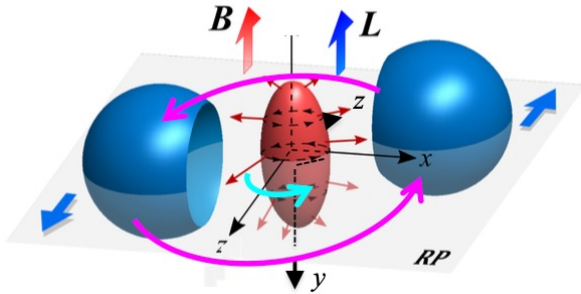


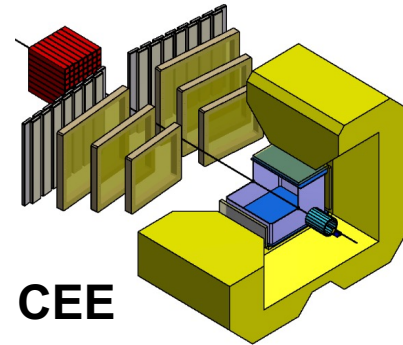
# Polarization and Spin Alignment in Heavy-Ion Collisions

## Contents

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



Shinichi Esumi, Inst. of Physics, Univ. of Tsukuba  
Tomonaga Center for the History of the Universe (TCHoU)

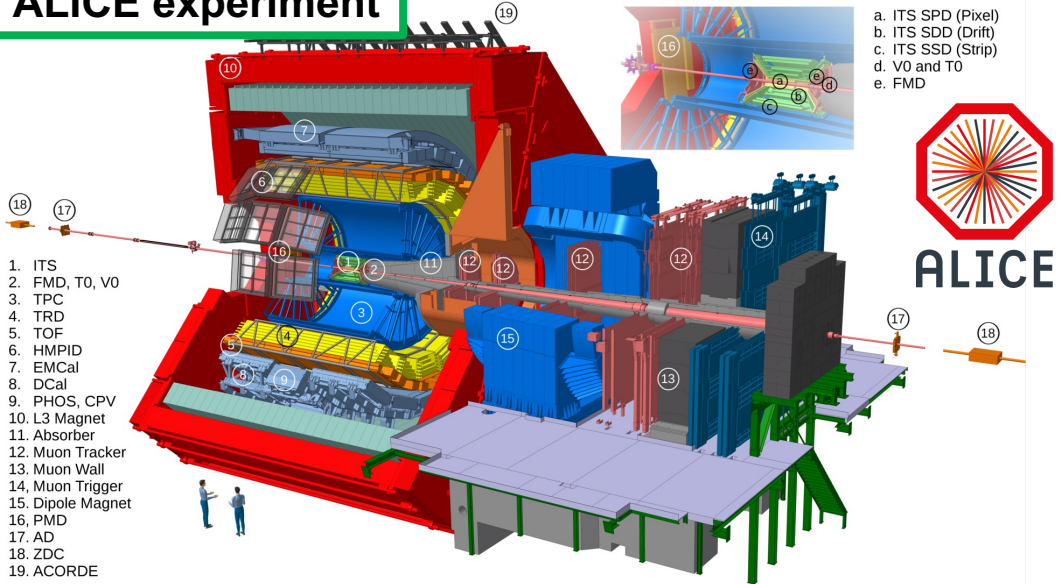


**The STAR experiment**  
at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory

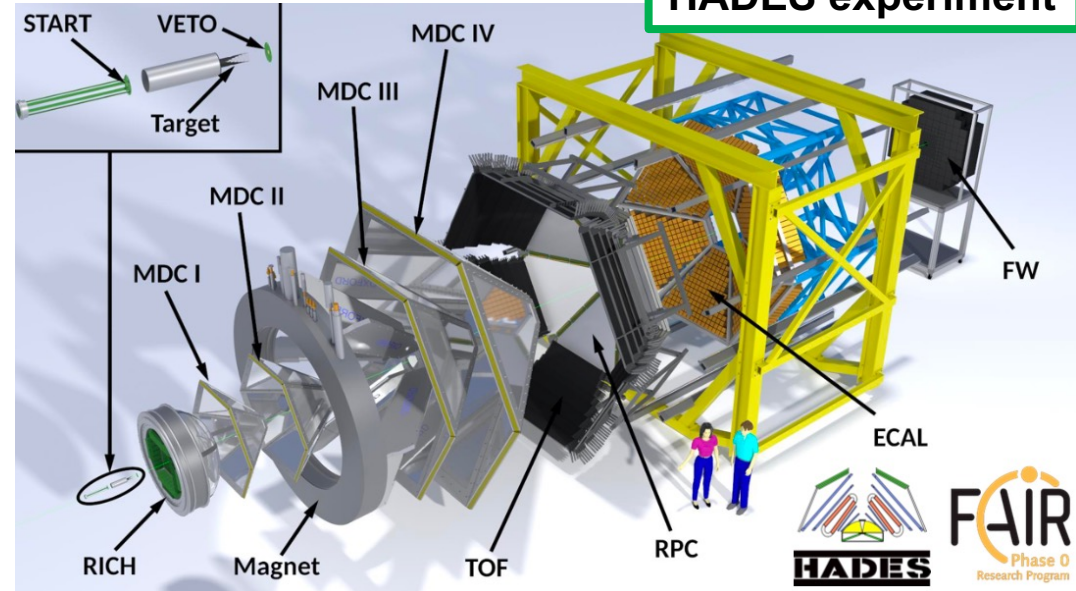


# ALICE, STAR and HADES detectors

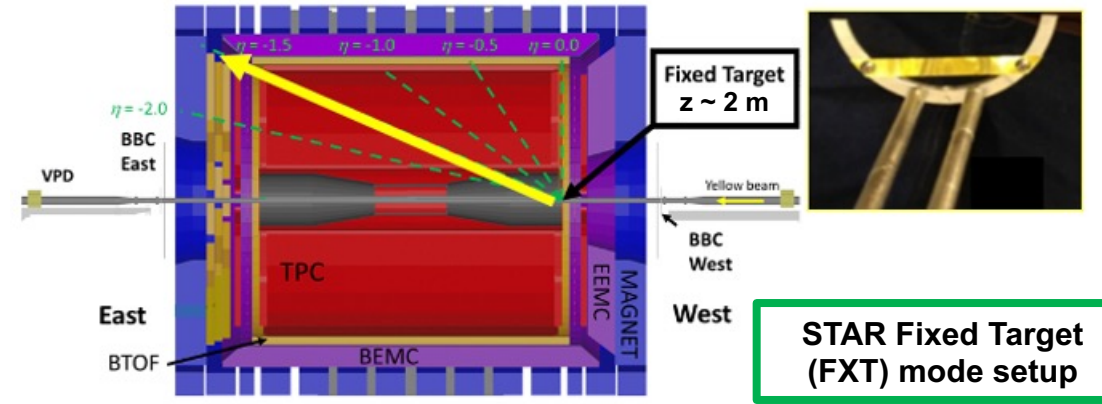
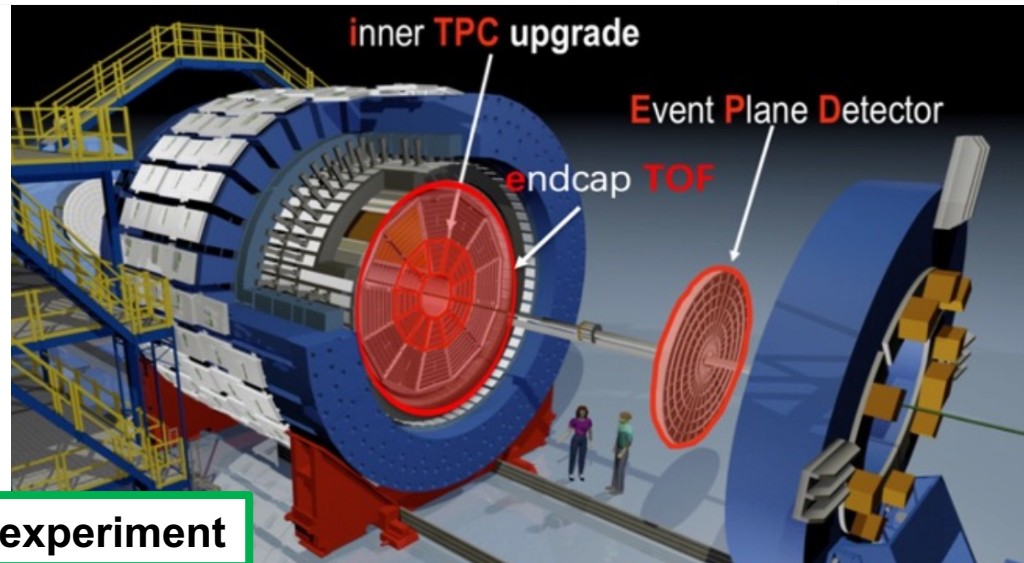
## ALICE experiment



## HADES experiment

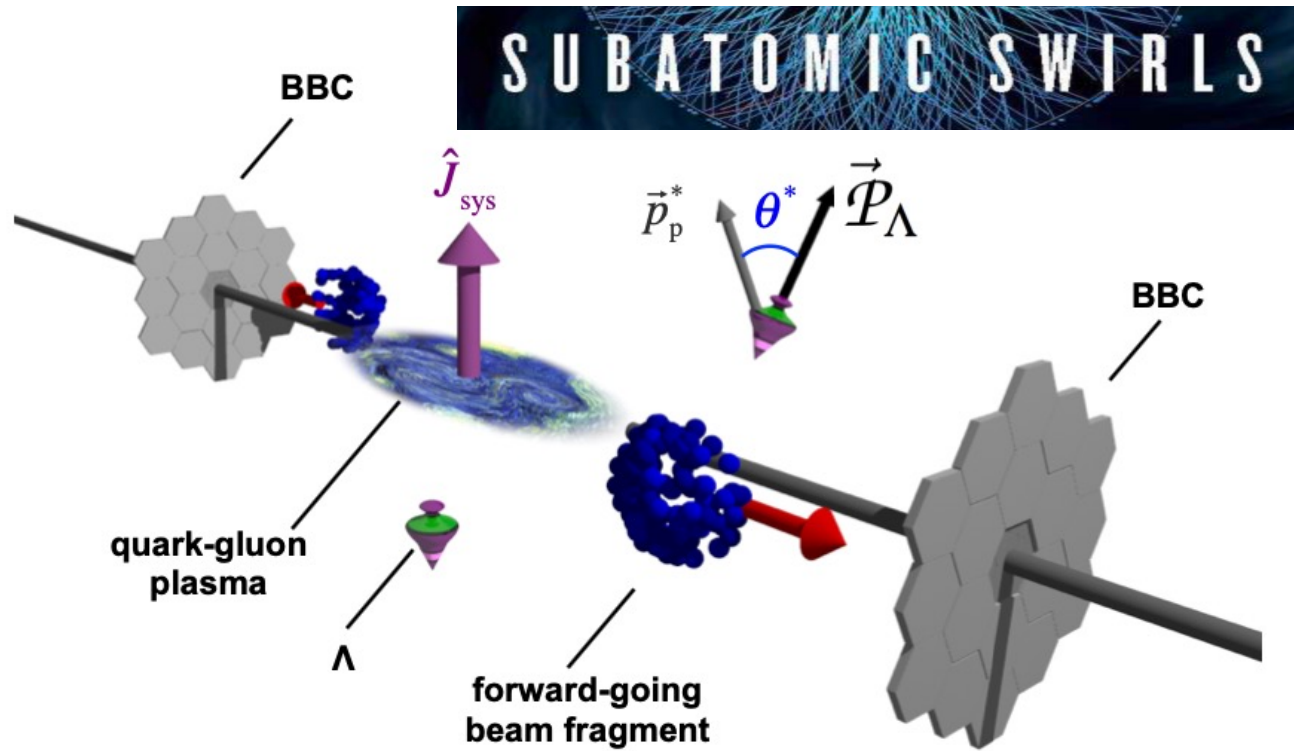


## STAR experiment





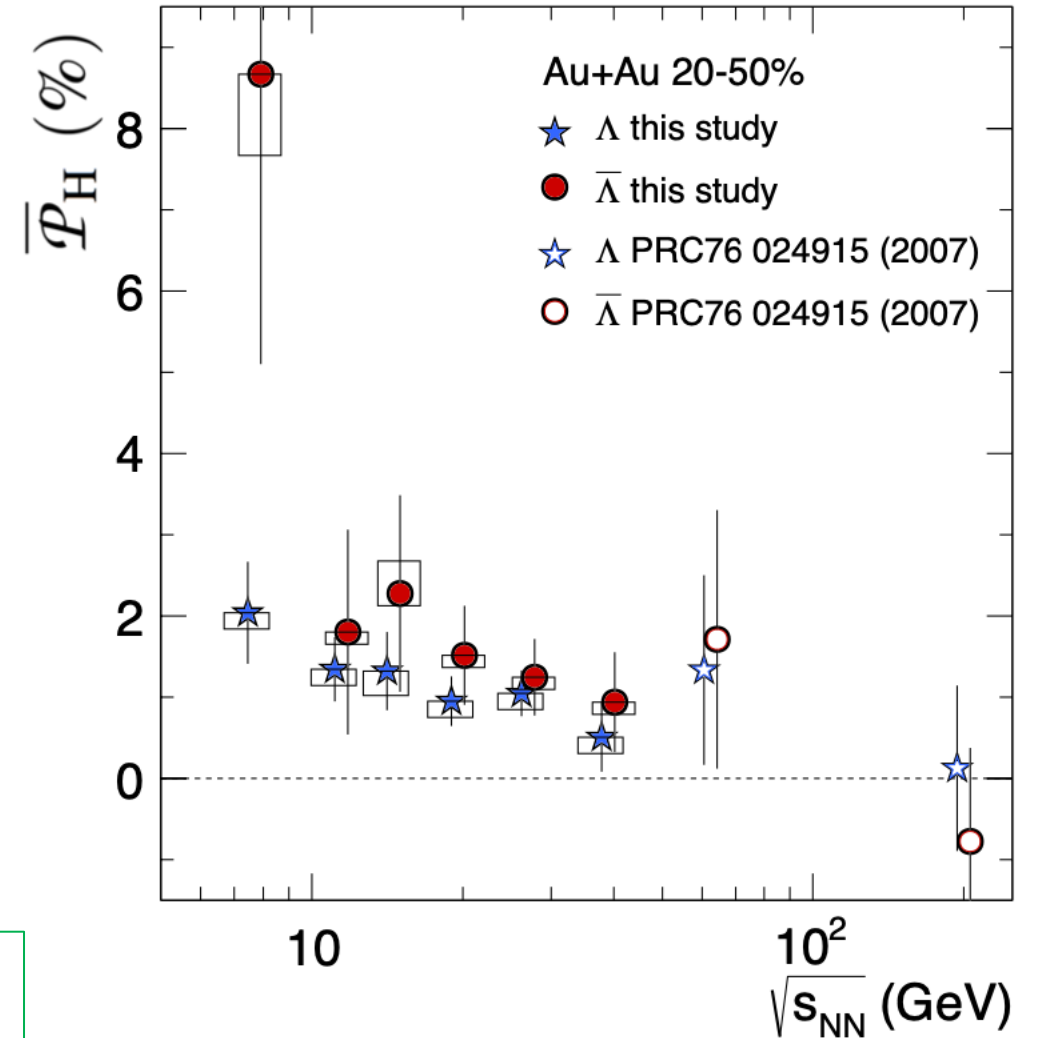
# Beam Energy Scan (BES-I) and earlier results



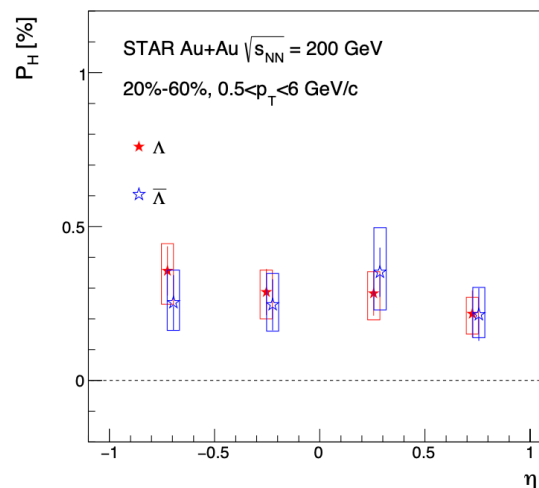
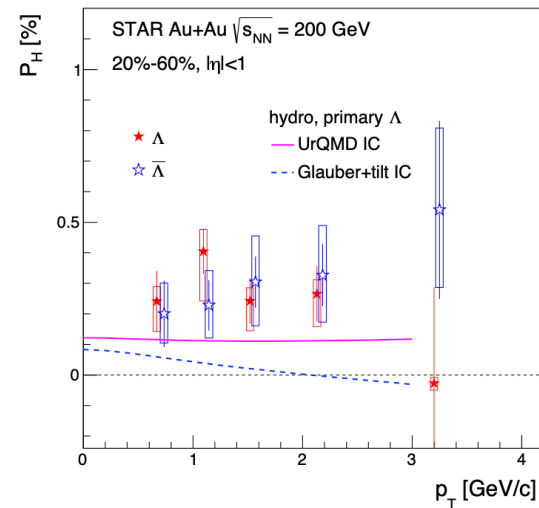
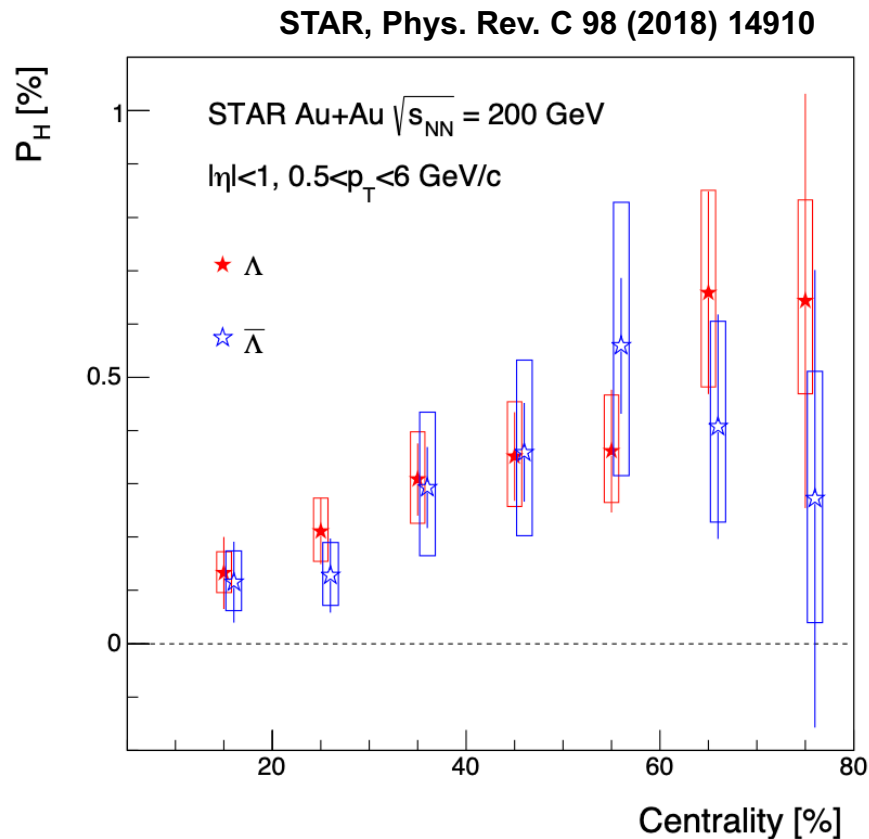
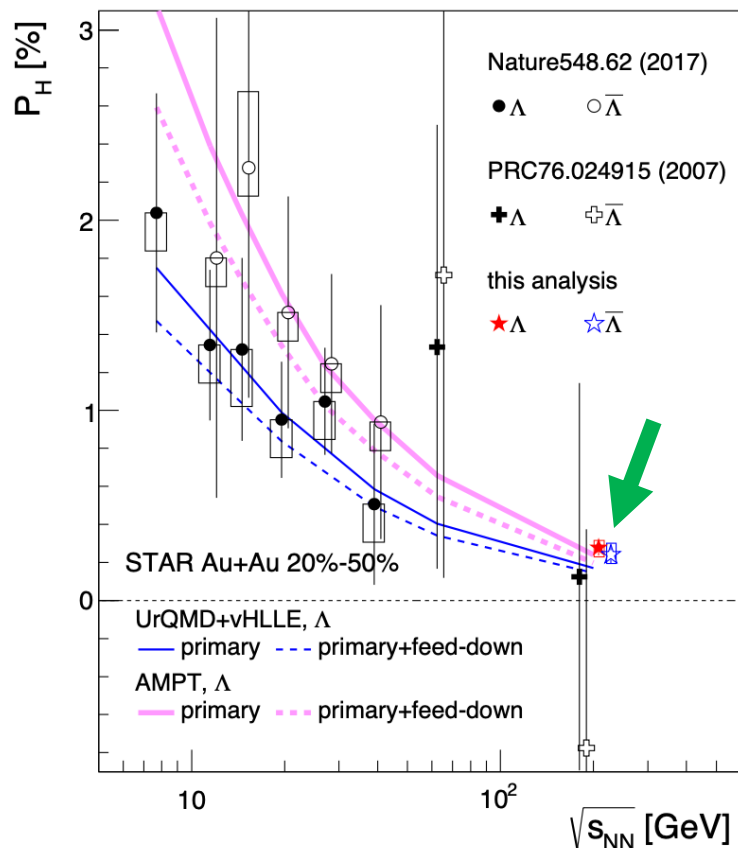
Global Lambda hyperon polarization in nuclear collisions:  
evidence for the most vortical fluid

- possible difference between  $\Lambda$  and  $\bar{\Lambda}$
- hint of B-field in addition to the angular momentum

STAR, Nature 548 (2017) 62



# Global Polarization at 200 GeV Au+Au collisions

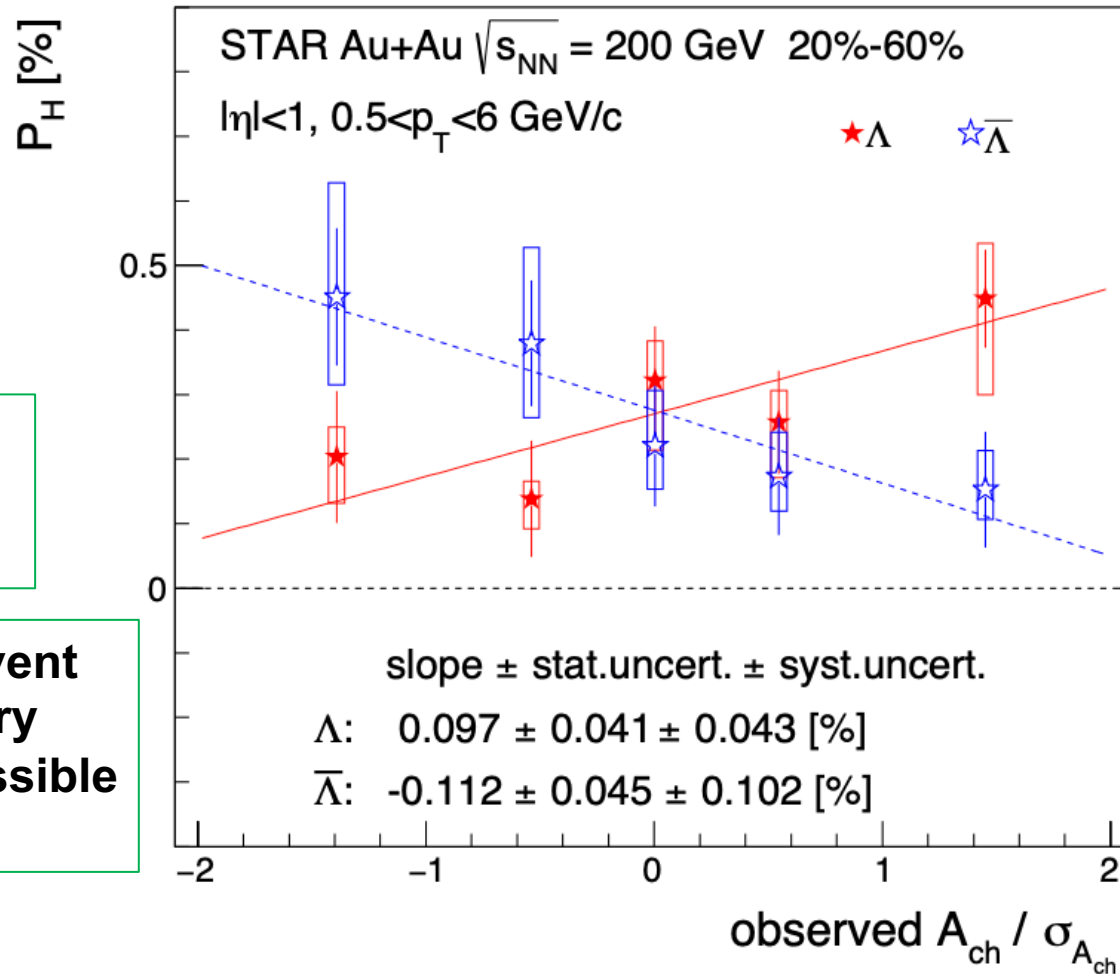


- high statistics data at 200 GeV
- clear centrality dependence
- similar between  $\Lambda$  and  $\bar{\Lambda}$
- minor  $p_T$  and  $\eta$  ( $|\eta| < 1$ ) dependence



# Charge asymmetry dependence at 200 GeV

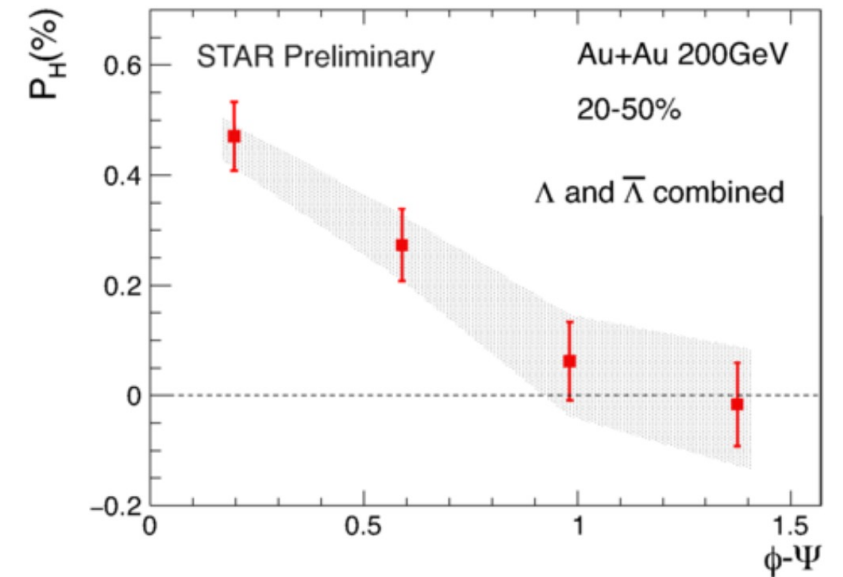
STAR, Phys. Rev. C 98 (2018) 14910



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

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

QM18, STAR  
Nucl. Phys. A 982 511 (2019)

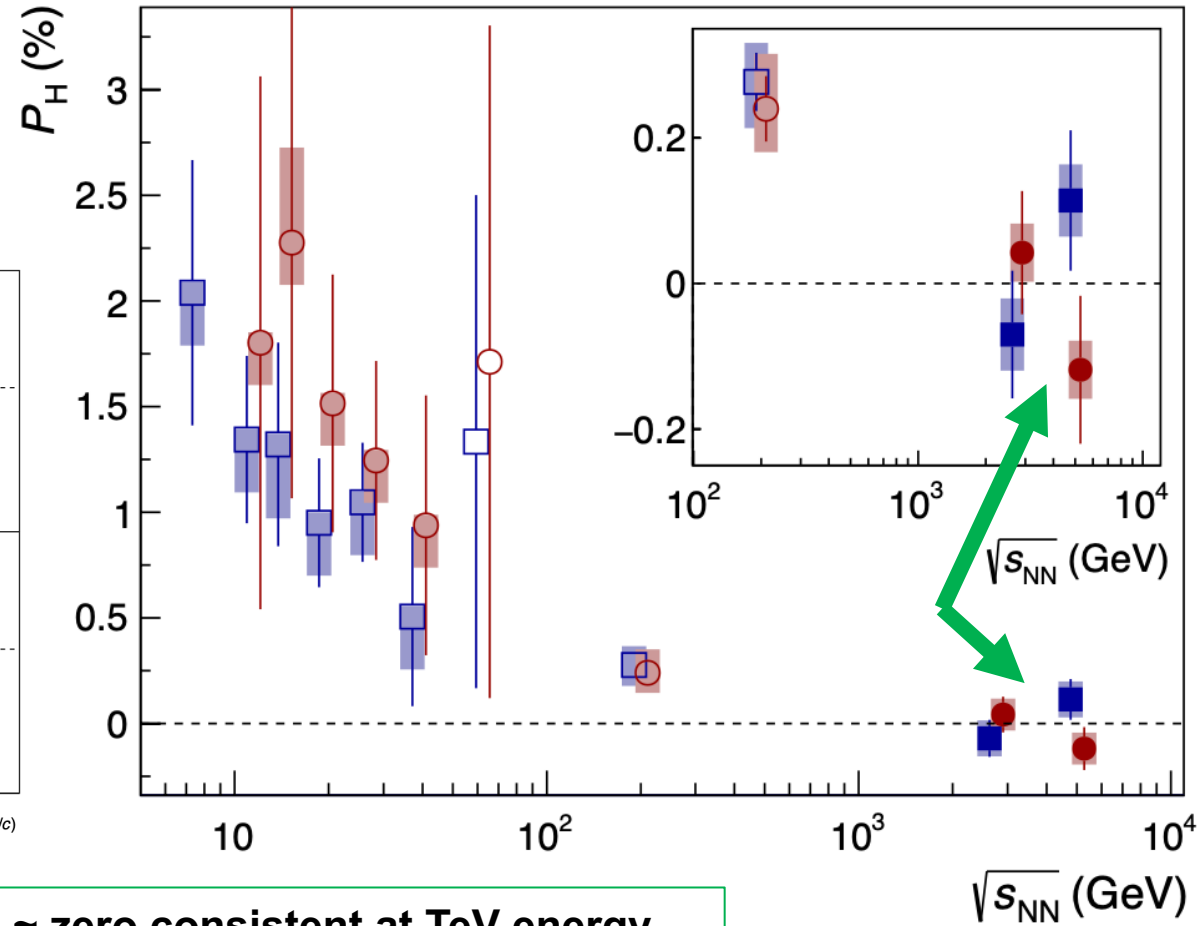
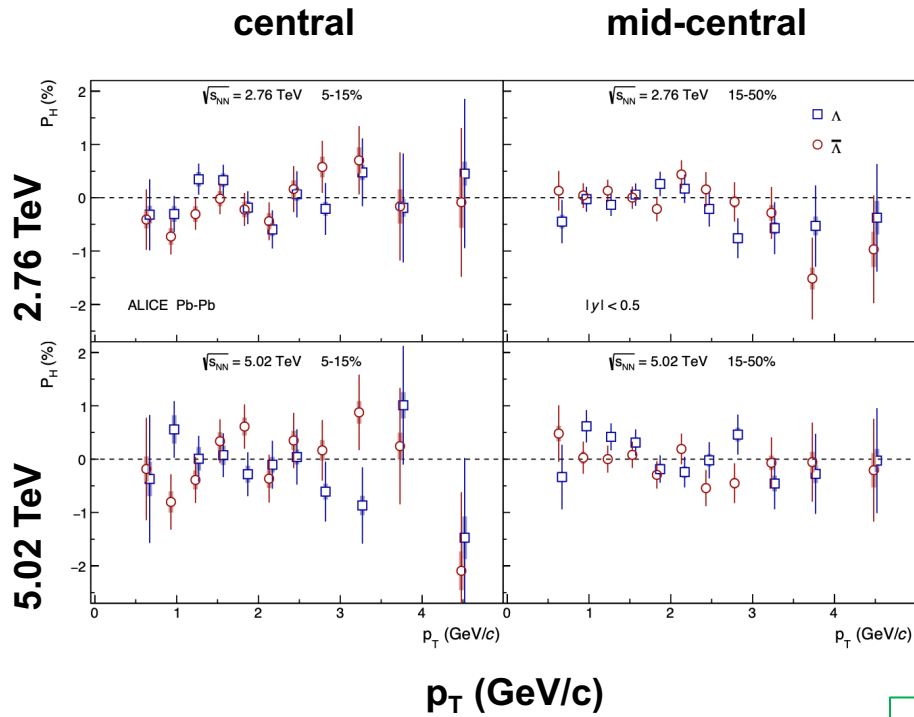


clear azimuthal angle dependence  
In-plane > Out-of-plane (like  $v_2$ )

# Global Polarization at LHC energies (ALICE)

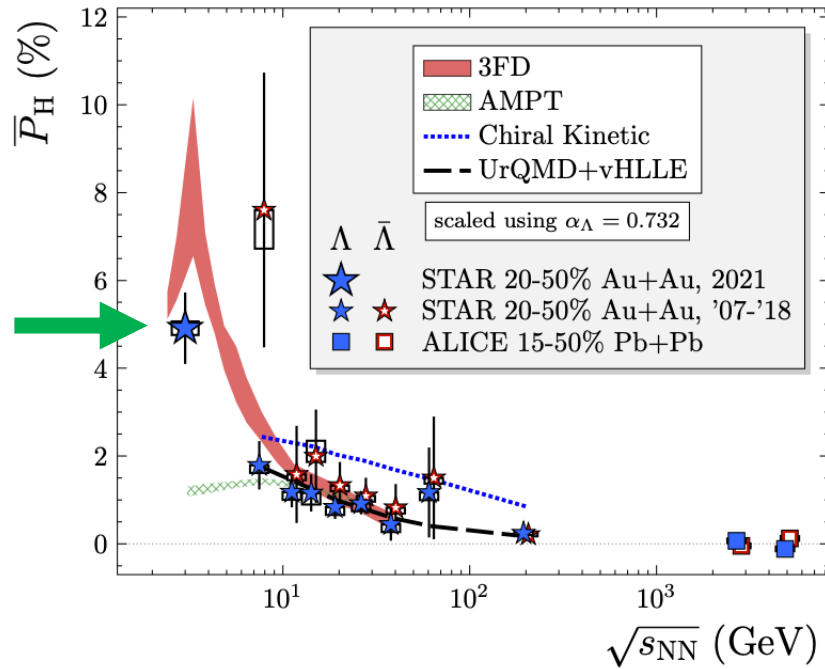


ALICE, Phys. Rev. C 101 (2020) 044611

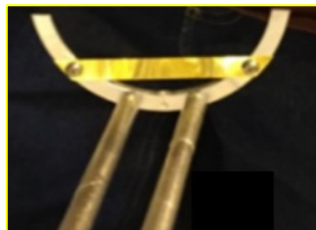
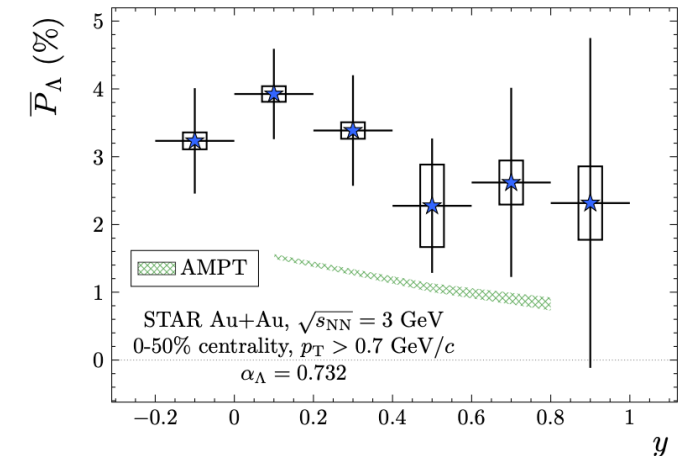
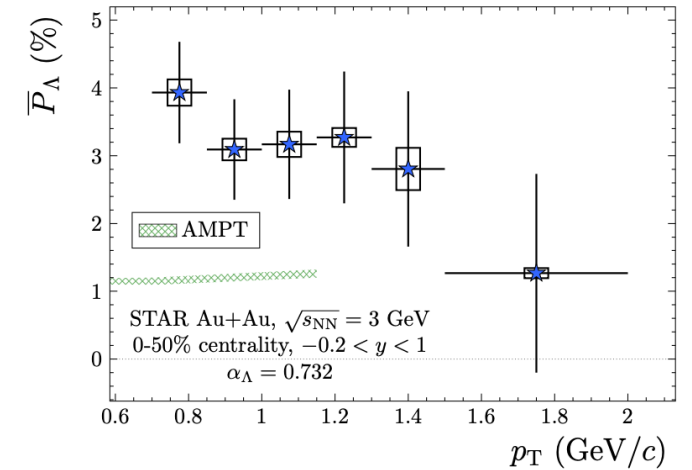
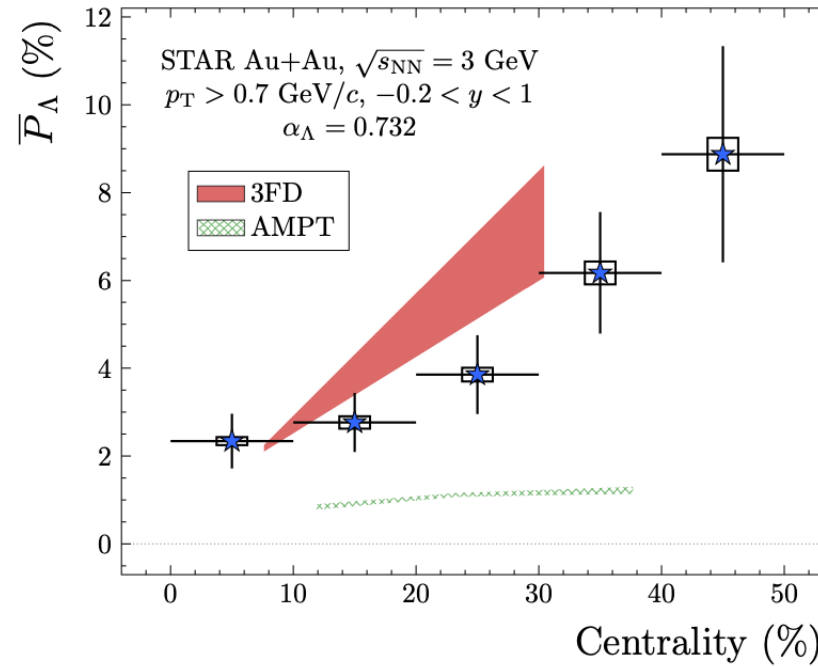


~ zero consistent at TeV energy

# Global Polarization at 3 GeV



STAR, Phys. Rev. C 104 (2021) 61901

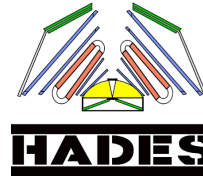


STAR FXT

- increasing trend towards lower beam energy
- similar centrality dependence
- minor  $p_T$  and rapidity dependence

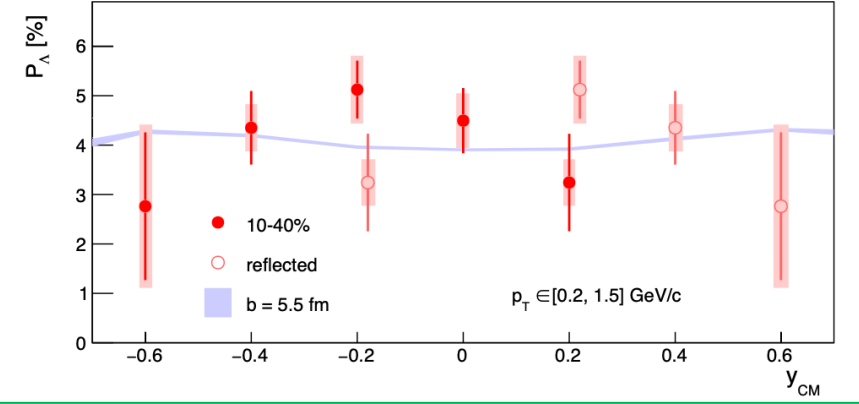
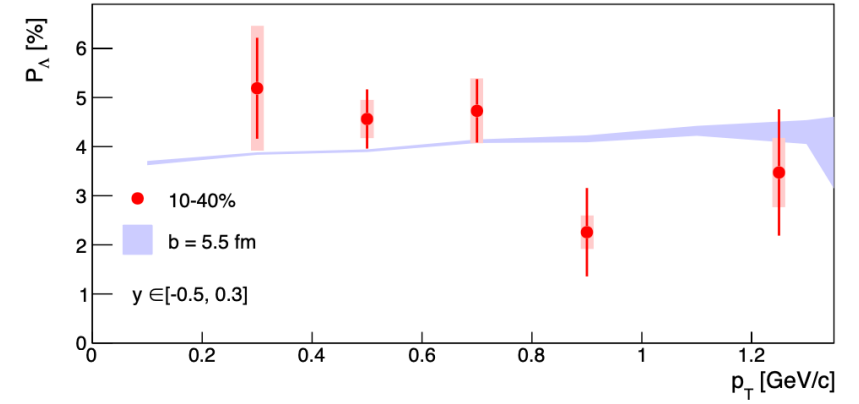
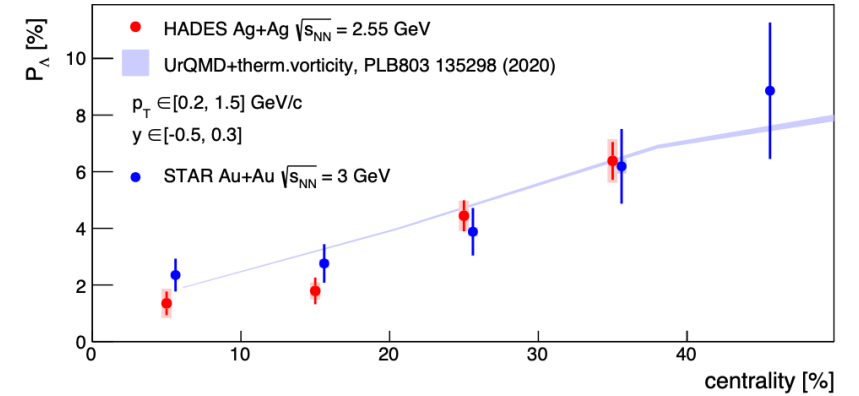
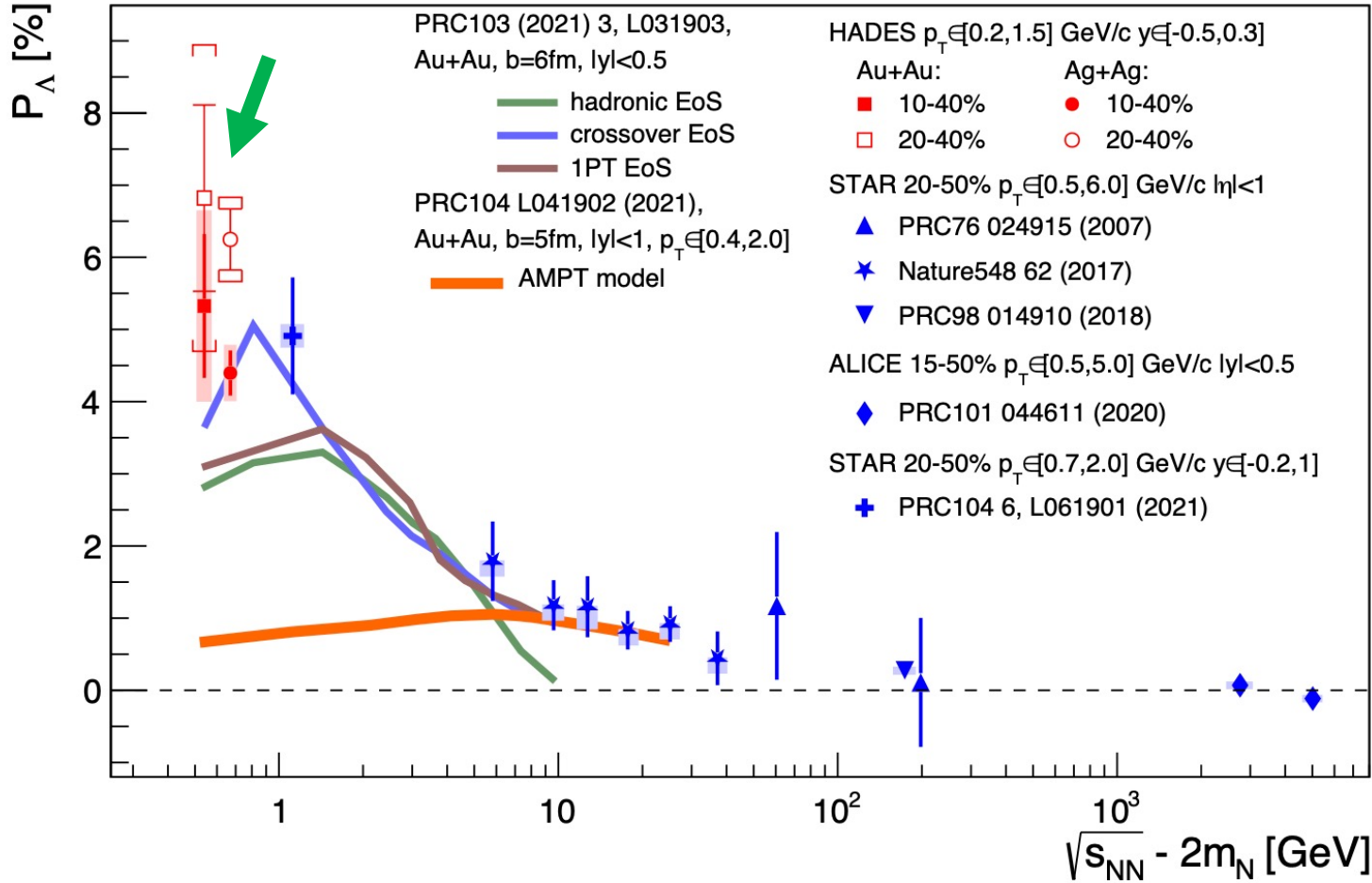


# Global Polarization in few-GeV (HADES)



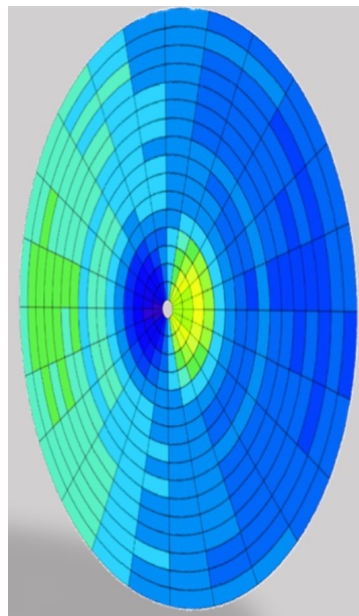
2.4~2.55 GeV

Phys. Lett. B 835 (2022) 137506



similar centrality and kinematic dependences

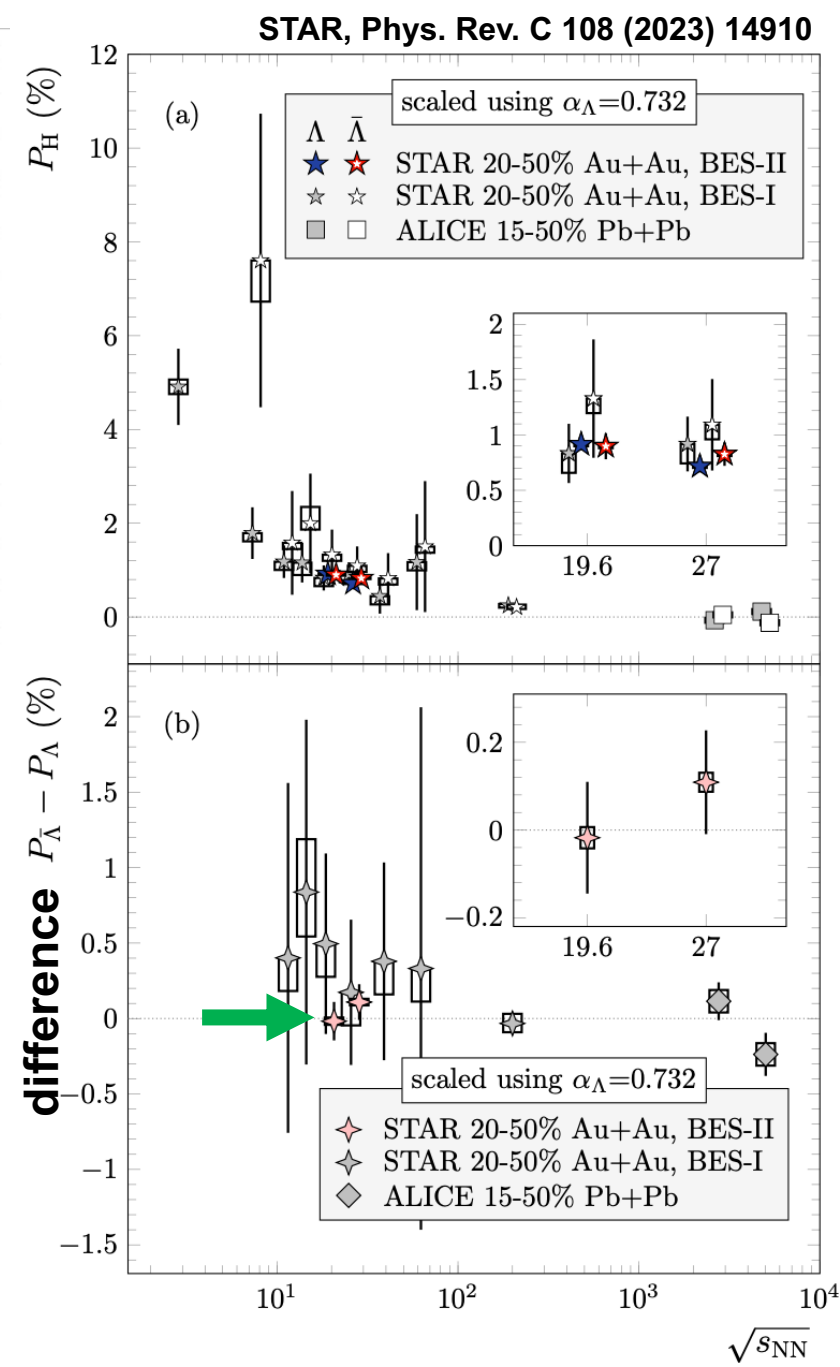
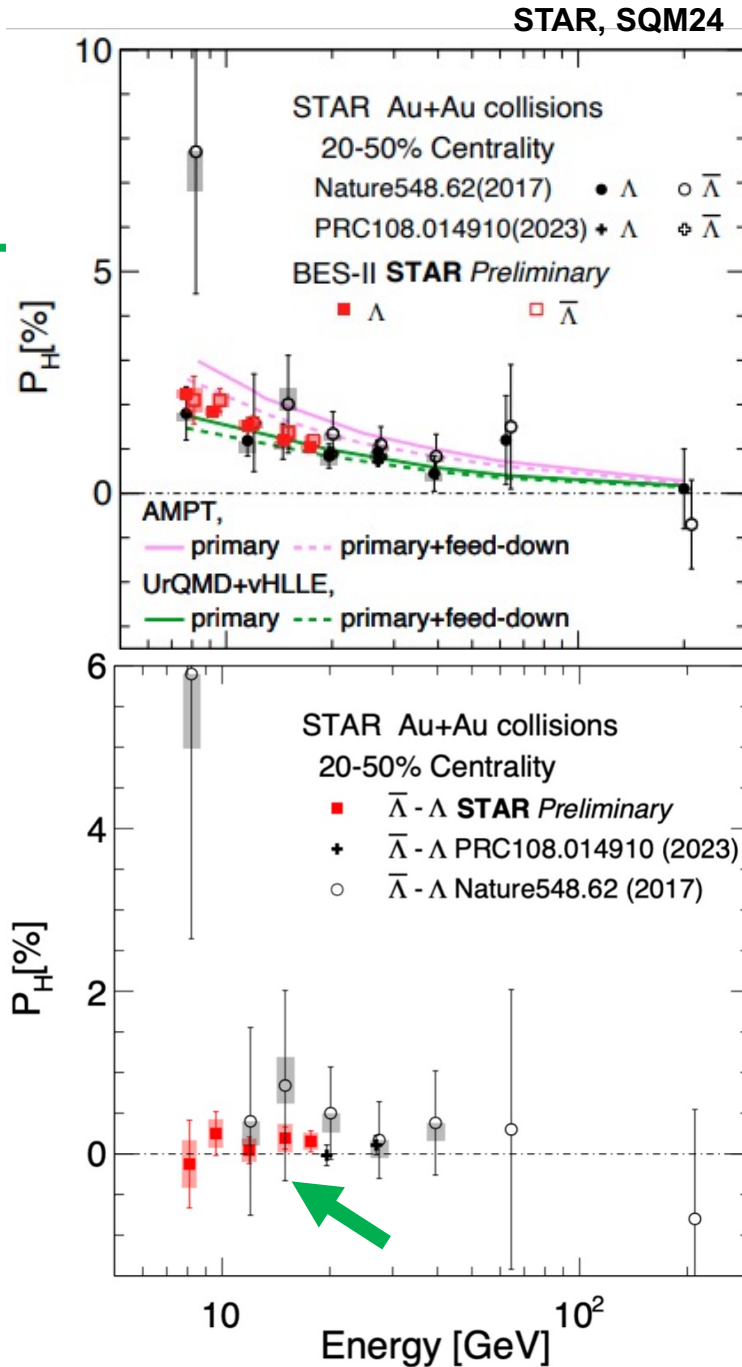
# Global Polarization at 19.6-27 GeV and lower beam energies in BES-II difference between $\Lambda$ and $\bar{\Lambda}$



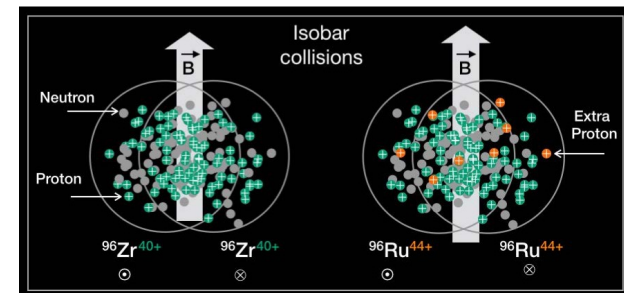
STAR EPD

BES-II statistics ( $\sim \times 20$  increased) improved E.P. resolution with EPD

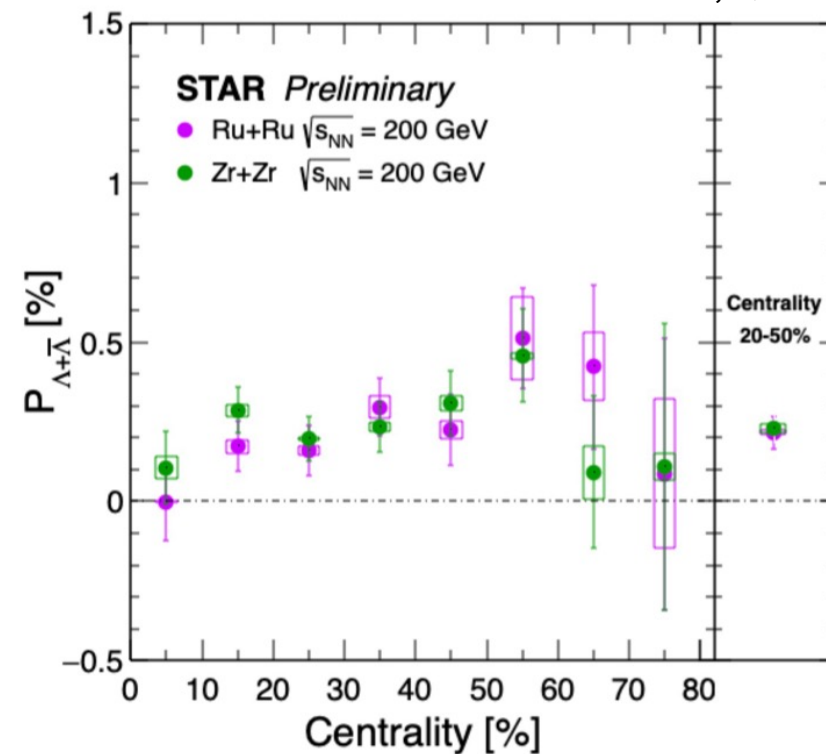
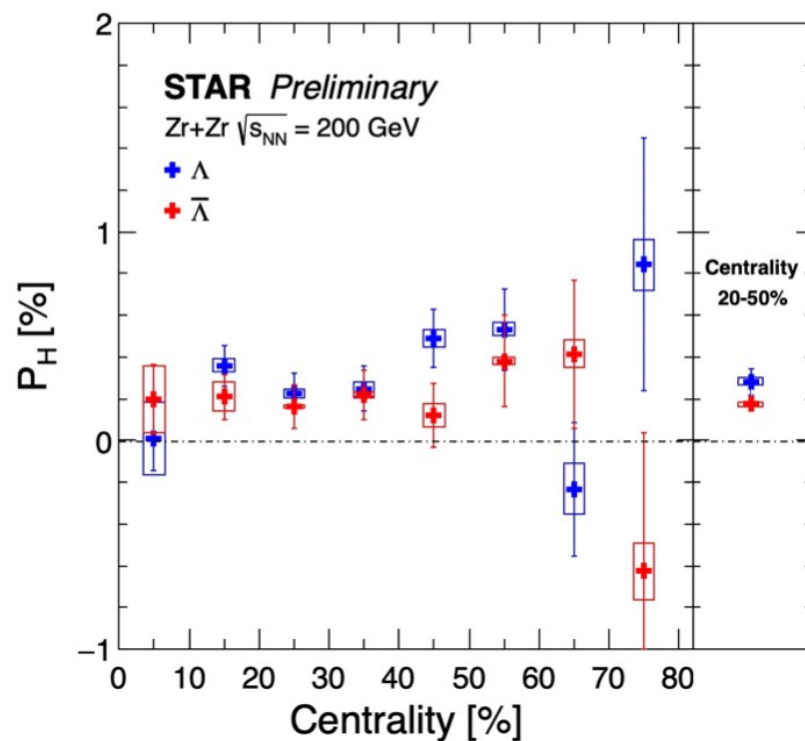
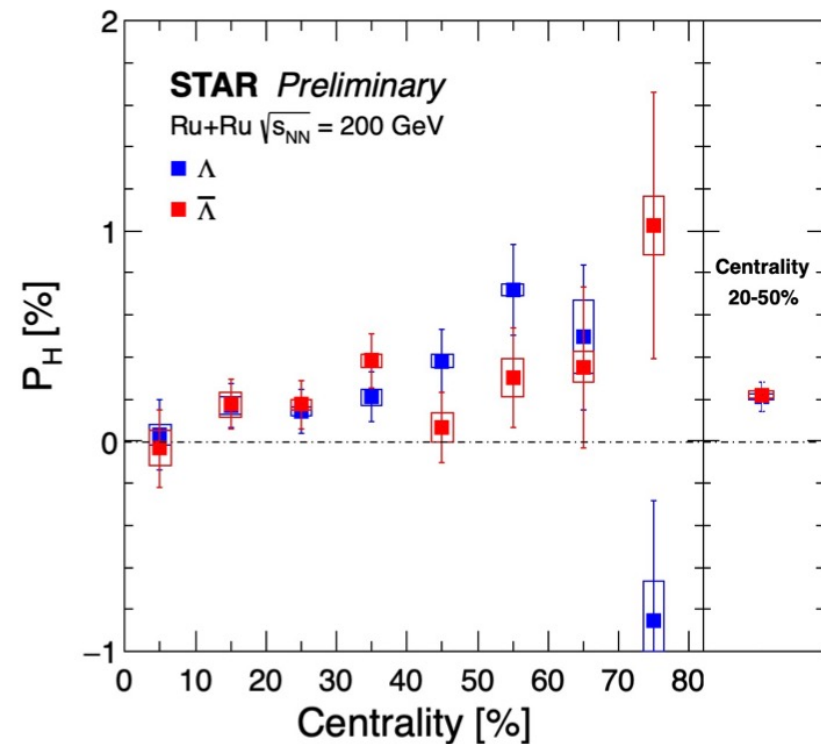
no hint of significant difference between  $\Lambda$  and  $\bar{\Lambda}$  (no B-field)



# Global Polarization in Isobar (Ru+Ru, Zr+Zr) collisions at 200 GeV



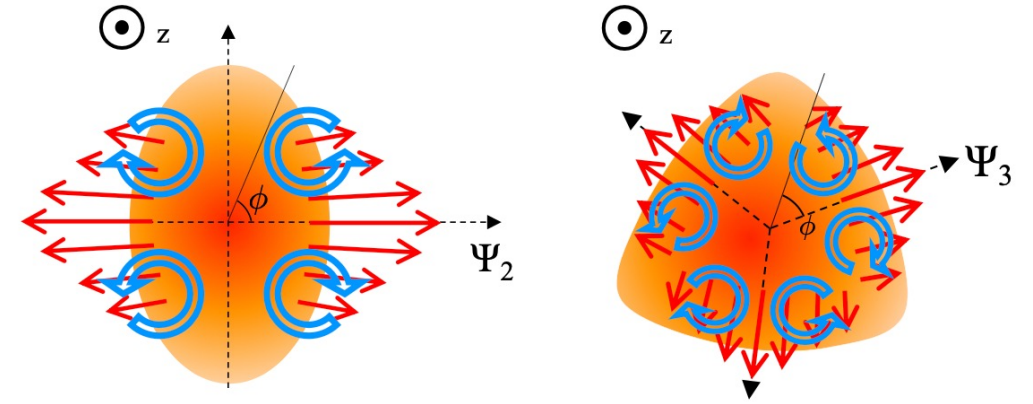
STAR, QM23



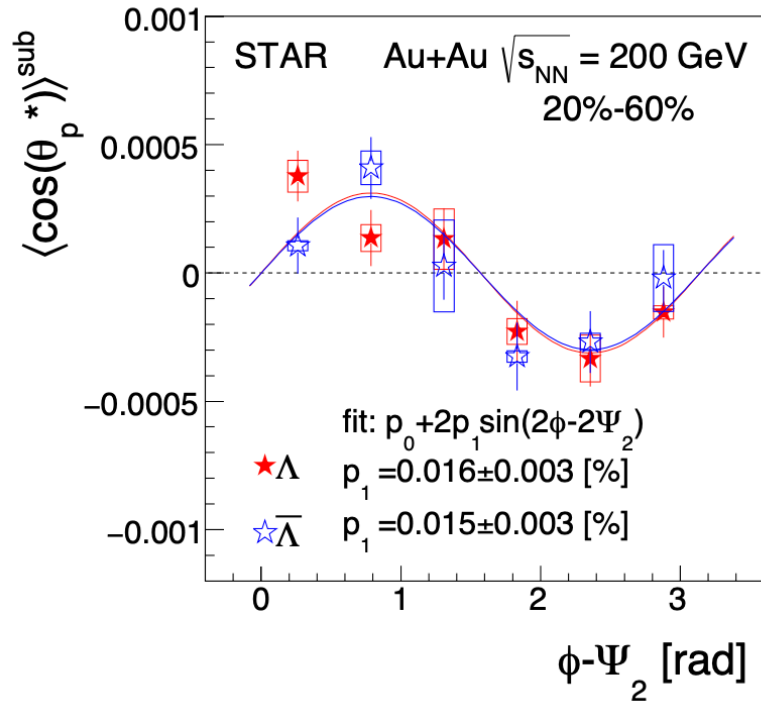
- comparable between  $\Lambda$  and  $\bar{\Lambda}$  and between two isobar systems (no hint of B-field)
- similar centrality dependences



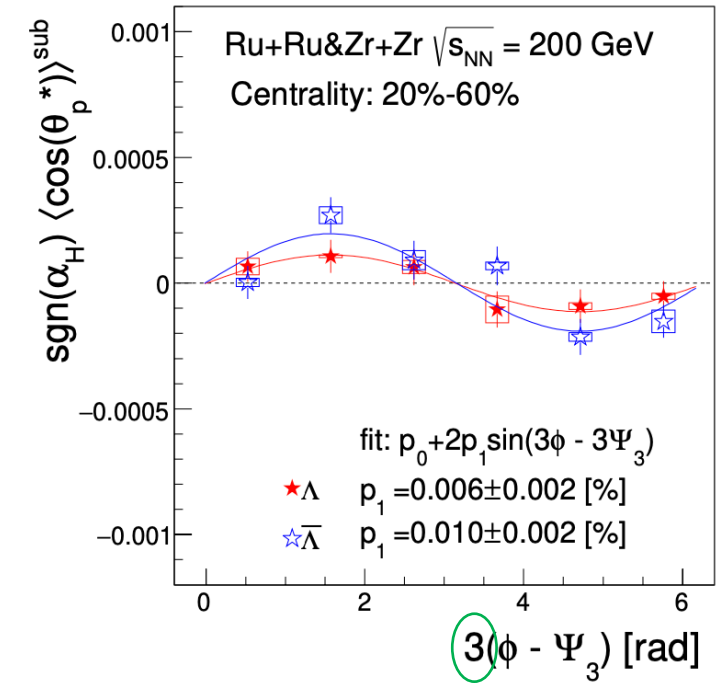
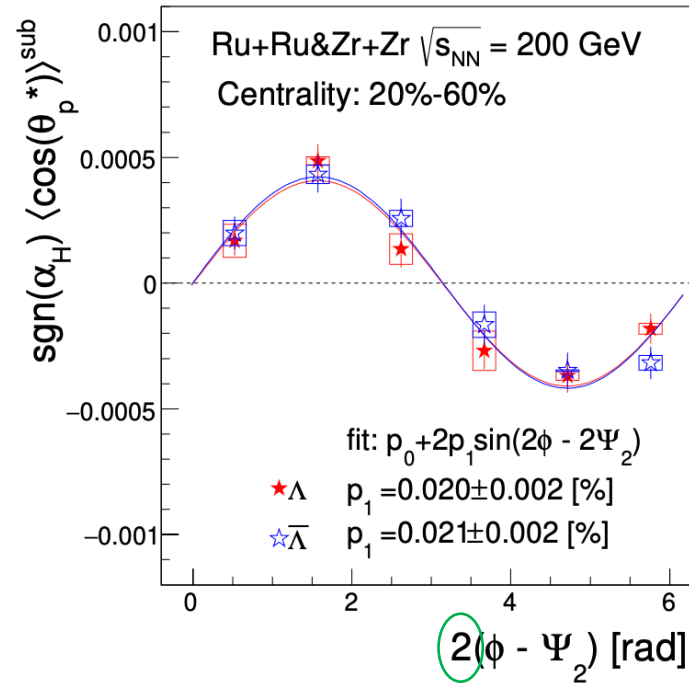
# Longitudinal (along z) Polarization via $v_2$ and $v_3$ expansions at 200 GeV



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

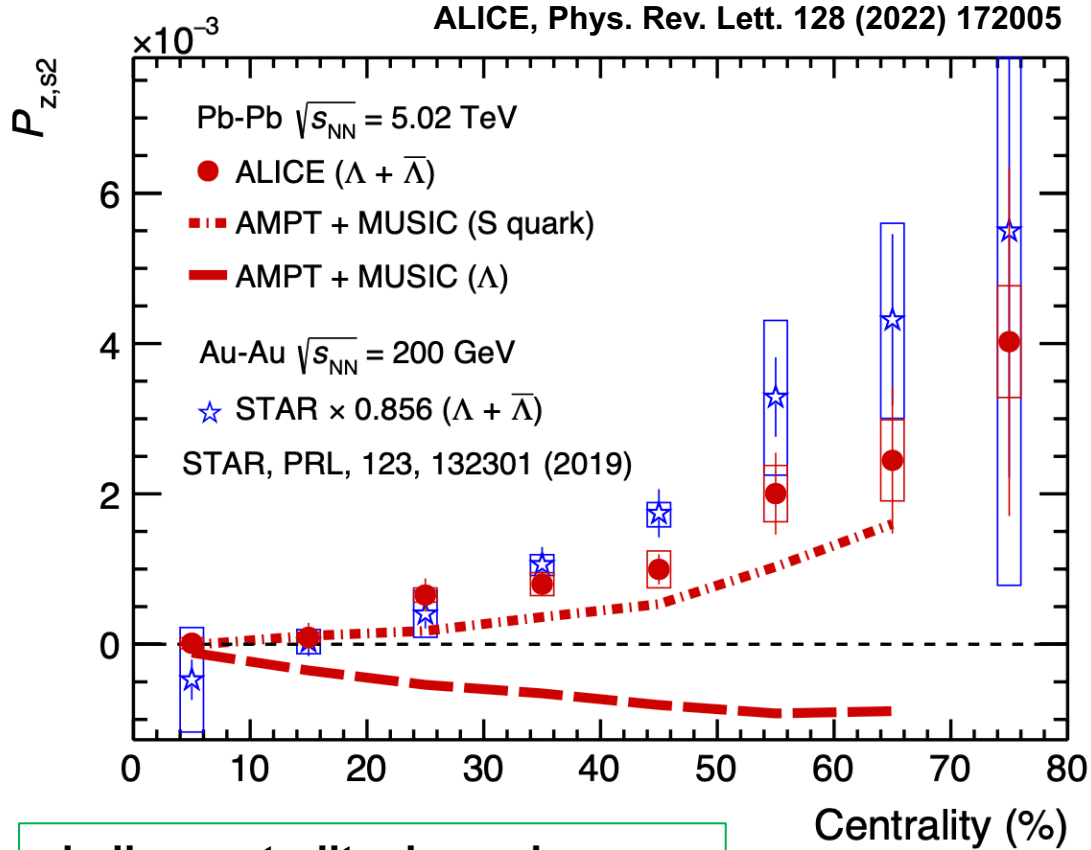


STAR, Phys. Rev. Lett. 131 (2023) 202301

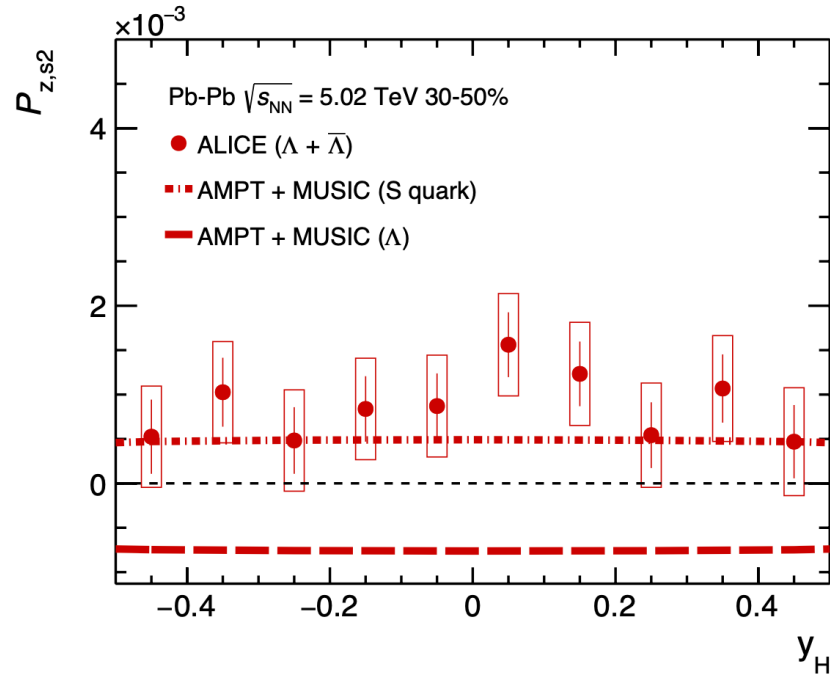
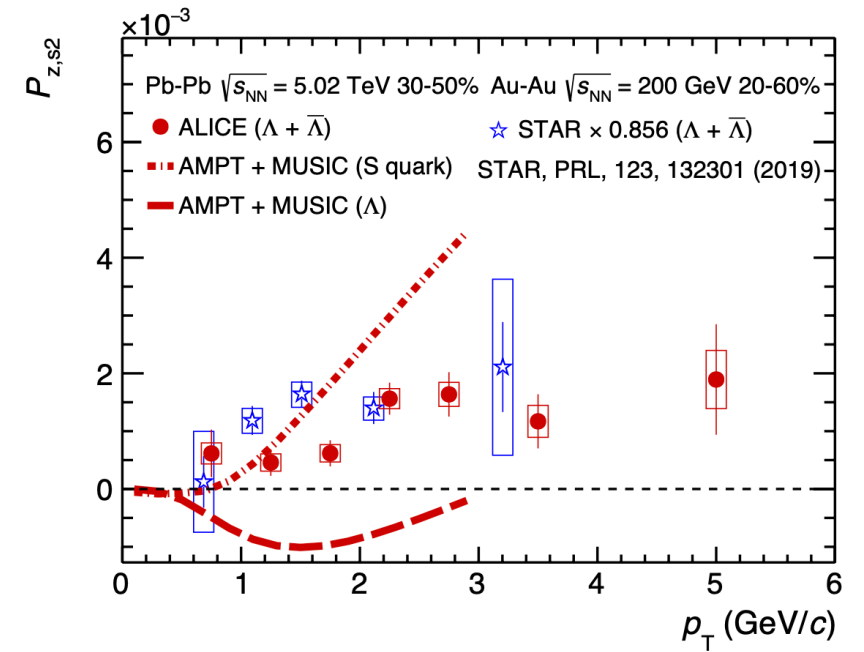


clear 2 and 3 fold asymmetry

# Longitudinal (along z) Polarization at LHC (ALICE)

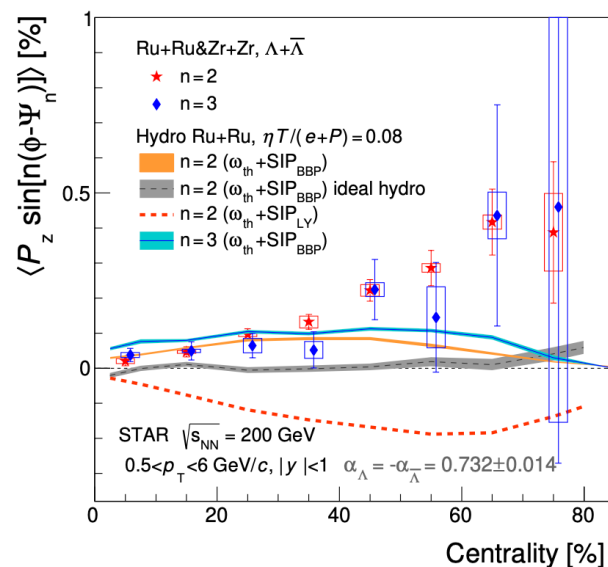
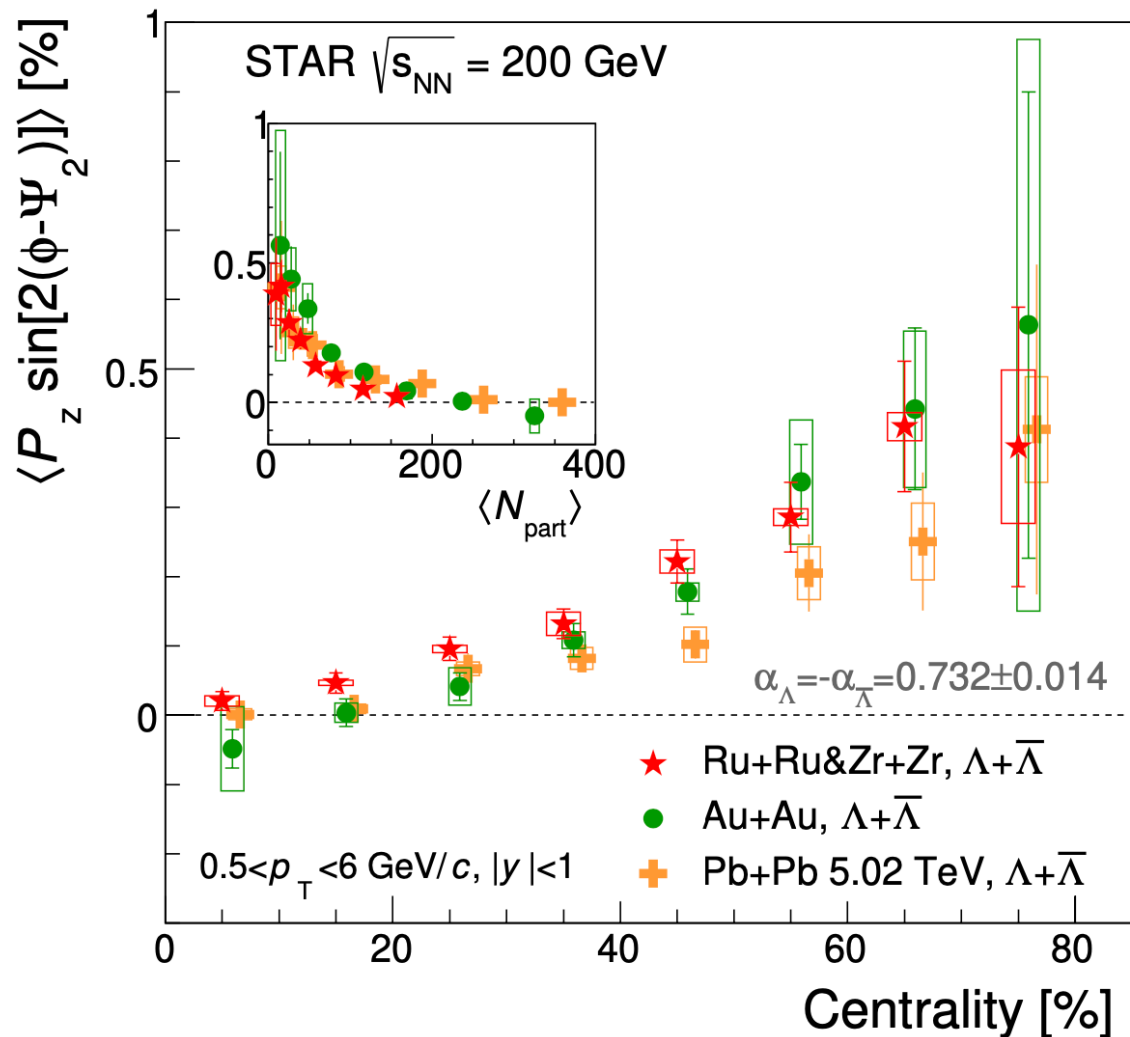


similar centrality dependences compared with RHIC

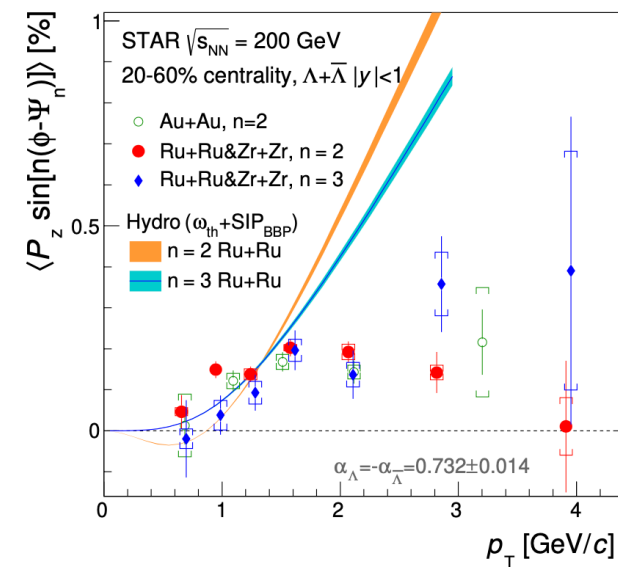


increasing  $p_T$  and mild rapidity dependences

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



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

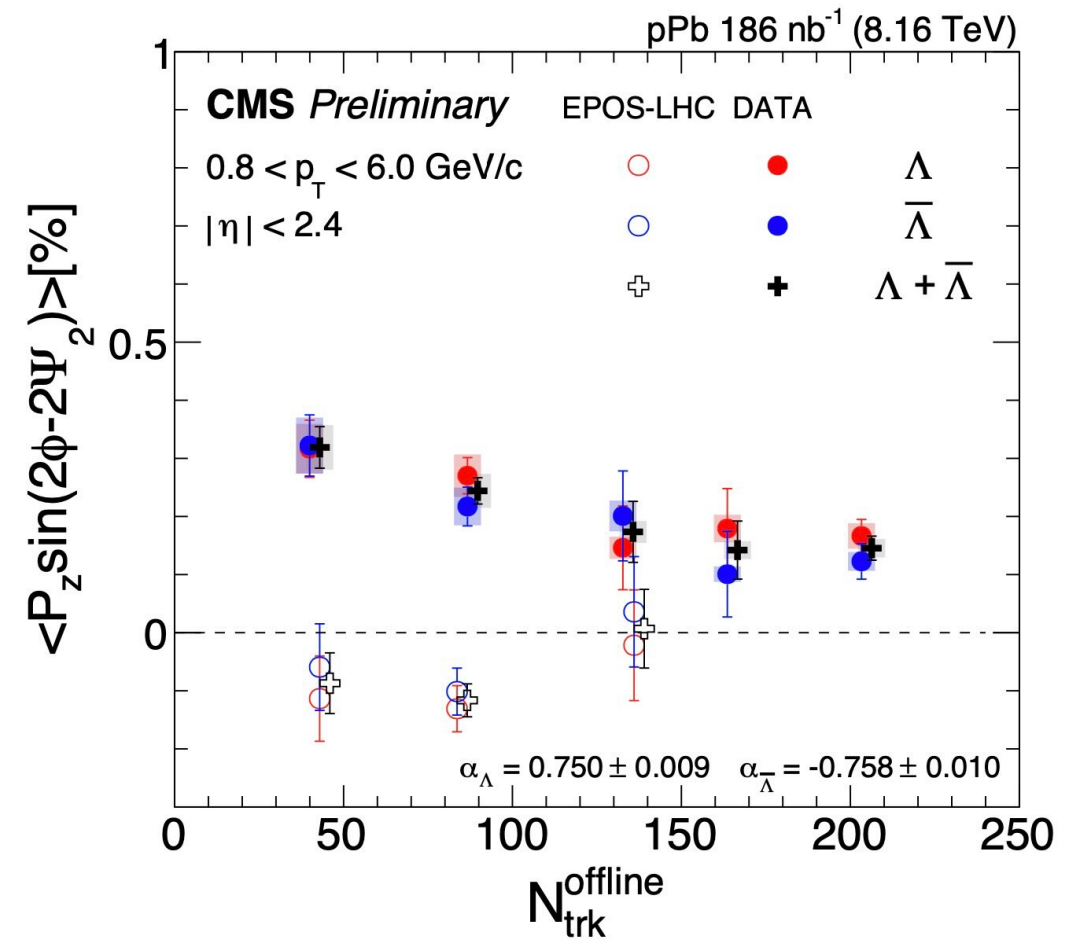
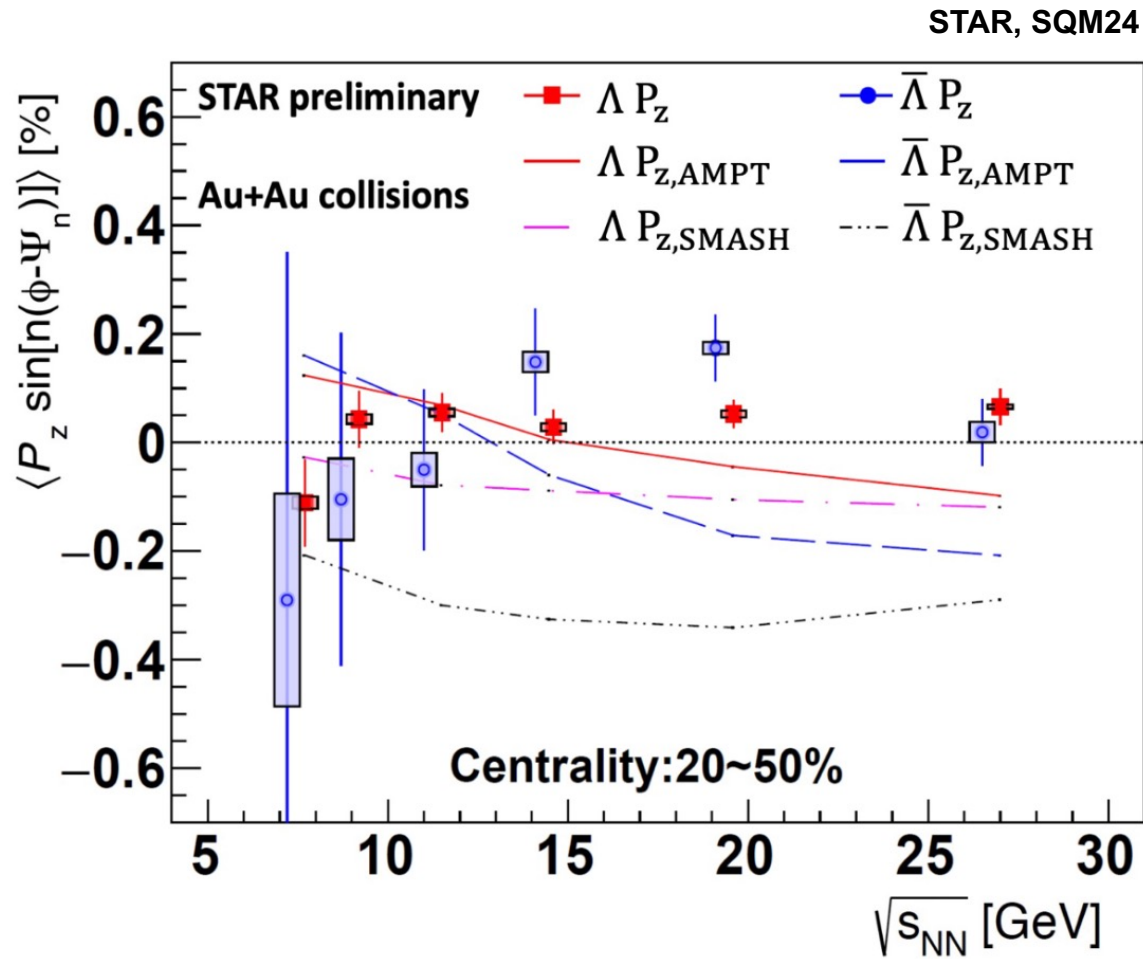


similar centrality (and  $p_T$ ) dependences between (1) energies, (2) systems and (3) orders (n=2, 3)

similarity between  $P_z$  (long-) and  $P_y$  (global-) shape as a function of centrality, which is more similar to  $v_1(\text{cent.})$  shape than to  $v_2(\text{cent.})$  shape

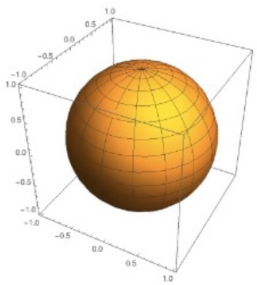


# Longitudinal (along z) Polarizations at RHIC-BES2 and LHC pA

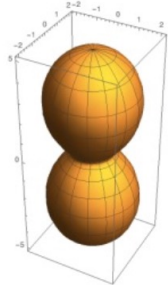


# Global Spin Alignment from the same rotating system

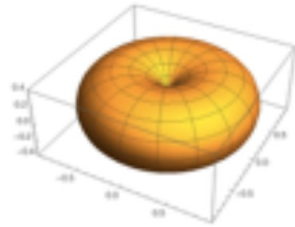
$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[ (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^* \right]$$



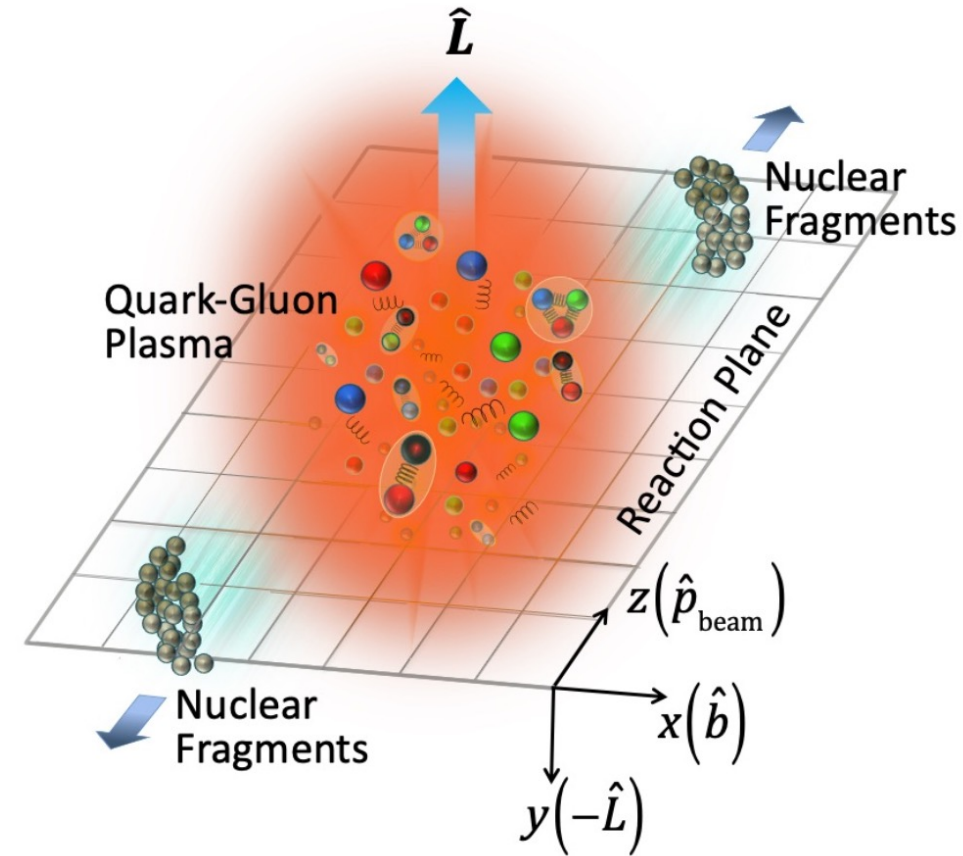
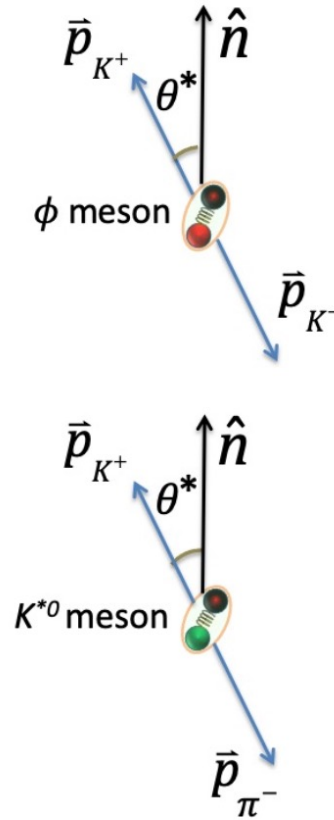
$$\rho_{00} = \frac{1}{3}$$



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



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



# $\rho_{00}$ of $\phi$ and $K^{*0}$ in BES-I and LHC

STAR, Nature 614 (2023) 244

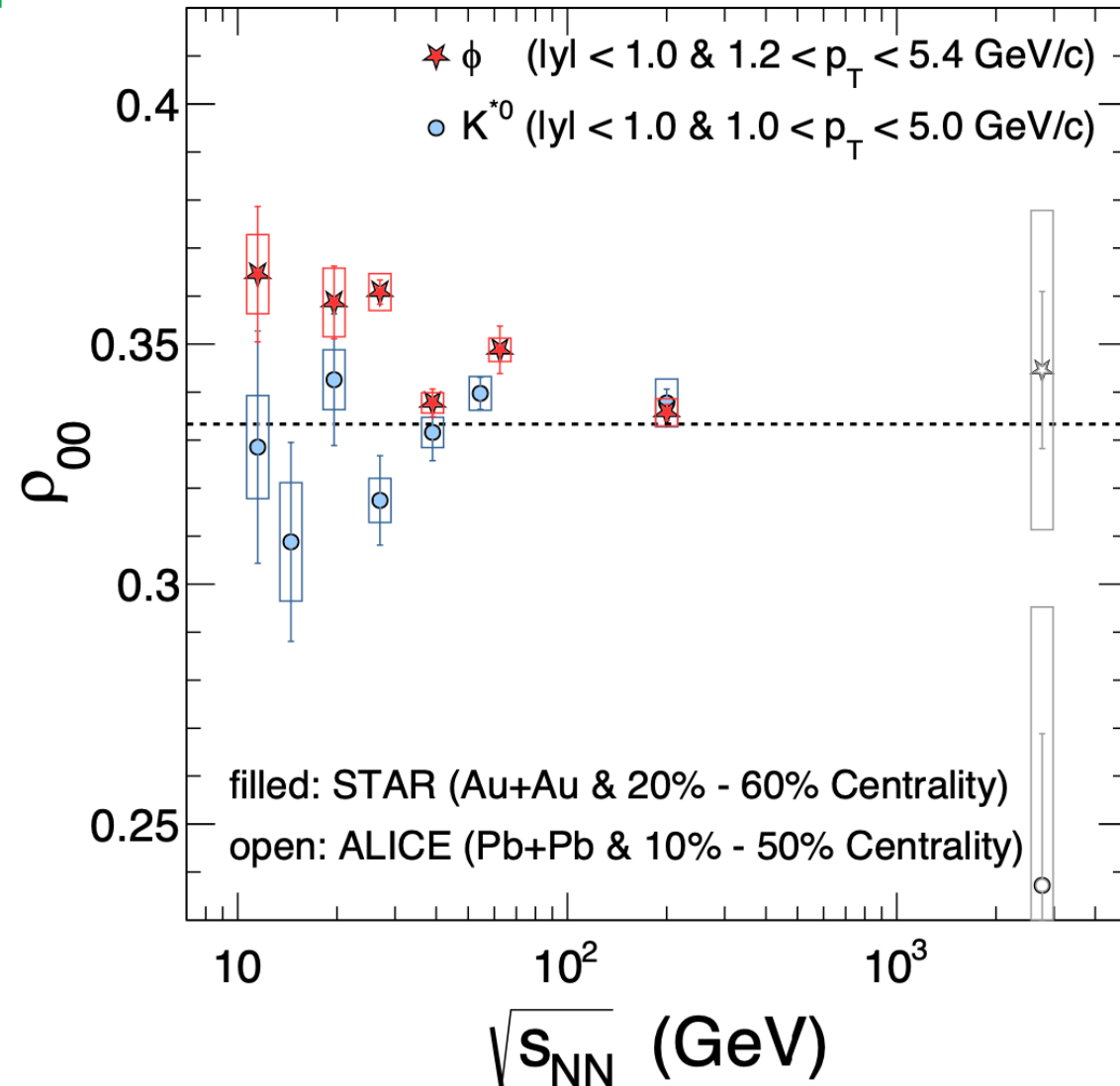
$\rho_{00} > 1/3$  for



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

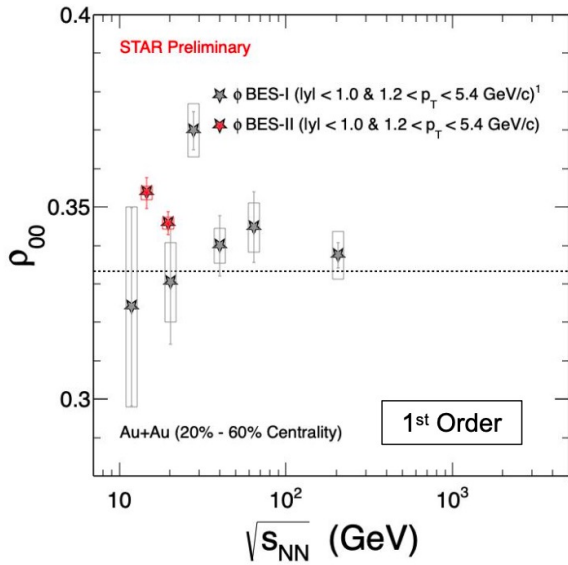


- global spin alignment (local field fluctuation)
- global polarization (global average field)

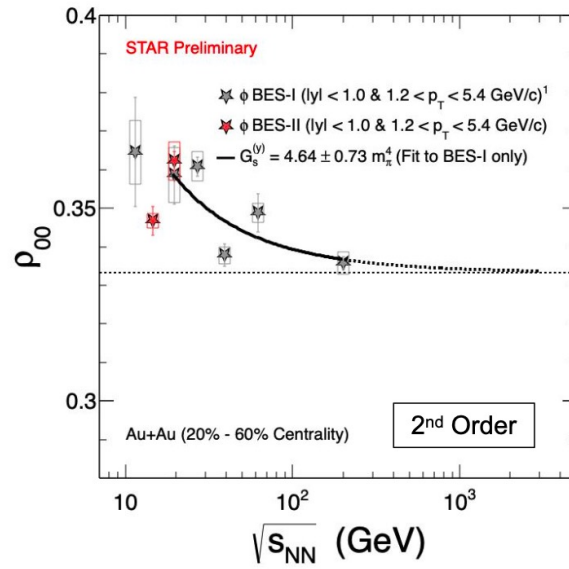


# $\rho_{00}$ of $\phi$ in BES-II (with BES-I)

1<sup>st</sup> order R.P.

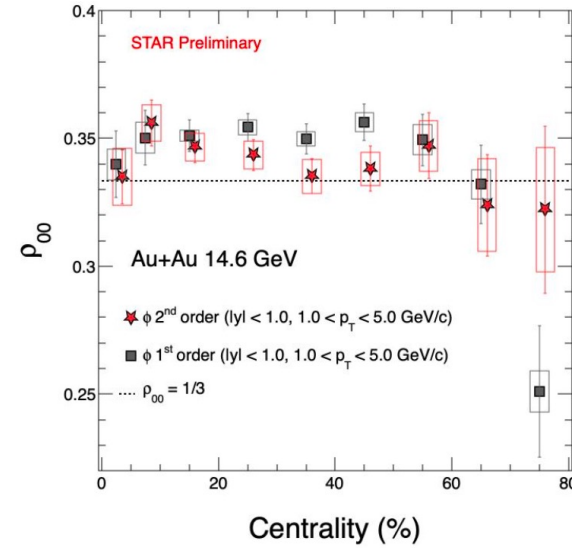


2<sup>nd</sup> order R.P.



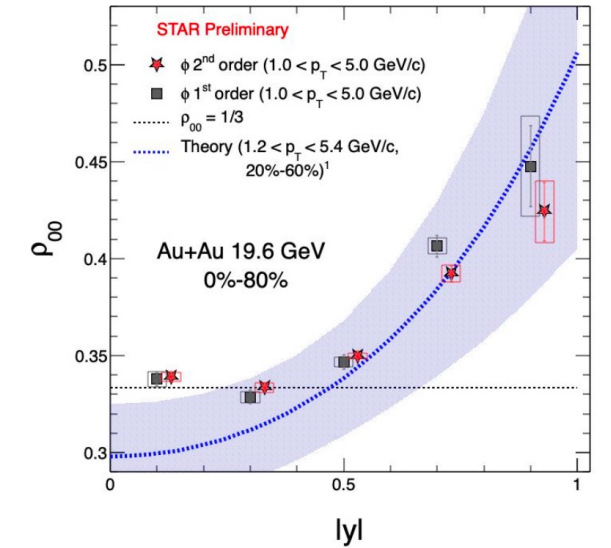
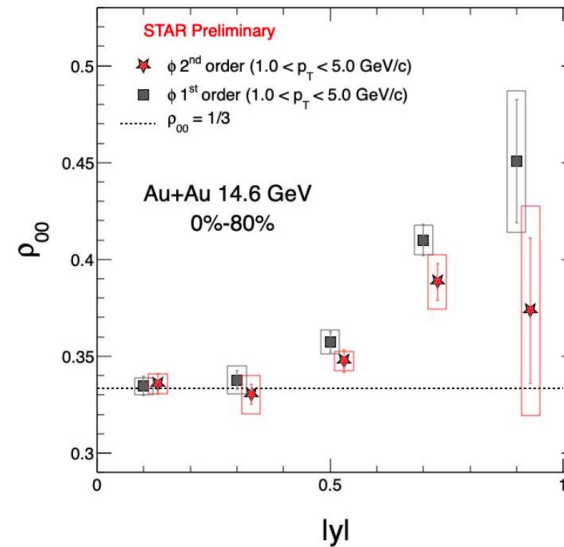
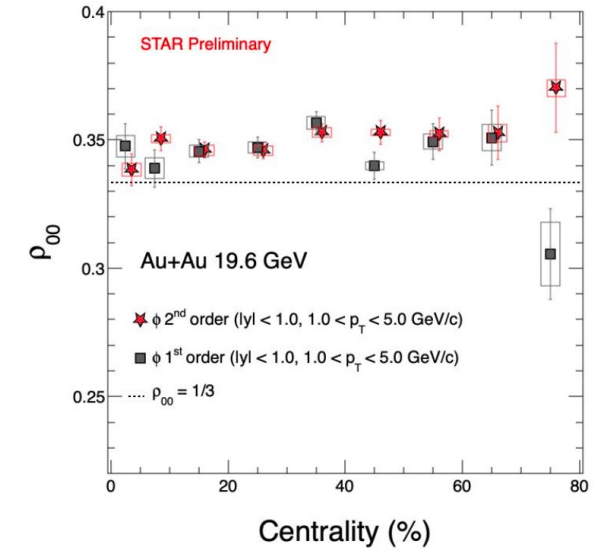
- consistency between 1<sup>st</sup> and 2<sup>nd</sup> order R.P.?
- strong/weak beam energy dependence?
- weak centrality dependence
- clear rapidity dependence

14.6 GeV



19.6 GeV

STAR, QM23



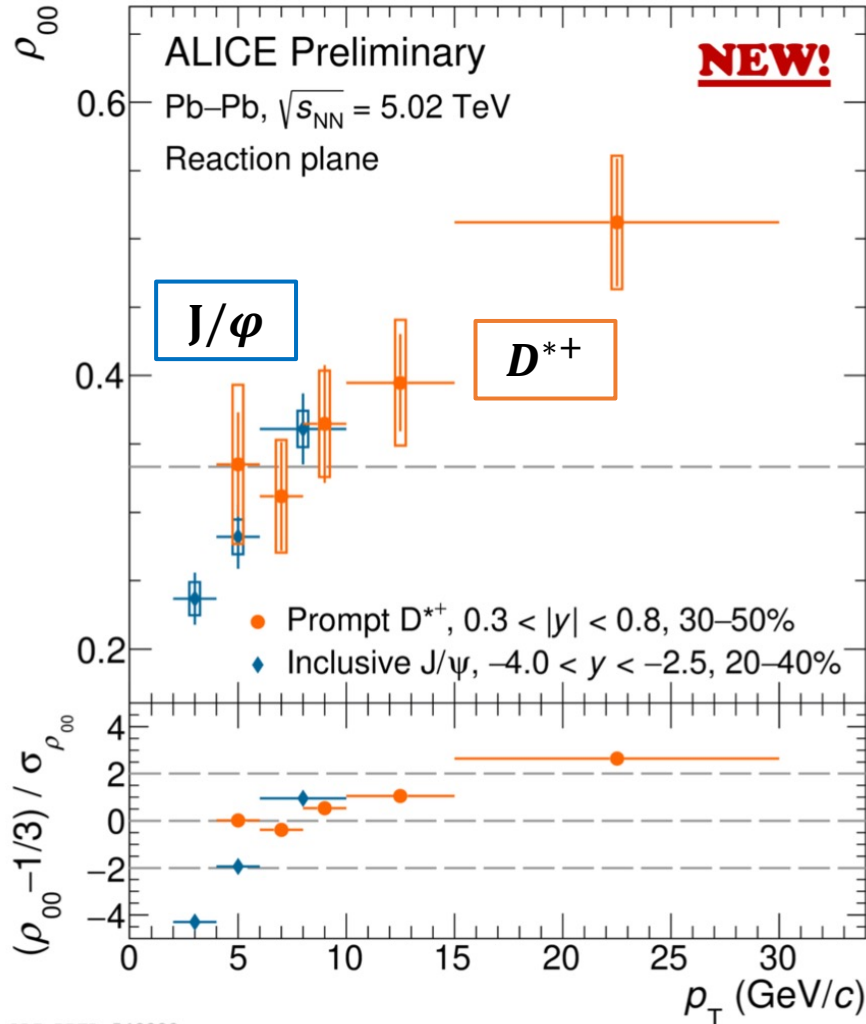


# $\rho_{00}$ of $J/\psi$ and $D^{*+}$ at LHC (and RHIC)

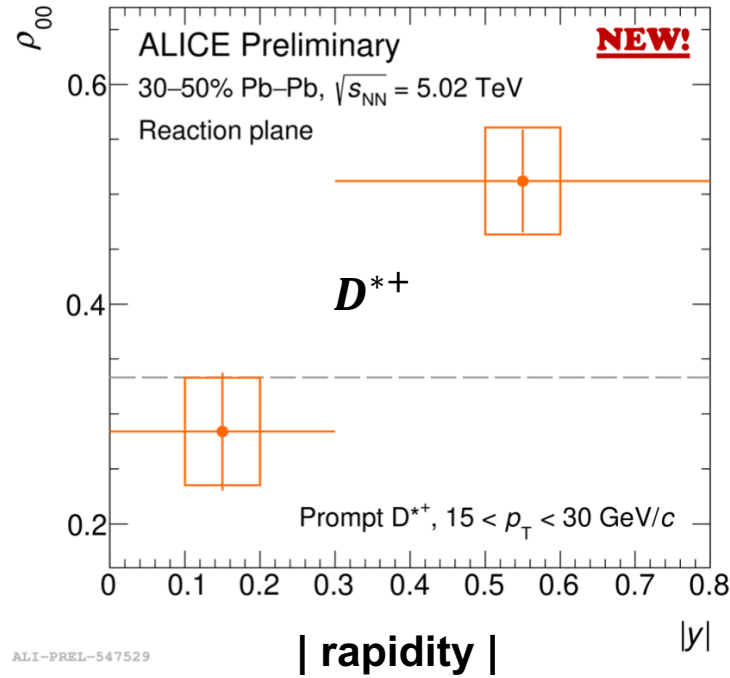


ALICE

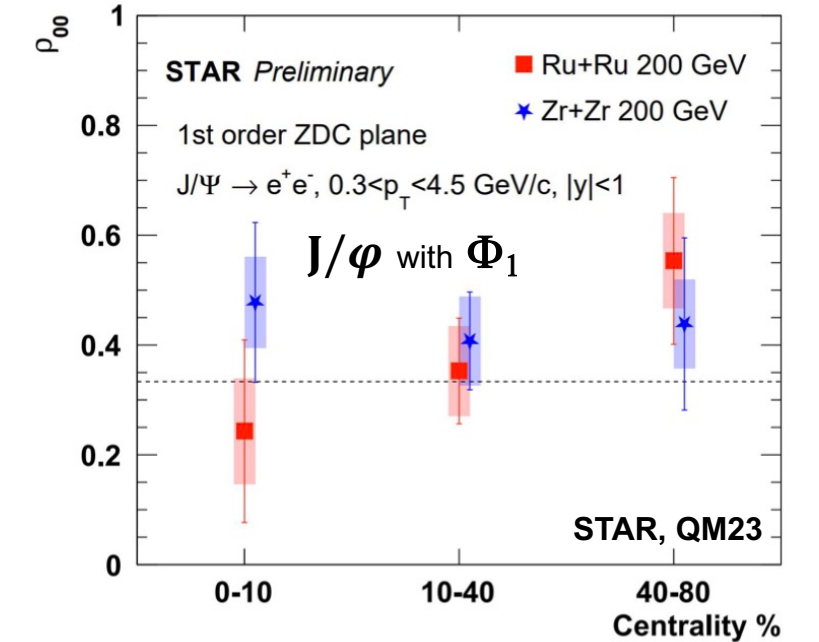
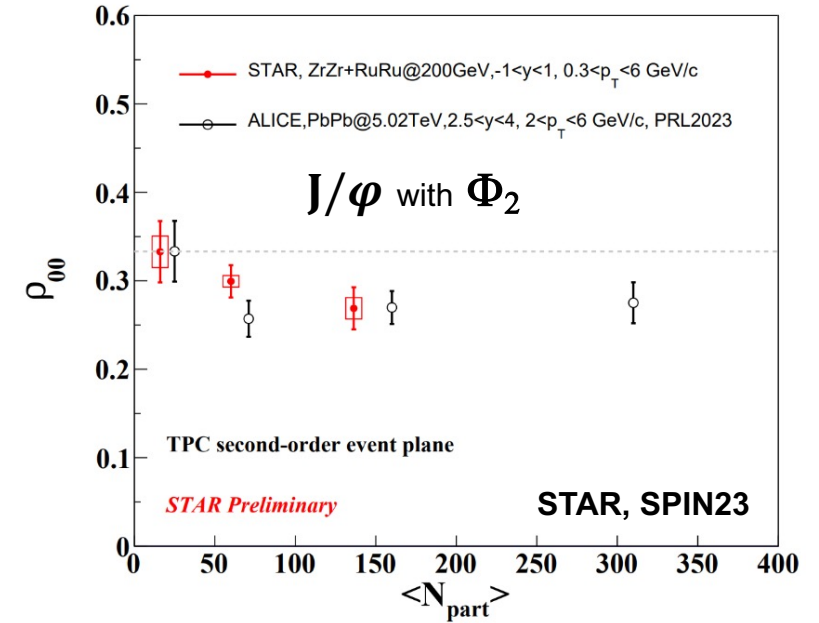
ALICE, QM23



ALICE, QM23



- clear  $p_T$  and rapidity dependences
- consistency between 1<sup>st</sup> and 2<sup>nd</sup> order R.P.?



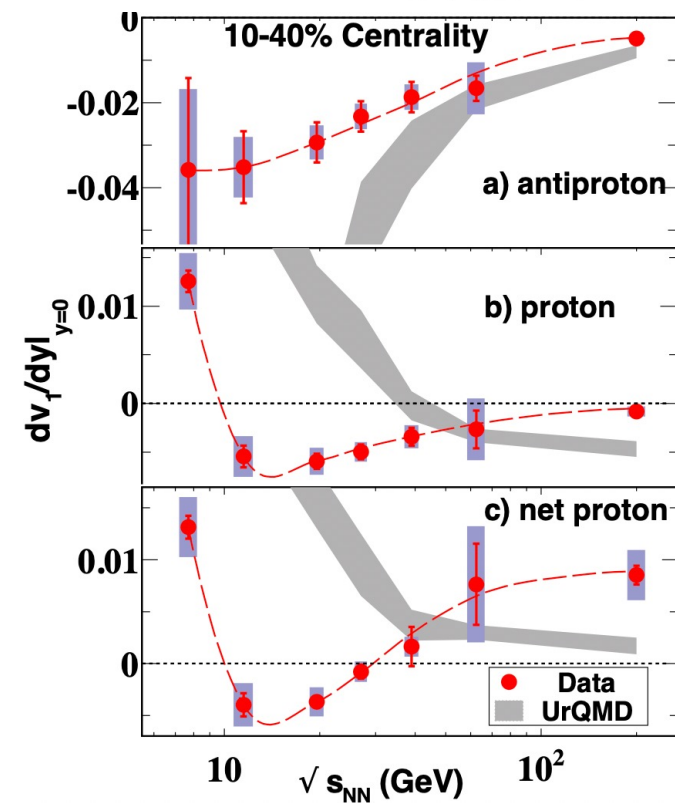
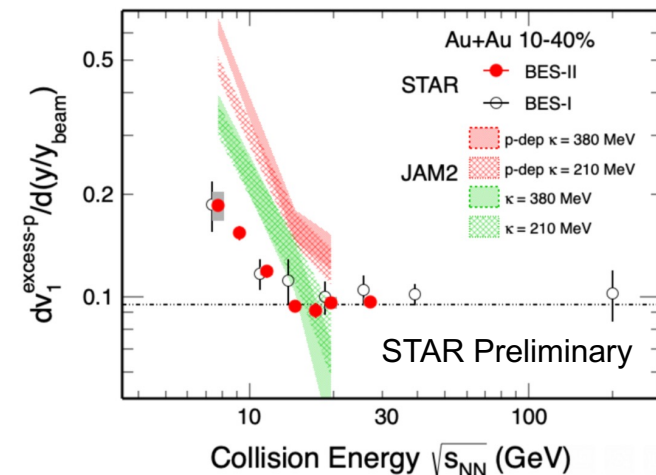
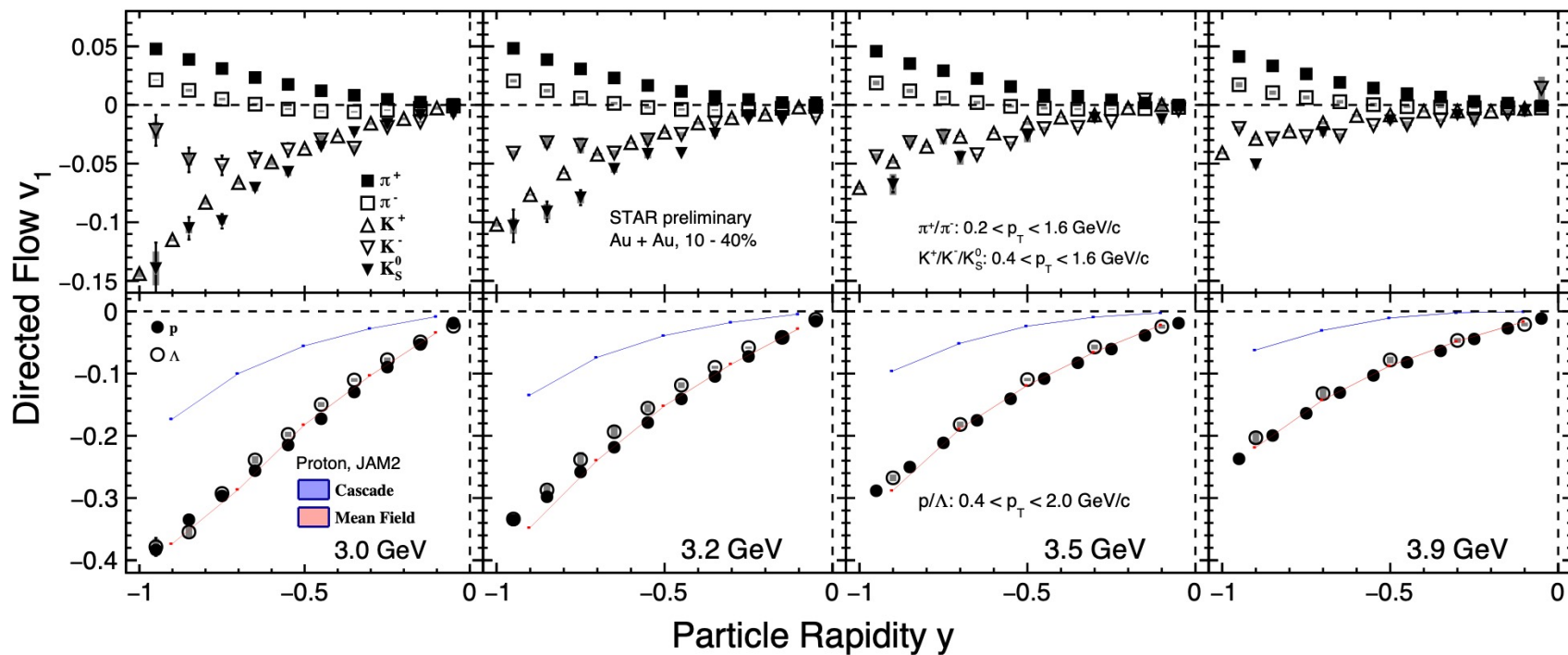
ALI-PREL-549222

# $v_1$ vs rapidity (FXT) and $v_1$ slope vs beam energies

$$v_1^{excess-p} = \frac{v_1(p) - v_1(pbar)}{1 - r}$$

$$v_1^{net-p} = \frac{v_1(p) - r v_1(pbar)}{1 - r}$$

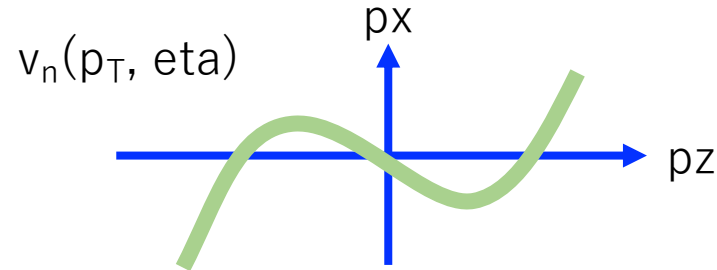
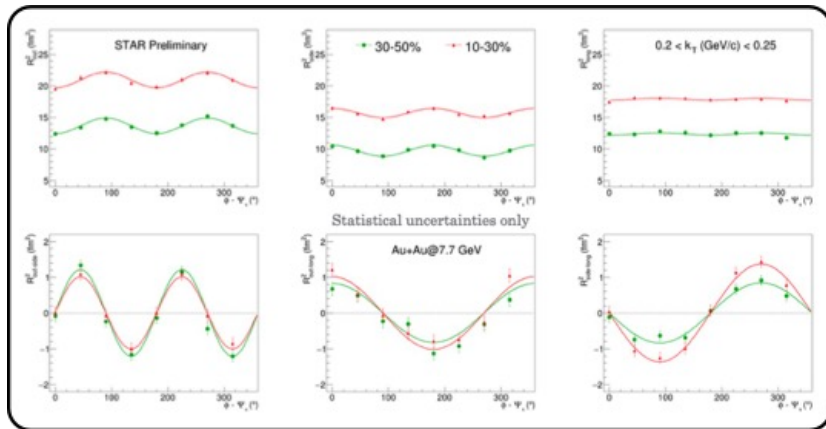
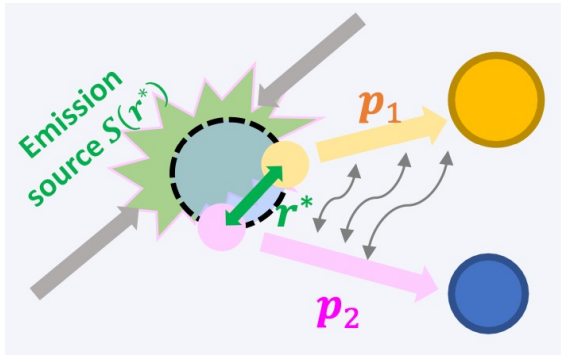
$$r = \frac{N_{pbar}}{N_p}$$



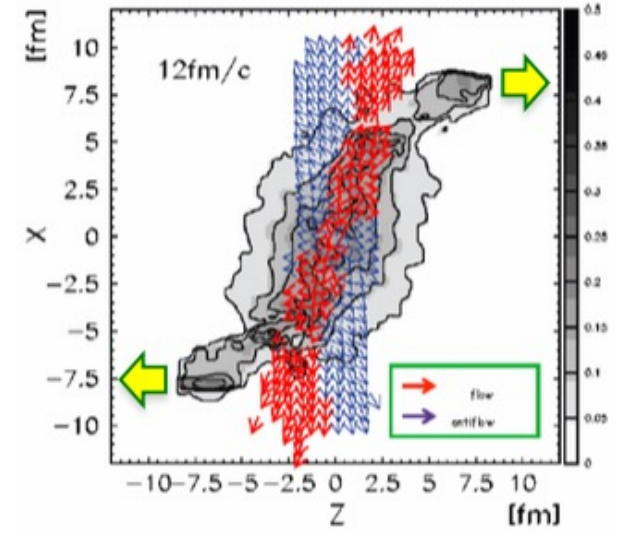
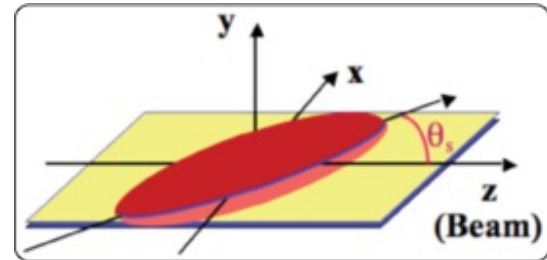
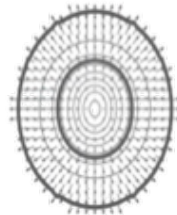
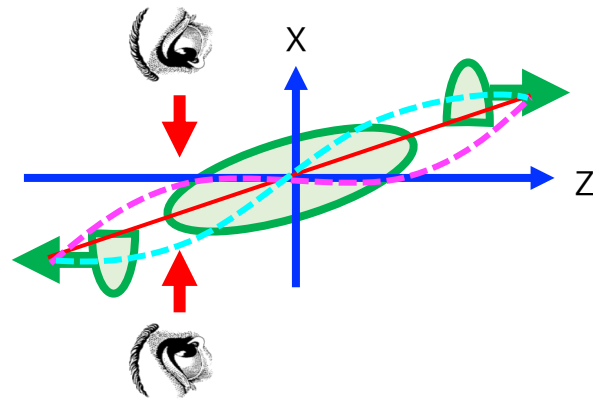
STAR, Phys. Rev. Lett. 112, 162301 (2014)

# Femto-Correlations

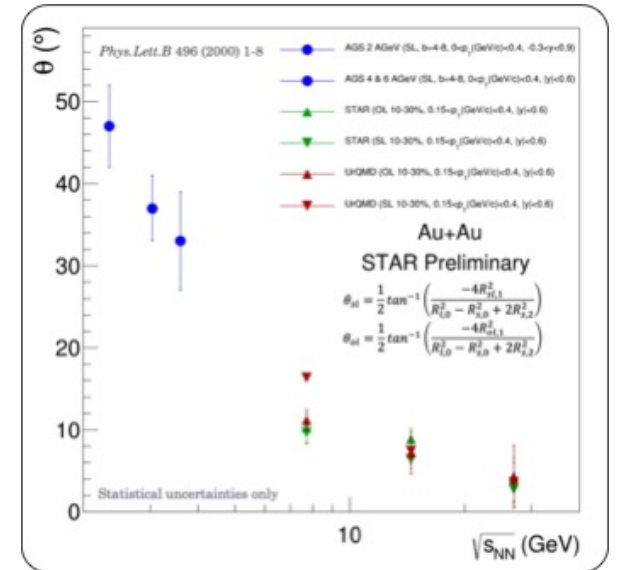
- geometry, expansion, interaction
- identical, non-identical correlation
- meson-meson, baryon-baryon



$\varepsilon_n(p_T, \eta)$



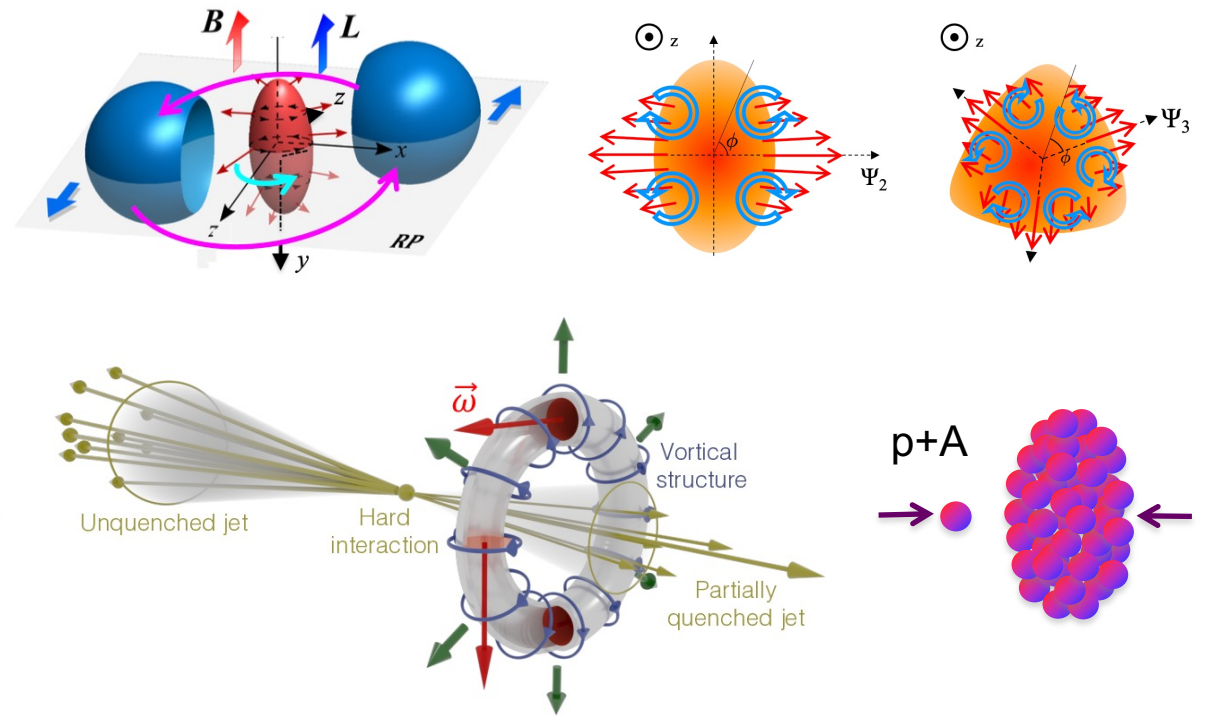
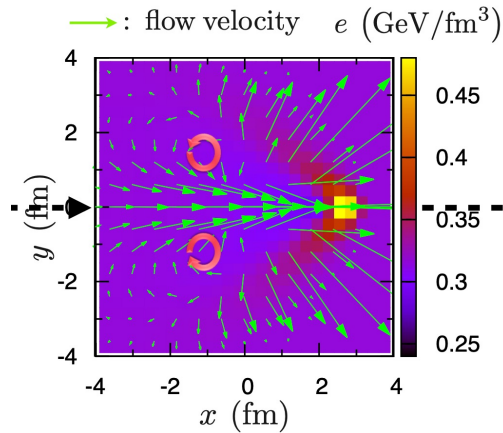
STAR, WWND2024



# Summary

- Global Polarization from GeV to TeV
- $\Lambda$  and  $\bar{\Lambda}$  difference and B-field effect
- Global and Longitudinal Polarization
- Global Spin Alignments
- **Other types of related signals**
- **Relation to flow and geometry**

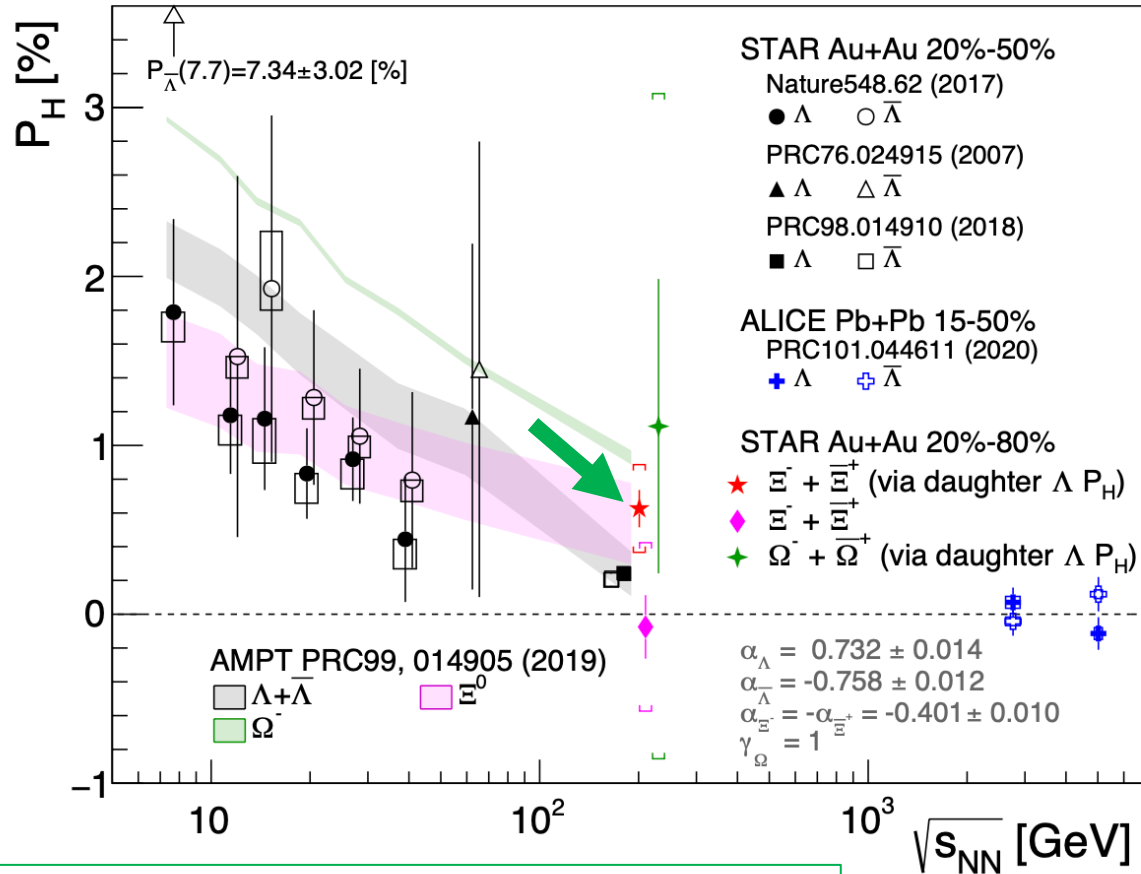
B. Bets et al., PRC 76 044901 (2007)  
 Y. Tachibana et al., NPA 904 1023c (2013)  
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# Global Polarization with $\Xi$ and $\Omega$ at 200 GeV

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somehow larger for multi-strange hyperon

