Lambda polarization in heavy-ion collisions

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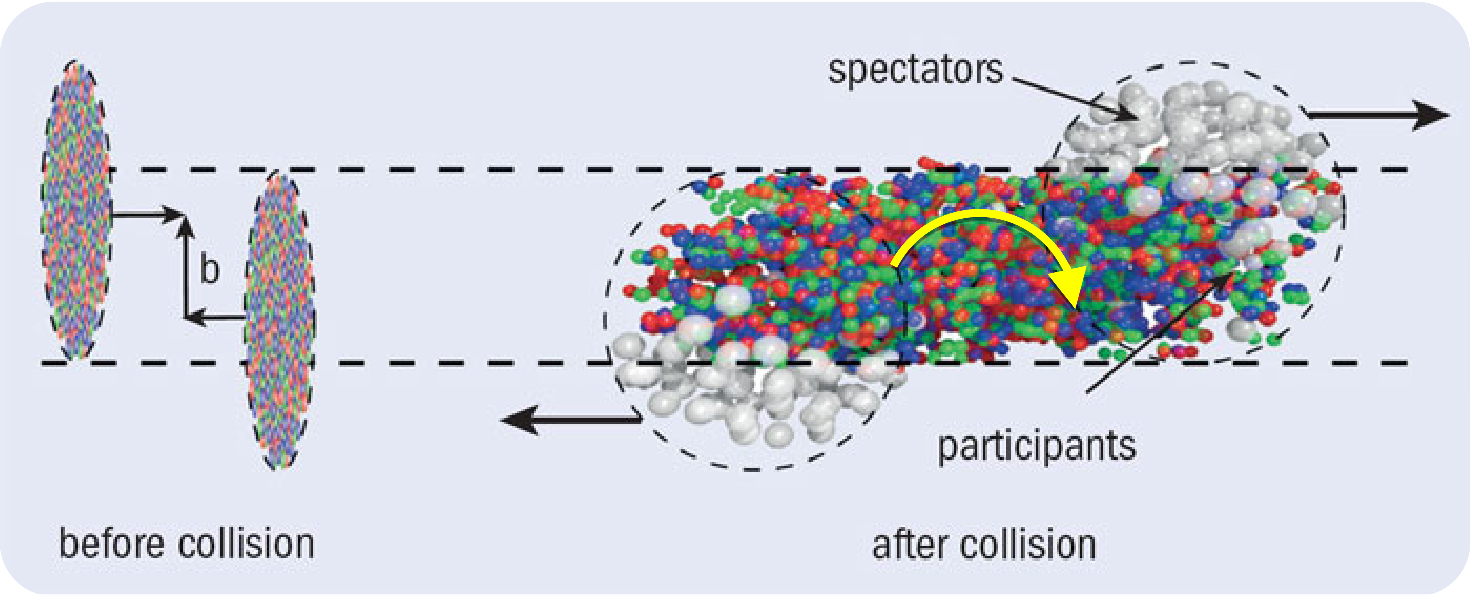
Early concept of quark polarization in HIC

Early ideas:

Initial angular momentum $\Longrightarrow$ polarized quarks $\Longrightarrow$ polarized hadrons

Z. T. Liang and X. N. Wang, Phys. Rev. Lett. 94, 102301 (2005) => predicted **tens of % polarizarion**
Z. T. Liang and X. N. Wang, Phys. Lett. B 629, 20 (2005)



Pic taken from:
Mike Lisa,
SQM2016

Change of theory paradigm

Early ideas:

Initial angular momentum $\Rightarrow$ polarized quarks $\Rightarrow$ polarized hadrons

Z. T. Liang and X. N. Wang, Phys. Rev. Lett. 94, 102301 (2005) => predicted **tens of % polarizarion**
Z. T. Liang and X. N. Wang, Phys. Lett. B 629, 20 (2005)

Later developments:

Initial angular momentum $\Rightarrow$ vortical fluid $\Rightarrow$ polarized hadrons

F. Becattini, V. Chandra, L. Del Zanna and E. Grossi, Annals Phys. 338, 32 (2013)

Spin-vorticity coupling (2010s)

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.

$$\hat{\rho} = \frac{1}{Z} \exp\left(-\hat{H}/T + \mu\hat{Q}/T + \omega\hat{J}/T\right)$$

- 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 arbitrary spin (a lat $\rho = \frac{1}{Z}\exp\left(-H/T + \mu Q/T + \omega J/T\right) P_V$ urface:

$$\langle S(x,p)\rangle = \frac{1}{2m}\frac{S(S+1)}{3}(1-f(x,p))\epsilon^{\mu\nu\rho\sigma}p_\sigma\partial_\nu\beta_\rho$$

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

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

Properties of the spin Cooper-Frye formula

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

$$\langle S(x,p) \rangle = \frac{1}{2m} \frac{S(S+1)}{3} (1 - f(x,p)) \epsilon^{\mu\nu\rho\sigma} p_\sigma \partial_\nu \beta_\rho$$

- 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
  - induced not only by "classical" vorticity, but also by temperature gradients or acceleration
- All non-zero spin hadrons are polarized $P \propto S(S+1)$

The formula allows to compute polarization at any given momentum.

The scheme to compute hyperon polarization

- Hydrodynamics with spin degrees of freedom is in initial stages of development
- No spin degrees of freedom in hadronic cascades either, therefore:

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

1. In a hydrodynamic model:

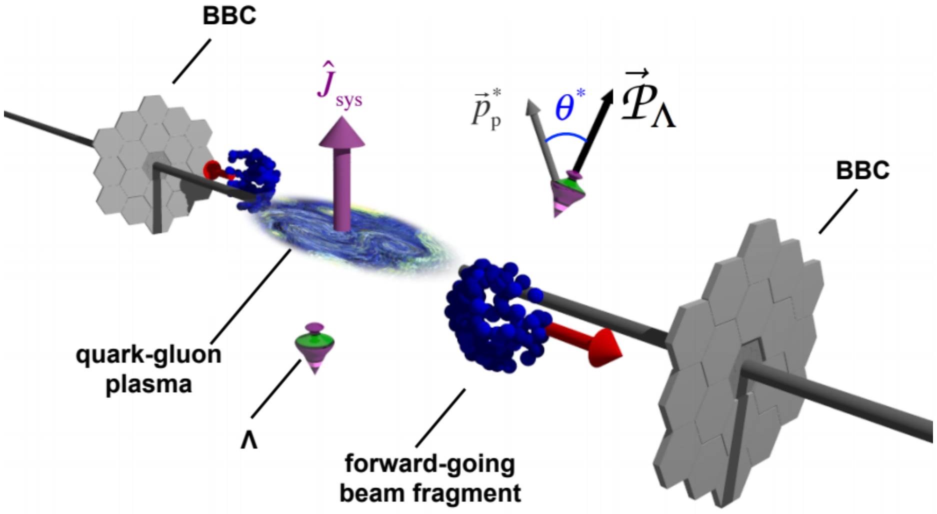
Hydrodynamic evolution → freeze-out/particlization → formula from above

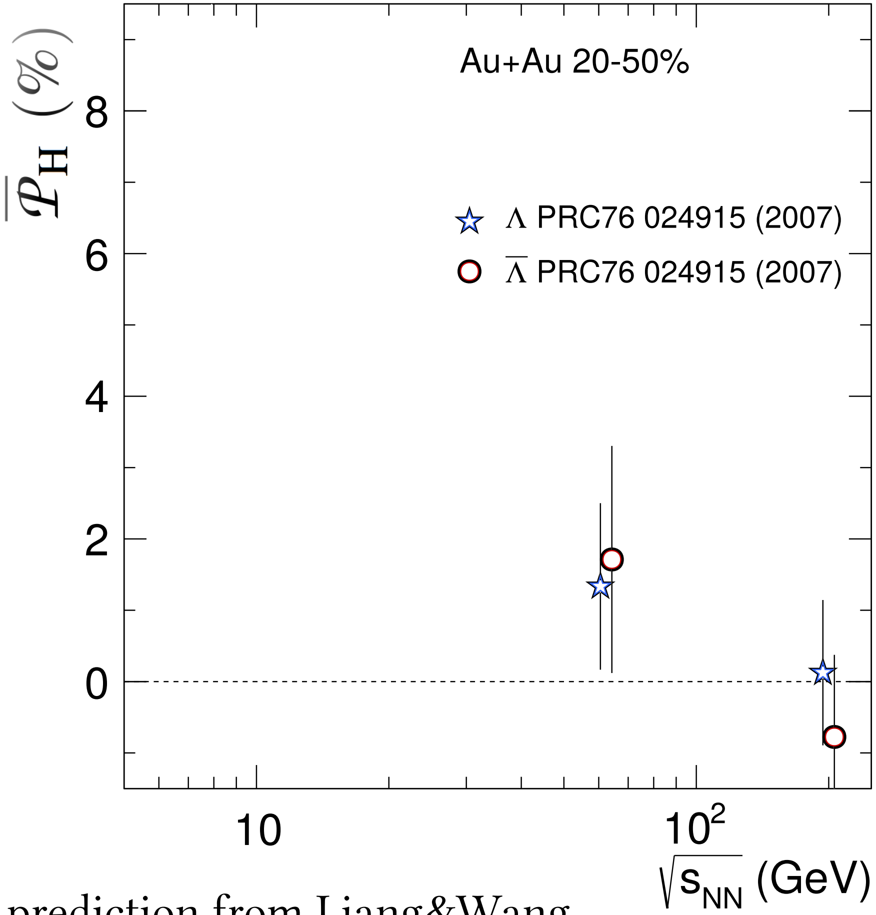
2. In a transport model:

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

The first experimental measurement (in HIC)

STAR collaboration, Phys. Rev. C 76, 024915 (2007)

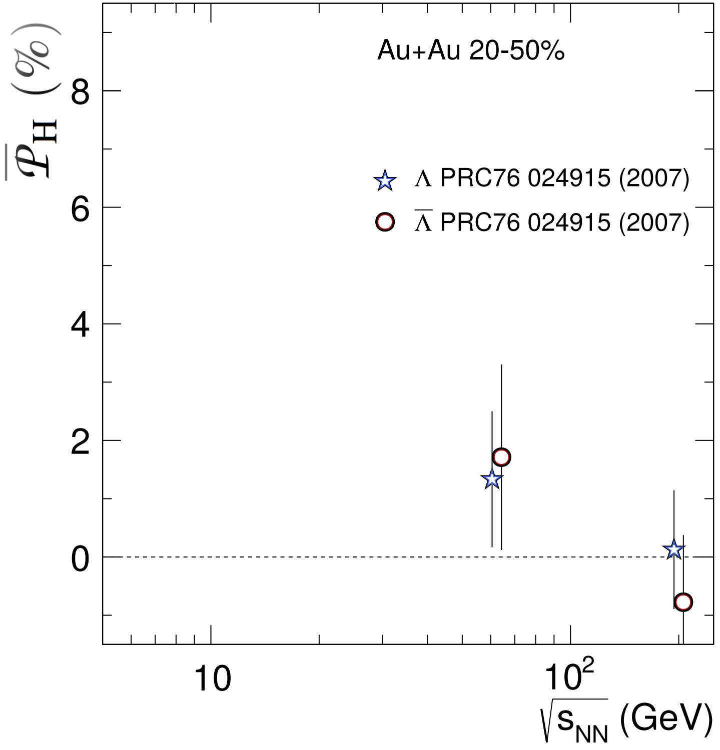




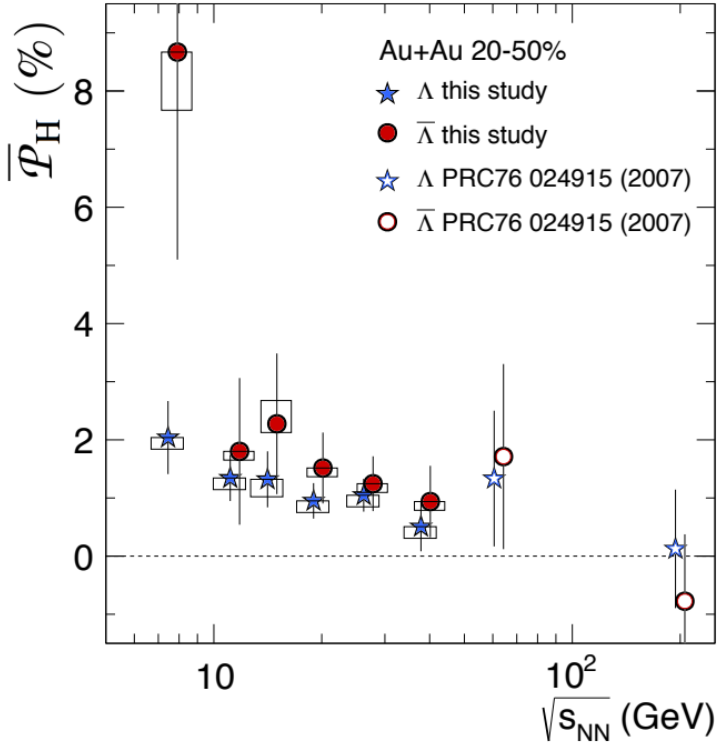
$$\mathcal{P}_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{1}{R_{EP}^{(1)}}\langle\sin(\psi_1 - \phi_p^*)\rangle$$

Result: upper limit $|P_H|<0.02$, much less than the prediction from Liang&Wang

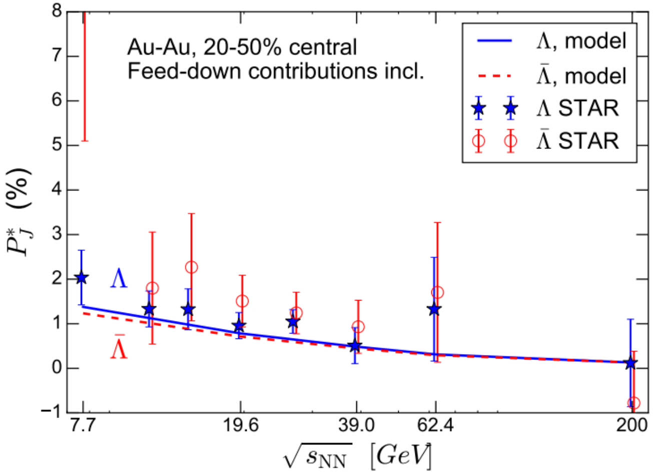
Updated measurement by STAR



STAR Collaboration, Nature 548, 62 (2017)

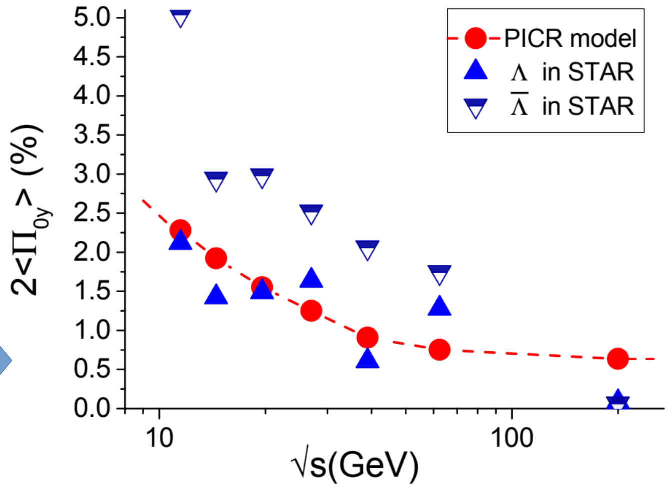


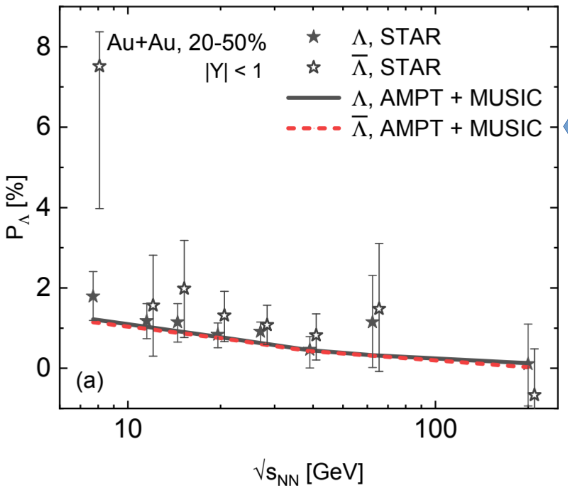
Global (p_T integrated) polarization: agreement with hydro models



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

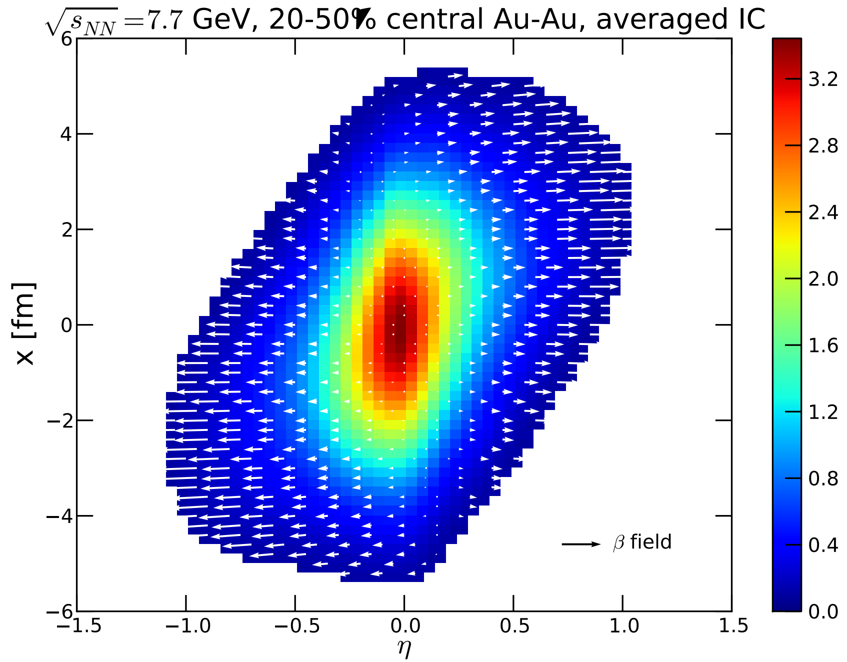
Why does the polarization decrease with sqrt(s)?

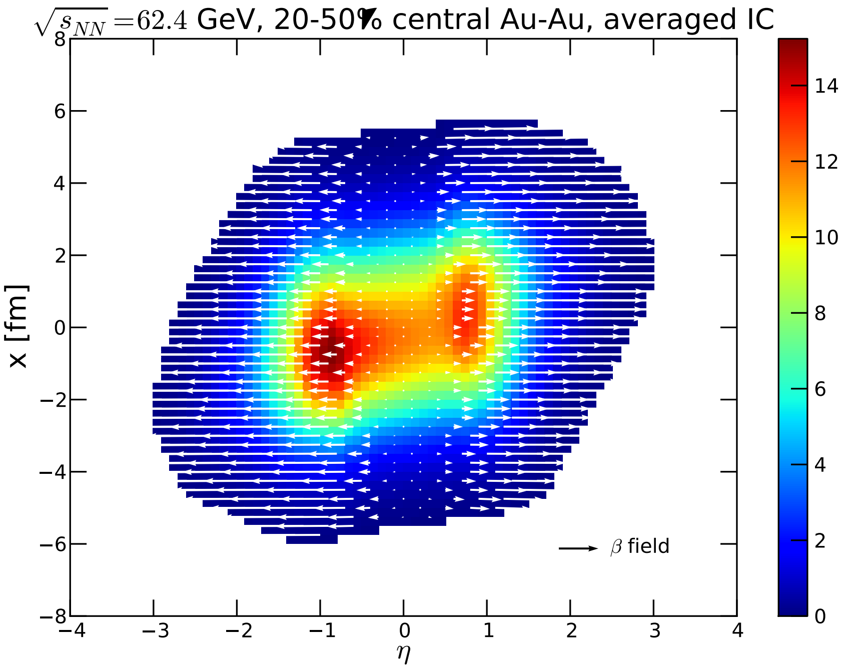
Low collision energies:

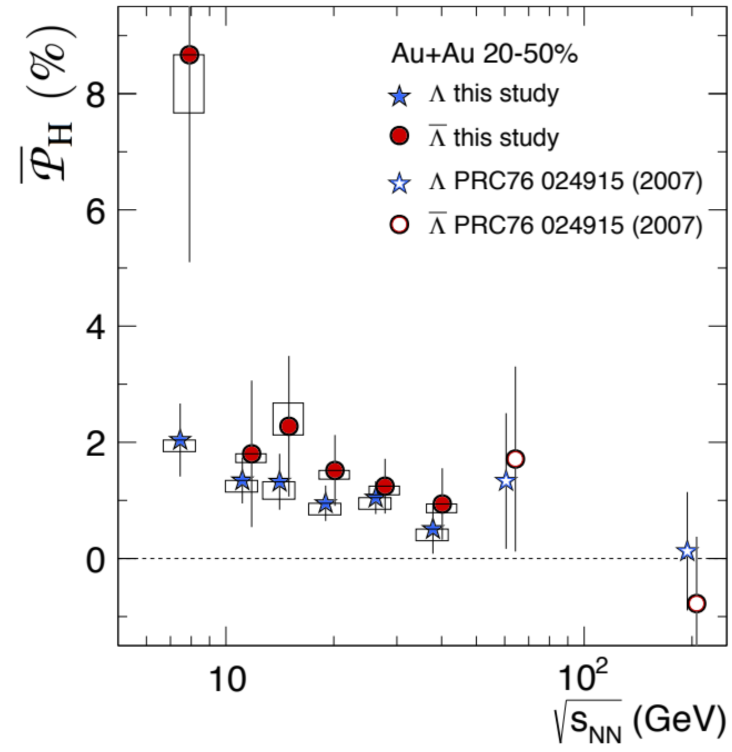
- baryon stopping
- angular momentum stays around midrapidity
- hydro phase is short

High collision energies:

- baryon transparency
- angular momentum carried away to forward/backward rapidities,
- hydro phase lasts longer







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 $\omega \approx 10^7 s^{-1}$.

STAR Collaboration, Nature 548, 62 (2017)

NB: the medium is not actually rotating.
Vorticity is generated by flow gradients.

$\Lambda - \bar{\Lambda}$ splitting

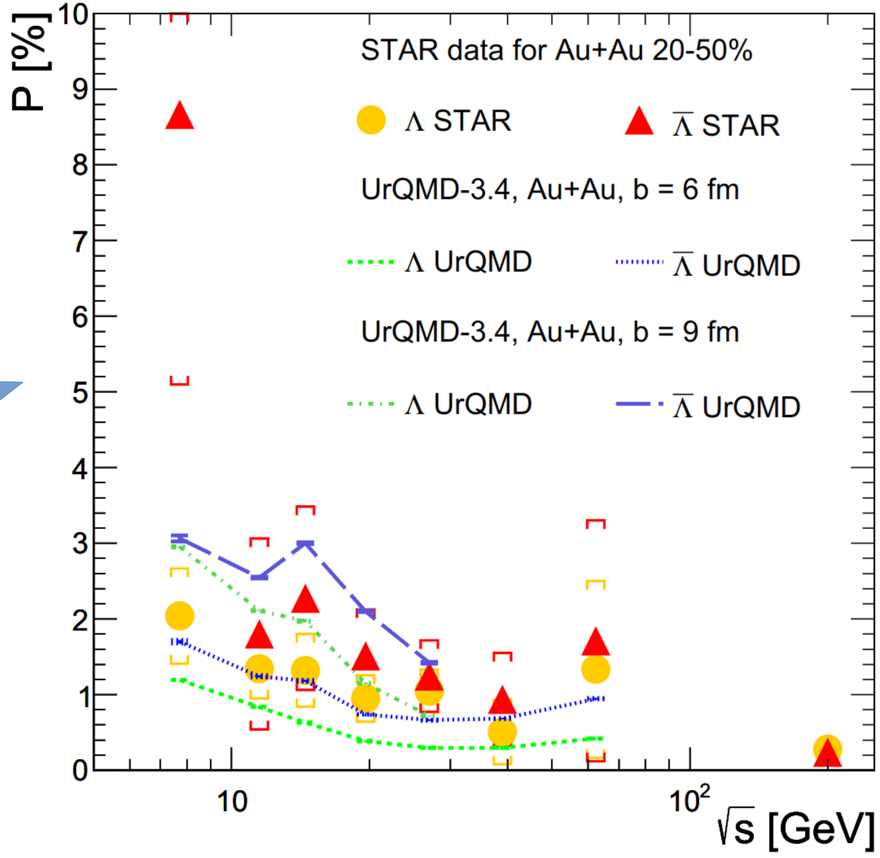
Explanations:

- magnetic field?

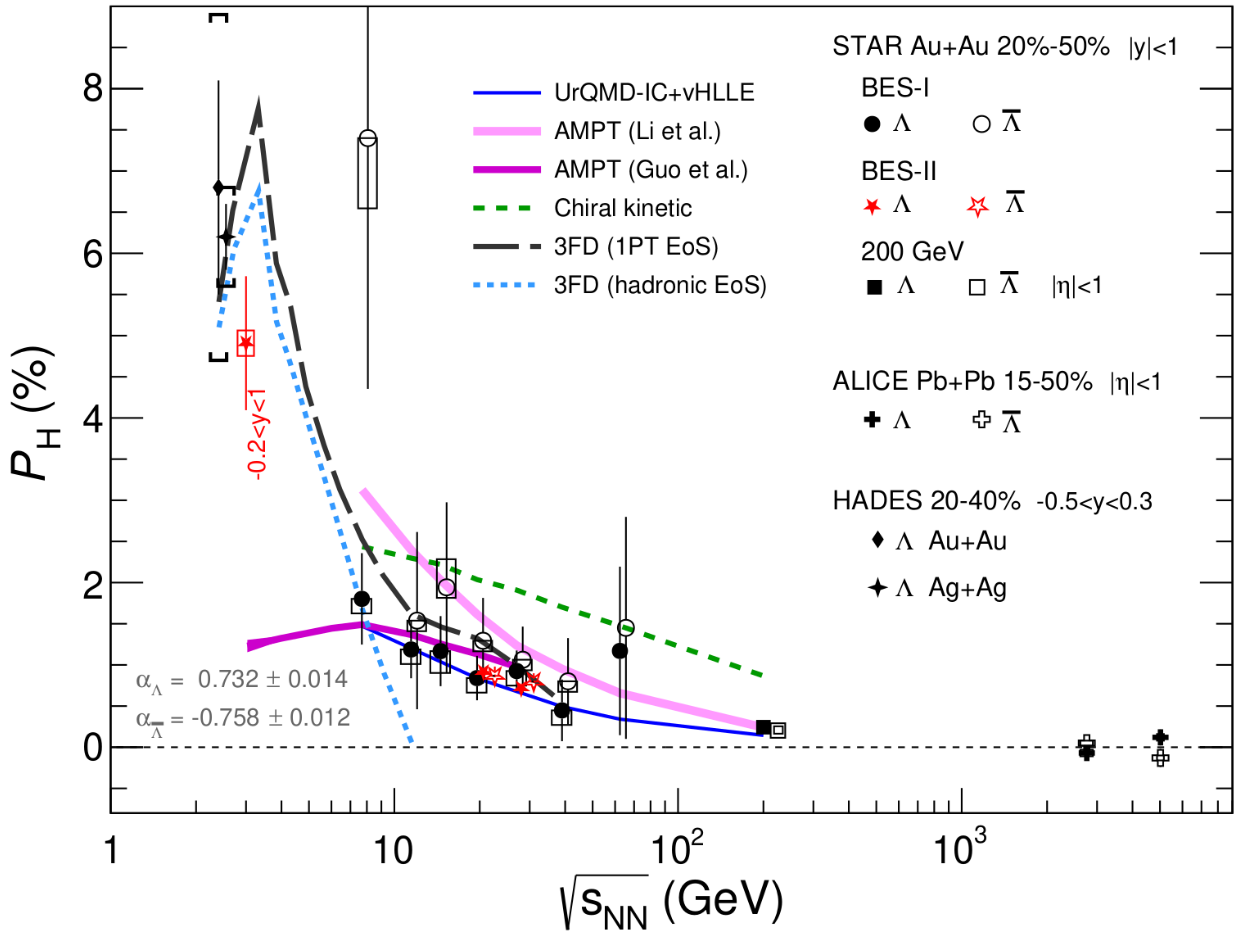
Becattini, IK, Lisa, Upsal, Voloshin, Phys. Rev. C 95, 054902 (2017)

- different production points

Vitiuk, L. Bravina, E. Zabrodin, Physics Letters B 803, 10 April 2020, 135298



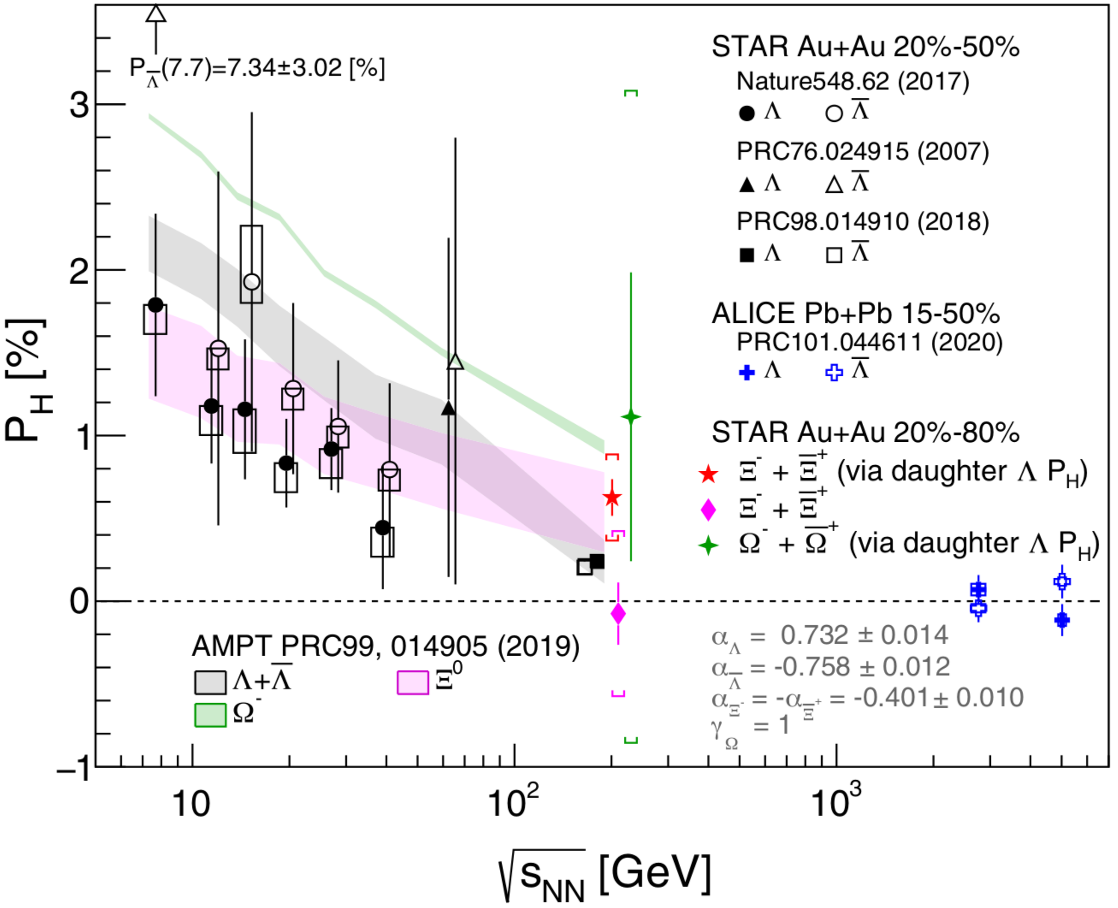
More experimental measurements (circa 2023)



Polarization remains high at HADES energies, $\sqrt{s}$~2.4 GeV,

whereas some models predict decrease when going to very low energies.

More baryon species

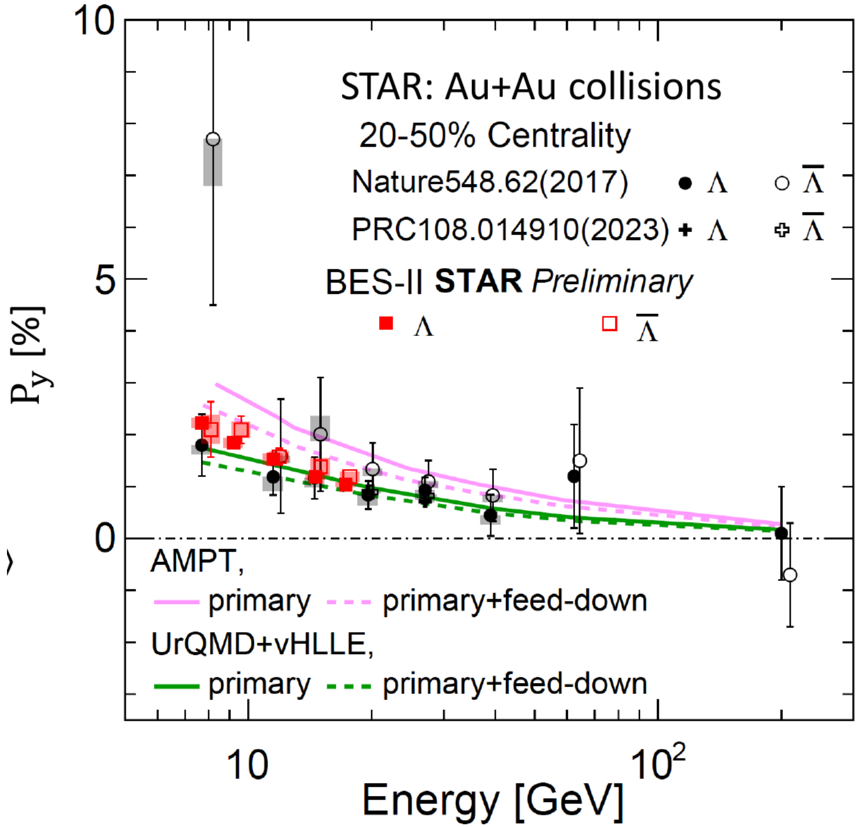


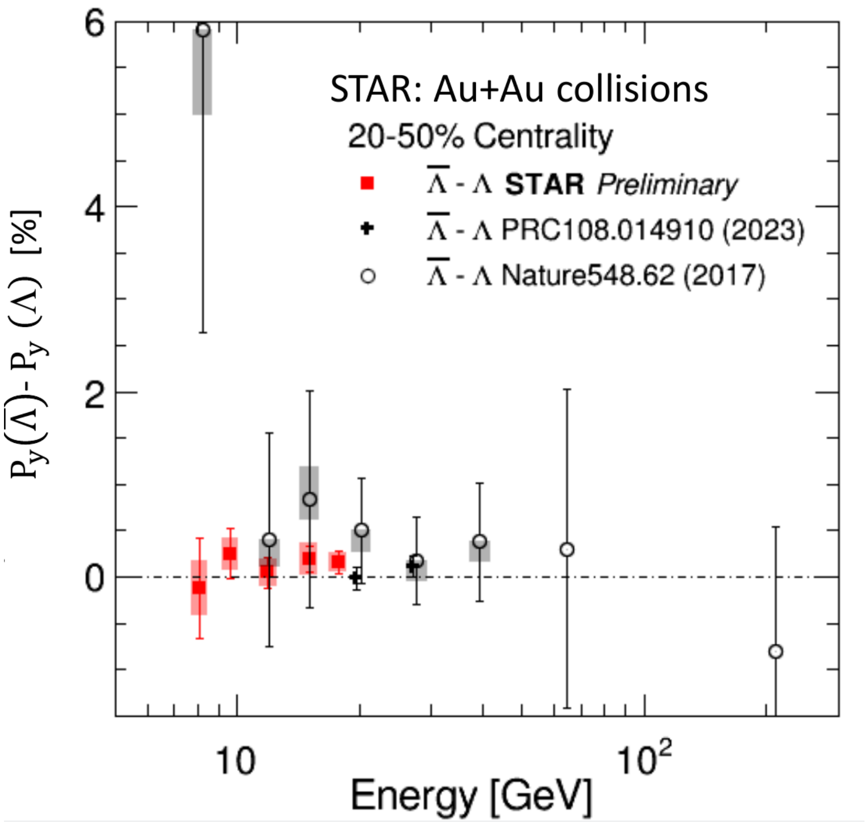
Ω baryon is predicted to have stronger polarization due to the S(S+1) factor.

Only measured at top RHIC, but looks consistent with model predictions.

2024 update: no Lambda – anti-Lambda splitting

Quiang Hu (STAR), SQM2024



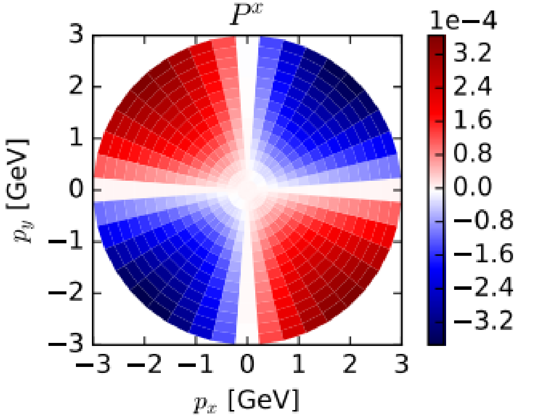


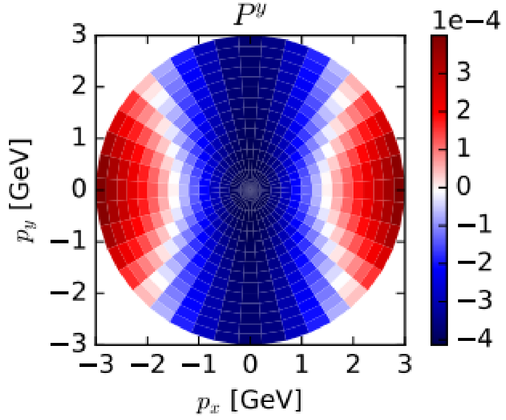
From BES-II data, no splitting between Λ and anti-Λ is observed. No magnetic field or no μ_B effect?

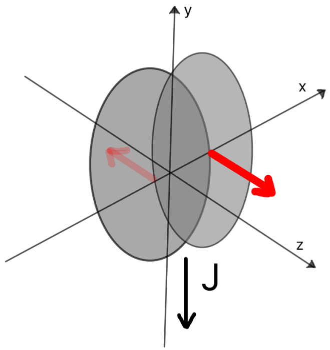
Local (p_T-differential) polarization

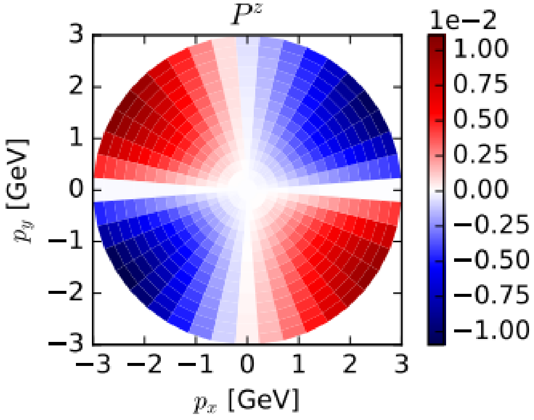
Local (p_T differential) hyperon polarization

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





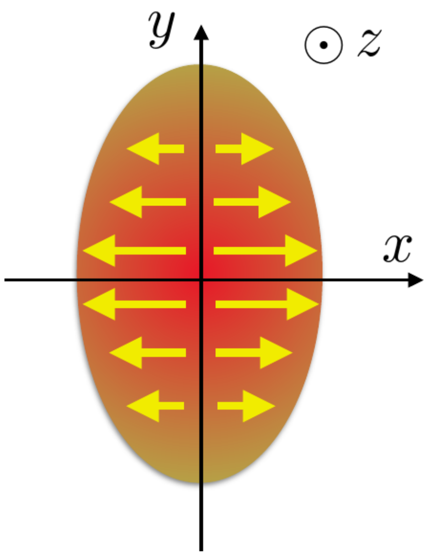


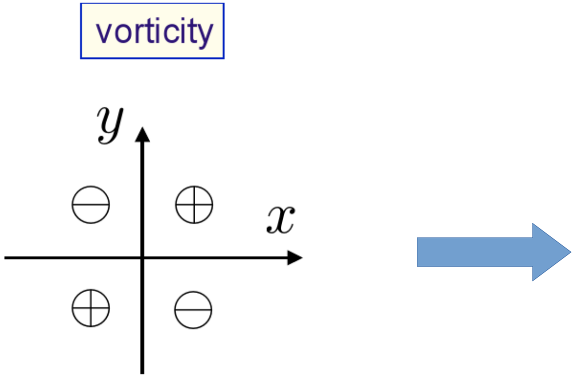


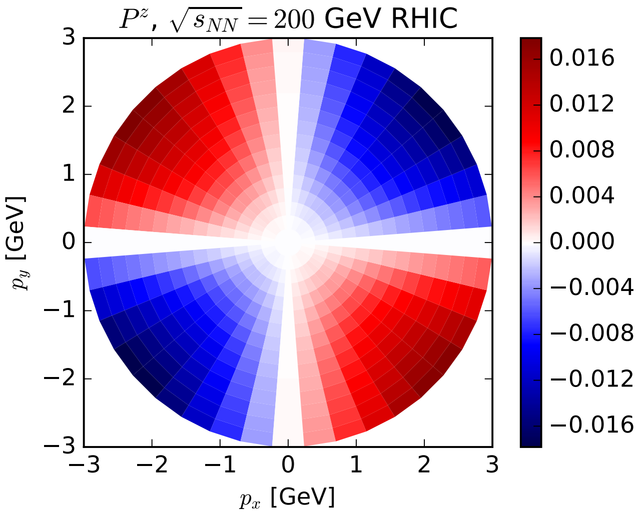
- When integrated over p_T, only P^y component survives
- However, at a given p_T and φ, all 3 components are non-zero

A closer look at the quadrupole structure

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



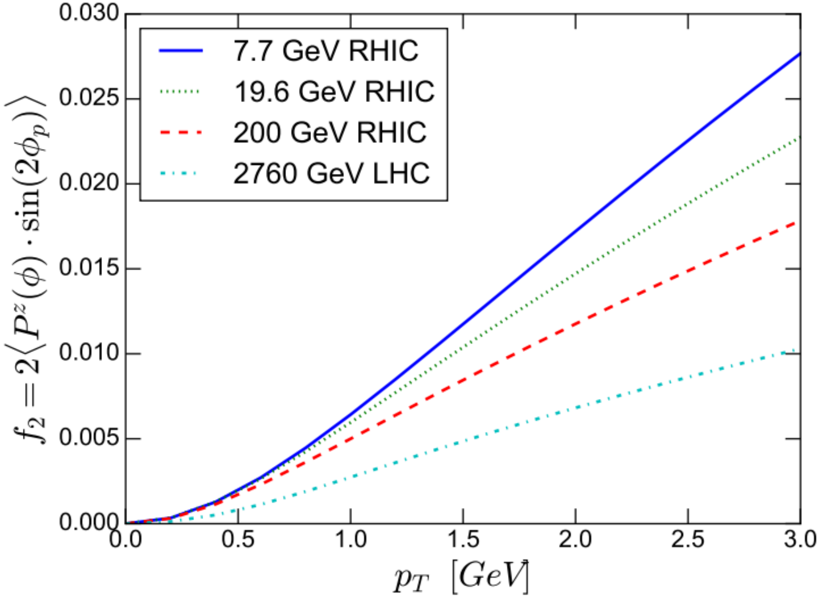




* It does not work quantitatively, since there are time derivatives and temperature gradients involved.

$P^z \Leftrightarrow$ anisotropic flow

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



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

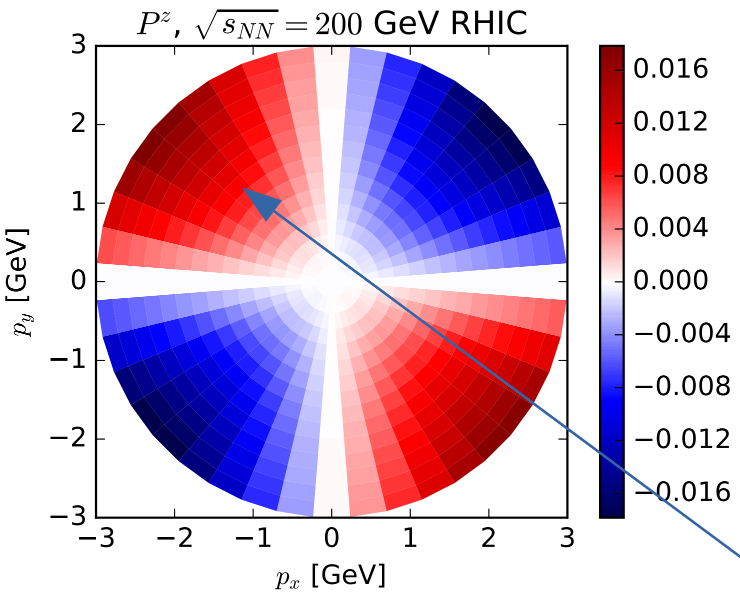
- Requires identification of event plane Ψ
- In a blast-wave model:

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

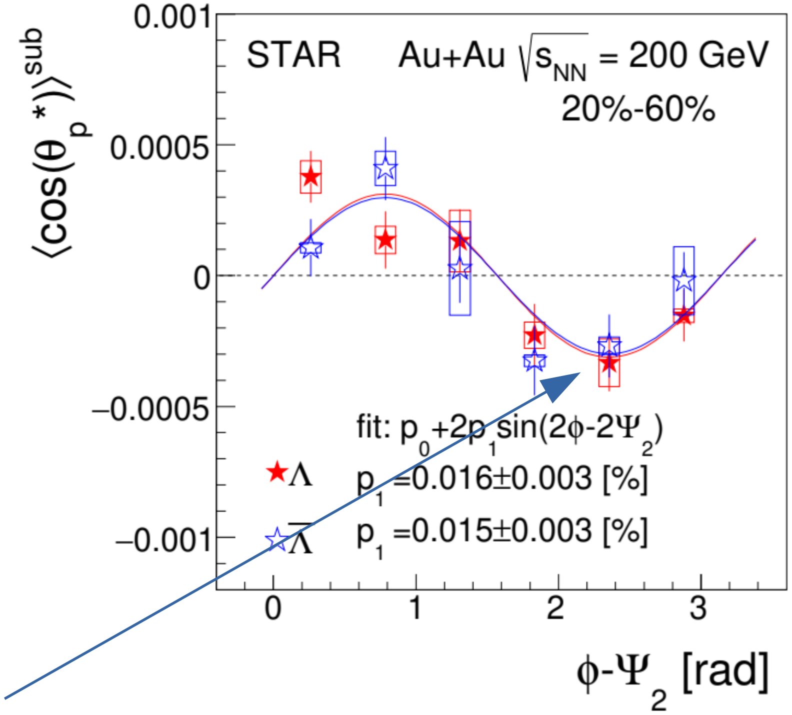
P^z emerges because of anisotropic transverse expansion, same way as v_2

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

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



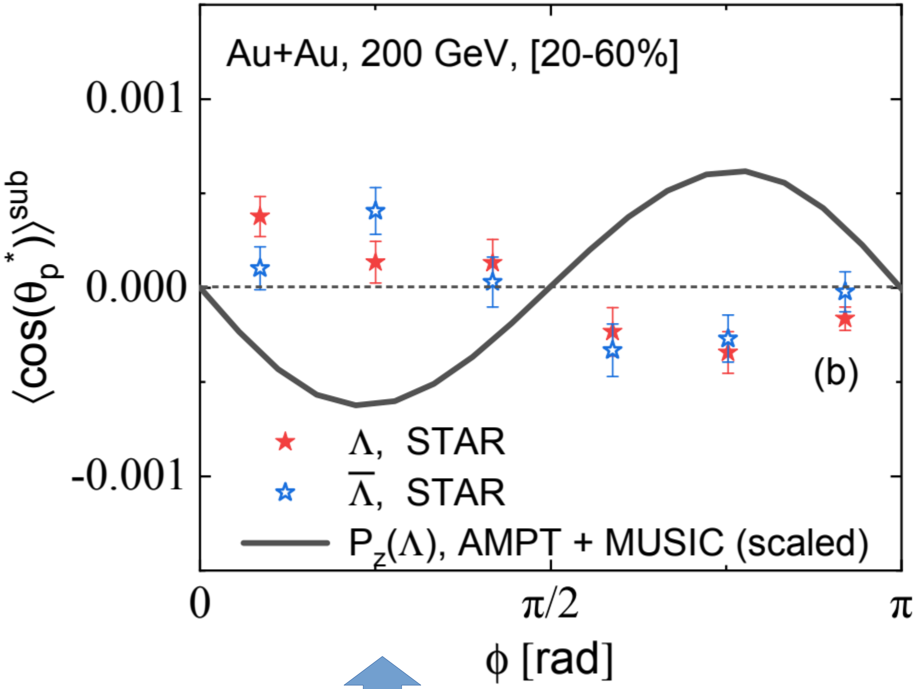
STAR measurement: Phys. Rev. Lett. 123, 132301 (2019)



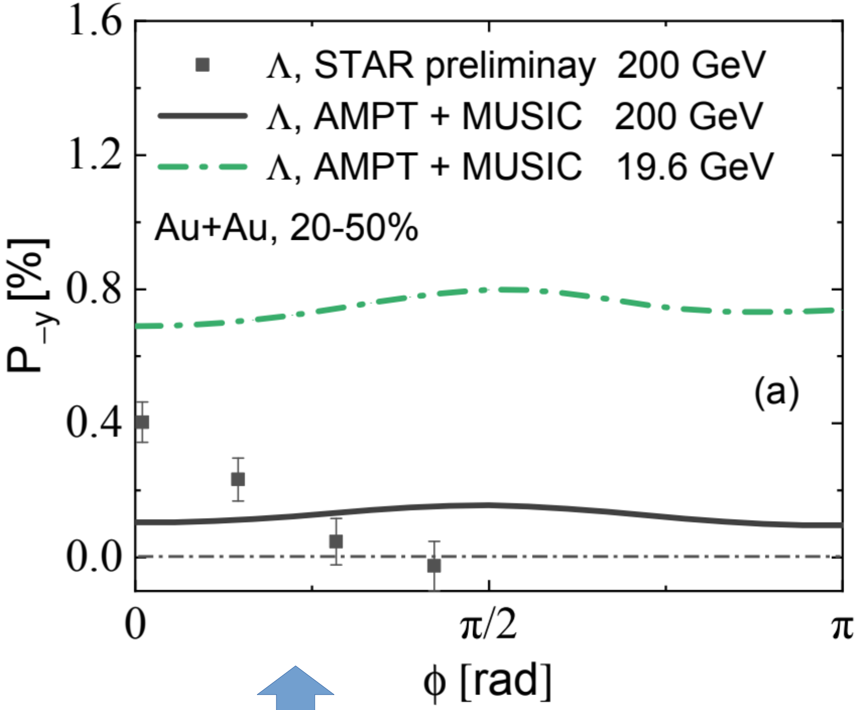
The signs are opposite!

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

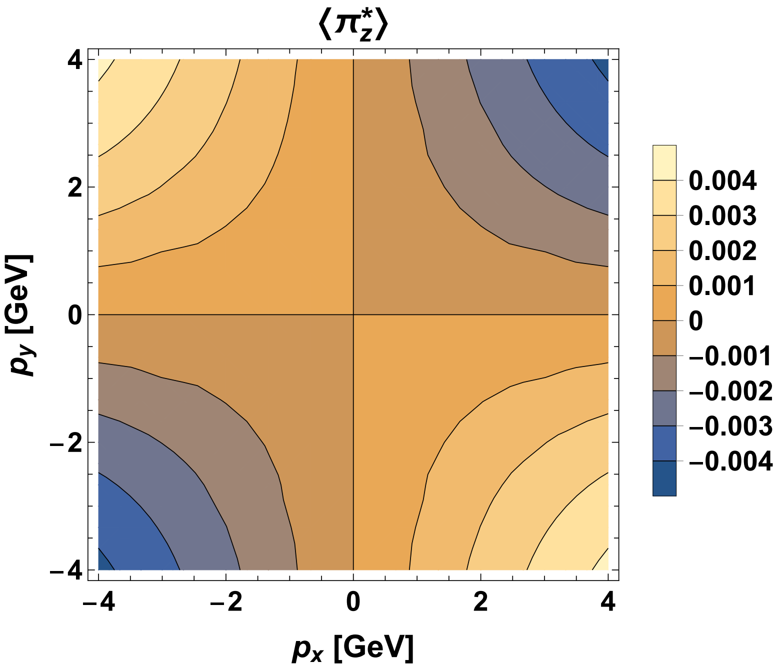


Puzzle #2

Early attempts to explain the sign puzzle

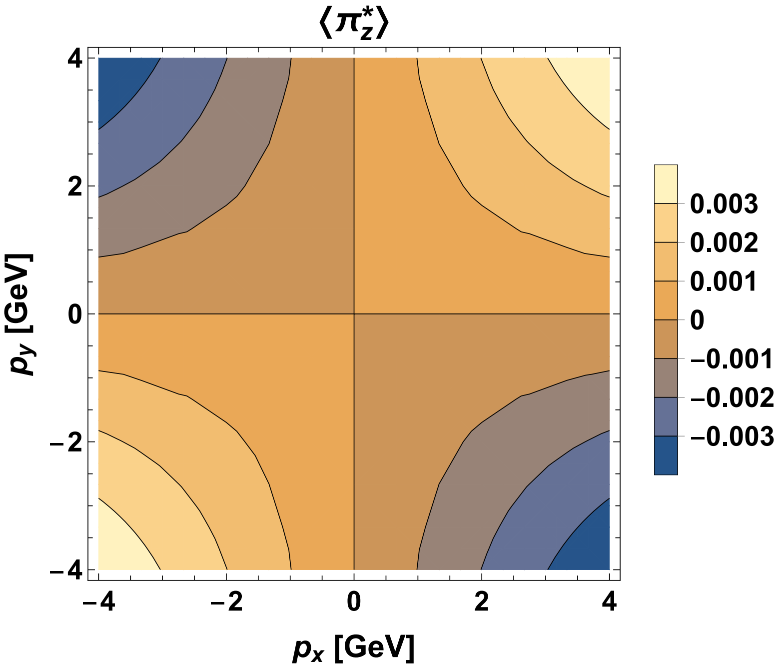
W. Florkowski, A. Kumar, R. Ryblewski, A. Mazeliauskas, Phys. Rev. C 100, 054907 (2019)

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

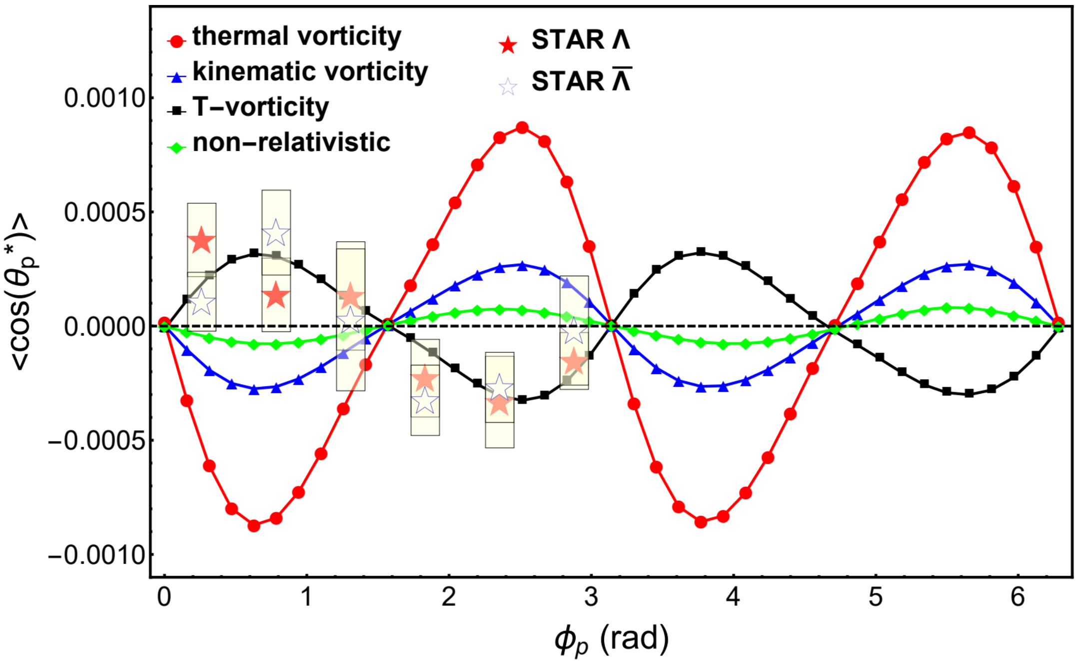


$$\varpi^{\mu\nu}_{\mathrm{proj}} = \varpi_{\alpha\beta}\Delta^\mu_\alpha \Delta^\nu_\beta$$

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)



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

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

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

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

Back to theory (2021)

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

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

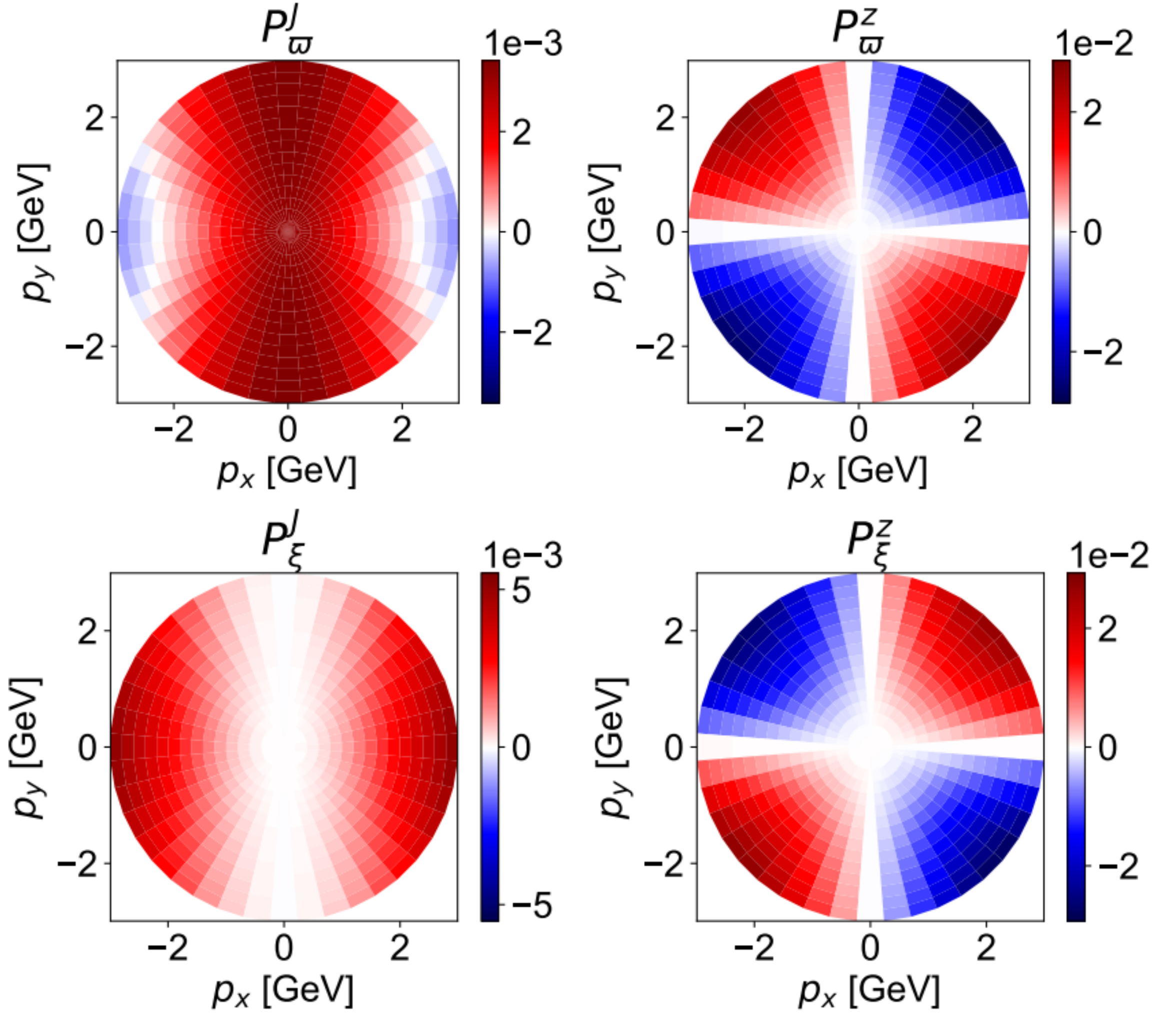
$$S^\mu_\varpi(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int_\Sigma \Sigma\cdot p\, n_F(1-n_F)\varpi_{\rho\sigma}}{\int_\Sigma \Sigma\cdot p\, n_F} \qquad \varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu\right)$$

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

new!

A 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

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

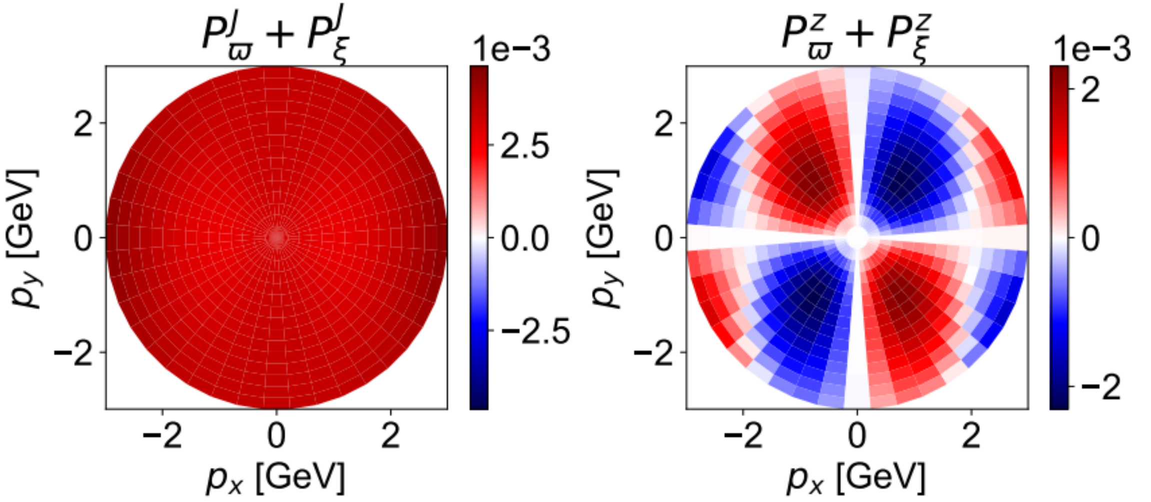
(old spin-vorticity coupling term)

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:

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

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

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

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

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

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

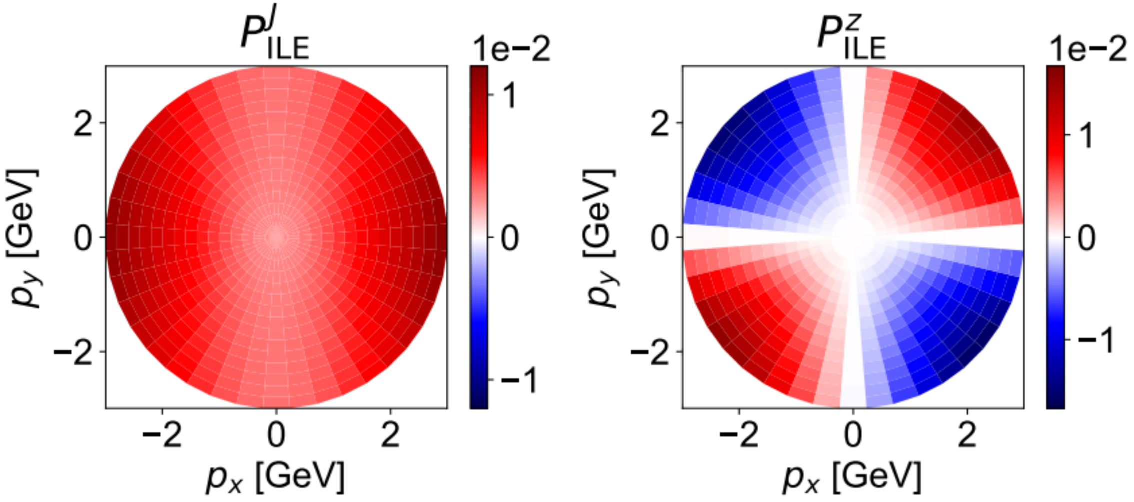
$$\hat{\rho} \simeq \frac{1}{Z_{\rm LE}} \exp\left[-\beta_\nu(x)\hat{P}^\nu + \; - \frac{1}{T} \partial_\lambda u_\nu(x) \int_\Sigma d\Sigma_\mu(y)(y-x)^\lambda \hat{T}^{\mu\nu}(y) \right].$$

Improving the original expansion (2)

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

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

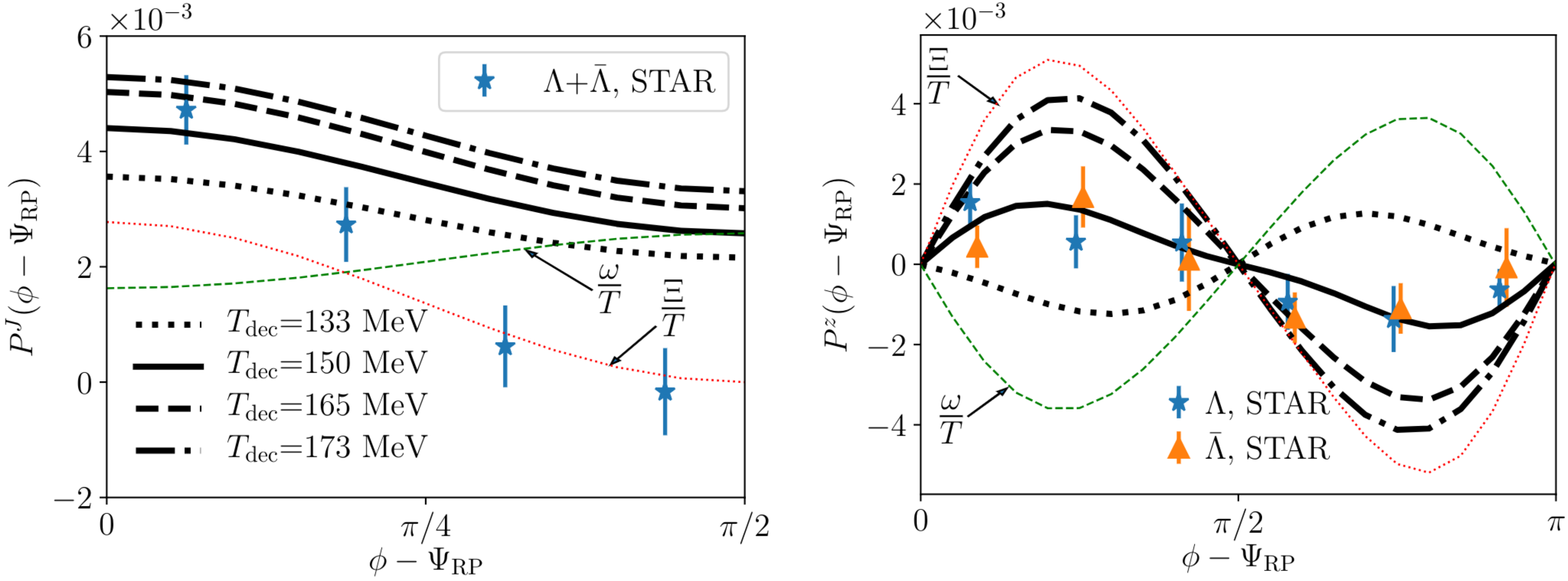
which depends on **kinematic vorticity** $\omega_{\rho\sigma} = \frac{1}{2} (\partial_\sigma u_\rho - \partial_\rho u_\sigma)$, which leads to the following result:



Good agreement with the experiment!

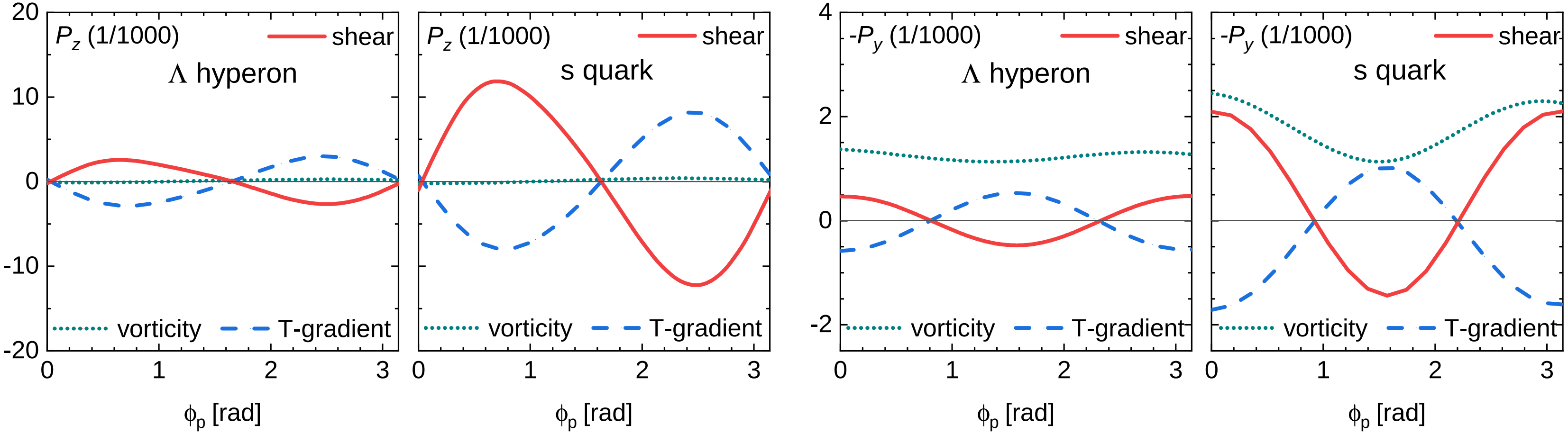
The updated formalism vs. the experimental data

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



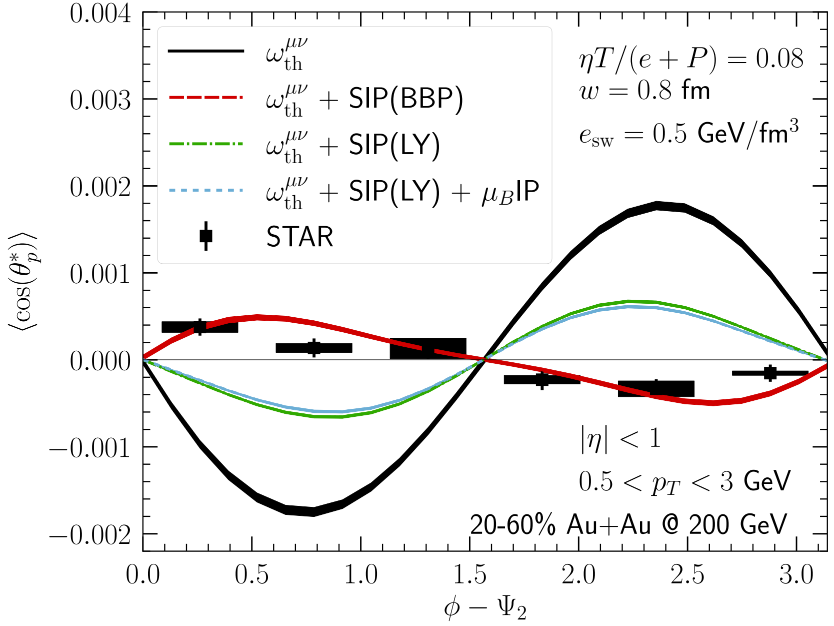
Baochi Fu, Shuai Y. F. Liu, Longgang Pang, Huichao Song, Yi Yin, arXiv:2103.10403

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-

The expression for the shear induced contribution isn't settled

Sahr Alzhrani, Sangwook Ryu, Chun Shen, arXiv:2203.15718



Becattini, Buzzegoli, Palermo (BBP) arXiv:2103.10917

$$\mathcal{A}^{\mu}_{\rm BBP} = -\varepsilon^{\mu\rho\sigma\tau}\left(\frac{1}{2}\omega_{\rho\sigma}p_\tau + \frac{1}{E}\hat{t}_\rho \xi_{\sigma\lambda}p^\lambda p_\tau\right).$$

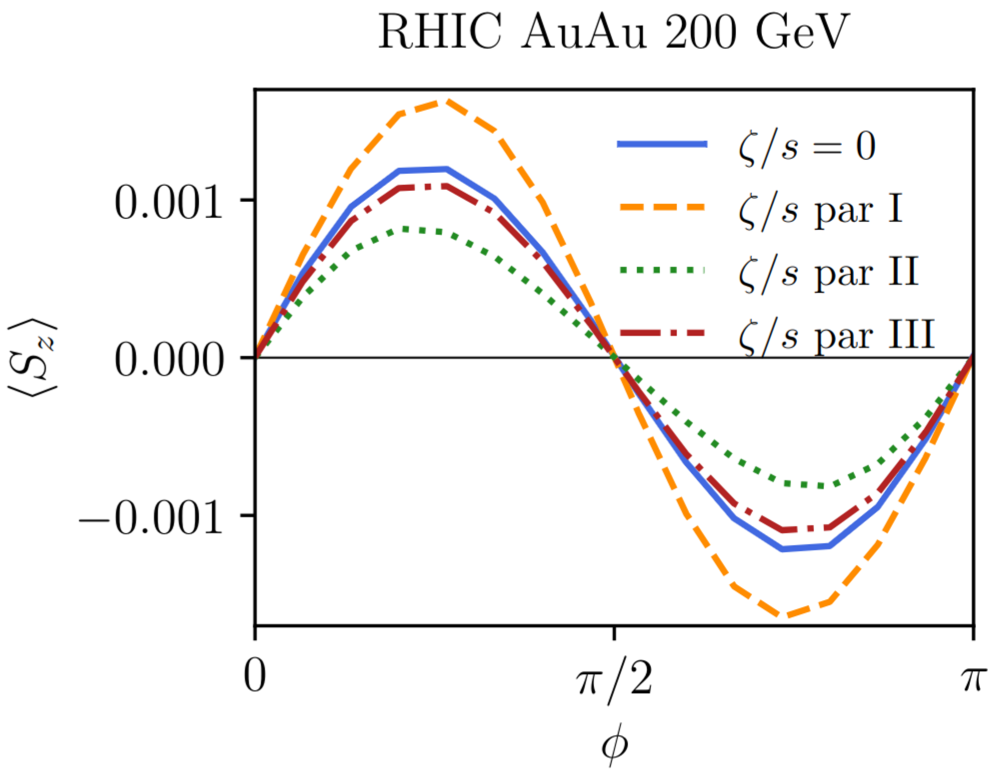
Shuai Liu, Yi Yin (LY), arXiv:2103.09200

$$\mathcal{A}^{\mu}_{\rm LY} = -\varepsilon^{\mu\rho\sigma\tau}\left[\frac{1}{2}\omega_{\rho\sigma}p_\tau + \frac{1}{E}u_\rho \xi_{\sigma\lambda}p^\lambda_\perp p_\tau + \frac{b_i}{\beta E}u_\rho p^\perp_\sigma \partial^\perp_\tau(\beta\mu_B)\right]$$

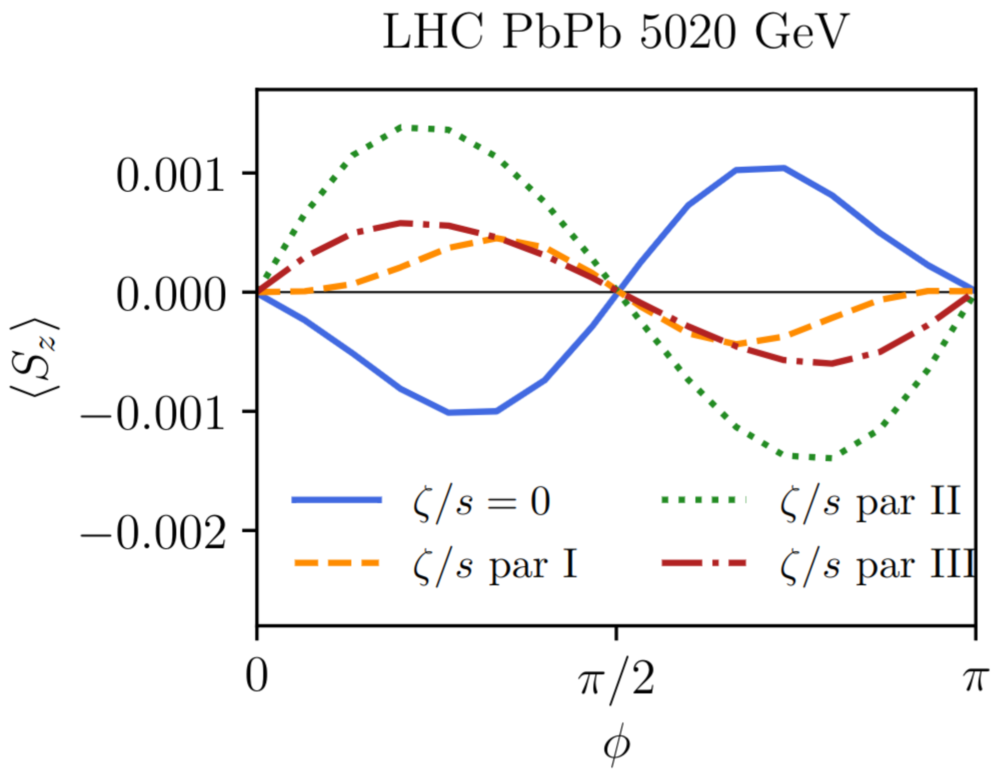
p*u instead?

Pz at RHIC + LHC: bulk viscosity is important

Palermo, Grossi, IK, Becattini, arXiv:2404.14295



Top RHIC: sign is correct regardless of ζ/s



5.02 TeV LHC: bulk viscosity is needed

More effects inducing local polarization

Liu, Huang, Sci.China Phys.Mech.Astron. 65 (2022) 272011

$$\langle S^\mu(x,p)\rangle = \frac{1}{2m}\frac{S(S+1)}{3}(1-f(x,p))\left\{\epsilon^{\mu\nu\rho\sigma}p_\sigma\partial_\nu\beta_\rho + 2\epsilon^{\mu\nu\rho\sigma}\frac{p_\rho}{p\cdot n}n_\sigma\left[p^\lambda(\xi_{\nu\lambda}+\Theta_{\nu\lambda}) + \frac{1}{4}\partial_\nu\frac{\mu}{T}\right]\right\}$$

spin potential (requires spin hydro) → $\Theta_{\nu\lambda}$

“spin Hall” → $\partial_\nu \frac{\mu}{T}$

thermal vorticity (well established) → $\epsilon^{\mu\nu\rho\sigma}p_\sigma\partial_\nu\beta_\rho$

thermal shear (~established) → $\xi_{\nu\lambda}$

Conclusions

- 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.
- p_T-differential P^J and P^z polarization components: a less settled picture.
  There are competing explanations for the P^z sign puzzle:
  - vorticity + thermal shear and iso-thermal freeze-out
  - vorticity + thermal shear and s-quark memory
- Overall, the p_T-differential polarization observables seem to be sensitive probes of the space-time dynamics.
- There seem to be more effects generating spin polarization in the fluid dynamic picture
- Fluid dynamics with spin DOF is at initial stages of development