Spin polarization measurements from STAR Beam Energy Scan program

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STAR

U.S. DEPARTMENT OF ENERGY | Office of Science

IMP

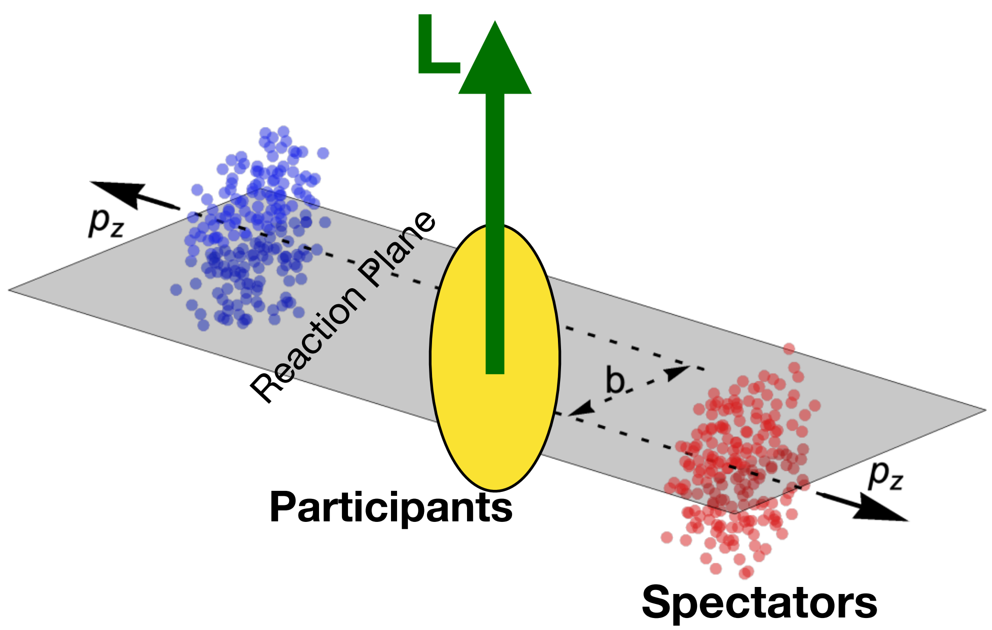
Outline

- Motivation for measuring the spin polarization
- STAR detector
- Measurements from STAR (Au+Au collisions at $\sqrt{s_{NN}}$ = 3 - 200 GeV):

  Global polarization of hyperons (Λ, Ξ, Ω)
  Local polarization of hyperons (Λ)
  Global spin alignment of vector mesons (ϕ, K*)

- Summary and outlook

Probe initial angular momentum



Becattini, et. al., Phys Rev. C. 77, 024906 (2008)

In non-central heavy-ion collisions

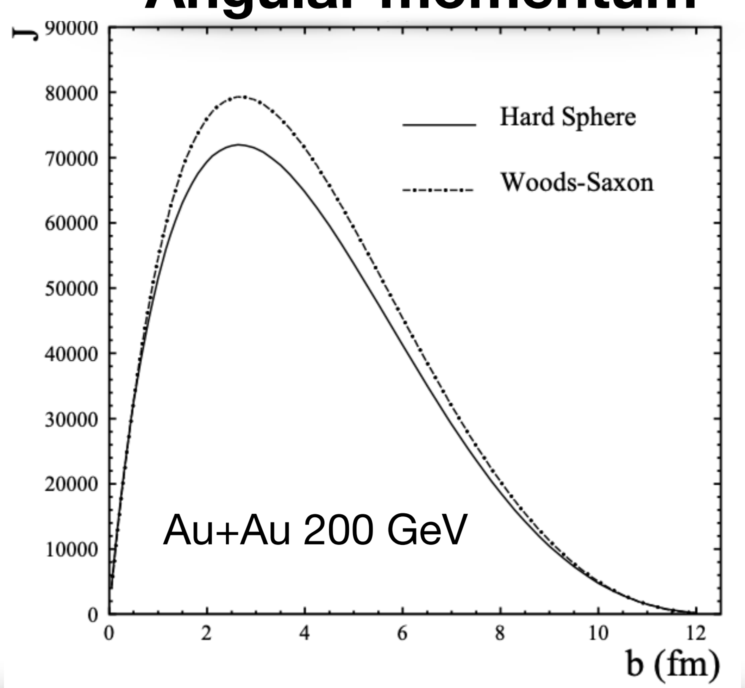
- A large orbital angular momentum (OAM) imparted into the system

$$L \sim bA\sqrt{s_{NN}} \sim 10^4\ \hbar$$

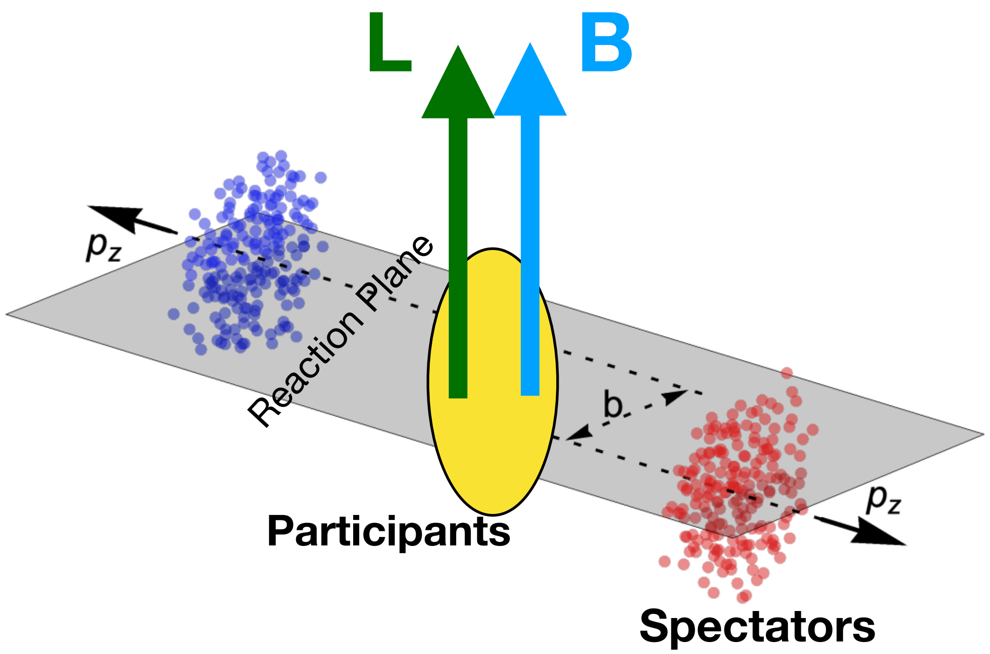
- Such a huge OAM can polarize quarks due to "spin-orbit" interaction.

Liang, et. al., Phys Rev Lett. B. 94, 102301 (2005)

Angular momentum

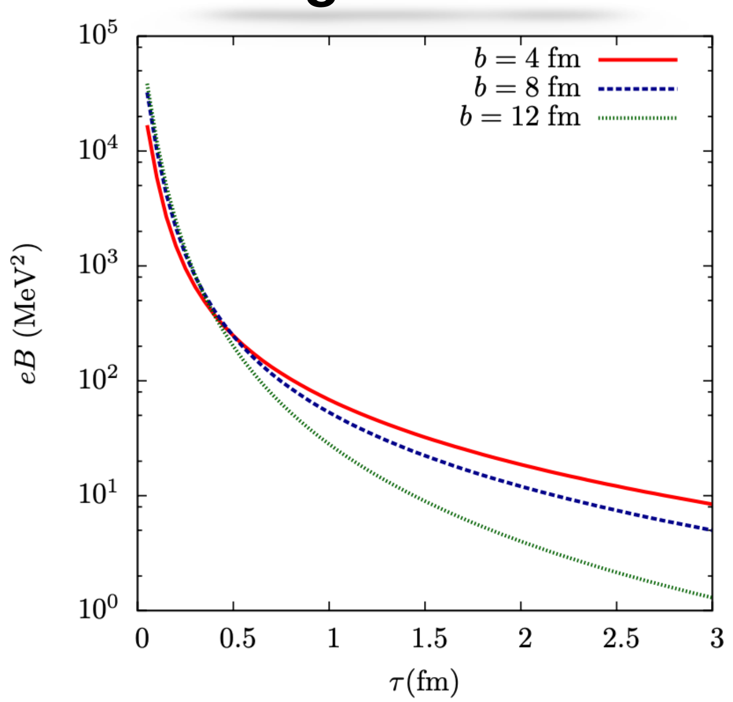


Probe initial magnetic field



Kharzeev, Nucl Phys A803, 227 (2008)

Magnetic field



In non-central heavy-ion collisions

- Initial strong magnetic field (**B**) is expected

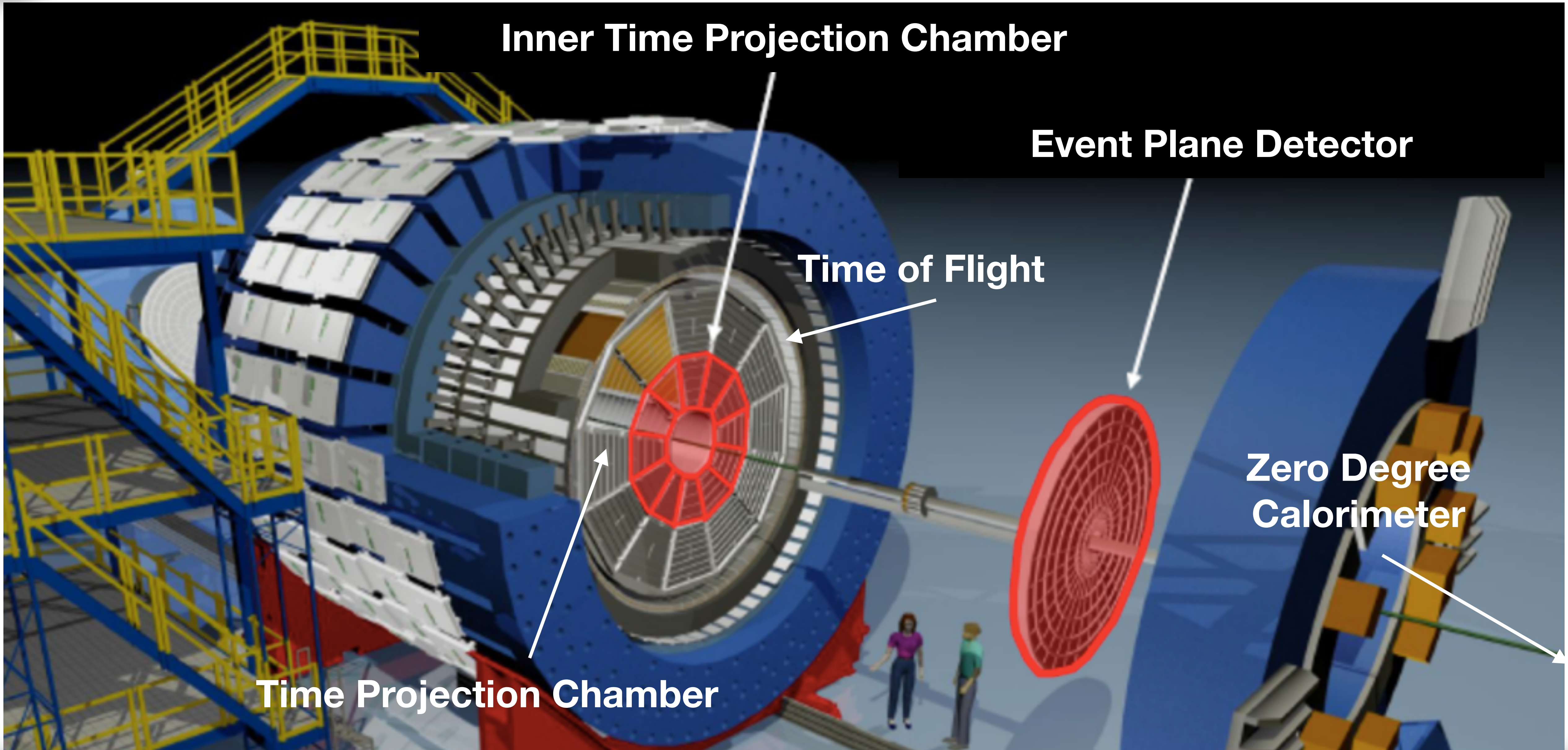
$$eB \sim m_\pi^2 \sim 10^{18} \text{ Gauss}$$

- Such strong **B** field can also polarize quarks. Can induce opposite spin polarization for particles and anti-particles due to opposite sign of magnetic moment

Through polarization measurement

- **Search for signatures of L and B**
- **Understand the properties of QGP medium under extreme conditions (L and B)**
- **Provide the unique opportunity to probe the spin degrees of freedom of the QGP**

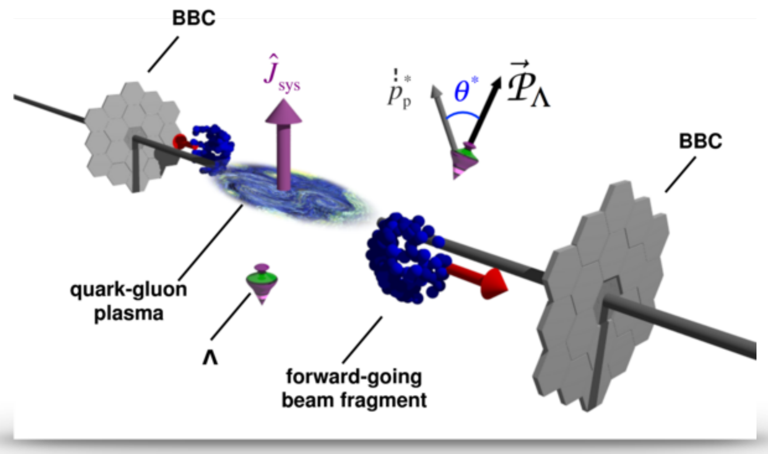
STAR Detector



- Uniform acceptance, full azimuthal coverage, excellent PID capability
- TPC: tracking, centrality and event plane
- EPD, ZDC, BBC: event plane
- TPC+TOF: particle identification

Global spin polarization of hyperons

Dataset and analysis



Collision system	Au+Au
Collision energy	3-200 GeV
Particle of interest	Λ, Ξ, Ω
rapidity	|y| < 1.0
Background	Side bands
Polarization axis	perpendicular to 1st order event plane (BBC/ZDC/EPD)

Global polarization is measured from the angular distributions using parity violating weak decay of hyperons ("self-analyzing"):

- $$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}^*_{\mathbf{H}} \cdot \mathbf{p}^*_{\mathbf{d}})$$

$\mathbf{P_H}$: Hyperon polarization

α_H : Hyperon decay parameter

$\mathbf{p_d}$: Daughter momentum direction

$*$: Measurements in parent's rest frame

Component perpendicular to reaction plane:

- $$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi^*_d) \rangle}{\mathrm{Res}(\Psi_1)}$$

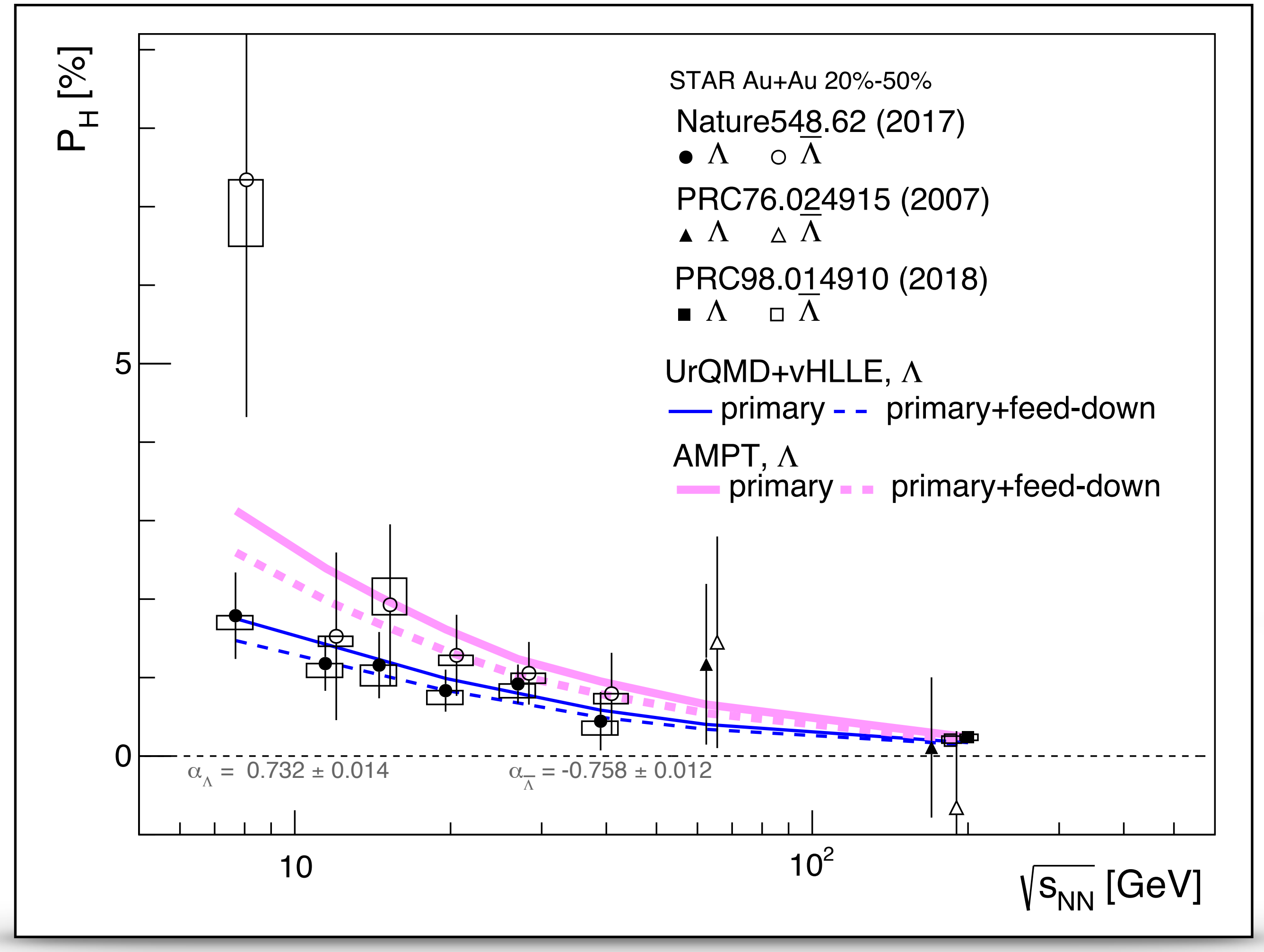
ϕ_d : Daughter azimuthal angle

Ψ_1: 1st order event plane

First observation of P_Λ

STAR: Nature 548, 62 (2017)

STAR: Phys Rev C 90, 014910 (2018)



Global polarization is measured from the angular distributions

- $$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\mathrm{Res}(\Psi_1)}$$
- Thermal vorticity

  $$\omega = k_B T (P_\Lambda + P_{\bar{\Lambda}})/\hbar$$

$$\omega \sim (9 \pm 1) \times 10^{21}\ s^{-1}$$

Becattini, et. al., Phys Rev. C. 95, 054902 (2017)

Most vortical fluid created at RHIC

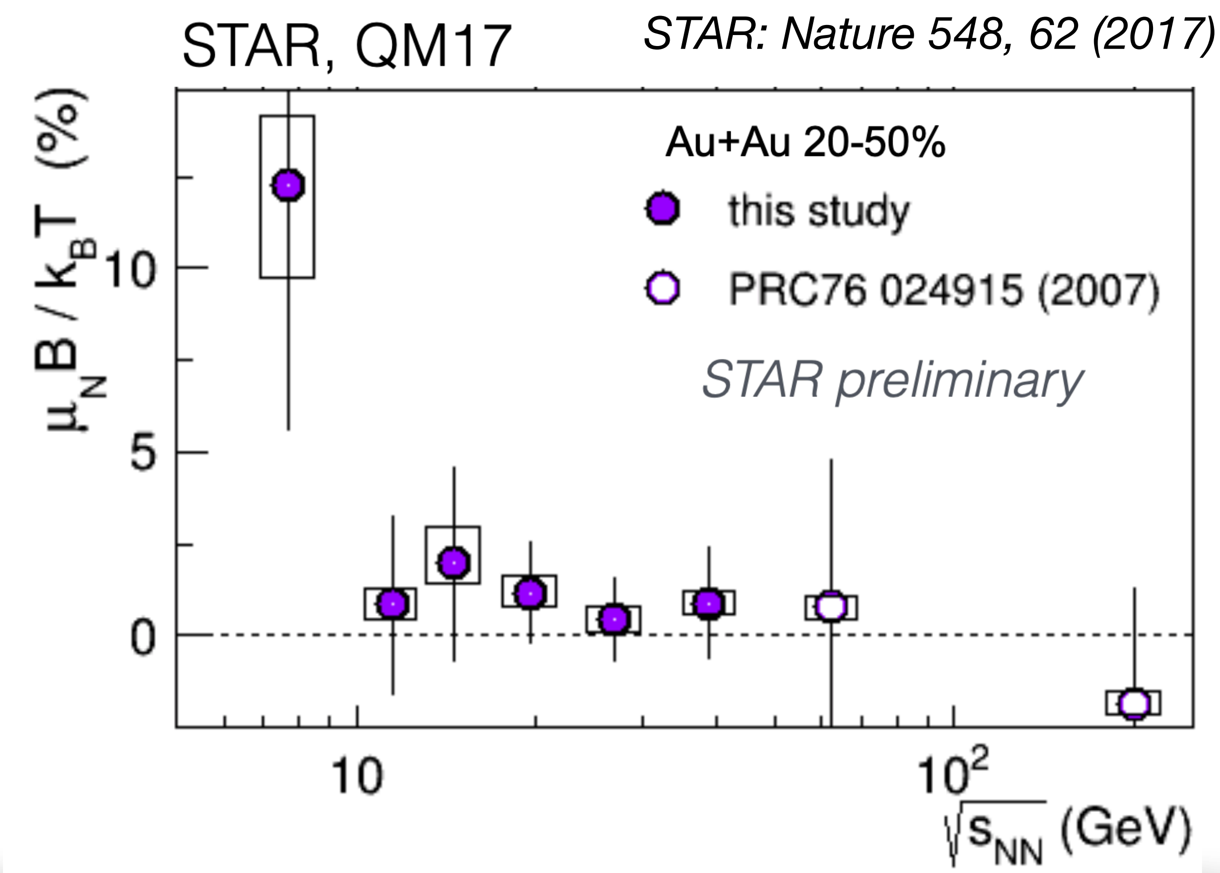
Hints of difference between Λ and anti-Λ

**Note: the decay parameter (α_Λ) has been updated and P_H is smaller by 12%

BES-III: Nature 15, 631 (2019), Ireland et al, Phys Rev Lett 123, 182301 (2019)

Zyla et al, (PDG), PTEP 083C01 (2020)

Possible constraint on B field by P_Λ



Global polarization is measured from the angular distributions

- $$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\mathrm{Res}(\Psi_1)}$$
- Magnetic field

$$\mathrm{B} = \frac{\mathrm{T}}{2\mu_\Lambda}(\mathrm{P}_\Lambda - \mathrm{P}_{\bar{\Lambda}})$$

$$B \sim 10^{-2}\, m_\pi^2$$

$\Delta P_\Lambda = 0.5\%$

T=160 MeV

Becattini, et. al., Phys Rev. C. 95, 054902 (2017)

Hints of difference between Λ and anti-Λ
(Effect from initial B field ?)**

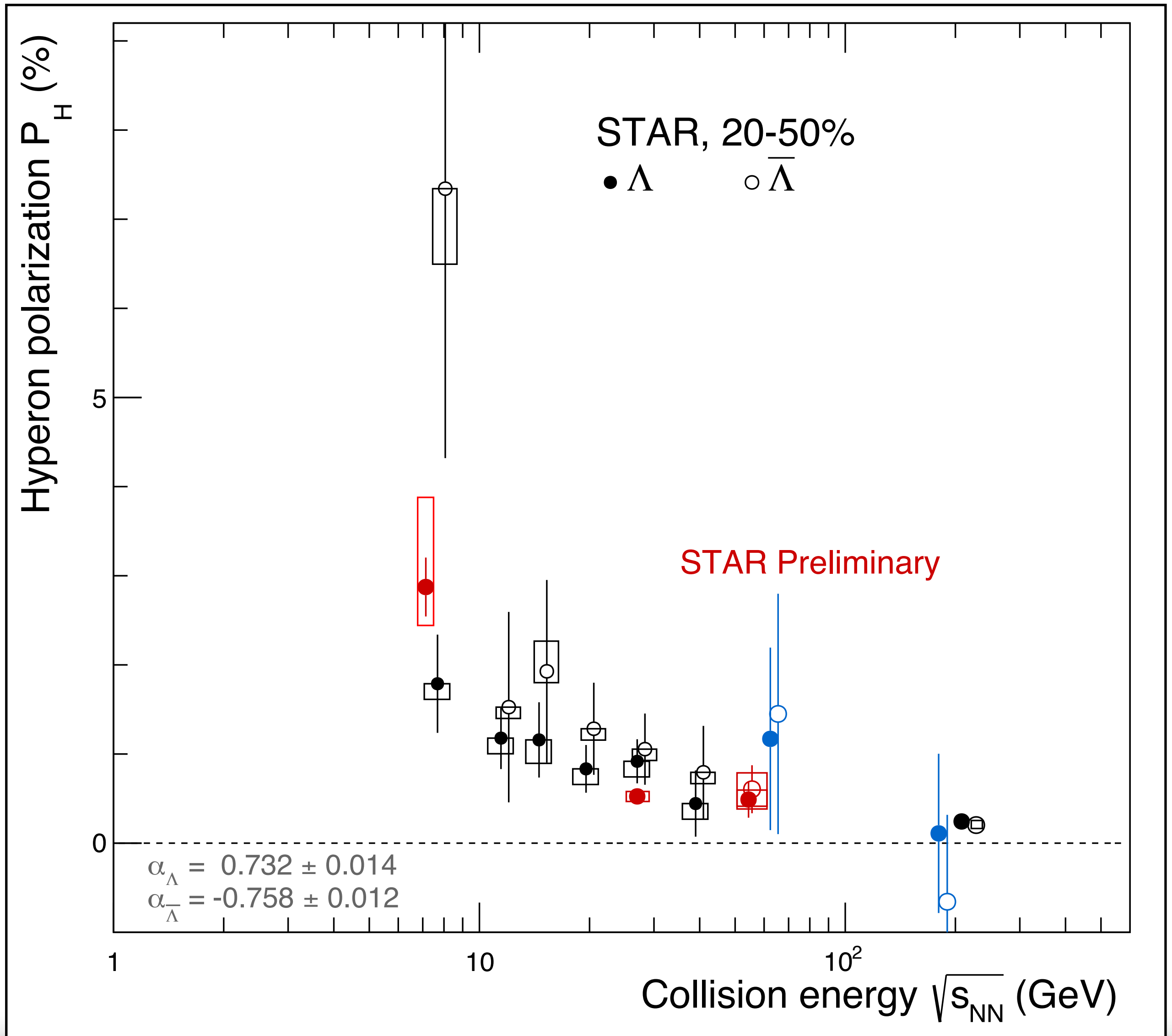
** Difference between Λ and anti-Λ can also be caused by

- Different freeze out for particles and anti-particles
- Different response to mesonic field generated by baryonic current
- …..

Vituik, et. al., Phys Lett. B. 803, 135298 (2020)
Csernai et al, Phys Rev C, 99, 021901 (2019)

New measurements of P_Λ from lower energies

STAR: Nature 548, 62 (2017)
STAR: Phys Rev C 90, 014910 (2018)



Hadronic dominant

Partonic dominant

STAR Preliminary

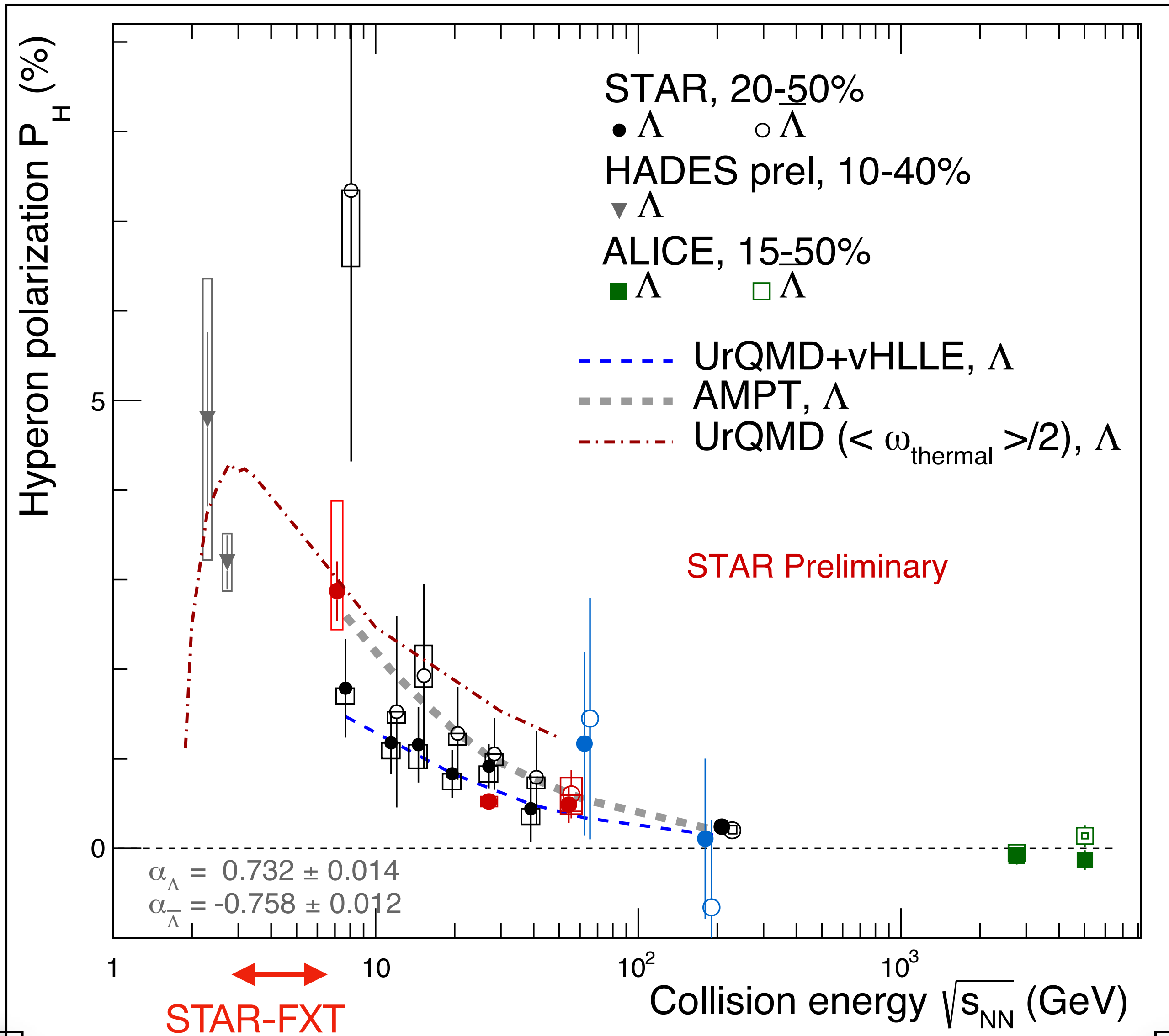
Au+Au Collider $\sqrt{s_{NN}}$ = 27, 54.4 GeV

Au+Au Fixed Target $\sqrt{s_{NN}}$ = 7.2 GeV

Preliminary P_Λ measurements follow the global trend of energy dependence

Beam energy dependence of P_Λ

STAR: Nature 548, 62 (2017)
STAR: Phys Rev C 90, 014910 (2018)



Hadronic dominant

STAR-BES-II

Partonic dominant

STAR Preliminary

Au+Au Collider $\sqrt{s_{NN}}$ = 27, 54.4 GeV

Au+Au Fixed Target $\sqrt{s_{NN}}$ = 7.2 GeV

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

Pb+Pb $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV

HADES Preliminary, SQM 2021

Au+Au $\sqrt{s_{NN}}$ = 2.4 GeV

Ag+Ag $\sqrt{s_{NN}}$ = 2.55 GeV

Theory calculations for P_Λ at low energies

Deng et. al, Phys.Rev.C 101, 064908 (2020)
Ivanov, Phys.Rev.C 103, L031903 (2021)
Guo et al, arXiv:2105.13481
.....

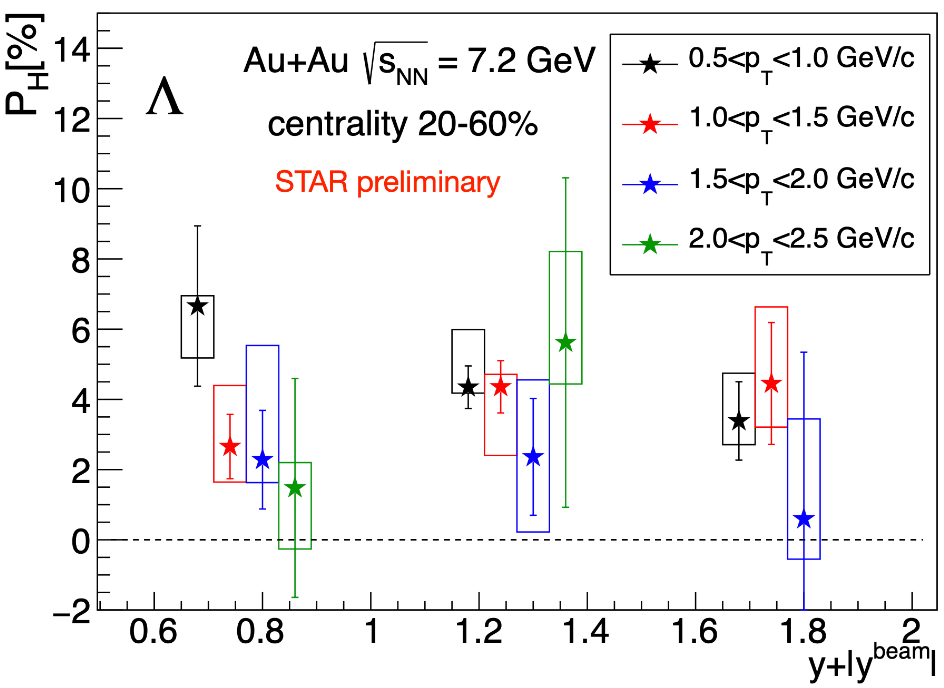
Expected, $P_\Lambda \sim 0$ at $\sqrt{s_{NN}} \sim 2m_N$

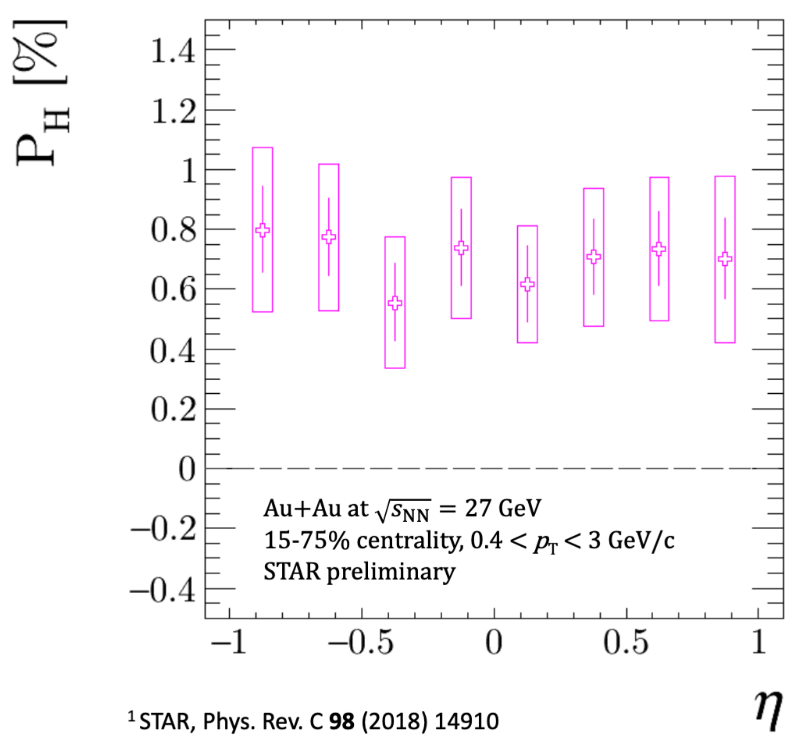
P_Λ follows increasing trend from 5.02 TeV down to 2.4 GeV

- **Hadronic dominant matter retains more vorticity (?)**
- **Where do we observe the highest polarization?**

η dependence of P_Λ

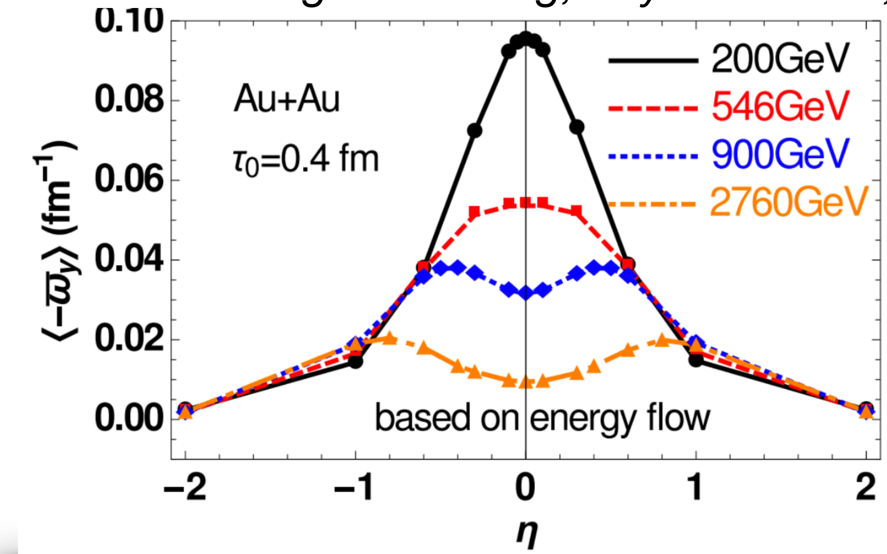
Data



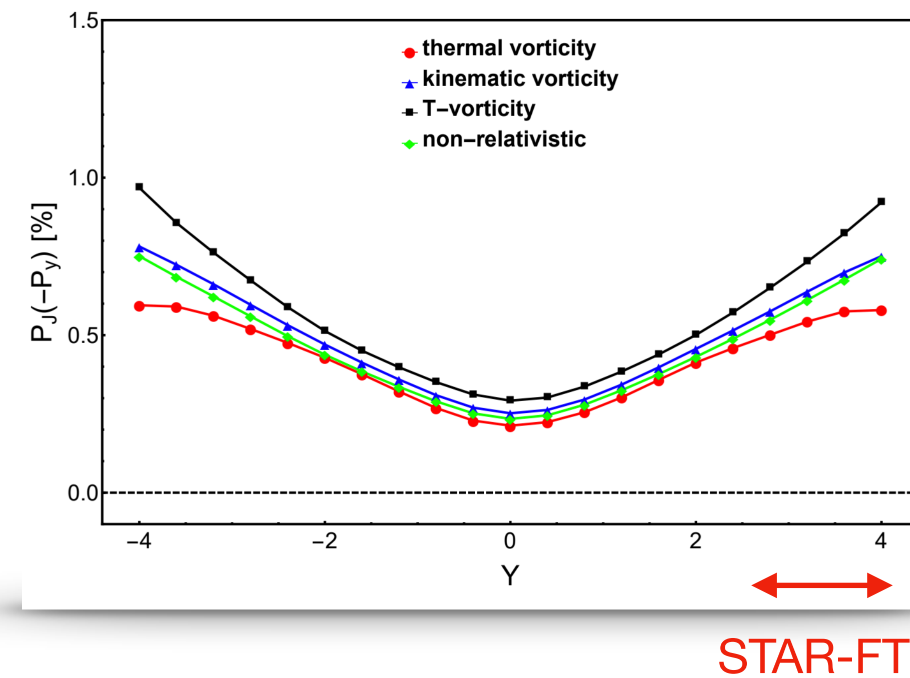


Model

Deng and Huang, Phys Rev C 93, 064907



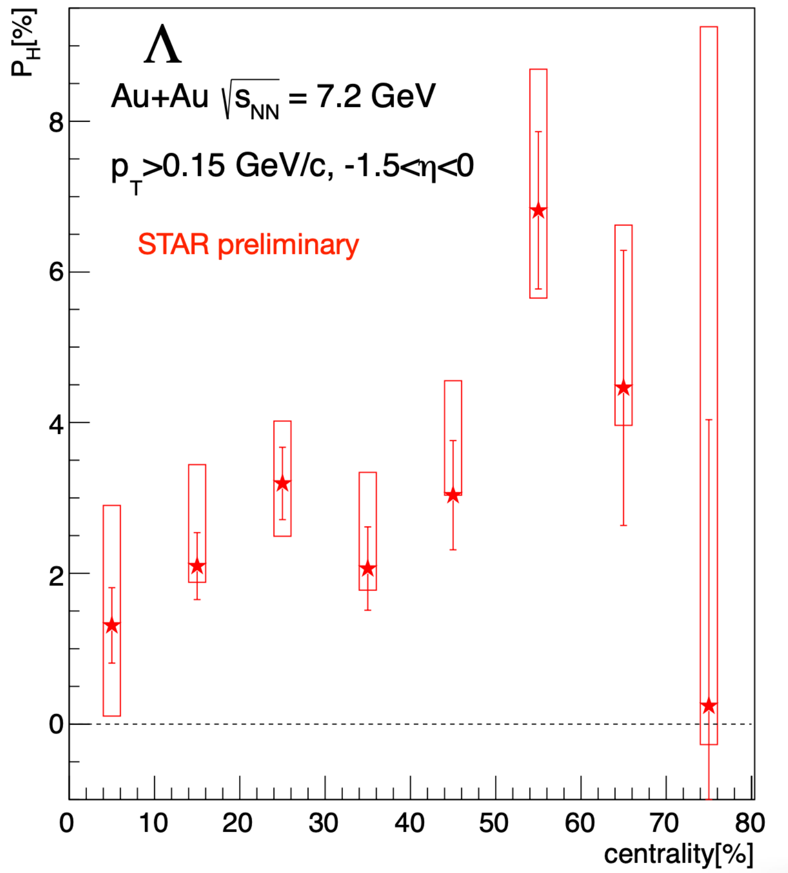
Wu et al, Phys Rev Research 1, 033058



- No significant y/η dependence observed within acceptance
- Rapidity dependence of P_Λ is different among various models

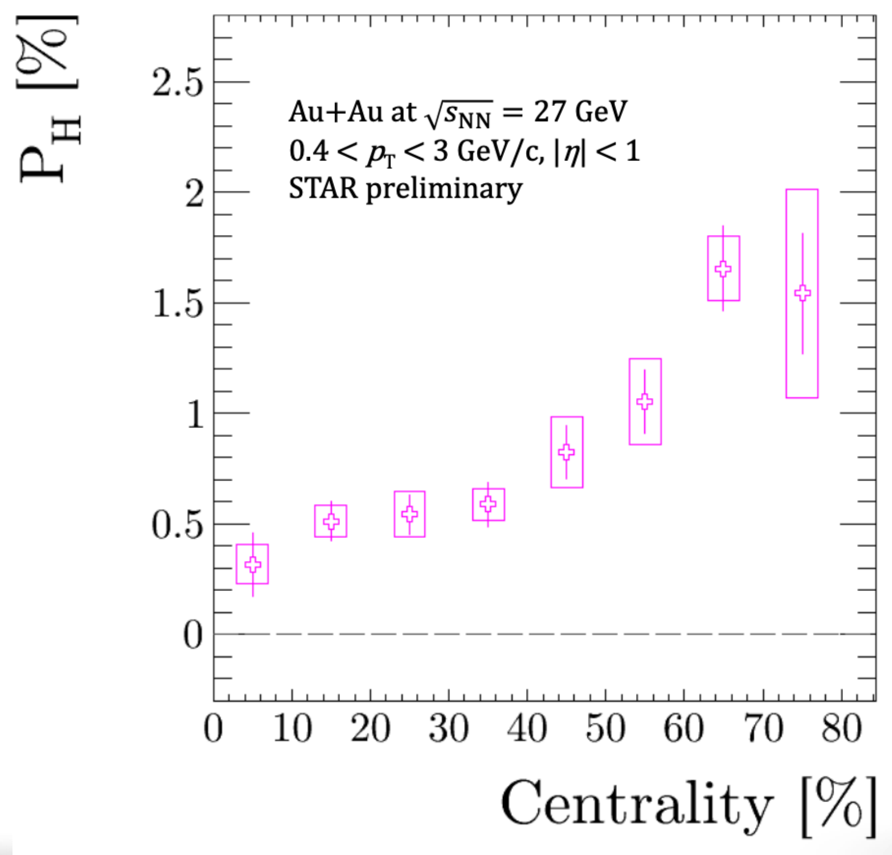
Centrality dependence of P_Λ

Au+Au $\sqrt{s_{NN}}$ = 7.2 GeV

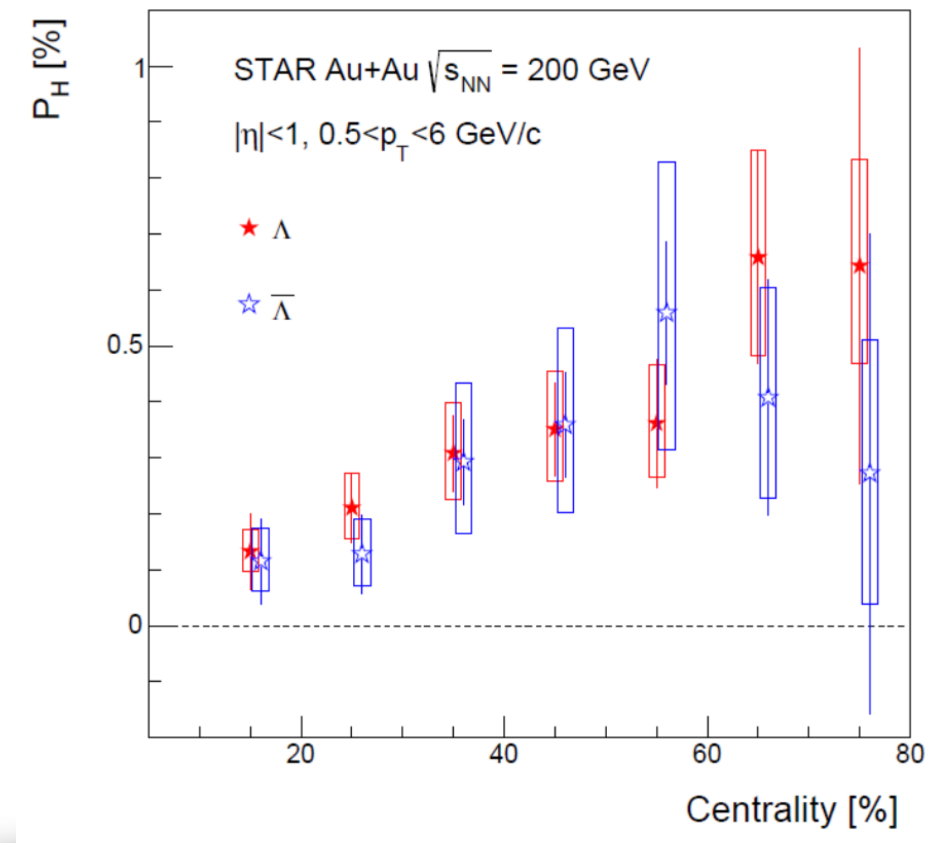


Central Peripheral

Au+Au $\sqrt{s_{NN}}$ = 27 GeV

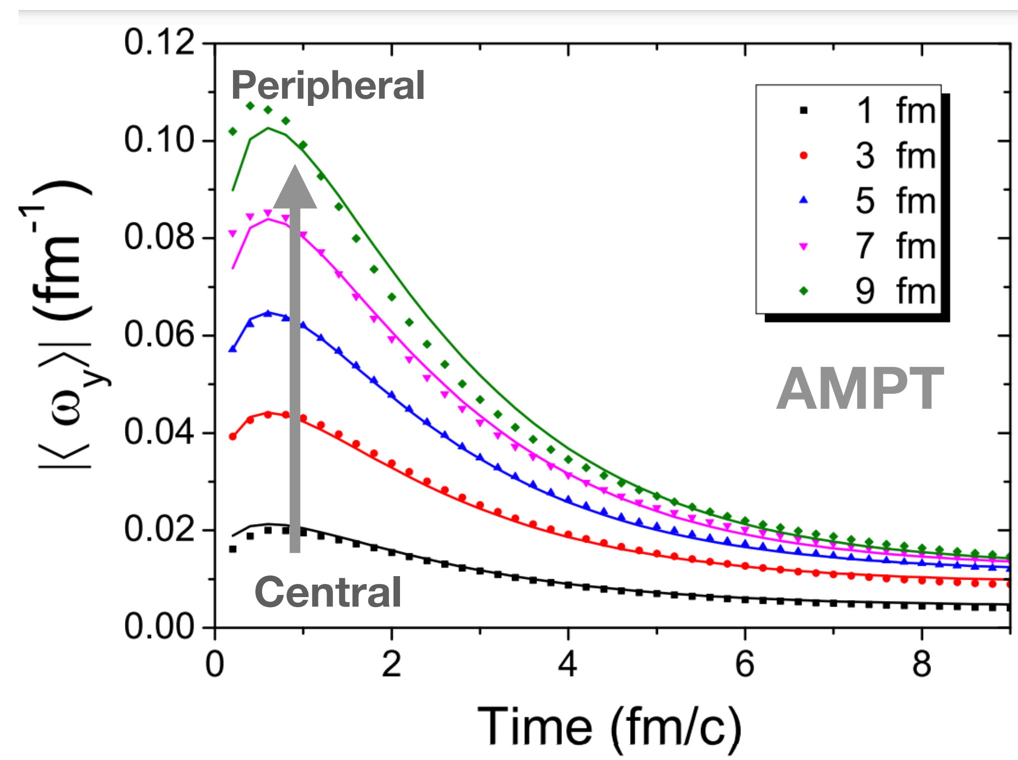


Au+Au $\sqrt{s_{NN}}$ = 200 GeV

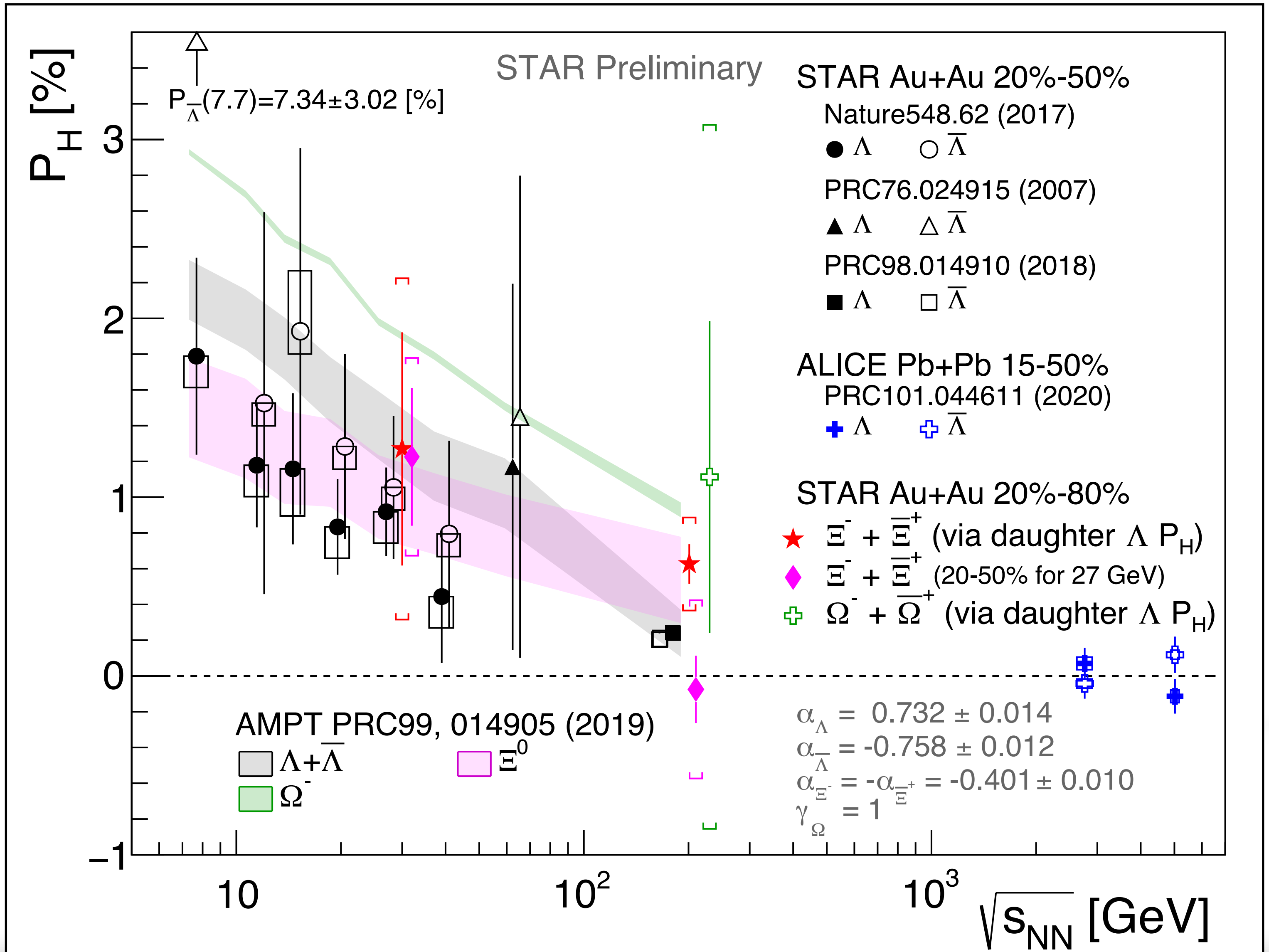


- P_Λ increases from central to peripheral collisions
- Similar pattern followed from 200 GeV down to 7.2 GeV
- Trend consistent with expectation from vorticity

Jiang et al, Phys Rev C 94, 044910 (2016)



First measurement of $P_{\Xi,\Omega}$



STAR Run:23-25

STAR: Phys Rev Lett 126, 162301 (2021)

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

Au+Au $\sqrt{s_{NN}}$ = 27 GeV

<u>At 200 GeV</u>

- $P_\Lambda = 0.24 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})\ \%$
- $P_\Xi = 0.47 \pm 0.10(\text{stat.}) \pm 0.23(\text{syst.})\ \%$
- $P_\Omega = 1.11 \pm 0.87(\text{stat.}) \pm 1.97(\text{syst.})\ \%$

Non-zero polarization for $P_{\Xi,\Omega}$

$P_{\Xi,\Omega}$ follows global trend of P_Λ

	Mass (GeV/c²)	Spin	μN
Λ (uds)	1.115683	1/2	0.613
Ξ (dss)	1.32171	1/2	-0.6501
Ω (sss)	1.67245	3/2	-2.02

- New $P_{\Xi,\Omega}$ measurements confirm the global nature of spin polarization

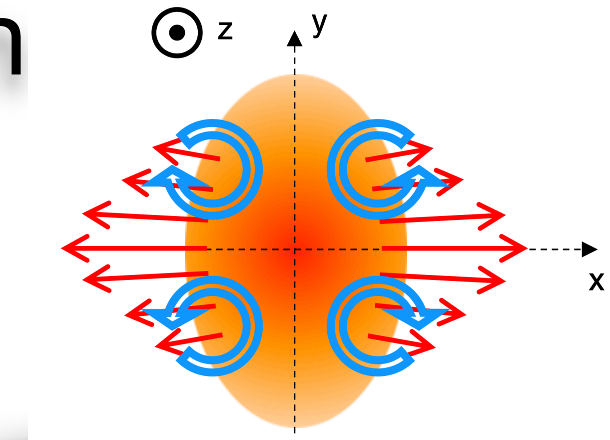
STAR

Local spin polarization of hyperons

- Local polarization is sensitive to space and time variation of vorticity and convolute with flow driven space-momentum correlation

- Focus on longitudinal polarization

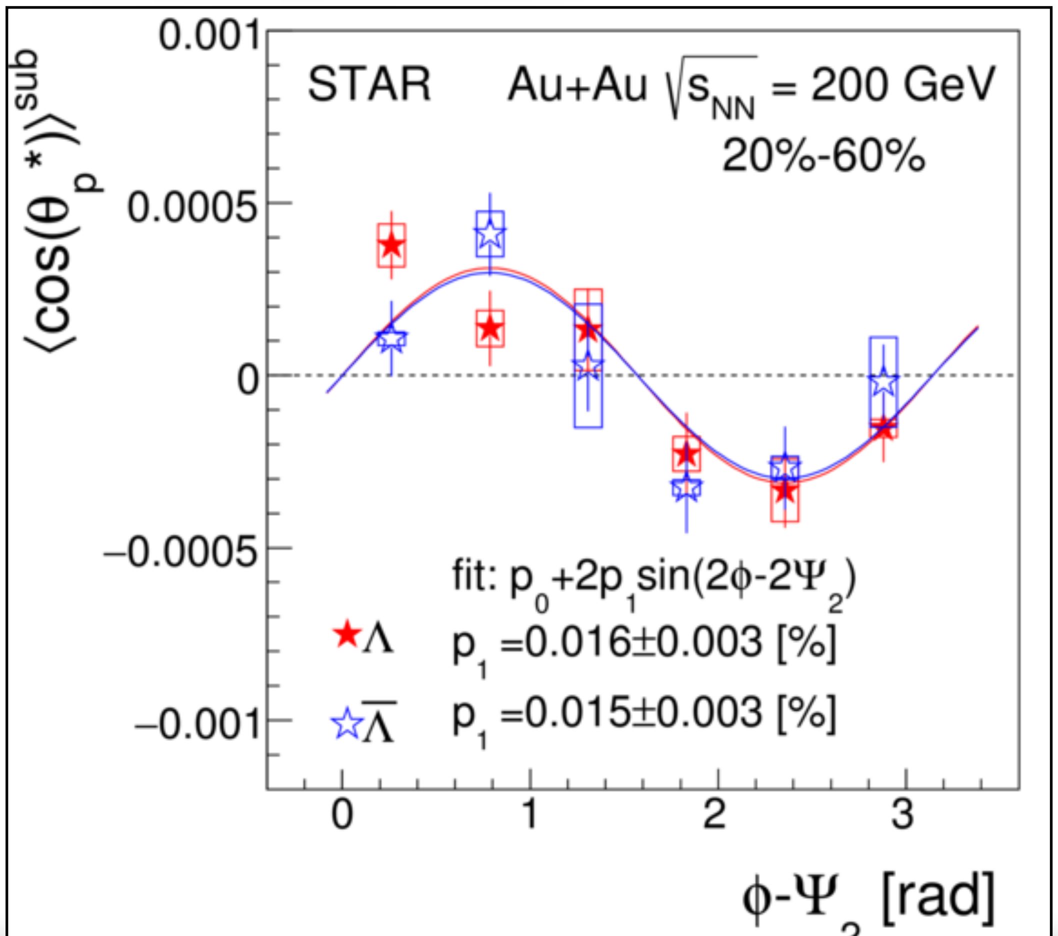
Local hyperon polarization



Longitudinal polarization *Becattini, Karpenko, Phys Rev. Lett. 120, 012302 (2018)*

- Elliptic flow is expected to generate a longitudinal component of polarization (P_z)
- $$P_z = \frac{3}{\alpha_H}\langle \cos\theta_p^* \rangle$$

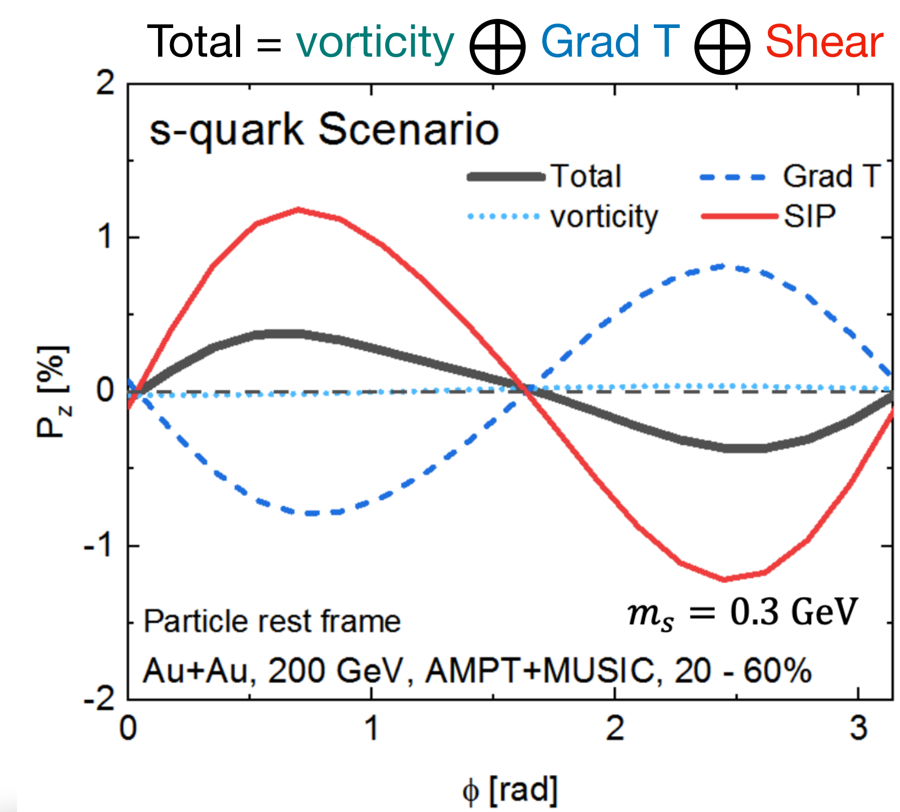
STAR: Phys Rev Lett 123, 132301 (2019)



Fu et al, arXiv:2103.10403

New developments:

Shear Induced Polarization (SIP)



See talk by Yi Yin

Sign puzzle in P_z

- Many models fail to capture the trend with proper sign

Other developments addressing spin puzzle:

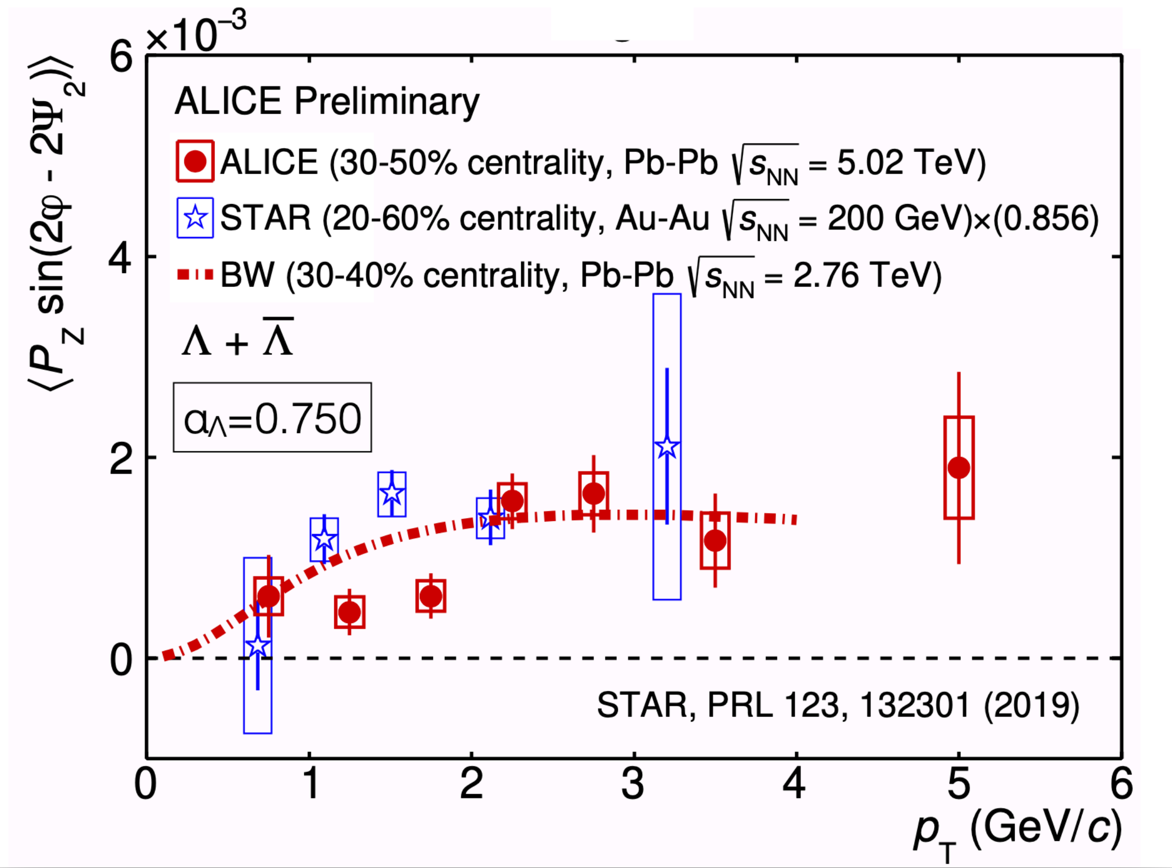
Liu et al, Phys Rev Lett 125, 062301

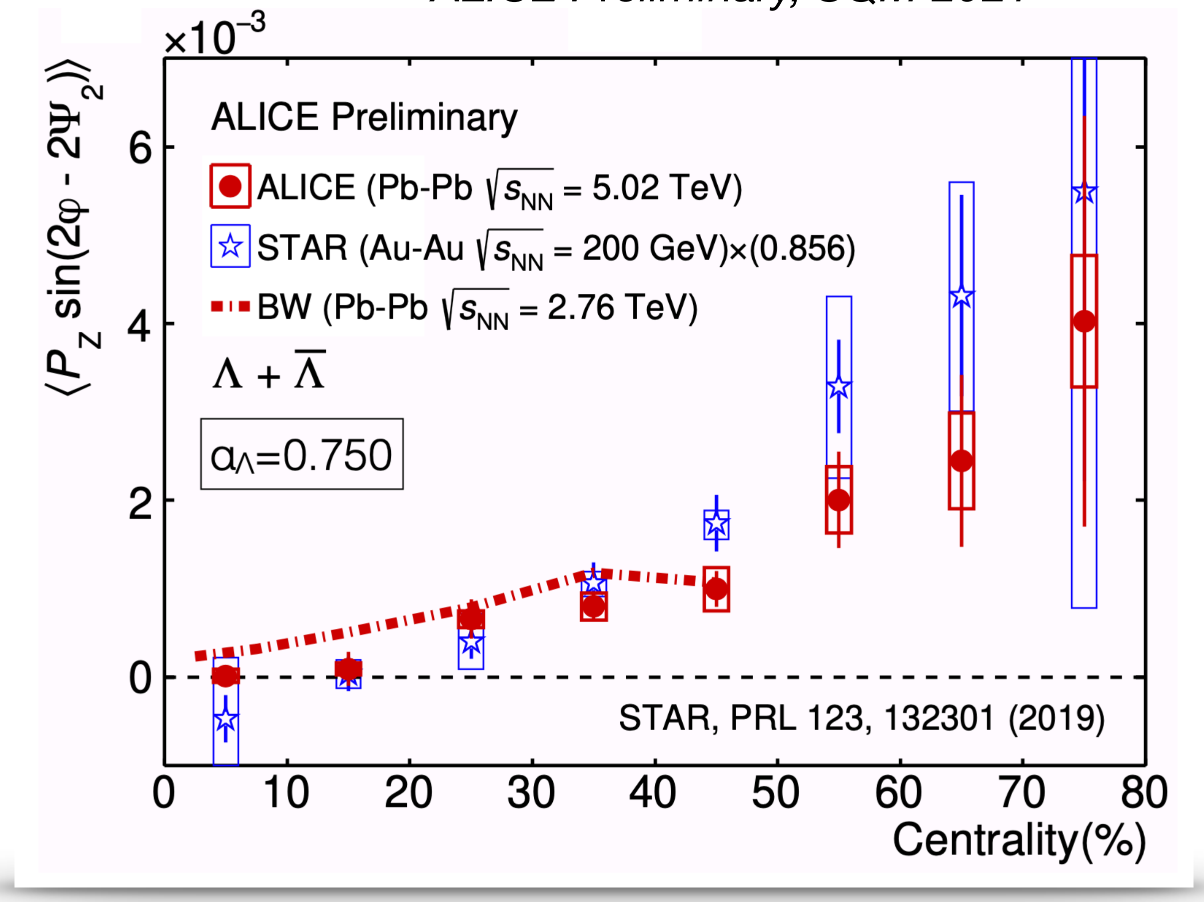
Becattini et al, arXiv:2103.14621

…

p_T and centrality dependence of P_z: RHIC vs LHC

STAR: Phys Rev Lett 123, 132301 (2019)
ALICE Preliminary, SQM 2021





Sign and trend of P_z consistent between RHIC and LHC

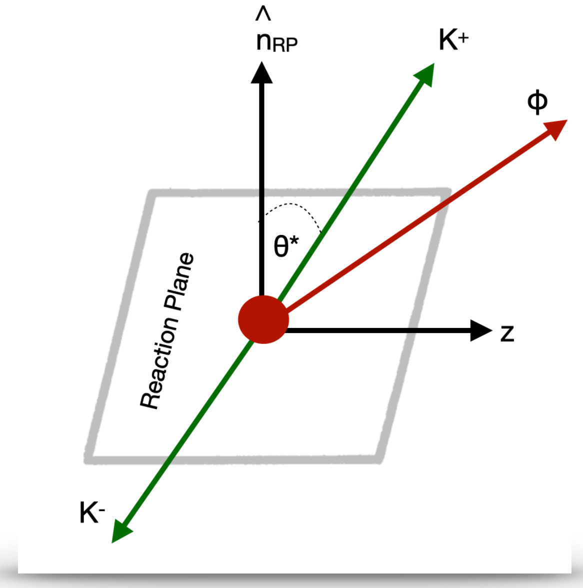
Although global hyperon polarization (P_y) has a strong beam energy dependence, the local polarization (P_z) does not seem to depend on beam energy

Global spin alignment of vector mesons

- Can offer information on spin dynamics of QCD medium
- Complementary to hyperon spin polarization

Baryons	Vs.	Mesons
Fermions		Bosons
Λ (uds), spin = 1/2		ϕ ($s\bar{s}$), spin = 1
Ξ (dss), spin = 1/2		K*($d\bar{s}$), spin = 1
Ω (sss), spin = 3/2		

Global spin alignment (ρ_{00})



Collision system	Au+Au
Collision energy	11-200 GeV
Particle of interest	ϕ,K*
Spin (J^P)	1^-
rapidity	$\lvert y \rvert < 1.0$
Background	Mixed event, Rotation background
Polarization axis	perpendicular to TPC 2nd order event plane

Global spin alignment can be measured from the angular distributions of vector mesons:

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

ρ_{00} : *00th* component of spin density matrix

θ^* : Angle between momentum of daughter and polarization axis in parent's rest frame

$\rho_{00} = 1/3$ → **No spin alignment**

$\rho_{00} \neq 1/3$ → **spin alignment**

Global spin alignment (ρ_{00})

Theoretical expectation of vector meson ρ_{00}

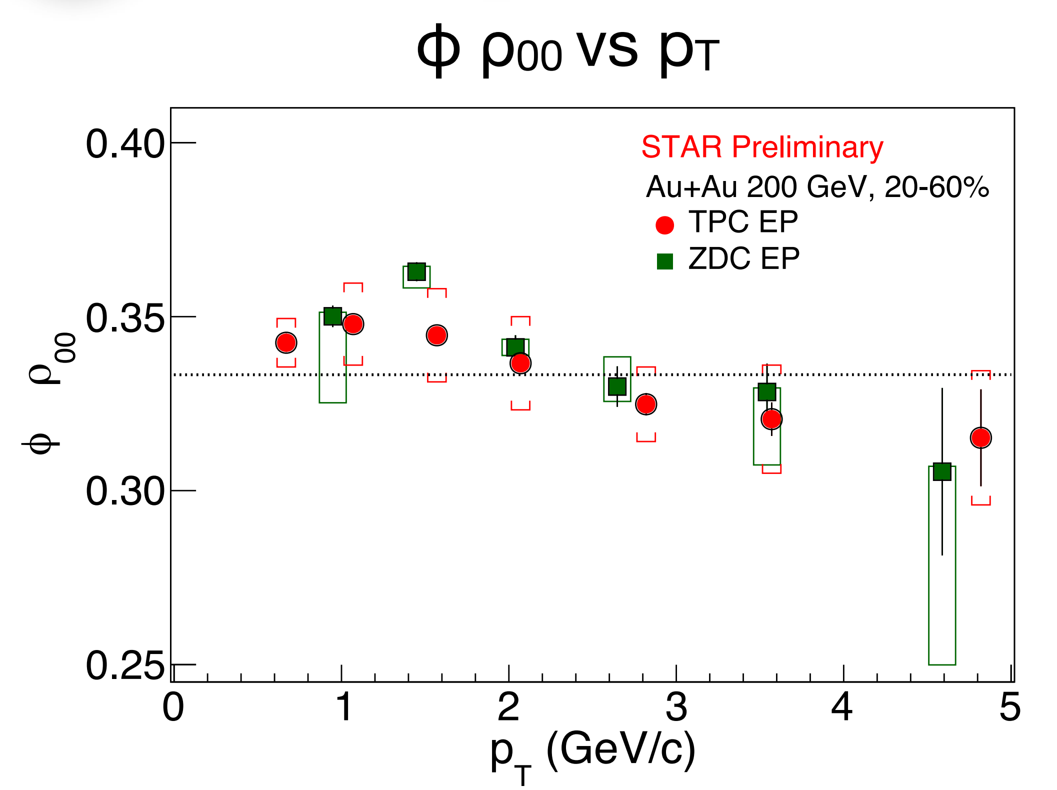
Vorticity	$\rho_{00}(\omega) < 1/3$
Magnetic field	$\rho_{00}(B) > 1/3$ Electrically neutral $\rho_{00}(B) < 1/3$ Electrically charged
Hadronization	$\rho_{00}(\text{rec}) < 1/3$ Recombination $\rho_{00}(\text{frag}) > 1/3$ Fragmentation
Mesonic field	$\rho_{00}(\phi) > 1/3$

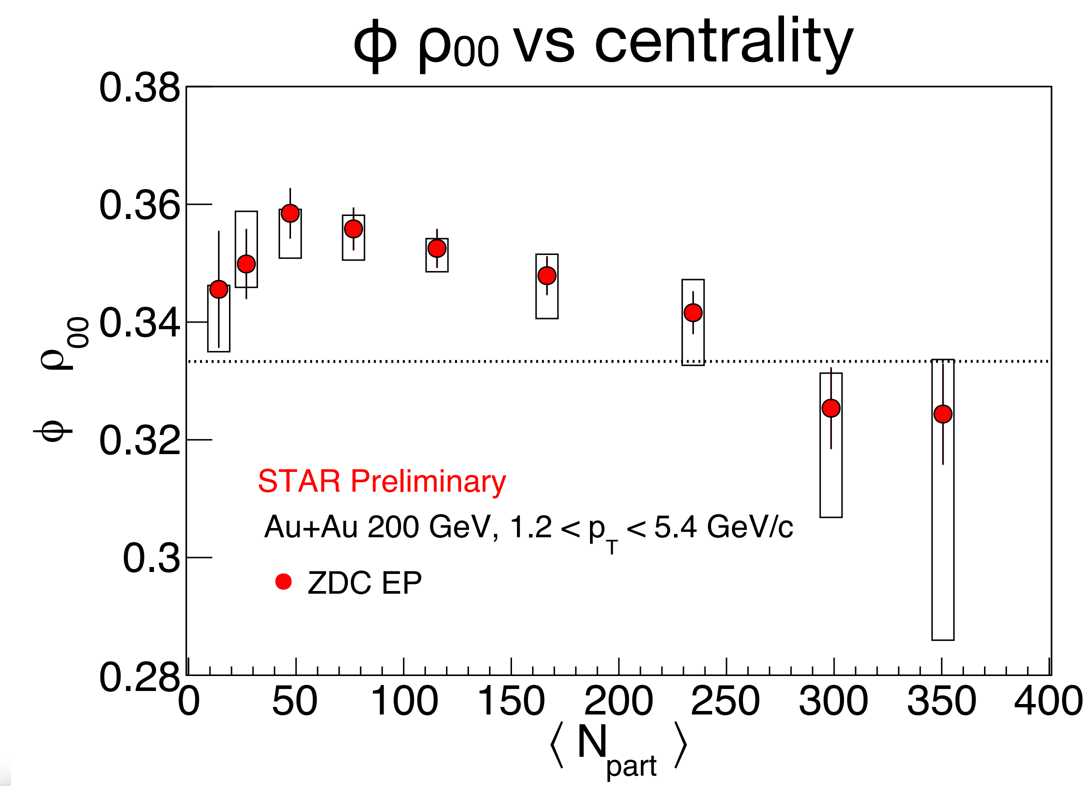
Expected contribution to ϕ ρ_{00}

- Including vorticity and magnetic field: and coalescence
  $(\rho_{00} - 1/3) \sim 10^{-5}$ (negative)
- Electric field:
  $(\rho_{00} - 1/3) \sim 10^{-5}$ (positive)
- Fragmentation:
  $(\rho_{00} - 1/3) \sim 10^{-5}$ (positive)
- ϕ meson field:
  $(\rho_{00} - 1/3) \sim 0.1$ (positive)
- ....

Liang and Wang: Phys. Rev. Lett 94, 102301 (2005)
Yang et. al, Phys Rev C 97, 034917 (2018)
Sheng et. al. Phys Rev D 101, 096005 (2020)
Sheng et. al. Phys Rev D 102, 056013 (2020)

p_T and centrality dependence of ρ_{00}





Non-trivial p_T dependence for ϕ ρ_{00}

Clear centrality dependence of ϕ ρ_{00}

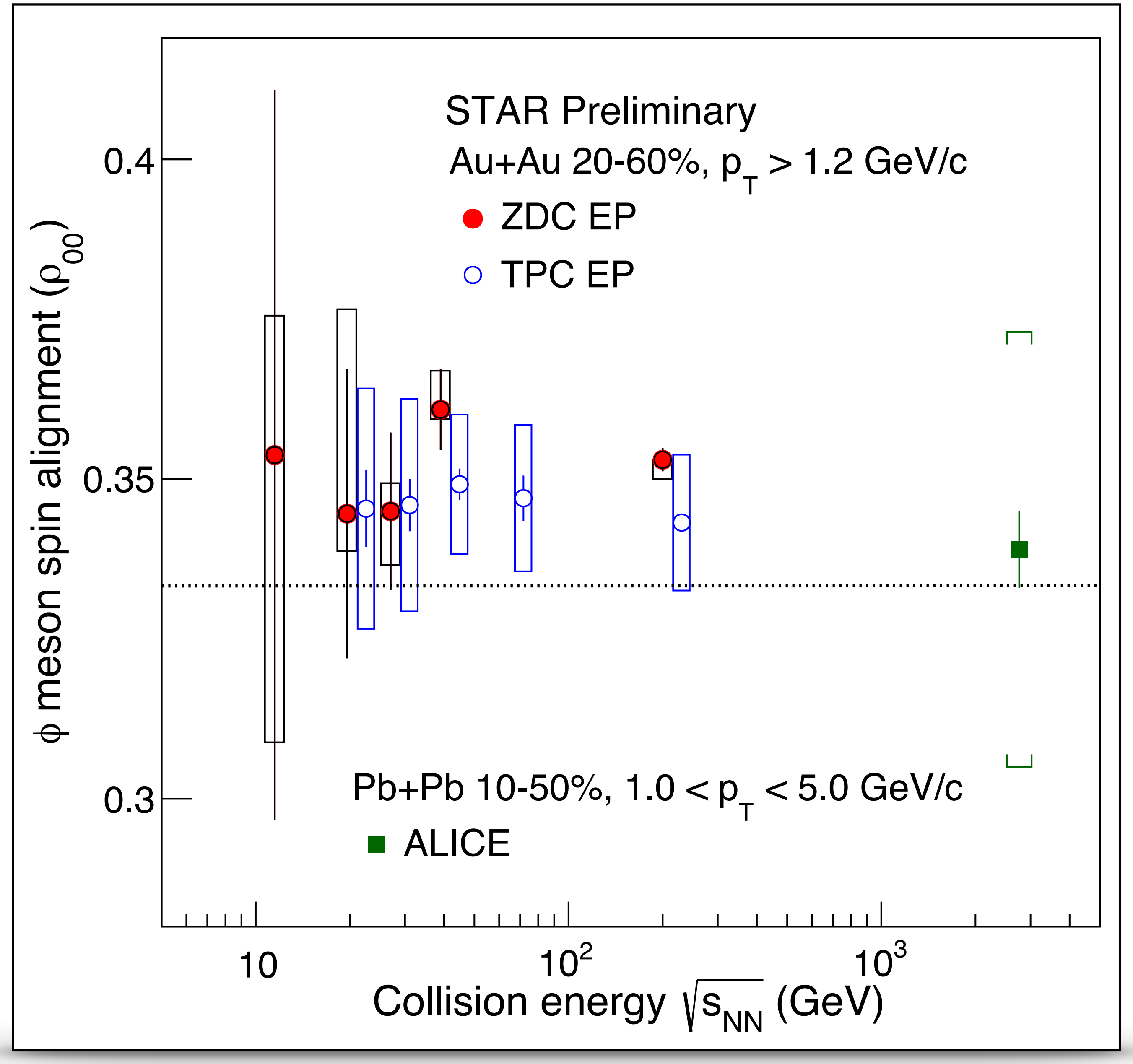
ϕ meson (20-60%):
$\rho_{00} > 1/3$ (STAR Preliminary)

Pb+Pb 2.76 TeV, 10-50% (ALICE)
K* $\rho_{00} < 1/3$ with 2.6σ
ϕ $\rho_{00} < 1/3$ with 1.9σ

ALICE: Phys Rev Lett 125, 012301 (2020)

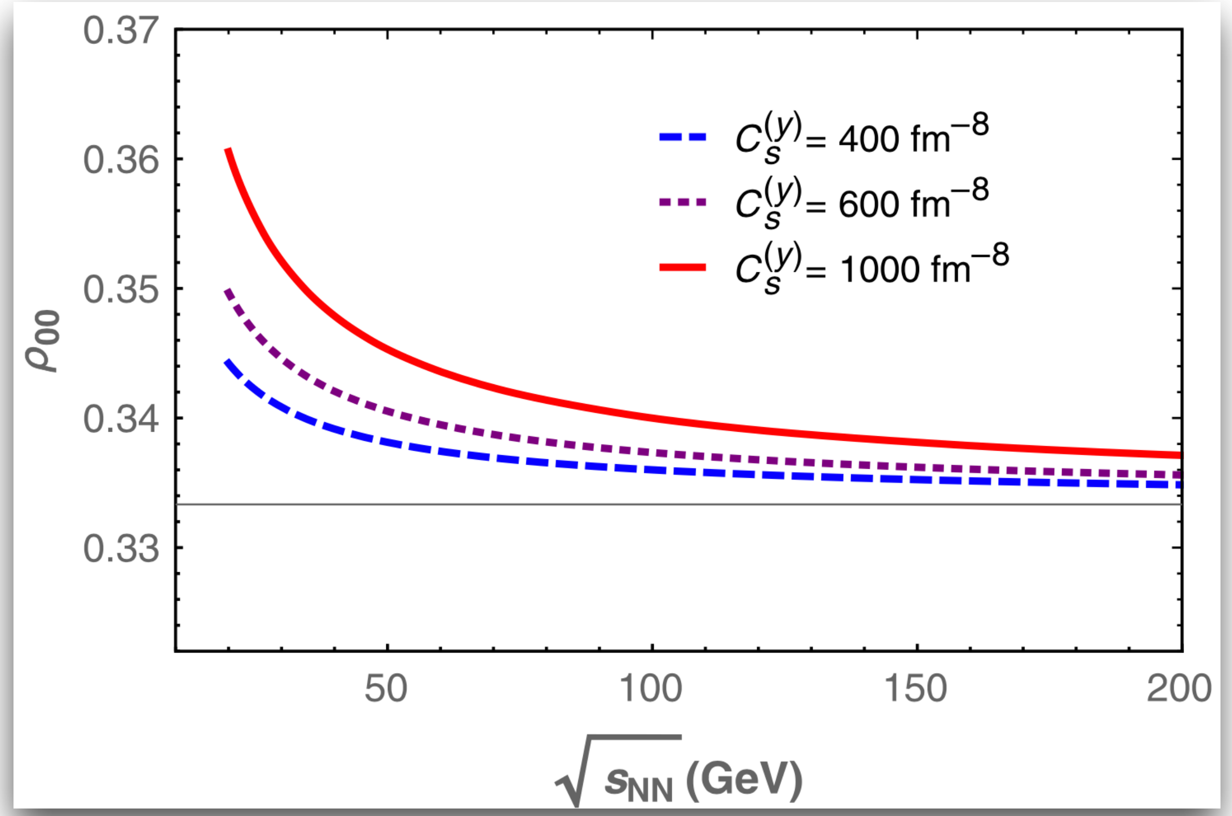
Energy dependence of ρ_{00}

ALICE: Phys Rev Lett 125, 012301 (2020)



Sheng et. al. Phys Rev D 101, 096005 (2020)

Sheng et. al. Phys Rev D 102, 056013 (2020)

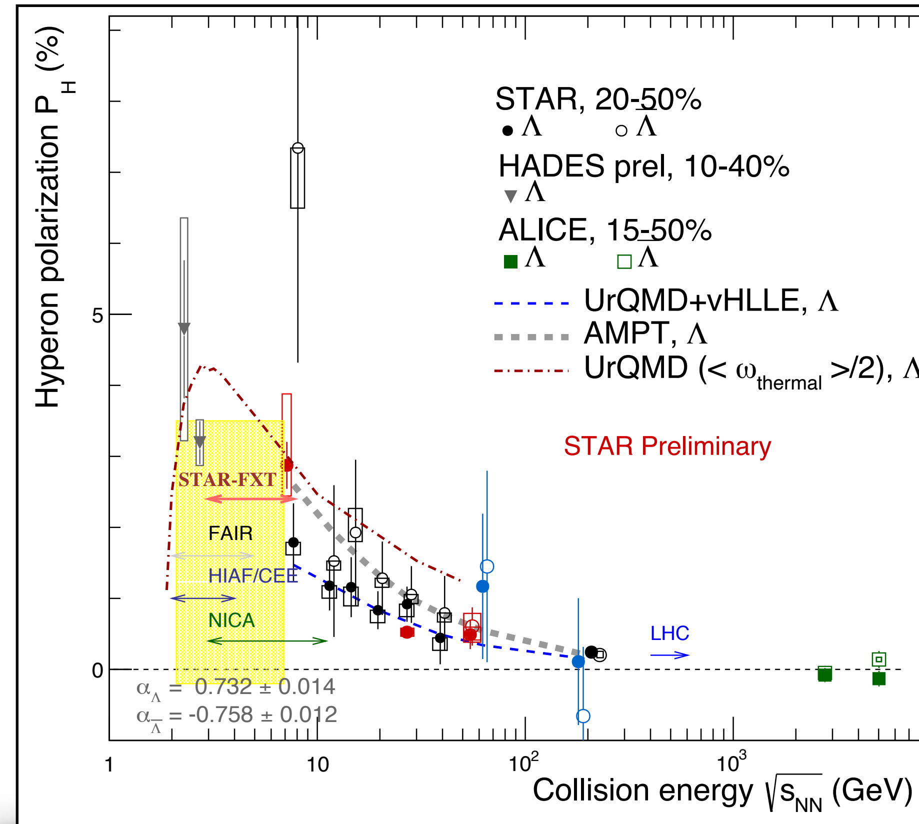


- Surprising large deviation of φ ρ_{00}
- Cannot be accommodated by conventional mechanism of polarization !
- The role of φ meson field has been identified as one possible mechanism to solve this puzzle

Summary

Hyperon spin polarization

- Observation of global nature of hyperon polarization at RHIC ($P_{\Lambda, \Xi, \Omega} > 0$ at RHIC)
- STAR preliminary measurements (down to 7.2 GeV) follow energy dependence trend
- Longitudinal polarization: sign problem with many models (Ongoing new theory developments)

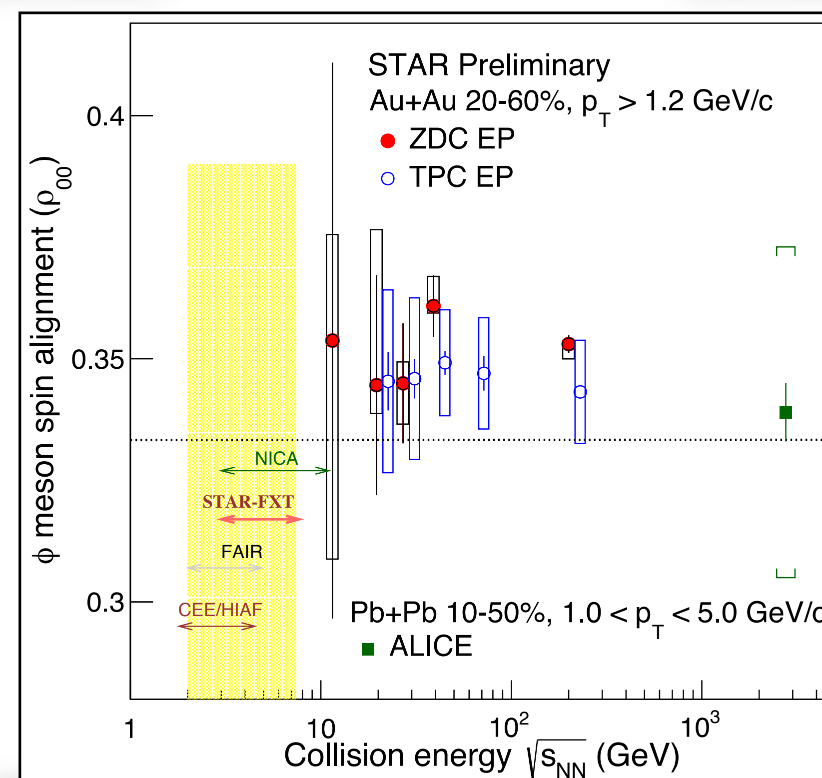


Hadronic dominant

Partonic dominant

Vector meson global spin alignment

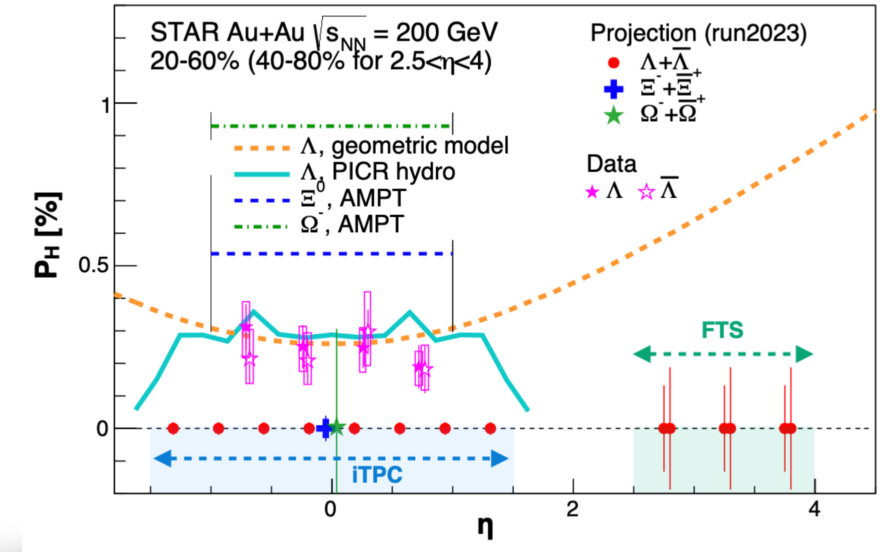
- Observation of surprisingly large ϕ meson spin alignment ($\rho_{00} > 1/3$ at RHIC)
- Difficult to reconcile with conventional mechanism of hyperon polarization



Outlook

Stay tuned for many exciting results from RHIC

STAR BUR 2021-2025

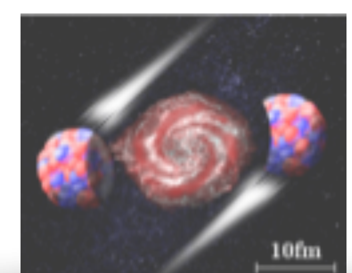


- High precision global and local spin polarization/alignment measurement from BES-II and FXT:
  Collider: $\sqrt{s_{NN}}$ = 7.7, 9.1, 11.5, 14.5, 17.3 and 19.6 GeV, 200 GeV (2023-25)
  Fixed Target: $\sqrt{s_{NN}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2 GeV
- Difference between particle and anti-particle polarization
- Polarization at forward rapidity using STAR forward upgrade

Phys Rev C 93, 064907, Phys Rev Research 1, 033058…

- Polarization at low beam energies (high baryon density matter) "Femto-nova program"

K. Fukushima et al: AAPPS Bull. 31 (2021)

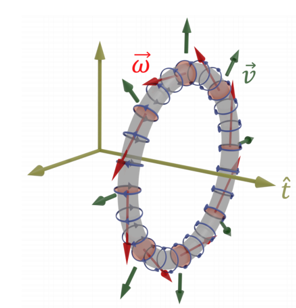


- Global spin alignment of J/Ψ (existence of vector meson field)

STAR BUR 2021-2025

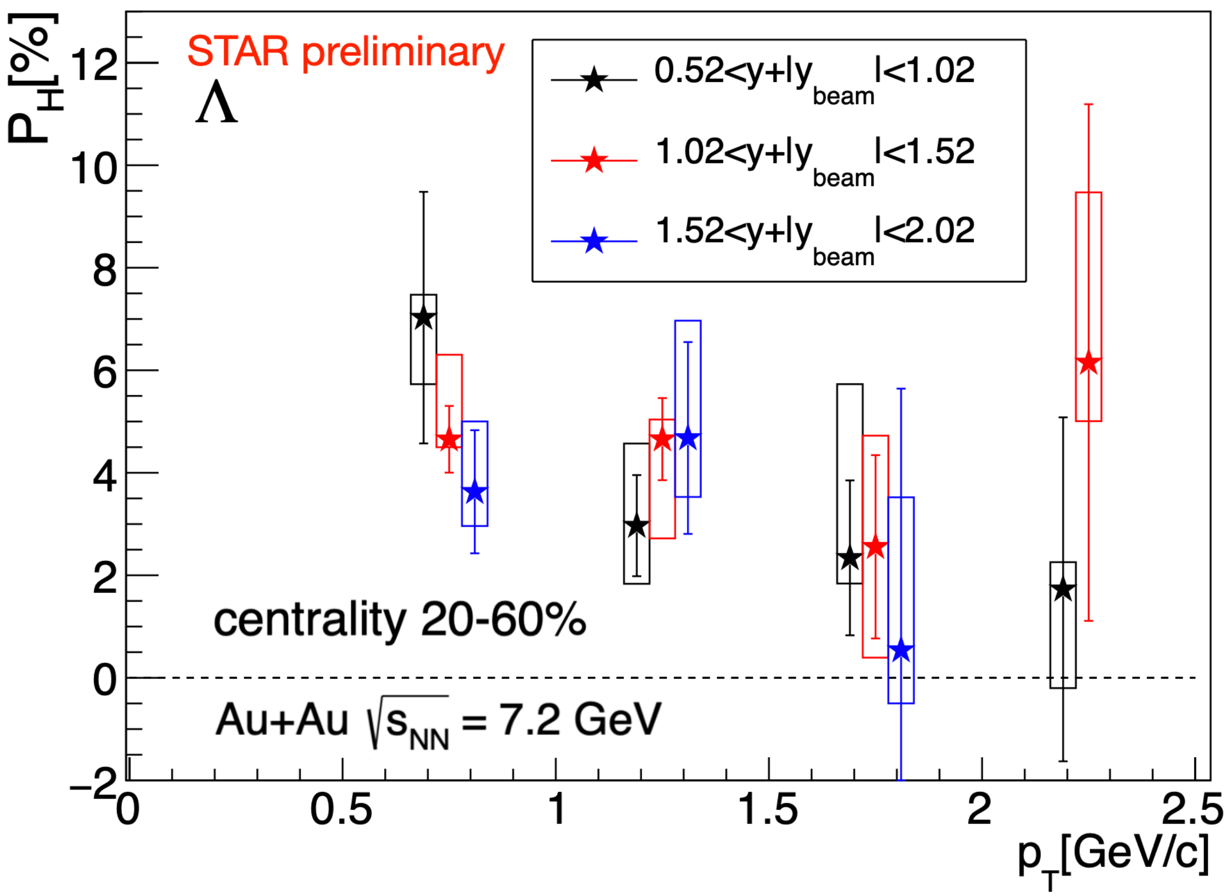
- Toroidal vortex structure in pA collisions

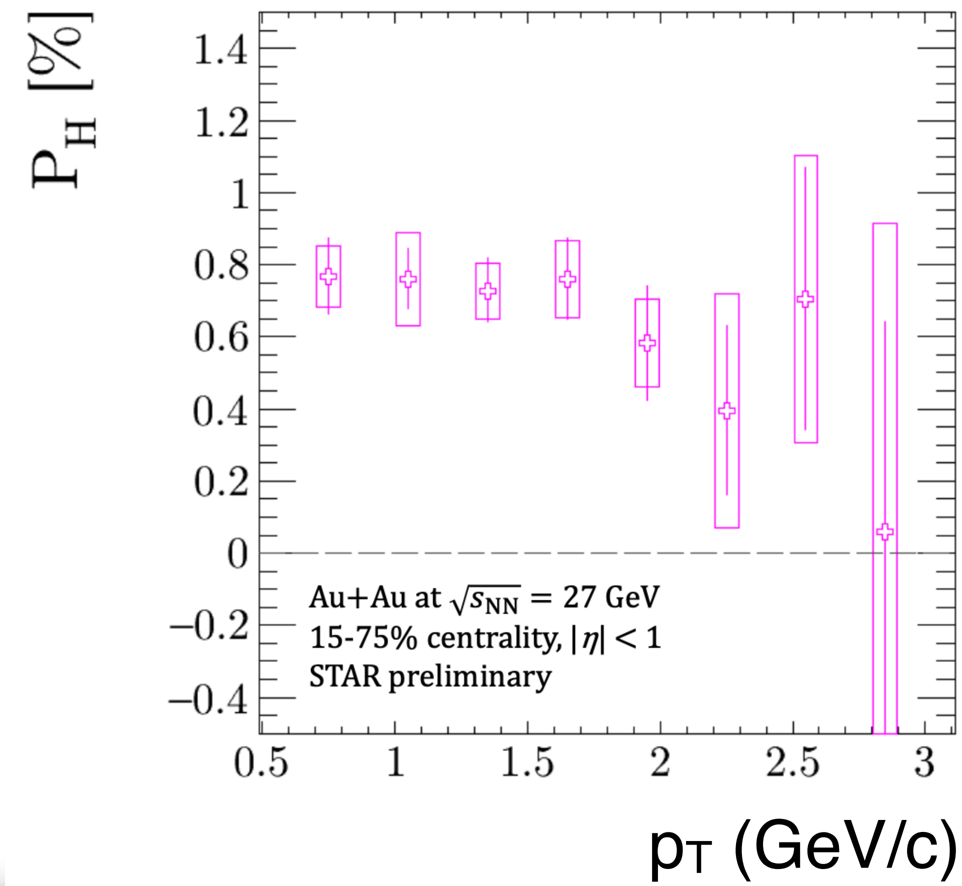
M. Lisa et al: 2101.10872



Back up slides

p_T dependence of P_Λ

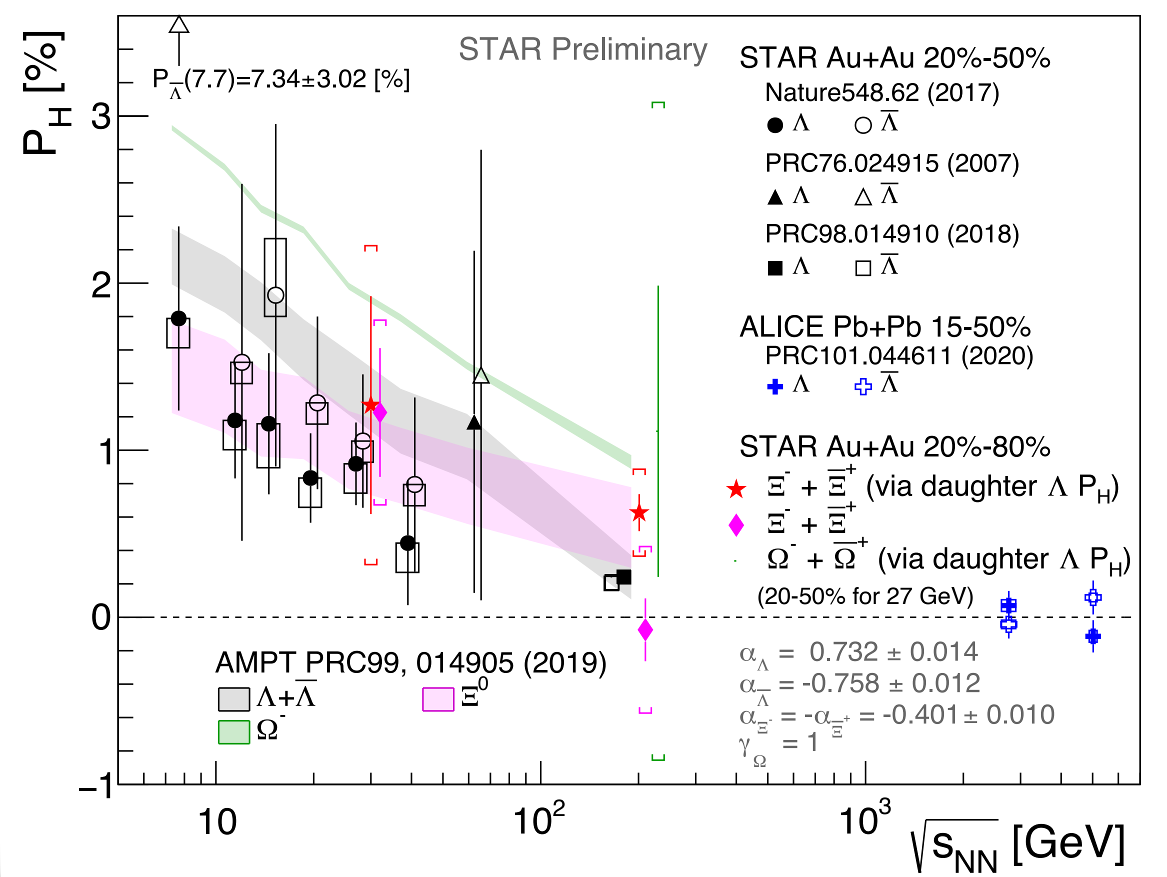




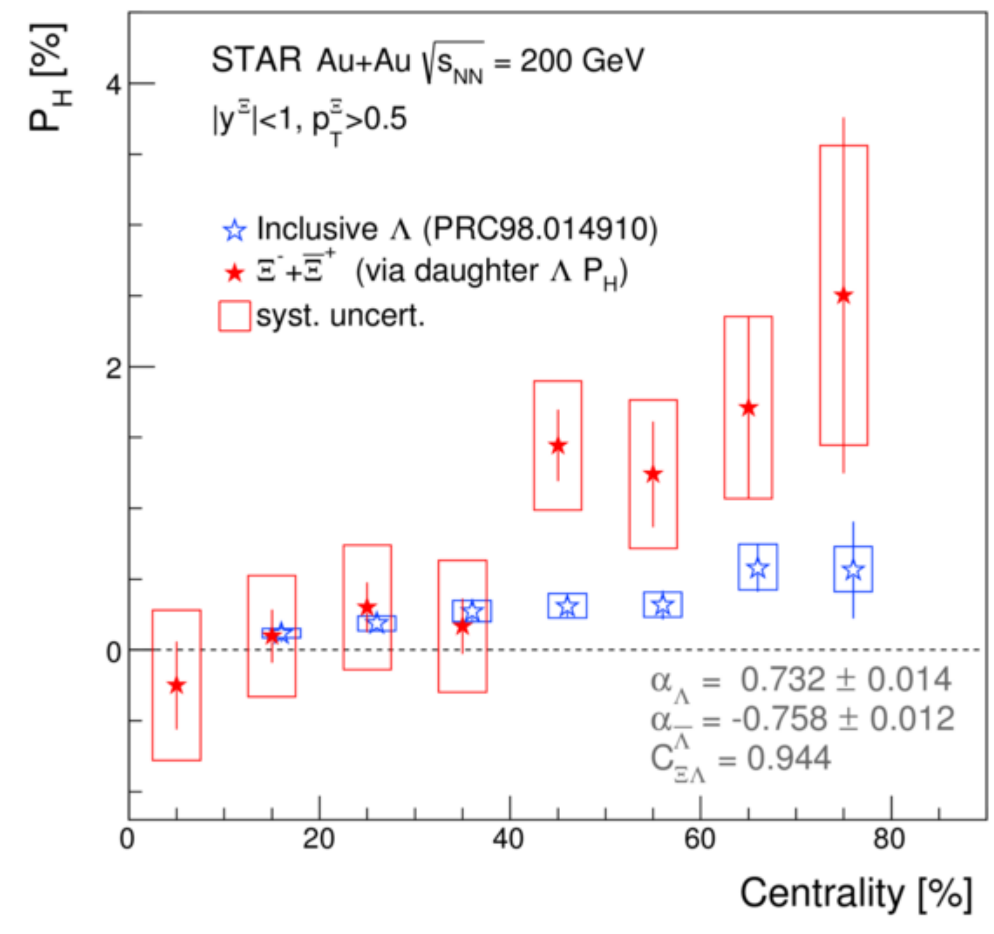
No significant p_T dependence

First measurement of P $_{\Xi, \Omega}$

STAR: Phys Rev Lett 126, 162301 (2021)



Phys. Rev. Lett. **126** (2021) 162301



Non zero polarization for P $_{\Xi, \Omega}$

P$_{\Xi, \Omega}$ follows energy dependence trend of P$_\Lambda$

P$_{\Xi,}$ follows centrality dependence trend of P$_\Lambda$