Polarization and Spin Alignment in Heavy-Ion Collisions

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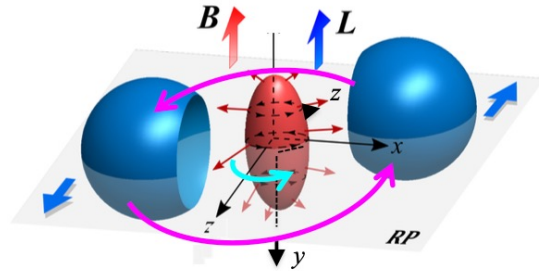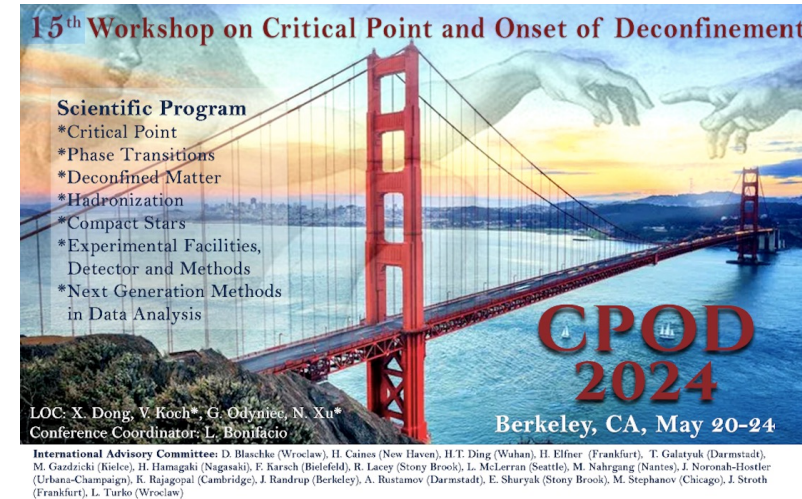
Contents

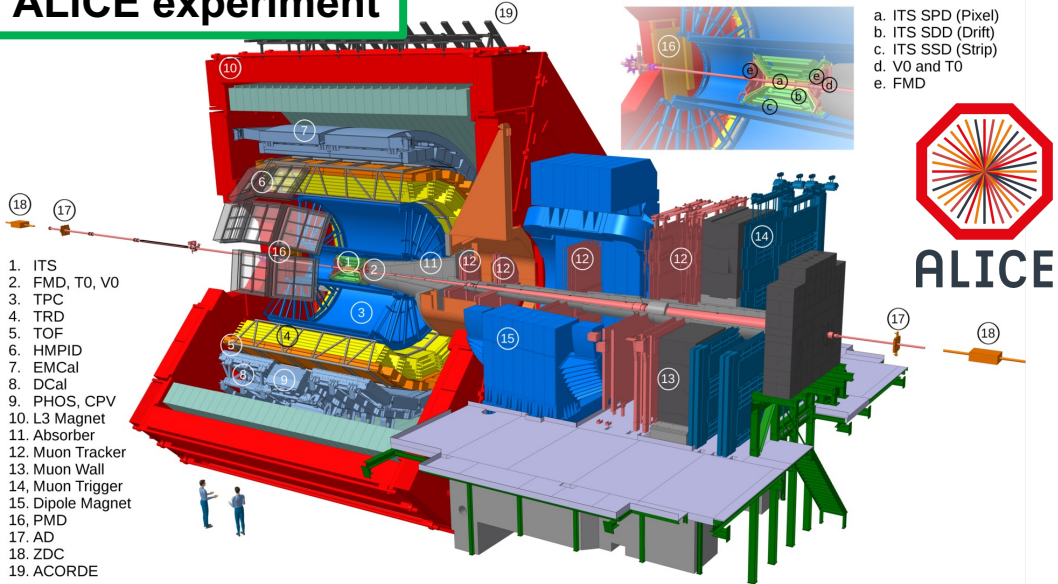- **ALICE, STAR and HADES experiments**
- **Global Polarization from GeV to TeV**
- **Λ and $\bar{\Lambda}$ difference and B-field effect**
- **Global and Longitudinal Polarization**
- **Global Spin Alignments**

ALICE, STAR and HADES detectors

ALICE experiment

a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE

ALICE

HADES experiment

START   VETO   MDC IV   MDC III   MDC II   MDC I
Target
RICH   Magnet   TOF   RPC   ECAL   FW

HADES   FAIR Phase 0 Research Program

STAR experiment

inner TPC upgrade
Event Plane Detector
endcap TOF

$\eta = -1.5$ $\eta = -1.0$ $\eta = -0.5$ $\eta = 0.0$
$\eta = -2.0$
BBC East
VPD
Fixed Target z ~ 2 m
TPC
Yellow beam
BBC West
East   West
BTOF   BEMC   EEMC   MAGNET

STAR Fixed Target (FXT) mode setup

Beam Energy Scan (BES-I) and earlier results

STAR, Nature 548 (2017) 62
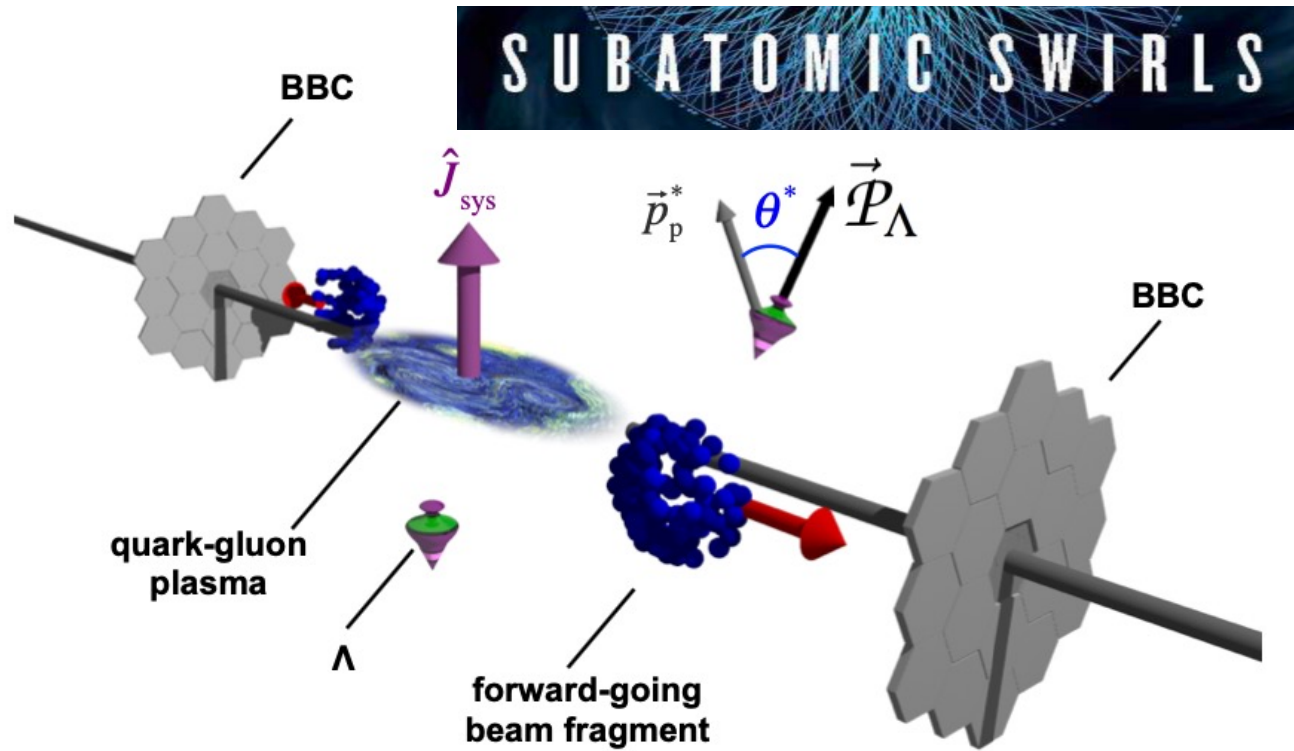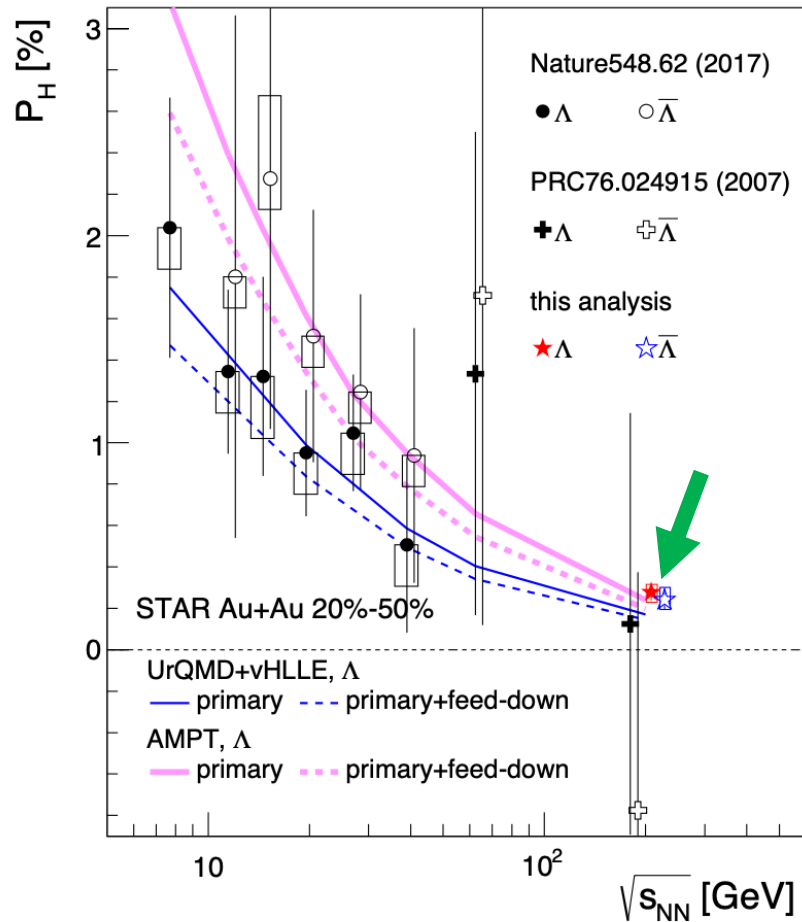

Global Lambda hyperon polarization in nuclear collisions:
evidence for the most vortical fluid

- possible difference between Λ and $\overline{\Lambda}$
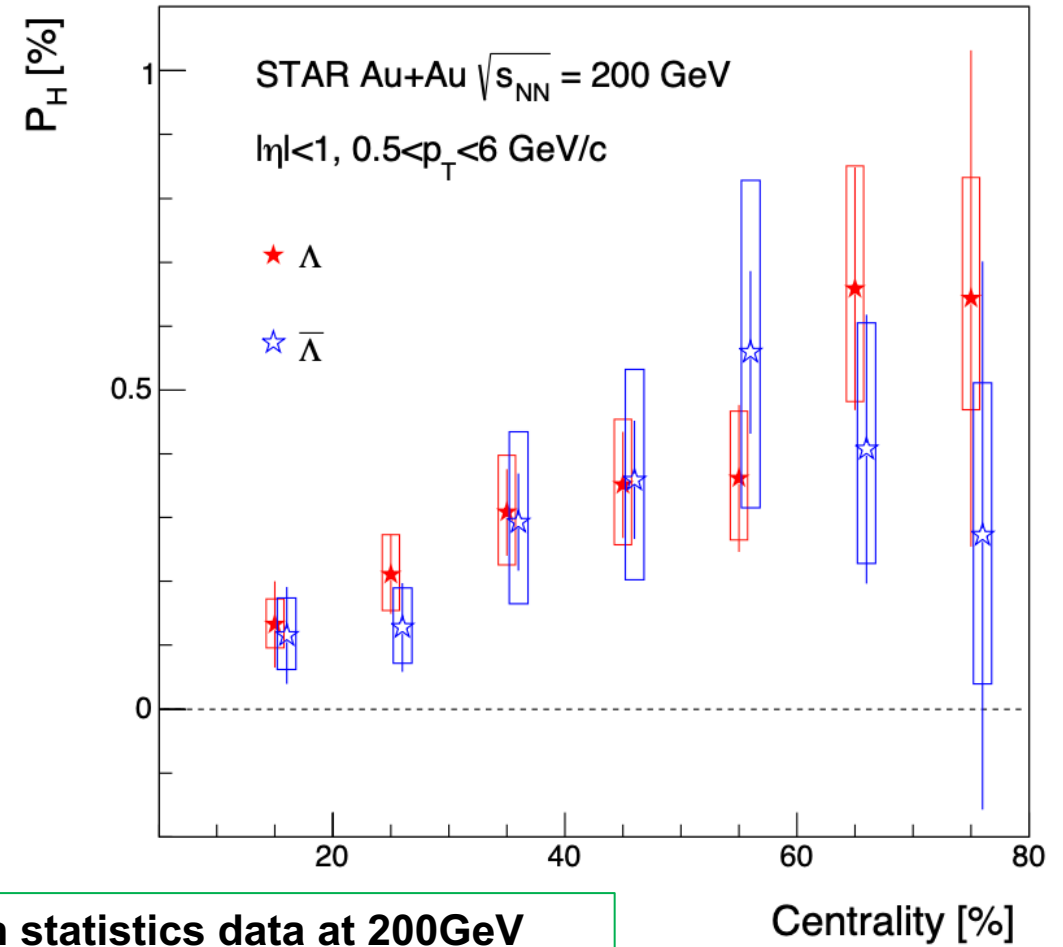- hint of B-field in addition to the angular momentum
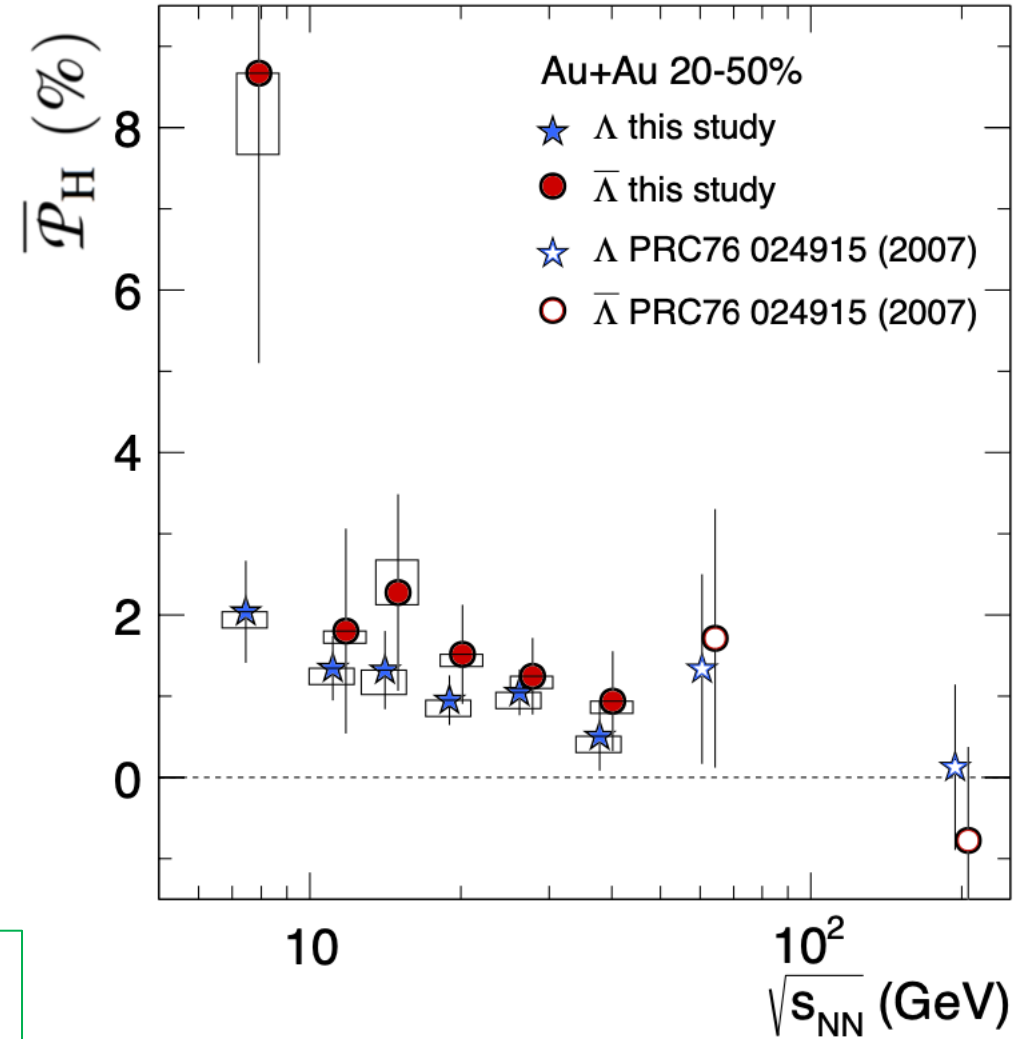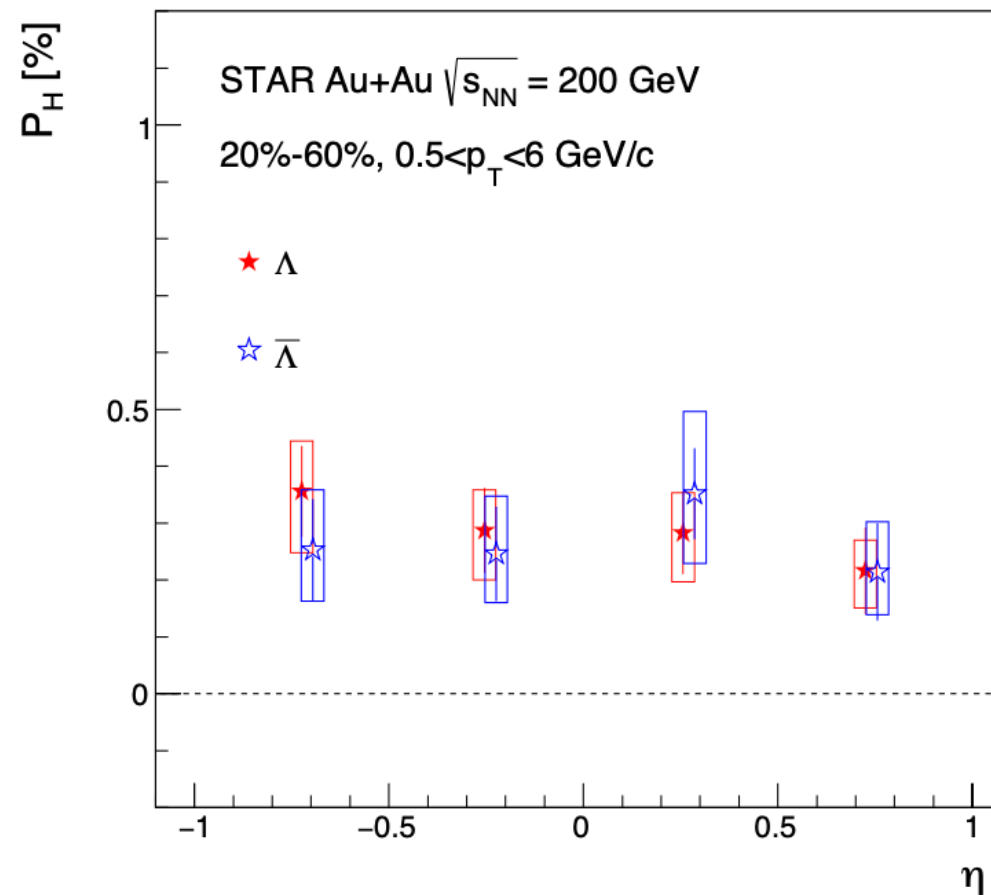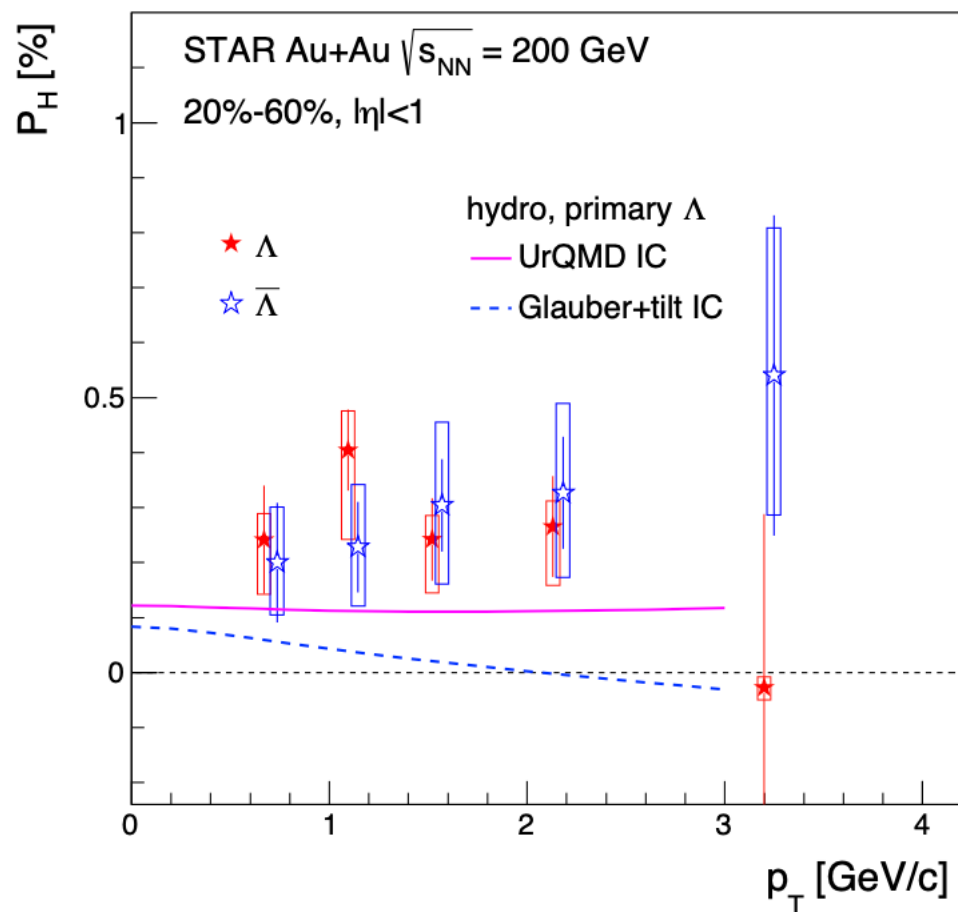
Global Polarization at 200 GeV Au+Au collisions

- **high statistics data at 200GeV**
- **clear centrality dependence**
- **similar between Λ and $\overline{\Lambda}$**

p_T and rapidity dependence at 200 GeV

STAR Au+Au $\sqrt{s_{NN}}$ = 200 GeV

20%-60%, $|\eta|<1$

★ Λ

☆ $\overline{\Lambda}$

hydro, primary Λ
— UrQMD IC
- - Glauber+tilt IC

STAR Au+Au $\sqrt{s_{NN}}$ = 200 GeV

20%-60%, $0.5<p_T<6$ GeV/c

★ Λ

☆ $\overline{\Lambda}$

minor p_T and η ($|\eta|<1$) dependence

Charge asymmetry dependence at 200 GeV

STAR, Phys. Rev. C 98 (2018) 14910

$$A_{ch} = \frac{N_+ - N_-}{N_+ + N_-}$$

clear event-by-event charge asymmetry dependence (possible B-field effect)

STAR Au+Au $\sqrt{s_{NN}}$ = 200 GeV 20%-60%

$|\eta|<1$, $0.5<p_T<6$ GeV/c

$\star \Lambda$ $\star \overline{\Lambda}$

slope ± stat.uncert. ± syst.uncert.

Λ: 0.097 ± 0.041 ± 0.043 [%]

$\overline{\Lambda}$: -0.112 ± 0.045 ± 0.102 [%]

observed $A_{ch} / \sigma_{A_{ch}}$
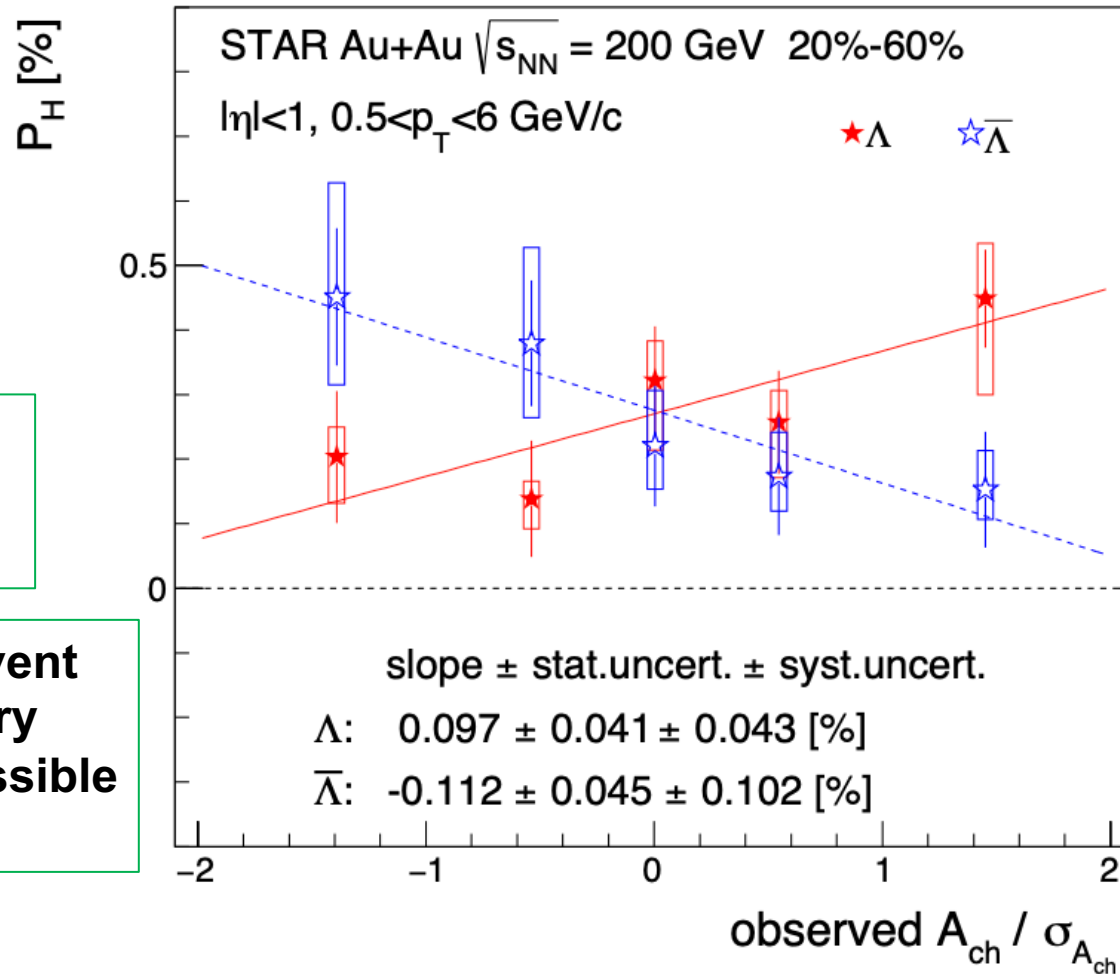
QM18, STAR
Nucl. Phys. A 982 511 (2019)

STAR Preliminary   Au+Au 200GeV

20-50%

Λ and $\overline{\Lambda}$ combined
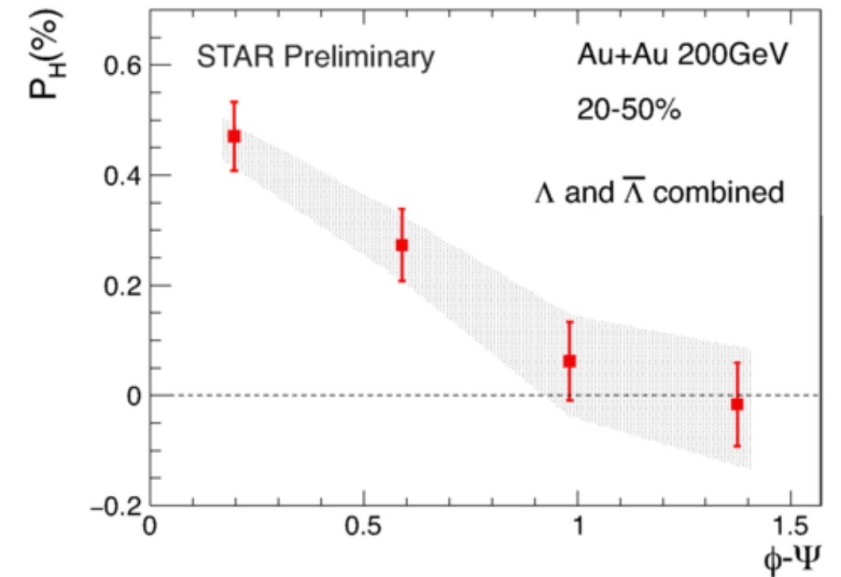
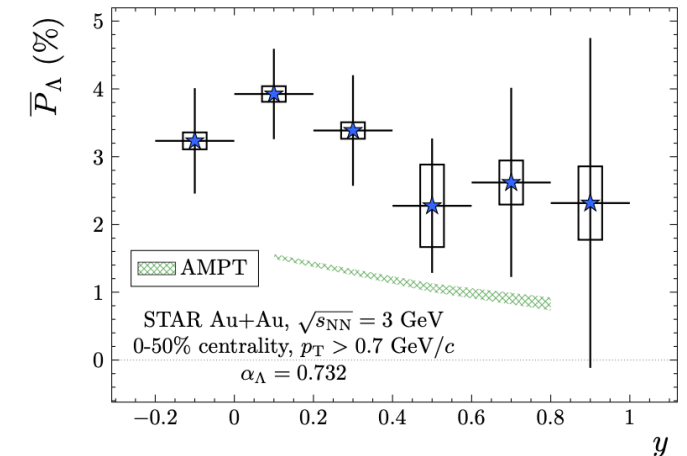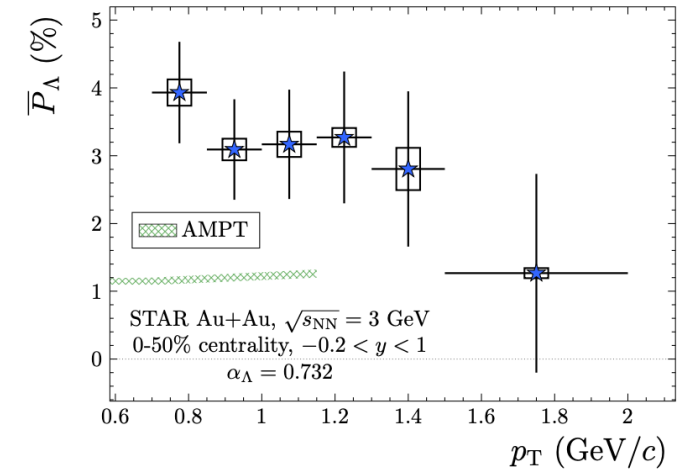**clear azimuthal angle dependence In-plane > Out-of-plane (like v2)**
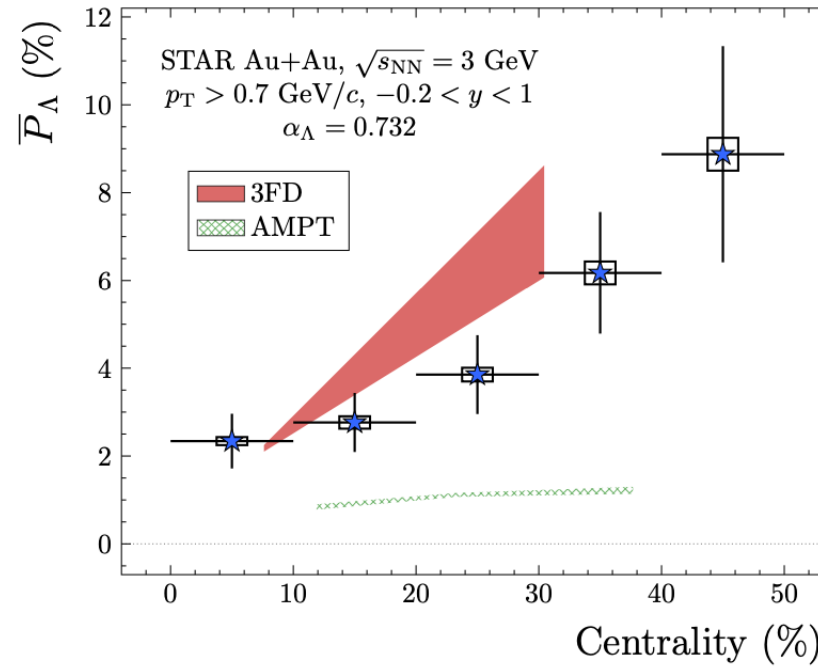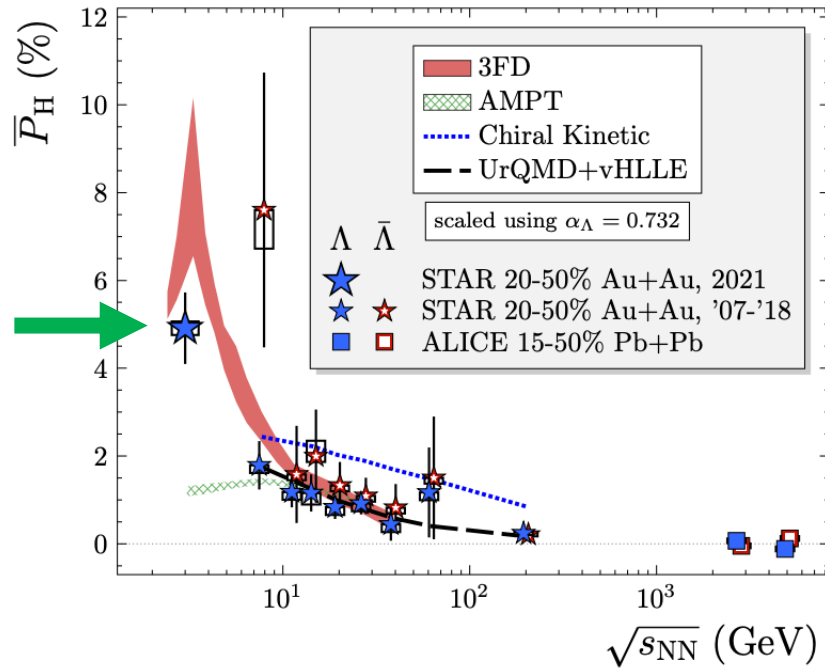
ALICE, Phys. Rev. C 101 (2020) 044611
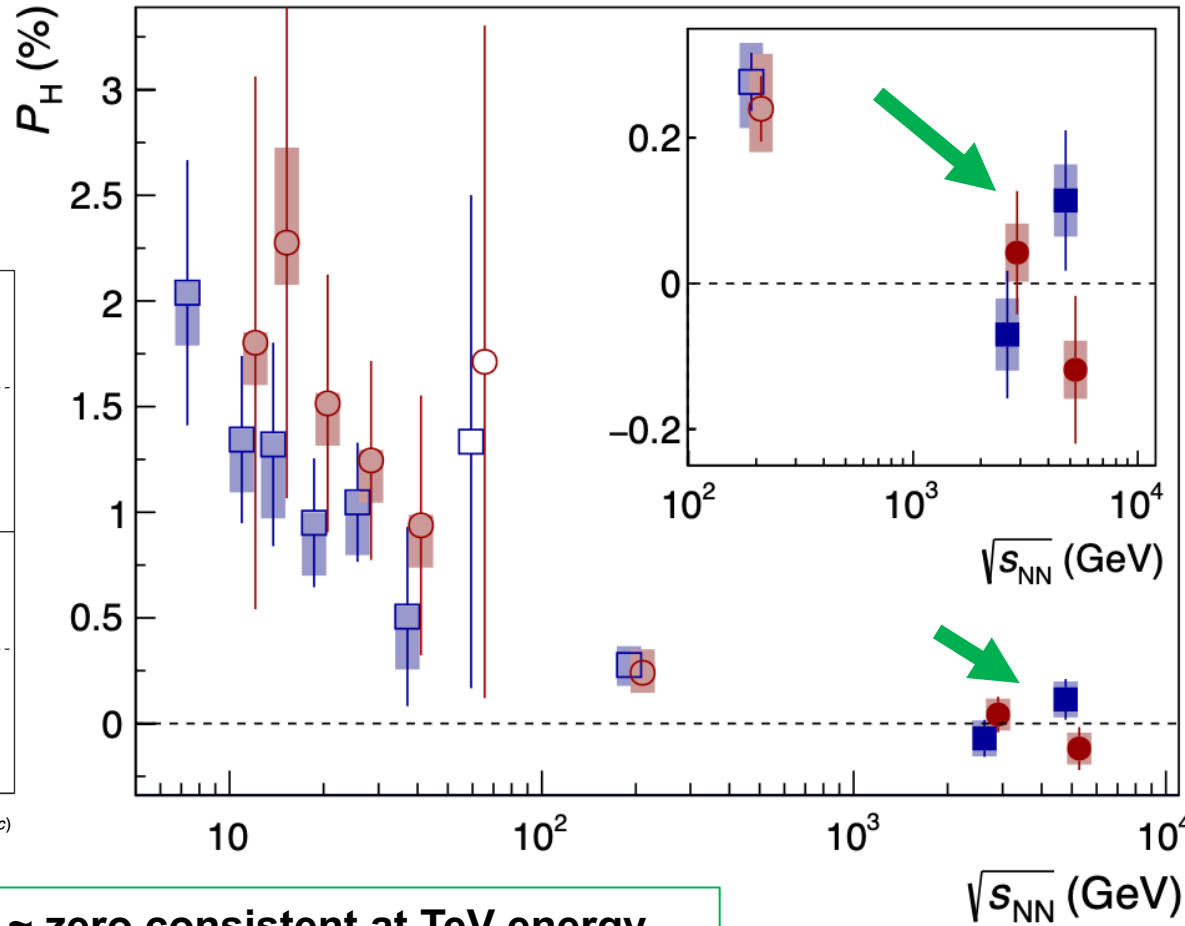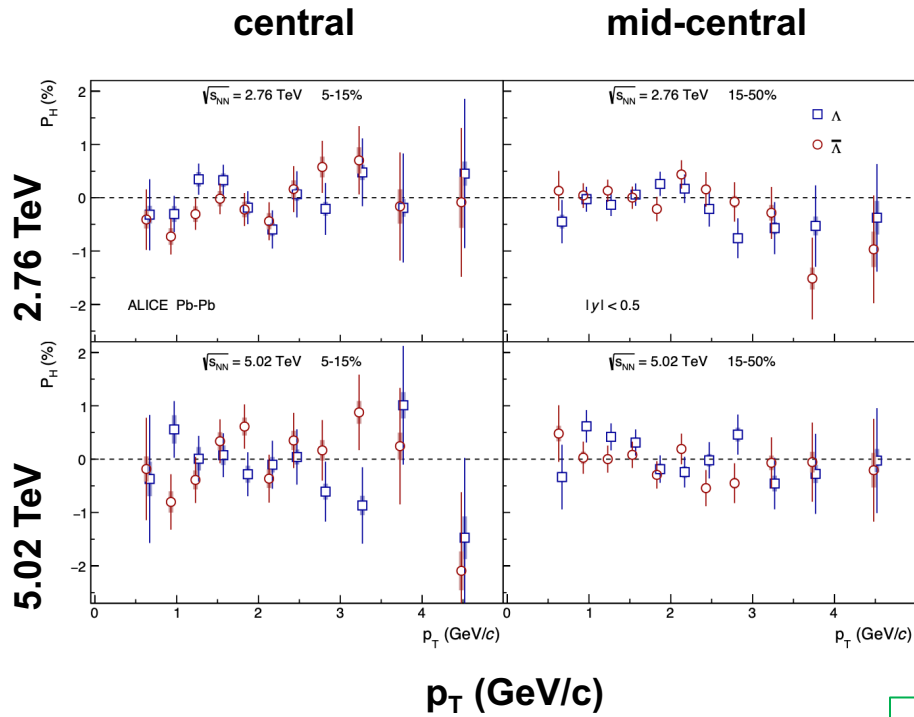
~ zero consistent at TeV energy
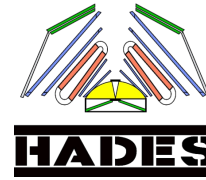
Global Polarization at 3 GeV

STAR, Phys. Rev. C 104 (2021) 61901
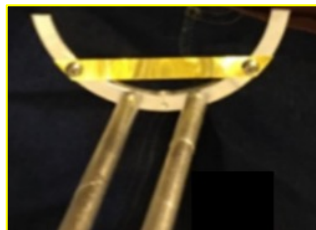
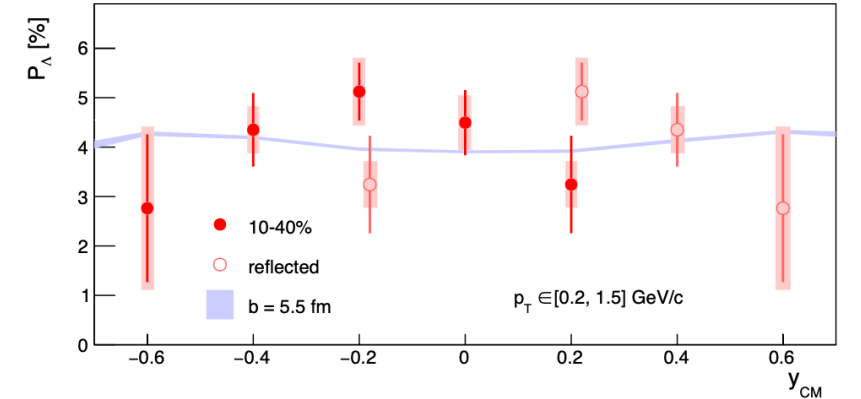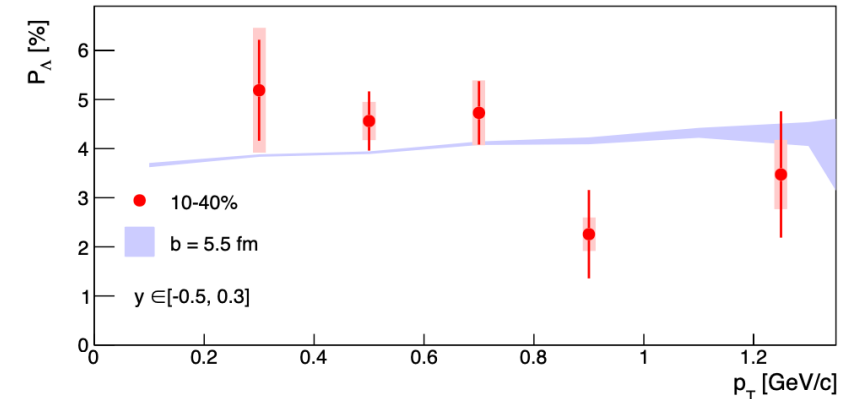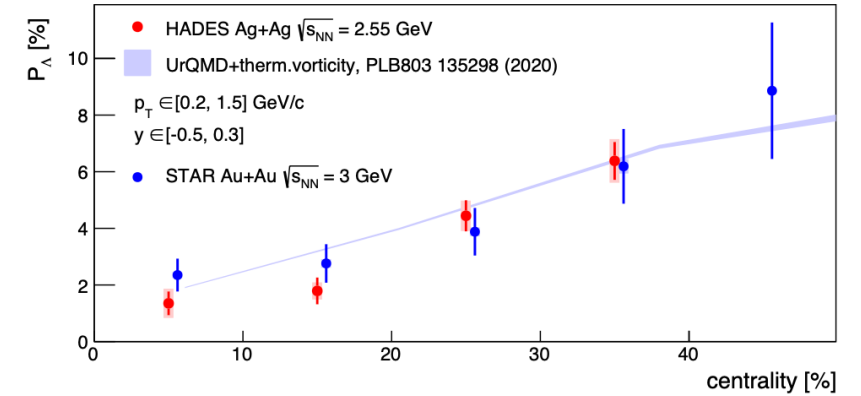- **increasing trend towards lower beam energy**
- **similar centrality dependence**
- **minor p_T and rapidity dependence**

STAR FXT

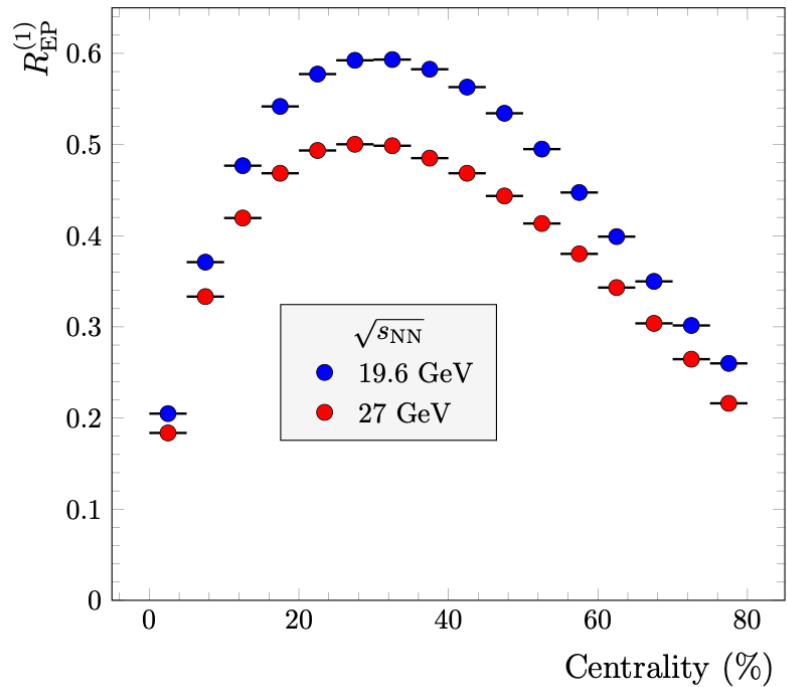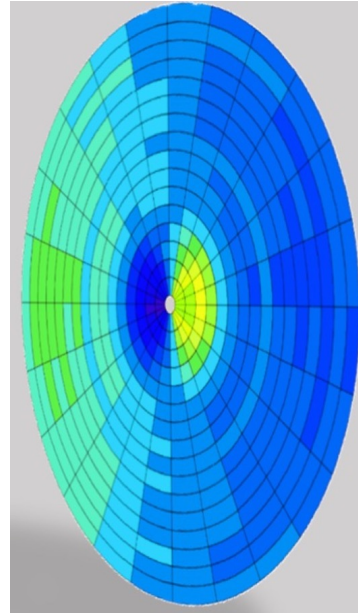# Global Polarization in few-GeV (HADES)

2.4~2.55 GeV

Phys. Lett. B 835 (2022) 137506
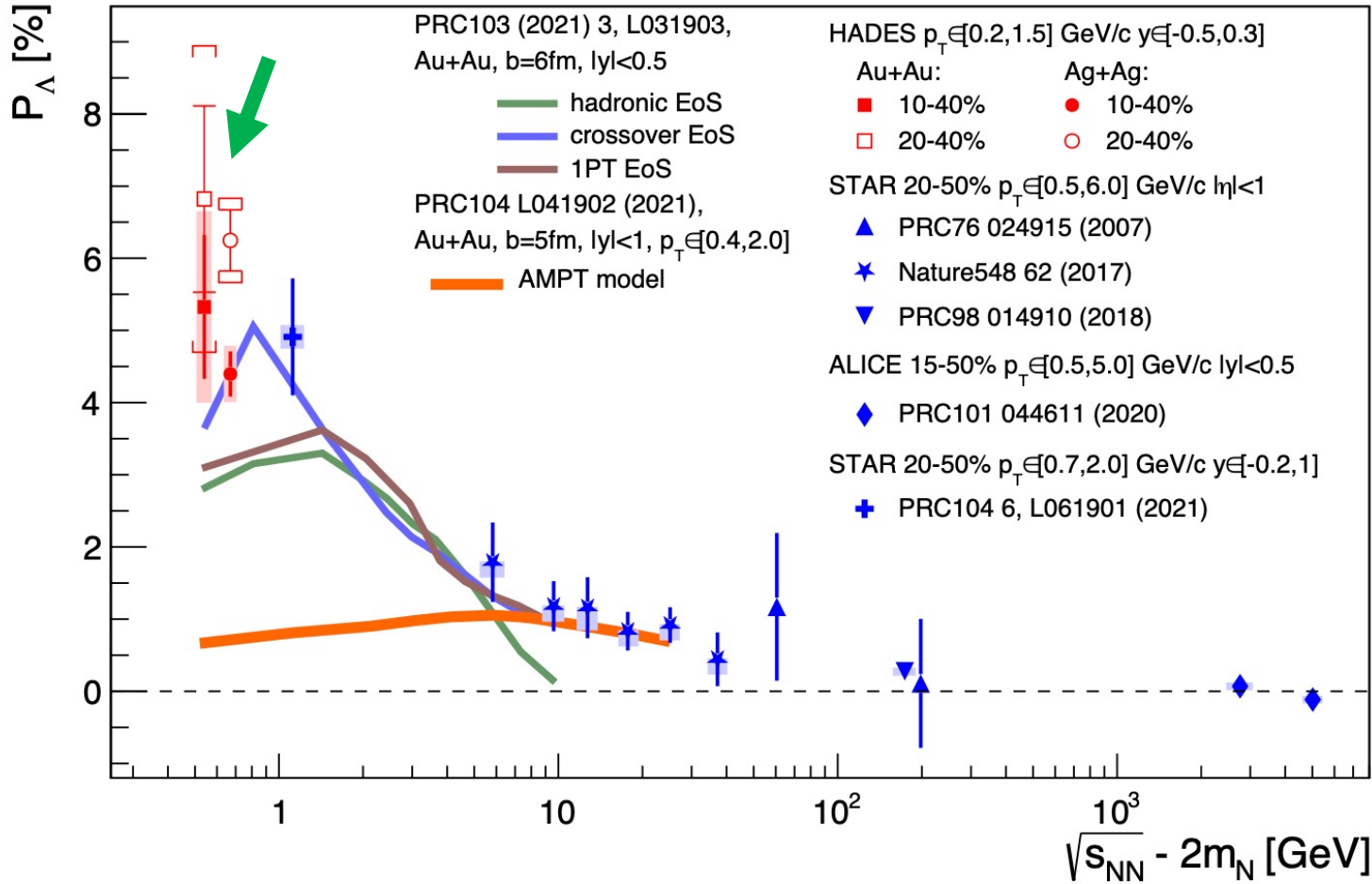
similar centrality and kinematic dependences

Global Polarization at 19.6-27 GeV (BES-II) : difference between Λ and $\overline{\Lambda}$

STAR, Phys. Rev. C 108 (2023) 14910

STAR EPD

BES-II statistics (~ x20 increased) improved E.P. resolution with EPD

no hint of significant difference between Λ and $\overline{\Lambda}$ (no B-field)
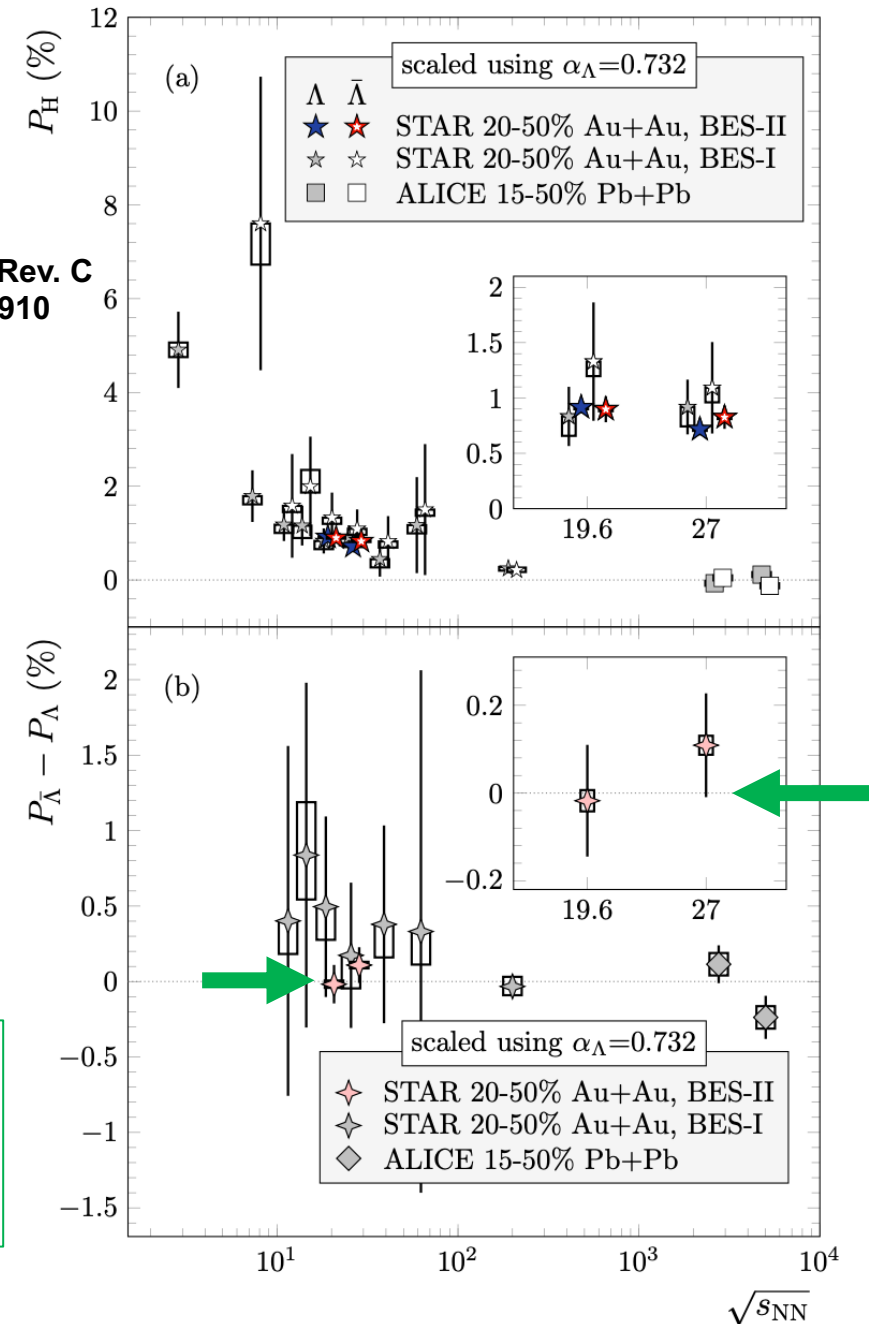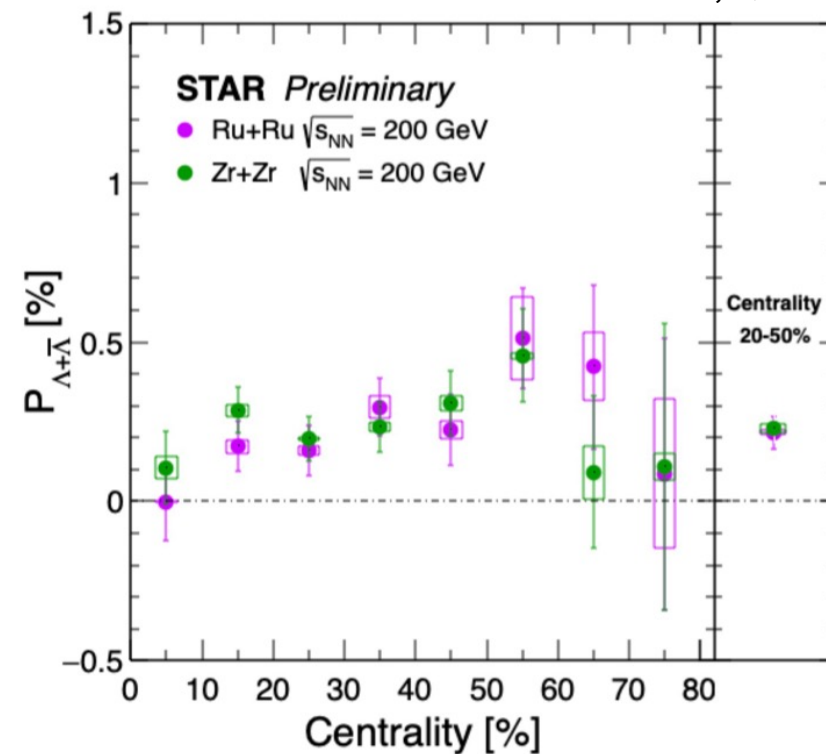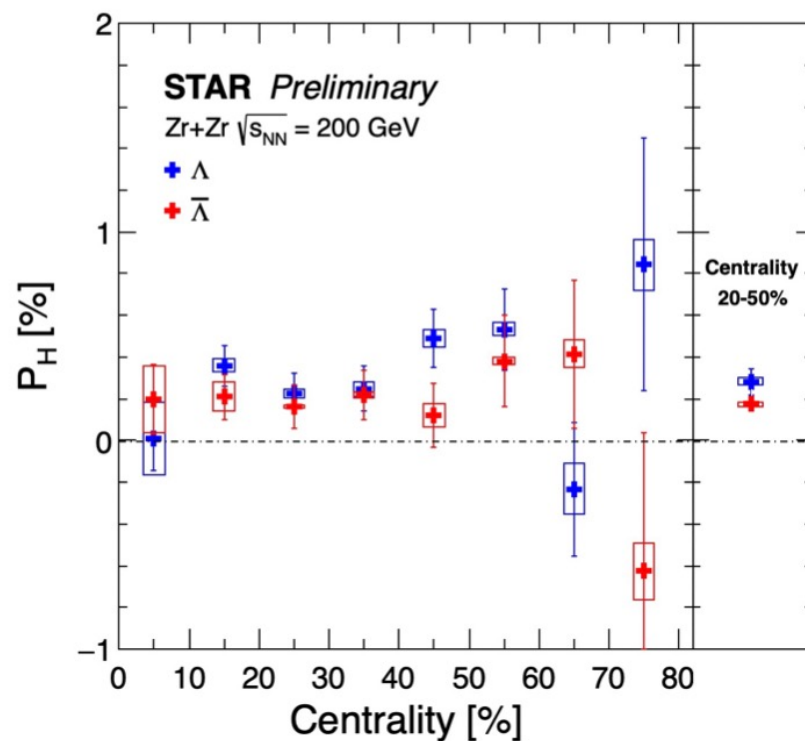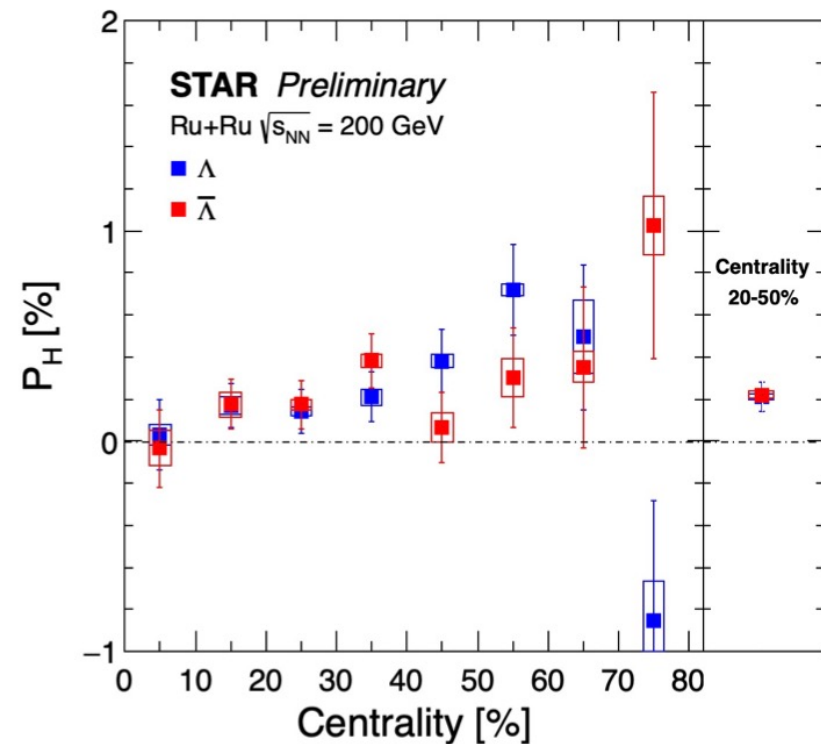
Global Polarization in Isobar (Ru+Ru, Zr+Zr) collisions at 200 GeV
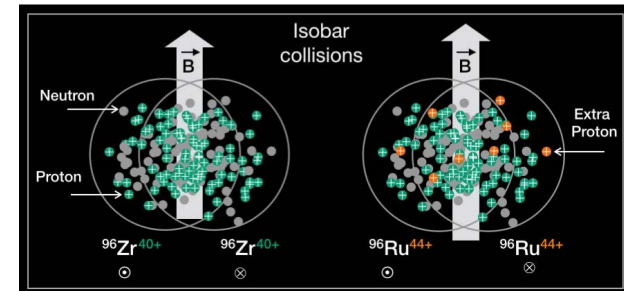
STAR, QM23
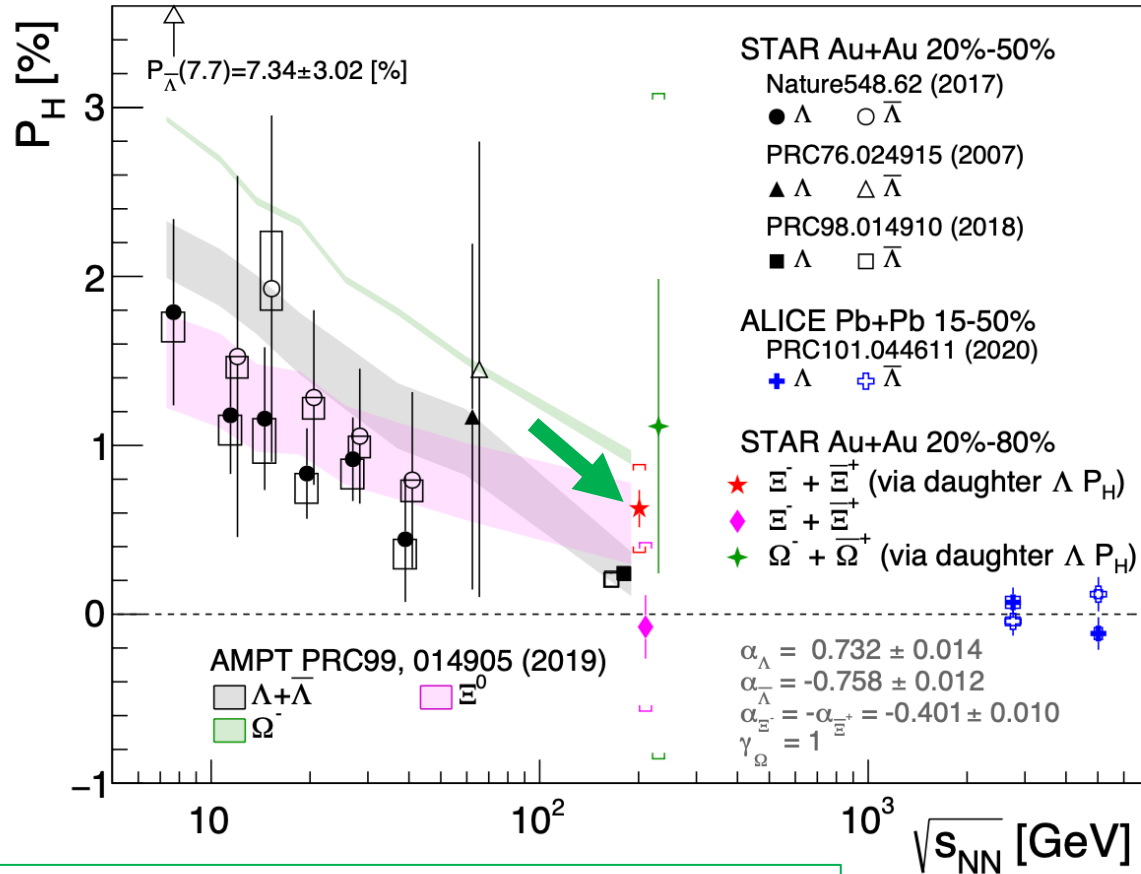

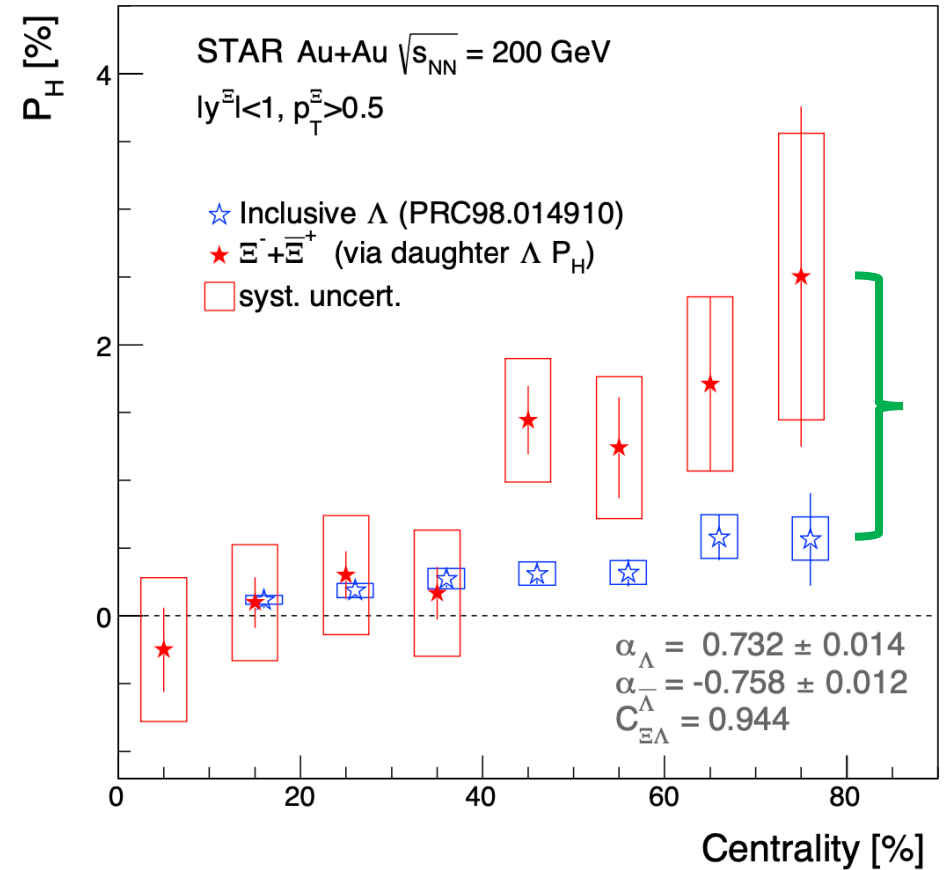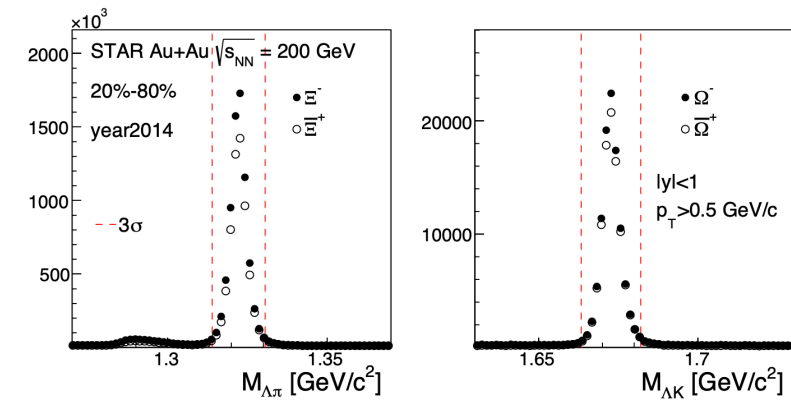- **comparable between Λ and $\overline{\Lambda}$ and between two isobar systems (no hint of B-field)**
- **similar centrality dependences**
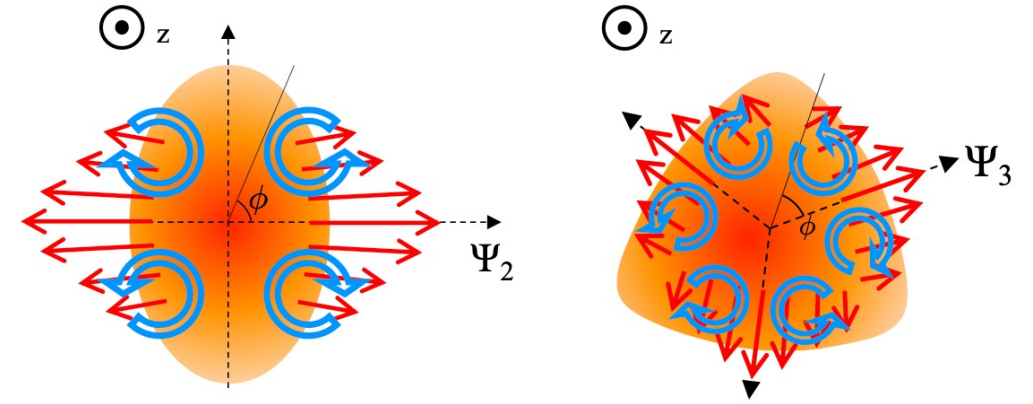
Global Polarization with Ξ and Ω at 200 GeV

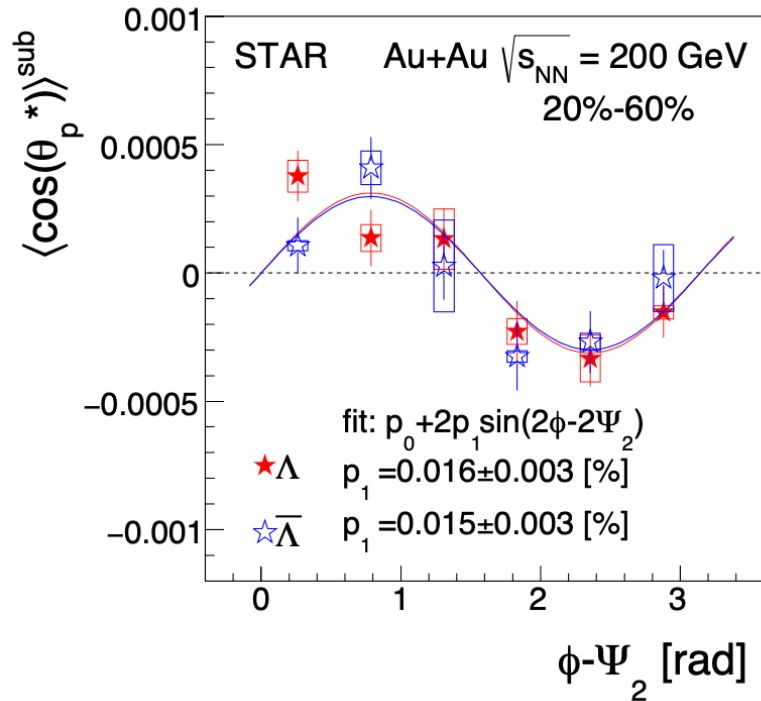STAR, Phys. Rev. Lett. 126 (2021) 162301

somewhat larger for multi-strange hyperon

Longitudinal (along z) Polarization via v_2 and v_3 expansions at 200 GeV

STAR, Phys. Rev. Lett. 123 (2019) 132301

STAR, Phys. Rev. Lett. 131 (2023) 202301

STAR   Au+Au $\sqrt{s_{NN}}$ = 200 GeV   20%-60%

fit: $p_0 + 2p_1 \sin(2\phi - 2\Psi_2)$
Λ p_1 = 0.016 ± 0.003 [%]
$\overline{\Lambda}$ p_1 = 0.015 ± 0.003 [%]

$\langle \cos(\theta_p^*) \rangle^{sub}$ $\phi - \Psi_2$ [rad]

Ru+Ru&Zr+Zr $\sqrt{s_{NN}}$ = 200 GeV
Centrality: 20%-60%

fit: $p_0 + 2p_1 \sin(2\phi - 2\Psi_2)$
Λ p_1 = 0.020 ± 0.002 [%]
$\overline{\Lambda}$ p_1 = 0.021 ± 0.002 [%]

$sgn(\alpha_H) \langle \cos(\theta_p^*) \rangle^{sub}$ $2(\phi - \Psi_2)$ [rad]

Ru+Ru&Zr+Zr $\sqrt{s_{NN}}$ = 200 GeV
Centrality: 20%-60%

fit: $p_0 + 2p_1 \sin(3\phi - 3\Psi_3)$
Λ p_1 = 0.006 ± 0.002 [%]
$\overline{\Lambda}$ p_1 = 0.010 ± 0.002 [%]

$sgn(\alpha_H) \langle \cos(\theta_p^*) \rangle^{sub}$ $3(\phi - \Psi_3)$ [rad]
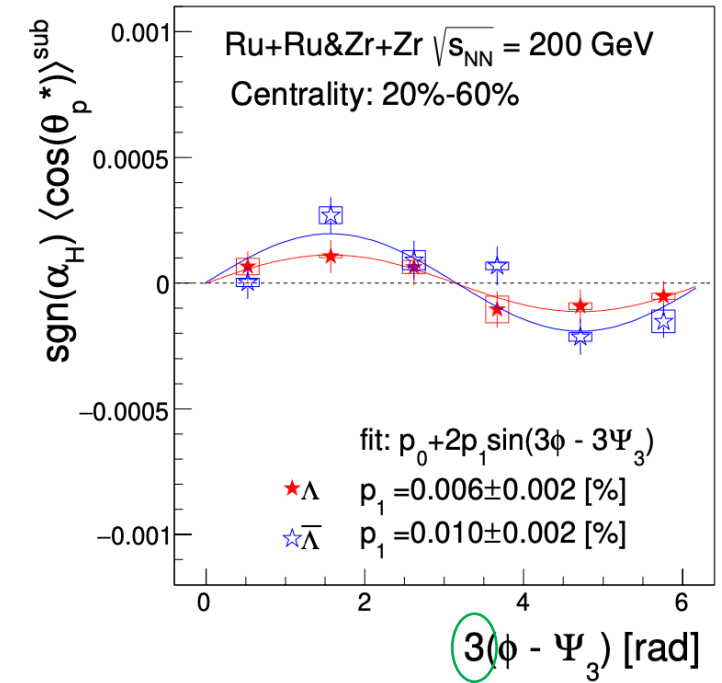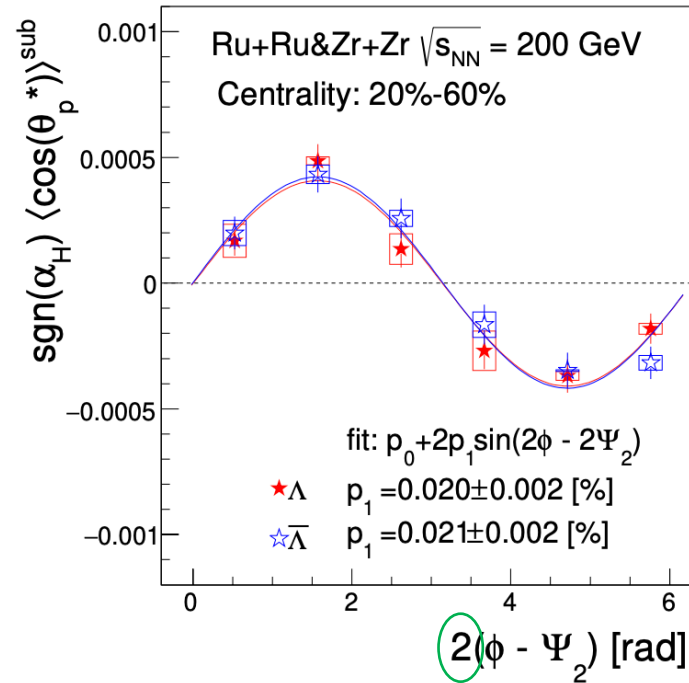
clear 2 and 3 fold asymmetry

Longitudinal (along z) Polarization at LHC (ALICE)

ALICE, Phys. Rev. Lett. 128 (2022) 172005

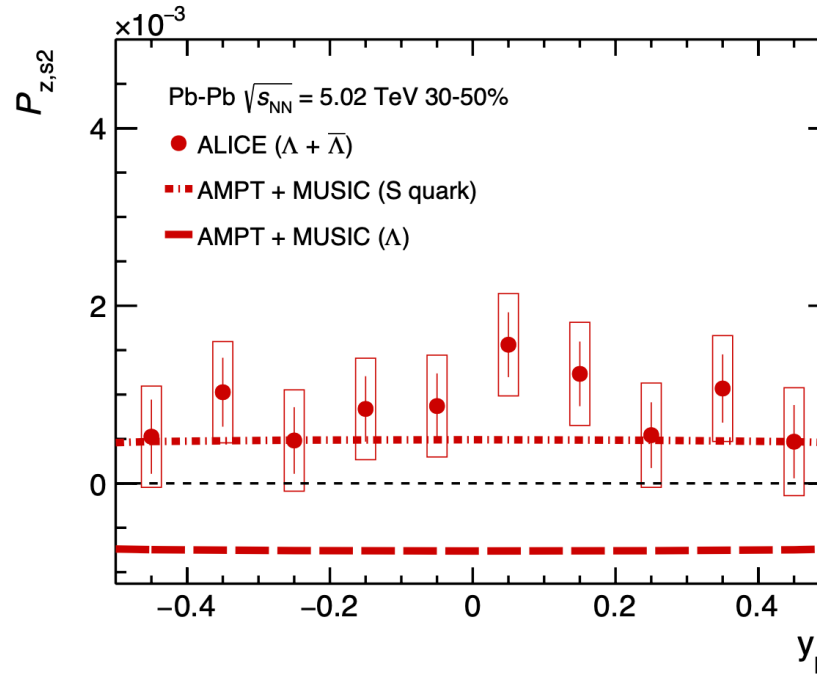Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
● ALICE ($\Lambda + \overline{\Lambda}$)
─·─ AMPT + MUSIC (S quark)
━━ AMPT + MUSIC (Λ)

Au-Au $\sqrt{s_{NN}}$ = 200 GeV
☆ STAR × 0.856 ($\Lambda + \overline{\Lambda}$)
STAR, PRL, 123, 132301 (2019)

Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV 30-50% Au-Au $\sqrt{s_{NN}}$ = 200 GeV 20-60%
● ALICE ($\Lambda + \overline{\Lambda}$)   ☆ STAR × 0.856 ($\Lambda + \overline{\Lambda}$)
─·─ AMPT + MUSIC (S quark)   STAR, PRL, 123, 132301 (2019)
━━ AMPT + MUSIC (Λ)

Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV 30-50%
● ALICE ($\Lambda + \overline{\Lambda}$)
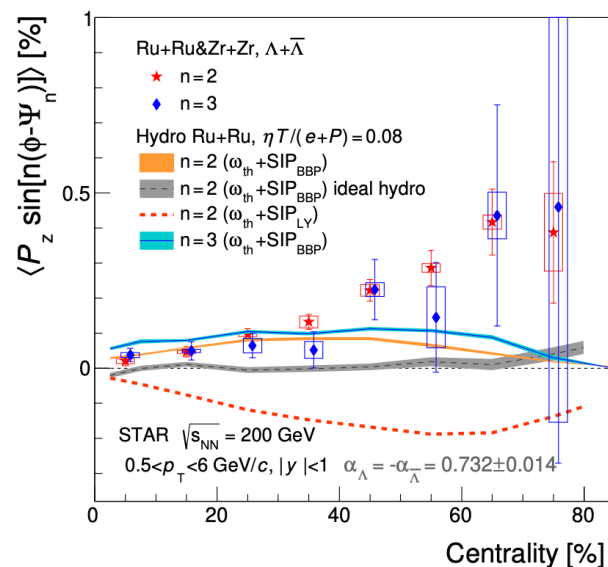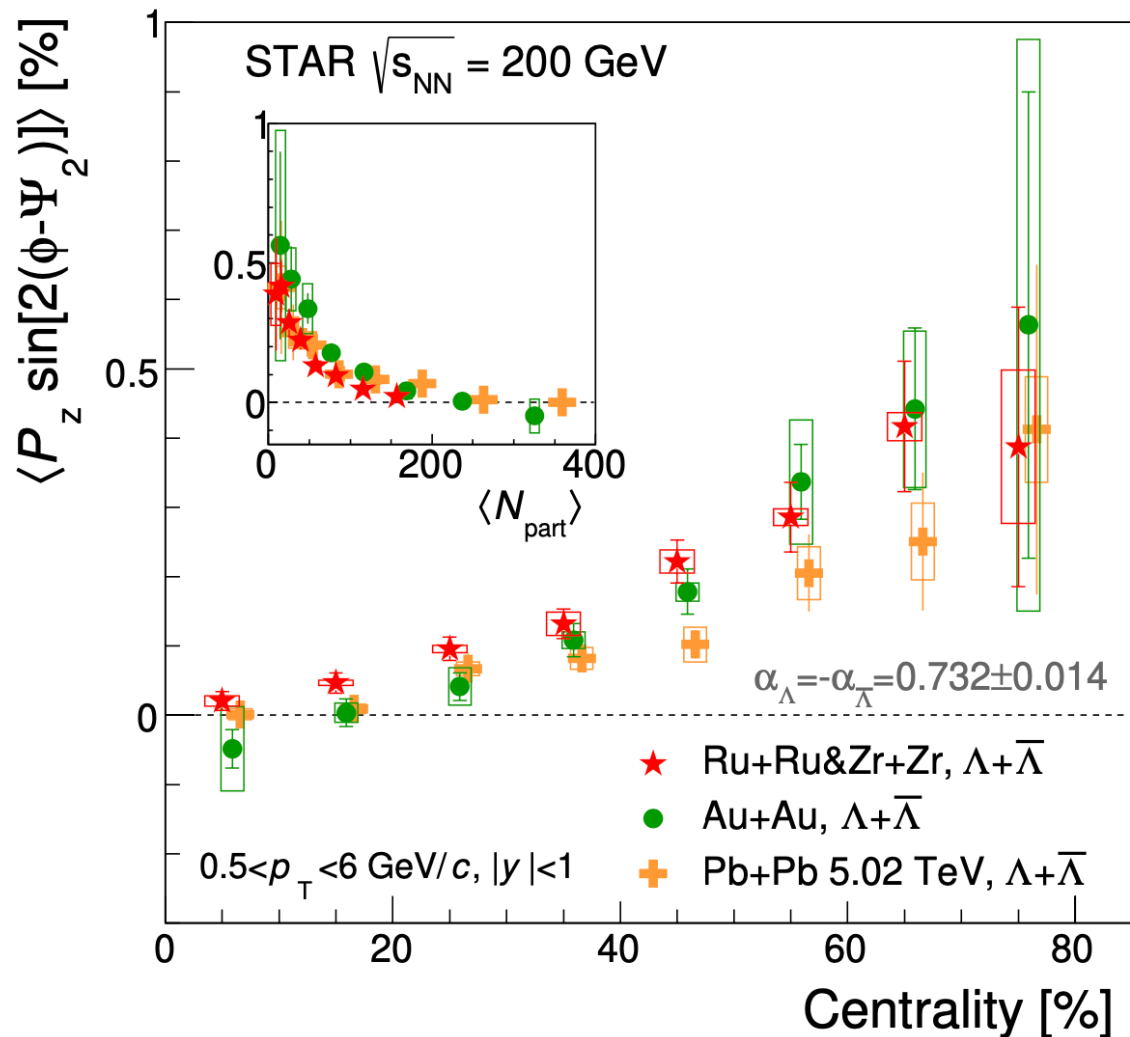─·─ AMPT + MUSIC (S quark)
━━ AMPT + MUSIC (Λ)
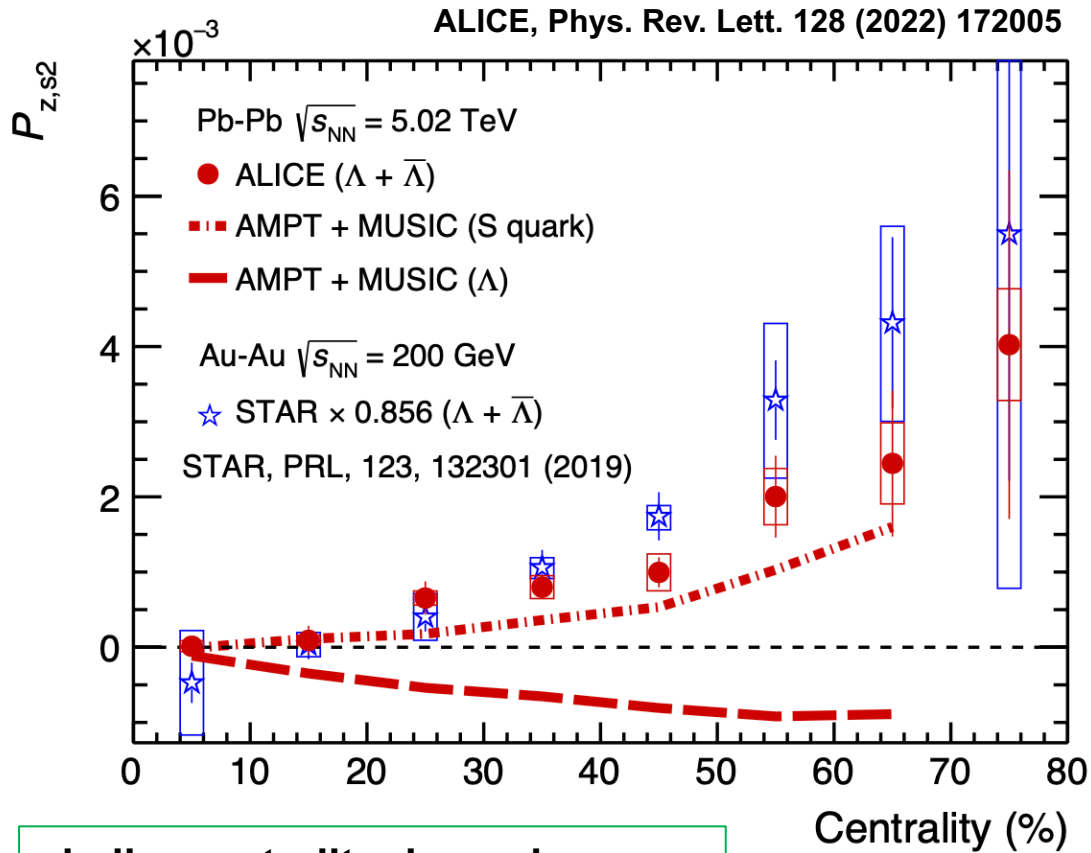
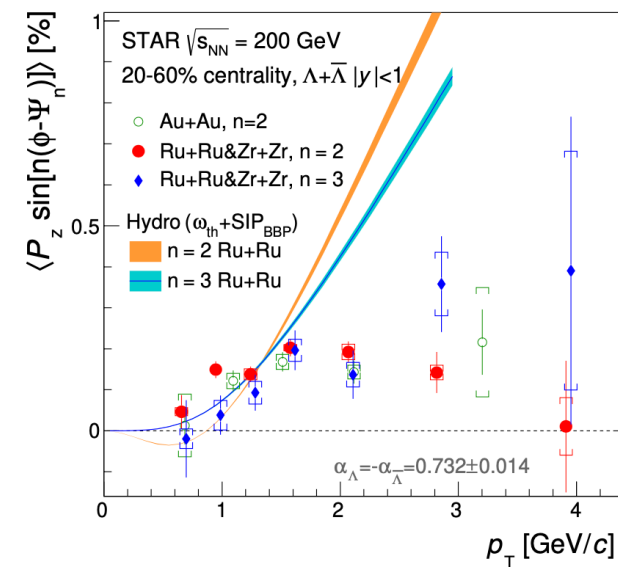**similar centrality dependences compared with RHIC**
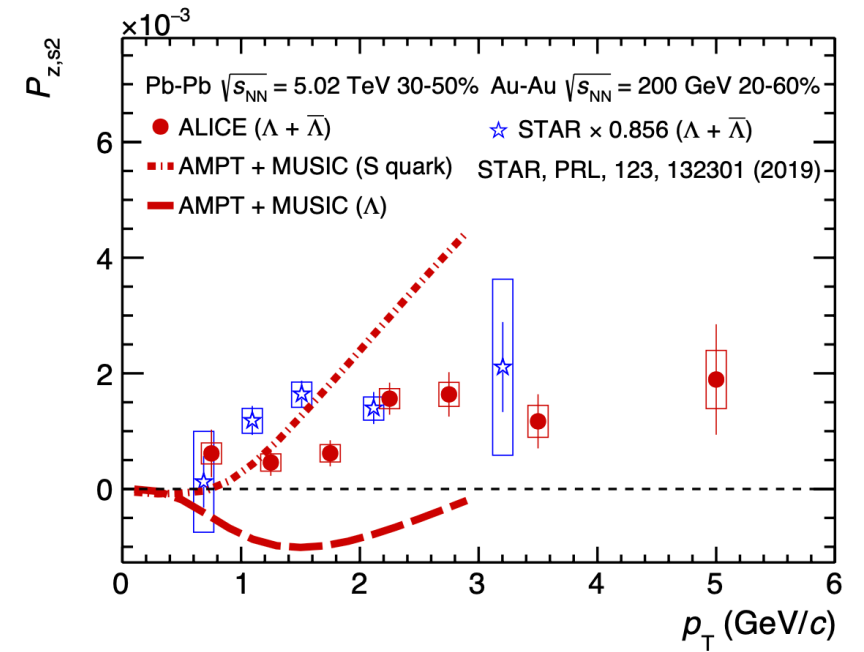
increasing p_T and mild rapidity dependences

Longitudinal (along z) Polarizations at RHIC&LHC including Isobar collisions

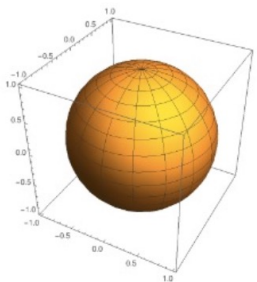
STAR, Phys. Rev. Lett. 131 (2023) 202301

similar centrality (and p_T) dependences between
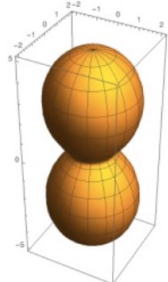(1) energies, (2) systems and (3) orders (n=2, 3)

similarity between P_Z (long-) and P_Y (global-) shape
as a function of centrality, which is more similar to
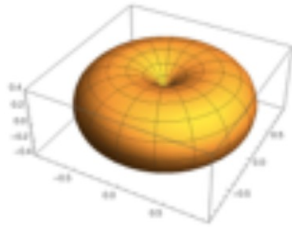v_1(cent.) shape than to v_2(cent.) shape

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* \right]$$
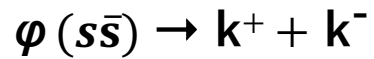
$$\rho_{00} = \frac{1}{3}$$

$$\rho_{00} > \frac{1}{3}$$

$$\rho_{00} < \frac{1}{3}$$
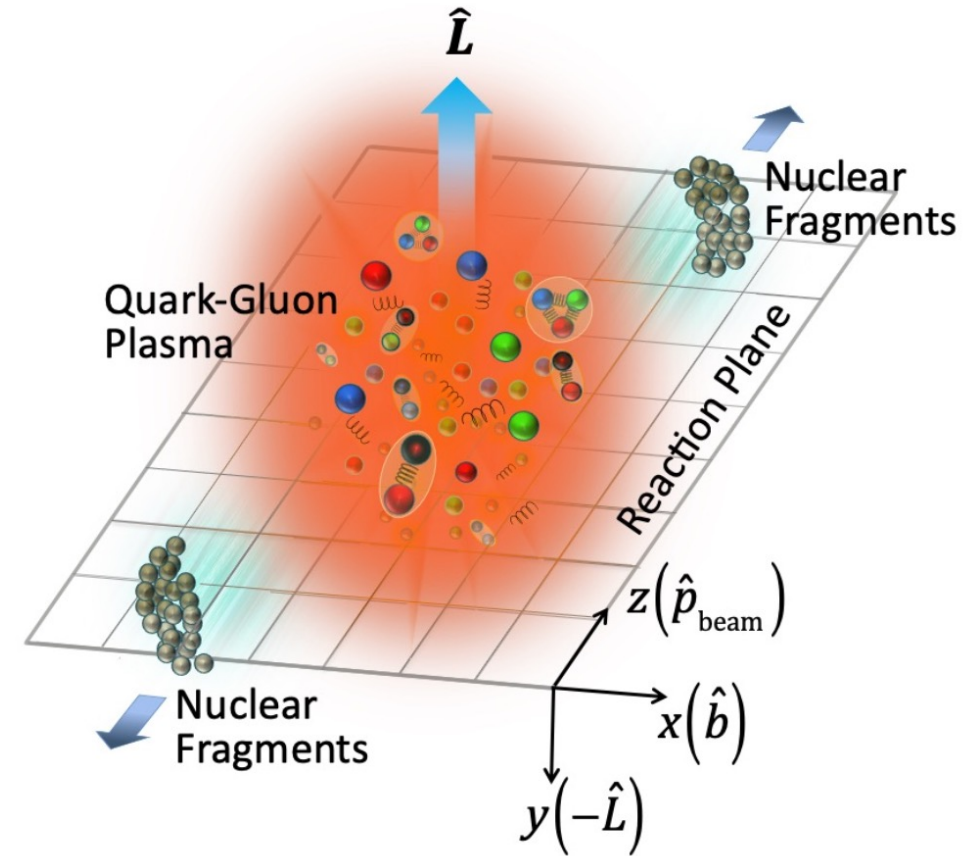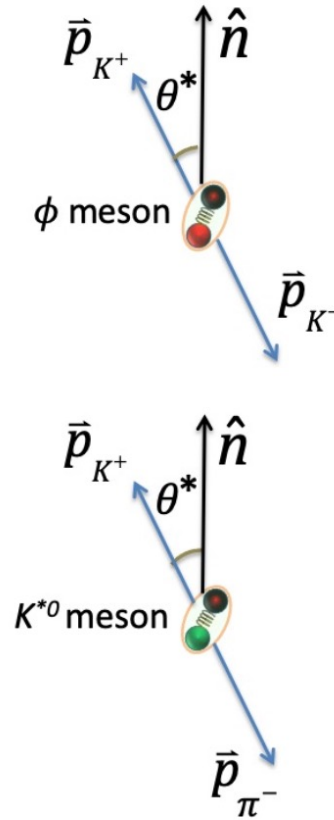
ρ_{00} of ϕ and K^{*0} in BES-I and LHC

$\rho_{00} > 1/3$ for

$$\varphi\,(s\bar{s}) \to k^+ + k^-$$

$\rho_{00} \sim 1/3 \;(< 1/3)$ for

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

- **global spin alignment (local field fluctuation)**

- **global polarization (global average field)**

Plot legend:
- ⭐ ϕ (|y| < 1.0 & 1.2 < p_T < 5.4 GeV/c)
- ● K^{*0} (|y| < 1.0 & 1.0 < p_T < 5.0 GeV/c)

filled: STAR (Au+Au & 20% - 60% Centrality)
open: ALICE (Pb+Pb & 10% - 50% Centrality)

Axes: ρ_{00} versus $\sqrt{s_{NN}}$ (GeV)
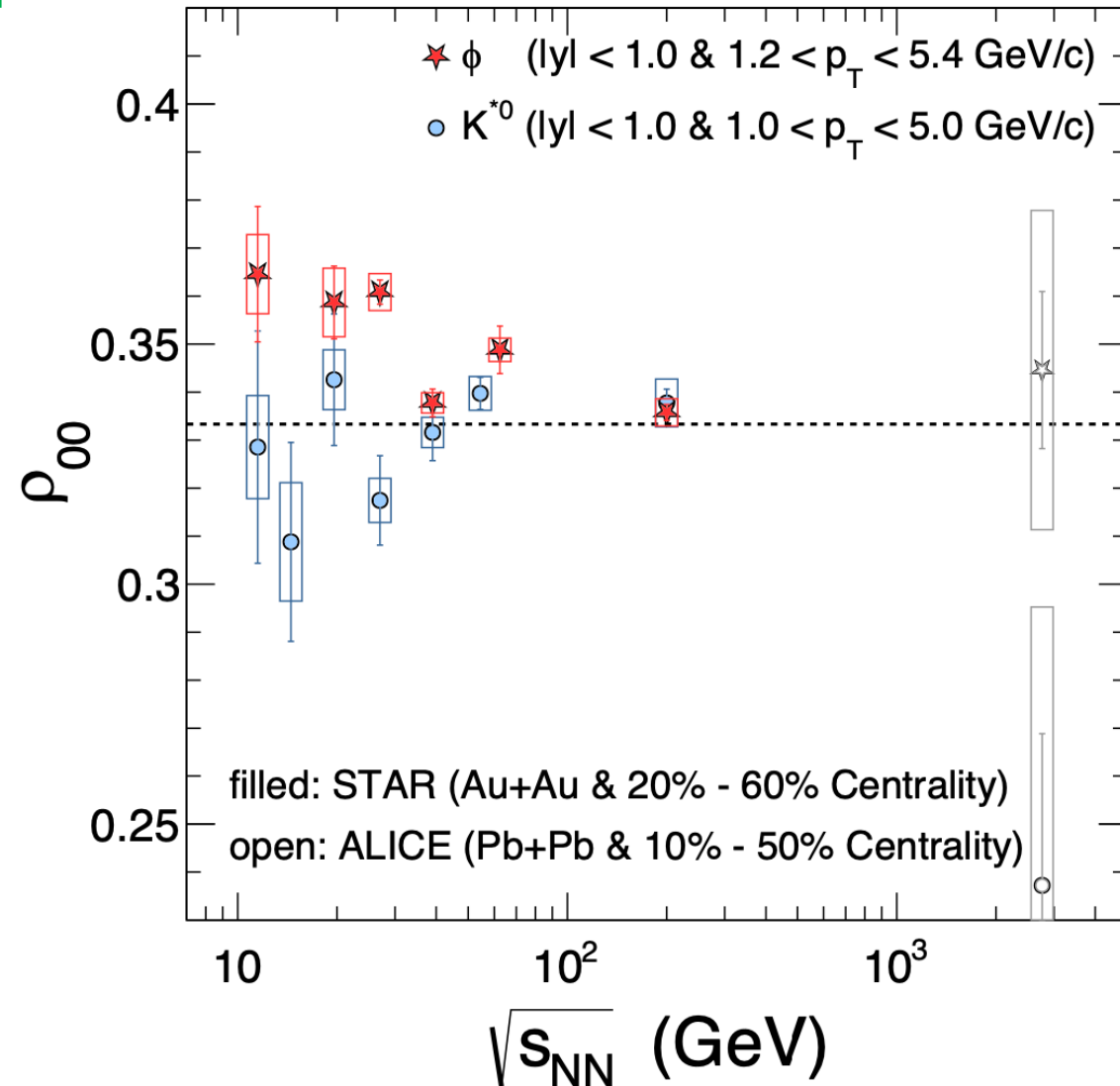
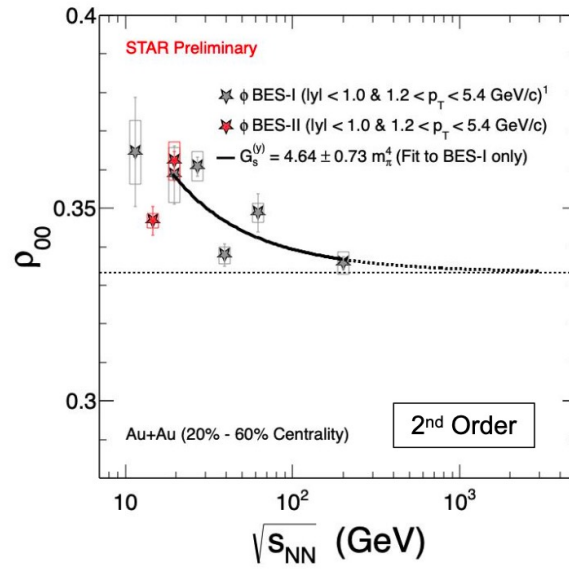# ρ_{00} of ϕ in BES-II (with BES-I)

1st order R.P.
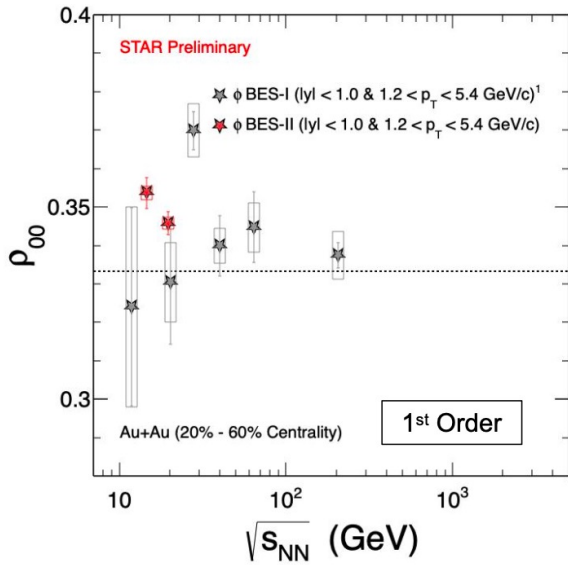
2nd order R.P.

14.6 GeV

19.6 GeV
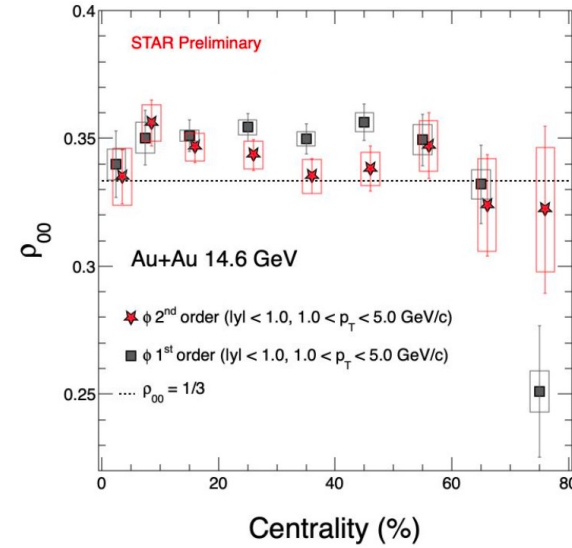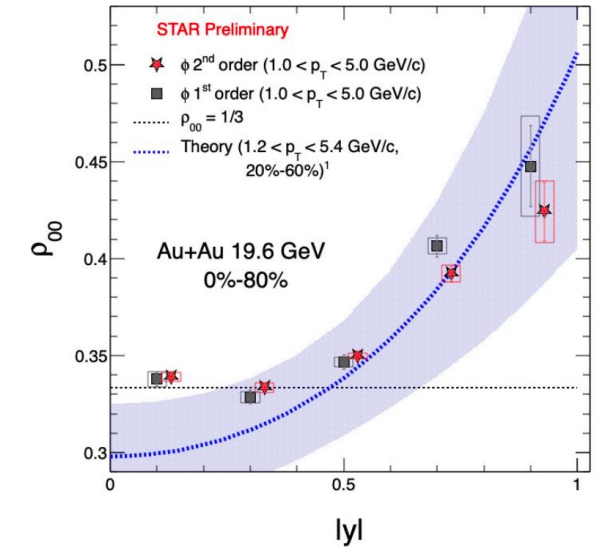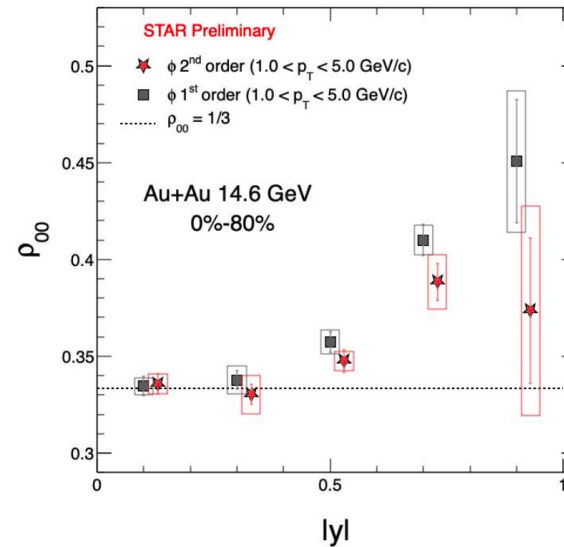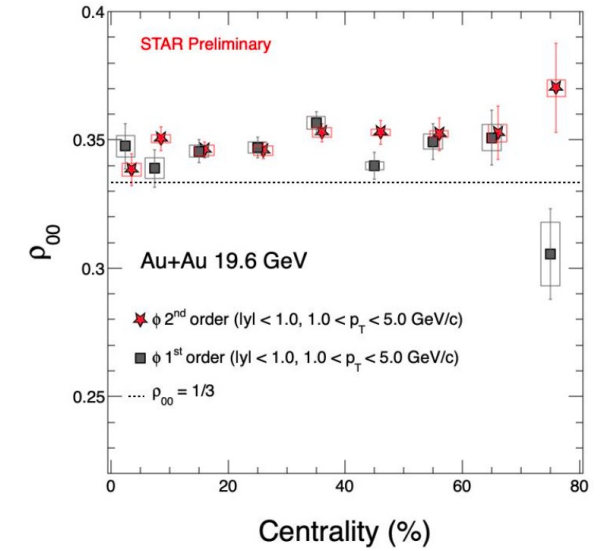
- **consistency between 1st and 2nd order R.P.?**
- **strong/weak beam energy dependence?**
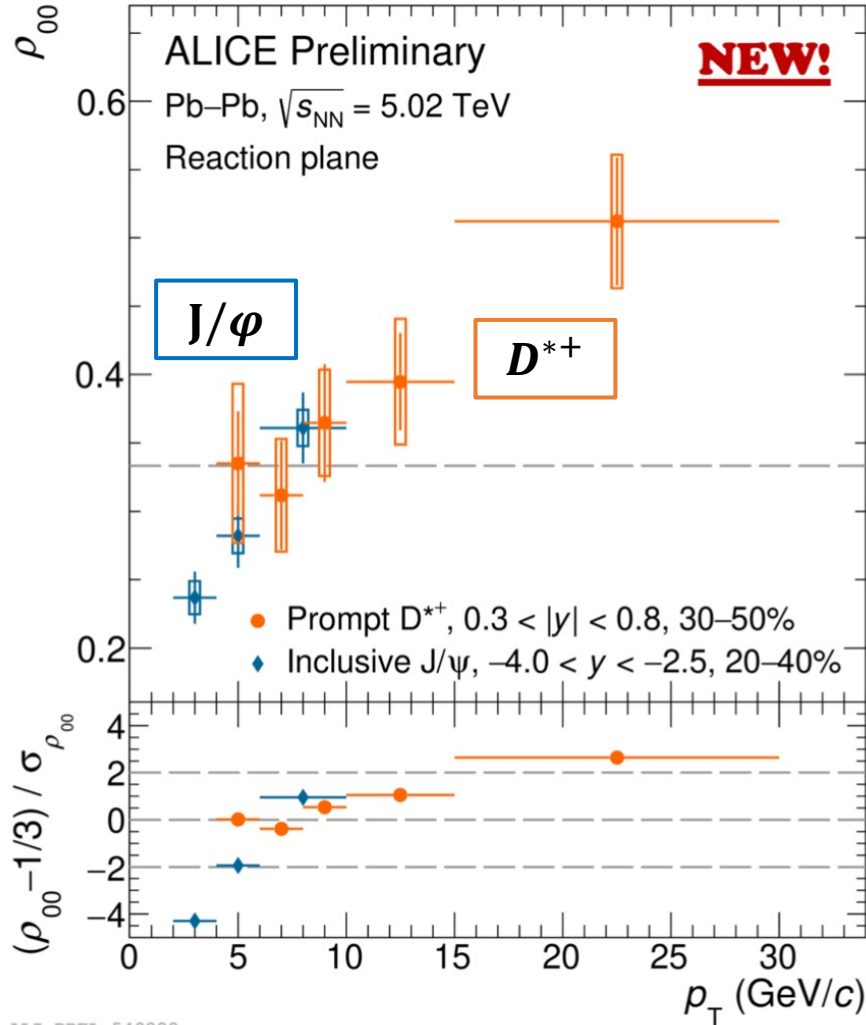- **weak centrality dependence**
- **clear rapidity dependence**

ρ_{00} of J/φ and D^{*+} at LHC (and RHIC)

ALICE, QM23

ALICE Preliminary
Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Reaction plane

NEW!

J/φ

D^{*+}

- Prompt D^{*+}, 0.3 < |y| < 0.8, 30–50%
- Inclusive J/ψ, –4.0 < y < –2.5, 20–40%

ALI-PREL-549222

p_T (GeV/c)

ALICE, QM23

ALICE Preliminary
30–50% Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Reaction plane

NEW!

D^{*+}

Prompt D*+, 15 < p_T < 30 GeV/c

ALI-PREL-547529
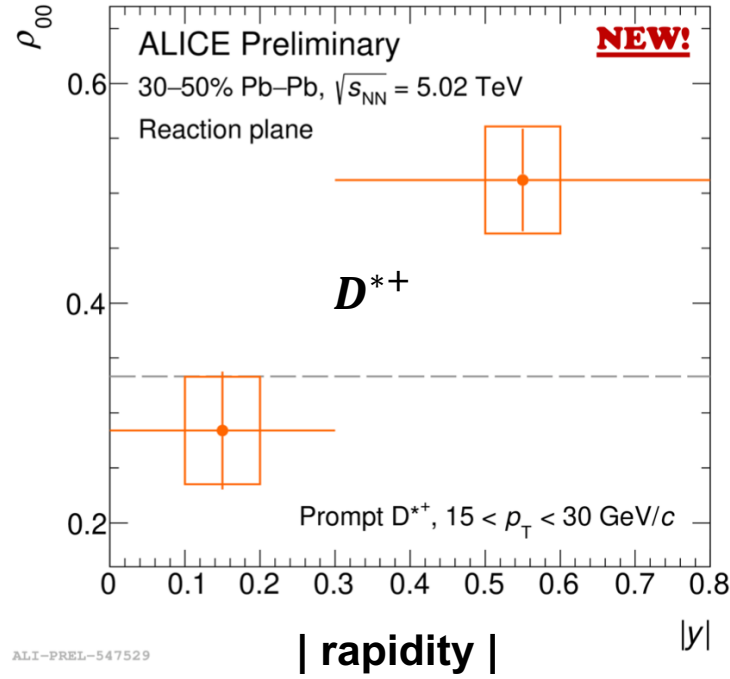
| rapidity |

- **clear p_T and rapidity dependences**
- **consistency between 1st and 2nd order R.P.?**

STAR, ZrZr+RuRu@200GeV,-1<y<1, 0.3<p_T<6 GeV/c
ALICE,PbPb@5.02TeV,2.5<y<4, 2<p_T<6 GeV/c, PRL2023

J/φ with Φ_2

TPC second-order event plane

STAR Preliminary

STAR, SPIN23

<N_{part}>

Ru+Ru 200 GeV
Zr+Zr 200 GeV

STAR Preliminary
1st order ZDC plane
J/Ψ → e⁺e⁻, 0.3<p_T<4.5 GeV/c, |y|<1

J/φ with Φ_1

STAR, QM23

Centrality %
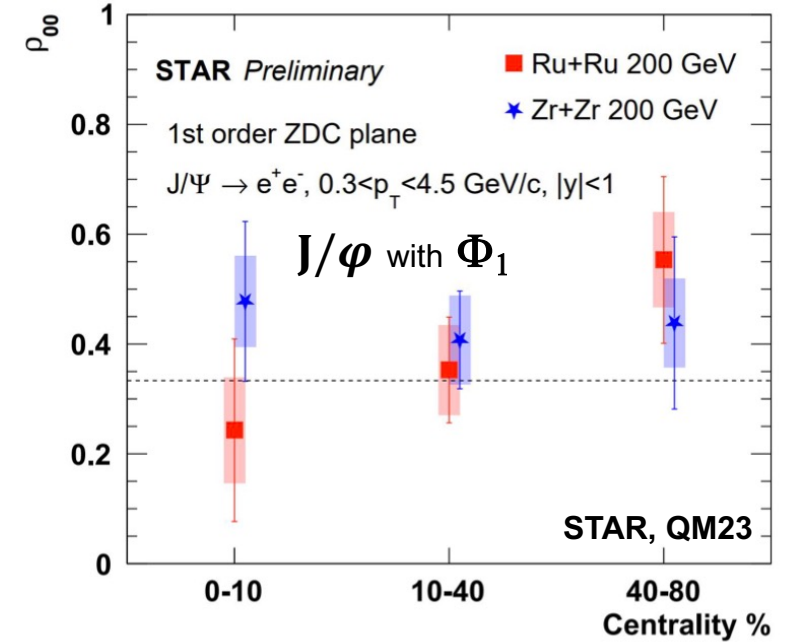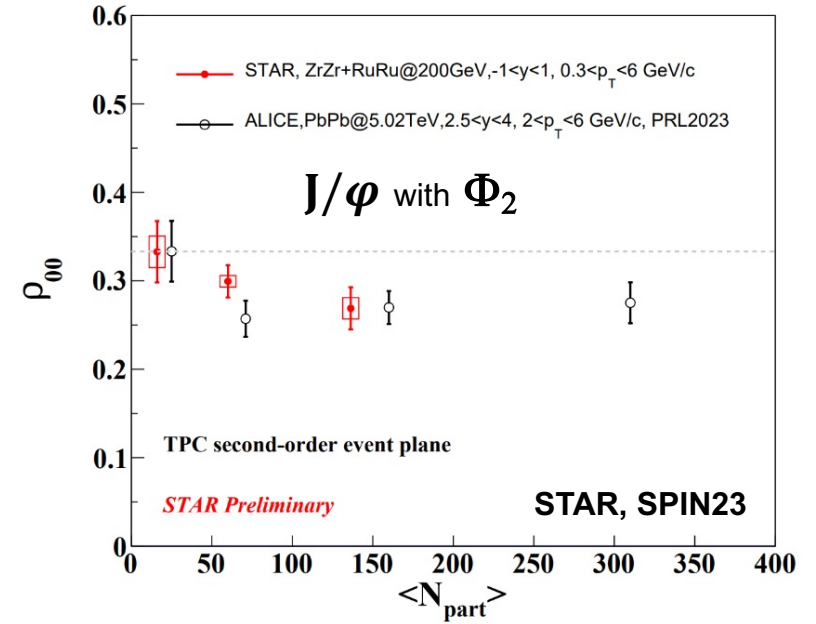
Summary

- **Global Polarization from GeV to TeV**
- **Λ and $\overline{\Lambda}$ difference and B-field effect**
- **Global and Longitudinal Polarization**
- **Global Spin Alignments**
- **Other types of related signals**
- **Direct relation to flow and geometry**
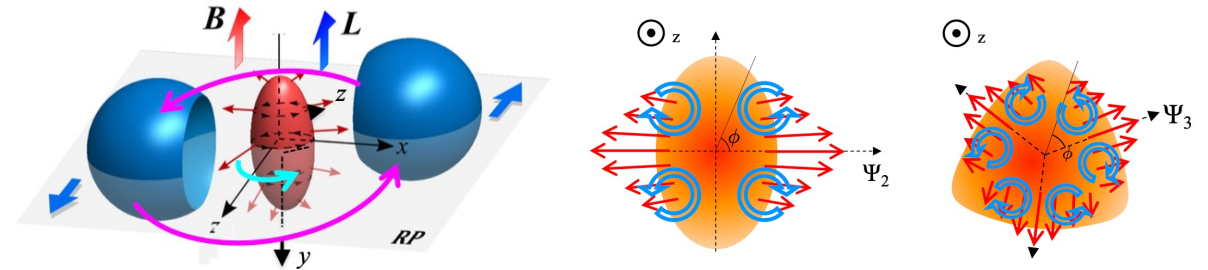
B. Bets et al., PRC 76 044901 (2007)
Y. Tachibana et al., NPA 904 1023c (2013)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)
W.M. Serenone et al, PLB 820 136500 (2021)
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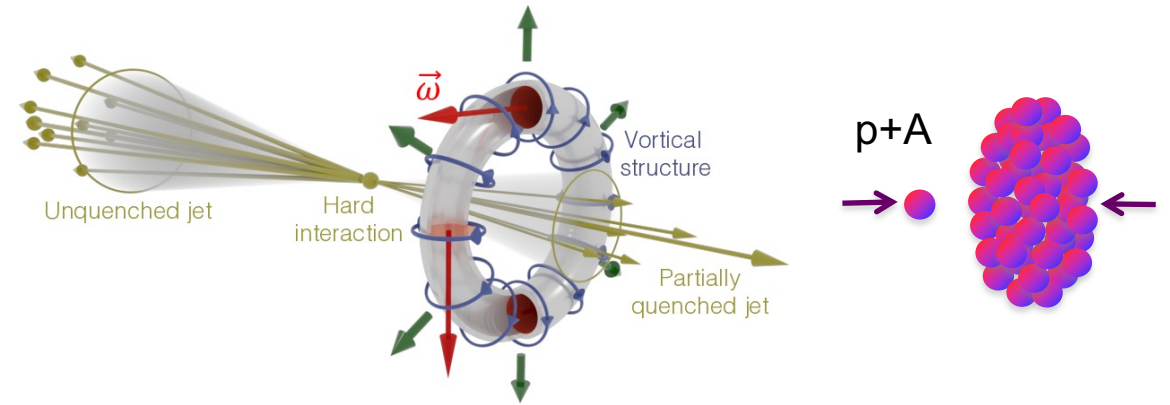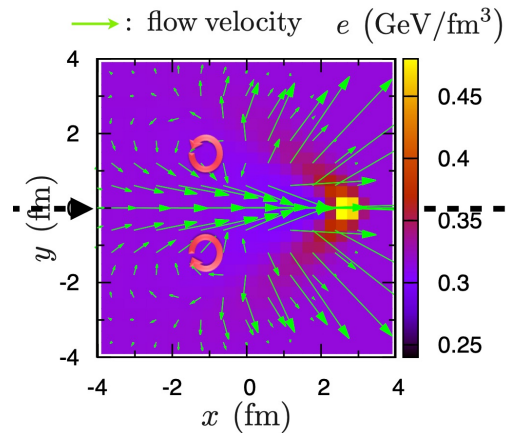
WHBM 2023 : 1st Workshop on Highly Baryonic Matter at RHIC-BES and Future Facilities (Tsukuba/Japan, last spring in 2023)
- - - beyond the Critical Point towards Neutron Stars - - - (https://conference-indico.kek.jp/event/205/)

… hoping to have one of the future CPOD meetings in Tsukuba/Japan …