Lambda polarization in heavy-ion collisions at RHIC energies from a hydrodynamic model: an update

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arXiv:2103.14621

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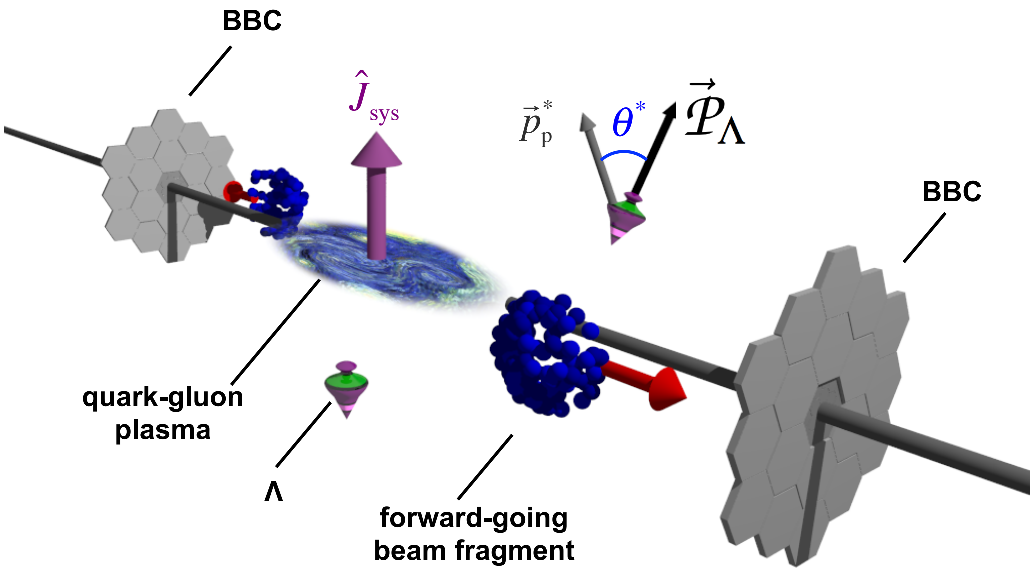
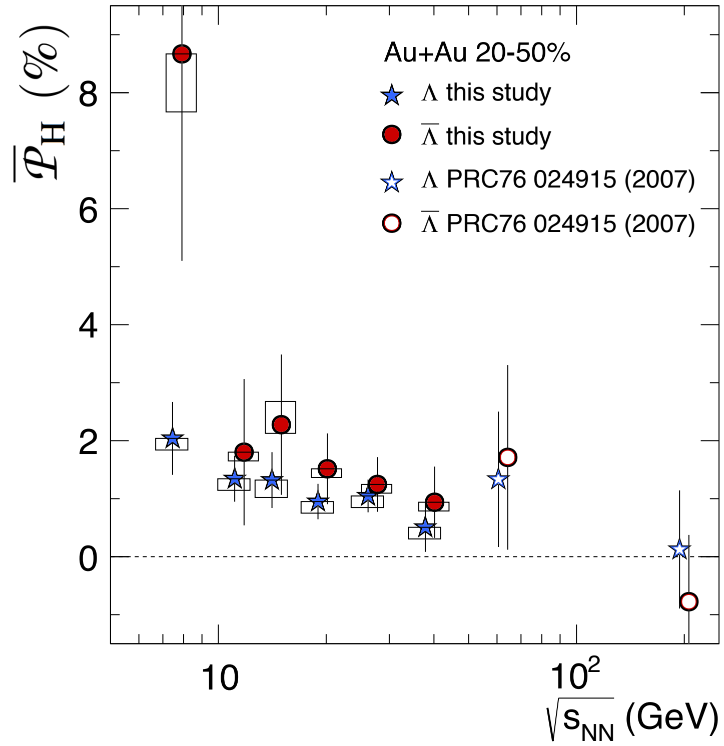
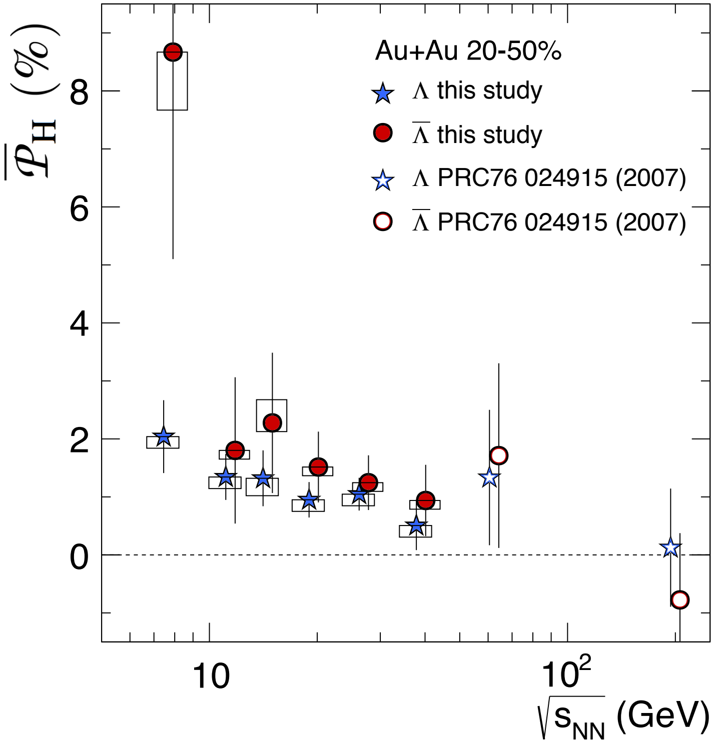
A rapid introduction into the topic

STAR Collaboration, Nature 548, 62 (2017)







STAR Collaboration, Nature 548, 62 (2017)

Such few % polarization indicates **an extremely large vorticity** $\omega \approx (9 \pm 1) \times 10^{21}\ s^{-1}$, far larger than anything else we observe in Nature.
The closest example is superfluid nanodroplets with $\omega \approx 10^{7} s^{-1}$.

Theory side

F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338 (2013) 32
Also: Ren-hong Fang, Long-gang Pang, Qun Wang, Xin-nian Wang, Phys. Rev. C 94 (2016), 024904

Mechanism: spin-vorticity coupling at local thermodynamic equilibrium.

- Cooper-Frye prescription: $$p^0 \frac{d^3N}{d^3p} = \int d\Sigma_\lambda p^\lambda \frac{1}{\exp\left(\frac{p \cdot u - \mu}{T}\right) \pm 1}$$
- For the spin 1/2 particles at the particlization surface: $\langle S(x,p) \rangle = \frac{1}{8m}(1 - f(x,p))\epsilon^{\mu\nu\rho\sigma} p_\sigma \partial_\nu \beta_\rho$

  where $\beta^\mu = u^\mu / T$ is the inverse four-temperature field.

$$\boxed{S^\mu(p) = \frac{\int d\Sigma_\lambda p^\lambda f(x,p) \langle S(x,p) \rangle}{\int d\Sigma_\lambda p^\lambda f(x,p)}}$$

- Polarization depends on the the thermal vorticity $\varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$
  - polarization is close or equal for particles and antiparticles
  - caused not only by velocity, but also temperature gradients

The scheme to compute hyperon polarization

Most of the calculations of hyperon polarization on the market are constructed as follows:

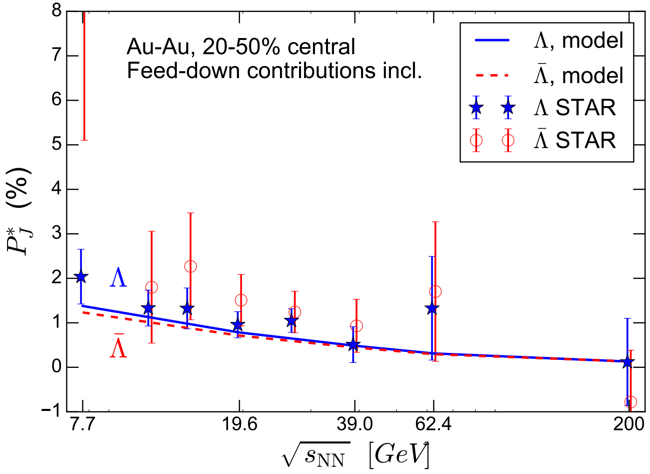
1. In a hydrodynamic model:

Hydrodynamic evolution → freeze-out/particlization → formula from above

2. In a transport model:

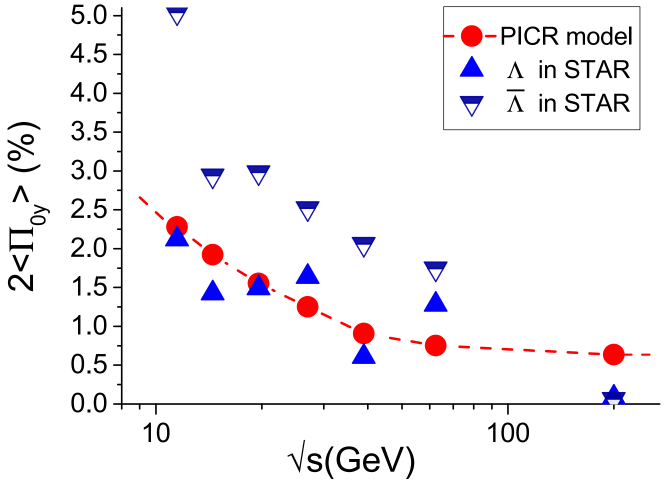
Parton/hadron cascade → coarse-graining → formula from above

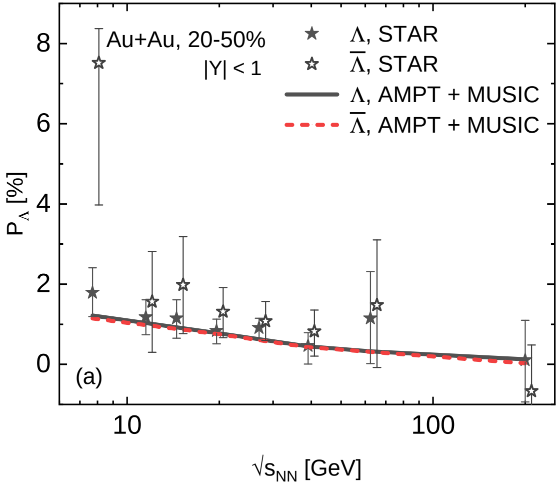
Global (p_T integrated) hyperon polarization in hydro models



IK, F. Becattini,
Eur. Phys. J. C 77, 213 (2017)
UrQMD + vHLLE

Y.L. Xie, D.J. Wang, L.P. Csernai,
Phys. Rev. C 95, 031901 (2017)
PICR



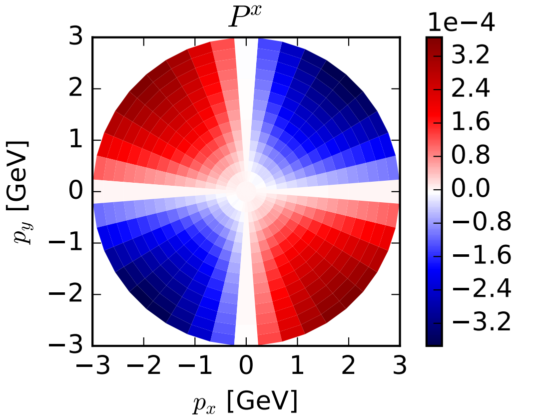


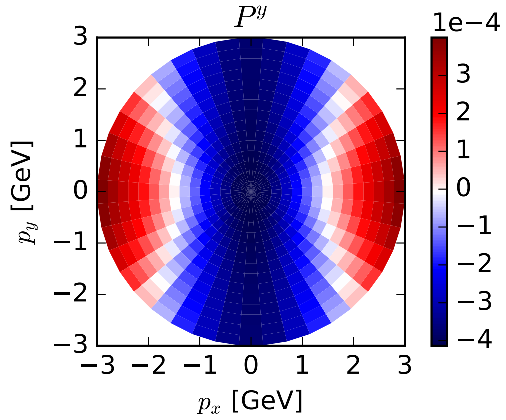
Baochi Fu, Kai Xu, Xu-Guang
Huang, Huichao Song
Phys. Rev. C 103, 024903 (2021)
AMPT+MUSIC

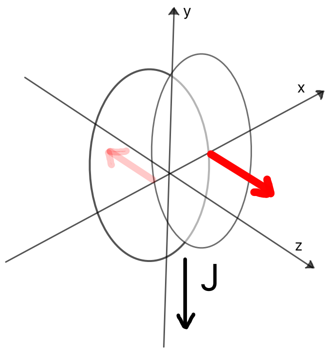
Same collision energy dependence in transport models+coarse graining

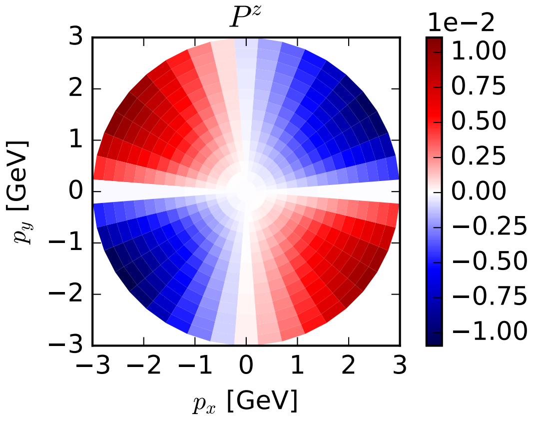
Local hyperon polarization

Calculation: 3D tilted Monte Carlo Glauber initial state + 3D viscous hydro (vHLLE)





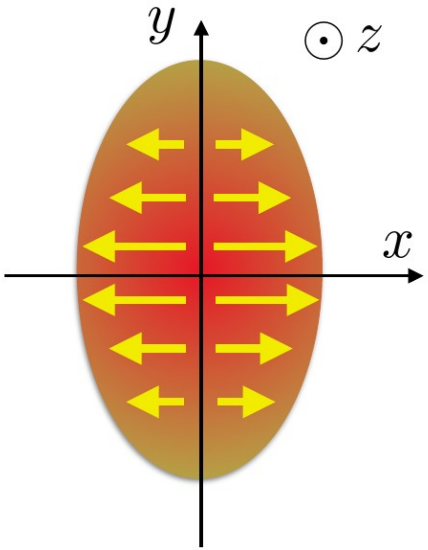


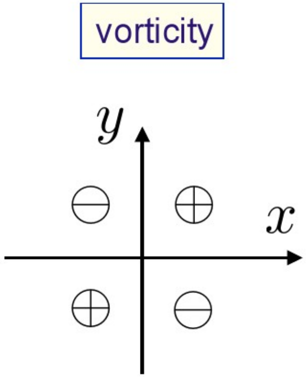


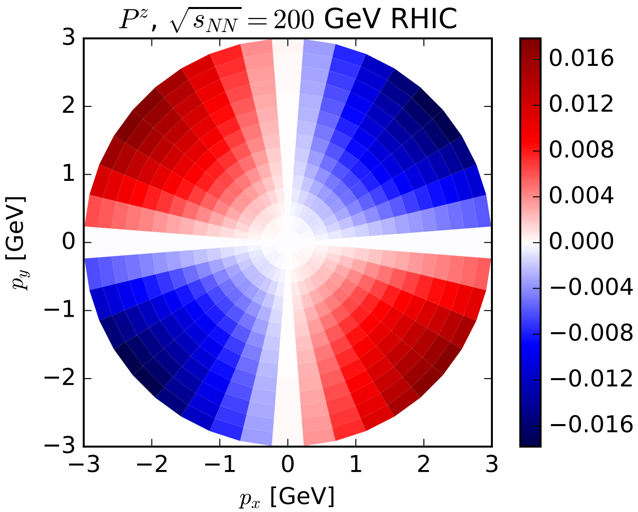
- When integrated over p_T, only P^y component survives
- However, at a given p_T and φ, all 3 components are non-zero

A closer look at the quadrupole structure

An oversimplified explanation* of the quadrupole structure (Sergei Voloshin @ QM2017):



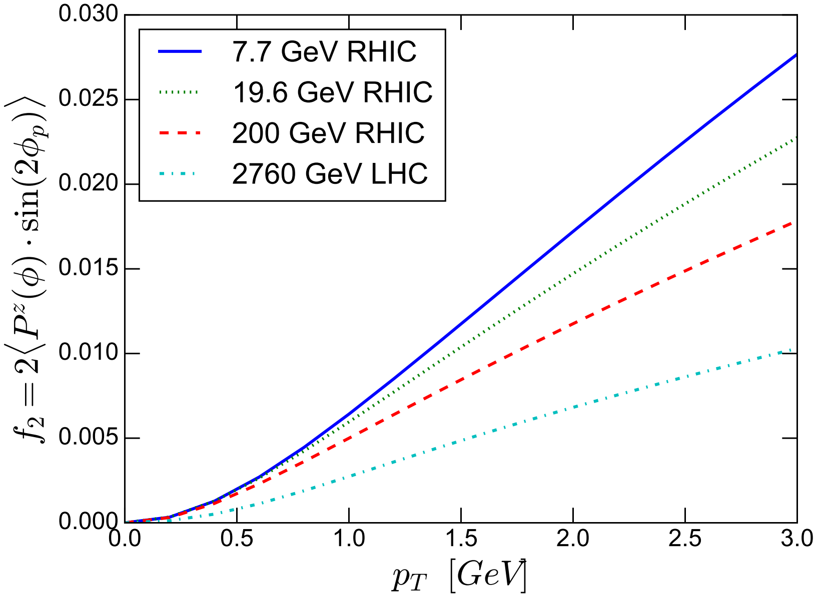




* It does not work quantitatively, since there are time derivatives and temperature gradients involved.

Fourier expansion for P^z

F. Becattini, IK, Phys. Rev. Lett. 120, 012302 (2018)



$$P^z(\mathbf{p_T}, y=0) = \sum_{k=1}^{\infty} f_{2k}(p_T)\sin 2k(\phi_p - \Psi)$$

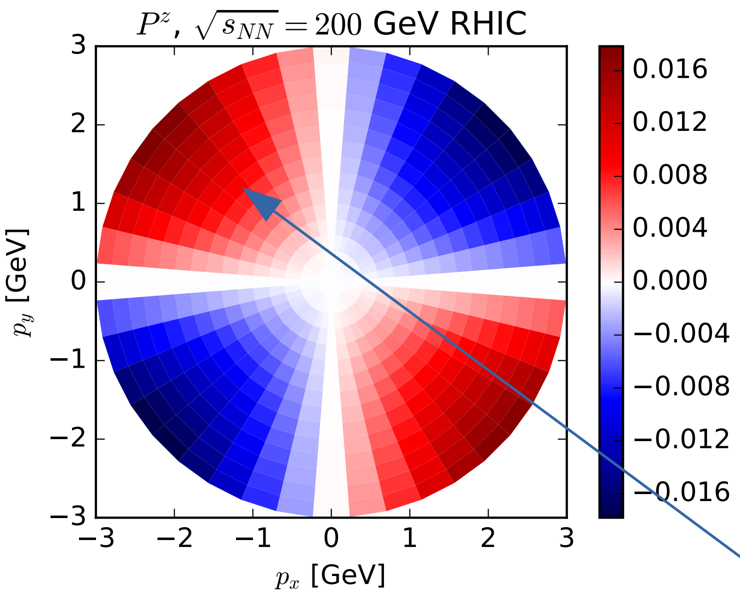
- Requires identification of event plane Ψ
- In a blast-wave model:

$$\boxed{f_2(p_T) = 2\frac{dT}{d\tau}\frac{1}{mT}v_2(p_T)}$$

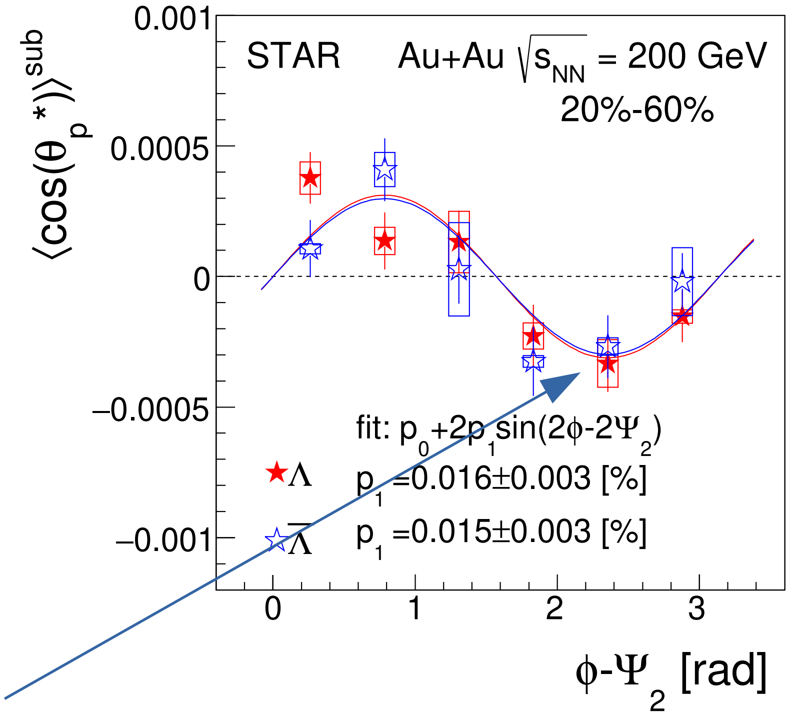
P^z emerges because of anisotropic transverse expansion, same way as v_2

Puzzle #1: P^z signs in a model and in experiment

Hydro model calculation:
Glauber IS + 3D viscous hydro (vHLLE)



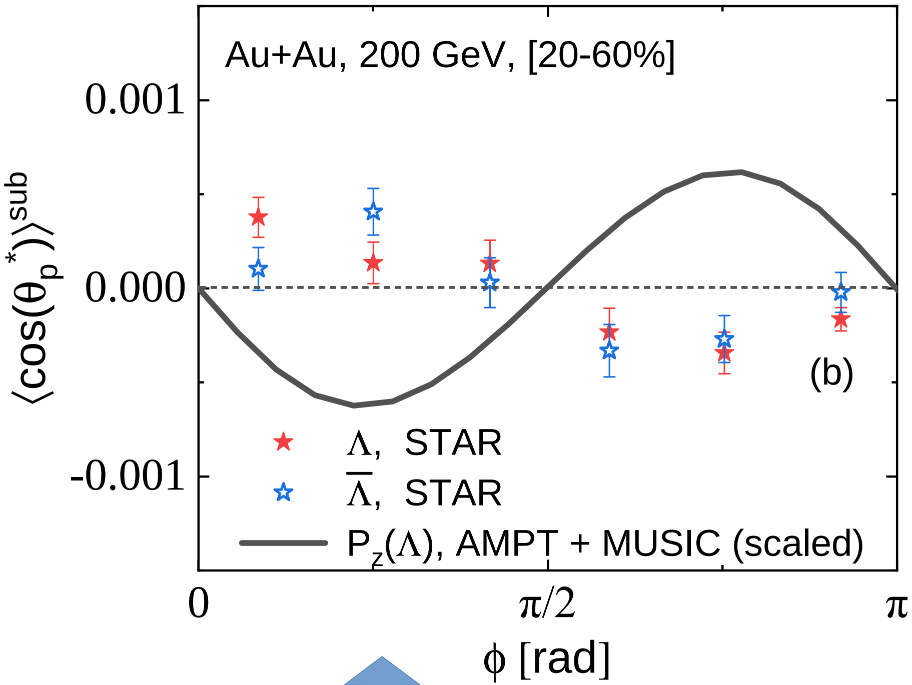
STAR measurement: Phys. Rev. Lett. 123, 132301 (2019)

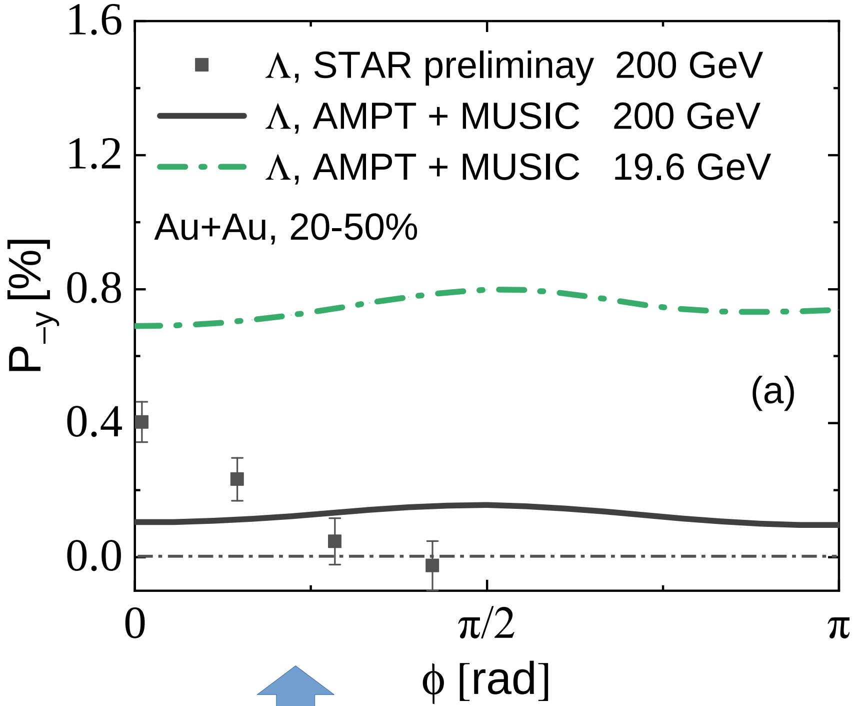


The signs are opposite!

Puzzle #2: φ dependence of P^J is wrong

B. Fu, K. Xu, X. Huang, H. Song, Phys. Rev. C 103, 024903 (2021) [2011.03740]





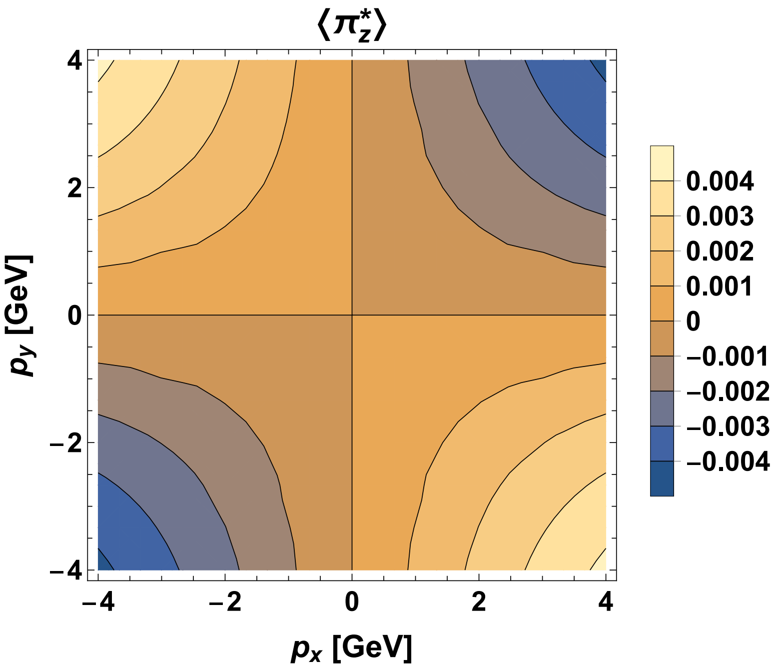
Puzzle #1

Puzzle #2

Early attempts to explain the sign puzzle

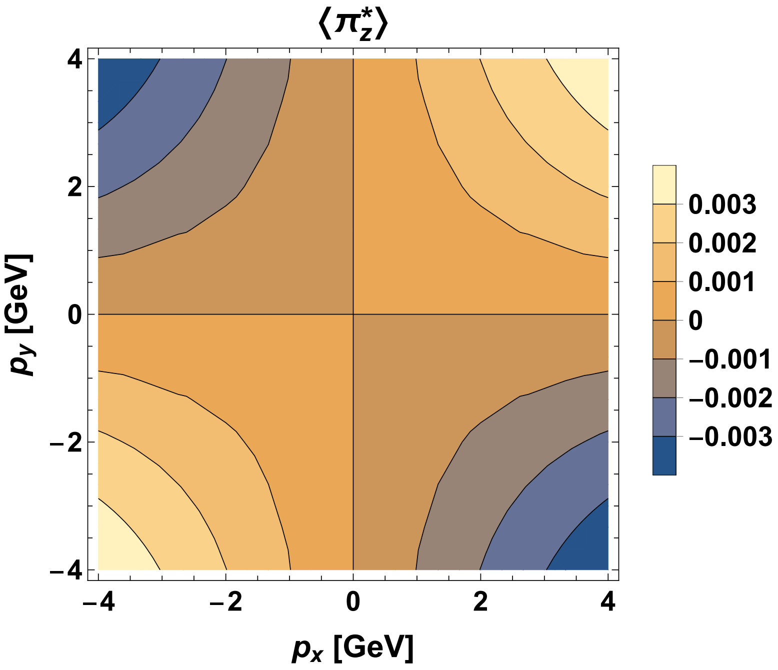
W. Florkowski, A. Kumar, R. Ryblewski, A. Mazeliauskas, Phys. Rev. C 100, 054907 (2019)

Polarization ~ standard thermal vorticity
(opposite sign to experiment)



$$\varpi^{\mu\nu} = -\frac{1}{2}\left(\partial^\mu \beta^\nu - \partial^\nu \beta^\mu\right)$$

Polarization ~ **projected** thermal vorticity

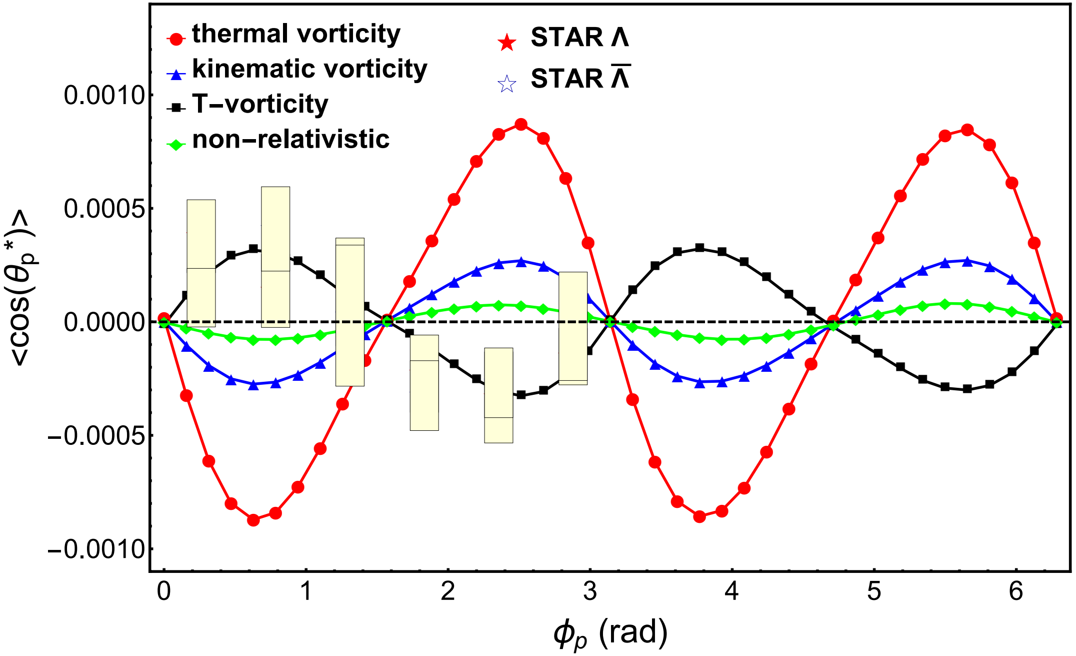


$$\varpi^{\mu\nu}_{\rm proj} = \varpi_{\alpha\beta}\Delta^\mu_\alpha\Delta^\nu_\beta$$

Trying out different definitions of vorticity

Hong-Zhong Wu, Long-Gang Pang, Xu-Guang Huang, Qun Wang,
Phys. Rev. Research 1, 033058 (2019) + QM2019 proceeding

AMPT IS (includes angular momentum) + 3D viscous hydro (CLVisc)



$$\omega^{(\mathrm{th})}_{\mu\nu} = -\frac{1}{2}\left({}_{\mu}\beta_{\nu} -{}_{\nu}\, \beta_{\mu}\right)$$

$$\omega^{(K)}_{\mu\nu} = -\frac{1}{2}(\partial_\mu u_\nu - \partial_\nu u_\mu)$$

$$\omega^{(T)}_{\mu\nu} = -\frac{1}{2}[\partial_\mu(Tu_\nu) - \partial_\nu(Tu_\mu)]$$

$$\omega^{(\mathrm{NR})}_{\mu\nu} = \epsilon_{\nu\mu\rho\eta}u^\rho\omega^\eta$$

Back to theory

In early 2021, it was realized that the local (i.e. at a given pT) polarization is induced not only by anti-symmetric (thermal vorticity) but also by symmetric (thermal shear) combinations of velocity/temperature gradients:

F. Becattini, M. Buzzegoli, A. Palermo, arXiv:2103.10917

$$S^\mu(p) = S^\mu_\varpi(p) + S^\mu_\xi(p)$$

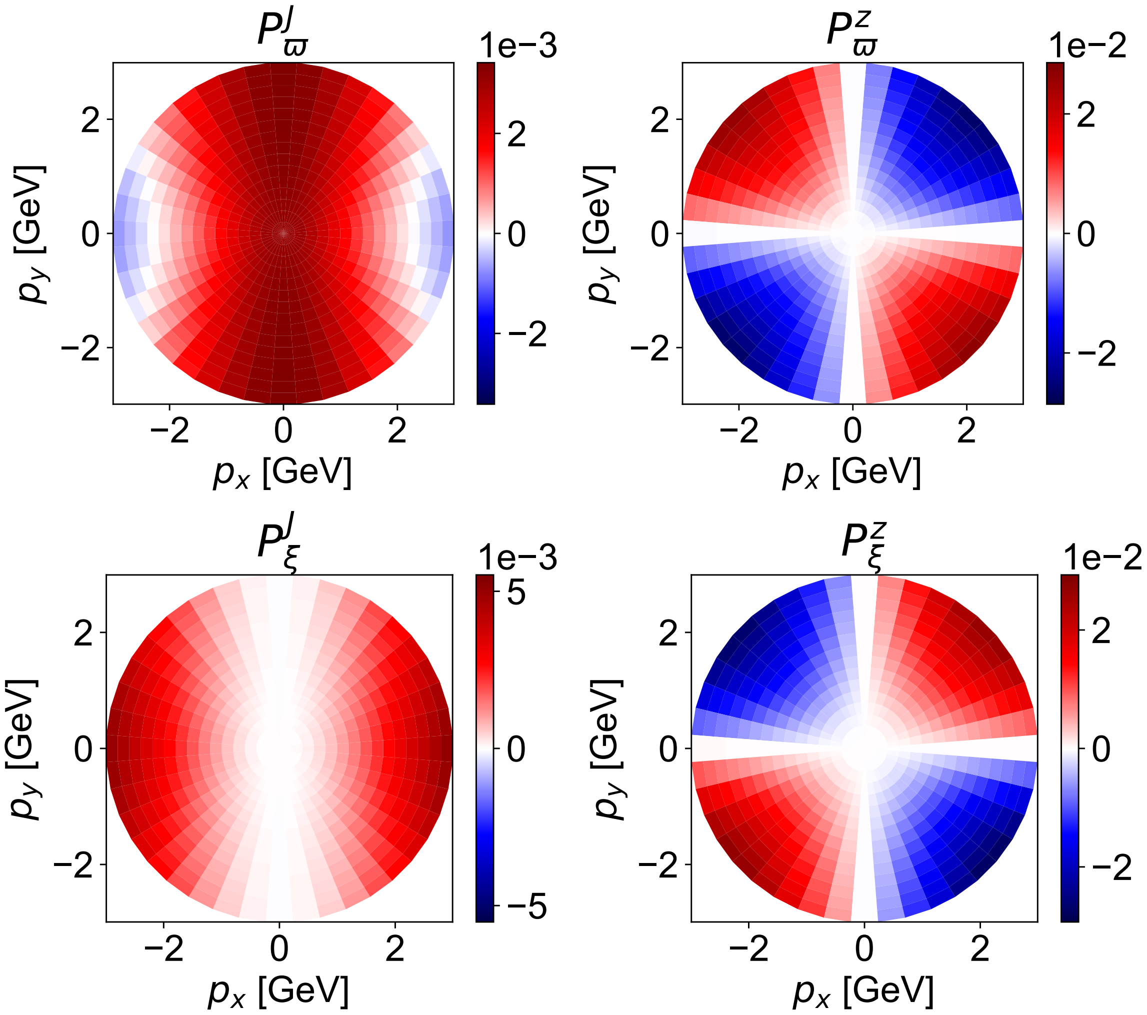
$$S^\mu_\varpi(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma \Sigma\cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma \Sigma\cdot p\, n_F} \qquad \varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu\right)$$

$$\boxed{S^\mu_\xi(p) = -\frac{1}{4m}\epsilon^{\mu\rho\sigma\tau}\frac{p_\tau p^\lambda}{\varepsilon}\frac{\int_\Sigma \Sigma\cdot p\, n_F(1-n_F)\hat{t}_\rho\xi_{\sigma\lambda}}{\int_\Sigma \Sigma\cdot p\, n_F} \qquad \xi_{\mu\nu} = \frac{1}{2}\left(\partial_\mu\beta_\nu + \partial_\nu\beta_\mu\right)}$$

new!

A possibly similar shear-induced polarization effect derived in: Shuai Y. F. Liu, Yi Yin, arXiv:2103.09200

Numerical results with the new term



F. Becattini, M. Buzzegoli, G. Inghirami, IK, A. Palermo, arXiv:2103.14621

$$\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int_\Sigma \Sigma\cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma \Sigma\cdot p\, n_F}$$

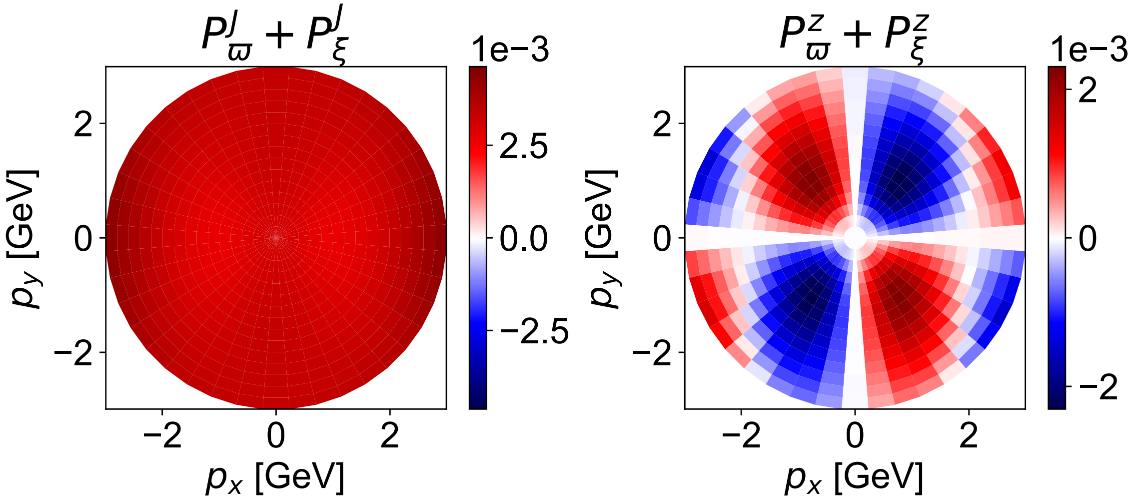
(old spin-vorticity coupling term)

Opposite sign of P^z **and** correct φ-dependence of P^J !!

$$-\frac{1}{4m}\epsilon^{\mu\rho\sigma\tau}\frac{p_\tau p^\lambda}{\varepsilon}\frac{\int_\Sigma \Sigma\cdot p\, n_F(1-n_F)\hat{t}_\rho \xi_{\sigma\lambda}}{\int_\Sigma \Sigma\cdot p\, n_F}$$

(new spin-shear coupling term)

When the old and the new terms are added together ...



The new term is not quite strong enough to overturn the vorticity term and change the sign of P^z.

As such, it doesn't explain the sign puzzle.

One more thing: improving the original expansion

In all cases, we start from the density operator in local equilibrium:

$$\beta_\nu = \frac{u_\nu}{T}$$

$$\hat{\rho}_{\mathrm{LE}} = \frac{1}{Z_{\mathrm{LE}}} \exp\left[-\int_\Sigma \Sigma_\mu \, \left(\hat{T}^{\mu\nu}\beta_\nu - \hat{j}^\mu \zeta\right)\right]$$

$$\beta_\nu(y) \simeq \beta_\nu(x) + \partial_\lambda \beta_\nu(x)(y-x)^\lambda$$

$$\hat{\rho} \simeq \frac{1}{Z_{\mathrm{LE}}} \exp\left[-\beta_\nu(x)\hat{P}^\nu + \; - \; \partial_\lambda\beta_\nu(x) \int_\Sigma \Sigma_\mu(y)(y-x)^\lambda \hat{T}^{\mu\nu}(y)\right],$$

Now, since the hypersurface Σ_μ is an iso-thermal one, T=const,

$$\hat{\rho} = \frac{1}{Z_{\mathrm{LE}}} \exp\left[-\frac{1}{T}\int_\Sigma \Sigma_\mu \, \hat{T}^{\mu\nu} u_\nu\right]$$

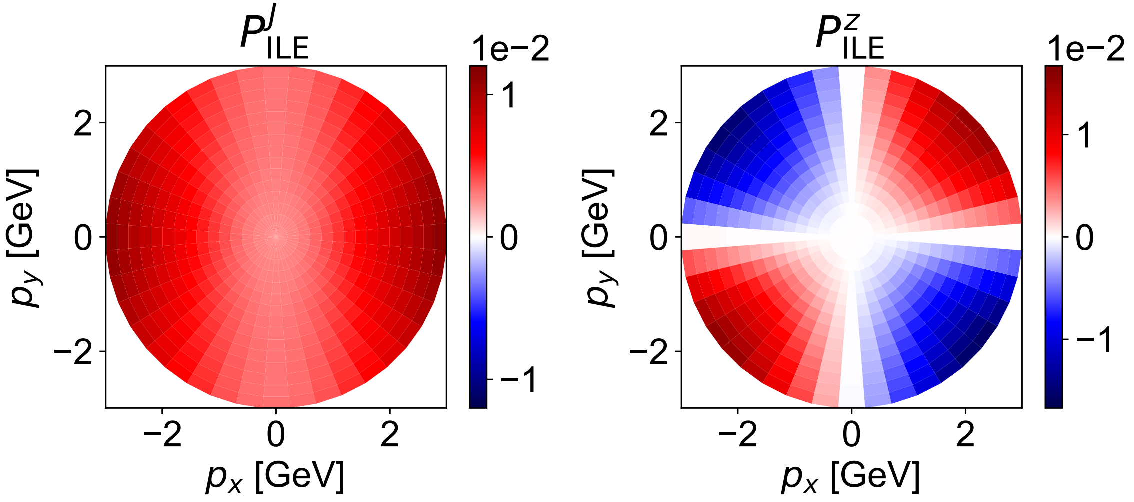
$$\hat{\rho} \simeq \frac{1}{Z_{\mathrm{LE}}} \exp\left[-\beta_\nu(x)\hat{P}^\nu + \; - \; \frac{1}{T}\partial_\lambda u_\nu(x) \int_\Sigma d\Sigma_\mu(y)(y-x)^\lambda \hat{T}^{\mu\nu}(y)\right].$$

Improving the original expansion (2)

The derivation from the previous slide leads to an updated formula for polarization of spin ½ hadrons:

$$S^{\mu}_{\mathrm{ILE}}(p) = \; - \epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma \Sigma \cdot p \, n_F (1-n_F) \left[\omega_{\rho\sigma} + 2 \, \hat{t}_\rho \frac{p^\lambda}{\varepsilon} \Xi_{\lambda\sigma} \right]}{8 m T_{\mathrm{dec}} \int_\Sigma \Sigma \cdot p \, n_F}$$

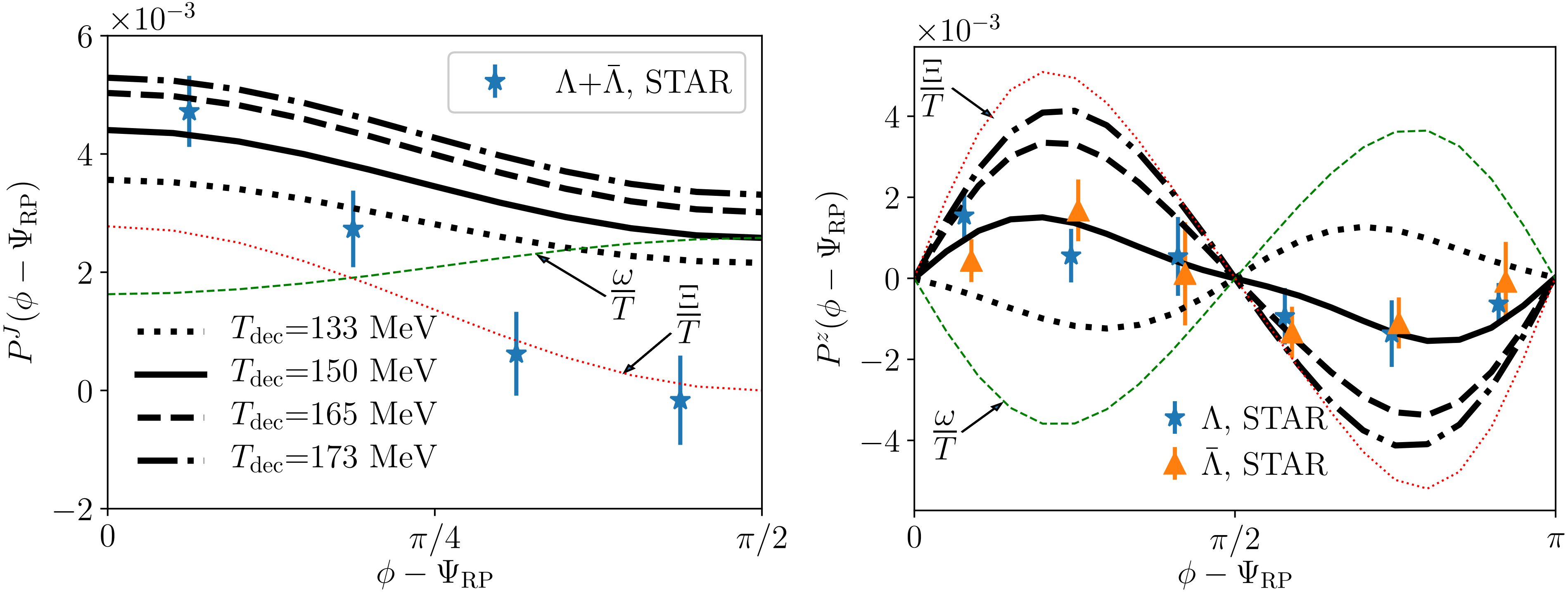
which depends on **kinematic vorticity** $\omega_{\rho\sigma} = \dfrac{1}{2} \left(\partial_\sigma u_\rho - \partial_\rho u_\sigma \right)$, which leads to the following result:



Good agreement with the experiment!

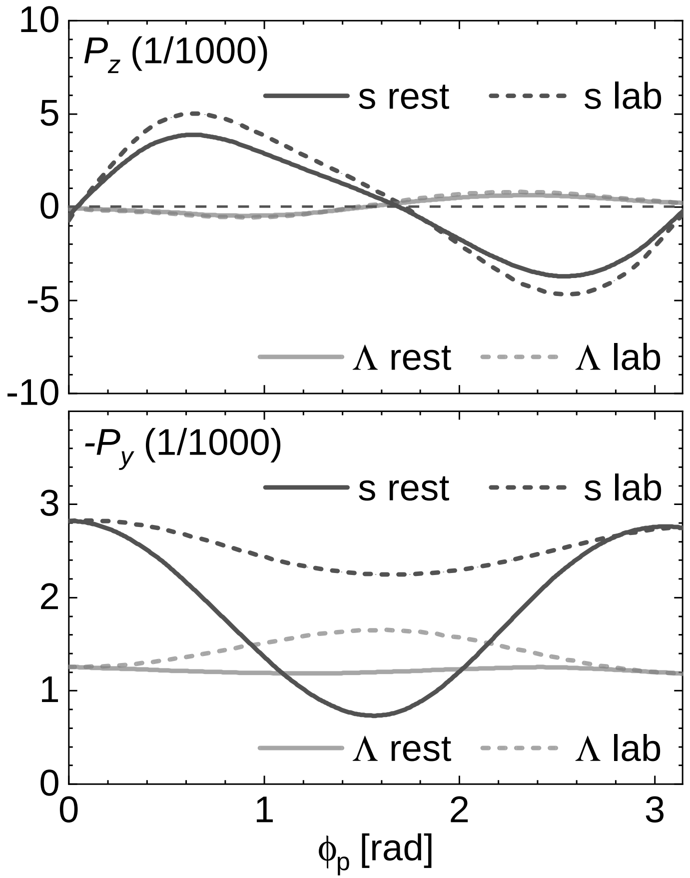
The updated formalism vs. the experimental data

F. Becattini, M. Buzzegoli, G. Inghirami, IK, A. Palermo, arXiv:2103.14621



A very good agreement for both P^J and P^z with T_{dec}=150 MeV freezeout.

A parallel idea: s-quark memory



Baochi Fu, Shuai Y. F. Liu, Longgang Pang, Huichao Song, Yi Yin, arXiv:2103.10403

Because the (new) shear term for polarization has a stronger mass dependence, there is a significant difference between the polarizations of original s-quark and the produced Lambda hyperon.

In the first scenario, namely the "Lambda equilibrium", we shall assume the spin relaxation rate is large enough so that Λ hyperons immediately response to the presence of hydrodynamic gradients once Λ are formed through hadronization. In the second scenario, we consider the opposite limit that Λ "inherits" the spin polarization from its constituent strange quark [53, 54], and the resulting spin polarization is frozen ever since the hadronization. This scenario will be referred to as the "strange memory". In reality, Λ spin polarization should evolve from the "strange memory" scenario towards that in the "Lambda equilibrium" scenario. Therefore com-

Conclusions

- Non-vanishing polarization of Lambda hyperons in relativistic heavy-ion collisions has been recently measured by STAR collaboration in the RHIC Beam Energy Scan (BES) program.
- The mean, p_T-averaged polarization component P^J is in consistent agreement with hydrodynamic and transport models for heavy-ion collisions at RHIC BES energies.
- The azimuthal angle dependence of P^J and P^z polarization components remained a puzzle.
- It has been recently found that polarization of hadrons produced from a hot and dense medium is generated not only by the spin-vorticity coupling but also by the spin-shear one.
- The new, spin-thermal shear term, when embedded into 3D viscous hydrodynamic models (vHLLE and ECHO-QGP), improves the agreement of the azimuthal dependence of P^J and P^z with the data, but it does not seem to be strong enough to solve the “sign puzzle” for the P^z.
- Furthermore, exploiting the fact that the freeze-out and hadron production happens at approximately constant temperature, one can improve the expansion scheme used to derive the spin-vorticity and spin-shear couplings, which seems to solve the sign puzzle for the P^z and considerably improve the azimuthal angle dependence of the P^J component.