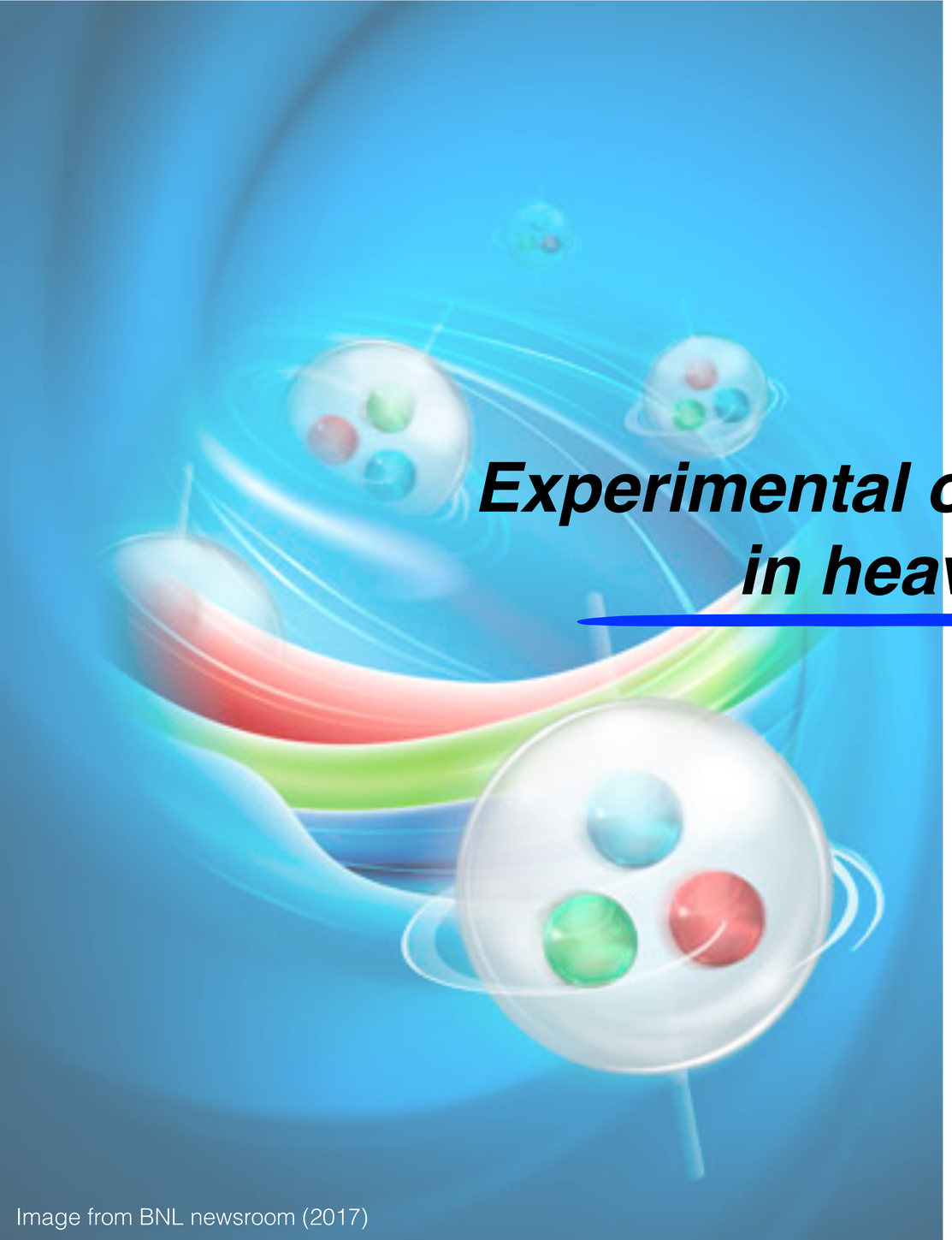


Experimental overview of spin physics in heavy-ion collisions

Takafumi Niida

筑波大学
University of Tsukuba

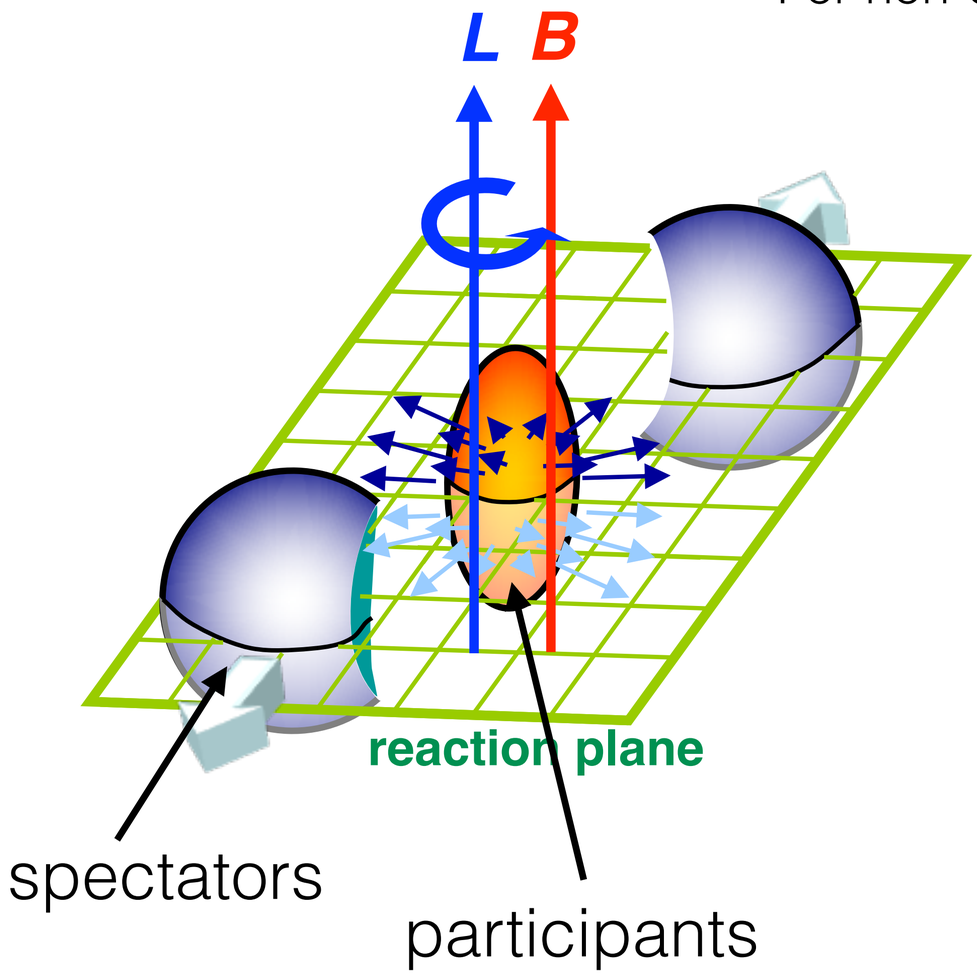
The 13th Circum-Pan-Pacific Symposium on High Energy Spin Physics

OCTOBER 27–30 Academia Sinica Taipei, Taiwan

2026 PacificSPIN

Image from BNL newsroom (2017)

Orbital angular momentum / Strong magnetic field



For non-central heavy-ion collisions,

Large orbital angular momentum of the system:

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$

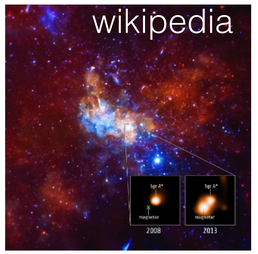
$$\sim bA\sqrt{s_{NN}} \sim 10^6 \hbar$$

Z.-T. Liang and X.-N. Wang, PRL94,102301(2005), PLB629(2005)20
S. Voloshin, nucl-th/0410089
B. Betz, M. Gyulassy, and G. Torrieri, PRC76, 044901 (2007)

Also, strong magnetic field created:

$$B \sim m_\pi^2/e$$

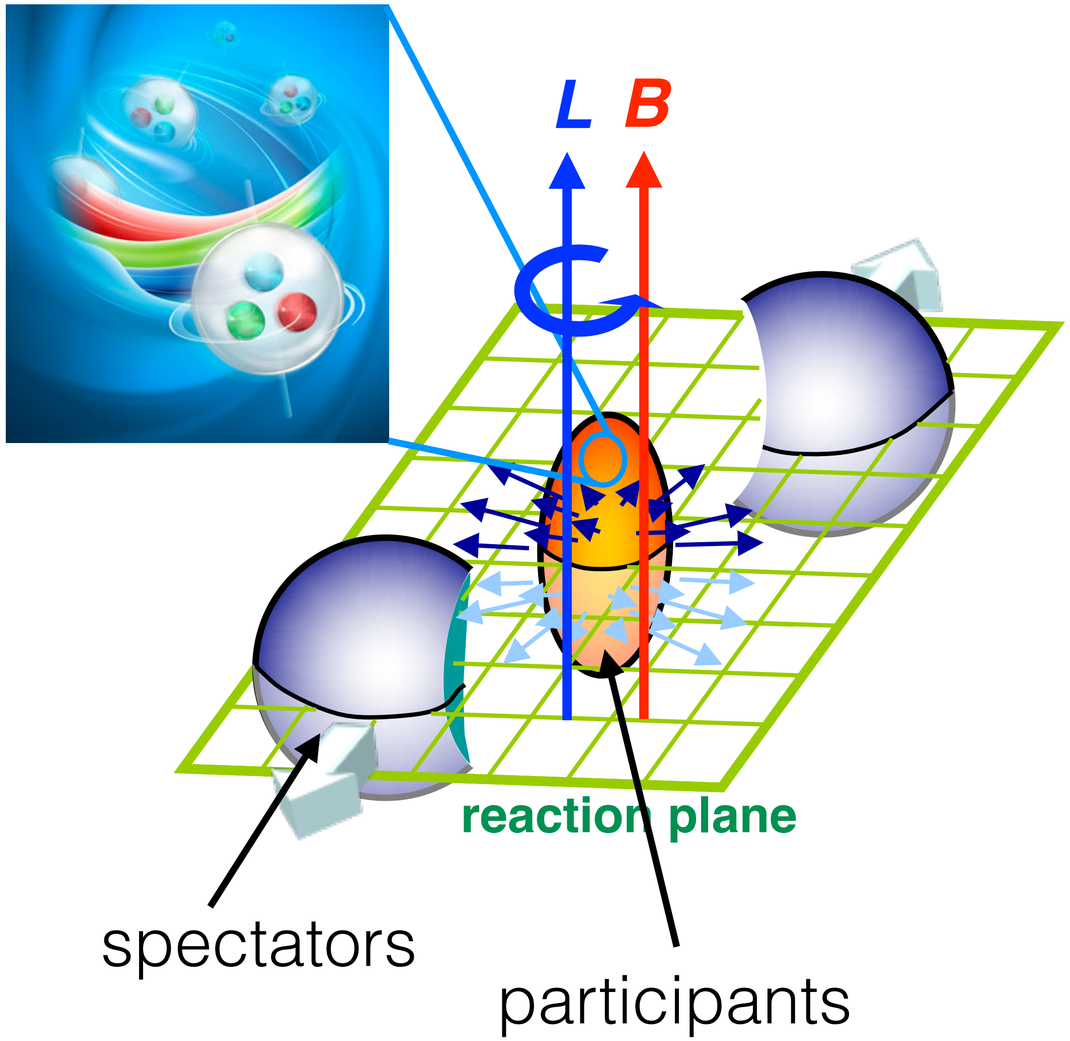
$$\sim 10^{14}\ \mathrm{T}$$



c.f. magnetar B~10^{11} T

D. Kharzeev et al., Nucl.Phys.A803, 227 (2008)
L. McLerran and V. Skokov, Nucl. Phys. A929, 184 (2014)

“Global” polarization

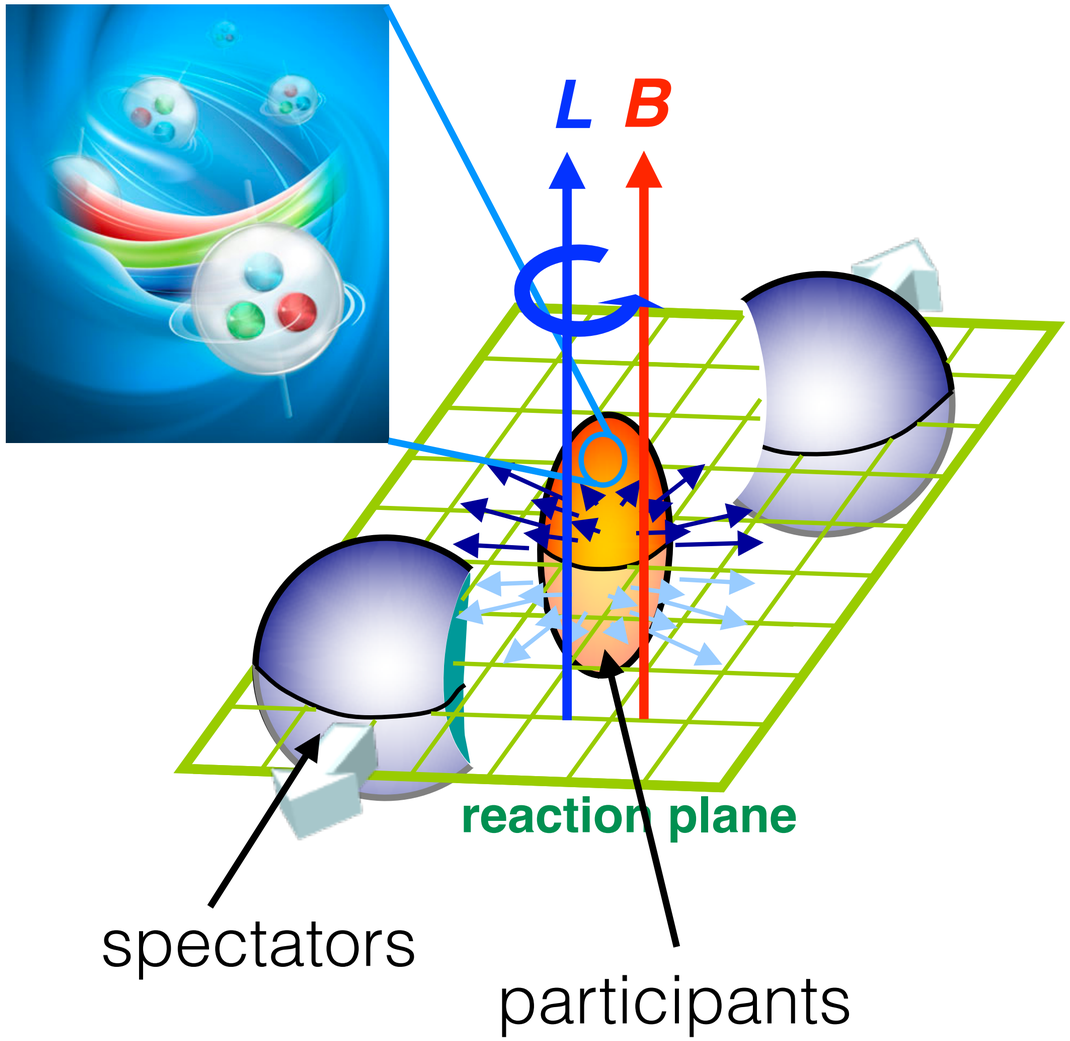


Rotating system under strong B-field:

- Particles “globally" polarized along ***L*** or ***B*** via spin-orbit/spin-magnetic couplings
- Particles and antiparticles are oppositely aligned along ***B***

Z.-T. Liang and X.-N. Wang, PRL94,102301(2005), PLB629(2005)20
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S. Voloshin, nucl-th/0410089
B. Betz, M. Gyulassy, and G. Torrieri, PRC76, 044901 (2007)

- Polarization ***P*** in non-relativistic limit assuming local thermodynamic equilibrium

$$\boldsymbol{P} = \frac{(S+1)(\boldsymbol{\omega} + \mu \boldsymbol{B}/S)}{3T}$$

S: spin
ω: vorticity

F. Becattini, F. Piccinini, and J. Rizzo, PRC77, 024906 (2008)

Polarization measurement

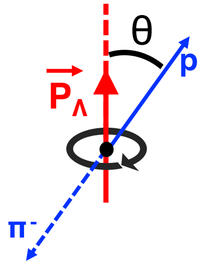
Parity-violating weak decay of hyperons

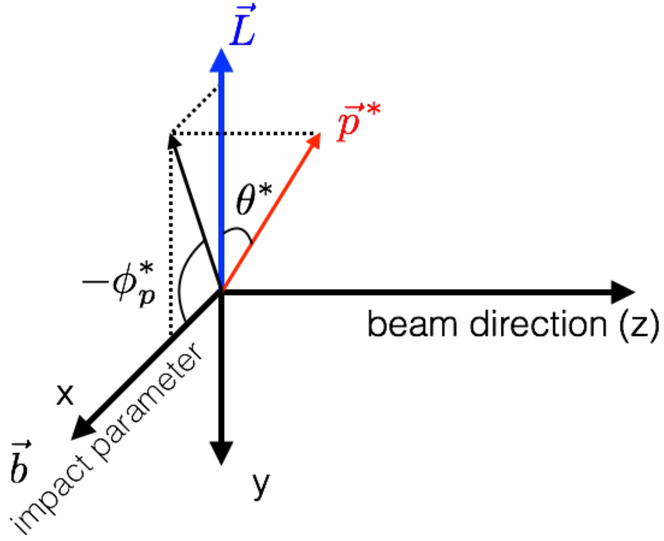
Daughter proton is preferentially emitted in the direction of Λ's spin (opposite for anti-proton)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*\right)$$

$\mathbf{P}_H$: hyperon polarization
$\hat{\mathbf{p}}_B$: unit vector of daughter proton momentum
α_H : hyperon decay parameter
asterisk(∗) denotes "in hyperon rest frame"

$\Lambda \to p + \pi^-$





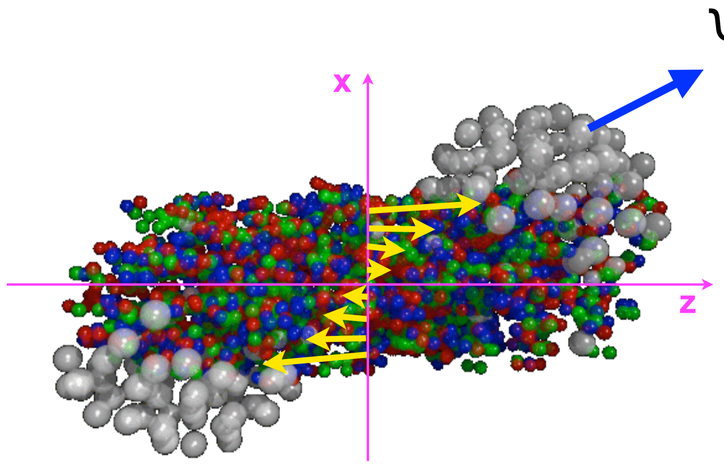
$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.747 \pm 0.009$
PDG2024

Polarization along the initial L direction

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

Ψ_1: first-order spectator-plane angle

STAR, PRC76, 024915 (2007)



Spectators fly away from the beam axis (at high energy)

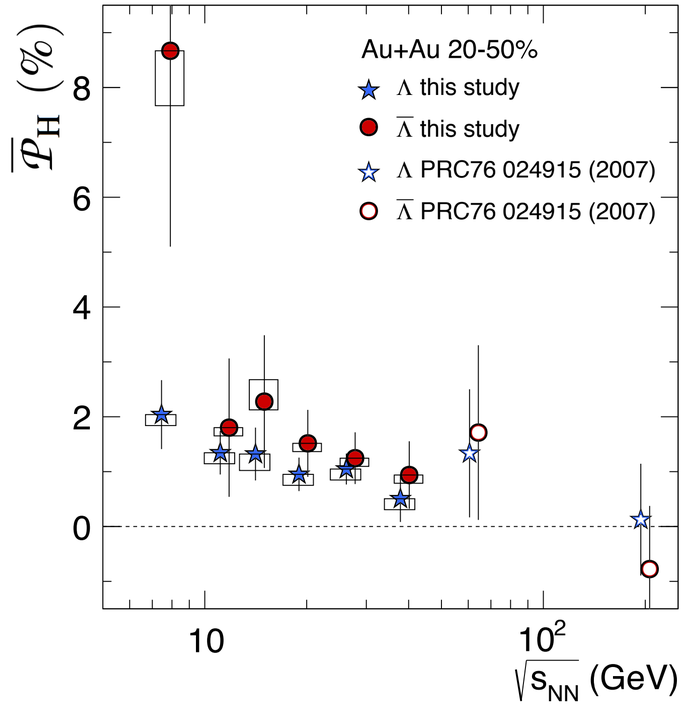
S. Voloshin and TN, PRC94.021901(R) (2016)

First observation of Λ global polarization



STAR, Nature 548, 62 (2017)





2005: Theory prediction
2007: First attempt of the measurement (null result)
…
2017: First observation by STAR experiment!

- Based on thermal vorticity field, relating it to spin

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T}$$

F. Becattini et al., Ann.Phys. 338 (2013), 32-49
F. Becattini et al., PRC95, 054902 (2017)

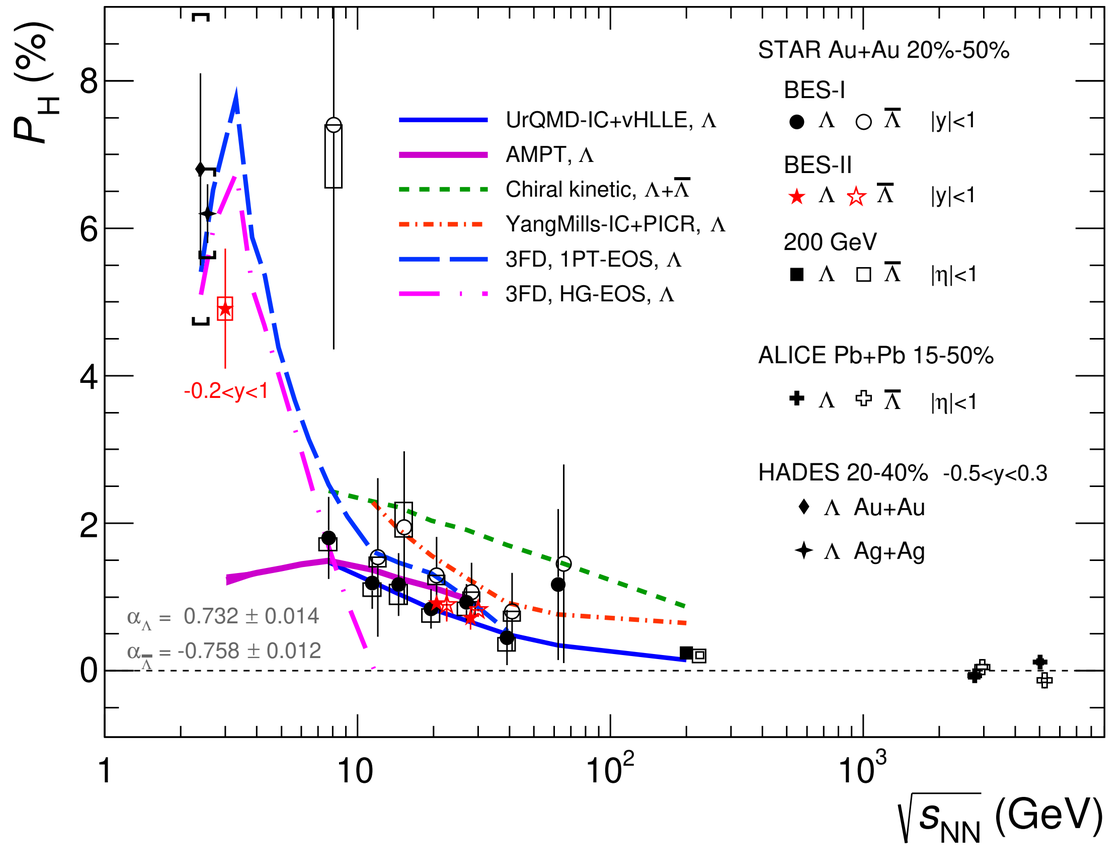
- ***The most vortical fluid ever observed***

$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T/\hbar \sim 10^{22}\,\mathrm{s}^{-1}$$

μ_Λ: Λ magnetic moment
T: Temperature at thermal equilibrium

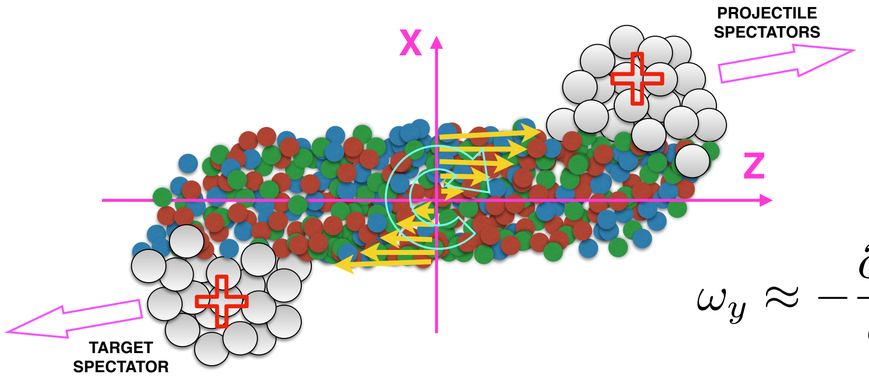
Λ global polarization vs. $\sqrt{s_{NN}}$

Reviews:
F.Becattini, M.Buzzegoli, TN, S.Pu, A.Tang, Q.Wang, Int.J.Mod.Phys.E33(2024)2430006
TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010



- Increasing trend toward lower energies, described well by various theoretical models

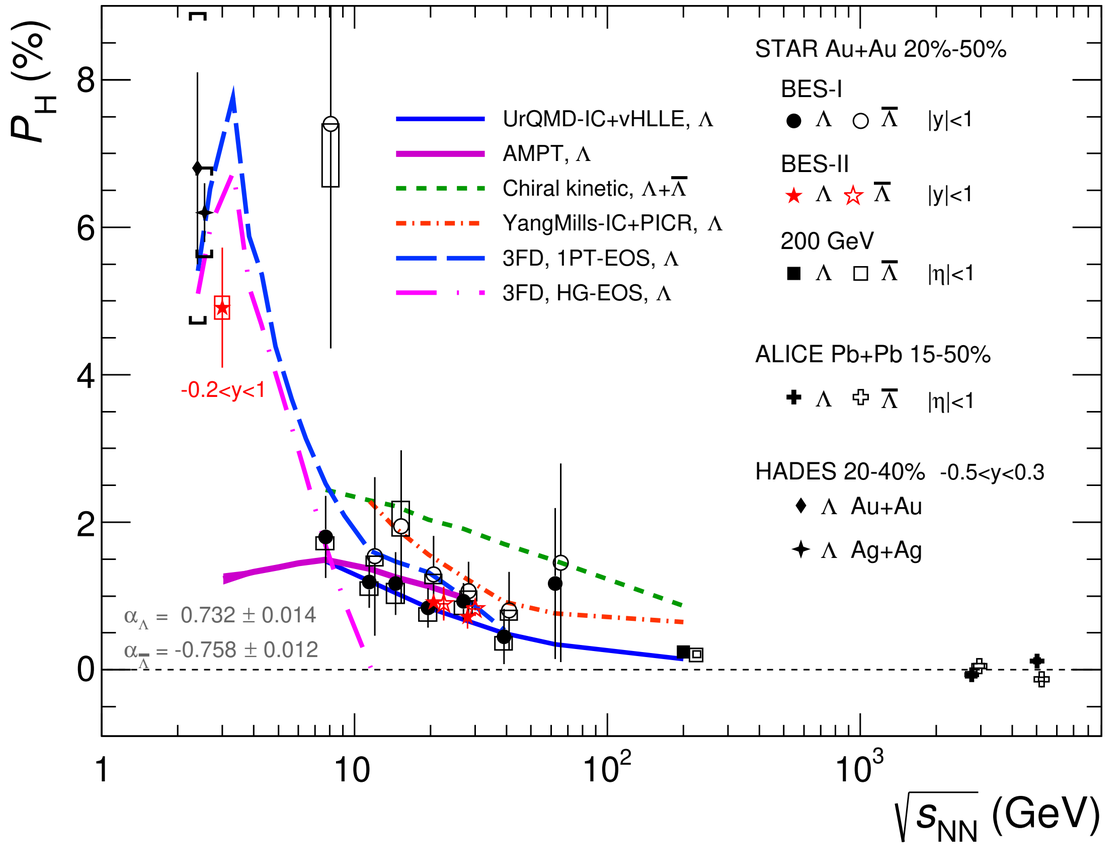
  I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
  H. Li et al., PRC96, 054908 (2017), AMPT
  Y. Sun and C.-M. Ko, PRC96, 024906 (2017), CKE
  Y. Xie et al., PRC95, 031901(R) (2017), PICR
  Y. B. Ivanov et al., PRC100, 014908 (2019), 3FD model
  …and more



$$\omega_y \approx -\frac{\partial v_z}{\partial x} \neq 0$$

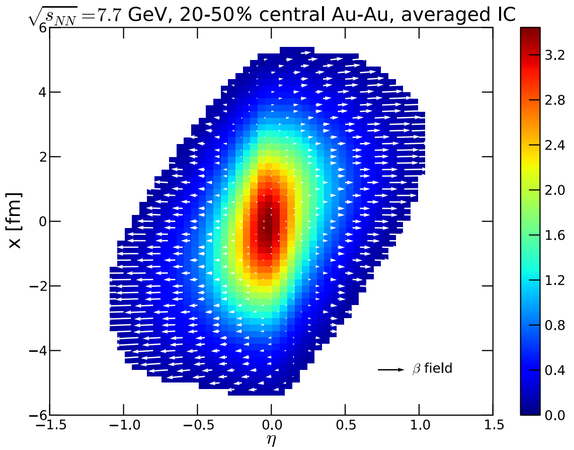
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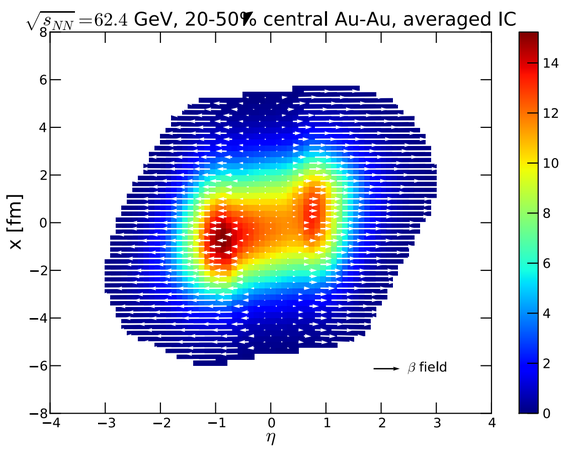


- Increasing trend toward lower energies, described well by various theoretical models

$\sqrt{s_{NN}}$ = 7.7 GeV



$\sqrt{s_{NN}}$ = 62.4 GeV

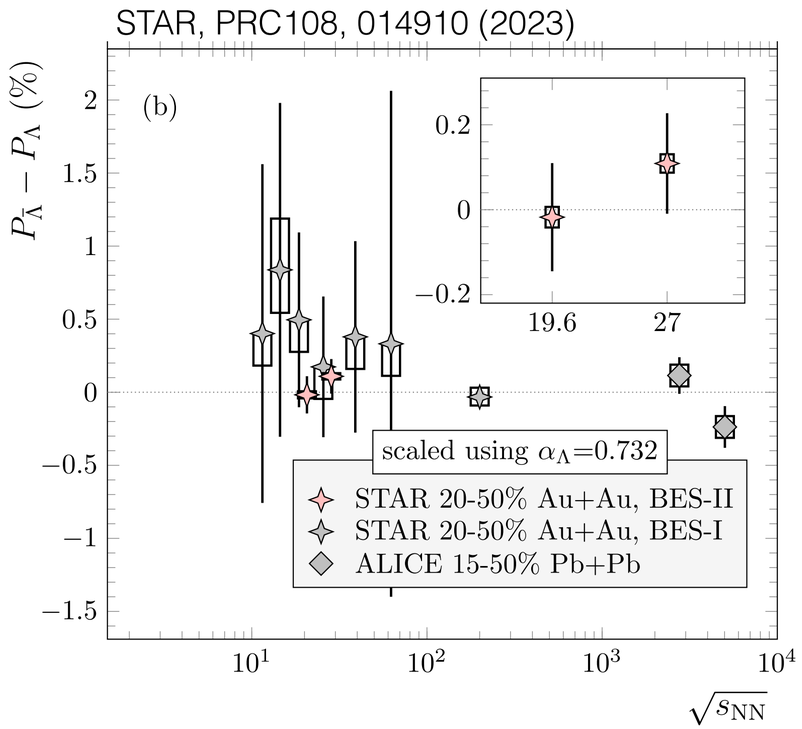


I.Karpenko and F.Becattini, EPJ(2017)77.213

From low to higher energies,
- Velocity shear decreases at mid-rapidity as the system approaches longitudinal boost invariance
- Dilution due to a longer system lifetime

Can polarization constrain the magnetic field ?





$$P_{\Lambda} \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_{\Lambda} B}{T}$$

$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_{\Lambda} B}{T}$$

μ_Λ: Λ magnetic moment

$$B = (P_{\bar{\Lambda}} - P_{\Lambda})T/(-2\mu_{\Lambda})$$
$$\approx 30\Delta P_{\Lambda} \times 10^{14}\ [T]$$
$$eB/m_{\pi}^2 \sim 10\Delta P_{\Lambda} \qquad \text{(T=120 MeV)}$$

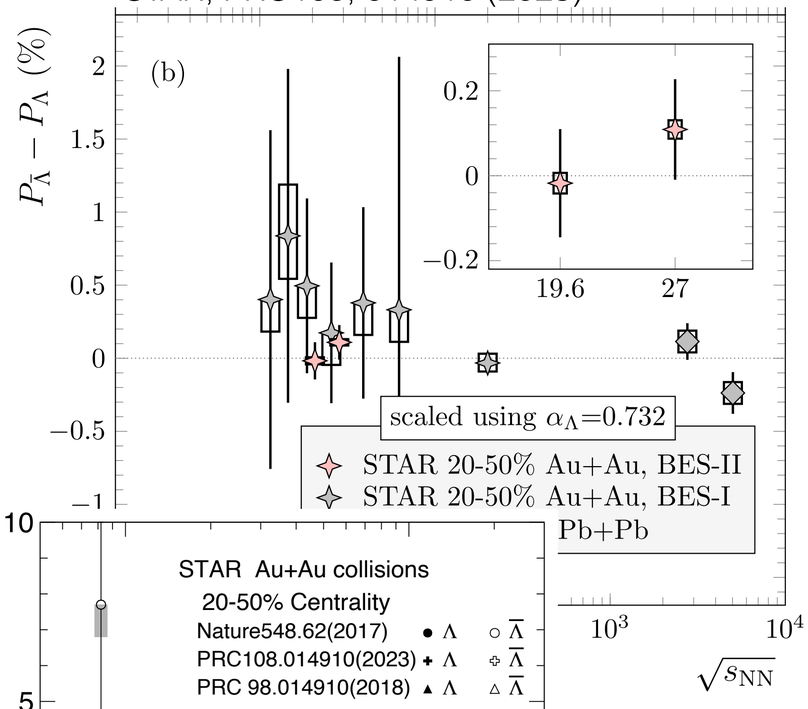
B. Muller and A. Schafer, PRD98, 071902(R) (2018)

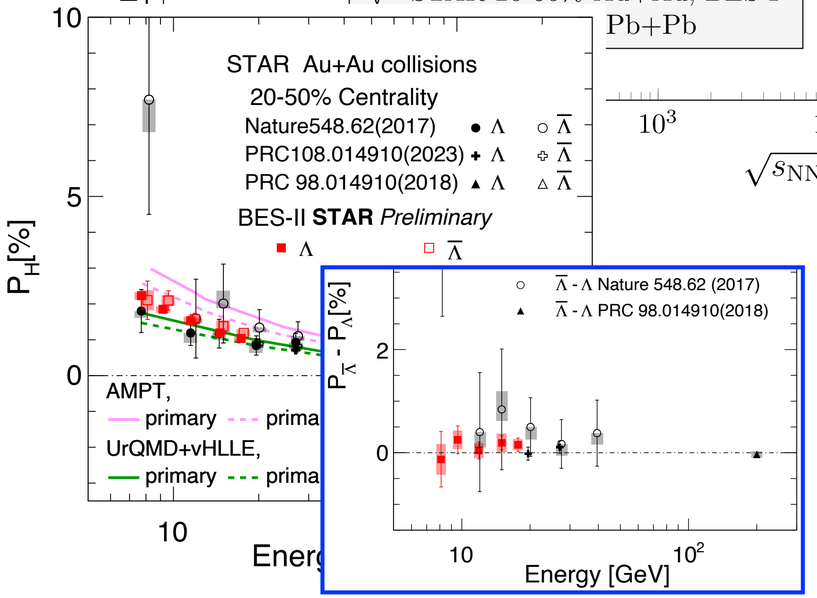
- No significant difference between Λ and anti-Λ

Can polarization constrain the magnetic field ?



STAR, PRC108, 014910 (2023)





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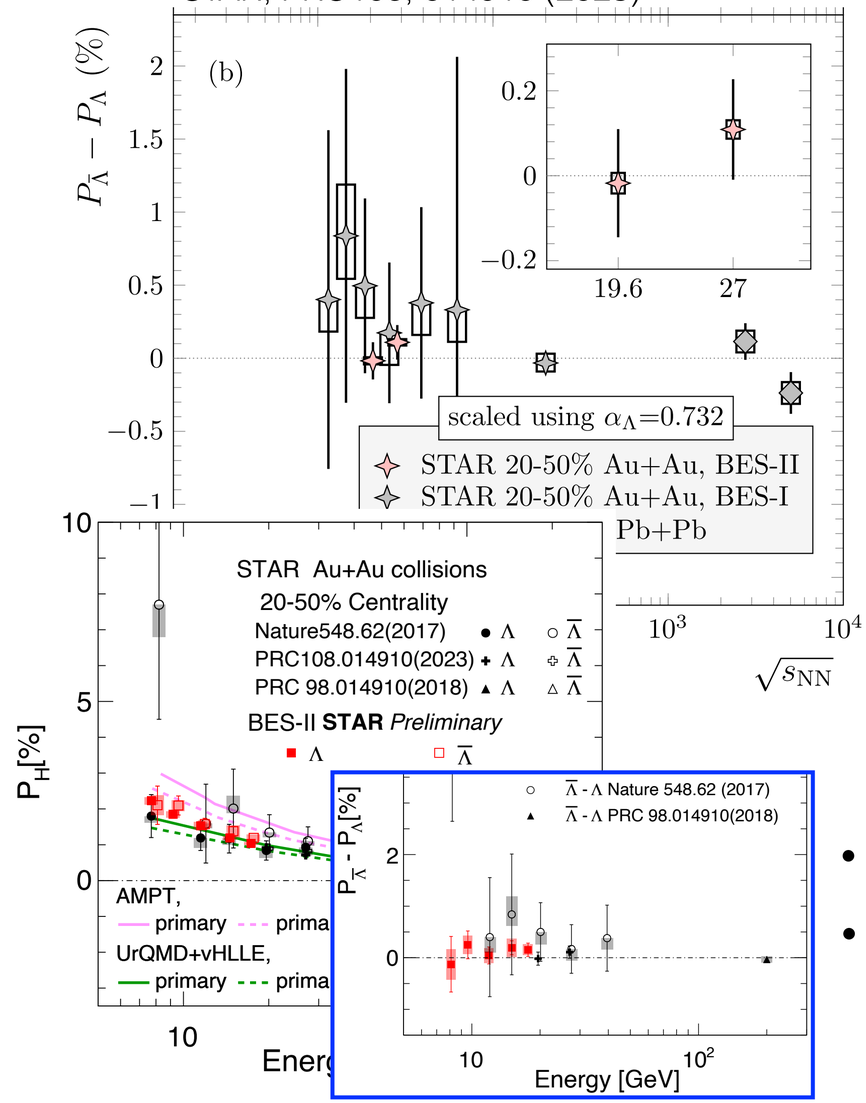
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STAR, QM2025

Can polarization constrain the magnetic field ?



STAR, PRC108, 014910 (2023)



STAR, QM2025

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

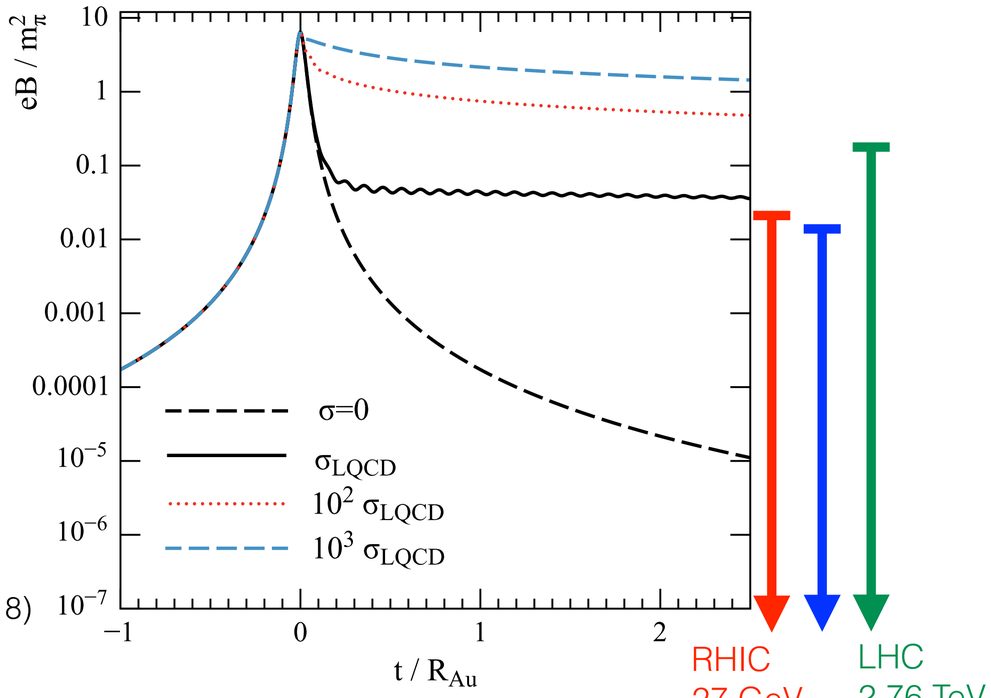
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B. Muller and A. Schafer, PRD98, 071902(R) (2018)

McLerran and Skokov, Nucl. Phys. A929, 184 (2014)



- No significant difference between Λ and anti-Λ
- Taking ΔP_Λ~0.3% (mean+2σ), the B-field at the late-stage would be <10^{13} T

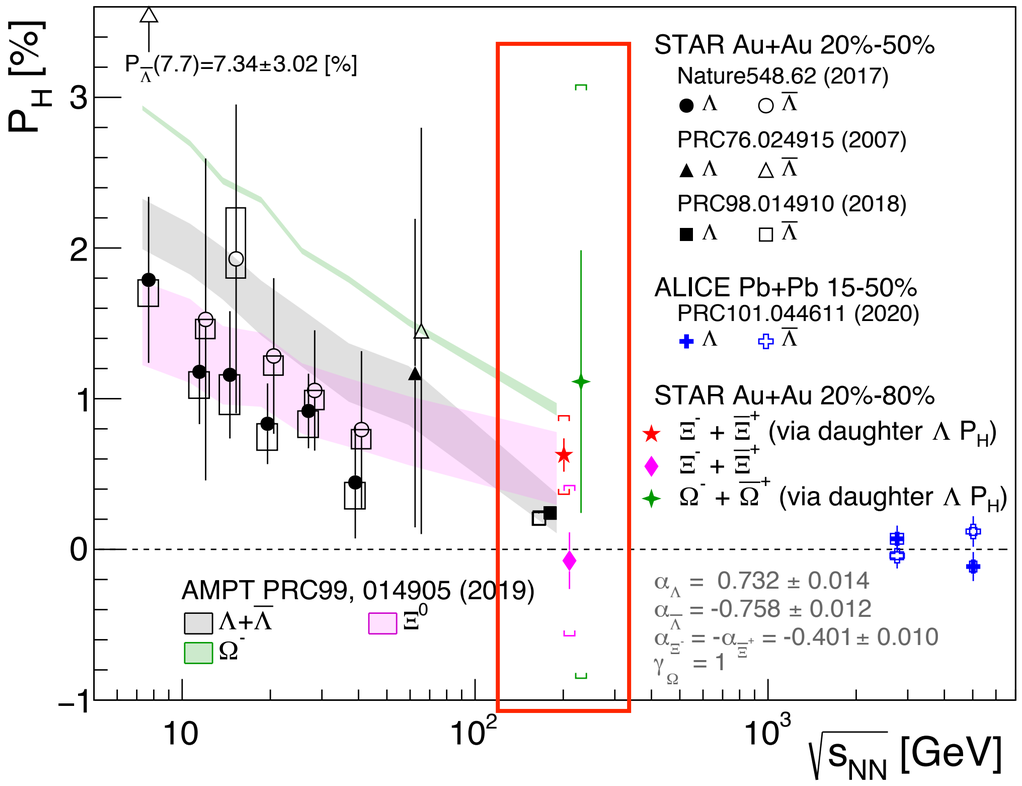
Note: The splitting, if any, could be other effects, e.g. finite μ_B and different freeze-out in space-time

Particle-species (spin) dependence?

- Thermal model predicts: $P_\Xi = P_\Lambda,\ P_\Omega = \frac{5}{3} P_\Lambda$

$$\mathbf{P} = \frac{\langle \mathbf{s} \rangle}{s} \approx \frac{(s+1)}{3} \frac{\boldsymbol{\omega}}{T}$$

F. Becattini et al., PRC95.054902 (2017)



STAR, PRL126, 162301 (2021)

- Hint of hierarchy in P_H but not significant yet

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

- Feed-down effect can explain $P_\Xi > P_\Lambda$
  - 10-15% reduction of primary P_Λ
  - ~25% increase of primary P_Ξ

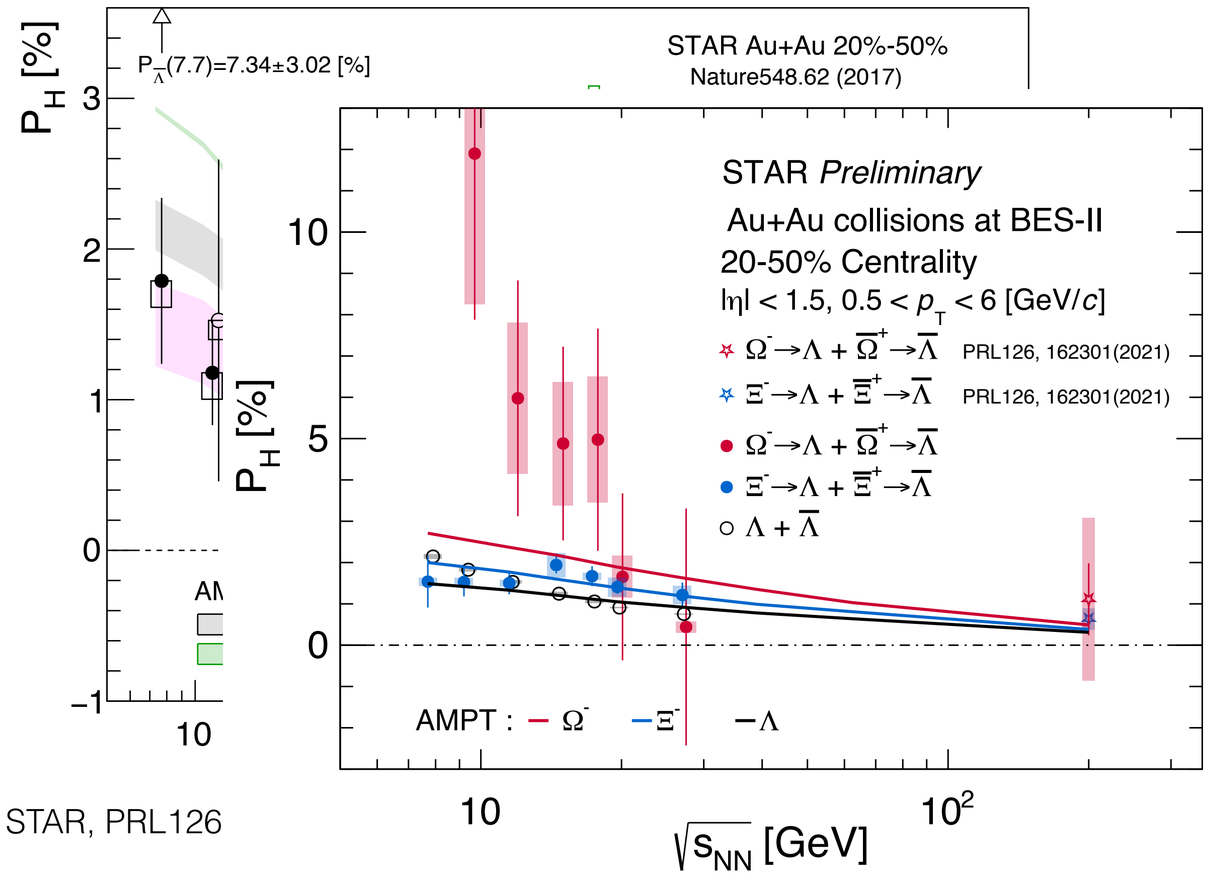
F. Becattini et al., PRC95.054902(2017)
H. Li et al., PLB827(2022)136971

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STAR, PRL126

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F. Becattini et al., PRC95.054902(2017)
H. Li et al., PLB827(2022)136971

Better significance of P_Ξ (~5σ) from STAR BES-II
A hint of larger P_Ω than P_Λ and P_Ξ

$$P_\Xi(\%) = 1.94 \pm 0.21 \pm 0.29\ (14.6\ \text{GeV})$$

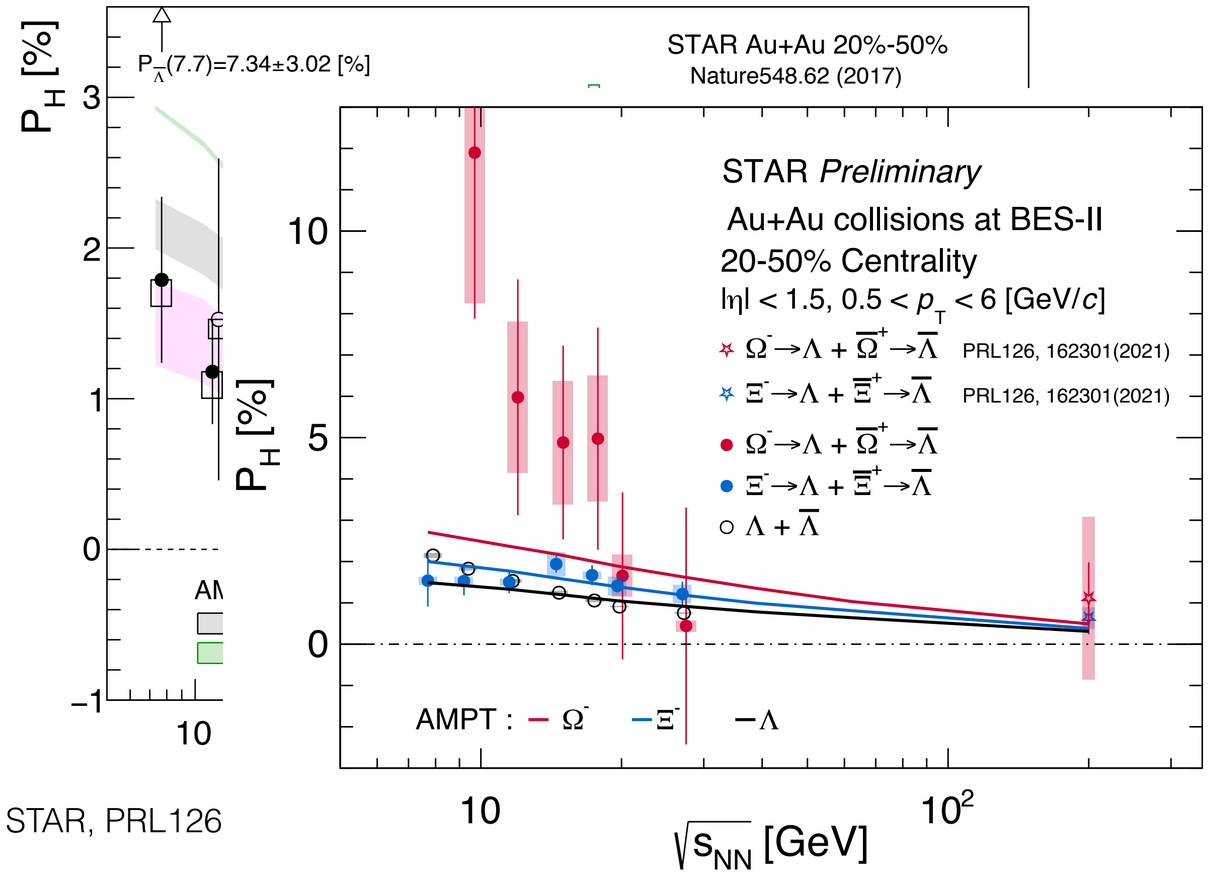
Further support for the global vorticity picture!

Particle-species (spin) dependence?

- Thermal model predicts: $P_\Xi = P_\Lambda,\ P_\Omega = \frac{5}{3} P_\Lambda$

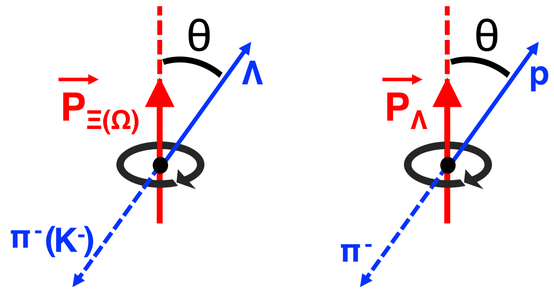
$$\mathbf{P} = \frac{\langle \mathbf{s} \rangle}{s} \approx \frac{(s+1)}{3} \frac{\boldsymbol{\omega}}{T}$$

F. Becattini et al., PRC95.054902 (2017)



STAR, PRL126

Ω^- (spin 3/2)



T.D. Lee and C.N. Yang, Phys. Rev.108.1645 (1957)

$$\mathbf{P}^*_\Lambda = C_{\Omega-\Lambda}\mathbf{P}^*_\Omega = \tfrac{1}{5}(1+4\gamma_\Omega)\,\mathbf{P}^*_\Omega. \qquad \alpha^2+\beta^2+\gamma^2=1$$

∗γ_Ω is unknown, but α_Ω, $\beta_\Omega \ll 1 \rightarrow \gamma_\Omega \sim \pm 1$

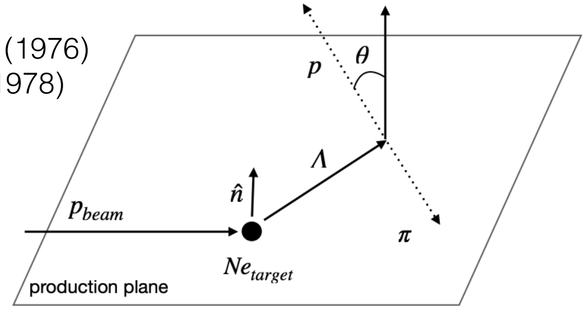
Polarization transfer factor could be $C_{\Omega\Lambda} \approx +1 \text{ or } -0.6$

Based on the global vorticity picture (P_Ω>0),
the measured daughter-Λ polarization favors γ_Ω>0!

Effect of transverse polarization?

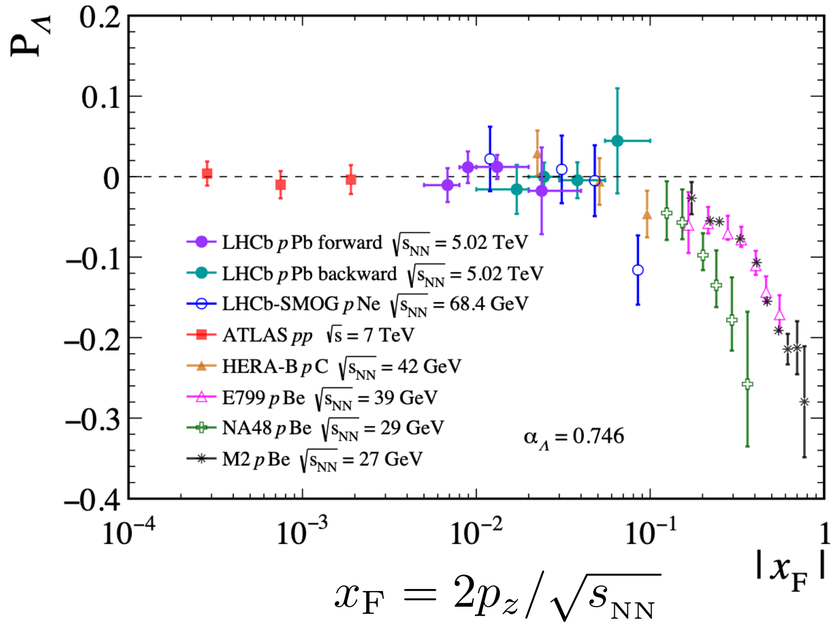
Bunce et al., Phys. Rev. Lett. 36, 1113 (1976)
Heller et al., Phys. Rev. Lett. 41, 607 (1978)
and many…

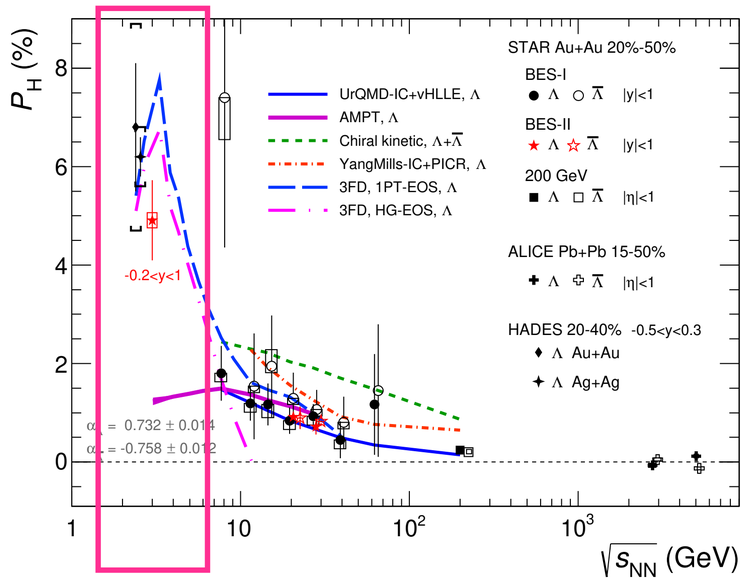
production plane $\vec{p}_{\rm beam} \times \vec{p}_{\Lambda}$



- Transverse polarization was first observed ~50 years ago, but the underlying mechanism is not yet fully understood
- Any relation to the global polarization?

LHCb, Phys. Rev. D112, 112022 (2025)





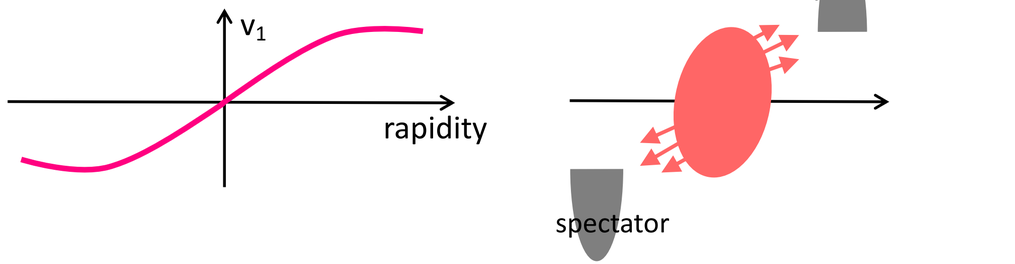
Effect of transverse polarization?

$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

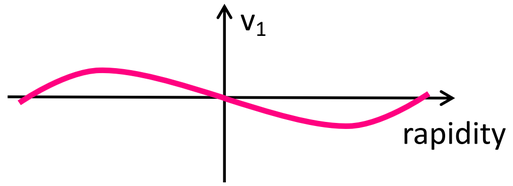
Transverse polarization wrt production plane (PP): $\vec{p}_{\rm beam} \times \vec{p}_\Lambda$

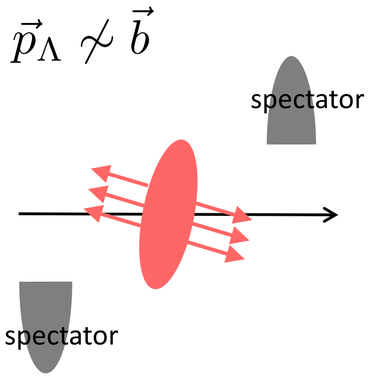
Global polarization wrt reaction plane (RP): $\vec{p}_{\rm beam} \times \vec{b}$

Low $\sqrt{s_{NN}}$ (large v_1)



High $\sqrt{s_{NN}}$ (small v_1)





PP and RP are correlated at low $\sqrt{s_{NN}}$, while they are less correlated at high $\sqrt{s_{NN}}$

Z.-T. Liang and X.-N. Wang, PRL94,102301(2005)
S. Voloshin, nucl-th/0410089

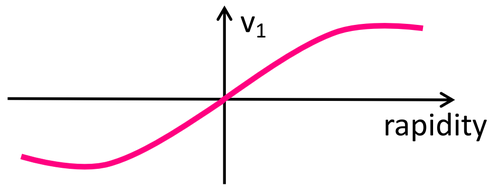
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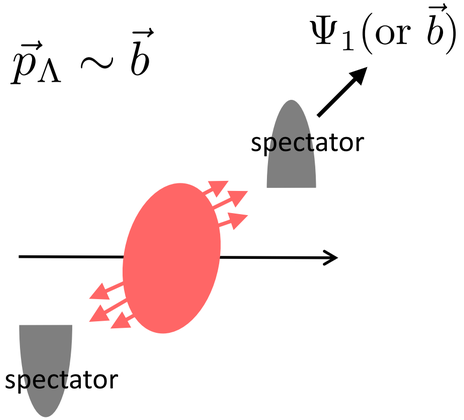
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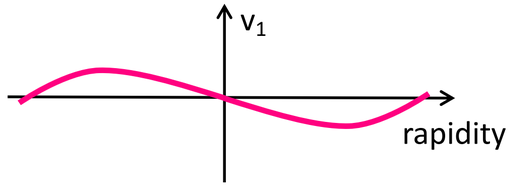
Global polarization wrt reaction plane (RP): $\vec{p}_{\rm beam} \times \vec{b}$

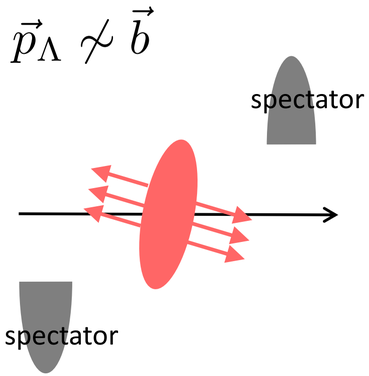
Low $\sqrt{s_{NN}}$ (large v_1)





High $\sqrt{s_{NN}}$ (small v_1)

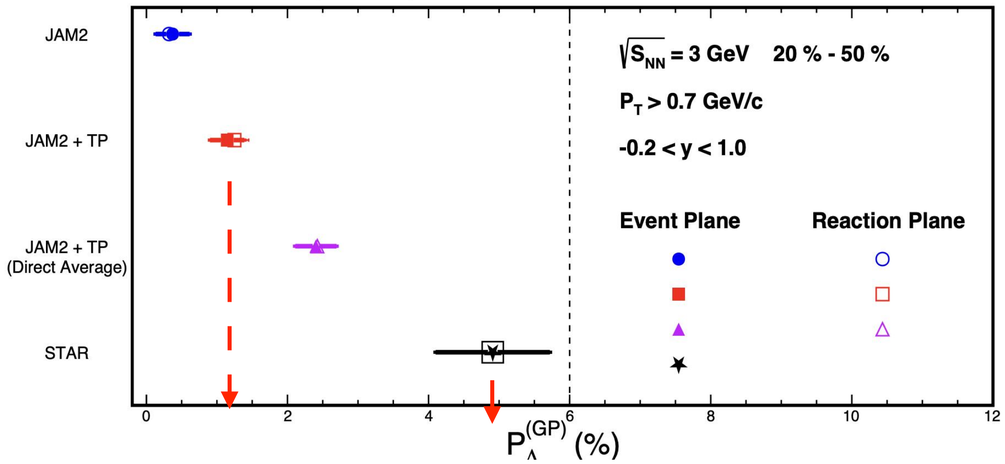




PP and RP are correlated at low $\sqrt{s_{NN}}$, while they are less correlated at high $\sqrt{s_{NN}}$

Z.-T. Liang and X.-N. Wang, PRL94,102301(2005)
S. Voloshin, nucl-th/0410089

No vorticity, only transverse P_Λ & v_1



F. Liu and Z. Tu, PRD113, 114051 (2026)

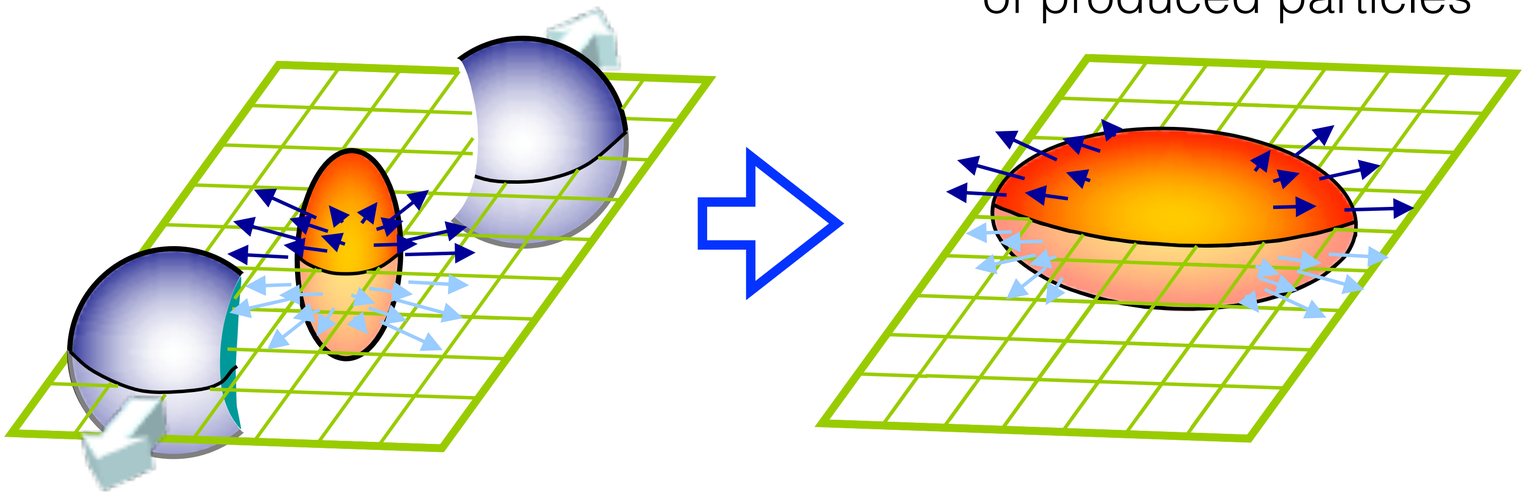
The model suggest ~20% contribution to the measured global polarization in 3 GeV Au+Au collisions. Under investigation experimentally…

Local vorticity associated with elliptic expansion?

S. Voloshin, SQM2017
F. Becattini and I. Karpenko, PRL120.012302 (2018)

Initial almond shape

Anisotropy at momentum-space of produced particles



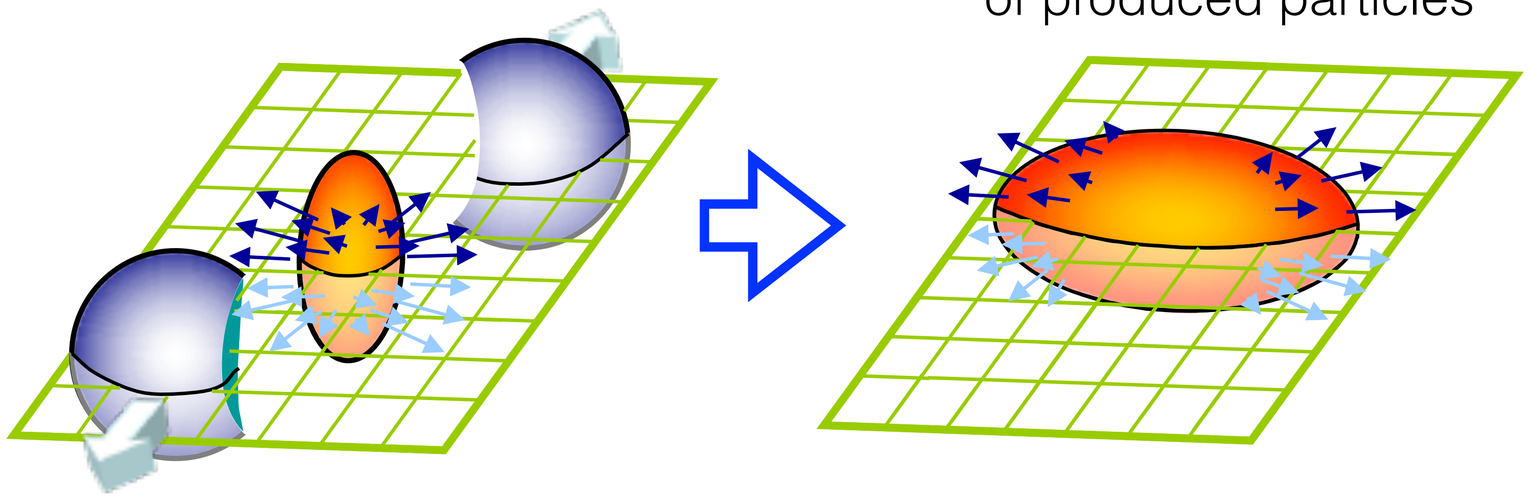
Stronger pressure gradient in-plane than out-of-plane
→ More particle emission in-plane: ”elliptic flow”

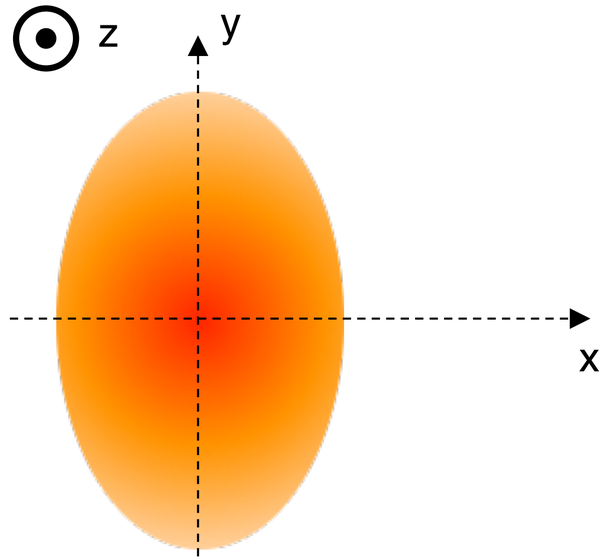
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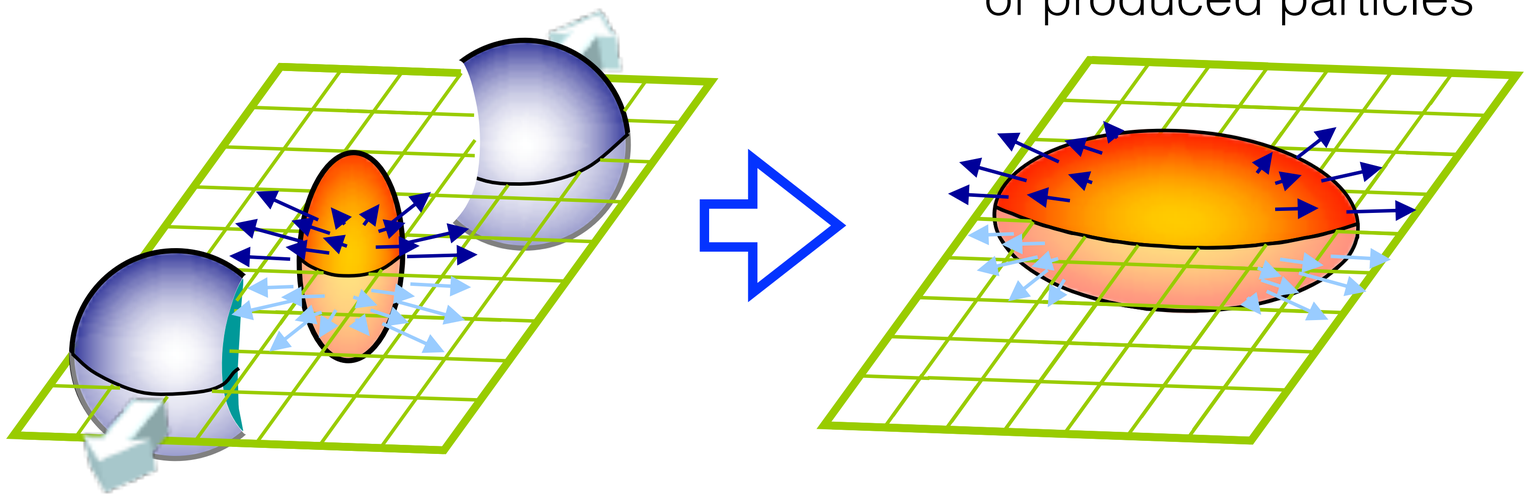
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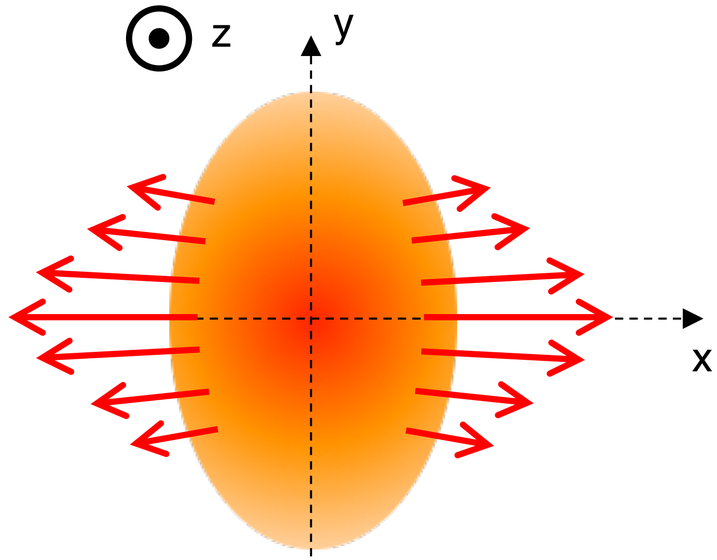
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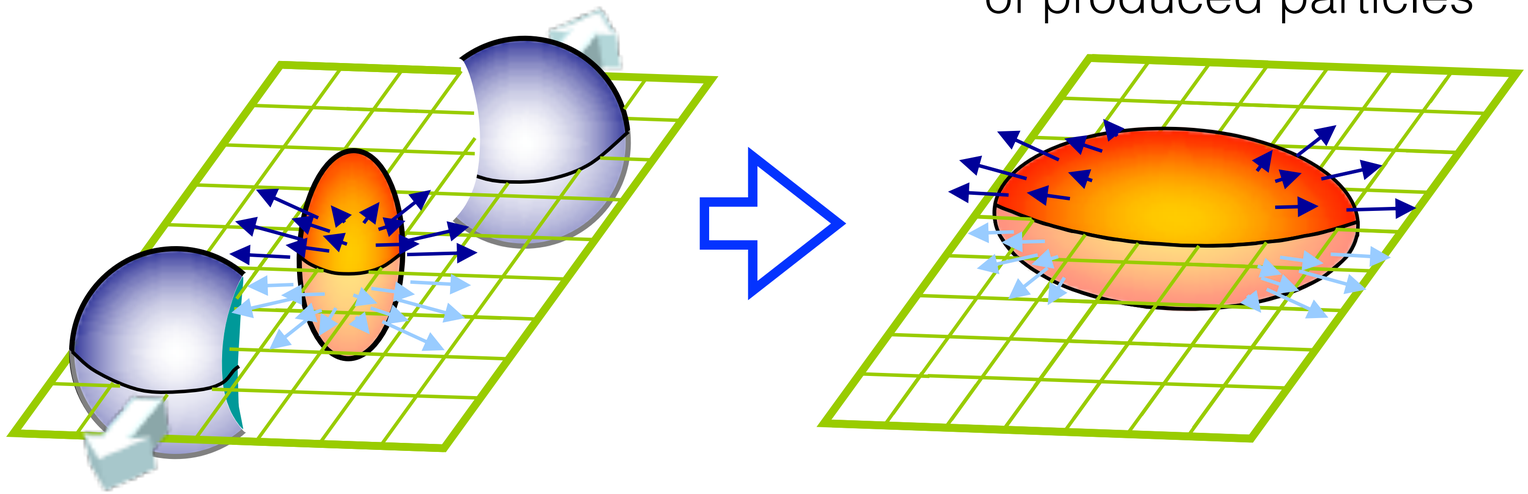
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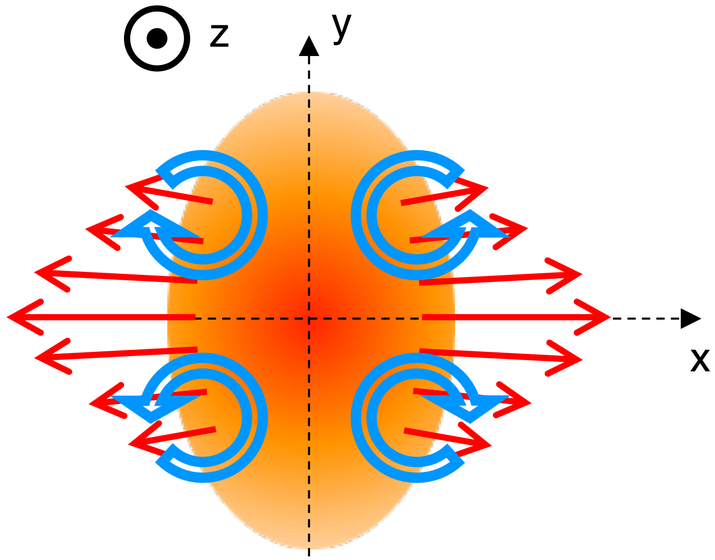
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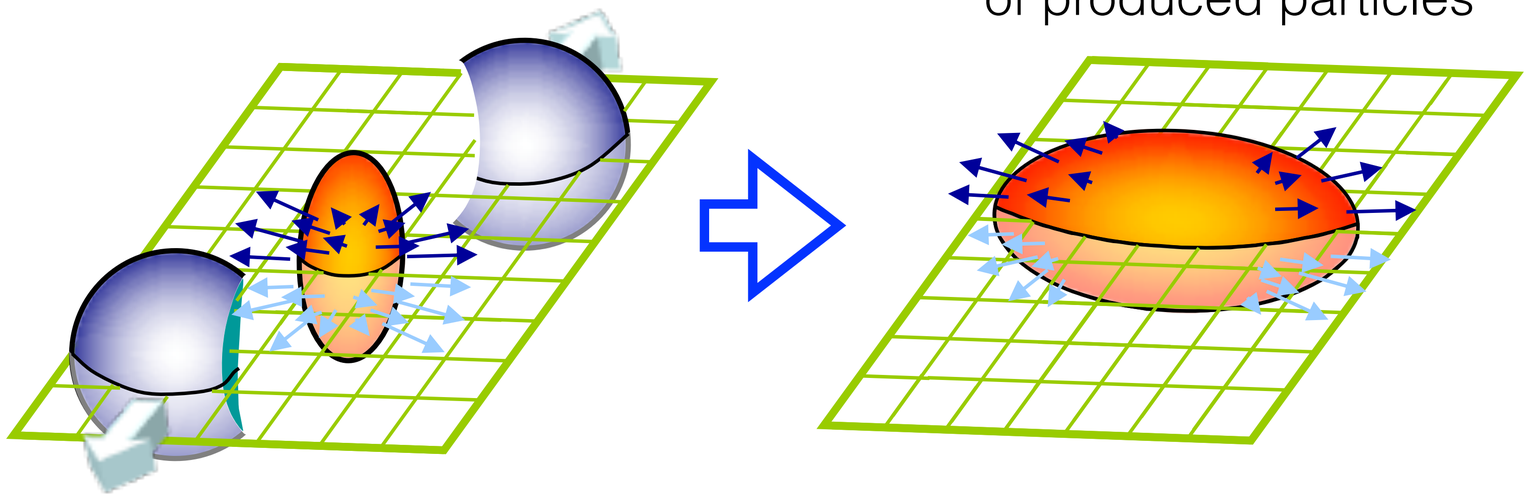
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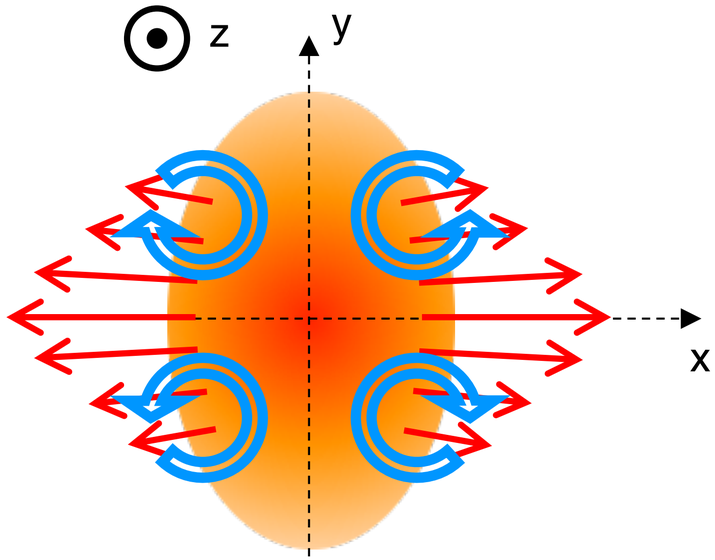
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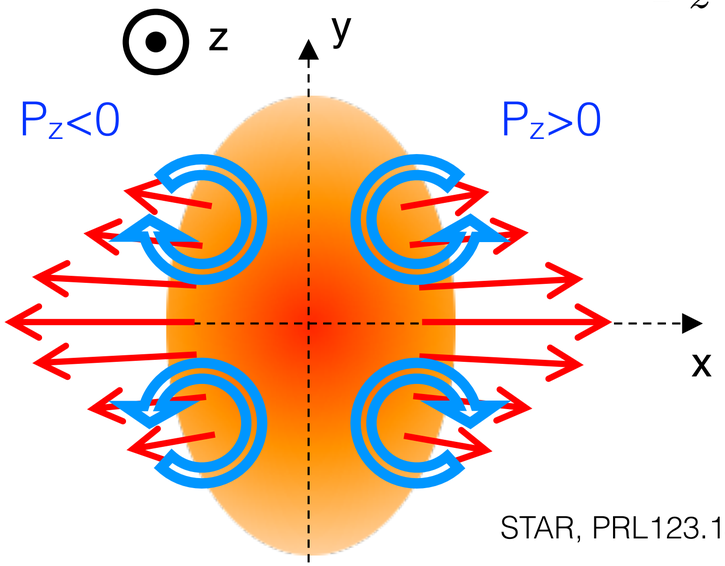


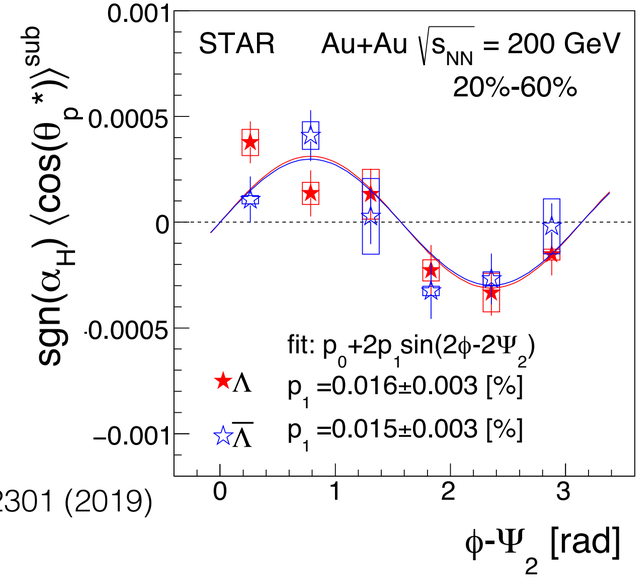
Stronger pressure gradient in-plane than out-of-plane
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Local vorticity is generated, where the rotational axis reverses the direction with the azimuthal angle

Polarization along the beam direction: P_z

$$P_z \propto \langle \cos\theta_p^* \rangle$$





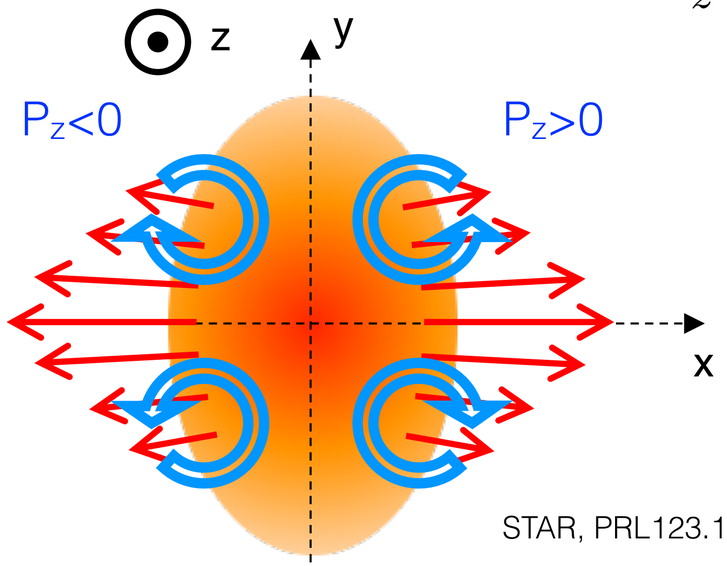
STAR, PRL123.132301 (2019)

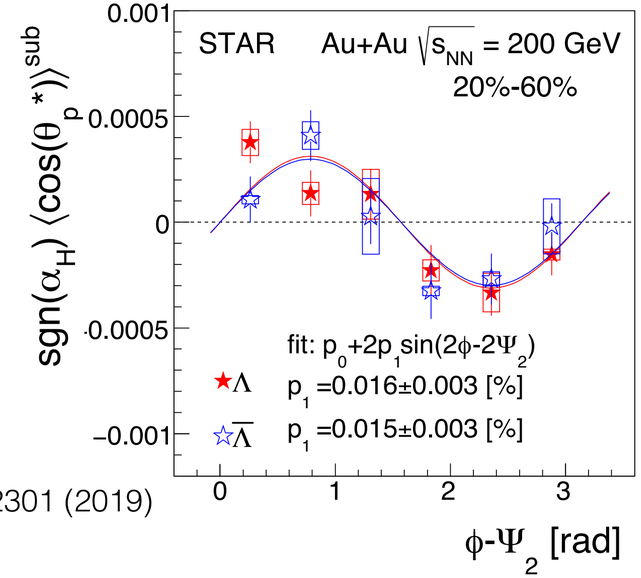
- Polarization along the beam direction expected from the elliptic flow

F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

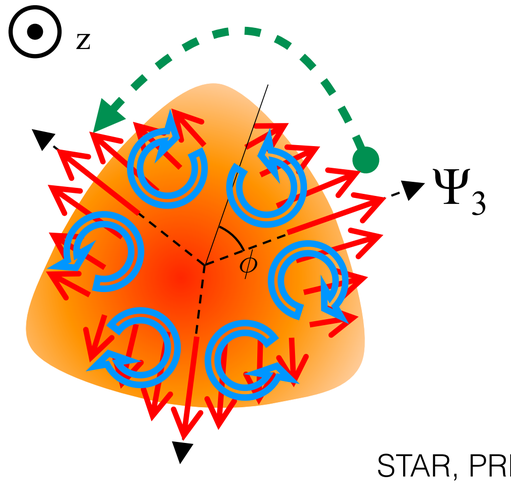
Polarization along the beam direction: P_z

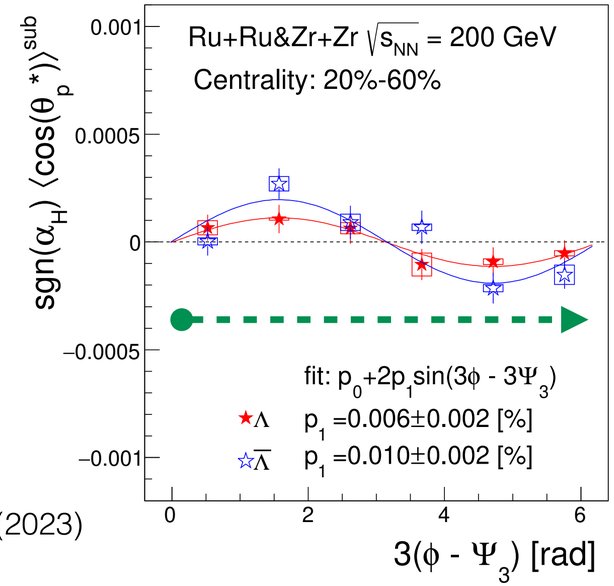
$$P_z \propto \langle \cos\theta_p^* \rangle$$





STAR, PRL123.132301 (2019)





STAR, PRL131, 202301 (2023)

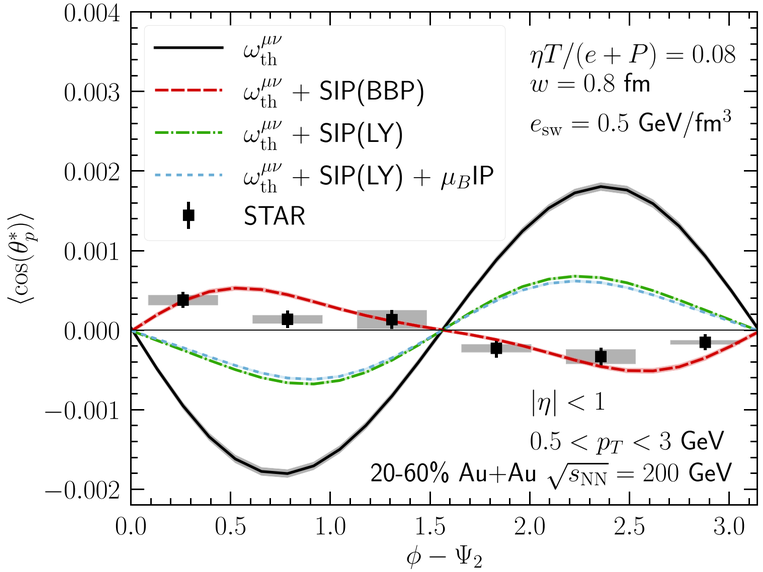
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S. Voloshin, EPJ Web Conf.171, 07002 (2018)

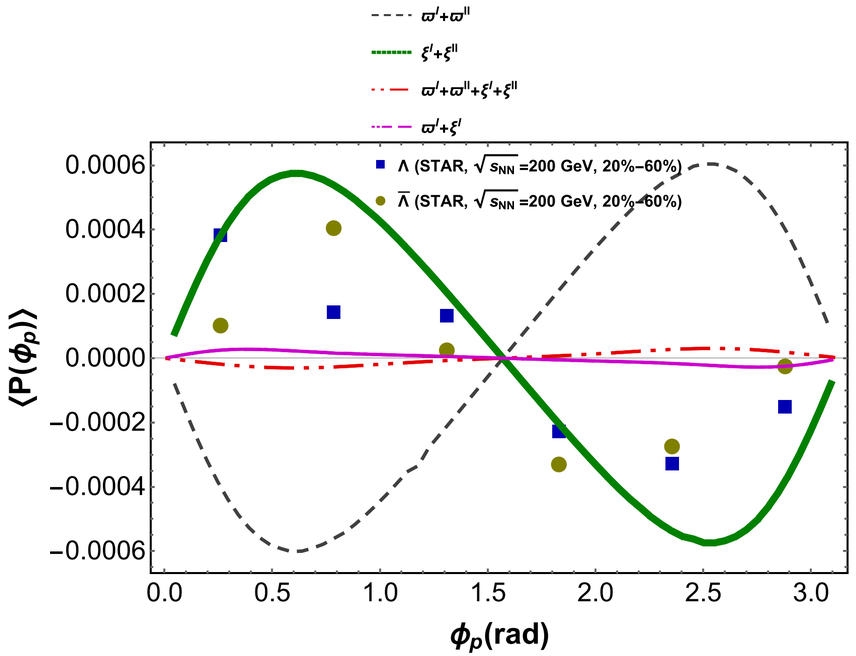
- More complex vortex pattern created in heavy-ion collisions

Anisotropic-flow-driven polarization!

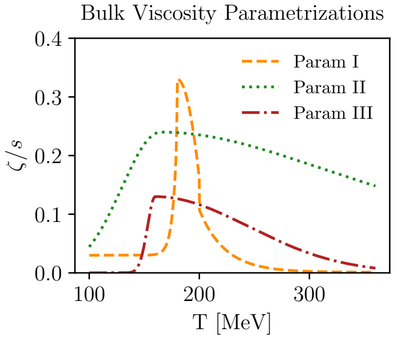
Spin sign puzzle still remains?



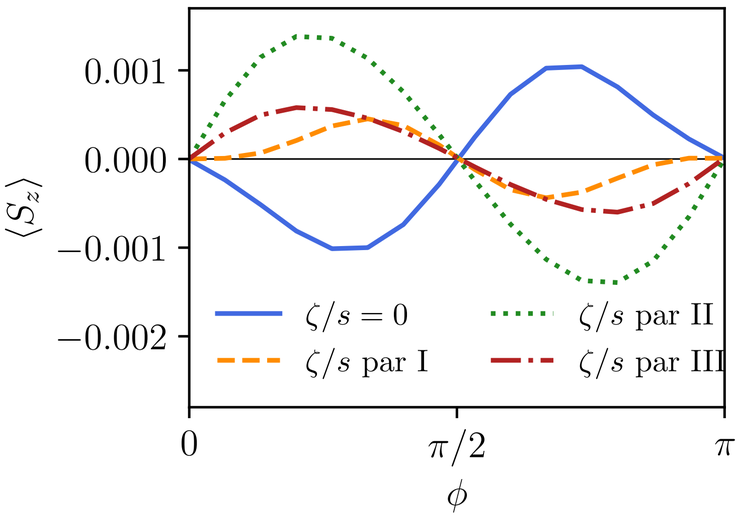
S. Alzharani et al., PRC106.014905 (2022)



W. Florkowski et al., PRC105, 064901 (2022)



LHC PbPb 5020 GeV



Palermo et al., EPJC84(2024)920

- The sign depends on the implementation detail of the shear induced polarization (SIP)
  - Large cancellation of thermal vorticity and SIP!
- Sensitivity to temperature dependence of bulk viscosity ζ/s(T)

See similar studies, e.g.
C. Yi et al., PRC104, 064901 (2021)
Y. Sun et al., PRC105, 034911 (2022)

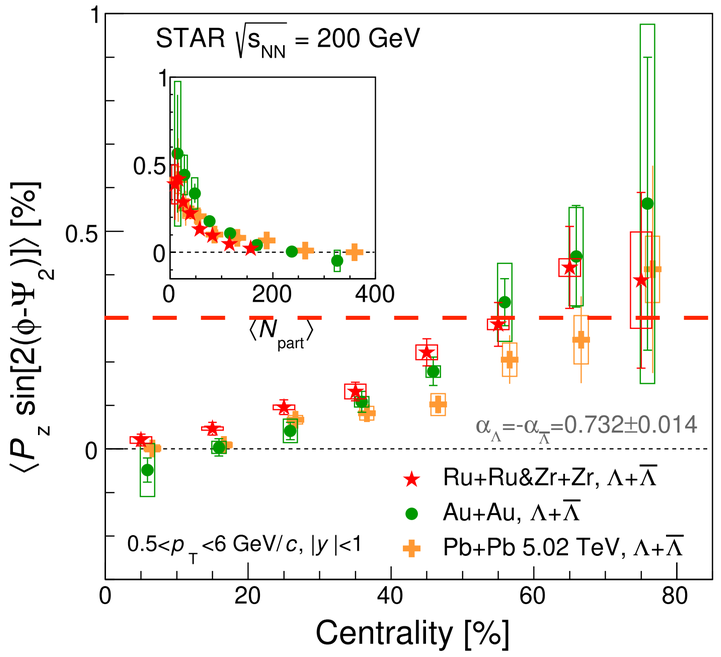
vorticity: $\omega_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma u_\rho - \partial_\rho u_\sigma\right)$

shear: $\Xi_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma u_\rho + \partial_\rho u_\sigma\right)$

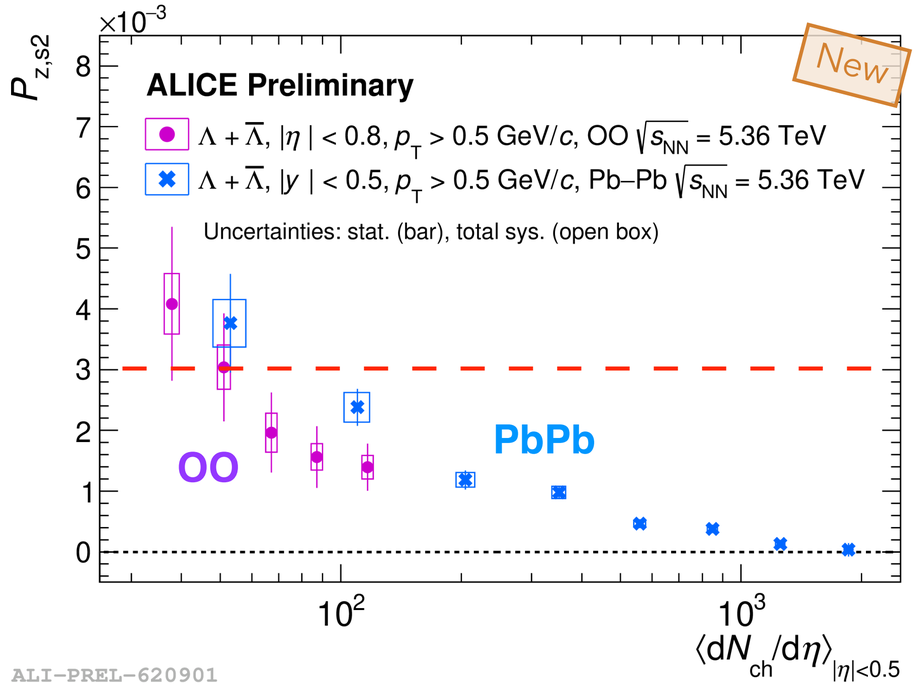
P_z from small to large systems

$$P_{z,s2} = \langle P_z \sin[2(\phi - \Psi_2)] \rangle$$

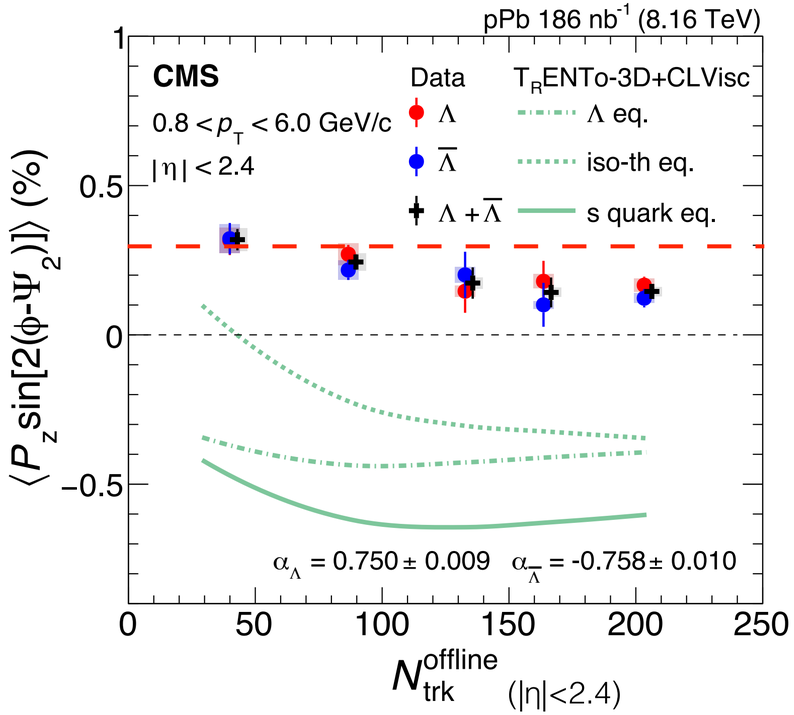
STAR, PRL131, 202301 (2023)



C. Jauch (ALICE), SQM2026



CMS, PRL135, 132301 (2025)



Au+Au vs. Ru+Ru/Zr+Zr vs. Pb+Pb

O+O vs. Pb+Pb

pPb

- Similar multiplicity dependence of P_z sine coefficients across all the systems
- But in pPb, the models fail to explain the data. How about for OO?
  - Color field may play a role, especially in small systems
- Another way to check collectivity in small systems, if it's vorticity-driven

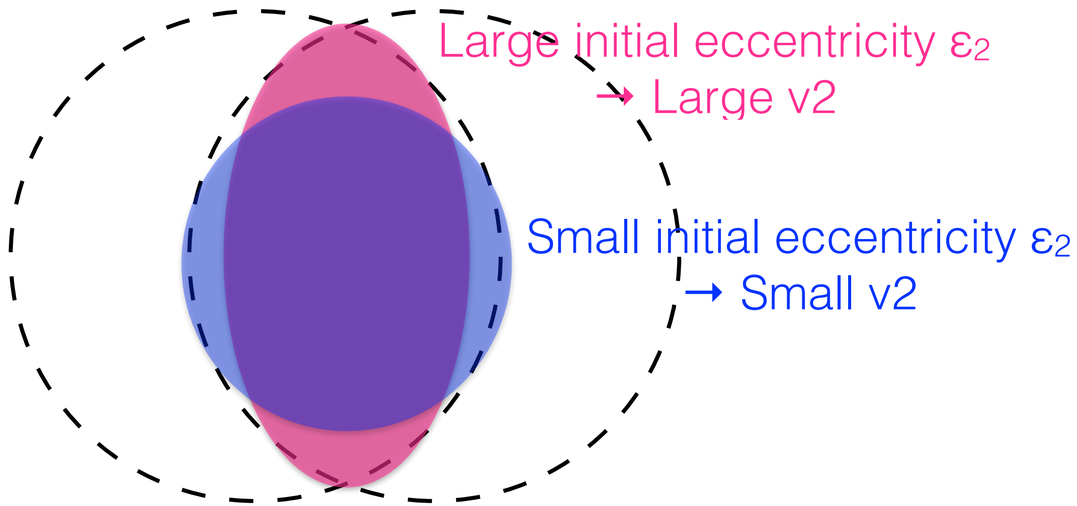
Zhenyu Chen, Oct. 27(Tue)

Di-Lun Yang, Oct. 27(Tue)

Haesom Song, Oct. 29(Thu)

P_z with Event Shape Engineering

within a fixed impact parameter

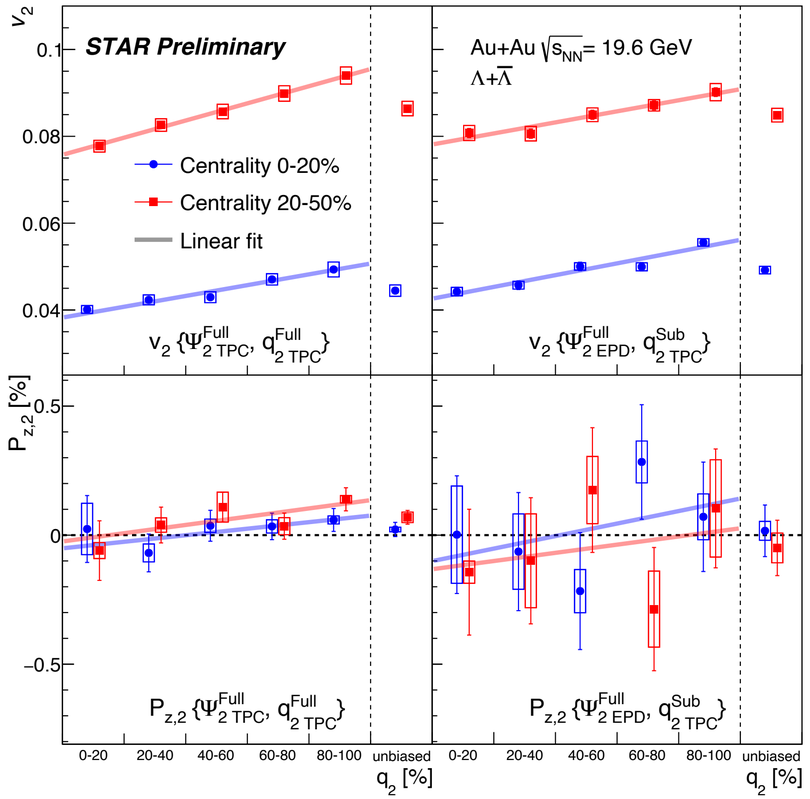


Flow vector q_2
(charged hadrons)

$$q_2 = \frac{|\vec{Q}_2|}{\sqrt{M}}$$

Λ local polarization $P_{z,2}$

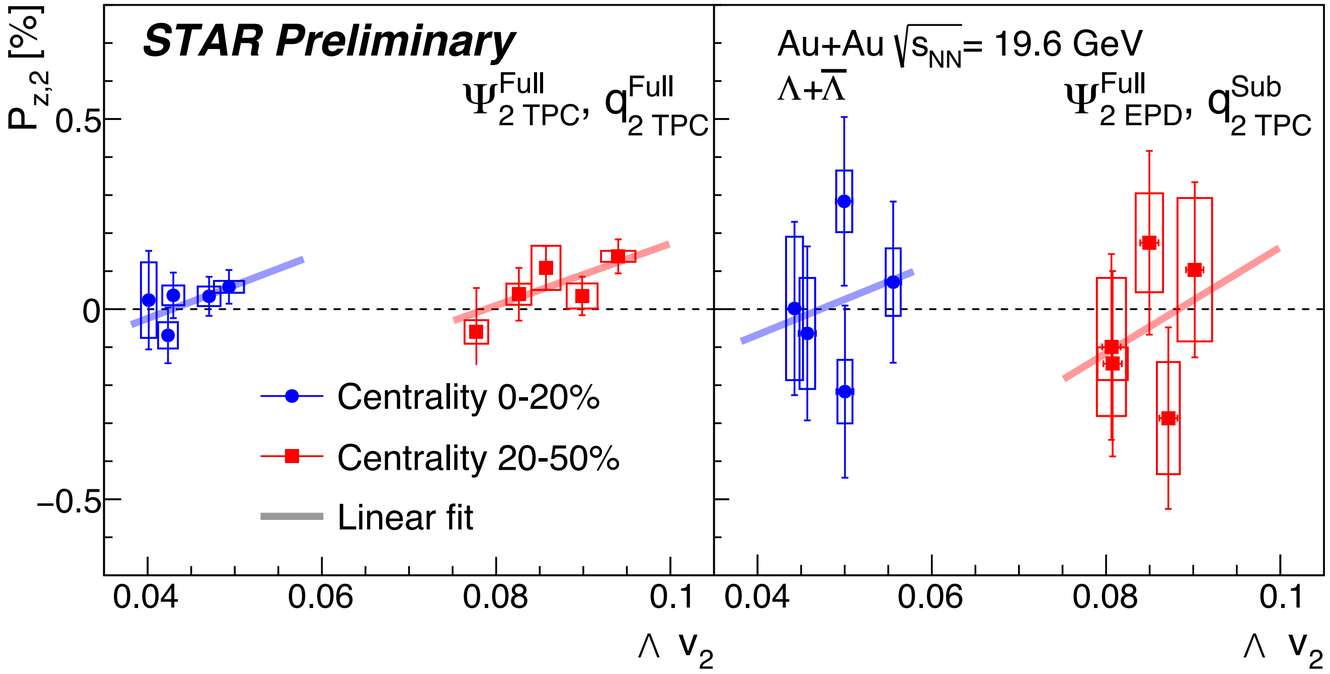
$$P_{z,2} = \langle P_z \sin[2(\phi - \Psi_2)] \rangle$$

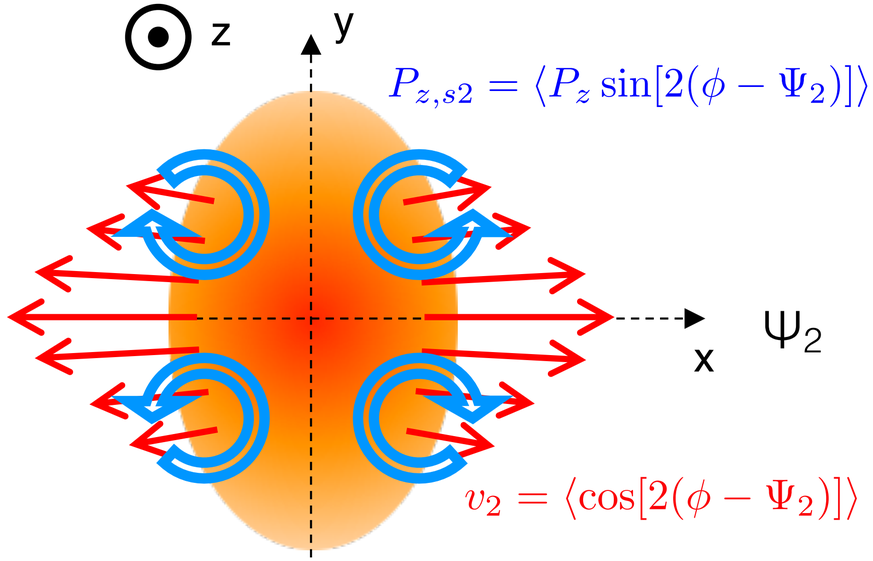


- First attempt to investigate the correlation between $P_{z,2}$ and v_2 with Event Shape Engineering

J. Schukraft et al., PLB719 (2013) 394

P_z with Event Shape Engineering





- First attempt to investigate the correlation between $P_{z,2}$ and v_2 with Event Shape Engineering

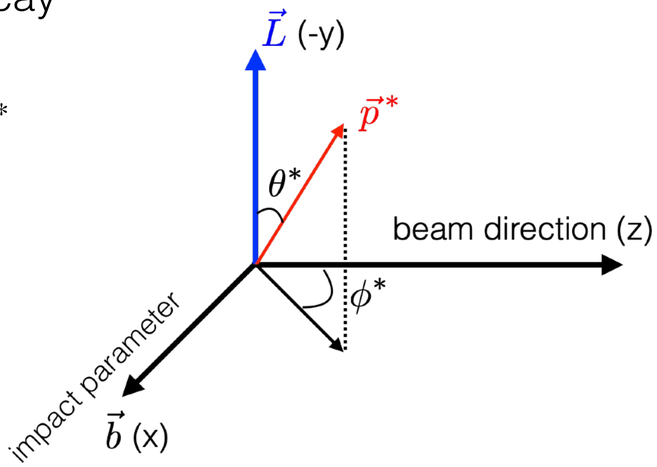
  J. Schukraft et al., PLB719 (2013) 394

- Positive trend of $P_{z,2}$ with v_2 (~2σ), consistent with anisotropic-flow-driven polarization
  - Suggestive negative intercept for $v_2 \to 0$? Other polarization mechanisms?

Global spin alignment of vector mesons

- Vector mesons (spin-1) can be used to study the polarization.
  Angular distribution of the decay products can be written with spin density matrix ρ_{hm}
  - Note: vector polarization cannot be determined because of parity conservation in strong decay

$$\frac{dN}{d\cos\theta^*} \propto \rho_{0,0}|Y_{1,0}|^2 + \rho_{1,1}|Y_{1,-1}|^2 + \rho_{-1,-1}|Y_{1,1}|^2 \propto \rho_{0,0}\cos^2\theta^* + \frac{1}{2}(\rho_{1,1}+\rho_{-1,-1})\sin^2\theta^*$$
$$\propto (1-\rho_{0,0}) + (3\rho_{0,0}-1)\cos^2\theta^*$$



- The diagonal element ρ_{00} represents probability of spin projection m=0
  - ρ_{00} = 1/3: unpolarized reference
  - $\rho_{00} \neq$ 1/3: spin alignment (unequal spin populations)

$$\rho_{00} < 1/3 : |1,0\rangle \text{ state suppressed}$$
$$\rho_{00} > 1/3 : |1,0\rangle \text{ state enhanced}$$

$$\hat{S}_z|S,m\rangle = m\hbar|S,m\rangle$$
$$\text{for spin-1, } S=1,\ m=-1,\ 0,\ +1$$

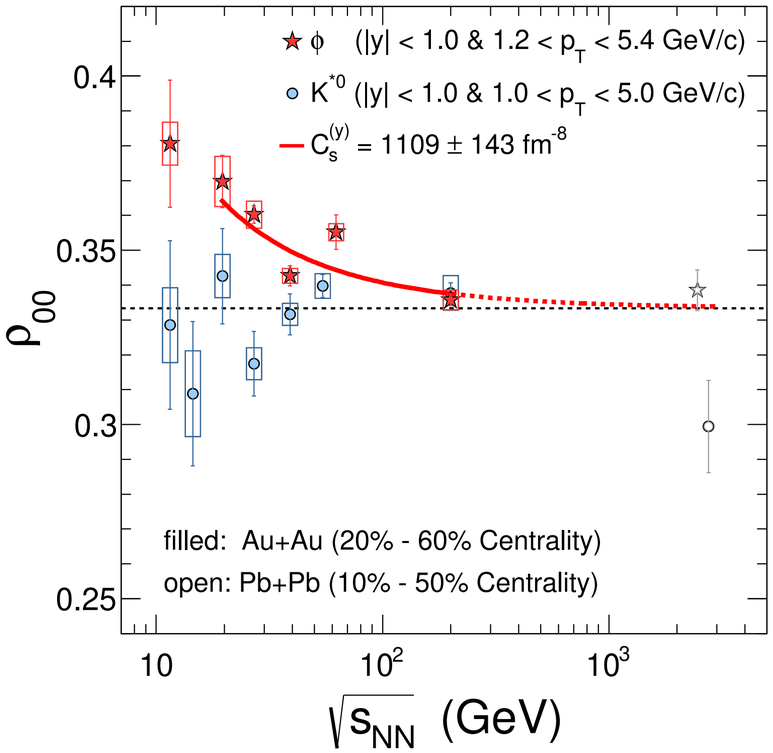
"Global": L direction is taken as a quantization axis

$$\rho_{00} = \frac{1}{3} + \frac{5}{2}(\langle\cos^2\theta^*\rangle - \frac{1}{3})$$
$$\rho_{00} = \frac{1}{3} - \frac{8}{3}\langle\cos[2(\phi^* - \Psi_{\mathrm{RP}})]\rangle$$

Surprisingly large signal of ρ_{00}

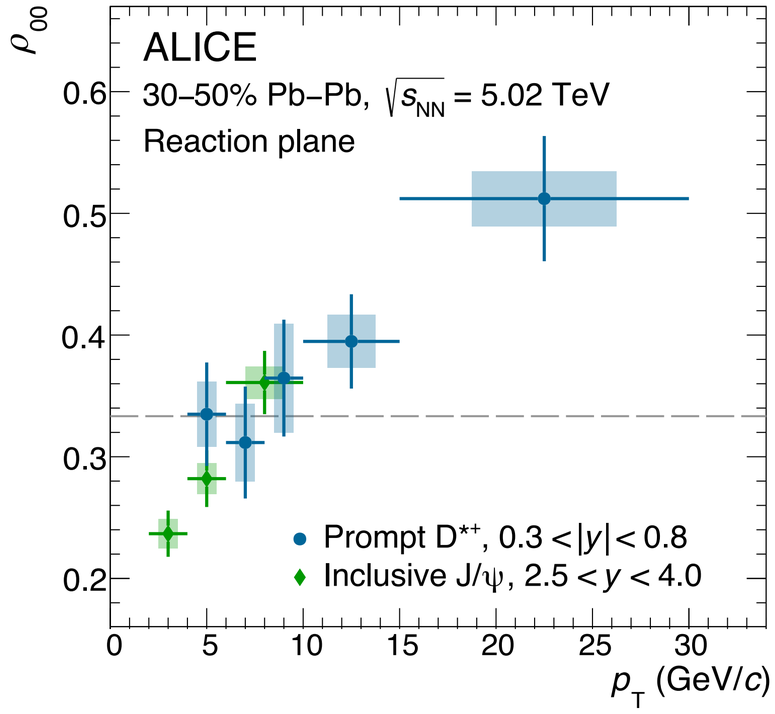
ϕ-mesons

STAR, Nature 614, 244 (2023)
ALICE, PRL125, 012301 (2020)



D*+, J/ψ

ALICE, PRL131.042303 (2023)
ALICE, JHEP10(2025)094



- Due to ϕ-meson field?

  X.-L. Sheng, L. Oliva, and Q. Wang, PRD101, 096005 (2020)
  X.-L. Sheng, Q. Wang and X.-N. Wang, PRD102, 056013 (2020)

- Due to the initial-state gluon field?

  A. Kumar, B. Muller, D.L. Yang, PRD108, 016020 (2023)
  D.L. Yang, PRD111, 056005 (2025)

- Large signal of (ρ_{00}-1/3) cannot be explained by vorticity and other conventional mechanisms

$$\rho_{00}^{(\mathrm{rec})} = \frac{1 - P_q^2}{3 + P_q^2} \qquad P_\Lambda \sim P_s \sim 1\%$$

$$\rightarrow \left|\rho_{00} - \frac{1}{3}\right| \sim 10^{-5}$$

Sensitivity to spin-spin correlation

J.-P. Lv, Z.-H. Yu, Z.-T. Liang, Q. Wang, and X.-N. Wang,
PRD109, 114003 (2024)

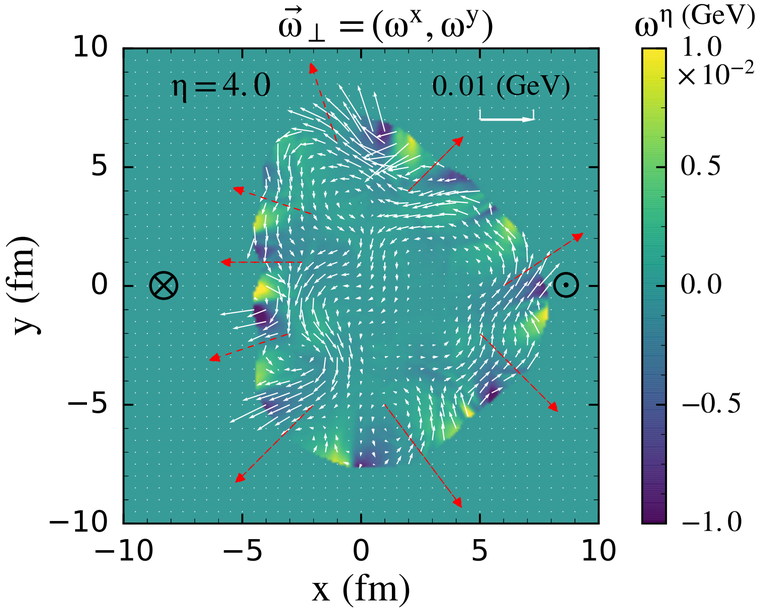
Hyperon polarization mainly probes **single-quark** polarization

$$P_\Lambda \sim \langle P_s \rangle$$

Vector-mesons spin alignment is sensitive to $q\bar{q}$ **spin correlation**

$$\rho_{00} \simeq \frac{1}{3} - \frac{4}{9}\left[C_{s\bar{s}} + (\langle P_s P_{\bar{s}} \rangle - \langle P_s \rangle \langle P_{\bar{s}} \rangle)\right]$$

L.-G. Pang et al., PRL117, 192301 (2016)



local vorticity fluctuations

Sensitivity to spin-spin correlation

J.-P. Lv, Z.-H. Yu, Z.-T. Liang, Q. Wang, and X.-N. Wang,
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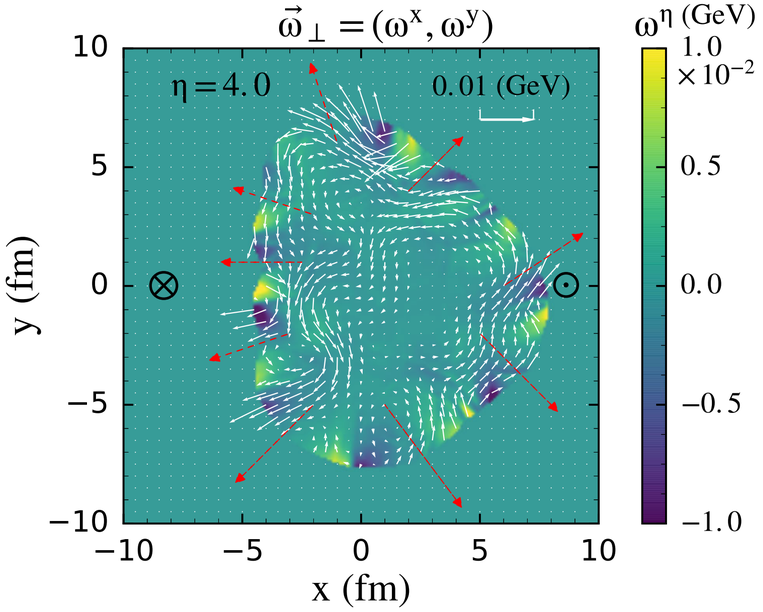
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Genuine correlation: direct correlation between s and sbar

Induced correlation: Correlation from fluctuations of local polarization

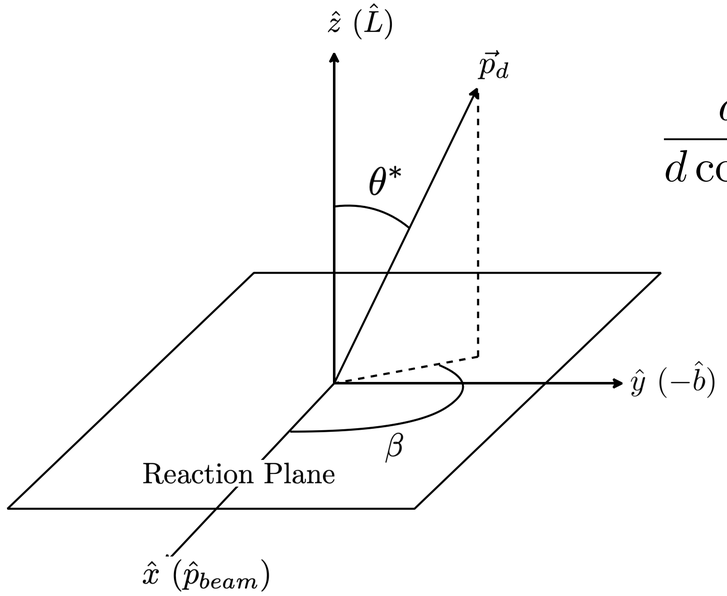
Even when $\langle P_s \rangle \approx \langle P_{\bar{s}} \rangle \approx 0$,
local polarization fluctuations can lead to $\langle P_s P_{\bar{s}} \rangle \neq 0$

L.-G. Pang et al., PRL117, 192301 (2016)



local vorticity fluctuations

Off-diagonal elements of spin density matrix



$$\frac{d^2N}{d\cos\theta^* d\beta} = \frac{3}{8\pi}\Big[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$
$$- \sqrt{2}\mathrm{Re}\,(\rho_{10}-\rho_{0-1})\sin 2\theta^*\cos\beta$$
$$+ \sqrt{2}\mathrm{Im}\,(\rho_{10}-\rho_{0-1})\sin 2\theta^*\sin\beta$$
$$- 2\mathrm{Re}\,(\rho_{1-1})\sin^2\theta^*\cos 2\beta$$
$$+ 2\mathrm{Im}\,(\rho_{1-1})\sin^2\theta^*\sin 2\beta\Big],$$

K.Schilling et al., NPB15(1970)397

Previously ignored
by integrating over β (angle in reaction plane)

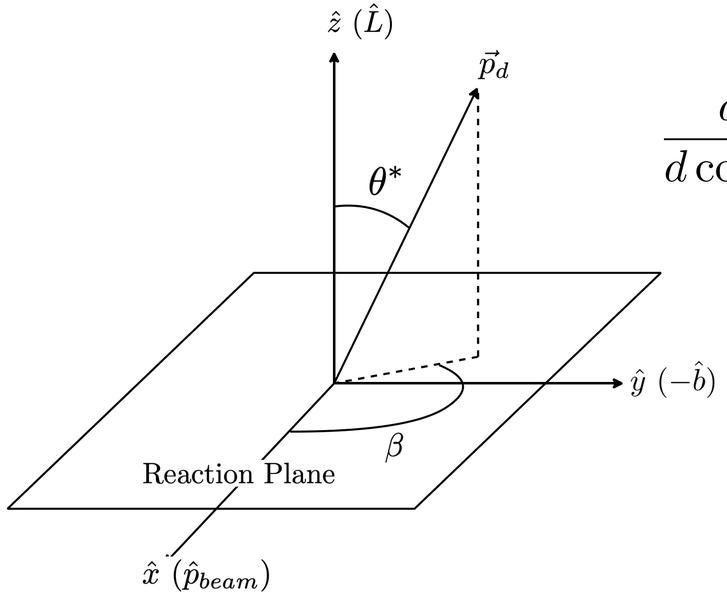
ρ_{nm}: Coherence between spin states n and m

$$\rho_{00} = \frac{1}{4\langle\cos 2\Delta\Psi_m\rangle}\Big[(3+\langle\cos 2\Delta\Psi_m\rangle)\,\rho_{00}^{\Psi_m}$$
$$+(-1+\langle\cos 2\Delta\Psi_m\rangle)\left(1+2\mathrm{Re}\left(\rho_{1-1}^{\Psi_m}\right)\right)\Big]$$

G.Wilks et al., PRC113, 044911 (2026)

Coupling of ρ_{00} and $\rho_{1\text{-}1}$ through the resolution of event plane angle
(quantization axis is perpendicular to EP)

Off-diagonal elements of spin density matrix



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$$- 2\mathrm{Re}\,(\rho_{1-1})\sin^2\theta^*\cos 2\beta$$
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Coupling of ρ_{00} and $\rho_{1\text{-}1}$ through the resolution of event plane angle
(quantization axis is perpendicular to EP)

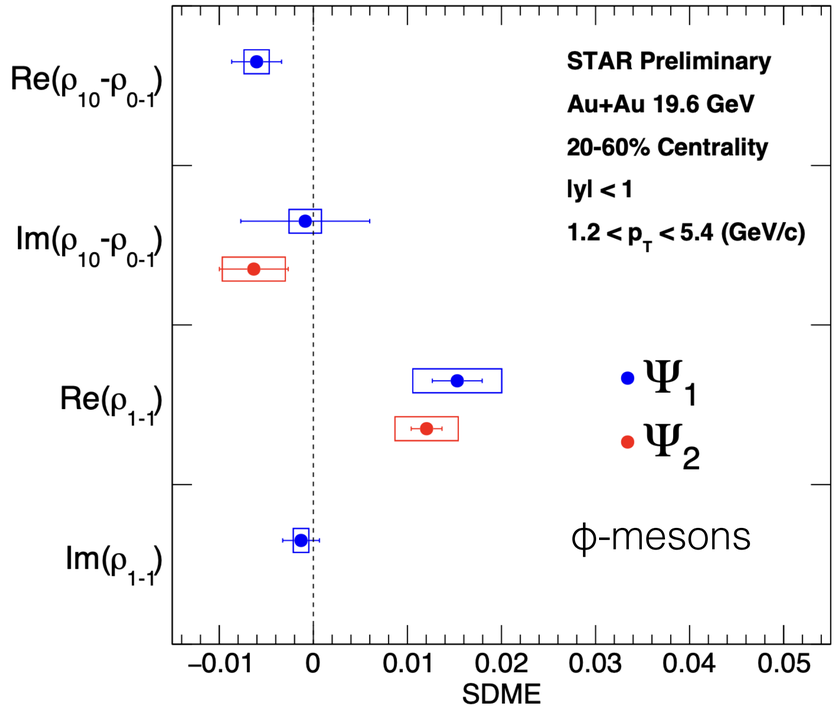
$$\mathrm{Re}(\rho_{1-1}) = \frac{1}{C_V}\left[c_{xx}^{(q_1\bar{q}_2)} - c_{yy}^{(q_1\bar{q}_2)} + P_{q_1x}P_{\bar{q}_2x} - P_{q_1y}P_{\bar{q}_2y}\right]$$

Contributions from spin-spin correlation

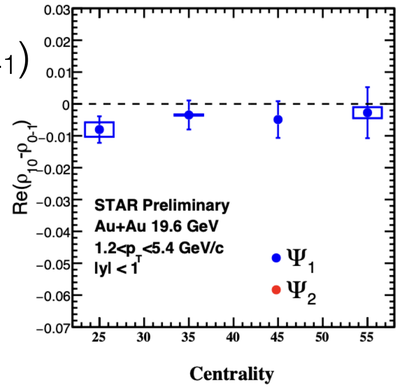
J.-P. Lv, Z.-H. Yu, Z.-T. Liang, Q. Wang, and X.-N. Wang,
PRD109, 114003 (2024)

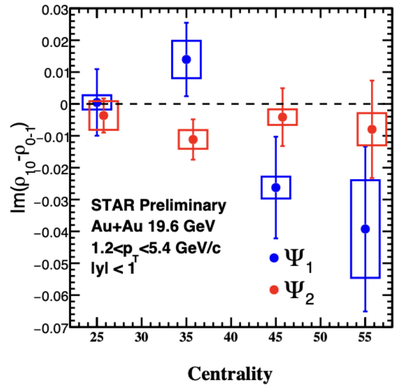
Off-diagonal elements of spin density matrix

G. Wilks and Z. Ye (STAR), SQM2026



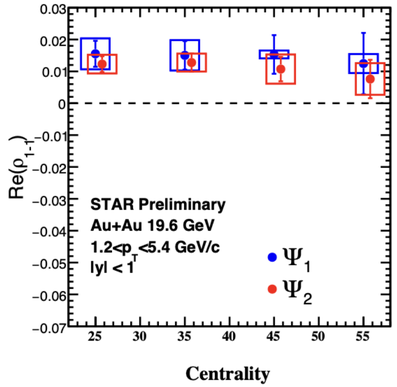
Re(ρ10-ρ0-1)

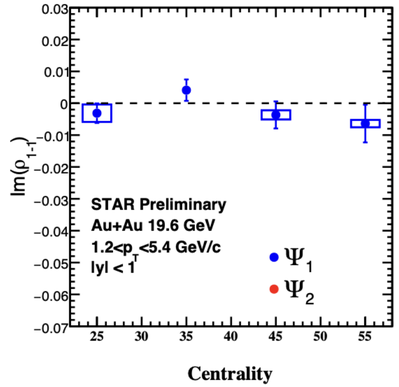




Im(ρ10-ρ0-1)

Re(ρ1-ρ-1)





Im(ρ1-ρ-1)

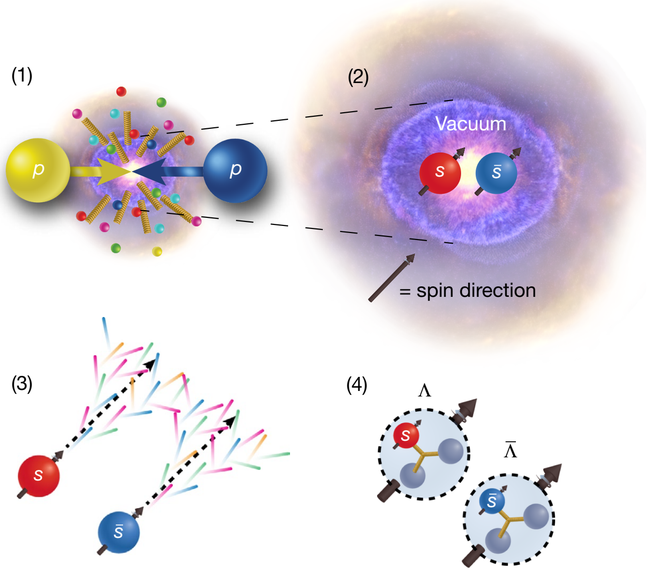
- First evidence of non-zero off-diagonal element Re($\rho_{1\text{-}1}$)
  - will bias 1D extraction of ρ_{00}
  - Possibly indicating non-zero s-sbar spin correlation

$$\mathrm{Re}(\rho_{1-1}) = \frac{1}{C_V}\left[c_{xx}^{(q_1\bar{q}_2)} - c_{yy}^{(q_1\bar{q}_2)} + P_{q_1x}P_{\bar{q}_2x} - P_{q_1y}P_{\bar{q}_2y}\right]$$

Contributions from spin-spin correlation

J.-P. Lv, Z.-H. Yu, Z.-T. Liang, Q. Wang, and X.-N. Wang, PRD109, 114003 (2024)

Spin-spin correlation



- The QCD vacuum has quantum numbers $J^{PC}=0^{++}$
- Assume qqbar pairs carry the vacuum quantum number, they are in the spin-triplet state (S=1) with correlated spins.

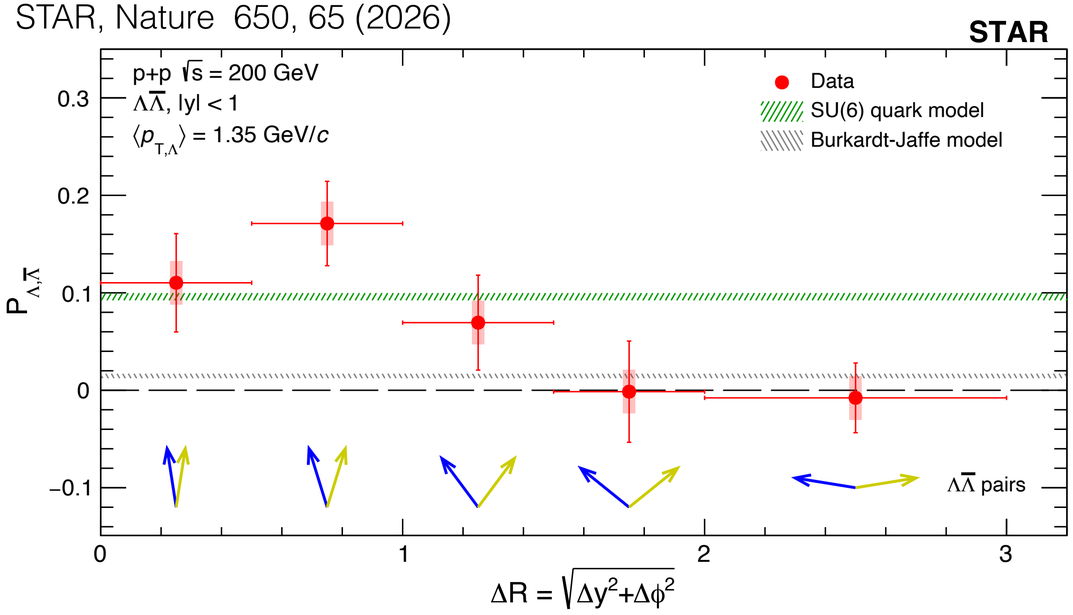
Ellis, Kharzeev, and Kotzinian, Z.Phys.C69, 467 (1996)

$$S = s_q + s_{\bar{q}}, \quad S = 1$$

$$S = 1, \; L = 1, \; J = 0$$

- $\Lambda\bar{\Lambda}$ spin-spin correlation in pp collisions at $\sqrt{s_{NN}}$ = 200 GeV

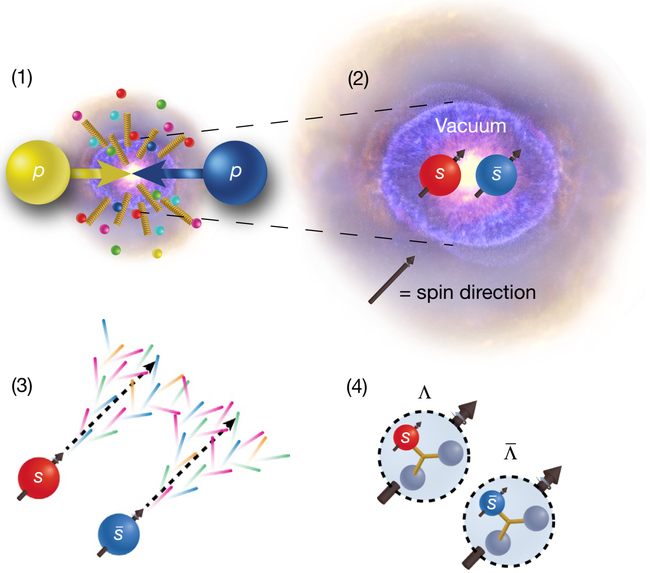
STAR, Nature 650, 65 (2026)



$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^{\star}} = \frac{1}{2}[1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos\theta^{\star}],$$

- Positive $\Lambda\bar{\Lambda}$ spin correlation at short small pair separation, consistent with zero at large separation (no significant correlation for identical pairs)

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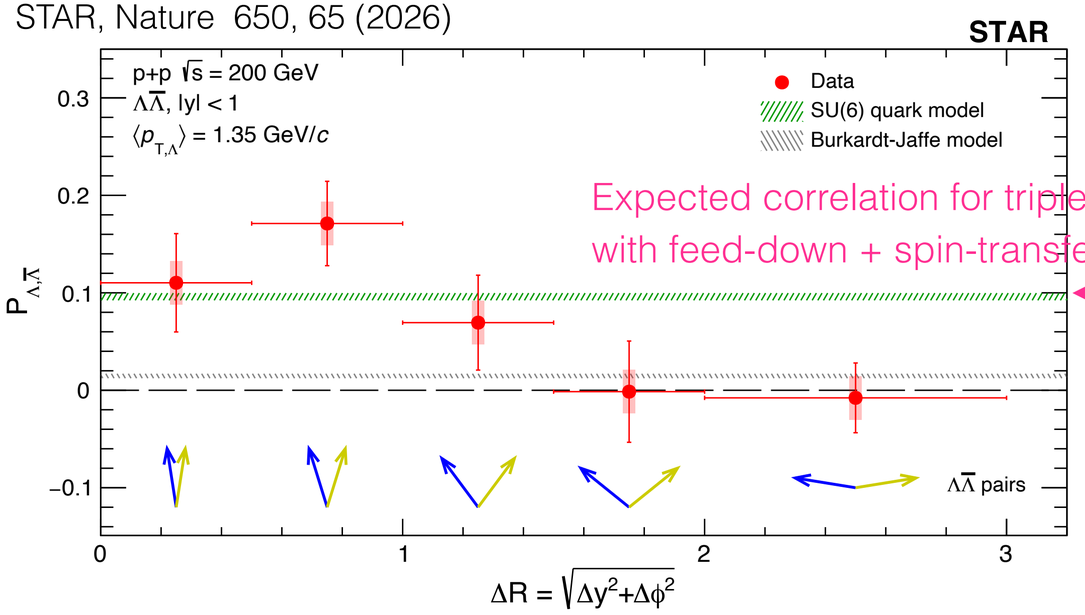
Ellis, Kharzeev, and Kotzinian, Z.Phys.C69, 467 (1996)

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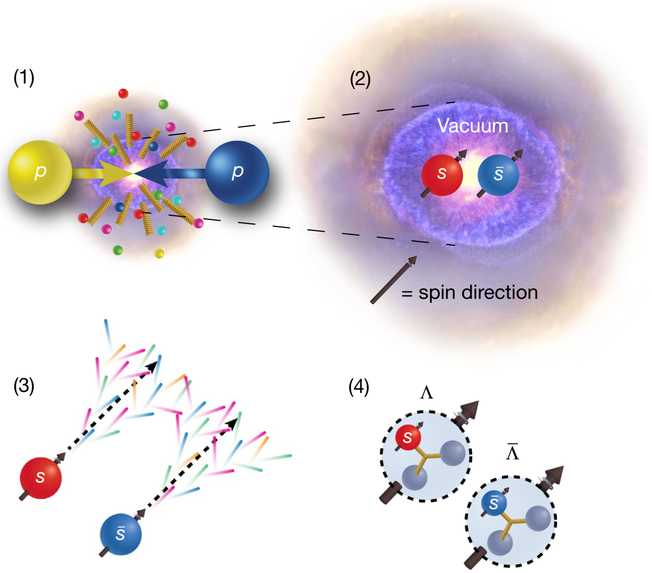
STAR, Nature 650, 65 (2026)



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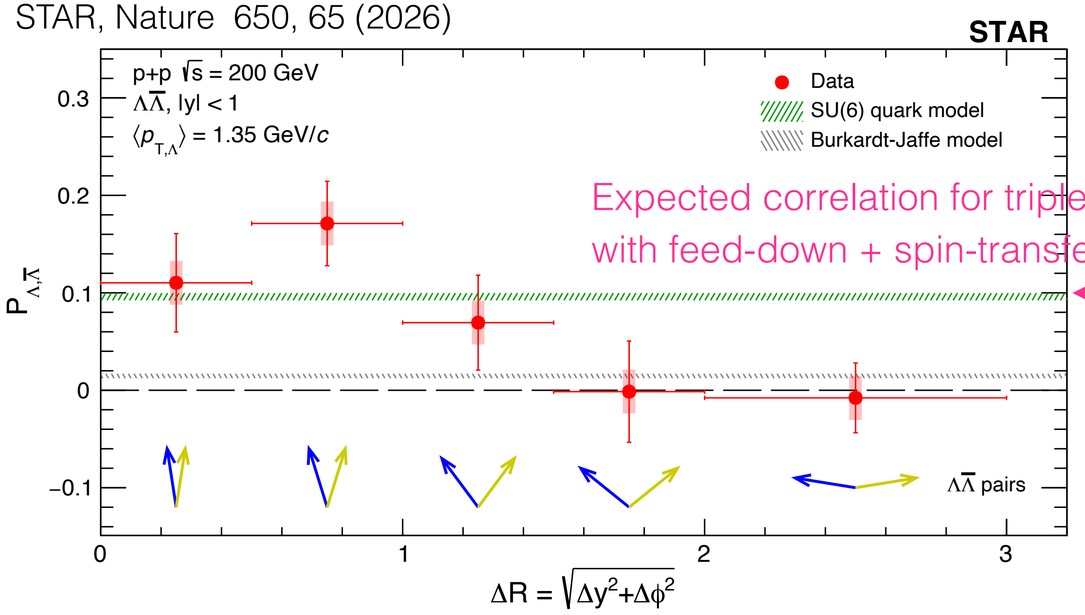
Ellis, Kharzeev, and Kotzinian, Z.Phys.C69, 467 (1996)

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STAR, Nature 650, 65 (2026)



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- Positive $\Lambda\bar{\Lambda}$ spin correlation at short small pair separation, consistent with zero at large separation (no significant correlation for identical pairs)
- New results in pp/pPb at LHC energy from CMS show different behavior

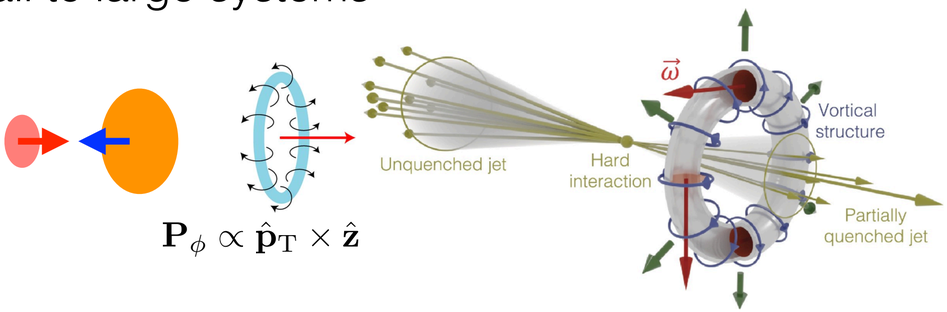
Zhenyu Chen, Oct. 27(Tue)

Summary and Outlook

- Observations of hyperon global and local polarization and vector meson spin alignment open new directions in the study of QCD matter and spin dynamics in heavy-ion collisions
- Substantial progress has been made in both experimental and theoretical studies but still many questions remain open

  - Precision measurements of Ω polarization to study spin dependence
  - Spin-spin correlation in heavy-ion collisions
  - Connection to QCD phase structure
    - Enhanced spin correlation near QCD CP? Phase diagram under rotation
  - Search for toroidal vortex
  - Polarization phenomena from small to large systems

H.-L. Chen et al., PRL135, 032302 (2025)
Y. Jiang and J. Liao, PRL117.192302(2016)
Y. Fujimoto et al., PLB816(2021)136184



S. Voloshin, EPJ Web Conf.171, 07002 (2018)
W. M. Serenone et al., PLB820 (2021) 136500
M. Lisa et al., PRC104, L011901 (2021)
Chinellato et al., Phys. Rev. C110, 054908 (2024)

Backup

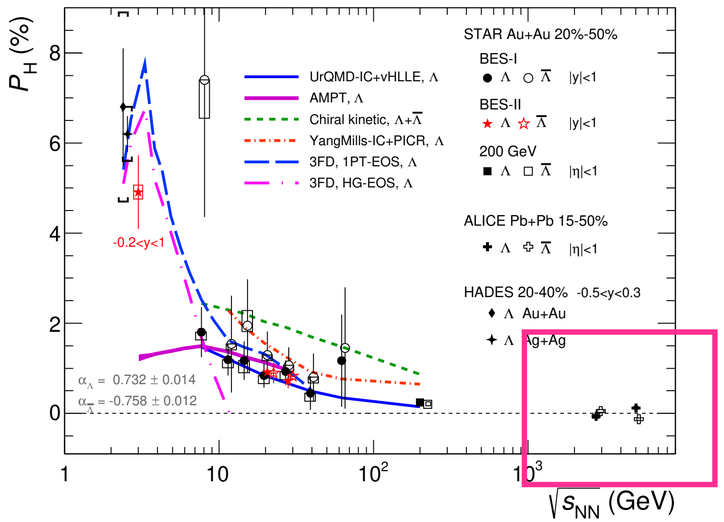
Λ global polarization vs. $\sqrt{s_{NN}}$

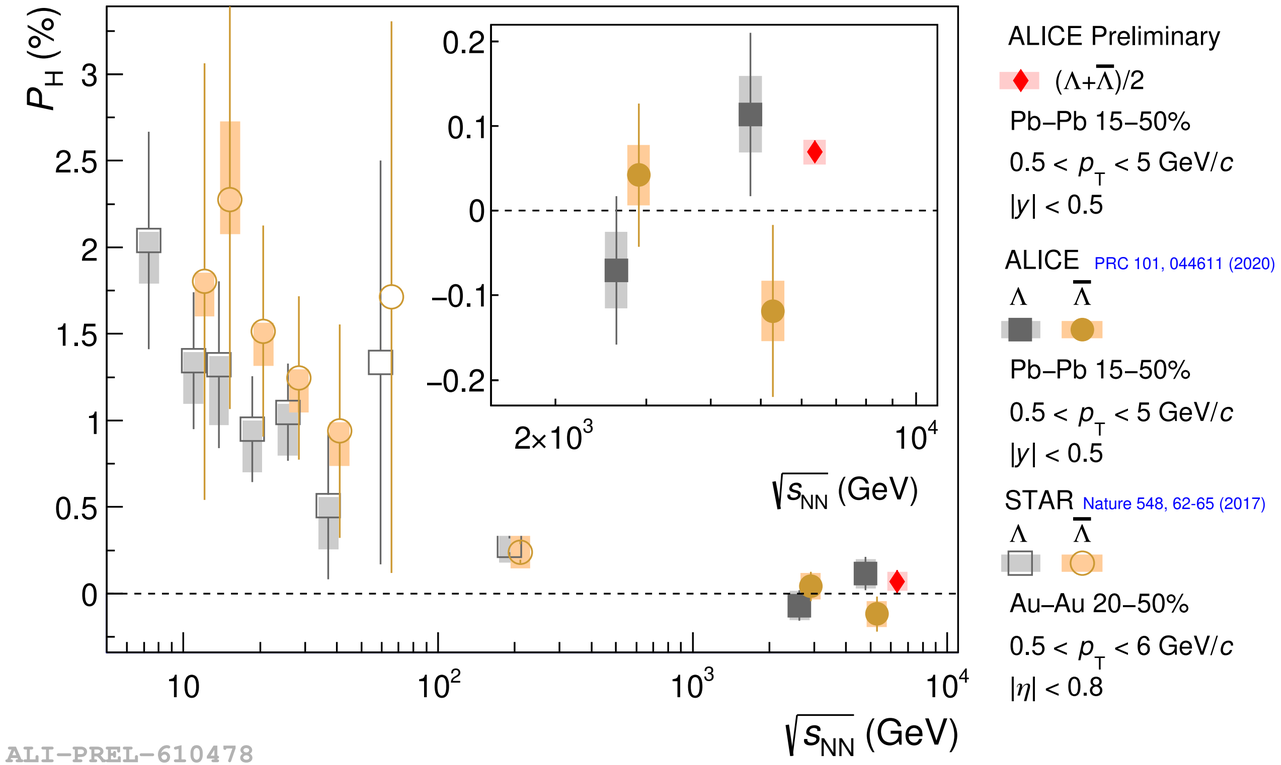
P. Das (ALICE), SPIN2025

Recent reviews

F.Becattini, M.Buzzegoli, TN, S.Pu, A.Tang, Q.Wang, Int.J.Mod.Phys.E33(2024)2430

TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010





- New ALICE result at 5.36 TeV shows P_Λ ~ 0.07% with 5σ significance
- Empirical estimate with directed flow: P_H^{LHC} ~0.05-0.1%

S. Voloshin, EPJ Web Conf.171, 07002 (2018)

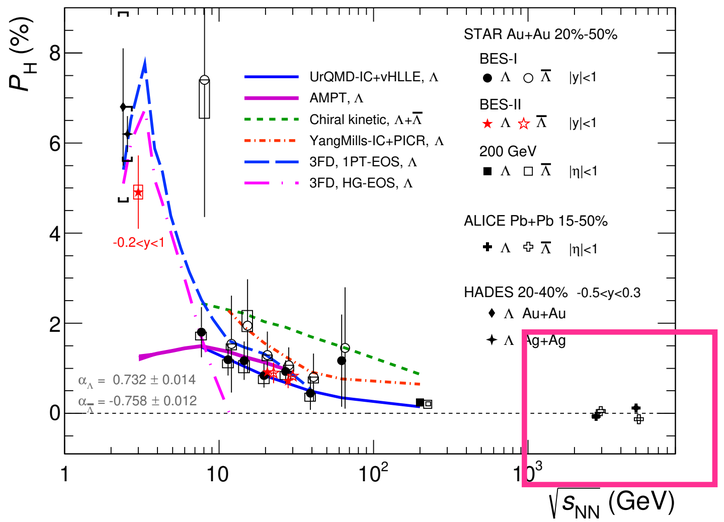
Λ global polarization vs. $\sqrt{s_{NN}}$

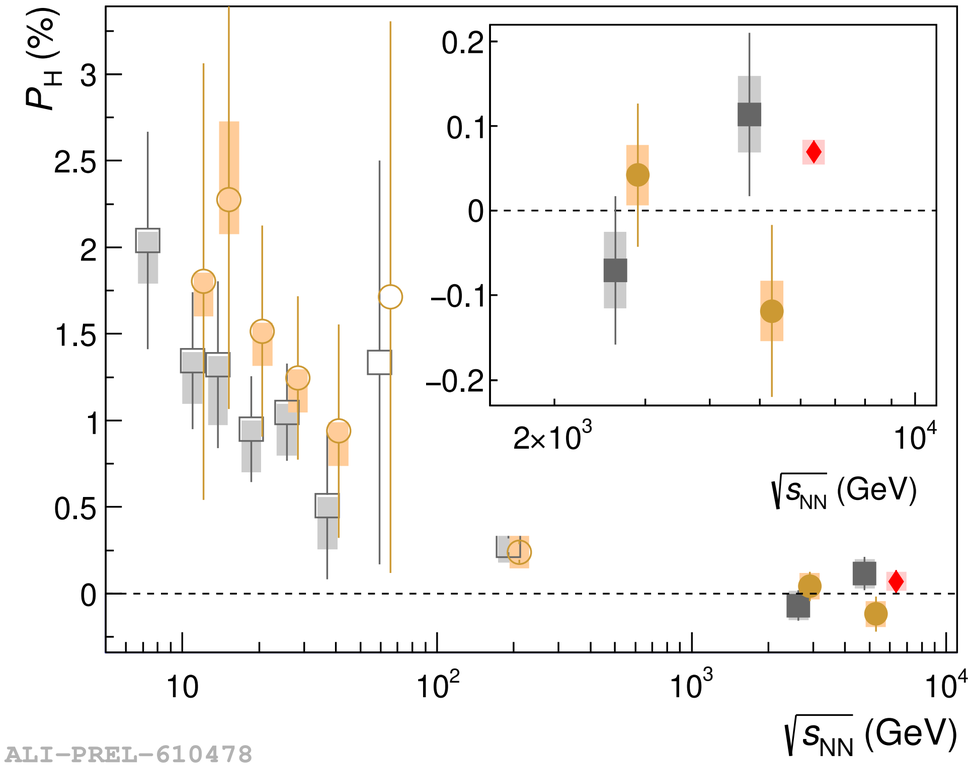
P. Das (ALICE), SPIN2025

Recent reviews

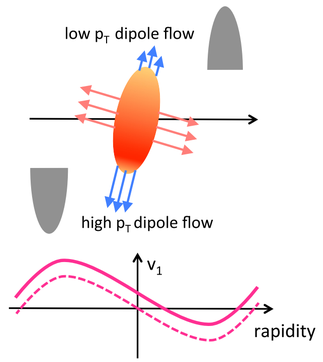
F.Becattini, M.Buzzegoli, TN, S.Pu, A.Tang, Q.Wang, Int.J.Mod.Phys.E33(2024)2430

TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010





(b) tilted source
+ asymmetric density gradient



STAR, PRC98.014915 (2018)

- Tilted source with longitudinal expansion can explain both v_1 and vorticity

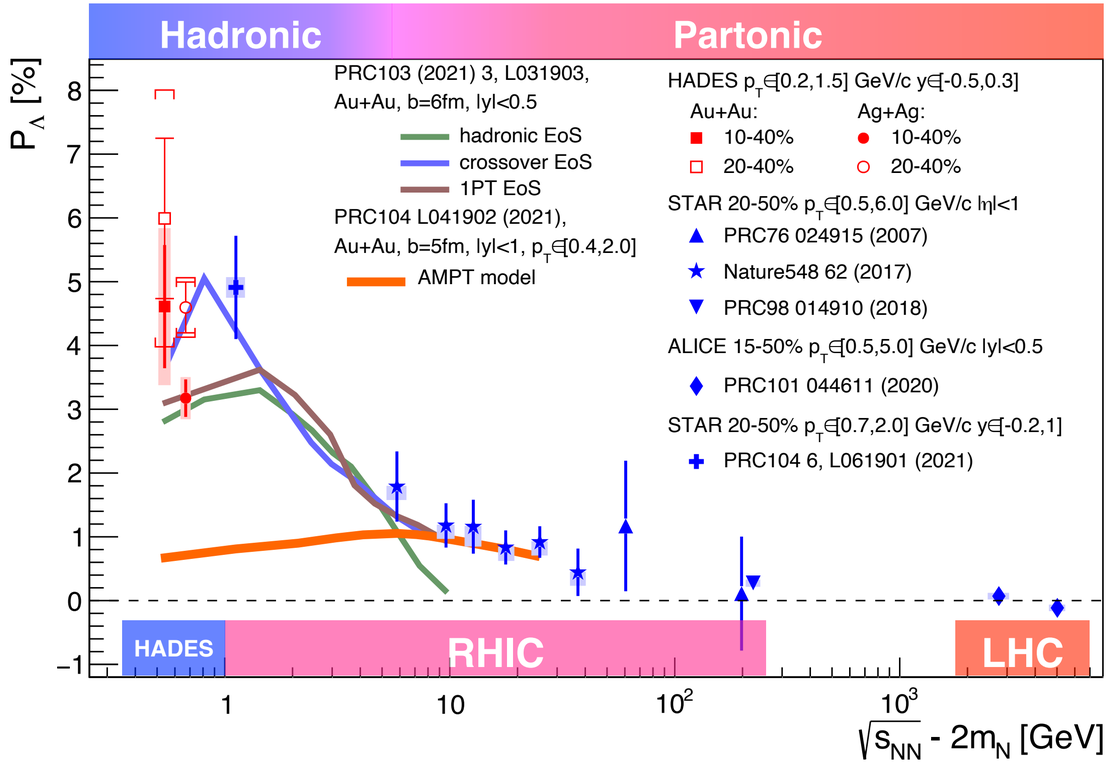
F. Becattini et al., Eur. Phys. J. C (2015)75:406

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S. Voloshin, EPJ Web Conf.171, 07002 (2018)

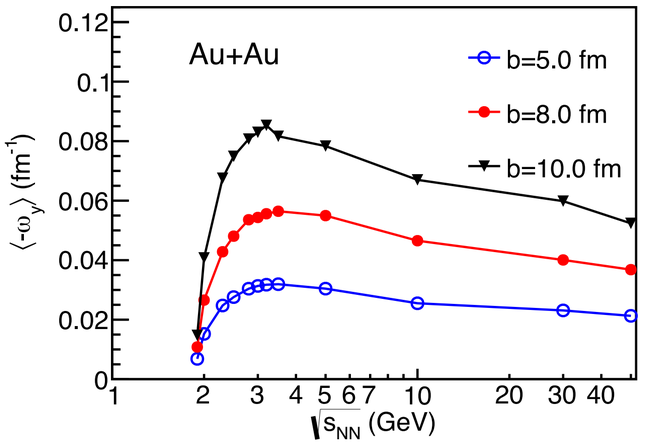
Λ global polarization at lower energies

STAR, PRC104, L061901 (2021)
HADES, PLB835(2022)137506

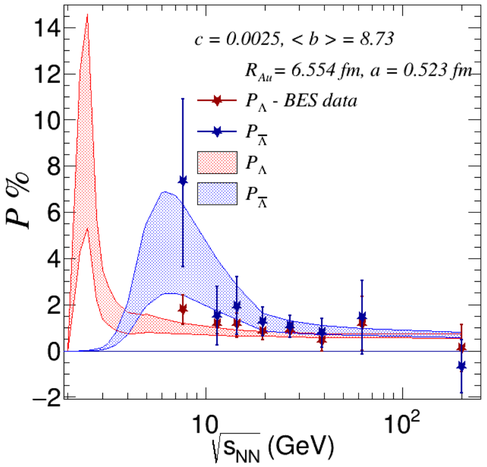


- New data from STAR/HADES at lower energies
- Continuous increase down to $\sqrt{s_{NN}}$~2.5 GeV
  - Predicted to have the maximum around $\sqrt{s_{NN}}$ = 3 GeV
    - Initial L & “stopping” to “transparency” at midrapidity

X.-G. Deng et al., PRC101.064908 (2020)



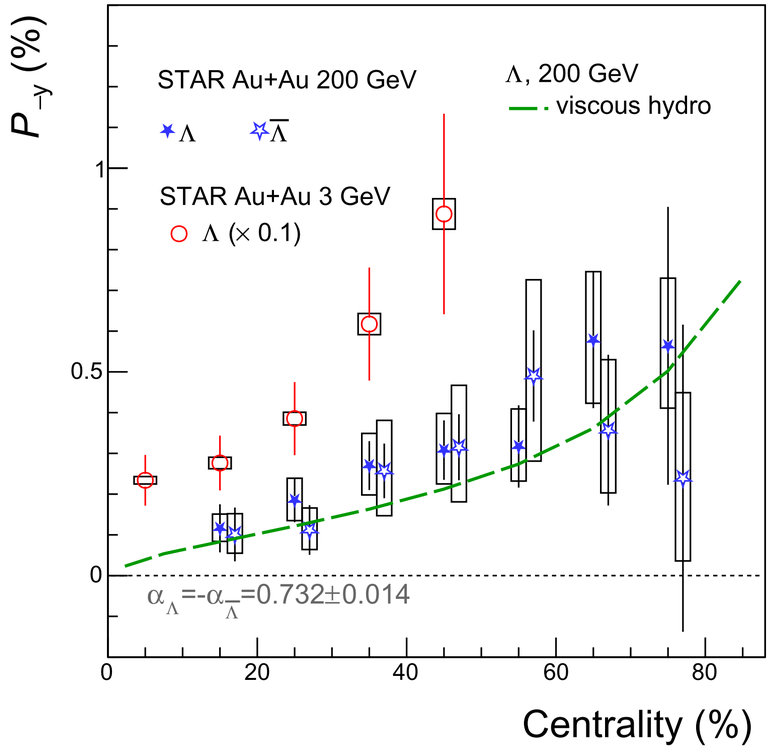
A. Ayala et al., PRC105.034907 (2022)

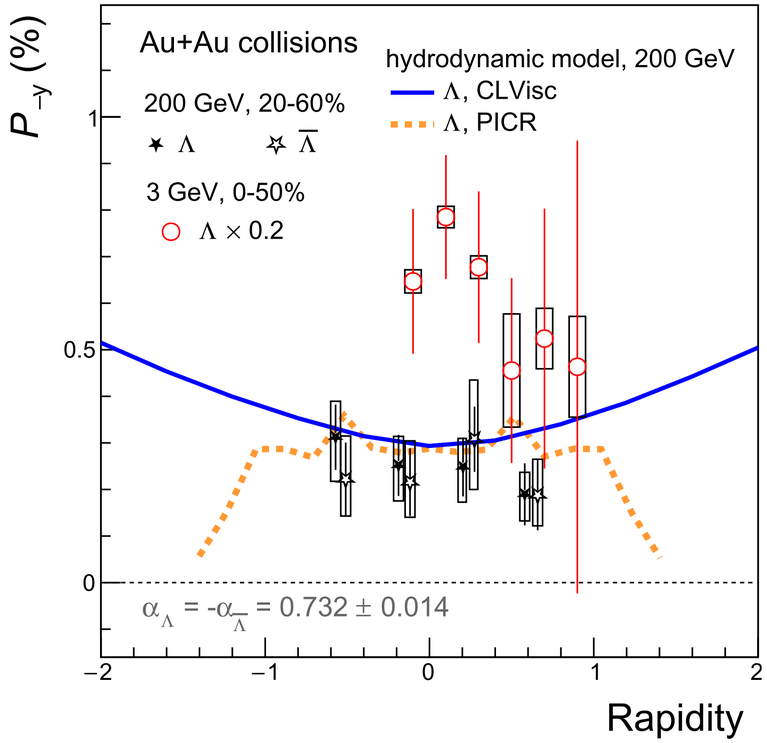


Centrality and rapidity dependence

Data: STAR, PRC98.014910(2018), PRC104.L061901(2021)
Models: S.Ryu et al., PRC104.054908(2021), H.Wu et al., PRRes.1033058(2019)

Figures: TN and S.Voloshin, Int.J.Mod.Phys.E33(2024)2430010

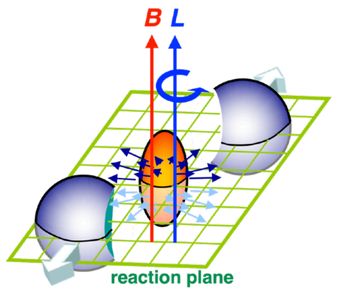


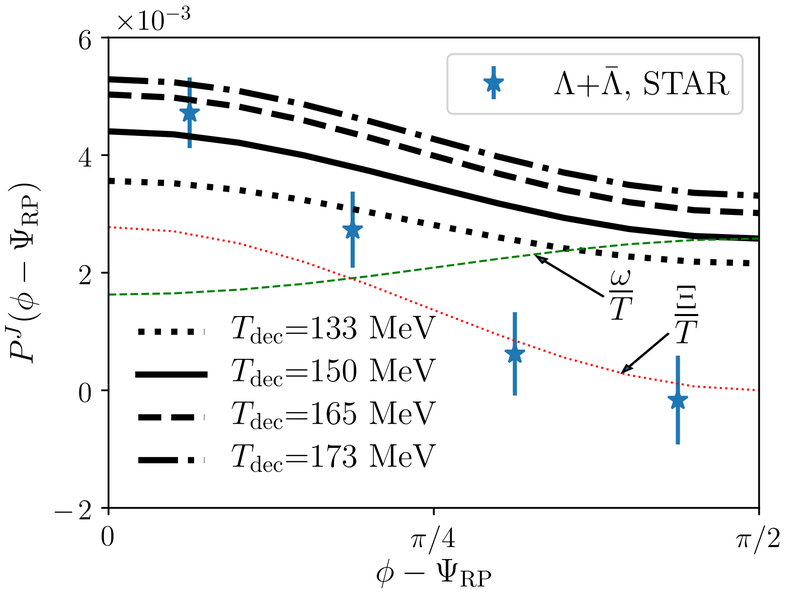


- Clear centrality dependence as expected from b-dependence of the initial *L*
- Rapidity dependence predicted differently. Still large uncertainty in the data

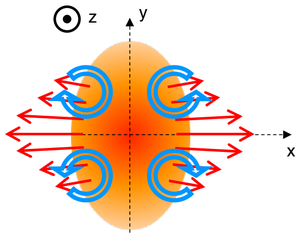
Spin sign puzzle

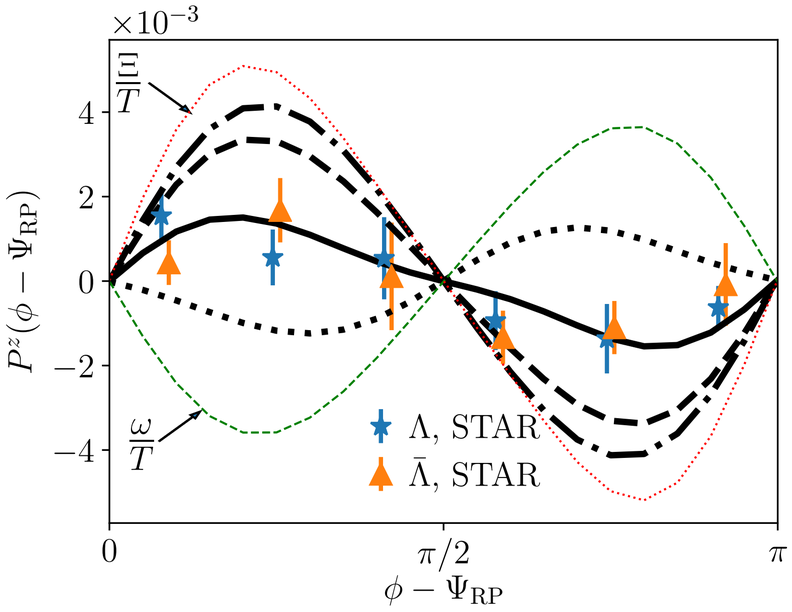
$P_J = P_y$





P_z





vorticity: $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$

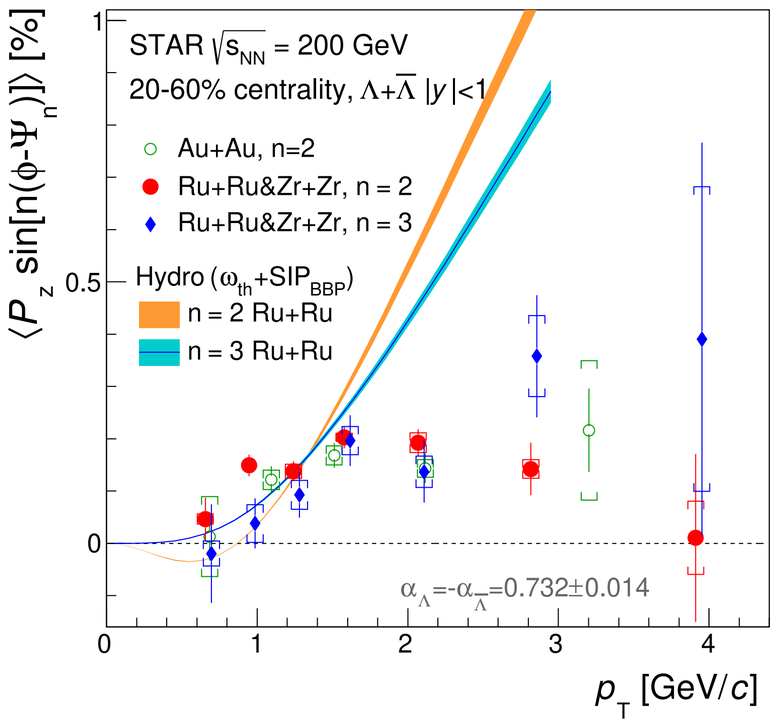
shear: $\Xi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho + \partial_\rho u_\sigma)$

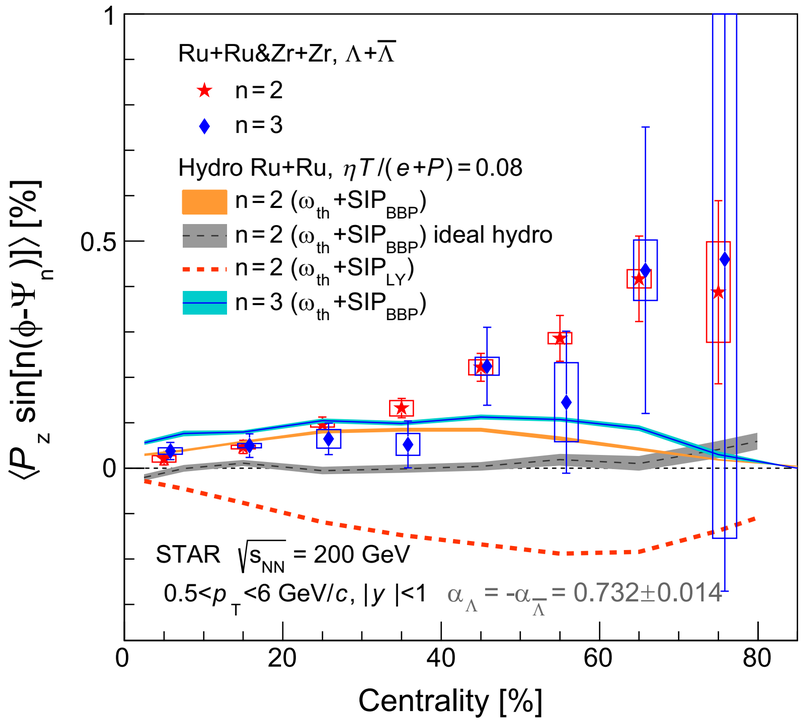
- Thermal vorticity can explain the “global” (average) polarization but not the sign of P_z or P_y modulation, referred to as “spin sign puzzle” in HIC
  - Non-equilibrium effect? Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
- Shear-induced polarization is needed to explain the data but…

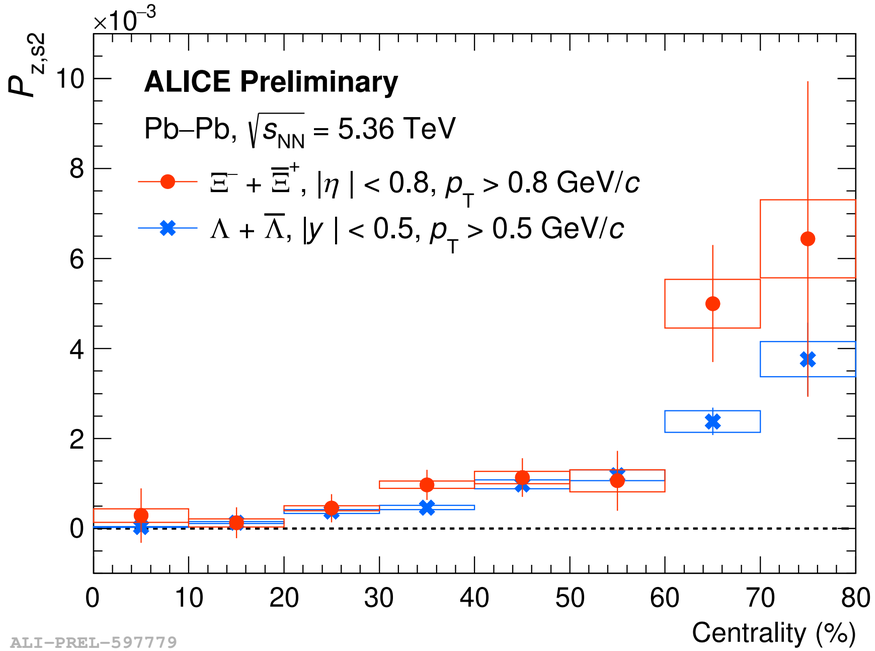
S. Liu, Y. Yin, JHEP07(2021)188
B. Fu et al., PRL127, 142301 (2021)
F. Becattini et al., PLB820(2021)136519
F. Becattini et al., PRL127, 272302 (2021)

More plots on $P_{z,2}$

STAR, PRL131, 202301 (2023)







- Similar p_T dependence to v_n, further supporting anisotropic-flow-driven polarization
- Sensitive to specific shear and bulk viscosities, and the initial conditions
- New measurement with Ξ hyperons at the LHC

Y. Sun and C.-M. Ko, PRC99, 011903(R) (2019)
S. Alzharani et al., PRC106.014905 (2022)
A. Palermo et al., EPJ Web Conf. 276 (2023) 01026

How to measure polarization for 3-body decay like Λ_c?

LHCb, JHEP07(2023)228

$$\Lambda \to p + \pi^-$$

$$\Lambda_c^+ \to p + K^- + \pi^+ \quad \text{(BR~6.37\%)}$$

Because of 3-body decay, the decay cannot be simply characterized by one parameter like α_Λ

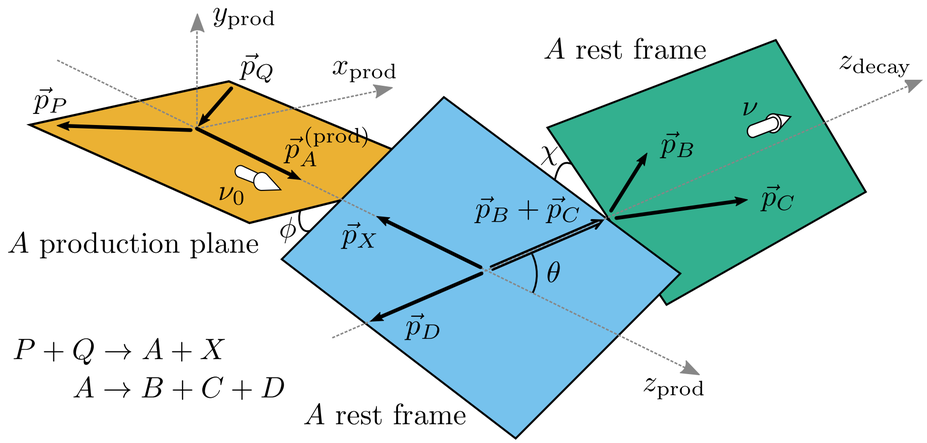
$$\frac{\Phi}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi} \propto 1 + \vec{P}\cdot\vec{h}\,,$$

$$\vec{h} = R(\phi,\theta,\chi)\vec{\alpha}\,,$$

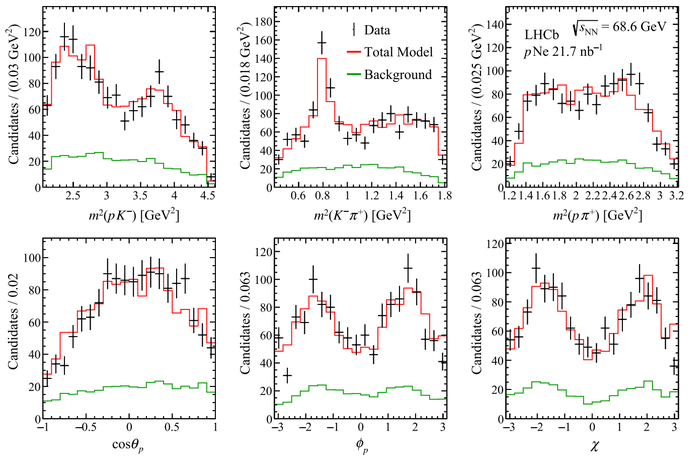
Γ : decay rate

$\vec{h}$: polarimeter vector

Φ : Lorentz–invariant phase space



Momentum distributions of 3 final-state particles carry the information of Λ_c spin

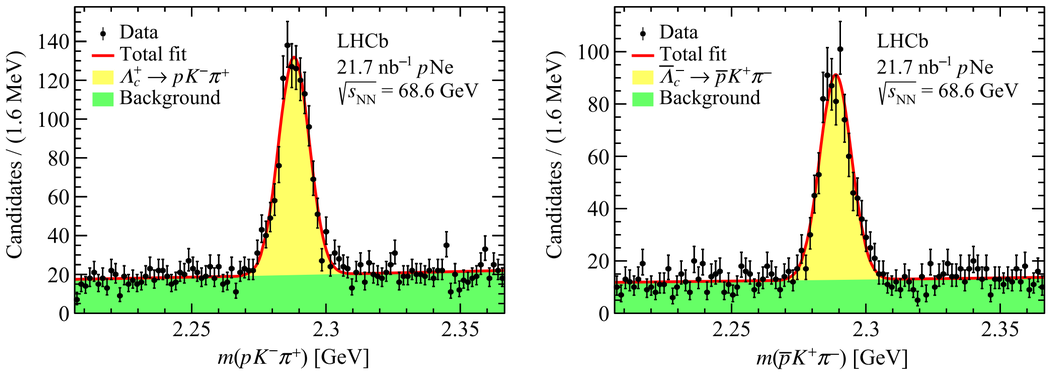


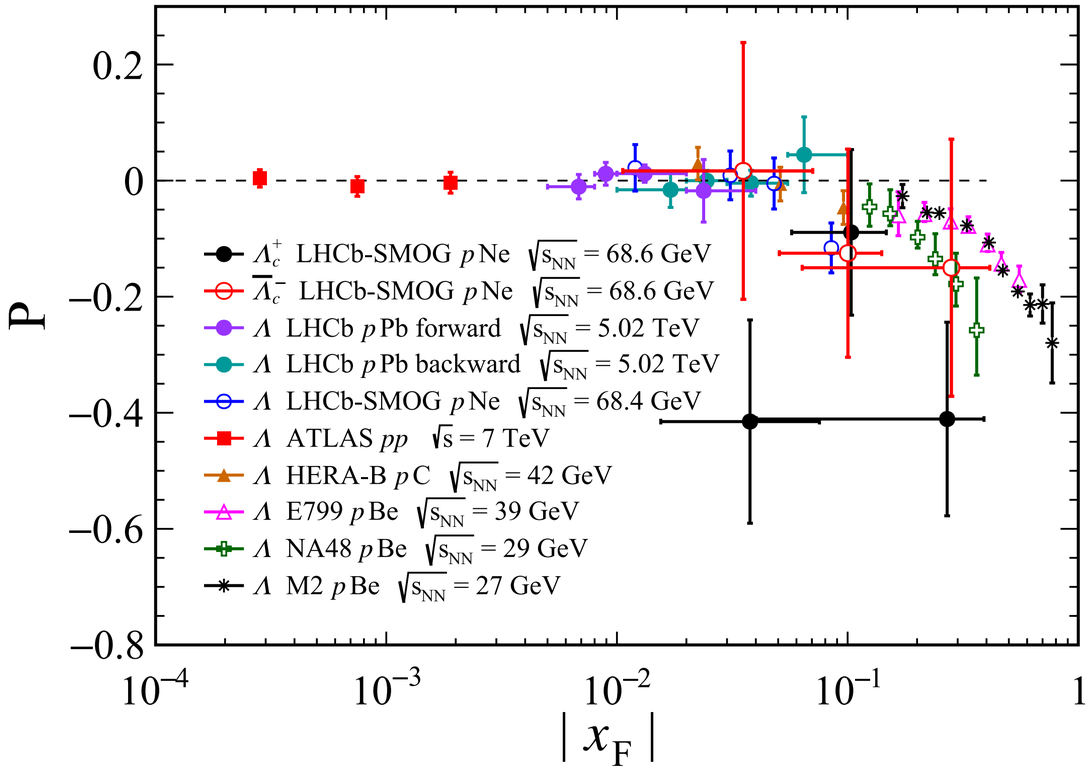
LHCb, PRL137.091901(2026)

The Dalitz plot reveals the resonant substructure of the three-body decay, which determines how sensitive each phase-space region is to the Λ_c polarization

Λ_c^+ transverse polarization

LHCb, PRL137, 091901 (2026)





- First separate measurement of Λ_c^+ and Λ_c^- transverse polarization in p+Ne at $\sqrt{s_{NN}}$ = 68.6 GeV

$$P_{\Lambda_c^+} = (24 \pm 9 \pm 2)\%,\ P_{\bar{\Lambda}_c^-} = (-8 \pm 12 \pm 3)\%$$

  - Polarization extracted from 5D amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$

- First study of x_F dependence of charmed-baryon polarization