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Hyperon Spin Observables in Au+Au Collisions at RHIC BES-II: Global and Local Polarization, Spin Correlations

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NSFC

Outline

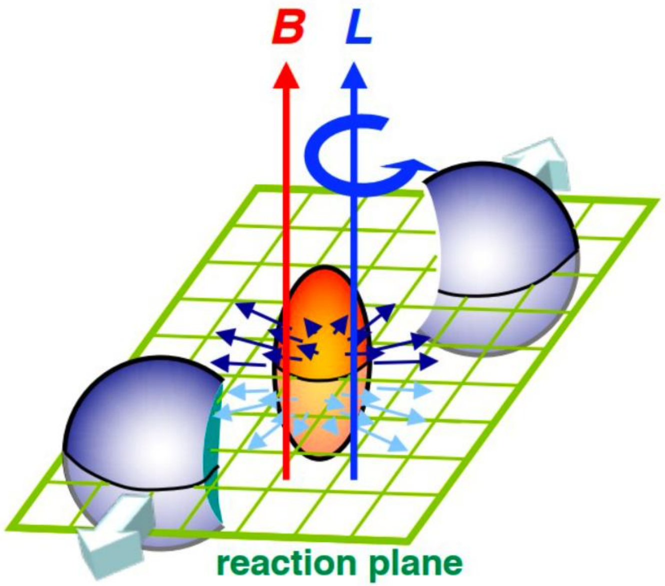
- Global polarization
  - Global polarization of Λ
  - Global polarization of Multi-strange hyperons(Ξ, Ω)

- Local polarization
  - Local polarization of Λ

- Measurement status of Λ–(anti)–Λ hyperon spin correlation in Au+Au Collisions

- Summary

Orbital angular momentum and polarization



Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94, 102301 (2005)

- Non-central HICs have large initial angular momentum and magnetic field

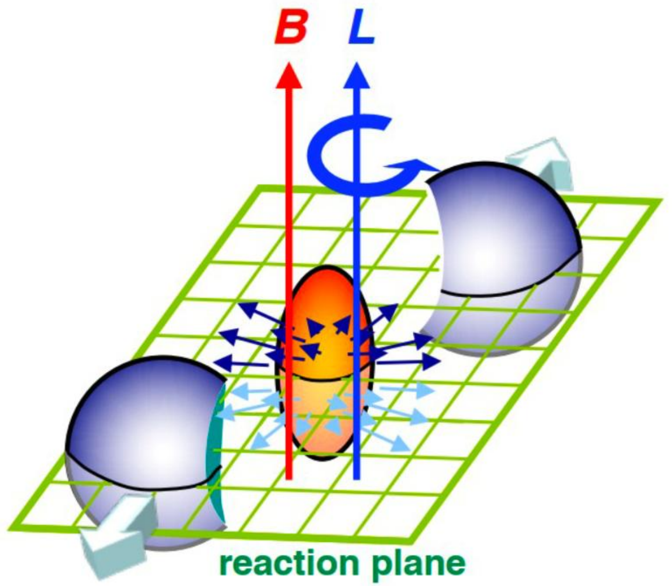
⇩

- Polarize quarks due to “spin-orbit” interaction

⇩

- Polarization of the final-state hadrons

Orbital angular momentum and polarization



Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94, 102301 (2005)

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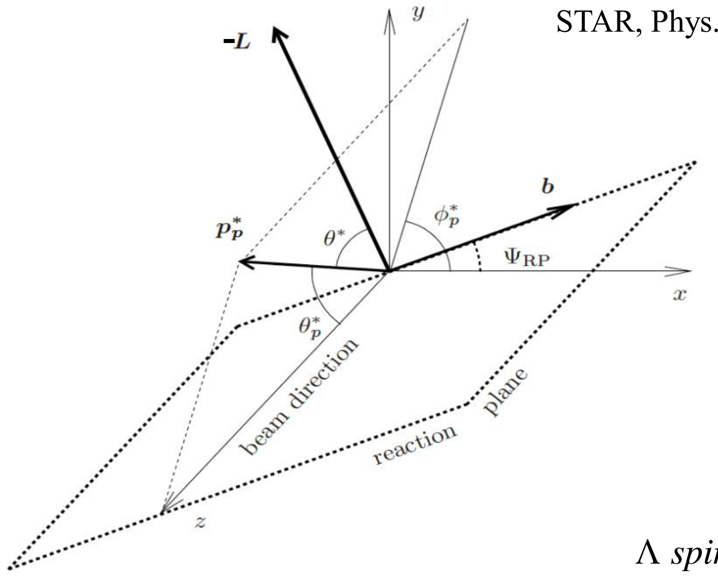
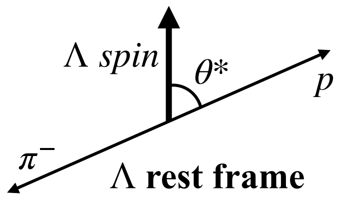
STAR, Phys. Rev. C 76, 024915 (2007)





$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1+\alpha_H P_H \cos\theta^*)$$

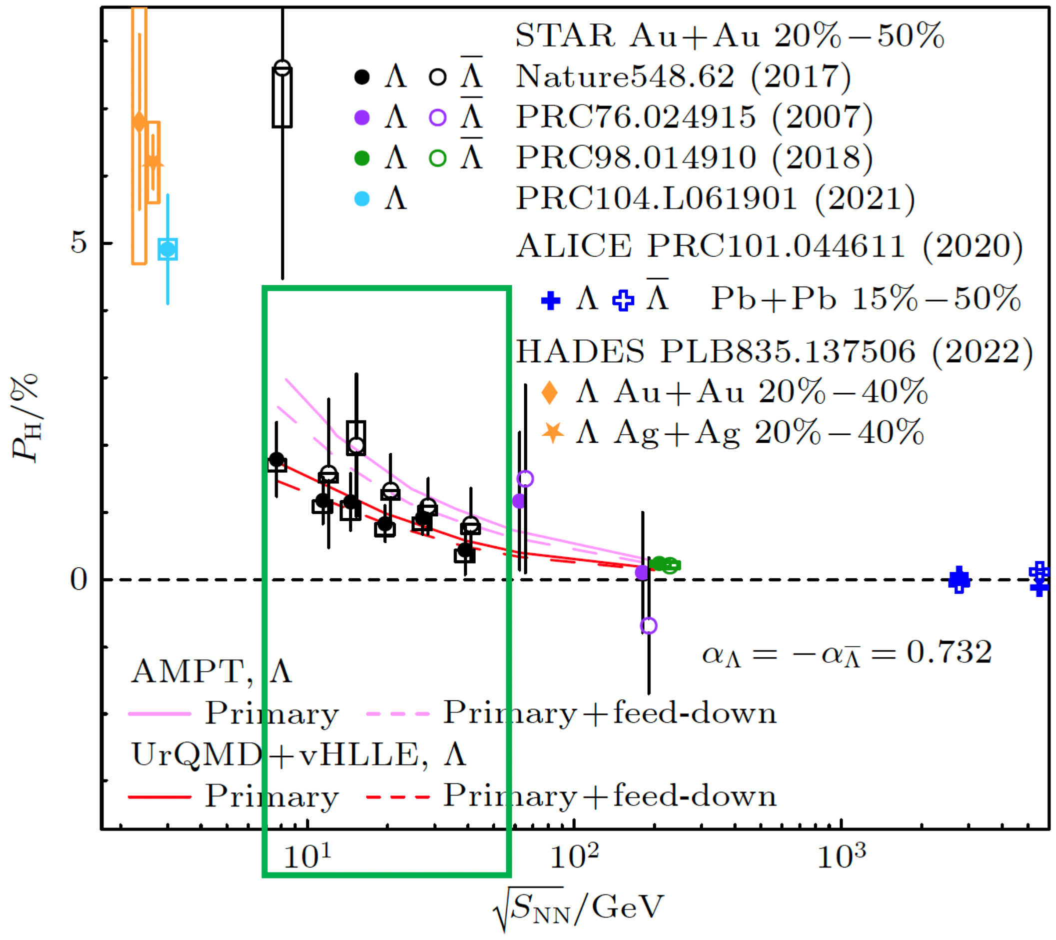
⇩

$$P_H = \frac{8}{\alpha\pi}\frac{1}{A_0}\frac{\langle \sin(\Psi_1 - \phi_p^*)\rangle}{Res(\Psi_1)}$$

- α_H is the hyperon decay parameter, $\alpha_\Lambda = 0.732 \pm 0.014$
- ϕ^* is the azimuthal angle of the daughter proton in Λ rest frame
- A_0 is an acceptance correction factor, $A_0 = \langle \sin\theta_p^* \rangle$

Observation of Λ global polarization

X. Sun et al., Acta Phys. Sin. Vol. 72, No. 7(2023)



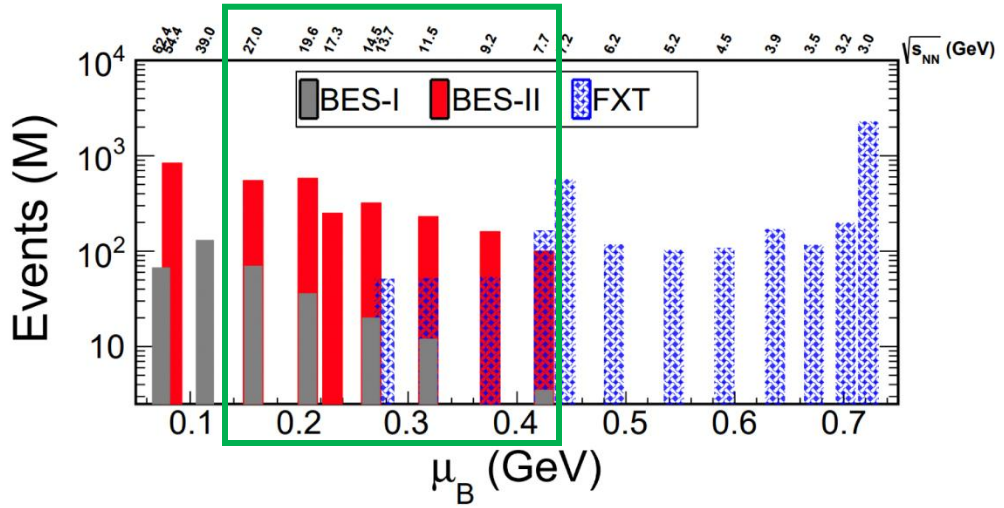
- Strongest vorticity observed in nature

$$\omega \sim 10^{21} s^{-1}$$

- How does the late-stage magnetic field affect global polarization?

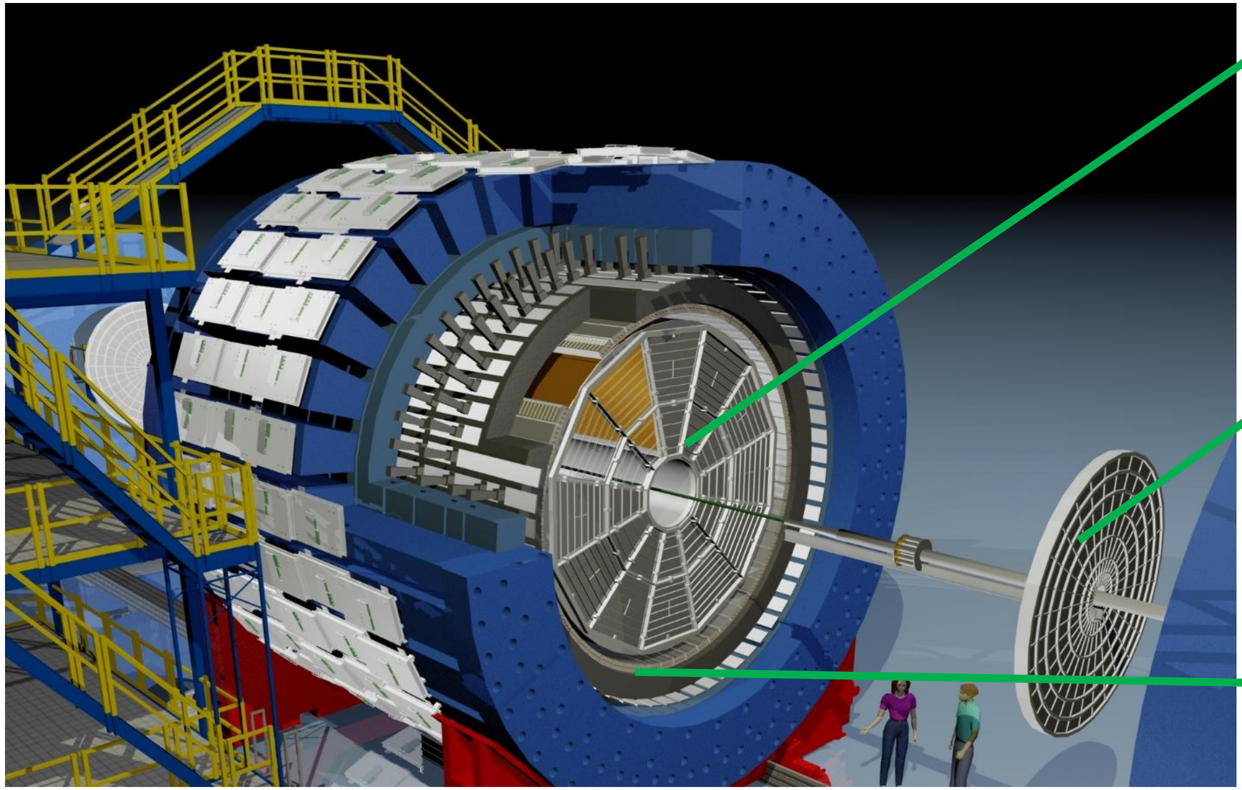
$$|B| \approx \frac{T_s |P_\Lambda - P_{\bar{\Lambda}}|}{2|\mu_\Lambda|}$$

F. Becattini et al., Phys. Rev. C 95.054902(2017)



- The BES-II by STAR collected an order of magnitude more data compared to BES-I, and collected two additional energy points(9.2, 17.3 GeV)

The STAR detector

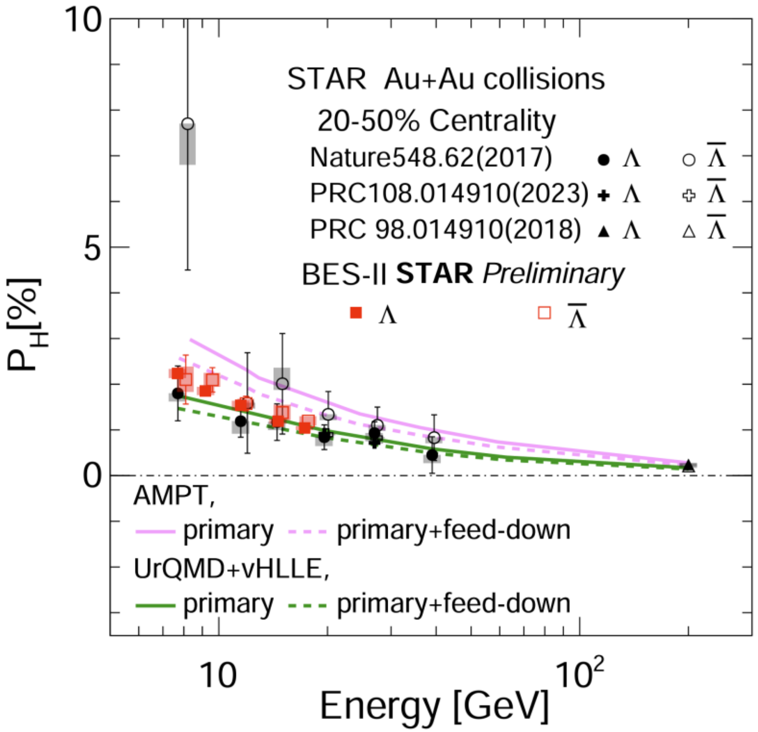


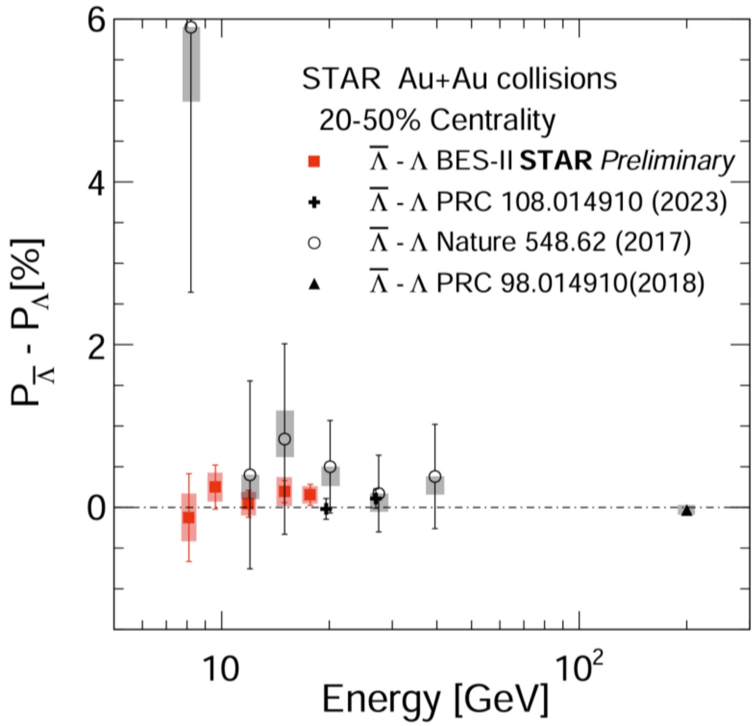
Sub-system relevant to this analysis:

- **Time Projection Chamber**
  - Particle reconstruction
  - The iTPC upgrade extended the pseudo-rapidity coverage from $|\eta| < 1$ to $|\eta| < 1.5$
- **Event Plane Detector**
  - Event plane reconstruction
  - $2.1 < |\eta| < 5.1$
  - Improved the event plane resolution
- **Time Of Flight**
  - PID via particle velocity
  - $|\eta| < 0.9$

Λ global polarization

UrQMD+vHLLE : I. Karpenko, F. Becattini Eur. Phys. J. C 77, 213 (2017)
AMPT: H. Li , L. Pang, Q. Wang, X. Xia Phys. Rev. C 96, 054908(2017)





F. Becattini et al., PRC.95.054902(2017)

$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

$$\Delta P_H = |P_{\bar{\Lambda}} - P_\Lambda| \approx \frac{2|\mu_\Lambda|B}{T}$$

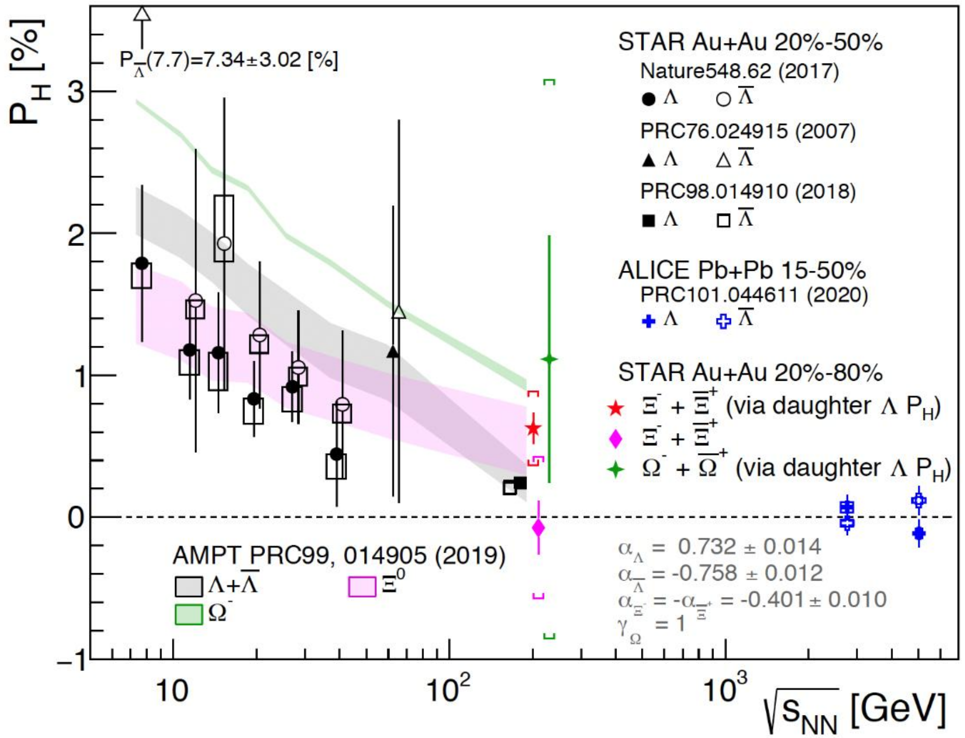
$T = 150\ MeV, \mu_\Lambda = -1.93 \times 10^{-1}\ MeV/T$

- Significant improvement in precision was achieved, collision energy dependence consistent with BES-I
  - $P_H = 1.17 \pm 0.40(stat) \pm 0.27(syst)$ % [**BES-I**] ⟹ $1.19 \pm 0.04(stat) \pm 0.05(syst)$% [**BES-II**] at 14.6 GeV
- No obvious splitting between Λ and $\bar{\Lambda}$ global polarization with high precision. Upper limit on late-stage magnetic field
  - $B \lesssim 10^{13}$ T (95% confidence level) STAR, Phys. Rev. C 108, 014910 (2023)

Global polarization of Ξ and Ω

Hyperon	Spin
Λ(uds)	1/2
Ξ^-(dss)	1/2
Ω^-(sss)	3/2

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

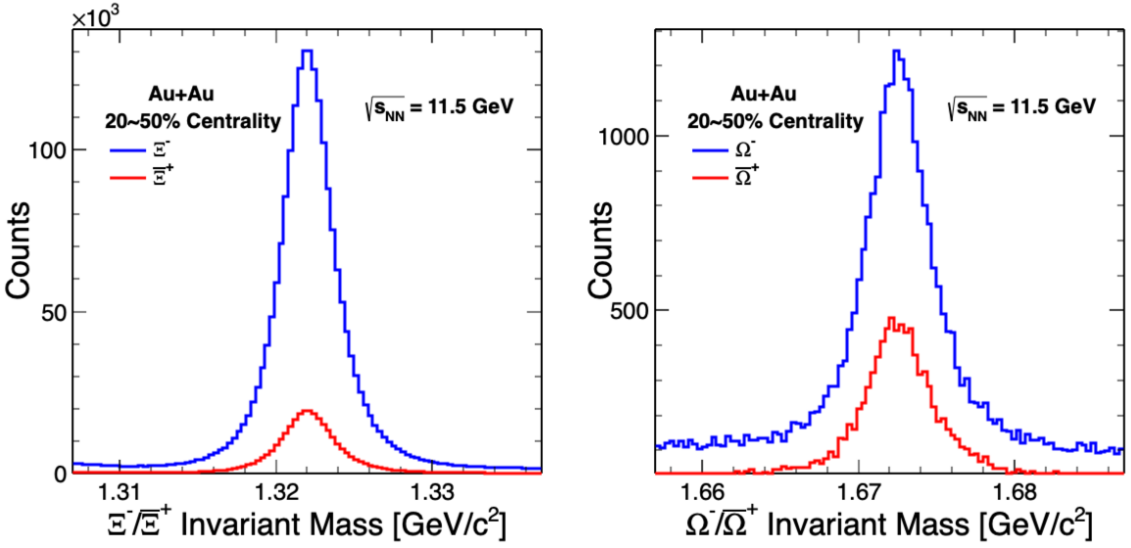


- **Multi-strange hyperons are expected to be polarized in similar way**
- The Ξ polarization is measured to be slightly larger than Λ. The Ω global polarization shows a hint of being even larger
- Is there a dependence of Ξ and Ω global polarization on collision energy?

Extraction of Ξ and Ω global polarization

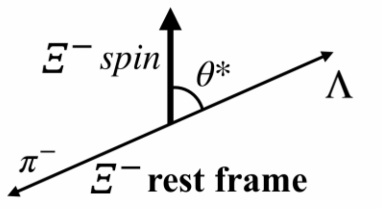
PDG2021

Hyperon	Decay mode	α_H	Spin
Λ(uds)	$\Lambda \rightarrow p + \pi^-$	0.732	1/2
Ξ^-(dss)	$\Xi^- \rightarrow \Lambda + \pi^-$	-0.401	1/2
Ω^-(sss)	$\Omega^- \rightarrow \Lambda + K^-$	0.0157	3/2

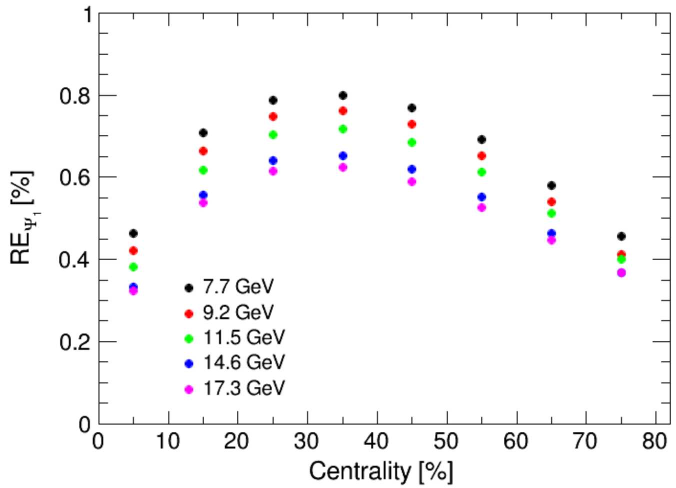


- Two methods for extracting the Ξ and Ω polarization
  - Measured via daughter Λ angle distribution in Ξ rest frame

$$P_H = \frac{8}{\alpha_H \pi} \frac{1}{A_0} \frac{\langle \sin(\Psi_1 - \phi^*) \rangle}{Res(\Psi_1)}$$



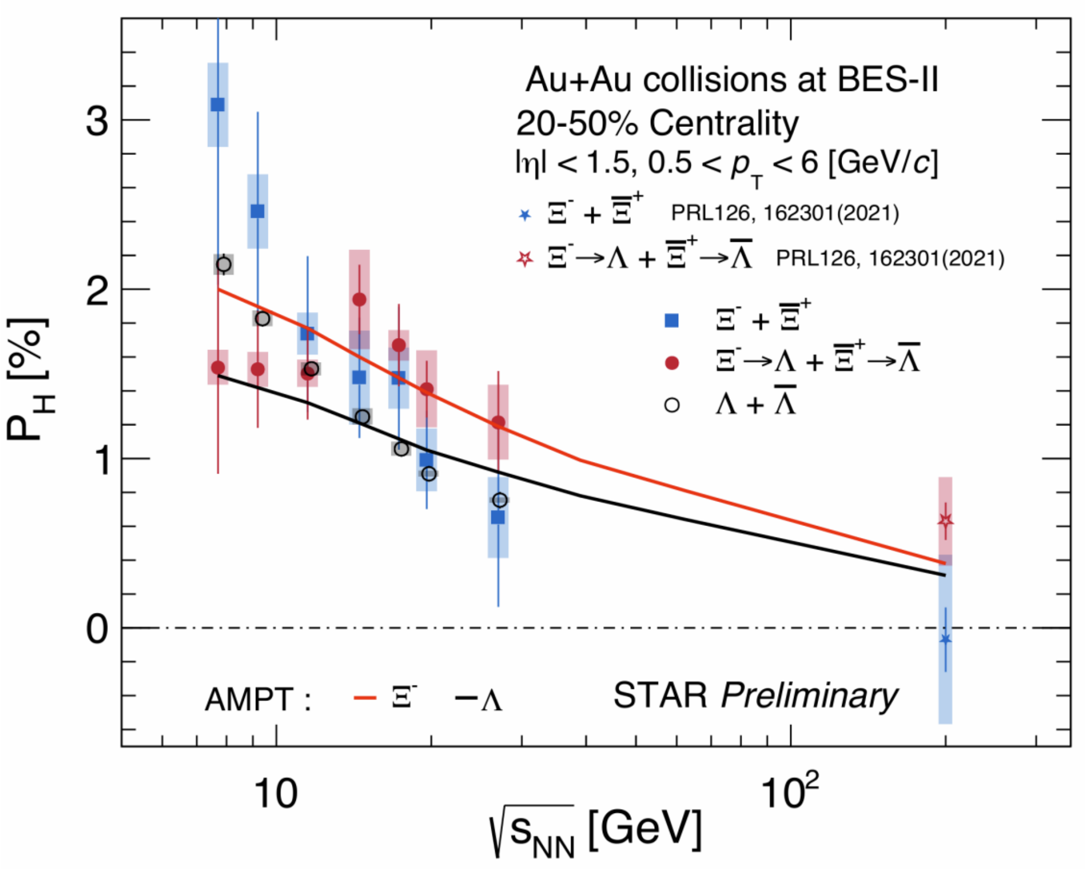
  - via daughter Λ polarization with spin transfer factor ($C_{\Xi^- \rightarrow \Lambda} = 0.944, C_{\Omega^- \rightarrow \Lambda} = 1.0$ is assumed)



- First-order event plane reconstructed by EPD

$\Xi^- + \bar{\Xi}^+$ global polarization

Model calculation:
H. Li, X. Xia, X. G. Huang, H. Z. Huang Phys. Lett. B 827, 136971 (2022)



- For the first time, significant global polarization of $\Xi^- + \bar{\Xi}^+$ has been observed(~ 5 σ)
  - $P_H = 1.940 \pm 0.205(stat.) \pm 0.293(syst.)$ at 14.6 GeV
- Global polarization of $\Xi^- + \bar{\Xi}^+$ decrease with collision energy
- $\Xi^- + \bar{\Xi}^+$ global polarization are consistent between direct and indirect measurement methods
- No obvious difference between $\Lambda + \bar{\Lambda}$ and $\Xi^- + \bar{\Xi}^+$ global polarization within uncertainties

$\Omega^- + \overline{\Omega}^+$ global polarization

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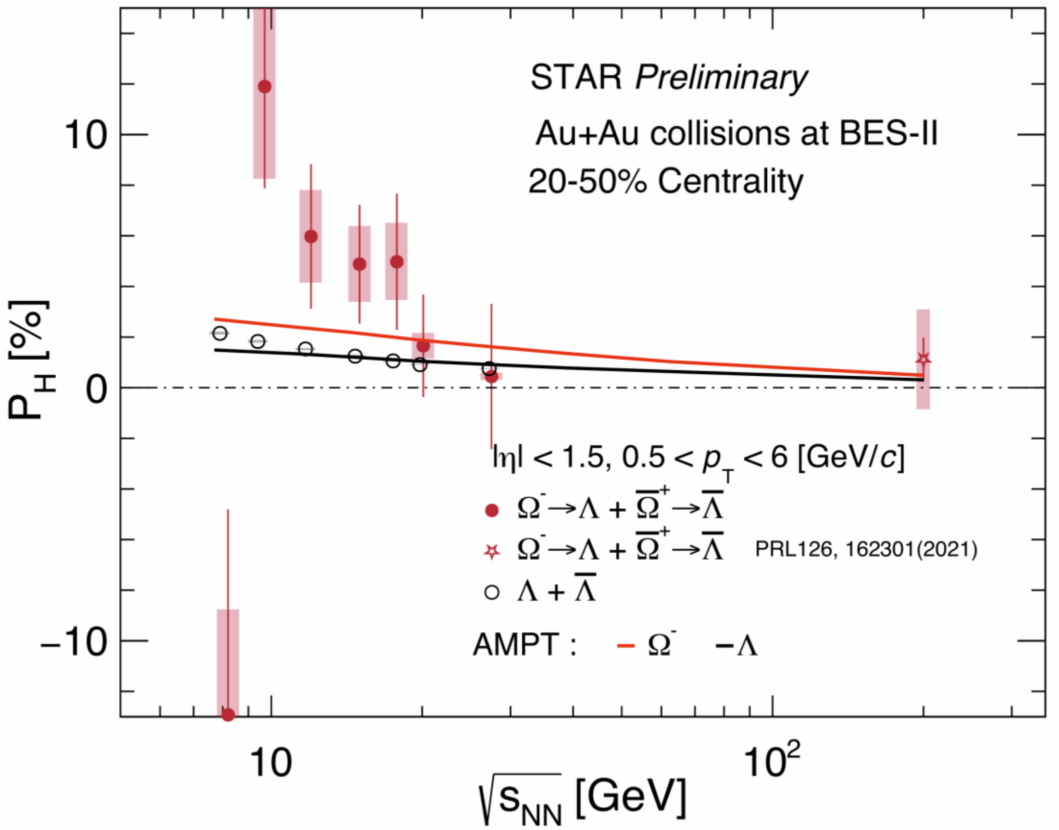
H. Li, X. Xia, X. G. Huang, H. Z. Huang Phys. Lett. B 827, 136971 (2022)

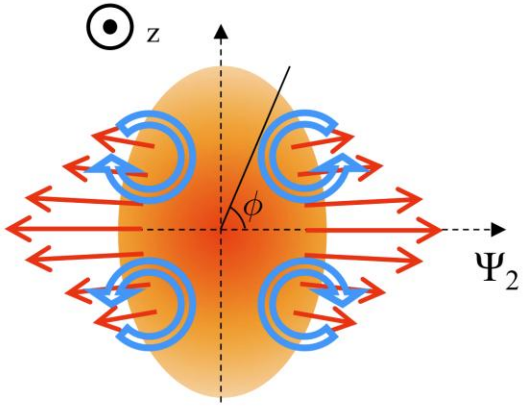


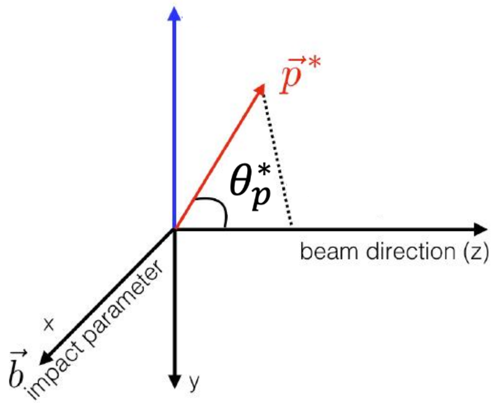
- Global polarization of $\Omega^- + \overline{\Omega}^+$ tend to decrease with collision energy
- A hint of larger $\Omega^- + \overline{\Omega}^+$ polarization than $\Lambda + \overline{\Lambda}$ in lower energies
- Possible **Λ, Ξ, Ω** global polarization difference?

$P_\Lambda \cong P_s$, assuming that $P_{u.d} \sim P_s$ ⟹ $P_\Xi \sim P_\Lambda$, $P_\Omega \sim \frac{5}{3} P_\Lambda$

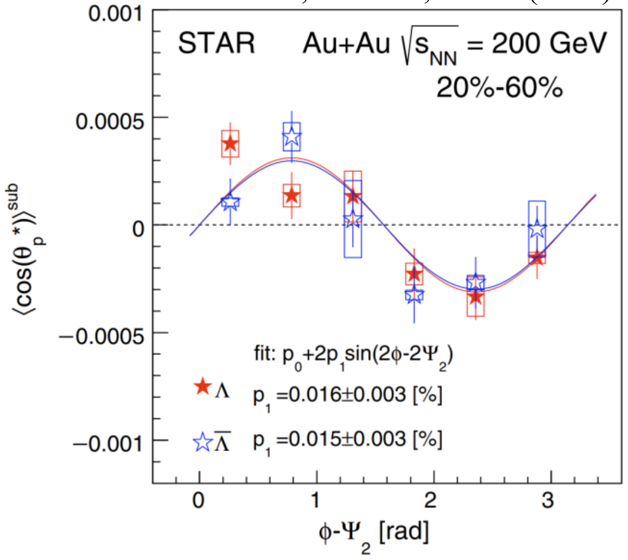
F. Becattini et al., Phys. Rev. C 95.054902(2017)

Introduction to local polarization

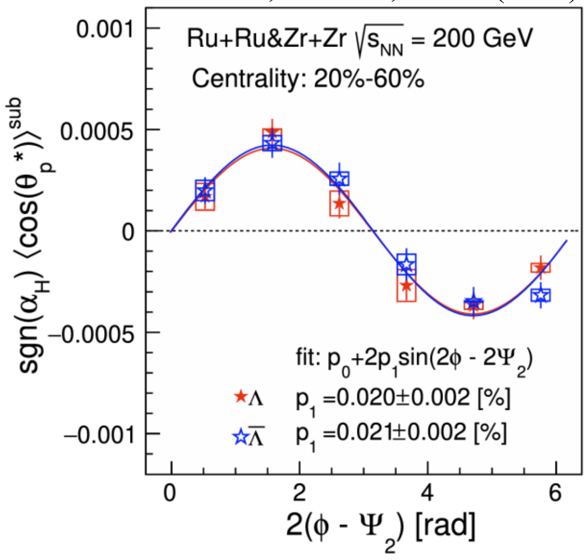




STAR,PRL.123,132301(2019)



STAR,PRL.131,202301(2023)

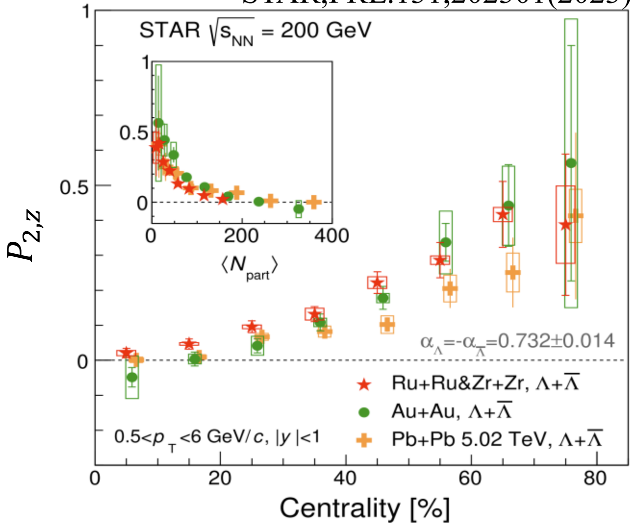


- Anisotropic expansion of QGP leads to vorticity and particle polarization

$$P_{2,z} = \frac{1}{\alpha_H \langle\cos^2\theta_p^*\rangle} \frac{\langle\cos\theta_p^* \sin[2(\phi_\Lambda - \Psi_2)]\rangle}{Res\{\Psi_2\}}$$

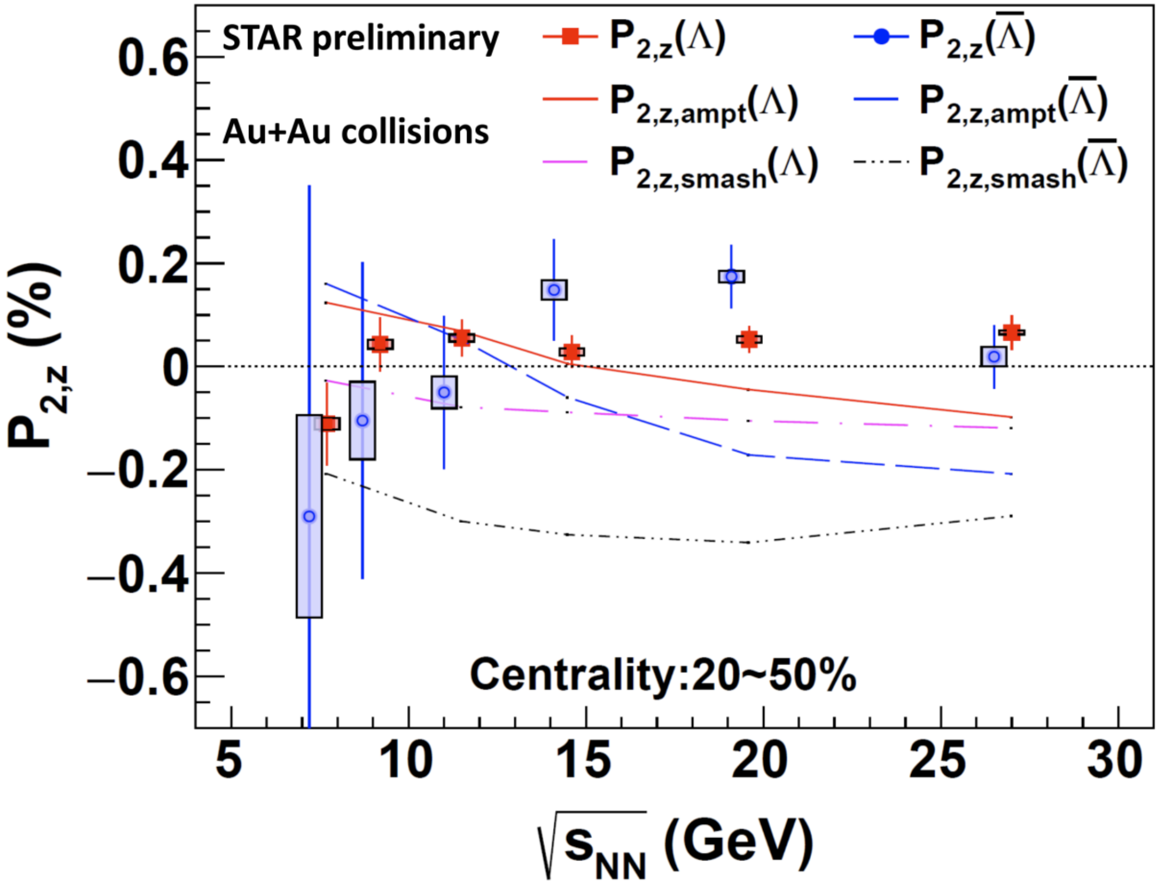
- Λ local polarization has been observed by STAR in Au+Au and isobar collisions at 200 GeV.

STAR,PRL.131,202301(2023)



Λ local polarization at BES-II

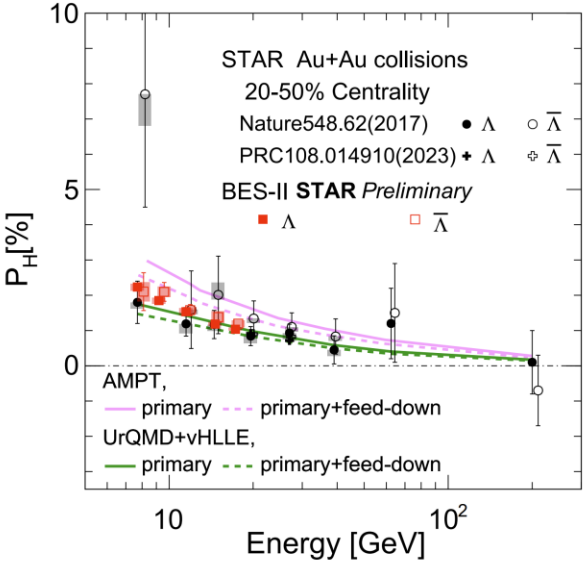
Model: X. Wu et al., PRC.105,064909(2022)



- Λ local polarization measured in Au+Au collisions at BES-II energies
- The magnitude of $P_{2,z}$ is small, with no significant collision energy dependence observed.

Introduction to spin correlations

- global polarization



$$P_q = P_{\bar{q}} \sim 10^{-2}$$

- spin alignment of ϕ-meson

ϕ − meson (|y| < 1.0 & 1.2 < p_T < 5.4 GeV/c)

$\sqrt{s_{NN}}$	ρ_{00}
11.5	0.365 ± 0.014 stat. $\pm$ 0.008 syst.
19.6	0.359 ± 0.008stat. $\pm$ 0.007 syst.
27	0.3608 ± 0.0025stat. $\pm$ 0.004 syst.

STAR Collaboration. Nature 614, 244–248 (2023).

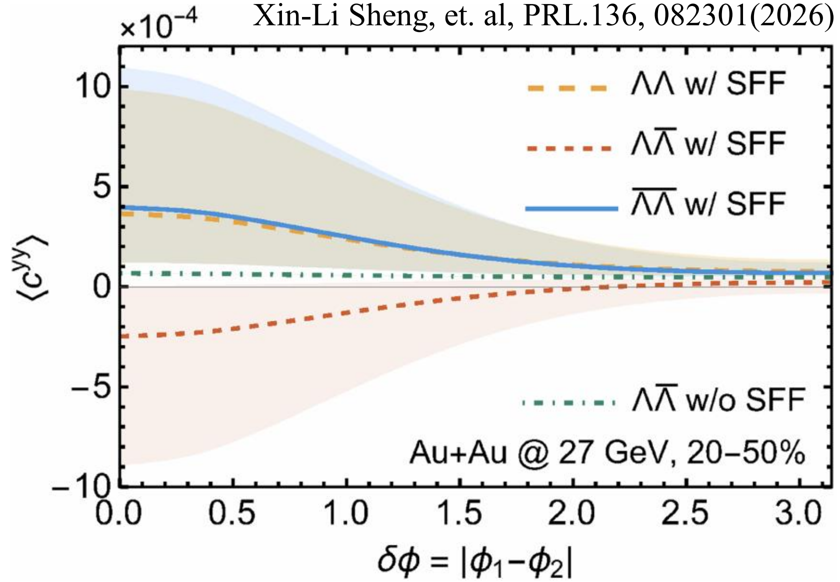
$$\rho_{00} - \frac{1}{3} \sim 10^{-2} \gg P_q^2(10^{-4})$$

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

This indicates a correlation between P_q and $P_{\bar{q}}$

J.-p. Lv, Z.-h. Yu, Z.-t. Liang, Q. Wang, and X.-N. Wang, Phys. Rev. D 109, 114003 (2024)

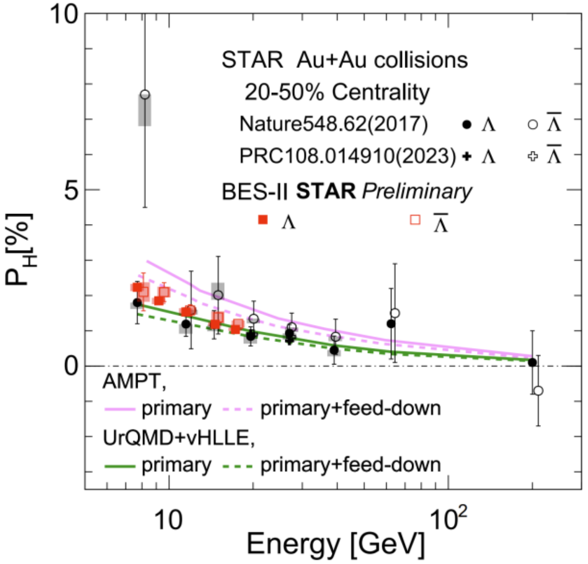
Xin-Li Sheng, et. al, PRL.136, 082301(2026)



- Models have predicted the spin correlation of Λ in heavy-ion collisions.

Introduction to spin correlations

❑ global polarization



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J.-p. Lv, Z.-h. Yu, Z.-t. Liang, Q. Wang, and X.-N. Wang, Phys. Rev. D 109, 114003 (2024)

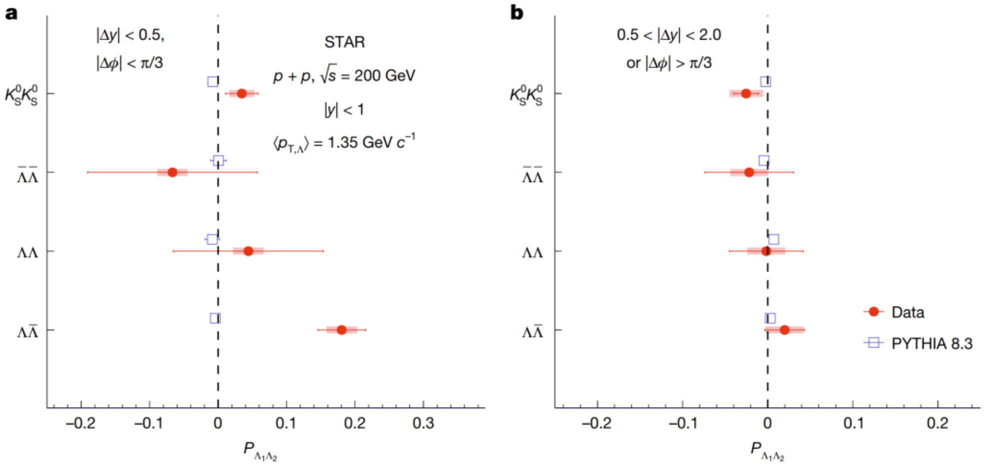
❑ Spin correlations in pp measurement.

$$\frac{dN}{d\cos(\theta^*_{12})} = 1 + \alpha_1 \alpha_2 P_{\Lambda_1 \Lambda_2} \cos(\theta^*_{12})$$

Gong, W. et al.,PhysRevD.106.L031501(2022)

θ^*_{12} is the angle between the momentum of the protons, each boosted to the rest frame of their parent particle

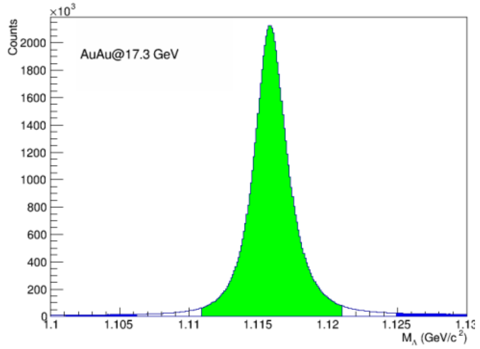
A nonzero correlation is observed in short-range $\Lambda\bar{\Lambda}$ pairs.

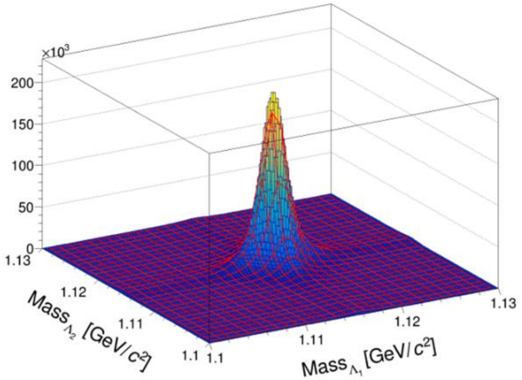


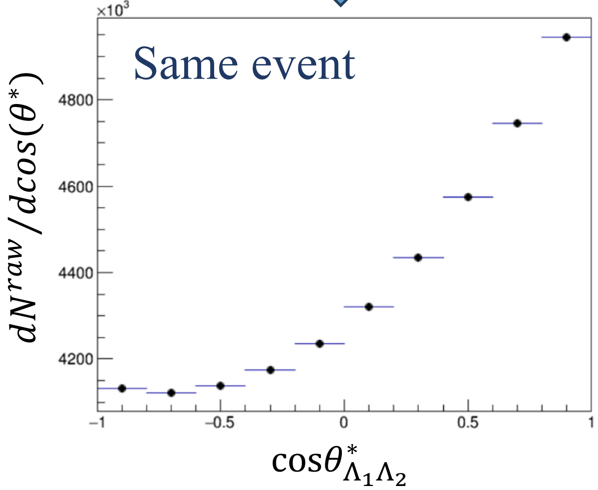
STAR Collaboration. Nature 650, 65–71 (2026).

Spin correlation measurement

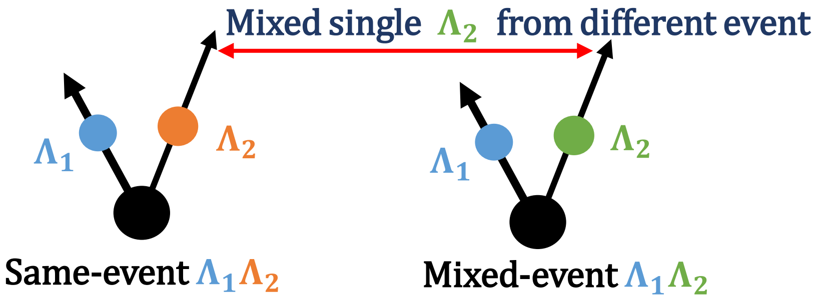
- Measured $dN^{raw}/dcos(\theta^*)$ distributions.

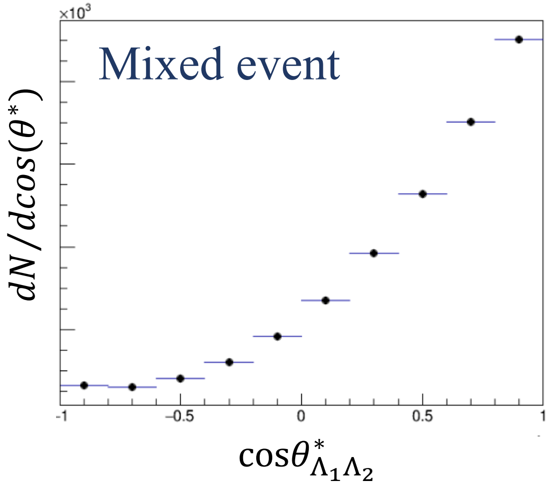






- Using the mixed-event method to correct for detector effects.

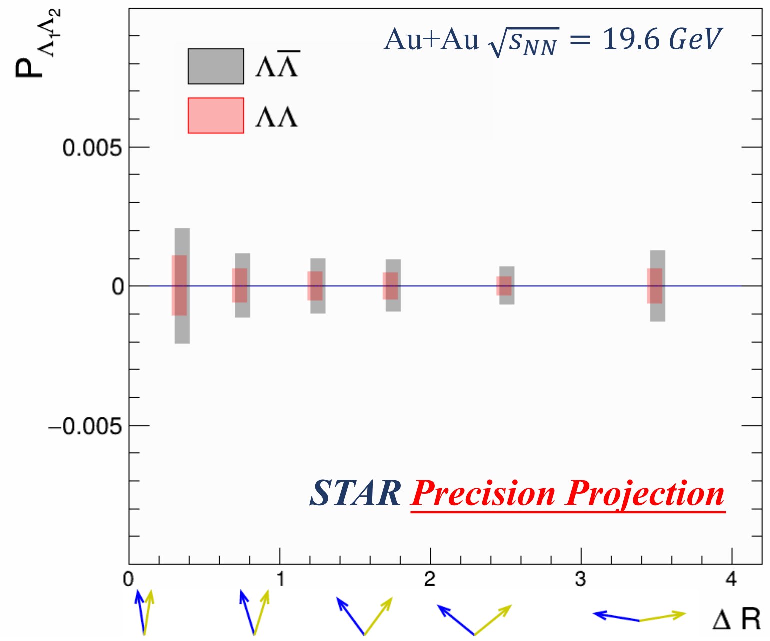




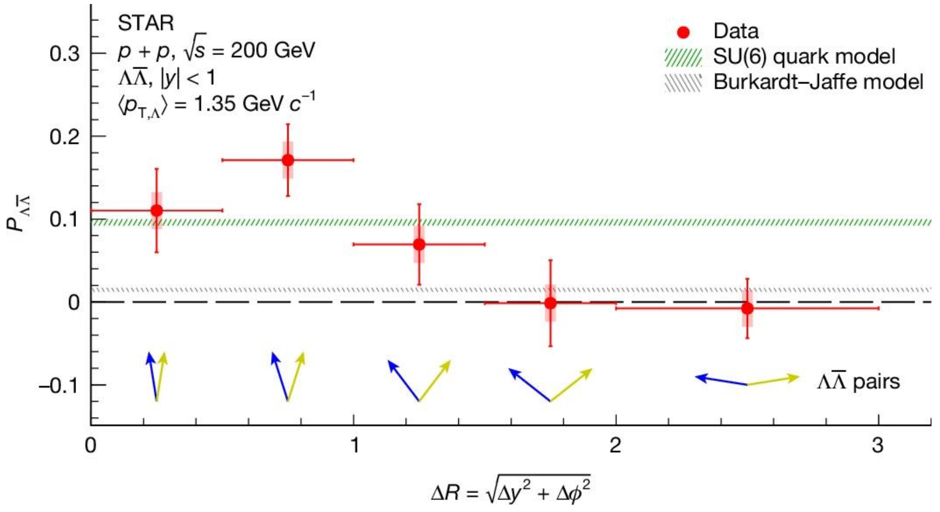
The spin correlation signal can be extracted by fitting the cos θ^* distribution after mixed-event correction.

$$\frac{dN}{d\cos(\theta^*_{12})} = 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*_{12})$$

$\Lambda\Lambda$ and $\Lambda\bar{\Lambda}$ spin correlation statistical projection



STAR Collaboration. Nature 650, 65–71 (2026).



- Measurement precision in Au+Au collisions is better than in pp collisions, detailed analysis is on-going.

Summary

- Global polarization of Λ, Ξ and Ω at BES-II
  - High precision measurements of Λ polarization with BES-II, no splitting between P_{Λ} and $P_{\bar{\Lambda}}$ within uncertainties
  - A significant $\Xi^- + \bar{\Xi}^+$ global polarization is observed (~5σ), and also decrease with collision energy. Hint of larger $\Omega^- + \bar{\Omega}^+$ polarization at lower energies observed.

- Local polarization of Λ at BES-II
  - The magnitude of $P_{2,z}$ is small, with no significant collision energy dependence observed.

- Spin correlation of Λ– (anti)– Λ in Au+Au collisions
  - Detector acceptance corrected using mixed-event method. Further checks are on-going.

Back Up

Why $C_{\Omega^- \to \Lambda} = 1.0$

K. B. Luk et al. Phys. Rev. D 38, 19 (1988)

The weak decay $\Omega^- \to \Lambda + K^-$ proceeds to the final states of orbital angular momentum L= 1,2 through the amplitudes A_L. The asymmetry parameters in the decay process can be written as:

$$\alpha = \frac{2\,\mathrm{Re}(A_1^* A_2)}{|A_1|^2 + |A_2|^2}, \quad \beta = \frac{2\,\mathrm{Im}(A_1^* A_2)}{|A_1|^2 + |A_2|^2}, \quad \gamma = \frac{|A_1|^2 - |A_2|^2}{|A_1|^2 + |A_2|^2}, \quad \alpha^2 + \beta^2 + \gamma^2 = 1 .$$

When the joint probability distribution for the decay chain is integrated over the A angular distribution, the angular distribution of the daughter proton is given by:

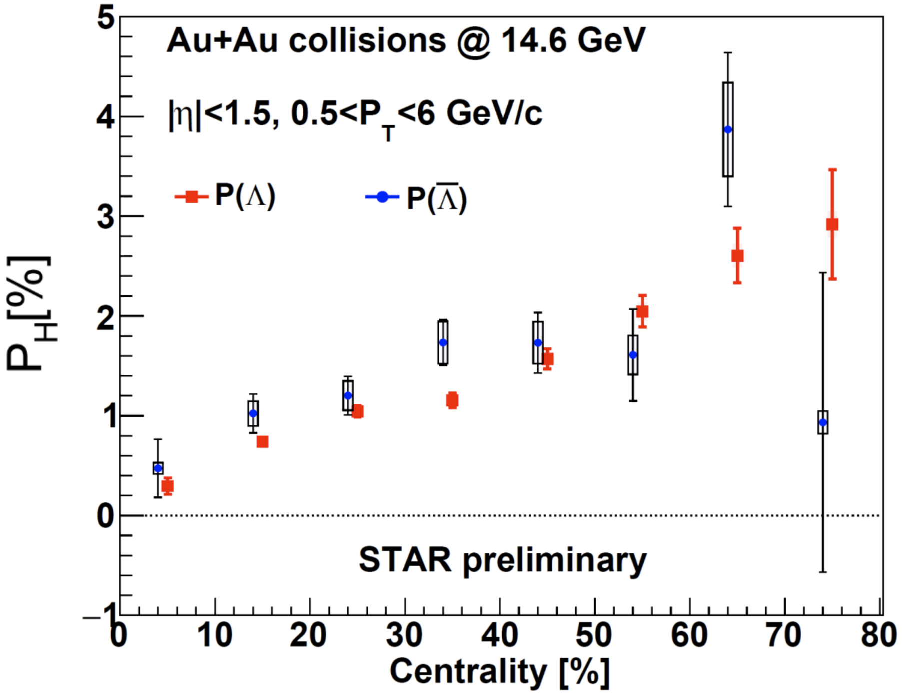
$$\frac{dn}{d\Omega_p} = \frac{1}{4\pi}(1 + \alpha_\Lambda \mathbf{P}_\Lambda \cdot \hat{\mathbf{p}}), \quad \frac{dN}{d\Omega_p} = \frac{1}{4\pi}\left[1 + \frac{\alpha_\Lambda}{2(J+1)}[1 + (2J+1)\gamma_\Omega]\mathbf{P}_\Omega \cdot \hat{\mathbf{p}}\right].$$

$$\Rightarrow \quad \mathbf{P}_\Lambda = \frac{1}{2(J+1)}[1 + (2J+1)\gamma_\Omega]\mathbf{P}_\Omega .$$

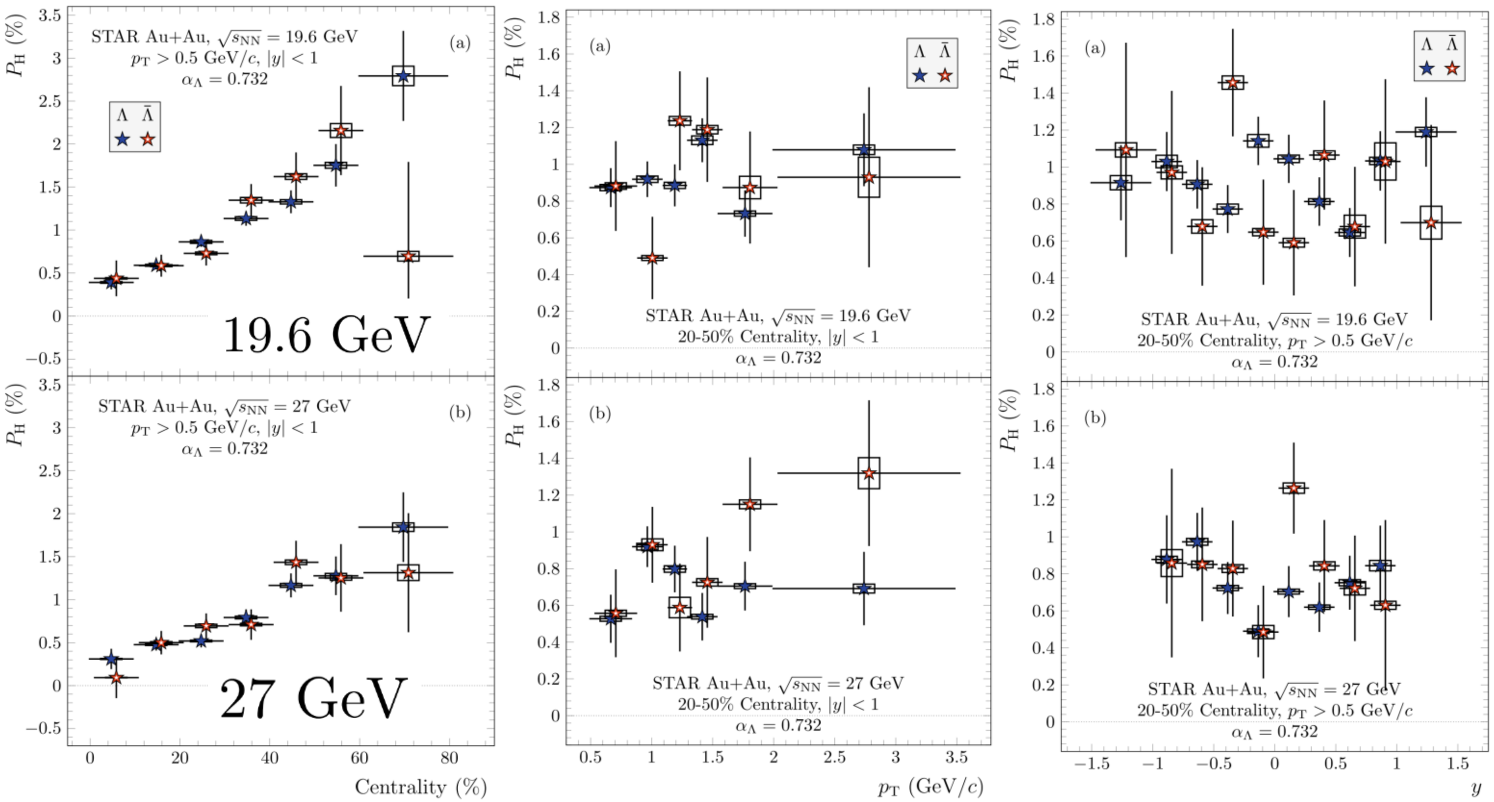
Using $J = \frac{3}{2}$:

$$\mathbf{P}_\Lambda = \begin{cases} \mathbf{P}_\Omega & \text{if } \gamma_\Omega = 1 , \\ -0.6\mathbf{P}_\Omega & \text{if } \gamma_\Omega = -1 \end{cases}$$

Result of Global Polarization from BES-II



STAR, Phys. Rev. C 108, 014910 (2023)



- Clear centrality dependence of Λ and $\bar{\Lambda}$
- Trend consistent with expectation from vorticity