

Hyperon spin polarization measurements from the STAR experiment at RHIC

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(for the STAR Collaboration)

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ENERGY

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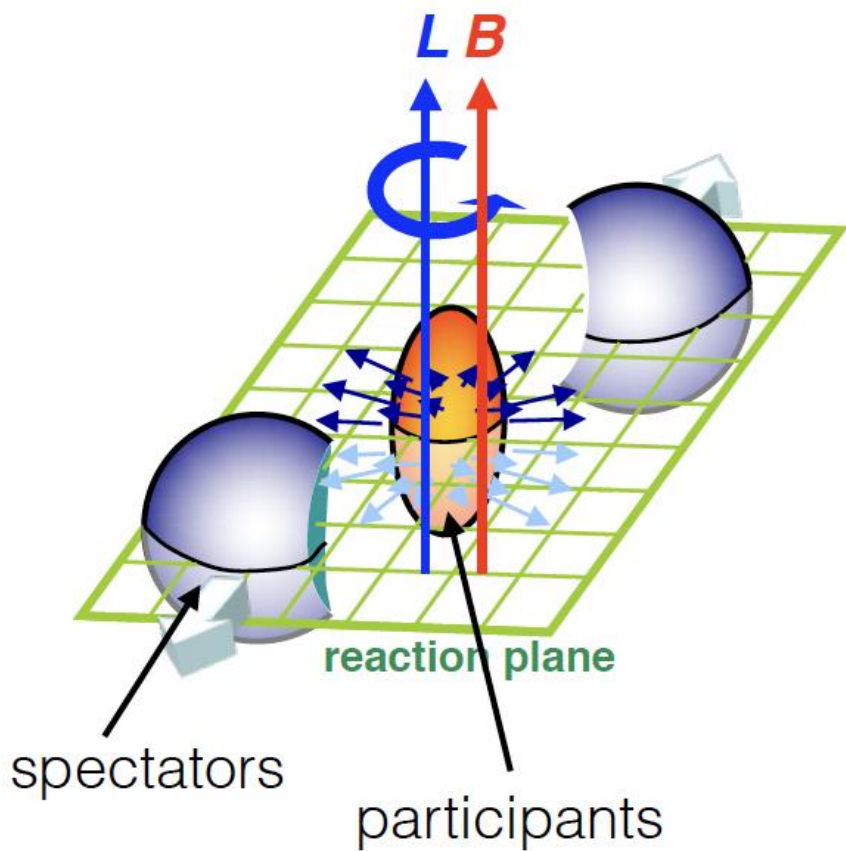
Office of
Science

中国物理学会高能物理分会

HIGH ENERGY PHYSICS BRANCH OF CPS



- Brief introduction on vorticity and polarizaiton
- Analysis process
- Recent STAR experiment results
 - Hyperon global polarization
 - Hyperon polarization along beam direction
- Summary and outlook



Orbital angular momentum

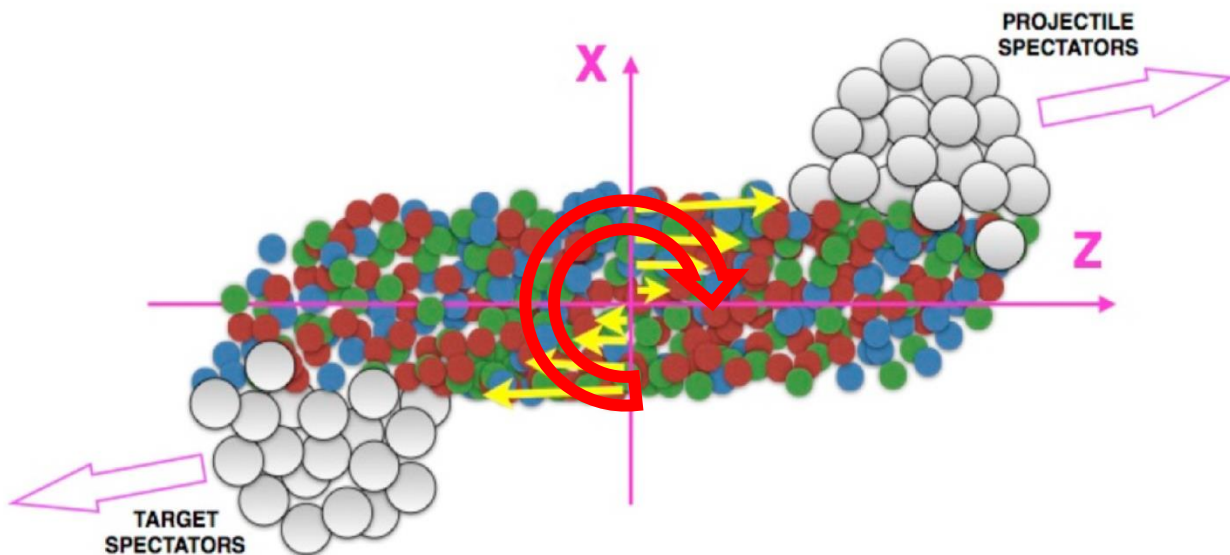
Z.-T. Liang and X.-N. Wang, PRL 94, 102301 (2005)

$$L \sim \frac{Ab\sqrt{s}}{2} \sim 10^6 \hbar$$

Expected to have strong magnetic field

$$eB \sim \gamma \alpha_{EM} \frac{Z}{b^2} \sim 10^{18} G \sim 10^{14} T$$

(RHIC Au+Au200 GeV, $b=10$ fm)



Orbital angular momentum

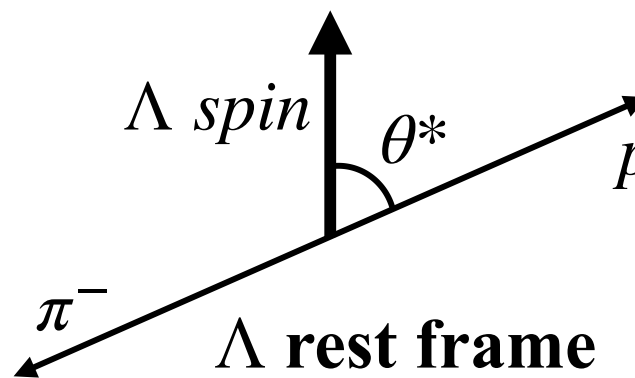


Local fluid vorticity $\omega = \frac{1}{2} \nabla \times v$



Leads to global polarization along L though spin-orbit coupling

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

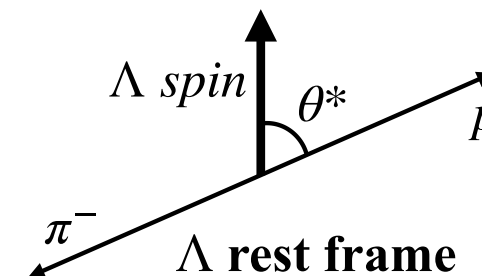


Z.-T. Liang and X.-N. Wang, PRL 94, 102301 (2005)

- “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

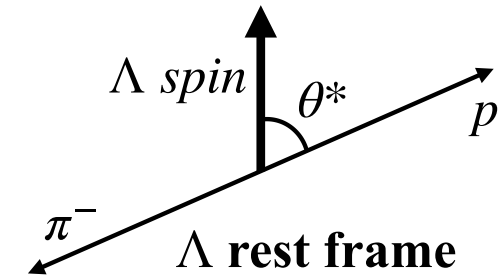


$\Lambda \rightarrow p + \pi^-$
 (BR:63.9%, $c\tau \sim 7.9\text{cm}$)

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

PDG2021

- “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%, $c\tau \sim 7.9\text{cm}$)

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

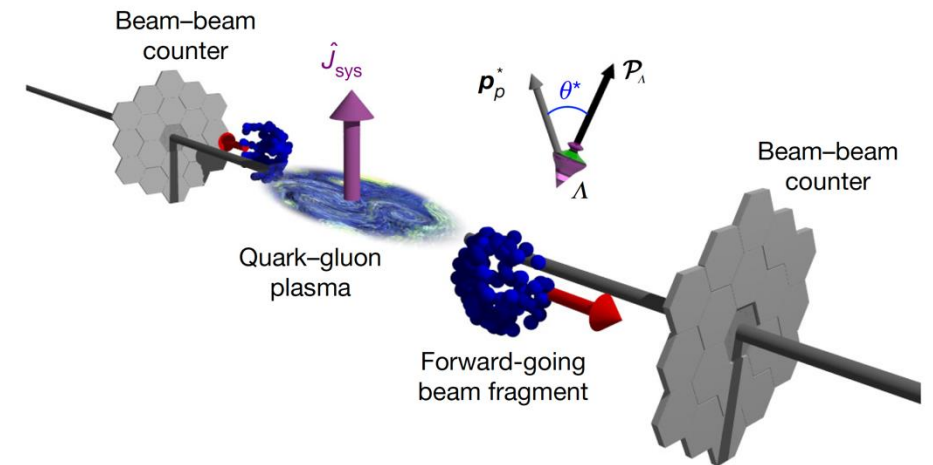
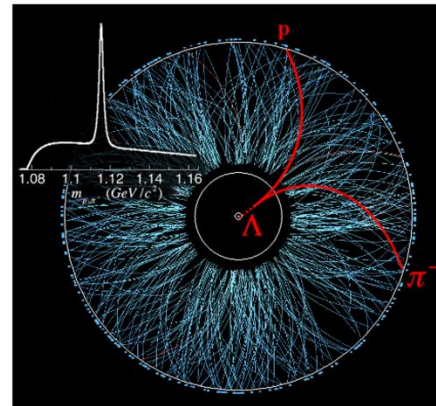
$$\alpha_{\Lambda} = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$$

A_0 : Acceptance correction factor

Ψ_1 : First-order event plane angle

$\text{Res}(\Psi_1)$: Event plane resolution

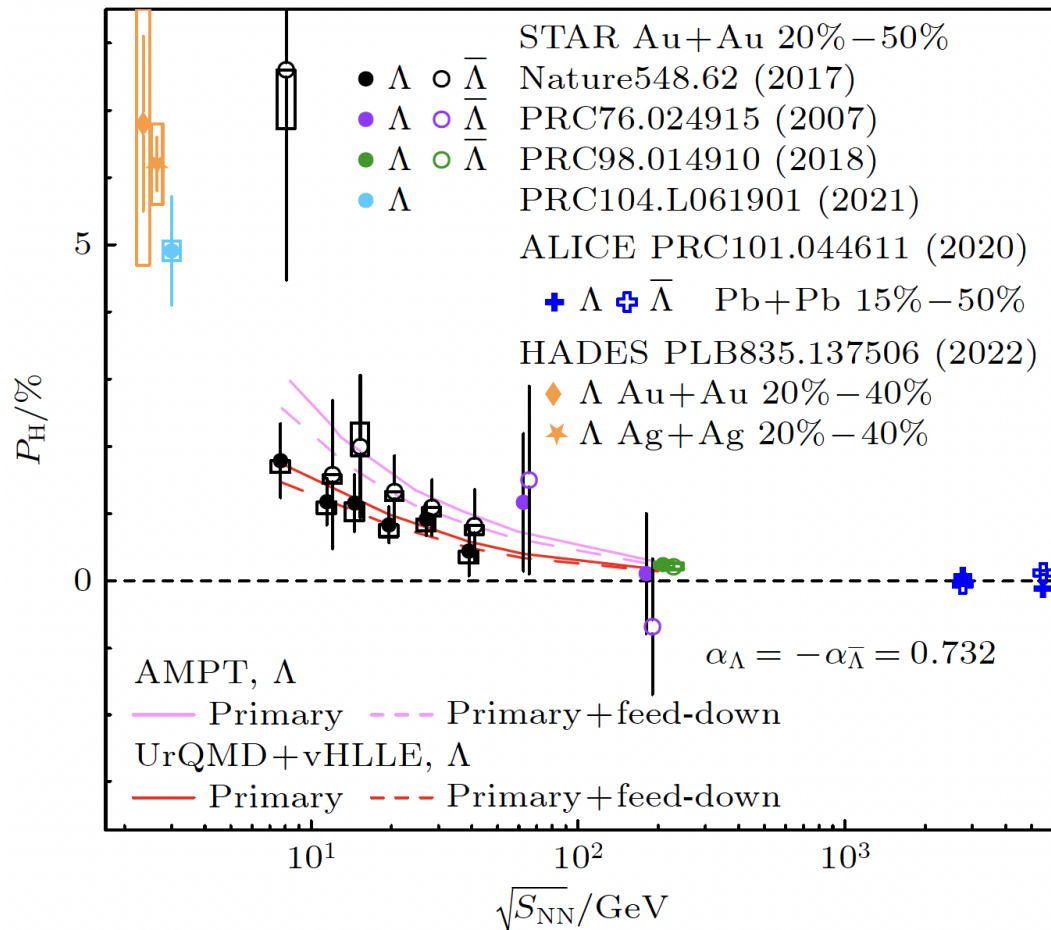
STAR, PRC76, 024915 (2007)



Observation of Λ global polarization

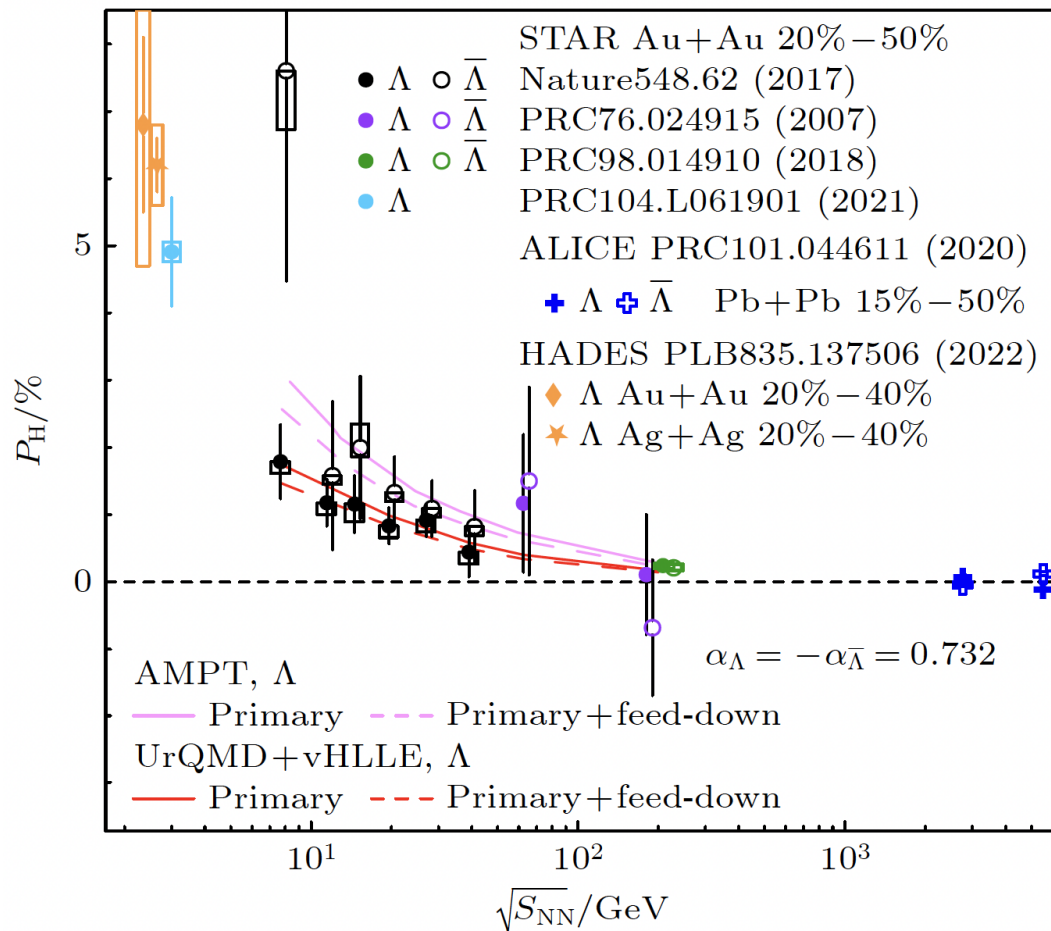


Acta Phys. Sin. Vol. 72, No. 7(2023) 072401



- 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)
- STAR, P_H at 19.6 and 27 GeV BES-II
PRC 108, 014910 (2023)

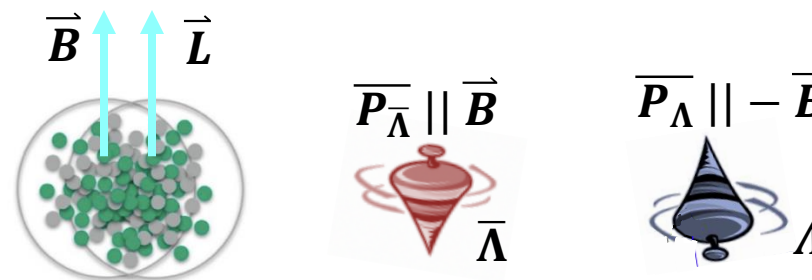
Acta Phys. Sin. Vol. 72, No. 7(2023) 072401



Significant collision energy dependence, described well by various theoretical models

- Liang and Wang, PRL 94,102301(2005),
- Gao, Chen, Deng, Liang, QW, 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
- Huang, Liao, QW, Xia, Lect. Notes Phys. 987, 281 (2021).
- Becattini, Rept. Prog. Phys. 85, No.12, 122301 (2022)
- QW, Liang, Ma (editors), ActaPhys. Sin. 72, No. 7 & 11 (2023)
- See also: Sun-Ko et al 2019; Xie-Wang-Csernai et al 2018-2021; Ivanov et al 2017-2019; Liao et al 2018- 2021; Deng-Huang-Ma 2021; Fu et al 2021; Pu et al 2022;

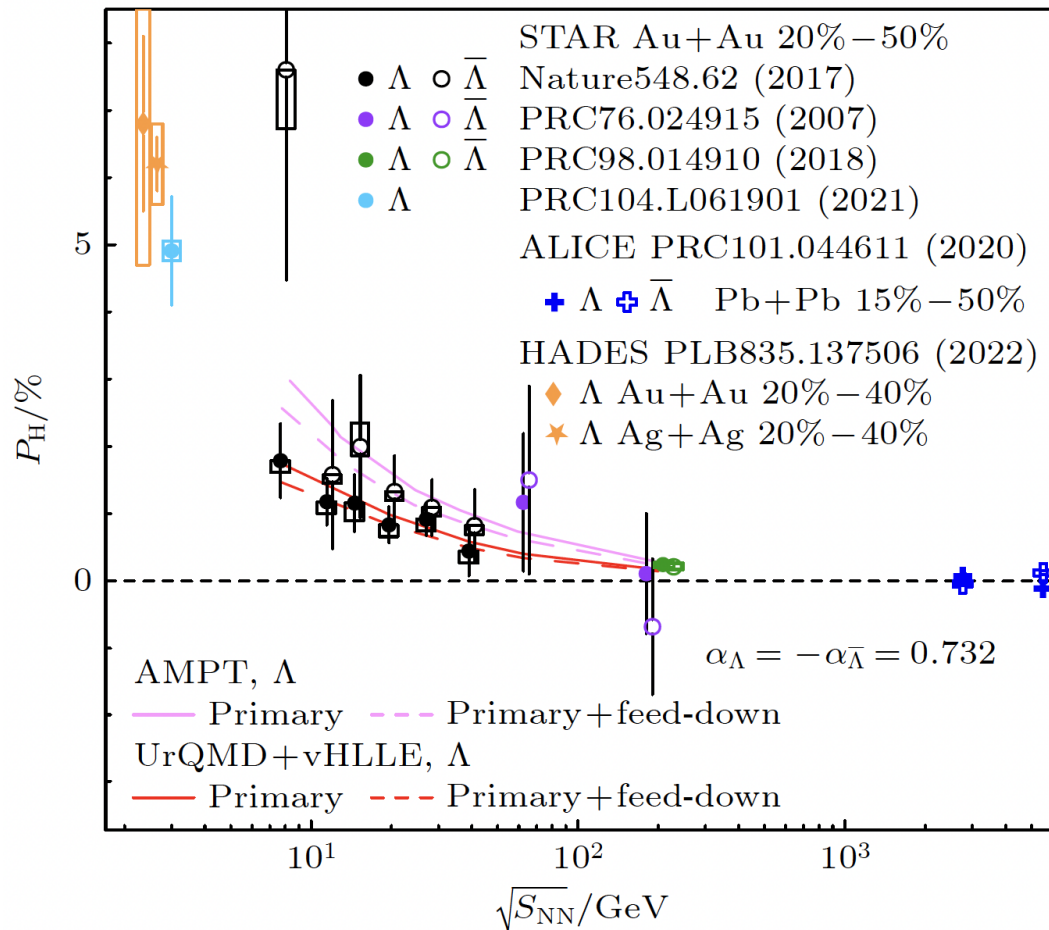
Possible difference between Λ and $\bar{\Lambda}$



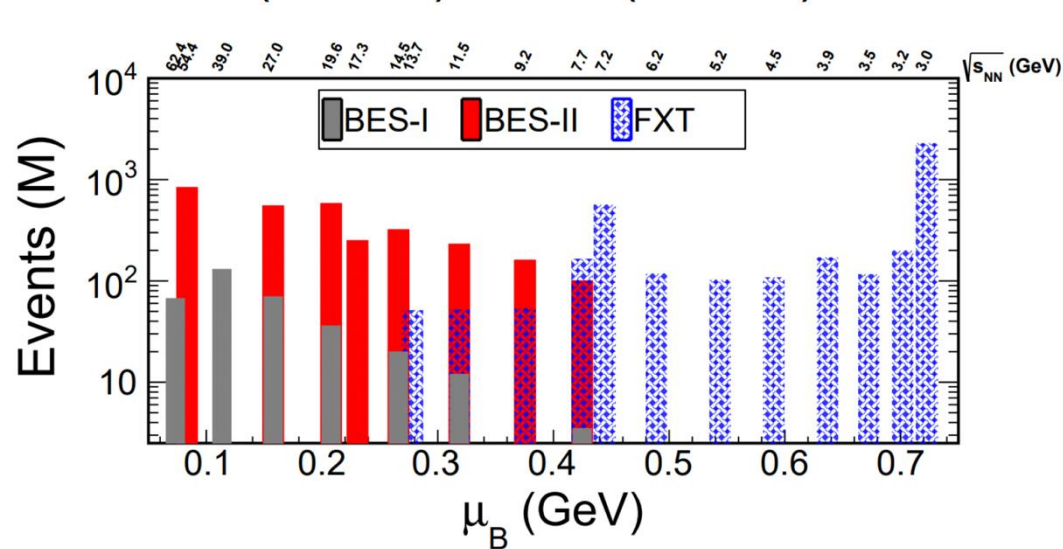
Energy dependence of Λ global polarization



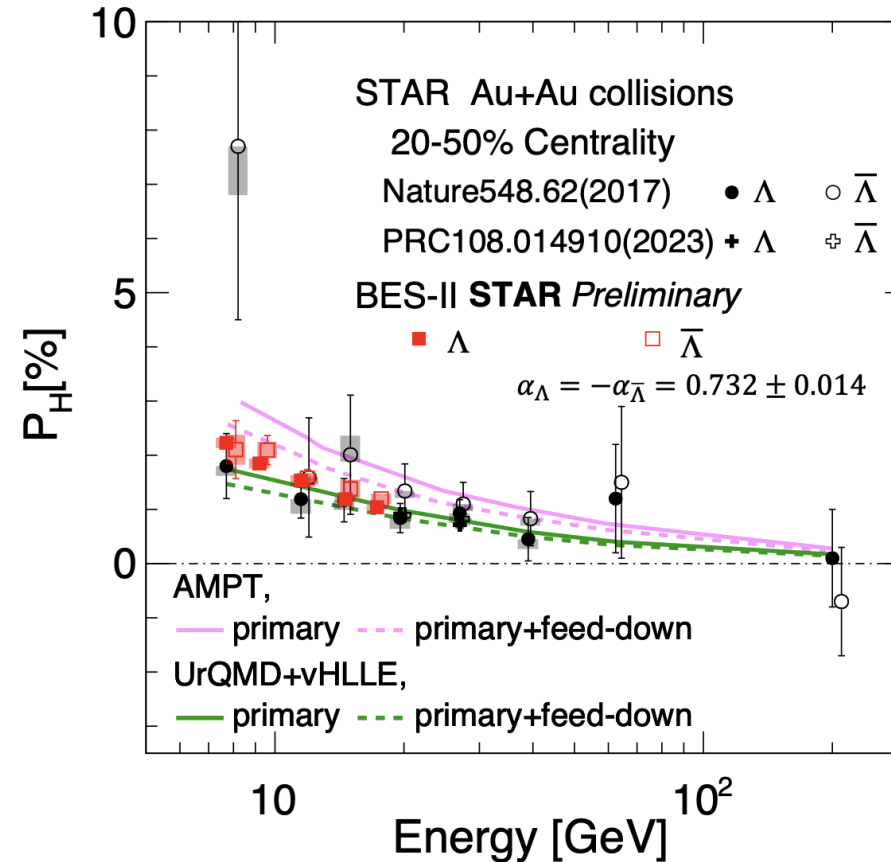
Acta Phys. Sin. Vol. 72, No. 7(2023) 072401



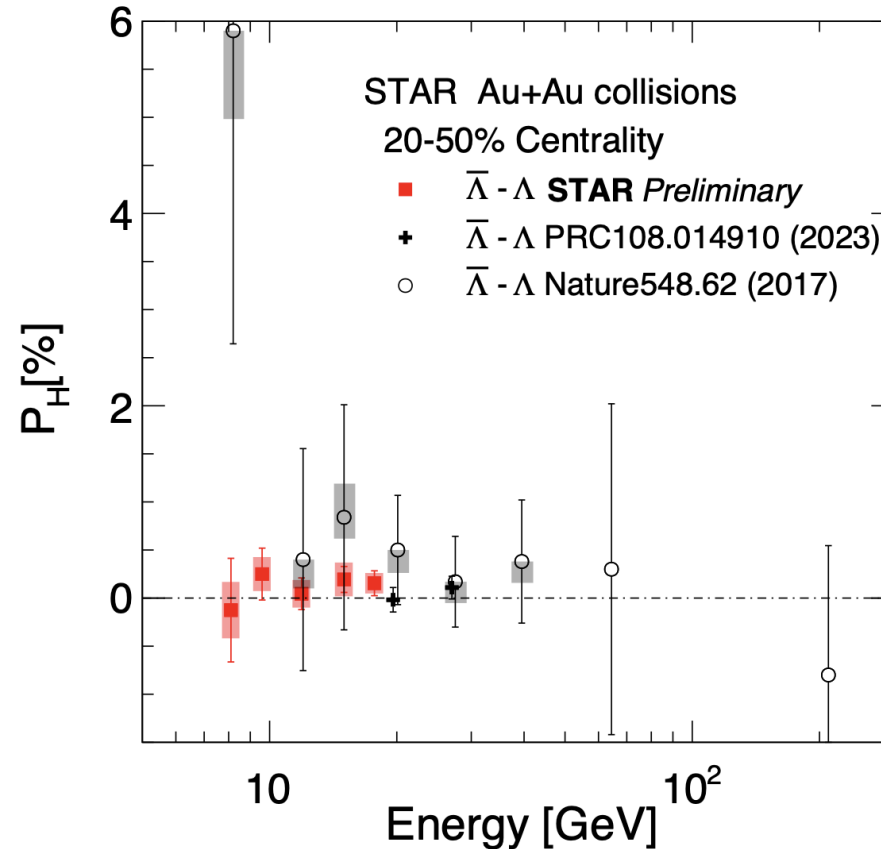
BES-I (2010-2017) and BES-II (2018-2021) statistics



- Greatly improved precision from BES-II
 - STAR, P_H at 19.6 and 27 GeV BES-II, no splitting
PRC108,014910(2023)
- More significant global polarization in lower energies
 - **STAR, new recent results**
BES-II Preliminary 7.7-17.3GeV
 Λ, Ξ^- global polarization



- ▣ 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



□ No splitting between Λ and $\bar{\Lambda}$ global polarization within uncertainties

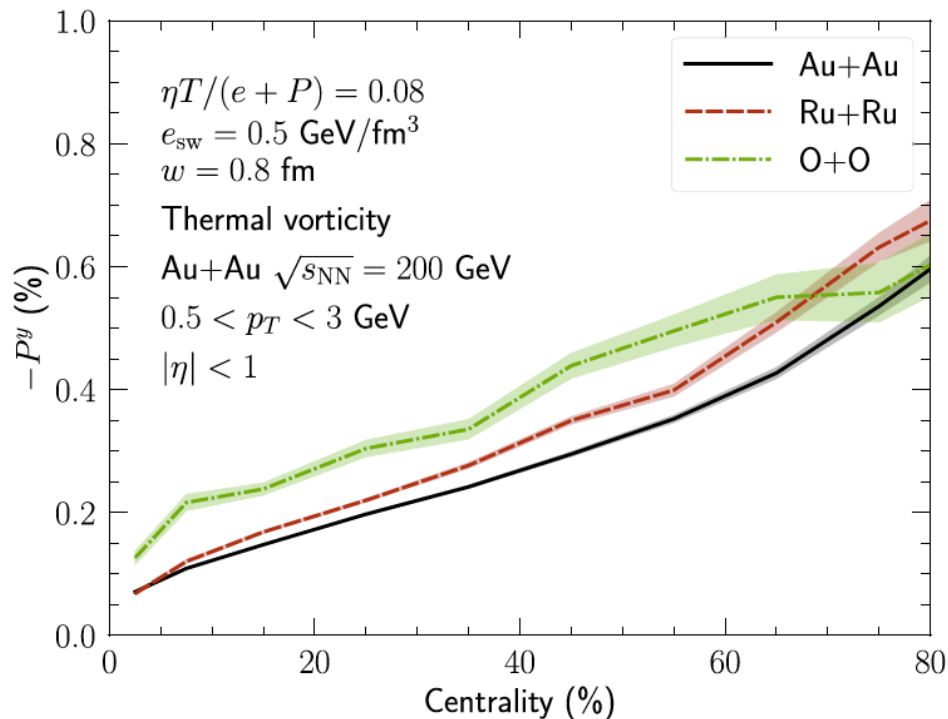
□ Upper limit on late stage magnetic field

- 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

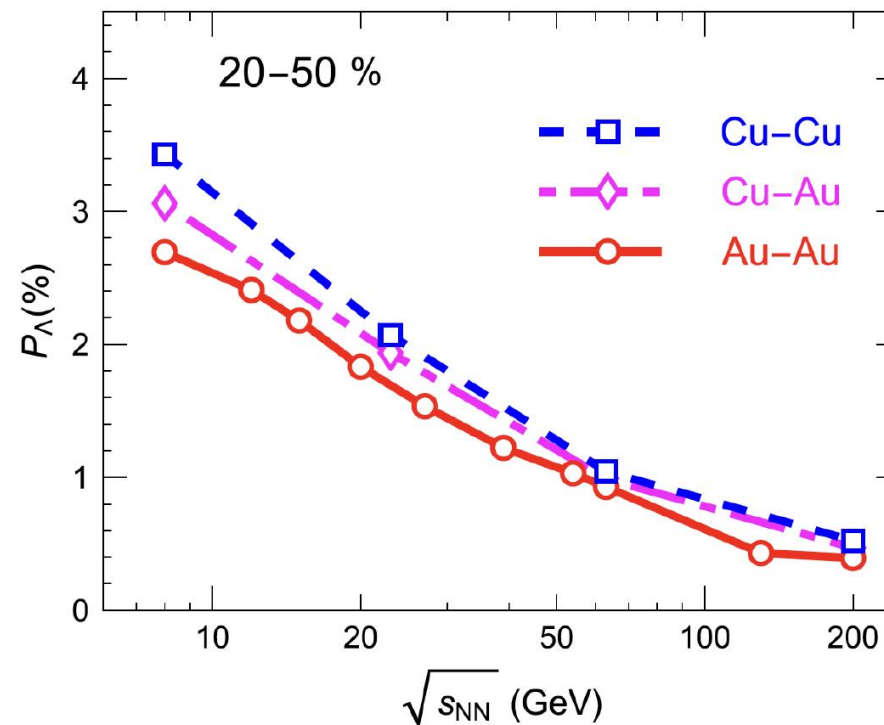
System size dependence of Λ global polarization



S. Alzhrani et al., PRC 106.014905



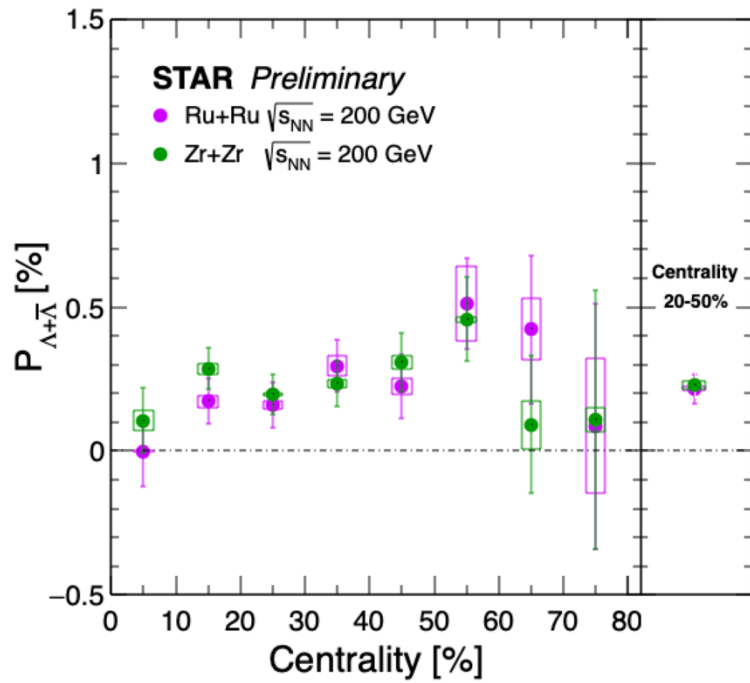
S.Z. Shi, K.L. Li, J.F. Liao, PLB 788 (2019) 409–413



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

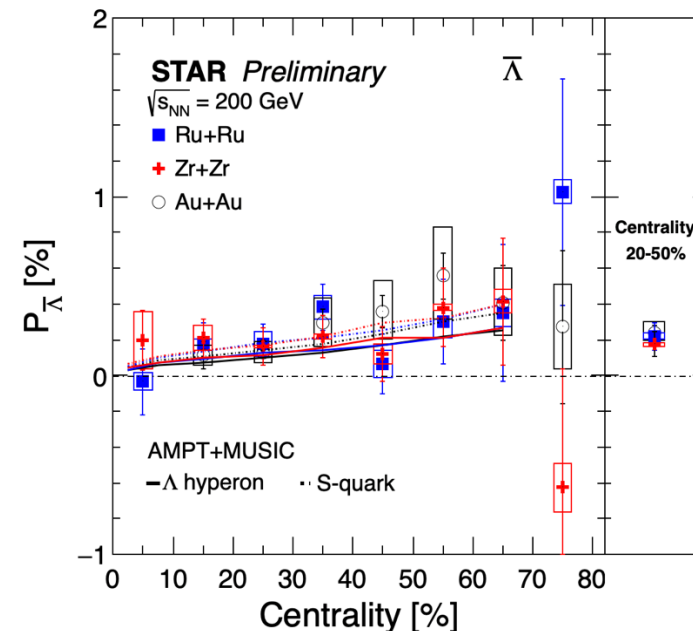
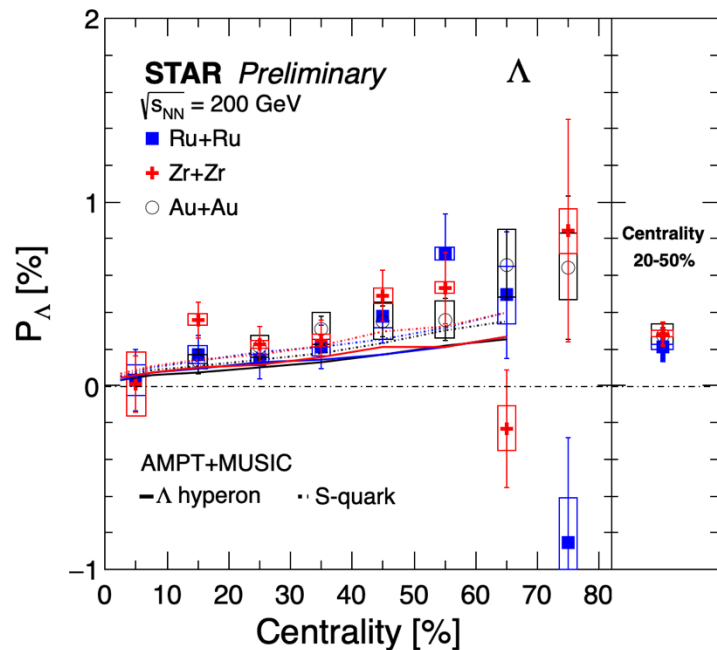
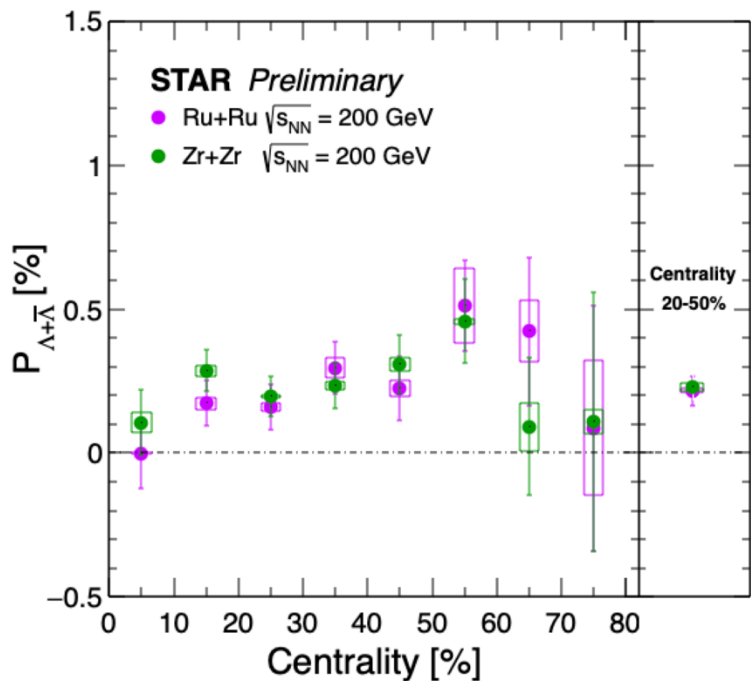


System size dependence of Λ global polarization



□ Significant global polarization observed in isobar collisions, P_{Λ} and $P_{\bar{\Lambda}}$ increase with centrality

System size dependence of Λ global polarization



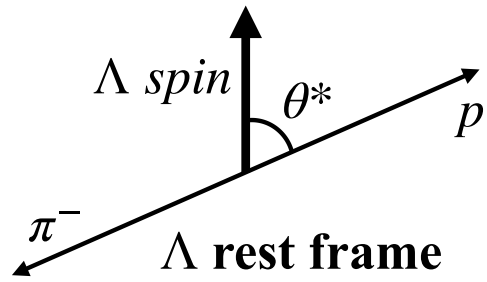
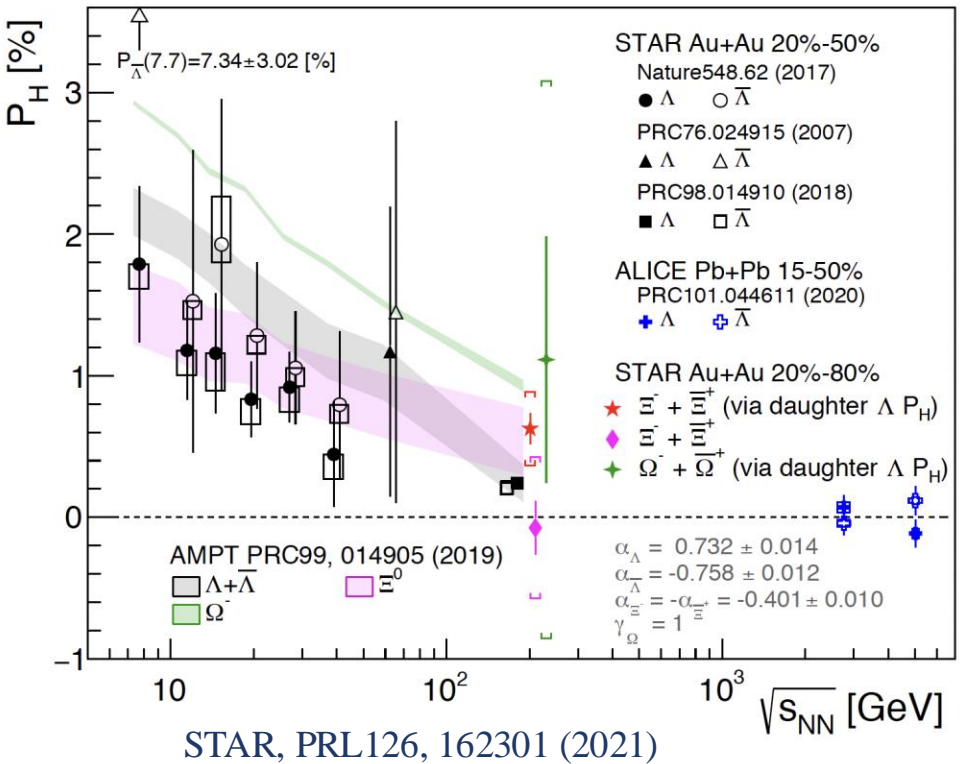
Model results from arXiv:2201.12970v1

- 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 larger Xi global polarization than Lambda due to earlier production and vorticity evolution

- Via daughter Lambda angle distribution in Xi rest frame
- Via daughter Lambda polarization with spin transfer factor ($C_{\Xi^- \rightarrow \Lambda} = 0.944$)



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

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

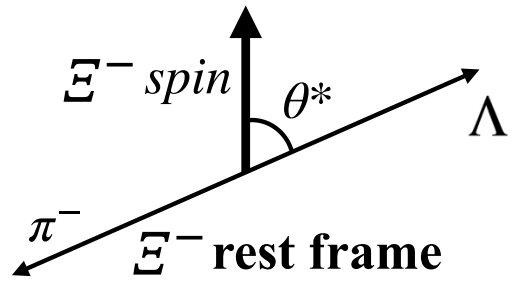
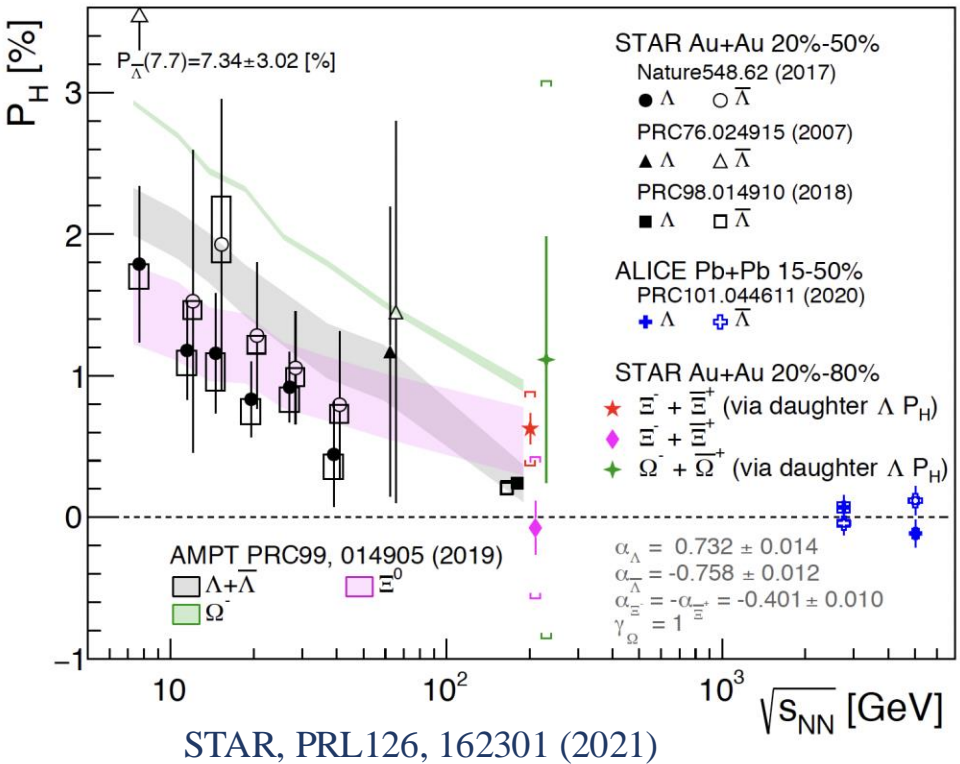
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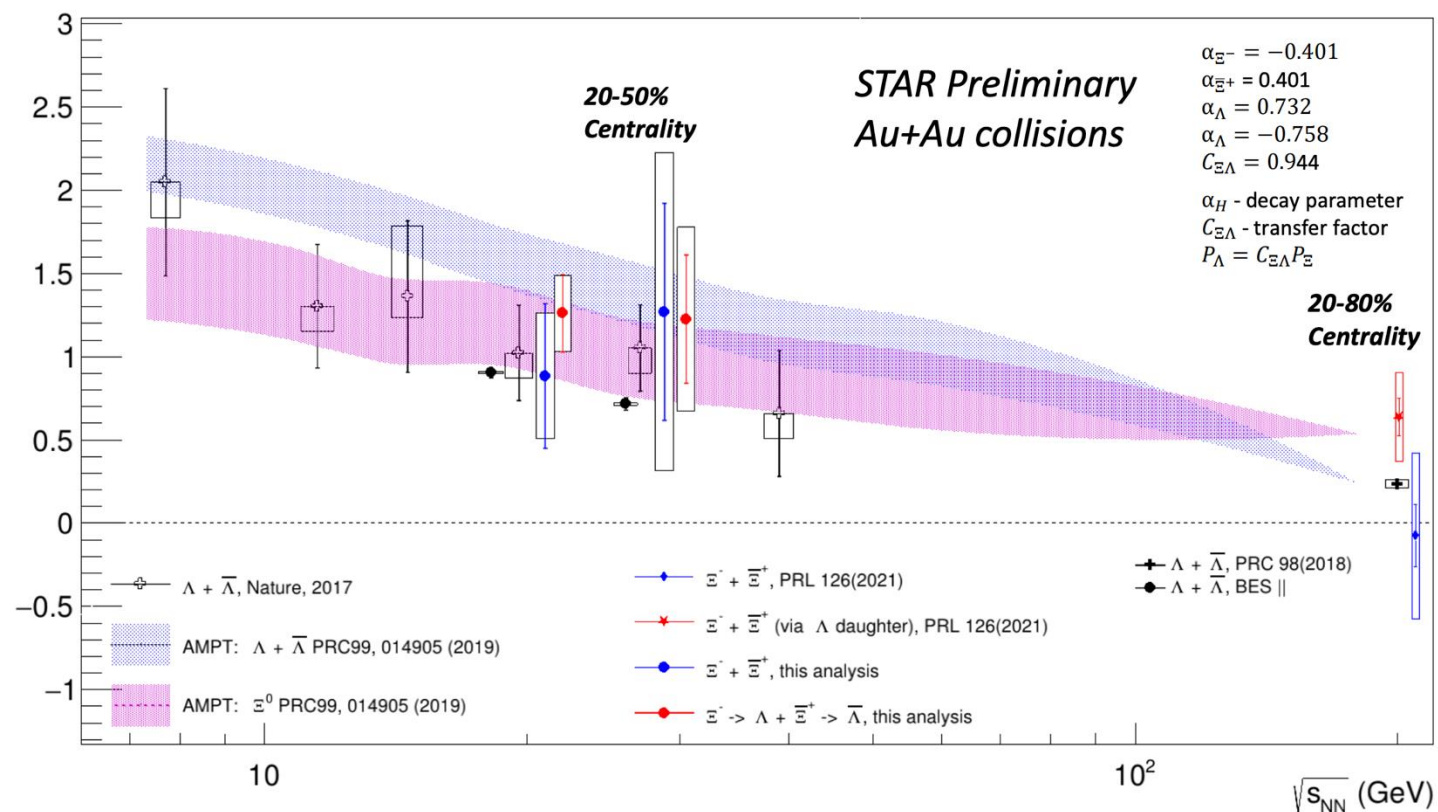
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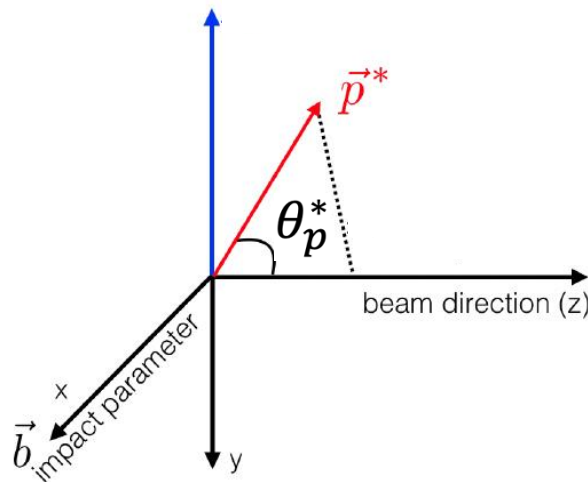
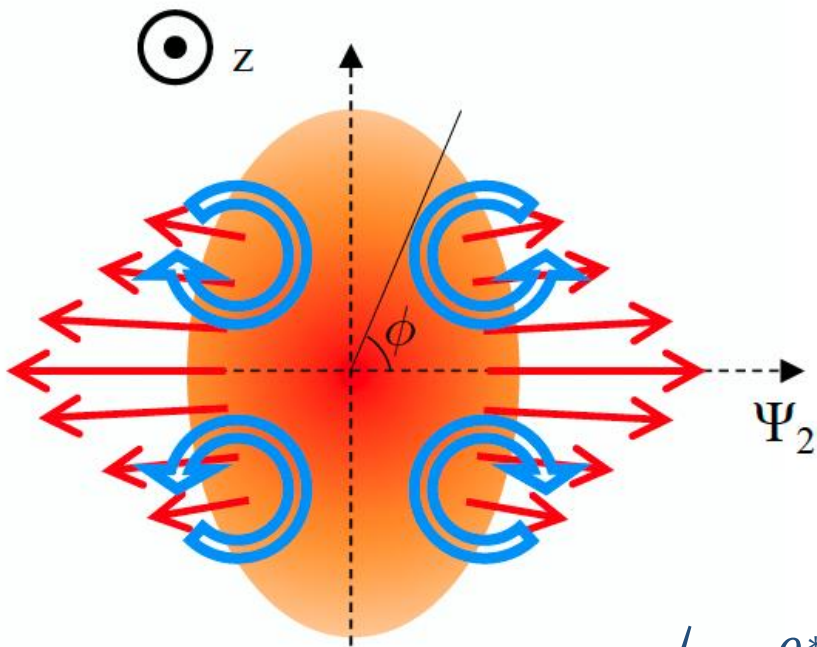
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PDG2021

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



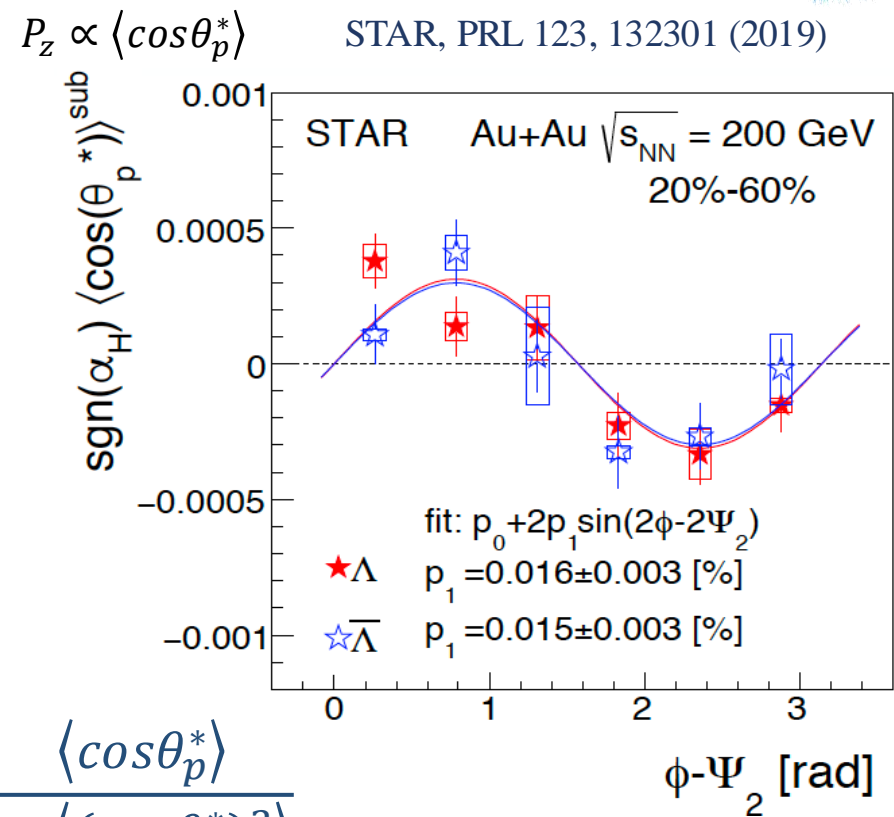
- Significant $\Xi^- + \bar{\Xi}^+$ global polarization observed in Au+Au at 19.6 and 27 GeV
- $\Xi^- + \bar{\Xi}^+$ global polarization measurement at lower BES-II energies underway



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

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

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



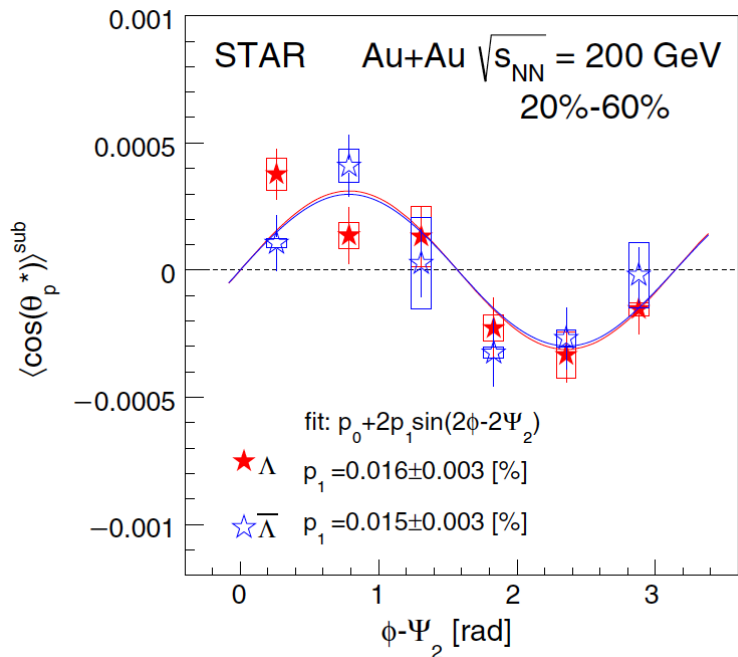
□ Elliptic flow indicates stronger expansion in-plane than out of plane

➡ Lead to polarization along the beam direction (P_z)

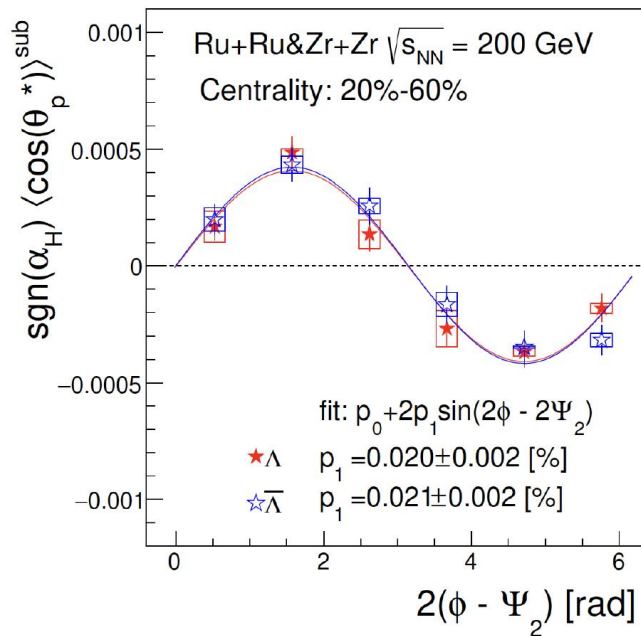
Azimuthal angle dependence of P_z



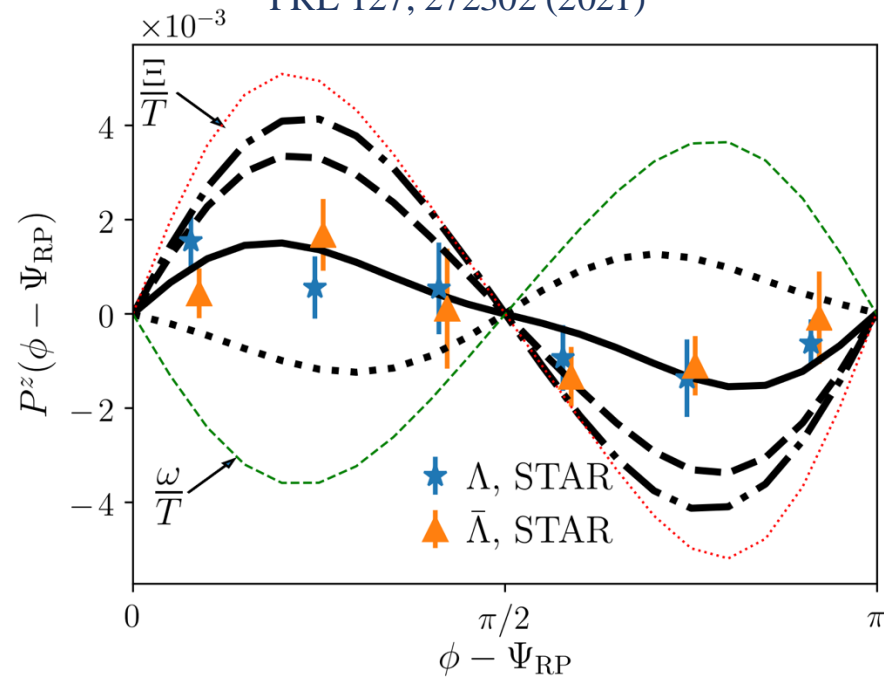
STAR, PRL 123, 132301 (2019)



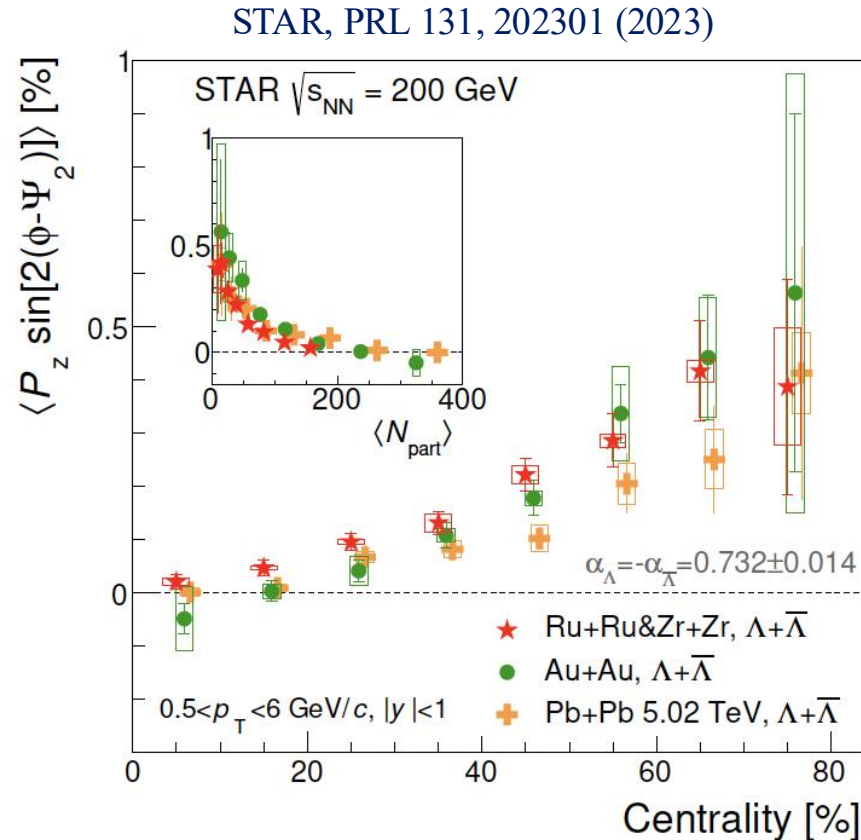
STAR, PRL 131, 202301 (2023)



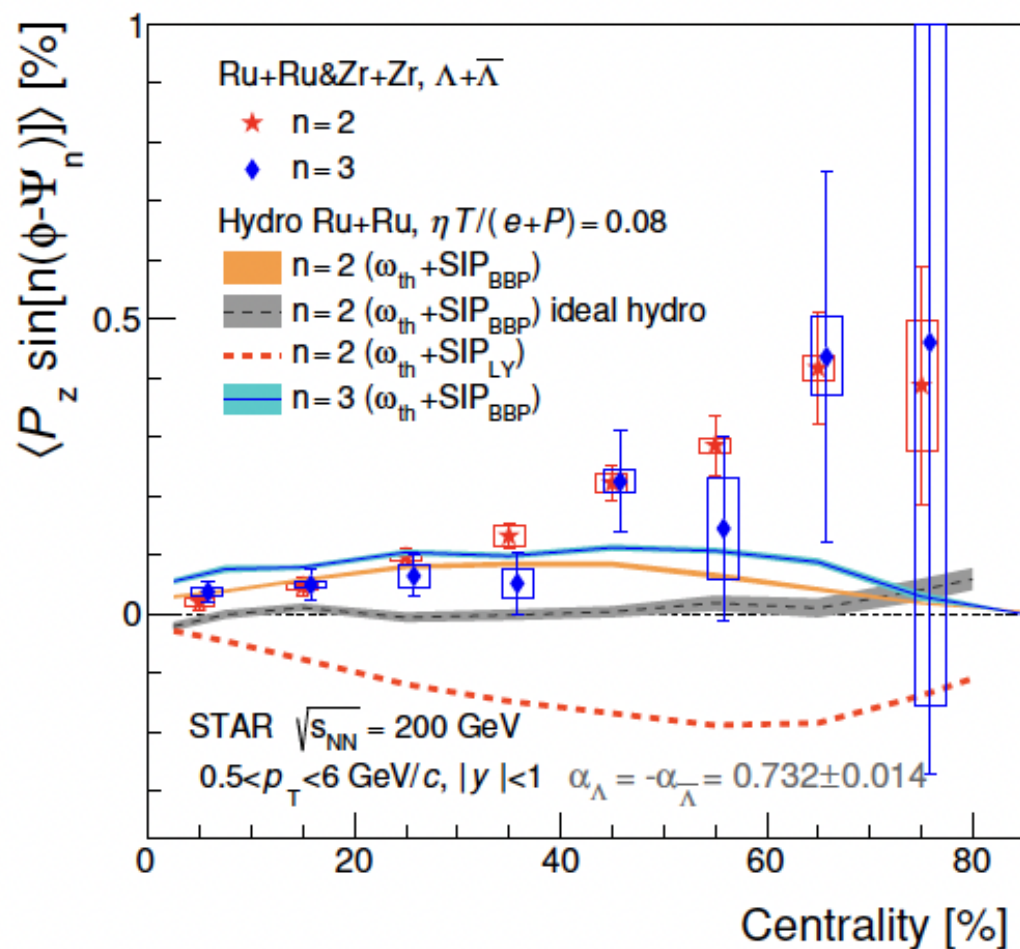
PRL 127, 272302 (2021)



- Clear azimuthal angle dependence observed in Au+Au and isobar collisions at 200 GeV
- New developments, Shear Induced Polarization(SIP), can describe trend of data



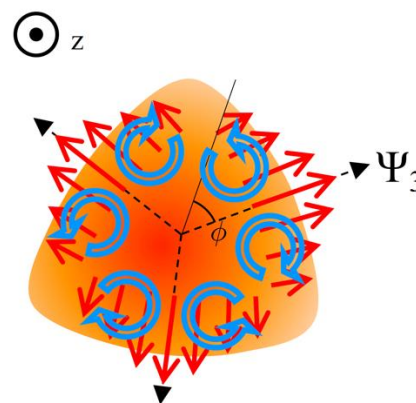
- P_Z from isobar collision comparable to Au+Au and Pb+Pb
 - ✓ No significant system size dependence observed at same energy

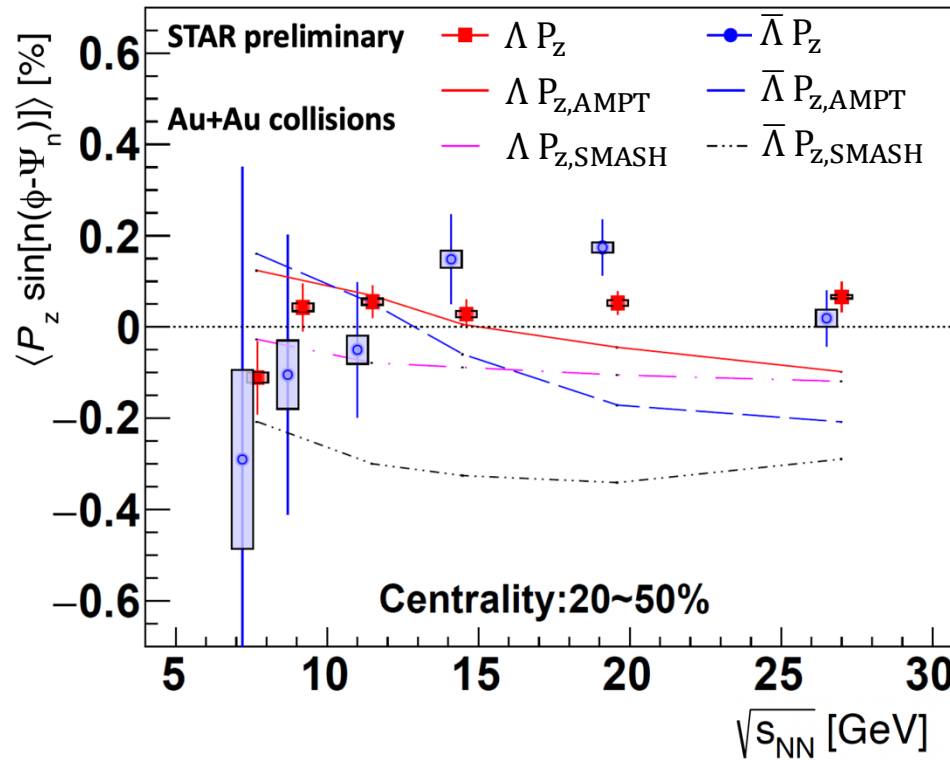


STAR, PRL 131, 202301 (2023)

- Significant P_z w.r.t third-order event plane observed, 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. Alzhvani et al., PRC 106.014905





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

- P_z in Au+Au collisions comparable from 7.7 to 200 GeV, Pb+Pb collision at 5.02 TeV
 - ✓ No significant collision energy dependence observed, hints of sign change at 7.7 GeV
 - $0.098 \pm 0.014(stat.)^{+0.019}_{+0.018}(syst.)$ in Au+Au 200 GeV STAR, PRL 123, 132301 (2019)
 - $0.082 \pm 0.011(stat.) \pm 0.014(syst.)$ in Pb+Pb 5.02 TeV ALICE, PRL128, 172005 (2022)

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 ${}^{96}_{44}\text{Ru} + {}^{96}_{44}\text{Ru}$, ${}^{96}_{40}\text{Zr} + {}^{96}_{40}\text{Zr}$ collisions at 200 GeV
- ❑ No collision system size dependence between Ru+Ru, Zr+Zr and Au+Au collisions at 200 GeV
- ❑ Significant $\Xi^- + \bar{\Xi}^+$ global polarization observed at 19.6, 27 GeV, measurements in lower energies underway

Polarization along beam direction (P_z)

- ❑ First observation of polarization along beam direction (P_z) w.r.t third-order event plane
- ❑ No significant system size dependence of P_z observed at same energy
- ❑ No significant collision energy dependence of P_z observed

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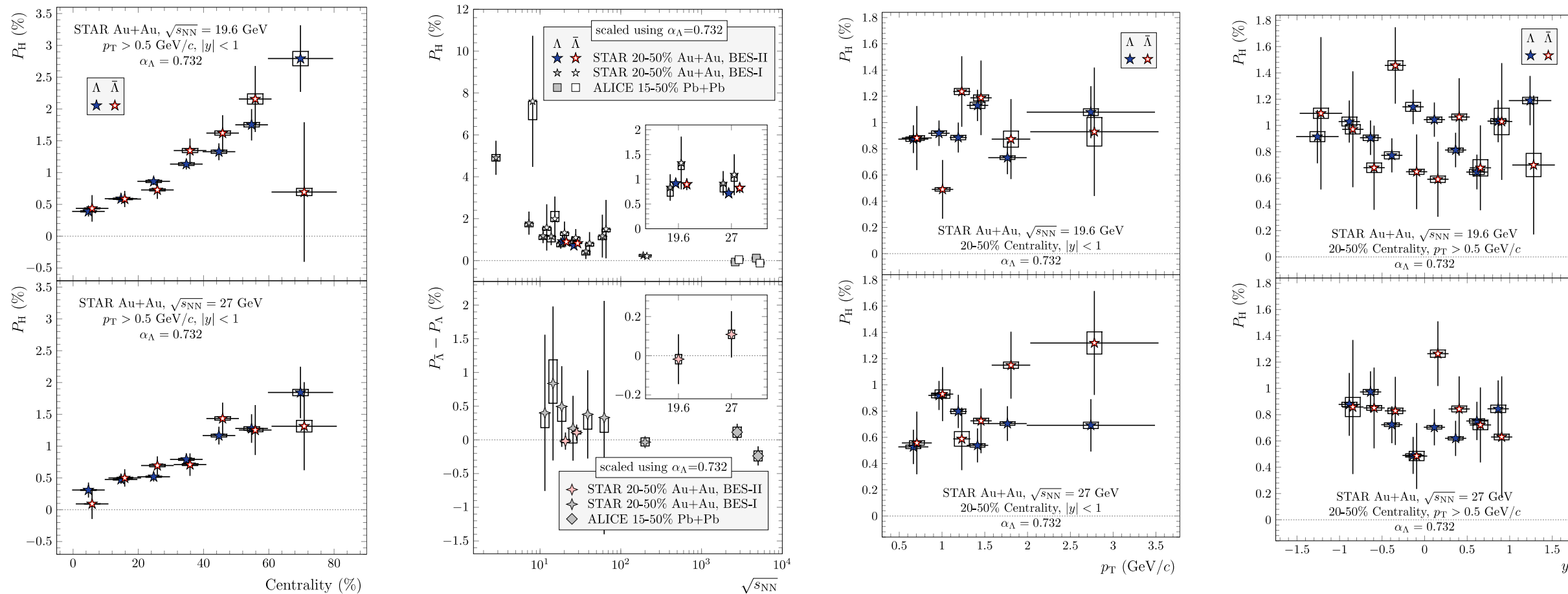
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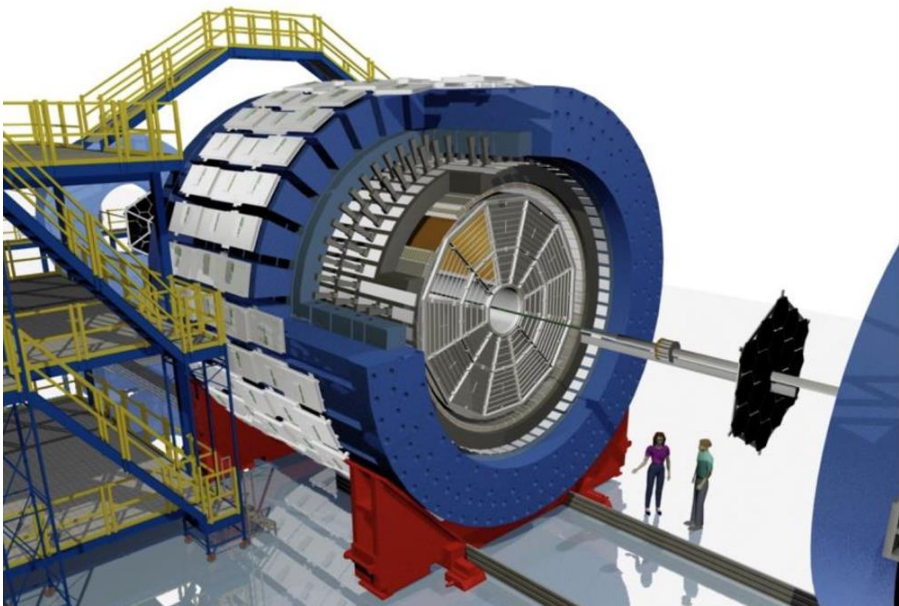
Thanks for your attention

Back Up

Global polarization collision energy dependence



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



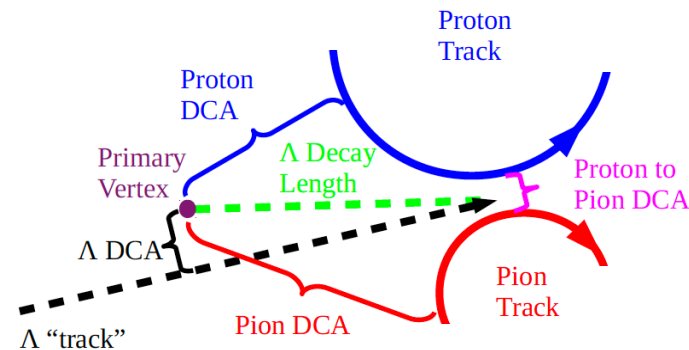
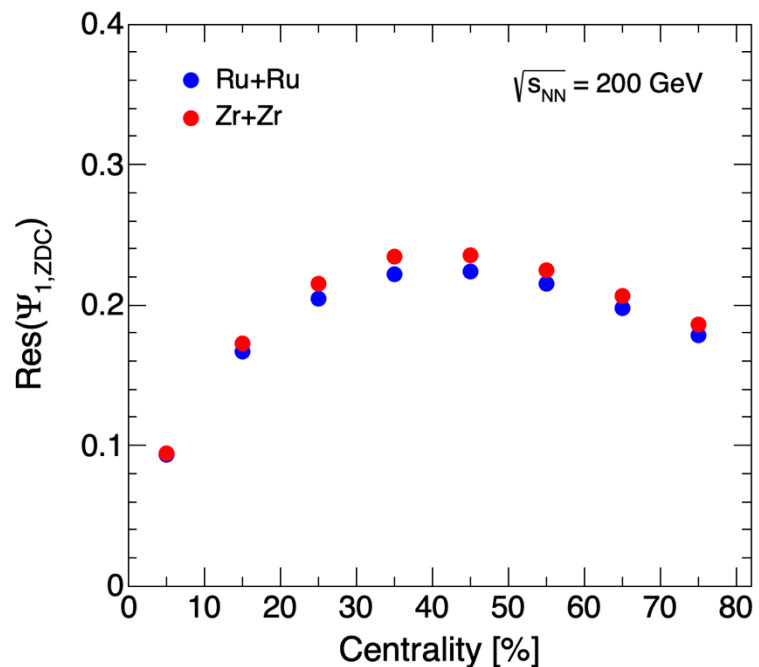
Event plane reconstruction:

Time Projection Chamber
Zero Degree Calorimeters

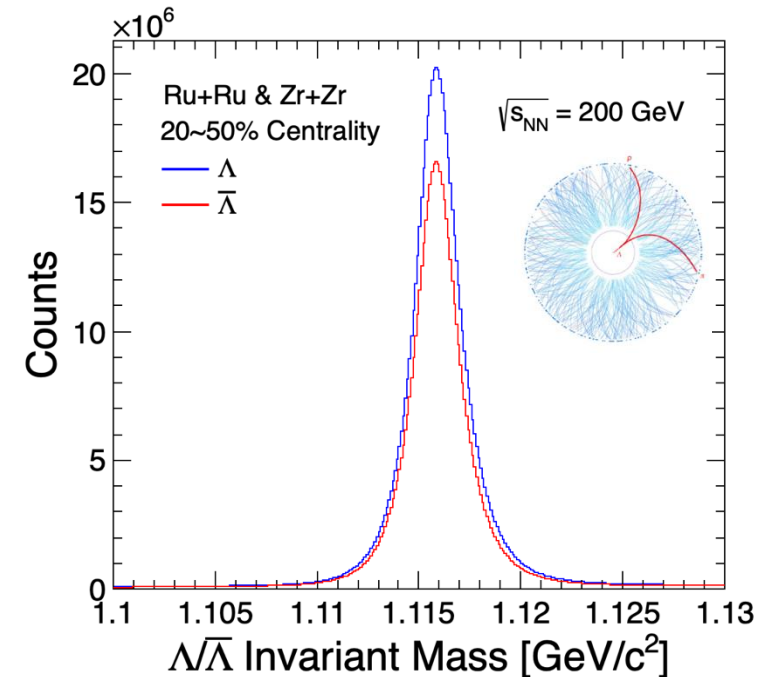
$\Lambda/\bar{\Lambda}$ reconstruction:

Time Projection Chamber
Time Of Flight

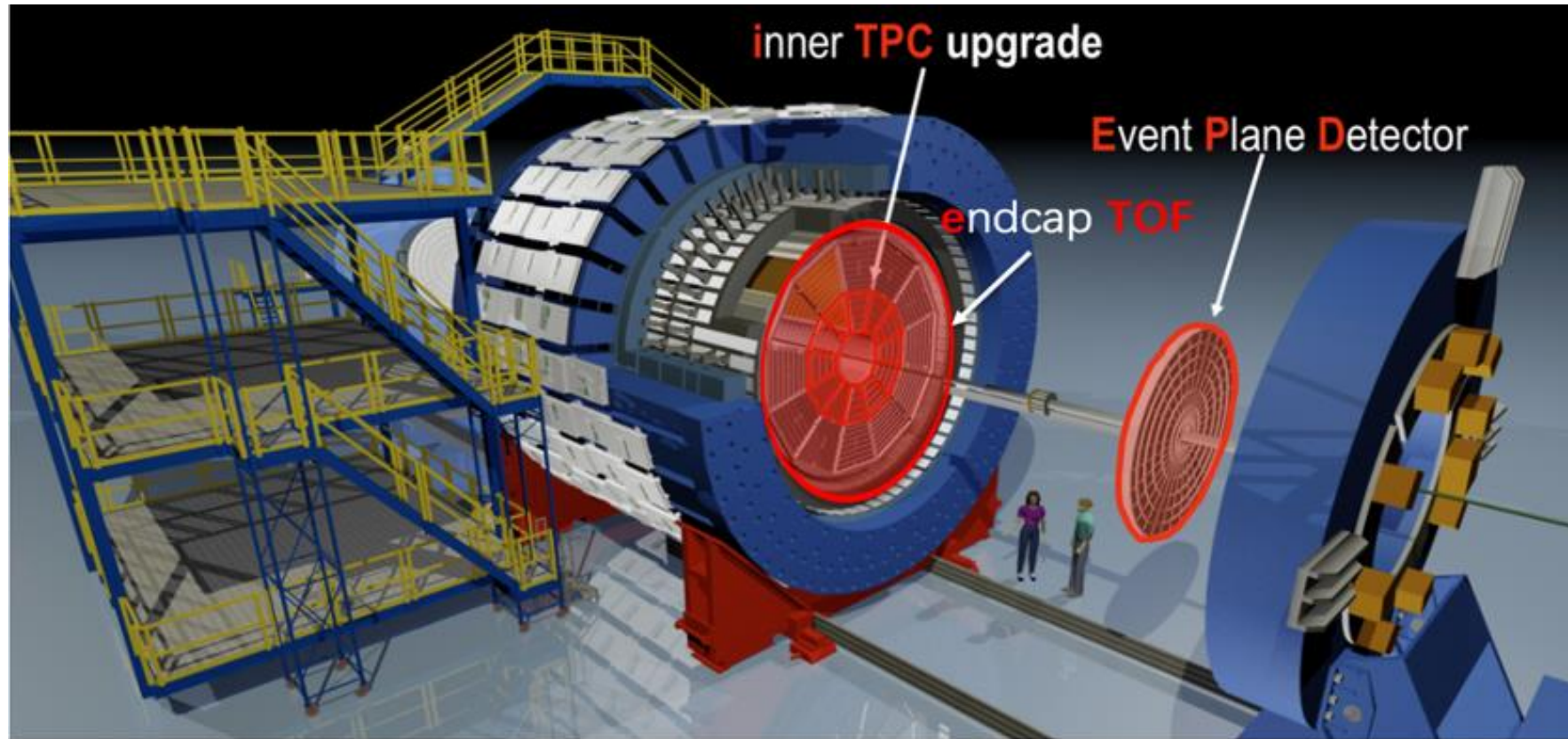
Event plane resolution



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



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

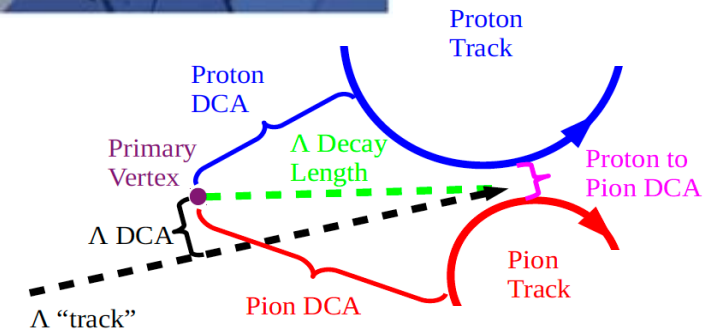


□ Event plane reconstruction:

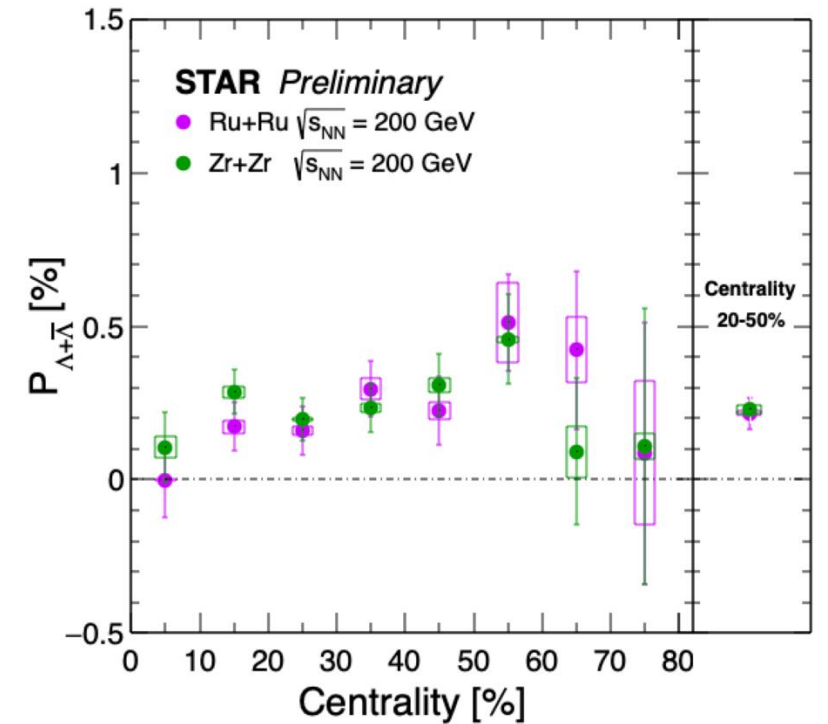
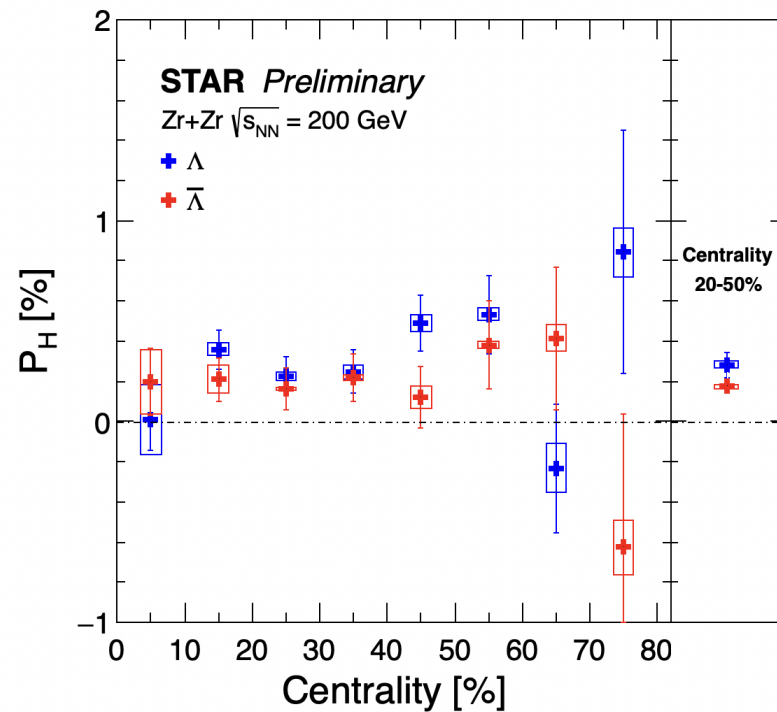
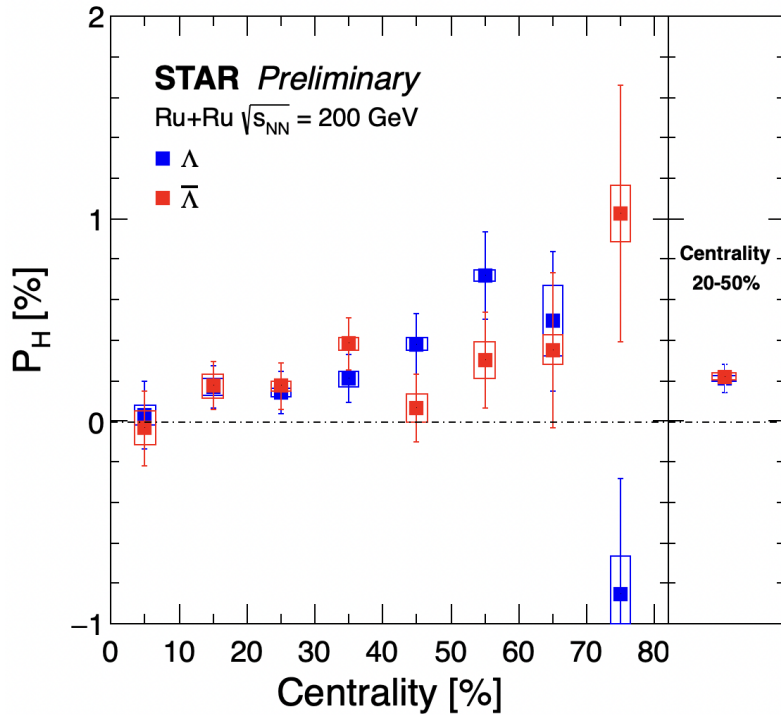
Time Projection Chamber
Event Plane Detector
Zero Degree Calorimeters

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

Time Projection Chamber
Time Of Flight

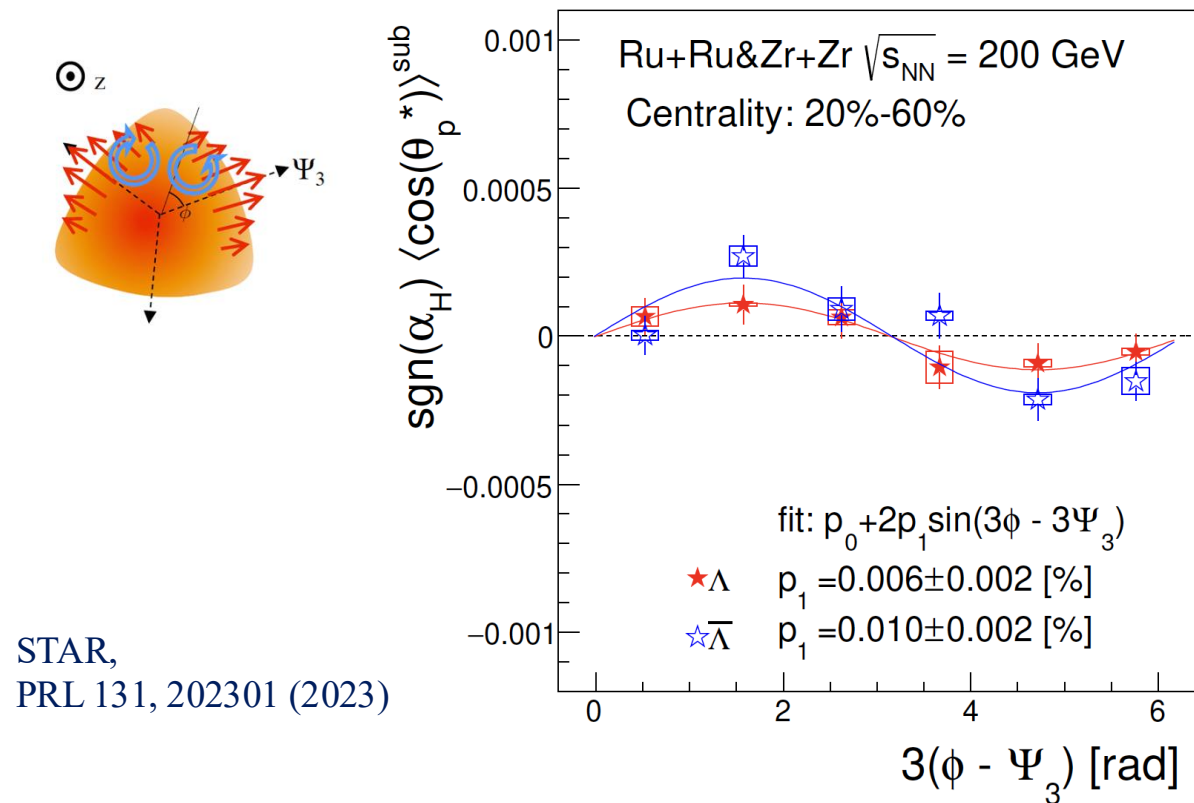
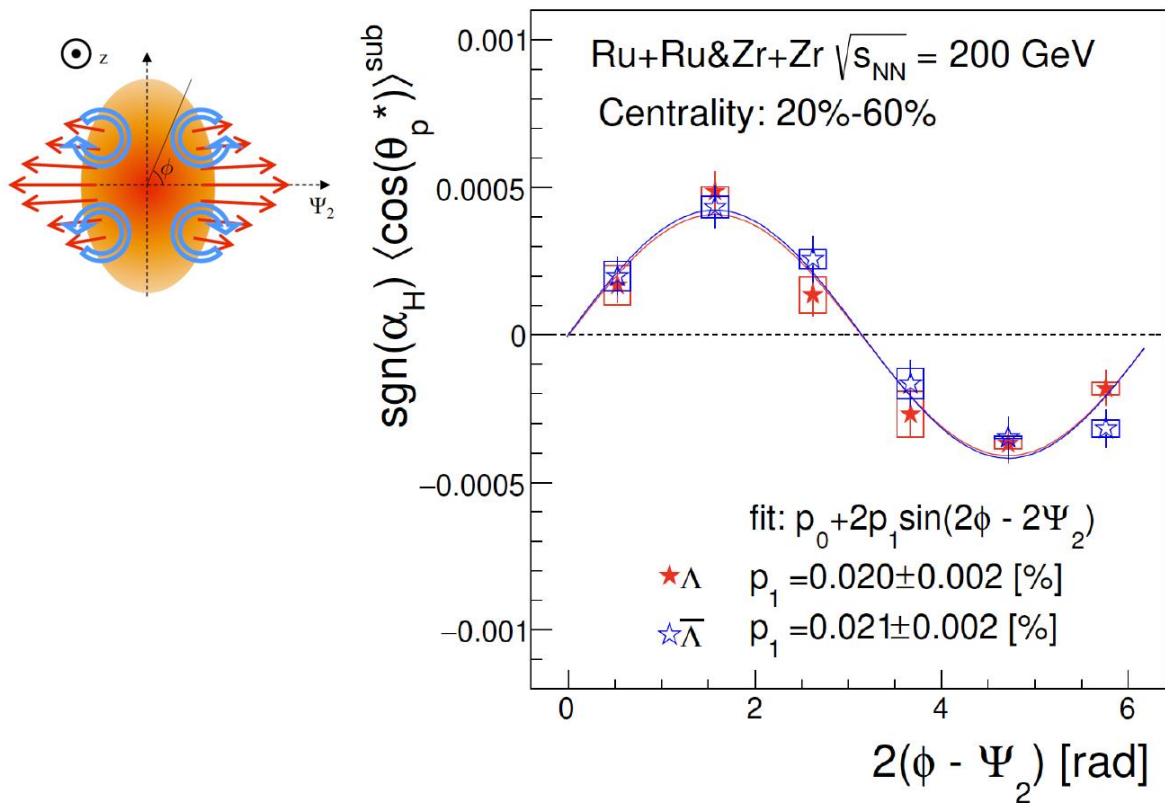


Global polarization in Ru+Ru and Zr+Zr at 200 GeV



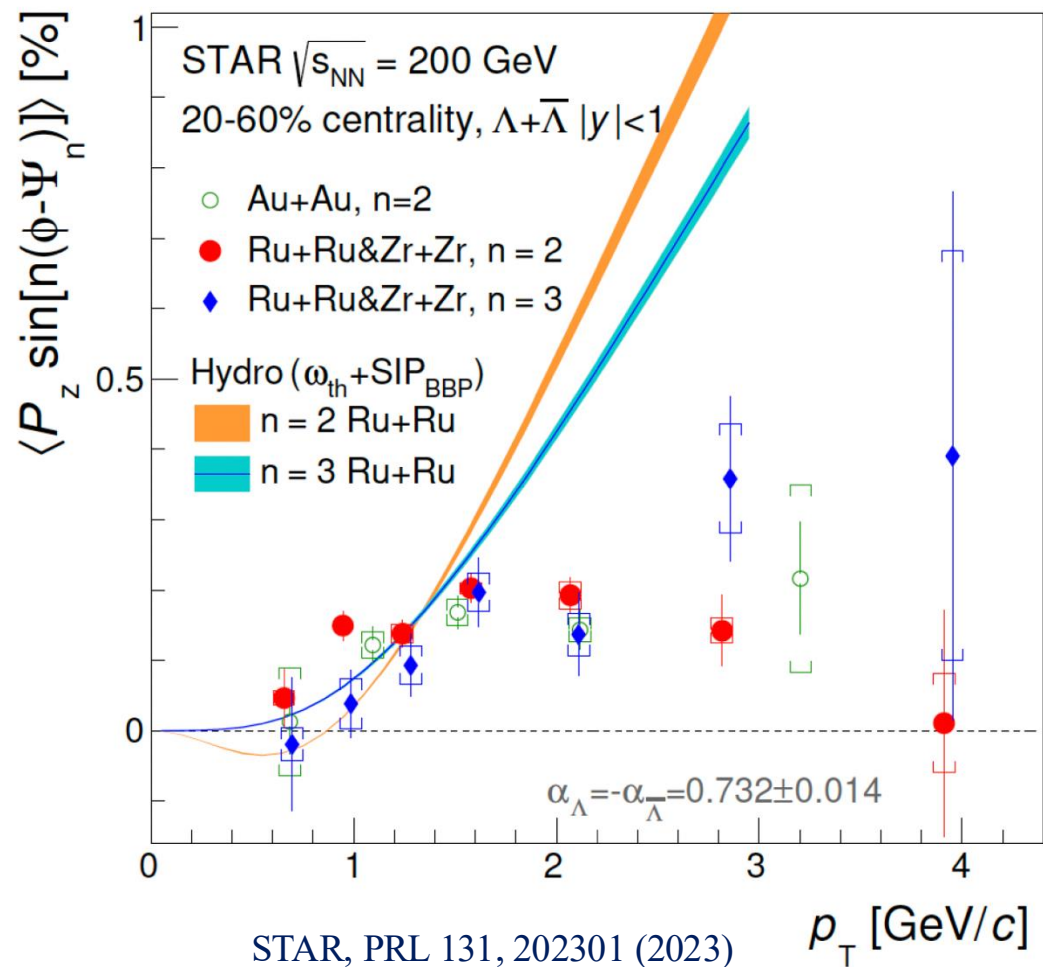
- ❑ Significant global polarization observed, P_{Λ} and $P_{\bar{\Lambda}}$ increase with centrality
- ❑ No significant difference between P_{Λ} and $P_{\bar{\Lambda}}$ in Ru+Ru and Zr+Zr collisions
- ❑ Global polarization of $\Lambda + \bar{\Lambda}$ are consistent between Ru+Ru and Zr+Zr collisions

Local polarization in Ru+Ru&Zr+Zr at 200 GeV



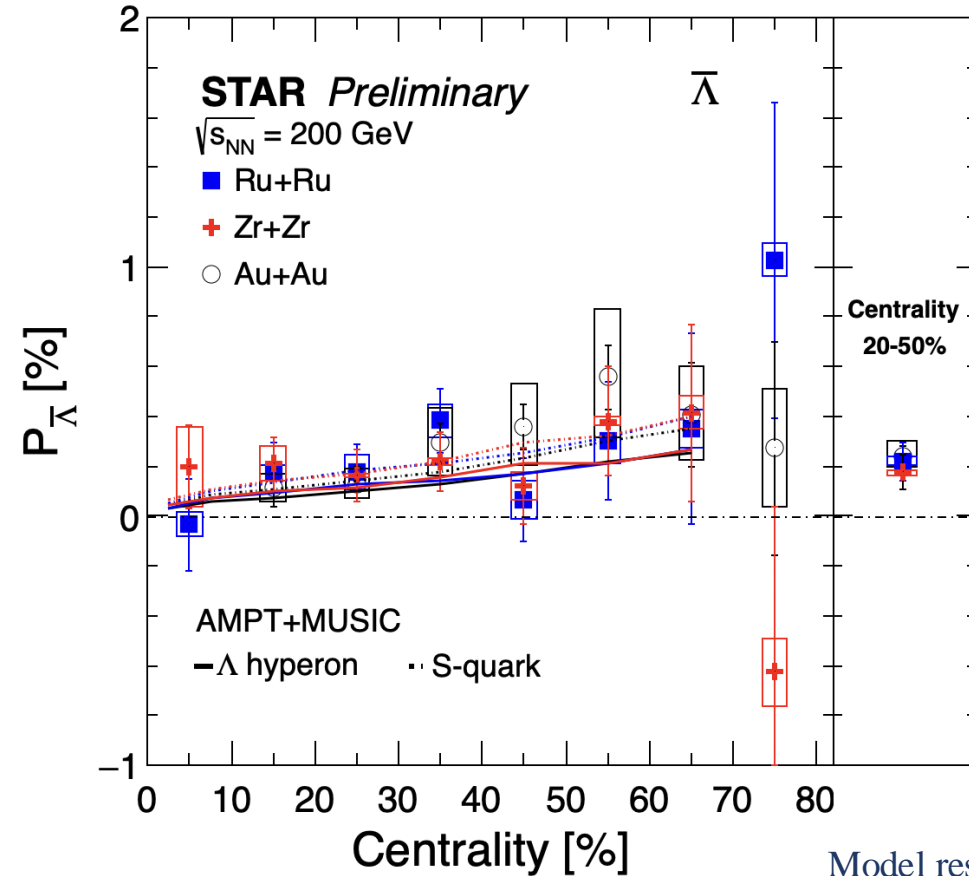
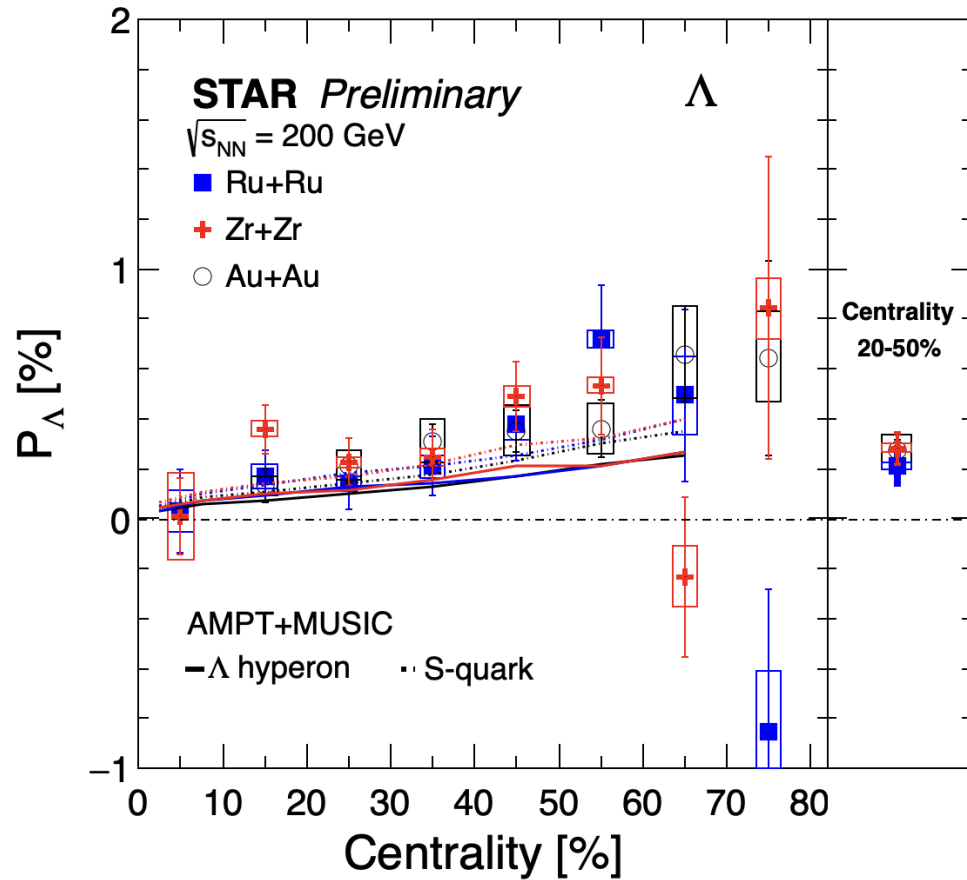
STAR,
PRL 131, 202301 (2023)

- Significant local polarization w.r.t second-order event plane observed in isobar collisions
- First observation of local polarization w.r.t the third-order event plane



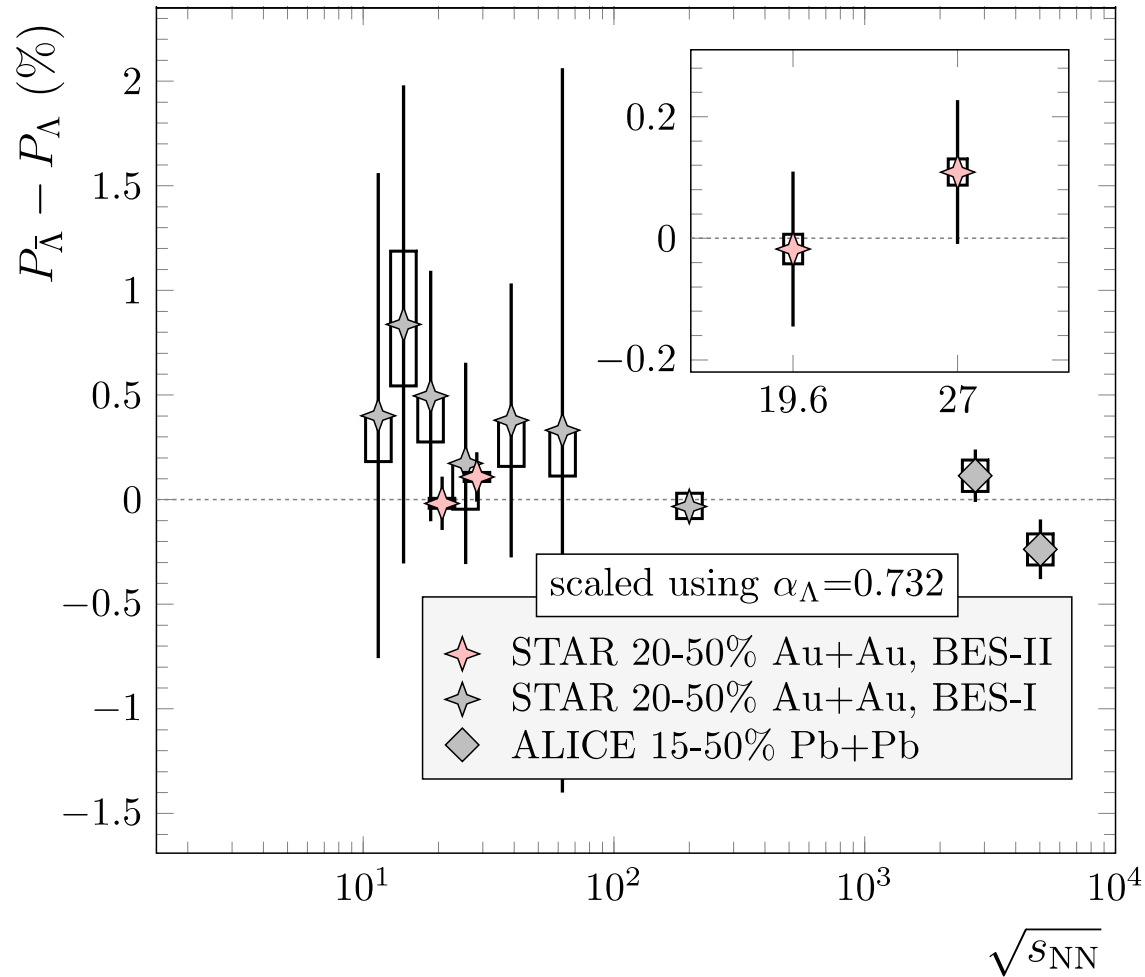
- Local polarization p_T dependence is observed
- Observed p_T dependence similar to that of elliptic (v_2) and triangular (v_3) flow
- Results are consistent between isobar and Au+Au collisions

Global polarization in Ru+Ru, Zr+Zr and Au+Au at 200 GeV



Model results from
 arXiv:2201.12970v1

□ Global polarization of Λ and $\bar{\Lambda}$ are consistent in isobar and Au+Au collision systems



□ No splitting of $\Lambda / \bar{\Lambda}$ 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

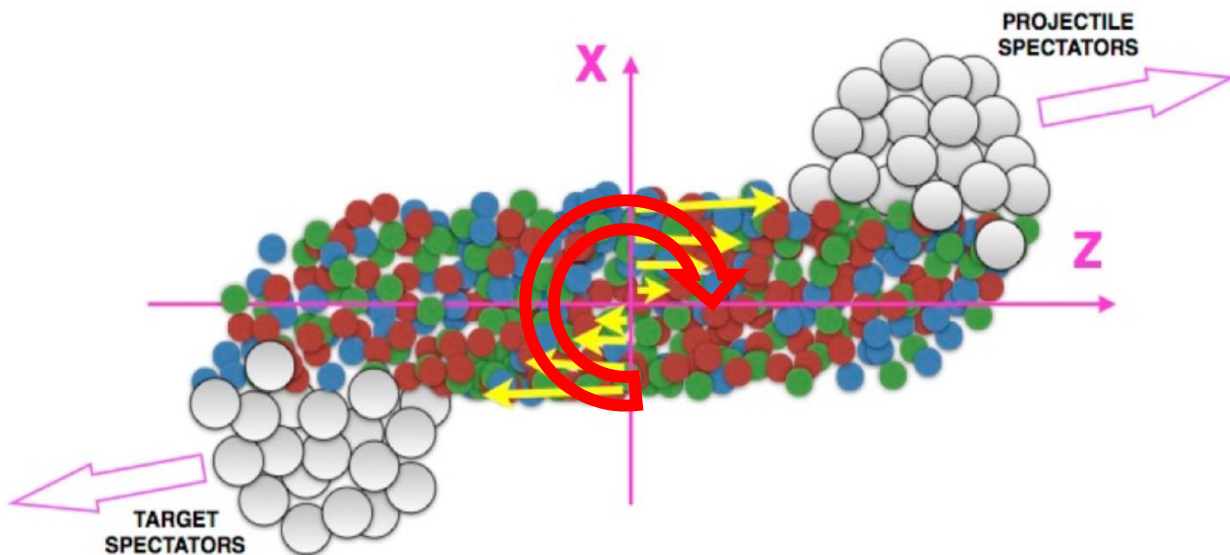
$T_s = 150$ MeV : the temperature of the emitting source

$\mu_{\Lambda} = -1.93 \times 10^{-14}$ MeV/T : the magnetic moment of the Λ hyperon

□ Upper limit on late stage magnetic field

- 95% confidence level
- $B < 9.4 \times 10^{12}$ T at 19.6 GeV
- $B < 1.4 \times 10^{13}$ T at 27 GeV

Vorticity in heavy ion collisions



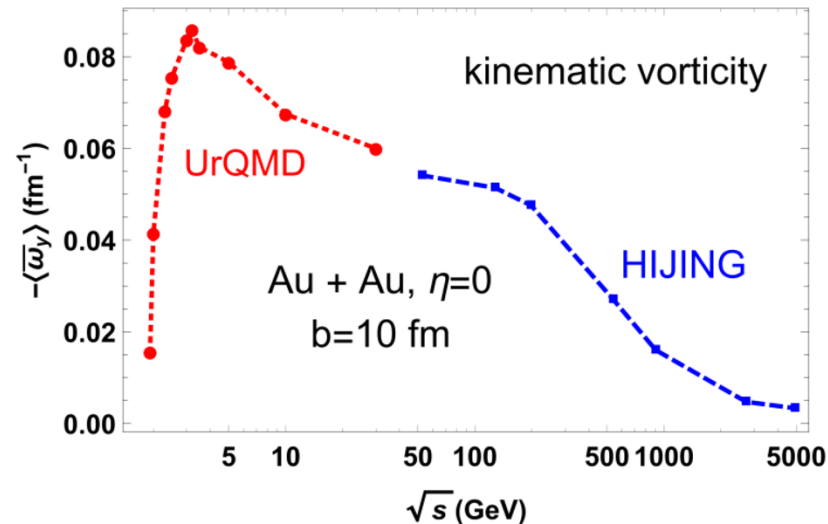
Orbital angular momentum



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)

X.-G. Deng, X.-G. Huang, et al. PRC 101, 064908



Energy dependence of initial vorticity

