Relativistic magnetohydrodynamics for spin polarized media

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based on:
Phys. Lett. B 814 136096 (2021); *Phys. Rev. D* 103, 014030 (2021); *Phys. Rev. Lett* 129, 192301 (2022)

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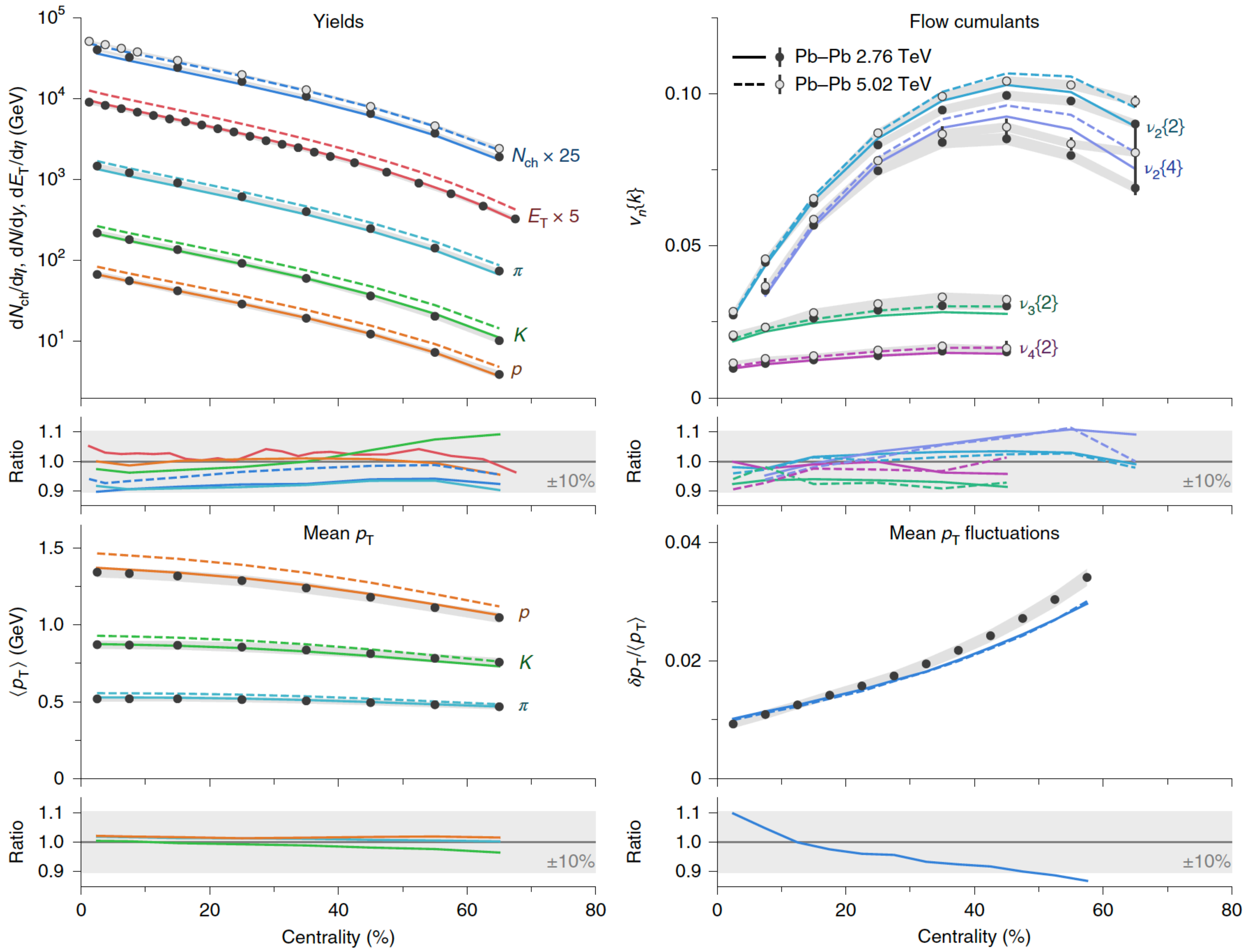
MOTIVATION

QGP EVOLVES HYDRODYNAMICALLY



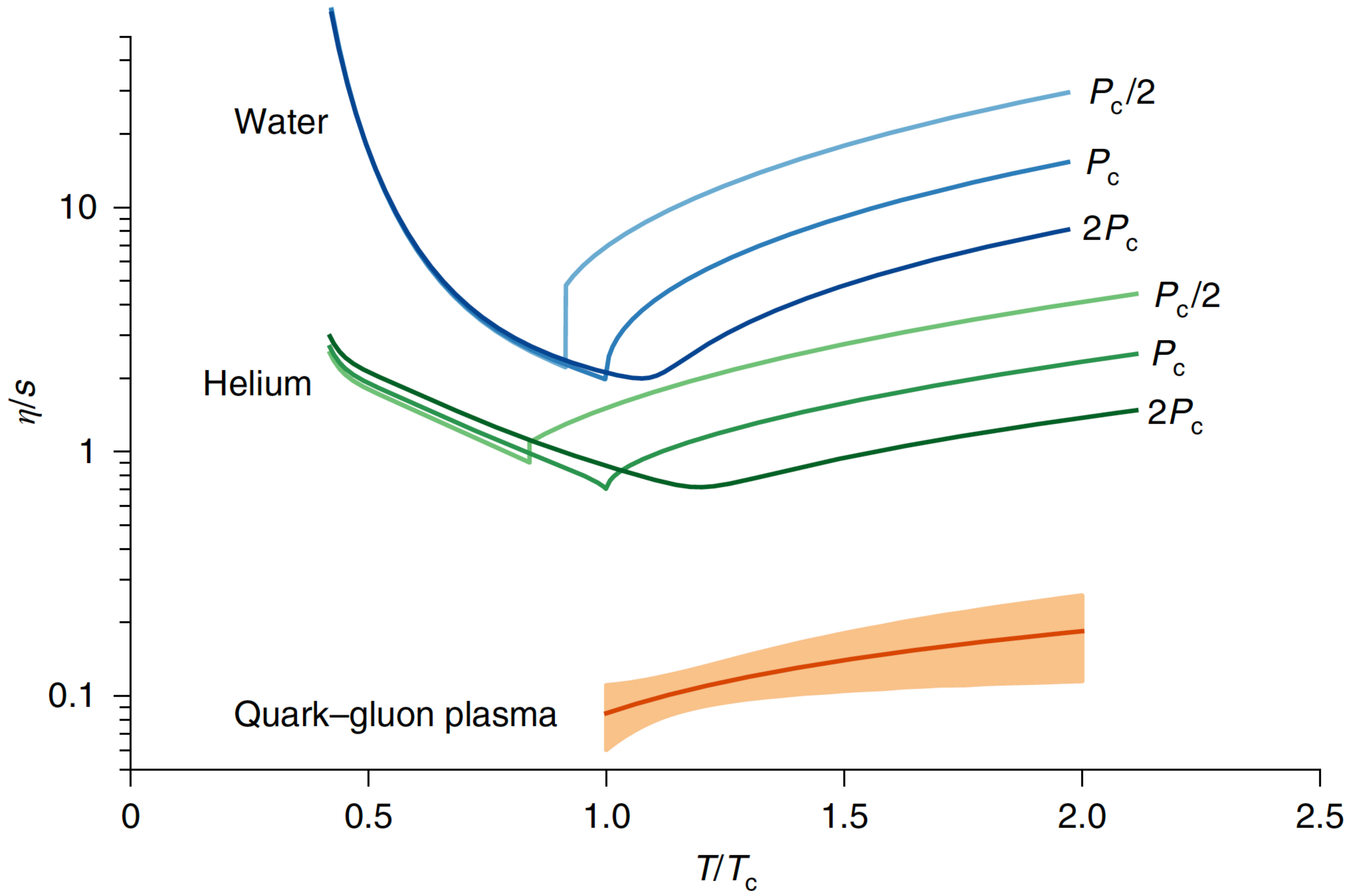
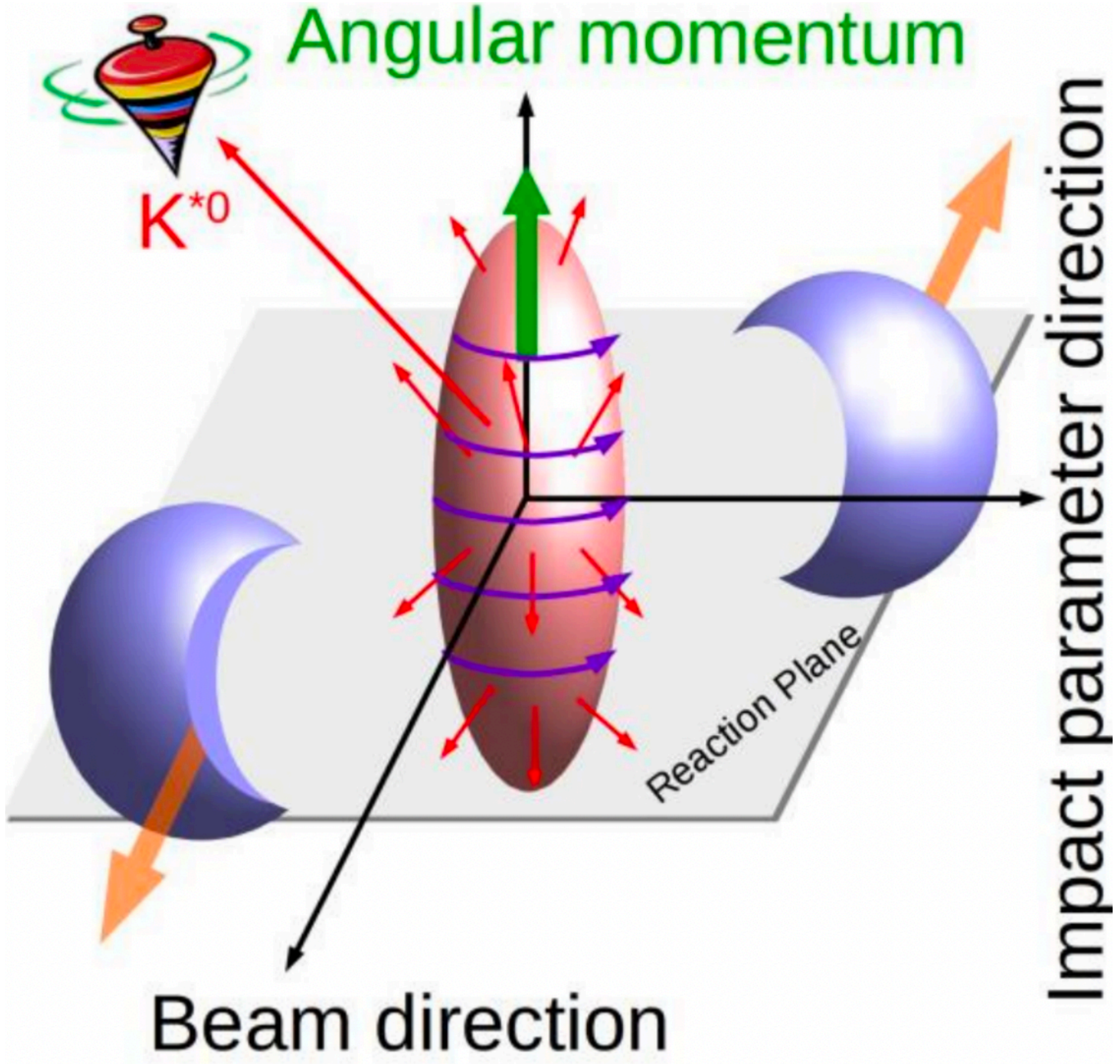


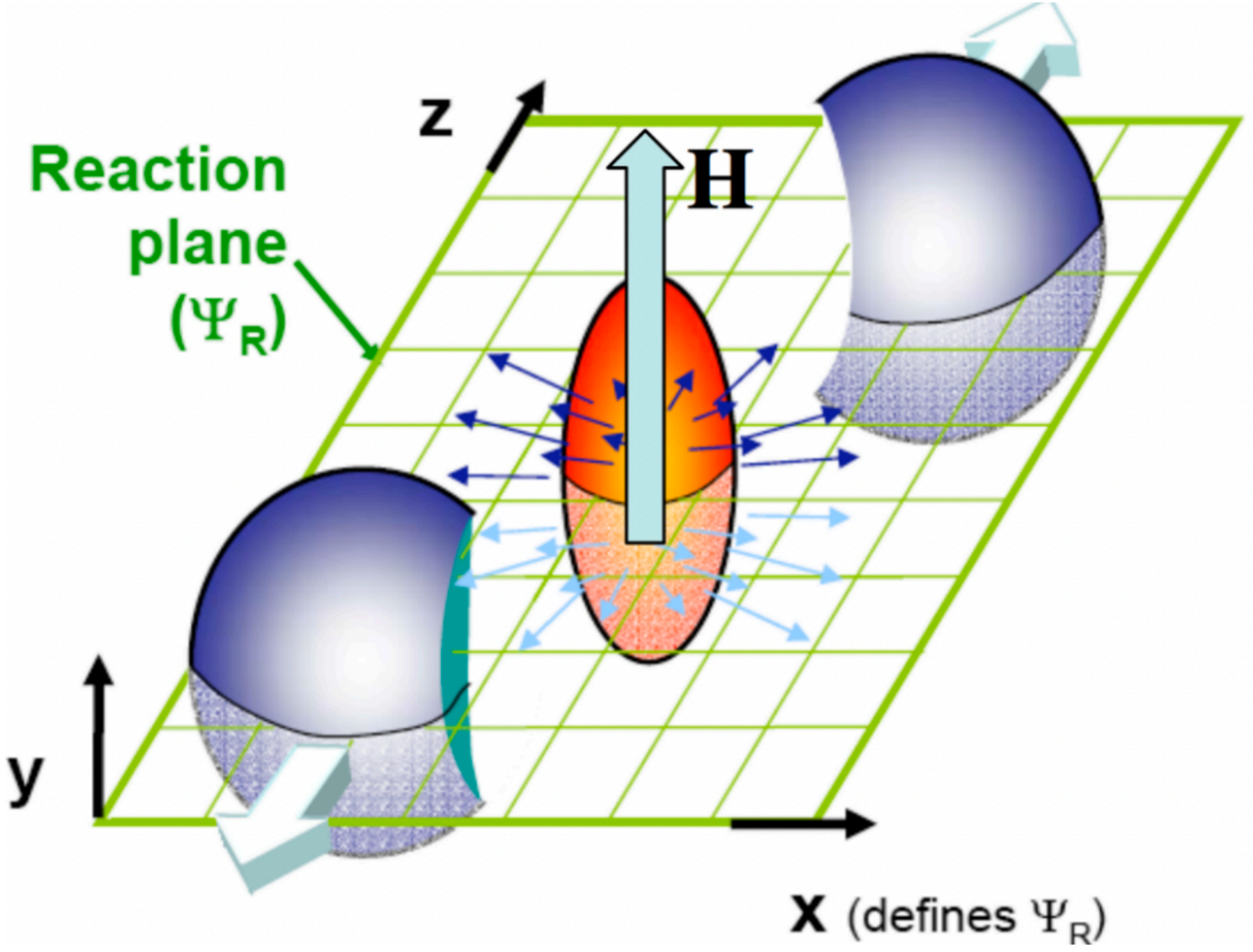
figure: J. Bernhard, J. Moreland, S. Bass, Nature Phys. 15, 1113–1117 (2019)

Well established properties of the produced QCD matter:

- Behaves like a fluid ➡ hydrodynamics applicable
- Low viscosity ➡ inclusion of dissipative effects required

NON-CENTRAL HEAVY-ION COLLISIONS





Non-central collisions are interesting:

- Large initial orbital angular momentum

F. Becattini, F. Piccinini, J. Rizzo, PRC 77 (2008) 024906

- Large magnetic field

A. Bzdak and, V. Skokov, PLB 710 (2012) 171-174

SPIN POLARIZATION DUE TO GLOBAL ORBITAL ANGULAR MOMENTUM

Part of the **angular momentum can be transferred from the orbital to the spin part**

Liang ZT, Wang XN. PRL 94:102301 (2005)
Betz B, Gyulassy M, Torrieri G. PRC 76:044901 (2007)
Gao JH, et al. PRC 77:044902 (2008)
Becattini F, Piccinini F, et al. J. Phys. G 35:054001 (2008)

$$\boldsymbol{J}_{\text{init}} = \boldsymbol{L}_{\text{init}} = \boldsymbol{L}_{\text{final}} + \boldsymbol{S}_{\text{final}}$$

Emitted **particles are expected to be polarized** along the fireball's global angular momentum.

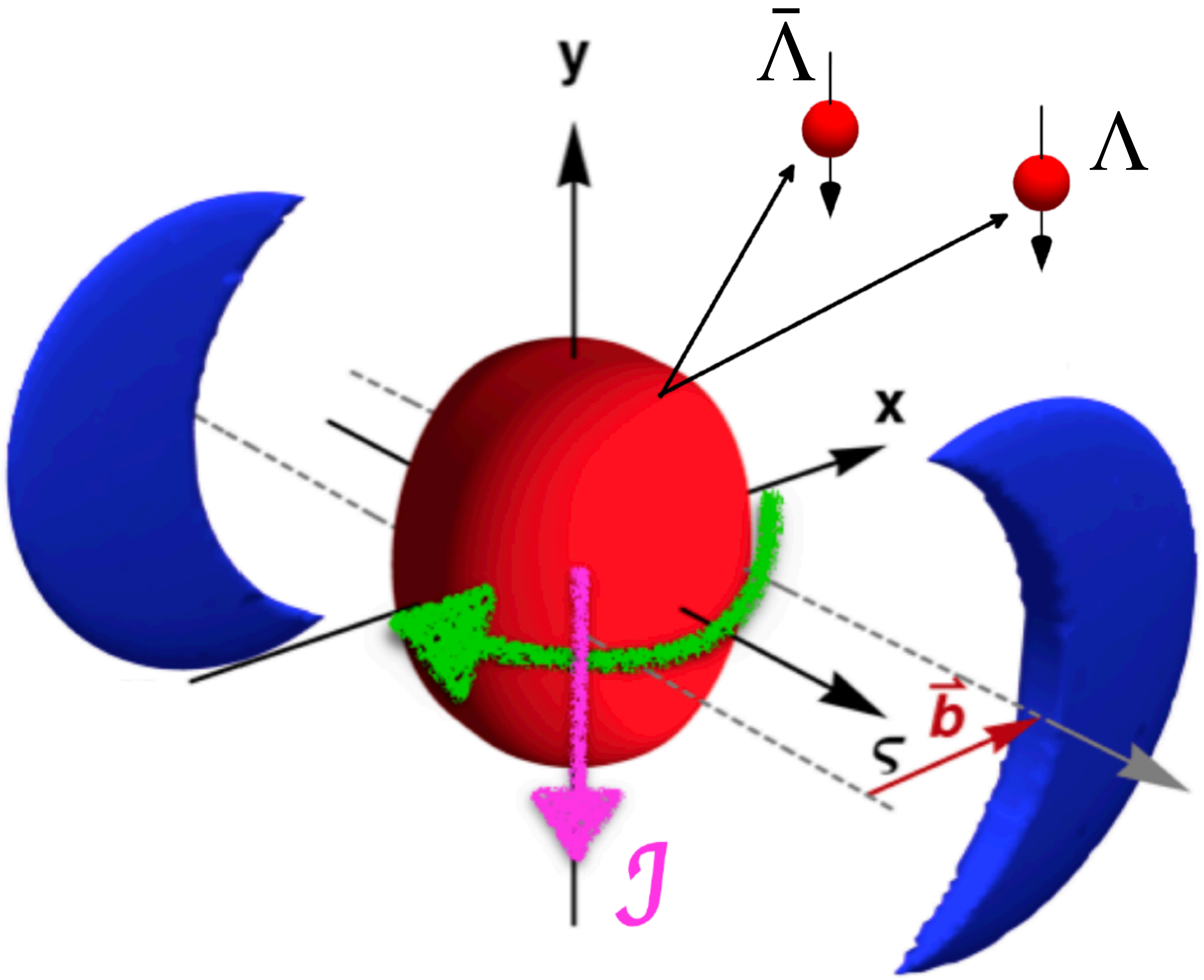
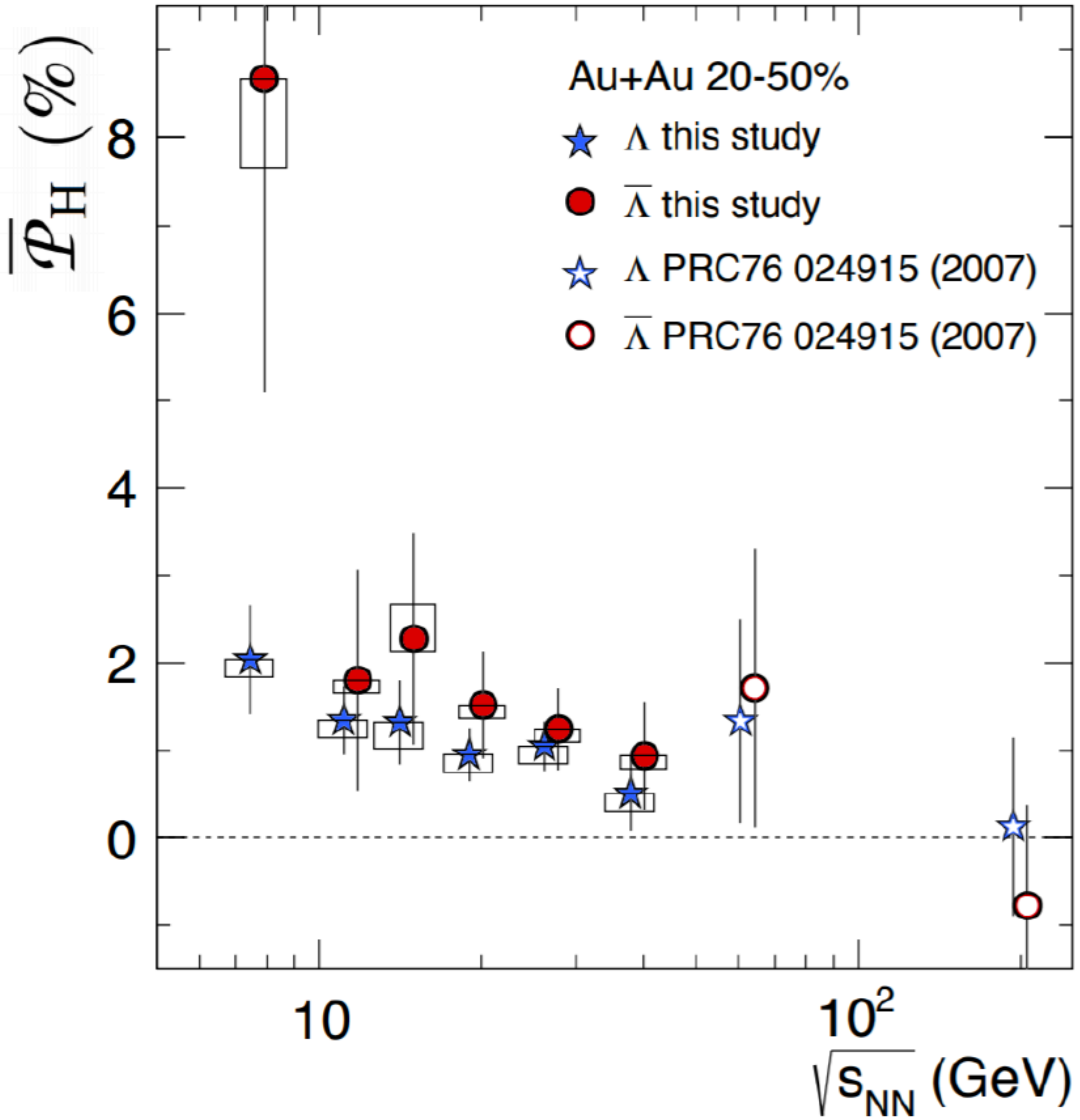


figure: R. Ryblewski

Measurement of Λ and $\bar{\Lambda}$ global spin polarization



L. Adamczyk et al. (STAR) (2017), Nature 548 (2017) 62-65

Spin polarization in equilibrated QGP — spin-thermal approach

In thermodynamic equilibrium one can establish a link between spin and vorticity

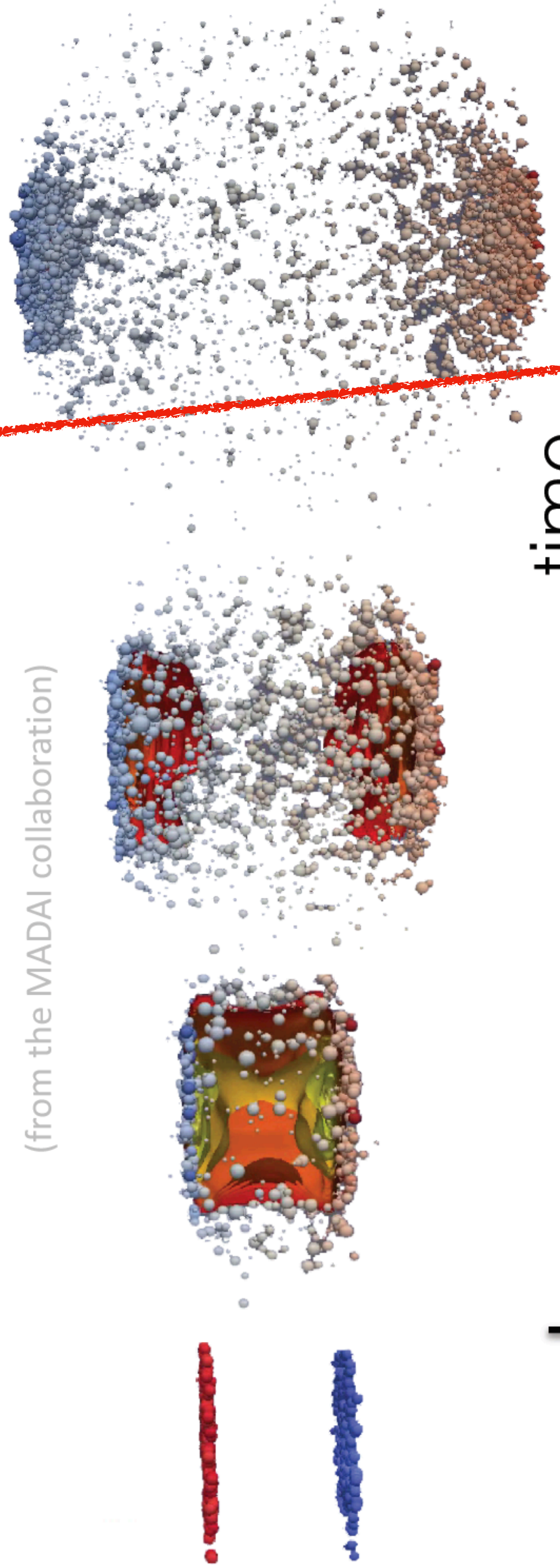
Becattini F, Chandra V, Del Zanna L, Grossi E. AP 338:32 (2013)
F. Becattini, L. Csernai, and D. J. Wang, PRC 88, 034905 (2013)
Fang R, Pang L,Wang Q,Wang X. PRC 94:024904 (2016)
F. Becattini, I. Karpenko, M. Lisa, I. Upsal, and S. Voloshin PRC 95, 054902 (2017)

$$S^{\mu}(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_{\tau}\frac{\int d\Sigma_{\lambda}p^{\lambda}n_F\left(1-n_F\right)\varpi_{\rho\sigma}}{\int d\Sigma_{\lambda}p^{\lambda}n_F}$$

$$\varpi_{\mu\nu} = -\frac{1}{2}\left(\partial_{\mu}\beta_{\nu} - \partial_{\nu}\beta_{\mu}\right) \qquad \beta^{\mu} = \frac{u^{\mu}}{T}$$

Spin is enslaved to thermal vorticity

Very attractive: Allows to extract polarization at the freeze-out hypersurface in any model which provides u^{μ}, T and μ.



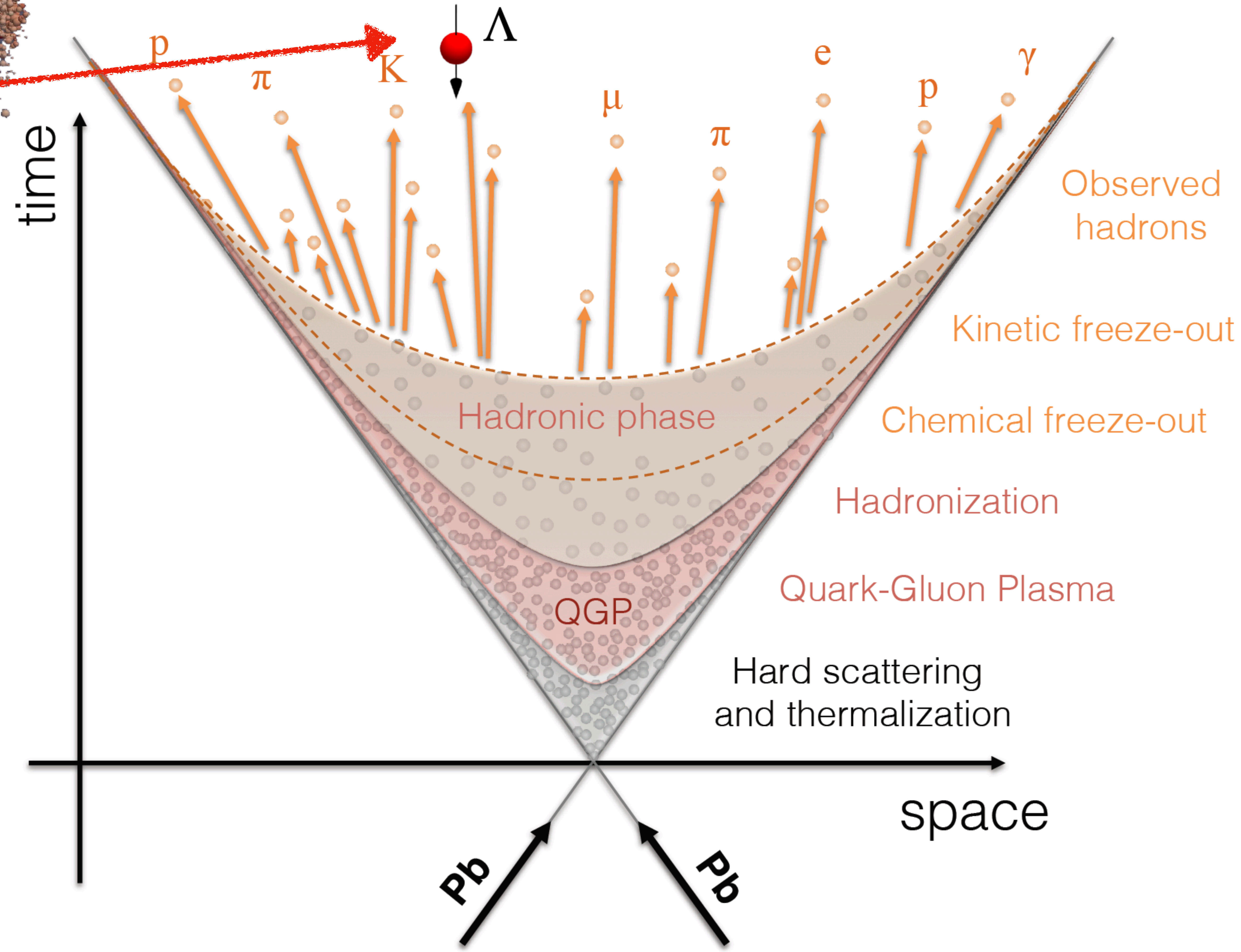


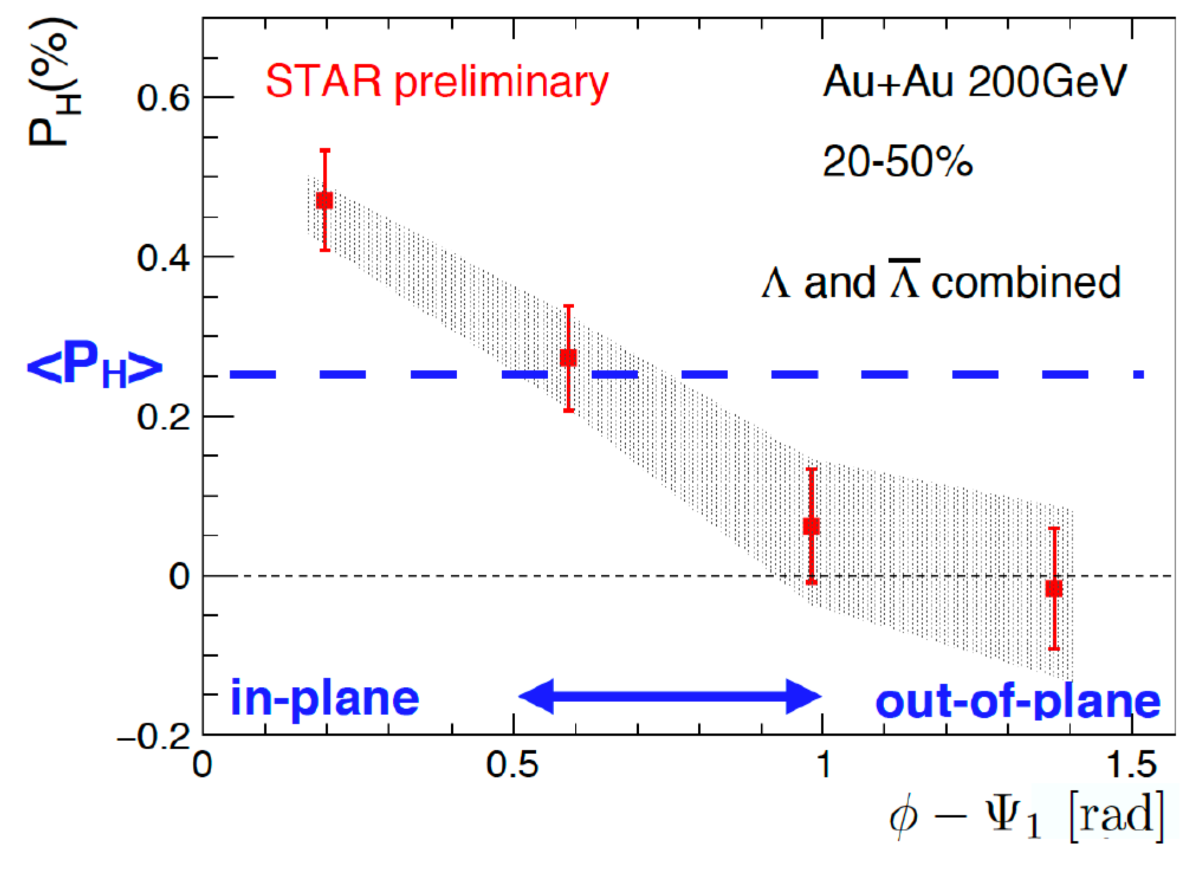
figure: D.D. Chin

Measurement vs spin-thermal approach: global polarization

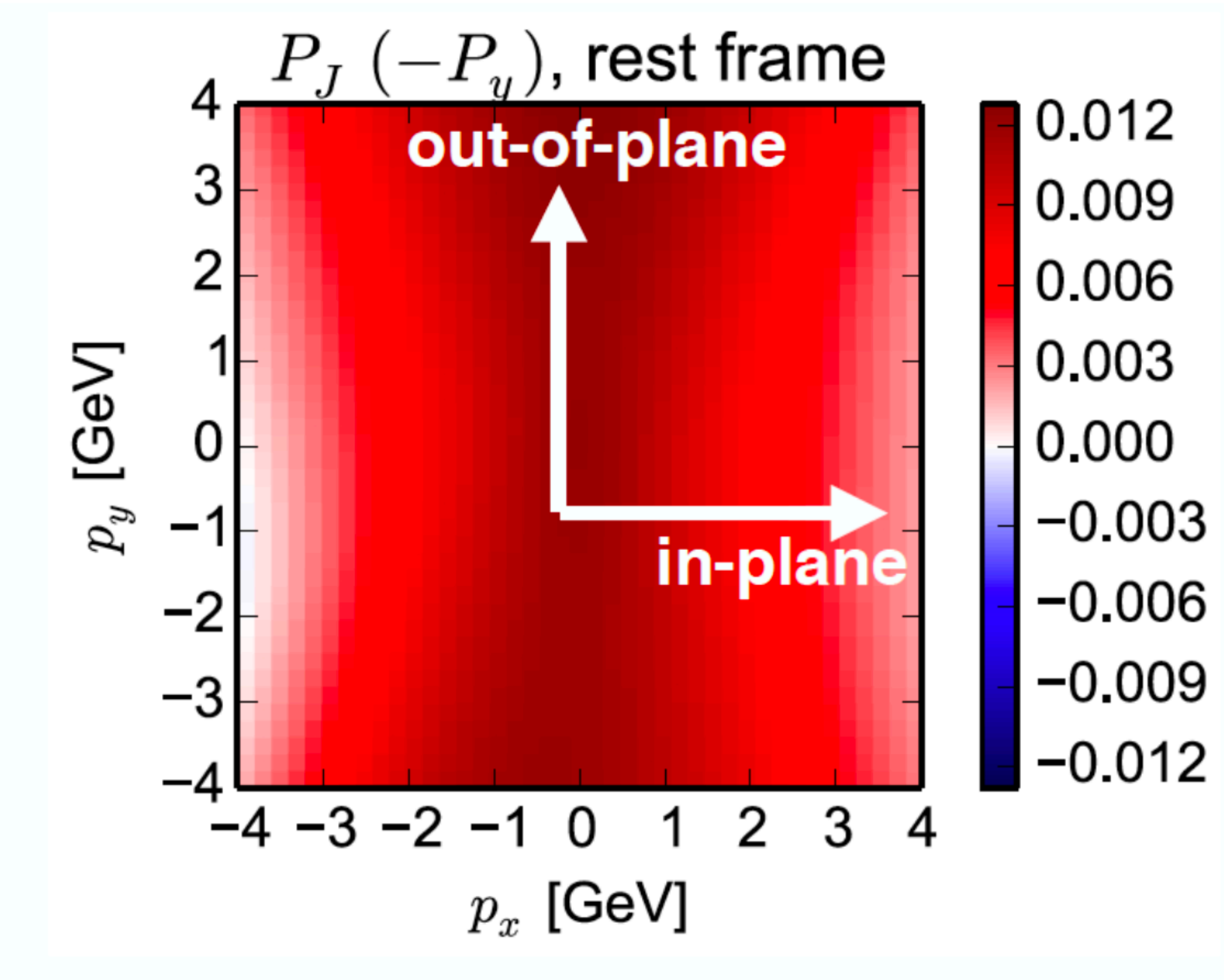
Global polarization data supports the spin-thermal approach

Signal is robust and agrees well with predictions of transport and hydrodynamic models

Azimuthal modulation is not captured

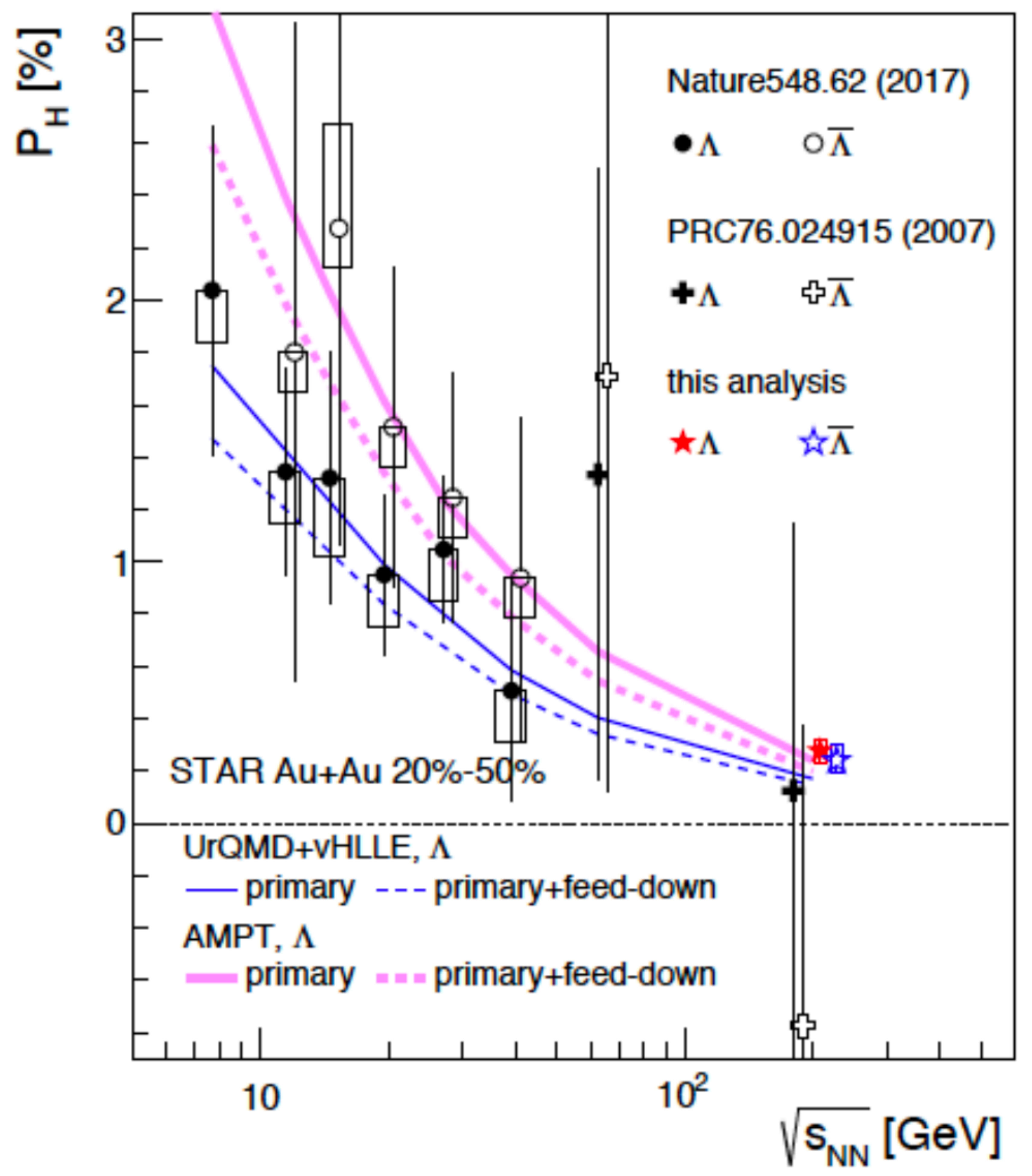


Credit: T.Niida, The 5th Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions, 2019



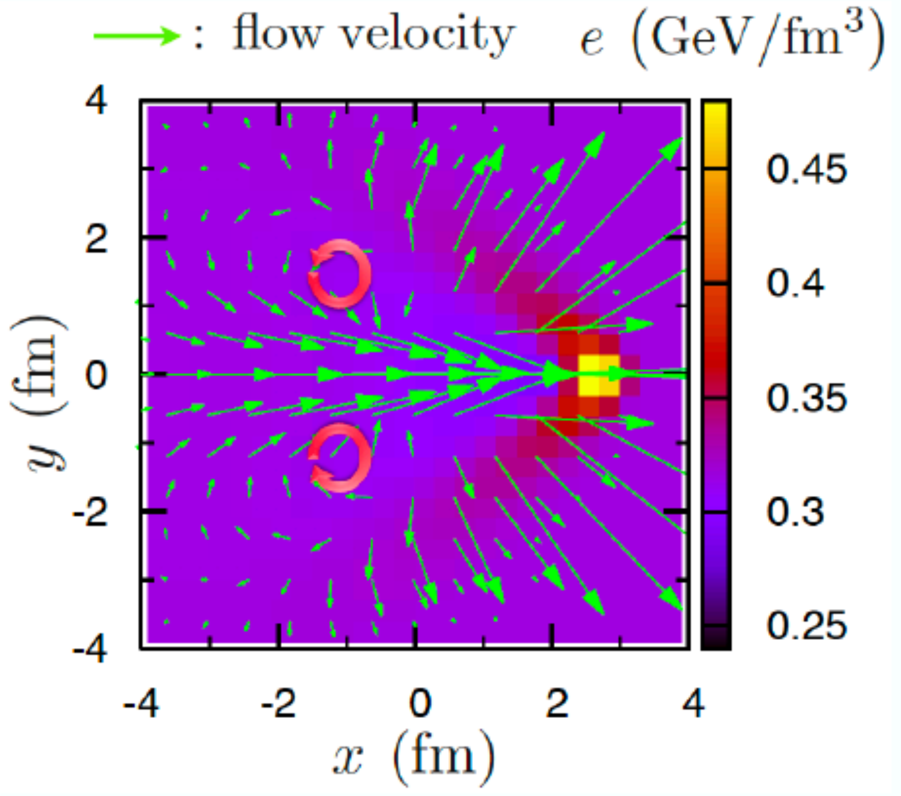
I. Karpenko, F. Becattini, EPJC 77, 213 (2017)

J. Adam, et al., Phys. Rev. C 98, 014910 (2018)

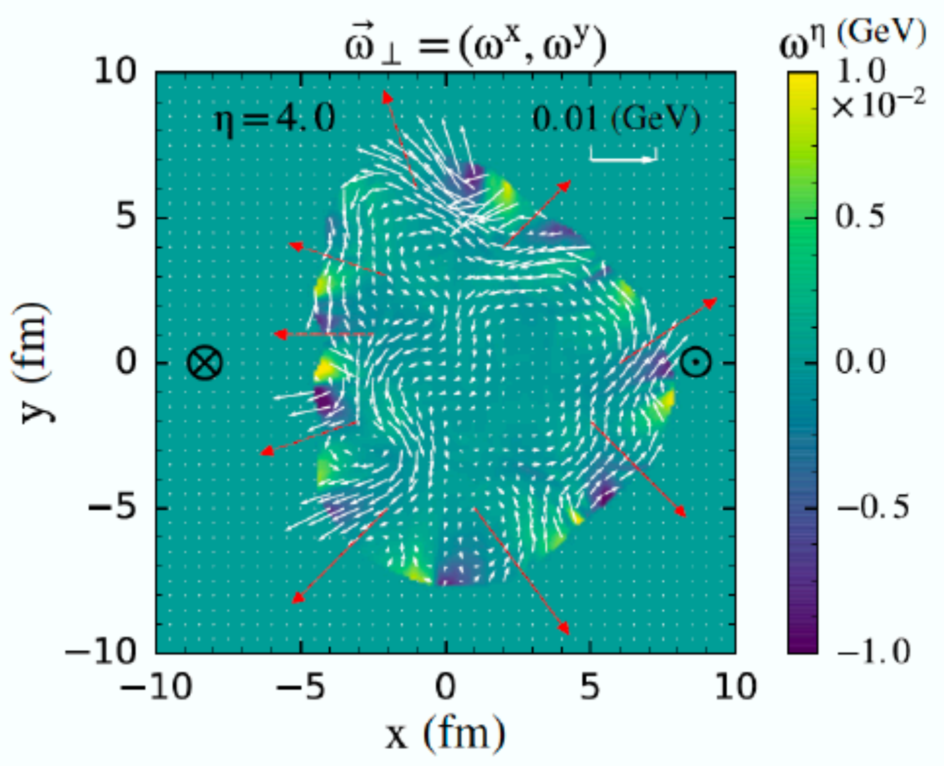


UrQMD+vHLLE: I. Karpenko, F. Becattini, EPJC 77, 213 (2017)
AMPT: H. Li, L. Pang, Q. Wang, and X. Xia, PRC 96, 054908 (2017)

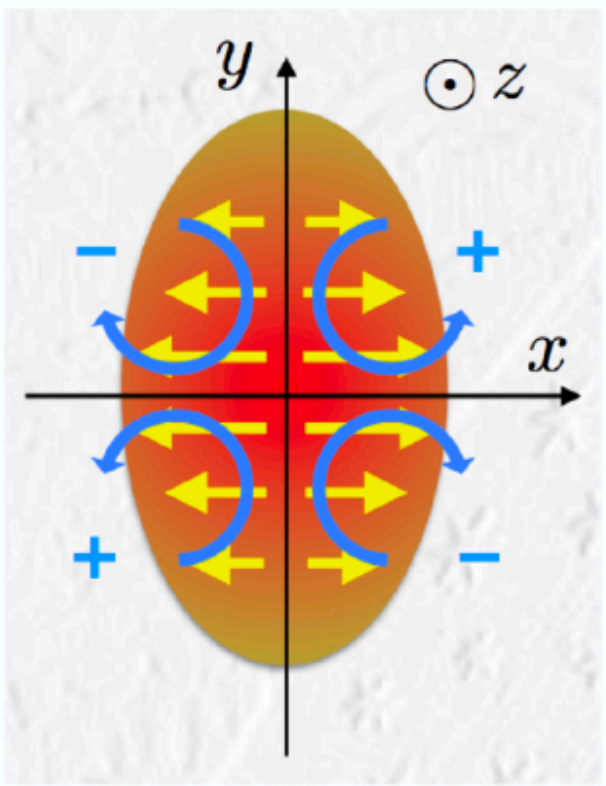
LONGITUDINAL (BEAM-AXIS) POLARIZATION



Y. Tachibana and T. Hirano, NPA904-905 (2013) 1023

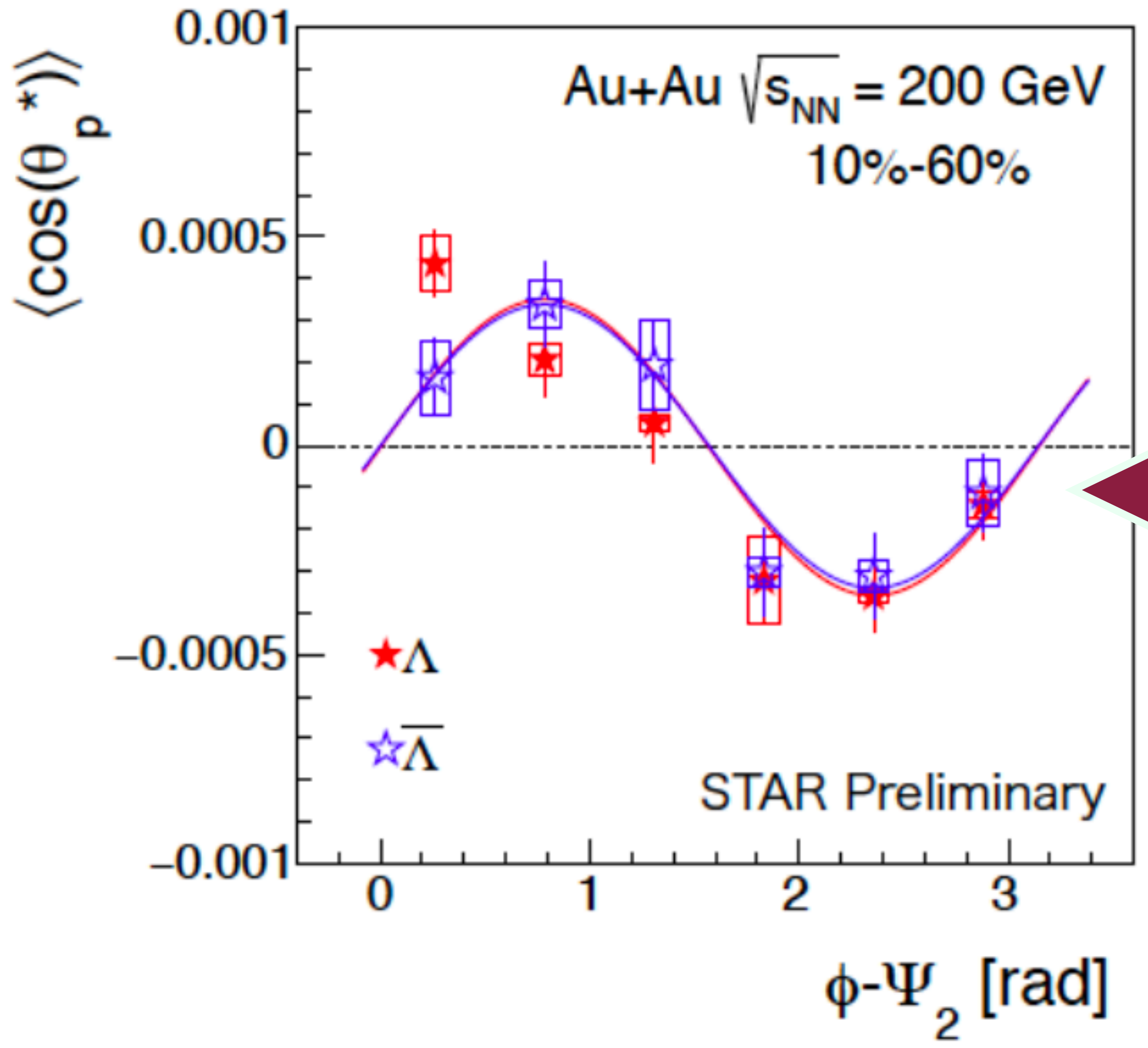


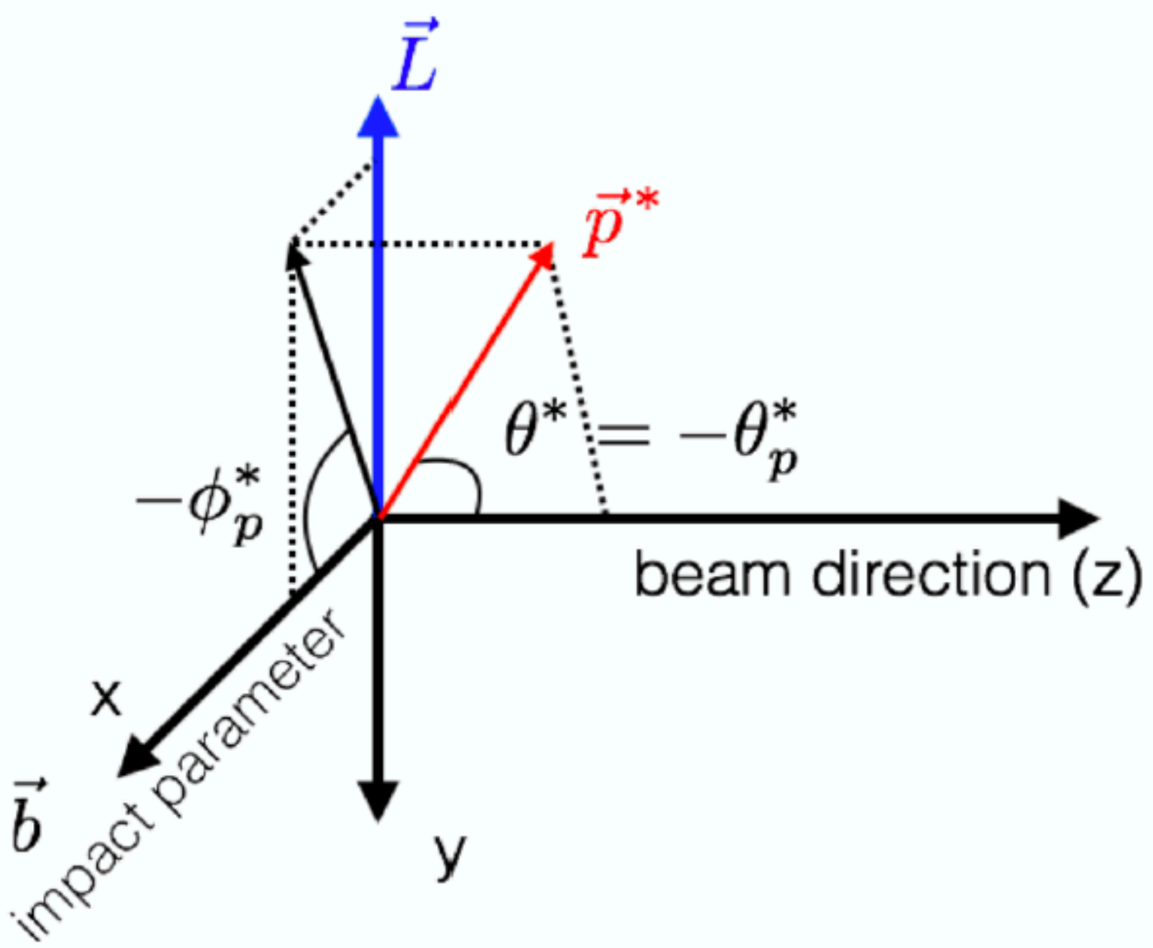
L.-G. Pang, H. Peterson, Q. Wang, and X.-N. Wang PRL117, 192301 (2016)



F. Becattini and I. Karpenko, PRL120.012302 (2018)
S. Voloshin, EPJ Web Conf.171, 07002 (2018)

Flow structures in the plane transverse to beam (jet, ebe fluctuations etc.) may generate longitudinal polarization





$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\rm H}\mathbf{P_H}\cdot\mathbf{p}_p^*)$$

$$\langle\cos\theta_p^*\rangle = \int \frac{dN}{d\Omega^*}\cos\theta_p^* d\Omega^*$$

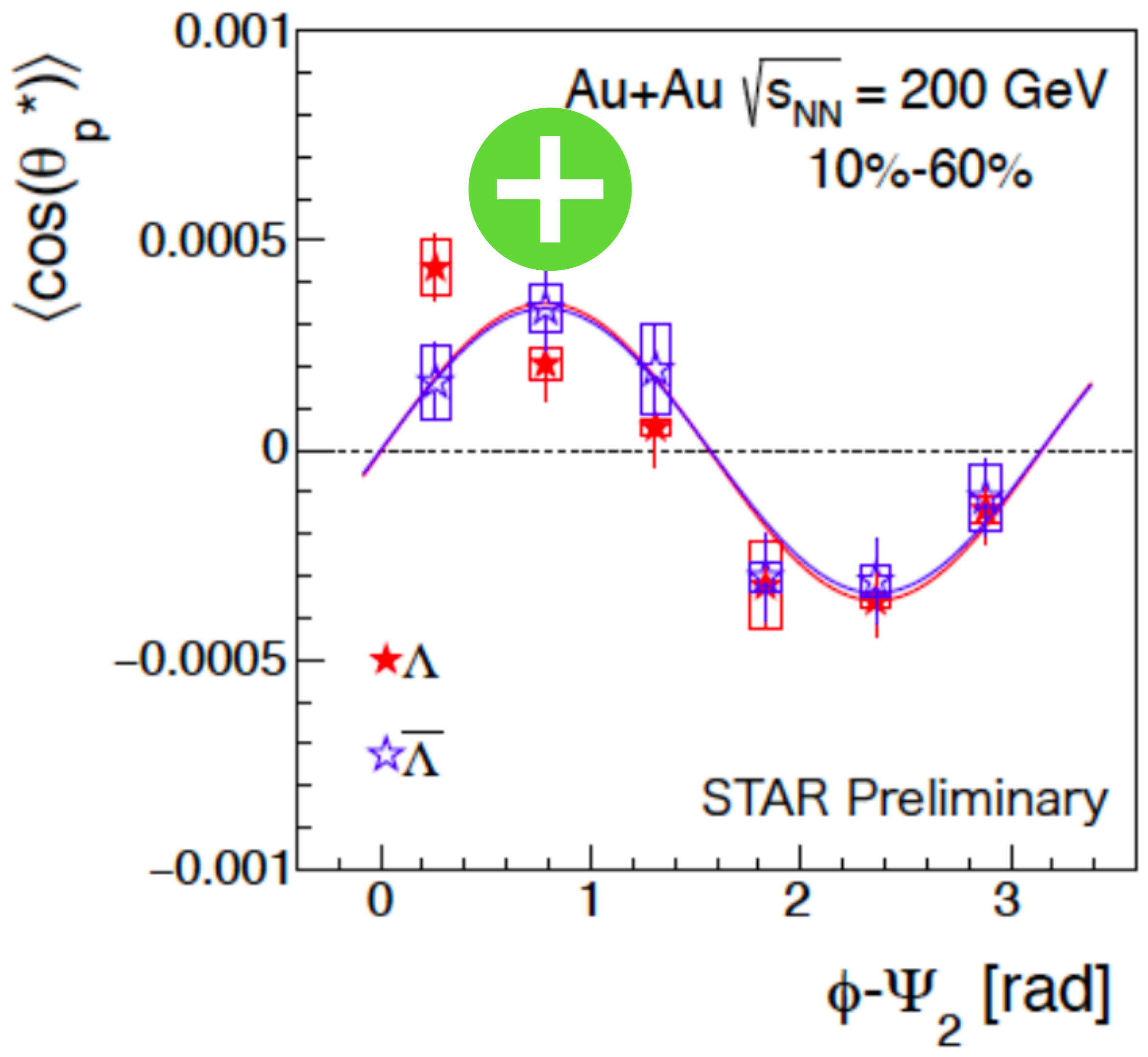
$$= \alpha_{\rm H} P_z \langle(\cos\theta_p^*)^2\rangle$$

$$\therefore\ P_z = \frac{\langle\cos\theta_p^*\rangle}{\alpha_{\rm H}\langle(\cos\theta_p^*)^2\rangle}$$

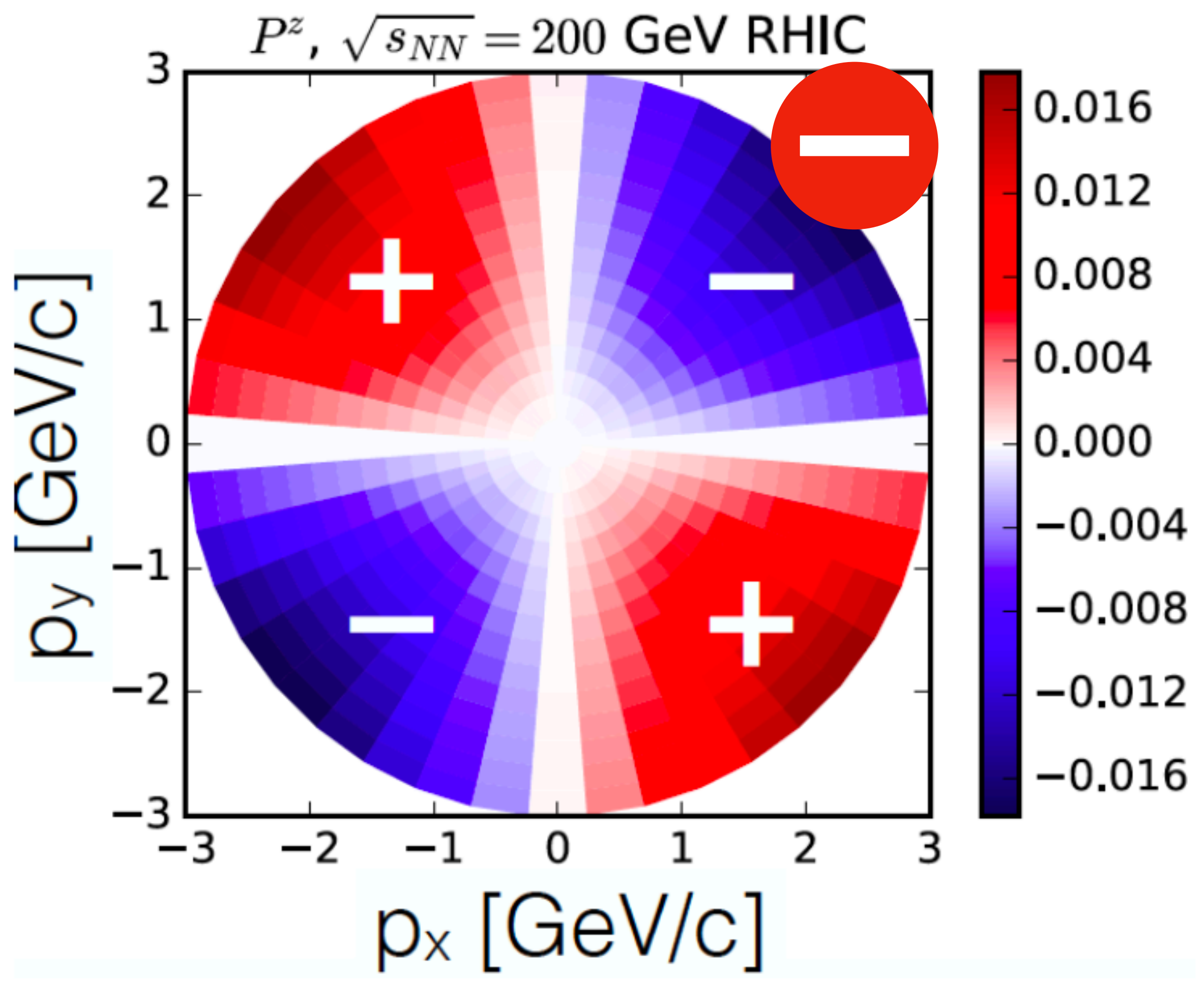
$$= \frac{3\langle\cos\theta_p^*\rangle}{\alpha_{\rm H}}$$ (if perfect detector)

$\alpha_{\rm H}$: hyperon decay parameter
θ_p^*: θ of daughter proton in Λ rest frame

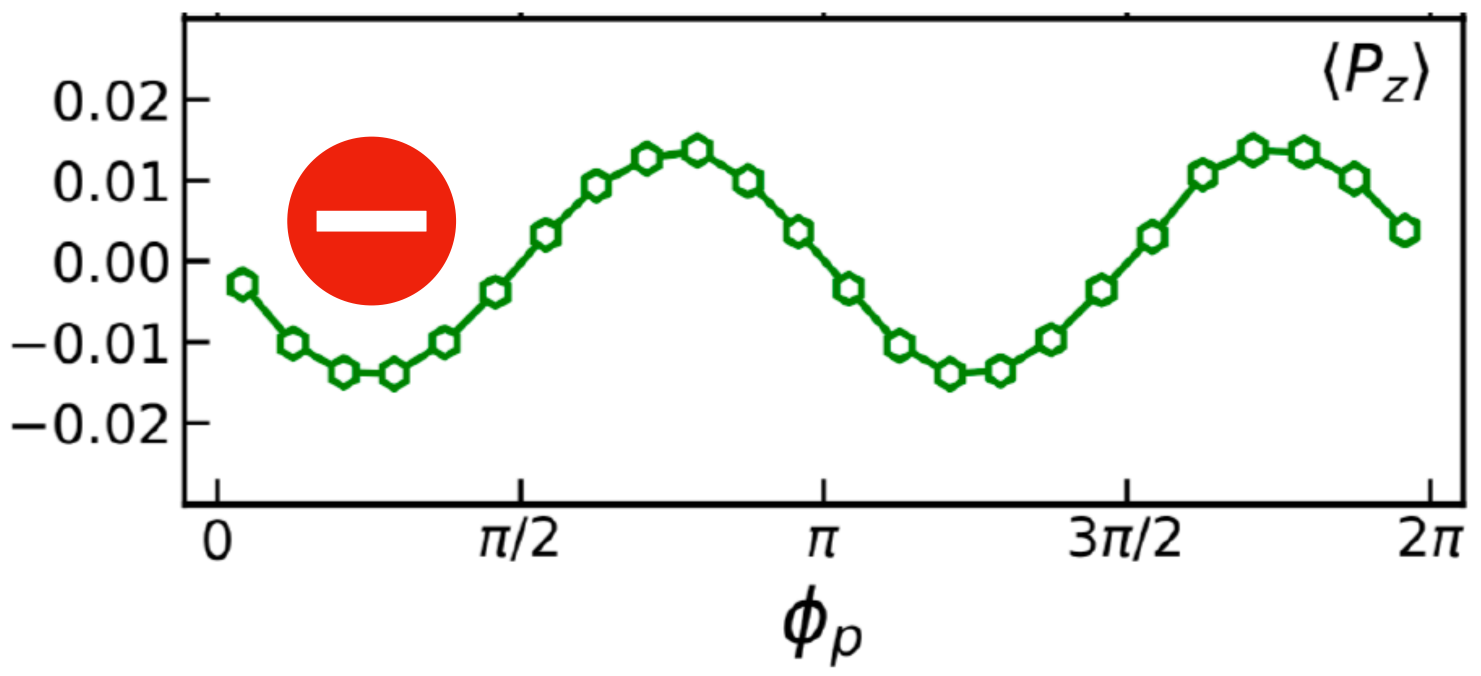
LONGITUDINAL POLARIZATION — 'SPIN SIGN' PUZZLE



T. Niida, NPA 982 (2019) 511514

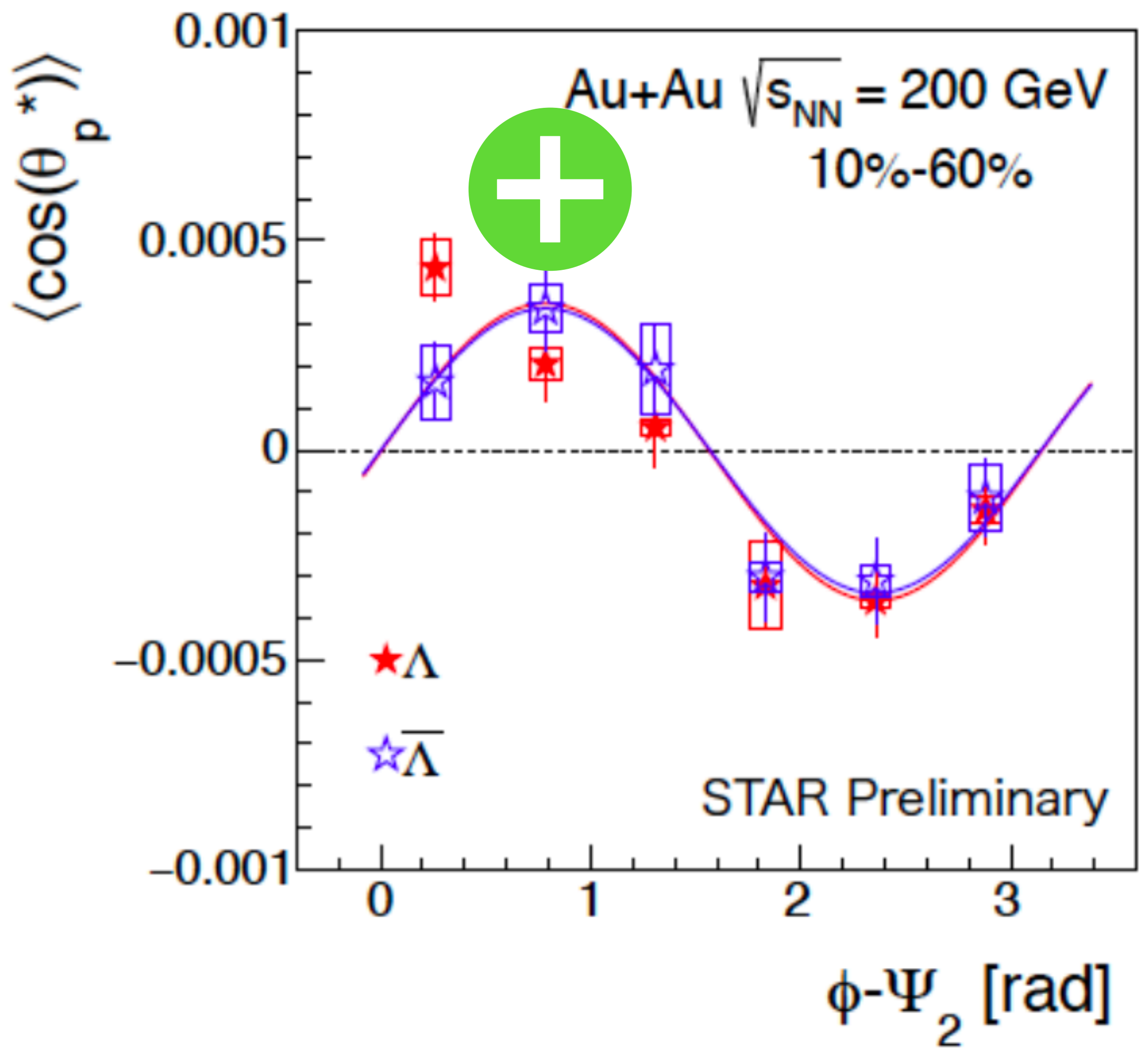


UrQMD+vHLLE: F. Becattini, I. Karpenko, PRL 120 (2018) no.1, 012302,

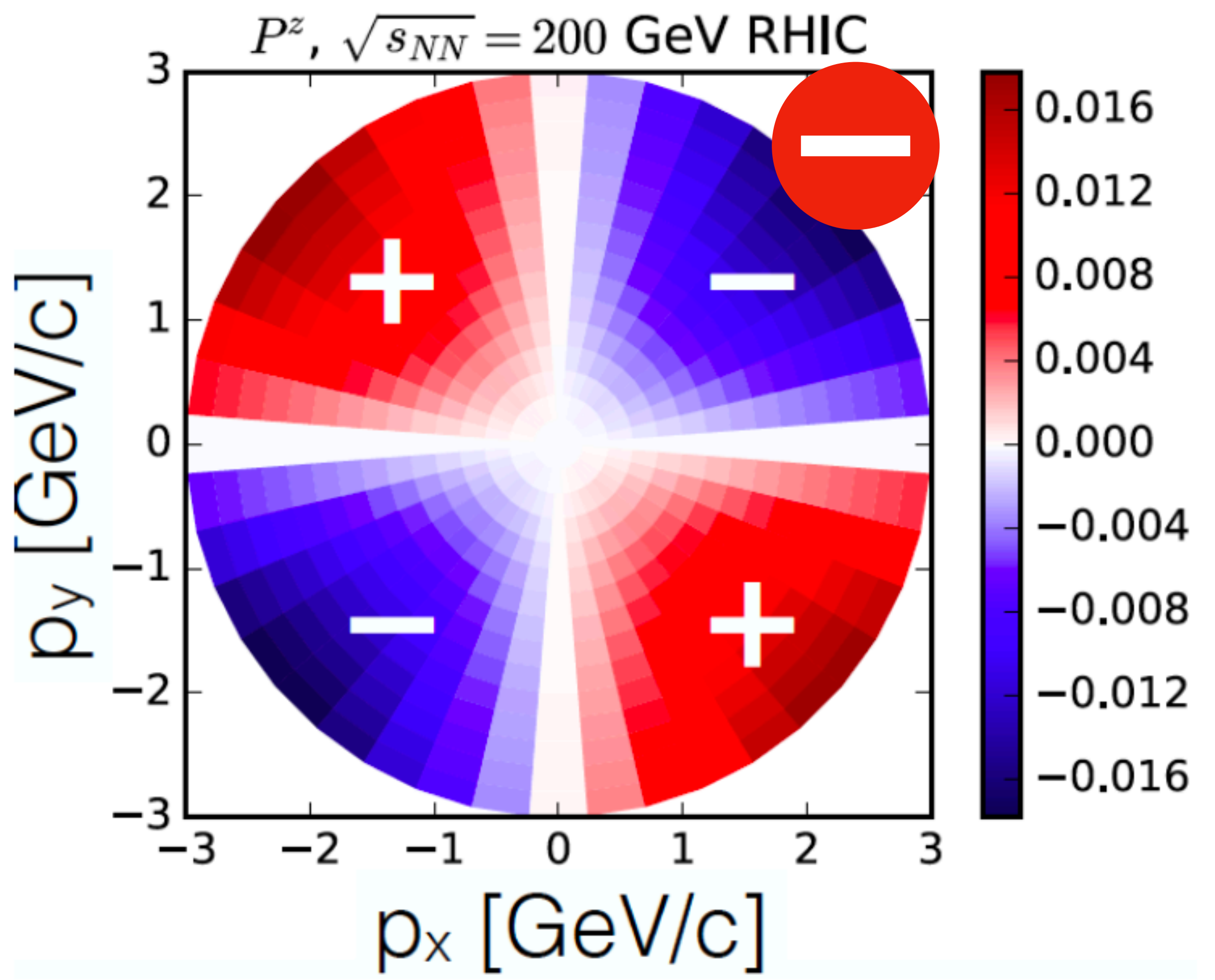


AMPT: X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)

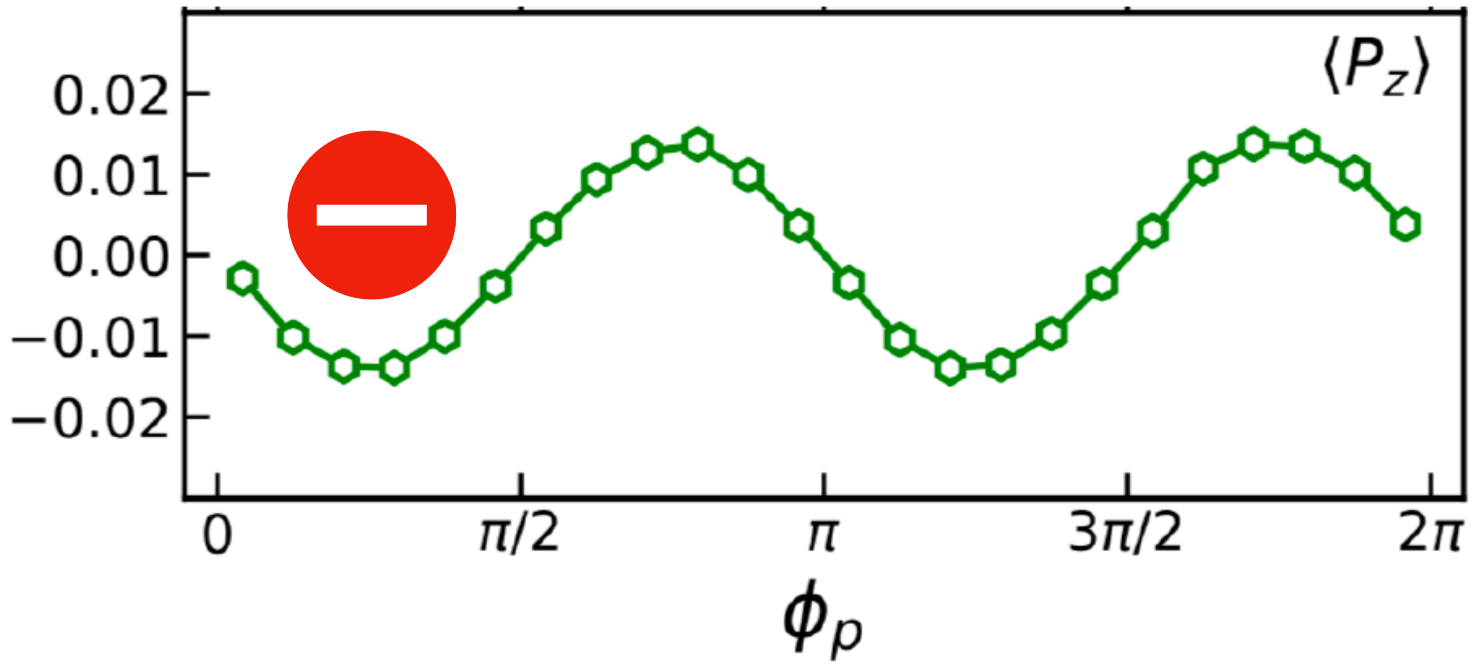
Longitudinal polarization — 'Spin sign' puzzle



T. Niida, NPA 982 (2019) 511514



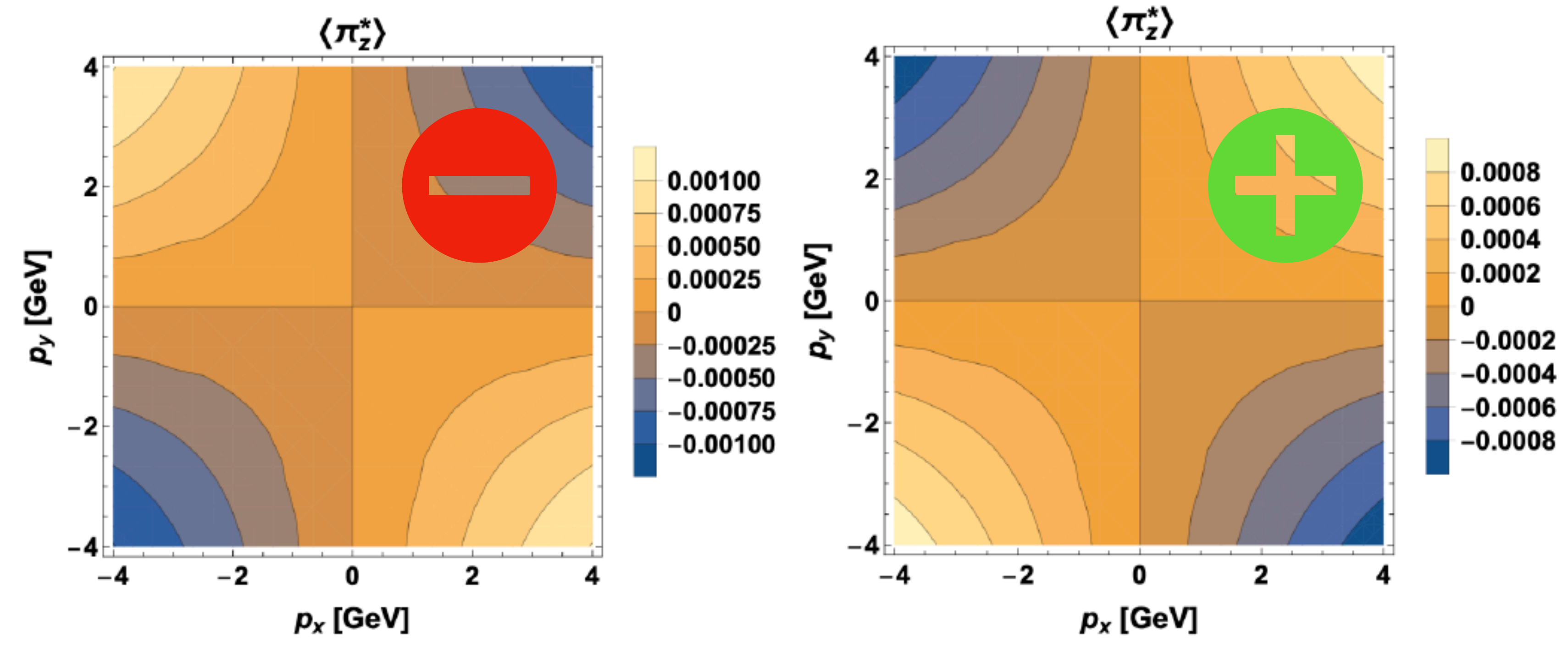
UrQMD+vHLLE: F. Becattini, I. Karpenko, PRL 120 (2018) no.1, 012302,



AMPT: X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)

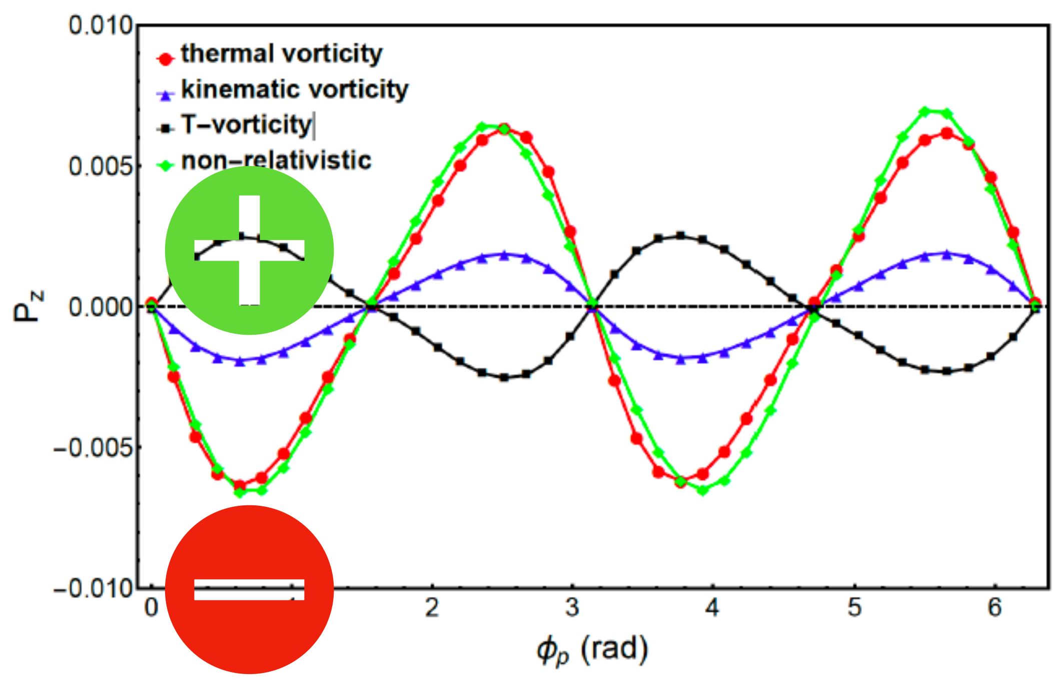
thermal model with projected vorticity $\omega_{\mu\nu} = \varpi_{\alpha\beta}\overline{\Delta}^{\alpha}_{\mu}\overline{\Delta}^{\beta}_{\nu}$

W.Florkowski, A. Kumar, A. Mazeliauskas, R.R., [1904.00002]

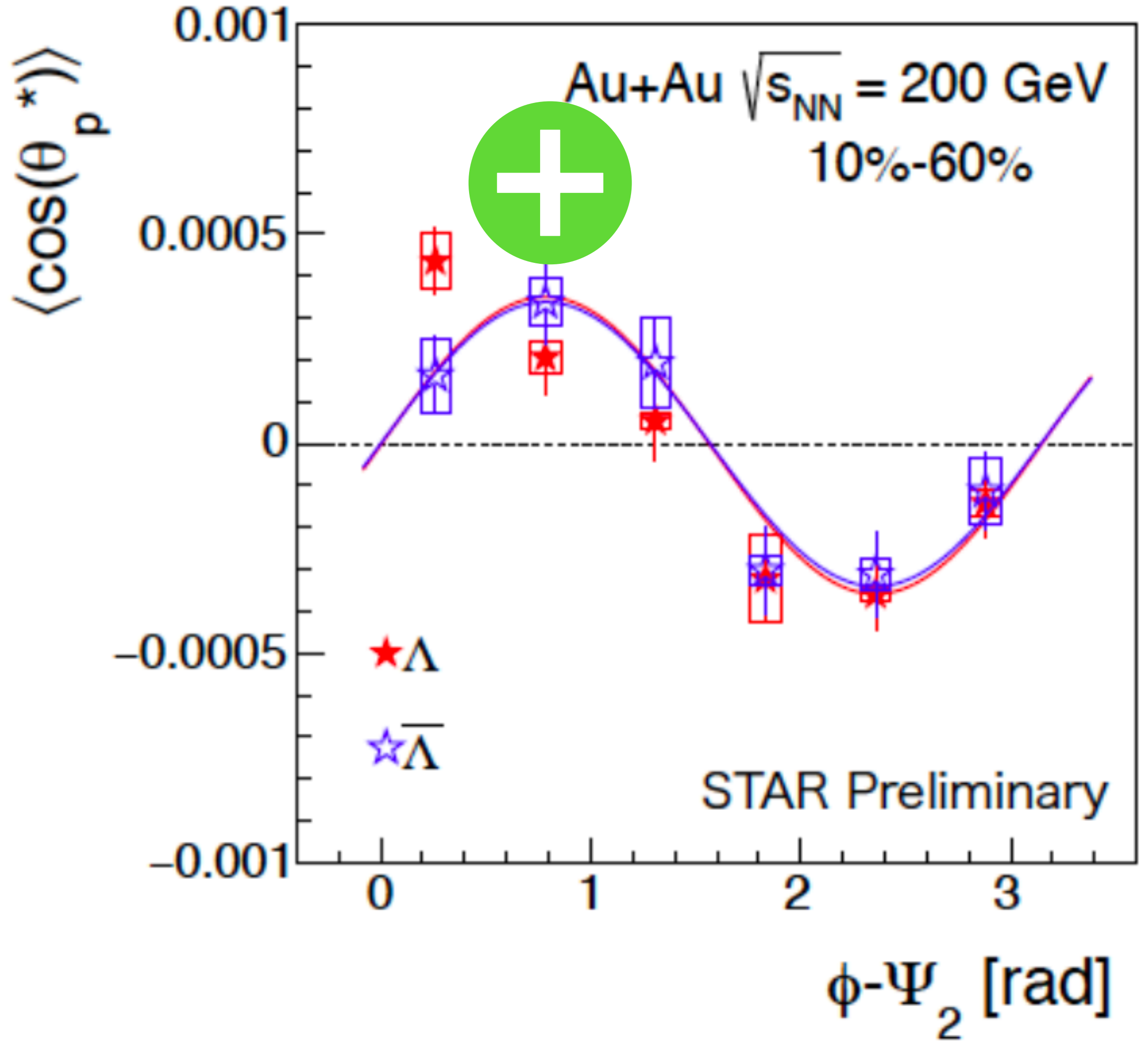


3D VH + AMPT IC with T-vorticity $\omega^{(T)}_{\mu\nu} = -\frac{1}{2}\left[\partial_\mu (Tu_\nu) - \partial_\nu \left(Tu_\mu\right)\right]$

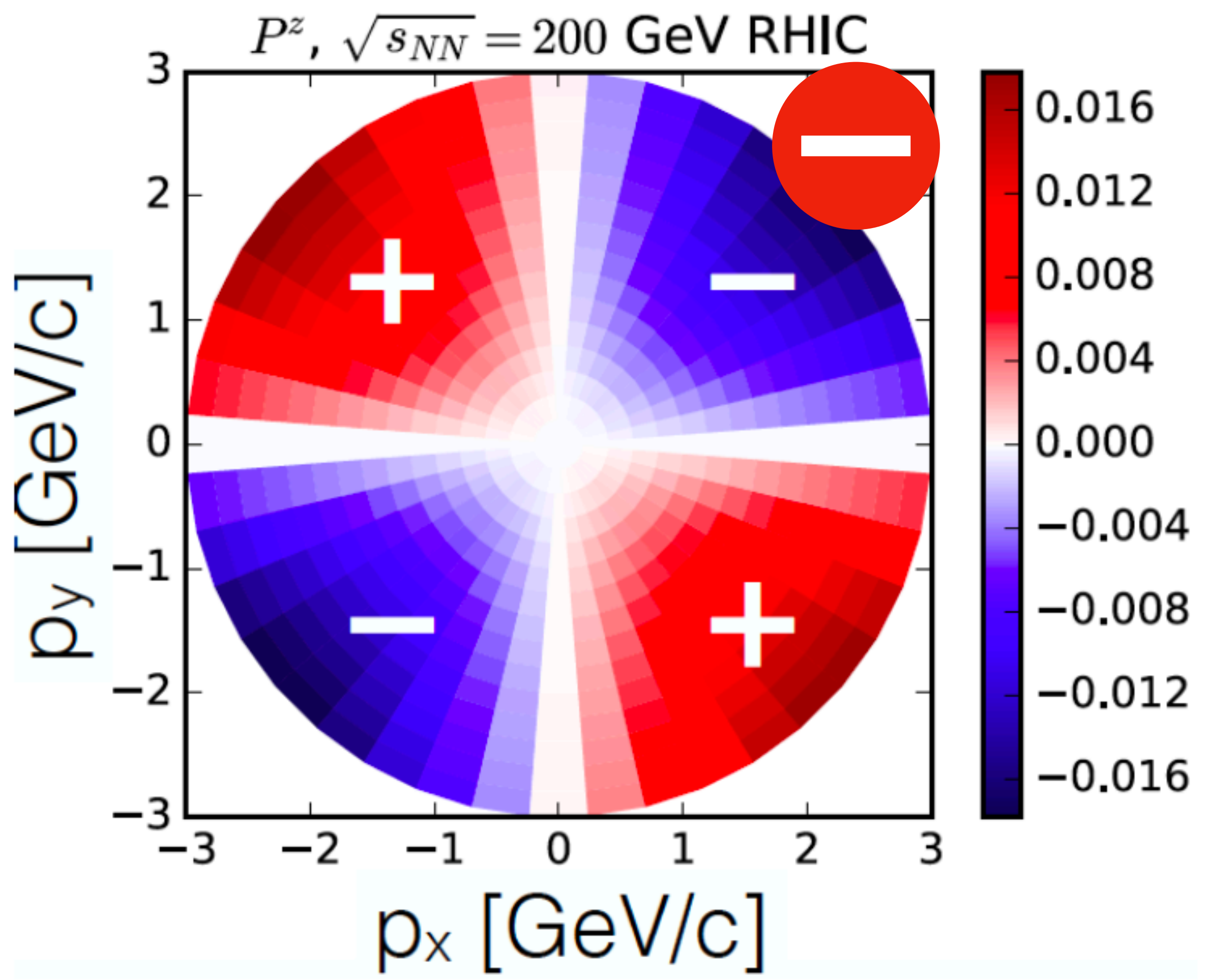
H-Z Wu, L-G Pang, X-G Huang, Q. Wang [1906.09385]



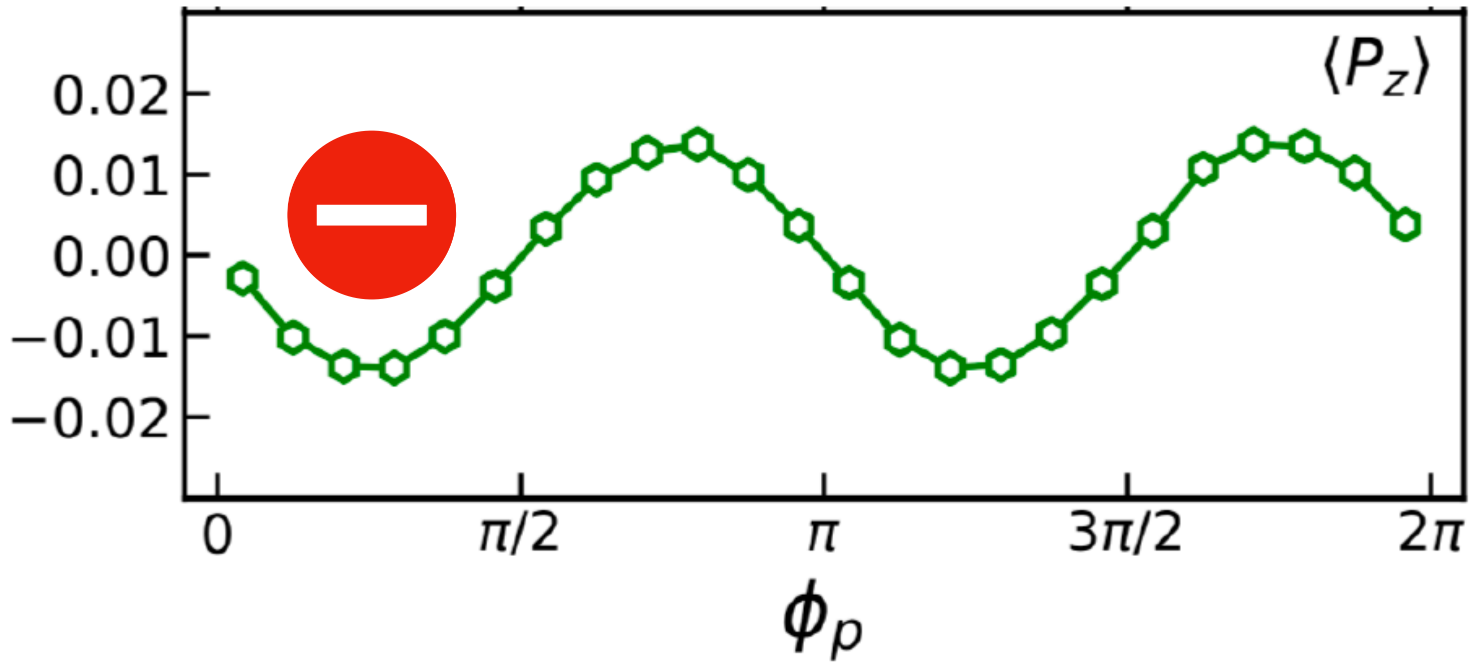
LONGITUDINAL POLARIZATION — 'SPIN SIGN' PUZZLE



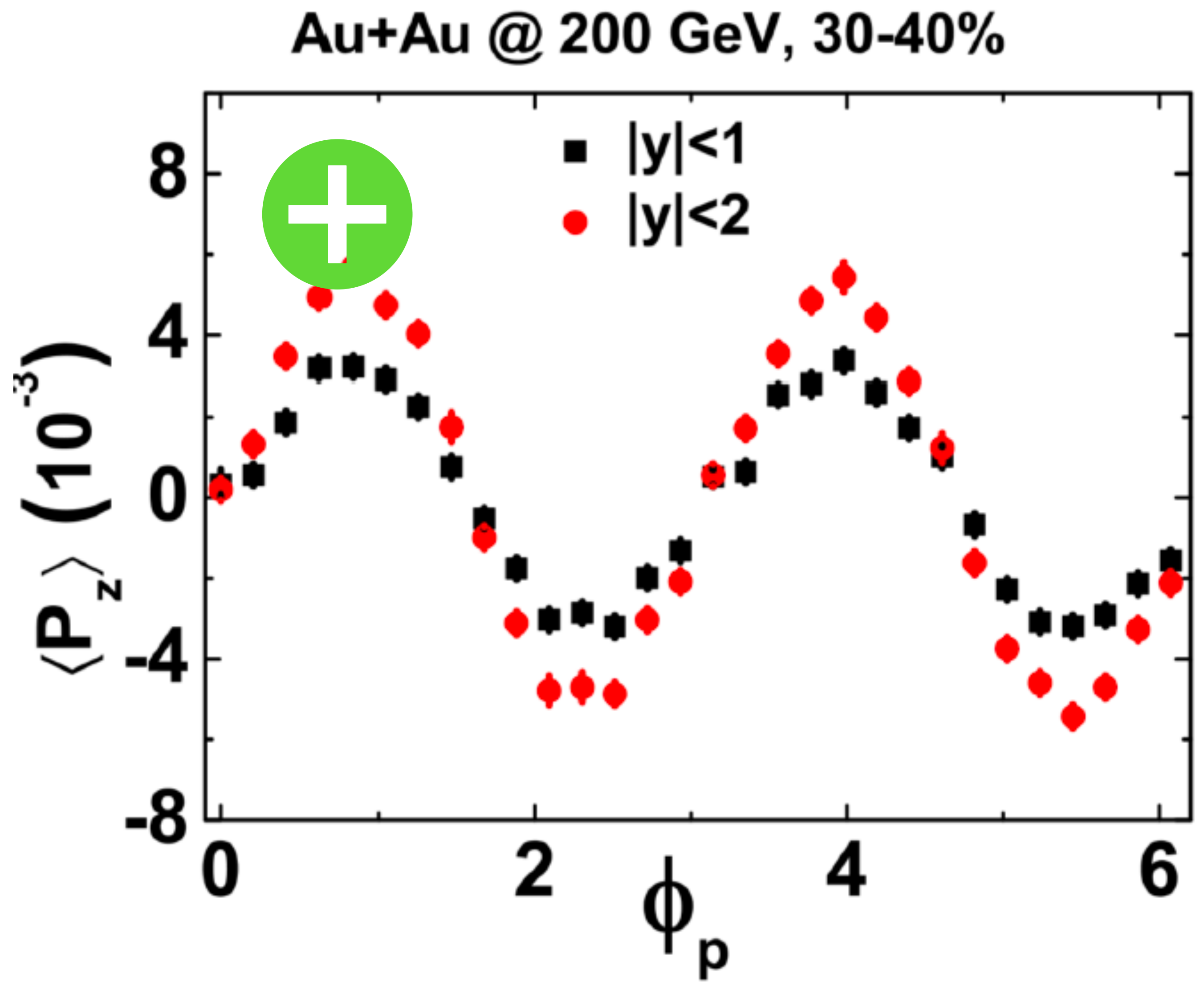
T. Niida, NPA 982 (2019) 511514

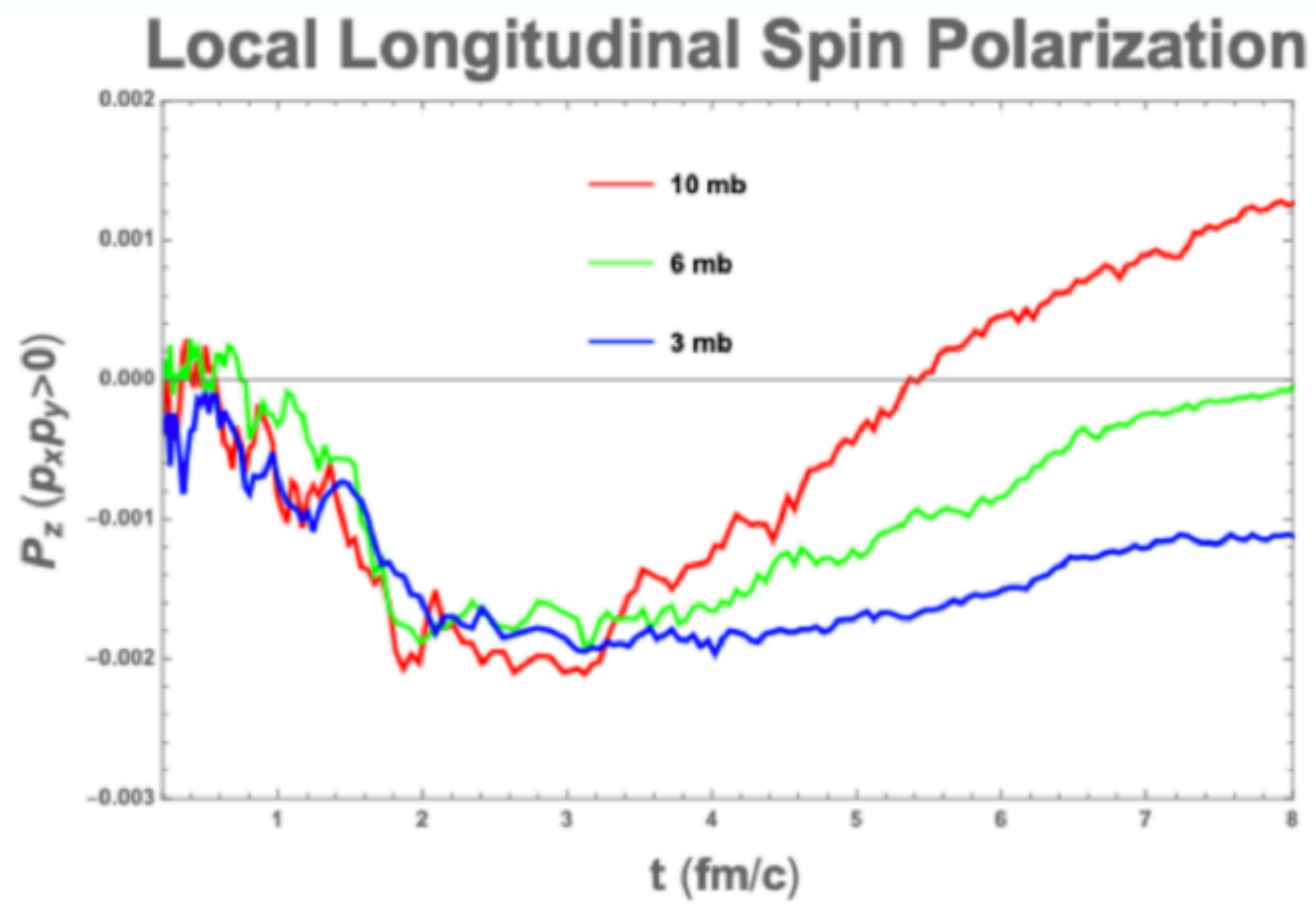


UrQMD+vHLLE: F. Becattini, I. Karpenko, PRL 120 (2018) no.1, 012302,



AMPT: X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905 (2018)





Y. Sun, C-M. Ko, Phys.Rev. C99 (2019) no.1, 011903

FLUID DYNAMICS OF SPIN?!

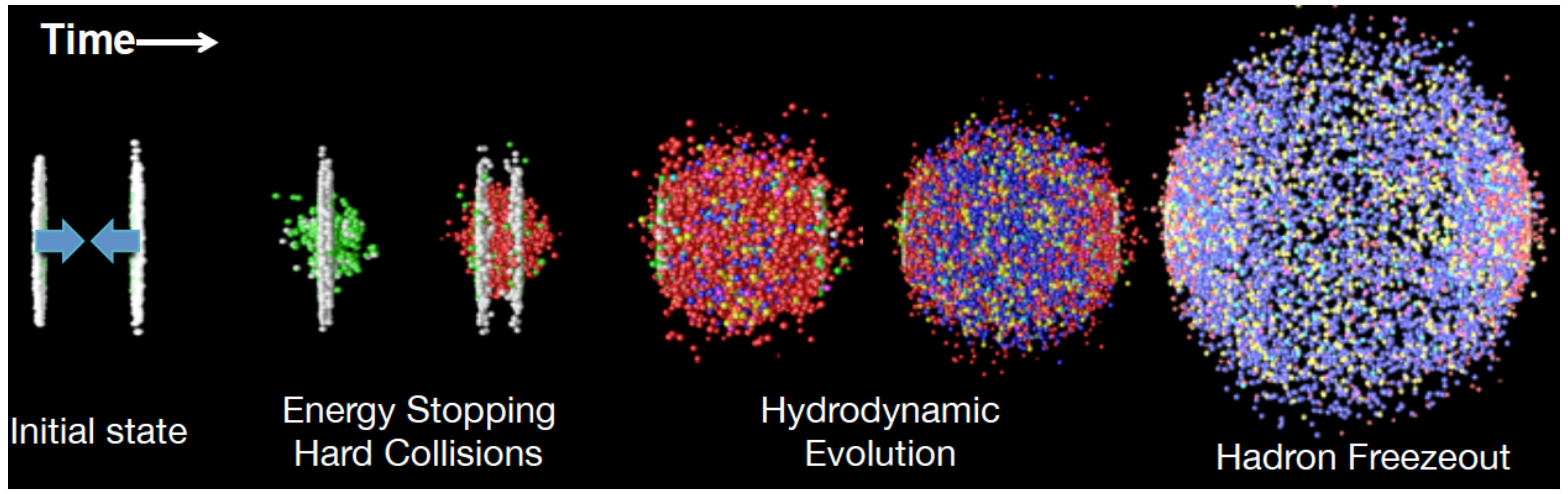
Spin-thermal approach does not capture properly phenomena seen in experiment.

Nonequilibrium dynamics of spin is suggested.

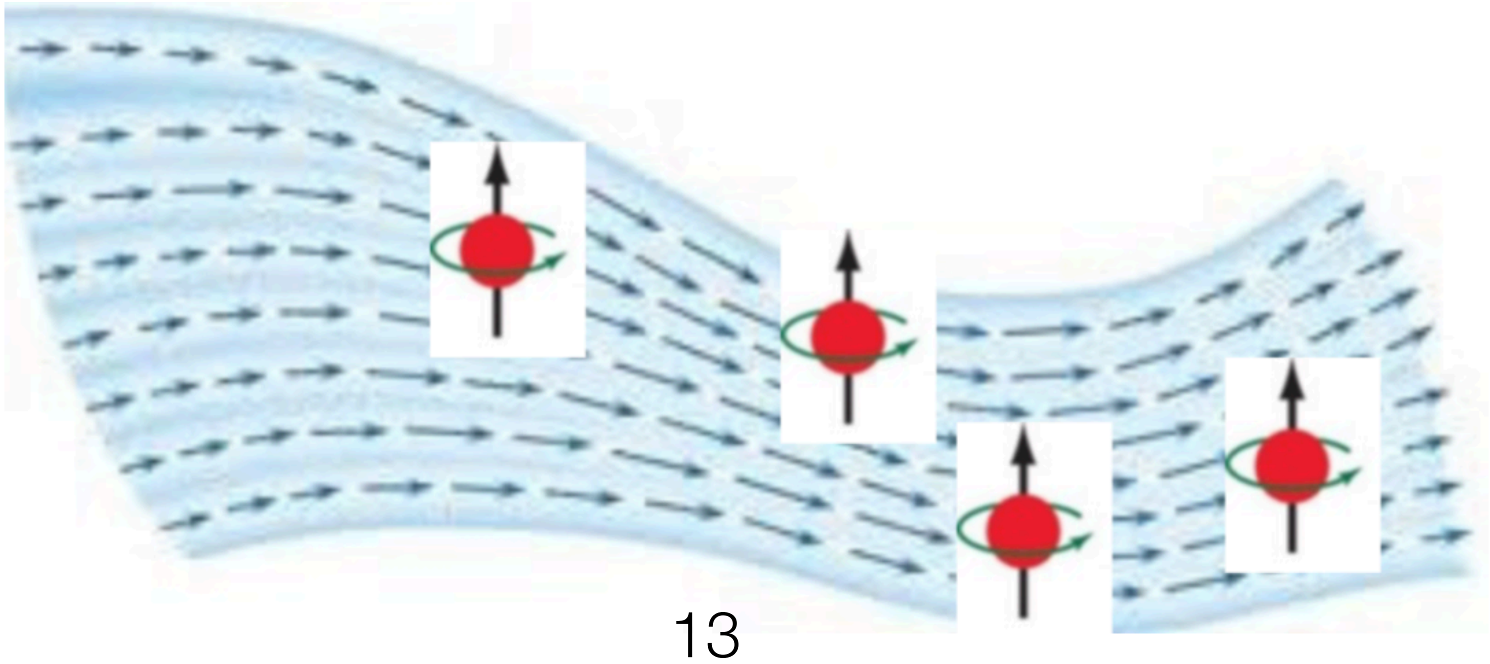
If spin polarization is trully hydrodynamic quantity it should not be enslaved to thermal vorticity.

W. Florkowski, B. Friman, A. Jaiswal, E. Speranza, PRC 97 (4) (2018) 041901

Relativistic fluid dynamics forms the core of HIC models



Fluid dynamics with spin



INCORPORATING SPIN IN HYDRODYNAMICS

Conservation of angular momentum and spin chemical potential

Conservation of charge (baryon number, electric charge, …)

$$\partial_\mu \widehat{N}^\mu(x) = 0 \qquad \text{(1 equation/charge)}$$

$\Rightarrow$ $\mu \equiv \xi T$

Conservation of energy and momentum

$$\widehat{J}_C^{\mu,\alpha\beta}(x) = \underbrace{x^\alpha \widehat{T}_C^{\mu\beta}(x) - x^\beta \widehat{T}_C^{\mu\alpha}(x)}_{\widehat{L}_C^{\mu,\alpha\beta}(x)} + \widehat{S}_C^{\mu,\alpha\beta}(x)$$

$$\partial_\mu \widehat{T}_C^{\mu\alpha}(x) = 0 \qquad \text{(4 equations)}$$

$\Rightarrow$ T, u^ν

The conservation of angular momentum implies introduction of new hydrodynamic variables — spin chemical potential

Conservation of total angular momentum

$$\partial_\mu \widehat{J}_C^{\mu,\alpha\beta}(x) = 0 \qquad \Rightarrow \qquad \partial_\mu \widehat{S}_C^{\mu,\alpha\beta}(x) = \widehat{T}_C^{\beta\alpha}(x) - \widehat{T}_C^{\alpha\beta}(x)$$

$\Rightarrow$ $\Omega_{\mu\nu} \equiv T\omega_{\mu\nu}$

Conservation of angular momentum and spin chemical potential

If the **energy-momentum tensor is symmetric** the spin tensor is conserved

W. Florkowski, B. Friman, A. Jaiswal, E. Speranza, PRC 97 (4) (2018) 041901
W. Florkowski, B. Friman, A. Jaiswal, R. R., E. Speranza, PRD 97 (2018) 116017
F. Becattini, W. Florkowski, E. Speranza, PLB 789 (2019) 419-425
W. Florkowski, A. Kumar, R. R., Prog. Part. Nucl. Phys. 108 (2019) 103709

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\lambda S^{\lambda,\mu\nu} = 0, \quad \partial_\mu N^\mu = 0$$

What are the constitutive relations which enter equations of motion?

$$T^{\mu\nu} = T^{\mu\nu}[\beta, \omega, \xi], \quad S^{\mu,\lambda\nu} = S^{\mu,\lambda\nu}[\beta, \omega, \xi], \quad N^\mu = N^\mu[\beta, \omega, \xi]$$

Fluid dynamics with spin should tell how the spin chemical potential evolves but not its origin — need for modeling of initial conditions!

Relativistic kinetic theory with spin

To include spin in kinetic theory, we start from the **Wigner function (WF)** that bridges the gap between QFT and RKT

$$\mathcal{W}_{\alpha\beta} = \frac{1}{4}\left(\mathcal{F} + i\gamma^5\mathcal{P} + \gamma^\mu\mathcal{V}_\mu + \gamma^5\gamma^\mu\mathcal{A}_\mu + \frac{1}{2}\Sigma^{\mu\nu}\mathcal{S}_{\mu\nu}\right)_{\alpha\beta}$$

$\mathcal{F} \rightarrow$ scalar component,

$\mathcal{P} \rightarrow$ pseudoscalar component,

$\mathcal{V}_\mu \rightarrow$ vector component,

$\mathcal{A}_\mu \rightarrow$ axial vector component,

$\mathcal{S}_{\mu\nu} \rightarrow$ tensor component.

$$\Sigma^{\mu\nu} = i\gamma^{[\mu}\gamma^{\nu]}$$

For spin-1/2 particles the Wigner function satisfies the **quantum kinetic equation**

$$\left[\gamma\cdot\left(p + \frac{i}{2}\partial\right) - m\right]\mathcal{W}_{\alpha\beta} = \mathcal{C}\left[\mathcal{W}_{\alpha\beta}\right]$$

[Xin-Li Sheng, PhD Thesis (2019), N. Weickgenannt *et al*, PRL 127 (2021) 5, 052301, PRD 100, 056018 (2019).]

Relativistic kinetic theory with spin

From the leading and next-to-leading orders of the **semi-classical expansion of the WF** in powers of *h*, one obtains **two independent kinetic equations for the scalar and axial-vector components**

	Scalar Component	*Axial Component*
Kin. Eq.	$k^\mu \partial_\mu \mathcal{F}(x,k) = \mathcal{C}_\mathcal{F}$	$k^\mu \partial_\mu \mathcal{A}^\nu(x,k) = \mathcal{C}^\nu_\mathcal{A}$
RTA	$C_\mathcal{F} = \frac{(k\cdot u)}{\tau_{\rm eq}}\Big[\mathcal{F}_{\rm eq}(x,k) - \mathcal{F}(x,k)\Big]$	$C^\nu_\mathcal{A} = \frac{(k\cdot u)}{\tau_{\rm eq}}\Big[\mathcal{A}^\nu_{\rm eq}(x,k) - \mathcal{A}^\nu(x,k)\Big]$
Dist. fn.	$\mathcal{F}^\pm(x,k) = 2m \int_{p,s} f^\pm(x,p,s)\ \delta^{(4)}(k \mp p)$	$\mathcal{A}^\mu_\pm(x,k) = 2m \int_{p,s} s^\mu f^\pm(x,p,s)\ \delta^{(4)}(k \mp p)$

$$\int_s (\cdots) \to (m/\pi\mathfrak{s}) \int d^4 s \delta(s\cdot s + \mathfrak{s}^2) \qquad \mathfrak{s}^2 = \tfrac{1}{2}(1+\tfrac{1}{2})$$

[S.B., W. Florkowski, A. Jaiswal, A. Kumar and, R. Ryblewski, PLB 814 (2021) 136096, PRD 103 (2021) 1, 014030]

Classical approach to spin hydrodynamics

In the classical treatments of particles with spin-1/2 one introduces internal angular momentum tensor of particles [M. Mathisson, APPB 6 (1937) 163–2900]

$$s^{\alpha\beta} = \frac{1}{m}\epsilon^{\alpha\beta\gamma\delta} p_\gamma s_\delta .$$

$s^{\alpha\beta}$ is antisymmetric *i.e.* $s^{\alpha\beta} = -s^{\beta\alpha}$ and satisfies Frenkel (or Weyssenhoff) $p_\alpha s^{\alpha\beta} = 0$.

The spin four vector can be obtained by above equation,

$$s^\alpha = \frac{1}{2m}\epsilon^{\alpha\beta\gamma\delta} p_\beta s_{\gamma\delta}$$

In particle rest frame (PRF) where $p^\mu = (m, 0, 0, 0)$, $s^\alpha = (0, \mathbf{s}_*)$ with the length of spin vector given by $-s^2 = -s^\alpha s_\alpha = |\mathbf{s}_*|^2 = \mathfrak{s}^2 = \frac{1}{2}\left(1 + \frac{1}{2}\right) = \frac{3}{4}$.

M.Mathisson

J. Weyssenhoff

RELATIVISTIC KINETIC THEORY WITH SPIN

The **distribution function** in the **extended phase-space** is a function of **spacetime**, **momentum**, and **internal angular momentum** of the particles

$$f^{\pm}(x, p, s)$$

Following Liouville theorem the **kinetic equation** governing the evolution of the distribution function can be written as
[Suttorp, de Groot, Nuovo Cimento A (1965-1970), van Weert Thesis (1970)]

$$p^{\mu}\partial_{\mu}^{(x)} f^{\pm} + m\mathcal{F}^{\mu}\partial_{\mu}^{(p)} f^{\pm} + m\mathcal{S}^{\mu\nu}\partial_{\mu\nu}^{(s)} f^{\pm} = \mathcal{C}[f^{\pm}]$$

where

$$\partial_{\mu}^{(x)} \equiv \frac{\partial}{\partial x^{\mu}}, \qquad \partial_{\mu}^{(p)} \equiv \frac{\partial}{\partial p^{\mu}}, \qquad \partial_{\mu\nu}^{(s)} \equiv \frac{\partial}{\partial s^{\mu\nu}}, \qquad \mathcal{F}^{\alpha} \equiv \frac{dp^{\alpha}}{d\tau} \qquad \mathcal{S}^{\alpha\beta} \equiv \frac{ds^{\alpha\beta}}{d\tau}$$

Using the Frenkel condition, one can derive the **force (Lorentz and Mathisson)** and **torque** term
[Suttorp, de Groot, Nuovo Cimento A (1965-1970), van Weert Thesis (1970), Nora W. et al. PRD 100 (2019) 5, 056018]

$$\mathcal{F}^{\alpha} = \frac{\mathfrak{q}}{m} F^{\alpha\beta} p_{\beta} + \frac{1}{2}\left(\partial^{\alpha} F^{\beta\gamma}\right) m_{\beta\gamma}$$

$$\mathcal{S}^{\alpha\beta} = 2\, F^{\gamma[\alpha}\, m^{\beta]}{}_{\gamma} - \frac{1}{m^2}\left(\chi - \frac{\mathfrak{q}}{m}\right) F_{\phi\gamma}\, s^{\phi[\alpha}\, p^{\beta]} p^{\gamma}$$

where **magnetic dipole moment** is $m^{\alpha\beta} = \chi\, s^{\alpha\beta}$

Relativistic kinetic theory with spin

In the limit of **infinite conductivity**, field strength tensor is

$$F^{\mu\nu} \rightarrow B^{\mu\nu} = \epsilon^{\mu\nu\alpha\beta} u_\alpha B_\beta$$

$$u_\mu B^\mu = 0 \qquad\qquad B_\mu B^\mu \leq 0$$

If the medium if magnetizable, then the **Maxwell's equations** are given by
[Balakin, Grav.Cosmol. 13 (2007) 163-177; Hehl and, Obukhov, Phys. Lett. A 311, 277 (2003)]

$$\partial_\mu H^{\mu\nu} = J^\nu, \qquad\qquad \partial_\mu \widetilde{F}^{\mu\nu} = 0,$$

$$\left(\widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}\right)$$

$$H^{\mu\nu} = F^{\mu\nu} + M^{\mu\nu}$$

Relativistic kinetic theory with spin

The **particle current**, **energy-momentum tensor**, and **spin tensor** of the fluid can be expressed as

[S.B., W. Florkowski, A. Jaiswal, A. Kumar and, R. Ryblewski, PLB 814 (2021) 136096, PRD 103, 014030 (2021)]

$$N^\mu = \int_{p,s} p^\mu \left(f^+ - f^-\right),$$

$$T_f^{\mu\nu} = \int_{p,s} p^\mu p^\nu \left(f^+ + f^-\right),$$

$$S^{\lambda,\mu\nu} = \int_{p,s} p^\lambda s^{\mu\nu} \left(f^+ + f^-\right)$$

while the **polarization-magnetization tensor** is

$$M^{\alpha\beta} = m \int_{p,s} m^{\alpha\beta} \left(f^+ - f^-\right)$$

Relativistic MHD with spin

Assuming that the microscopic interactions **preserve conservation laws** one requires

$$\int_{p,s} \mathcal{C}[f] = 0,$$

$$\int_{p,s} p^\mu \mathcal{C}[f] = 0,$$

$$\int_{p,s} s^{\mu\nu} \mathcal{C}[f] = 0$$

Zeroth, first, and 'spin' moment of the kinetic equation (**in absence of the torque term**) then lead to

$$\partial_\mu N^\mu = 0$$

$$\partial_\nu T_f^{\mu\nu} = F^\mu{}_\alpha J_f^\alpha + \frac{1}{2}\left(\partial^\mu F^{\nu\alpha}\right) M_{\nu\alpha}$$

$$\partial_\lambda S^{\lambda,\mu\nu} = 0$$

$$N^\mu = n u^\mu + n^\mu \qquad J_\mathrm{f}^\mu = \mathfrak{q} N^\mu \qquad T_\mathrm{f}^{\mu\nu} = \epsilon u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

Relativistic MHD with spin

Using RTA kinetic equation we can write the **first-order gradient correction** as

$$f^{\pm}(x,p,s) = f^{\pm}_{\text{eq}}(x,p,s) + \delta f^{\pm}(x,p,s).$$

$$\delta f^{\pm}_{(1)} = -\mathcal{D} f^{\pm}_{\text{eq}},$$

$$\mathcal{D} = \frac{\tau_R}{(u\cdot p)}\left(p^{\alpha}\frac{\partial}{\partial x^{\alpha}} + \mathcal{F}^{\alpha}\frac{\partial}{\partial p^{\alpha}}\right)$$

The **equilbrium distribution function** has the form (we use the small polarization limit)

$$f_{\text{eq}} = \frac{1}{1+\exp\left[\beta(u\cdot p) - \xi - \frac{1}{2}\,\omega : s\right]}$$

$$f_{\text{eq}} = f_0 + \frac{1}{2}\,(\omega : s)\, f_0 \tilde{f}_0,$$

$$f_0 \equiv \{1+\exp\left[\beta(u\cdot p) - \xi\right]\}^{-1} \qquad \tilde{f}_0 \equiv 1 - f_0$$

RELATIVISTIC MHD WITH SPIN

The expressions for dissipative currents in terms of the nonequilibrium correction to the distribution function are

$$\Pi = -\frac{\Delta_{\alpha\beta}}{3} \int_{p,s} p^\alpha p^\beta \left(\delta f^+ + \delta f^-\right)$$

$$\pi^{\mu\nu} = \Delta^{\mu\nu}_{\alpha\beta} \int_{p,s} p^\alpha p^\beta \left(\delta f^+ + \delta f^-\right)$$

$$n^\mu = \Delta^\mu_\alpha \int_{p,s} p^\alpha \left(\delta f^+ - \delta f^-\right)$$

$$\delta S^{\lambda,\mu\nu} = \int_{p,s} p^\lambda s^{\mu\nu} \left(\delta f^+ + \delta f^-\right)$$

RELATIVISTIC MHD WITH SPIN

Equilibrium polarization-magnetization tensor is

$$M^{\mu\nu}_{\mathbf{eq}} = a_1(T,\mu)\,\omega^{\mu\nu} + a_2(T,\mu)\,u^{[\mu}u_\gamma\omega^{\nu]\gamma}$$

In global equilibrium, spin polarization tensor corresponds to rotation of the fluid.

$$\omega^{\mu\nu}|_{\mathrm{geq}} \propto \varpi^{\mu\nu} = \left(\partial^\mu\beta^\nu - \partial^\nu\beta^\mu\right)/2$$

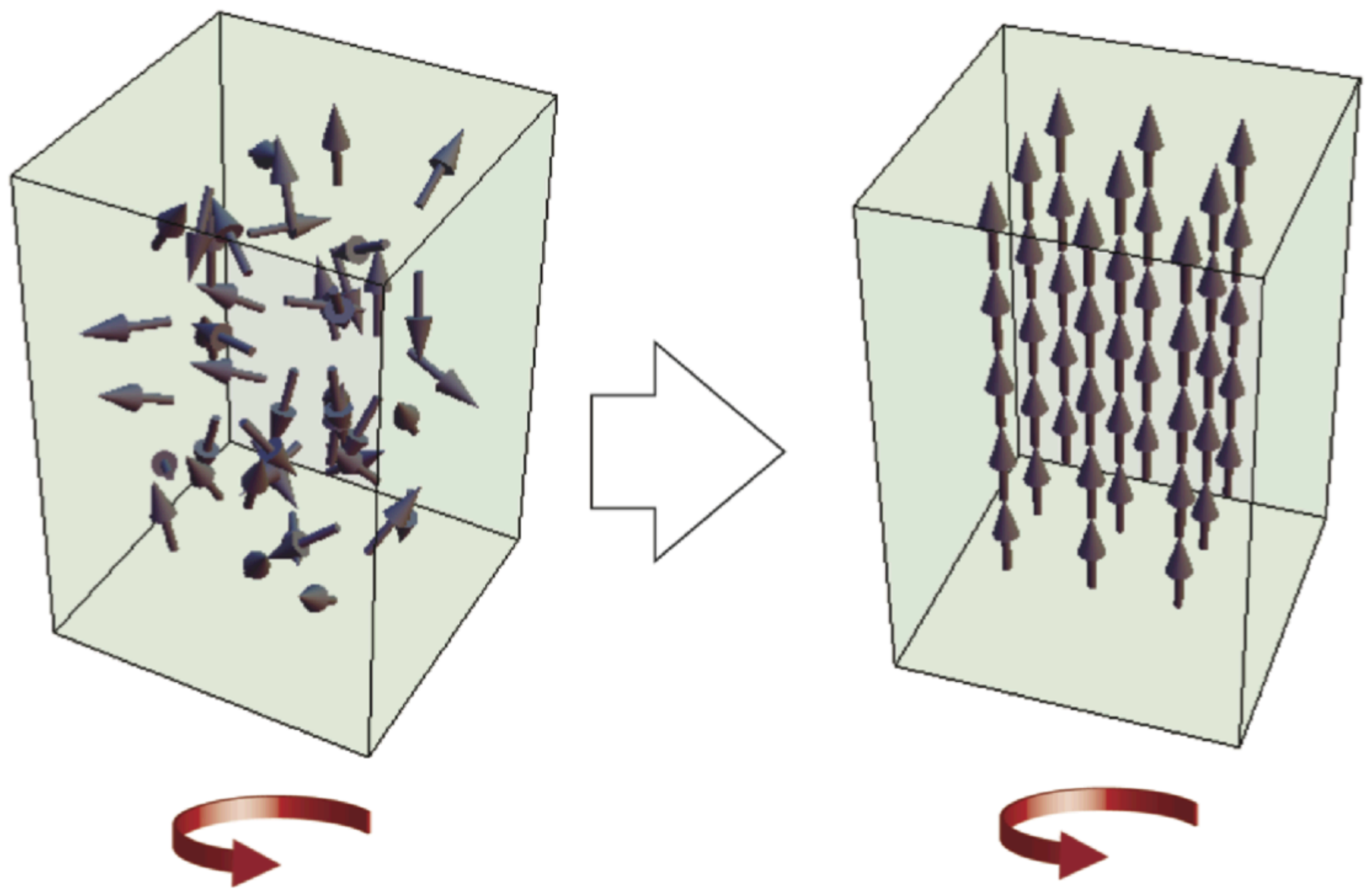


figure: Journal of the Physical Society of Japan 90, 081003 (2021)

We conclude that **rotation of the fluid produces magnetization**, which is precisely the physics of **Barnett effect**.

Relativistic MHD with spin

Using the spin matching condition we obtain the **evolution equation for the spin polarization tensor**

$$\dot{\omega}^{\mu\nu} = \mathcal{D}_{\Pi}^{\mu\nu}\,\theta + \mathcal{D}_{\mathrm{n}}^{\mu\nu\gamma}\,(\nabla_\gamma \xi) + \mathcal{D}_{\mathrm{a}}^{\mu\nu\gamma}\,\dot{u}_\gamma + \mathcal{D}_{\pi}^{\mu\nu\rho\kappa}\,\sigma_{\rho\kappa} + \mathcal{D}_{\Omega}^{\mu\nu\rho\kappa}\,\Omega_{\rho\kappa} + \mathcal{D}_{\Sigma}^{\mu\nu\phi\rho\kappa}\,(\nabla_\phi \omega_{\rho\kappa})$$

$$\Omega_{\mu\nu} \equiv (\partial_\mu u_\nu - \partial_\nu u_\mu)/2$$

We observe that the above equation contains information about the **connection between evolution of spin polarization tensor and fluid vorticity.**

$\mathcal{D}_{\Omega}^{\mu\nu\rho\kappa}$ vanishes in absence of electromagnetic field which leads us to conclude that the **conversion between spin-polarization and vorticity proceeds via coupling with electromagnetic field**.

Relativistic MHD with spin

The expressions for **dissipative currents** in terms of the nonequilibrium corrections to the distribution function are

$$X = \tau_{\text{eq}} \Big[\beta_{X\Pi}\, \theta + \beta^{\alpha}_{Xn} \left(\nabla_\alpha \xi\right) + \beta^{\alpha}_{Xa} \dot{u}_\alpha + \beta^{\alpha\beta}_{X\pi} \sigma_{\alpha\beta} + \beta^{\alpha\beta}_{X\Omega} \Omega_{\alpha\beta} + \beta^{\alpha\beta}_{XF} \left(\nabla_\alpha B_\beta\right) + \beta^{\alpha\beta\gamma}_{X\Sigma} \left(\nabla_\alpha \omega_{\beta\gamma}\right) \Big],$$

where

$$X \equiv n^\mu,\ \Pi,\ \pi^{\mu\nu},\ \delta S^{\lambda,\mu\nu}$$

Demanding that the divergence of the above entropy current is positive definite we identify which first-order gradient terms are dissipative

$$\Pi = -\zeta\theta, \quad n^\mu = \kappa^{\mu\alpha} \left(\nabla_\alpha \xi\right), \quad \pi^{\mu\nu} = \eta^{\mu\nu\alpha\beta} \sigma_{\alpha\beta},$$
$$\delta S^{\mu,\alpha\beta} = \Sigma^{\mu\alpha\beta\lambda\gamma\rho} \left(\nabla_\lambda \omega_{\gamma\rho}\right).$$

Conclusions

We presented the first kinetic theory formulation of **relativistic dissipative nonresistive magnetohydrodynamics with spin** in the limit of small polarization.

We demonstrated that multiple transport coefficients, dissipative as well as non-dissipative, are present.

We showed that our framework naturally leads to the **emergence of the relativistic analog of Barnett effect**.

We show that the **coupling between the magnetic field and spin polarization appears at gradient order**.

Simulation based on our unified framework has the potential of explaining the difference of Λ and anti-Λ polarization.

THANK YOU FOR YOUR ATTENTION.