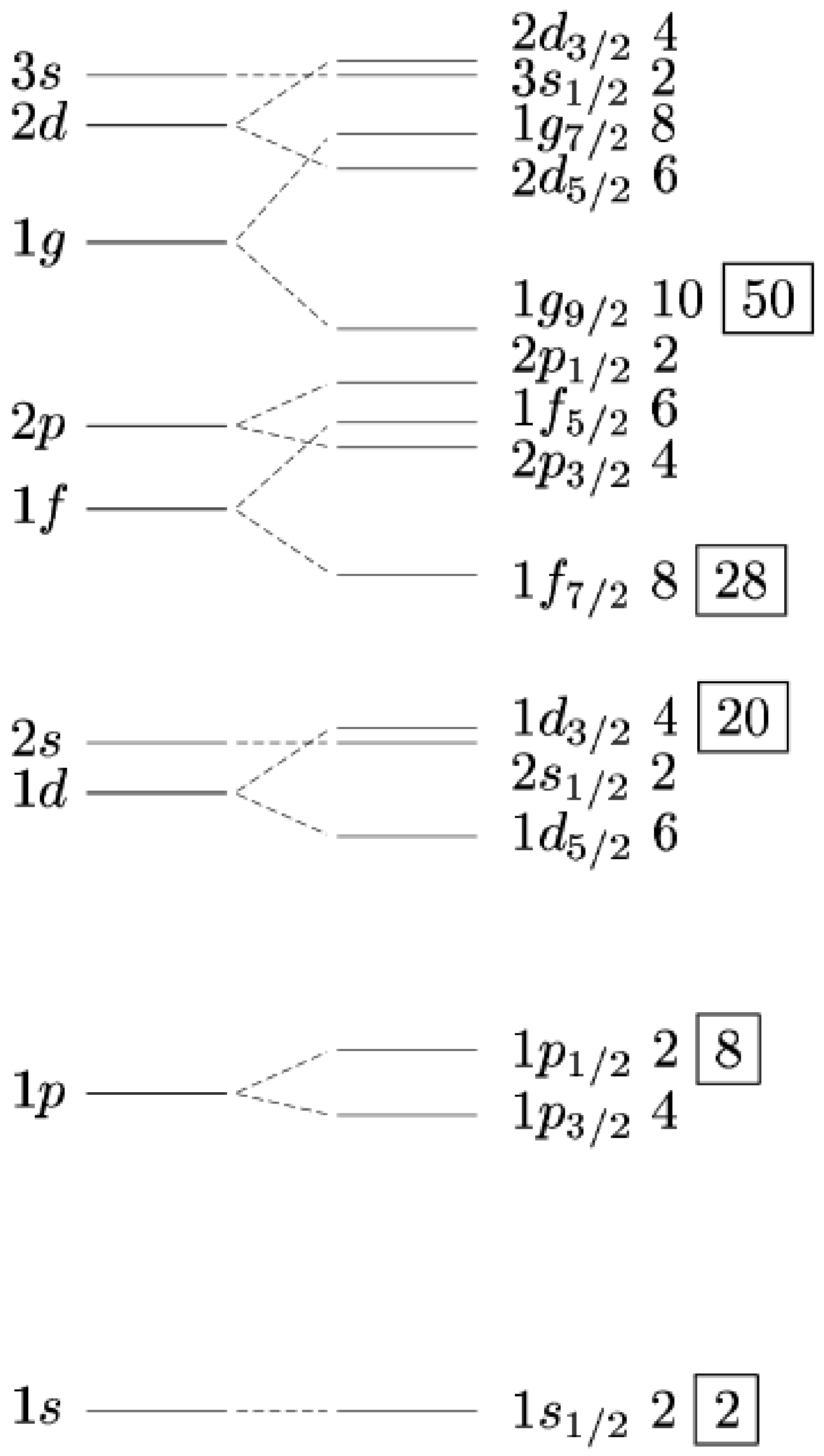
Spin-Orbit Interaction

In quantum physics, the **spin–orbit interaction** **($\hat{s} \cdot (\vec{E} \times \vec{P})$)** a relativistic interaction of a particle's **spin** with its motion inside a **potential**.

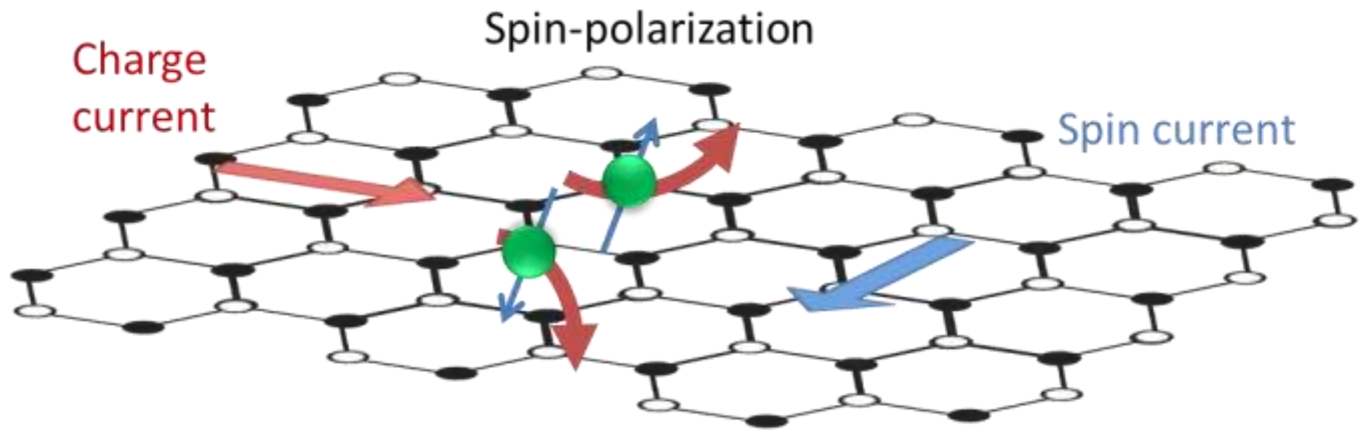
Fine Structure



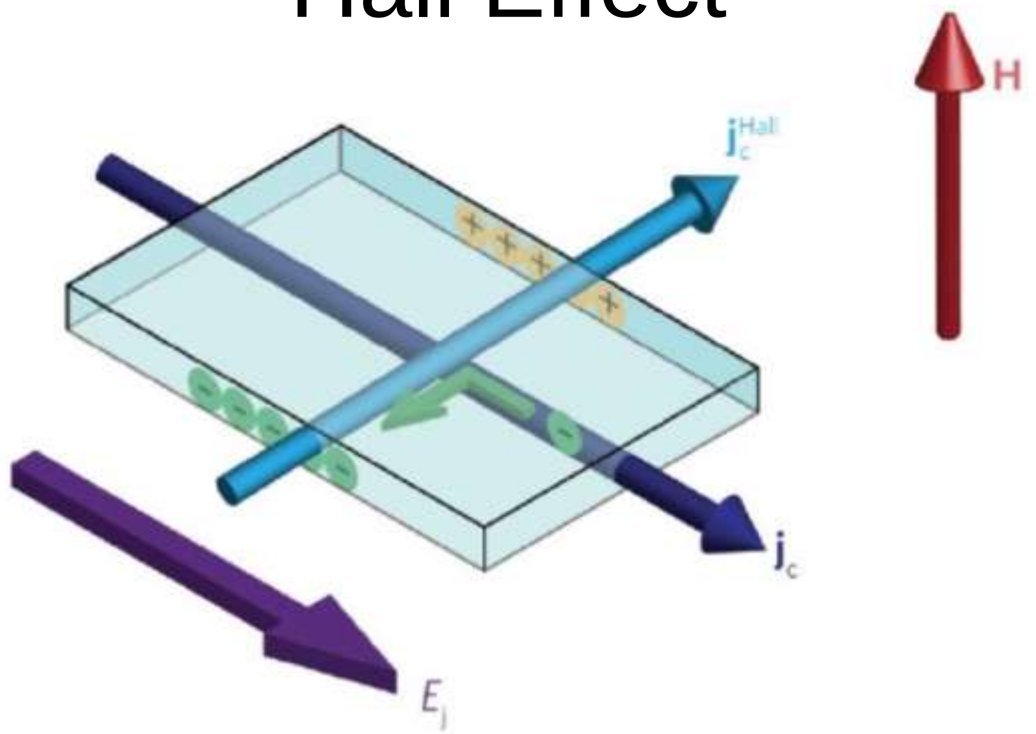
Shell Model



Spin Hall Effect

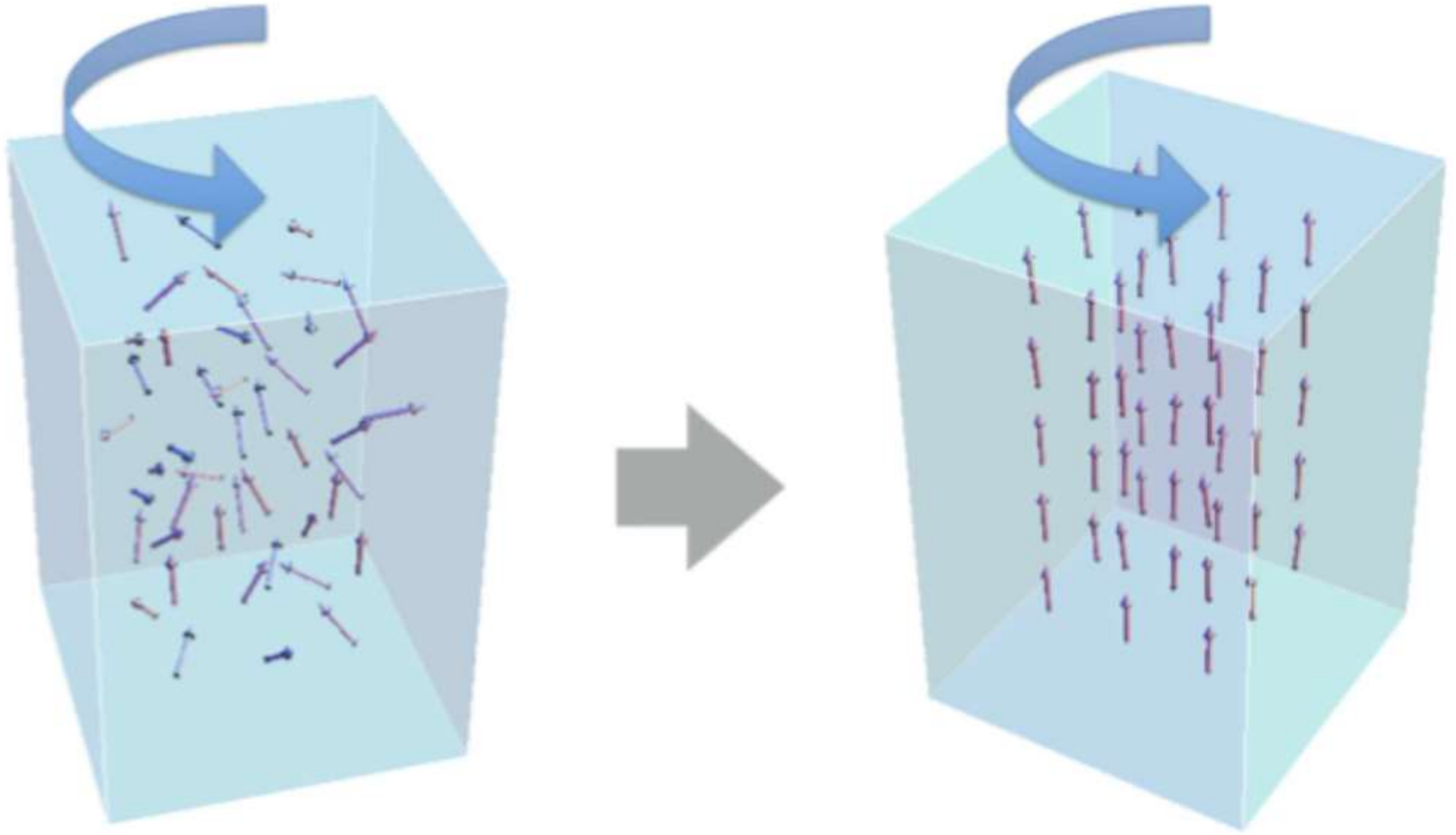


Hall Effect



Barnett Effect and Einstein-de Haas Effect

Barnett Effect

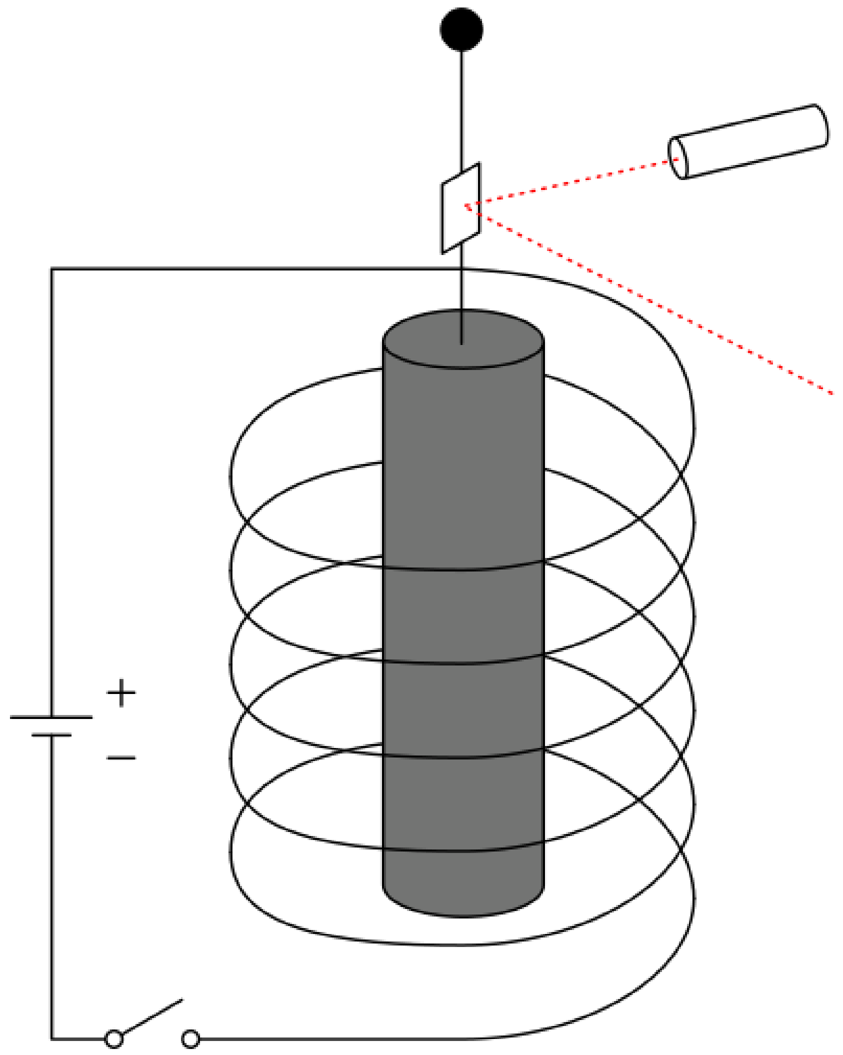


Rotation ➜ Polarization

- Spontaneous magnetization
- Polarization (spin-orbital coupling)

Barnett, Phys. Rev. 6 (4) 239, (1915)
Barnett, Rev. Mod. Phys. 7, 129 (1935)

Einstein-de Haas Effect

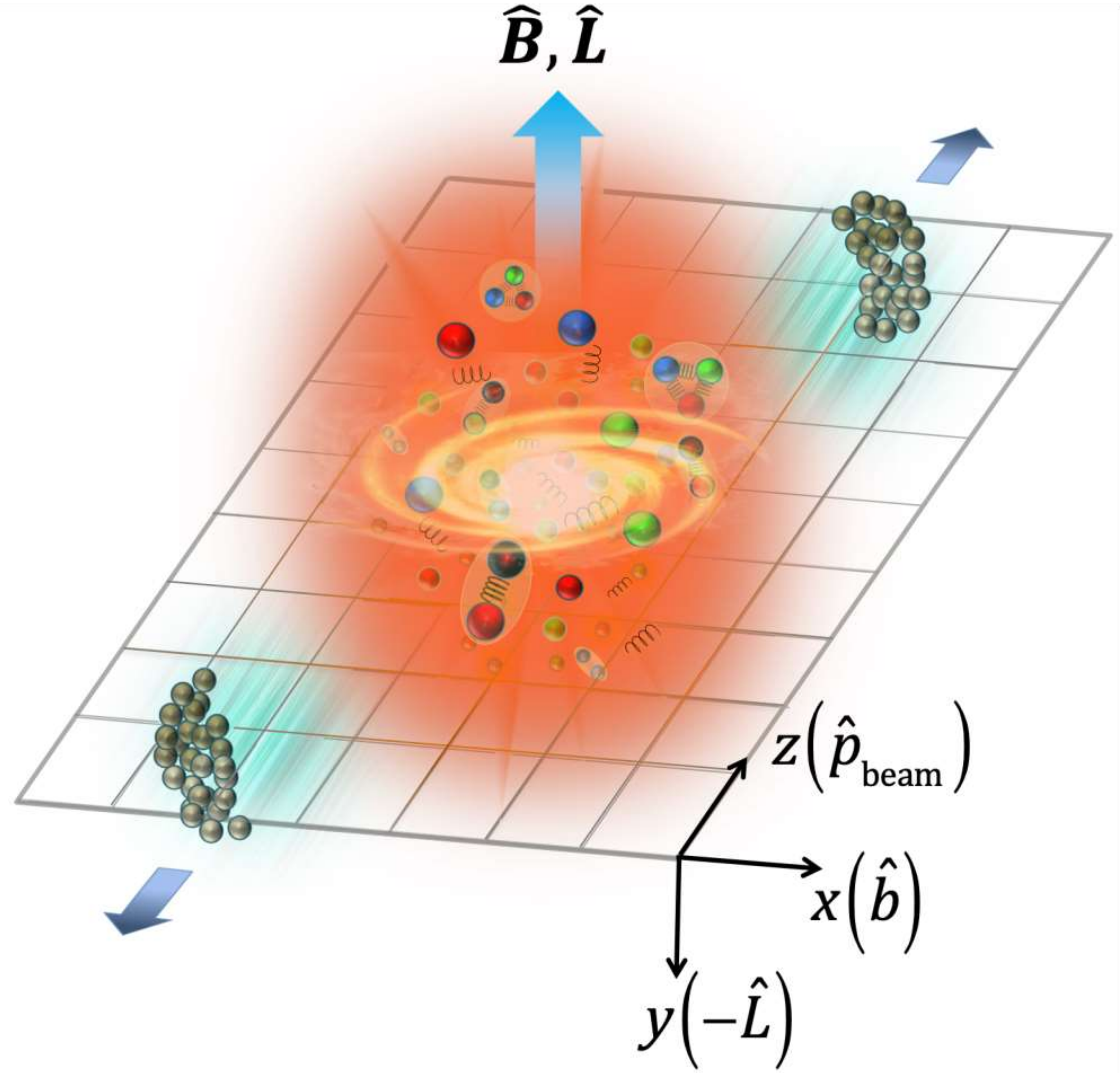


Polarization ➜ Rotation

- Magnetic field causes polarization of electrons
- $\Delta L_{mechanical} = -\Delta L_{electron}$

Einstein, de Hass, DPG, Vanhandlungen 17, 152 (1915)

Global Spin Polarization in HIC



- 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]

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

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Editor: J.-P. Blaizot

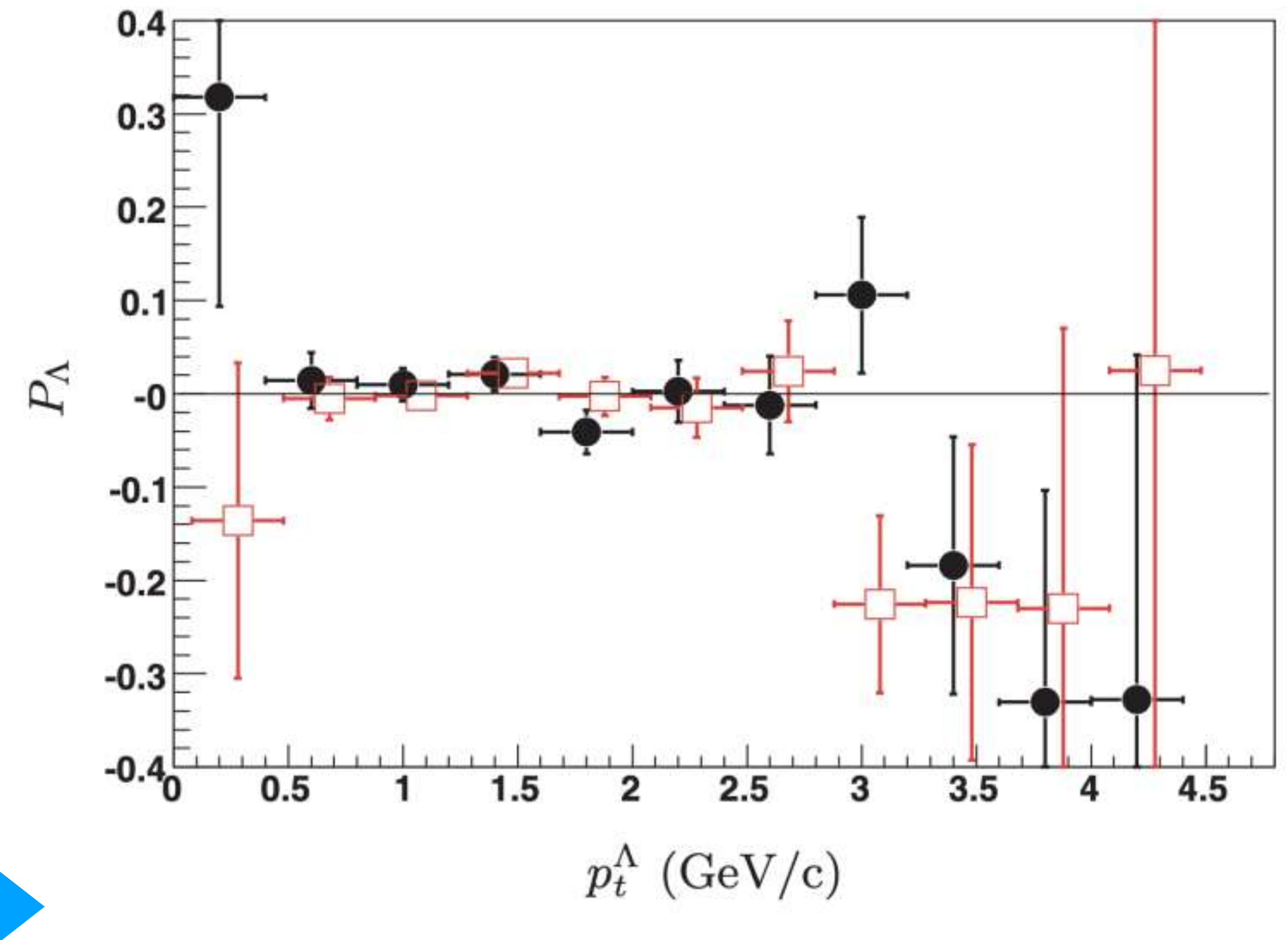
Abstract

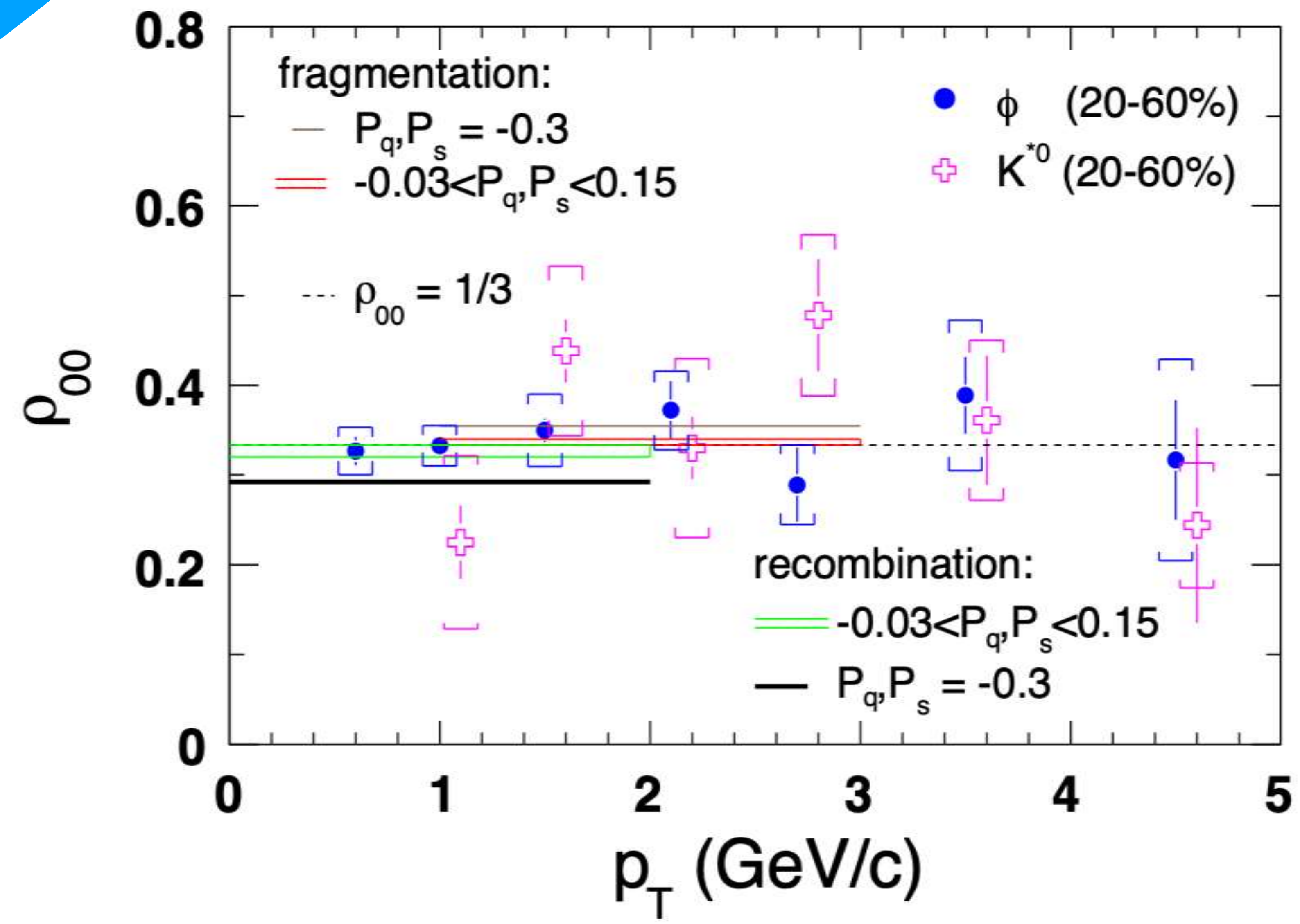
We discuss the consequence of global polarization of the produced quarks in non-central heavy-ion collisions on the spin alignment of vector mesons. We show that the alignment is quite different for different hadronization scenarios. These results can be tested directly by measuring the vector mesons' 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)

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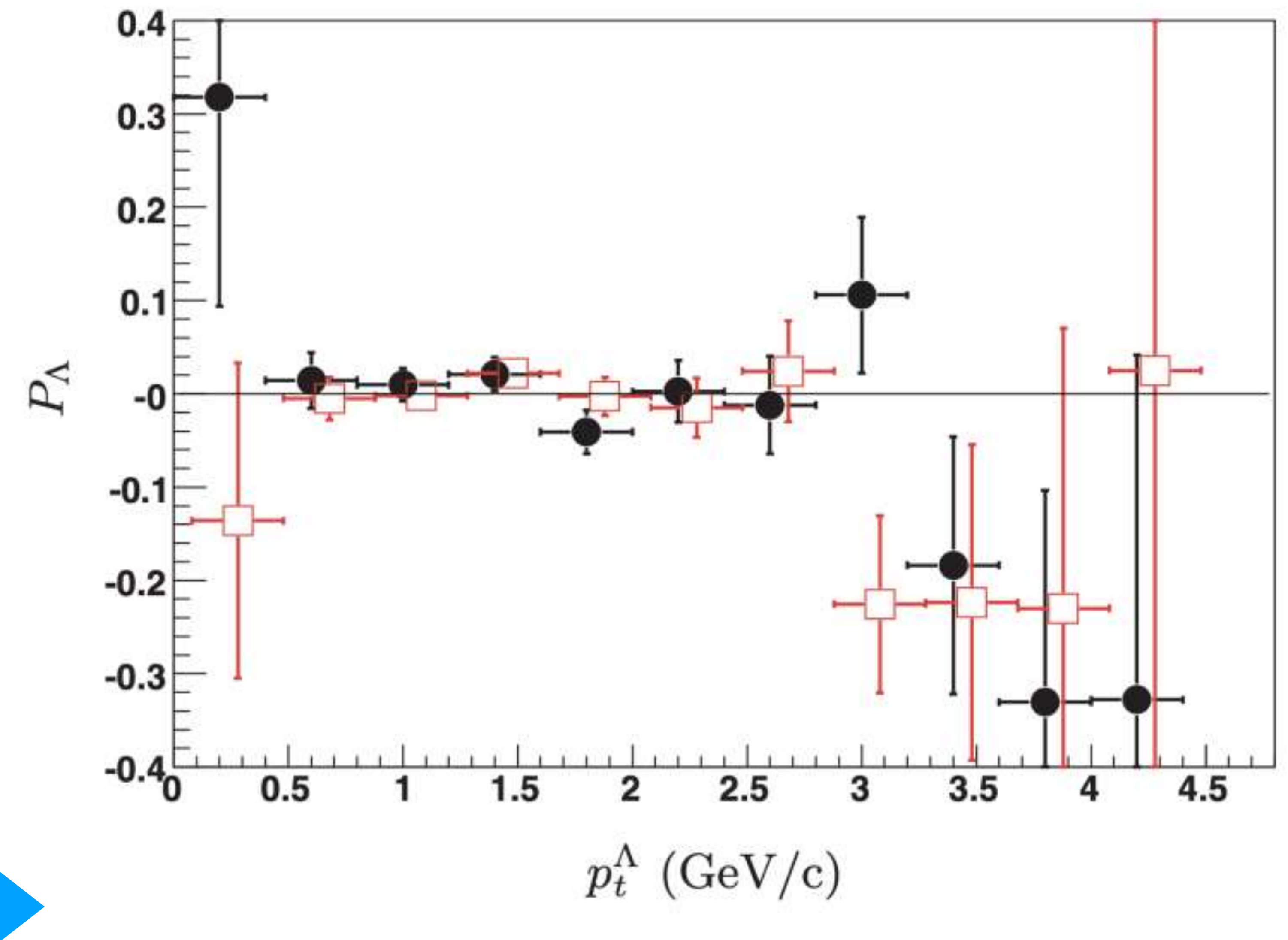

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No significant results reported, due to limited statistics.

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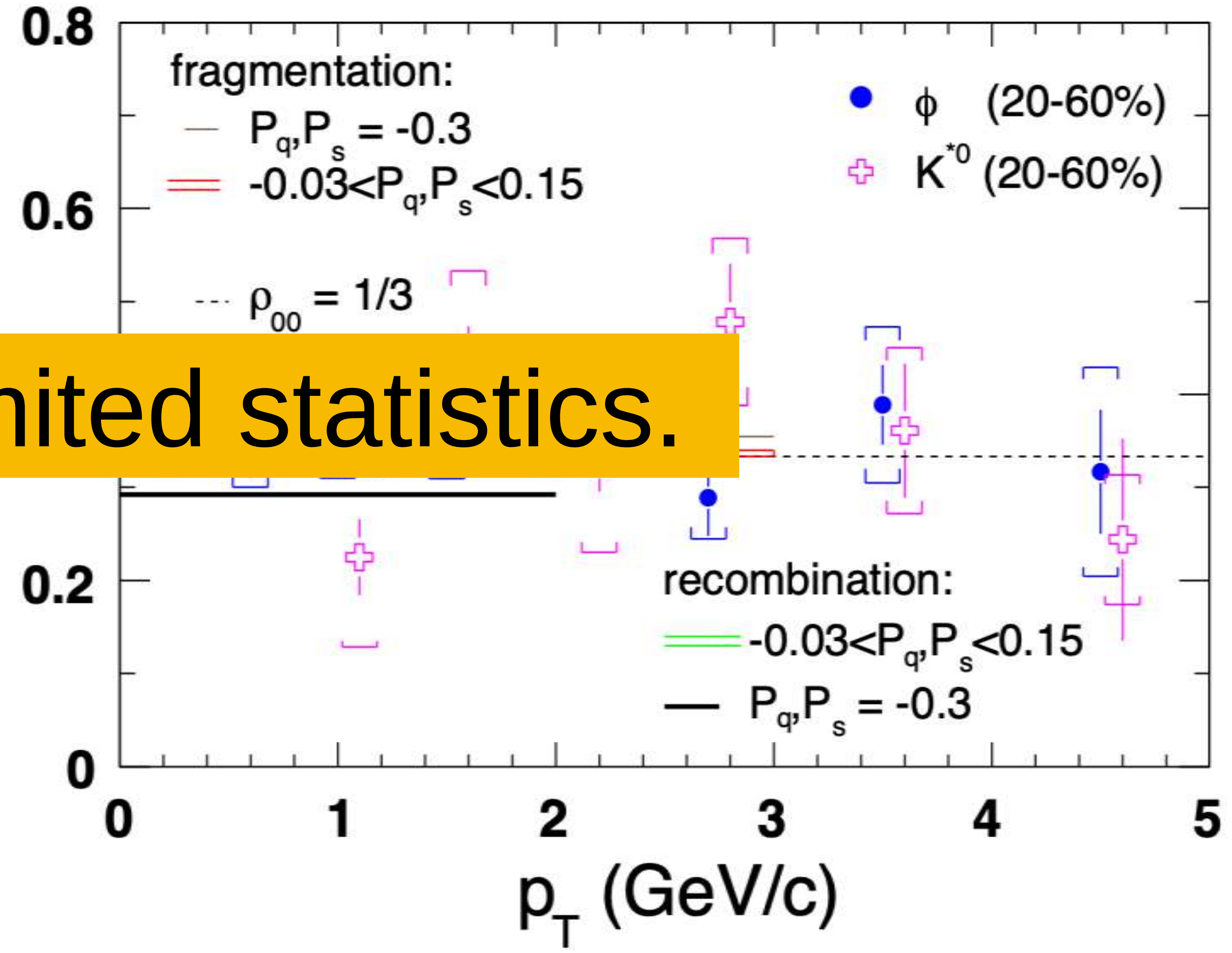
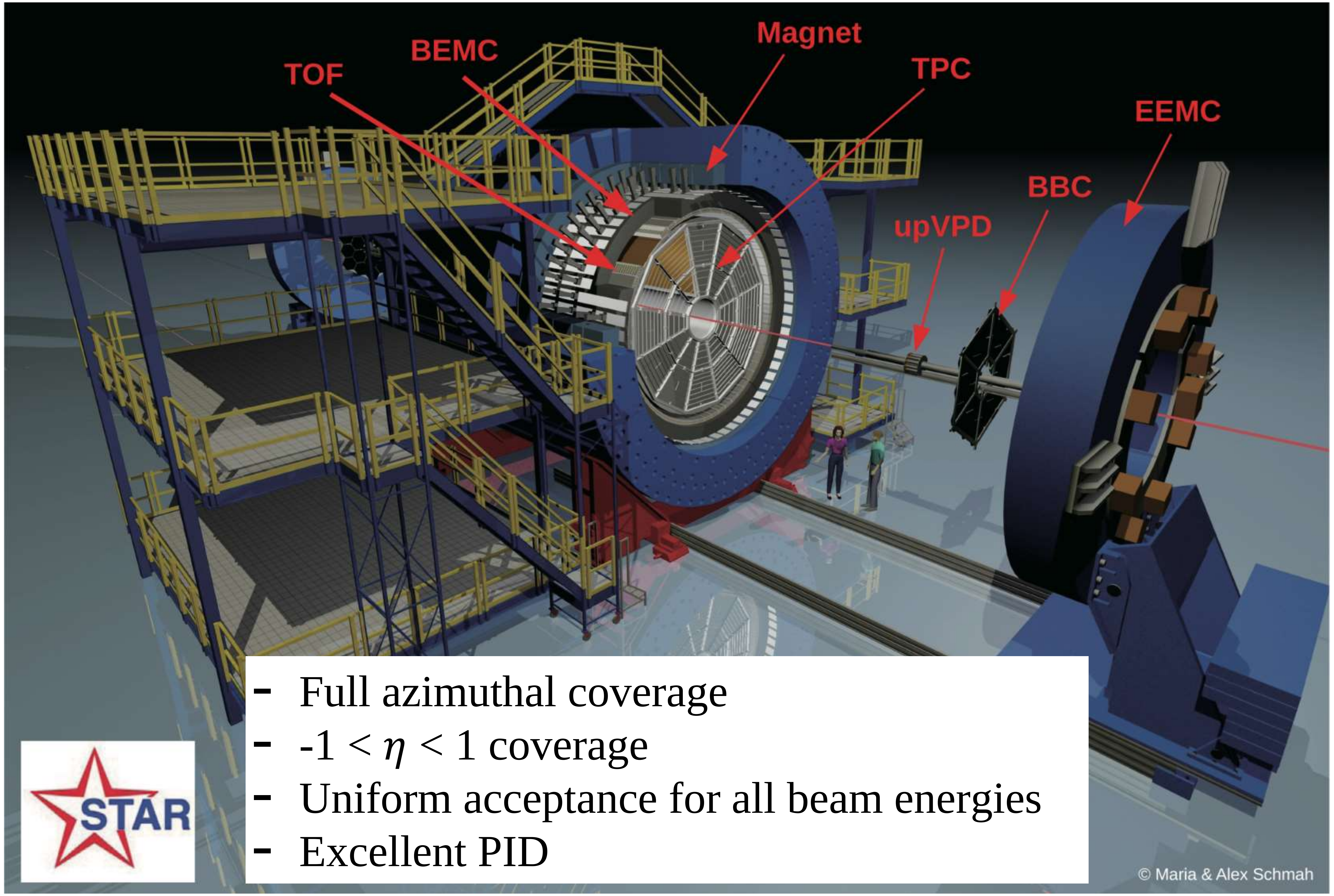


STAR, PRC 77, 061902(R) (2008)

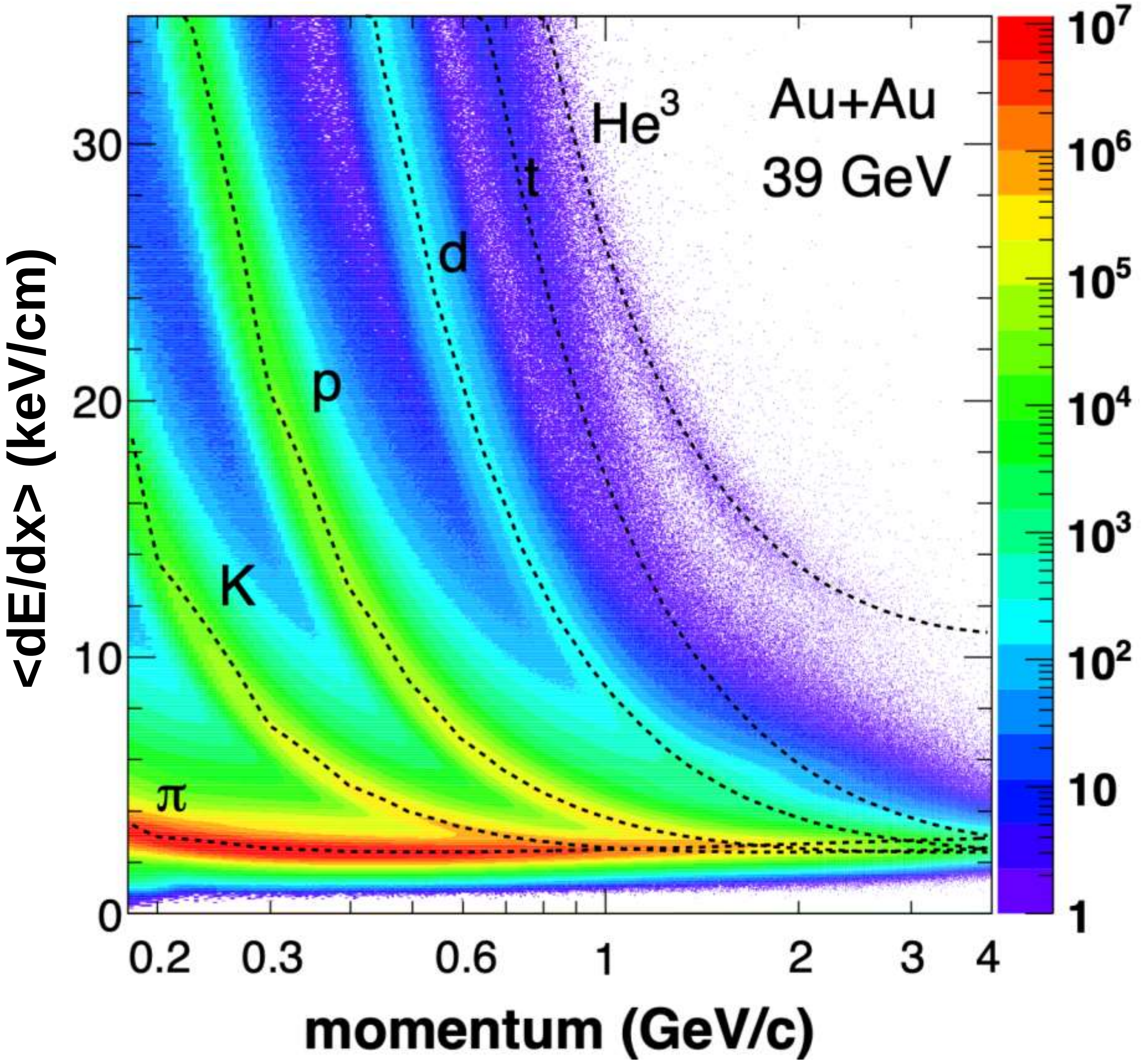
STAR Detector at BESI



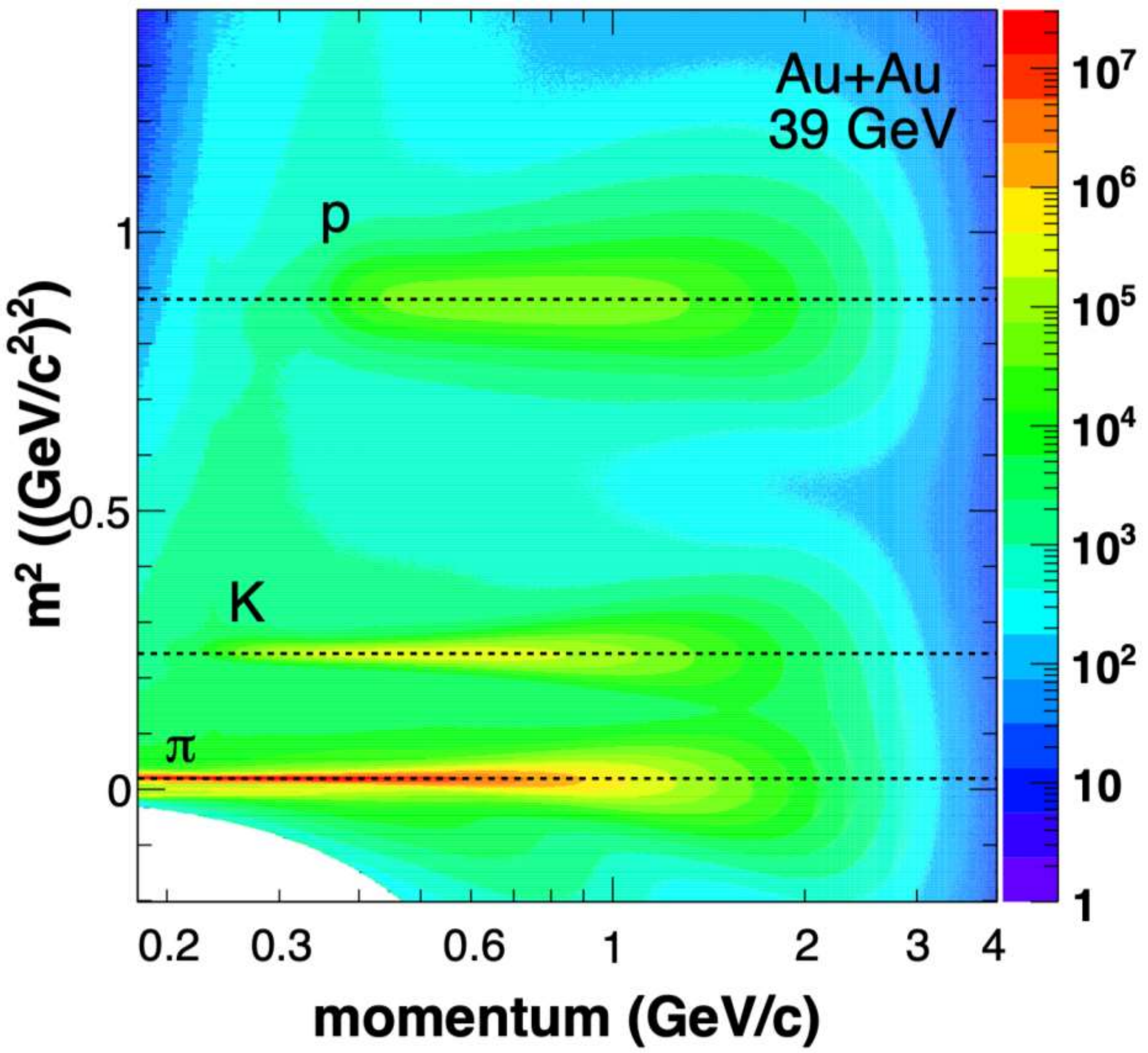
- Full azimuthal coverage
- -1 < η < 1 coverage
- Uniform acceptance for all beam energies
- Excellent PID

Particle Identification

TPC

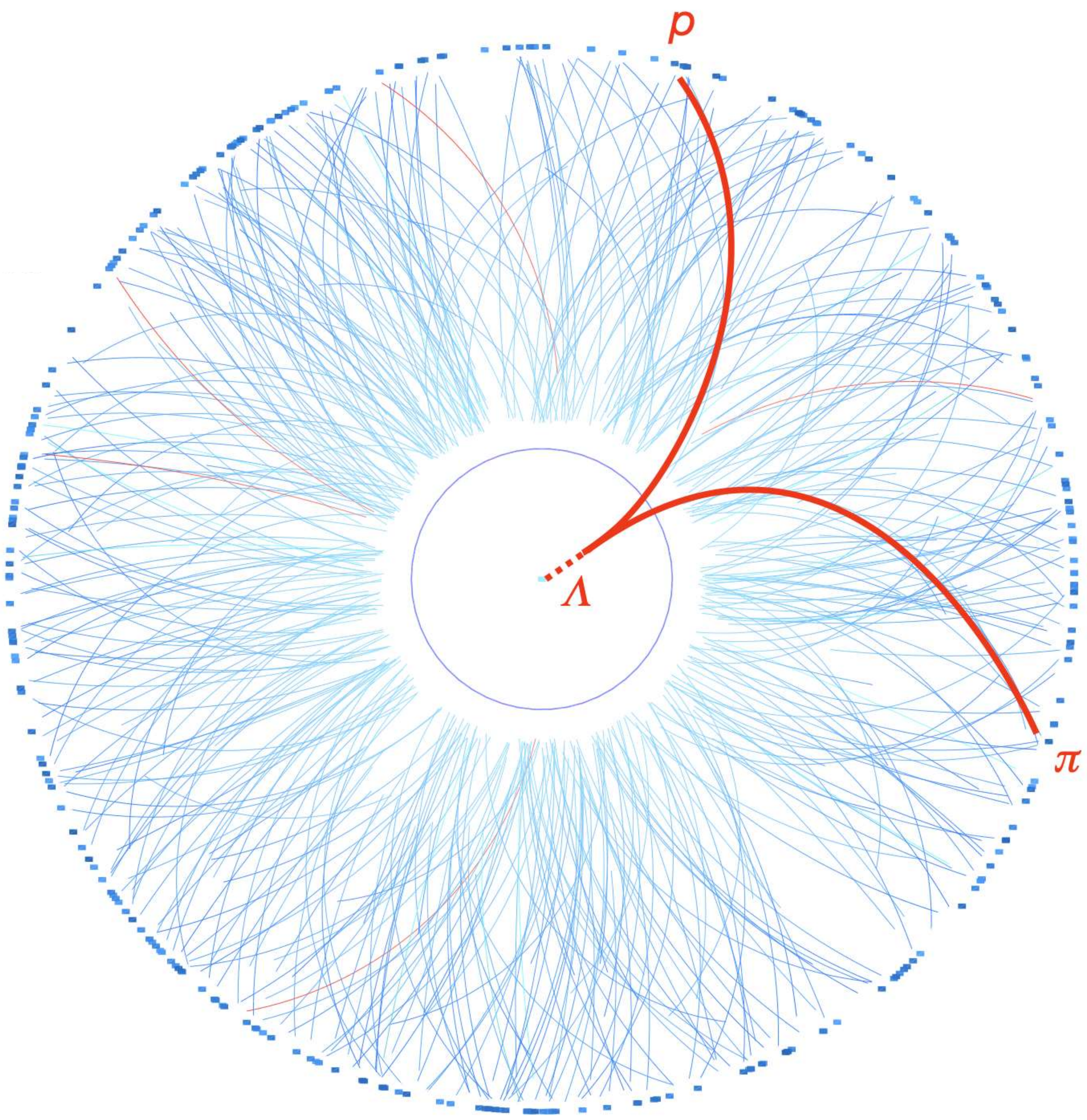


ToF

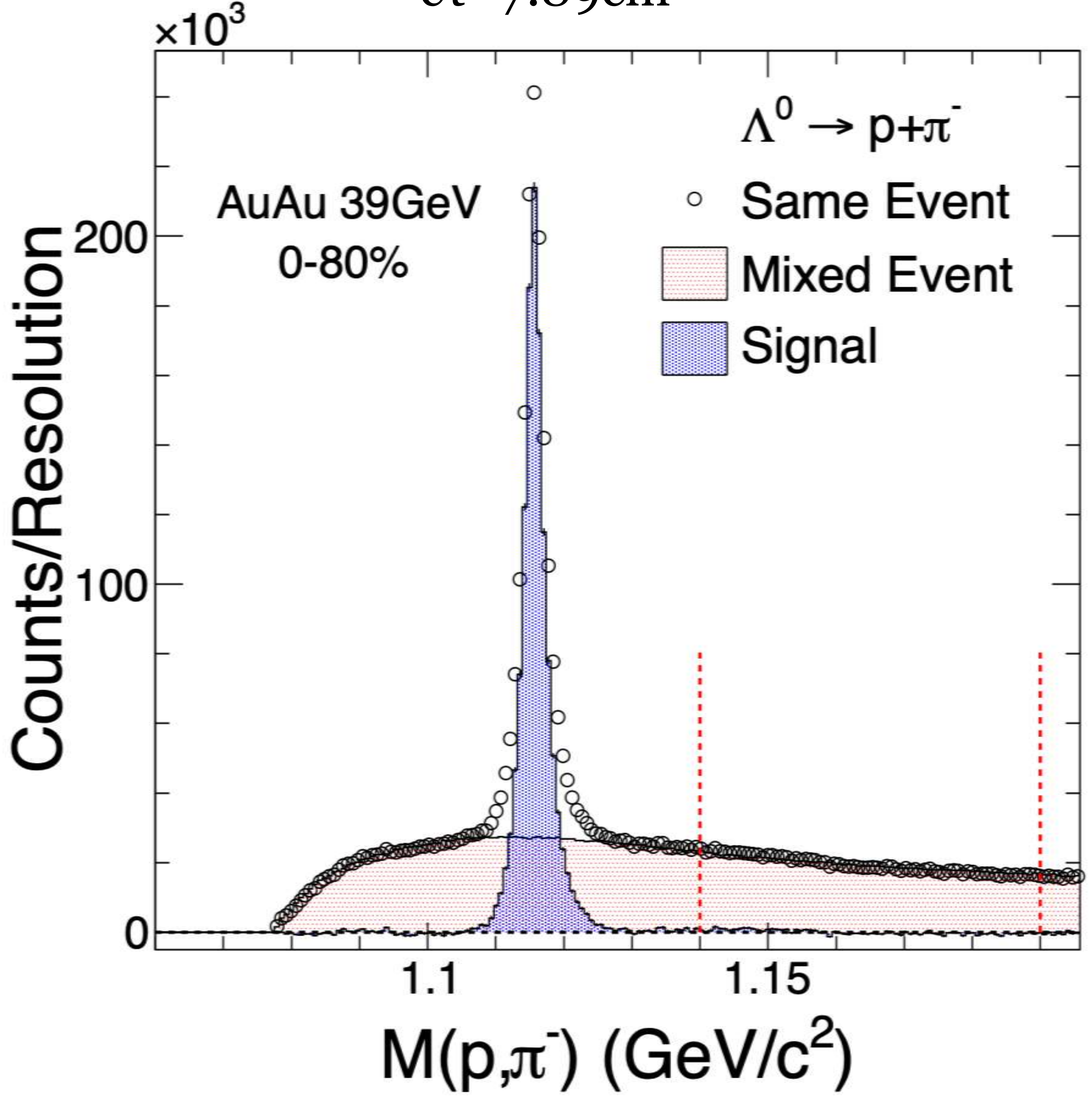


- TPC use energy loss information to identify particles
- ToF measures time of flight to calculate particle mass

Λ-Hyperon Reconstruction

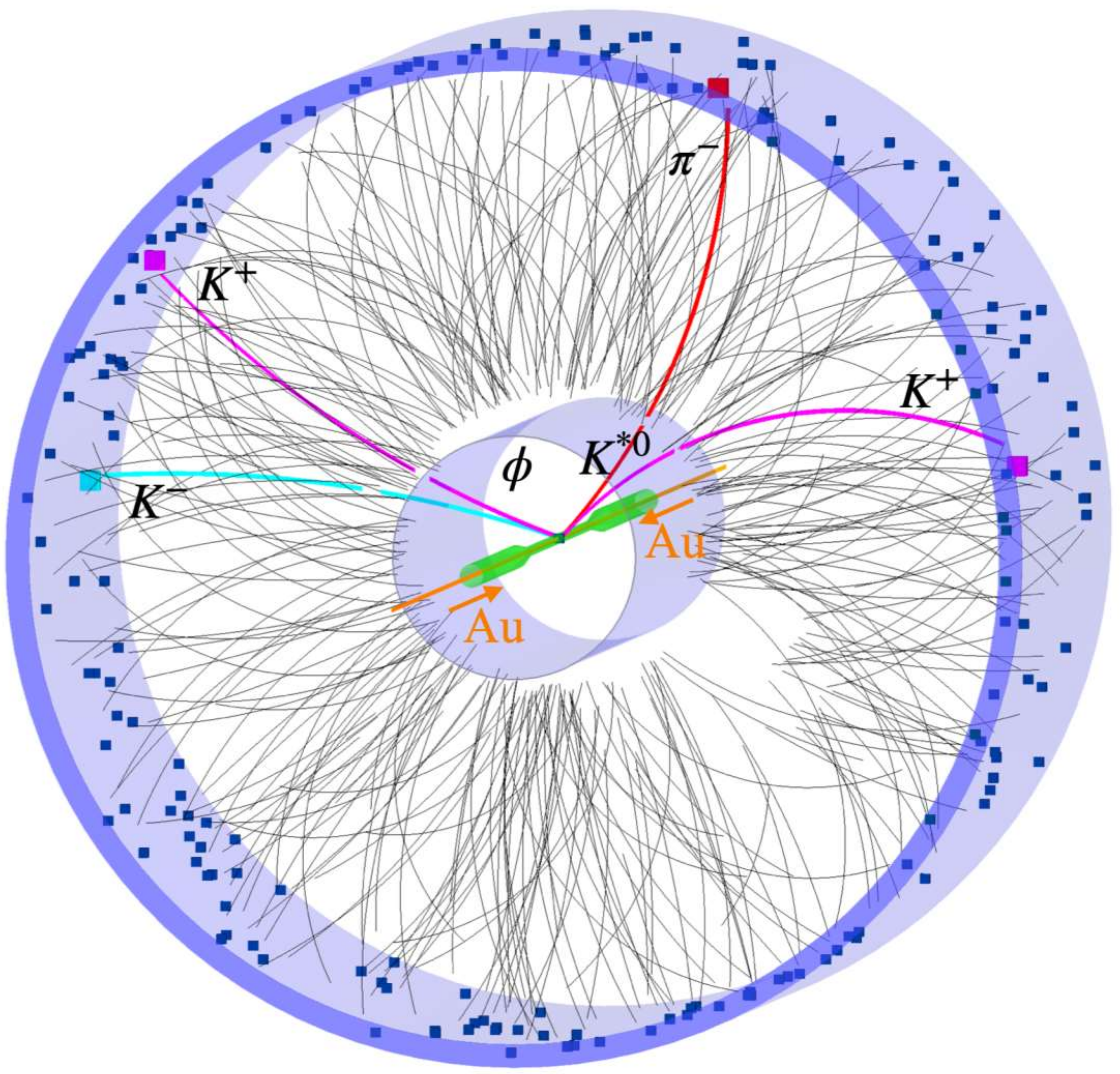


cτ~7.89cm

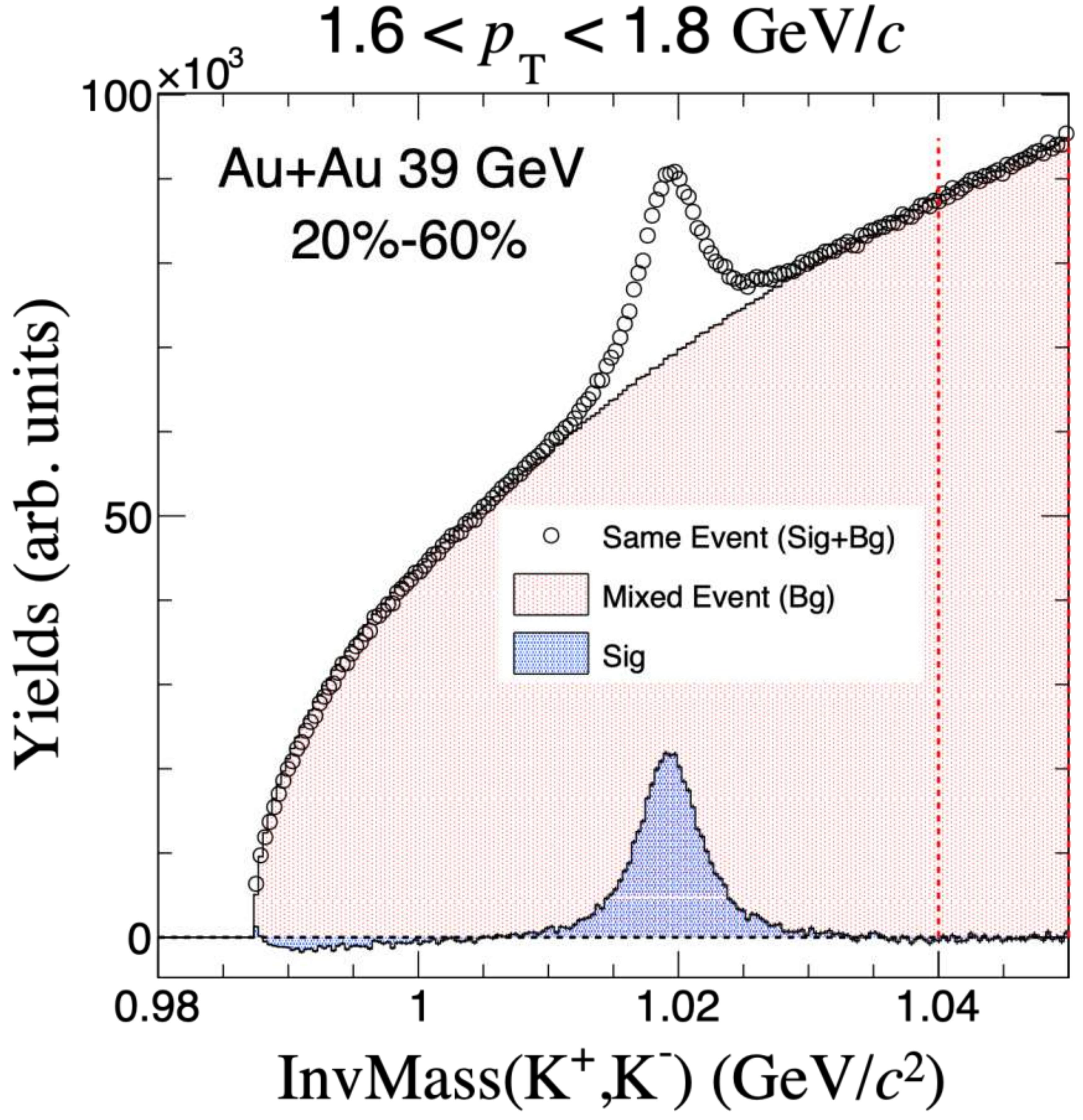


$$\Lambda(uds) \rightarrow p + \pi^-$$

ϕ-meson Reconstruction

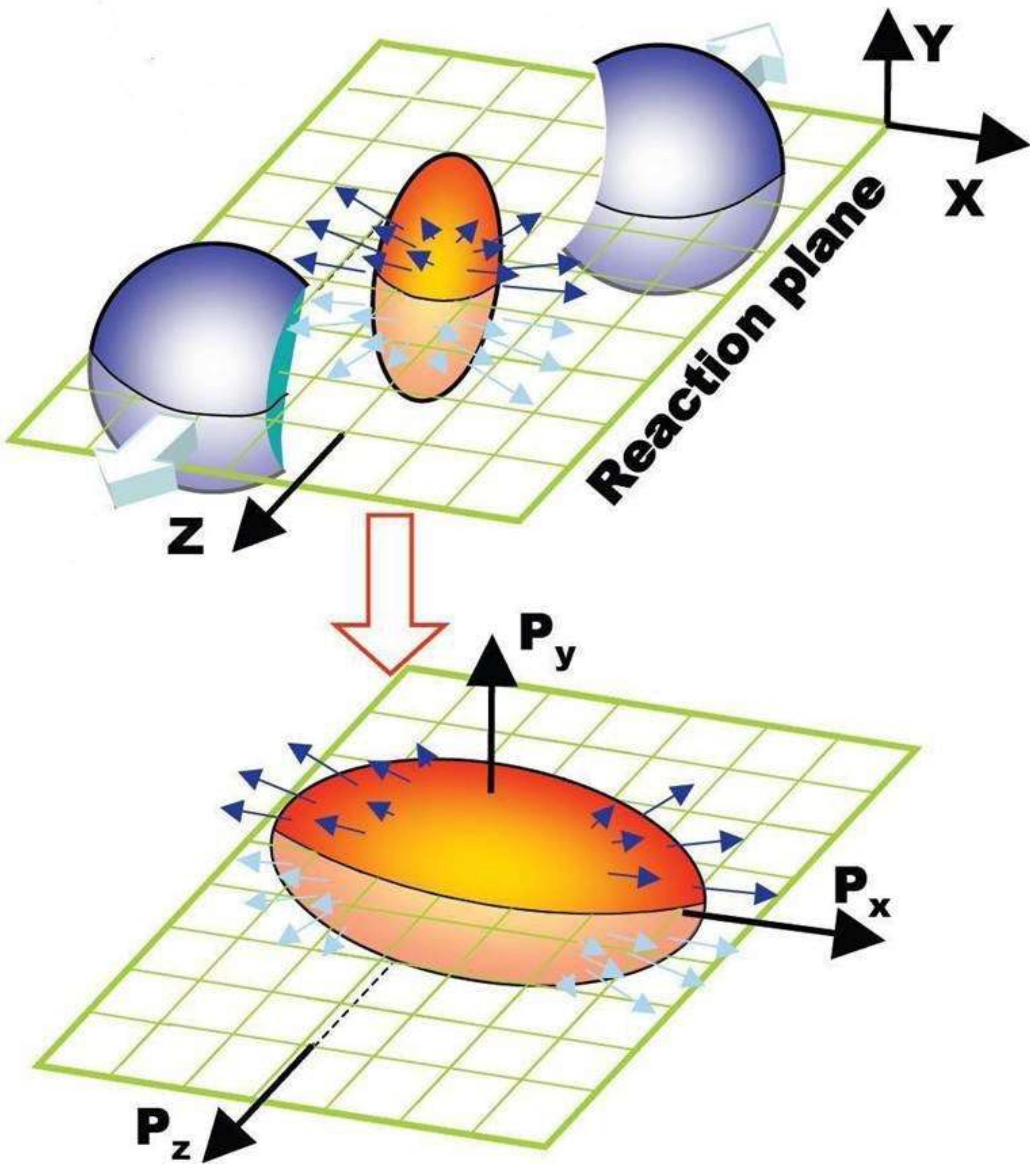


cτ~46.5fm



$$\phi(s\bar{s}) \rightarrow K^+ + K^-$$
$$K^{*0}(d\bar{s}) \rightarrow K^+ + \pi^-$$

Introduction to Collective Flow & Event Plane



$$E\frac{d^3N}{dp^3}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\varphi-\psi_R)]\right)$$

Spatial anisotropy ε_n

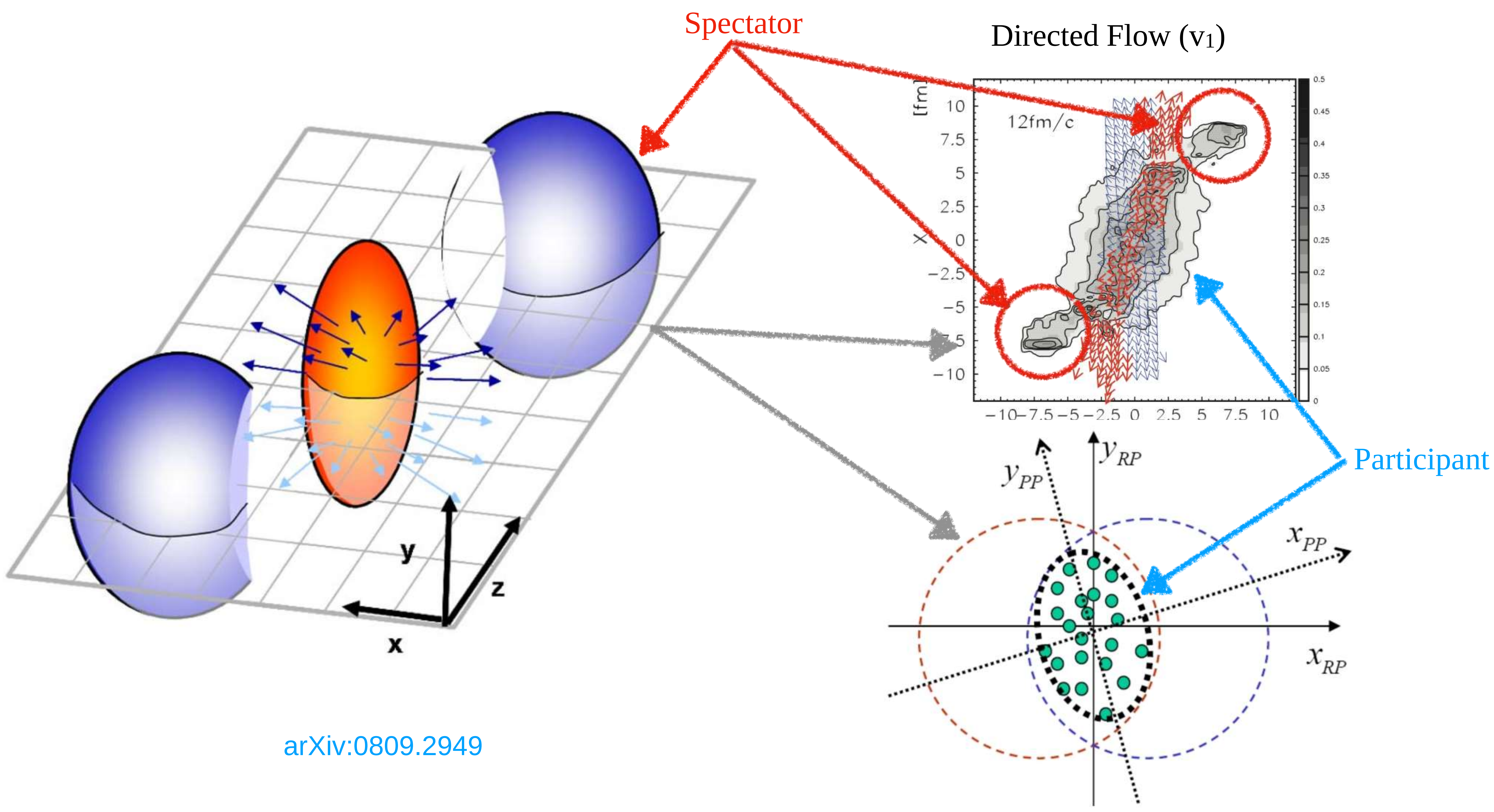
⇩ ⇩

Momentum anisotropy v_n

- Pressure gradient driven evolution
- Sensitive to the early stage evolution

Phys. Rev. C58,1671 (1998)

Different Flow & Event Plane Harmonics



arXiv:0809.2949

Elliptic Flow (v_2)

Experimental Observables: Polarization

STAR, Nature 548, 62 (2017)

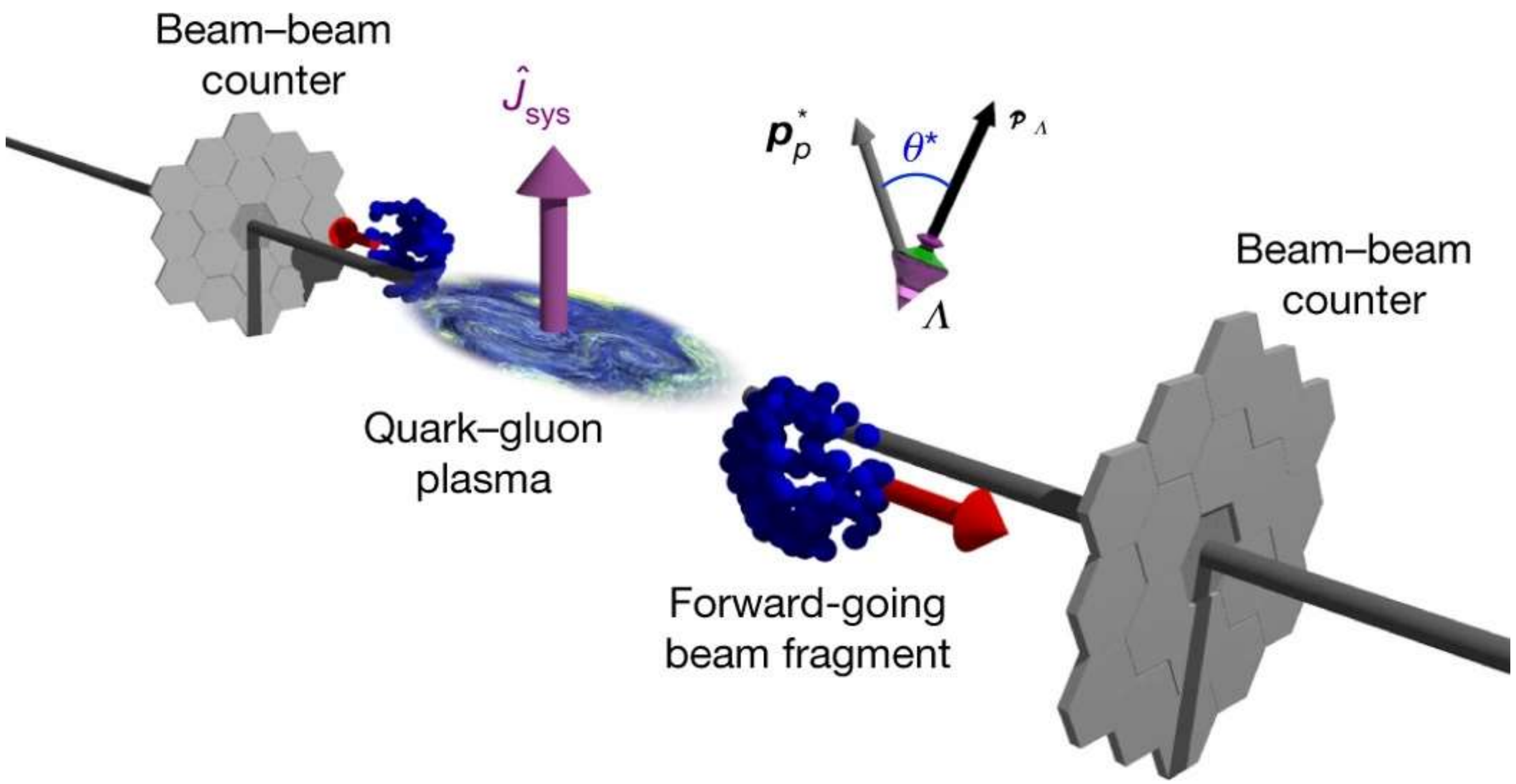
Λ-hyperon (J = 1/2⁺):

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

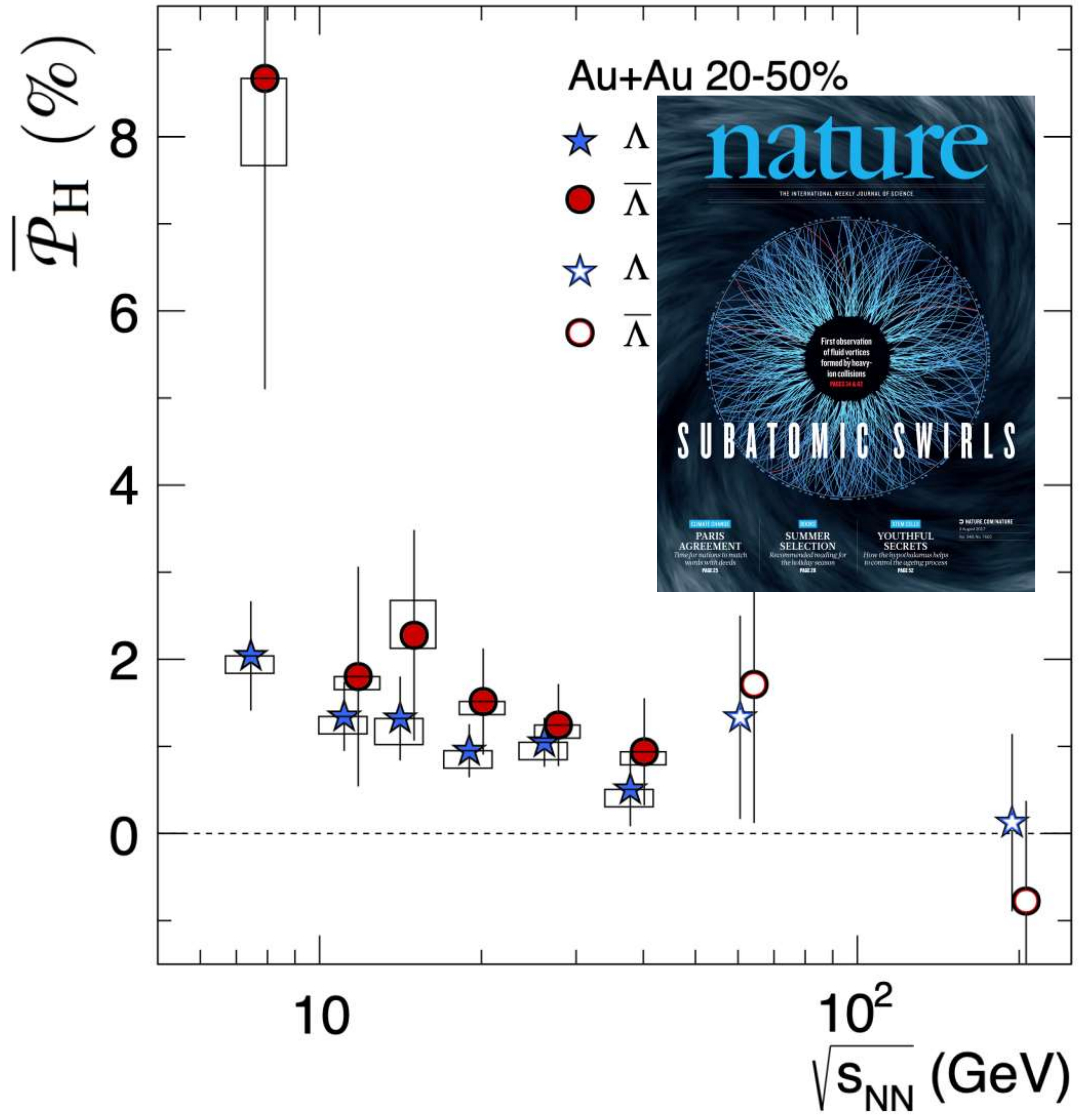
$$\overline{P}_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{\langle \sin(\Psi_1 - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}$$



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

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)

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

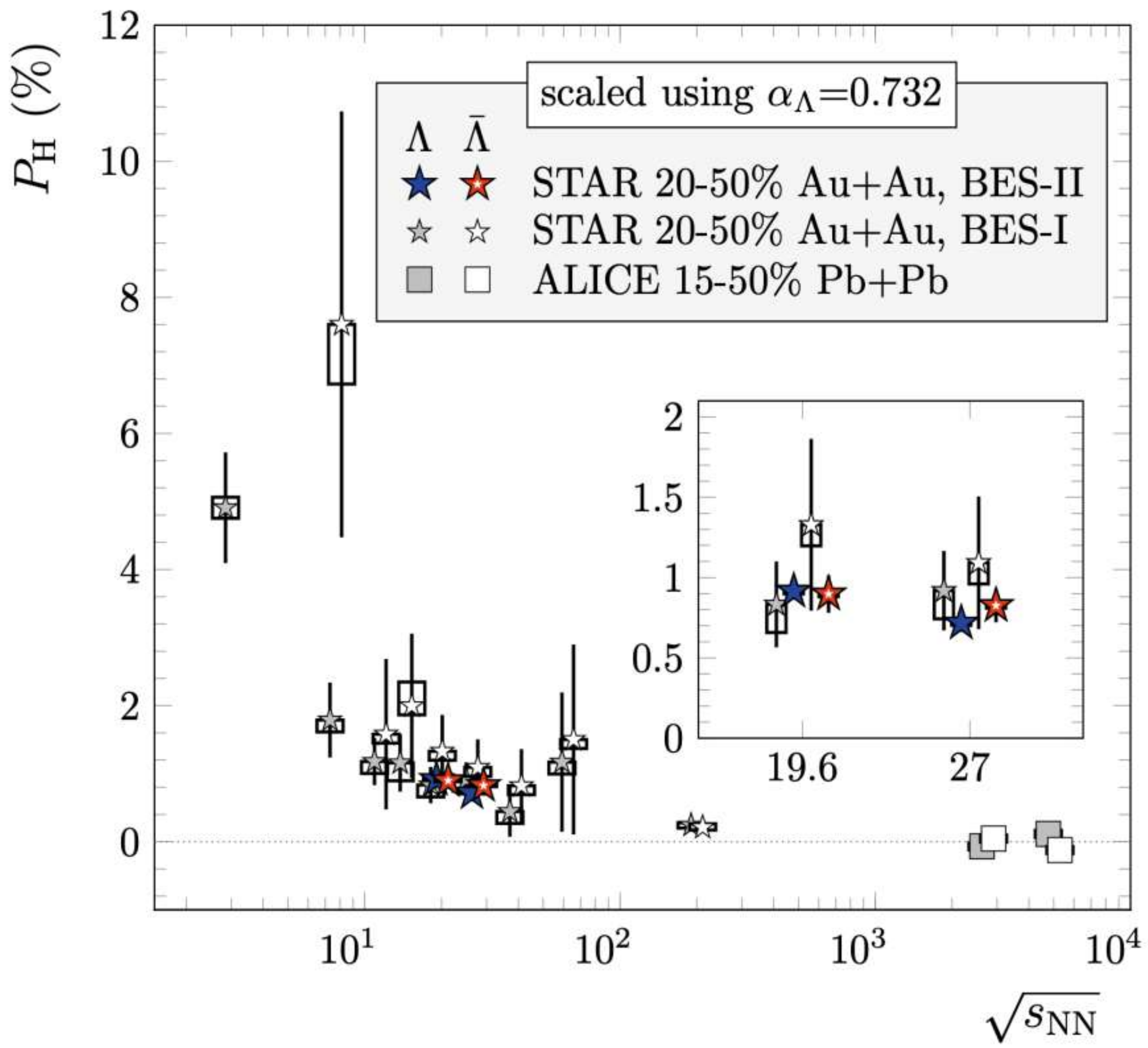
$$\omega \approx k_B T(P_\Lambda + P_{\bar{\Lambda}})/\hbar \sim 10^{22} s^{-1}$$

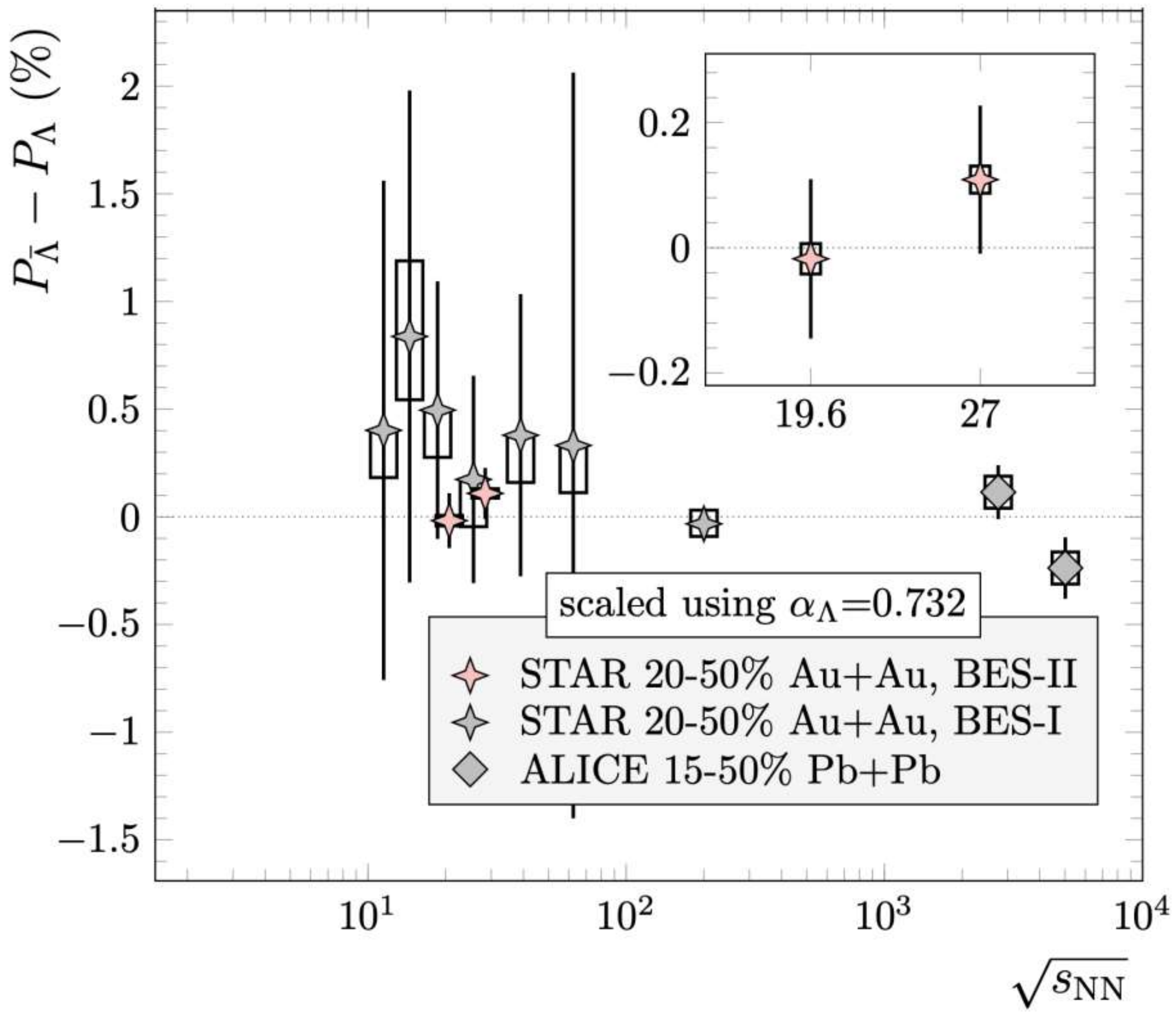
$$|B| \approx \mathrm{T}_s |P_{\bar{\Lambda}} - P_\Lambda| / 2|\mu_\Lambda| \sim ?$$

Most Vortical Fluid!

Λ Global Polarization at BES-II

STAR, PRC 108, 14910 (2023)

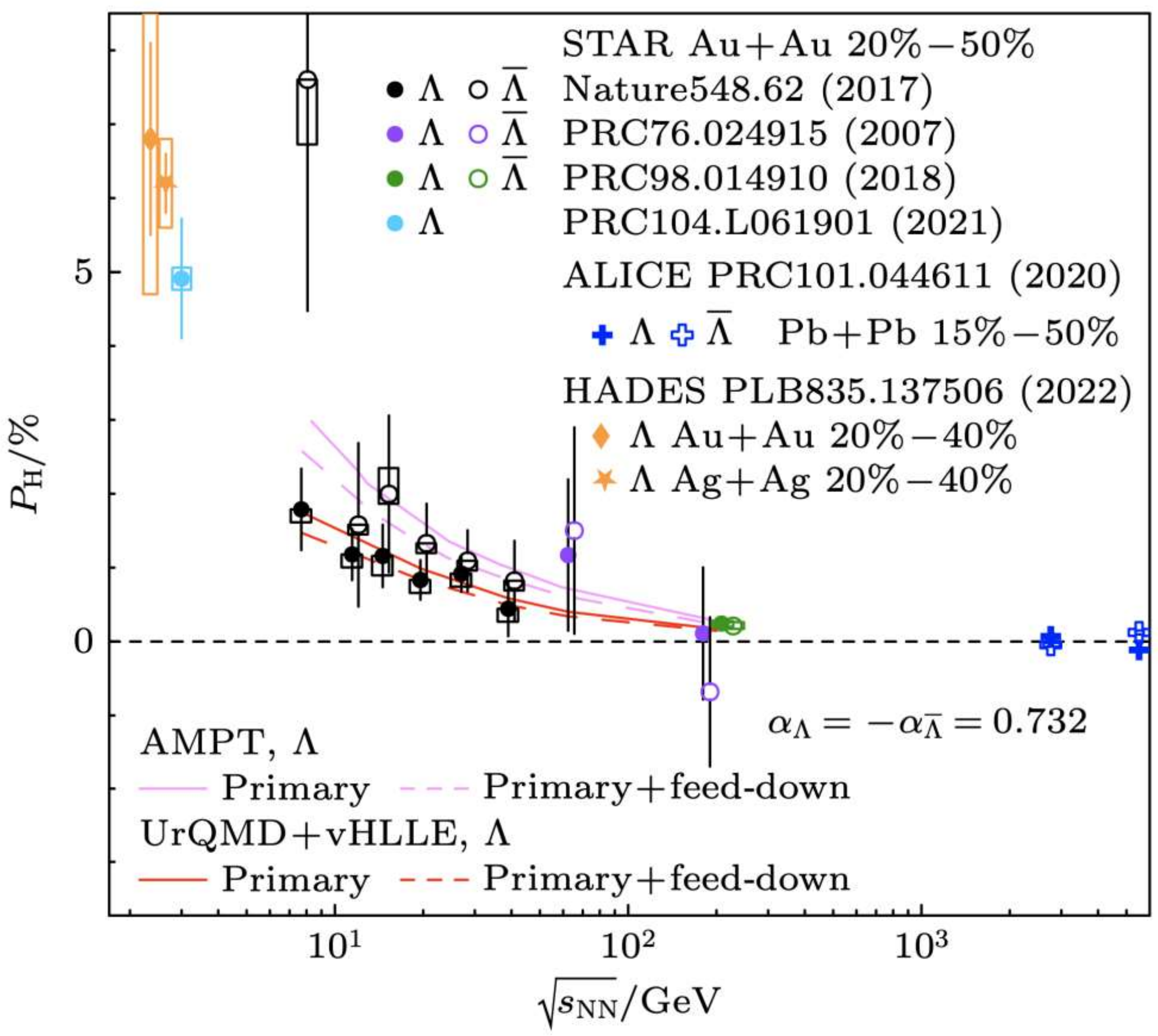


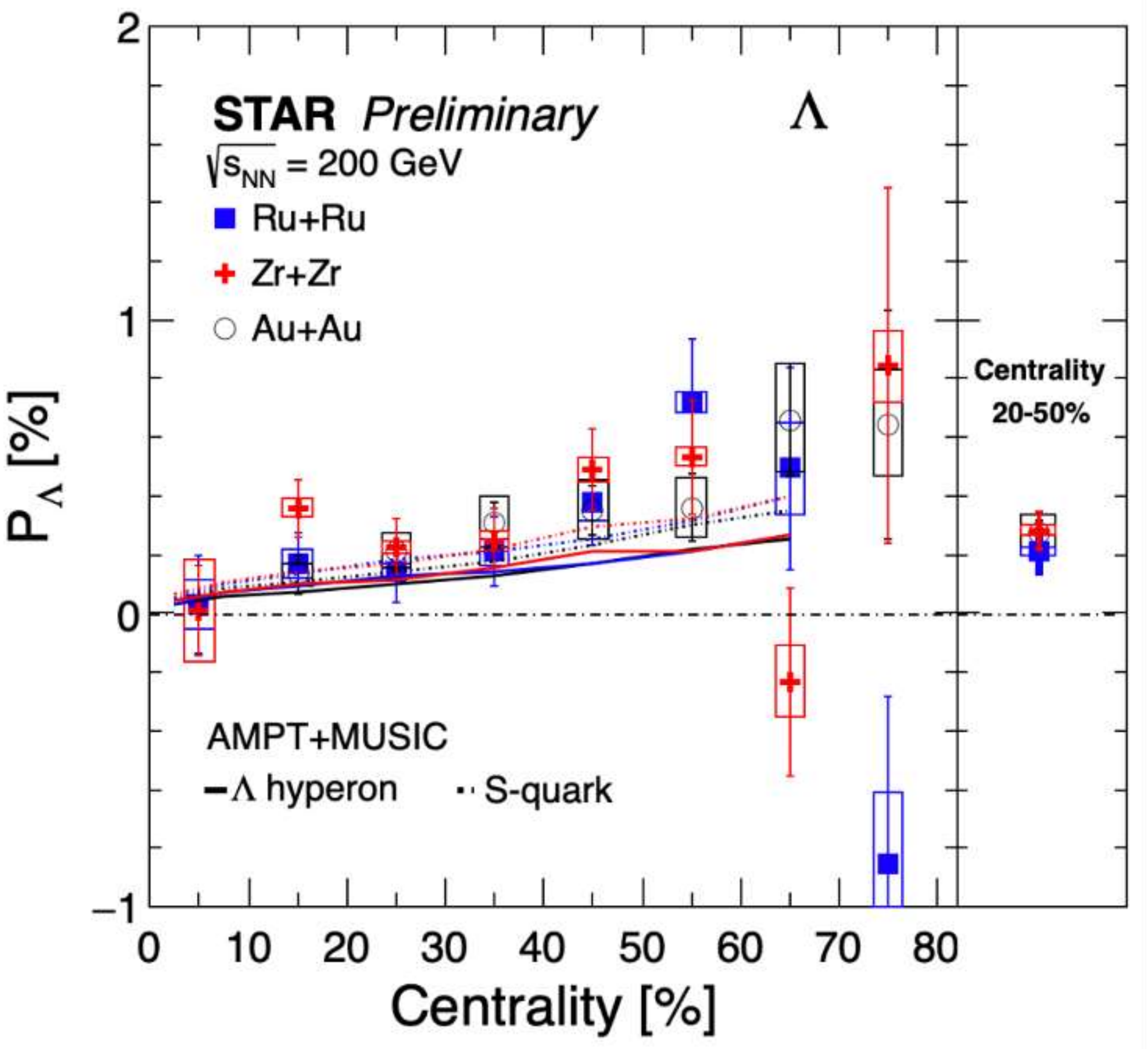


- About 10 times increases in statistics than BES-I
- Upper limit on late stage magnetic field (95% confidence level)
  - B < 9.4×10^{12} T at 19.6 GeV
  - B < 1.4×10^{13} T at 27 GeV

Λ Global Polarization

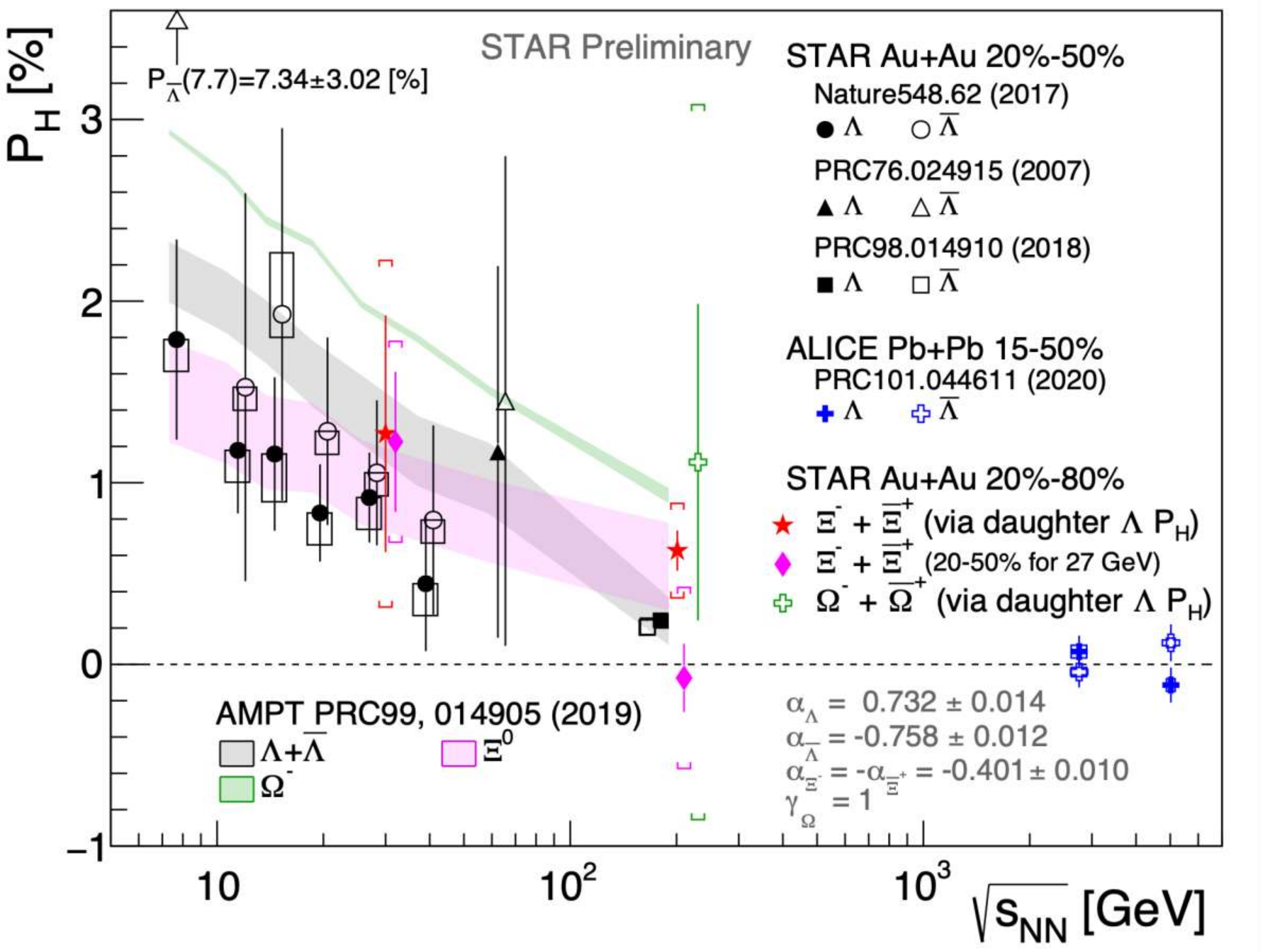
Acta Phys. Sin. Vol. 72, No. 7(2023) 072401





- 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

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



Phys. Rev. Lett. 126. 162301 (2021)

At 200 GeV

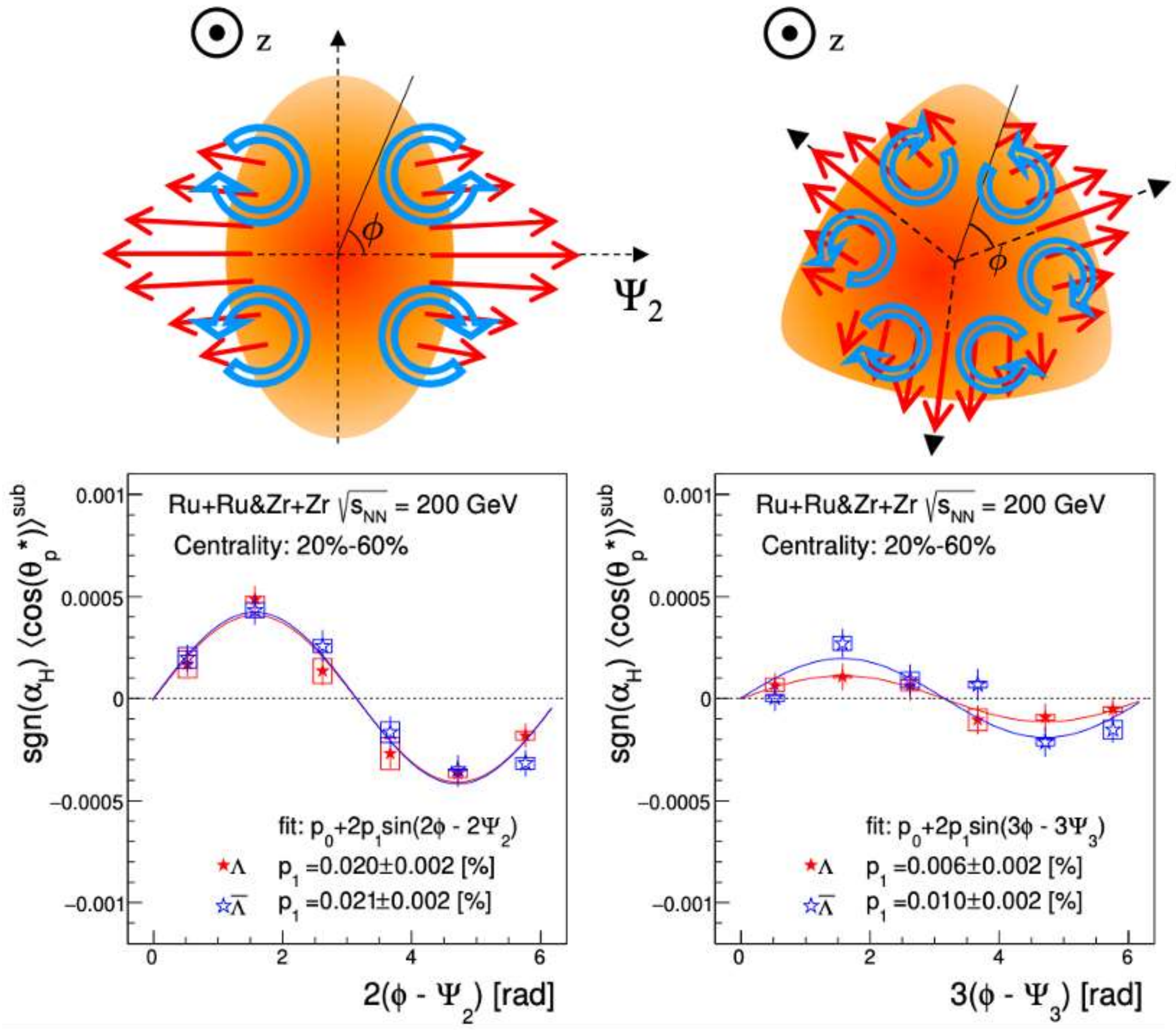
- $P_\Lambda = 0.24 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})\%$
- $P_\Xi = 0.47 \pm 0.10(\text{stat.}) \pm 0.23(\text{syst.})\%$
- $P_\Omega = 1.11 \pm 0.87(\text{stat.}) \pm 1.97(\text{syst.})\%$

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

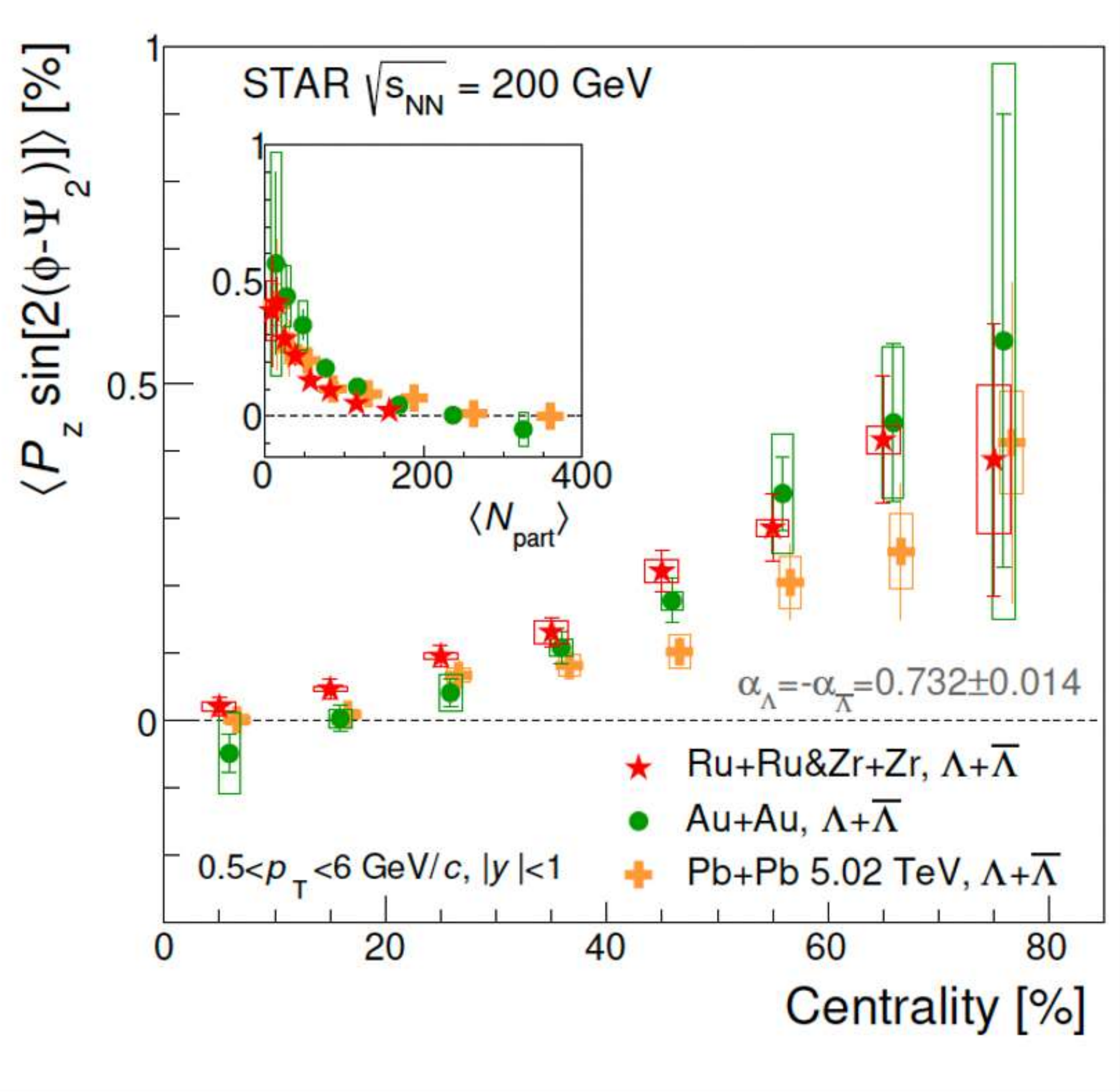
	Mass (GeV/c^2)	Spin	μ_N
Λ (uds)	1.116	1/2	0.613
Ξ (dss)	1.322	1/2	-0.6501
Ω (sss)	1.672	3/2	-2.02

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

Λ Local Polarization



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: $P \propto \pm p \times E$

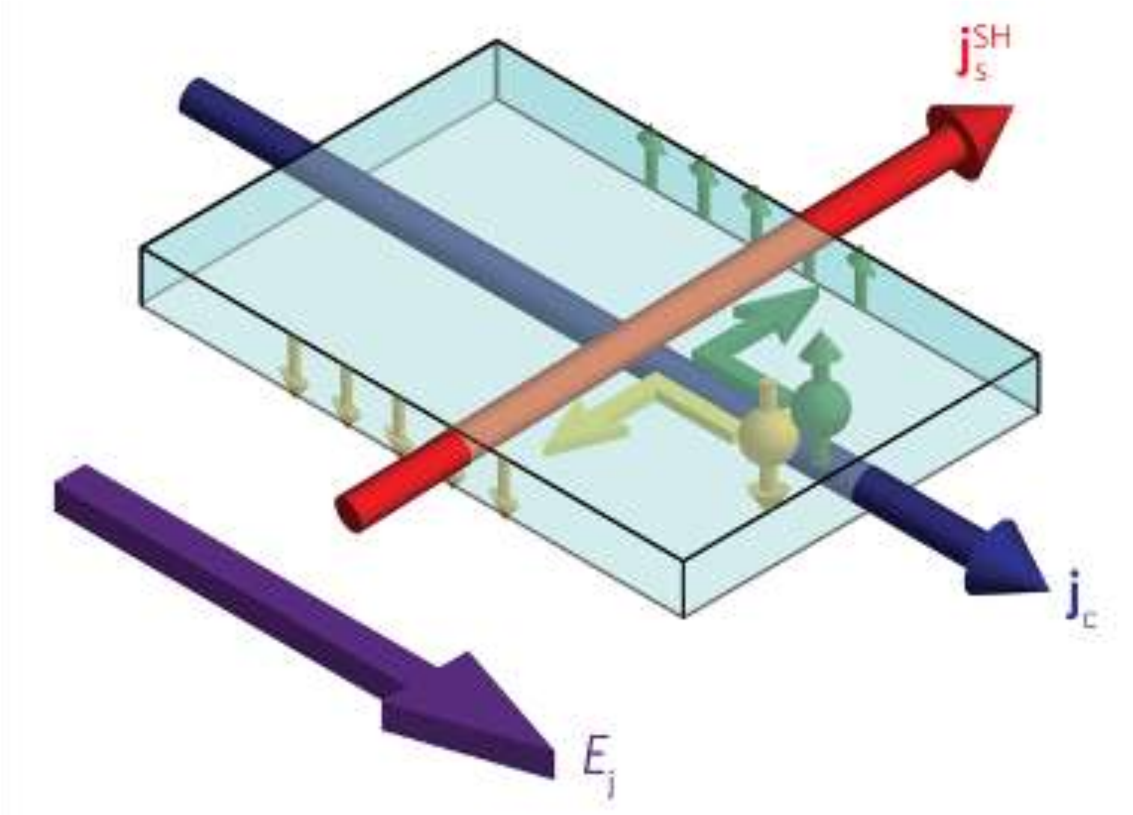
Electric filed (E) —Spin-Orbit Interaction→ Spin splitting in opposite directions

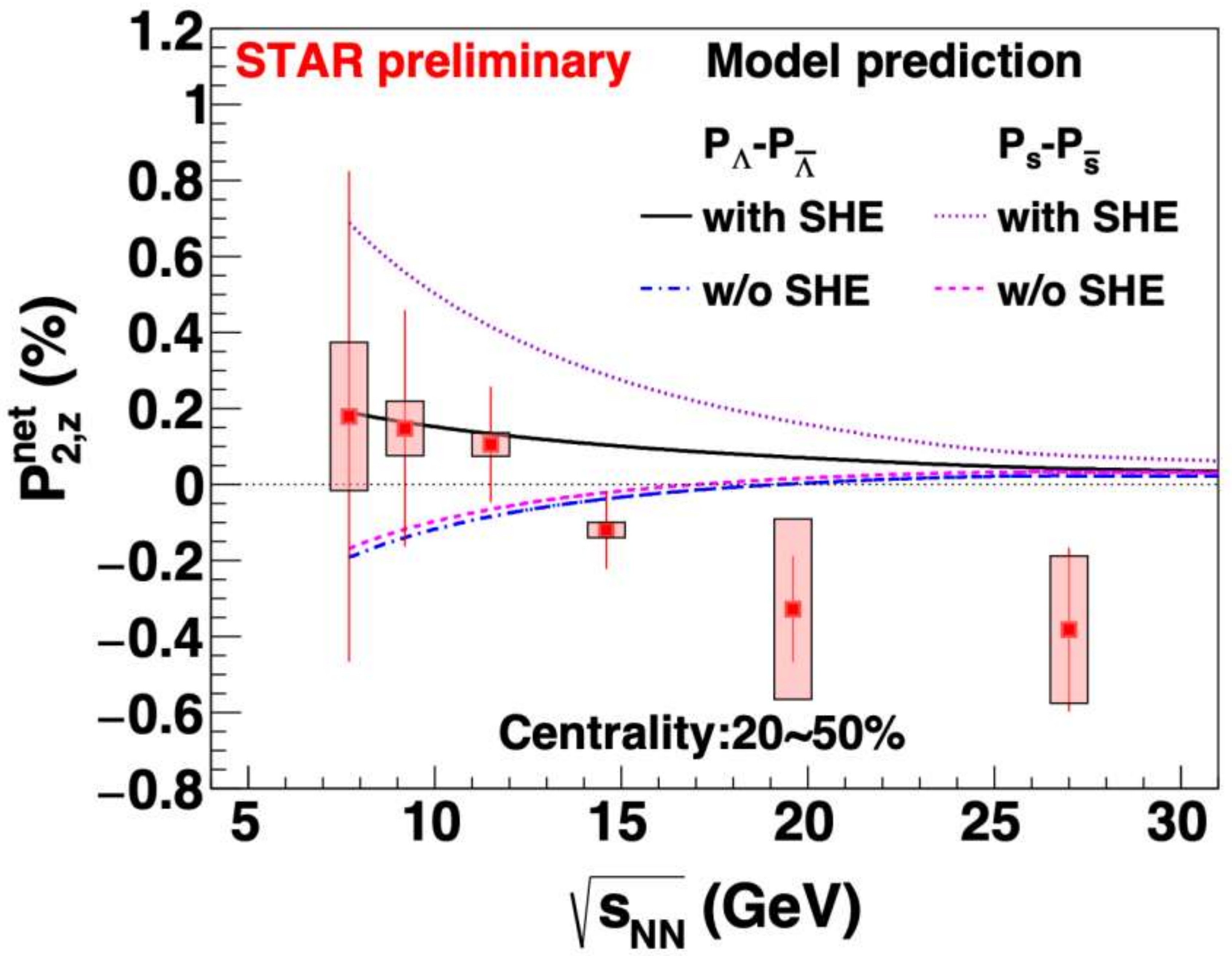
Spin Hall Effect in hot QCD matter: $P \propto \pm p \times \nabla\mu_B$

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

$$P_{2,z}^{net} = \langle P_Z^{net}(\phi) sin2\phi \rangle \qquad P_Z^{net}(\phi) = P_Z^{\Lambda}(\phi) - P_Z^{\overline{\Lambda}}(\phi)$$

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.





Hints of sign change with decreasing energy

Q. Hu @ SQM 2024

Experimental Observables: Alignment

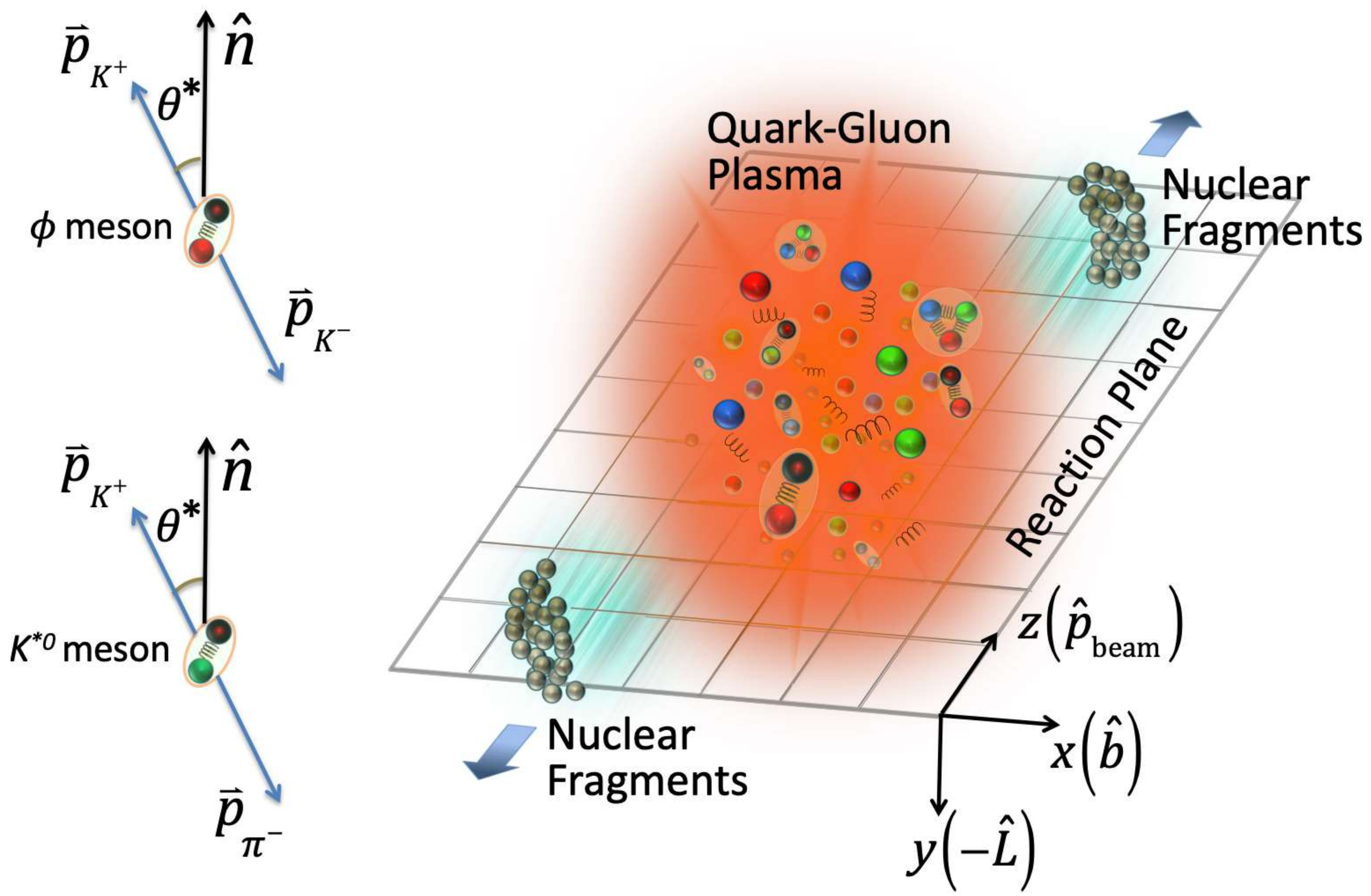
ϕ-mesons (J = 1[-]):

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**



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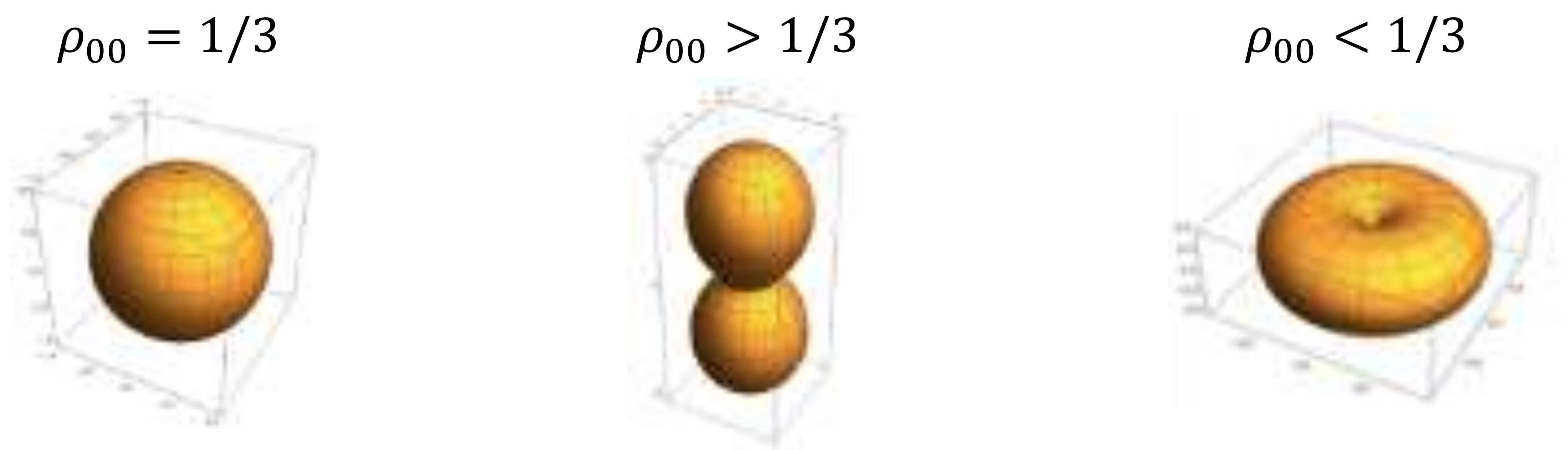
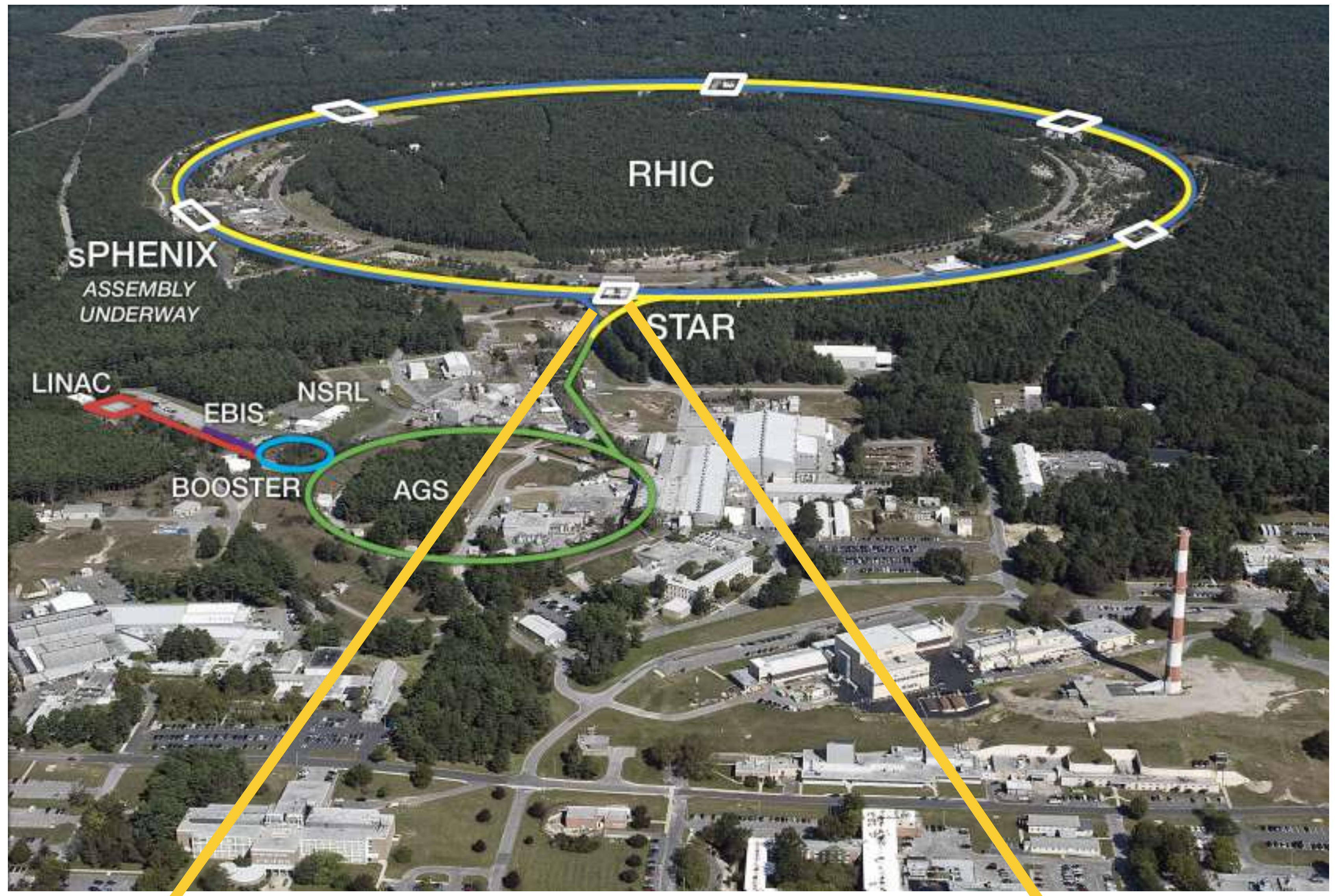
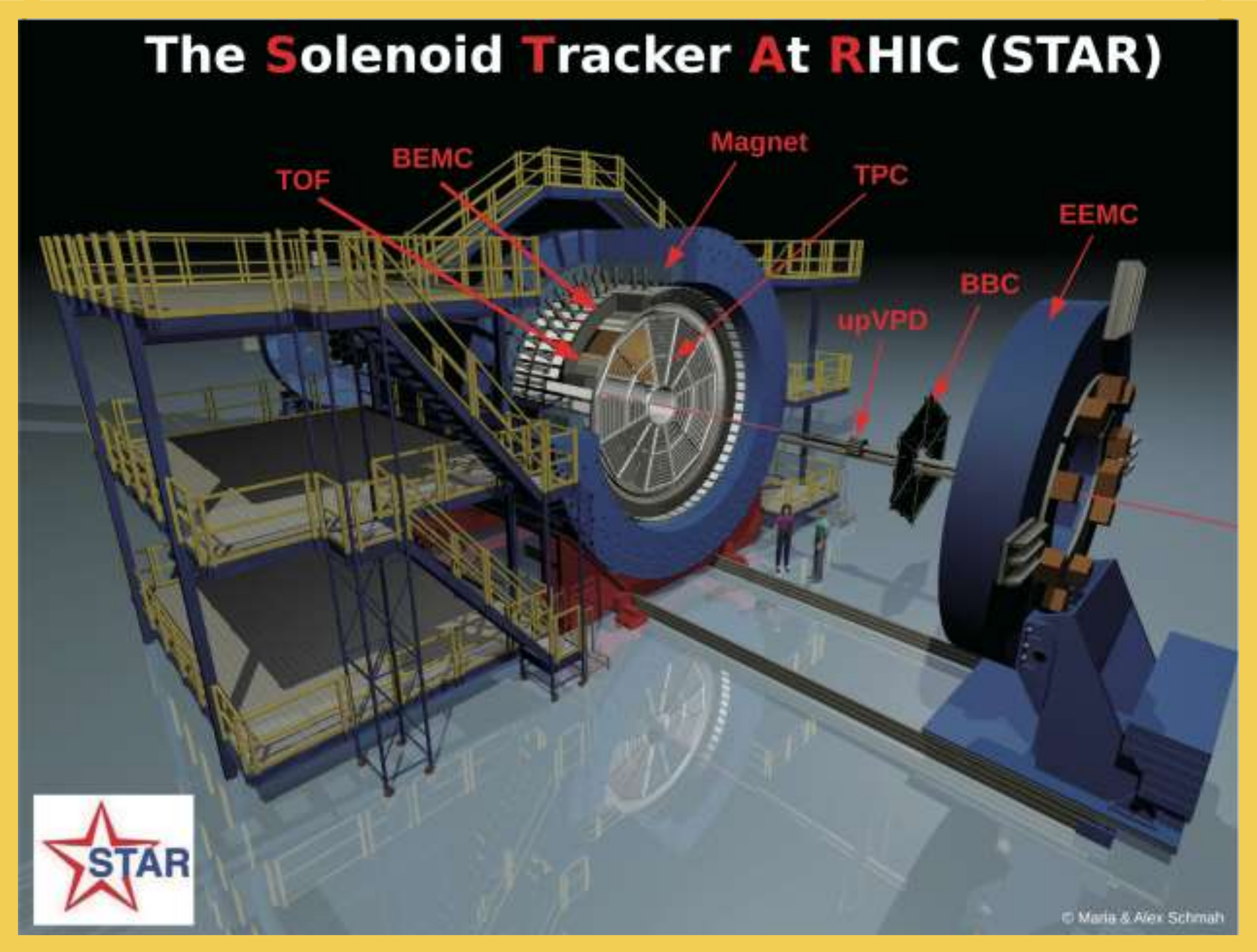
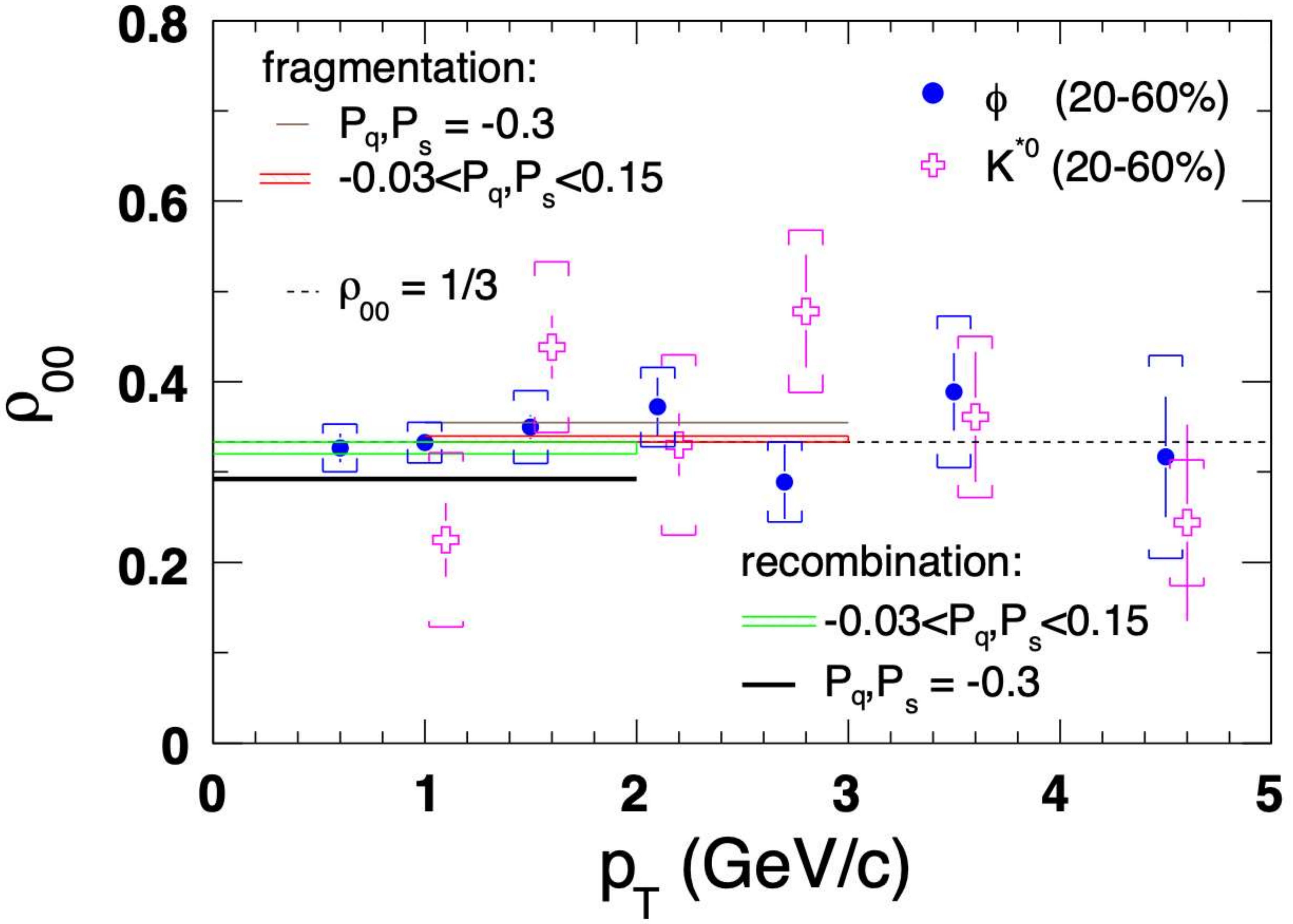


Global Spin Alignment: Early Efforts at RHIC



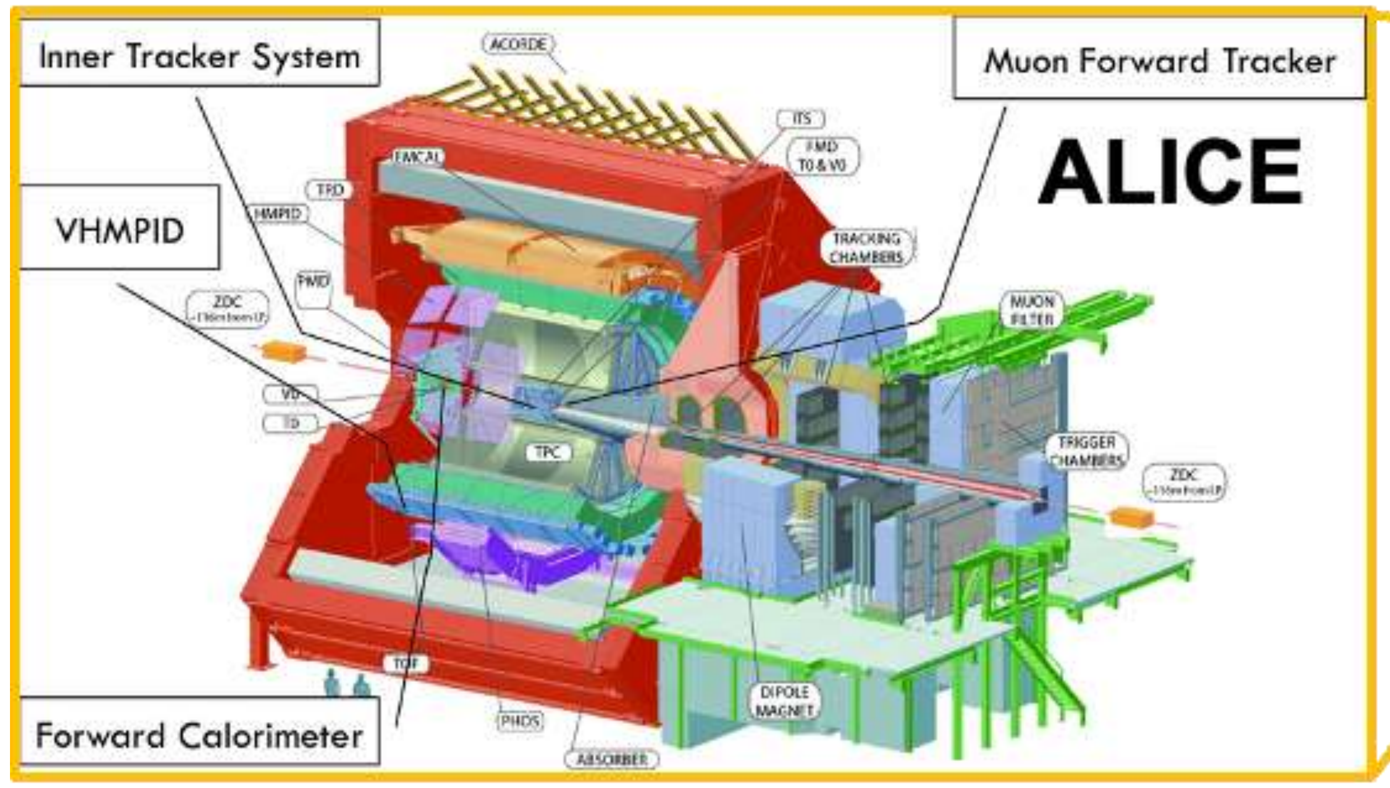


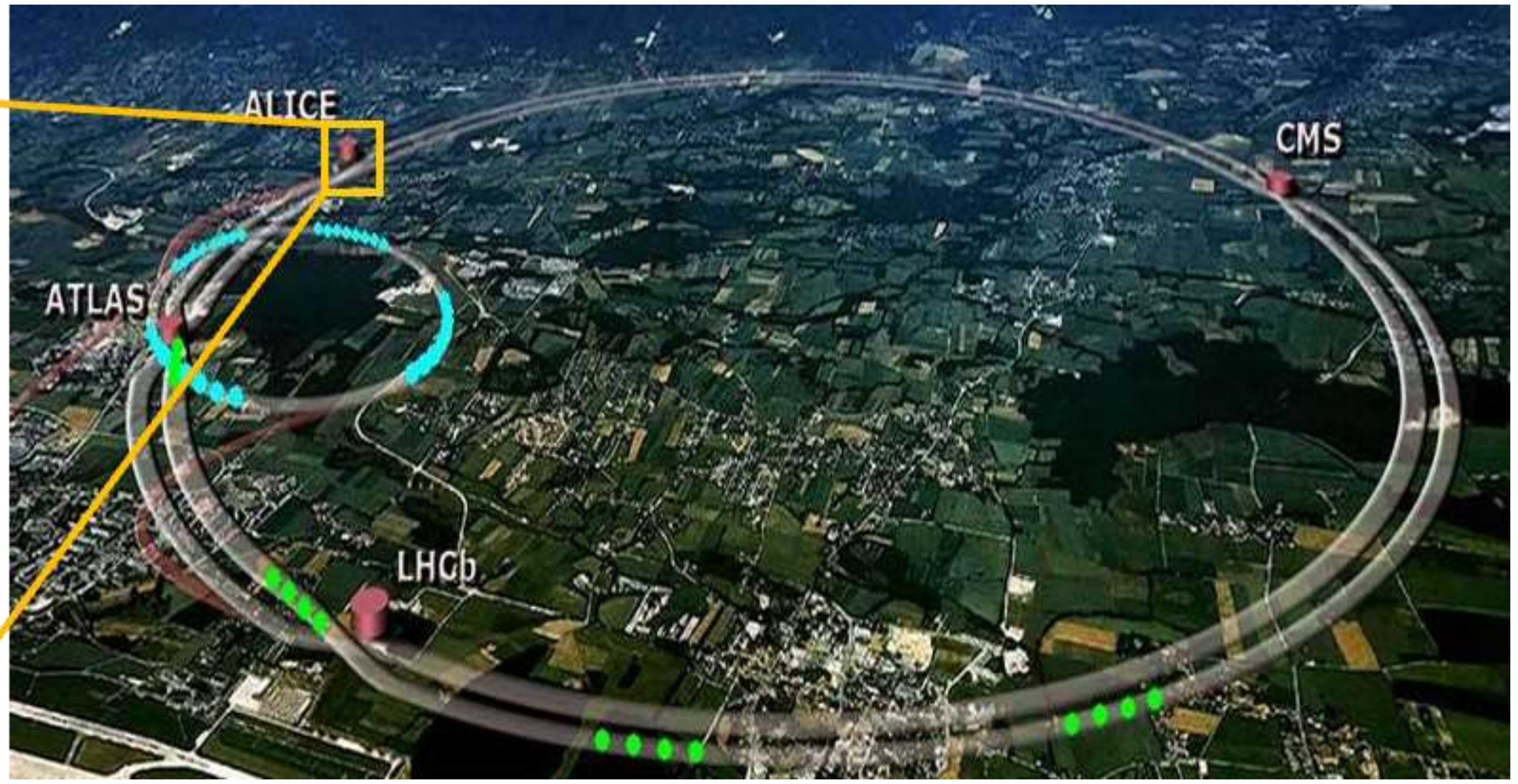
STAR, PRC 77 061902 (R) (2008)

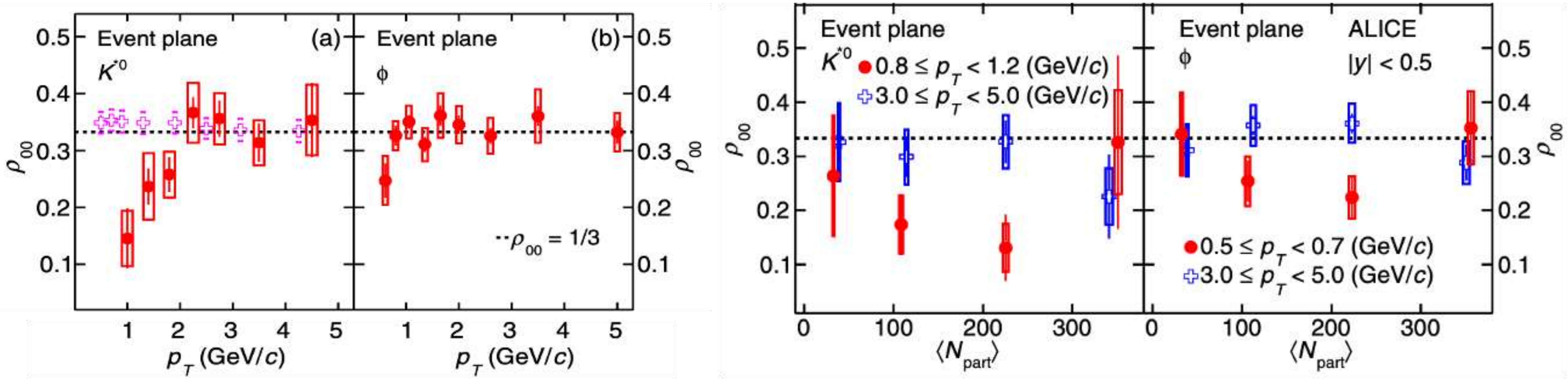


No significant results reported, due to limited statistics

Global Spin Alignment : ALICE Results





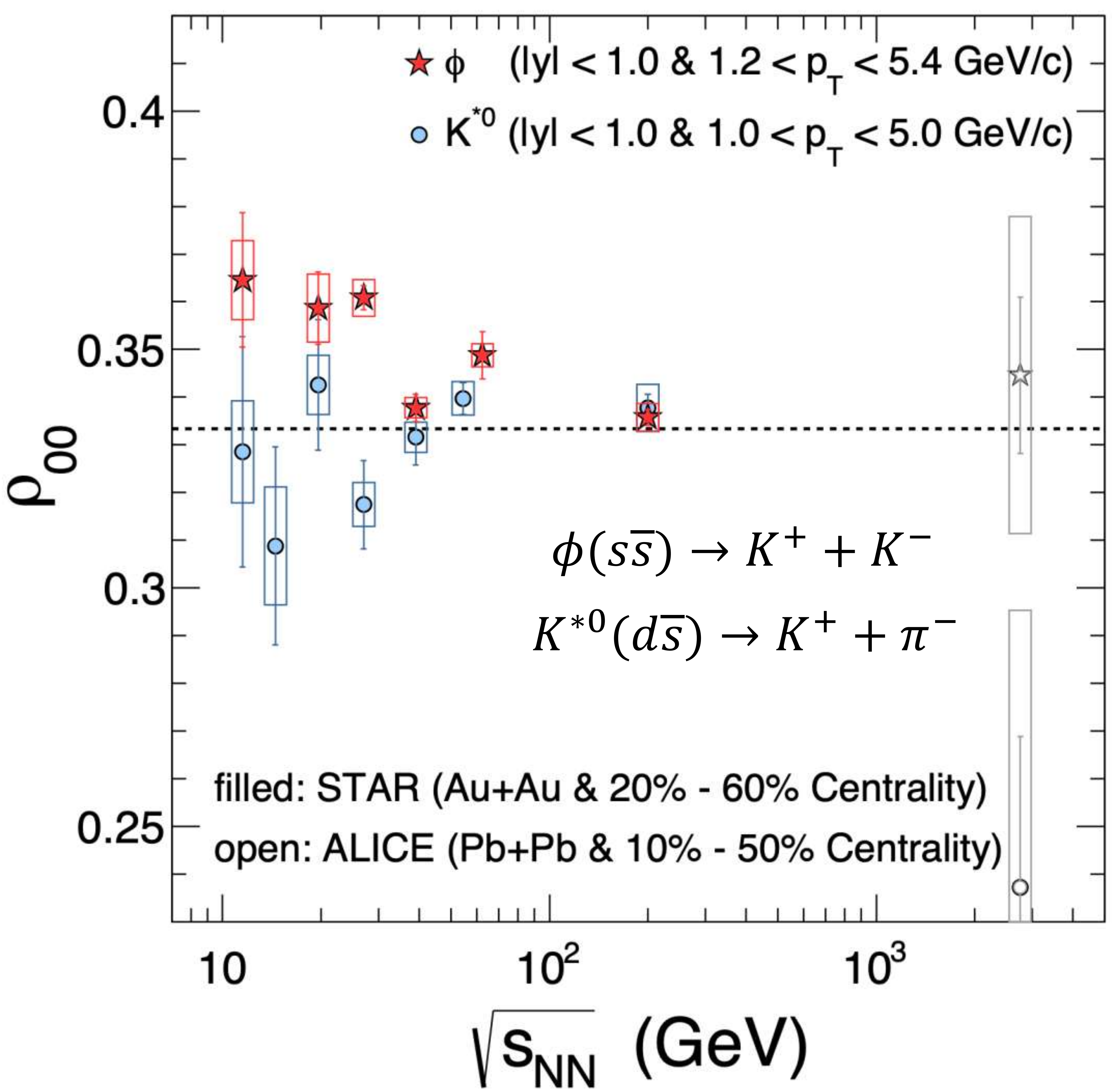


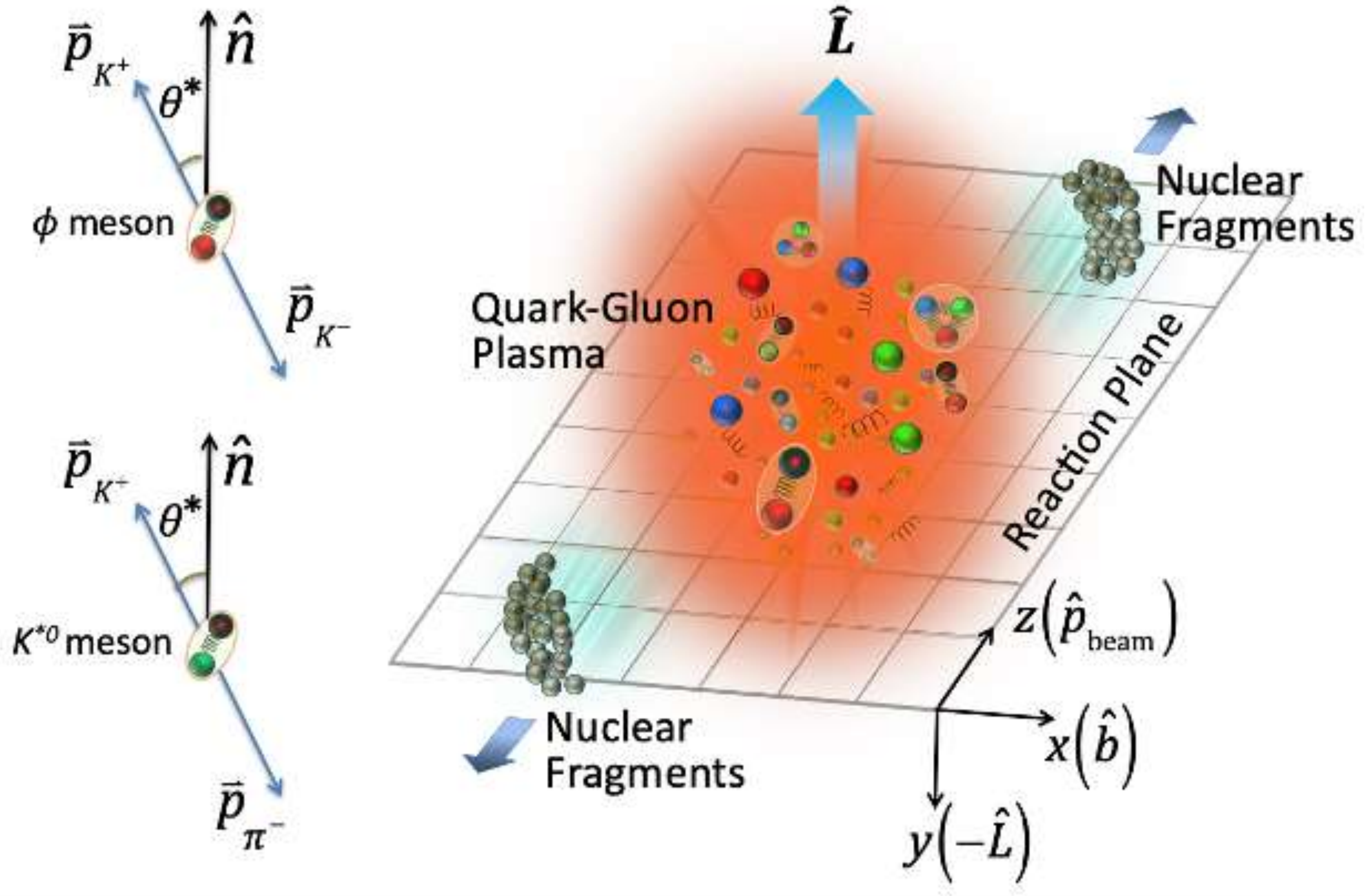
ALICE, PRL 125 012301 (2020)

Evidence of Spin-Orbital Angular Momentum interaction

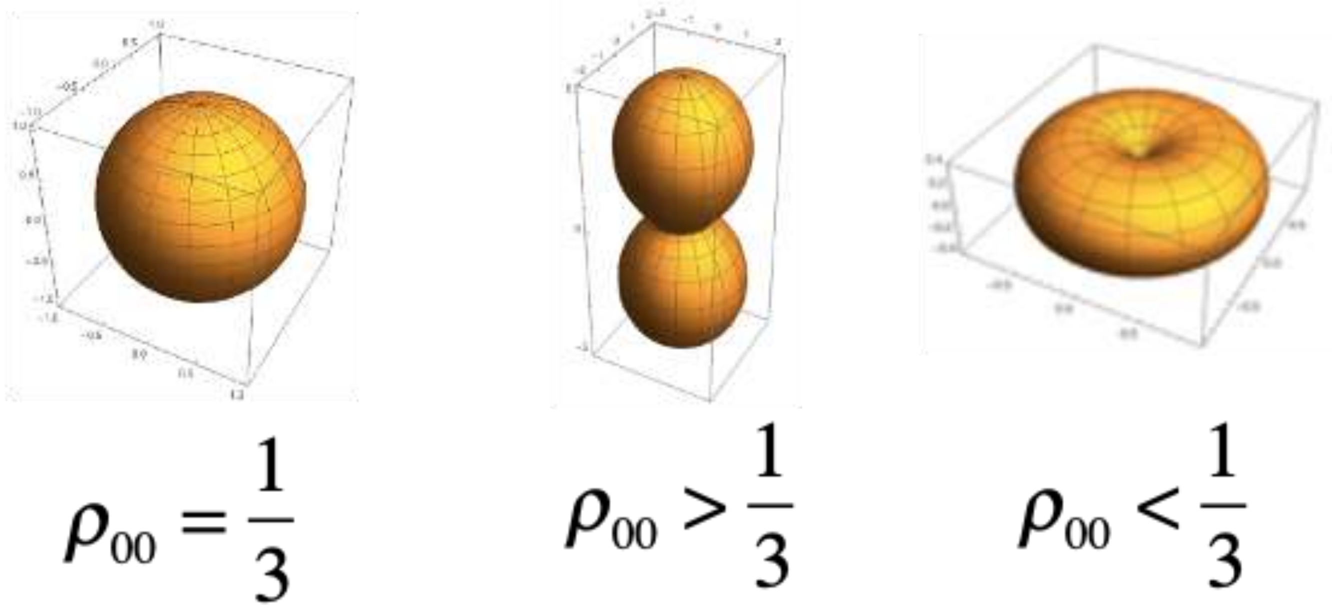
Global Spin Alignment at STAR BES-I

STAR, Nature 614, 233-248 (2023)





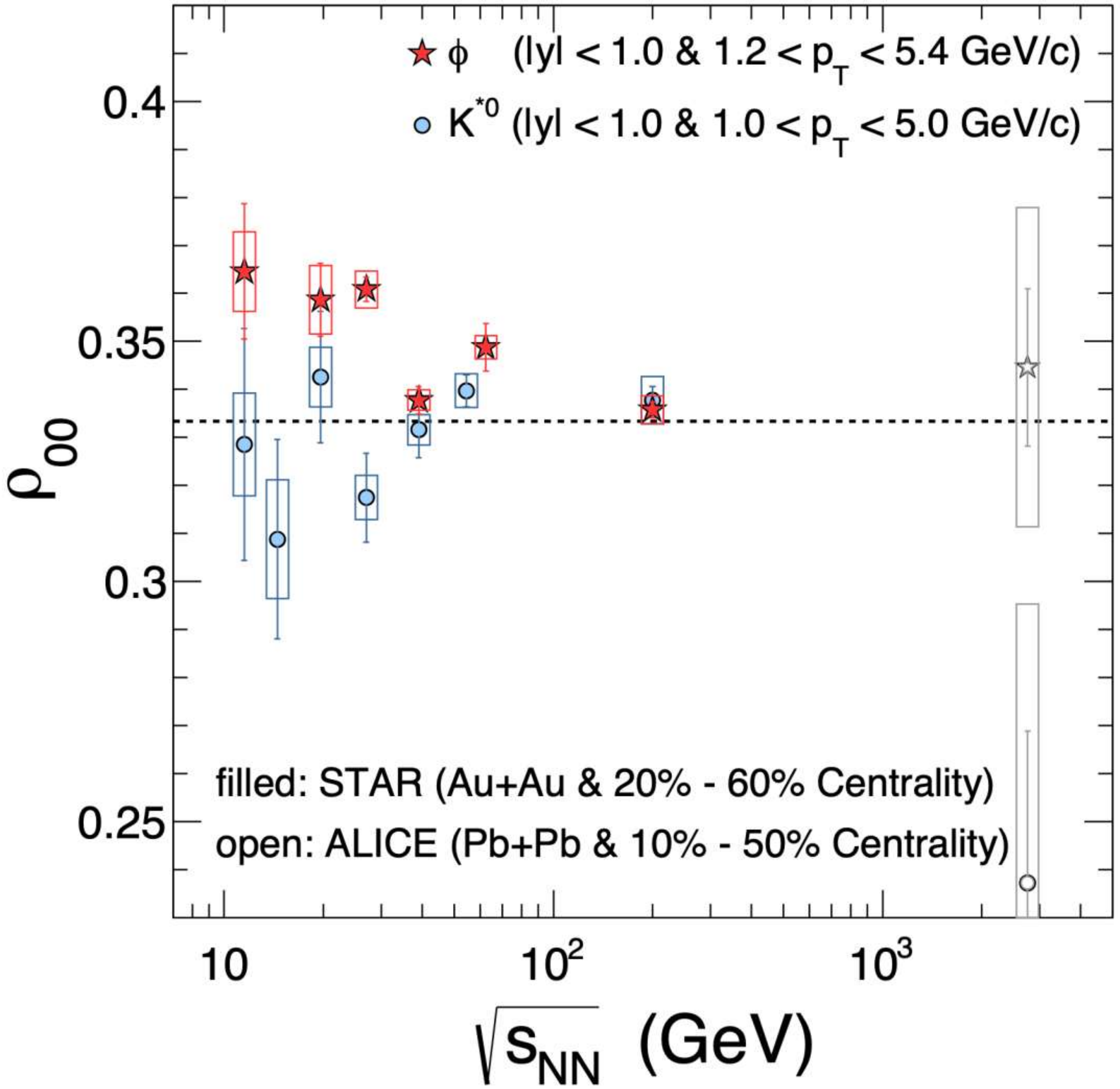
$$\frac{dN}{dcos\theta^*} \propto (1-\rho_{00}) + (3\rho_{00}-1)cos^2\theta^*$$



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

Global Spin Alignment at STAR BES-I

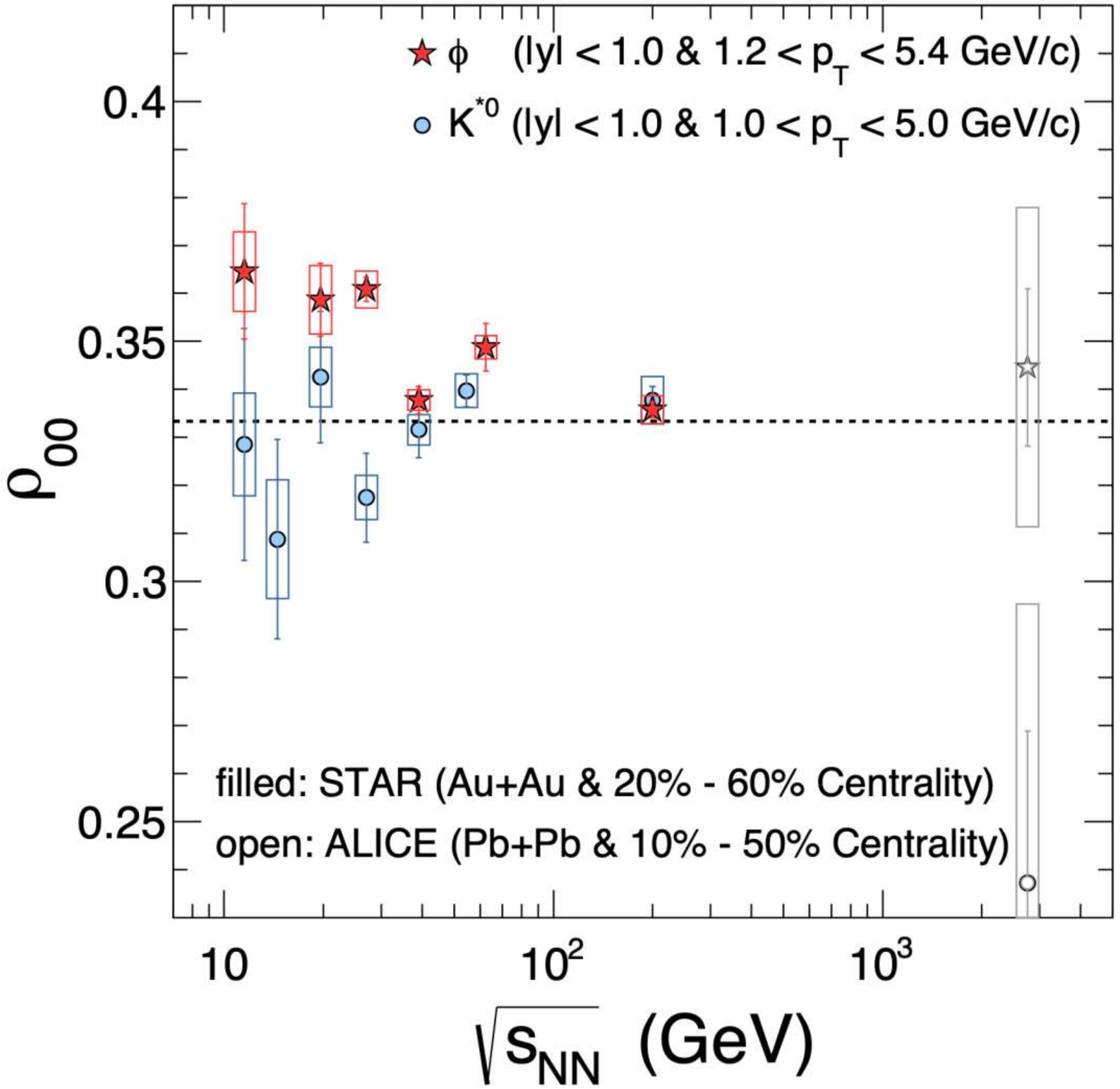
STAR, Nature 614, 233-248 (2023)



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 BES-I

STAR, Nature 614, 233-248 (2023)

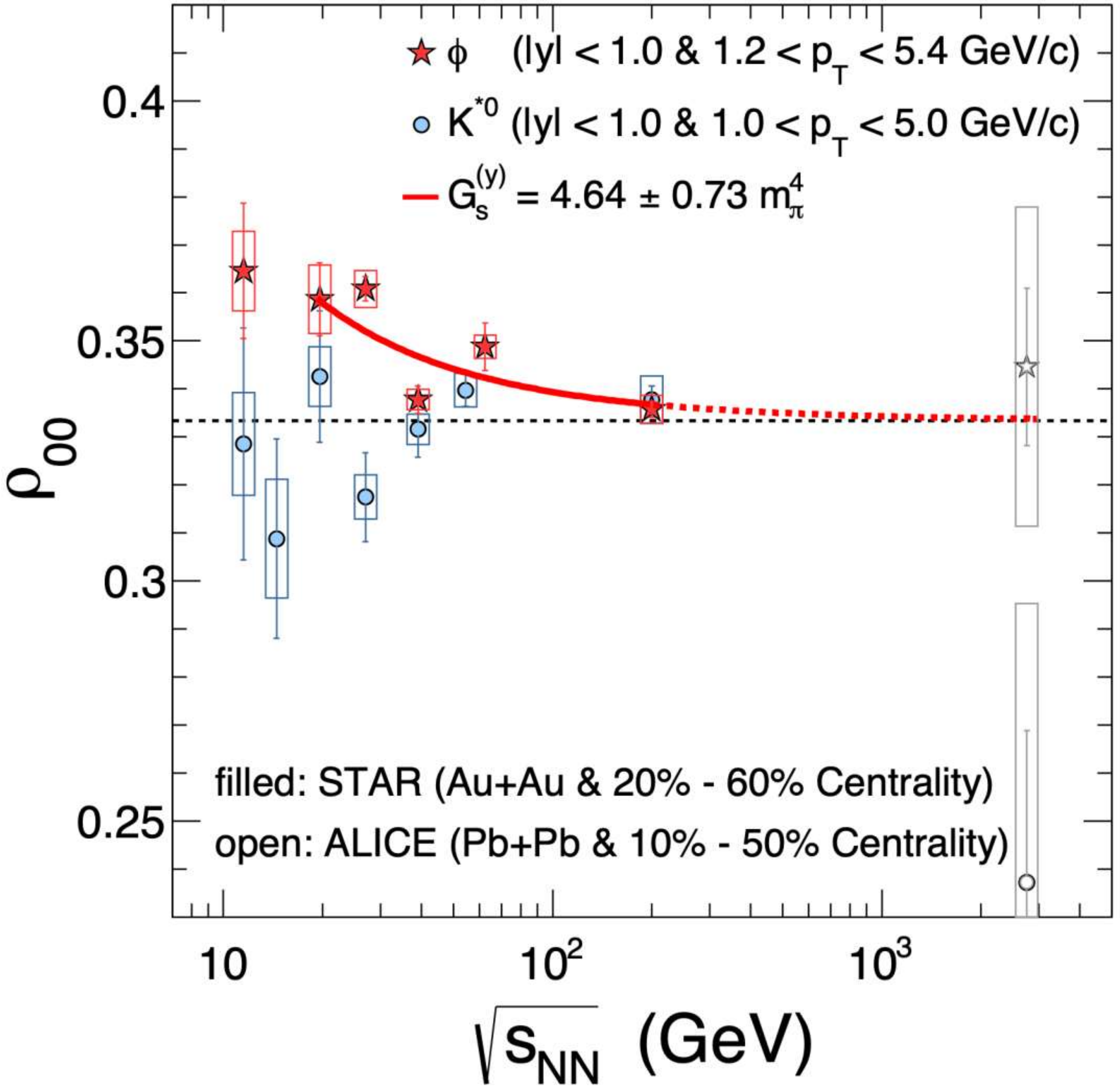


$$\rho_{00}(\phi) = \frac{1}{3} + C_\Lambda + C_\epsilon + C_E + C_F + C_L + C_A + C_\phi + C_g$$

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 BES-I

STAR, Nature 614, 233-248 (2023)



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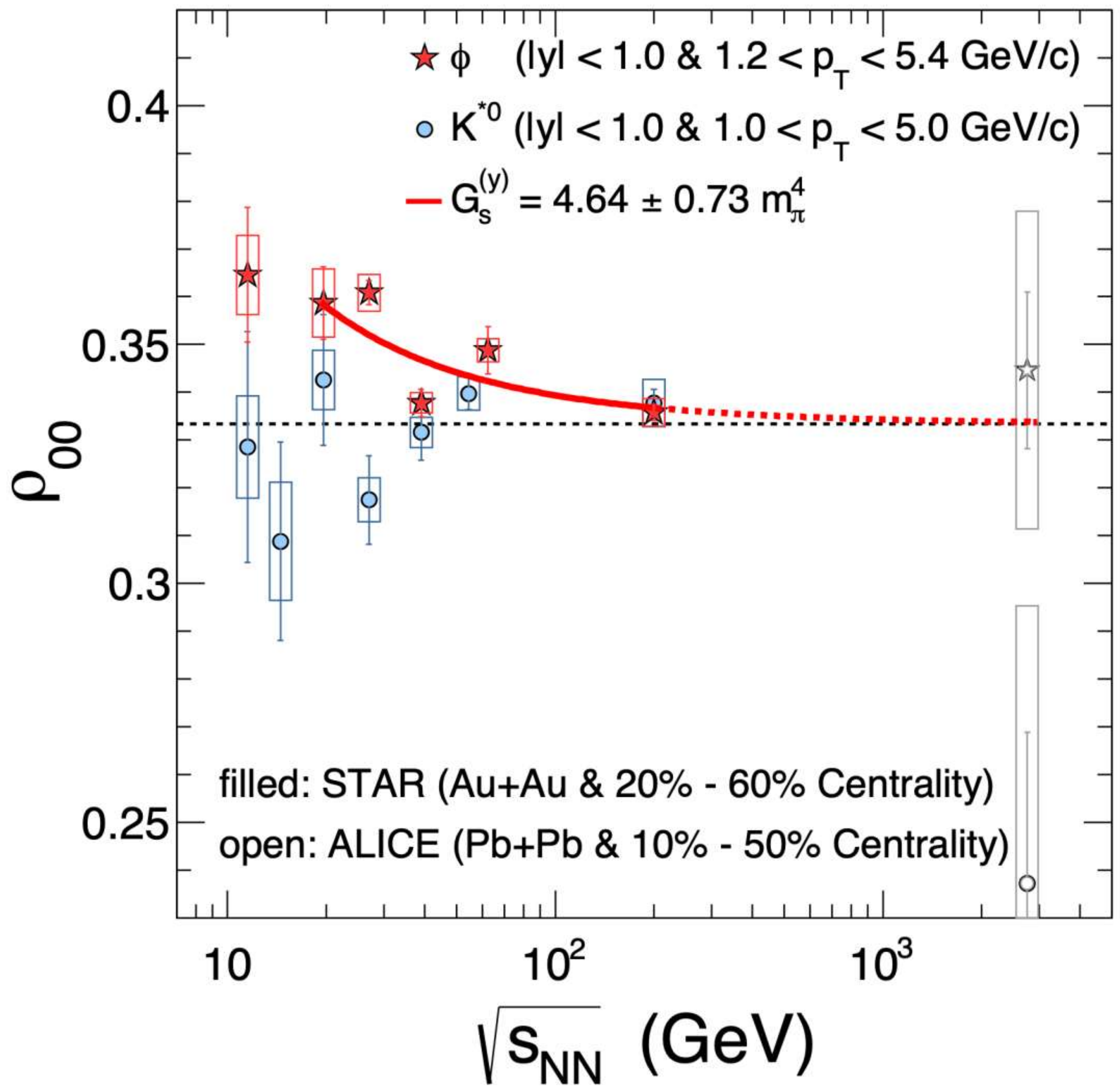
Global Spin Alignment at STAR BES-I

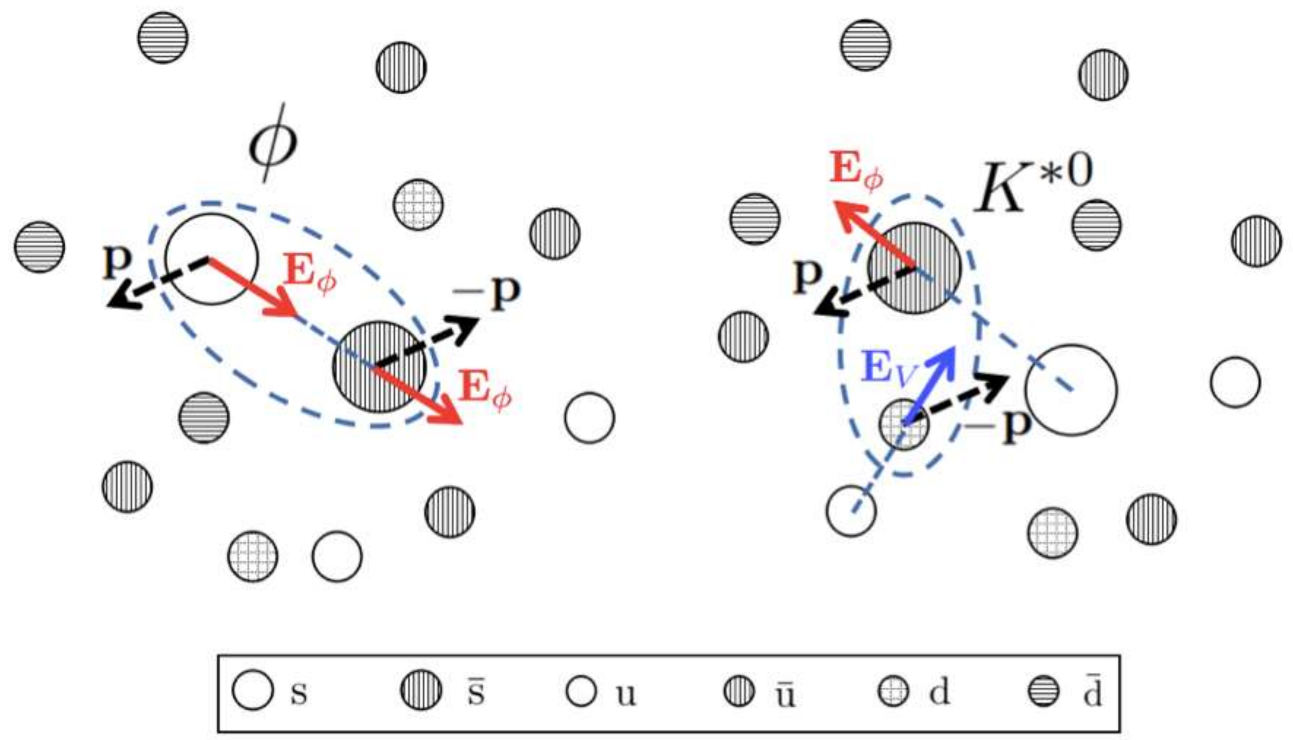
STAR, Nature 614, 233-248 (2023)



What do we learn?

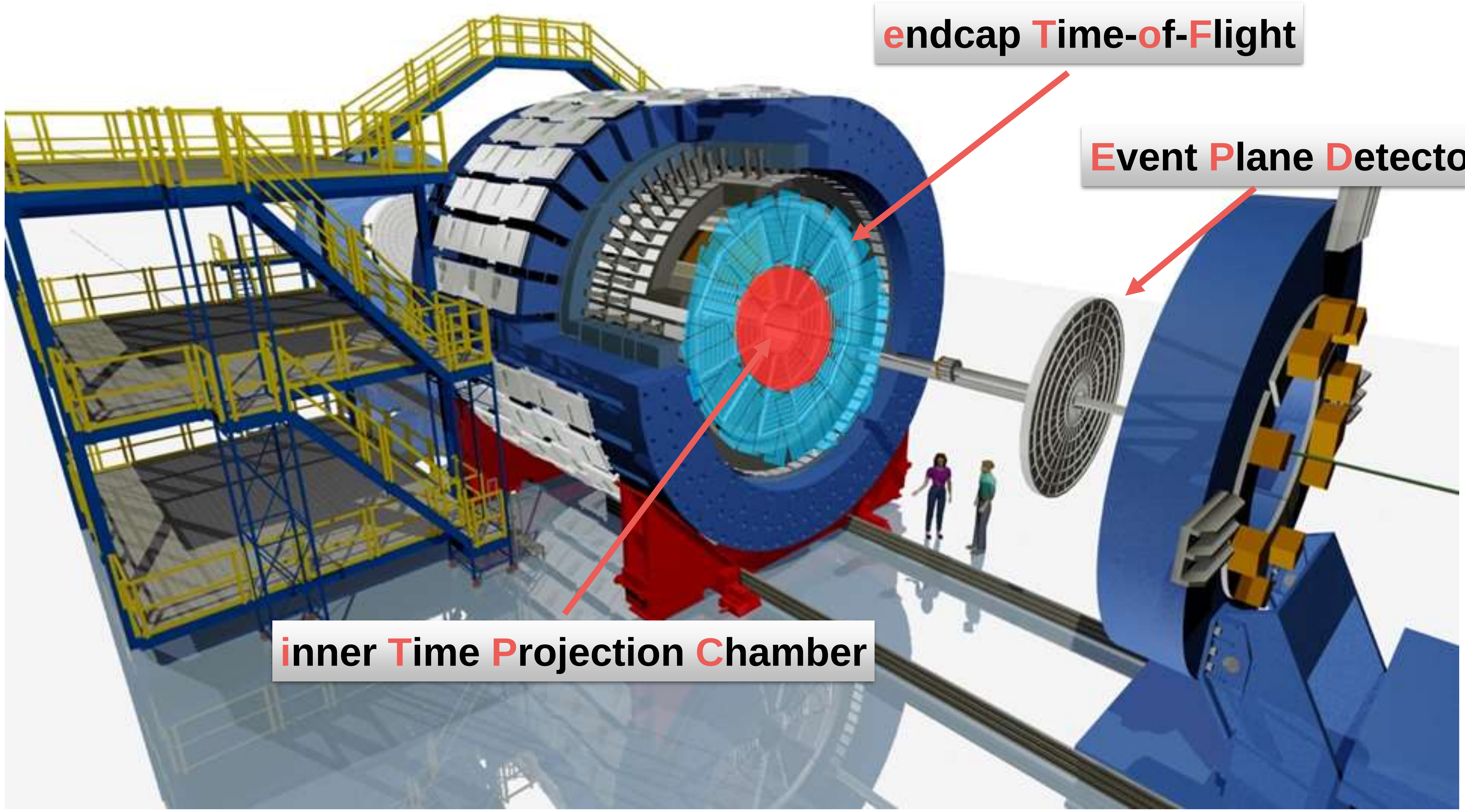
$$\rho_{00}^{V} - \frac{1}{3} \sim \langle P_q P_{\bar{q}} \rangle \qquad \rho_{00}^{V} - \frac{1}{3} \gg P_{\Lambda}^{2} \approx P_{q}^{2}$$

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



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

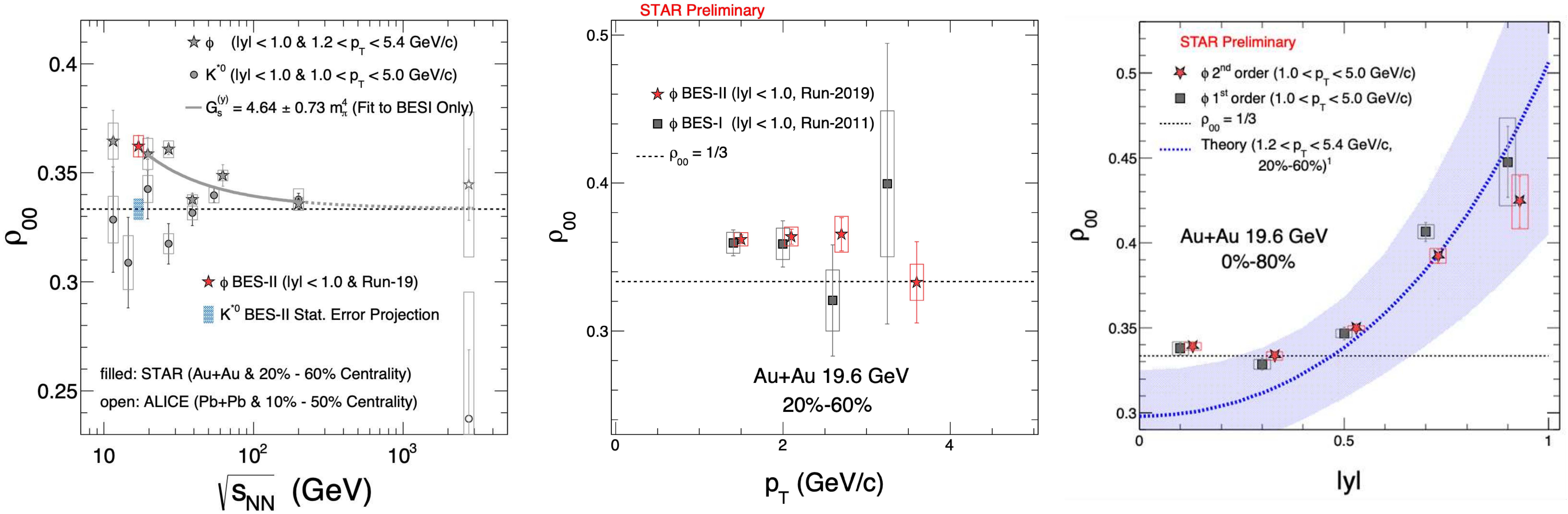
STAR Detector for BESII and Isobar



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

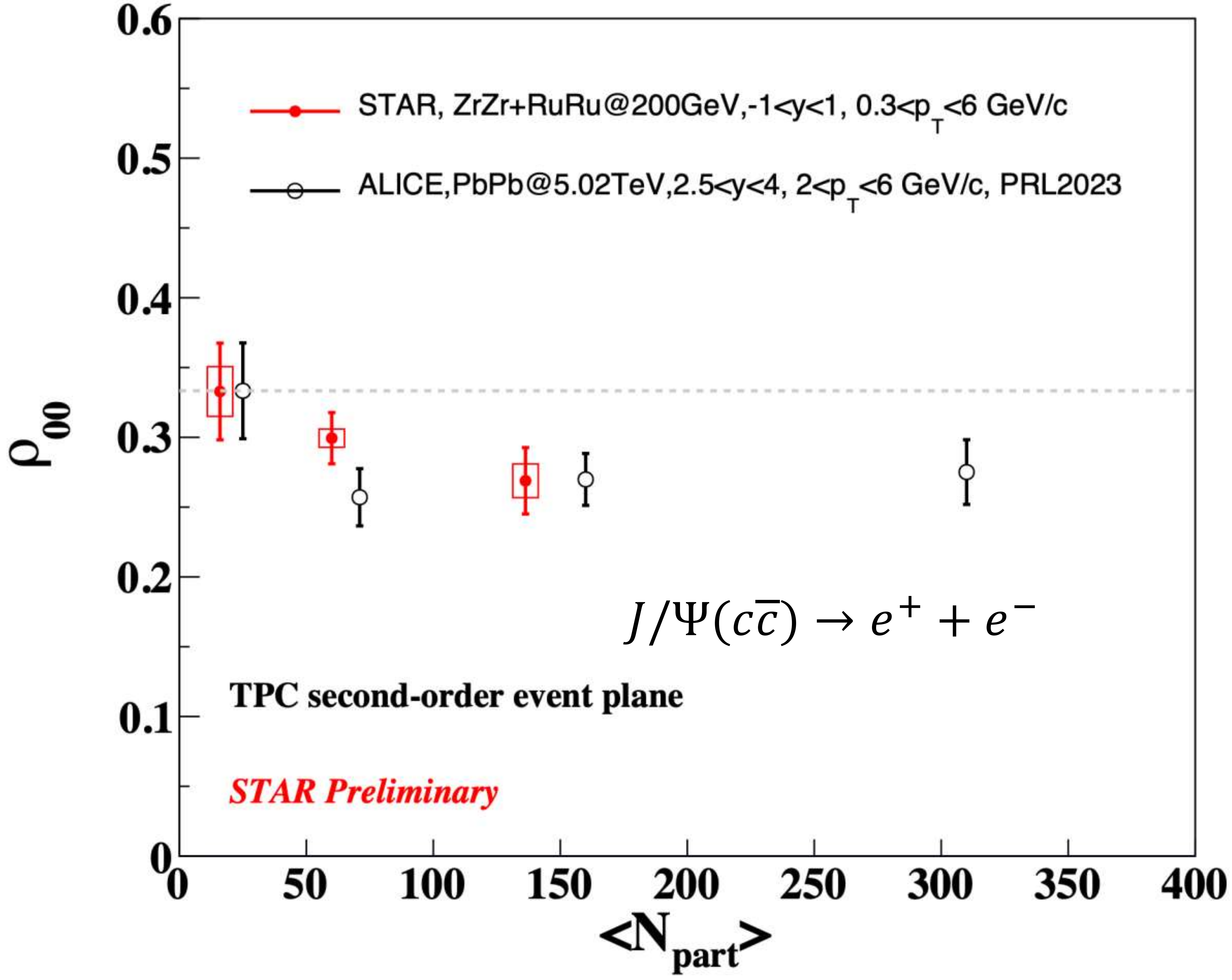
Global Spin Alignment at STAR BES-II

G. Wilks for STAR @ SQM2022 & Spin 2023



- >10x more statistics (3.0 - 19.6 GeV), increased acceptance and better EP resolution (iTPC + EPD)
- ρ00II, 19.6 GeV = 0.3622 ± 0.0026 (stat.) ± 0.0049 (sys.)
- ρ00II, 19.6 GeV > 1/3 with 5.3σ
- Strong rapidity dependence

What about J/Psi?



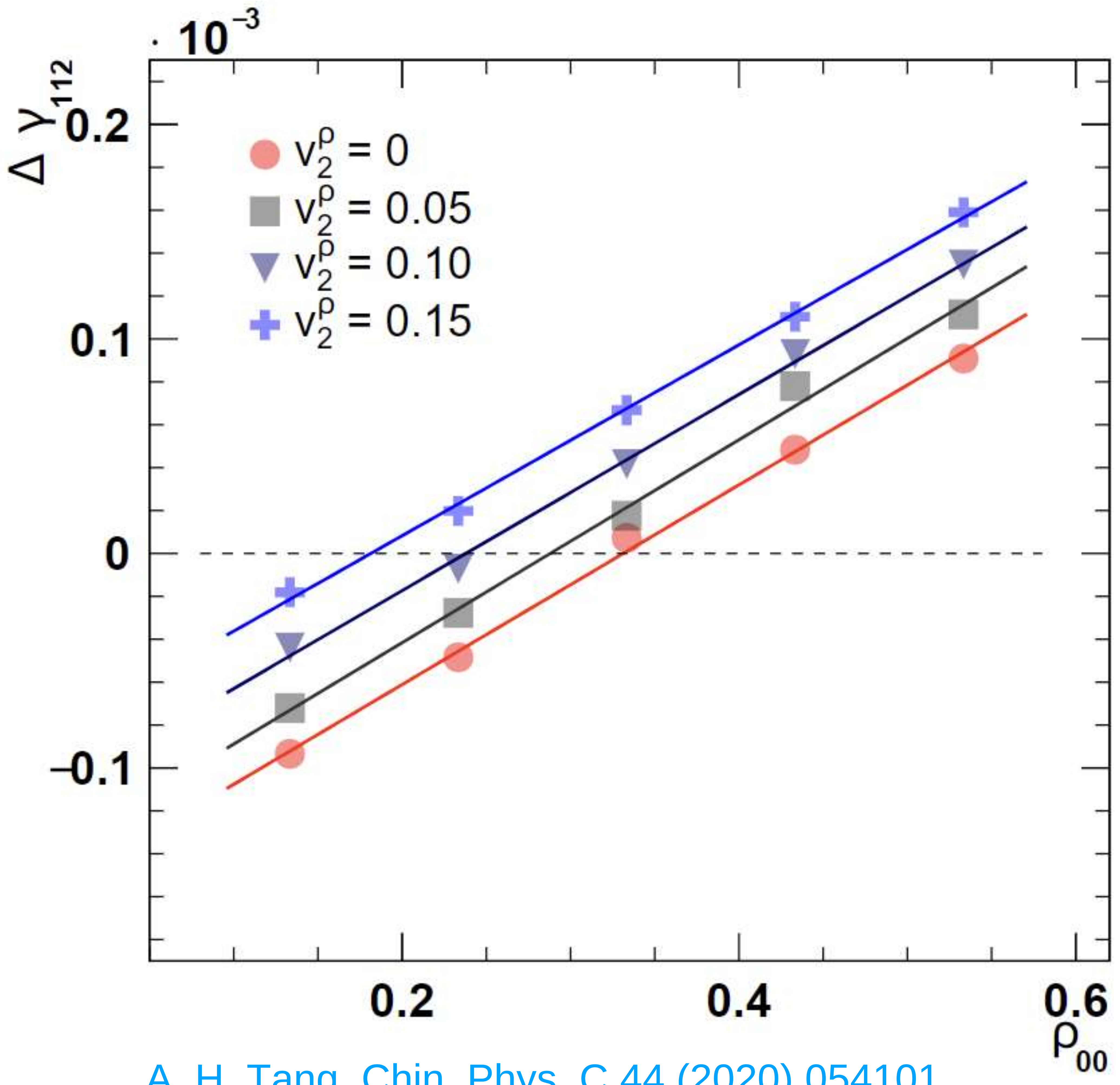
Q. Yang @ QPT 2023

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

- 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}?

What about ρ^0 meson?

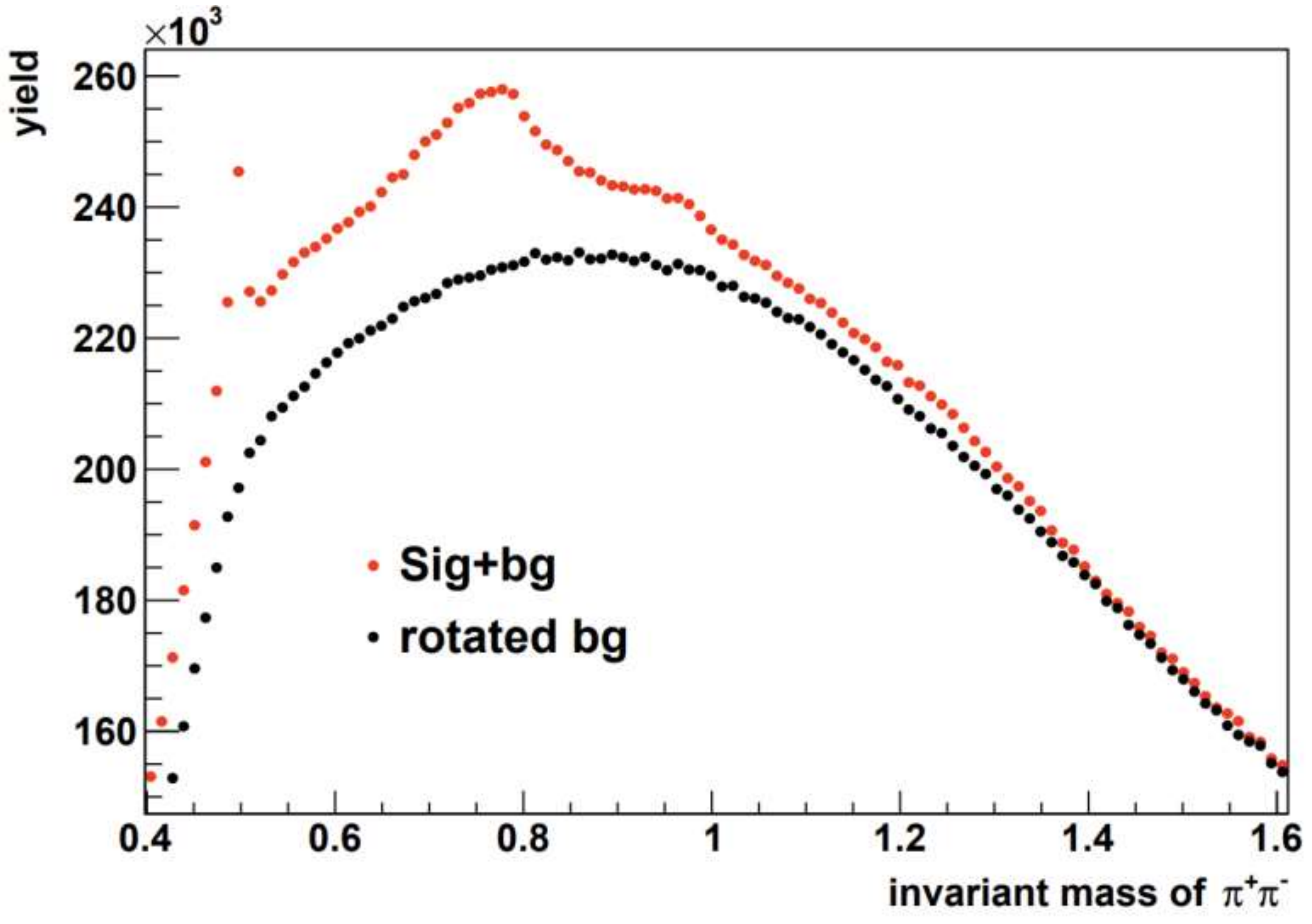


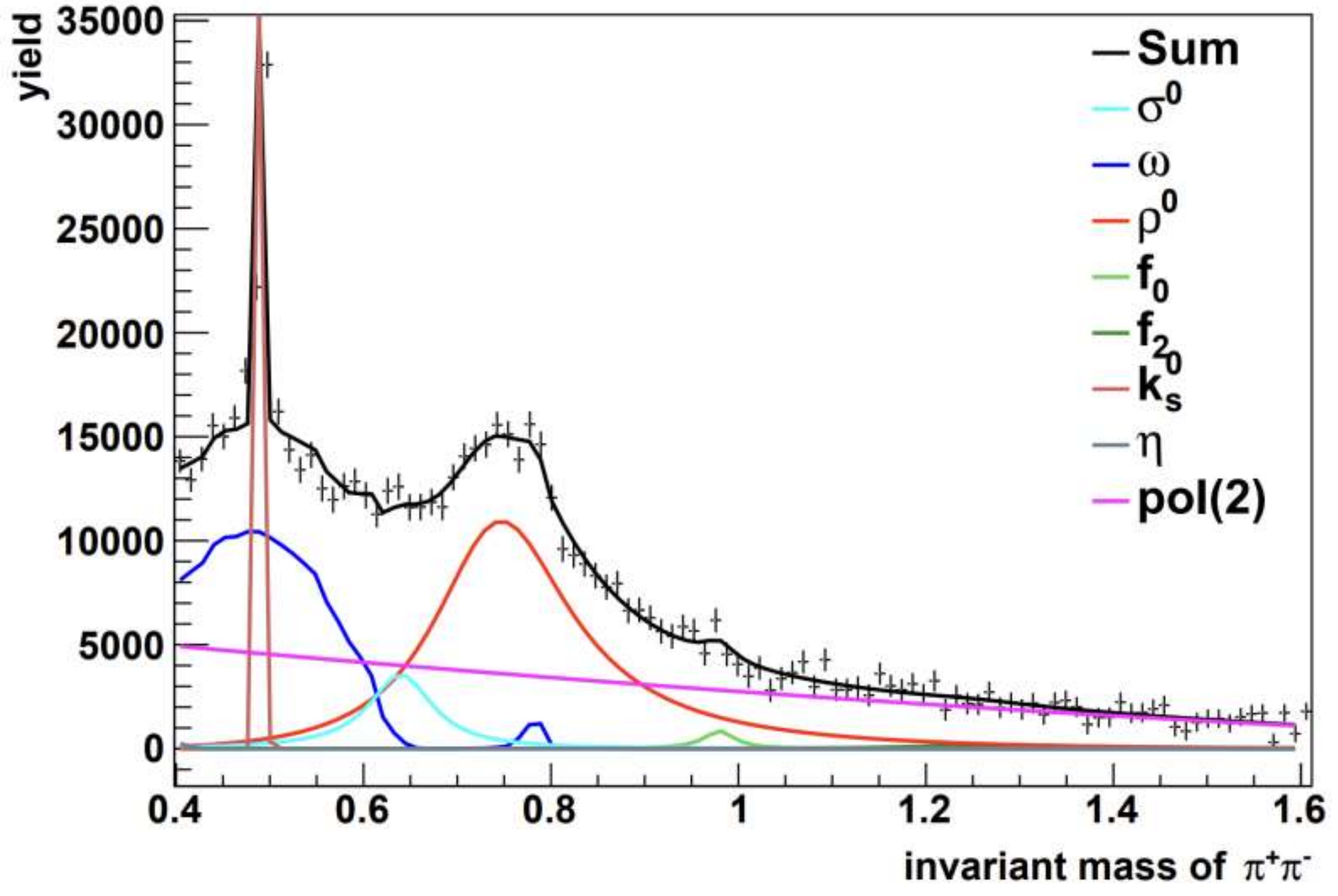
A. H. Tang, Chin. Phys. C 44 (2020) 054101
D. Shen et. al., Phys. Lett. B 839 (2023) 137777

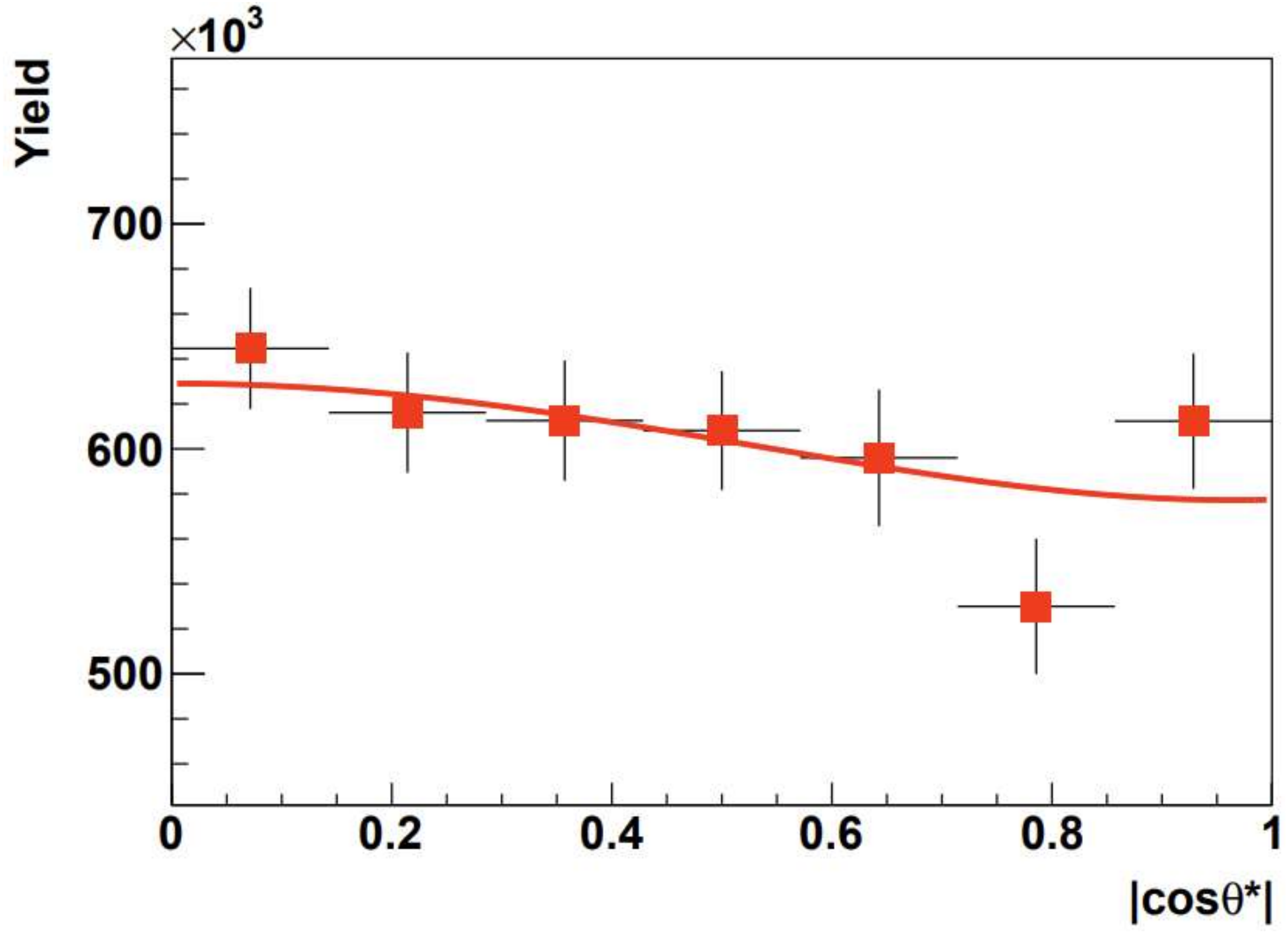
- Global spin alignment of ρ^0 meson can contribute to background in CME observables, similar to resonance v_2 effect
- ρ_{00} > 1/3 will enhance apparent values of CME observables
- ρ_{00} < 1/3 will decrease apparent values of CME observables
- Toy model simulations of the π−π $\Delta\gamma_{112}$ correlation as a function of ρ^0 meson ρ_{00} with various inputs of v_2^ρ.

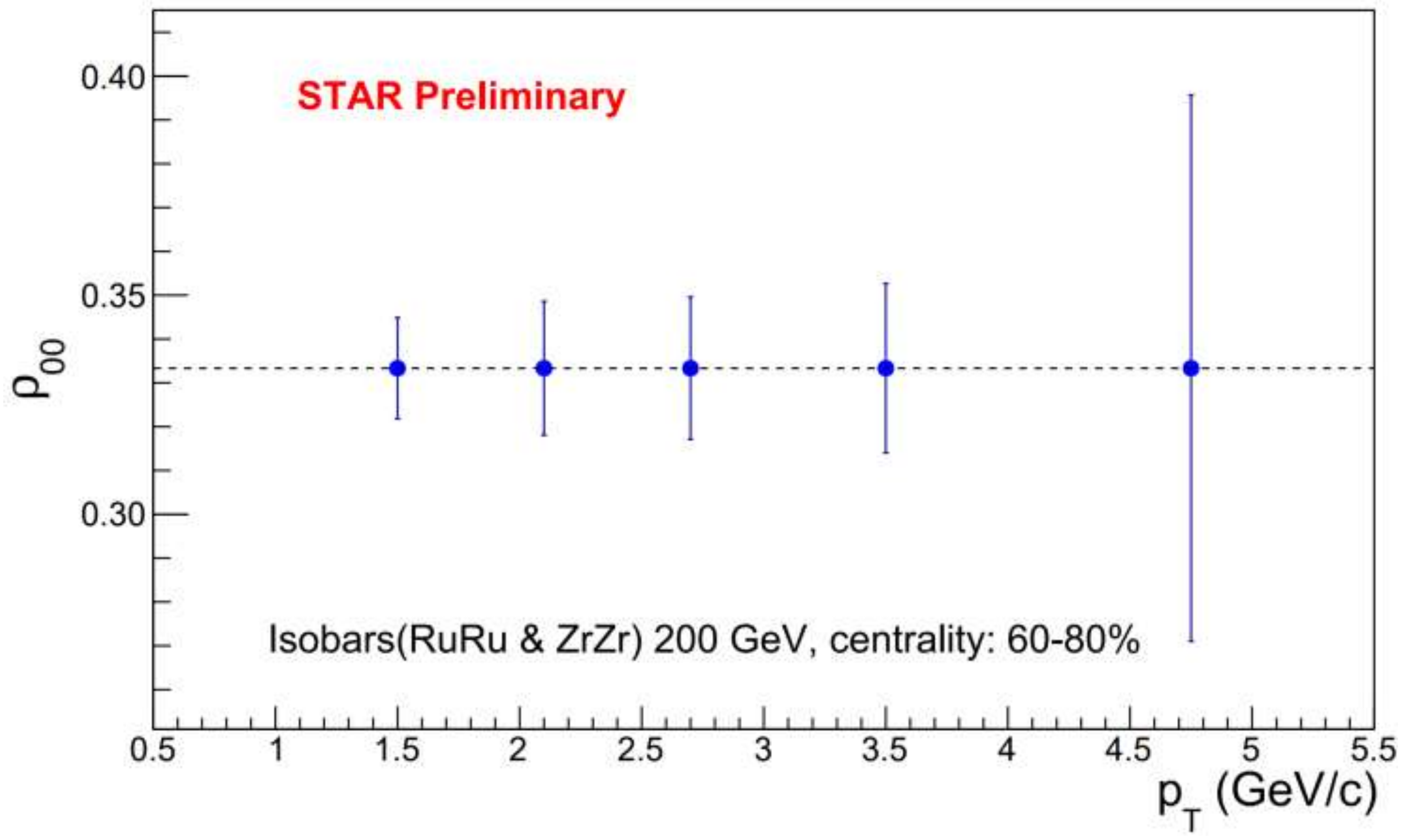
To assess its effect in CME observables, it would be desirable to study ρ^0 meson ρ_{00}

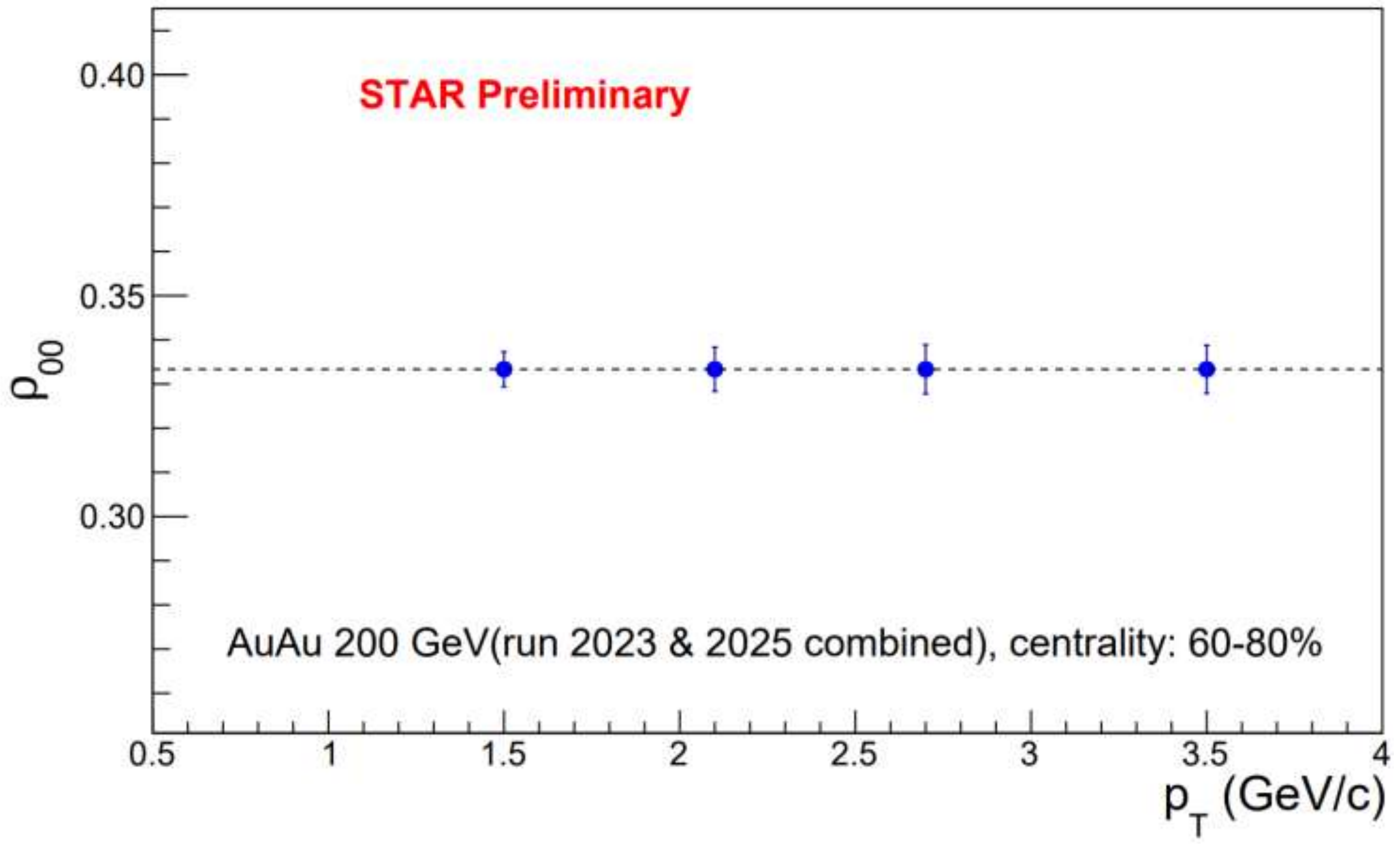
What about ρ^0 meson?





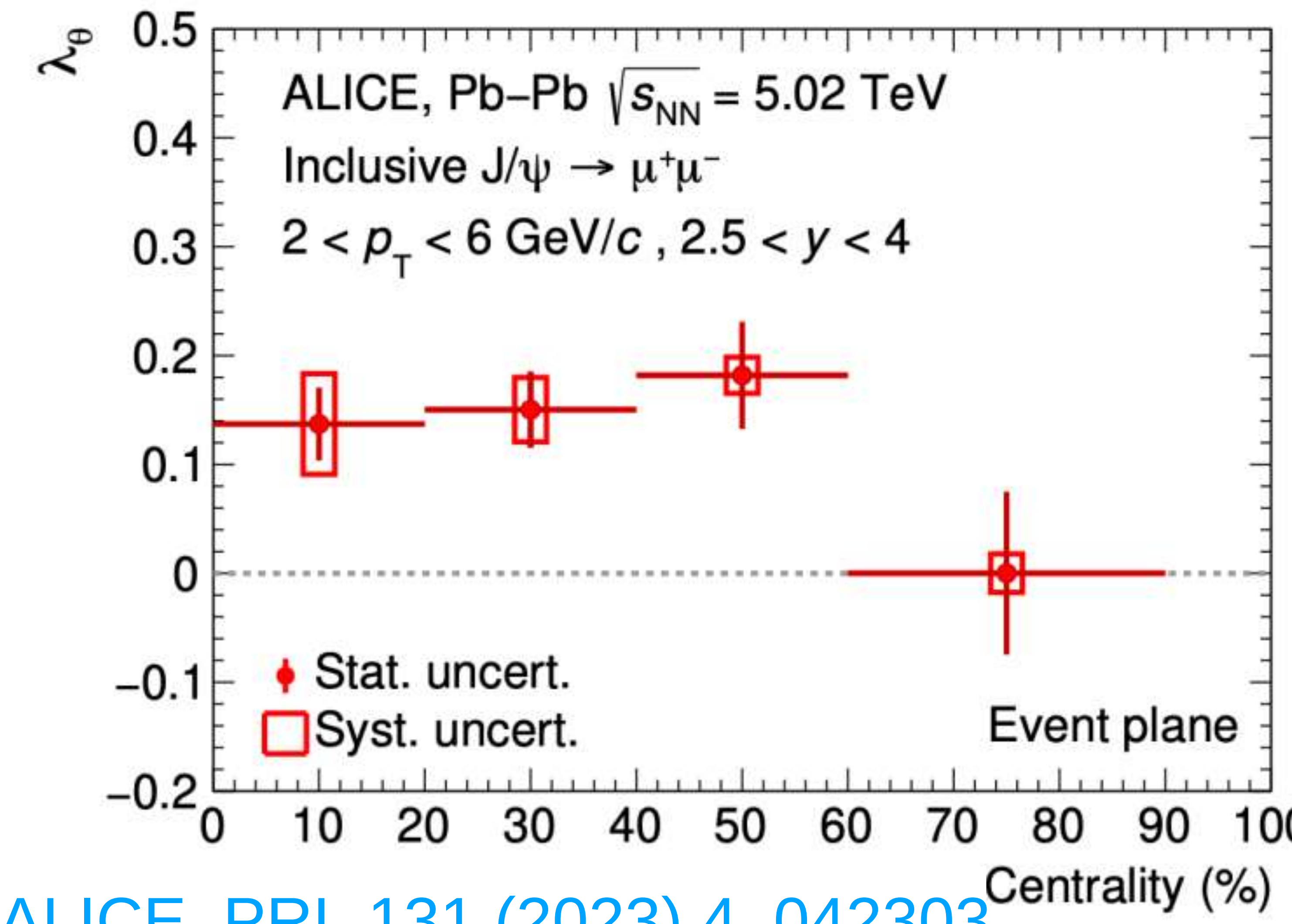




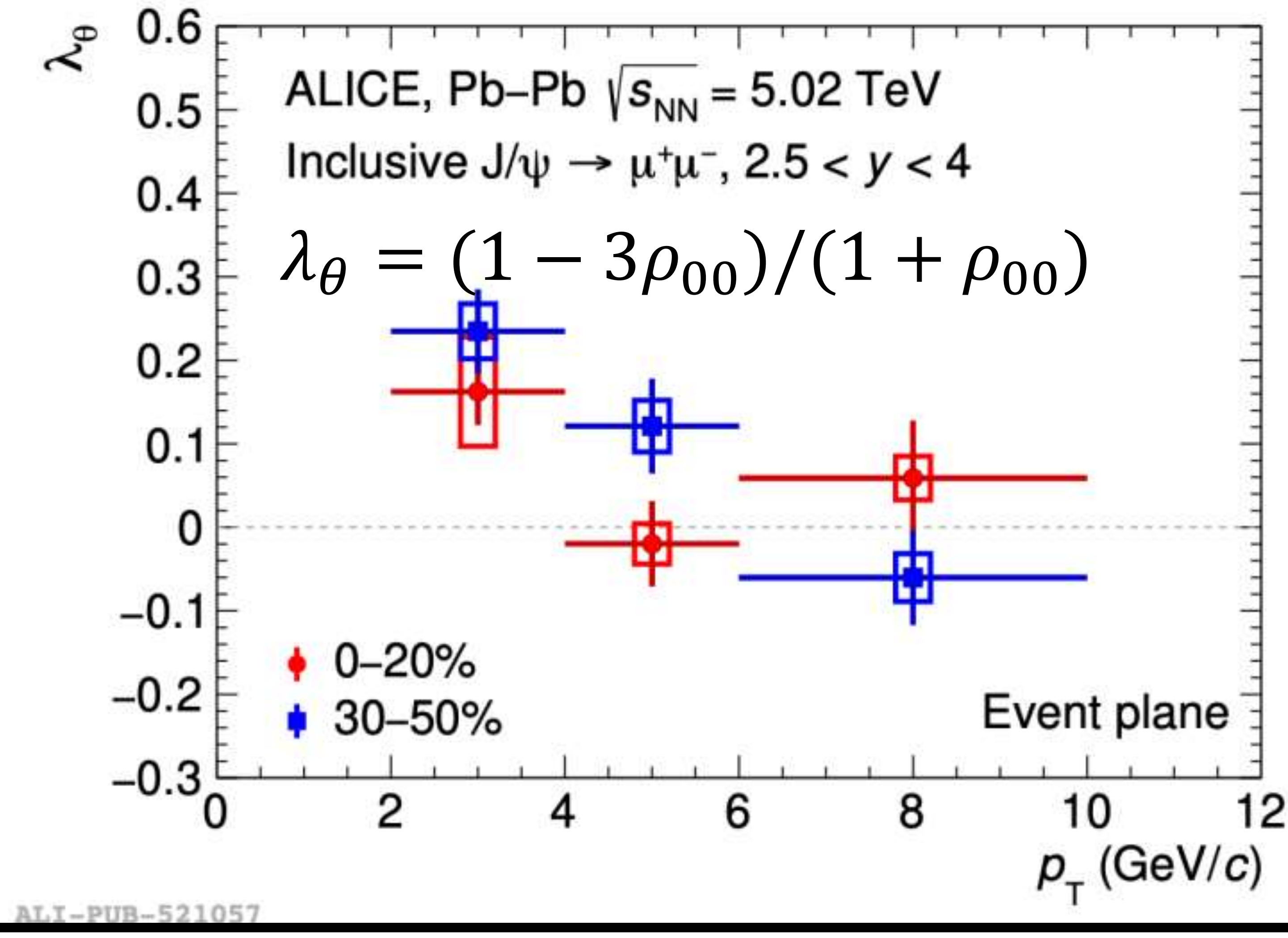


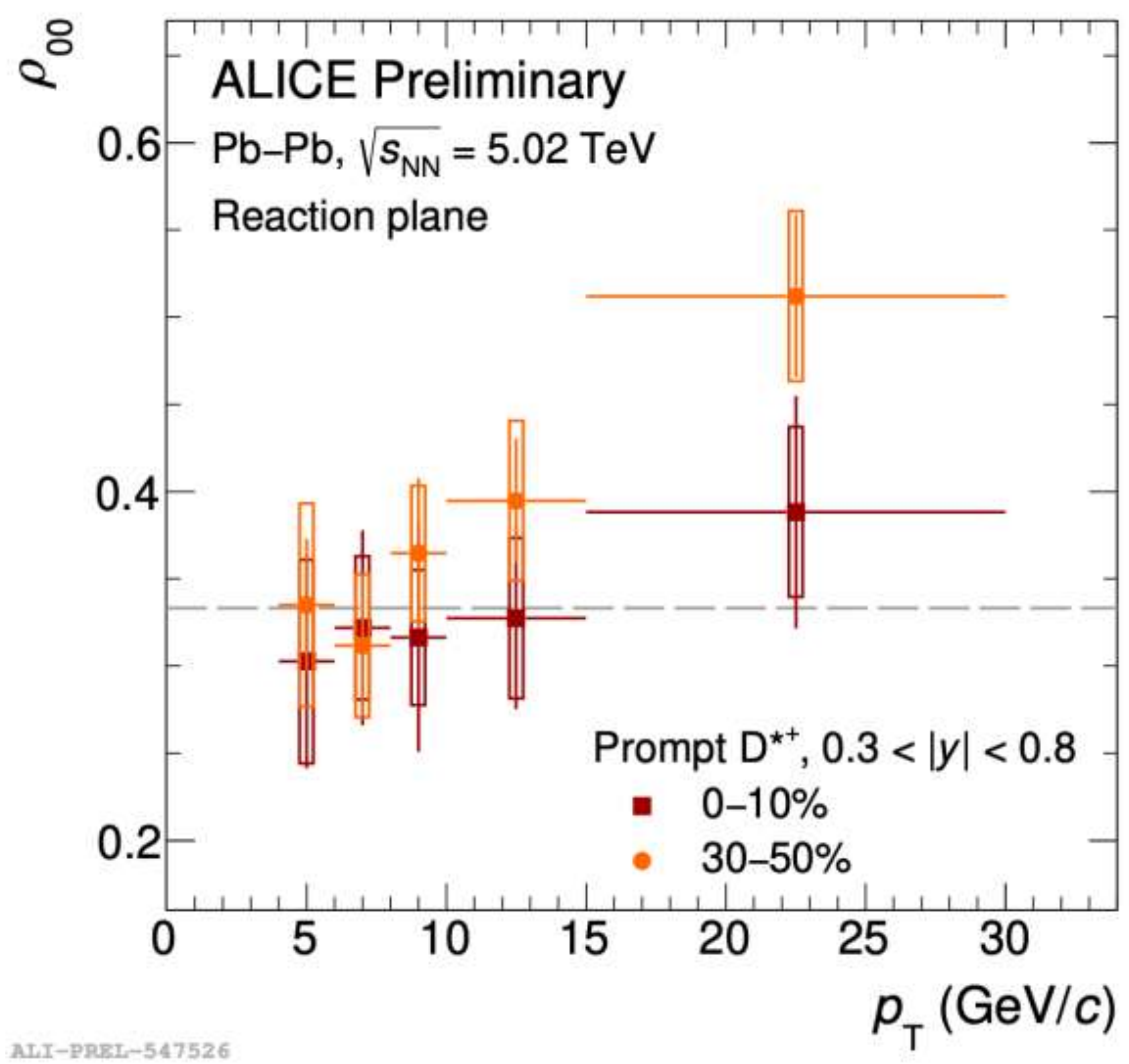
Complicated analysis but promising results!

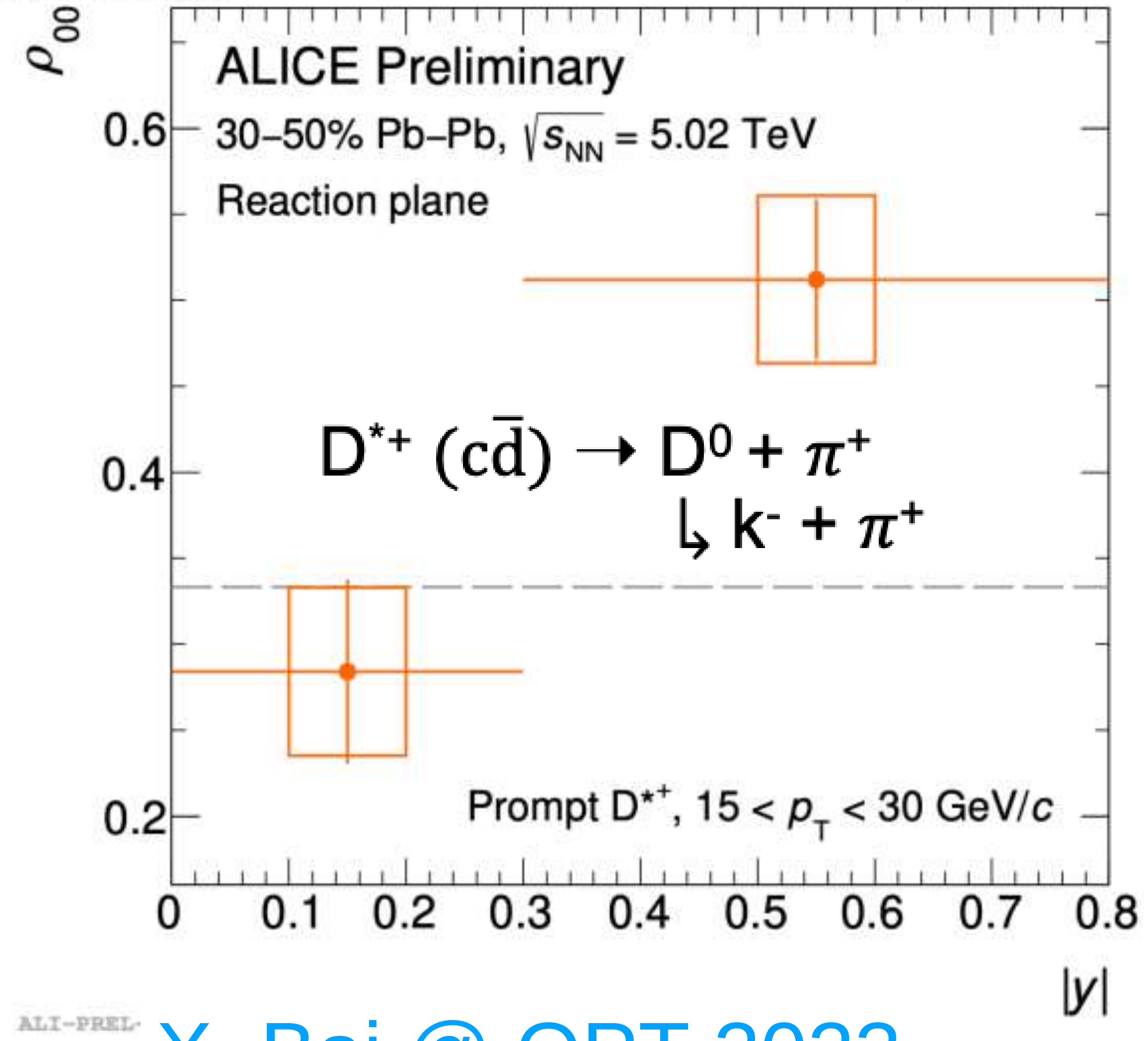
Global Spin Alignment at ALICE



ALICE, PRL 131 (2023) 4, 042303







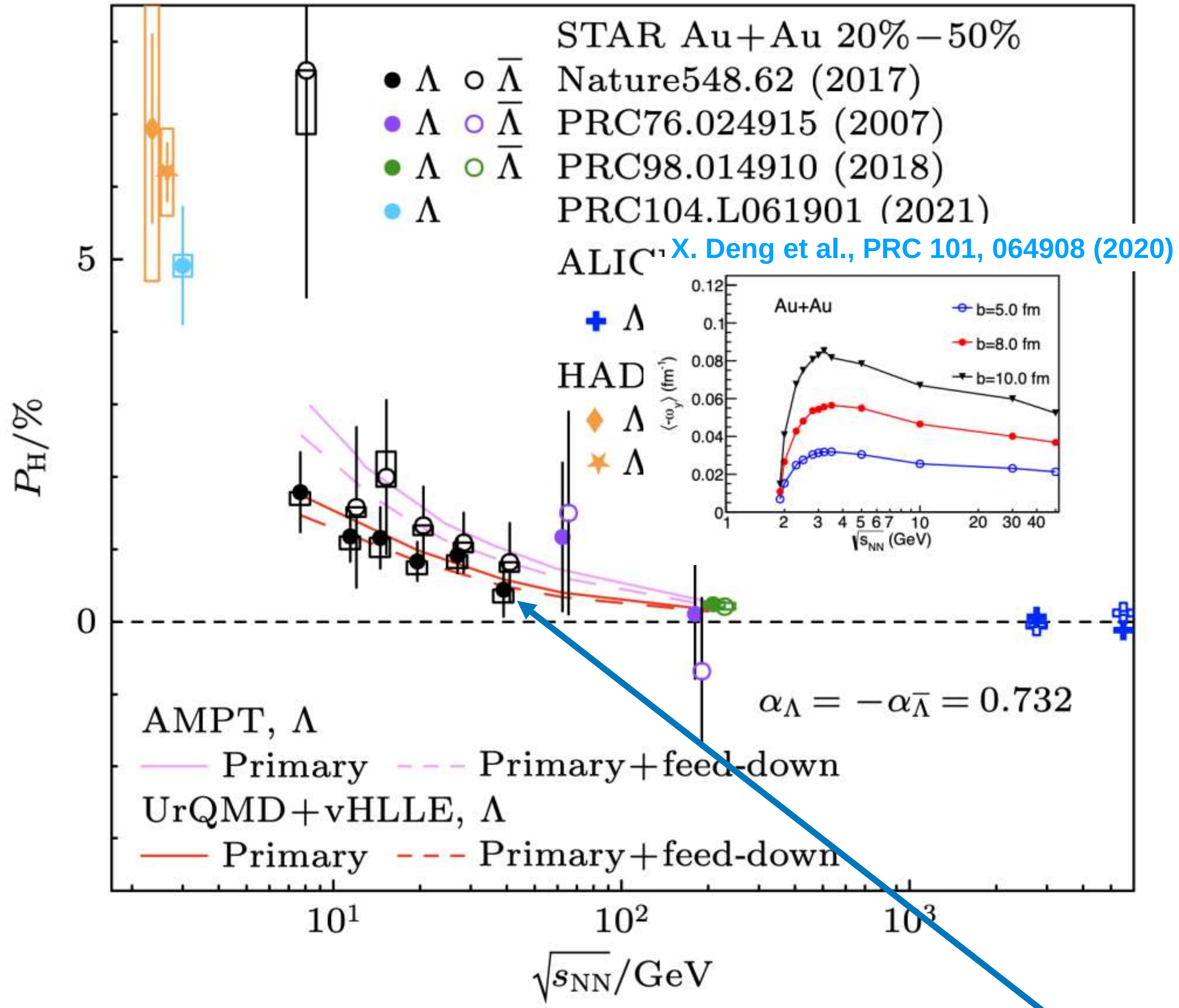
X. Bai @ QPT 2023

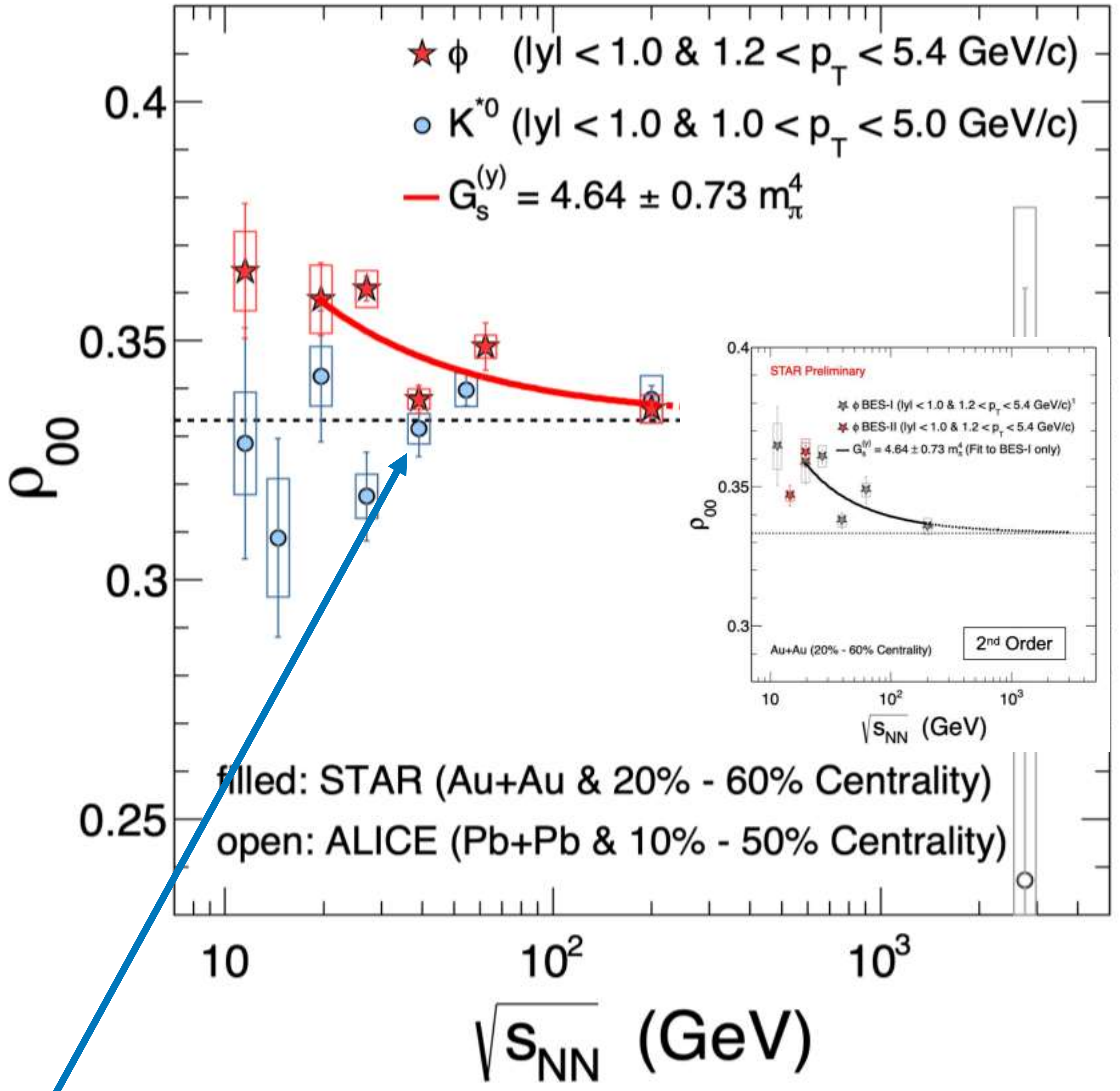
- Significant polarization (~**3.5**σ) observed in semicentral collisions (40-60%) in 2 < p_T < 6 GeV/c
- The significance of the polarization reaches ~**3.9**σ at low p_T (2 < p_T < 4 GeV/c) in 30-50%

- 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!

Puzzle?



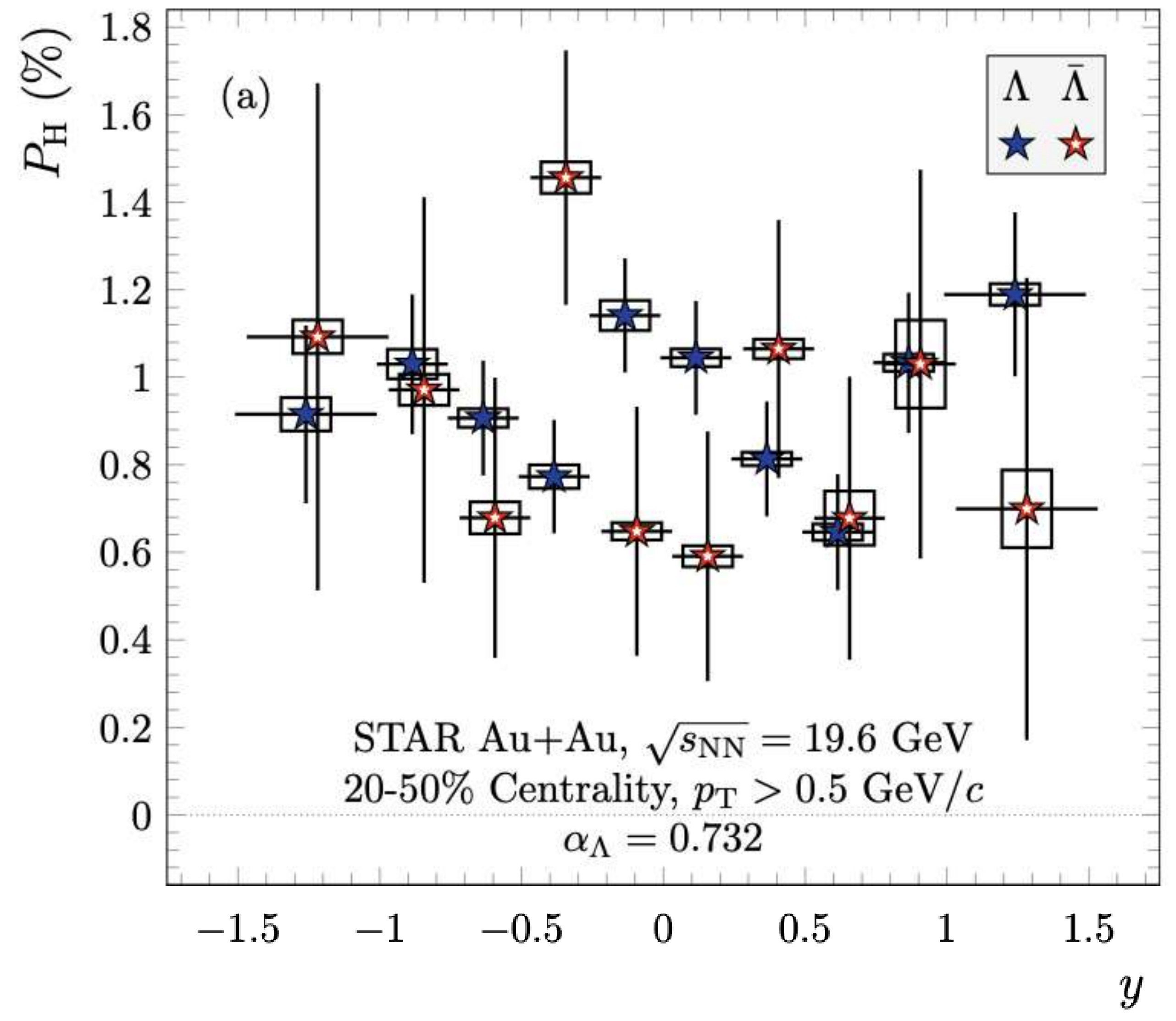


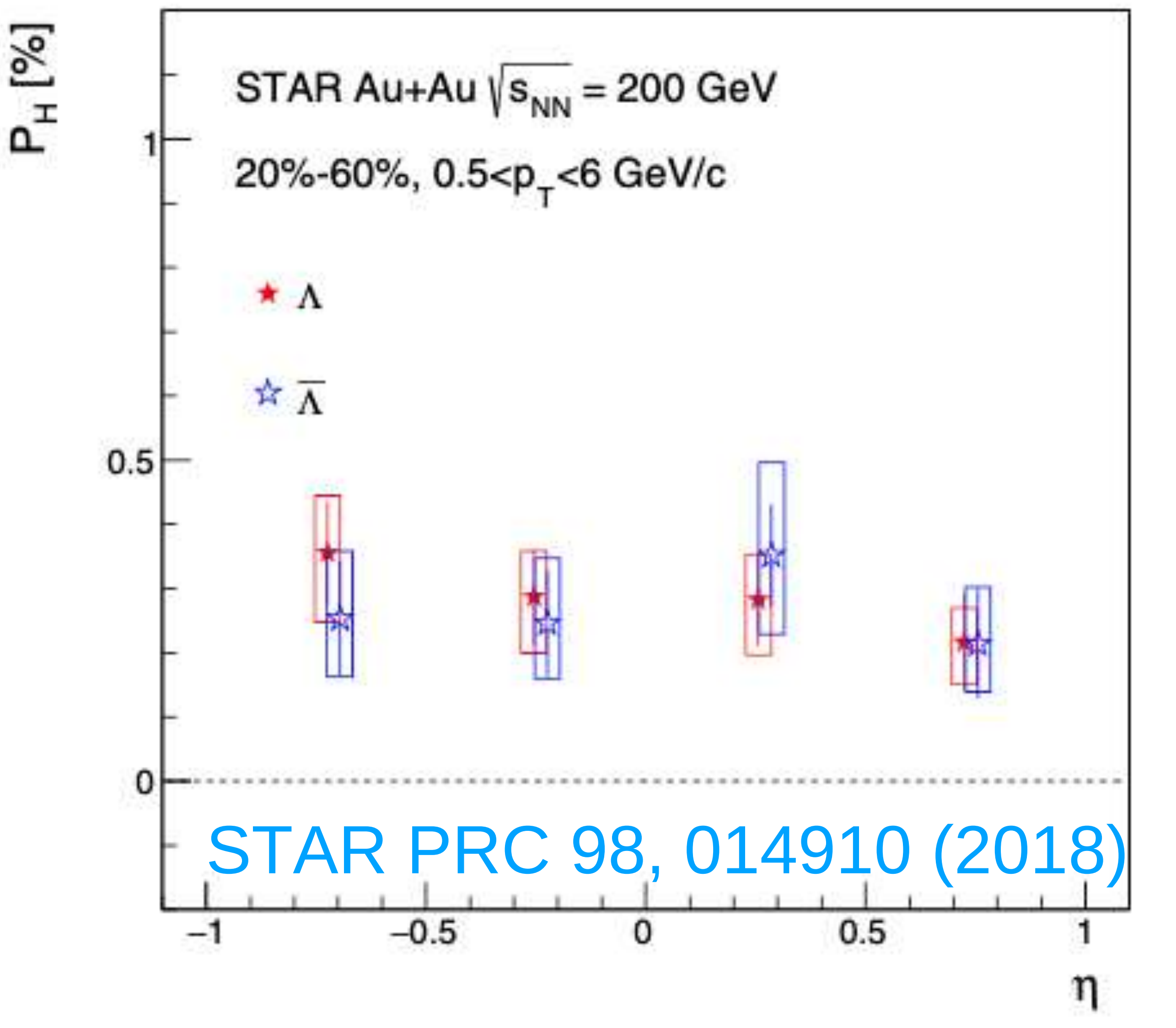
At 39 GeV both P_H and $\Delta\rho_{00}$ are ~ 0 within 1σ

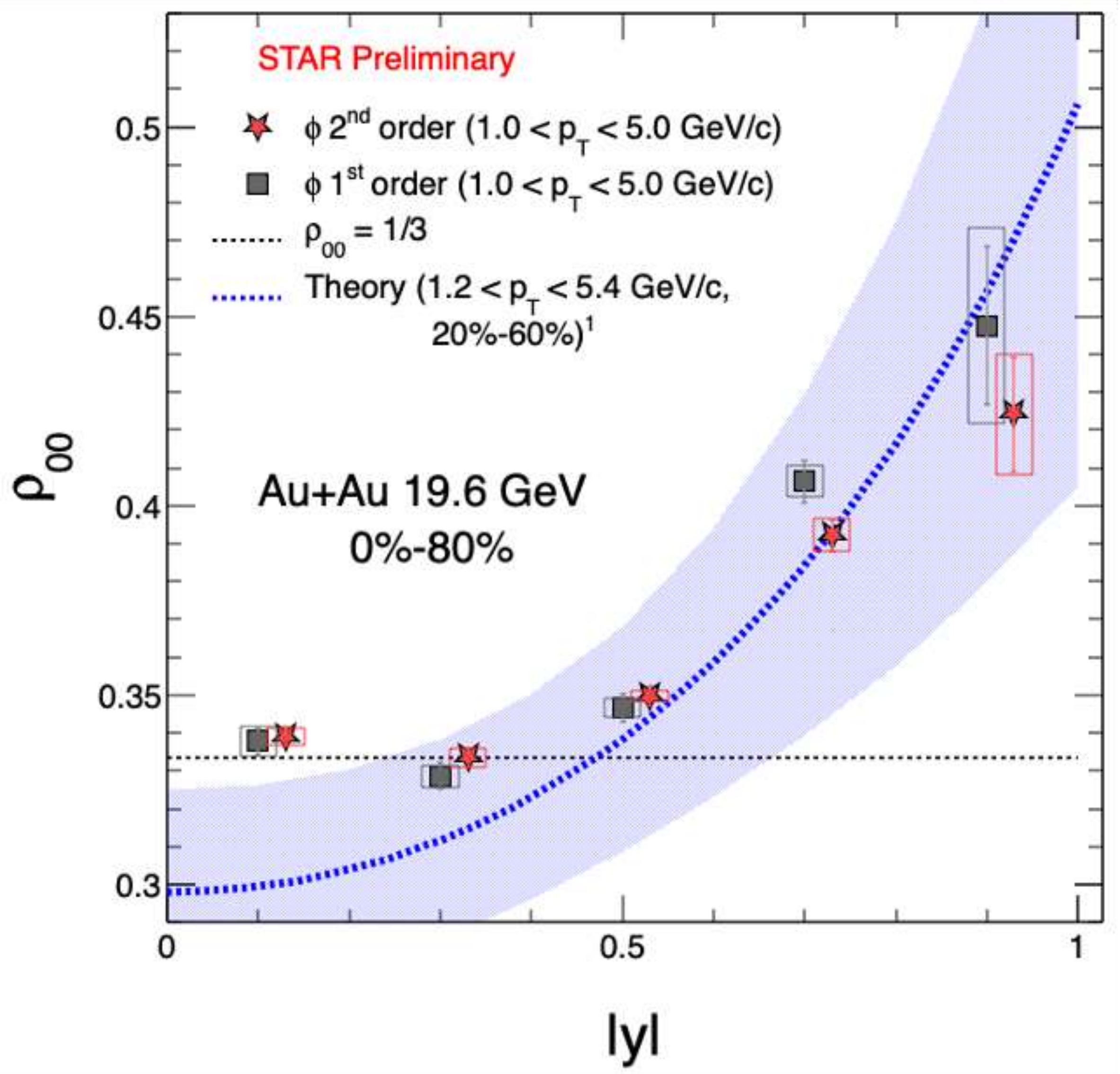
Where will P_H and ρ_{00} turn down?

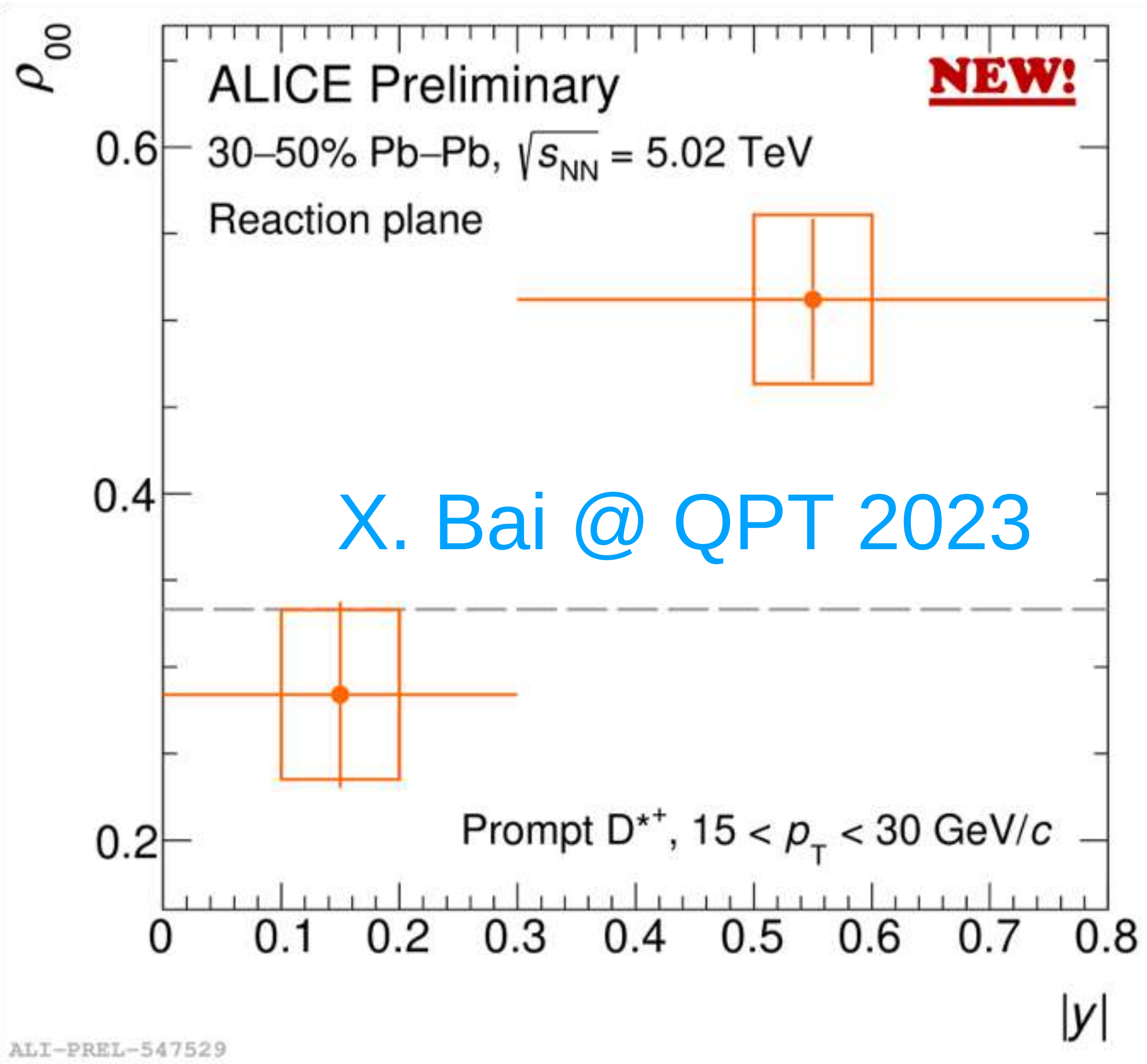
Puzzle?

STAR, PRC 108, 14910 (2023)









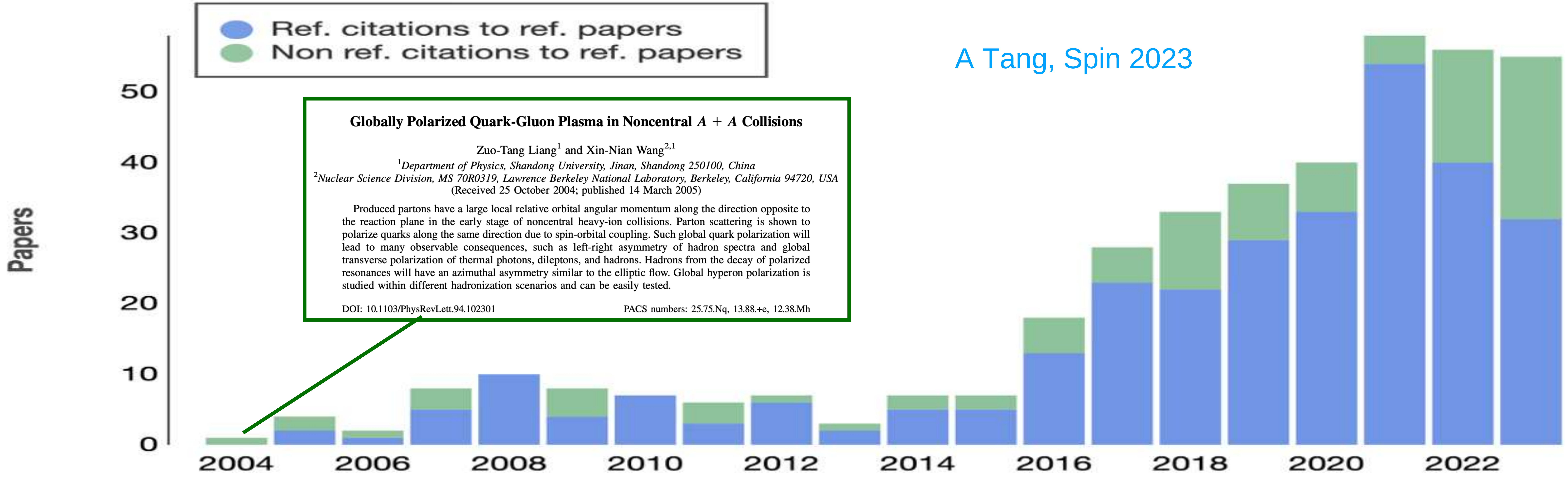
G. Wilks for STAR, Spin 2023
Theory curve : X.L. Sheng, et al., arXiv:2308.14038

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

Theory guidance needed!

How Did We Get Here?

A Tang, Spin 2023



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)

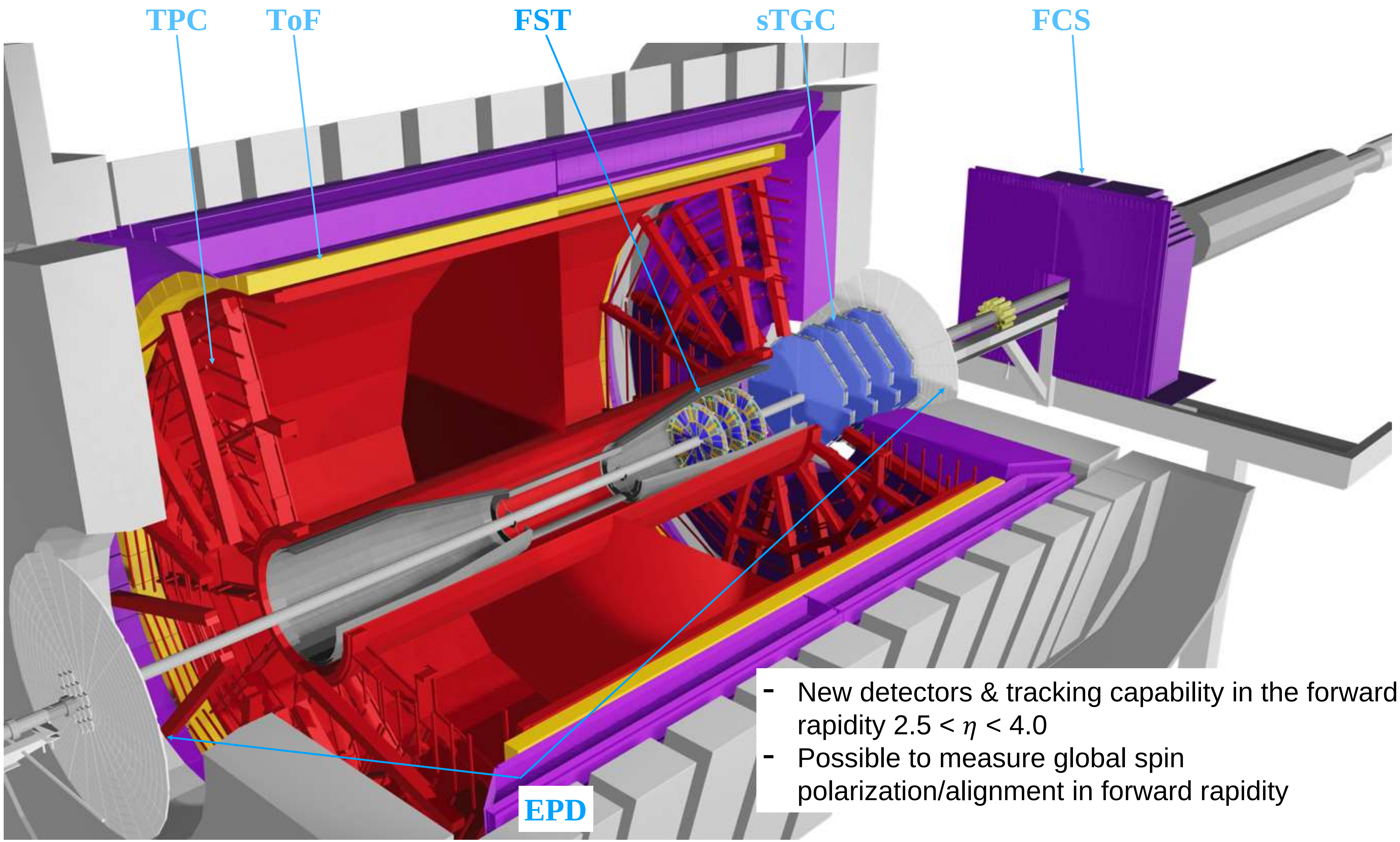
ALICE,
HADES …

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

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

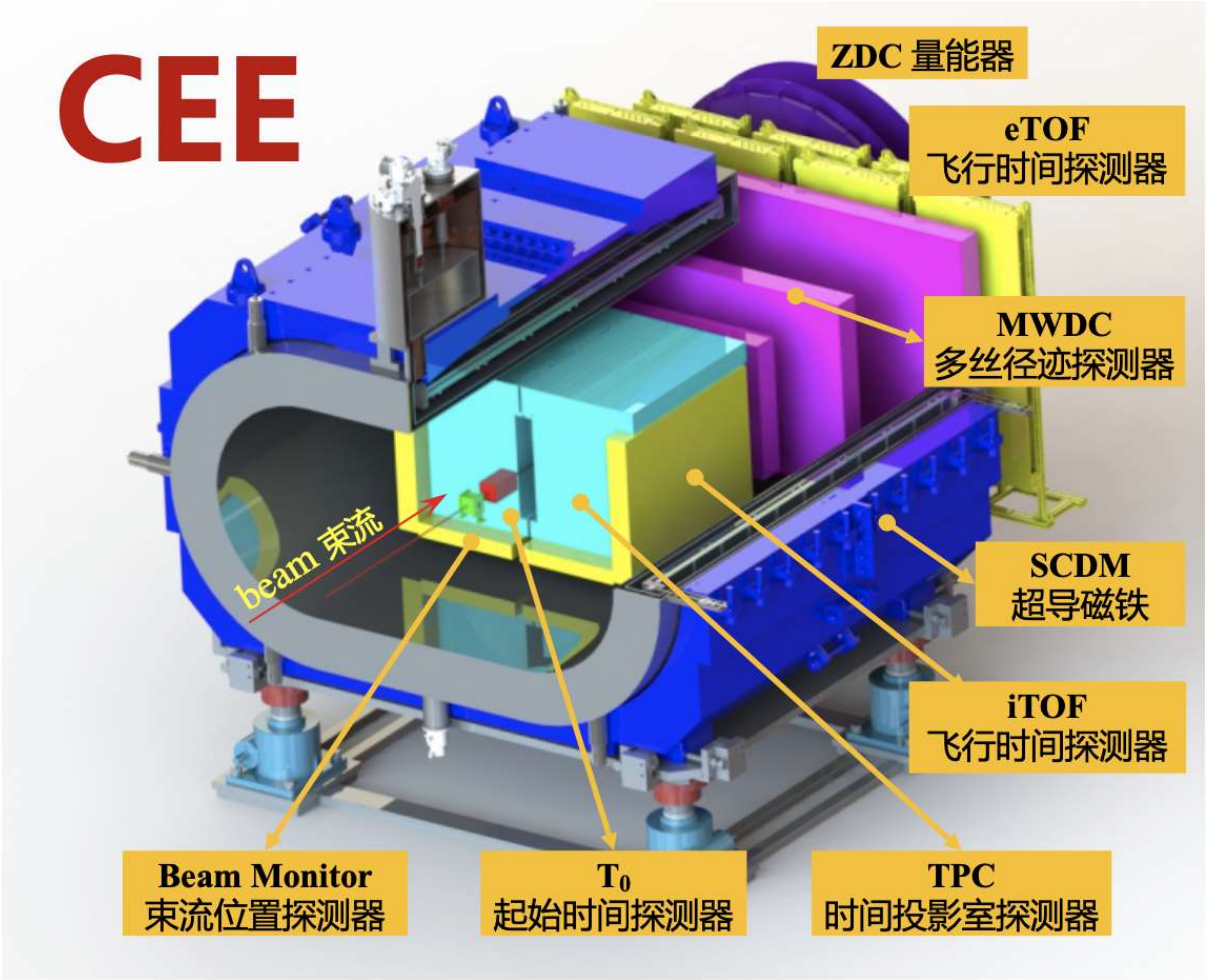
Not mentioned : many theory and phenomenological studies between 2004-2022

STAR Detector for 2022-2025



- New detectors & tracking capability in the forward rapidity $2.5 < \eta < 4.0$
- Possible to measure global spin polarization/alignment in forward rapidity

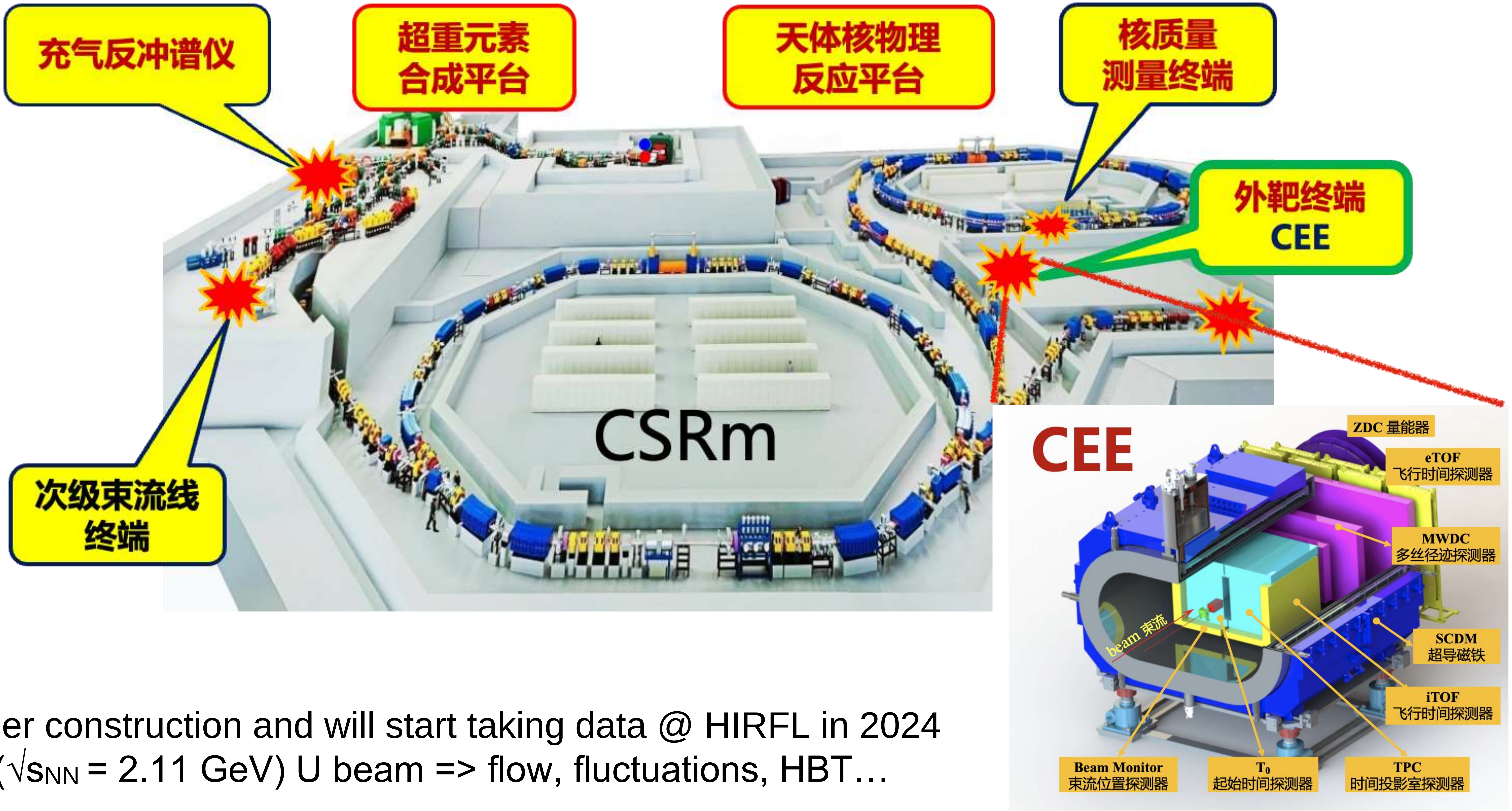
CSR External-target Experiment



- Study QCD phase structure in high baryon density region; Search QCD critical point and phase boundary
- Study EOS in high baryon density region
- Study hyper-nuclei production mechanism in high baryon density region: extract hyperon-nucleon interaction parameters & understand phase structure of nuclear matter inside dense star

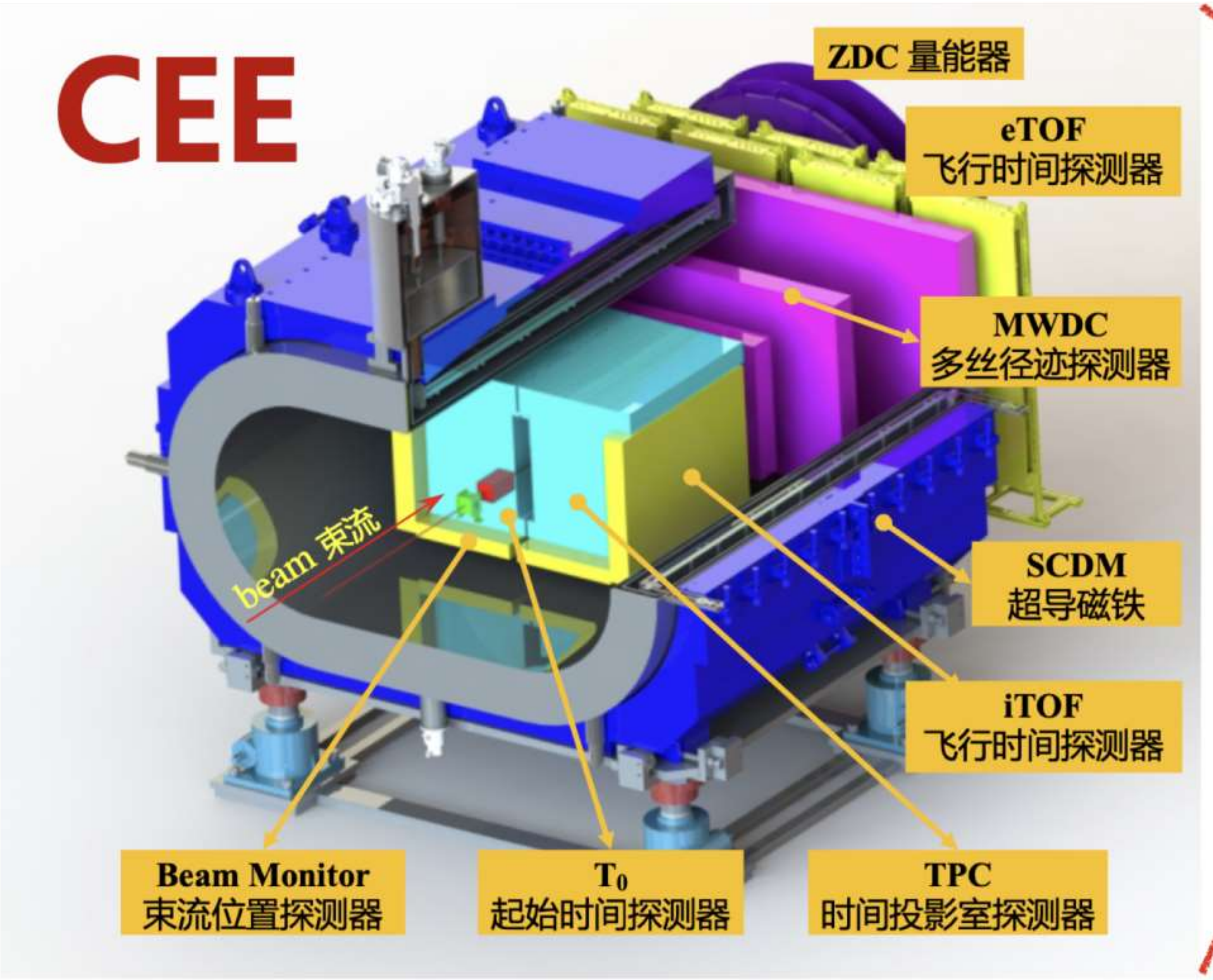
CEE started construction at 2020 & will start take data at the second half of 2024!

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, HBT…

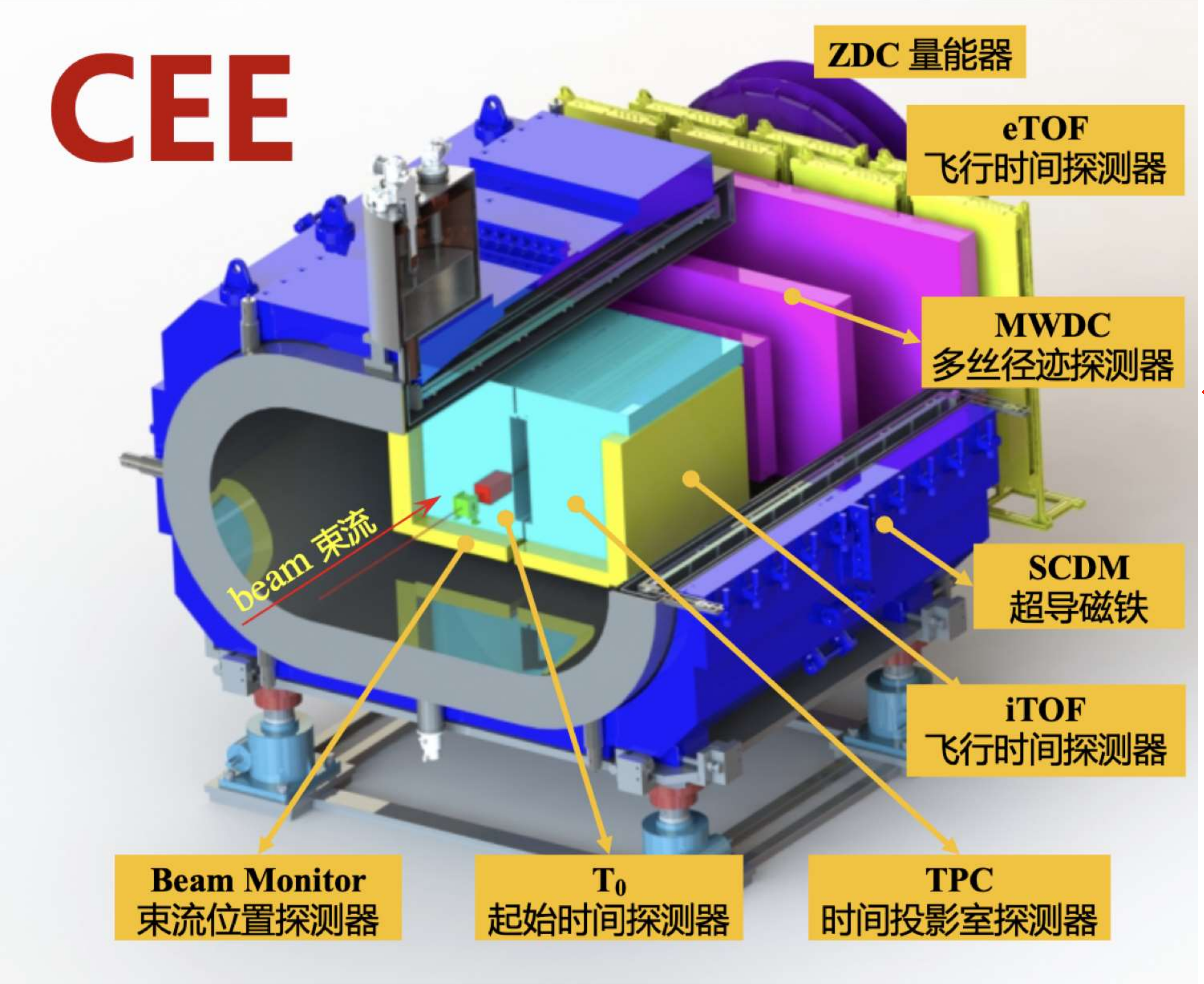
Feature Measurement @ HIAF-CEE

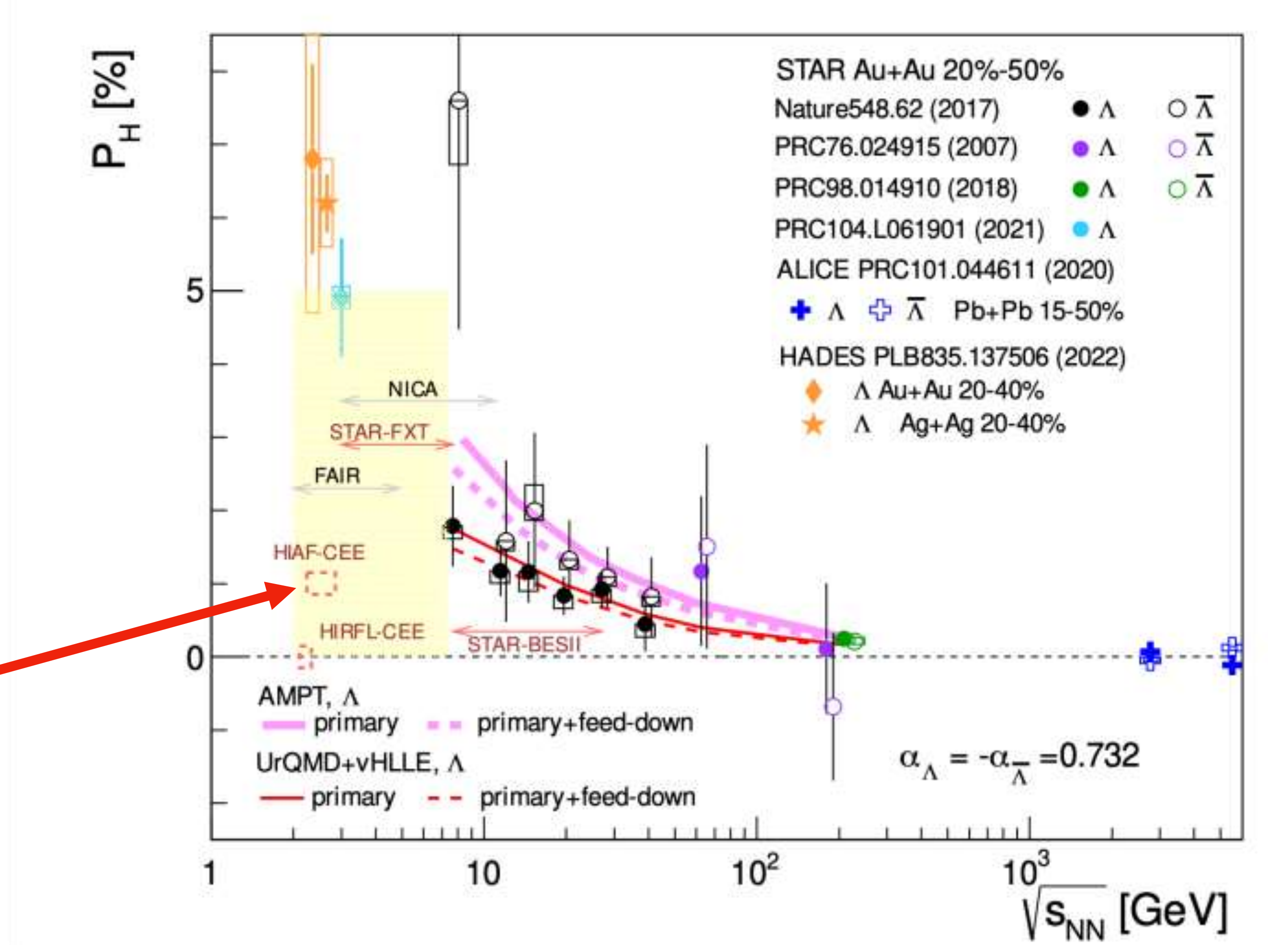


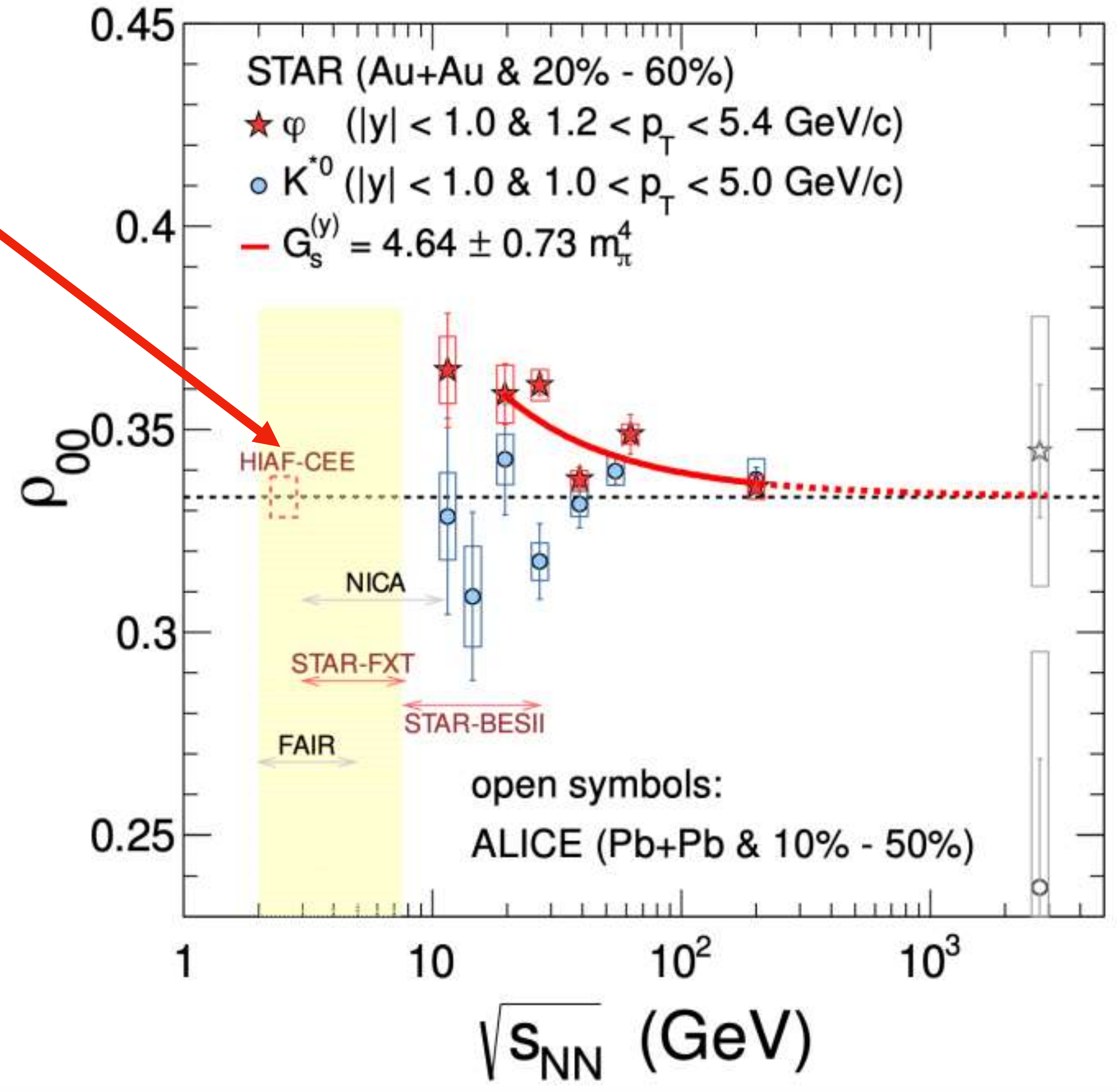
- HIAF is under construction and will start delivering beam in 2025
- 0.8-9.1 GeV/u U beam => global polarization

	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

Future Measurement in High Baryon Density Region







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

Summary

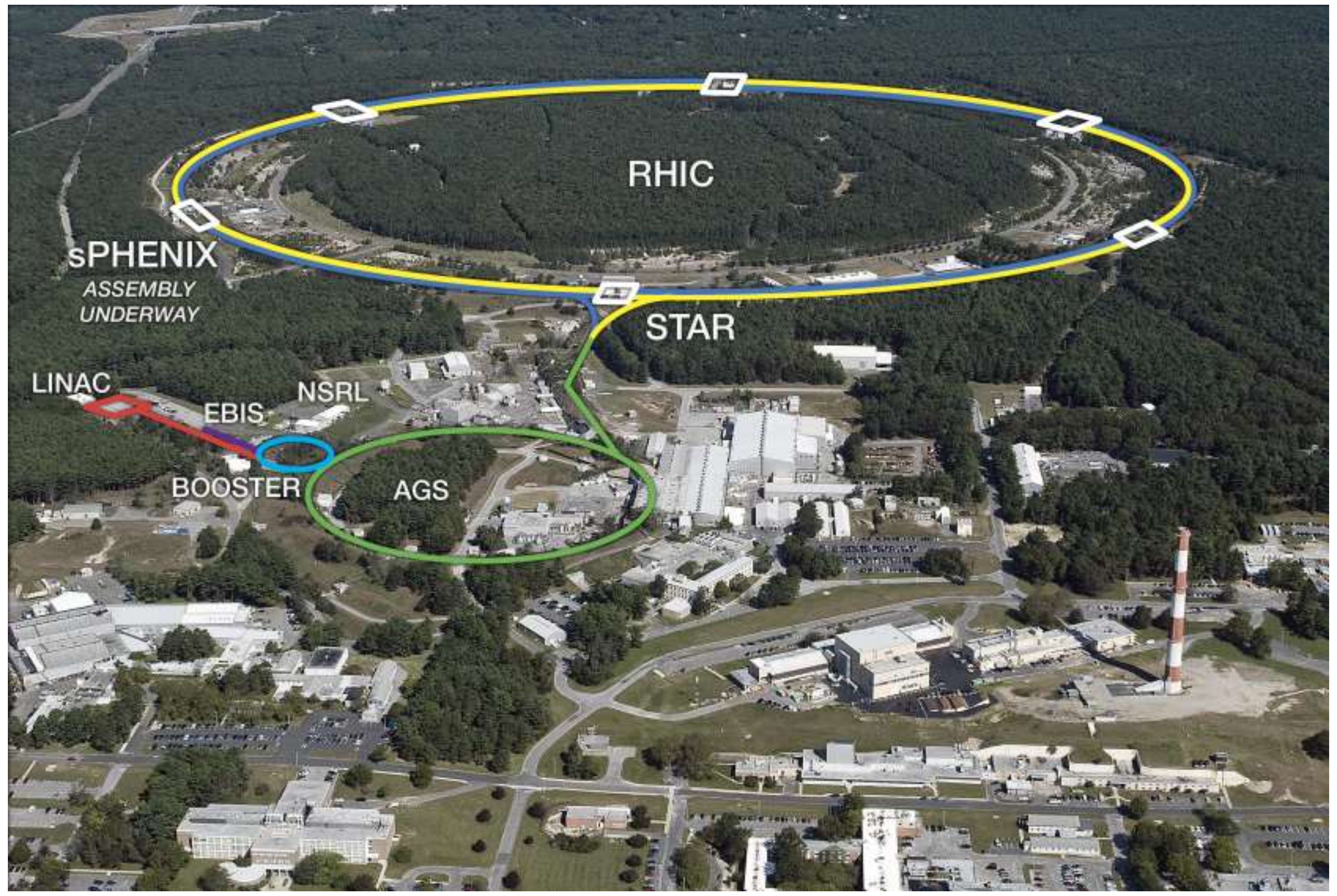
- Spin in heavy ion collisions is an emerging and promising field of study that probes the fascinating behavior of particles' global spin feature under extreme conditions.
- Observed the most vortical fluid known in the world, as well as tantalizing clues of a strongly fluctuating strong force field.
- Theory guidance needed: to understand alignment of ρ, K*, ϕ, J/Ψ …

Thanks for your attention!

Xu Sun
Phone Number: 18627822467
Email: xusun@impcas.ac.cn

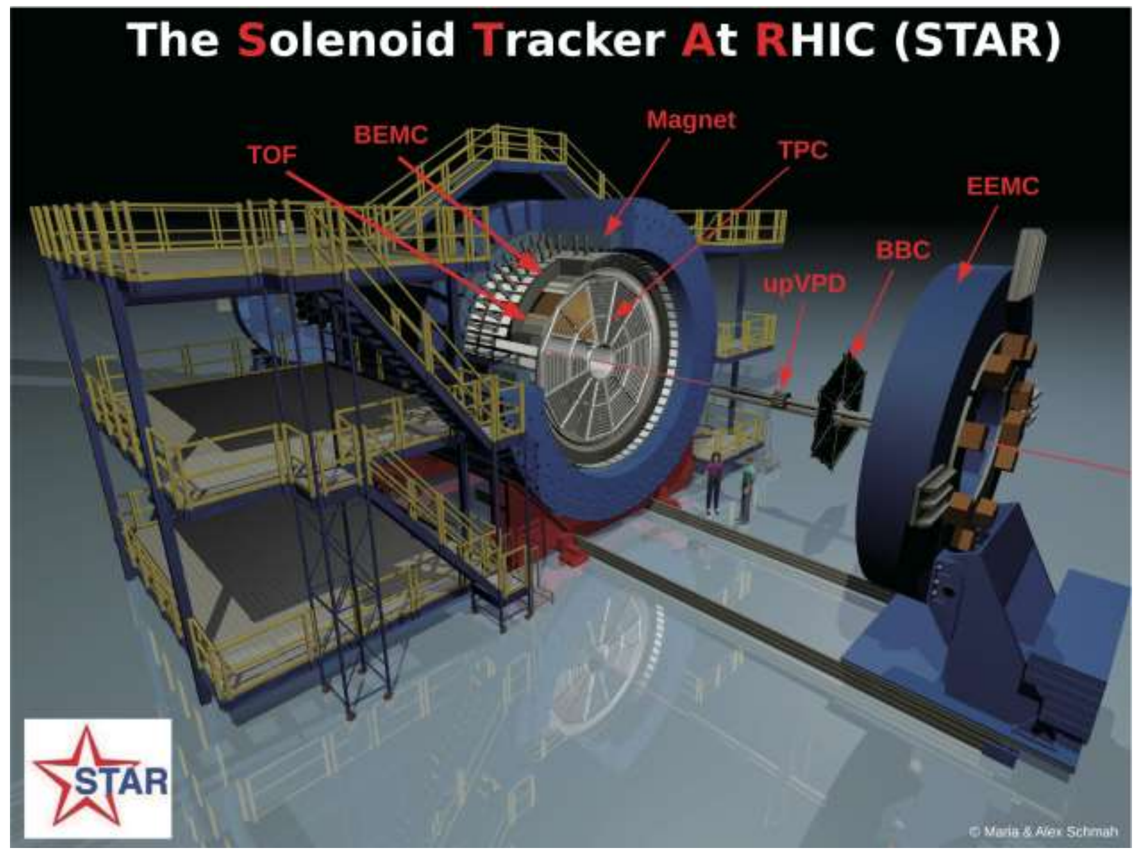
Backups

Relativistic Heavy Ion Collisions

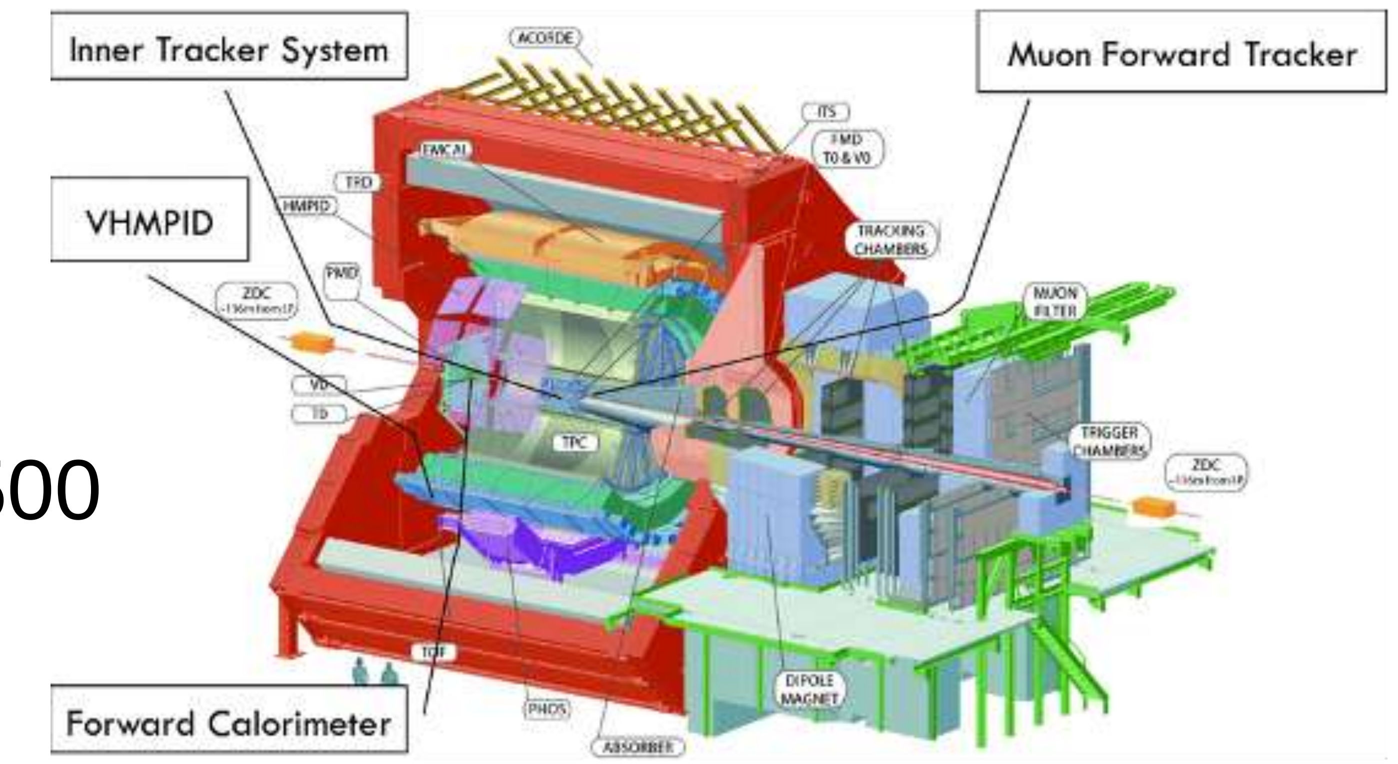


Relativistic Heavy Ion Collider—RHIC
Circumference 3.8 km

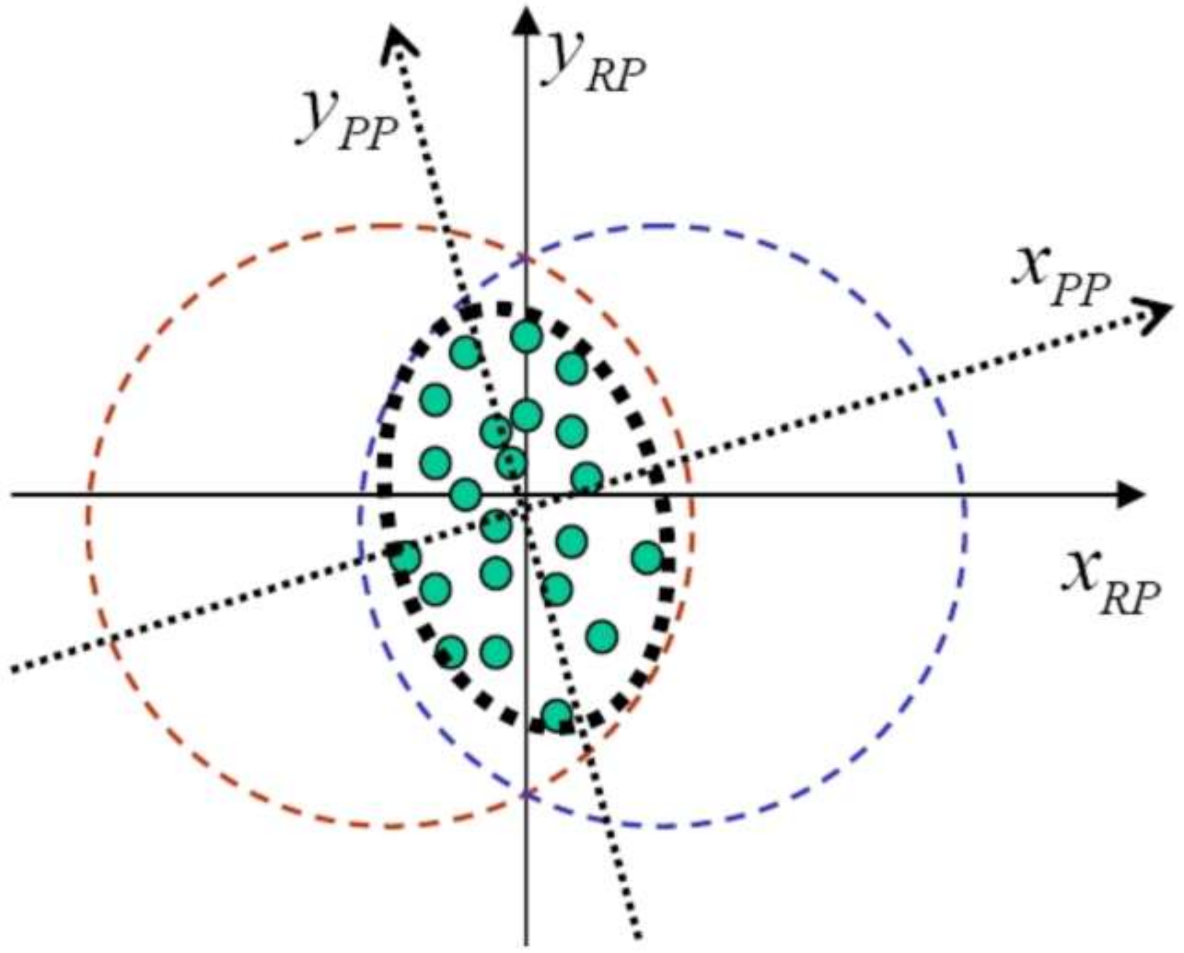
Large Hadron Collider—LHC
Circumference 27 km

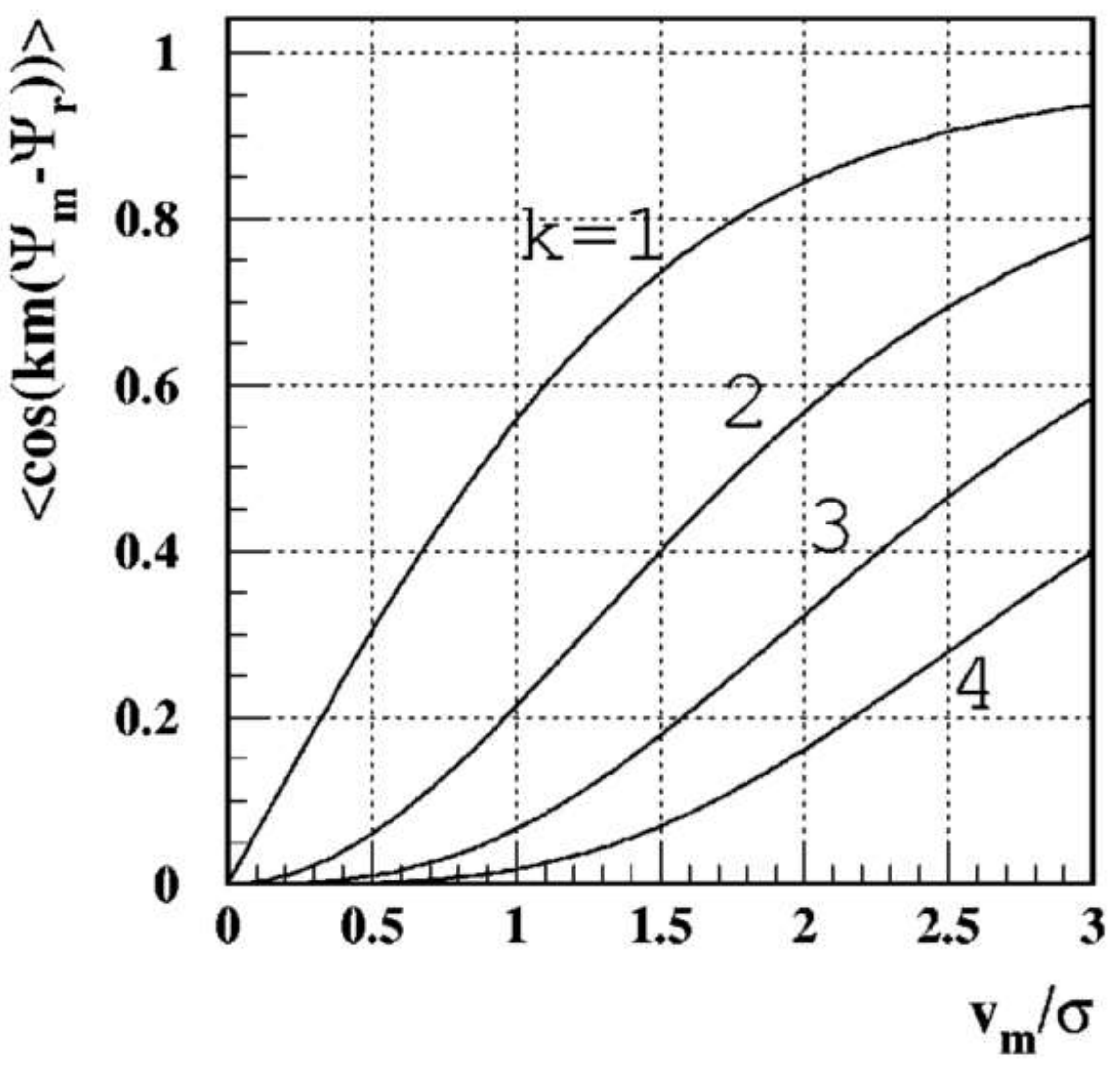


12 Counties 43
56 Institutions193
~600 Collaborators ~3500



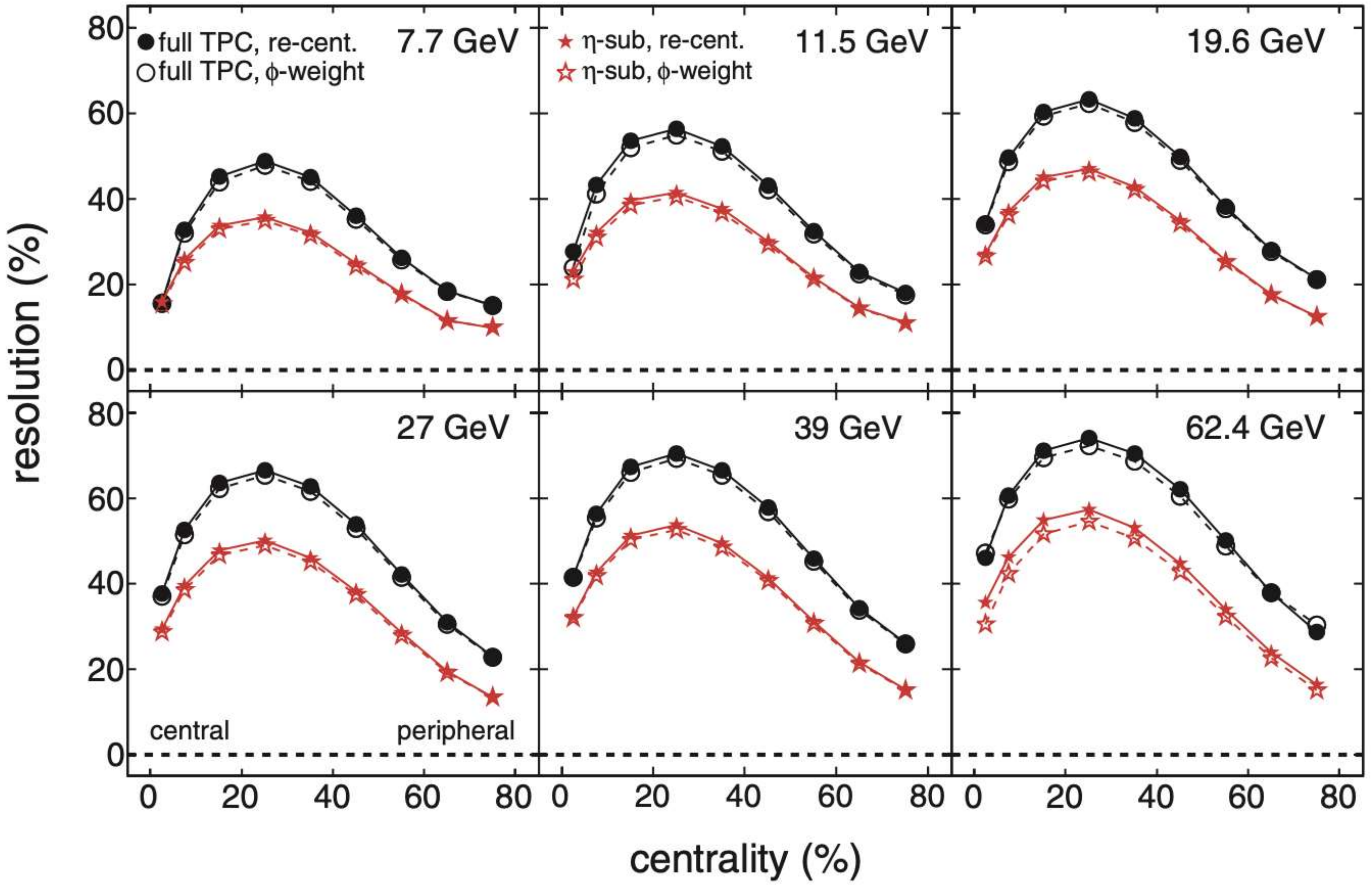
Event Plane Resolution





Phys. Rev. C58,1671 (1998)

$$R_n = \langle cos[n(\Psi_n - \Psi_{RP})]\rangle$$



STAR Collaboration, Phys. Rev. C88,014902 (2013)

Λ-Hyperon: Spin Probe

In the Lambda rest frame, the total angular momentum is the spin of Lambda
J_z = 1/2, there are two possible decay channel: $s_{1/2}$ (a_s) and $p_{1/2}$(a_p). Assuming that the initial Lambda i

$$f(x) = (a_s + a_p \cos\theta) \uparrow + a_p \sin\theta e^{i\phi} \downarrow$$

θ is the angle between proton momentum and Lambda spin direction in the Lambda rest frame

if proton momentum and Lambda spin are in same direction (State A): $\theta = 0 \quad A = a_s + a_p$

if proton momentum and Lambda spin are in opposite direction (State B): $\theta = \pi \quad B = a_s - a_p$

decay-angular distribution of proton in Lambda rest frame:

$$\frac{dN}{d\Omega} \propto 1 - \alpha \cos\theta$$

Λ-Hyperon: Spin Probe

the definition of α:

$$\alpha = -\frac{2Re(a_s a_p^*)}{|a_s|^2 + |a_p|^2}$$

α is decay parameter which characterises the degree of mixing of particles in the decay

T.D. Lee and C.N. Yang, Phys. Rev. 108, 1645 (1957)

re-write α:

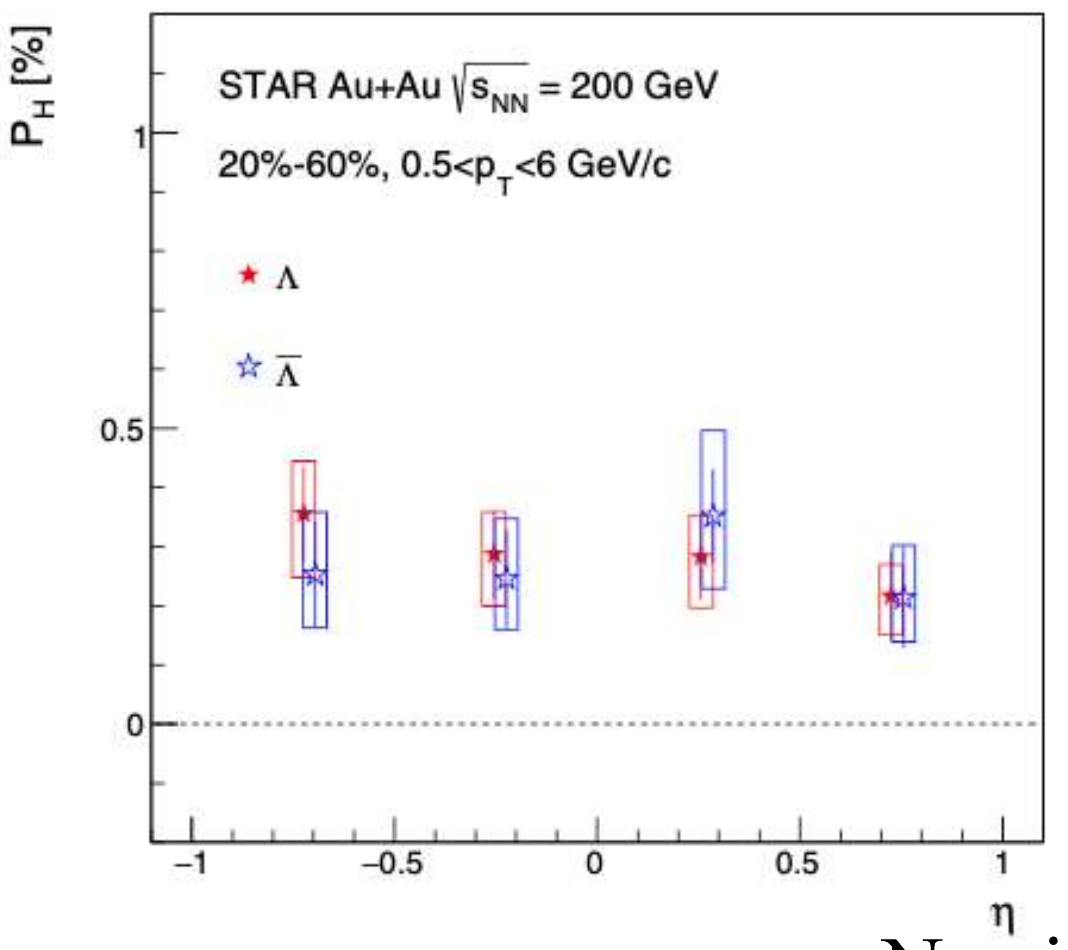
$$\alpha = \frac{|a_s + a_p|^2 - |a_s - a_p|^2}{|a_s + a_p|^2 + |a_s - a_p|^2} = \frac{A^2 - B^2}{A^2 + B^2}$$

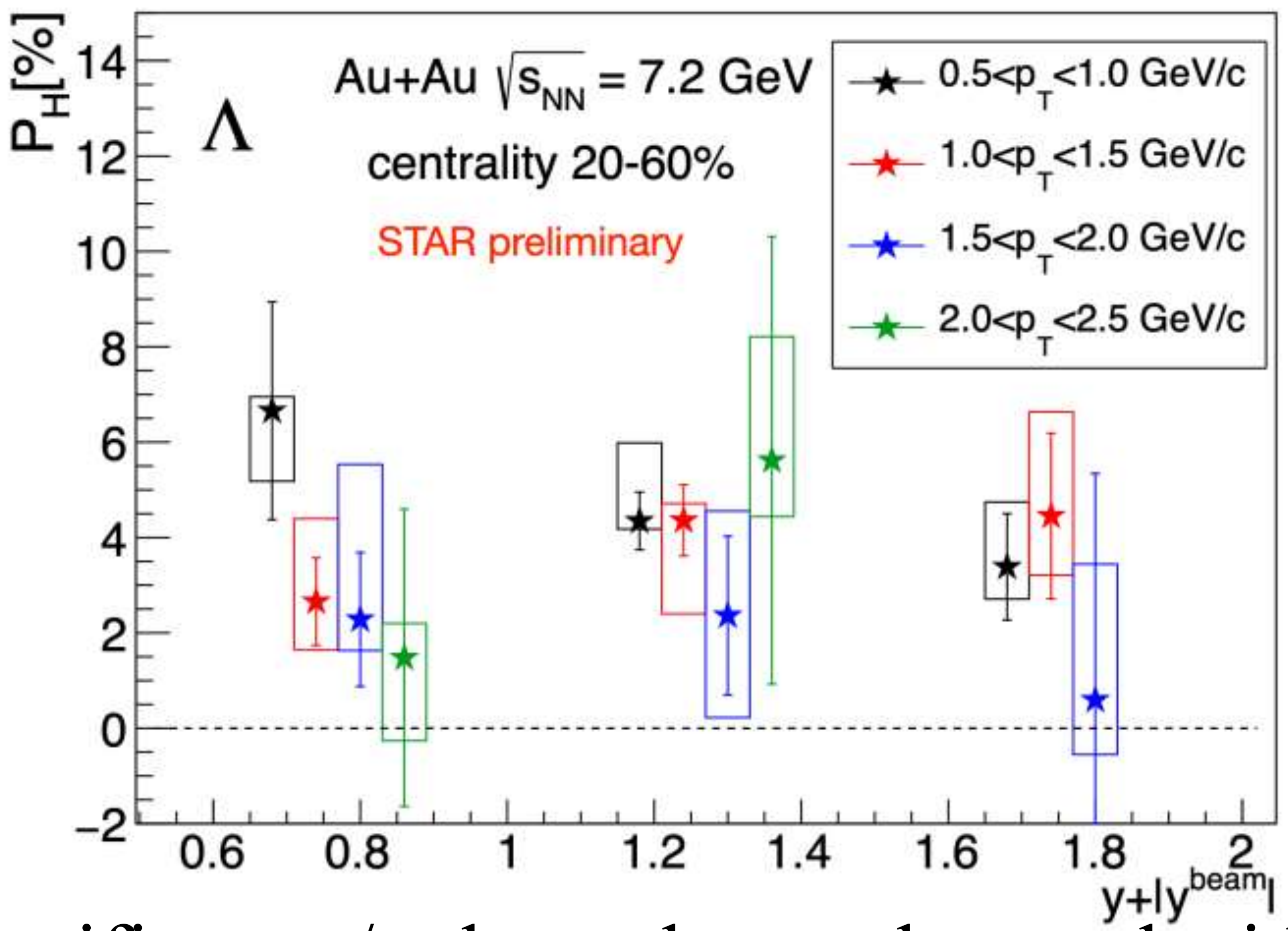
- α = 0.732 (PDG book) is the relative difference between State A and State B, which means proton prefers to emit from the spin direction of Λ
- α = -0.732 for $\bar{\Lambda}$ => anti-proton prefers to emit from the opposite spin direction of $\bar{\Lambda}$

η Dependence of P_Λ

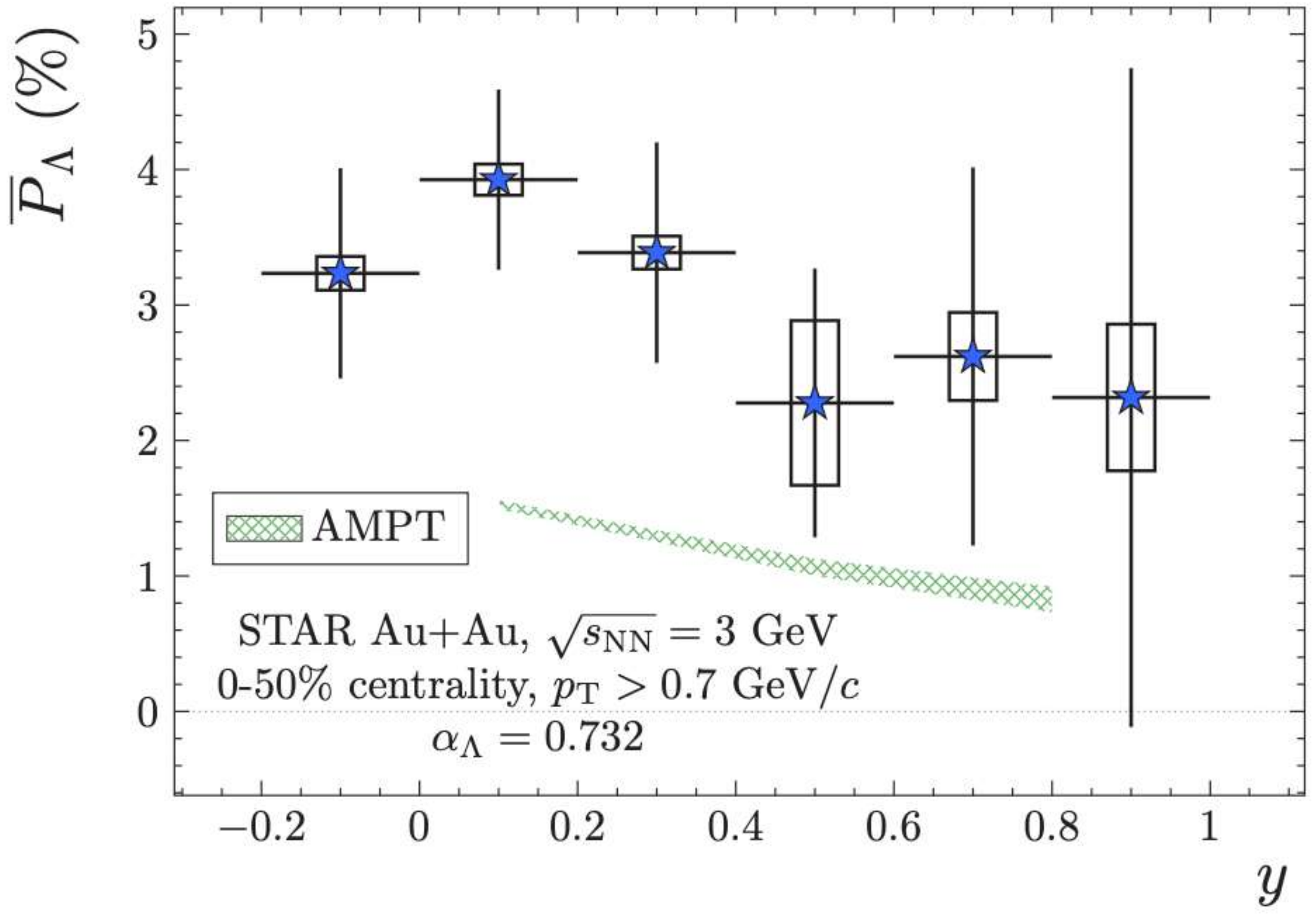
Data

Phys. Rev. C 98, 014910 (2018)





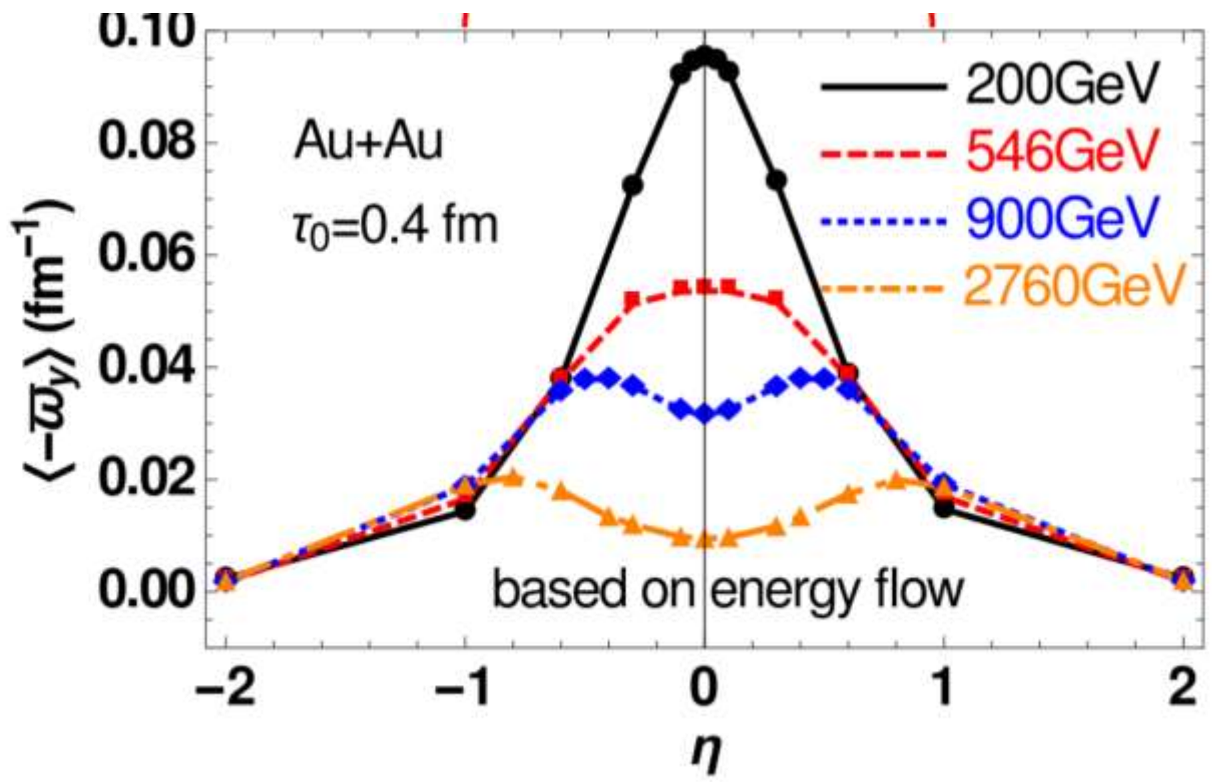
Phys. Rev. C 104, L061901 (2021)



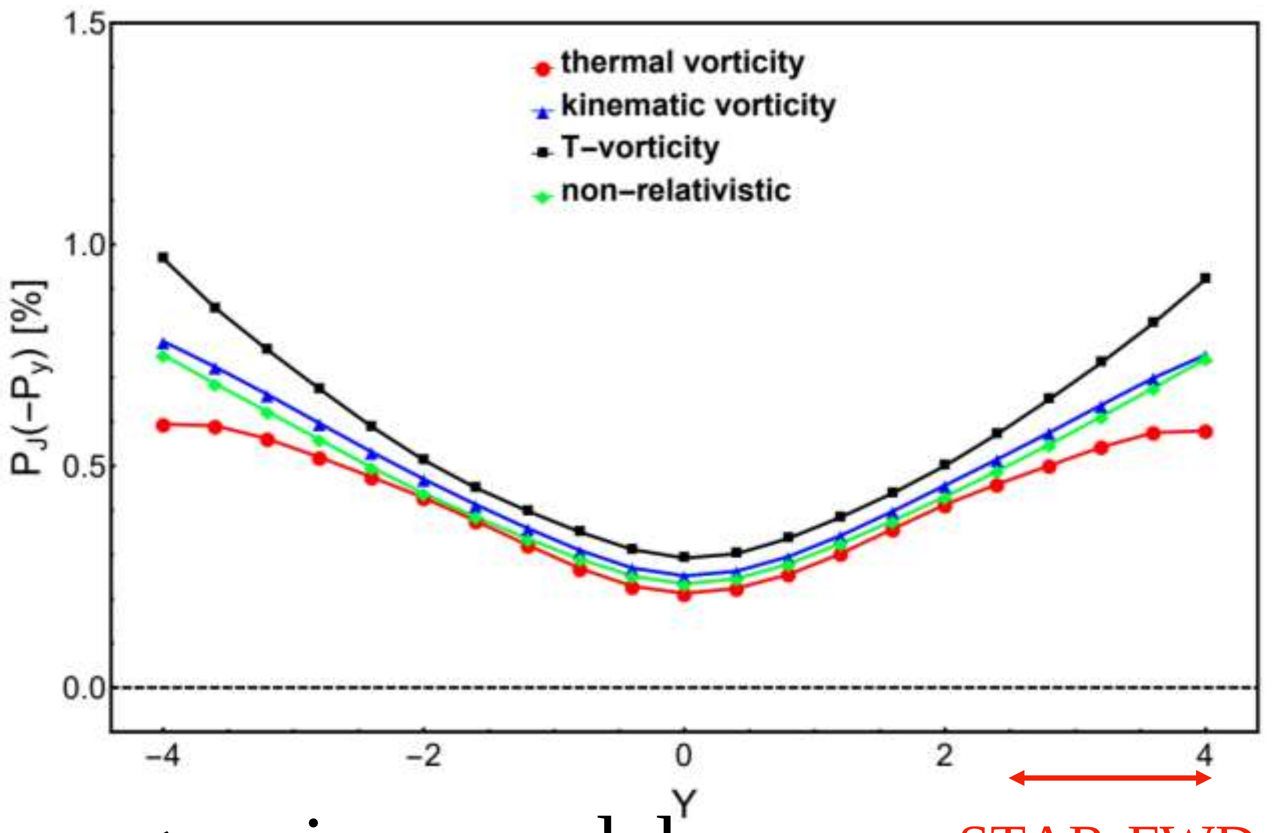
No significant y/η dependence observed within acceptance

Model

Phys Rev C 93, 064907 (2016)



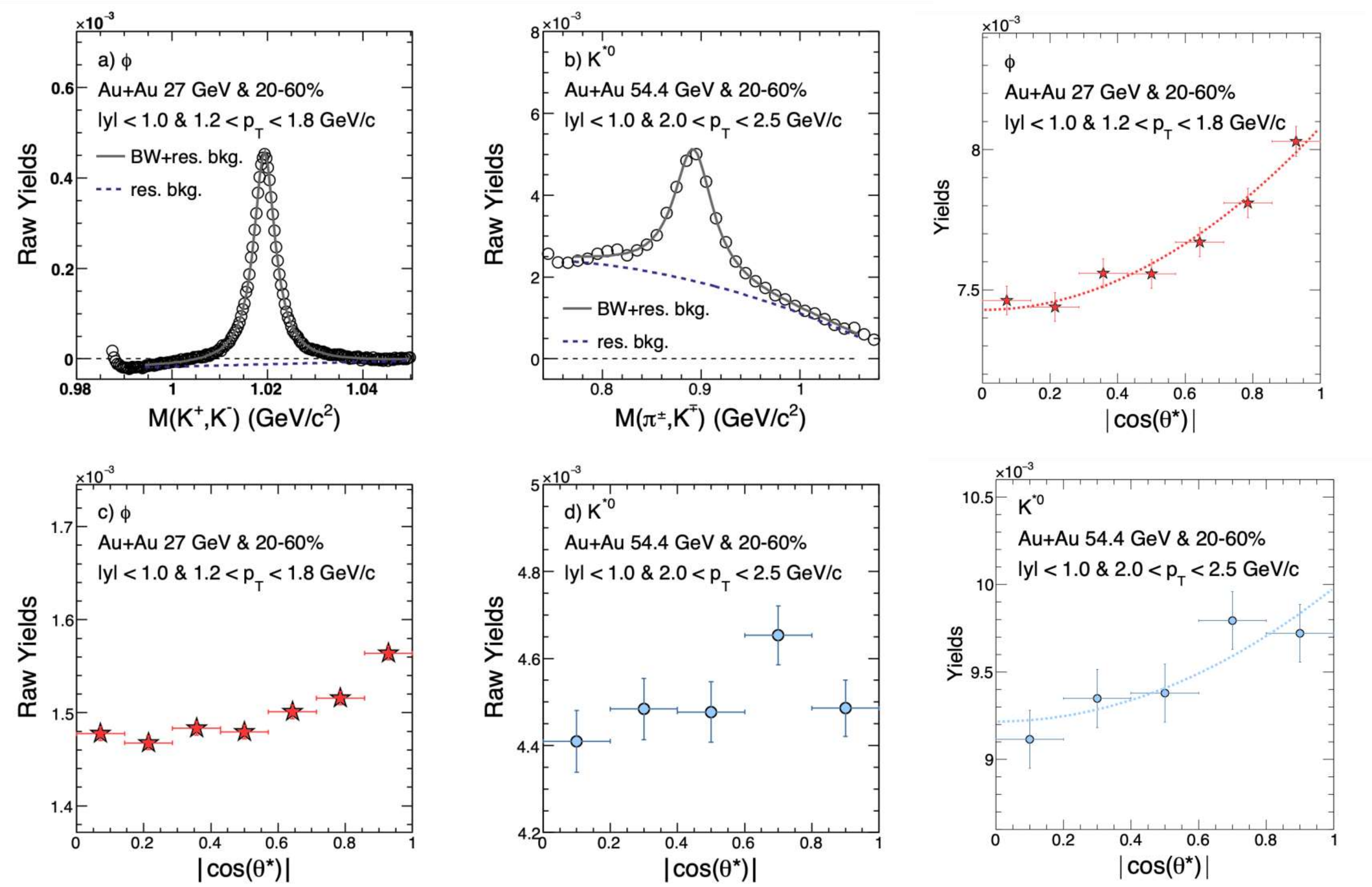
Phys Rev Research 1, 033058 (2019)



STAR-FWD

Rapidity dependence of P_Λ is different among various models

Signal Extraction



ϕ-meson Vector Field

Like electric charges in motion can generate an EM field, s and $\bar{s}$ quarks in motion can generate an effective ϕ-meson field.

The ϕ-meson field can polarize s and $\bar{s}$ quarks with a large magnitude due to strong interaction, in analogy to how EM field polarize (anti)quarks.

$$P^{y}_{s/\bar{s}}\left(\mathrm{t}, \mathbf{x}, \mathbf{P}_{s/\bar{s}}\right) = \frac{1}{2}\omega_y + \frac{1}{2m_s}\hat{\mathbf{y}}\cdot\left(\varepsilon\times\mathbf{P}_{s/\bar{s}}\right) \quad \text{<= vorticity}$$

$$\pm\frac{Q_s}{2m_sT}B_y \pm \frac{Q_s}{2m_s^2T}\hat{\mathbf{y}}\cdot\left(\boldsymbol{E}\times\mathbf{P}_{s/\bar{s}}\right) \quad \text{<= EM field}$$

$$\pm\frac{g_\phi}{2m_sT}B_{\phi,y} \pm \frac{g_\phi}{2m_s^2T}\hat{\mathbf{y}}\cdot\left(\boldsymbol{E}_\phi\times\mathbf{P}_{s/\bar{s}}\right) \quad \text{<= strong force field}$$

"magnetic" components

"electric" components

Quark version of the spin-orbit force. Not accessible via P_Λ.

The connection to strong force fields , if fully established, opens a potential new avenue for studying the behavior of strong force fields.

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