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Polarization in relativistic nuclear collisions

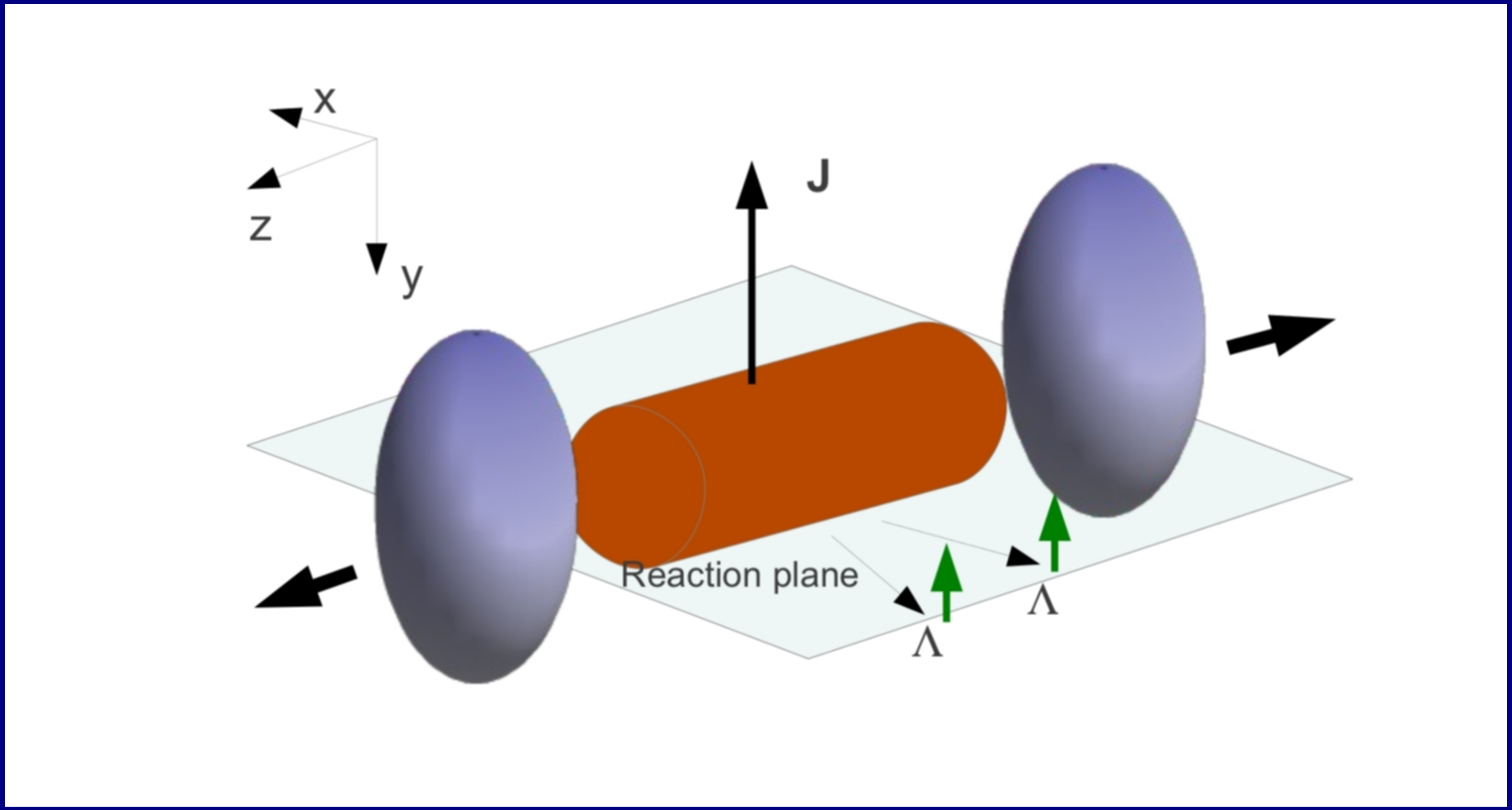
OUTLINE

- Introduction
- Status of the field and outlook
- Importance of numerical computation and plan

WP1 meeting March 6 2023

Peripheral collisions: large angular momentum

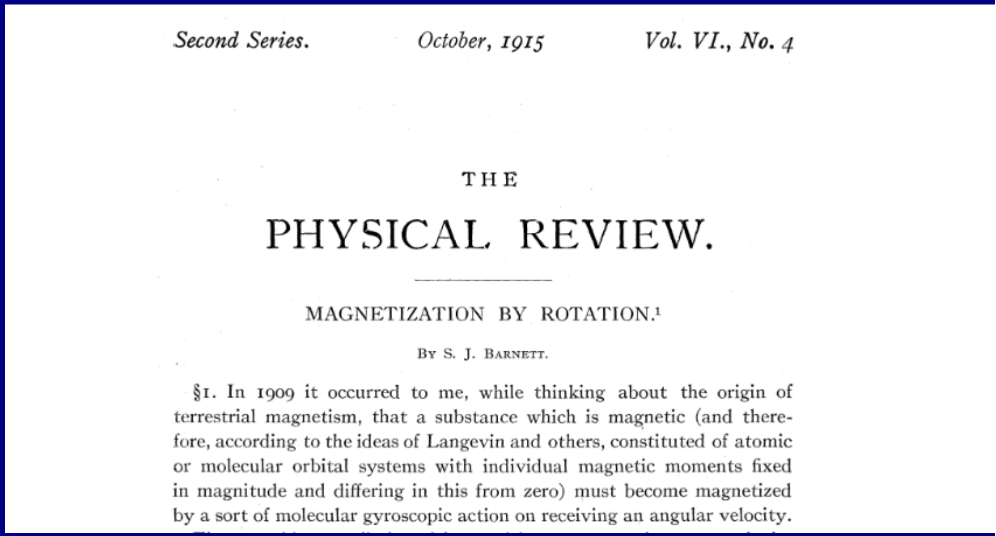
Peripheral collisions ➡ Angular momentum ➡ Global polarization w.r.t reaction plane



Barnett effect

S. J. Barnett, *Magnetization by Rotation,*

Phys. Rev. 6, 239–270 (1915).



Second Series. October, 1915 Vol. VI., No. 4

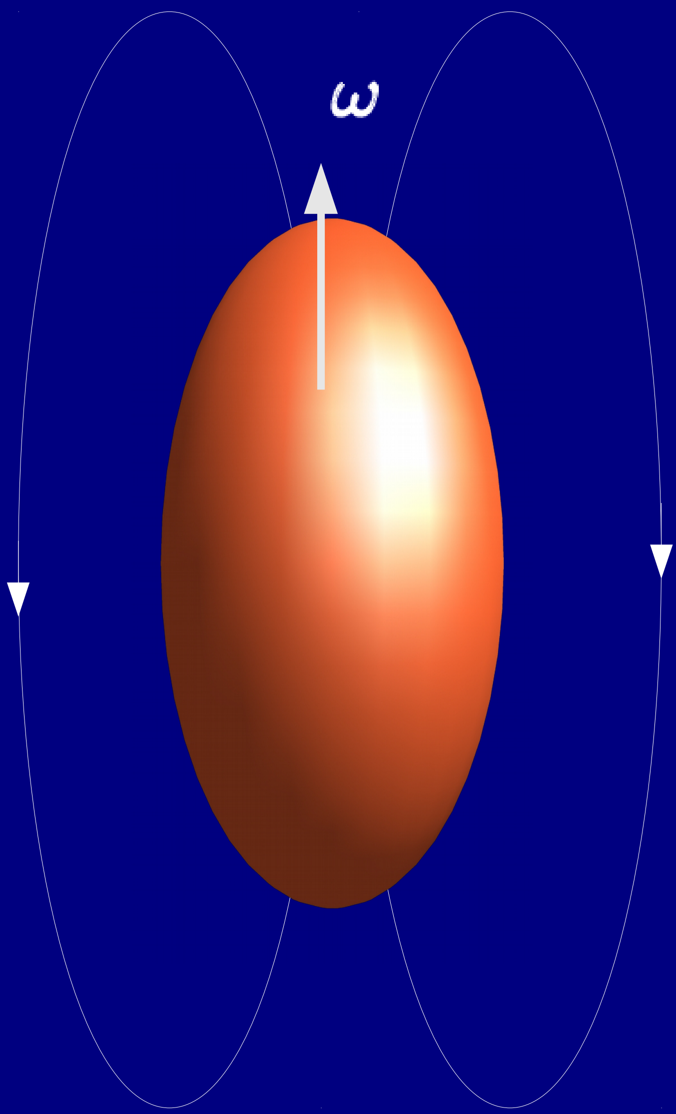
THE

PHYSICAL REVIEW.

MAGNETIZATION BY ROTATION.[1]

By S. J. Barnett.

§1. In 1909 it occurred to me, while thinking about the origin of terrestrial magnetism, that a substance which is magnetic (and therefore, according to the ideas of Langevin and others, constituted of atomic or molecular orbital systems with individual magnetic moments fixed in magnitude and differing in this from zero) must become magnetized by a sort of molecular gyroscopic action on receiving an angular velocity.



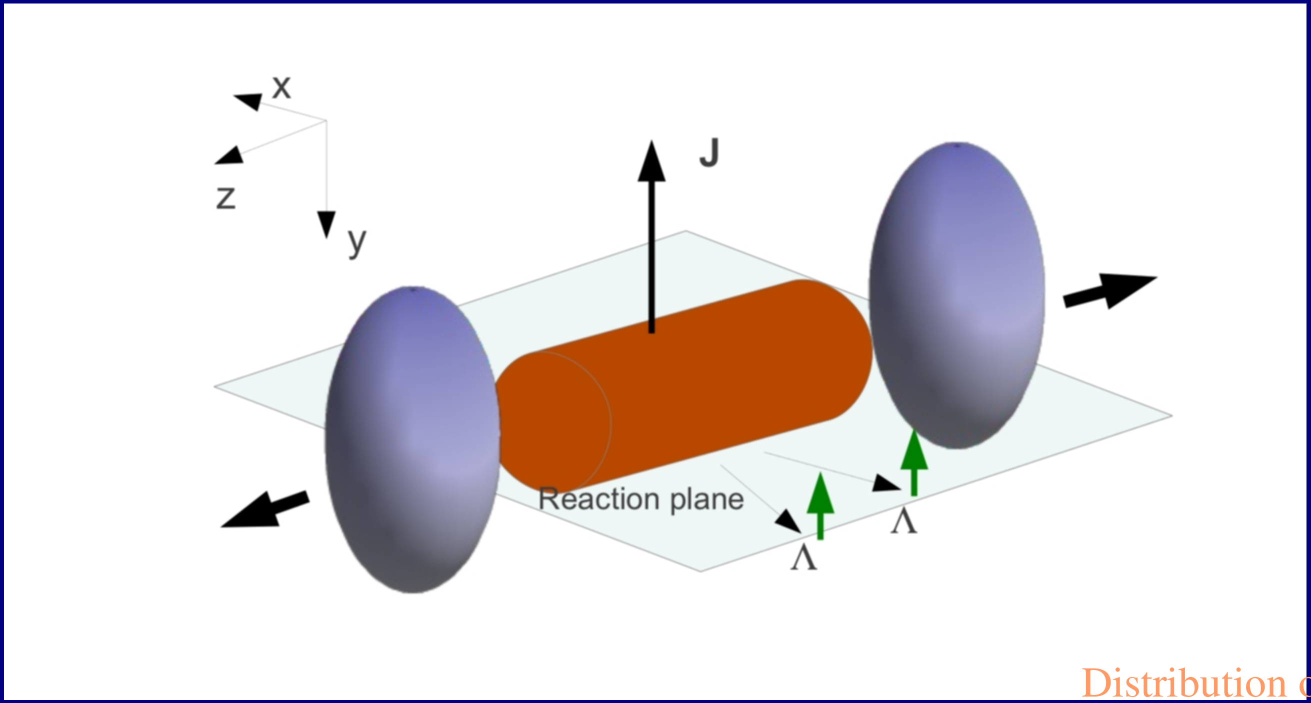
Spontaneous magnetization of an uncharged body when spun around its axis, in quantitative agreement with the previous polarization formula

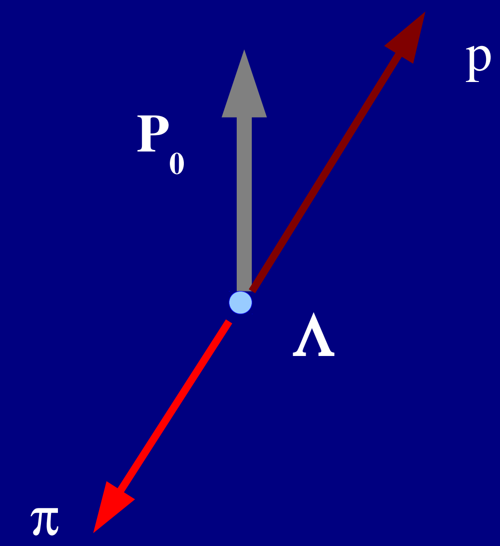
$$M = \frac{\chi}{g}\omega$$

It can be seen as a dissipative transformation of the orbital angular momentum into spin of the constituents. The angular velocity decreases and a small magnetic field appears; this phenomenon is accompanied by a heating of the sample. Requires a spin-orbit coupling.

How to observe it: global Λ polarization

Because of parity violation, the polarization vector of Λ can be measured in its decay Into a proton and a pion





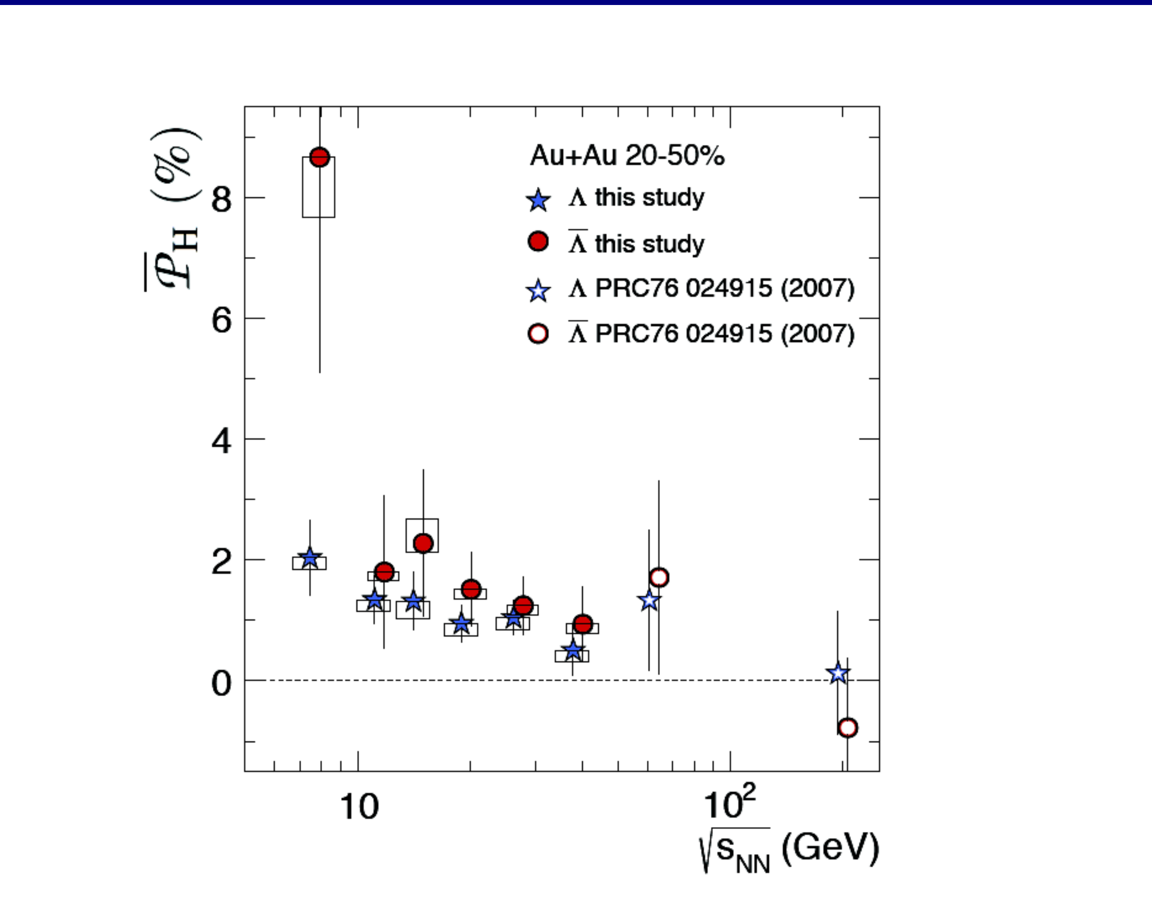
Distribution of protons in the Λ rest frame

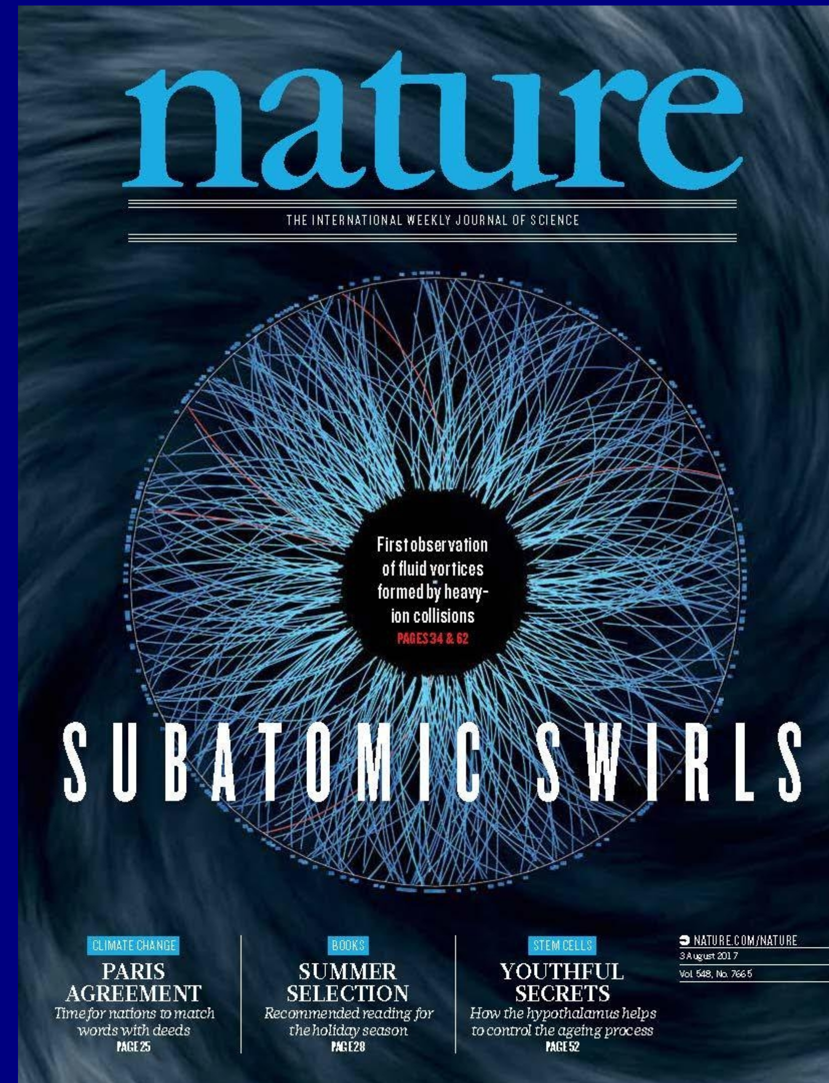
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \frac{1}{4\pi}(1 + \alpha \mathbf{P}_0 \cdot \hat{\mathbf{p}}^*) \qquad \mathbf{P}_0(p) = \mathbf{P}(p) - \frac{\mathbf{p}}{\varepsilon(\varepsilon + m)}\mathbf{P}(p)\cdot\mathbf{p}$$

α = 0.642 → 0.75 (!) PDG 2020

First positive signal of this phenomenon found in 2017

STAR Collaboration, *Global Lambda hyperon polarization in nuclear collisions,* Nature 548 62-65, 2017

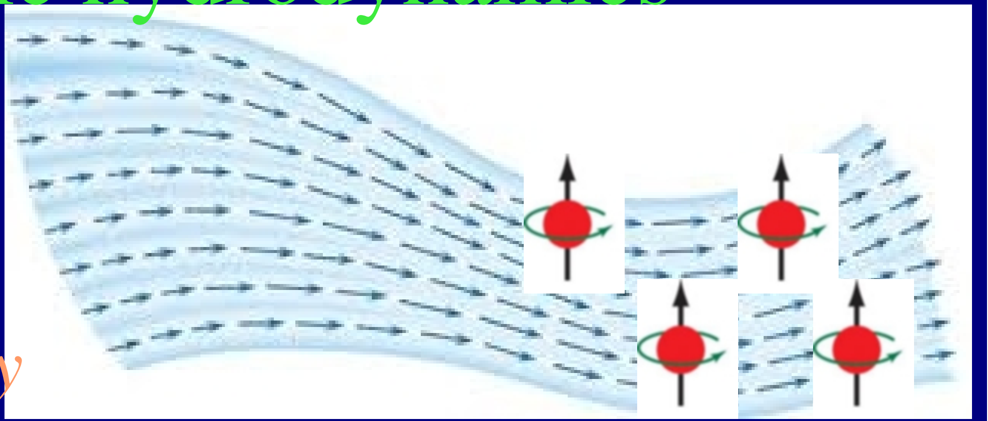




Particle and antiparticle have the same polarization sign.
This shows that the phenomenon cannot be driven
by a mean field (such as EM) whose coupling is *C-odd.*
Definitely favours the thermodynamic (equipartition) interpretation

Polarization and relativistic hydrodynamics

F. B., V. Chandra, L. Del Zanna, E. Grossi,
Ann. Phys. 338 (2013) 32
F. B., *Polarization in relativistic fluids: a QFT derivation*
Lecture Notes in Physics



Spin, local equilibrium and relativity

It is crucial to use a *quantum-relativistic* formalism from the onset
Definition of a *relativistic spin* four-vector

For a single particle

$$S^\mu = -\frac{1}{2m}\epsilon^{\mu\nu\lambda\rho}\langle\widehat{J}_{\nu\lambda}\widehat{P}_\rho\rangle$$

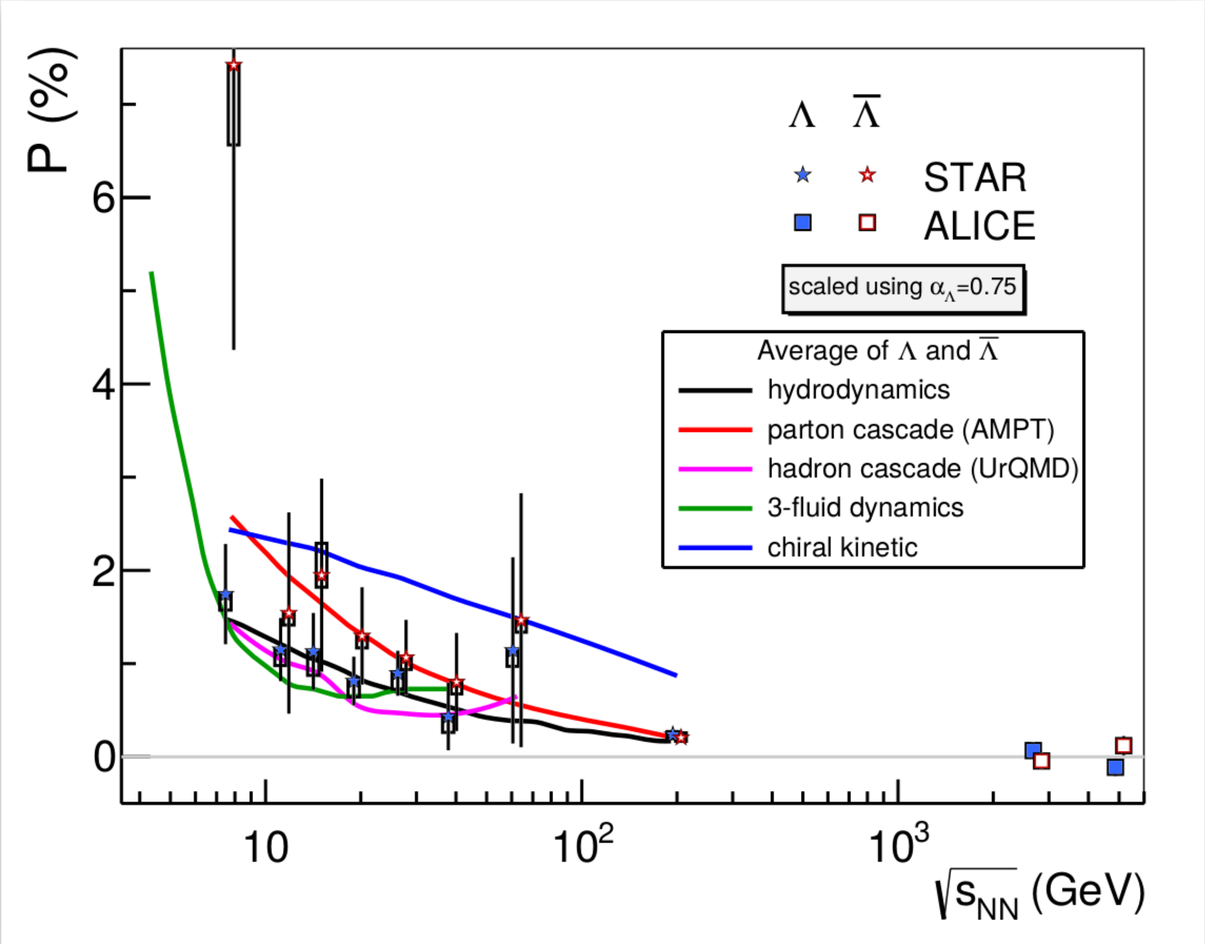
$$\langle\widehat{X}\rangle = \mathrm{tr}(\widehat{\rho}\widehat{X})$$

Relativistic Spin vs Pauli-Lubanski vs Polarization

$$S^\mu = \frac{1}{m}W^\mu = SP^\mu$$

Comparison with the data (date Jan 2020)

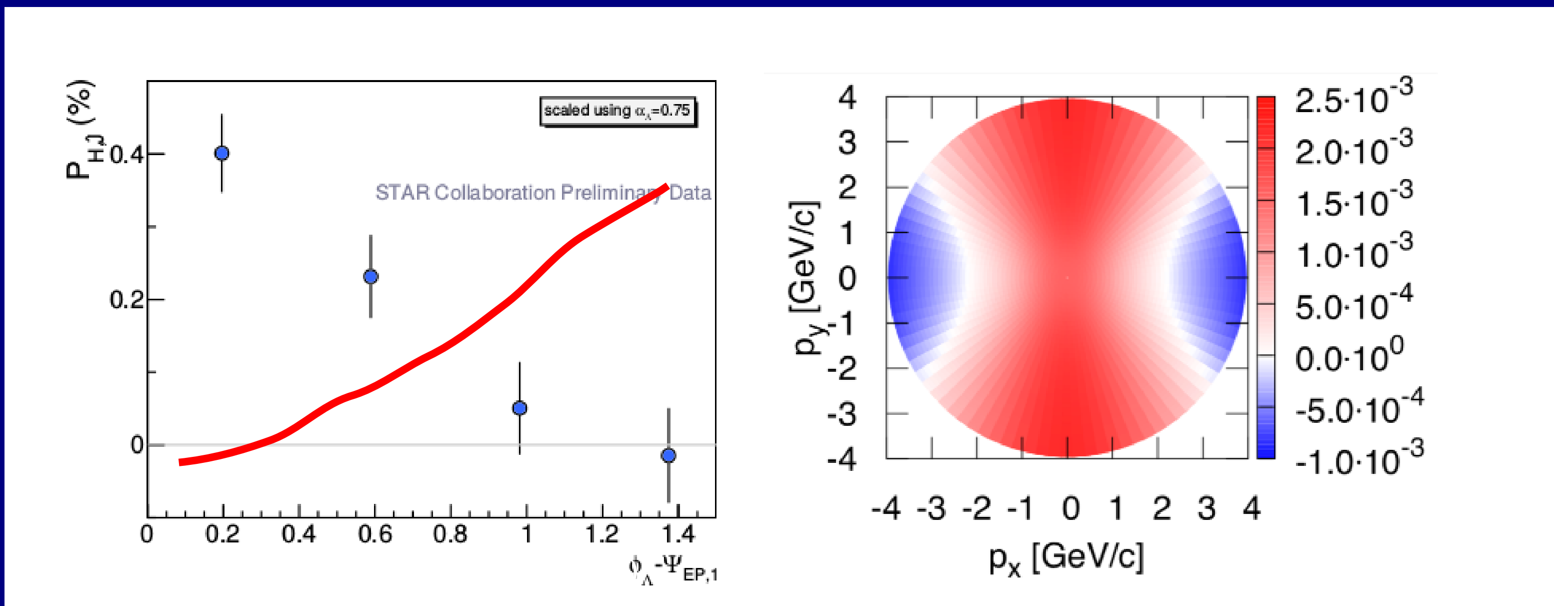
F. B., M. Lisa, Polarization and vorticity in the QGP, Ann. Rev. Part, Nucl. Sc. 70, 395 (2020)



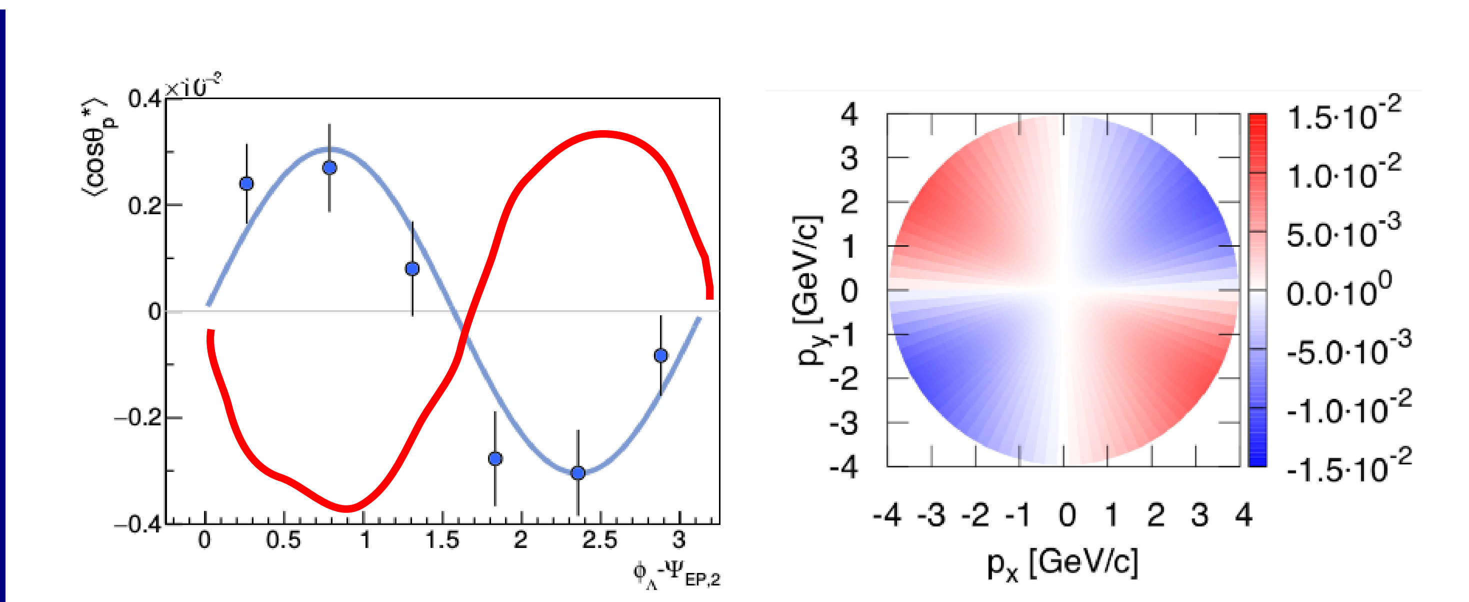
$$S^\mu(p) = \frac{1}{8m}\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int_\Sigma \mathrm{d}\Sigma_\tau p^\tau n_F (1-n_F)\partial_\nu \beta_\rho}{\int_\Sigma \mathrm{d}\Sigma_\tau p^\tau \; n_F}$$

Different models of the collision, same formula for polarization

Puzzles: momentum dependence of polarization (until march 2021)



Theory prediction



Not the effect of decays:

X. L. Xia, H. Li, X.G. Huang and H. Z. Huang, Phys. Rev. C 100 (2019), 014913

F. B., G. Cao and E. Speranza, Eur. Phys. J. C 79 (2019) 741

Recent development: spin-thermal shear coupling

$$\widehat{\rho}_{\rm LE} \simeq \frac{1}{Z}\exp[-\beta_\mu(x)\widehat{P}^\mu + \frac{1}{2}\varpi_{\mu\nu}(x)\widehat{J}^{\mu\nu}_x - \frac{1}{2}\xi_{\mu\nu}(x)\widehat{Q}^{\mu\nu}_x + \ldots]$$

$$S^\mu(p) = \frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_\sigma \frac{\int_\Sigma {\rm d}\Sigma_\tau p^\tau n_F(1-n_F)\partial_\nu\beta_\rho}{\int_\Sigma {\rm d}\Sigma_\tau p^\tau \, n_F}$$

$$n_F = ({\rm e}^{\beta\cdot p-\xi}+1)^{-1}$$

It is a NON-dissipative effect!

$$S^\mu_\xi(p) = -\frac{1}{4m}\epsilon^{\mu\nu\sigma\tau}\frac{p_\tau p^\rho}{\varepsilon}\frac{\int_\Sigma {\rm d}\Sigma\cdot p\, n_F(1-n_F)\hat{t}_\nu\xi_{\sigma\rho}}{\int_\Sigma {\rm d}\Sigma\cdot p\, n_F},$$

F. B., M. Buzzegoli, A. Palermo, Phys. Lett. B 820 (2021) 136519

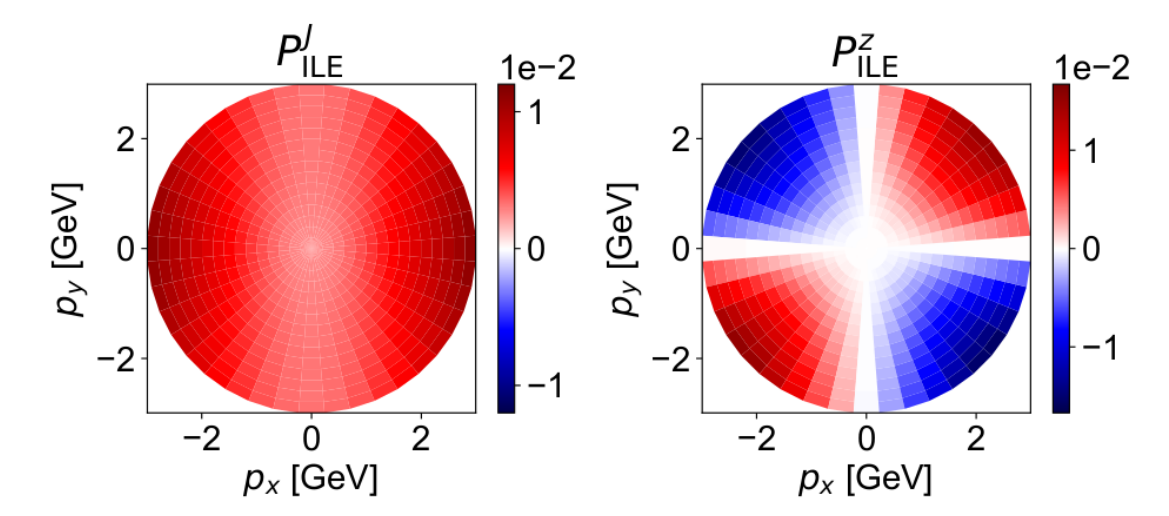
Same (though not precisely the same) formula obtained by Liu and Yin with a different method:

S. Liu, Y. Yin, JHEP 07 (2021) 188

The additional local equilibrium term has been confirmed in more analyses:

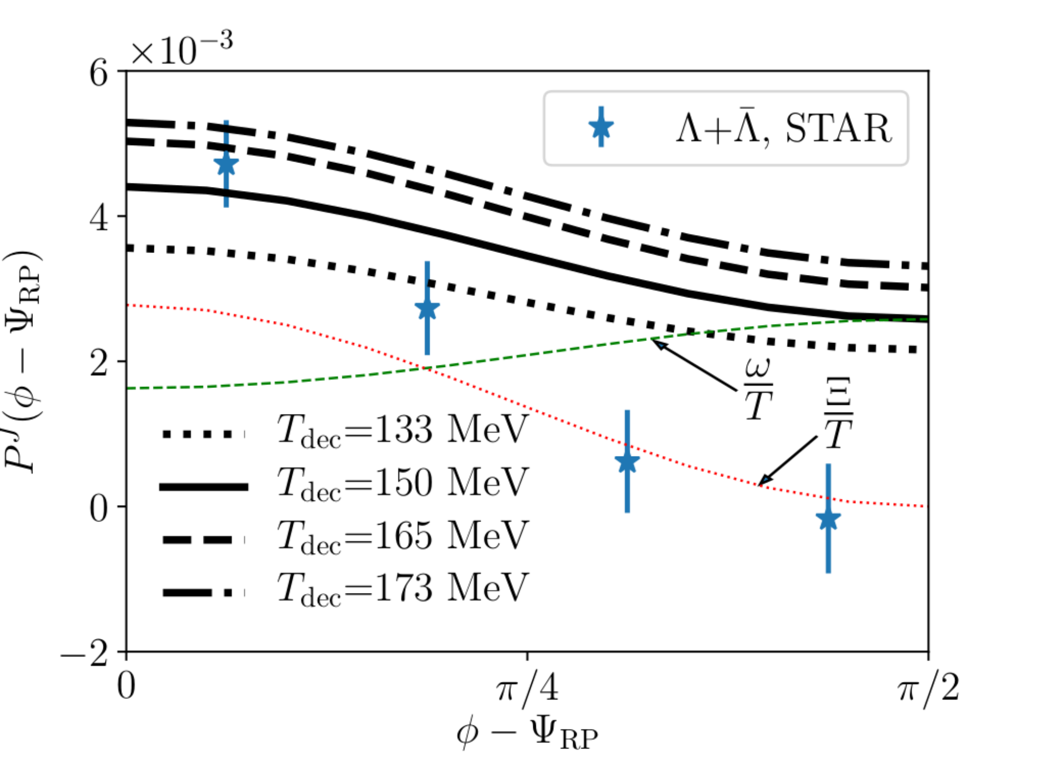
C. Yi, S. Pu, D. L. Yang, Phys.Rev.C 104 (2021) 6, 064901
Y. C. Liu, X. G. Huang, arXiv 2109.15301, Sci.China Phys.Mech.Astron. 65 (2022) 7, 272011

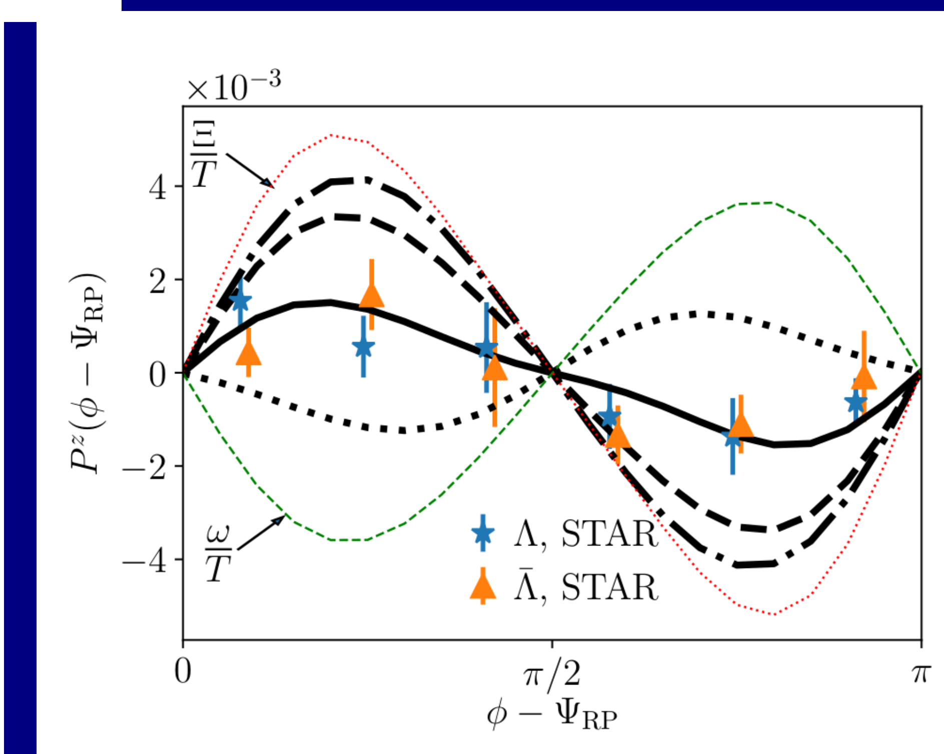
Isothermal local equilibrium: results



Apply the new formula (for primary hadrons)

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





Recent study of Λ polarization with shear contribution

S. Alzhrani, S. Ryu, C. Shen, Phys.Rev.C 106 (2022) 1, 014905,

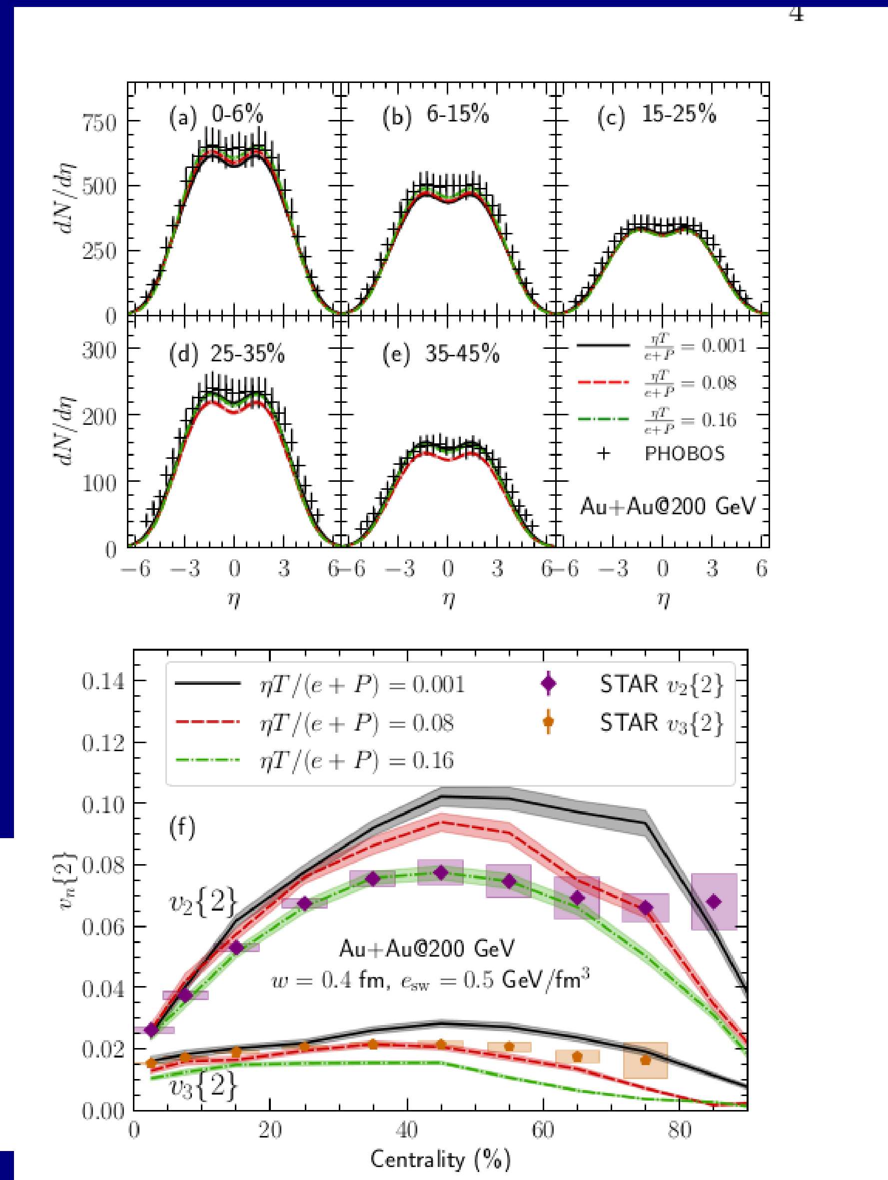
A model study at 200 GeV

3+1 D viscous hydro with specific initial conditions designed in:

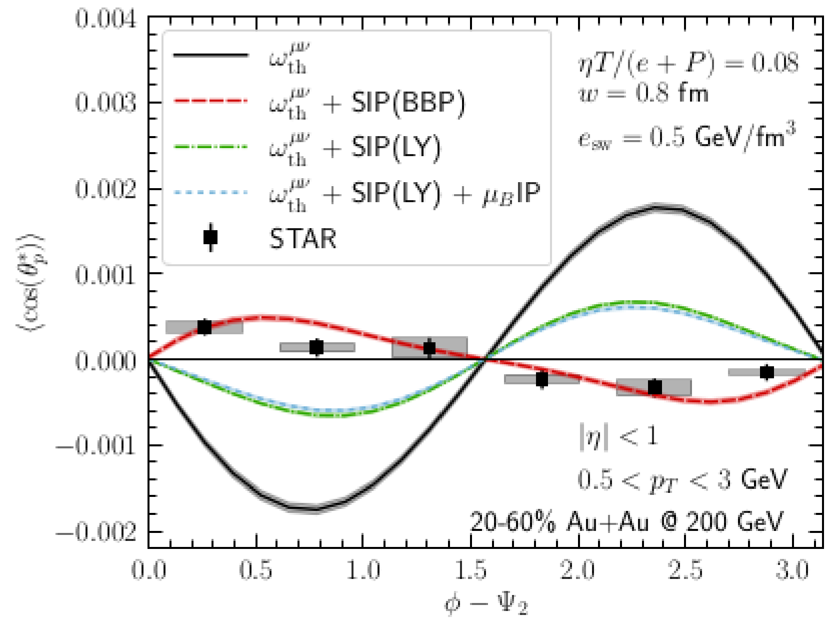
C. Shen and S.Alzhrani,
Phys. Rev. C 102, 014909 (2020),
arXiv:2003.05852 [nucl-th].

S. Ryu, V. Jupic, C. Shen,
Phys. Rev. C 104, 054908 (2021)

Parameter	Description	Value
w [fm]	initial hot spot width	0.4, 0.8, 1.2
η_0	space-time rapidity plateau size	2.5
σ_η	space-time rapidity fall off width	0.5
f	initial longitudinal flow fraction	0.15
τ_0 [fm/c]	hydrodynamics starting time	1
$\eta T/(e+P)$	specific shear viscosity	0, 0.08, 0.16
$e_{\rm sw}$ [GeV/fm^3]	particlization energy density	0.25, 0.5



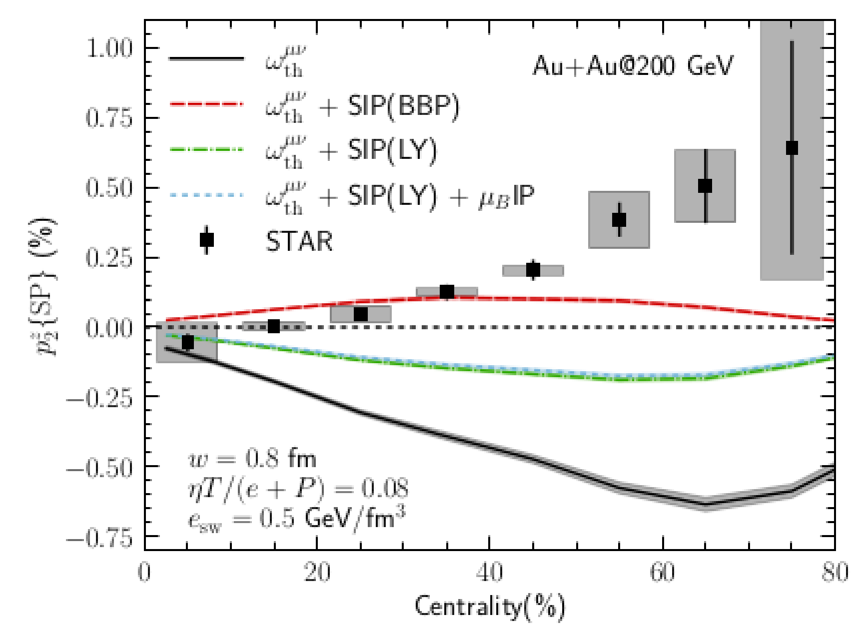
Results – Longitudinal polarization



Dependence of the longitudinal component of the spin polarization vector on the azimuthal angle of the Λ

Different predictions of VHLLE and ECHO-QGP (see previous slides)

Dependence of the dominant Fourier component (sin 2ϕ) on centrality



Spin polarization as a probe of new and long-sought phenomena

- *Local parity violation in nuclear collisions*

F.B. , M. Buzzegoli, A. Palermo, G. Prokhorov, Phys.Lett.B 822 (2021) 136706

- *QCD critical point*

S. K. Singh and J. e. Alam, arXiv:2110.15604

- *Jet energy loss in the QGP*

W. M. Serenone et al. Phys.Lett.B 820 (2021) 136500

COMPUTING PLAN

- Match different EXISTING codes of different stages of the relativistic nuclear collision simulation (initial state, relativistic hydrodynamics, kinetic stage)
  - ONGOING

- Study the sensitivity of spin polarization to variation of physical parameters and the initial conditions
  - NEXT

- Production of phyics output
  - MAIN GOAL

- Develop a new hydrodynamic code with evolved functions and parametrizations; use of a frame with stable and causal first-order equations
  - LONG RUN

Partecipanti: F.B., E. Grossi (RTD Firenze), A. Palermo, Xin-Li Sheng (pdoc)
: + 1 RTDA