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Polarization in relativistic heavy ion collisions

OUTLINE

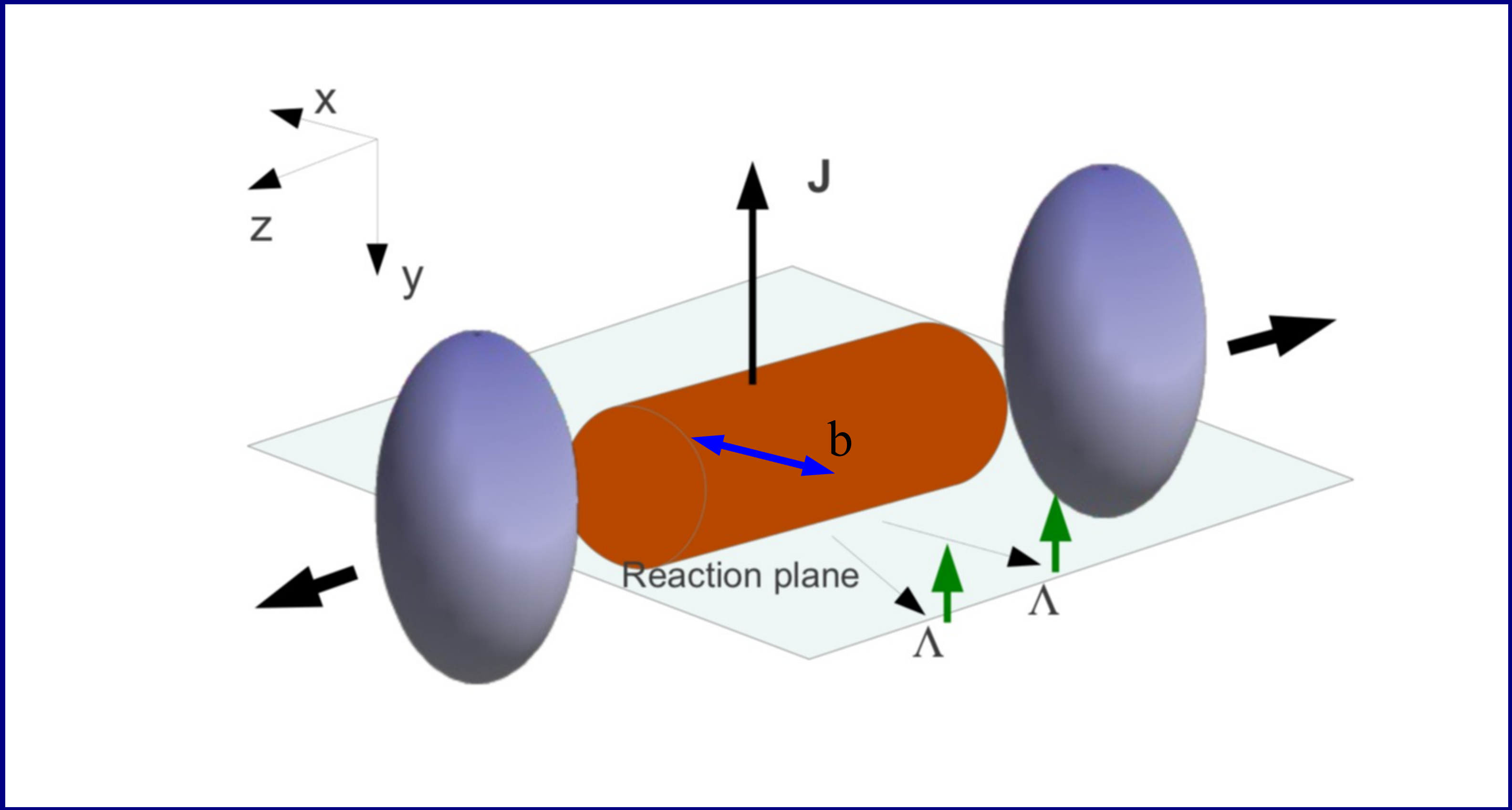
- Introduction
- Spin polarization in a relativistic fluid at local thermodynamic equilibrium
- Analysis of Λ polarization in heavy ion collisions at very high energy
- Spin polarization as a probe of Quark Gluon Plasma

QCD@work, Trani, June 18-21 2024

Global polarization in relativistic nuclear collisions

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

By parton spin-orbit coupling: Z. T. Liang, X. N. Wang, Phys. Rev. Lett. 94 (2005) 102301
By local equilibration: F. B., F. Piccinini, J. Rizzo, Phys. Rev. C 77 (2008) 024906



Polarization and vorticity

Local equilibrium at the freeze-out implies a connection between spin polarization and (thermal) vorticity

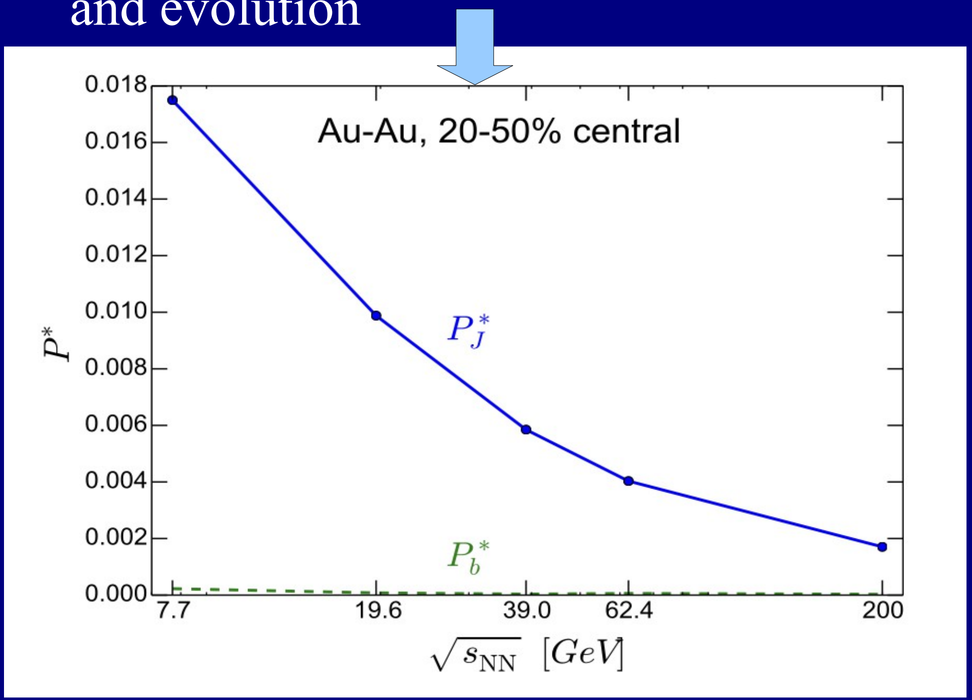
F.B., V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338, 32 (2013)

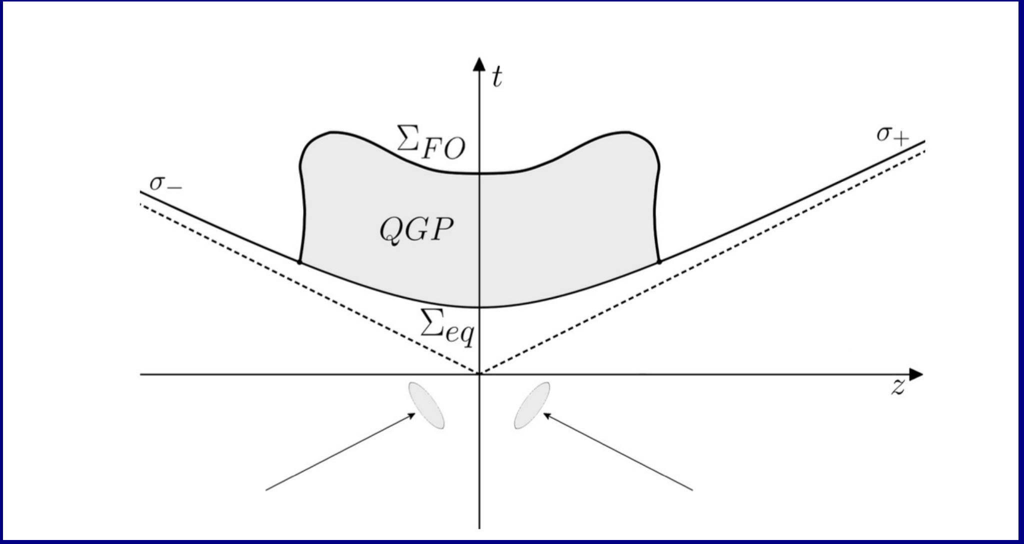
$$n_F = (\mathrm{e}^{\beta\cdot p - \xi} + 1)^{-1}$$

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

$$\beta = \frac{1}{T} u$$

Quantitative prediction of 3+1D hydrodynamic model of QGP production and evolution



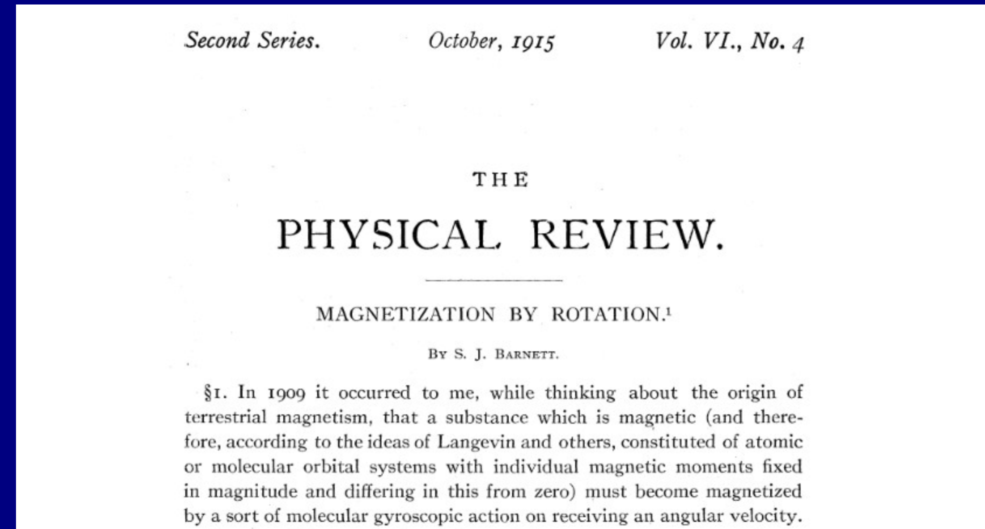


I. Karpenko, F.B., Eur. Phys. J. C 77 (2017) 213

Barnett effect

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

Phys. Rev. 6, 239–270 (1915).


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

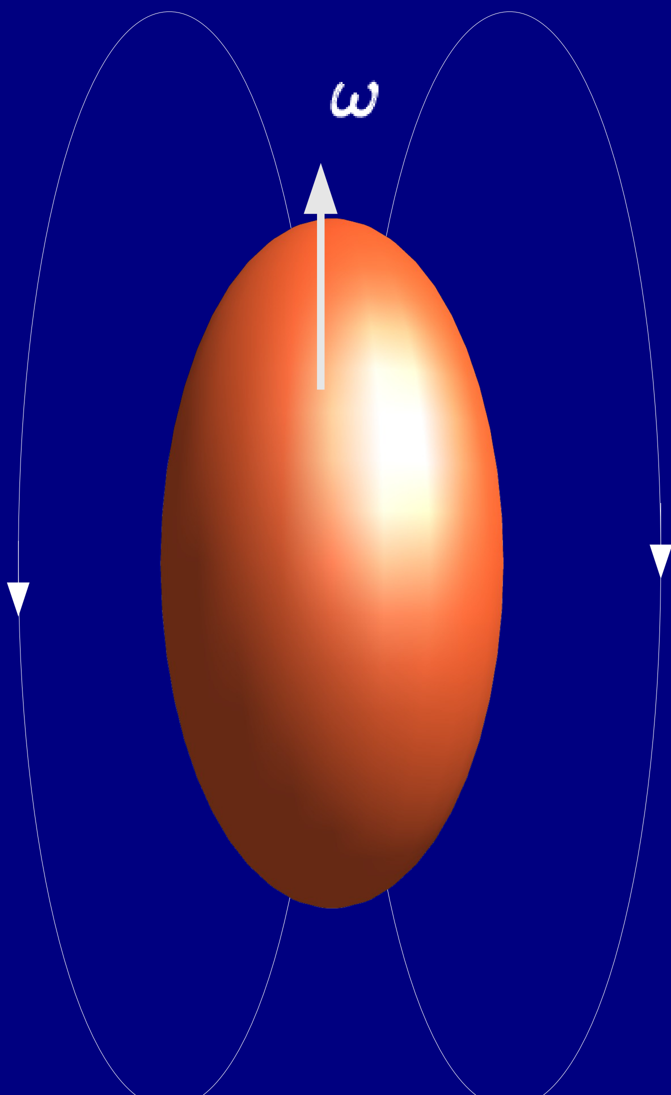
THE

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.



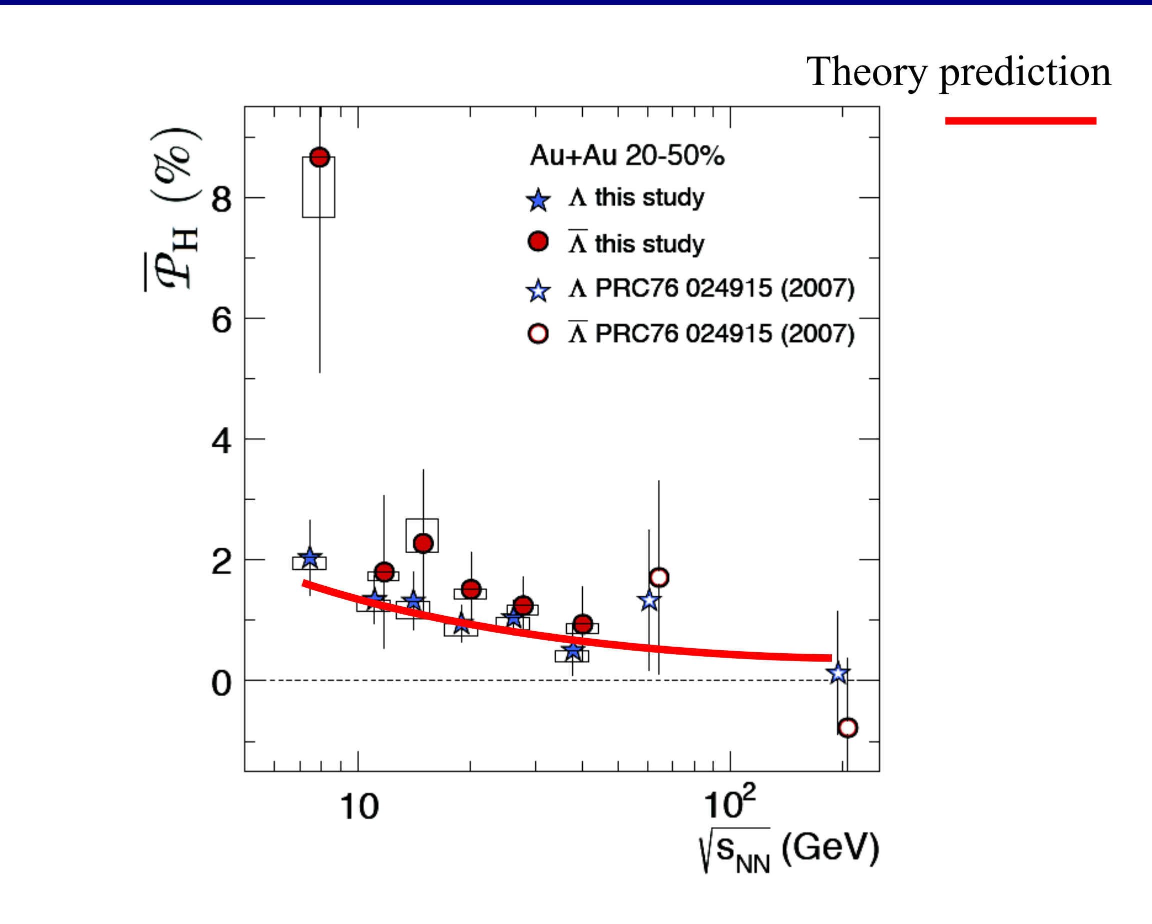
Spontaneous magnetization of an uncharged body when spun around its axis

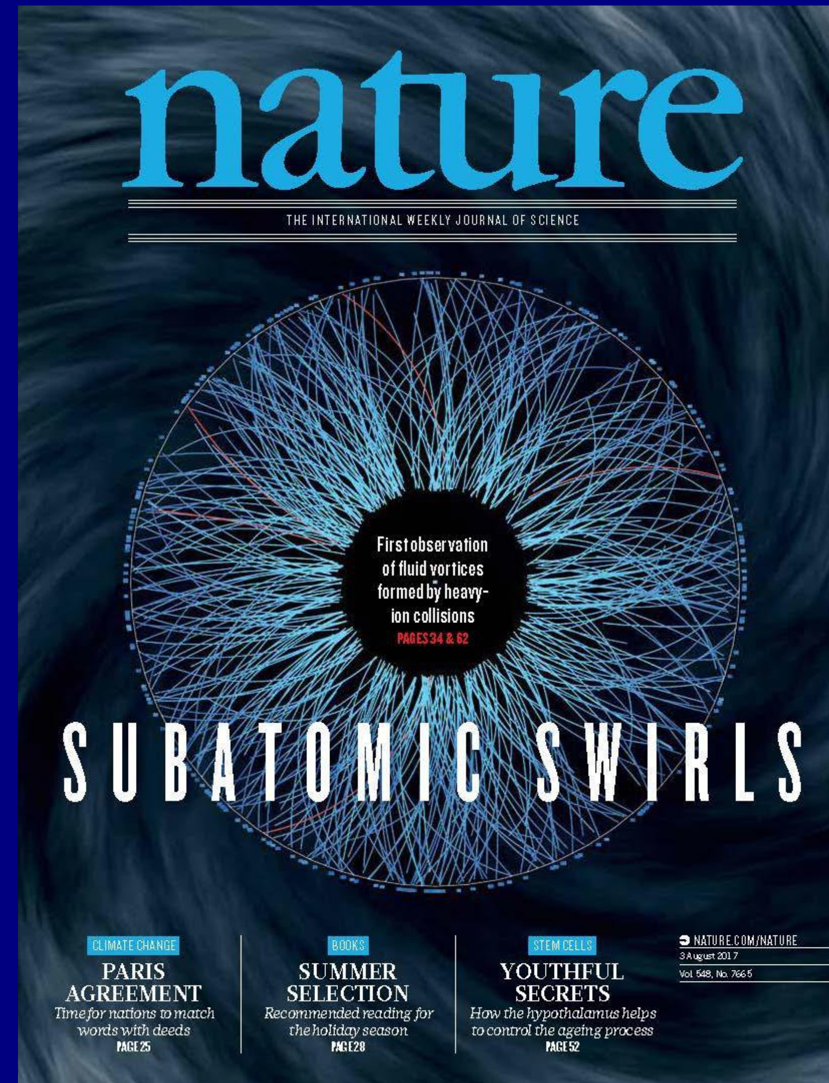
$$P \simeq \frac{S+1}{3}\frac{\hbar\omega}{KT} \quad \Rightarrow \quad M = \frac{\chi}{g}\omega$$

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.

Discovery of polarization in heavy ion collisions

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.*
In agreement with the predictions based on spin-vorticity formula

A very short theory summary

F. B., Lecture Notes in Physics 987, 15 (2021) arXiv:2004.04050

Spin polarization vector for spin ½ particles:

$$S^\mu(p) = \frac{1}{2} \frac{\int \mathrm{d}\Sigma \cdot p \, \mathrm{tr}_4(\gamma^\mu \gamma^5 W_+(x,p))}{\int \mathrm{d}\Sigma \cdot p \, \mathrm{tr}_4 W_+(x,p)}$$

Wigner function:

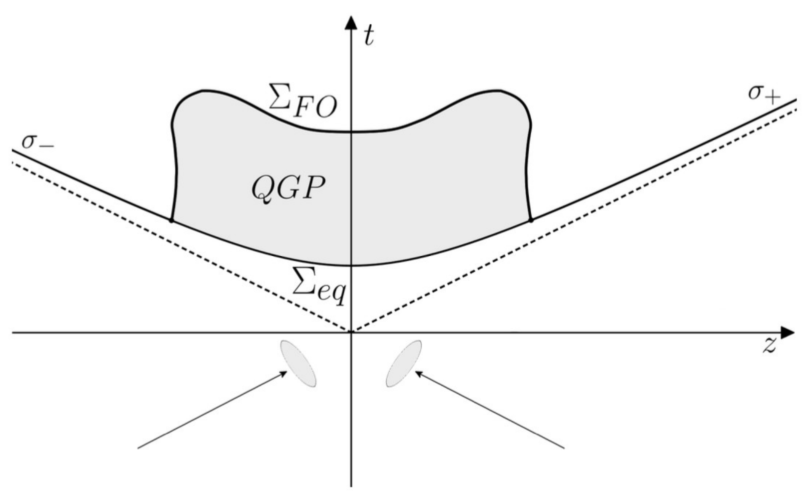
$$W(x,k) = \mathrm{Tr}(\widehat{\rho} \widehat{W}(x,k))$$

Local equilibrium density operator:

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

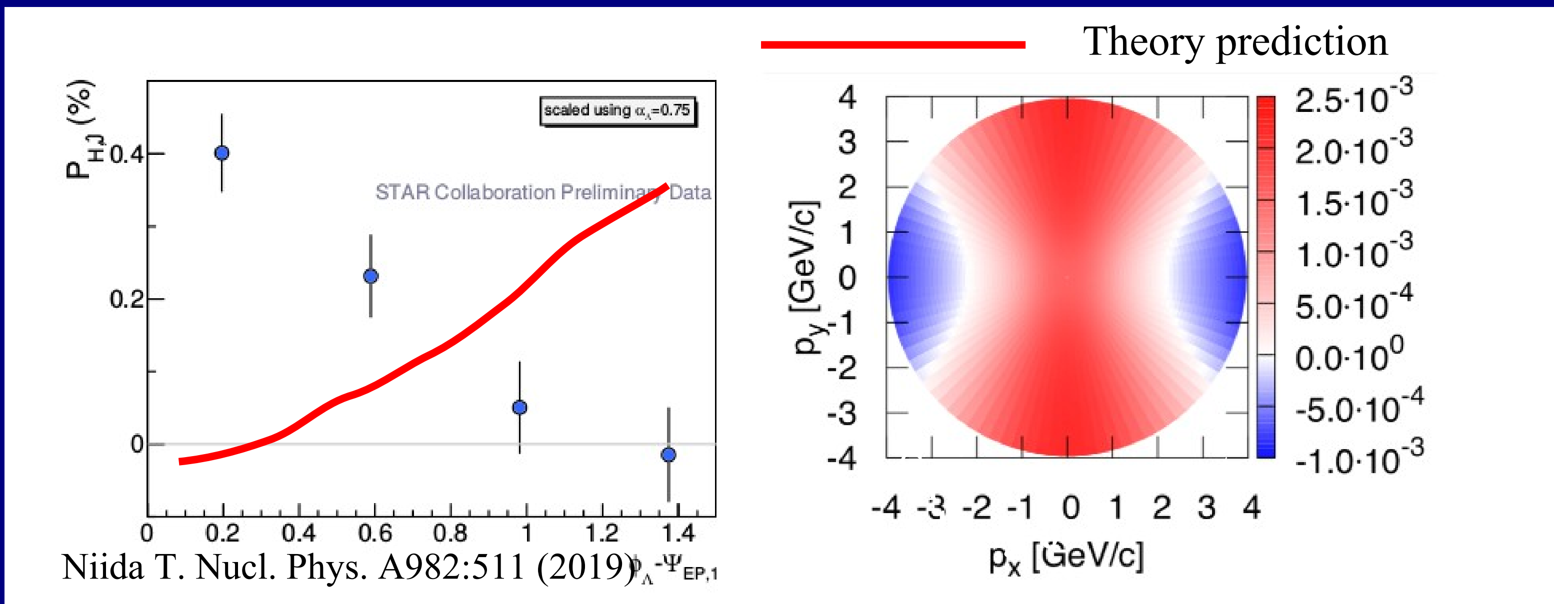
$$\beta = \frac{1}{T} u$$

$$\zeta = \frac{\mu}{T}$$

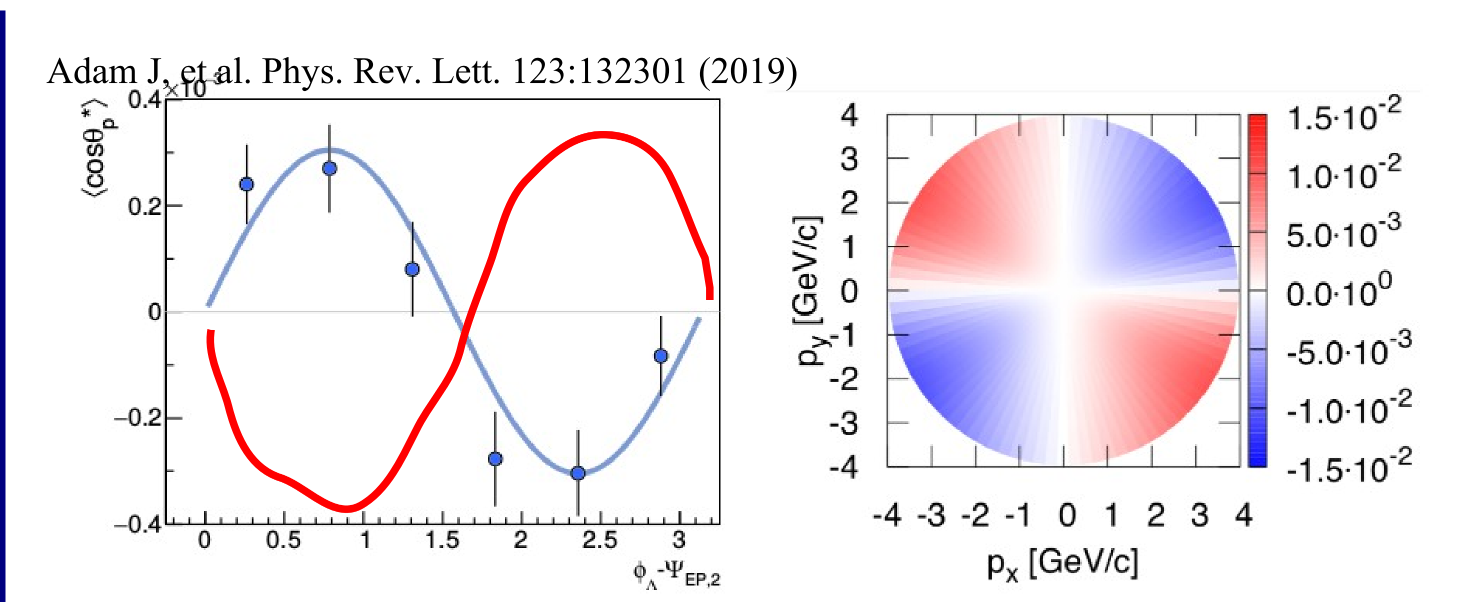


Puzzle: momentum dependence of polarization

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



Spin component along J at p_z=0



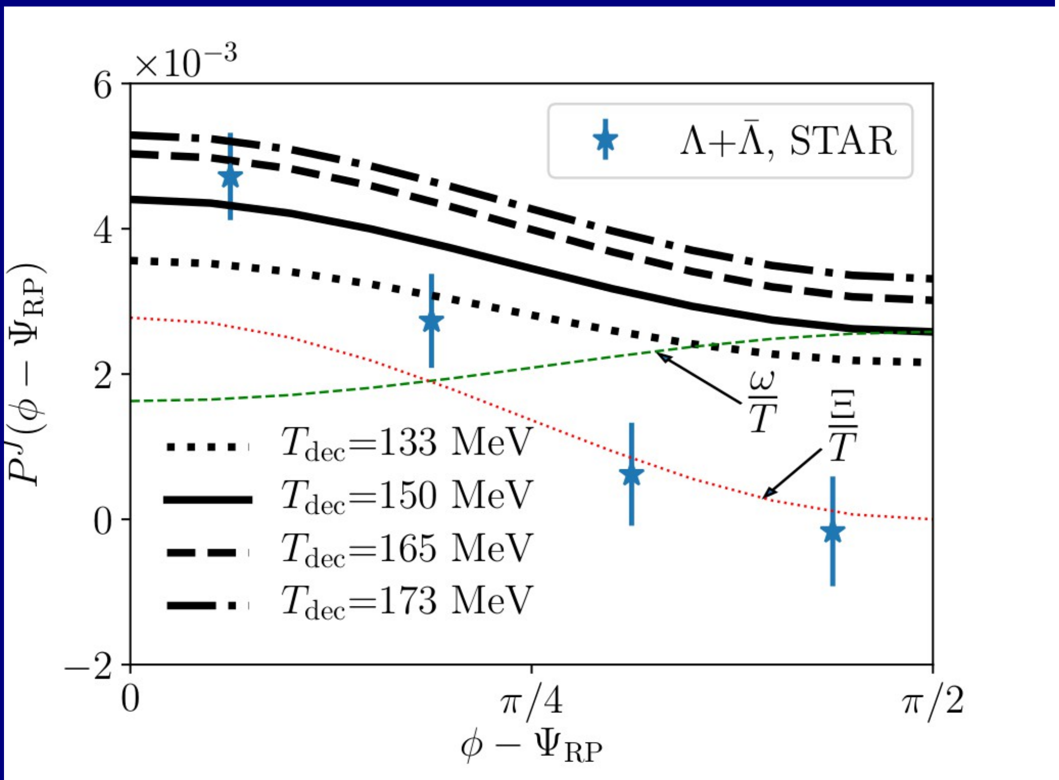
Spin component along beam line at p_z=0

New terms found: spin-thermal shear coupling

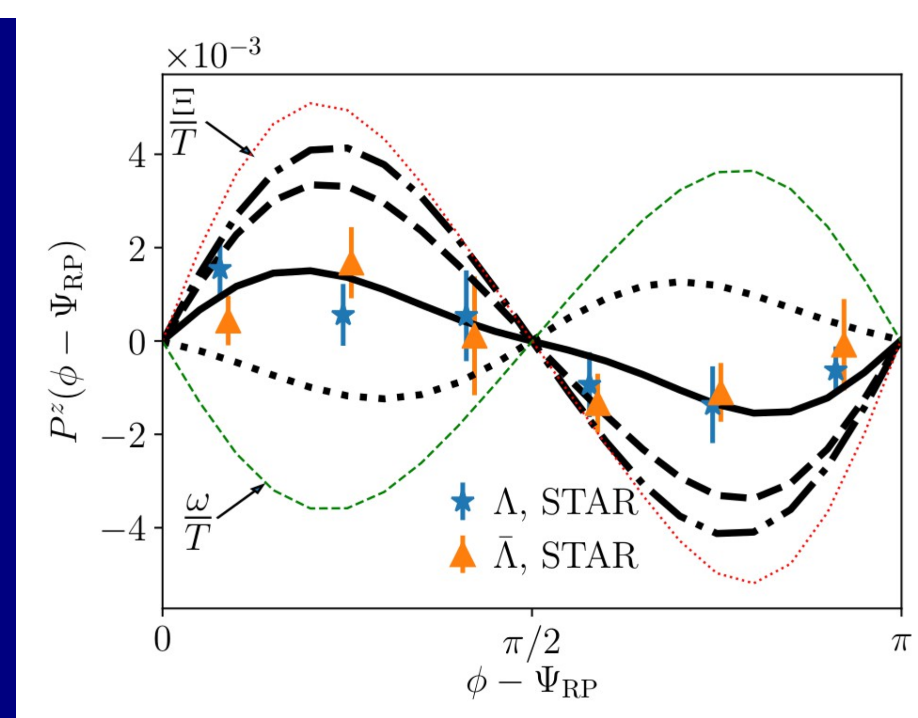
$$S^\mu_\xi(p) = -\frac{1}{4m}\epsilon^{\mu\nu\sigma\tau}\frac{p_\tau p^\rho}{\varepsilon}\frac{\int_\Sigma \mathrm{d}\Sigma\cdot p\, n_F(1-n_F)\hat{t}_\nu \xi_{\sigma\rho}}{\int_\Sigma \mathrm{d}\Sigma\cdot p\, n_F},$$

$$\xi_{\mu\nu} = \frac{1}{2}\left(\partial_\mu\beta_\nu + \partial_\nu\beta_\mu\right).$$

F. B., M. Buzzegoli, A. Palermo, Phys. Lett. B 820 (2021) 136519
S. Liu, Y. Yin, JHEP 07 (2021) 188
Confirmed by C. Yi, S. Pu, D. L. Yang, Phys.Rev.C 104 (2021) 6, 064901
Y. C. Liu, X. G. Huang, Sci.China Phys.Mech.Astron. 65 (2022) 7, 272011



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



F. B., M. Buzzegoli, A. Palermo, G. Inghirami and I. Karpenko, Phys. Rev. Lett. 127 (2021) 272302

What can polarization tell us about QGP?

$$S^\mu(p) = -\frac{\epsilon^{\mu\rho\sigma\tau} p_\tau}{8m \int_\Sigma d\Sigma \cdot p \, n_F} \int_\Sigma d\Sigma \cdot p \times n_F(1-n_F) \left[\varpi_{\rho\sigma} + 2\hat{t}_\rho \frac{p^\lambda}{E_p} \xi_{\lambda\sigma} - \frac{\hat{t}_\rho \partial_\sigma \zeta}{2E_p} \right]$$

$$n_F = \frac{1}{\exp[\beta \cdot p - \mu q] + 1},$$

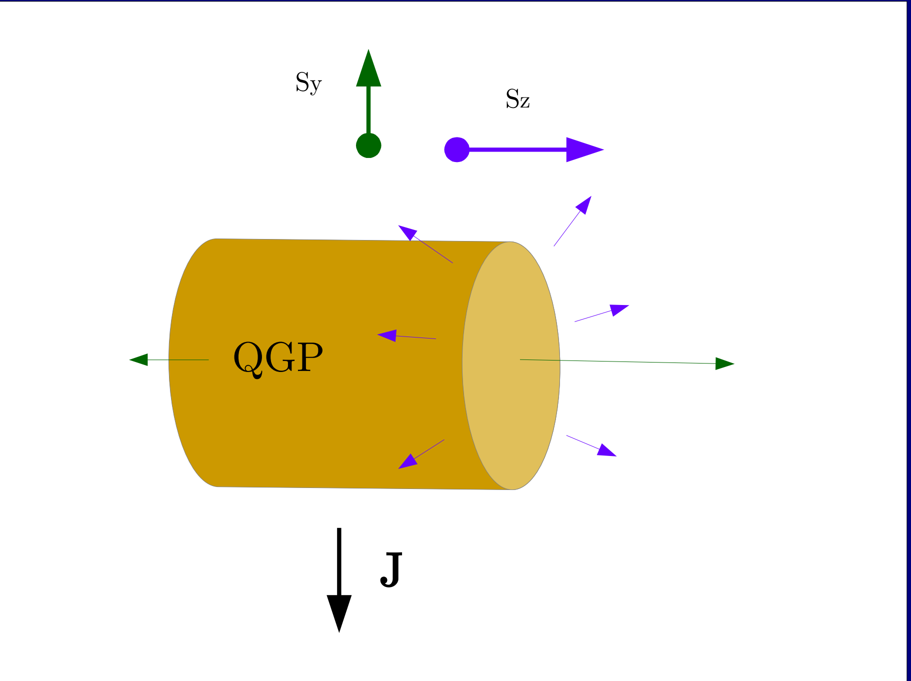
$$\varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_\mu \beta_\nu - \partial_\nu \beta_\mu\right).$$

$$\xi_{\mu\nu} = \frac{1}{2}\left(\partial_\mu \beta_\nu + \partial_\nu \beta_\mu\right).$$

$$\beta = \frac{1}{T} u$$

$$\zeta = \frac{\mu}{T}$$

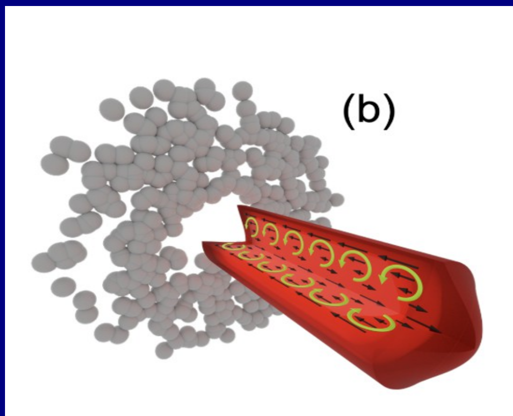
Spin polarization, unlike any other observable, at the leading order depends on hydrodynamic GRADIENTS, therefore it is a very sensitive probe of hydrodynamic motion

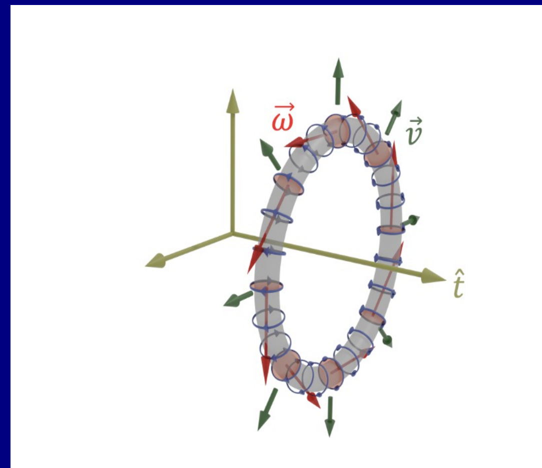


S_y sensitive to longitudinal expansion

S_z sensitive to radial expansion

Polarization as a probe of jets and critical point





$$\mathcal{R}^{\hat{t}}_{\Lambda} \equiv \frac{\epsilon^{\mu\nu\rho\sigma} S_\mu n_\nu \hat{t}_\rho p_\sigma}{|S||\epsilon^{\mu\nu\rho\sigma} n_\nu \hat{t}_\rho p_\sigma|} \quad .$$

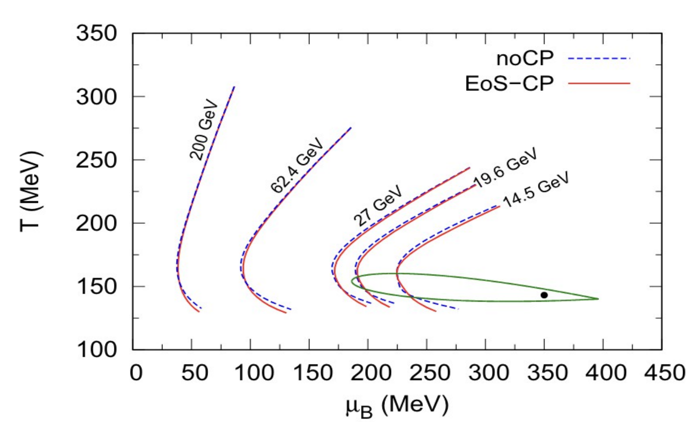
Shooting a proton or a jet through a heavy nucleus is expected to produce vortex rings, which can possibly be detected through spin polarization

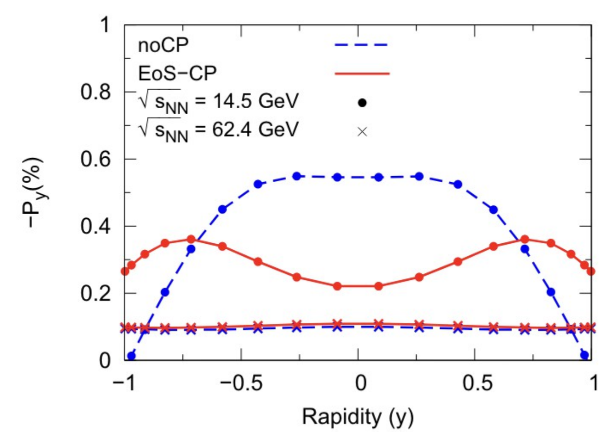
V. H. Ribeiro et al., Phys.Rev.C 109 (2024) 1, 014905; M. Lisa et al., Phys.Rev.C 104 (2021) 1, 011901

Polarization as a probe of the QCD critical point

Critical behaviour of viscous coefficients

$$\zeta = \zeta_0 \left(\frac{\xi}{\xi_0}\right)^3 \ , \ \eta = \eta_0 \left(\frac{\xi}{\xi_0}\right)^{0.05}$$





S. K. Singh, Jan e-Alam, Eur. Phys. J. C 83 (2023) 585

Sensitivity to initial conditions and viscosity

a new numerical calculation at very high energy

A. Palermo, F.B., E. Grossi, I. Karpenko, arXiv:2404.14295

Recent hydro calculations of Λ polarization in relativistic heavy ion collisions

S. Alzhrani, S. Ryu, and C. Shen, Phys. Rev. C **106**, 014905 (2022), arXiv:2203.15718 [nucl-th].
F. Becattini, M. Buzzegoli, G. Inghirami, I. Karpenko, and A. Palermo, Phys. Rev. Lett. **127**, 272302 (2021), arXiv:2103.14621 [nucl-th].
B. Fu, S. Y. F. Liu, L. Pang, H. Song, and Y. Yin, Phys. Rev. Lett. **127**, 142301 (2021), arXiv:2103.10403 [hep-ph].
X.-Y. Wu, C. Yi, G.-Y. Qin, and S. Pu, Phys. Rev. C **105**, 064909 (2022), arXiv:2204.02218 [hep-ph].
Z.-F. Jiang, X.-Y. Wu, H.-Q. Yu, S.-S. Cao, and B.-W. Zhang, Acta Phys. Sin. **72**, 072504 (2023).
Z.-F. Jiang, X.-Y. Wu, S. Cao, and B.-W. Zhang, Phys. Rev. C **108**, 064904 (2023), arXiv:2307.04257 [nucl-th].
V. H. Ribeiro, D. Dobrigkeit Chinellato, M. A. Lisa, W. Matioli Serenone, C. Shen, J. Takahashi, and G. Torrieri, Phys. Rev. C **109**, 014905 (2024), arXiv:2305.02428 [hep-ph].

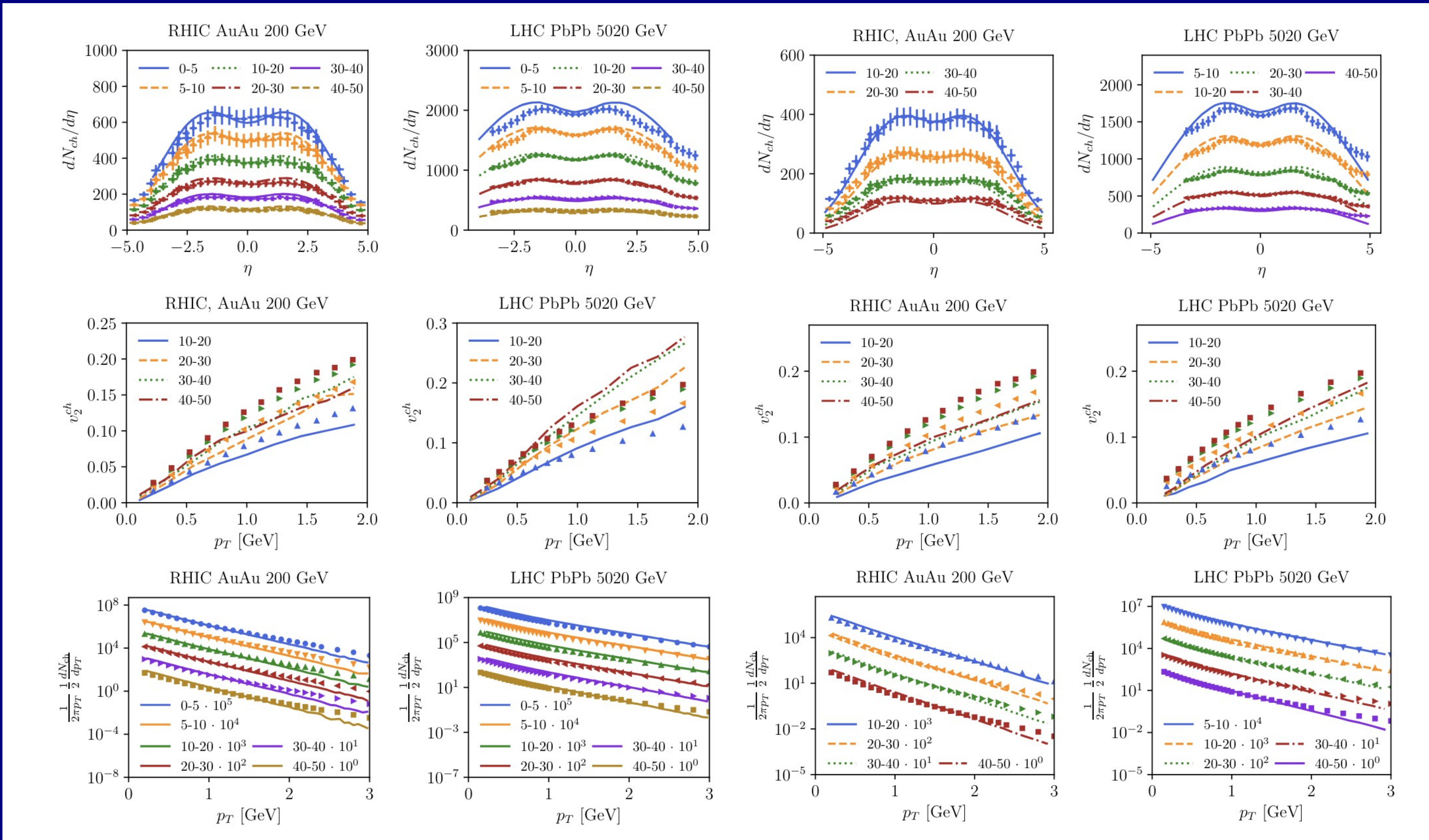
Numerical implementation of 3+1 D causal viscous hydrodynamics (VHLLE) with statistical hadronization and particle rescattering (afterburner SMASH)

Initial state model: SUPERMC (C. Shen et al.), GLISSANDO (Monte-Carlo Glauber)

Polarization transferred to Λ in secondary decays of Σ^0 and Σ^* taken into account

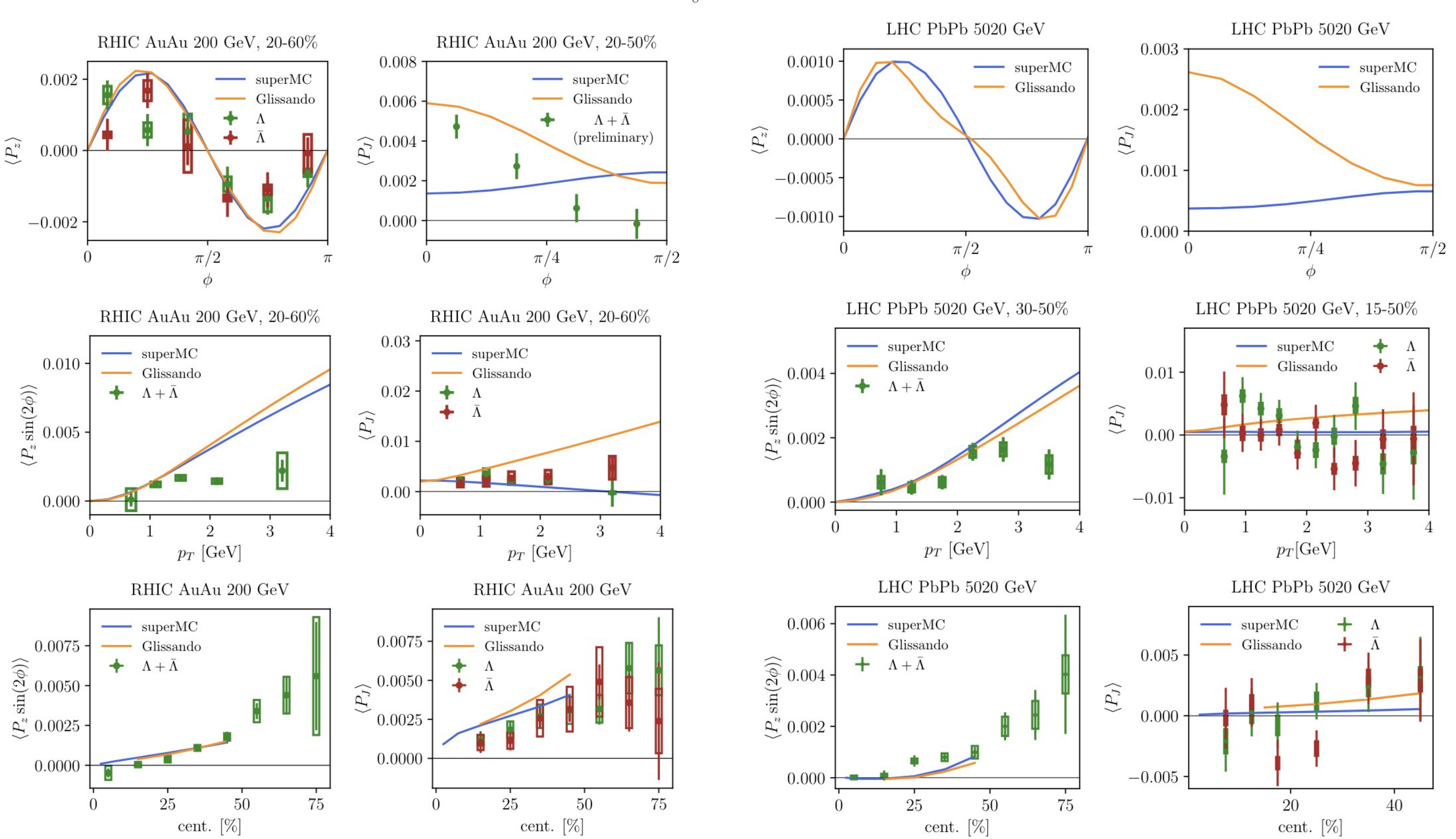
Qualification of the code

Benchmark distributions



SUPERMC GLISSANDO

RESULTS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RHIC AuAu 200 GeV, 20-60%
superMC
Glissando
Λ
Λ̄
⟨P_z⟩
ϕ
RHIC AuAu 200 GeV, 20-50%
superMC
Glissando
Λ + Λ̄
(preliminary)
⟨P_J⟩
ϕ
LHC PbPb 5020 GeV
superMC
Glissando
⟨P_z⟩
ϕ
LHC PbPb 5020 GeV
superMC
Glissando
⟨P_J⟩
ϕ
RHIC AuAu 200 GeV, 20-60%
superMC
Glissando
Λ + Λ̄
⟨P_z sin(2ϕ)⟩
p_T [GeV]
RHIC AuAu 200 GeV, 20-60%
superMC
Glissando
Λ
Λ̄
⟨P_J⟩
p_T [GeV]
LHC PbPb 5020 GeV, 30-50%
superMC
Glissando
Λ + Λ̄
⟨P_z sin(2ϕ)⟩
p_T [GeV]
LHC PbPb 5020 GeV, 15-50%
superMC
Glissando
Λ
Λ̄
⟨P_J⟩
p_T [GeV]
RHIC AuAu 200 GeV
superMC
Glissando
Λ + Λ̄
⟨P_z sin(2ϕ)⟩
cent. [%]
RHIC AuAu 200 GeV
superMC
Glissando
Λ
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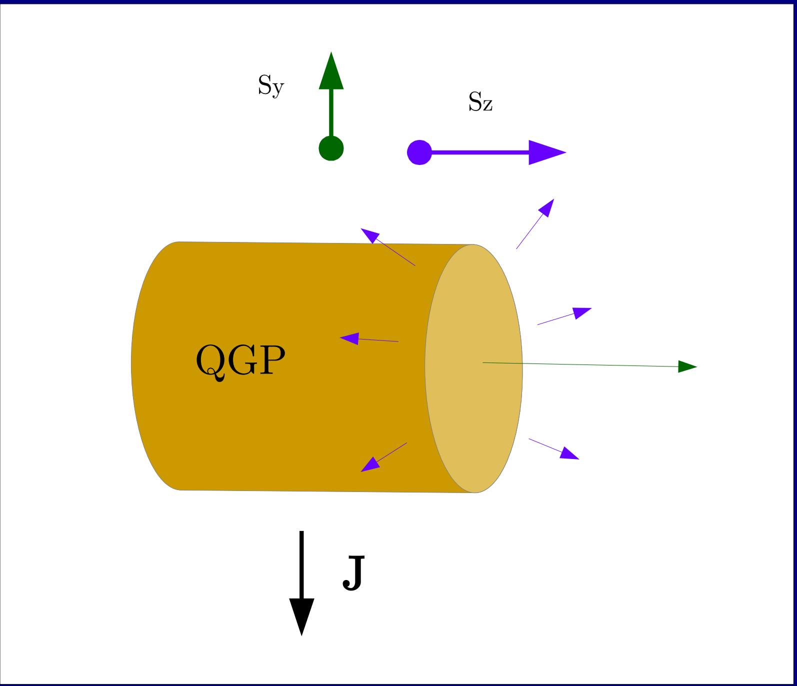
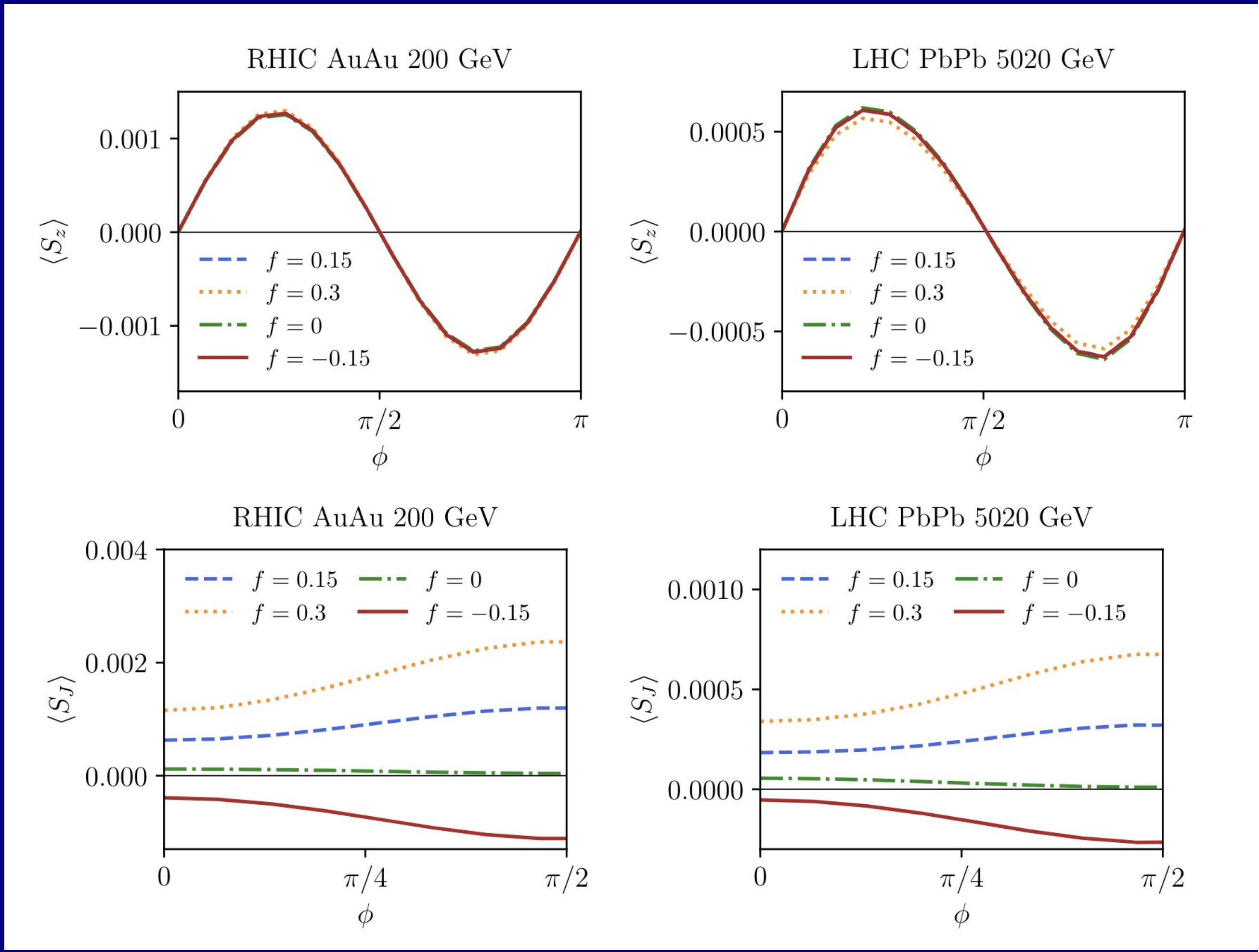
cent. [%]
LHC PbPb 5020 GeV
superMC
Glissando
Λ + Λ̄
⟨P_z sin(2ϕ)⟩
cent. [%]
LHC PbPb 5020 GeV
superMC
Glissando
Λ
Λ̄
⟨P_J⟩
cent. [%]

Sensitivity to initial longitudinal flow

Variation of SUPERMC flow parameter

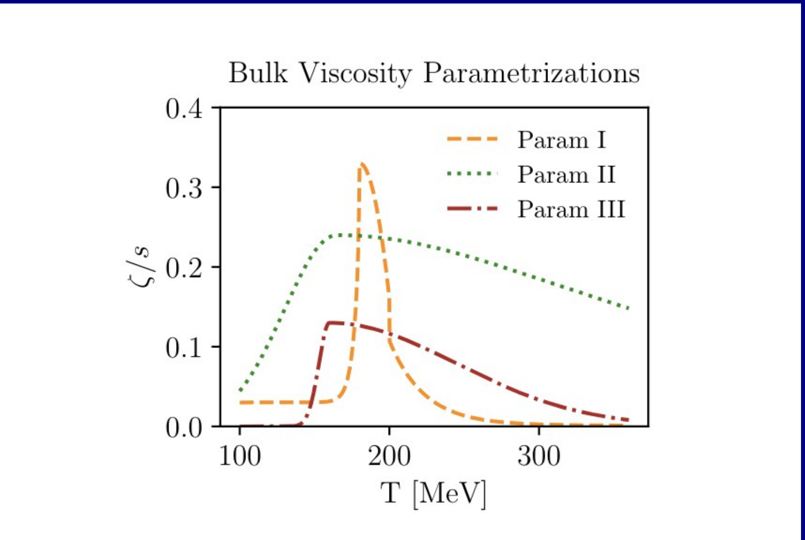
$$T^{\tau\tau} = \rho \cosh(f\, y_{CM})$$
$$T^{\tau\eta} = \frac{\rho}{\tau} \sinh(f\, y_{CM})$$

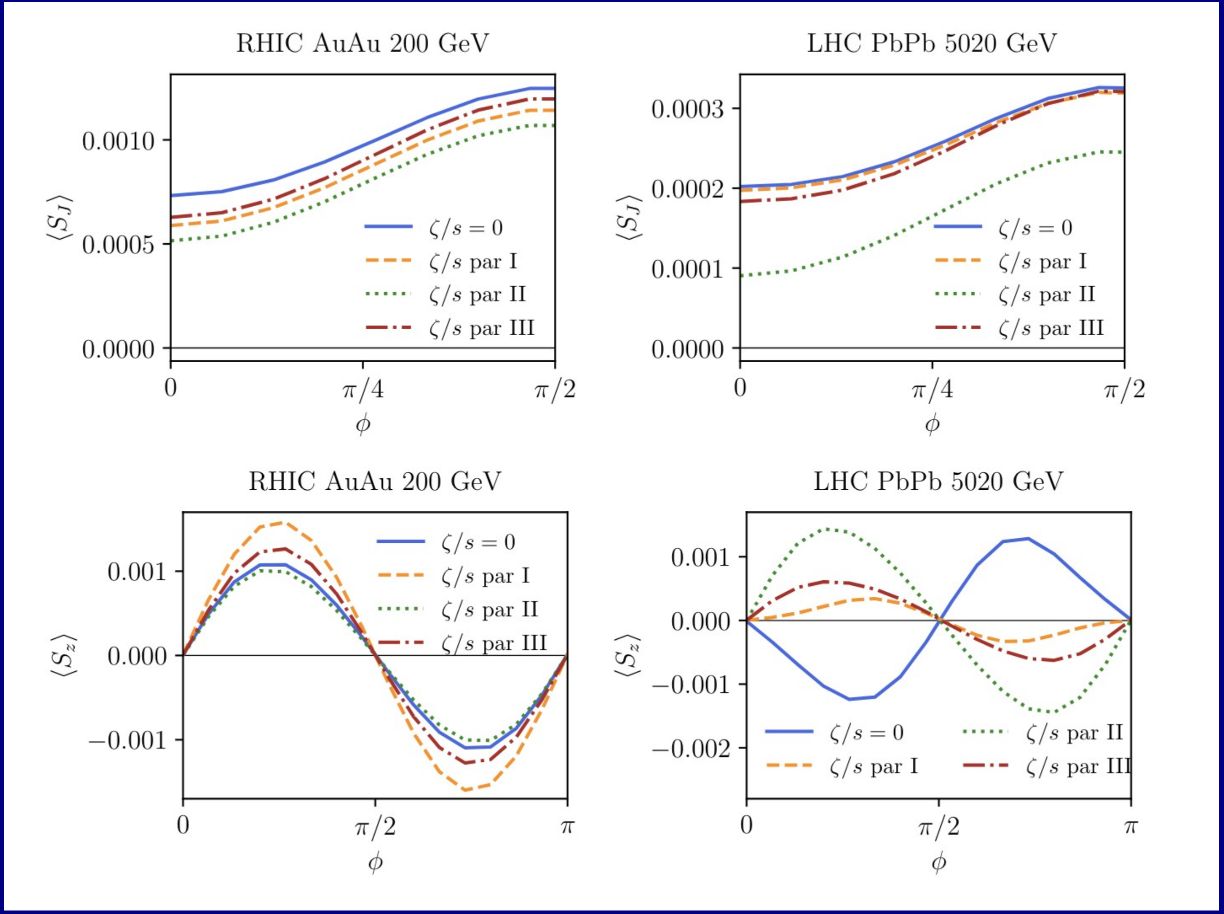




Sensitivity to bulk viscosity

While polarization seems not to depend much on shear viscosity, it turns out to be very sensitive to bulk viscosity at the highest LHC energy





Why?

Analysis of the different gradient components of the polarization

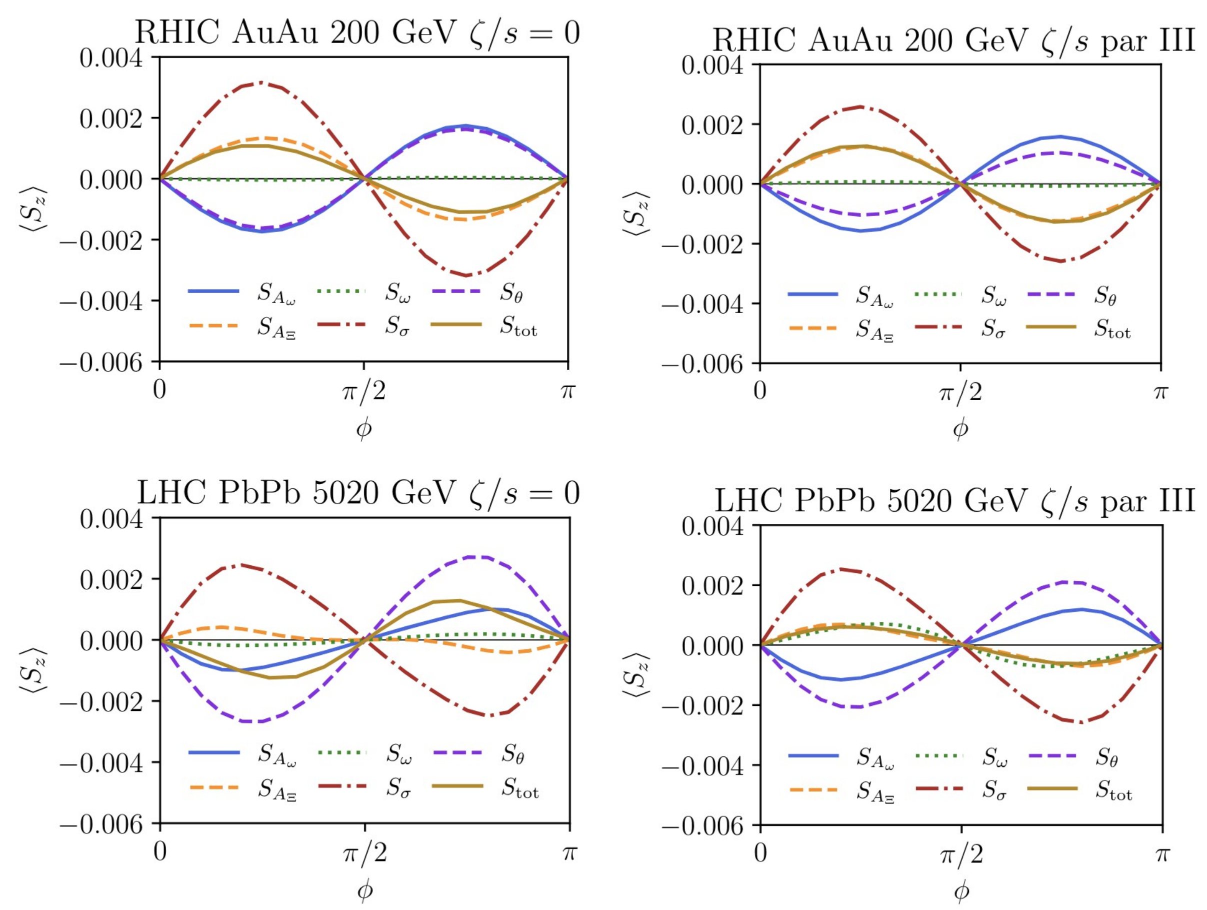
$$S^\mu_{A_\omega} = -\epsilon^{\mu\nu\rho\sigma} p_\sigma \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F (1-n_F)\ A_\nu u_\rho}{8mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F},$$

$$S^\mu_{\omega} = \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F (1-n_F)\ [\omega^\mu u \cdot p - u^\nu \omega \cdot p]}{4mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F},$$

$$S^\mu_{A_\Xi} = -\epsilon^{\mu\rho\sigma\tau} \hat{t}_\rho \frac{p_\tau}{\varepsilon} \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F (1-n_F) [u_\sigma A \cdot p + A_\sigma u \cdot p]}{8mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F},$$

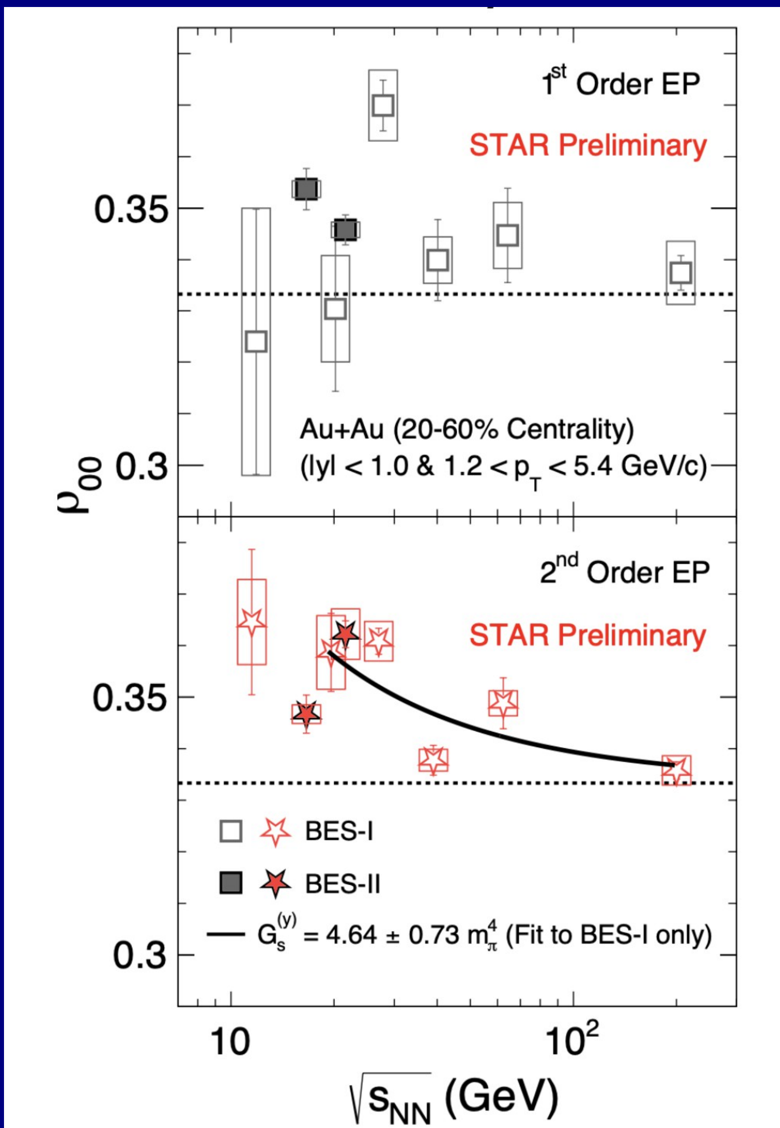
$$S^\mu_{\sigma} = -\epsilon^{\mu\rho\sigma\tau} \hat{t}_\rho p_\tau \frac{p^\lambda}{\varepsilon} \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F (1-n_F) \sigma_{\lambda\sigma}}{4mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F},$$

$$S^\mu_{\theta} = -\epsilon^{\mu\rho\sigma\tau} \hat{t}_\rho p_\tau \frac{p^\lambda}{\varepsilon} \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F (1-n_F) \theta \Delta_{\lambda\sigma}}{12mT_H \int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F}.$$



Vector meson spin alignment

$\phi \longrightarrow K^+ \, K^-$



G. Wilks (STAR coll.) SQM 2024

Spin density matrix:

$$\Theta(\boldsymbol{k}) = \frac{1}{3}\mathbb{1} + \frac{1}{2}\sum_{i=1}^{3} P^i(\boldsymbol{k}) S^i + \frac{1}{\sqrt{6}} \sum_{i,j=1}^{3} \mathfrak{T}^{ij}(\boldsymbol{k})(S^i S^j + S^j S^i),$$

Tensor component

Spin alignment much larger than expected from local equilibrium calculations at the leading order in the gradient expansion

Dissipative contribution calculation in
S. Y. F. Liu, Feng-Li, arXiv: 2206.11890

Alternative models proposed by several authors (see next talk by K. Xu)

Summary and outlook

- Spin polarization is a new powerful probe of Quark Gluon Plasma and its full potential is yet to be explored

- Local equilibrium+hydrodynamic model reproduces the measured Λ polarization

- Vector mesons spin alignment larger than expected: a dissipative correction to local equilibrium or an indication of other mechanisms?