Vorticity measurements from the STAR experiment at RHIC

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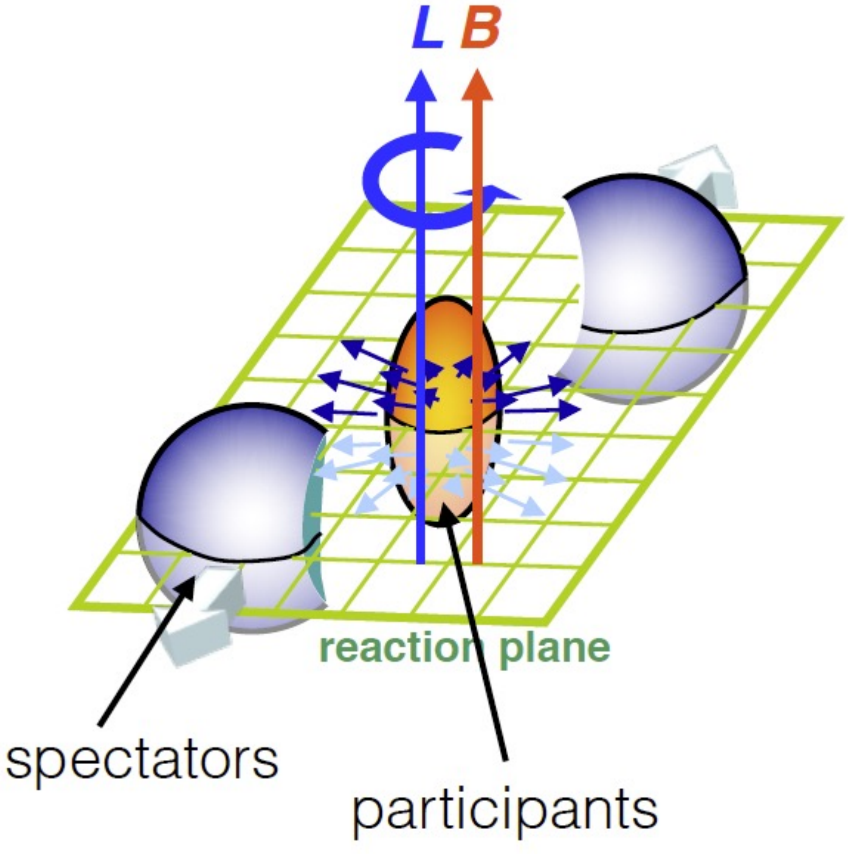
Outline

- 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/magnetic field in heavy ion collisions



Orbital angular momentum

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

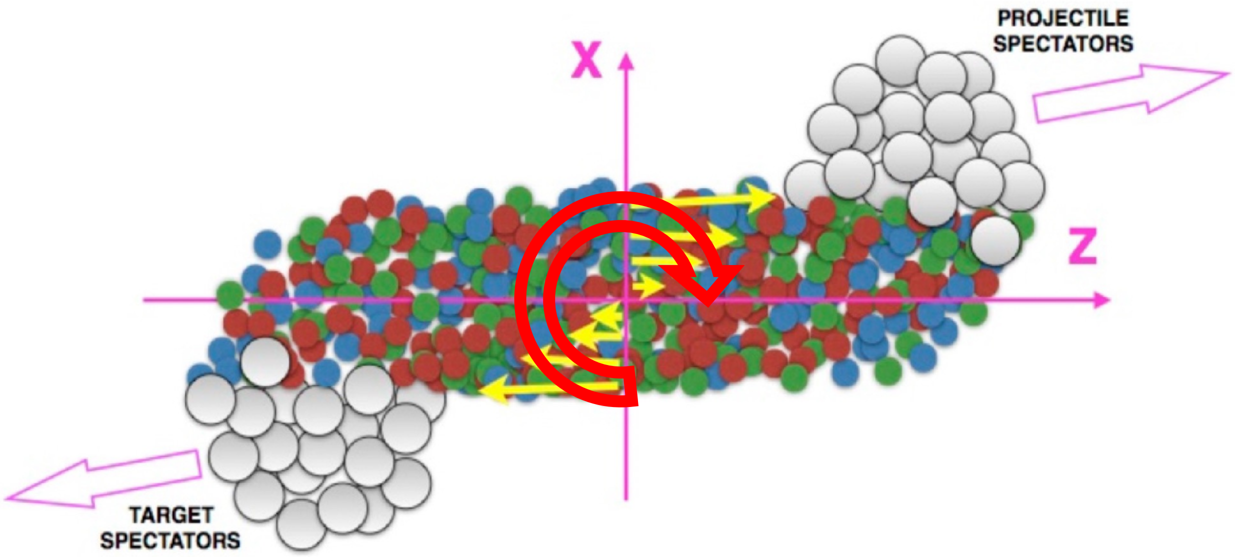
$$L \sim \frac{Ab\sqrt{s}}{2} \sim 10^{6}\hbar$$

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)

Vorticity in heavy ion collisions

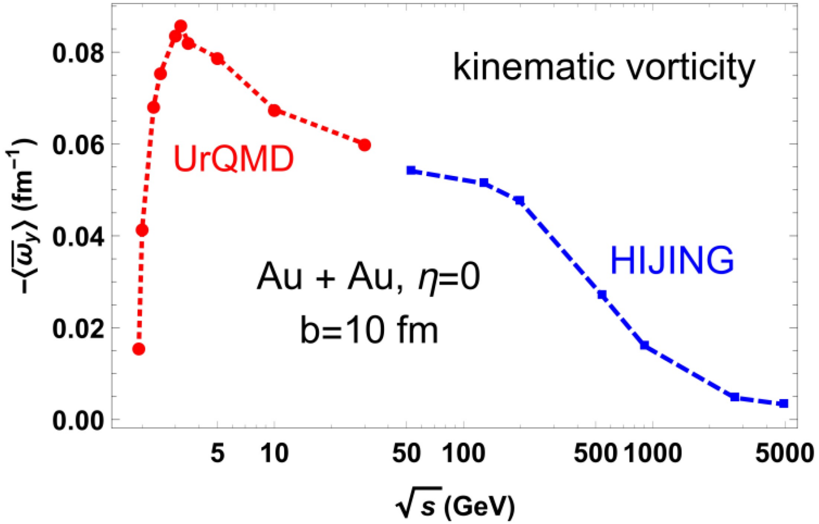


Orbital angular momentum

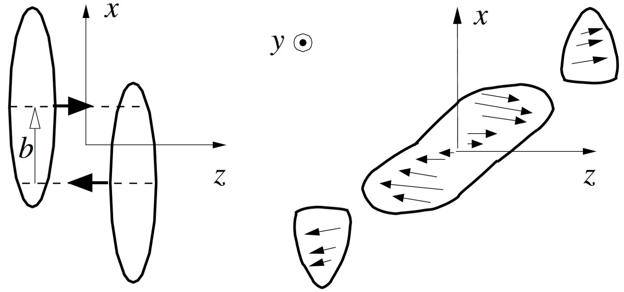
Local fluid vorticity $\omega = \frac{1}{2}\nabla\times v$

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

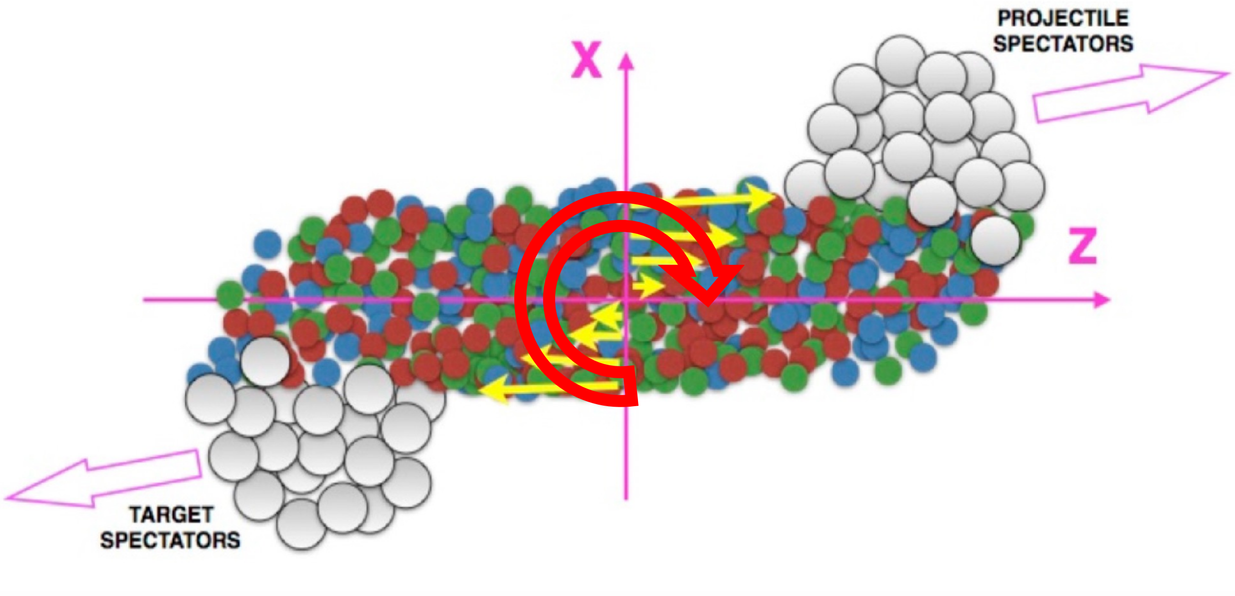
X.-G. Deng, X.-G. Huang, et al. PRC 101, 064908



Energy dependence of initial vorticity



Vorticity and polarization



Orbital angular momentum

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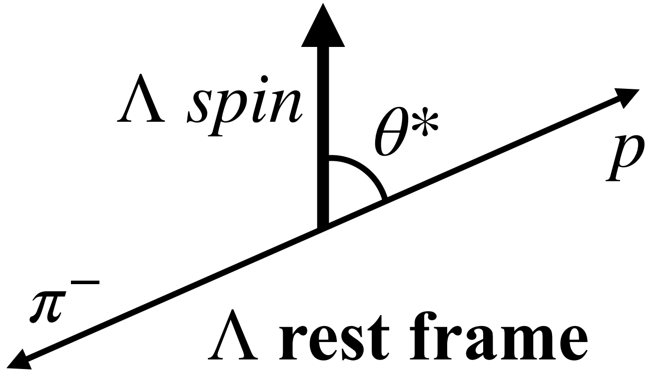
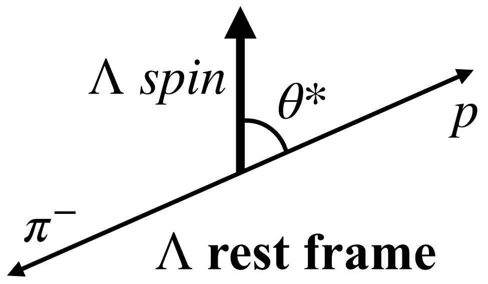


Leads to global polarization along ***L*** though spin-orbit coupling

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



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

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

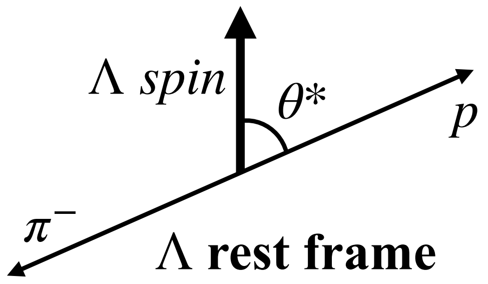
α_H : hyperon decay parameter
P_H : hyperon polarization
θ^* : polarization angle

Hyperon	Deacy mode	α_H	Spin
Λ(uds)	$\Lambda \rightarrow p + \pi^-$	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

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.

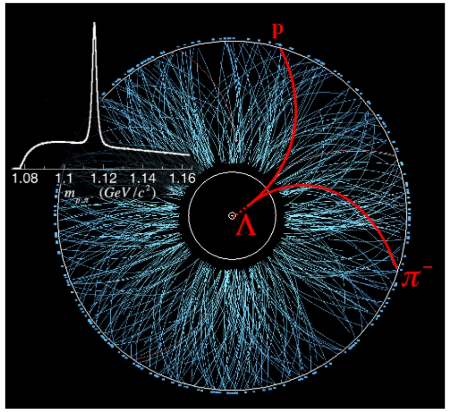


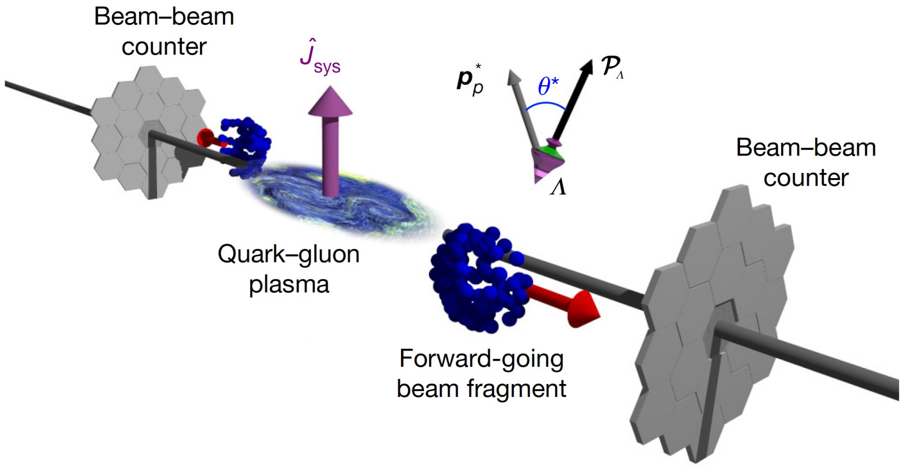
$\Lambda \rightarrow p + \pi^-$
(BR:63.9%,cτ~7.9cm)

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

$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$
A_0: Acceptance correction factor
Ψ_1: First-order event plane angle
$Res(\Psi_1)$: Event plane resolution

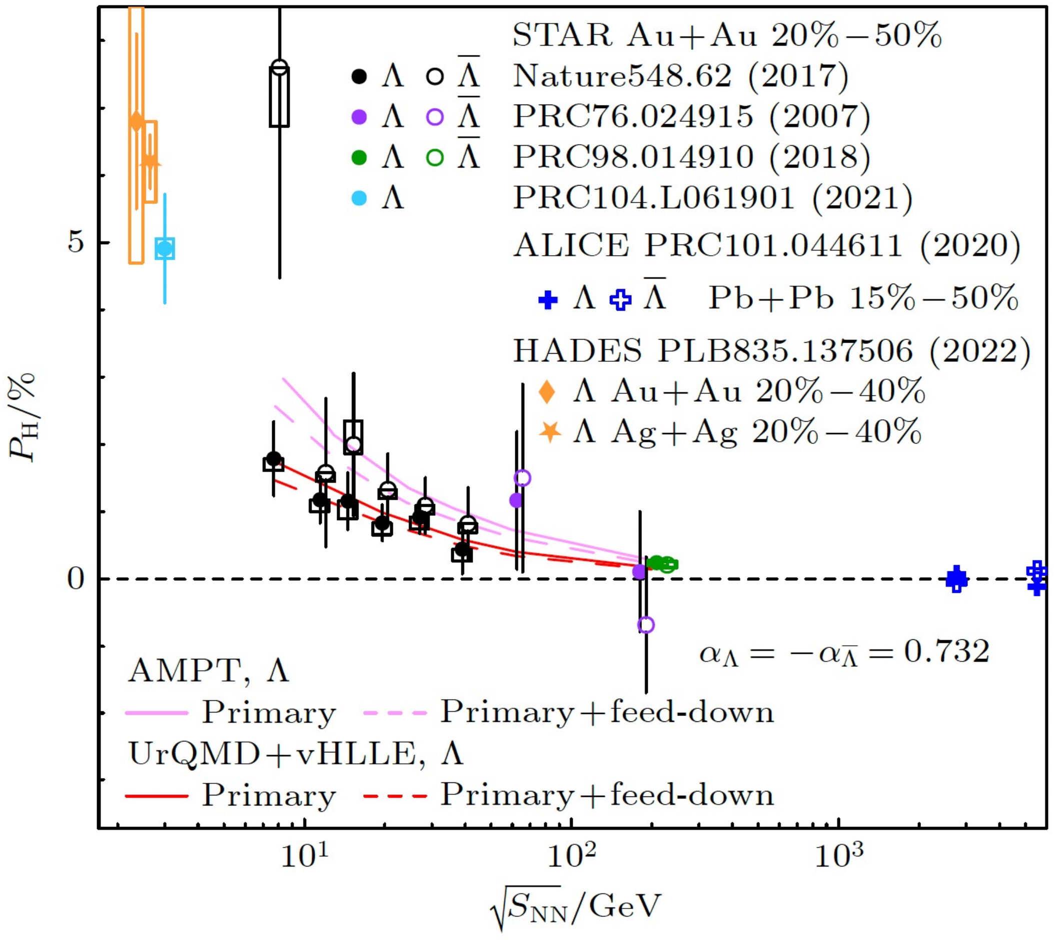
STAR, PRC76, 024915 (2007)





Observation of Λ global polarization

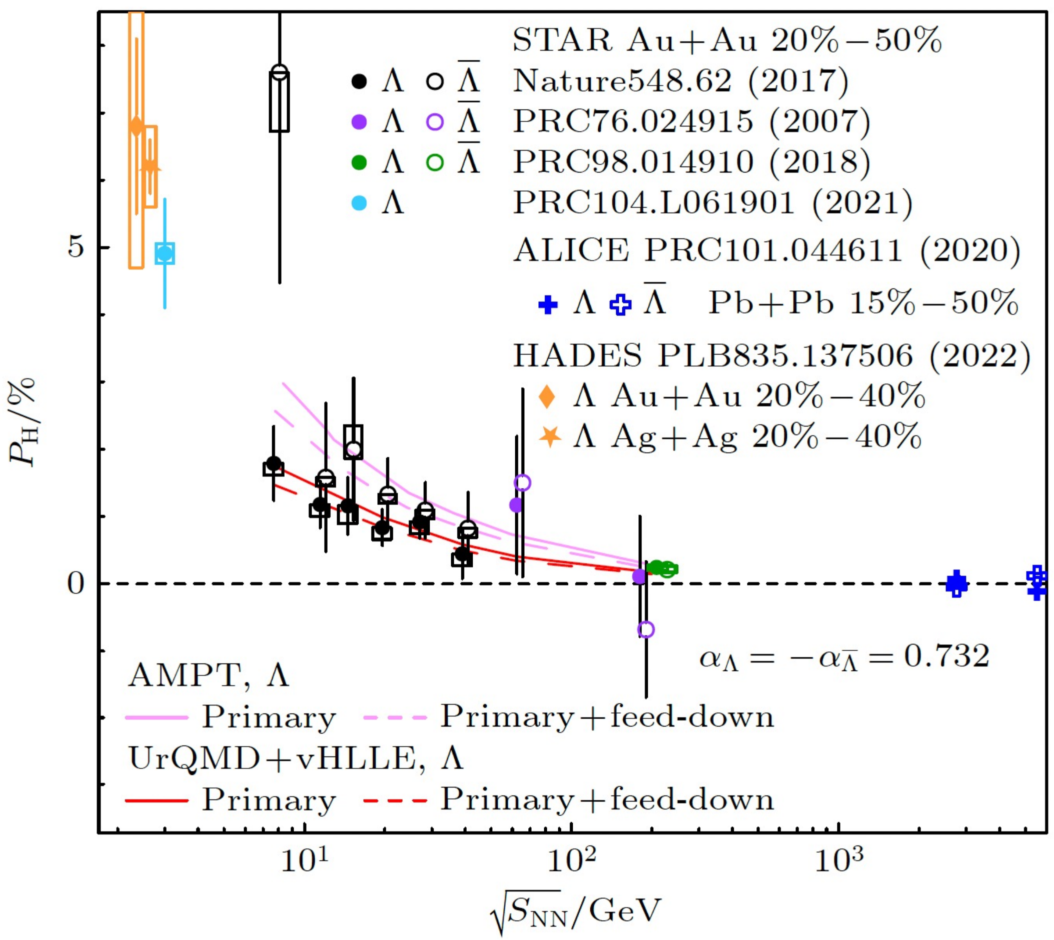
Acta Phys. Sin. Vol. 72, No. 7(2023) 072401



- 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, no splitting
  - PRC108,014910(2023)
- STAR, new recent results
  - BES-II Preliminary 7.7-17.3GeV
  - Λ, Ξ^- global polarization

Energy dependence of Λ global polarization

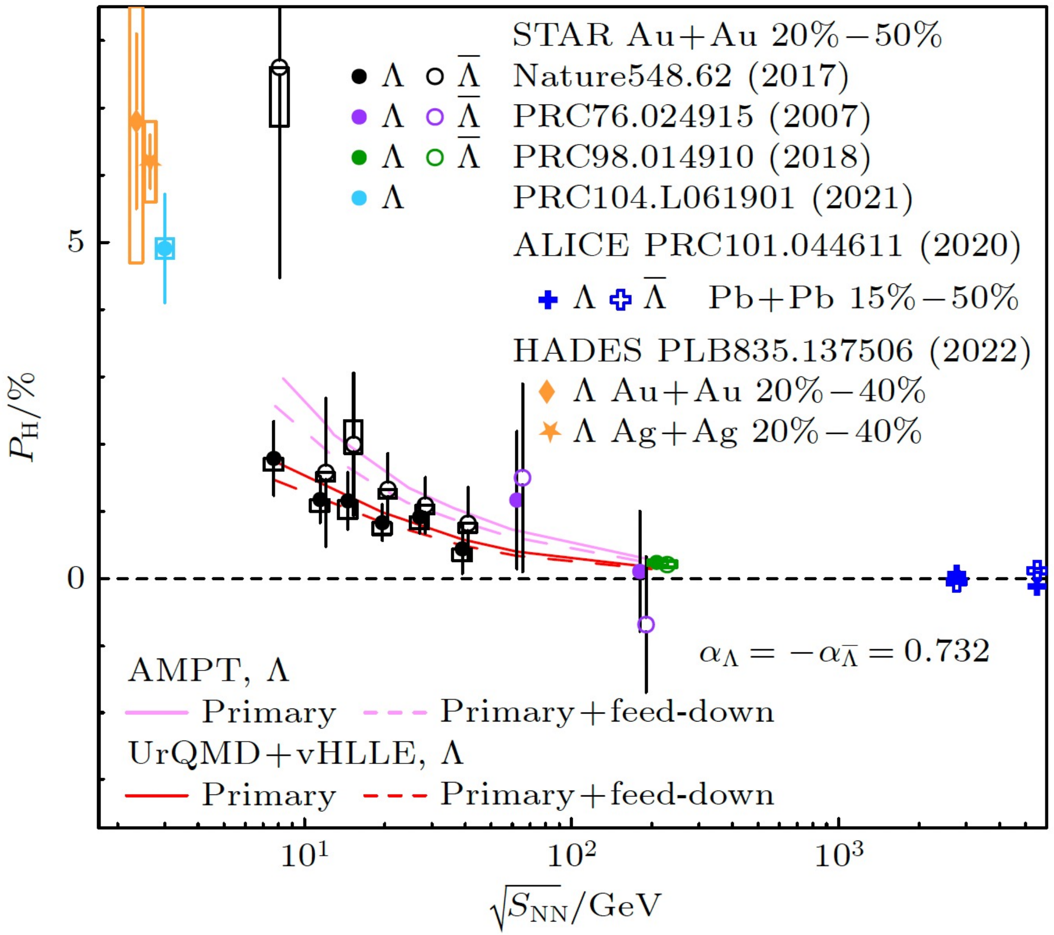
Acta Phys. Sin. Vol. 72, No. 7(2023) 072401

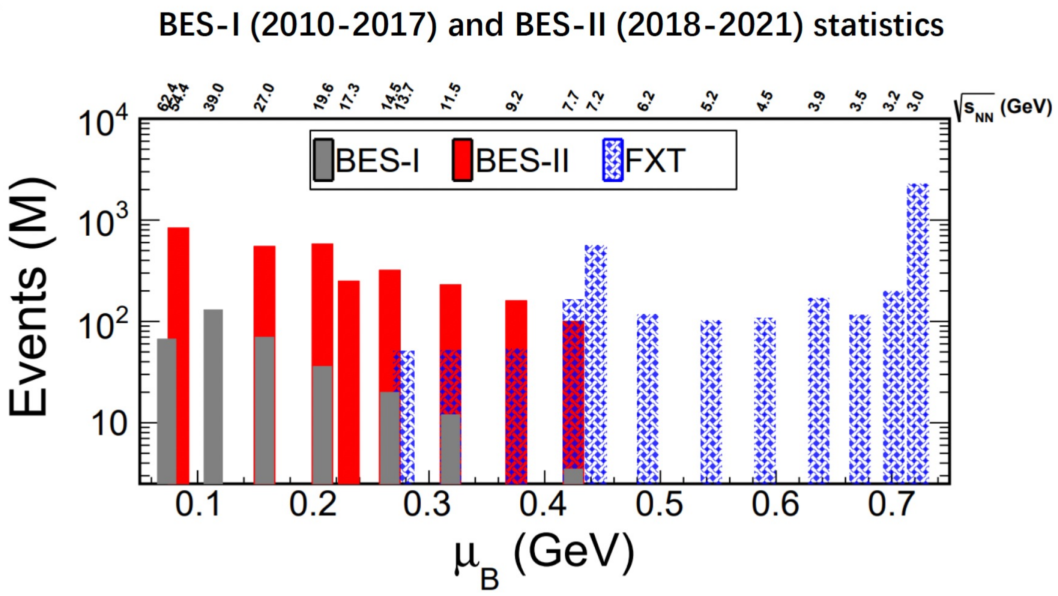


- Significant collision energy dependence, described well by various theoretical models
  - Liang and Wang, PRL 94,102301(2005),
  - Voloshin, nucl-th/0410089
  - Gao, Chen, Deng, Liang, QW, Wang, PRC 77, 044902(2008)
  - I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
  - H. Li et al., PRC 96, 054908 (2017), AMPT
  - Becattini, Lisa, Ann. Rev. Nucl. Part. Sci. 70, 395 (2020).
  - 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)
  - …….
- Possible difference between Λ and $\bar{\Lambda}$

Energy dependence of Λ global polarization

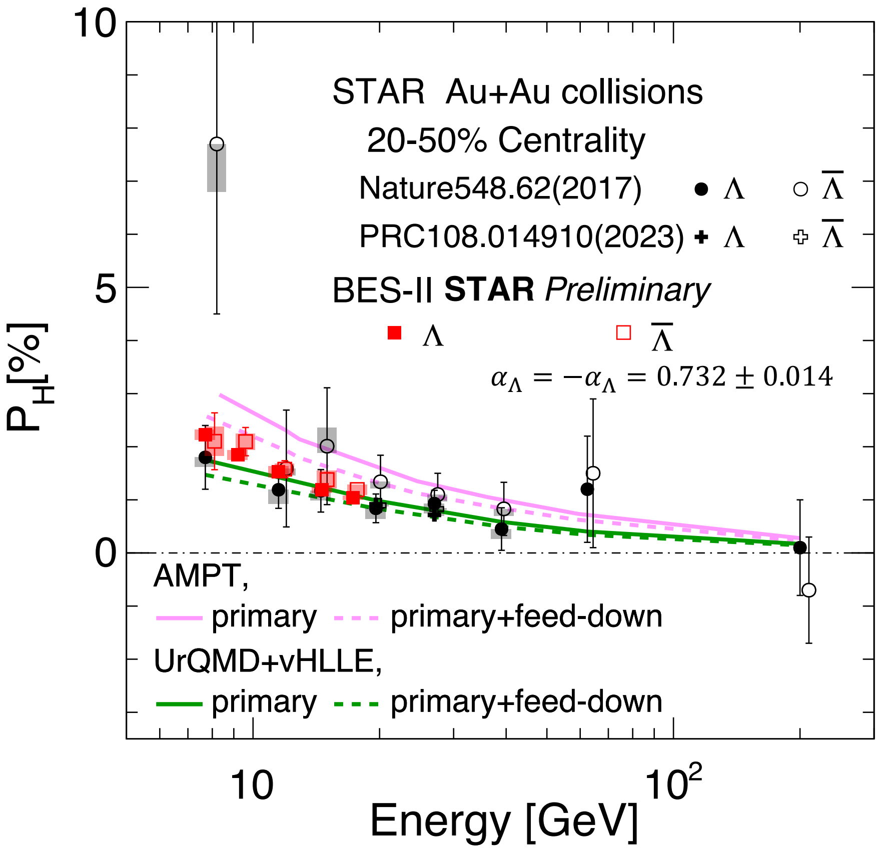
Acta Phys. Sin. Vol. 72, No. 7(2023) 072401





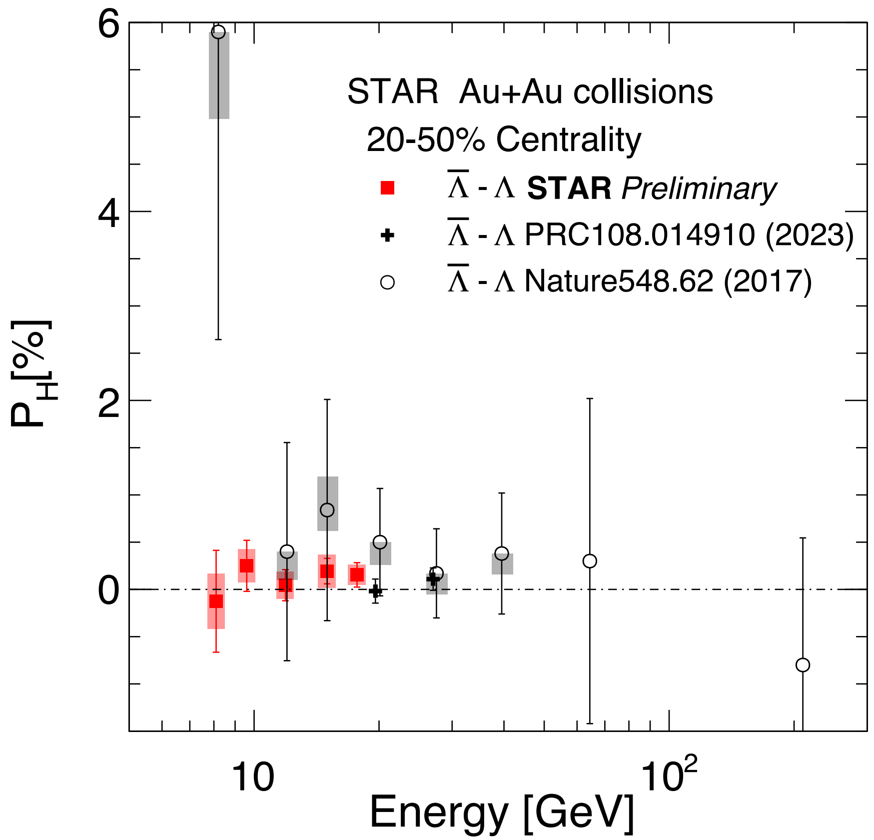
- Greatly improved precision from Beam Energy Scan phase-II
- More significant global polarization in lower energies

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

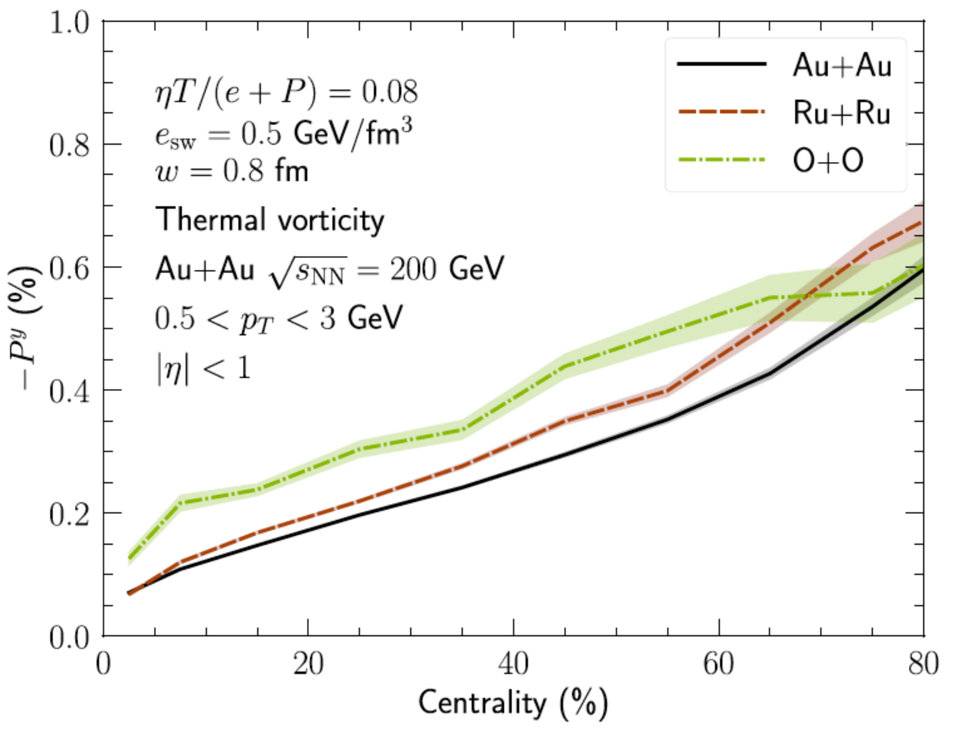
Magnetic field effect of global polarization : from BES-II



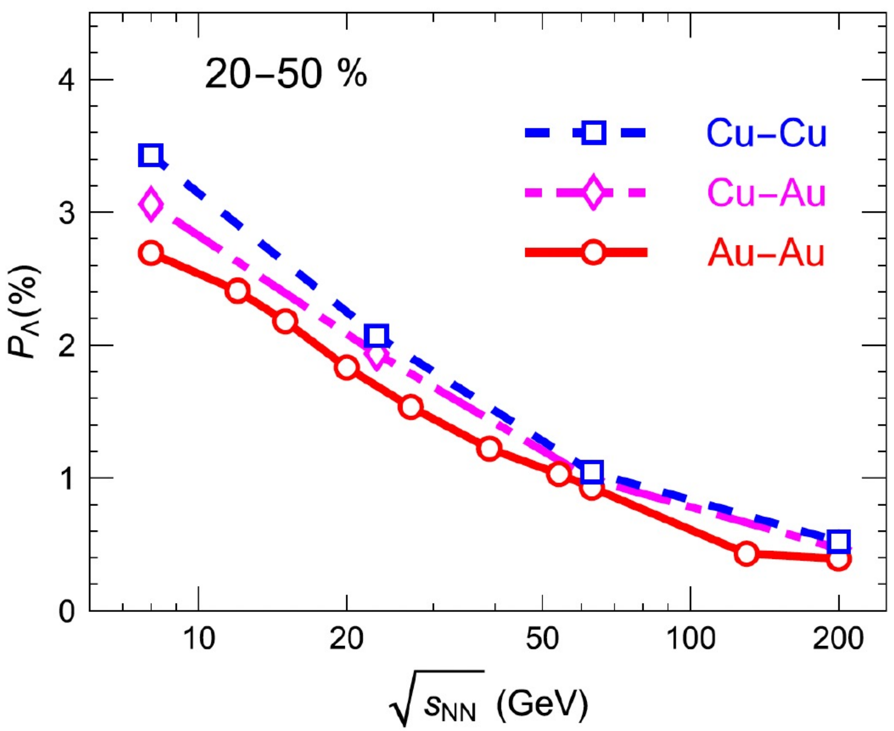
- ❑ No splitting between Λ and $\bar{\Lambda}$ global polarization within uncertainties
- ❑ Upper limit on late stage magnetic field
  - 95% confidence level STAR, PRC 108,014910(2023)
  - $B < 9.4\times10^{12}\ T$ at 19.6 GeV
  - $B < 1.4\times10^{13}\ T$ at 27 GeV

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

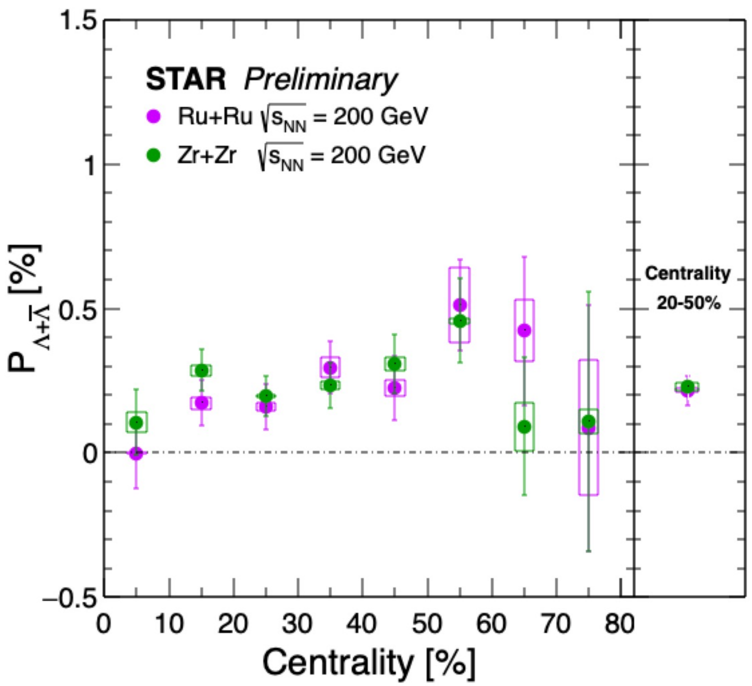


- Longer system lifetime dilutes the vorticity/polarization
- Collision system size dependence of global polarization?

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

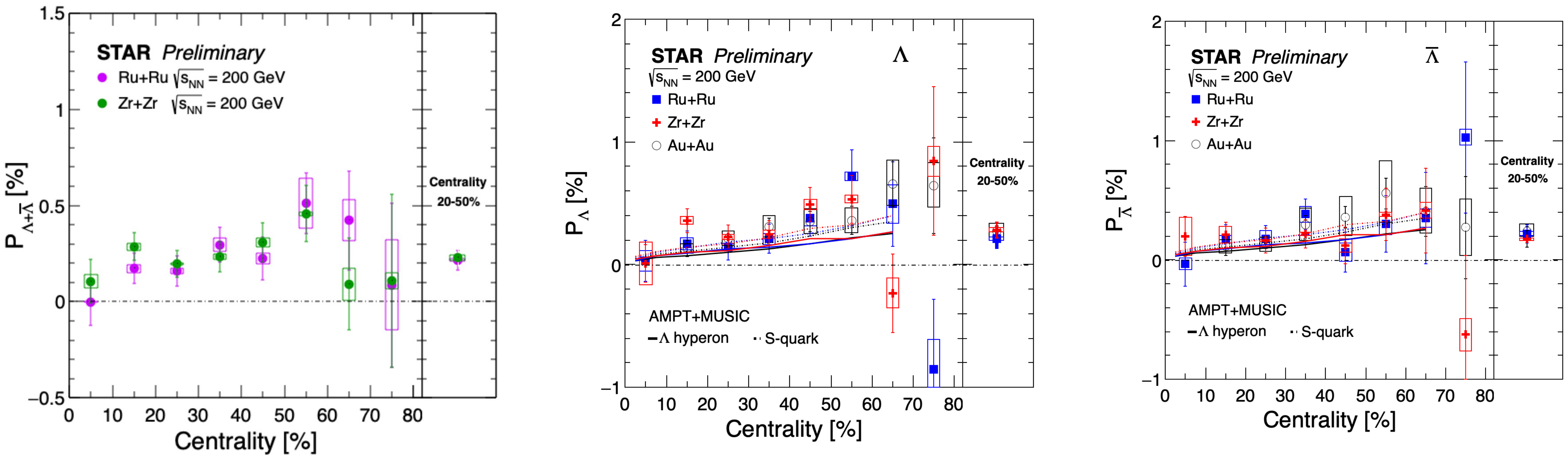
? → $P_\Lambda^{Au} < P_\Lambda^{Ru} \approx P_\Lambda^{Zr} < P_\Lambda^{Cu} < P_\Lambda^{O}$

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

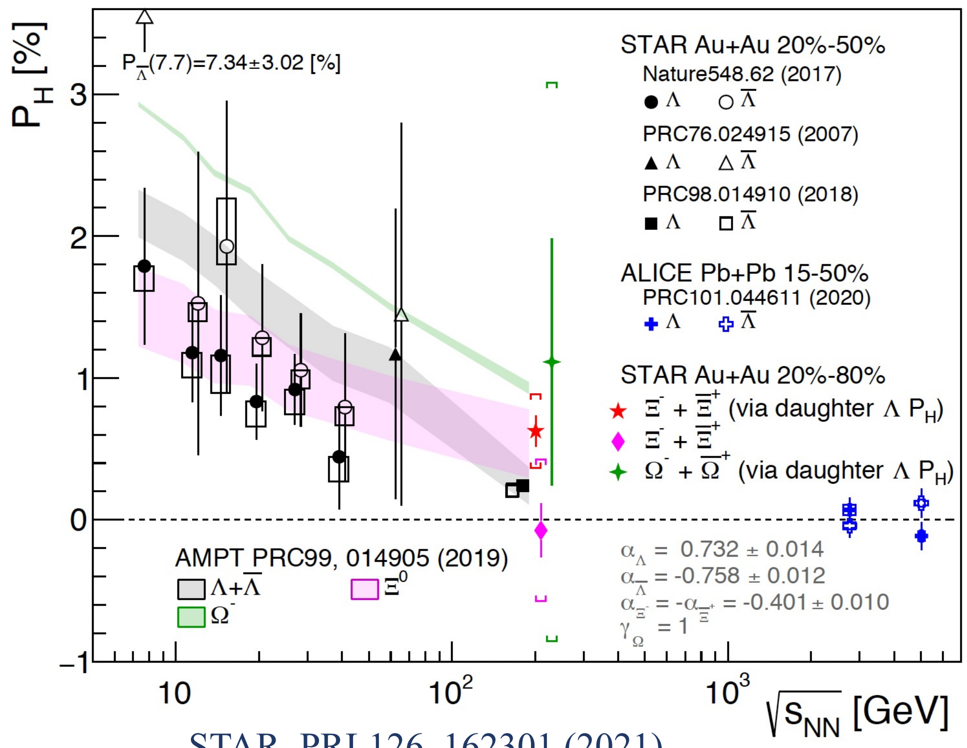


Model results from arXiv:2201.12970v1

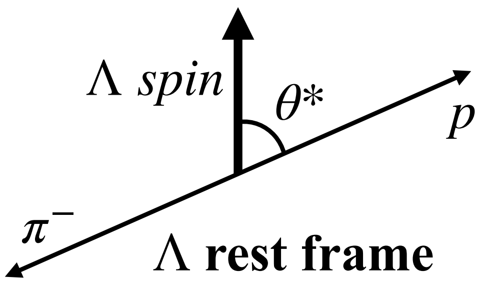
- Significant global polarization observed in isobar collisions, P_{Λ} and $P_{\bar{\Lambda}}$ increase with centrality
- Global polarization of $\Lambda + \bar{\Lambda}$ are consistent between Ru+Ru, Zr+Zr and Au+Au collisions within uncertainty

$\Xi^- + \bar{\Xi}^+$ 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($C_{\Xi^- \to \Lambda} = 0.944$)



STAR, PRL126, 162301 (2021)



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α_H : hyperon decay parameter
P_H : hyperon polarization
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Hyperon	Deacy mode	α_H	Spin
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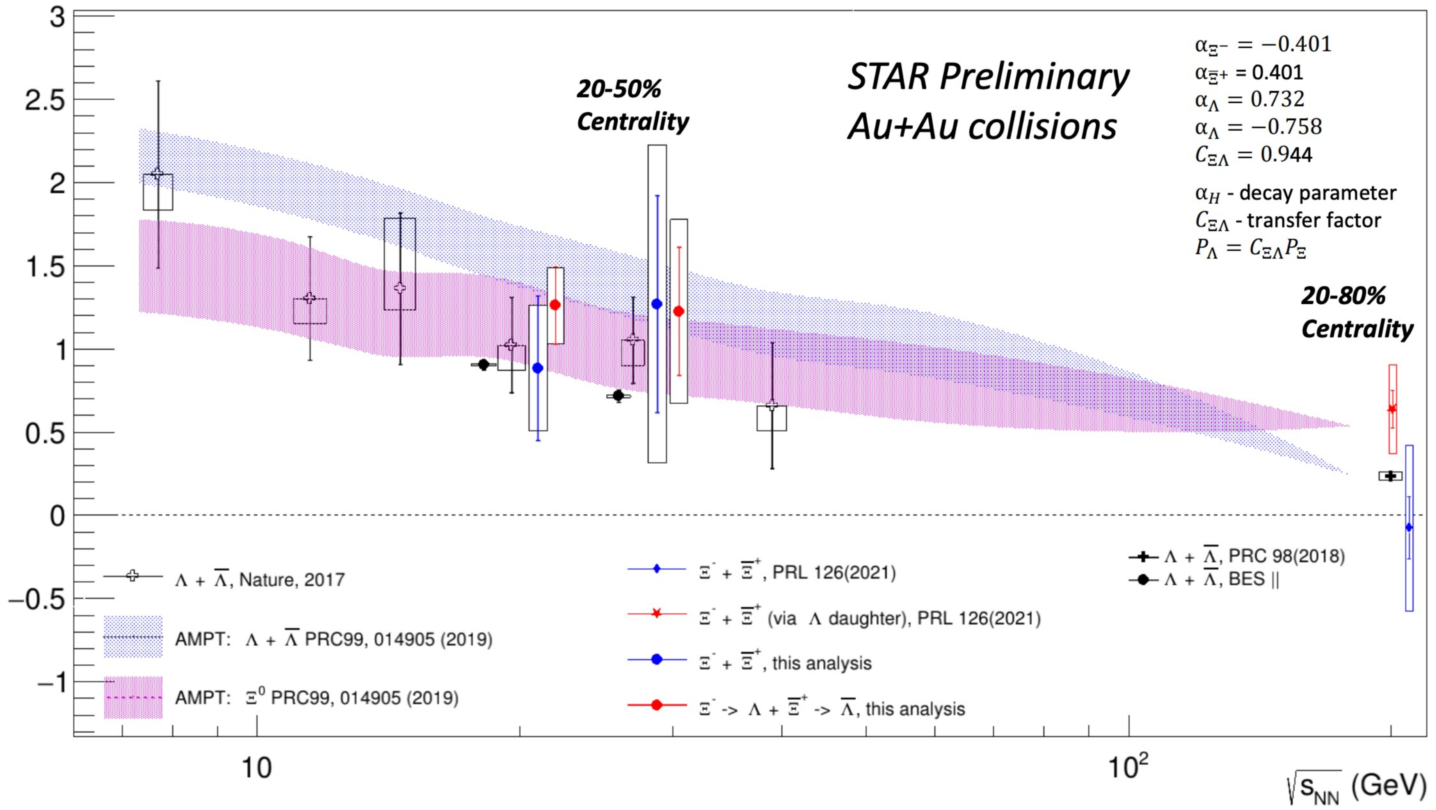
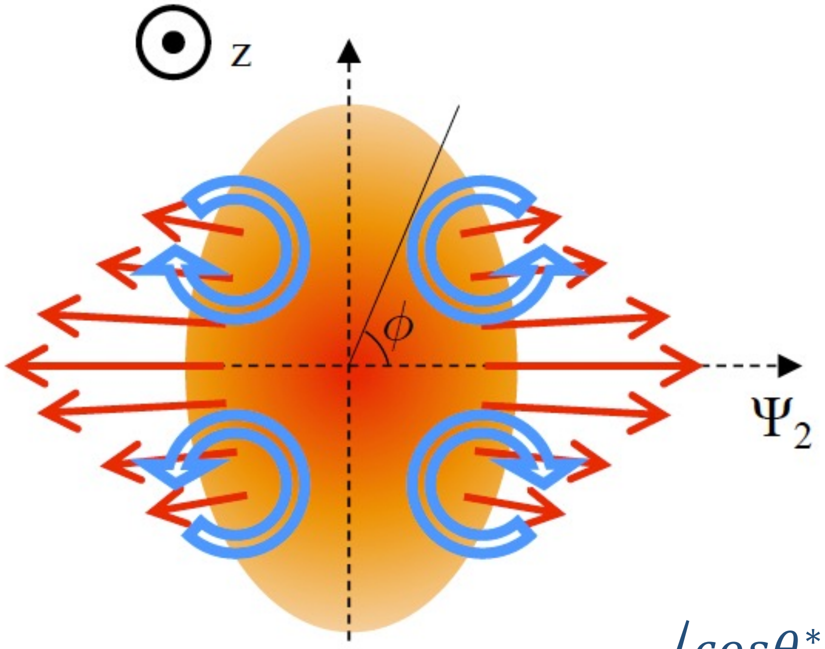
PDG2021

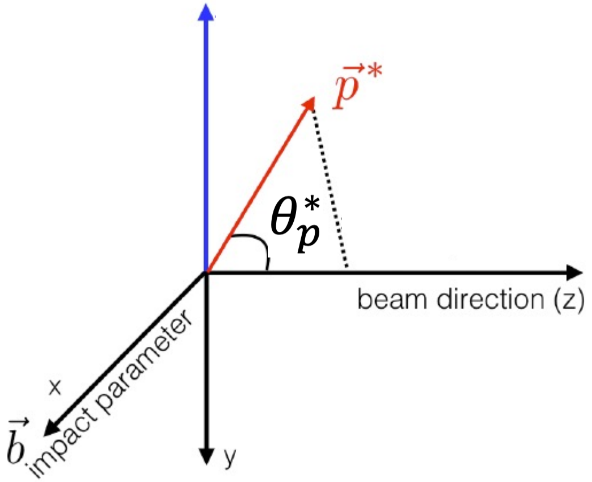
Energy dependence of $\Xi^- + \bar{\Xi}^+$ global polarization



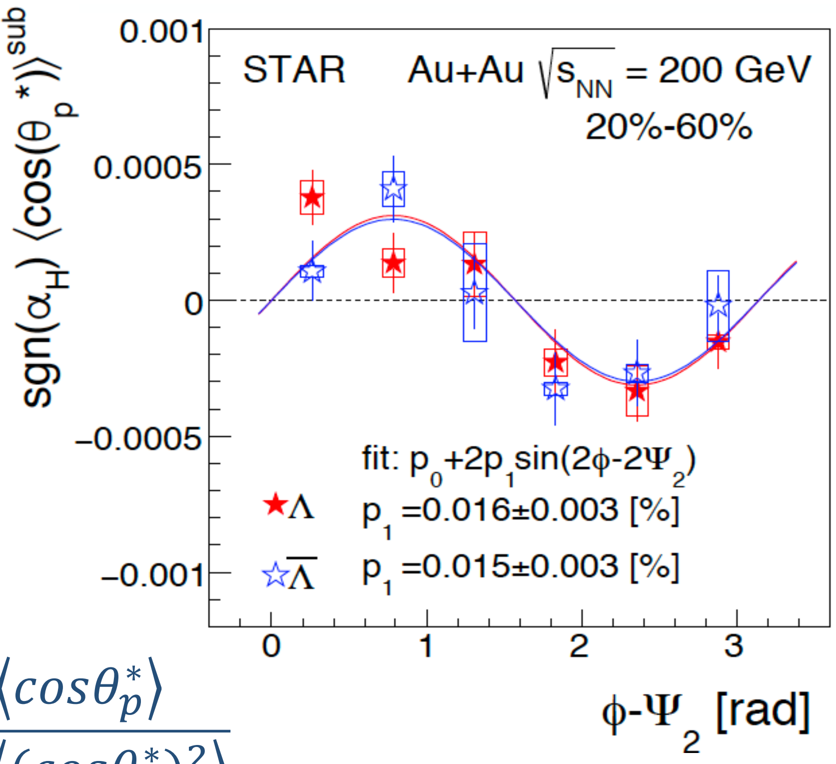
- Significant $\Xi^- + \bar{\Xi}^+$ global polarization observed in Au+Au at 19.6 and 27 GeV
- $\Xi^- + \bar{\Xi}^+$ global polarization measurement at lower BES-II energies underway

Local vorticity and polarization in heavy ion collisions





$P_z \propto \langle cos\theta_p^* \rangle$ STAR, PRL 123, 132301 (2019)



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

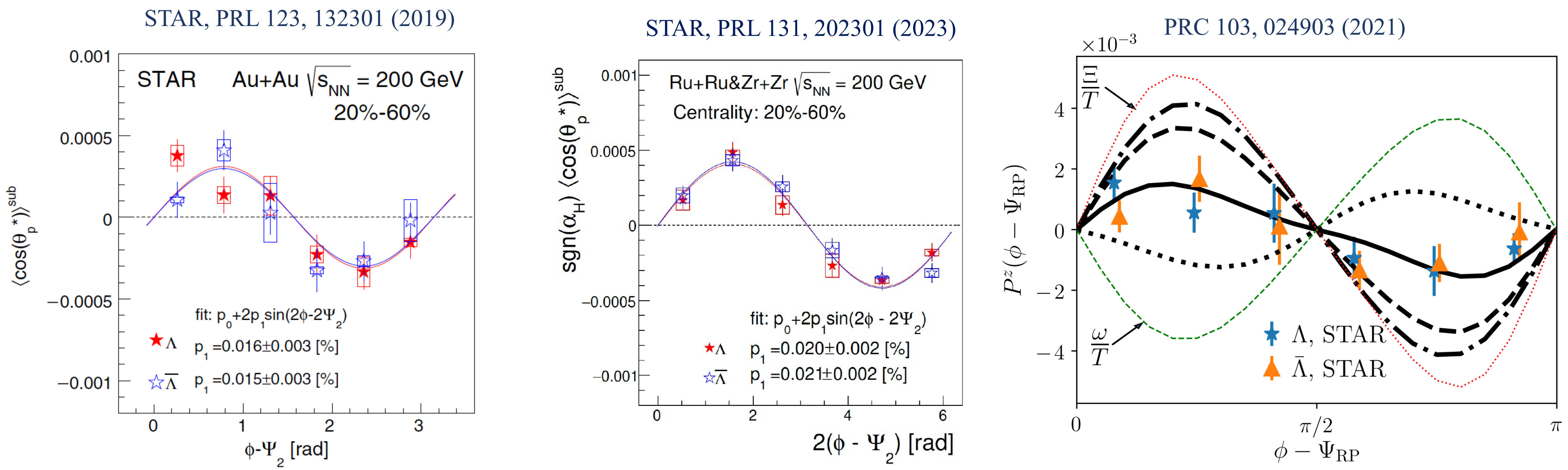
$$= \alpha_\Lambda P_z \langle (cos\theta_p^*)^2 \rangle$$

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

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

  → Lead to polarization along the beam direction (P_z)

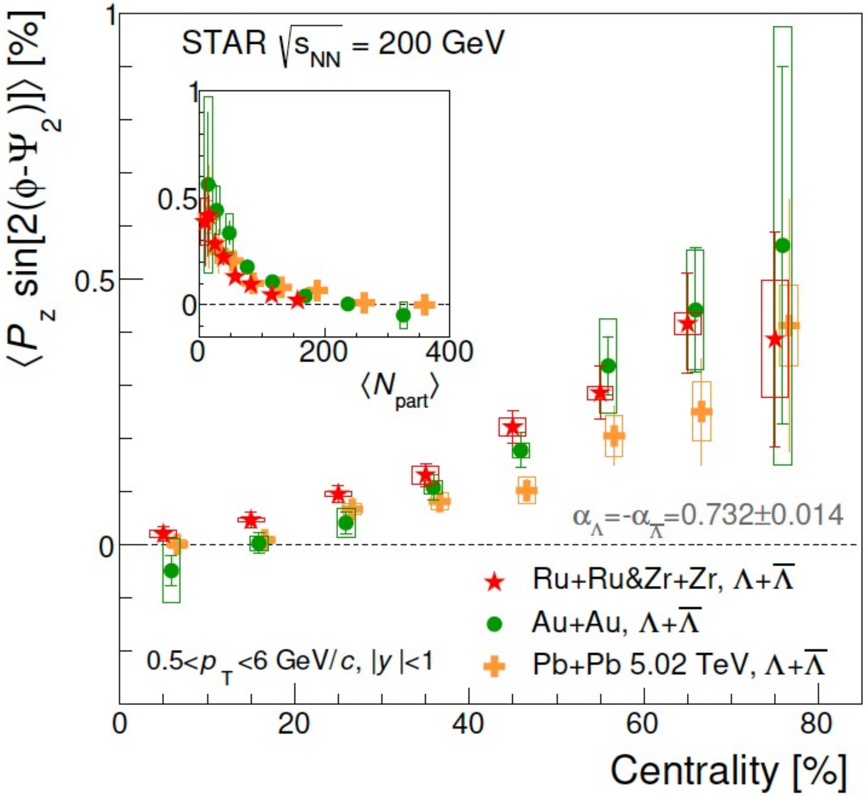
Azimuthal angle dependence of P_z



- 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

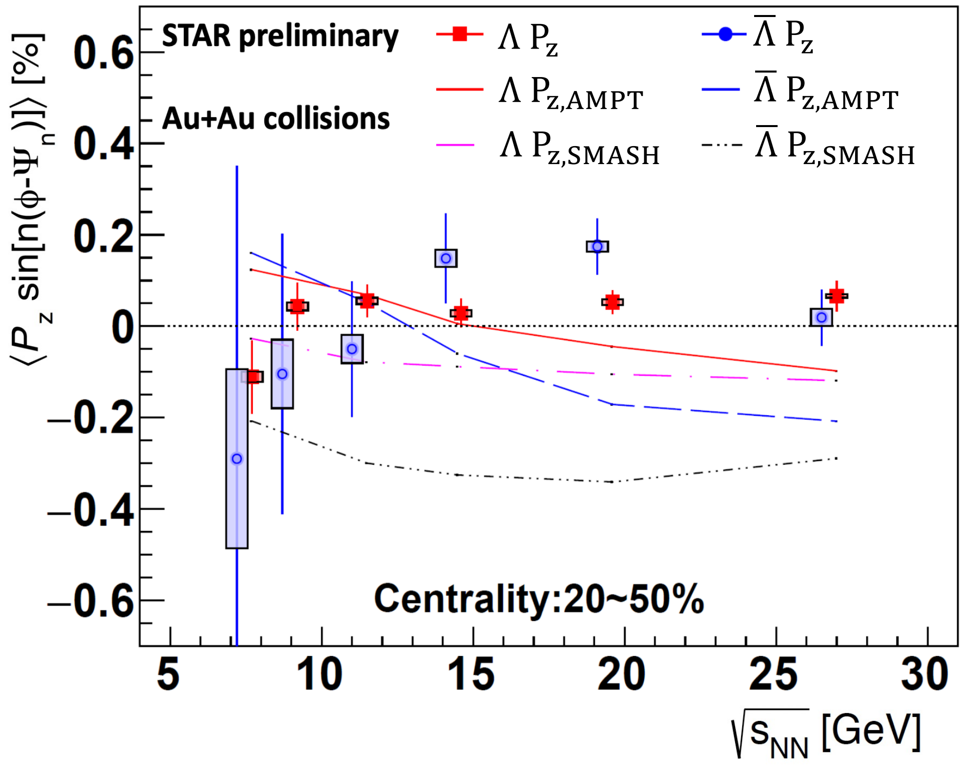
System size dependence of P_z

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

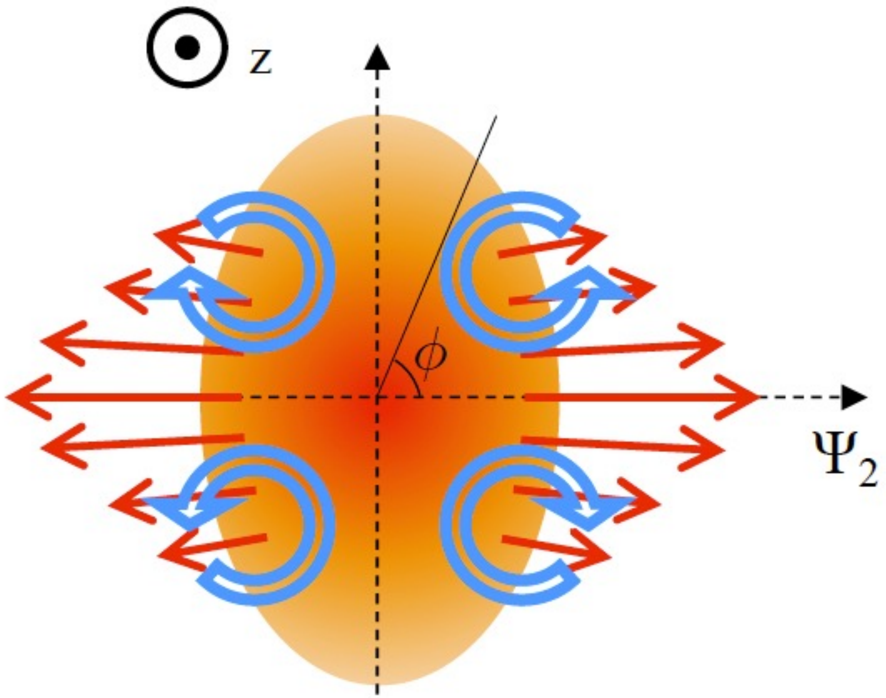
Energy dependence of P_z

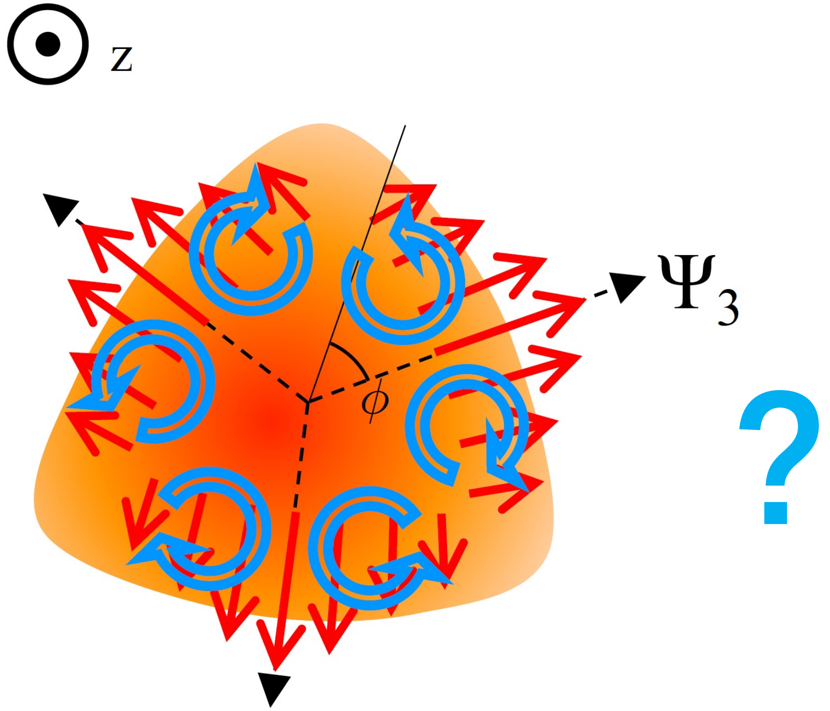


Model: X. Wu et al., PRC 105 (2022) 064909

- 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)

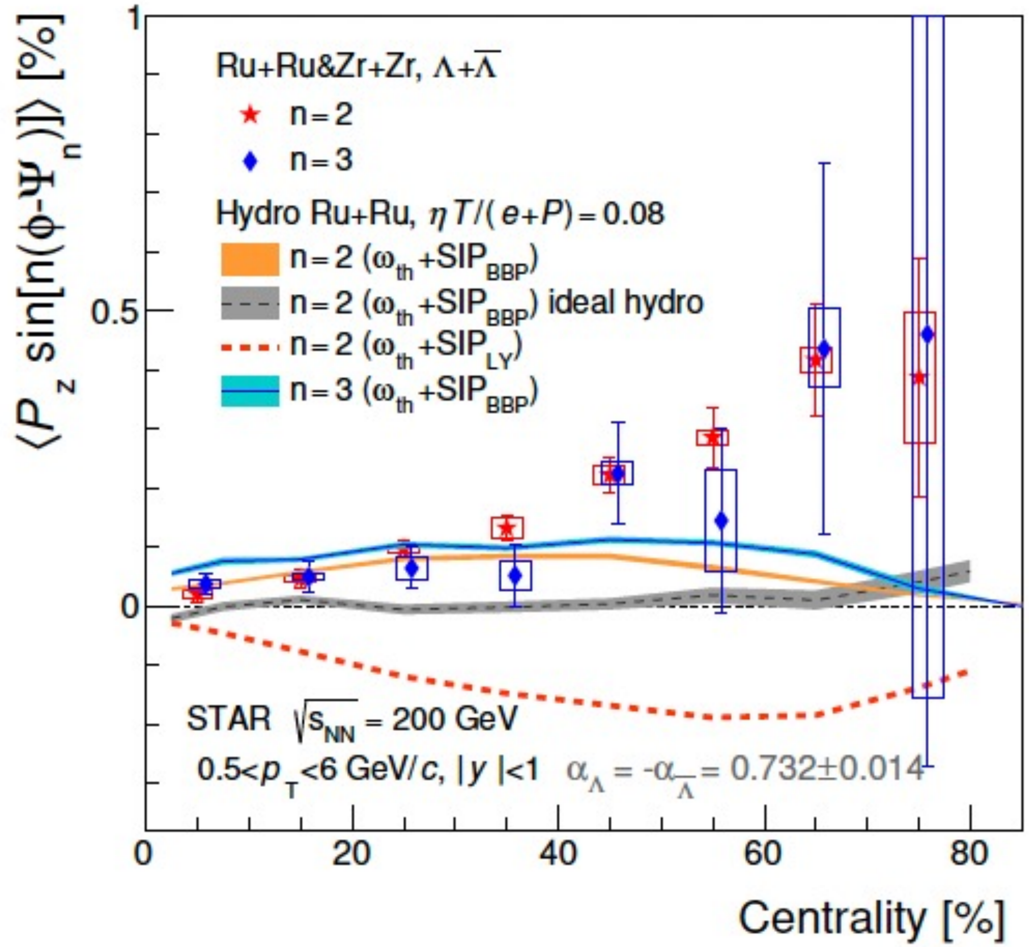
P_z from higher harmonic flow





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

P_z relative to 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

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 ${}^{96}_{44}$Ru + ${}^{96}_{44}$Ru, ${}^{96}_{40}$Zr + ${}^{96}_{40}$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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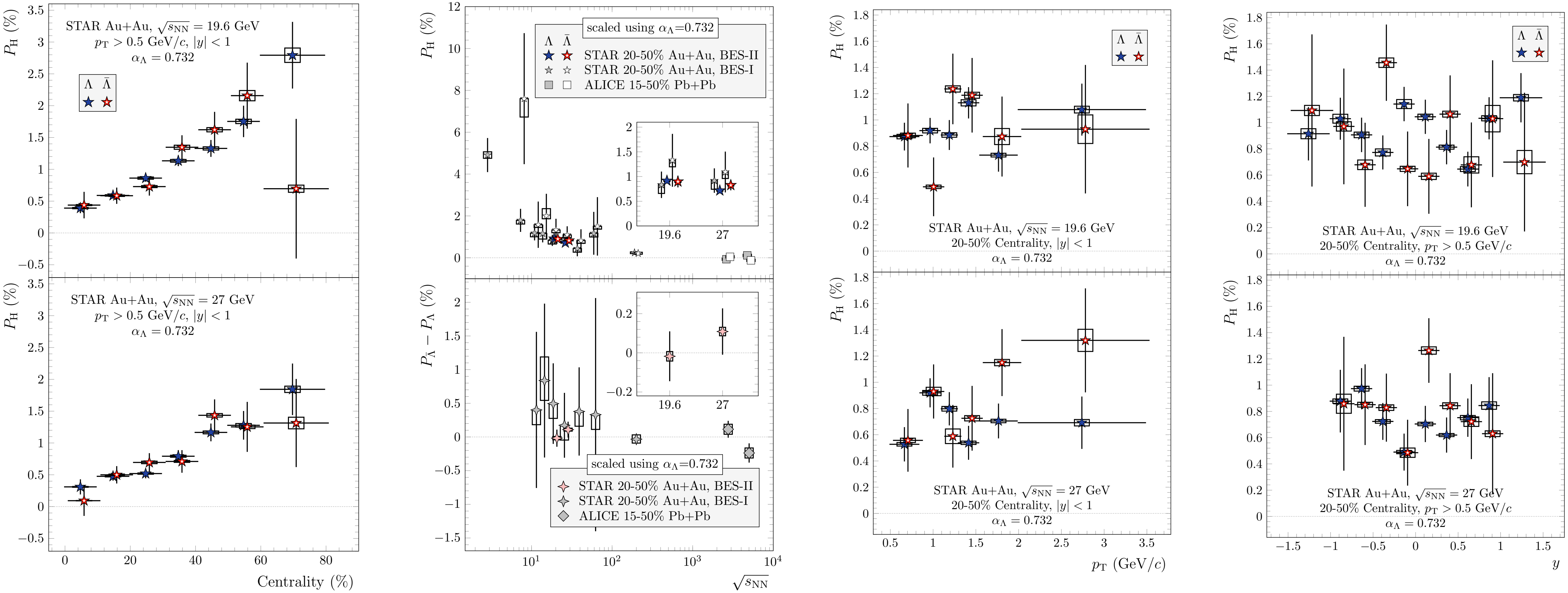
Thanks for your attention

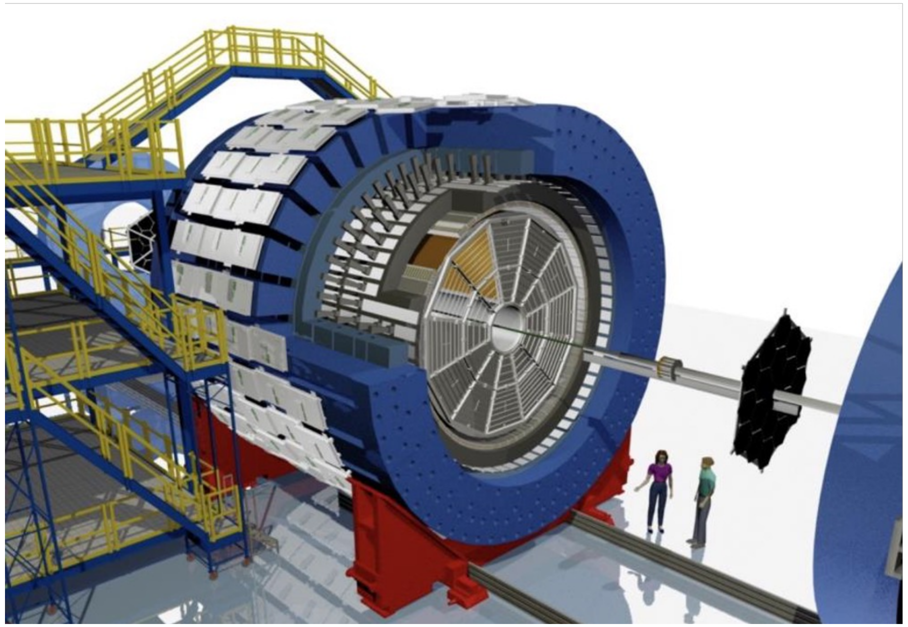
Back Up

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

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



Event plane reconstruction:

Time Projection Chamber

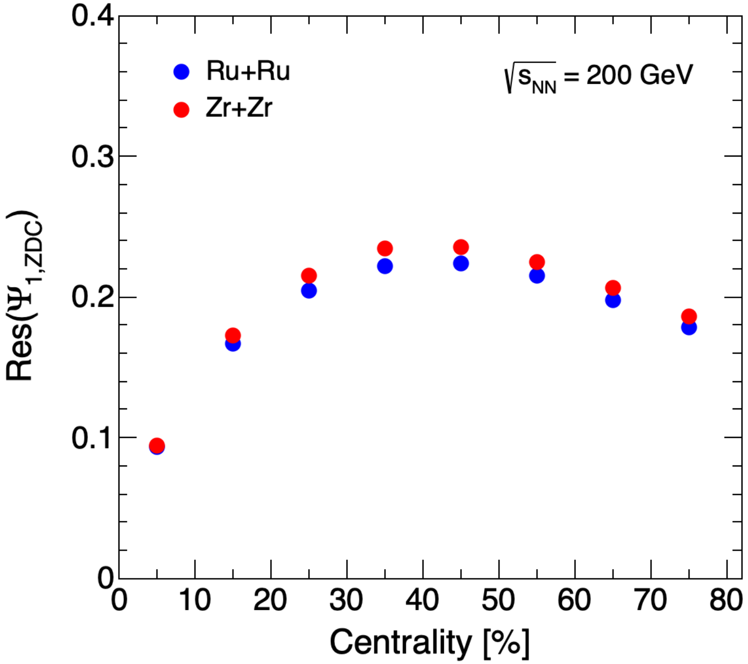
Zero Degree Calorimeters

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

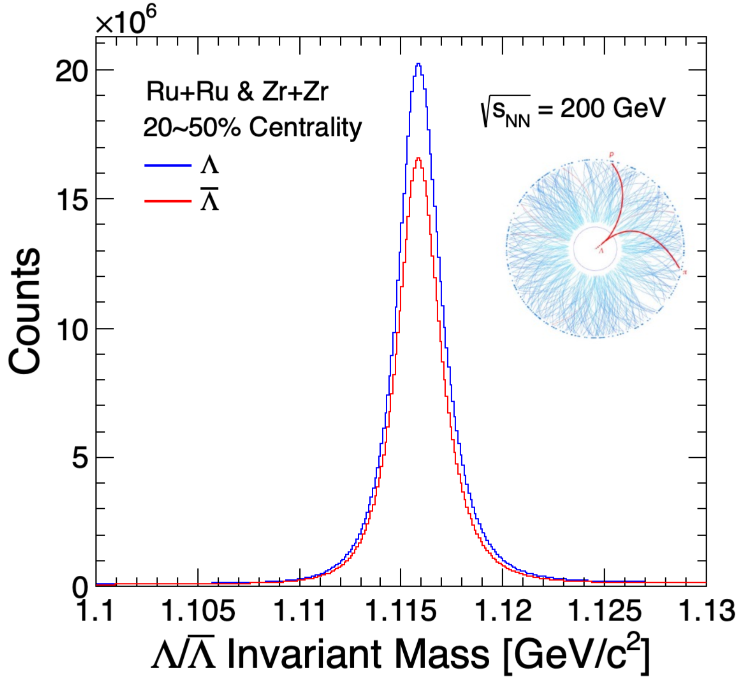
Time Projection Chamber

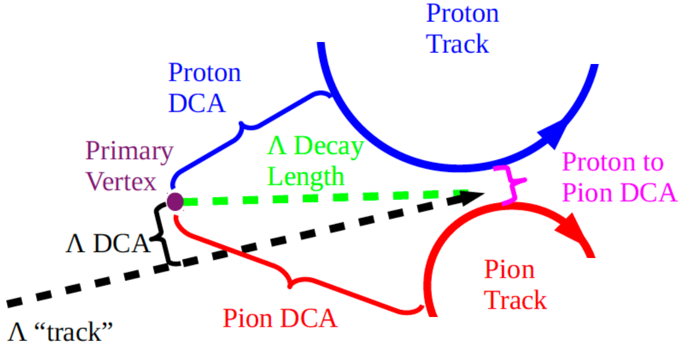
Time Of Flight

Event plane resolution



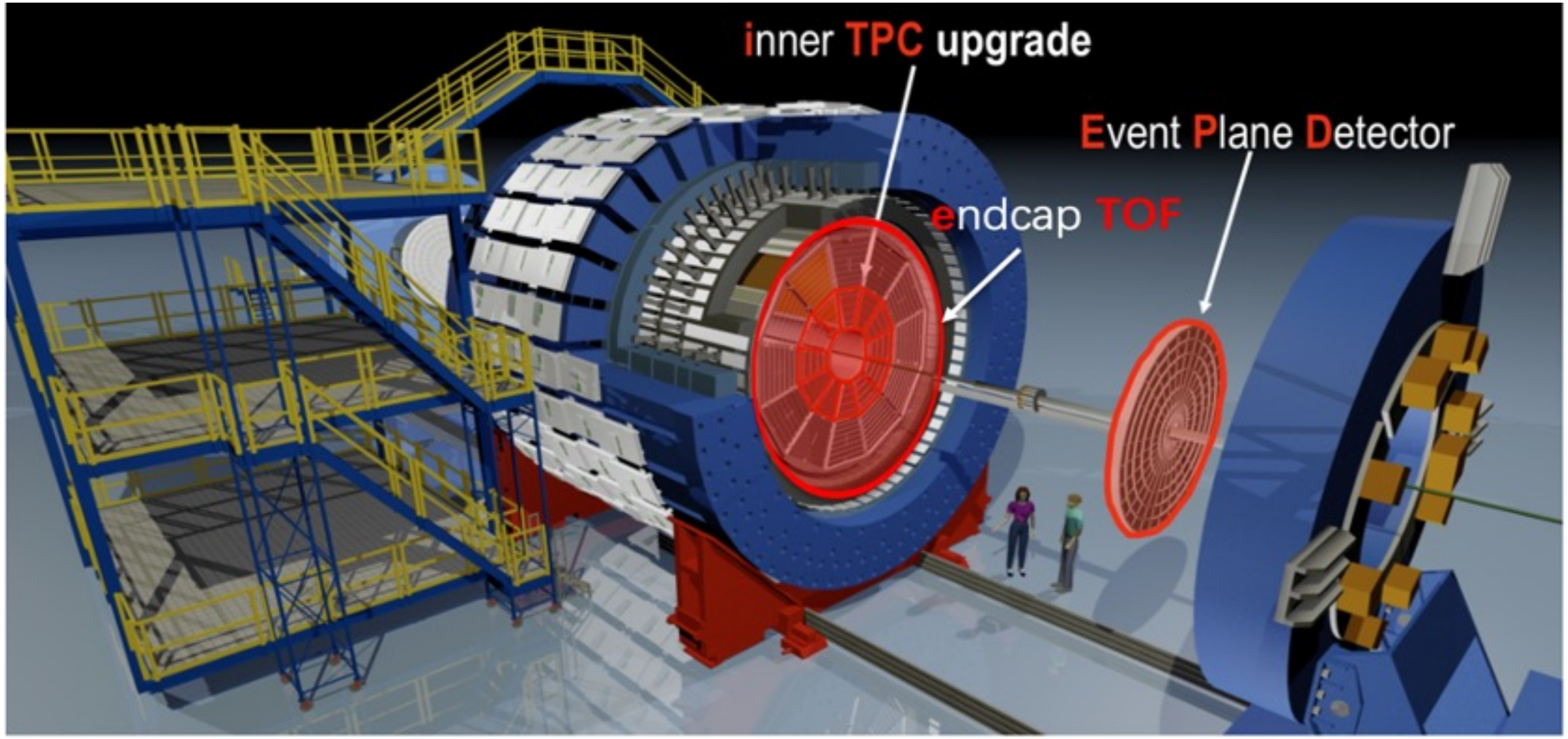
$\Lambda/\bar{\Lambda}$ reconstructed with TPC tracks



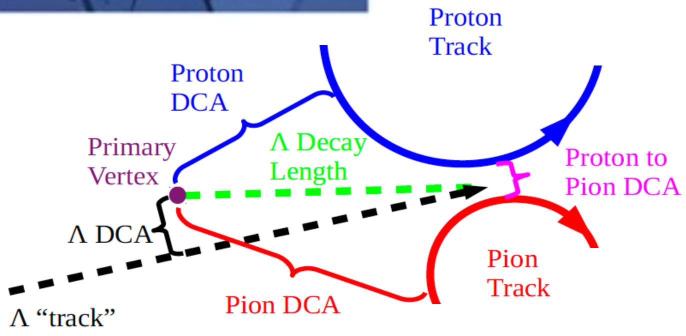


- $\Lambda \rightarrow p + \pi^-$
- $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$
- Background fraction < 3%

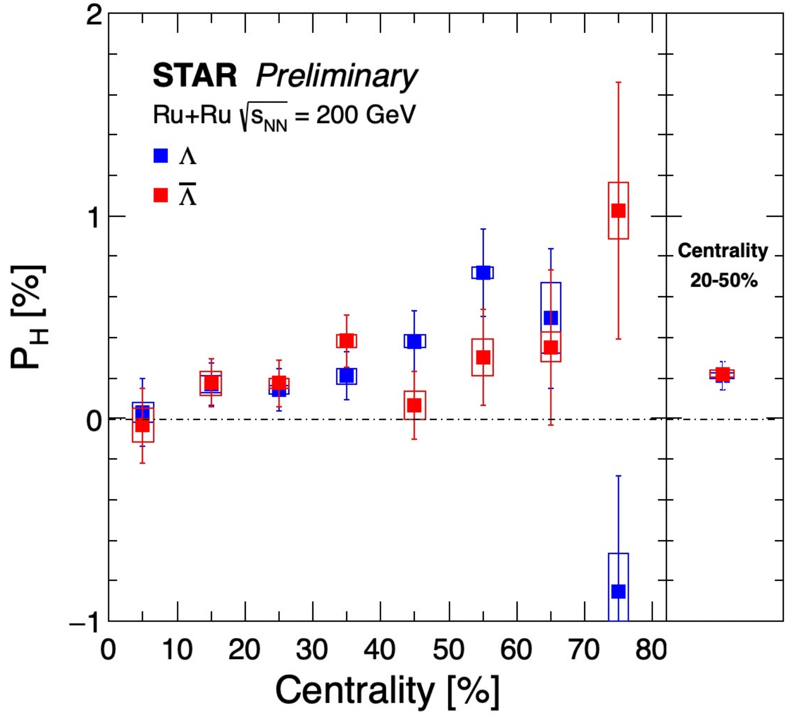
STAR detector

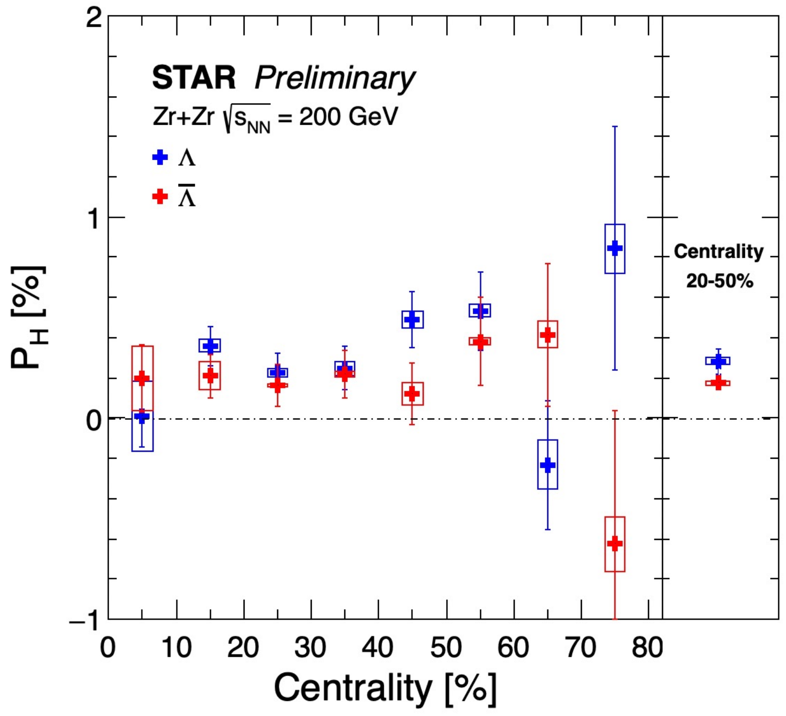


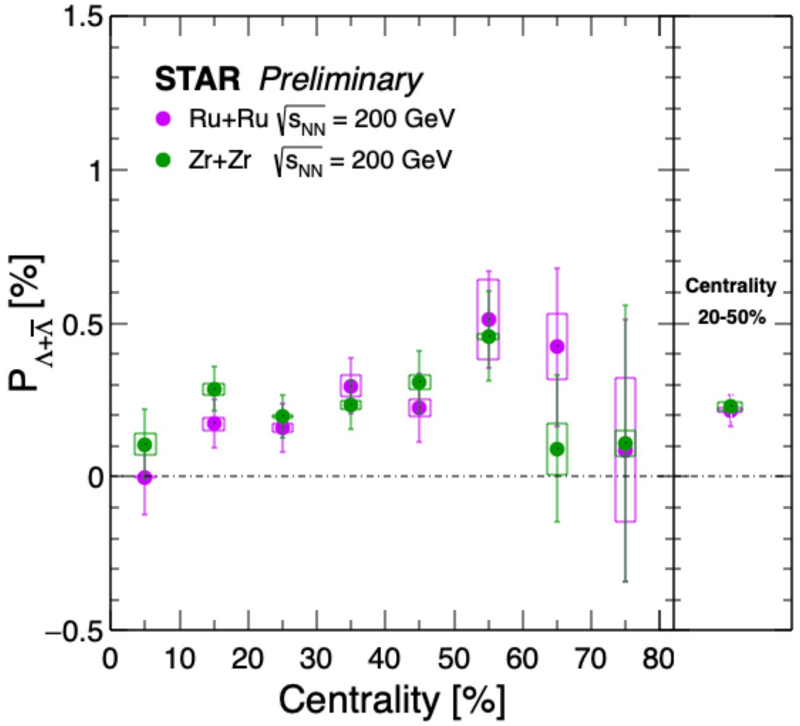
- **Event plane reconstruction:**
  - Time Projection Chamber
  - Event Plane Detector
  - Zero Degree Calorimeters
- **$\Lambda/\bar{\Lambda}$ reconstruction:**
  - Time Projection Chamber
  - Time Of Flight



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

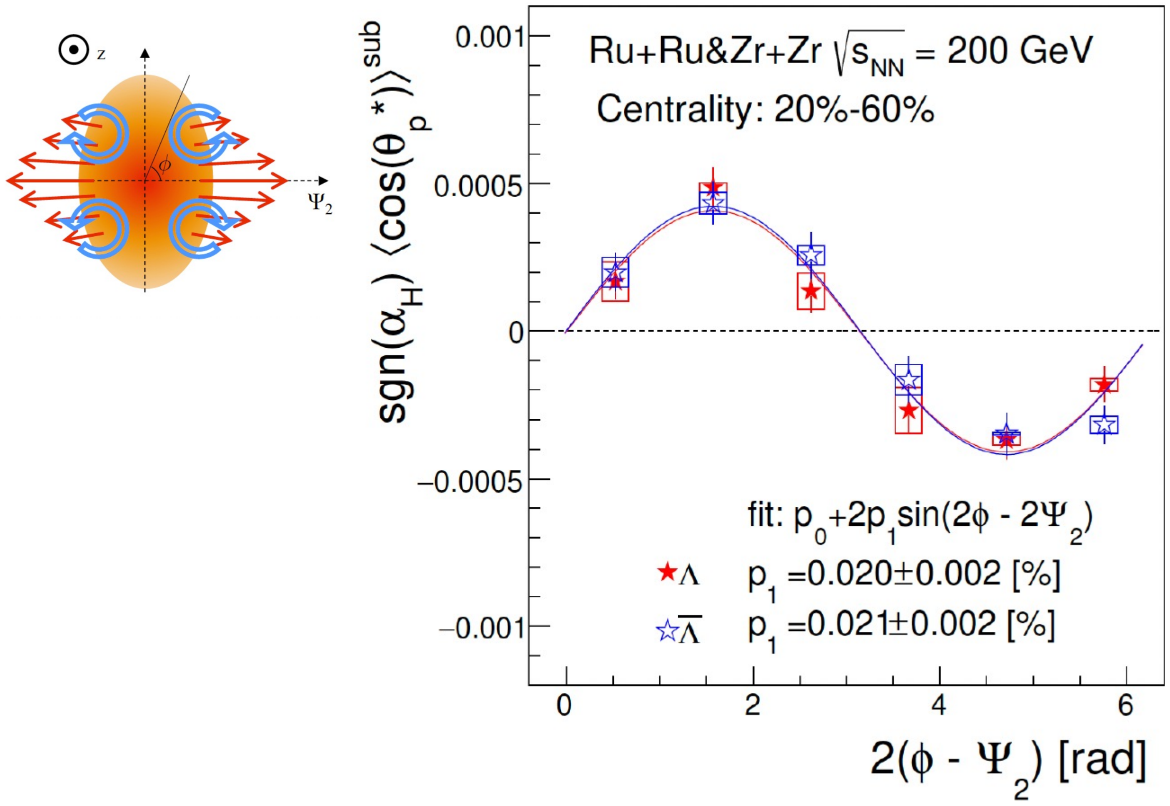


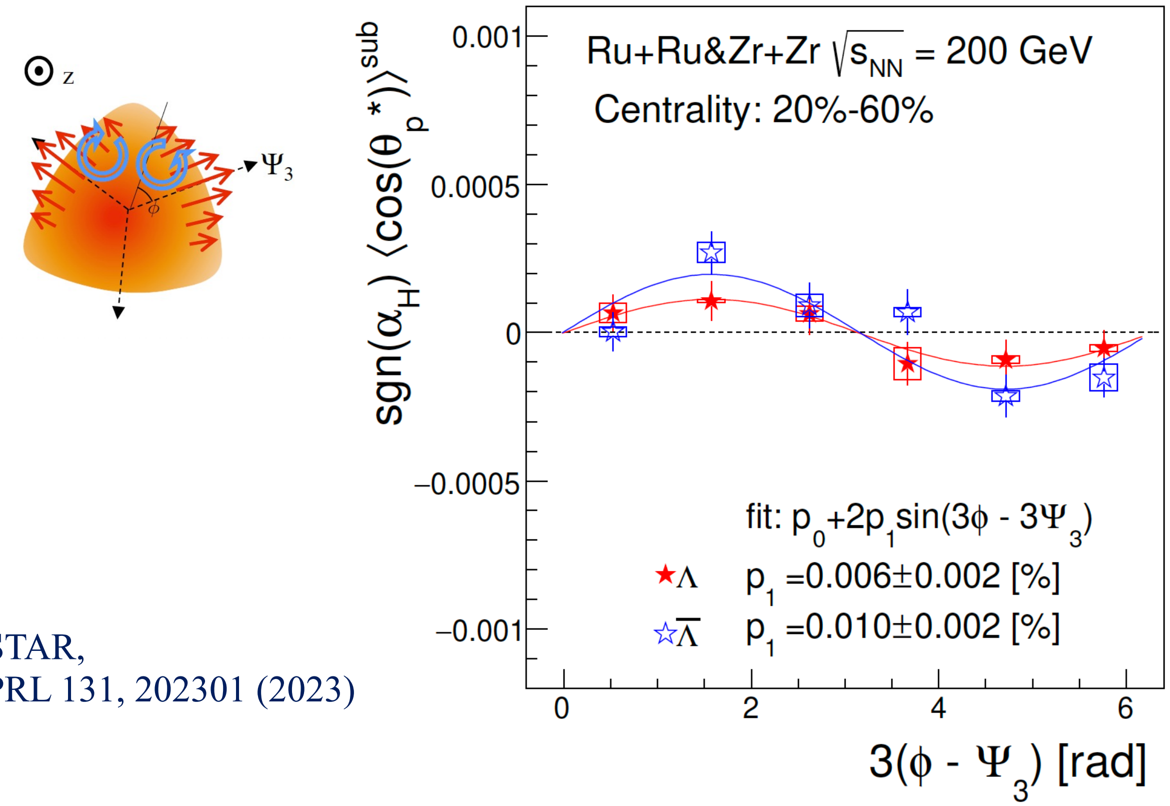




- Significant global polarization observed, P_{Λ} and $P_{\bar{\Lambda}}$ increase with centrality
- No significant difference between P_{Λ} and $P_{\bar{\Lambda}}$ in Ru+Ru and Zr+Zr collisions
- Global polarization of $\Lambda + \bar{\Lambda}$ are consistent between Ru+Ru and Zr+Zr collisions

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

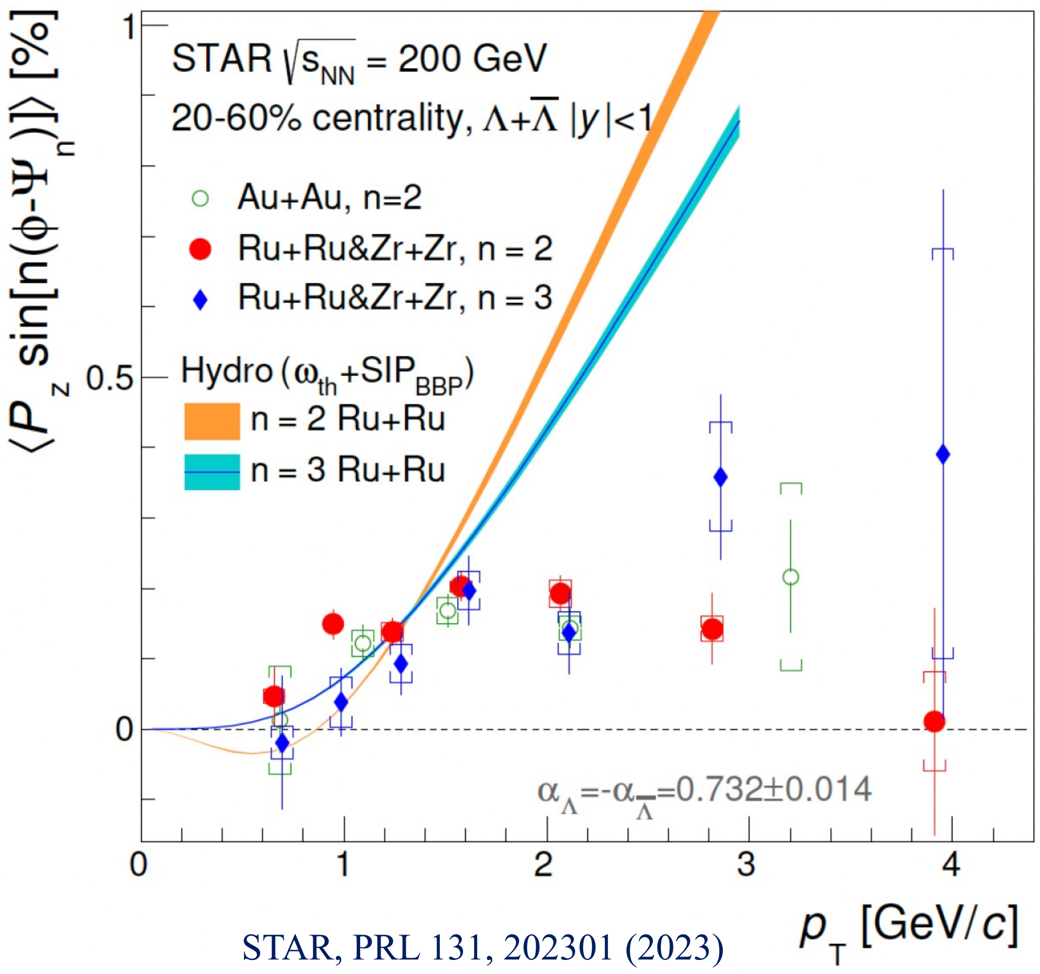




STAR,
PRL 131, 202301 (2023)

- 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

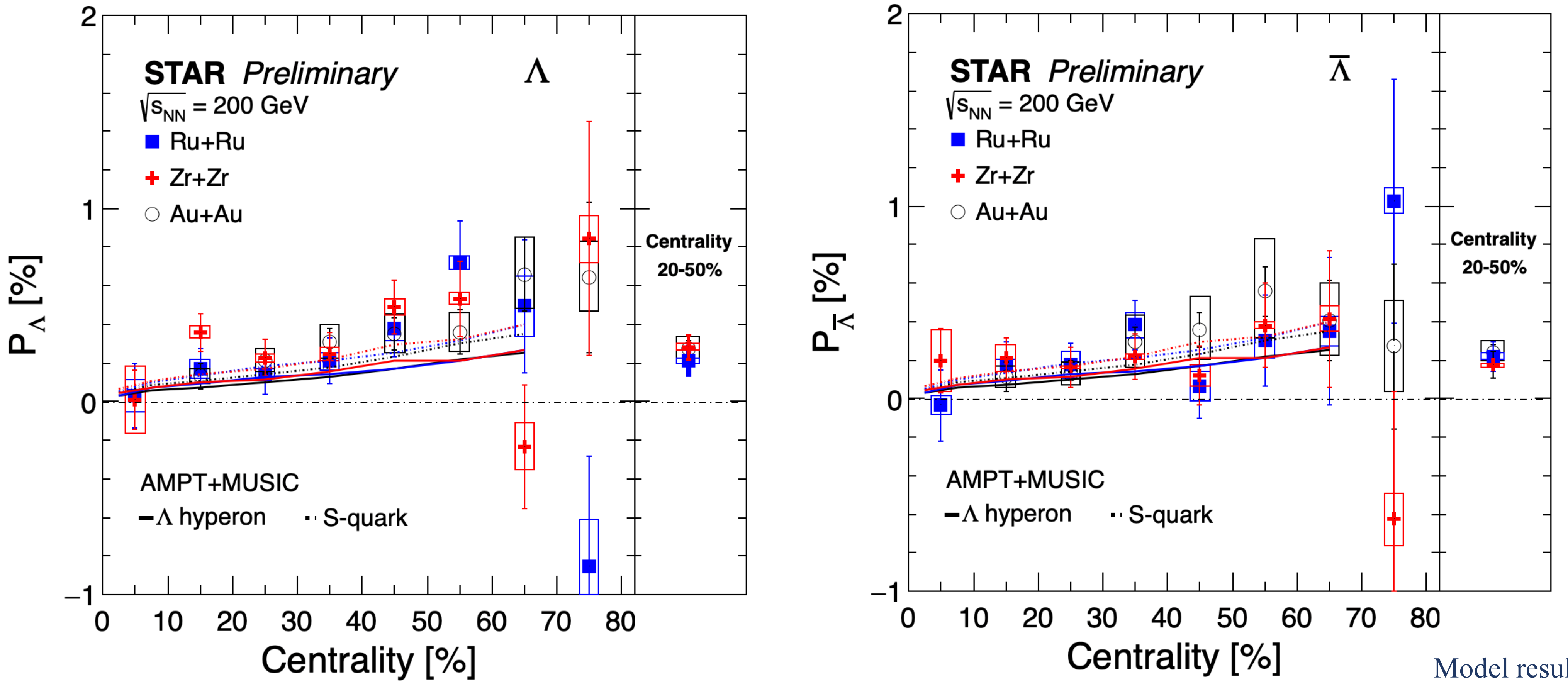
p_T dependence of local polarization



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 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

Energy dependence of P_z

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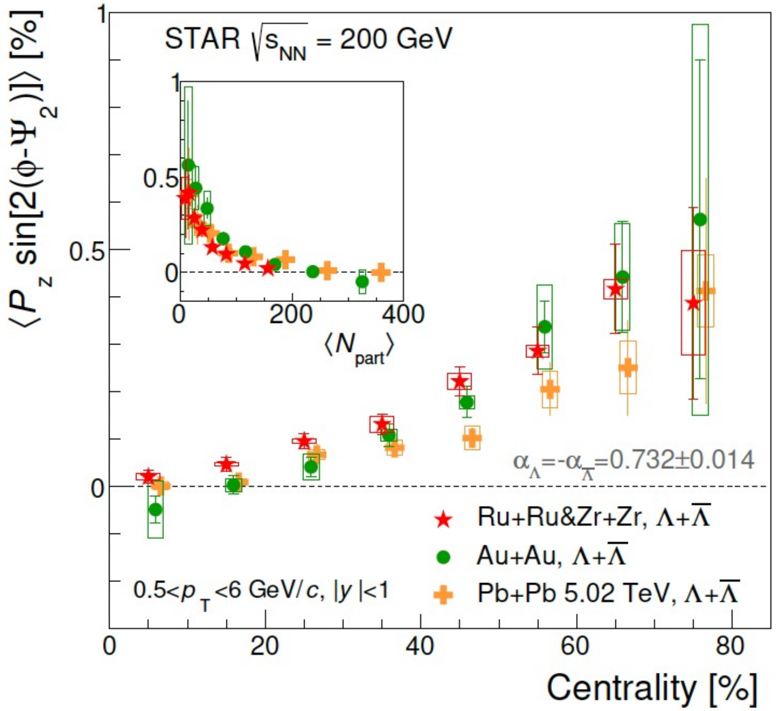
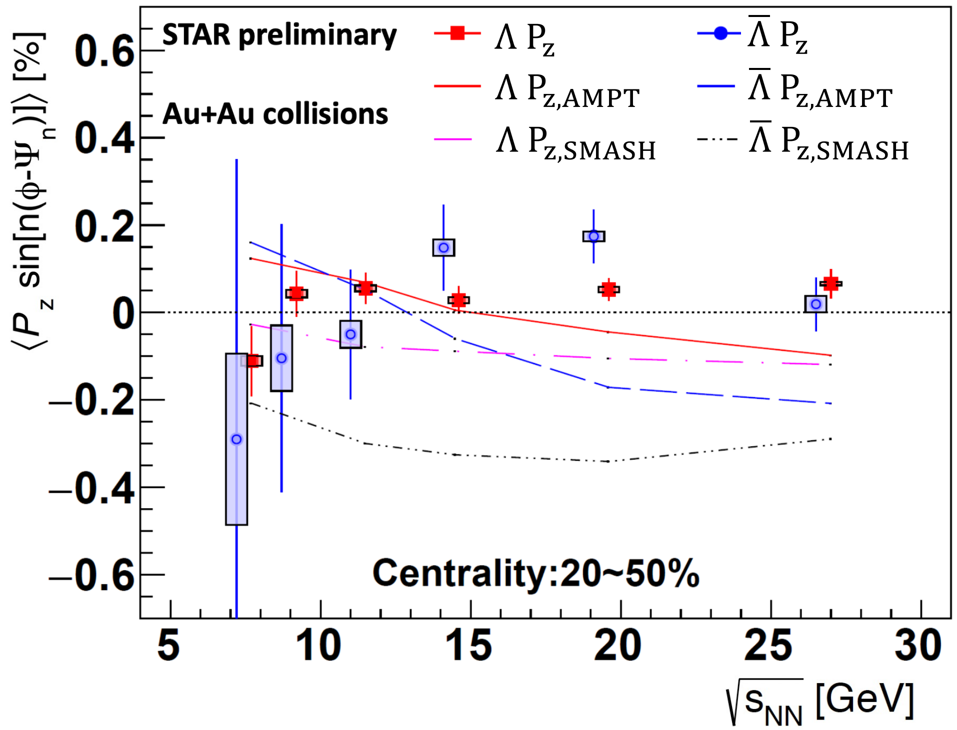
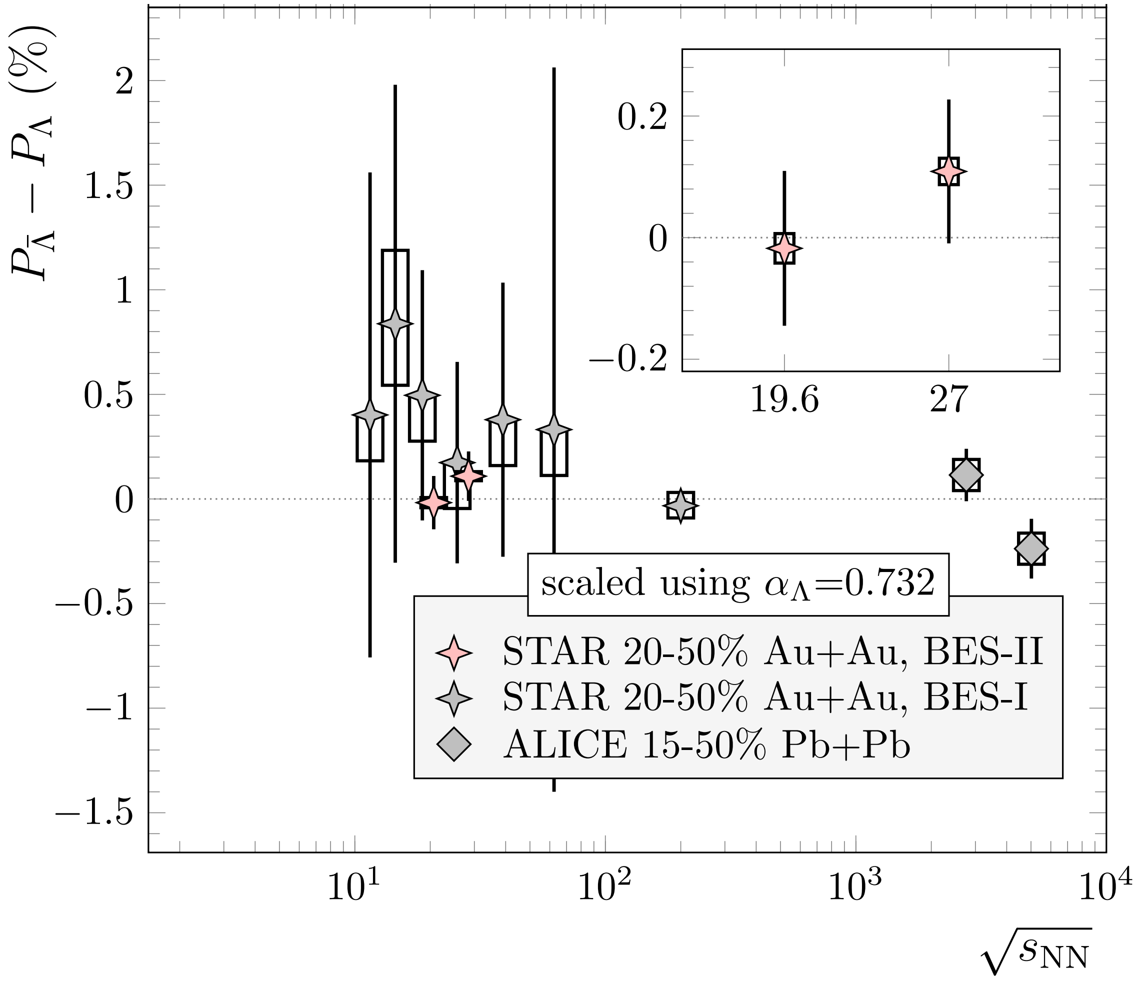




Model: X. Wu et al., PRC 105 (2022) 064909

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

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)