重离子碰撞自旋理论综述

浦实
中国科学技术大学

第一届强相互作用自旋物理会议，青岛

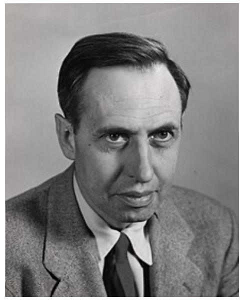
2026.07.27

Discovery of spin in physics

This year marks the 101th anniversary of the discovery of spin and the 21th anniversary of the proposal for spin polarization in relativistic heavy-ion collisions.

Wolfgang Pauli

Ralph Kronig



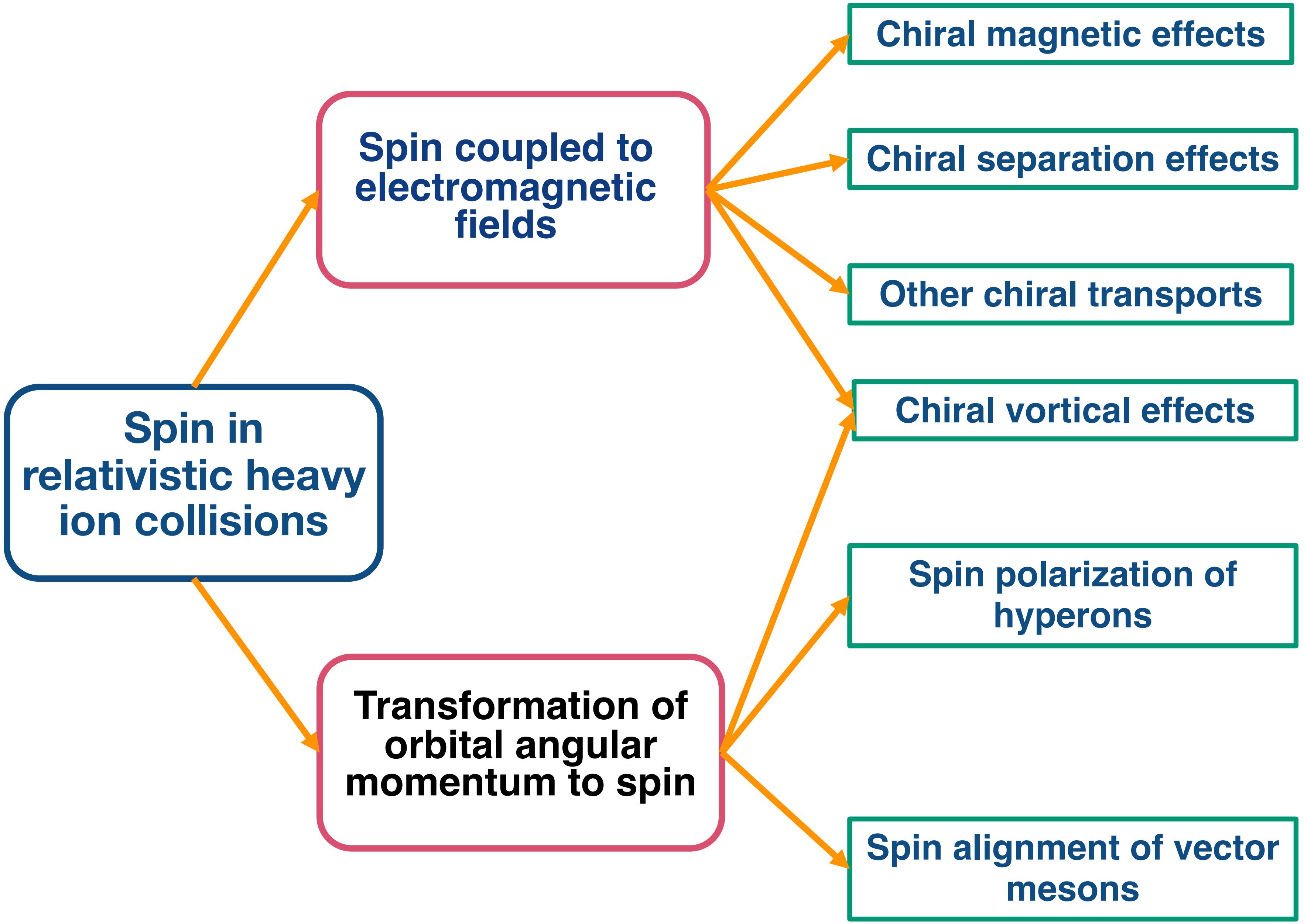
George Uhlenbeck

Samuel Goudsmit

Llewellyn H. Thomas

Wolfgang Pauli

1924	1925	1925	1926	1927
two valued -ness not describable classically	self-rotation of the electron	Published the first paper on spin	Thomas procession	spin in quantum mechanics

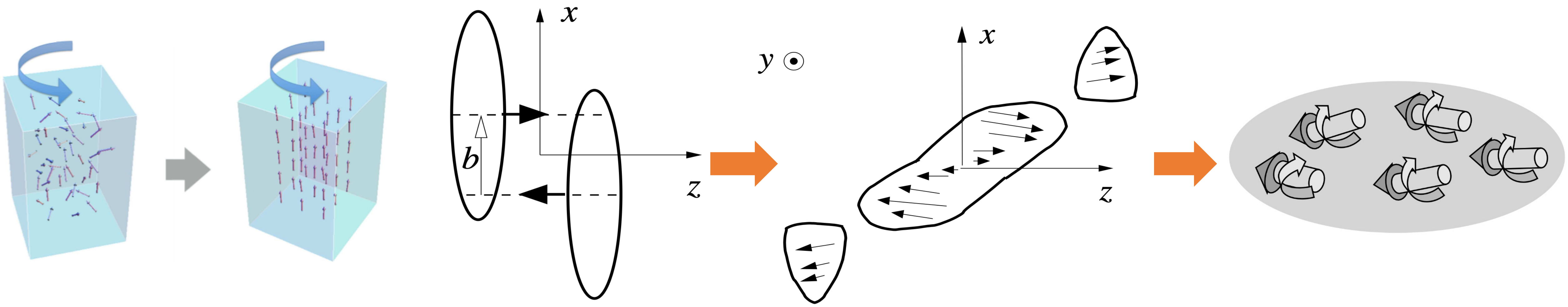

Spin in relativistic heavy ion collisions
Spin coupled to electromagnetic fields
Transformation of orbital angular momentum to spin
Chiral magnetic effects
Chiral separation effects
Other chiral transports
Chiral vortical effects
Spin polarization of hyperons
Spin alignment of vector mesons

Outline

- Global polarization
- Local polarization
- Spin alignment
- Spin correlation
- Summary

Global polarization

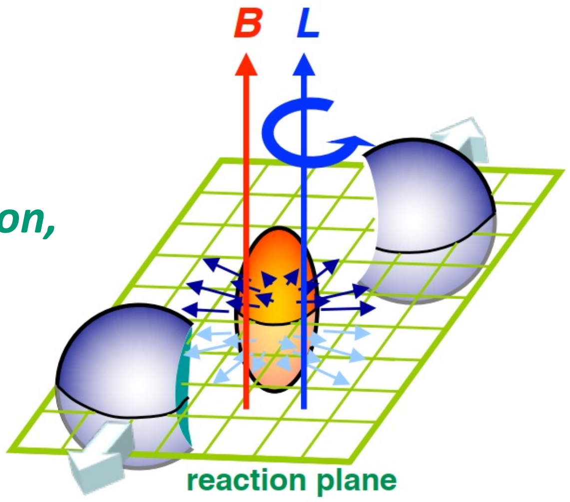
Spin polarization in heavy-ion collisions



Barnett effect:

Rotation $\Longrightarrow$ Magnetization

Barnett, Magnetization by rotation, Phys Rev. (1915) 6:239–70.

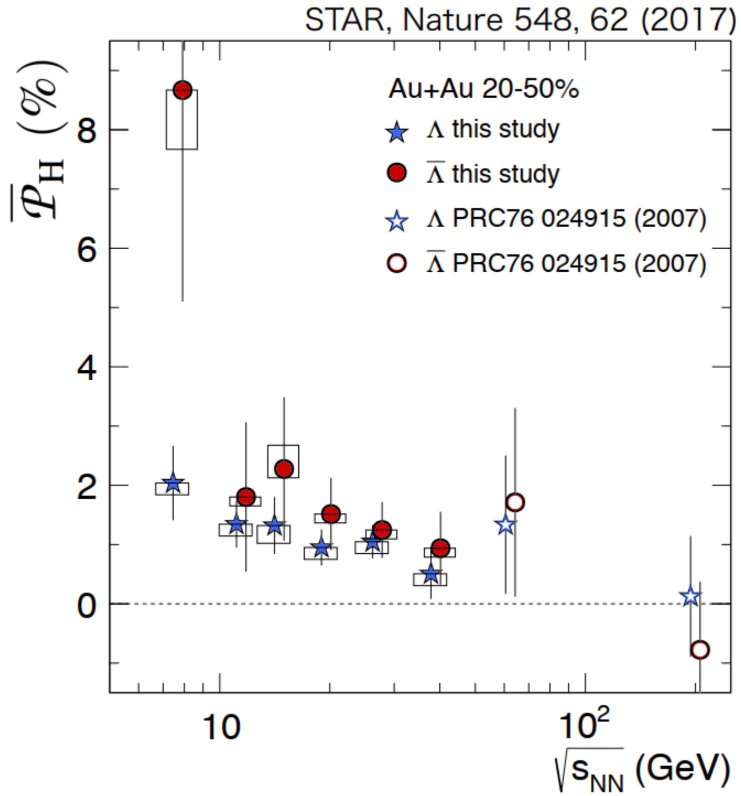


- **Huge global orbital angular momenta ($L\sim10^5\hbar$) are produced in HIC.**

- **Global orbital angular momentum leads to the polarizations of Λ hyperons and spin alignment of vector mesons through spin-orbital coupling.**

  Liang, Wang, PRL (2005); PLB (2005);
  Gao, Chen, Deng, Liang, Wang, Wang, PRC (2008)

Global polarization for Λ and $\bar{\Lambda}$ hyperons



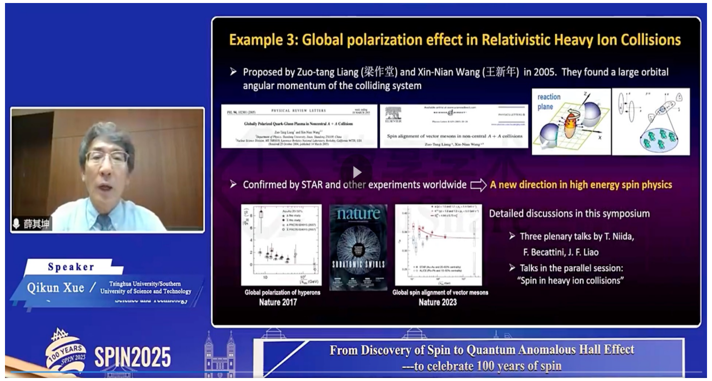
Estimation given by Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC (2017)

$$\mathbf{P}_{\Lambda} \simeq \frac{\omega}{2T} + \frac{\mu_{\Lambda}\mathbf{B}}{T}$$

$$\mathbf{P}_{\bar{\Lambda}} \simeq \frac{\omega}{2T} - \frac{\mu_{\Lambda}\mathbf{B}}{T}$$

ω = (9 ± 1)x10^{21}/s, greater than previously observed in any system.

QGP is most vortical fluid so far.



One of the most important discoveries in spin physics in China.

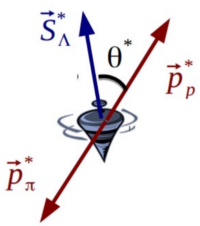
相对论重离子碰撞中的整体极化现象是中国高能自旋物理中最重要的发现之一。

parity-violating decay of hyperons

In case of Λ's decay, daughter proton preferentially decays in the direction of Λ's spin (opposite for anti-Λ)

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

α: Λ decay parameter (=0.642±0.013)
P_{Λ}: Λ polarization
p_p^*: proton momentum in Λ rest frame

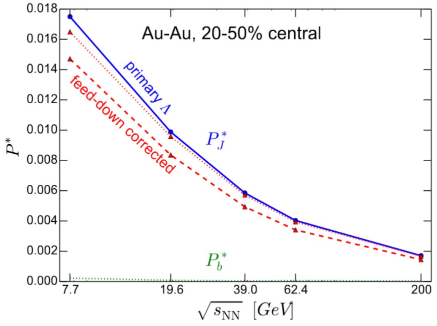


$\Lambda \to p + \pi^+$
(BR: 63.9%, cτ~7.9 cm)

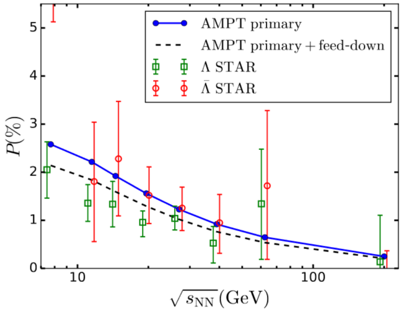
Liang, Wang, PRL (2005)
Betz, Gylulassy, Torrieri, PRC (2007)
Becattini, Piccinini, Rizzo, PRC (2008)
Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC (2017)
Fang, Pang, Q. Wang, X. Wang, PRC (2016)
...

Phenomenological models for global polarization

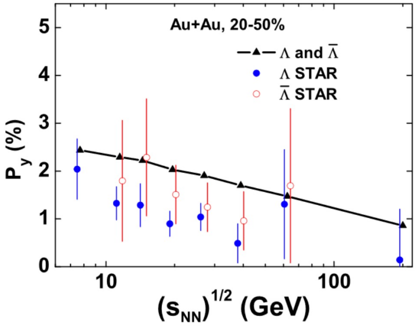
Global polarization can be well described by thermal vorticity at high and medium collision energies.



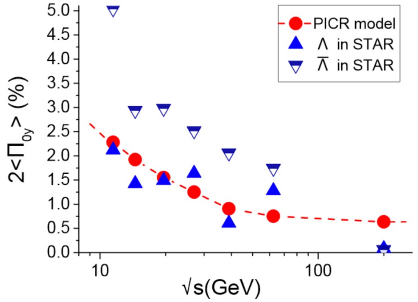
Karpenko, Becattini, EPJC(2017)



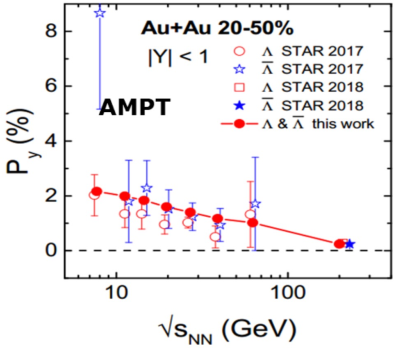
Li, Pang, Wang, Xia PRC(2017)



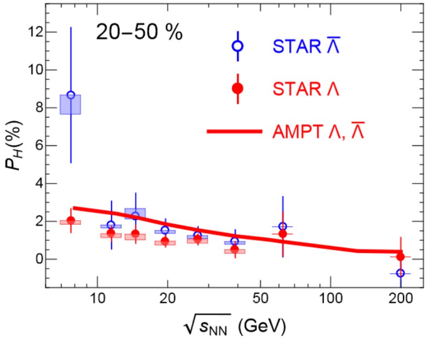
Sun, Ko, PRC(2017)



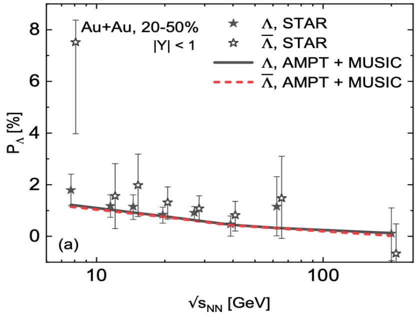
Xie, Wang, Csernai, PRC(2017)



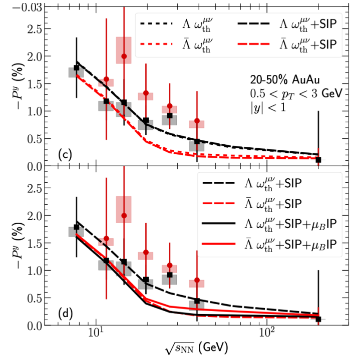
Wei, Deng, Huang, PRC(2019)



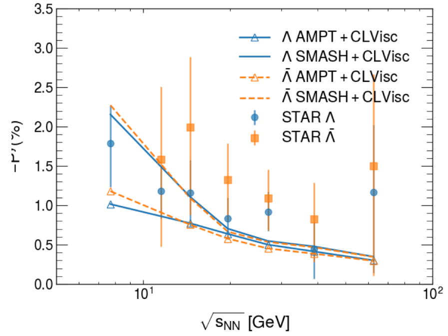
Shi, Li, Liao, PLB(2018)



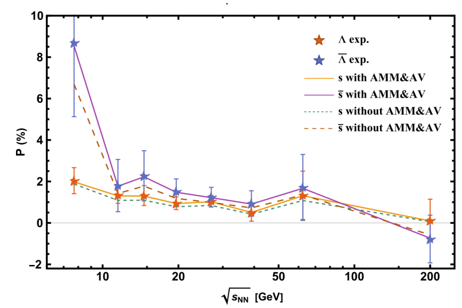
Fu, Xu, Huang, Song, PRC (2021)



S. Ryu, V. Jupic, C. Shen, PRC (2021)

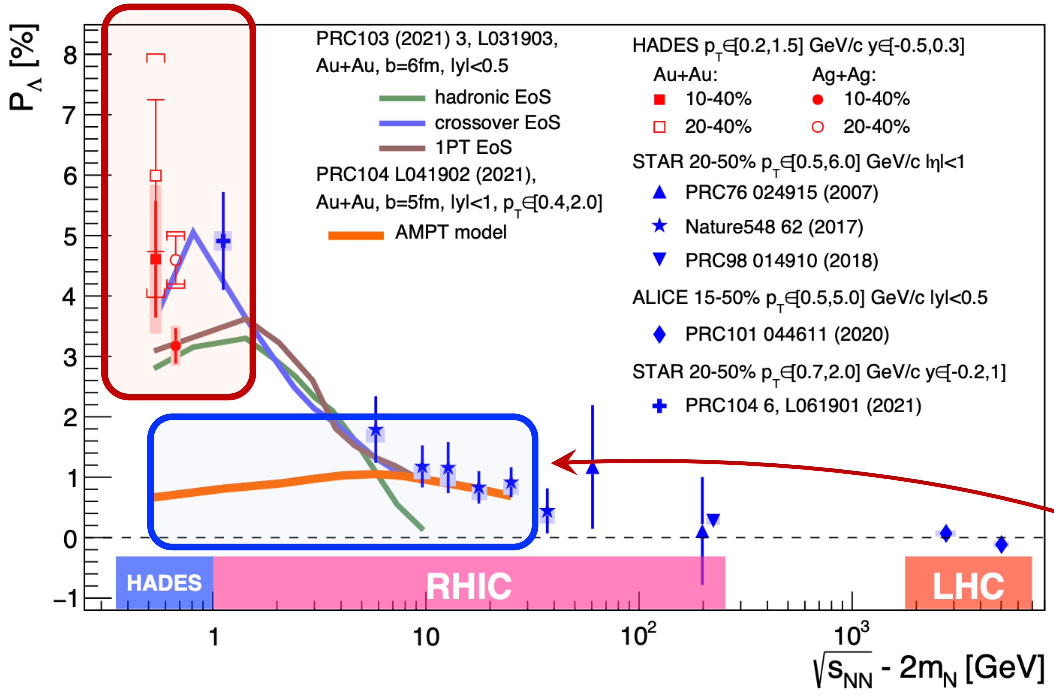


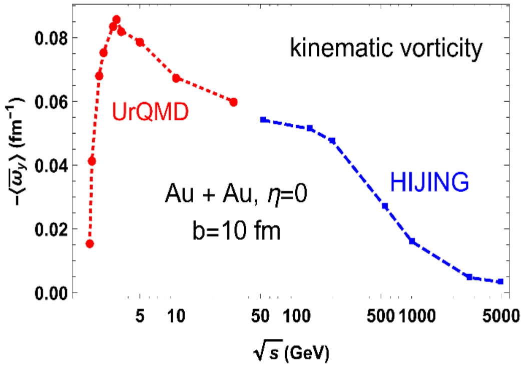
Y.X. Wu, C. Yi, G.Y. Qin, SP, PRC (2022)



Xu, Lin, Huang, Huang, PRDL (2022)

Puzzle: Global polarization at low energies





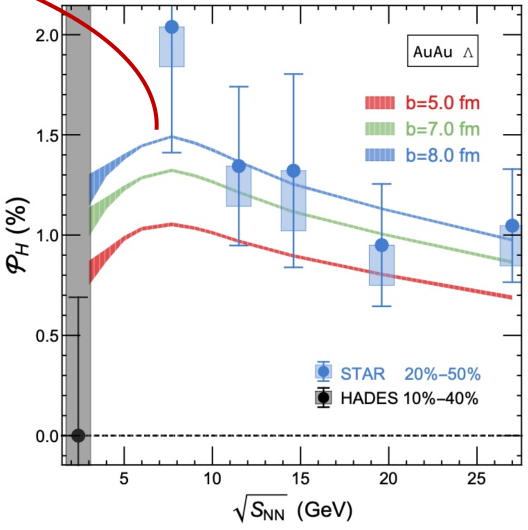
Deng, Huang PRC 2016, PRC 2020

Summary of previous studies:

- The peak for vorticity is around 3 GeV.
- The peak for global polarization is around 3 - 7 GeV.
- The amplitude for global polarization is much less than observed in experiments.

Low energy collisions:
Hadron gas
Kinetic approaches
? Puzzles

High energy collisions:
Quark gluon plasma
Hydrodynamics approaches
✓ Well described



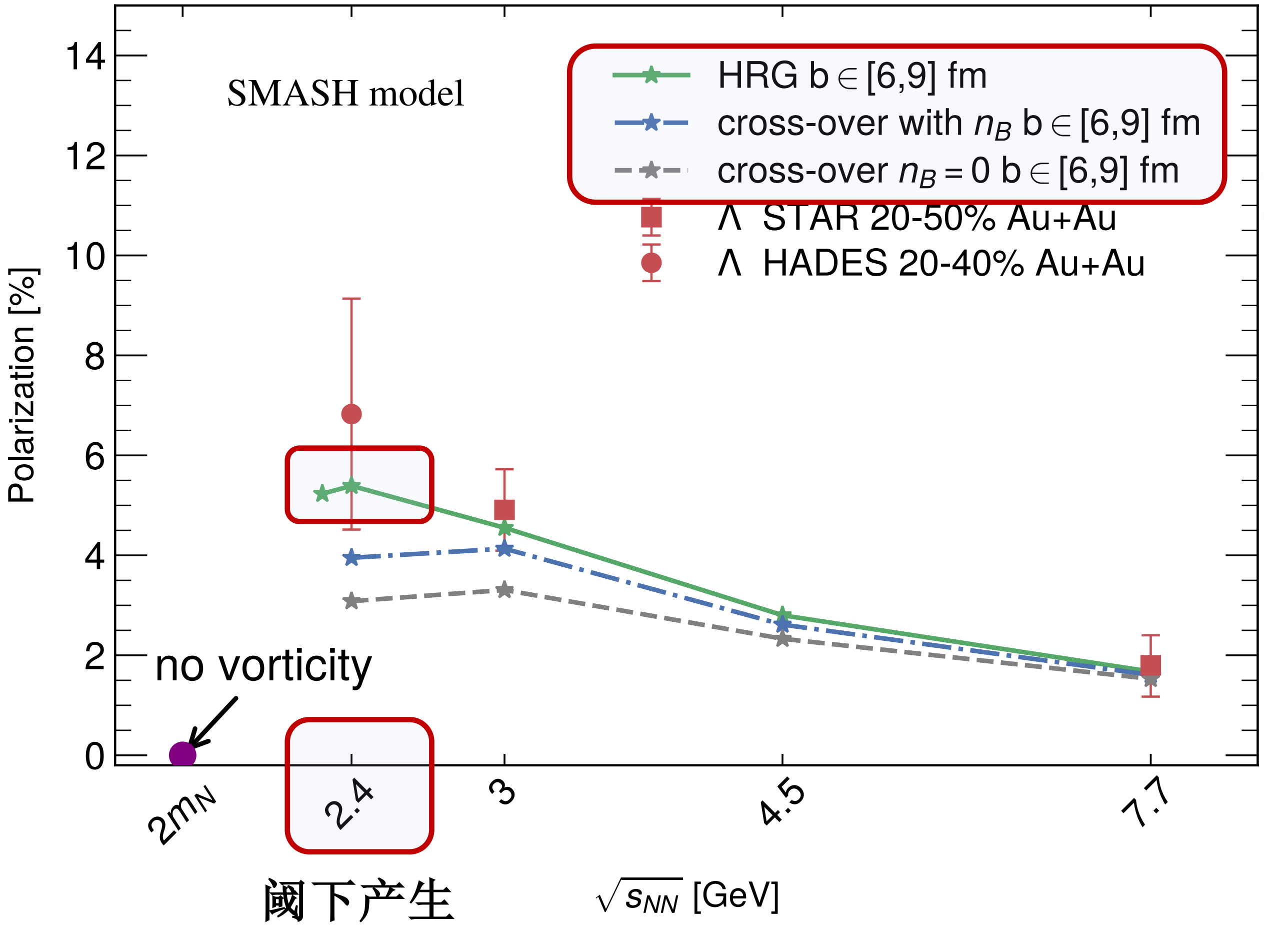
Sun Xu et al., Acta Phys. Sin. 72(7), 072401 (2023)
HADES, Phys. Lett. B (2022) 137506

Guo, Liao, et. al, PRC 2021

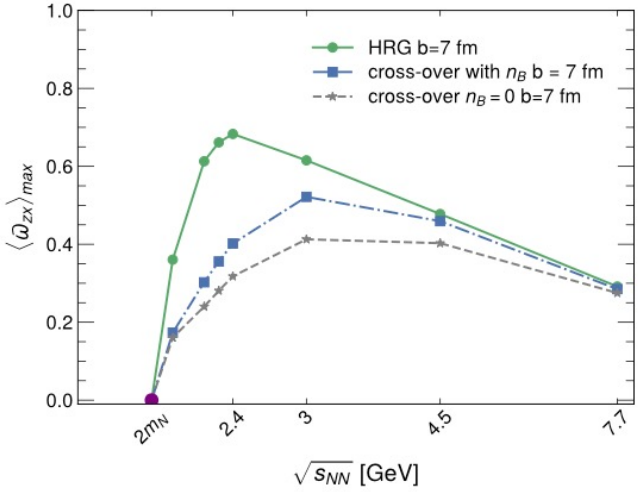
Puzzle:

- Kinetic approach fails to describe the global polarization at low energy collisions?
- New possible effects or mechanism in low energy collisions?

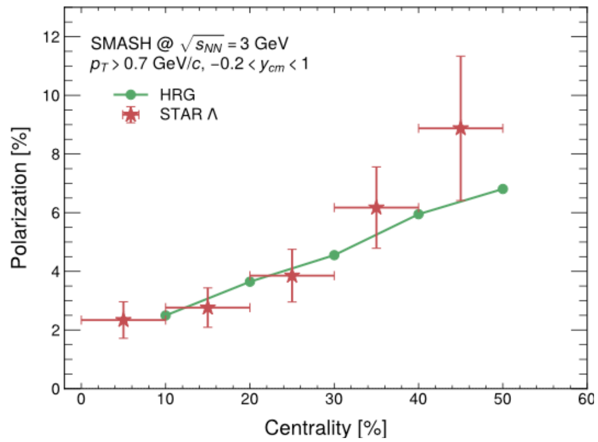
Revisited global polarization at low energies



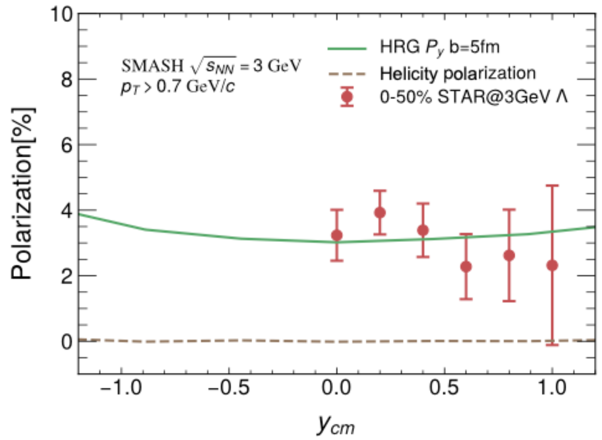
Cong Yi, SP, L.G. Pang, G.Y. Qin, Xin-nian Wang, arXiv:2603.27521



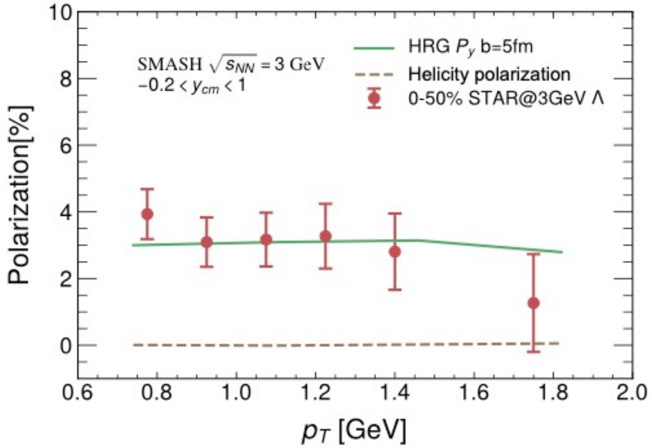
Averaged thermal vorticity



Centrality dependence

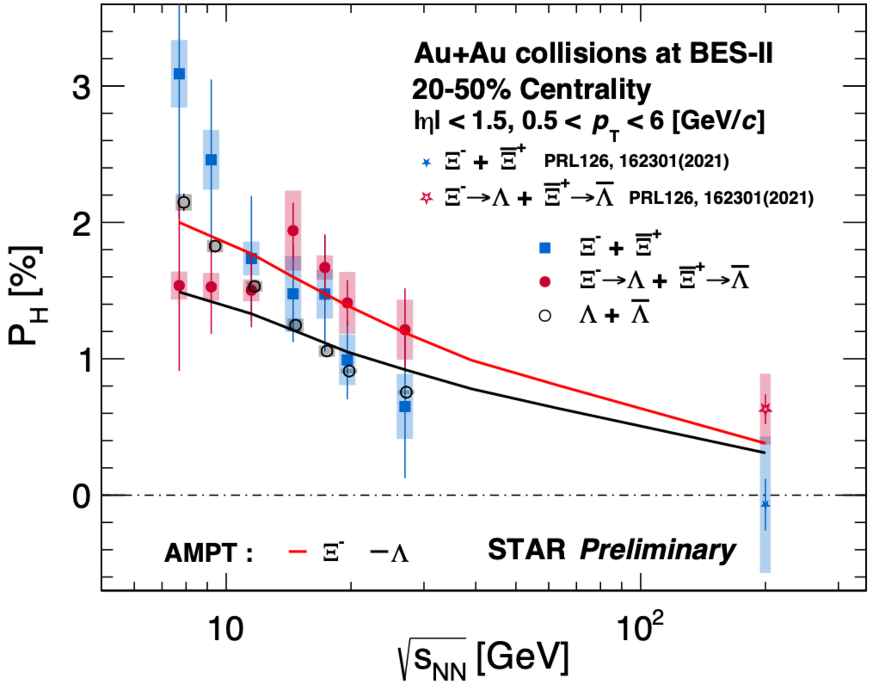


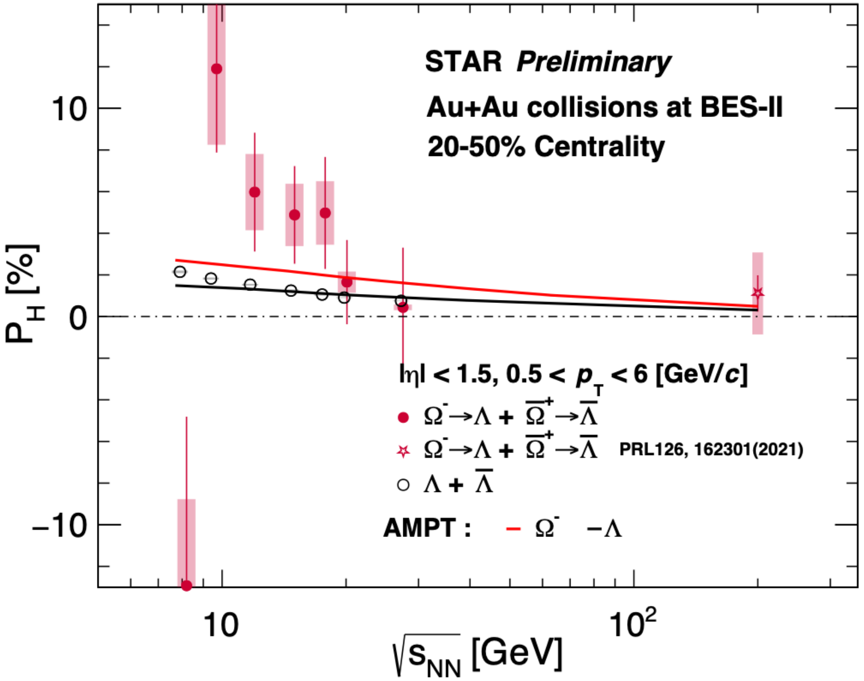
Rapidity dependence

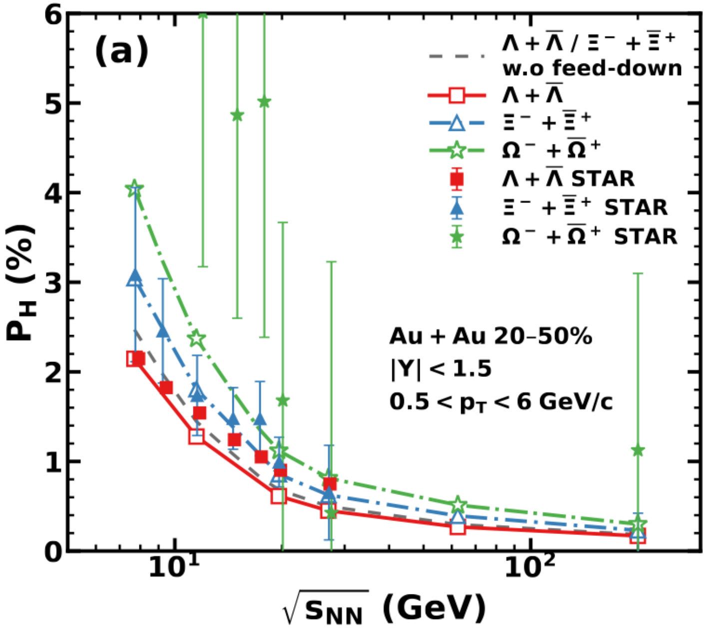


pT dependence

Global polarization for other hyperons (I)







In the quark model,

$$P_\Lambda \cong P_s$$

assuming that $P_{u,d} \sim P_s$, one can get

$$P_\Sigma \sim P_\Lambda,\ P_\Xi \sim P_\Lambda,\ P_\Omega \sim \frac{5}{3} P_\Lambda$$

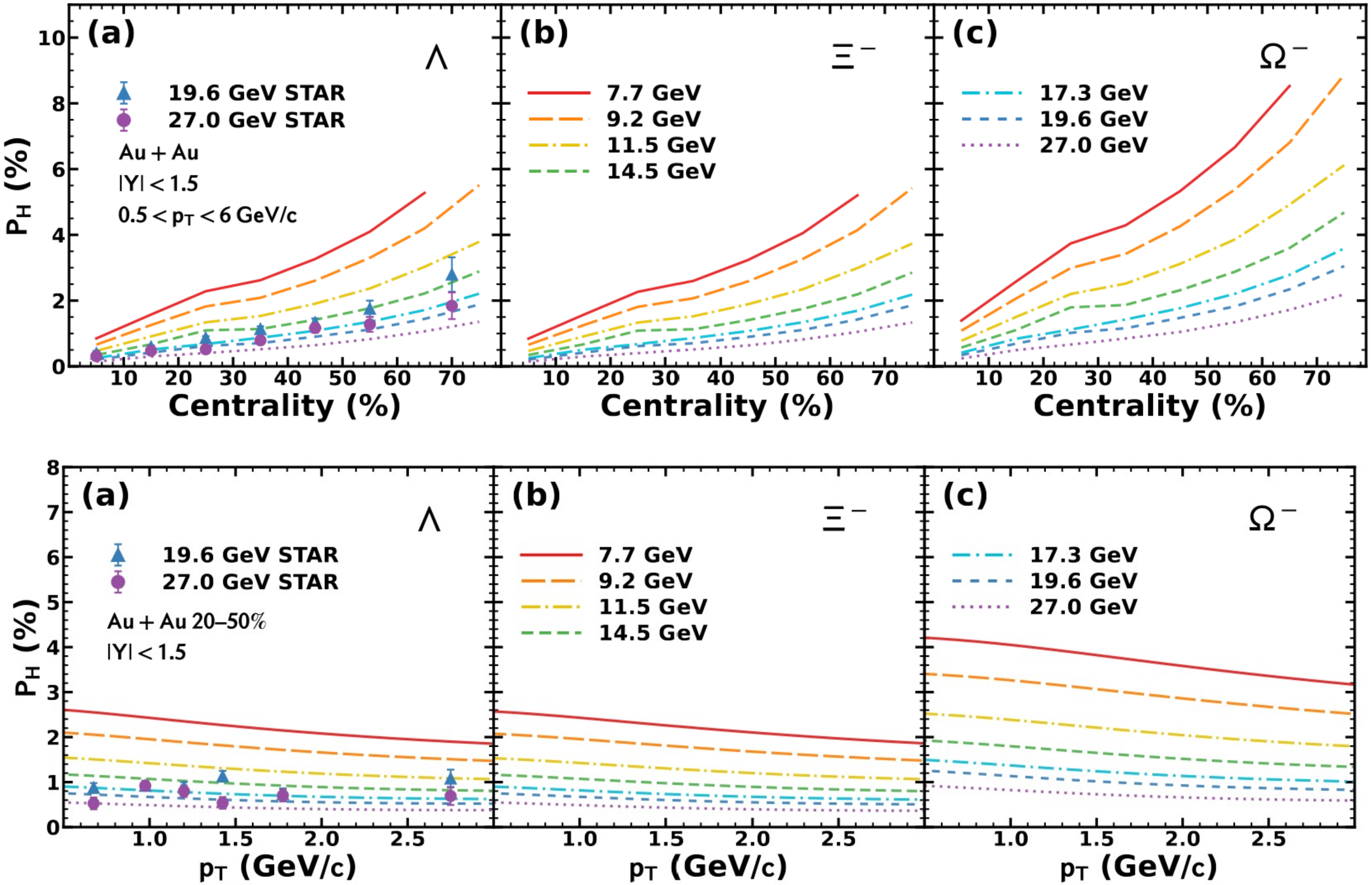
Liang, Wang, PRL (2005)
Also see:
Li, Xia, Huang, Huang, PLB (2022)

First measurement in BES-II energy:

- No significant difference between Ξ and Λ global polarization
- Hint of larger global polarization of Ω than Λ hyperon

G.H. Li, C. Yi, X.Y. Wu, Q.Y. Qin, SP, arXiv: 2606.10341

Global polarization for other hyperons (II)

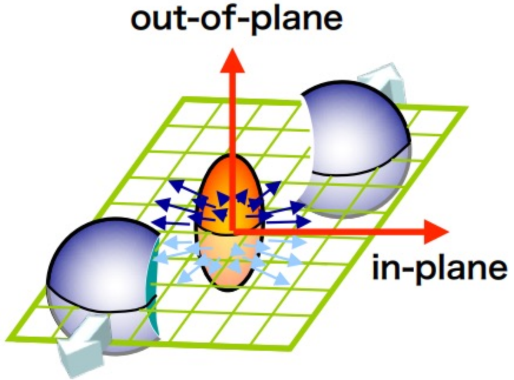


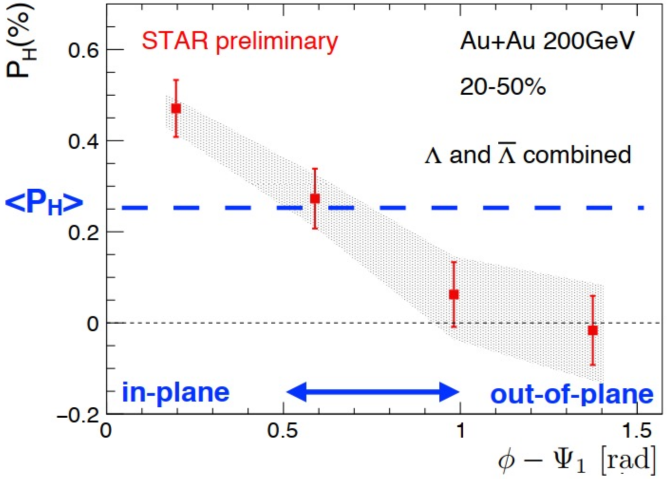
Theoretical prediction for 7.7 – 27 GeV:

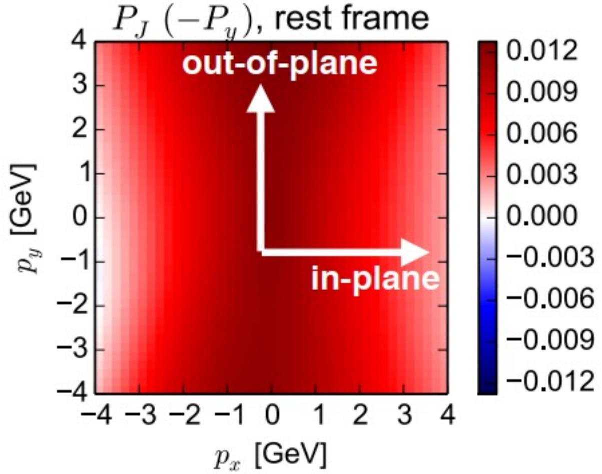
G.H. Li, C. Yi, X.Y. Wu, Q.Y. Qin, SP, arXiv: 2606.10341

Local polarization

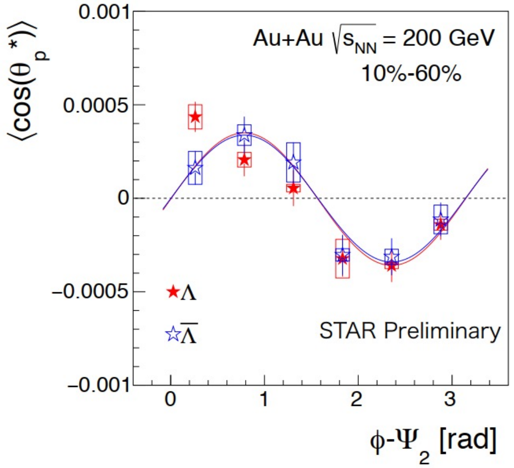
Local polarization and sign problem

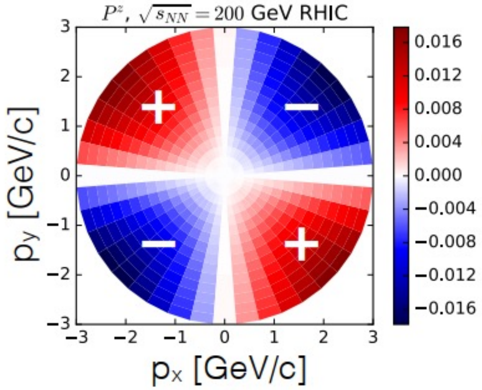


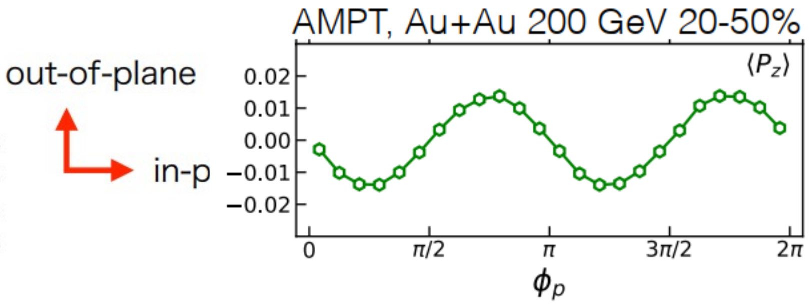




STAR, PRL 123, 132301 (2019)







- **UrQMD :** Becattini, Karpenko, PRL (2018)
- **AMPT:** Xia, Li, Tang, Wang, PRC (2018)

Polarization and axial current

- **The polarization tensor is connected to the axial current in phase space by modified Cooper-Frye formula**
  Karpenko, Becattini, EPJC. (2017); Fang, Pang, Wang, Wang, PRC (2016)

$$\mathcal{S}^{\mu}(\mathbf{p})=\frac{\int d\Sigma\cdot p\boxed{\mathcal{J}_{5}^{\mu}(p,X)}}{2m_{\Lambda}\int d\Sigma\cdot\mathcal{N}(p,X)},$$

Polarization pseudo-vector ~ Spin tensor in phase space

- **The expression for the spin tensor in phase space can be computed using statistical quantum field theory, quantum kinetic theory, Kubo formula and other effective theories.**

Becattini's group, Rischke's group, Florkowski's group, …
Chinese groups:
Xin-Nian Wang @ CCNU, Zuo-Tang Liang @ SDU, Peng-fei Zhuang @ THU, Qun Wang, SP @ USTC, Mei Huang, Feng Li @ CAS, Xu-Guang Huang, Li Yan @ Fudan, Yin Yi @ CUHK, Huichao Song @ PKU, Defu Hou @CCNU, Jianhua Gao @ SDU, Shu Lin @ SYSU, Shuai Liu @ HNU, …

Polarization induced by different sources

$$\mathcal{S}^\mu(\mathbf{p}) = \mathcal{S}^\mu_{\mathrm{thermal}} + \mathcal{S}^\mu_{\mathrm{shear}} + \mathcal{S}^\mu_{\mathrm{accT}} + \mathcal{S}^\mu_{\mathrm{chemical}} + \mathcal{S}^\mu_{\mathrm{EB}}$$

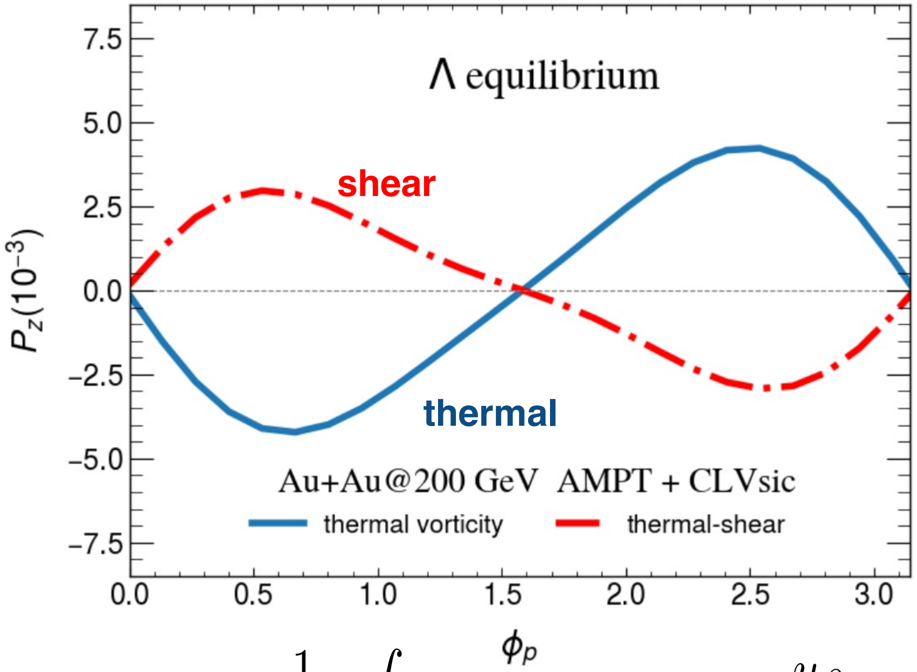
Polarization induced by	Thermal vorticity	Shear viscous tensor	Fluid acceleration	Gradient of chemical potential	Electromagnetic fields

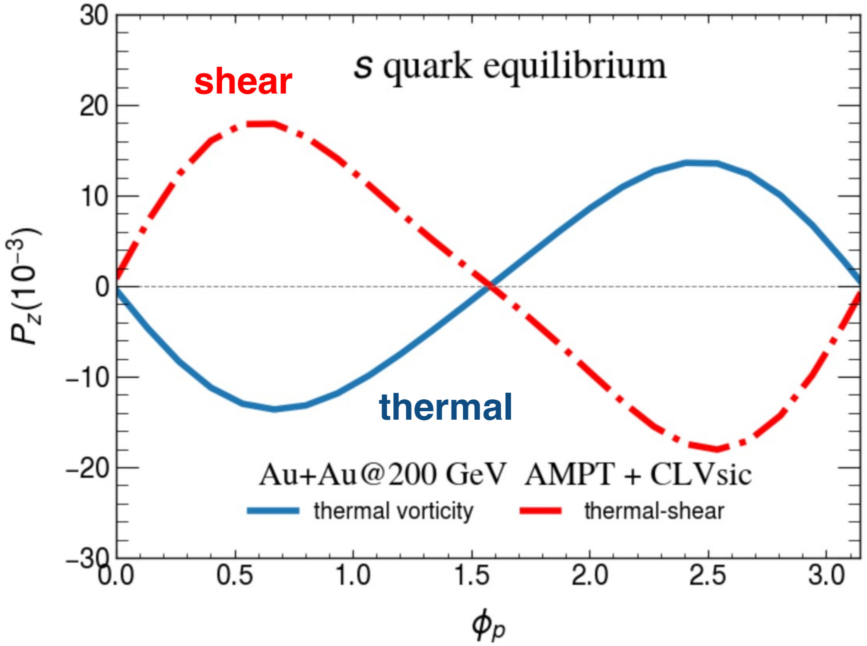
Yi, SP, Yang, PRC (2021); Wu, Yi, Qin, SP, PRC (2022); Hidaka, SP, Yang, PRD (2018)

Polarization induced by	
Thermal vorticity 热涡旋	$\mathcal{S}^\mu_{\mathrm{thermal}}(\mathbf{p}) = \frac{\hbar}{8m_\Lambda N}\int d\Sigma^\sigma p_\sigma f_V^{(0)}(1-f_V^{(0)})\boxed{\epsilon^{\mu\nu\alpha\beta}p_\nu\partial_\alpha\frac{u_\beta}{T}},$
Shear viscous tensor 剪切粘滞张量	$\mathcal{S}^\mu_{\mathrm{shear}}(\mathbf{p}) = -\frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta}{(u\cdot p)T}\frac{1}{2}\boxed{\{p^\sigma(\partial_\sigma u_\nu+\partial_\nu u_\sigma)-Du_\nu\}}$
Fluid acceleration 流体加速	$\mathcal{S}^\mu_{\mathrm{accT}}(\mathbf{p}) = -\frac{\hbar}{8m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{1}{T}\epsilon^{\mu\nu\alpha\beta}p_\nu u_\alpha\boxed{\left(Du_\beta-\frac{1}{T}\partial_\beta T\right)},$
Gradient of chemical potential 化学势/温度梯度	$\mathcal{S}^\mu_{\mathrm{chemical}}(\mathbf{p}) = \frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta\boxed{\partial_\nu\frac{\mu}{T}},$
Electromagnetic fields 电磁场	$\mathcal{S}^\mu_{\mathrm{EB}}(\mathbf{p}) = \frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\left(\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta\boxed{E_\nu+\frac{B^\mu}{T}}\right)$

Shear induced polarization: s quark scenario

s quark equilibrium: The spin of Λ hyperons is assumed to be primarily carried by the constituent s quark. One needs to take the s quark's mass instead of mass of *Λ* in the simulation. **Fu, Liu, Pang, Song, Yin, PRL 2021**





$$\mathcal{S}^{\mu}_{\text{thermal}} \propto \frac{1}{\boxed{m_N}} \int d\Sigma \cdot p \ldots \epsilon^{\mu\nu\alpha\beta} p_\nu \partial_\alpha \frac{u_\beta}{T},$$

$$\mathcal{S}^{\mu}_{\text{shear}} \propto \frac{1}{\boxed{m_N}} \int d\Sigma \cdot p \ldots \frac{1}{\boxed{(u \cdot p)}} \epsilon^{\mu\nu\alpha\beta} \ldots$$

Also see:

Yi, Pu, Yang, PRC (2021);

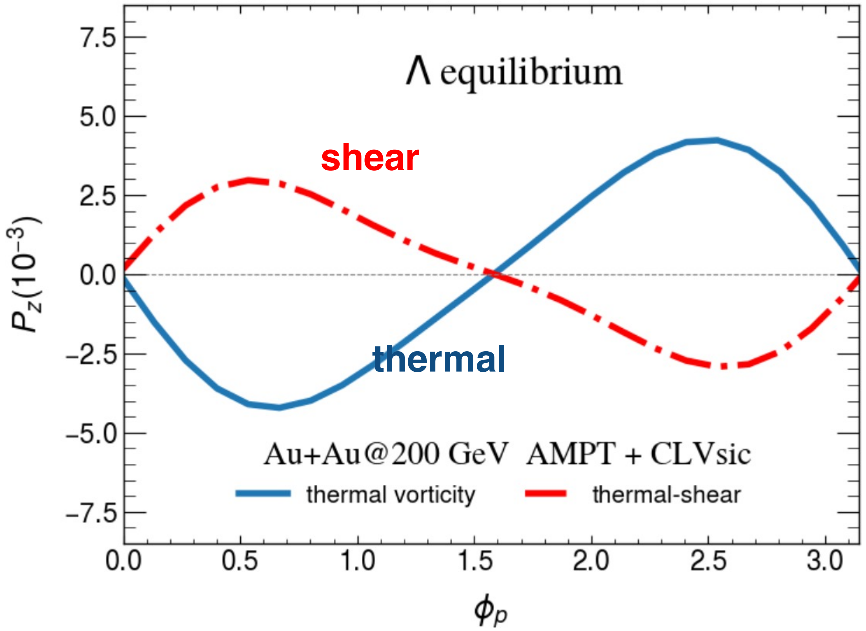
Yi, Wu, Qin, Pu, PRC (2022);

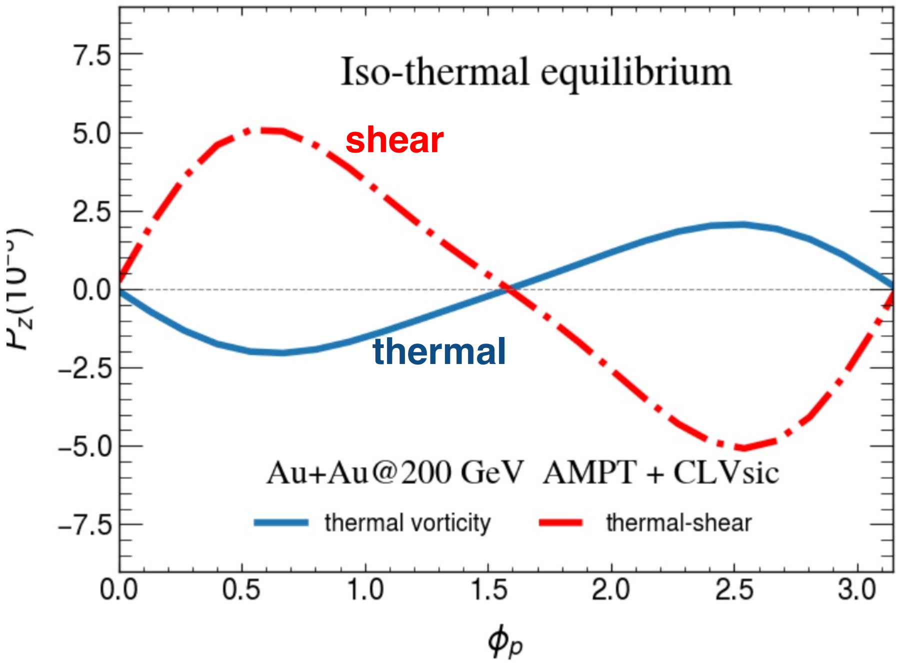
Ryu, Jupic, Shen, PRC (2021)

Shear induced polarization: isothermal equilibrium

Isothermal equilibrium: The temperature of the system at the freeze-out hyper-surface is assumed to be constant.

Becattini, Buzzegoli, Palermo, Inghirami, Karpenko, PRL 2021





Lessons learned:

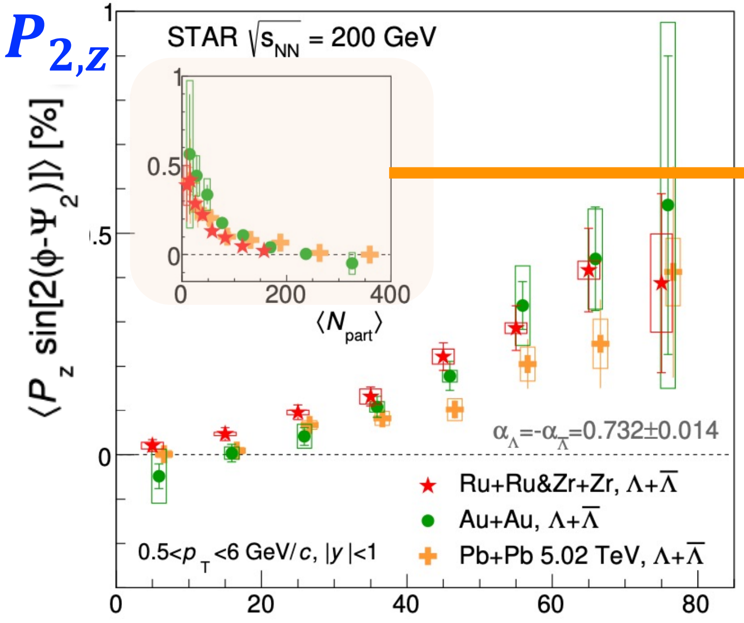
Temperature gradient plays a crucial role to the local spin polarization.

New update: an improved formula, no assumption of isothermal equilibrium.

X.L. Sheng, F. Becattini, D. Roseli, arXiv:2509.14301

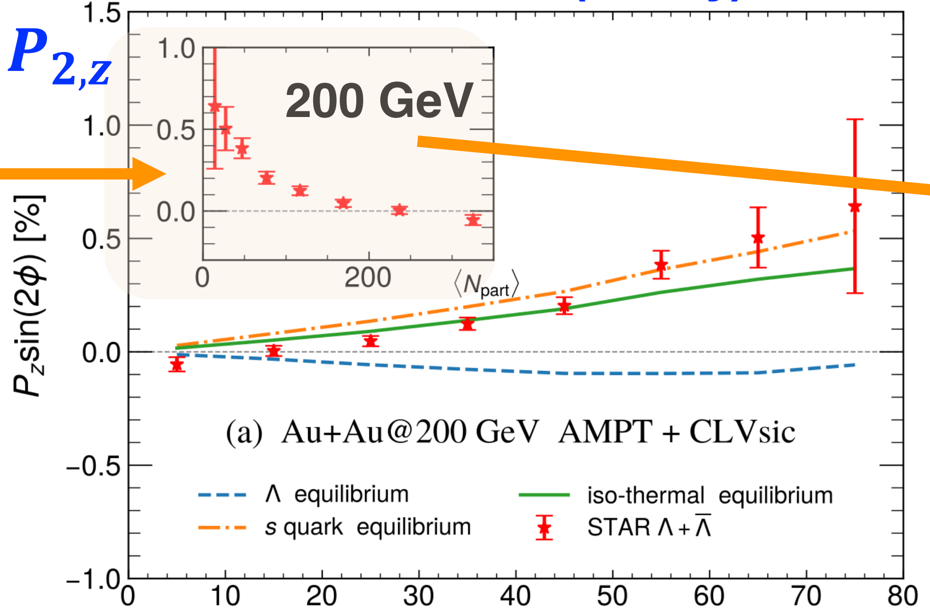
New Puzzle: Local polarization in pPb systems

AA collisons (exp)



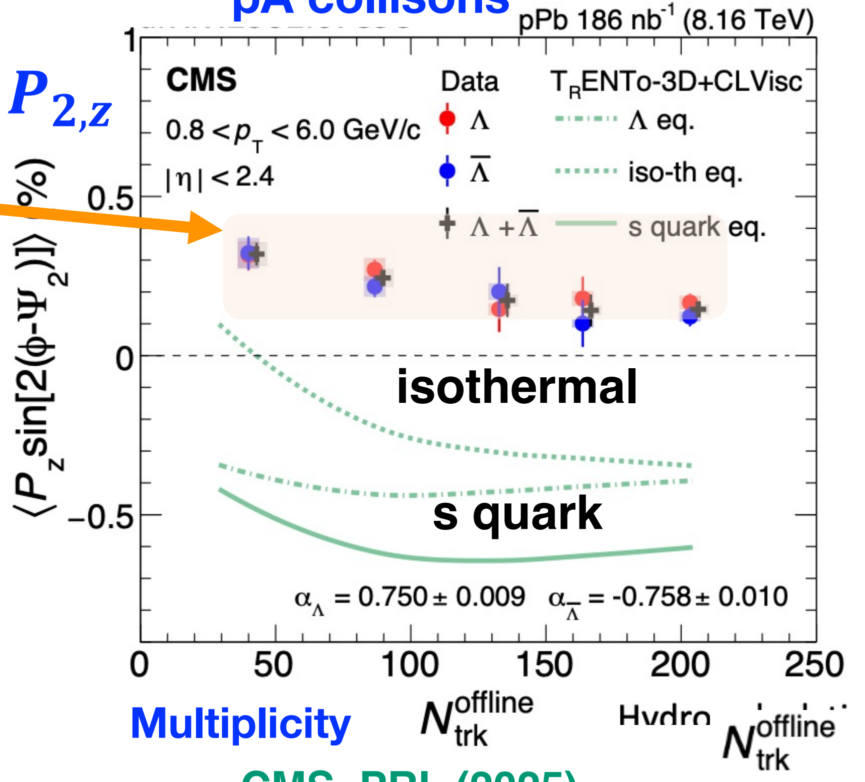
STAR, PRL 123, 132301 (2019)
ALICE, PRL 128, 172005 (2022)

AA collisons (theory)



Yi, et. al., arXiv: 2509.00377

pA collisons



CMS, PRL (2025)

Prediction: Yi, Wu, Zhu, SP, Qin, PRC (2025)

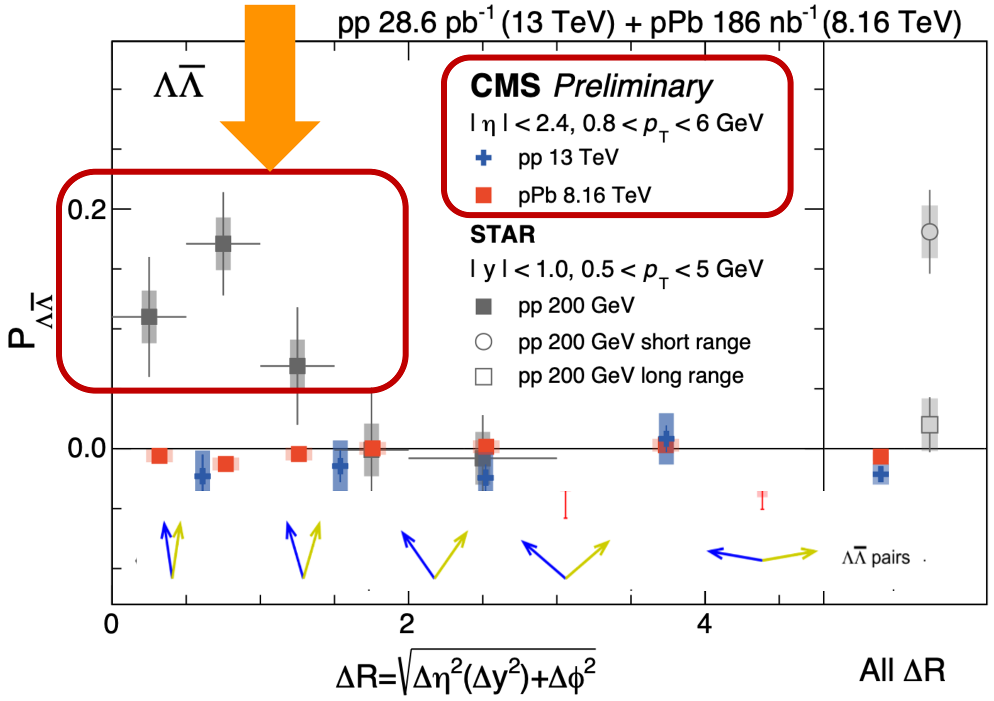
- **P_z in pA systems is closely aligned with that observed in AA systems.**
- **Hydrodynamic simulations across three scenarios fail to describe the data.**

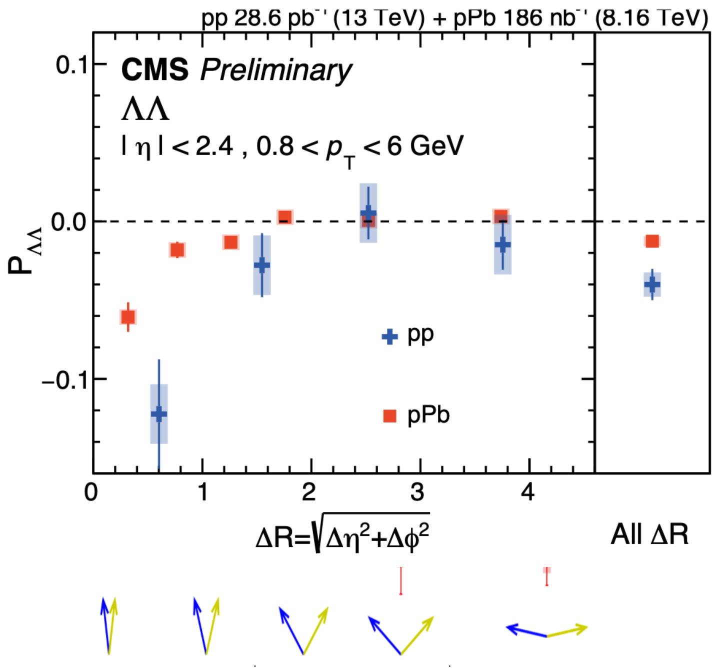
Weak system and collision energy dependence

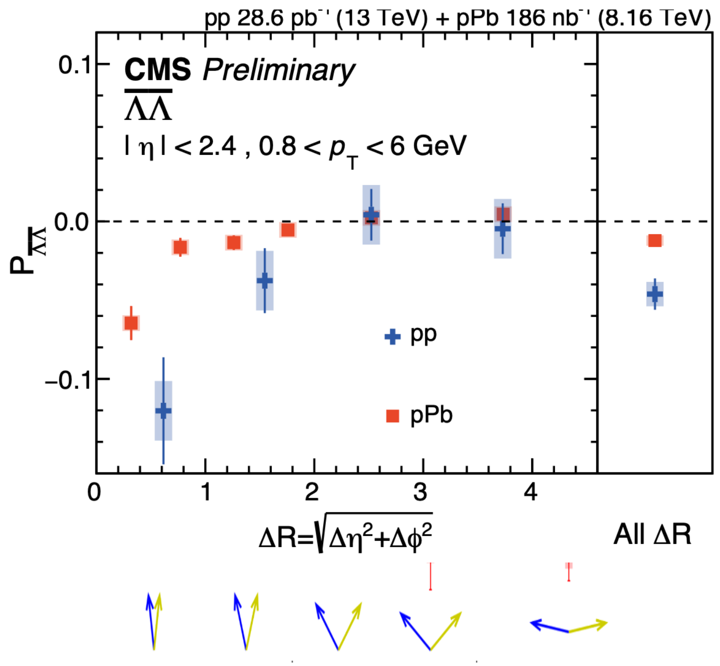
Spin correlation

Spin correlation in STAR and CMS

STAR, Nature
650, 44-45 (2026)

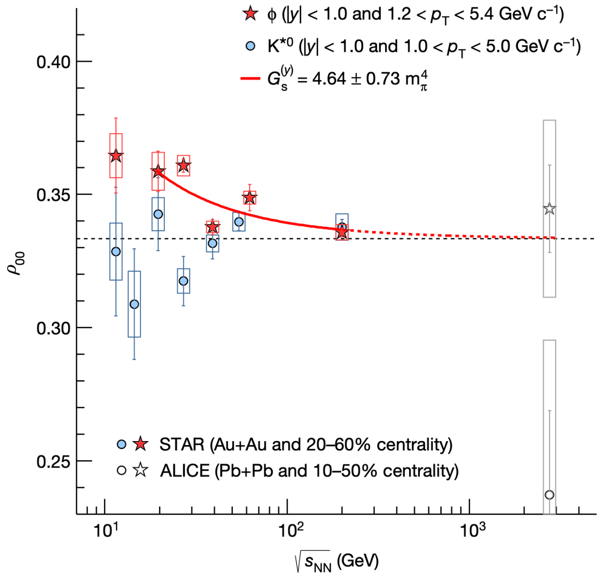






CMS-PAS-HIN-26-002

Spin correlation of hyperons and spin alignment



STAR, Nature 614, 244 (2023)

- **Lesson:**
  Large spin alignment of ϕ suggests strong spin correlation of s and $\bar{s}$

$$\rho_{00}^{\phi} - \frac{1}{3} \sim \langle P_s P_{\bar{s}} \rangle \neq \langle P_s \rangle \langle P_{\bar{s}} \rangle \qquad \langle \rho_{00}^{\phi} \rangle \sim \frac{1 - \bar{c}_{zz;\phi}^{(s\bar{s})} - \langle P_s \rangle^2}{3 + \bar{c}_{zz;\phi}^{(s\bar{s})} + \langle P_s \rangle^2},$$

- **Since** $P_{\Lambda/\bar{\Lambda}} \sim P_{s/\bar{s}}$,

$$\langle c_{zz}^{\Lambda\bar{\Lambda}} \rangle \sim \bar{c}_{zz;\Lambda\bar{\Lambda}}^{(s\bar{s})} + \langle P_s \rangle^2,$$

one can further estimate the spin correlation of Λ and $\bar{\Lambda}$,

Definition of spin correlation for hyperons

$$c_{nn}^{H_1\bar{H}_2} = \frac{f_{++}^{H_1\bar{H}_2} + f_{--}^{H_1\bar{H}_2} - f_{+-}^{H_1\bar{H}_2} - f_{-+}^{H_1\bar{H}_2}}{f_{++}^{H_1\bar{H}_2} + f_{--}^{H_1\bar{H}_2} + f_{+-}^{H_1\bar{H}_2} + f_{-+}^{H_1\bar{H}_2}},$$

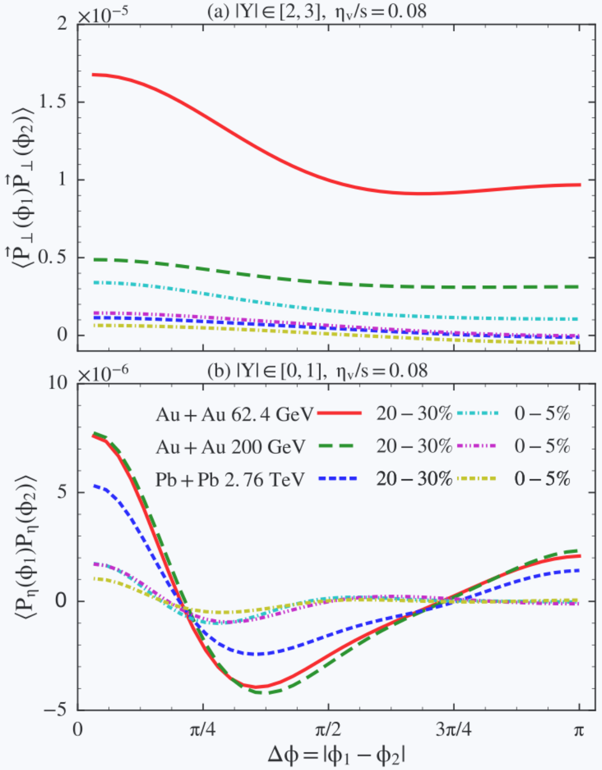
Lv, Yu, Liang, Wang, Wang PRD (2024)

Theoretical developments on spin correlation: strong force dominates

Short range correlation $\sim 10^{-4}$

Early pioneer work: estimated by vorticity effects:

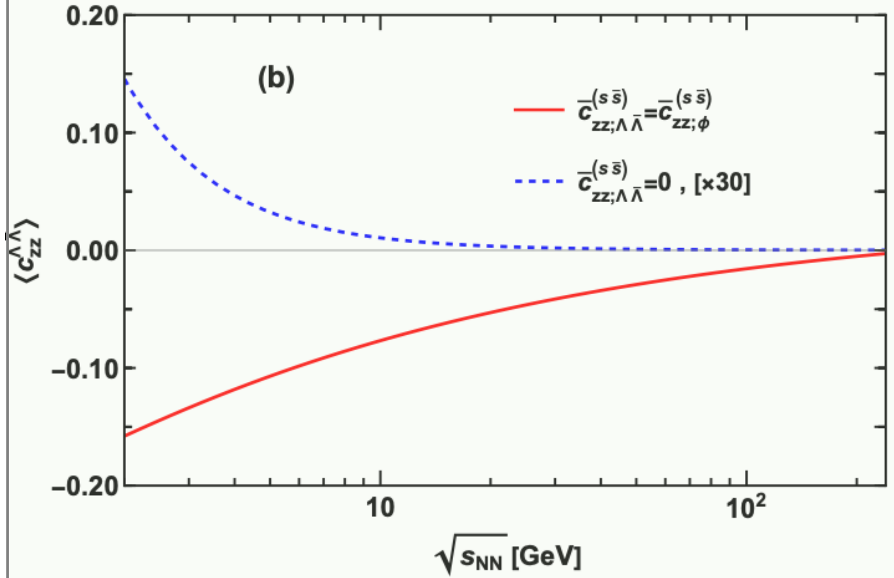
Pang, Petersen, Wang, Wang, PRL (2016)



Short range correlation $\sim 10^{-1} - 10^{-3}$

Estimated by the spin alignment of ϕ meson

Lv, Yu, Liang, Wang, Wang PRD (2024)



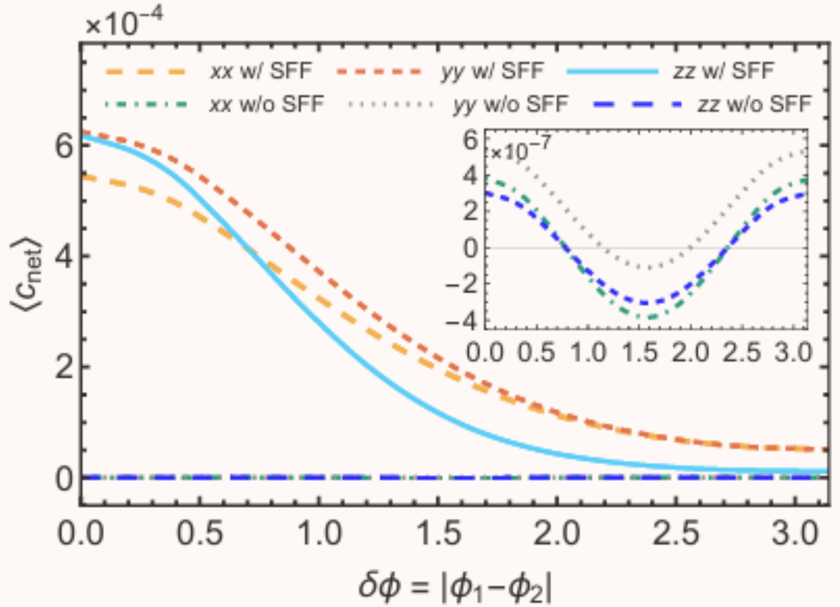
$$\langle \rho_{00}^{\phi} \rangle \sim \frac{1 - \bar{c}^{(s\bar{s})}_{zz;\phi} - \langle P_s \rangle^2}{3 + \bar{c}^{(s\bar{s})}_{zz;\phi} + \langle P_s \rangle^2},$$

$$\langle c_{zz}^{\Lambda\bar{\Lambda}} \rangle \sim \bar{c}^{(s\bar{s})}_{zz;\Lambda\bar{\Lambda}} + \langle P_s \rangle^2,$$

Long range correlation $\sim 10^{-4}$

Prediction from spin alignment of of ϕ meson (improved), strong field fluctuations dominate

Sheng, Wu, Rischke, Wang, 2508.03496



$$c_{\rm net}^{ab} \equiv \frac{1}{2}(c^{ab}_{\Lambda\Lambda} + c^{ab}_{\bar{\Lambda}\bar{\Lambda}}) - c^{ab}_{\Lambda\bar{\Lambda}}$$

Some other developments from our group

Puzzle: An Initial-State or Final-State Problem?

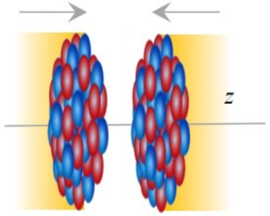
Polarization induced by Thermal vorticity 热涡旋	$$\mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) = \frac{\hbar}{8m_{\Lambda}N}\int d\Sigma^{\sigma}p_{\sigma}f_V^{(0)}(1-f_V^{(0)})\boxed{\epsilon^{\mu\nu\alpha\beta}p_{\nu}\partial_{\alpha}\frac{u_{\beta}}{T}},$$

- **Final-state problem:**
  Does only the fluid profile near the freeze-out hypersurface matter?

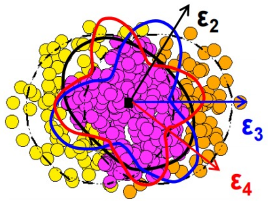
- **Initial-state problem:**
  How is orbital angular momentum converted into polarization?

Puzzle: initial vs final state problem?

nuclear collision

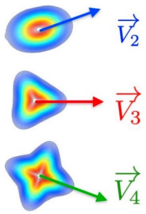


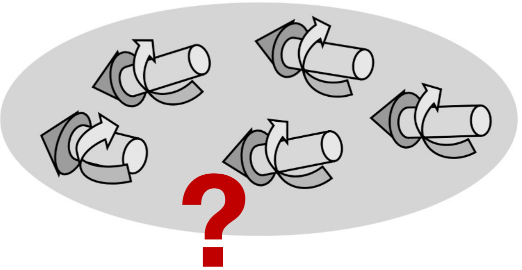
Initial state



Anisotropic pressure gradients

Final state





Structure and fluctuation of nuclear

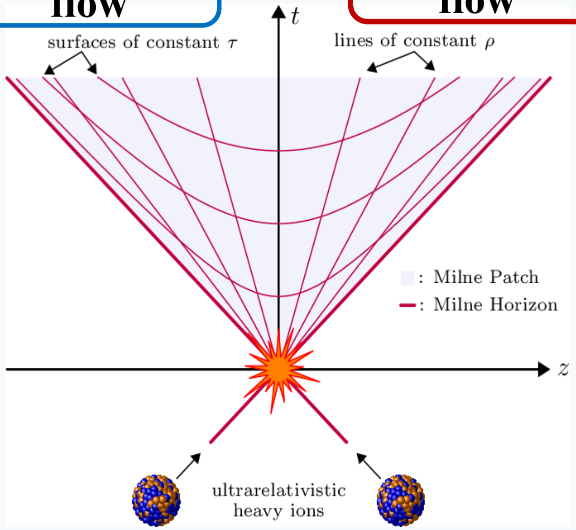
Anisotropy of energy density in coordinate space. (ϵ_n)

Final-state momentum-space anisotropy. (v_n)

Polarization?

Bjorken flow

Gubser flow



Gubser, PRD (2010);
Gubser, Yarom, NPB (2011)

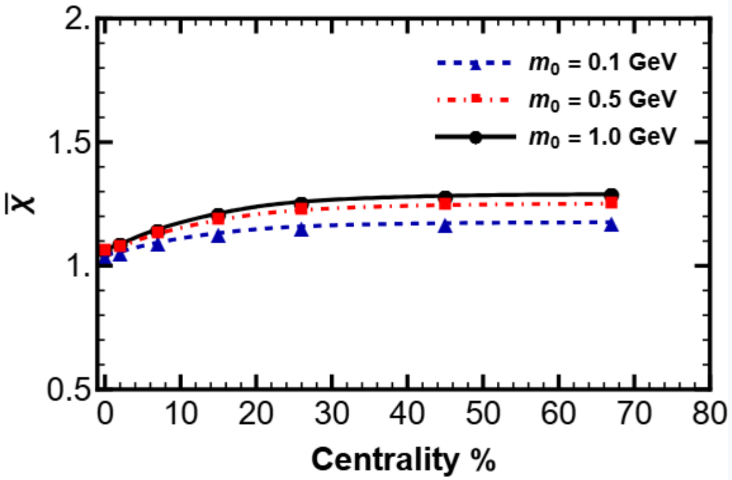
$$T_0 \to T = T_0[1 + \delta(\rho)S(\Theta,\phi)],$$

$$\begin{aligned} u^\mu &\to u^\mu + \delta u^\mu \\ \delta u^\mu &= \left(0, \frac{2L\tau}{L^2 + x_\perp^2}\boxed{v_s(\rho)\partial_\Theta S(\Theta,\phi)}, \tau\boxed{v_s(\rho)\partial_\phi S(\Theta,\phi)}, 0\right) \\ &+\mathcal{O}(\tau^2) \end{aligned}$$

ϕ dependence is introduced through the perturbations

Hatta, Noronha, Torrieri, B.W.Xiao, PRD (2014)
Hatta, Monnai, B.W.Xiao, PRD(2015)

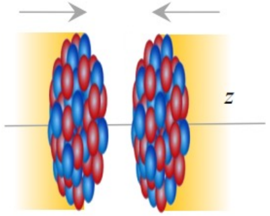
$$\boxed{\frac{v_4}{v_2^2} = \frac{1}{2} + \mathcal{O}(p_T^{-1}).}$$



Ren, Hu, Xu, SP, PRD (2026)

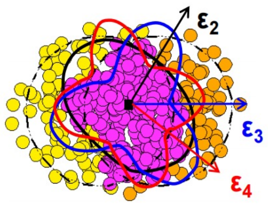
Puzzle: initial vs final state problem?

nuclear collision



Structure and fluctuation of nuclear

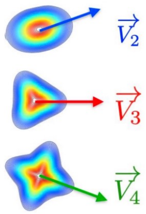
Initial state



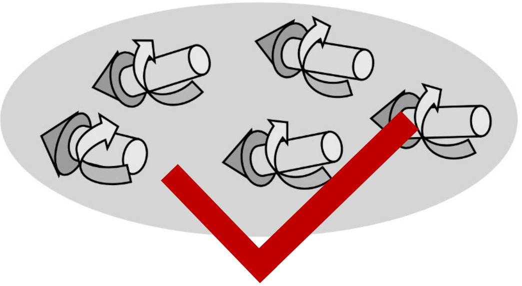
Anisotropy of energy density in coordinate space. (ϵ_n)

Anisotropic pressure gradients

Final state



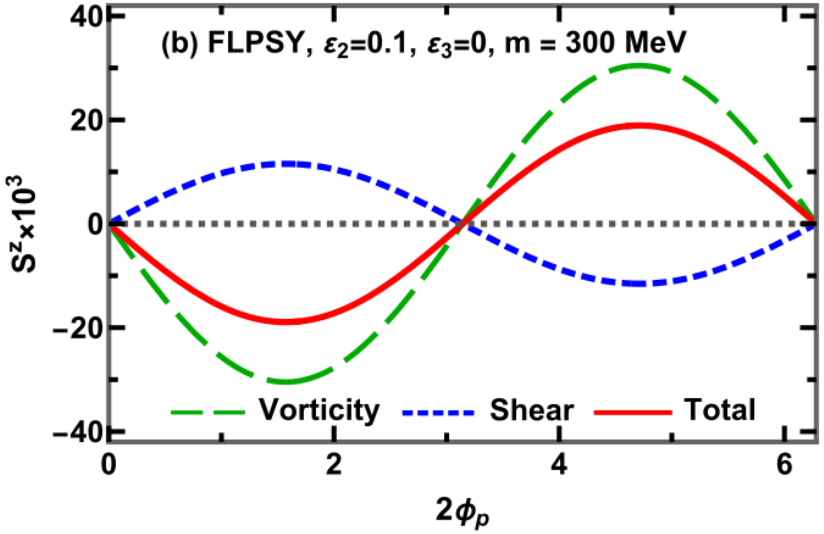
Final-state momentum-space anisotropy. (v_n)



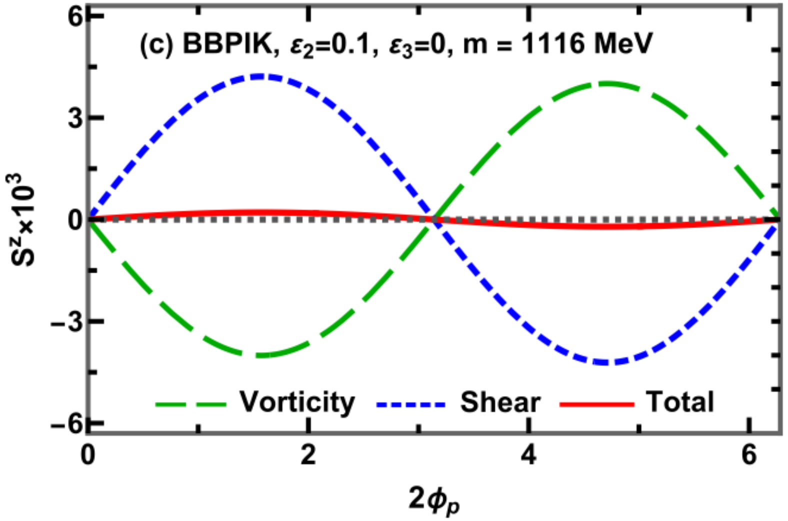
Polarization?

Given an initial eccentricity ϵ_2, we get the longitudinal polarization.

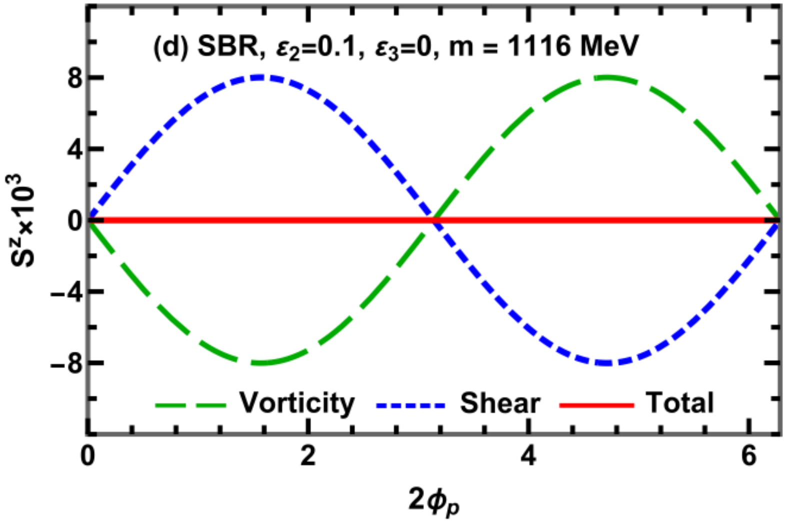
s quark equilibrium



Isothermal equilibrium



Improved isothermal equilibrium



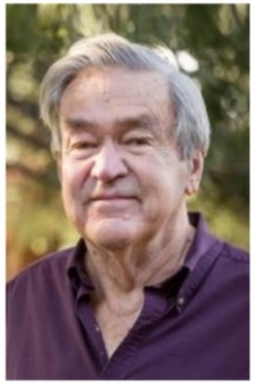
Z. Cao, K. Fukushima, SP, D.L. Wang, in preparation

Summary and outlook

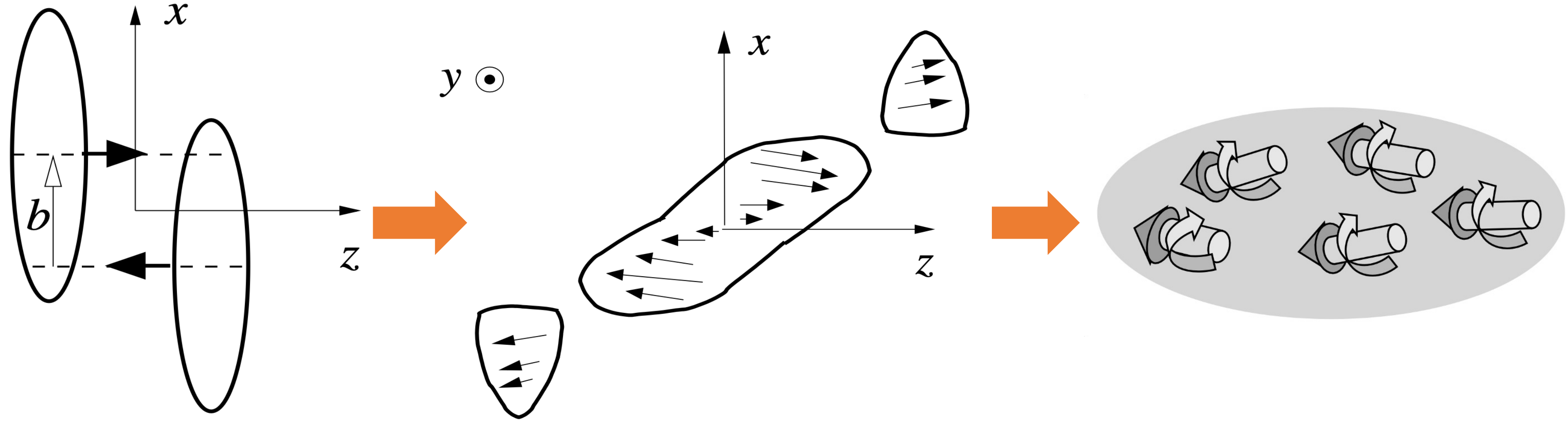
Summary

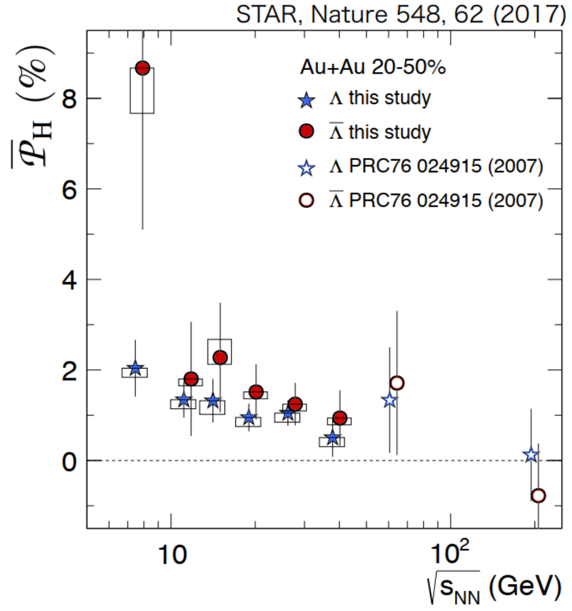
Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection.

----- J.D. Bjorken

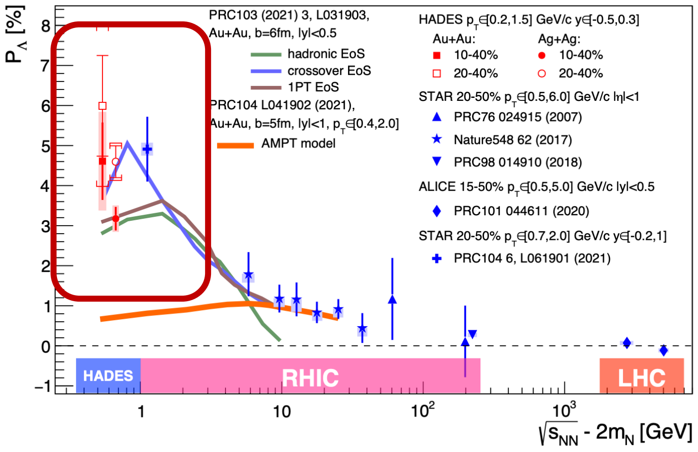


Not for the physics of heavy ion collisions.

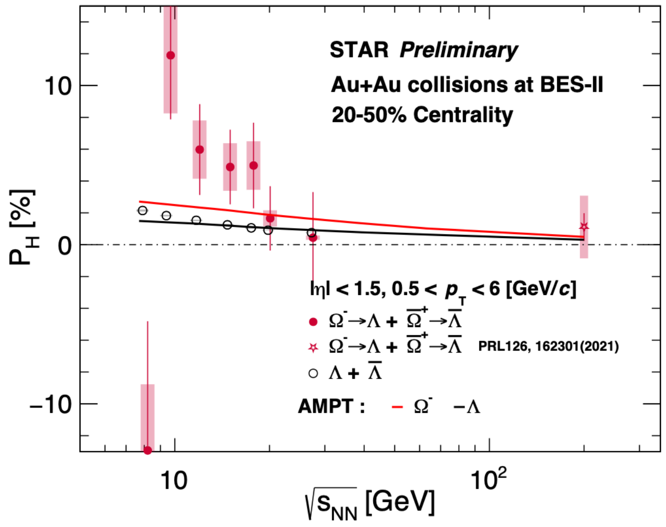




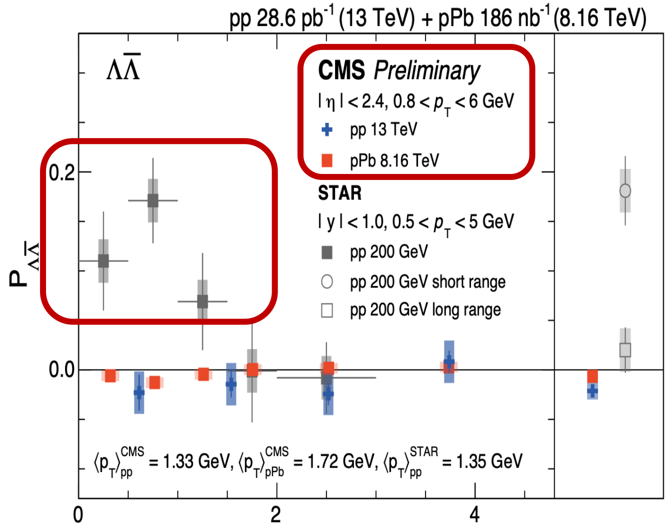
Puzzles



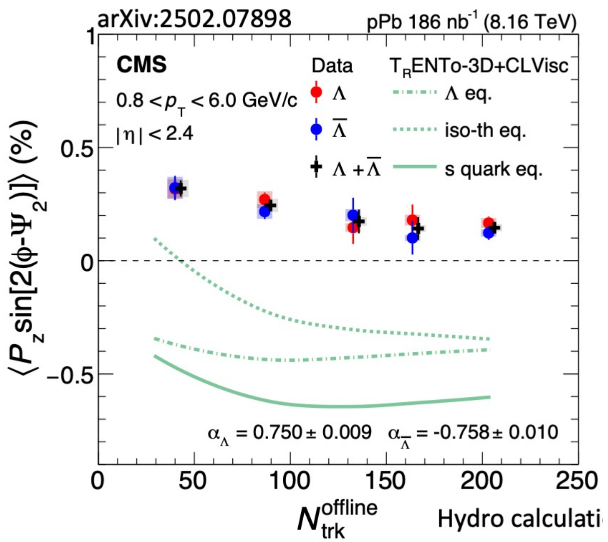
Global polarization at low energy collisions



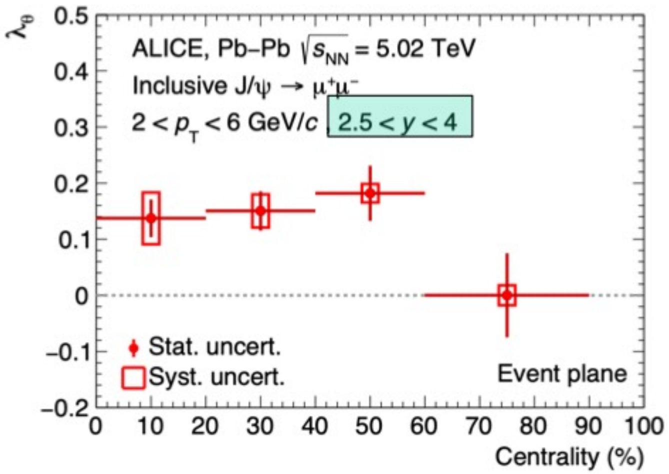
Global polarization of Omega



Spin correlation in pp collisions



Spin polarization in pPb collisions



Spin alignment of J/Psi

Thank you for your time!

Any comments and suggestions are welcome!

Backup