Measurements of Global and Local Polarization of Hyperons in Heavy Ion Collisions from STAR

Xingrui Gou (for the STAR Collaboration)

Shandong University

PacificSpin2024

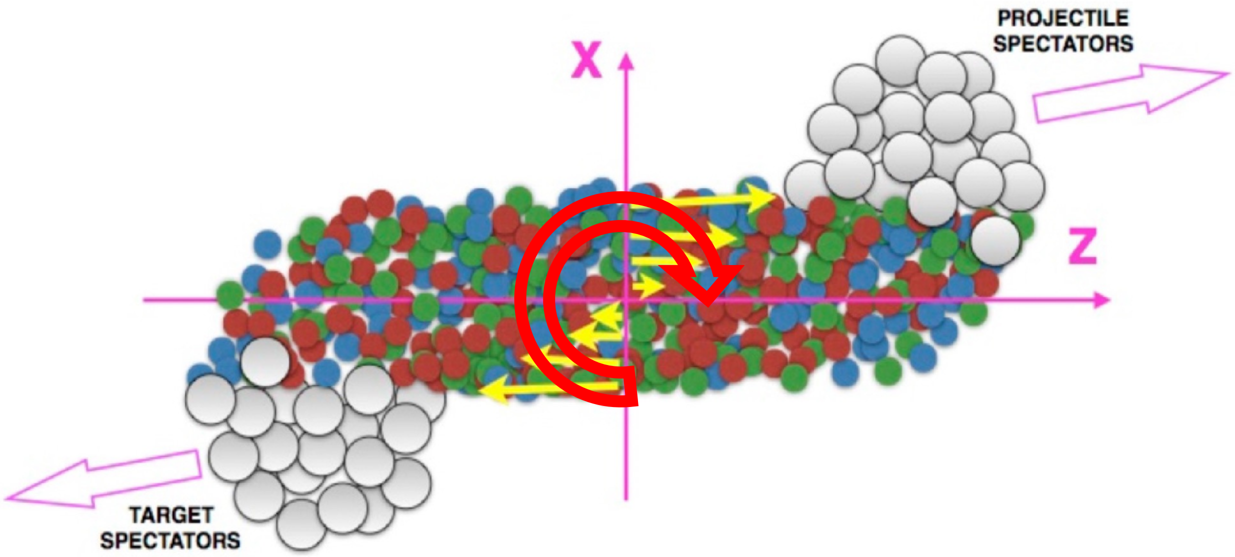
2024/11/8 - 13 China·Hefei

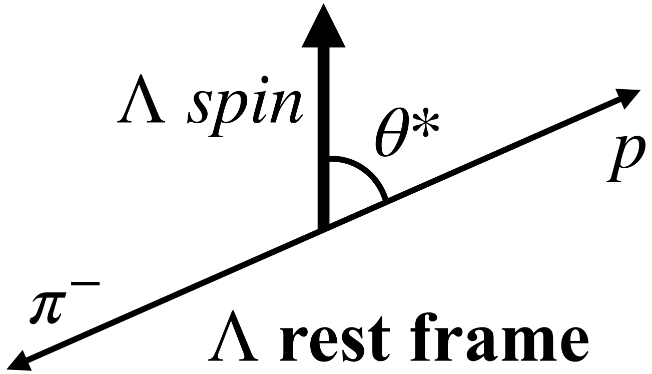
Supported in part by

Outline

- Brief introduction on orbital angular momentum and polarization
- Global polarization analysis process
- Recent STAR experiment results
  - Hyperon global polarization
  - Hyperon polarization along beam direction
- Summary

Orbital angular momentum and polarization





Orbital angular momentum

Local fluid vorticity $\omega = \frac{1}{2}\nabla\times v$

The most vortical fluid $\sim 10^{20} - 10^{21} s^{-1}$
(Au+Au@RHIC at ***b***=10 fm)

Leads to global polarization along ***L*** though spin-orbit coupling

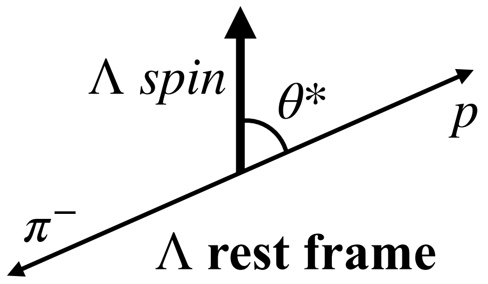
Z.-T. Liang and X.-N. Wang, PRL 94, 102301 (2005)

Global polarization measurement

- “Self-analyzing”, parity-violating weak decay channel of hyperons
  - Daughter baryon is preferentially emitted in the direction of the hyperon spin

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

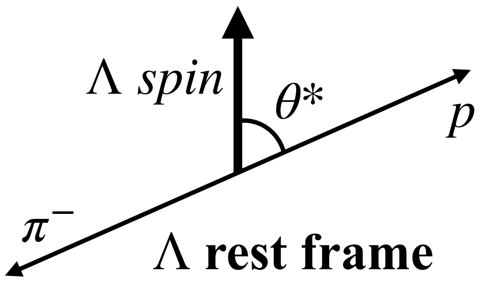
α_H : hyperon decay parameter
P_H : hyperon polarization
θ^* : polarization angle



$\Lambda \rightarrow p + \pi^-$
(BR:63.9%,cτ~7.9cm)

Global polarization measurement

- "Self-analyzing", parity-violating weak decay channel of hyperons
  - Daughter baryon is preferentially emitted in the direction of the hyperon spin
  - Measured via the distribution of the azimuthal angle of the hyperon decay baryon (in the hyperon rest frame) with respect to the reaction plane.



$\Lambda \rightarrow p + \pi^-$

(BR:63.9%,cτ~7.9cm)

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

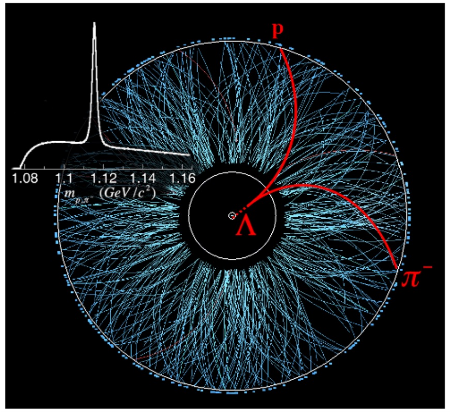
$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$

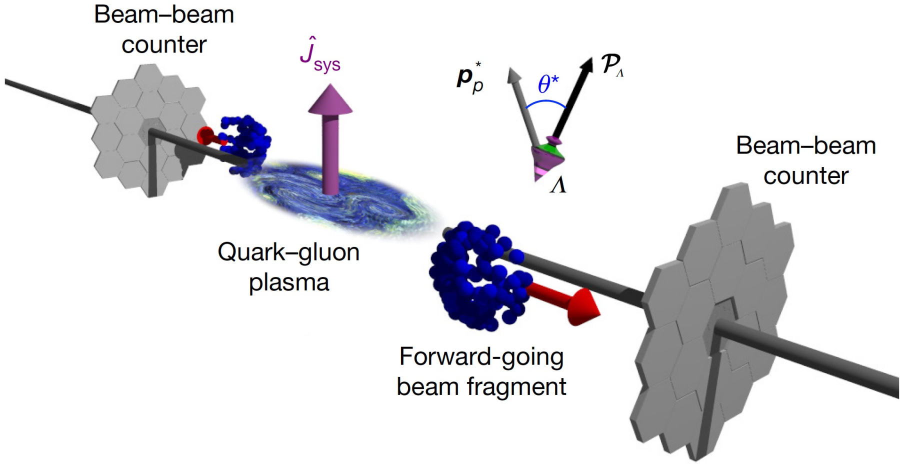
A_0: Acceptance correction factor

Ψ_1: First-order event plane angle

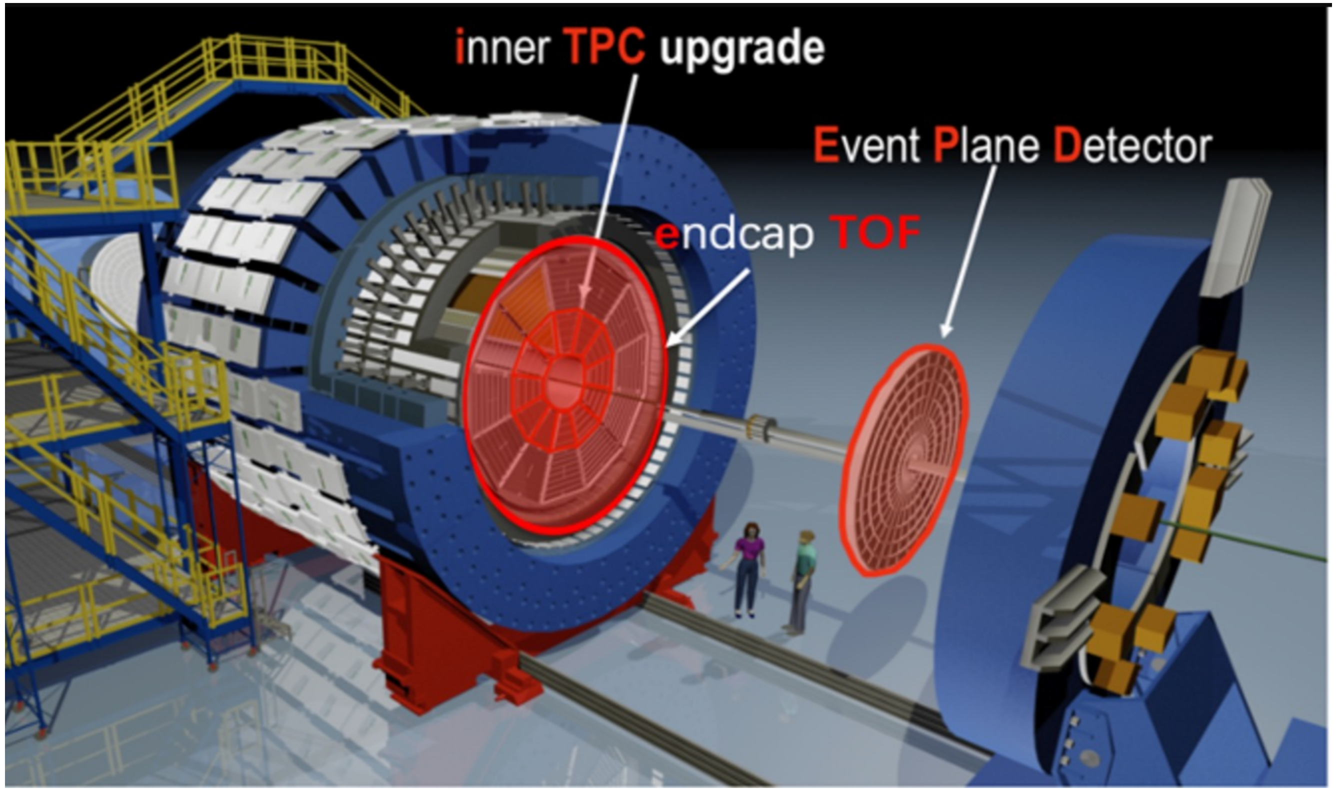
$Res(\Psi_1)$: Event plane resolution

STAR, PRC76, 024915 (2007)

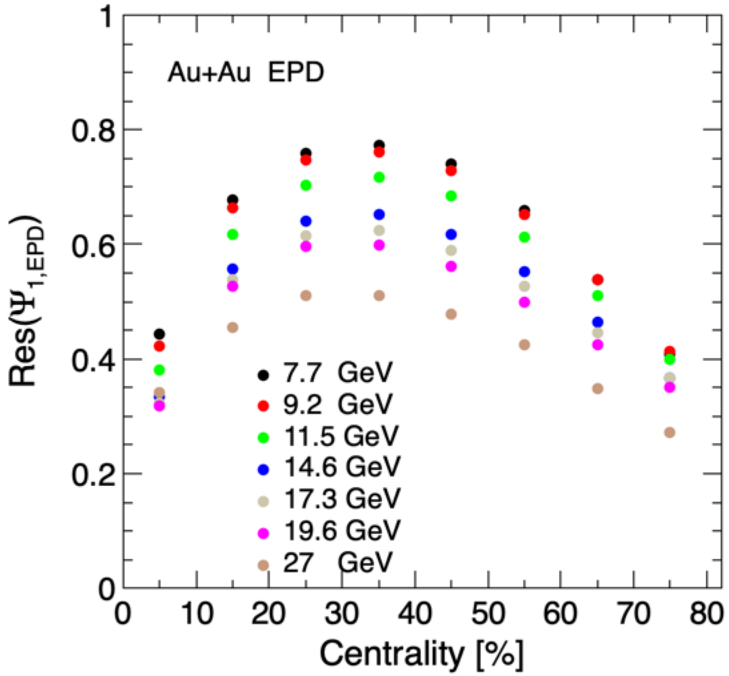




STAR detector and event plane reconstruction

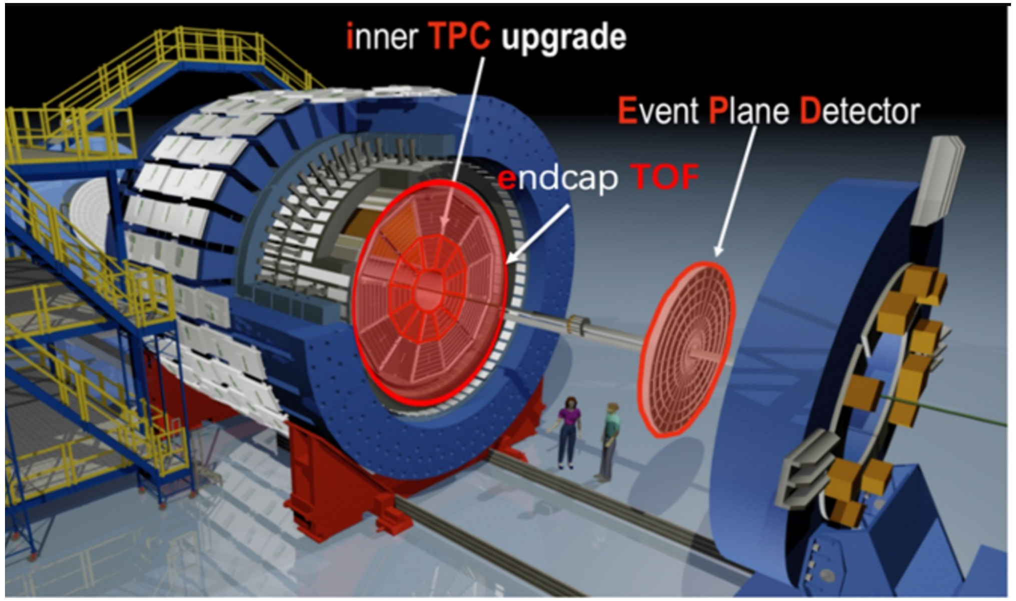


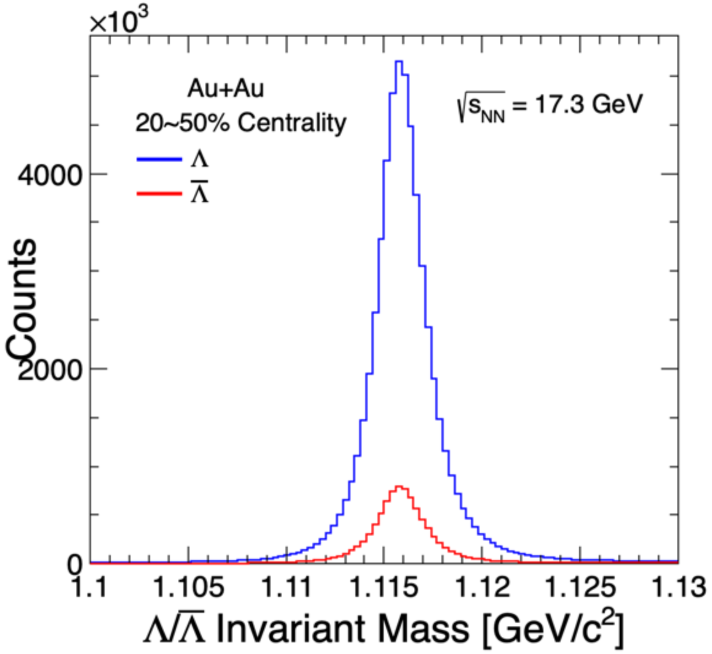
Event plane resolution

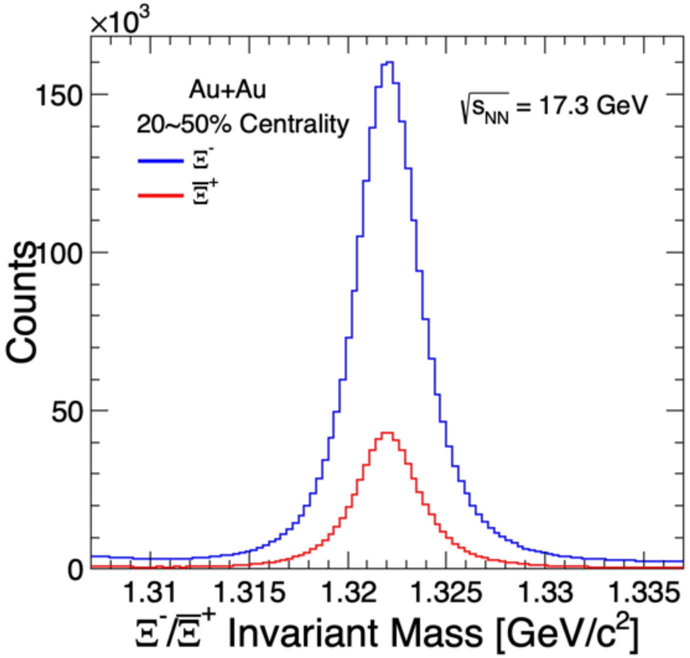


- **Event plane reconstruction:**
  - Time Projection Chamber
  - Event Plane Detector
  - Zero Degree Calorimeters

STAR detector and $\Lambda/\bar{\Lambda}$, $\Xi^-/\bar{\Xi}^+$ reconstruction

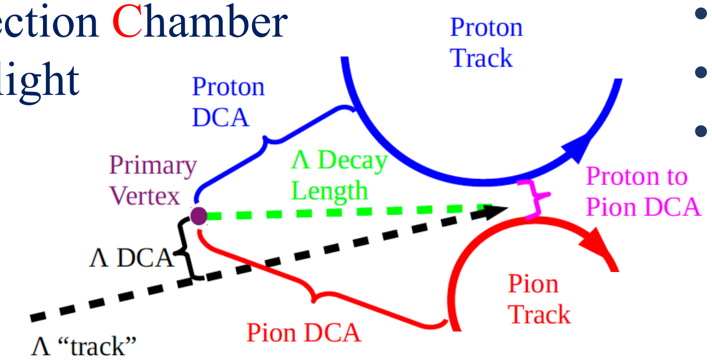






☐ Hyperon reconstruction:

- ➢ Time Projection Chamber
- ➢ Time Of Flight

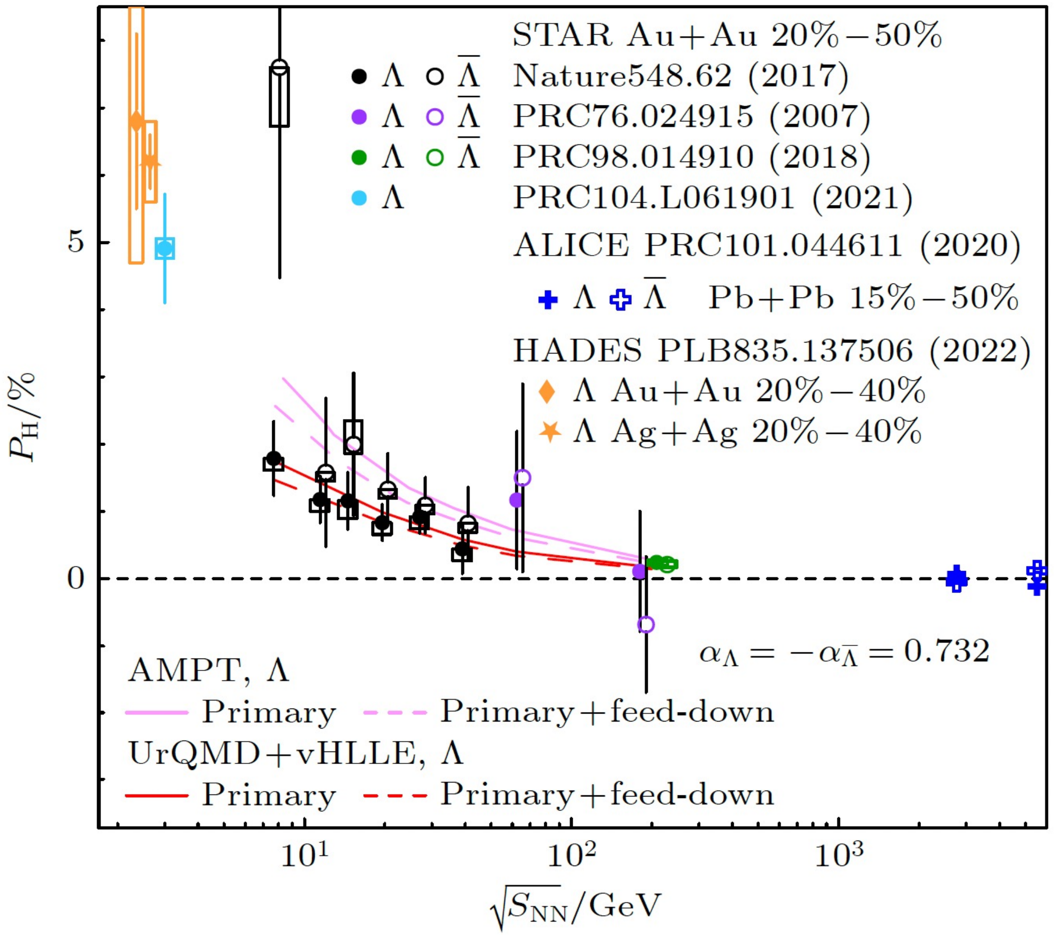


- $\Lambda \rightarrow p + \pi^-$
- $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$
- Background fraction < 3%

- $\Xi^- \rightarrow \Lambda + \pi^-$, $\Lambda \rightarrow p + \pi^-$
- $\bar{\Xi}^+ \rightarrow \bar{\Lambda} + \pi^+$, $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$
- Background fraction < 8%

Observation of Λ global polarization

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



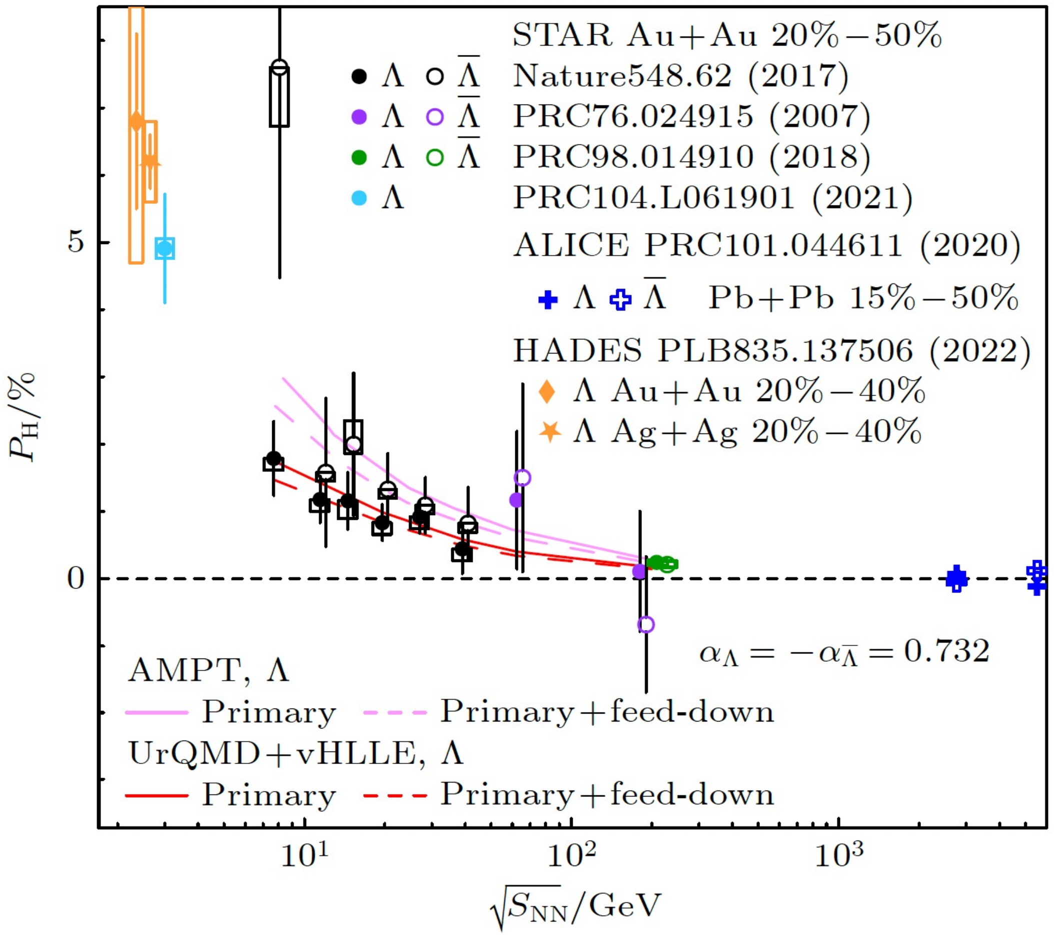
- STAR, first measurement in AuAu 200 GeV, P_H<2%
  - PRC 76, 024915 (2007)
- STAR, first observation in BES-I
  - Nature 548, 62 (2017)
- STAR, high precise P_H at 200 GeV
  - PRC 90, 014910 (2018)
- ALICE, LHC energy region
  - PRC 101, 044611 (2020)
- STAR, P_H at 3 GeV
  - PRC 104, L061901 (2021)
- HADES energy region, consistent with STAR
  - PLB 835,137506(2022)

➢ *Possible difference between Λ and $\bar{\Lambda}$ due to magnetic field effect?*

- STAR, P_H at 19.6 and 27 GeV BES-II, no splitting
  - PRC108,014910(2023)
- STAR, new results
  - Λ, Ξ global polarization

Energy dependence of Λ global polarization

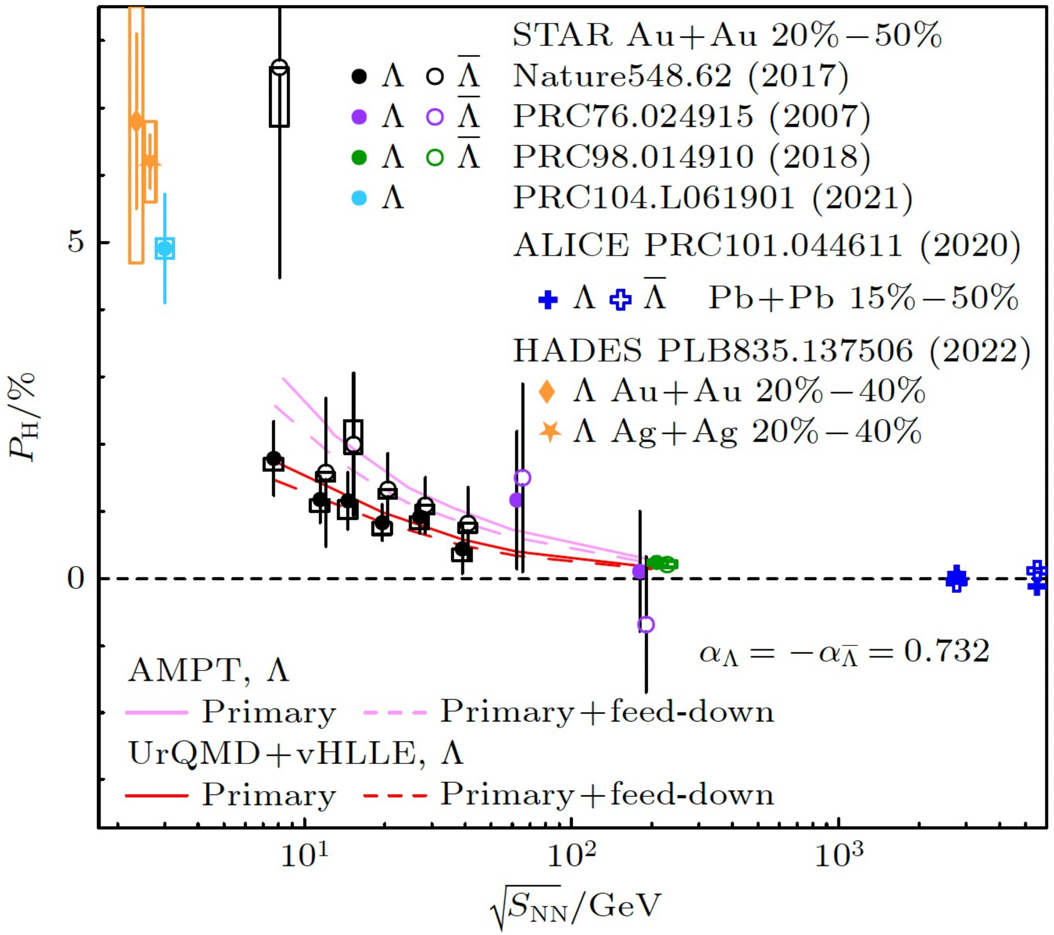
Acta Phys. Sin. Vol. 72, No. 7(2023) 072401



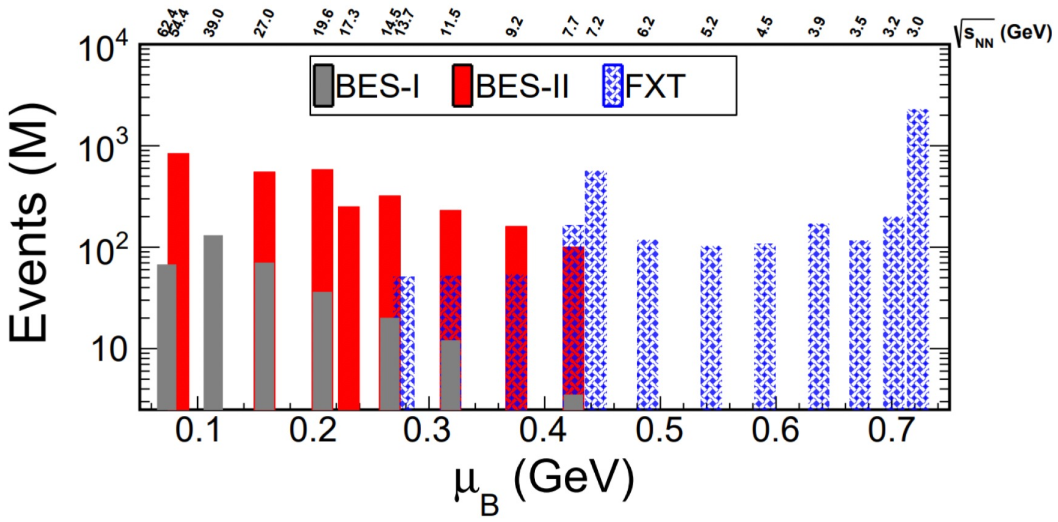
- Significant collision energy dependence, described well by various theoretical models
  - Liang and Wang, PRL 94,102301(2005),
  - Gao, Chen, Deng, Liang, Wang, Wang, PRC 77, 044902(2008)
  - I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
  - H. Li et al., PRC 96, 054908 (2017), AMPT
  - Becattini, Lisa, Ann. Rev. Nucl. Part. Sci. 70, 395 (2020).
  - Huang, Liao, Wang, Xia, Lect. Notes Phys. 987, 281 (2021).
  - Becattini, Rept. Prog. Phys. 85, No.12, 122301 (2022)
  - Wang, Liang, Ma, ActaPhys. Sin. 72, No. 7 & 11 (2023)
  - Lv, Yu, Liang, Wang, Wang, PRD 109 (2024) 11, 114003
  - Zhang, Lv, Yu, Liang, 2406.03840(2024)
  - Sun, et al., 2405.12015(2024). ·······

Energy dependence of Λ global polarization

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

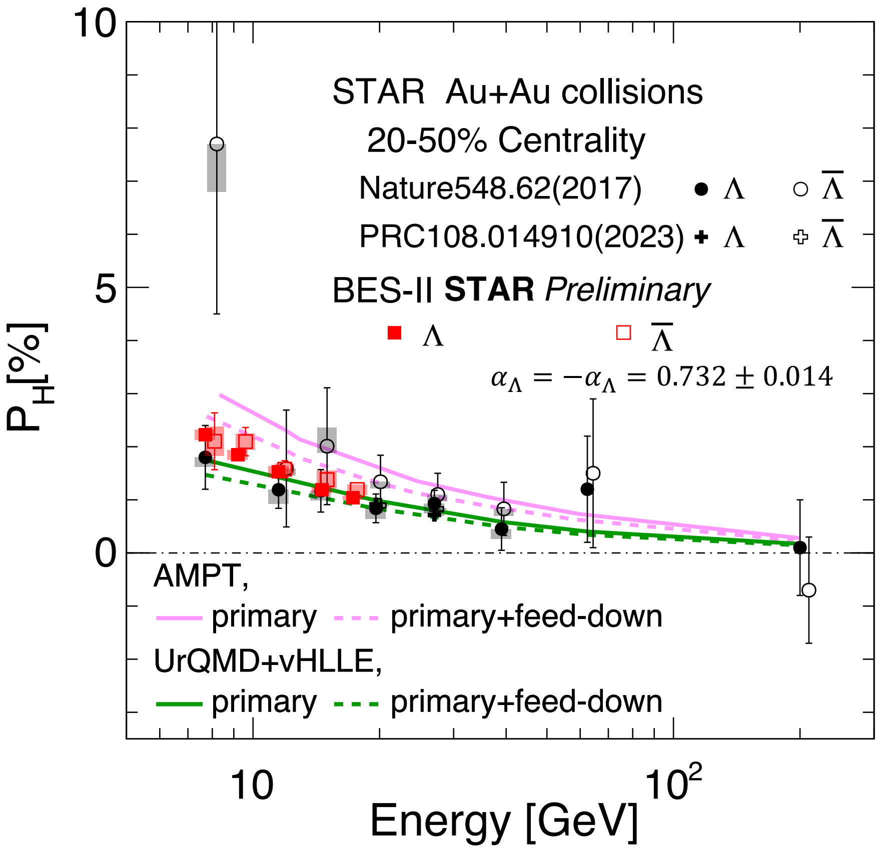


BES-I (2010-2017) and BES-II (2018-2021) statistics



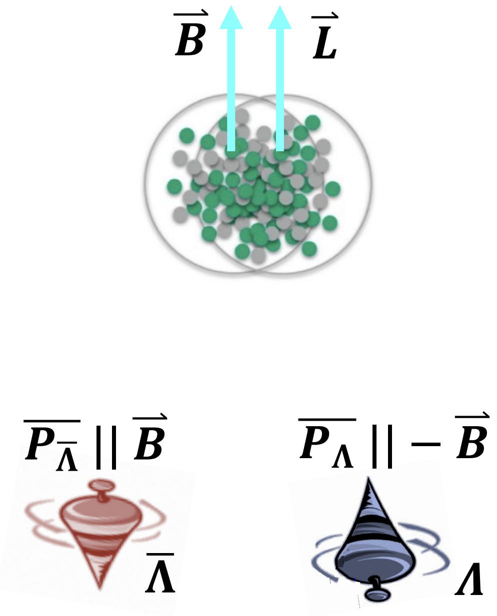
- Greatly improved precision from Beam Energy Scan phase-II at 7.7, 9.2, 11.5, 14.6, 17.3 GeV

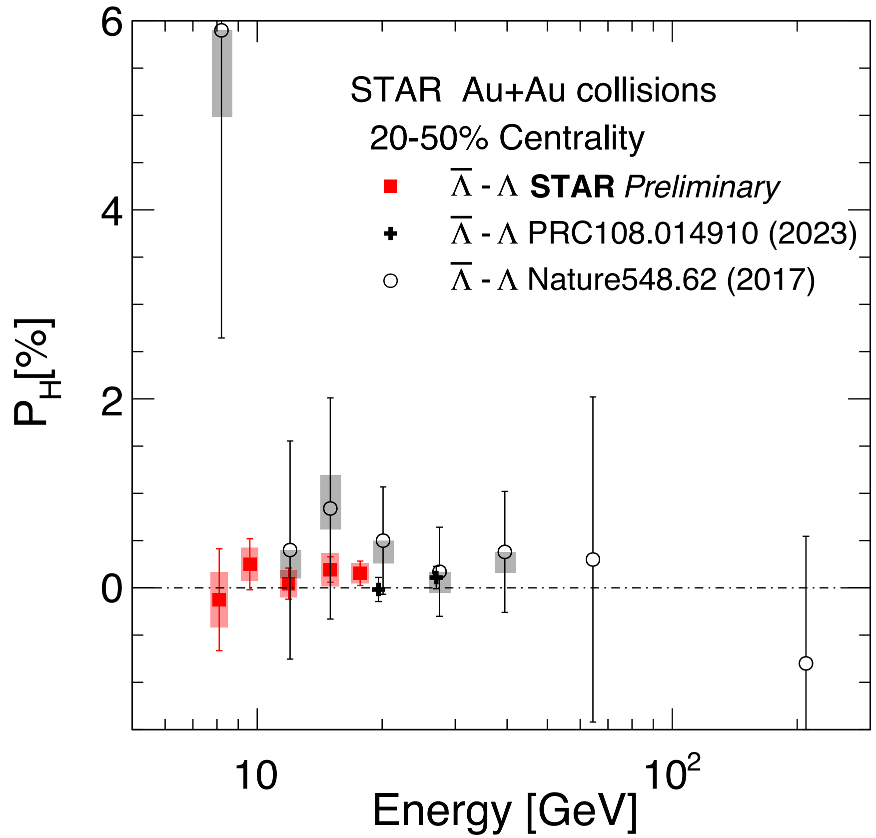
Energy dependence of Λ global polarization : from BES-II



- New STAR preliminary results at $\sqrt{s_{NN}}$ = 7.7-17.3 GeV from BES-II
- Significant improvement in precision was achieved, collision energy dependence consistent with BES-I

Splitting of Λ and $\bar{\Lambda}$ global polarization : from BES-II

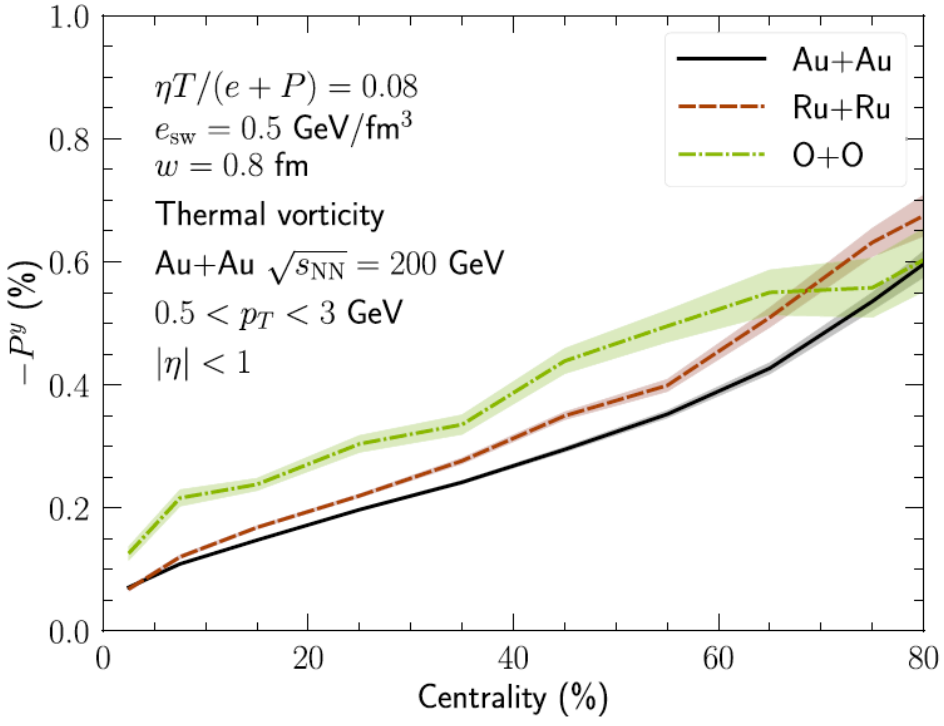




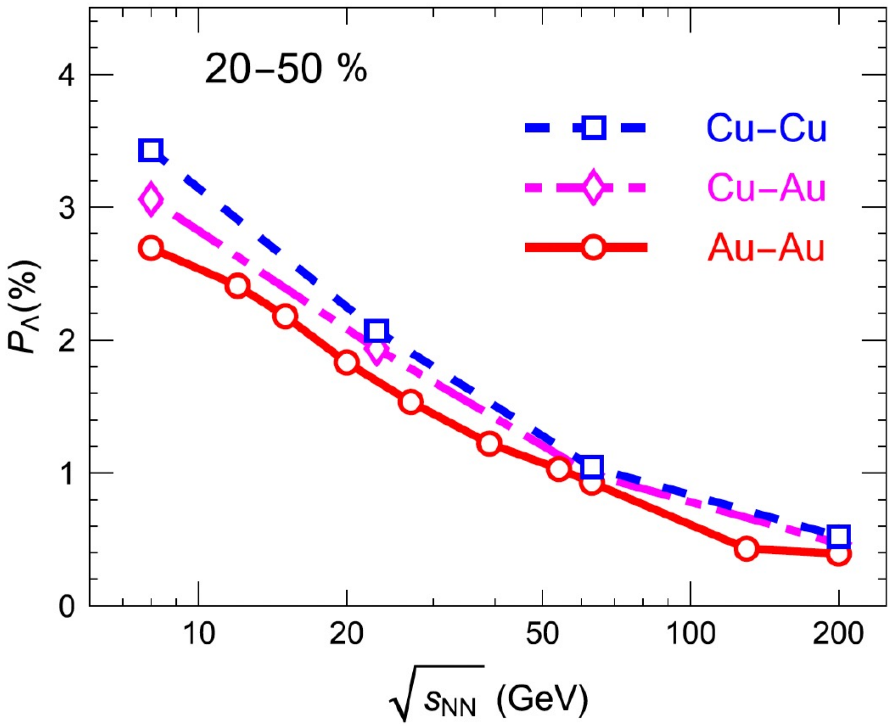
- No obvious splitting between Λ and $\bar{\Lambda}$ global polarization with high precision
- Upper limit on late stage magnetic field
  - 95% confidence level STAR, PRC 108,014910(2023)
  - $B < 9.4{\times}10^{12}\ T$ at 19.6 GeV
  - $B < 1.4{\times}10^{13}\ T$ at 27 GeV

System size dependence of Λ global polarization

S. Alzhrani et al., PRC 106.014905



S.Z, Shi, K.L. Li, J.F. Liao, PLB 788 (2019) 409–413

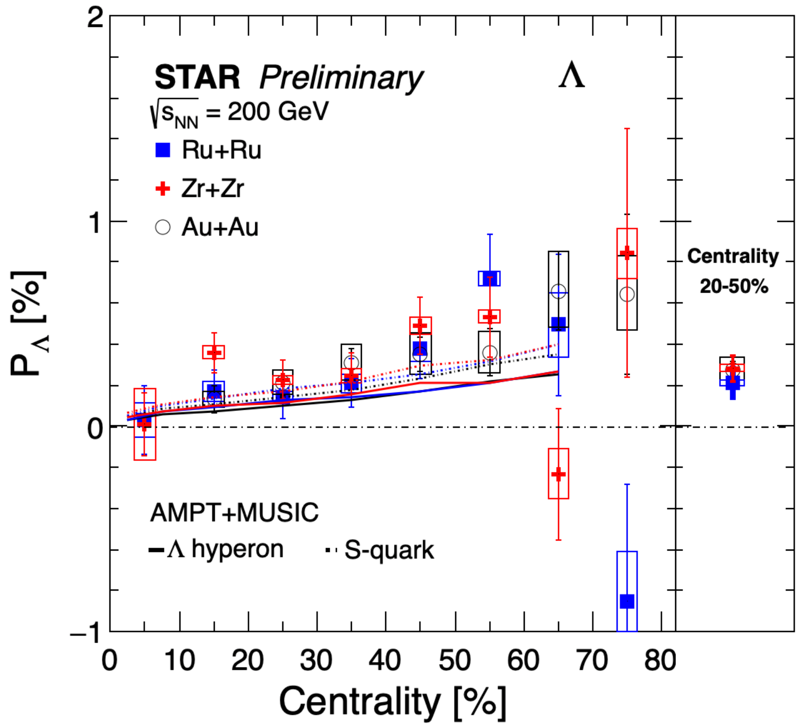


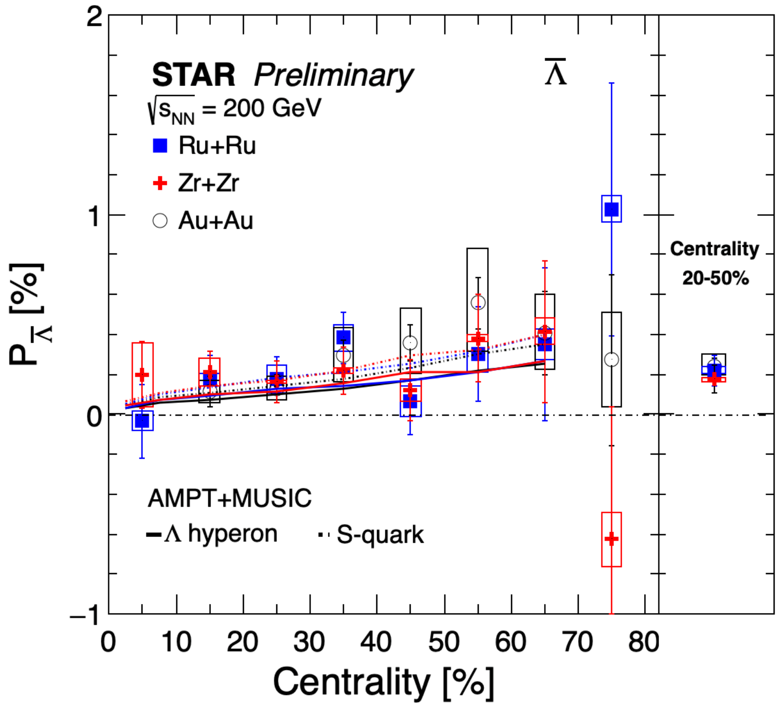
- Longer system lifetime dilutes the vorticity/polarization
- Collision system size dependence of global polarization?

$^{197}_{79}Au > ^{96}_{44}Ru, ^{96}_{40}Zr > ^{63}_{29}Cu > ^{16}_{8}O$

? $\rightarrow$ $P_\Lambda^{Au} < P_\Lambda^{Ru} \approx P_\Lambda^{Zr} < P_\Lambda^{Cu} < P_\Lambda^{O}$

Measurements of Λ global polarization in isobar collisions

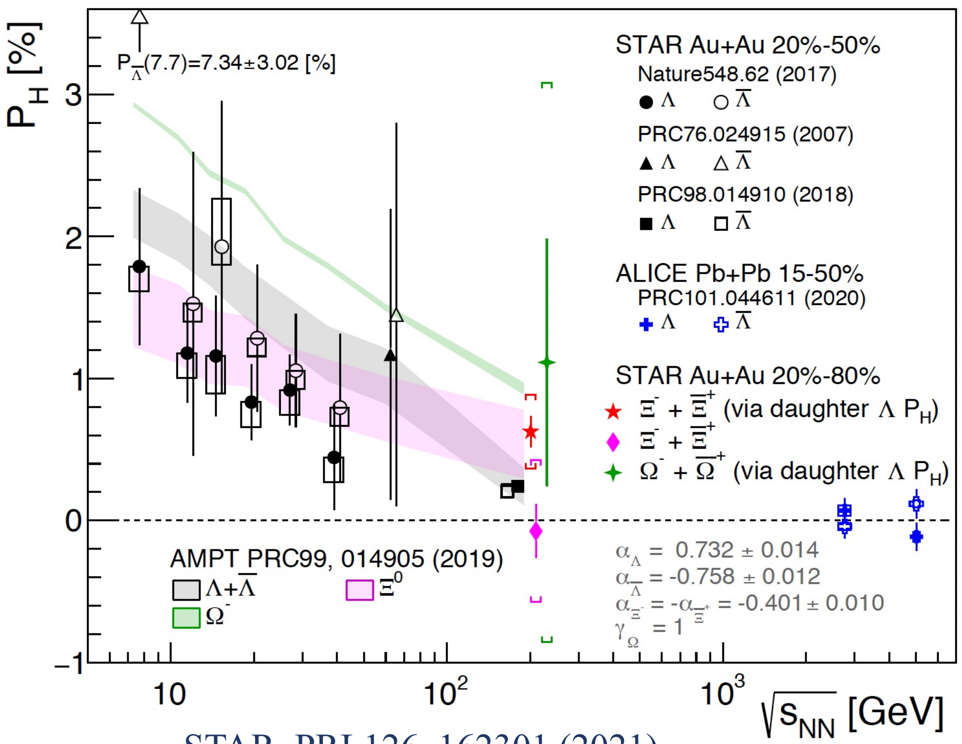




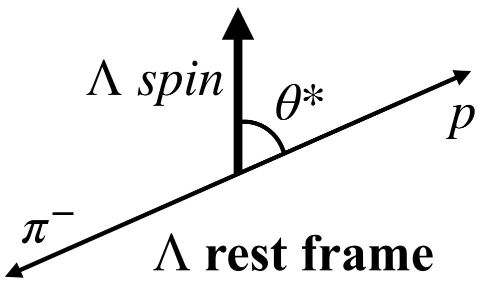
- Significant global polarization observed in isobar collisions, P_Λ and $P_{\bar{\Lambda}}$ increase with centrality
- Global polarization of $\Lambda + \bar{\Lambda}$ are consistent between Ru+Ru, Zr+Zr and Au+Au collisions within uncertainty

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

- Possible difference between Ξ global polarization and Λ due to earlier production and vorticity evolution
- Two measurement methods
  - Via daughter Λ angle distribution in Ξ rest frame
  - Via daughter Λ polarization with spin transfer factor($C_{\Xi^- \to \Lambda} = 0.944$)



STAR, PRL126, 162301 (2021)



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

α_H : hyperon decay parameter
P_H : hyperon polarization
θ^* : polarization angle

Hyperon	Deacy mode	α_H	Spin
Λ(uds)	$\Lambda \to p + \pi^-$	0.732	1/2
$\Xi^-(dss)$	$\Xi^- \to \Lambda + \pi^-$	-0.401	1/2

PDG2021

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

- Possible difference between Ξ global polarization and Λ due to earlier production and vorticity evolution
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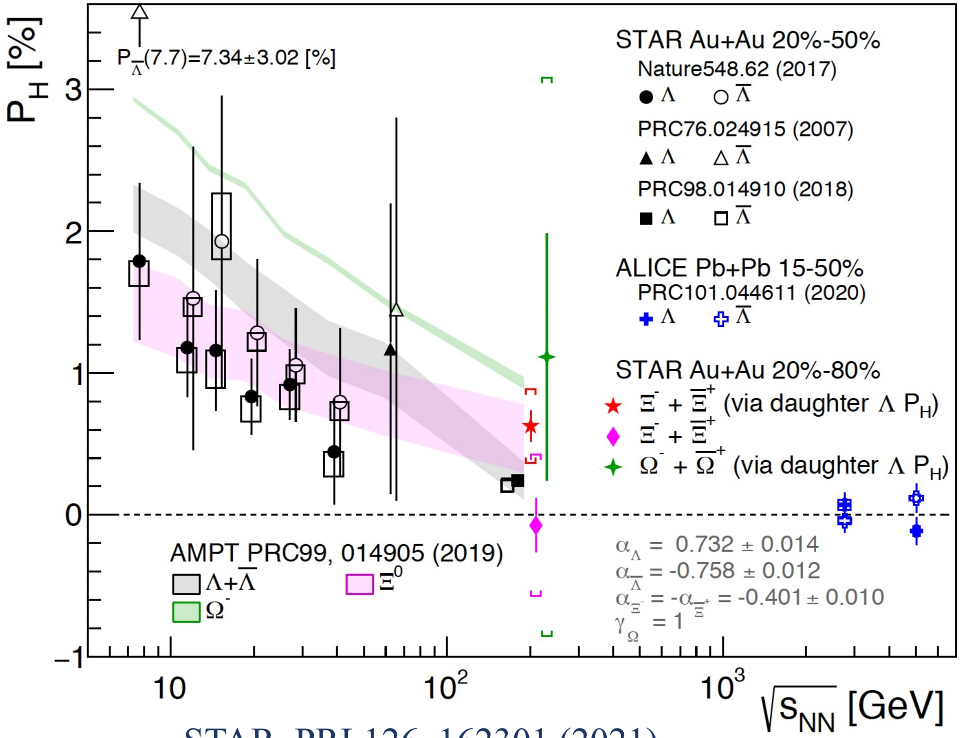
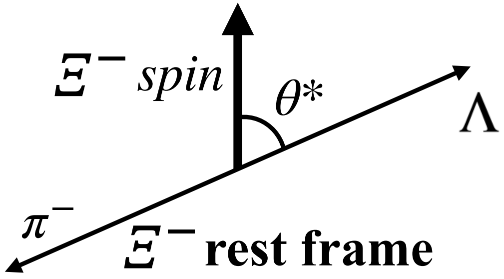
  - Via daughter Λ polarization with spin transfer factor($C_{\Xi^- \to \Lambda} = 0.944$)



STAR, PRL126, 162301 (2021)



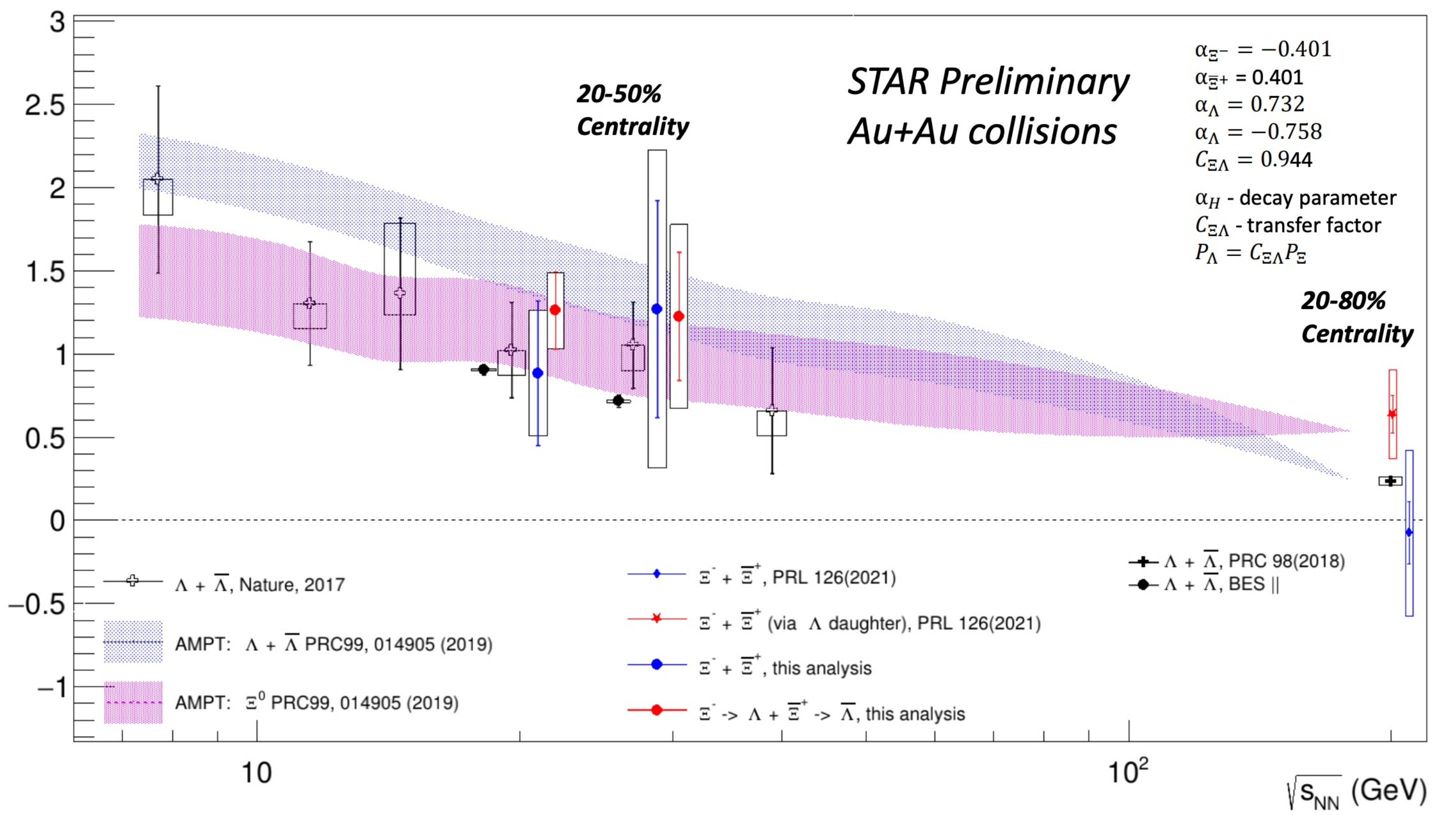
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H P_H cos\theta^*)$$

α_H : hyperon decay parameter
P_H : hyperon polarization
θ^* : polarization angle

Hyperon	Deacy mode	α_H	Spin
$\Lambda(uds)$	$\Lambda \to p + \pi^-$	0.732	1/2
$\Xi^-(dss)$	$\Xi^- \to \Lambda + \pi^-$	-0.401	1/2

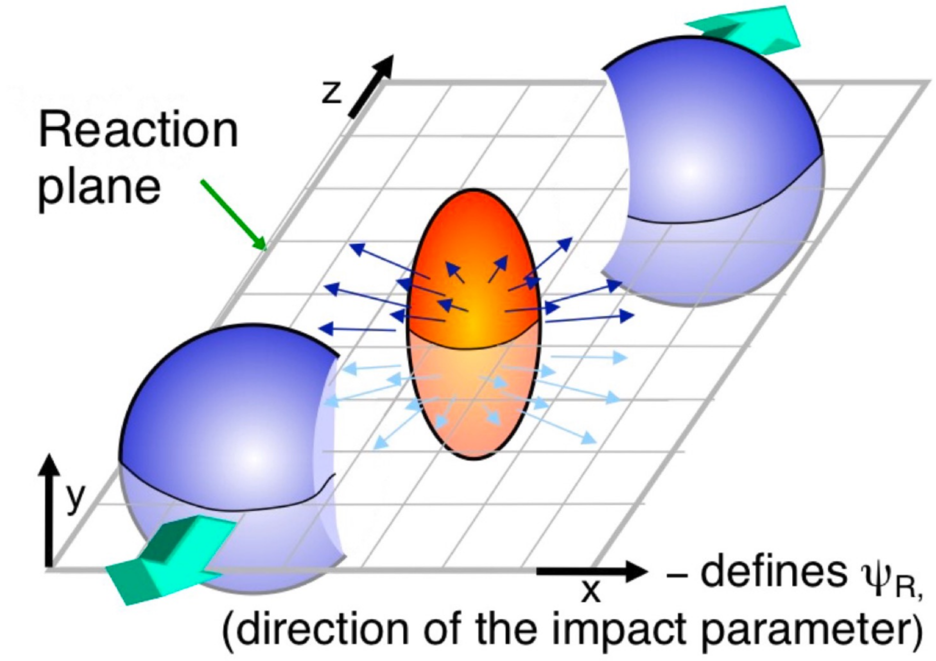
PDG2021

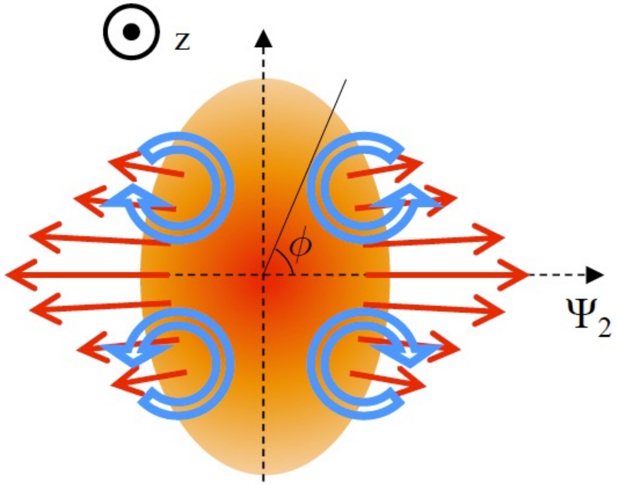
Energy dependence of $\Xi^- + \bar{\Xi}^+$ global polarization

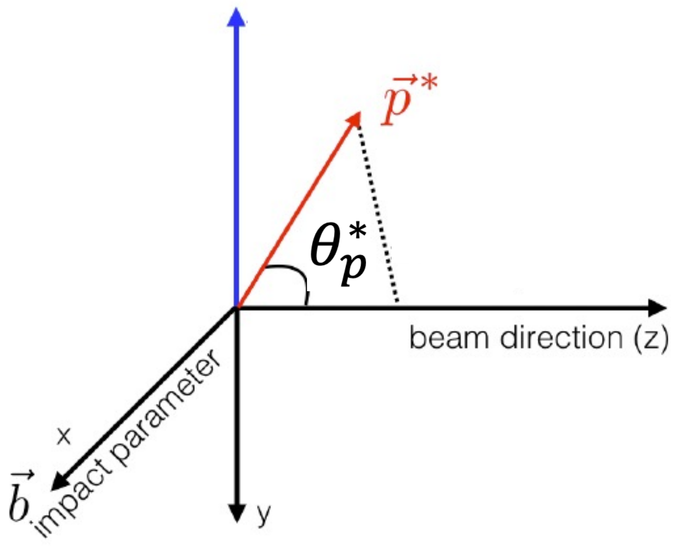


- Significant $\Xi^- + \bar{\Xi}^+$ global polarization observed in Au+Au at 19.6 and 27 GeV
- $\Xi^- + \bar{\Xi}^+$ global polarization measurement at lower BES-II energies underway

Local vorticity and polarization in heavy ion collisions







- Elliptic flow indicates stronger expansion in-plane than out of plane

  ⟹ Lead to polarization along the beam direction (P_z)

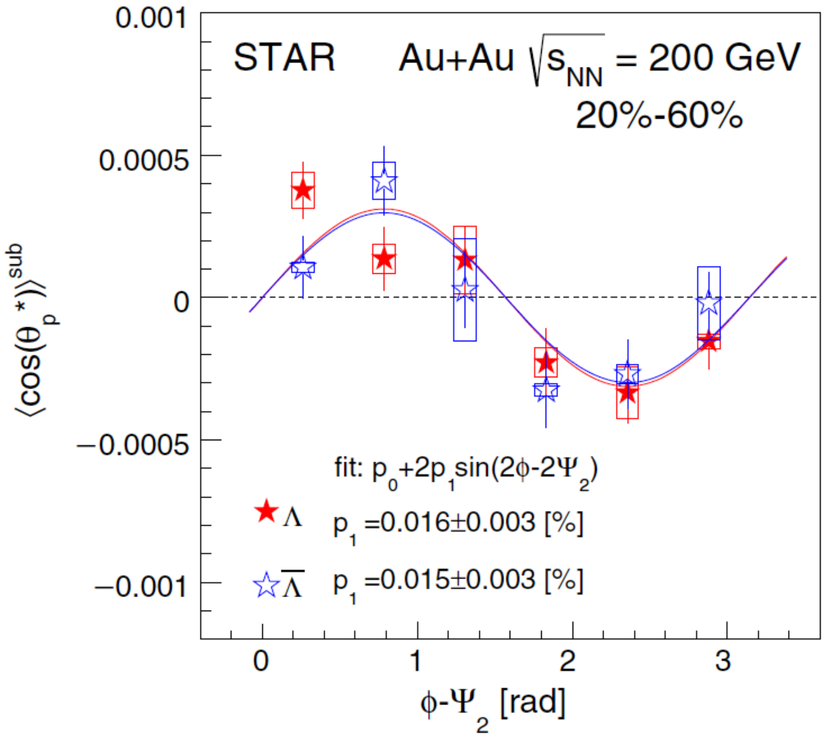
$$\langle cos\theta_p^*\rangle = \int \frac{dN}{d\Omega^*} cos\theta_p^* d\Omega^*$$

$$= \alpha_\Lambda P_z \langle (cos\theta_p^*)^2 \rangle$$

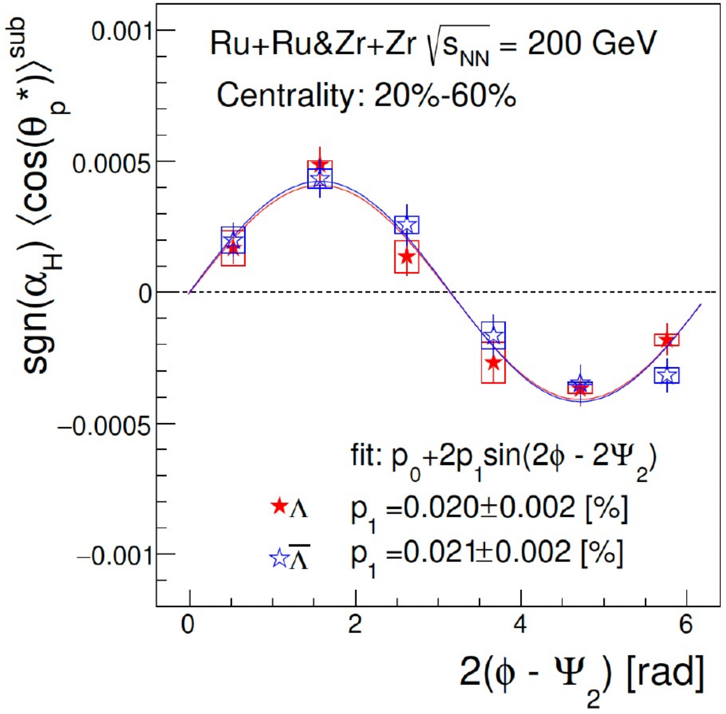
$$P_z = \frac{\langle cos\theta_p^*\rangle}{\alpha_\Lambda \langle (cos\theta_p^*)^2 \rangle}$$

Azimuthal angle dependence of P_z

STAR, PRL 123, 132301 (2019)



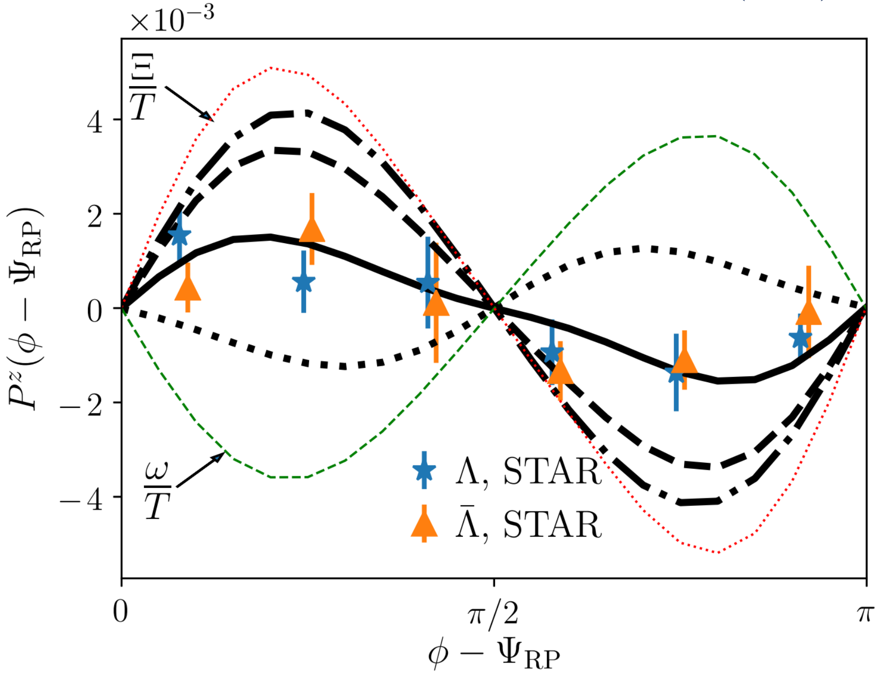
STAR, PRL 131, 202301 (2023)



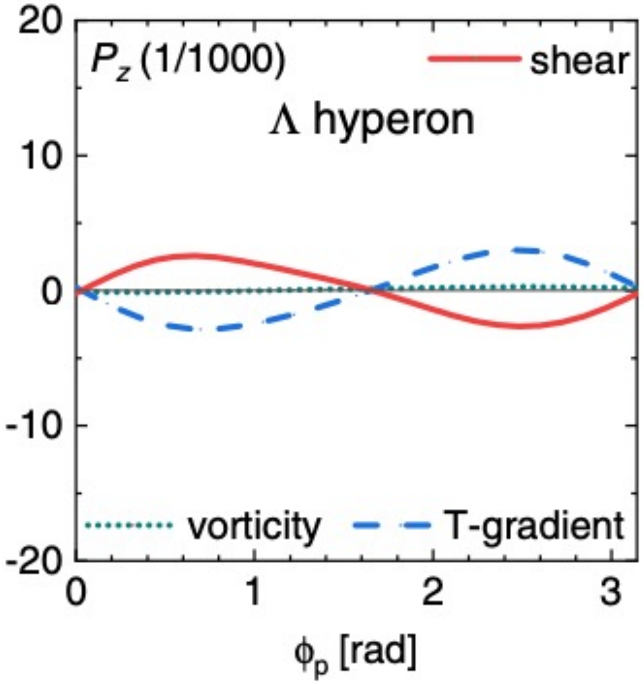
- Clear azimuthal angle dependence observed in Au+Au and isobar collisions at 200 GeV

Azimuthal angle dependence of P_z

F. Becattini, et al., PRL127, 272302 (2021)



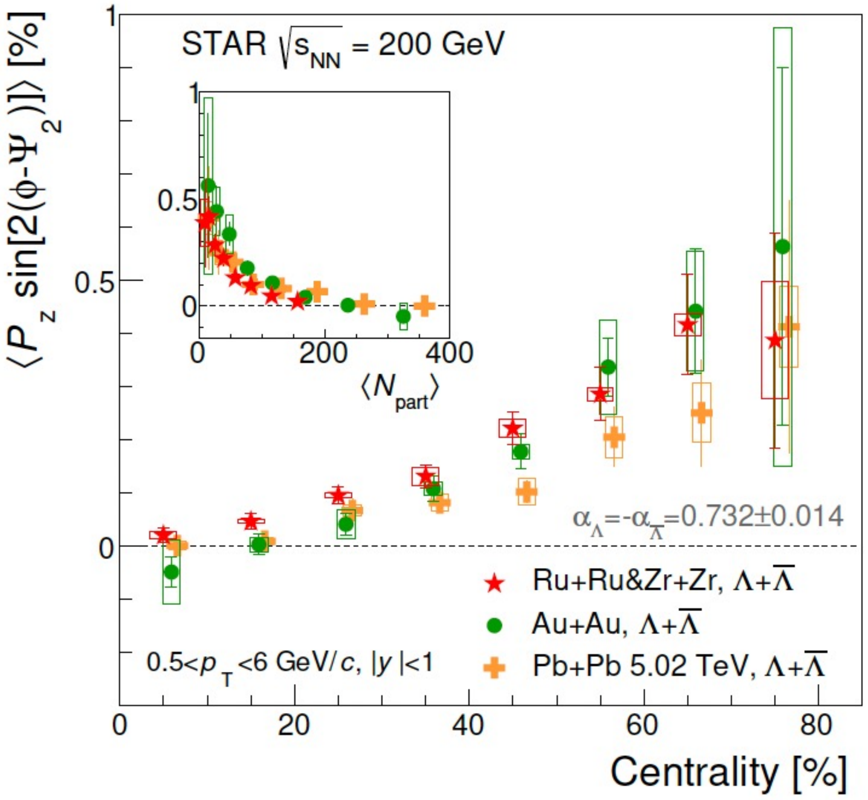
Baochi Fu, et al., PRL 127, 142301 (2021)



- Clear azimuthal angle dependence observed in Au+Au and isobar collisions at 200 GeV
- New developments, Shear Induced Polarization(SIP), may solve the 'P_z puzzle'

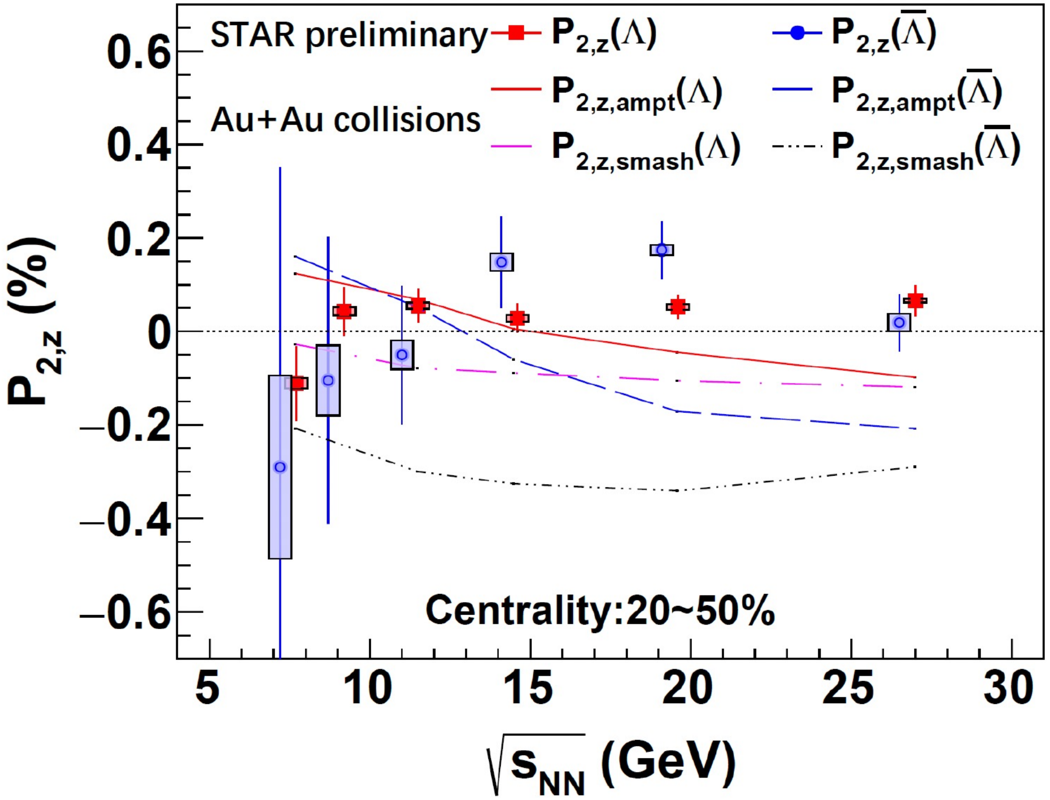
System size dependence of P_z

STAR, PRL 131, 202301 (2023)



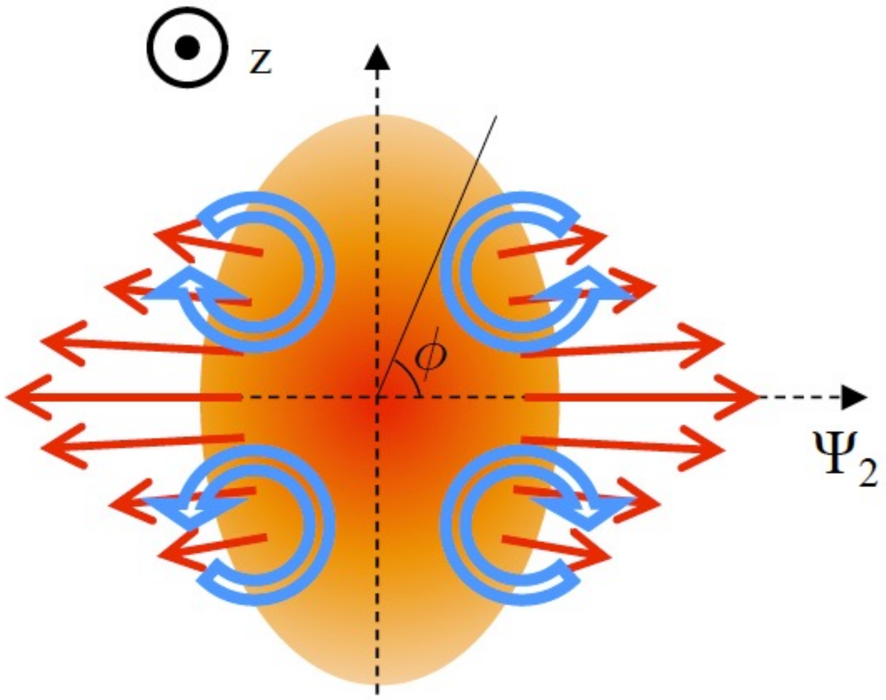
- P_z from isobar collision comparable to Au+Au and Pb+Pb
  - ✓ No significant system size dependence observed at same energy

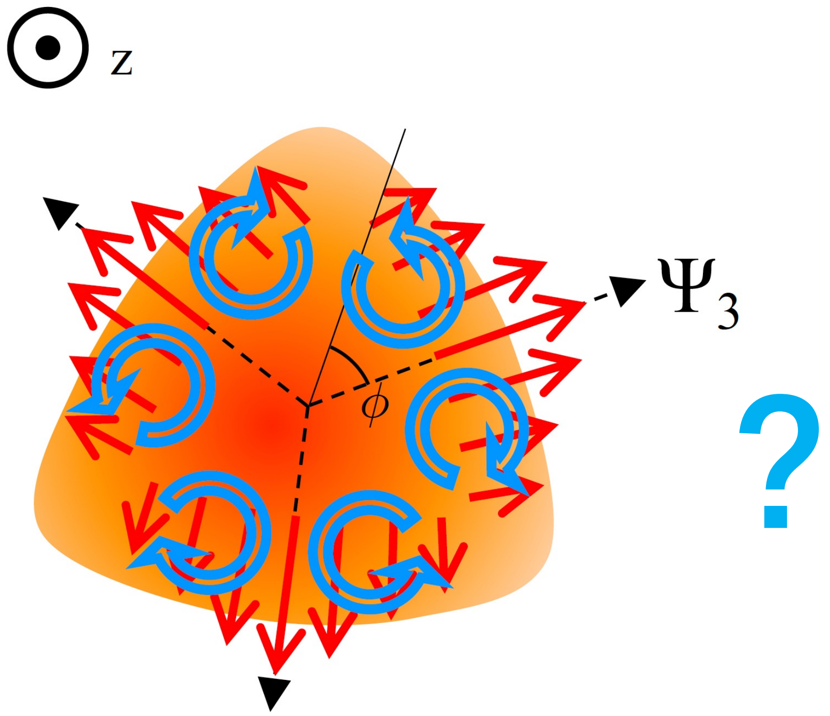
Measurements of P_z with BES-II



- First measurements of P_z in Au+Au collisions from 7.7 to 27 GeV with BES-II
  - ✓ No significant collision energy dependence observed

P_z from higher harmonic flow

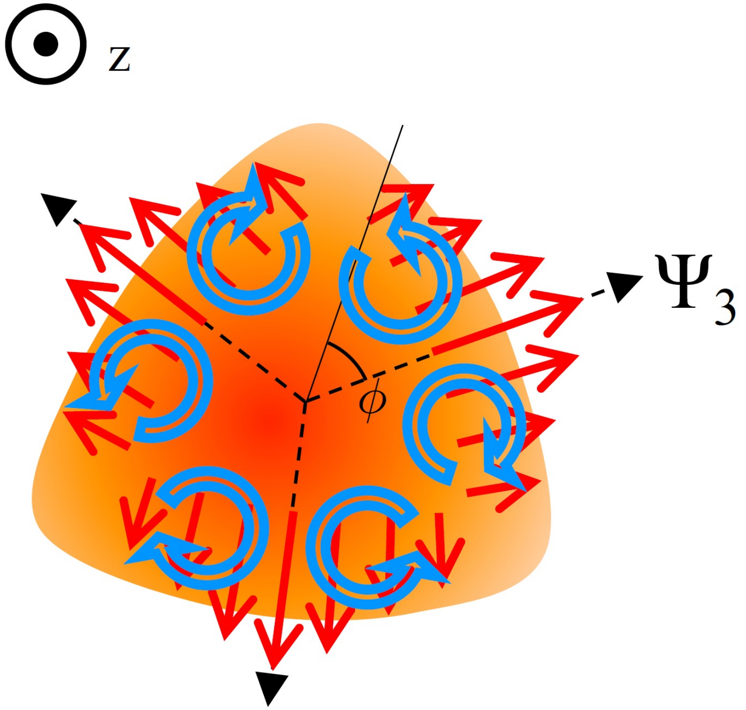


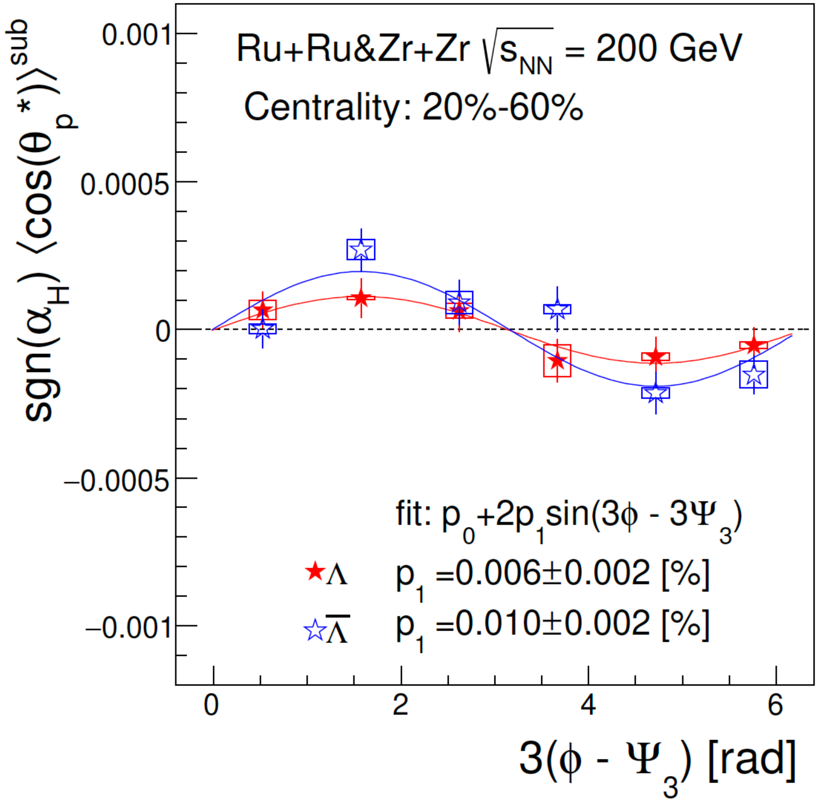


- Measurements P_z relative to higher harmonic event planes provide new insights into polarization phenomena

P_z from higher harmonic flow

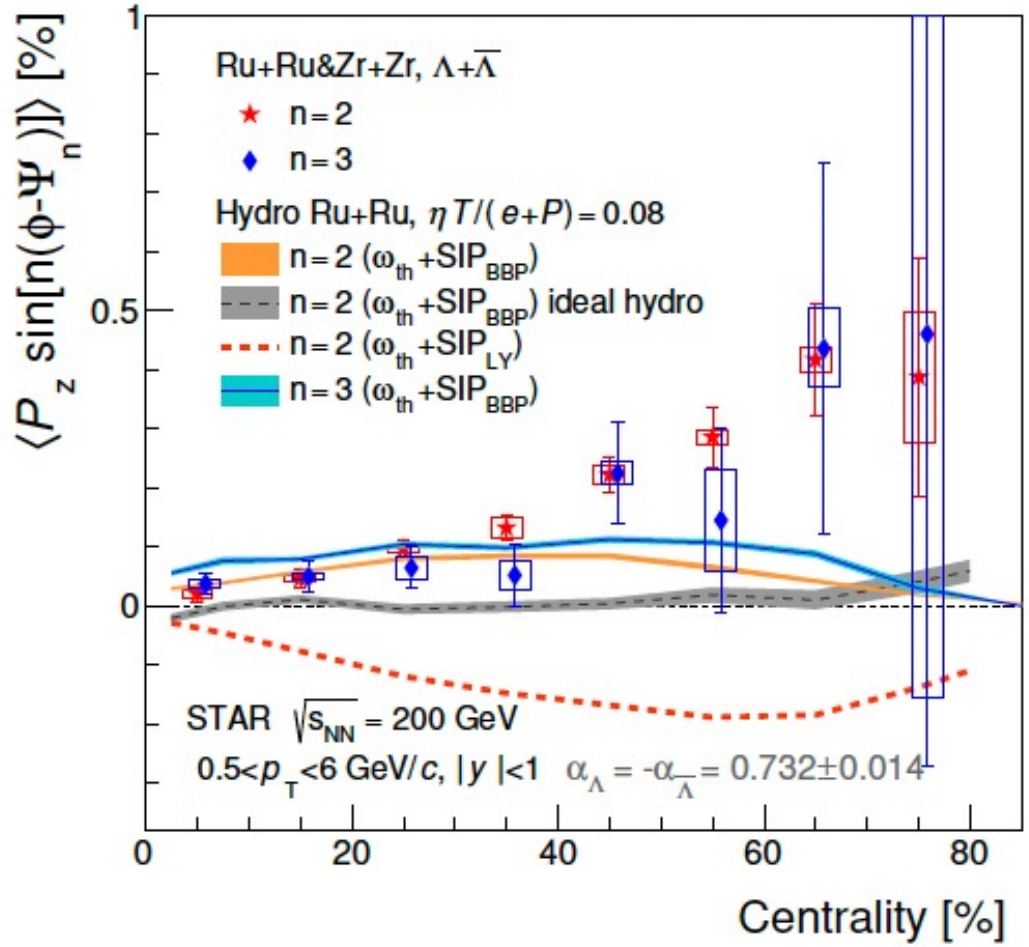
STAR, PRL 131, 202301 (2023)





- First observation of P_z w.r.t the third-order event plane

P_z w.r.t third order event plane



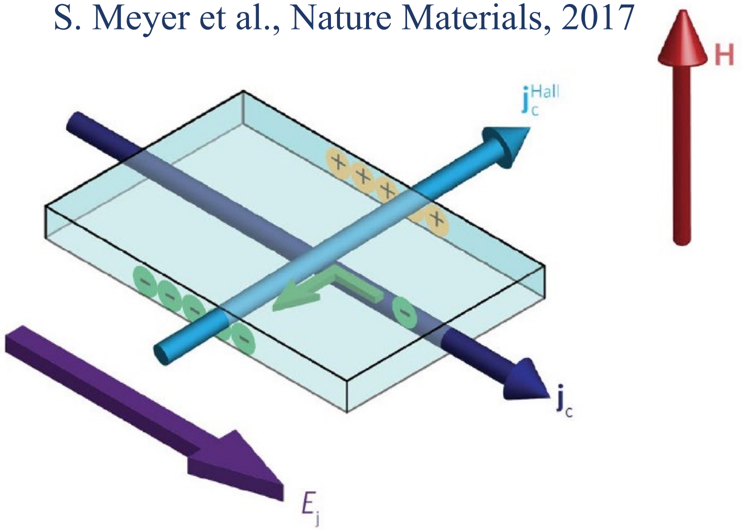
STAR, PRL 131, 202301 (2023)

- Significant P_z w.r.t third-order event plane observed
- P_z w.r.t second-order event plane increases with centrality
- Comparable P_z w.r.t second and third order event plane, indicating v_3-driven polarization
- Hydrodynamic models with shear term reasonably describe the data for central collisions, but not for peripheral collisions

S. Alzhrani et al., PRC 106.014905

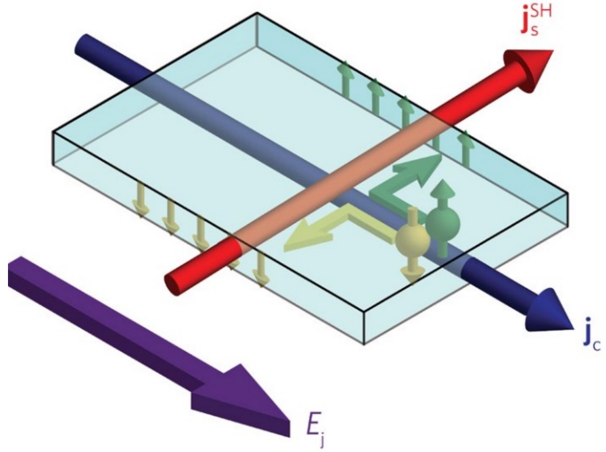
Spin Hall effect (SHE)

S. Meyer et al., Nature Materials, 2017



HE: charge imbalance (1879)

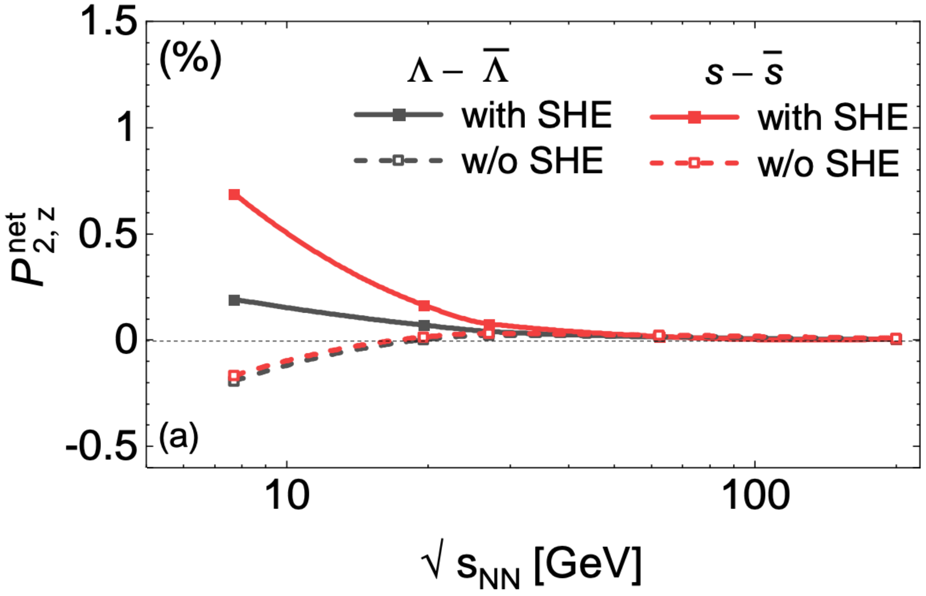
$$P \propto p \times E$$



SHE: spin imbalance (2004)

$$P \propto p \times \nabla \mu_B$$

Baochi Fu et al., arXiv:2201.12970v1



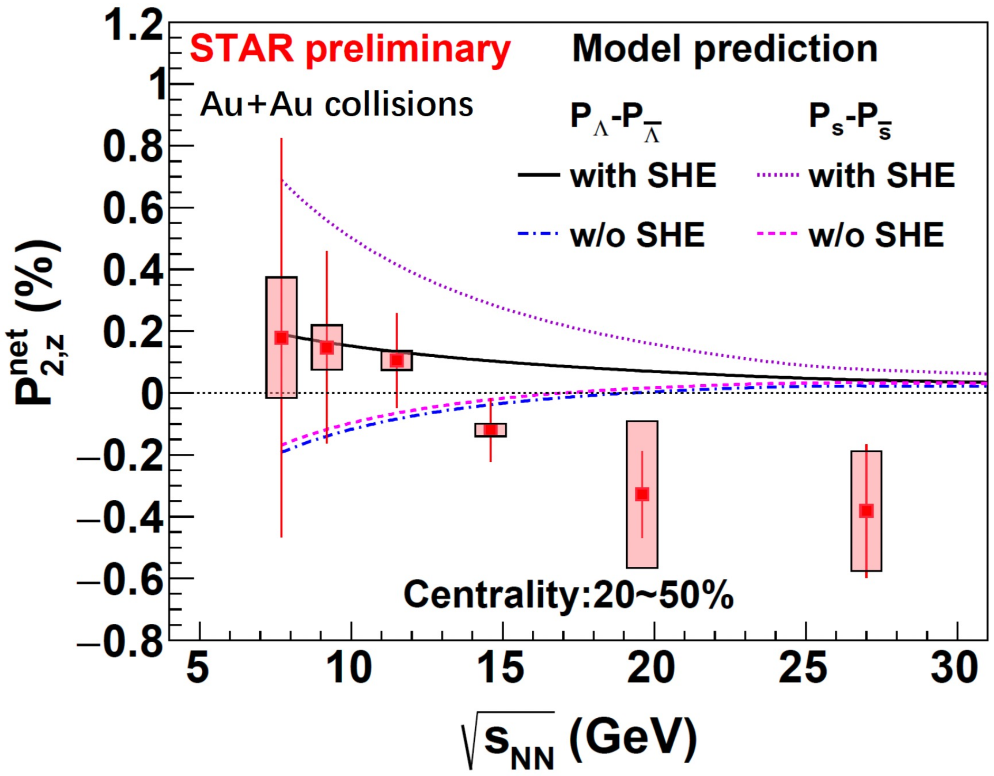
- SHE driven by baryon chemical potential gradient, leads to the splitting between Λ and $\bar{\Lambda}$ polarization
- Prediction of collision energy dependence of net-Λ polarization

$$P_{2,z} = < P_z \sin(2\Delta\phi) >$$

$$P^{net}_{2,z} = P_{2,z}(\Lambda) - \overline{P_{2,z}}(\Lambda)$$

$$\Delta\phi = \phi_\Lambda - \psi_2$$

Measurements of spin Hall effect(SHE)



$$P_{2,z} = < P_z \sin(2\Delta\phi) >$$

$$P_{2,z}^{net} = P_{2,z}(\Lambda) - \overline{P_{2,z}}(\Lambda)$$

$$\Delta\phi = \phi_\Lambda - \psi_2$$

- SHE driven by baryon chemical potential gradient, leads to the splitting between Λ and $\bar{\Lambda}$ polarization
- Prediction of collision energy dependence of net-Λ polarization
- No SHE effect observed within uncertainty

Summary

Global polarization

- Significant improvement in precision was achieved in BES-II
- No splitting observed between Λ and $\bar{\Lambda}$ global polarization in Au+Au collisions at 7.7 - 27 GeV and ${}^{96}_{44}\mathrm{Ru} + {}^{96}_{44}\mathrm{Ru}$, ${}^{96}_{40}\mathrm{Zr} + {}^{96}_{40}\mathrm{Zr}$ collisions at 200 GeV
- Significant $\Xi^- + \bar{\Xi}^+$ global polarization observed at 19.6, 27 GeV, measurements in lower energies underway
- No collision system size dependence between Ru+Ru, Zr+Zr and Au+Au collisions at 200 GeV

Polarization along beam direction (P_z)

- First observation of P_z w.r.t third-order event plane
- First measurements of P_z in Au+Au collisions from 7.7 to 27 GeV with BES-II
- No spin Hall effect observed within uncertainty

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STAR

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Thanks for your attention

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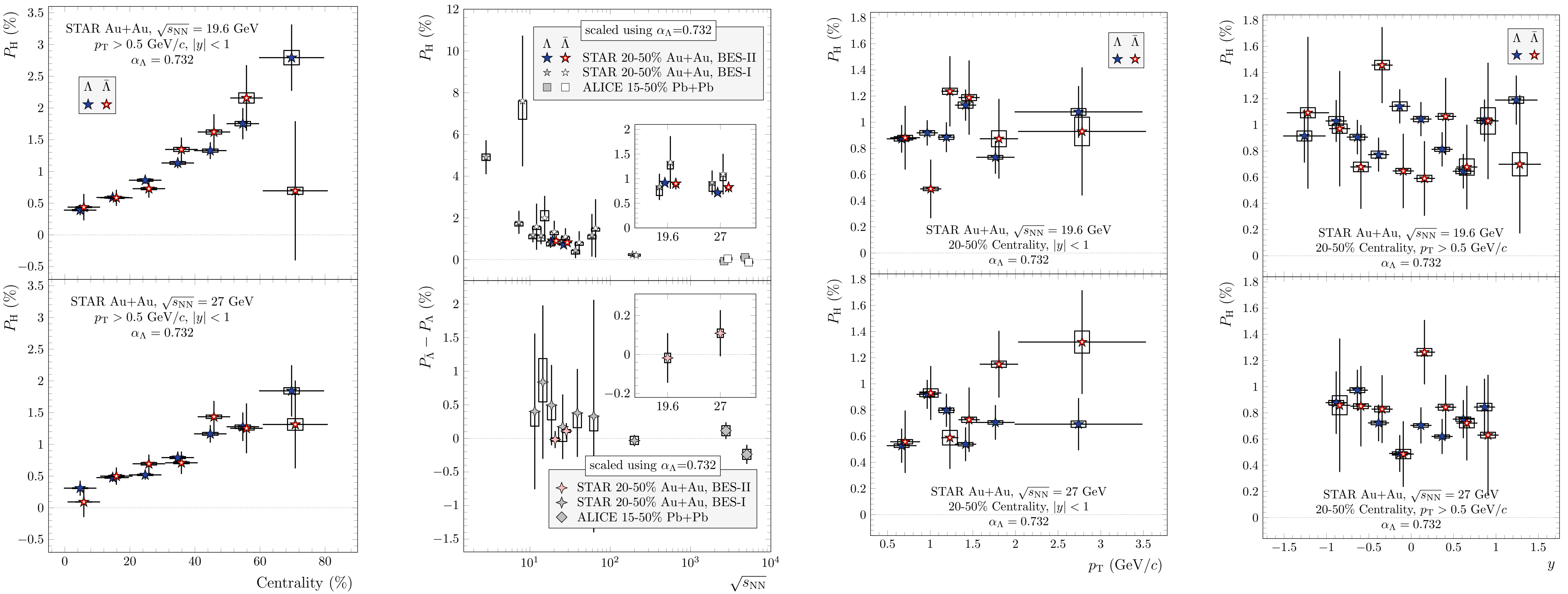
Back Up

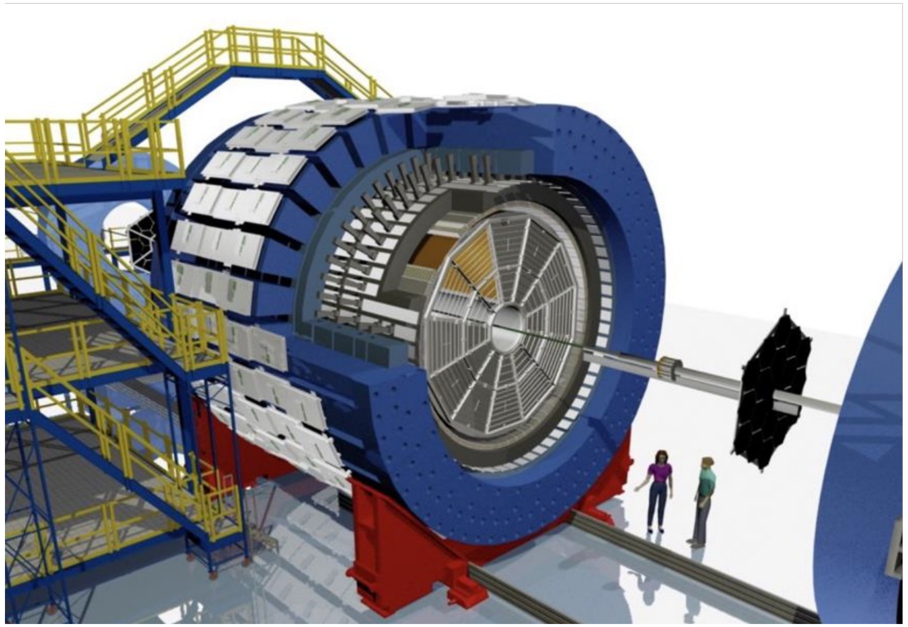
Global polarization collision energy dependence



- Significant global polarization centrality dependence observed
- Lambda and Anti-Lambda global polarization are consistent
- No observed dependence of global polarization on p_T

STAR, PRC 108, 014910 (2023)

STAR detector and $\Lambda/\bar{\Lambda}$ reconstruction



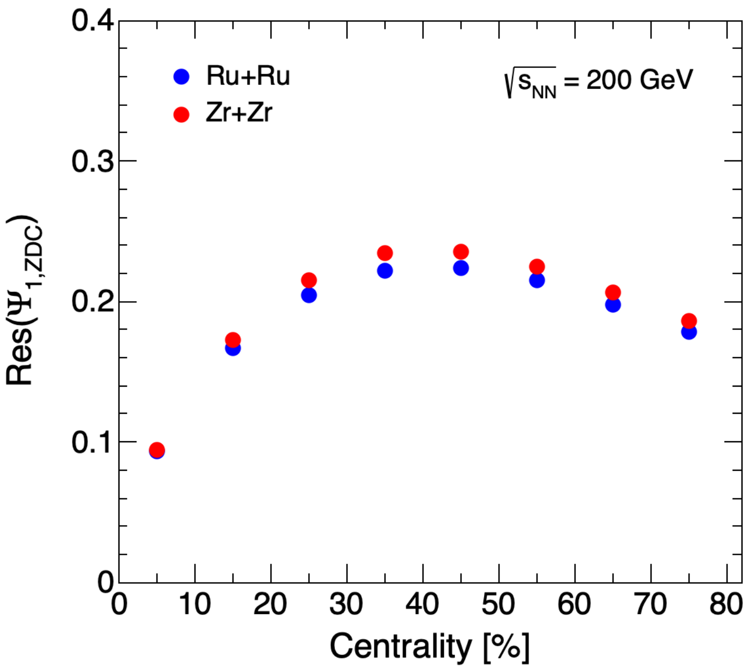
Event plane reconstruction:

Time Projection Chamber
Zero Degree Calorimeters

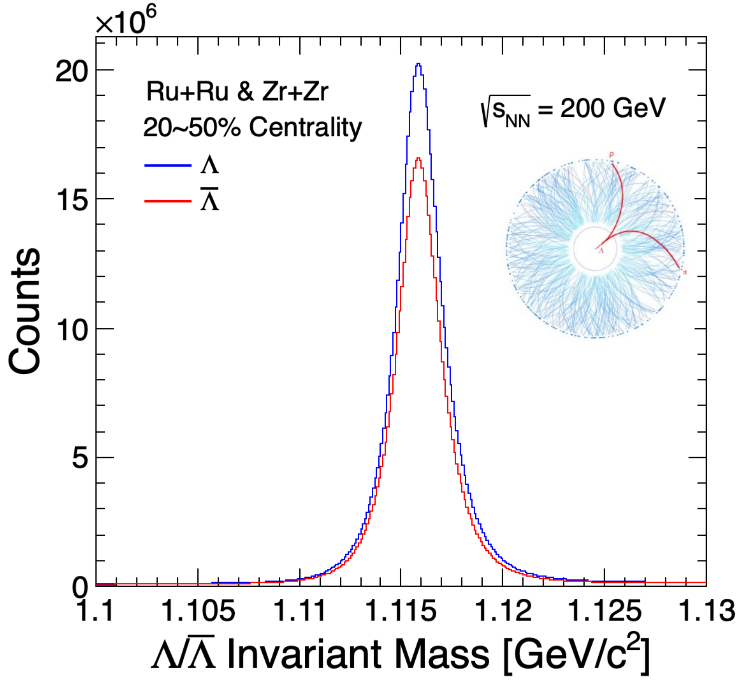
$\Lambda/\bar{\Lambda}$ reconstruction:

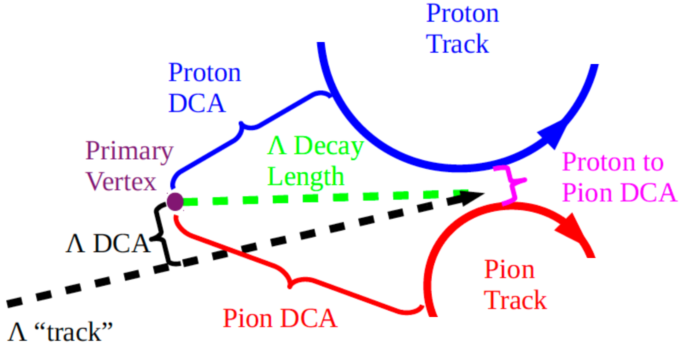
Time Projection Chamber
Time Of Flight

Event plane resolution



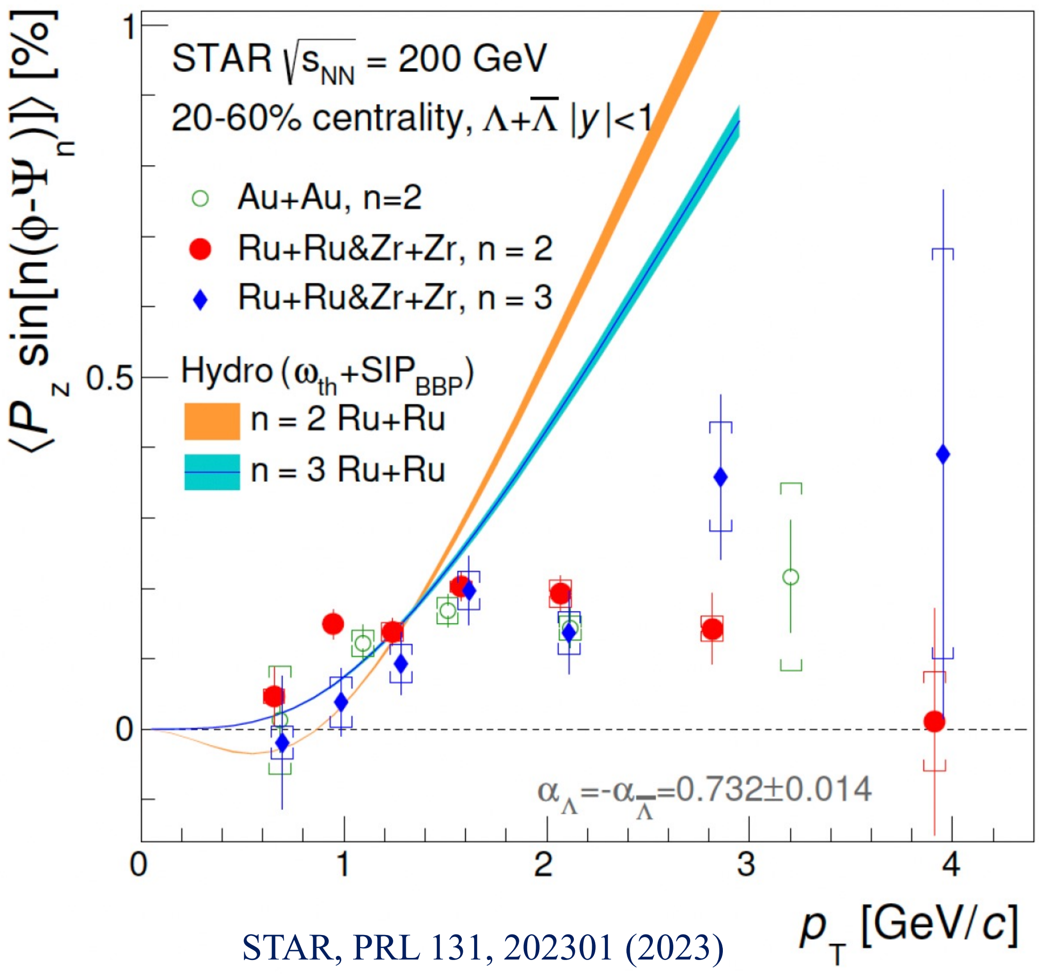
$\Lambda/\bar{\Lambda}$ reconstructed with TPC tracks





- $\Lambda \rightarrow p + \pi^-$
- $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$
- Background fraction < 3%

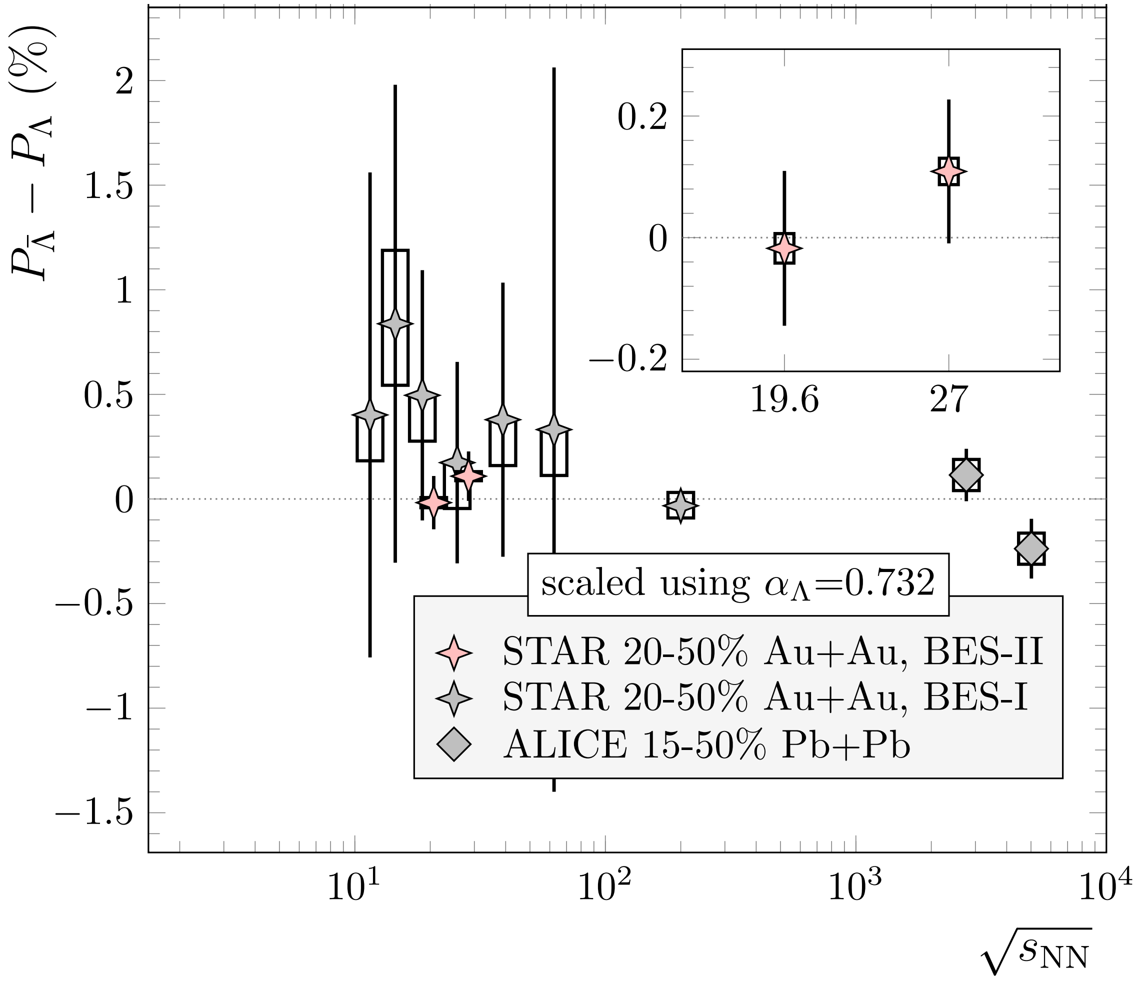
p_T dependence of local polarization



STAR, PRL 131, 202301 (2023)

- Local polarization p_T dependence is observed
- Observed p_T dependence similar to that of elliptic (v_2) and triangular (v_3) flow
- Results are consistent between isobar and Au+Au collisions

Global polarization in Au+Au with BES-II data (19.6, 27 GeV)



- No splitting of Λ / $\bar{\Lambda}$ observed

Au+Au	19.6 GeV	27 GeV
$P_{\bar{\Lambda}} - P_{\Lambda}$ (%)	$-0.018 \pm 0.127(stat.) \pm 0.024(sys.)$	$0.109 \pm 0.118(stat.) \pm 0.022(sys.)$

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

T_s =150 MeV : the temperature of the emitting source

$\mu_\Lambda = -1.93\times10^{-14}$ MeV/T : the magnetic moment of the Λ hyperon

- Upper limit on late stage magnetic field
  - 95% confidence level
  - $B < 9.4\times10^{12}$ T at 19.6 GeV
  - $B < 1.4\times10^{13}$ T at 27 GeV

STAR, PRC 108, 014910 (2023)