

Polarization overview

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A. Palermo, E. Grossi, I. Karpenko, F. Becattini, Eur. Phys. J. C 84 (2024) 920
S. K. Singh, E. Grossi, F. Becattini, arXiv:2605.29383



EMMI Workshop: Light-ion collisions
Kirchhoff-Institut für Physik, Heidelberg — 21–25 September 2026

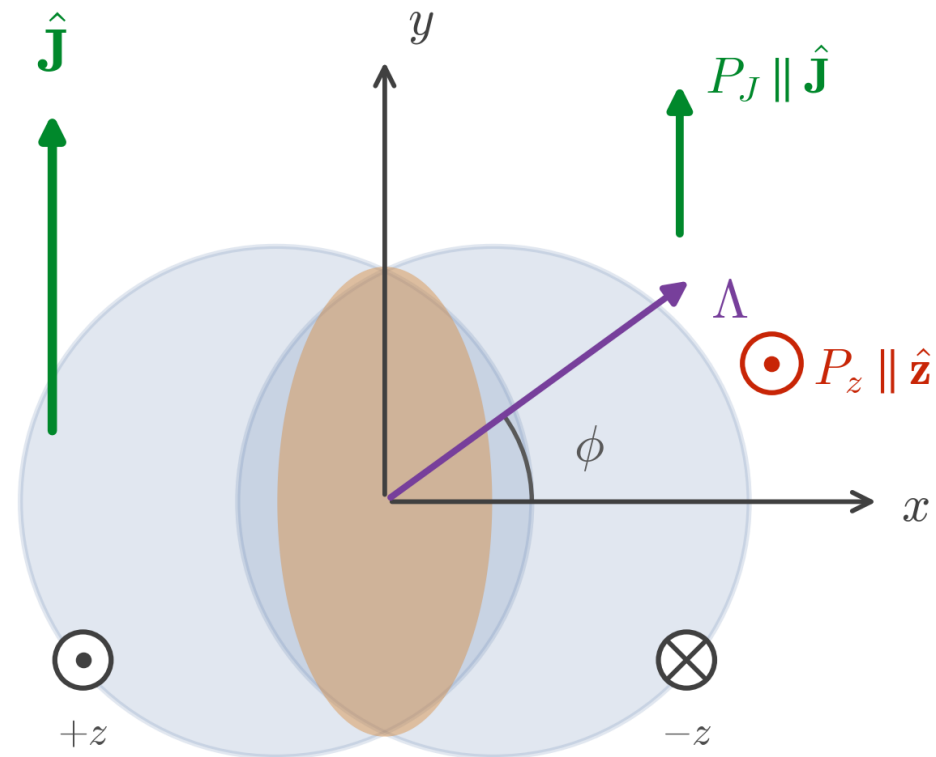


Spin polarization in heavy ion collisions

- Non-central collisions carry a huge orbital angular momentum, $J \sim 10^3\text{--}10^5 \hbar$
- Part of it is transferred to the spin of the emitted hadrons
- Λ is self-analyzing: the daughter proton remembers the spin direction

$$\frac{1}{N} \frac{dN}{d\Omega^*} = \frac{1}{4\pi} \left(1 + \alpha \mathbf{\Pi}_0 \cdot \hat{\mathbf{p}}^* \right), \quad \alpha_\Lambda = 0.732$$

[STAR, Nature 548 (2017) 62] · [ALICE, PRC 101 (2020) 044611]



$$P_J \equiv \langle \mathbf{P} \cdot \hat{\mathbf{J}} \rangle \quad (\text{global}) , \quad P_z(\phi) \equiv \langle \mathbf{P} \cdot \hat{\mathbf{z}} \rangle \quad (\text{local})$$

Two components, measured separately: along the angular momentum and along the beam

Where polarization comes from

[Becattini, Chandra, Del Zanna, EG, Ann. Phys. 338 (2013) 32]

The Cooper–Frye formula gives the momentum distribution at freeze-out, with spin entering only as a degeneracy factor:

$$\varepsilon \frac{dN}{d^3p} = \int_{\Sigma} d\Sigma_{\mu} p^{\mu} f(x, p) , \quad \beta^{\mu} = \frac{u^{\mu}}{T_0} , \quad \xi = \frac{\mu_0}{T_0}$$

At local thermodynamical equilibrium the polarization states are unevenly populated — extending the formula to spin ½ gives

Cooper–Frye for polarization

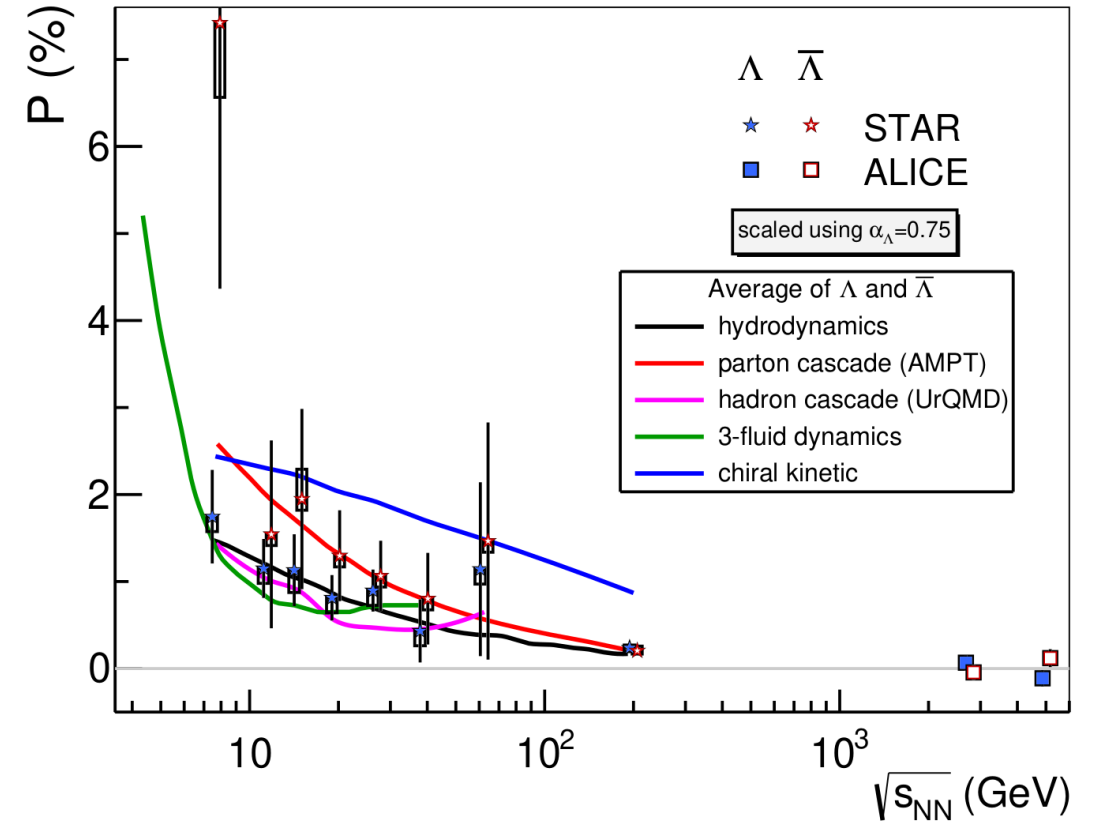
$$\langle \Pi_{\mu}(p) \rangle = \frac{1}{8} \epsilon_{\mu\rho\sigma\tau} \frac{p^{\tau}}{m} \frac{\int d\Sigma_{\lambda} p^{\lambda} n_F (1 - n_F) \partial^{\rho} \beta^{\sigma}}{\int d\Sigma_{\lambda} p^{\lambda} n_F}$$

- No free parameters: the hydrodynamic fields at freeze-out fix the polarization
- Even with no flow, a steady temperature gradient polarizes transversely to the momentum:

$$\mathbf{\Pi} = (1 - n_F) \frac{\hbar}{8mkT^2} (0, \nabla T \times \mathbf{p})$$

Where we stand

- Global polarization decreases with energy and is well reproduced by hydrodynamics
- Local (longitudinal) polarization came out with the opposite sign to the data for years
- Numerous attempts to explain it: thermal shear, different formulations of the shear tensor, spin hydrodynamics
- Polarization can become a quantitative probe, and the comparison with data is still improving

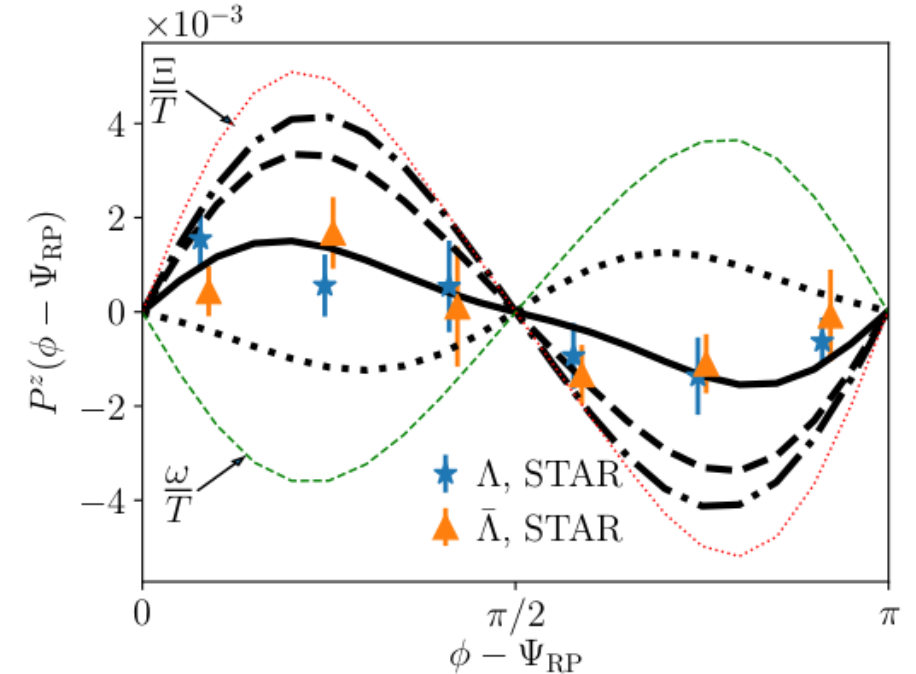


[Becattini, Buzzegoli, Palermo, Karpenko, Inghirami, PRL 127 (2021) 272302]

Thermal shear fixes the sign

F. Becattini, M. Buzzegoli, A. Palermo, I. Karpenko, G. Inghirami, PRL 127 (2021) 272302]

- Thermal vorticity alone (ω/T , green) gives the opposite sign to the data
- The thermal shear (Ξ/T , red) has the right sign, and is larger
- It couples to a non-conserved operator, so it depends on the decoupling hypersurface
- At high energy that surface is nearly isothermal: only gradients of u survive

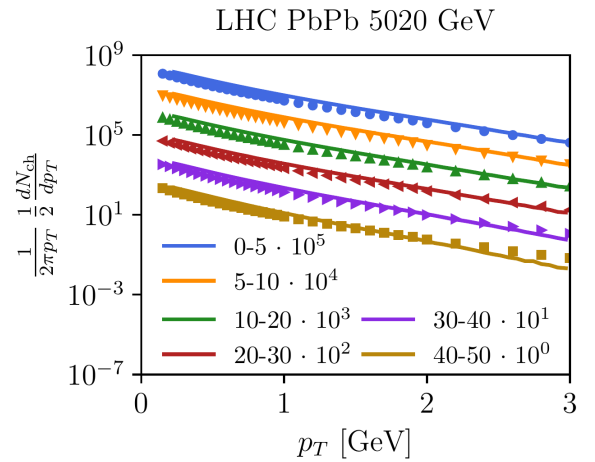
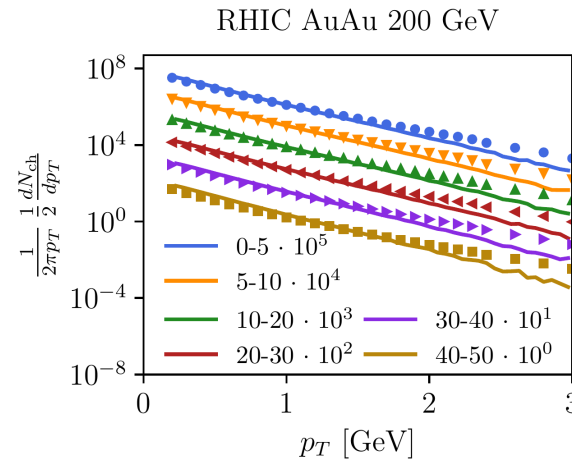
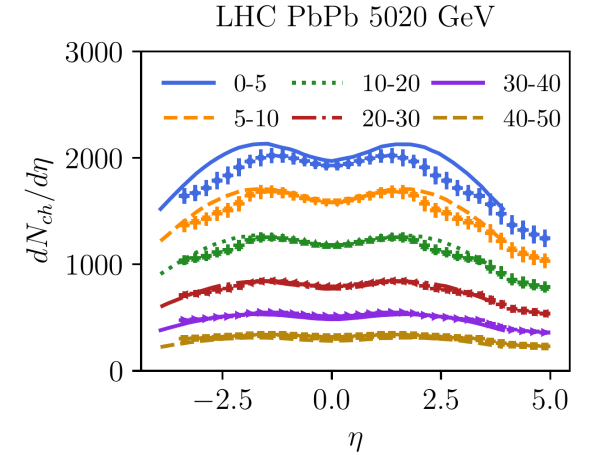
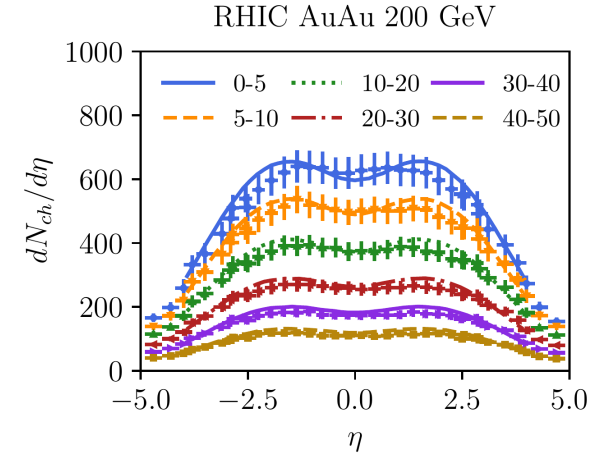


$$S^\mu(p) = -\epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma d\Sigma \cdot p n_F (1 - n_F) \left[\omega_{\rho\sigma} + 2 \hat{t}_\rho \frac{p^\lambda}{\epsilon} \Xi_{\lambda\sigma} \right]}{8mT_H \int_\Sigma d\Sigma \cdot p n_F}$$

Numerical setup

A. Palermo, E. Grossi, I. Karpenko, F. Becattini, Eur. Phys. J. C 84 (2024) 920

- Averaged initial state: superMC and GLISSANDO
- Hydrodynamics: vHLE, constant η/s and temperature-dependent ζ/s
- Afterburner: SMASH:
- Polarization is computed at freeze-out only
— the afterburner carries no spin



superMC: [Shen, Alzhani, PRC 102 (2020) 014909]

GLISSANDO 2: [Rybczyński, Stefanek, Broniowski, Bożek, Comput. Phys. Commun. 185 (2014) 1759]

vHLE: [Karpenko, Huovinen, Bleicher, Comput. Phys. Commun. 185 (2014) 3016]

SMASH: [Weil et al., PRC 94 (2016) 054905]

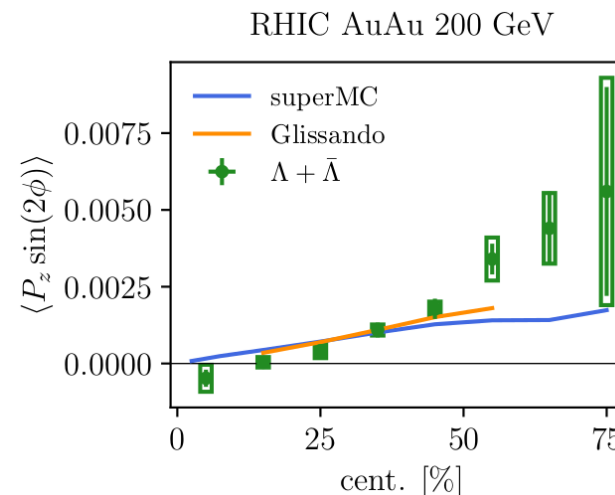
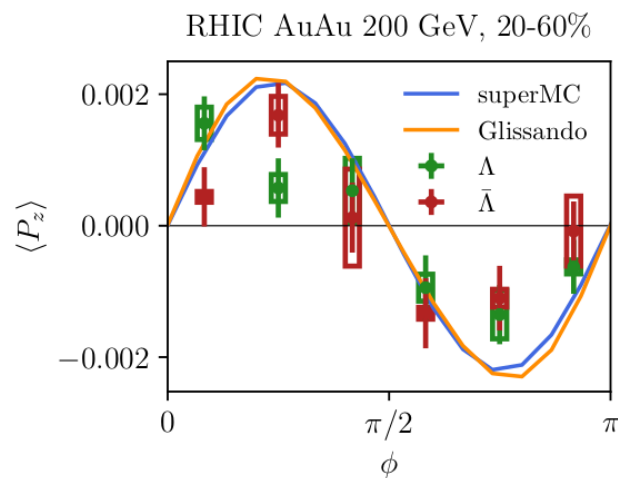
Sampler: [Schäfer, Karpenko, Wu, Hammelmann, Elfner, EPJA 58 (2022) 230]

SMASH: [Weil et al., PRC 94 (2016) 054905]

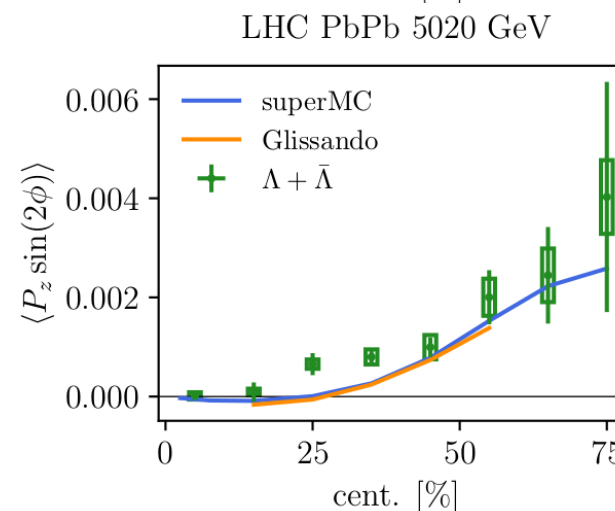
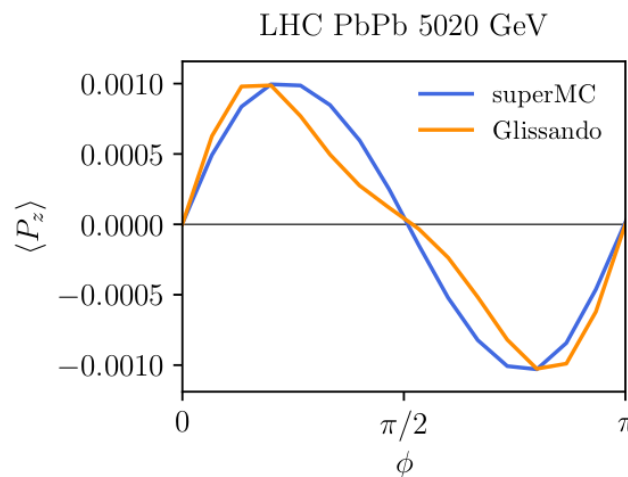
Longitudinal polarization

- The azimuthal modulation and its growth towards peripheral collisions are reproduced at both energies
- The two initial-state models are almost indistinguishable in this sector

RHIC



LHC

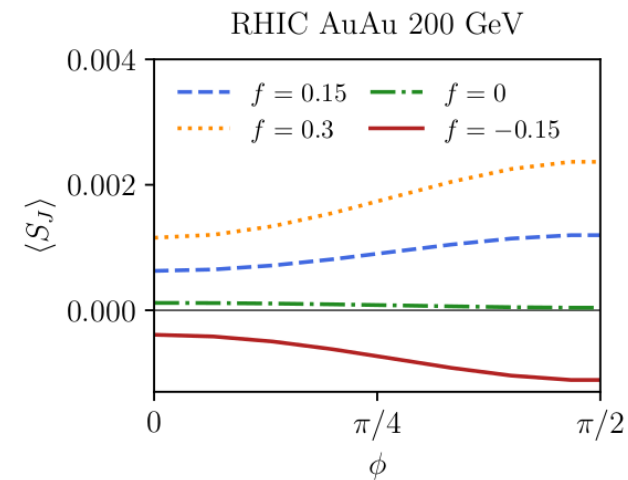
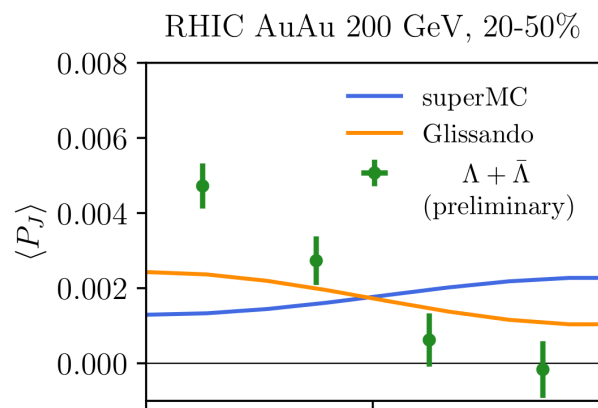


Good agreement in the longitudinal sector at both RHIC and the LHC

Transverse polarization probes the initial longitudinal flow

- The centrality dependence is almost identical for the two initial states — the azimuthal one is not
- superMC rises with ϕ , GLISSANDO falls; neither follows the preliminary STAR points
- In superMC the shape is set by the initial longitudinal flow, controlled by f :

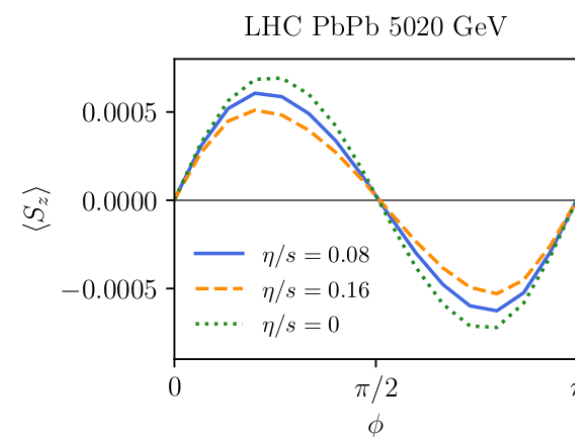
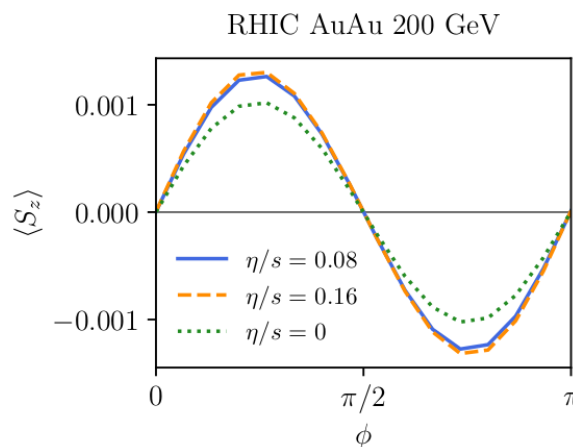
$$T^{\tau\tau} = \rho \cosh(f y_{\text{CM}}) , \quad T^{\tau\eta} = \frac{\rho}{\tau} \sinh(f y_{\text{CM}})$$



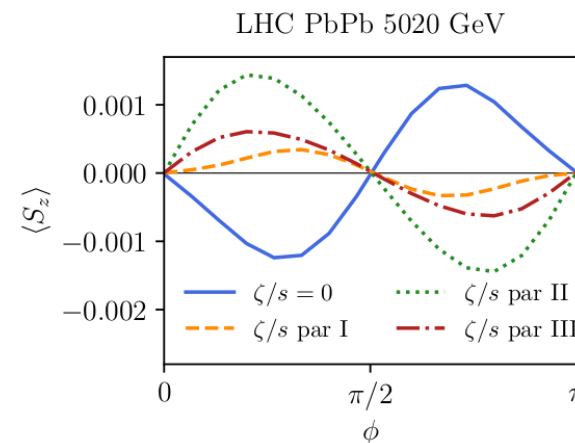
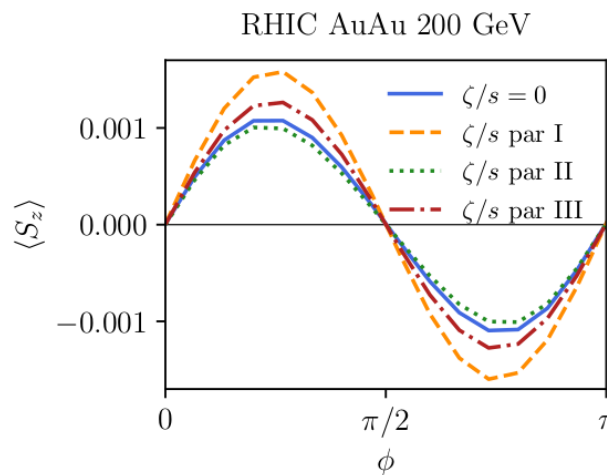
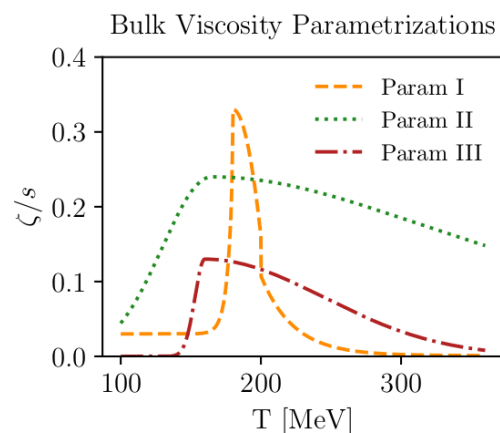
Shear and bulk viscosity

- Shear viscosity has a minor effect on both components of the polarization
- **Bulk viscosity has a significant effect, and can change the sign of the longitudinal polarization**
- The effect grows with collision energy; the transverse component is affected only mildly

η/s



ζ/s

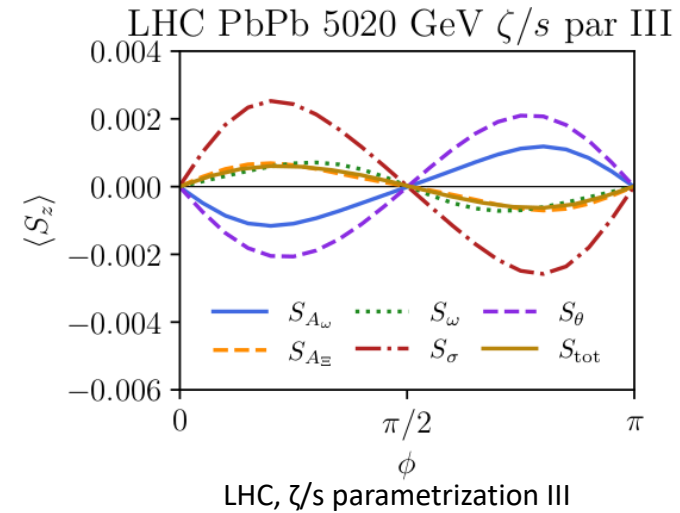
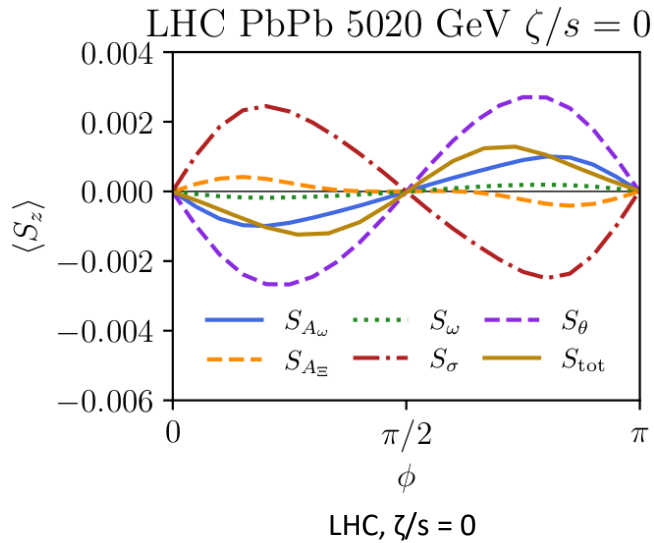


Why does bulk viscosity matter so much?

$$\omega_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} \omega^\rho u^\sigma + \frac{1}{2} (A_\mu u_\nu - A_\nu u_\mu)$$

$$\Xi_{\mu\nu} = \frac{1}{2} (A_\mu u_\nu + A_\nu u_\mu) + \sigma_{\mu\nu} + \frac{1}{3} \theta \Delta_{\mu\nu}$$

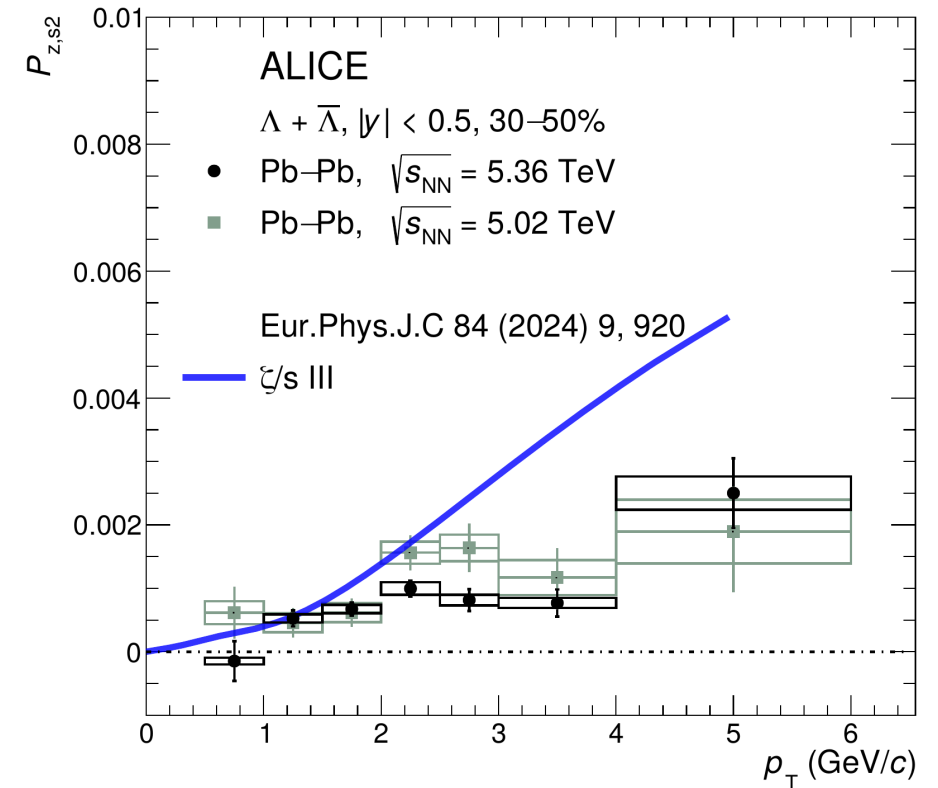
$$S^\mu = \underbrace{S_\omega^\mu}_{\text{rotation}} + \underbrace{S_{A_\omega}^\mu + S_{A_\Xi}^\mu}_{\text{acceleration}} + \underbrace{S_\sigma^\mu}_{\text{shear}} + \underbrace{S_\theta^\mu}_{\text{expansion}}$$



Bulk viscosity does not create polarization: it reorganizes rotation, acceleration, shear and expansion

New: ALICE Run 3, Pb–Pb at 5.36 TeV

- Longitudinal Λ and anti- Λ polarization w.r.t. the second- and third-order event planes
- **Bulk viscosity is needed to reproduce the sign of the measured polarization**
- Consistent with the 5.02 TeV measurement, with much smaller uncertainties
- Third-order polarization is comparable in size to the second-order one — unlike the flow harmonics
- The measured p_T dependence is still only partially reproduced

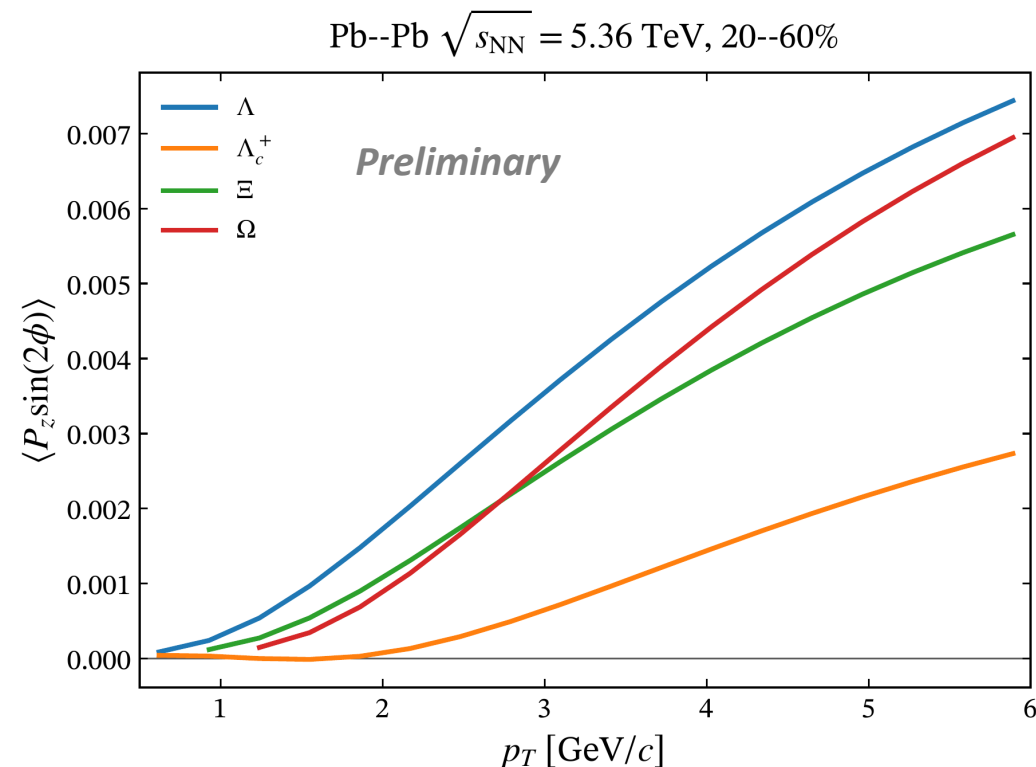
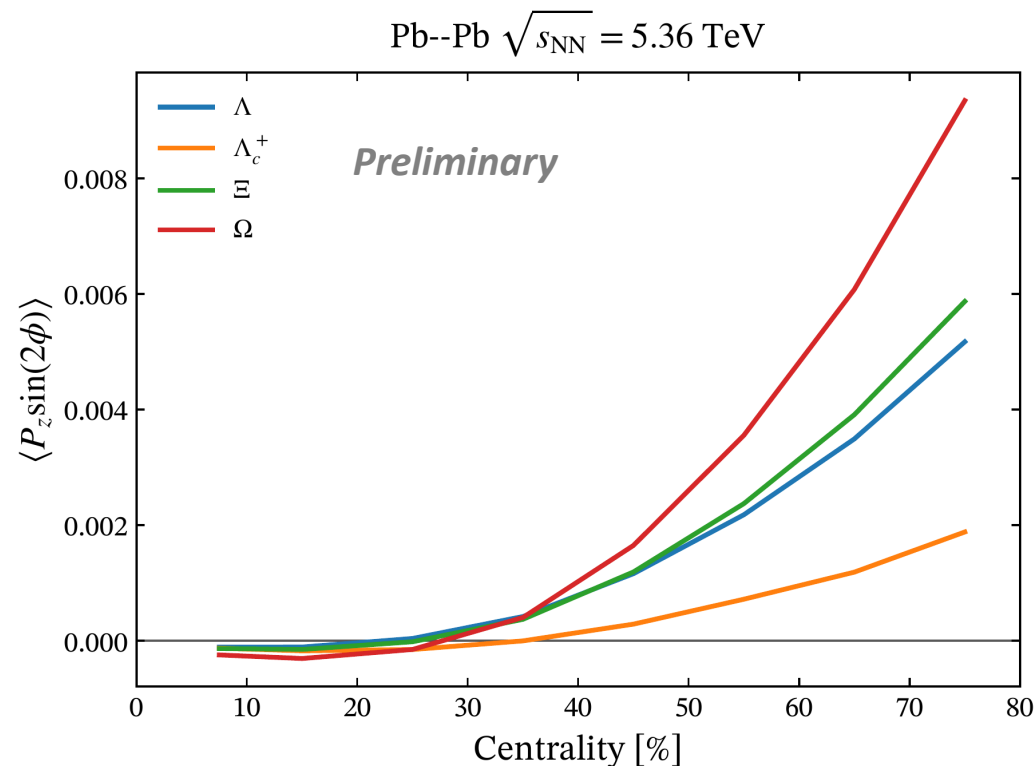


the blue curve is our EPJC 84 (2024) 920 calculation, ζ/s III

[ALICE Collaboration, arXiv:2606.18070] · [Alzhrani, Ryu, Shen, PRC 106 (2022) 014905]

Predictions for other species at 5.36 TeV

In collaboration with D. Roselli, A. Vignoli, F. Palli and A. Palermo

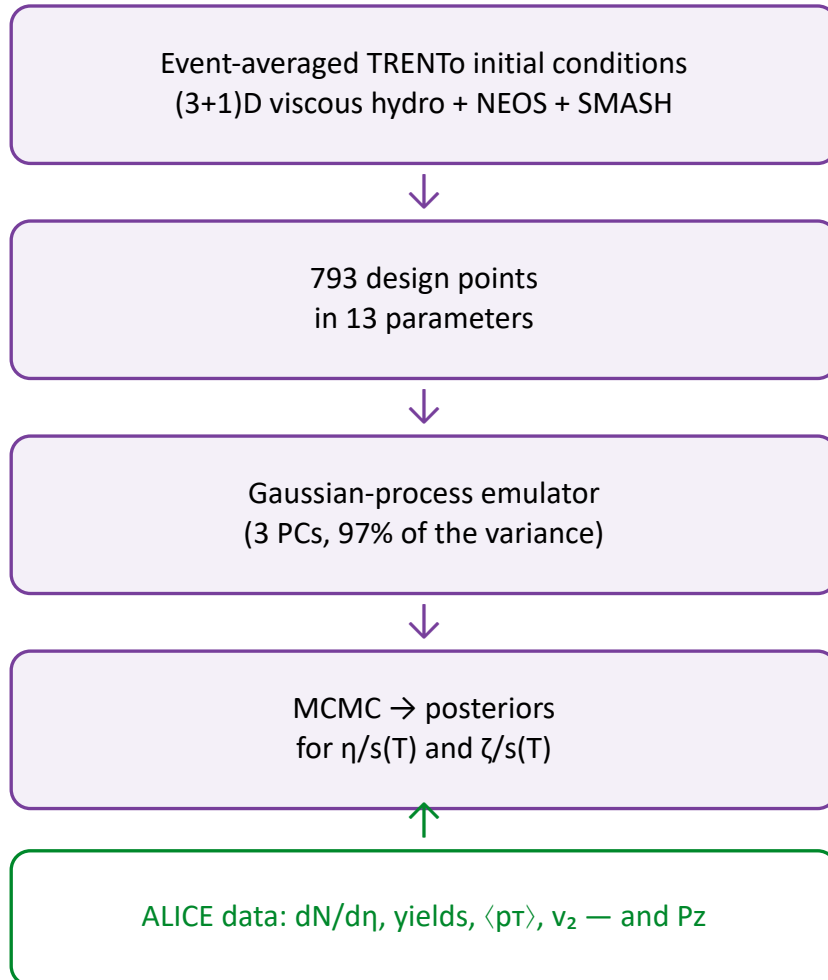


- Same framework and freeze-out surface applied to Ξ , Ω and Λ_c^+ : same sine modulation, same steep rise towards peripheral collisions
 - Ω is the largest in peripheral events, Λ_c^+ is suppressed by roughly a factor of three, and the p_T onset is species-dependent
- A measurable hierarchy across species — a further test of the same mechanism

New: can polarization constrain η/s and ζ/s ?

S. K. Singh, E. Grossi, F. Becattini, arXiv:2605.29383

Pz added to a standard global Bayesian analysis of Pb–Pb at 5.02 TeV — so far these have used only momentum-space observables

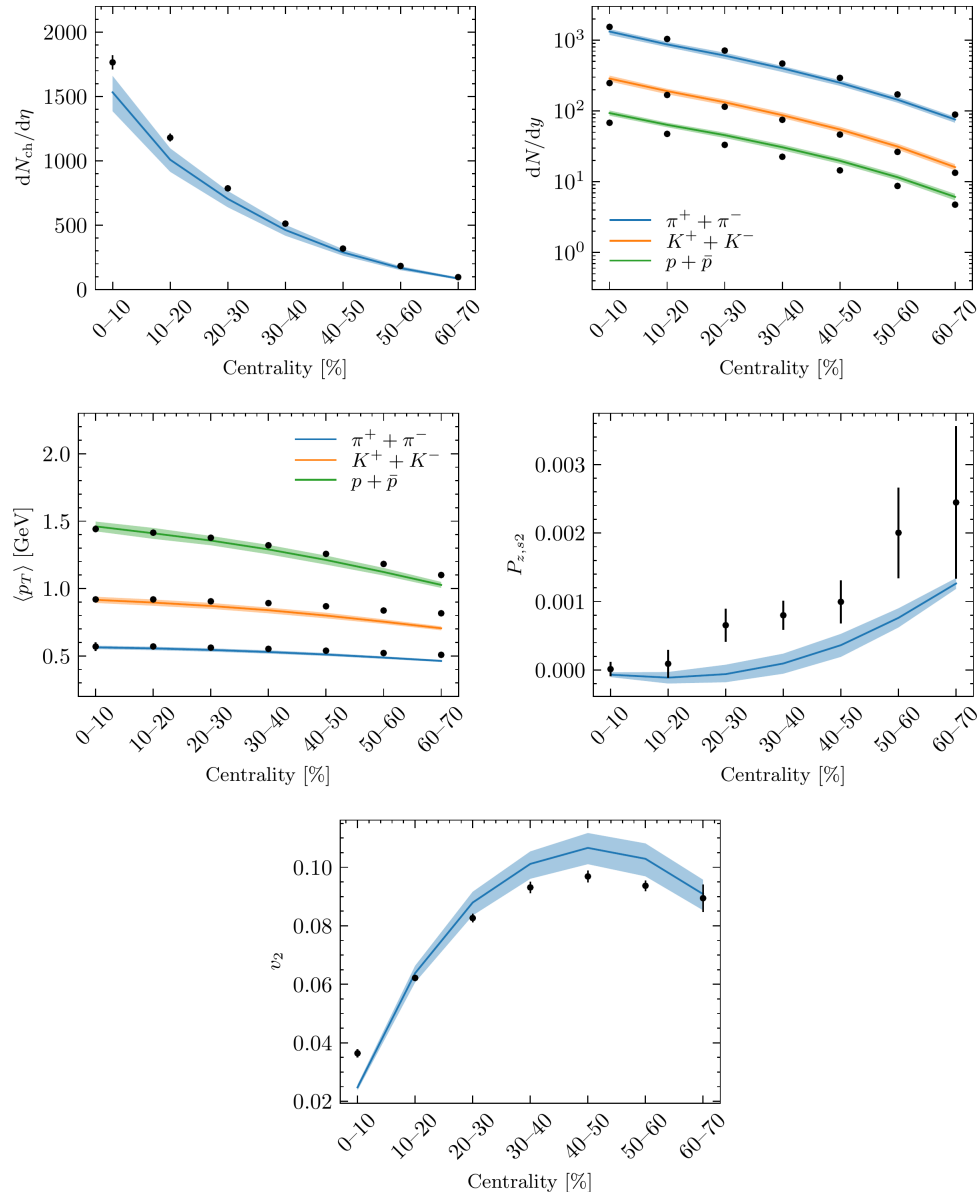


Parameter	Prior	MAP with Pz	without Pz
Initial state			
η_0	1.5 – 3.5	2.54	2.50
$\sigma\eta$	1.0 – 2.5	1.38	1.44
ηB_0	4.0 – 6.0	5.15	4.57
σB_{in}	1.8 – 3.0	2.14	2.74
f (longitudinal flow)	0.0 – 0.4	0.17	0.16
τ_0 [fm]	0.6 – 1.2	0.83	1.0
Transport coefficients			
$(\eta/s)_{min}$	0.05 – 0.25	0.07	0.06
$(\eta/s)_{slope}$	0.0 – 3.0	0.76	1.44
$(\eta/s)_{curv}$	–1.0 – 1.0	0.07	0.23
$(\zeta/s)_{max}$	0.0 – 0.3	0.16	0.12
$(\zeta/s)_{width}$	0.0 – 0.3	0.19	0.07
$(\zeta/s)_{T_0}$	0.1 – 0.3	0.16	0.15
Particlization			
ϵ_{sw} [GeV/fm ³]	0.35 – 0.65	0.54	0.48

Only the bulk viscosity moves when Pz is included

Observables

[S. K. Singh, E. Grossi, F. Becattini, arXiv:2605.29383]

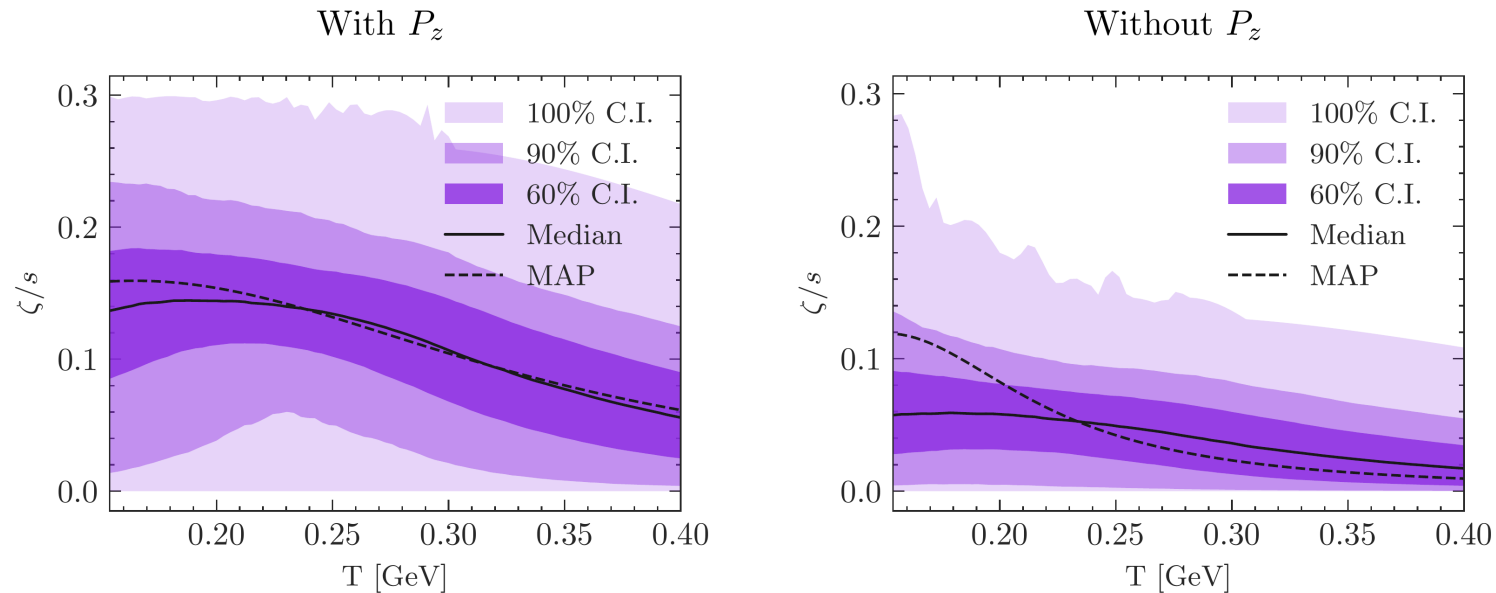


- Posterior predictive check: the bands are the 5–95% interval, propagated through the emulator trained with Pz
- Multiplicity, identified yields, $\langle p_T \rangle$ and v_2 are all reproduced
- Pz rises towards peripheral collisions as measured, though the band sits below the data in mid-central events
- The same parameters account for the momentum-space and the spin observables at once

A single fit reproduces the bulk and the spin together

New: polarization pulls ζ/s upward

- Including P_z shifts the median ζ/s up by about a factor of two
- η/s is essentially unchanged — consistent with its weak effect on polarization
- The shift is not yet statistically significant at the 68% credibility level

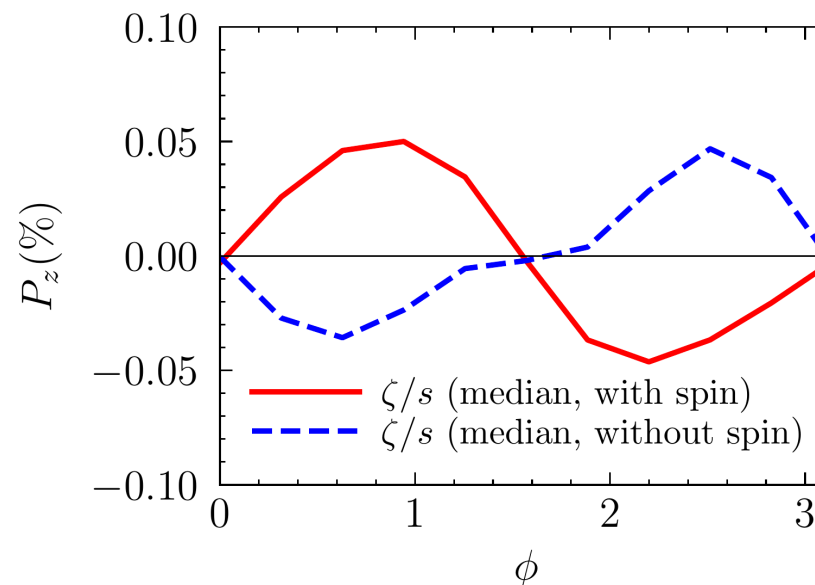
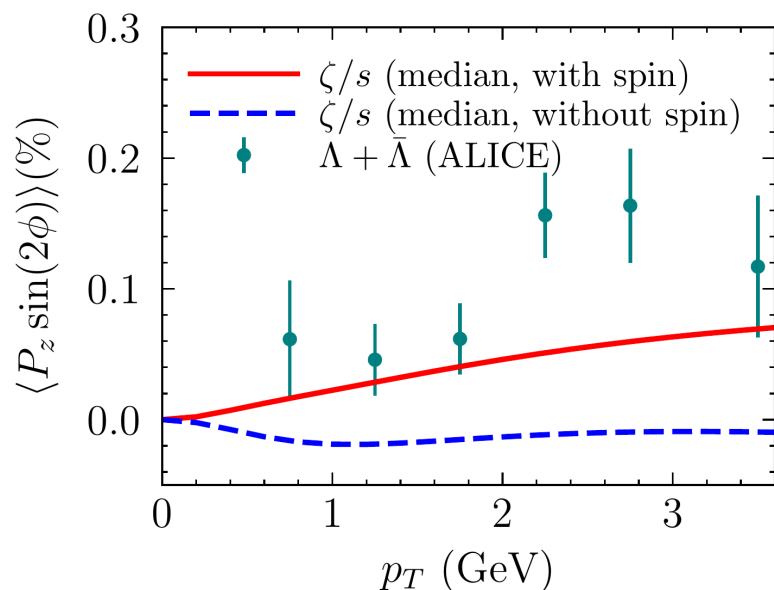


[S. K. Singh, E. Grossi, F. Becattini, arXiv:2605.29383, Figs. 7–8]

Spin polarization carries information on transport that momentum observables alone do not

Only the fit that includes P_z gets the sign right

- Both parameter sets describe the spectra, $\langle p_T \rangle$ and v_2 equally well
- **The sign of P_z is reproduced only with the ζ/s extracted including polarization (red)**
- With the ζ/s from the fit without spin (blue dashed), the longitudinal polarization has the wrong sign



[S. K. Singh, E. Grossi, F. Becattini, arXiv:2605.29383, Fig. 15]

Momentum-space observables cannot tell the two apart — the polarization can

Beyond local equilibrium: spin as a dynamical field

[Sapna, S. K. Singh, D. Wagner, Phys. Rev. C 112 (2025) 054902]

- Everything so far assumes spin reaches local equilibrium by freeze-out — does it?
- Dissipative spin hydrodynamics: the spin potential (ω_0 , κ_0) and a spin-shear stress tensor evolve dynamically
- Evolution equations and transport coefficients from quantum kinetic theory with non-local collisions
- They relax towards thermal vorticity, with relaxation times fixed by the microscopic interaction:

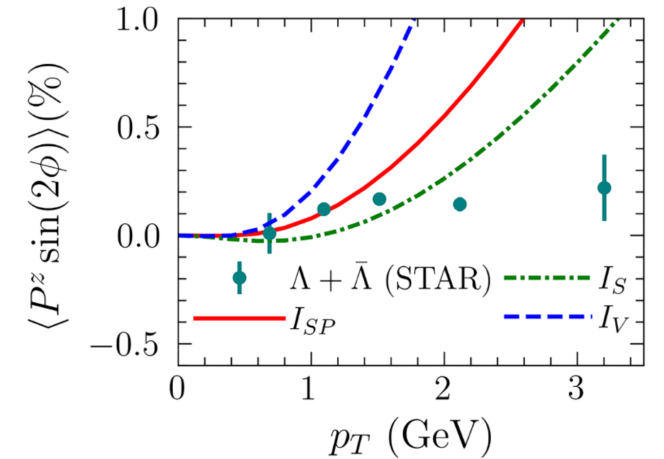
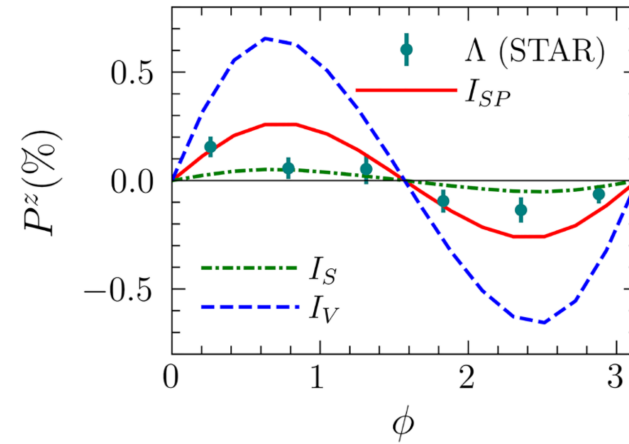
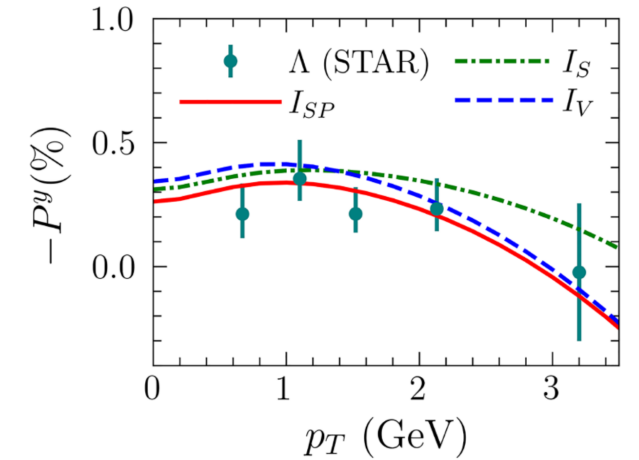
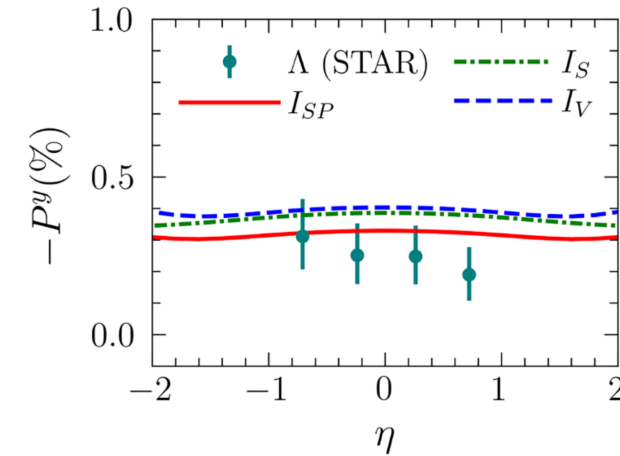
$$u \cdot \partial \omega_0^\mu = -\frac{\omega_0^\mu - \varpi_\omega^\mu}{\tau_\omega} , \quad u \cdot \partial \kappa_0^\mu = -\frac{\kappa_0^\mu - \varpi_\kappa^\mu}{\tau_\kappa} , \quad u \cdot \partial t^{\mu\nu} = -\frac{t^{\mu\nu}}{\tau_t} + \dots$$

Three microscopic interactions between the constituents — scalar, scalar + pseudoscalar (NJL), vector:

$$\mathcal{L}_S = G(\bar{\psi}\psi)^2 , \quad \mathcal{L}_{SP} = G[(\bar{\psi}\psi)^2 + (\bar{\psi}\gamma_5\psi)^2] , \quad \mathcal{L}_V = -G(\bar{\psi}\gamma^\mu\psi)^2$$

Does spin thermalize?

- The spin potential starts at zero and relaxes towards thermal vorticity
- **At 200 GeV spin thermalization is a reasonable approximation**
- The spin-shear stress plays the role of the thermal shear, and its size depends strongly on the interaction
- Global polarization (top) is barely affected by the interaction type
- The sign of the longitudinal polarization (bottom) is not: only the NJL-like case follows the data



[Sapna, S. K. Singh, D. Wagner, PRC 112 (2025) 054902]

The olarization becomes a window on the microscopic interaction

Conclusions

- Polarization at local equilibrium is parameter-free: the hydrodynamic fields at freeze-out fix it
- Transverse polarization is very sensitive to the initial longitudinal flow
- Bulk viscosity sets the sign of the longitudinal polarization at LHC — now confirmed by ALICE at 5.36 TeV
- In a Bayesian analysis, adding P_z pulls ζ/s upward by a factor ~ 2
- Dissipative spin hydrodynamics supports local equilibrium at RHIC, and links the sign of the longitudinal polarization to the microscopic interaction

Polarization can constrain initial conditions and transport coefficients

Francesco Palli, next talk — “Spin polarization from heavy ions to O–O collisions”

Enrico Speranza — “Probing the Quark–Gluon Plasma with Spin Correlations”

THANK YOU FOR YOUR ATTENTION