Hydrodynamic study of Λ spin polarization

from qualitative towards quantitative investigation

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With L.-G. Pang, H. Song and Y. Yin

The 26th international symposium on spin physics (SPIN2025), 2025-09-24, Qingdao

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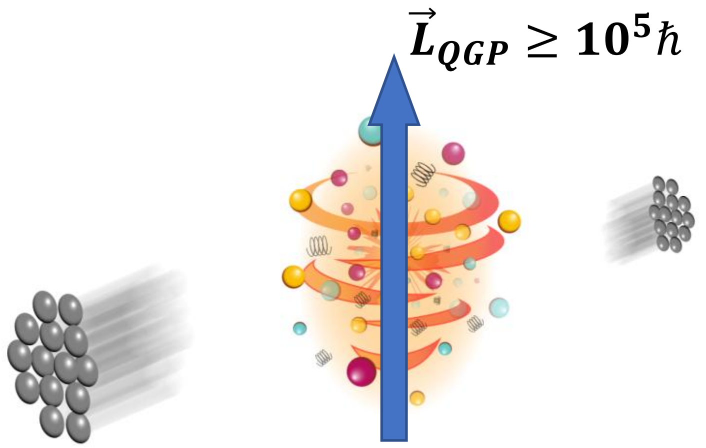
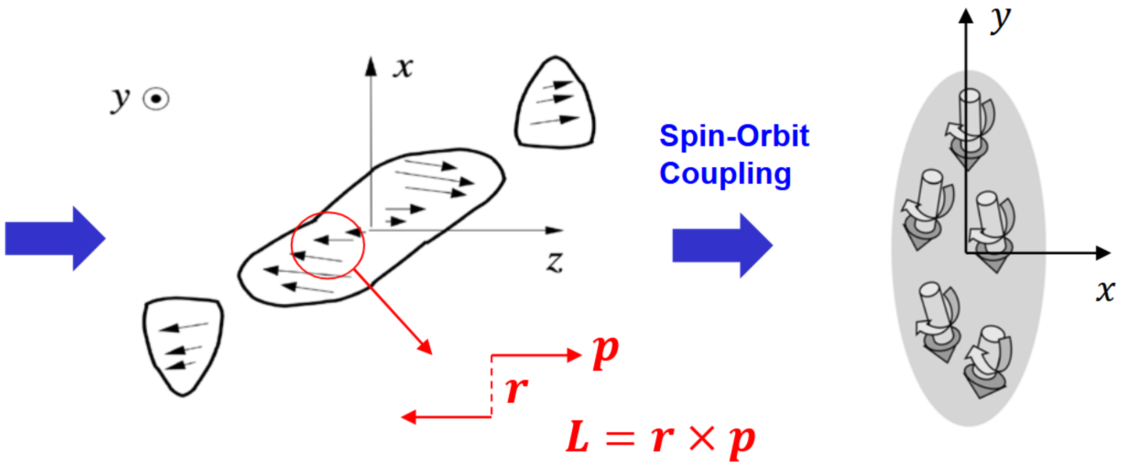
Global Spin Polarization





- Large angular momentum in non-central HIC

$$\vec{L}_{QGP} \propto \vec{L}_{OAM} \perp \hat{n}_{RP}$$

- Global quark spin polarization (spin-orbital coupling)

$$\vec{S}_q \parallel \vec{L}_{QGP}$$

- Global polarization of the emitted hadrons

$$\vec{S}_{\text{hadron}} \parallel \vec{L}_{QGP}$$

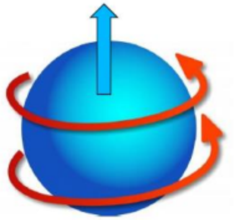
Global quark polarization ⇒

- **Hyperon polarization**
- **Meson spin alignment**
- **Λ spin correlation**

Z. T. Liang & X. N. Wang,
PRL 94 (2005) 102301, PLB 629 (2005) 20-26

Closely Connected with other fields

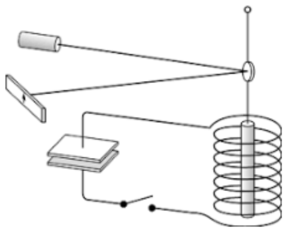
- **Barnett effect: rotation → polarization**



$$\vec{J} \rightarrow \vec{s}$$

Barnett, Phys. Rev. 6 (4) 239, (1915)
Barnett, Rev. Mod. Phys. 7, 129 (1935)

- **Einstein-de Haas Effect: polarization → rotation**



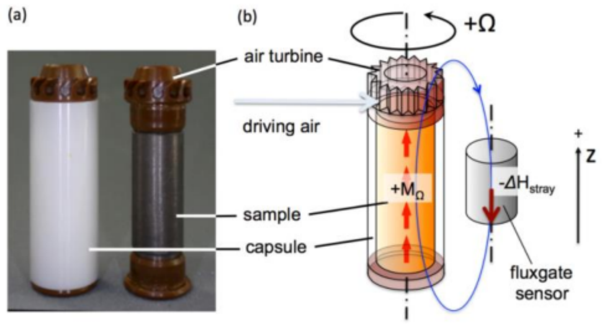
$$\vec{s} \rightarrow \vec{J}$$

Einstein, de Hass, DPG Vanhandlungen 17, 152 (1915)

Nuclear magnetic resonance

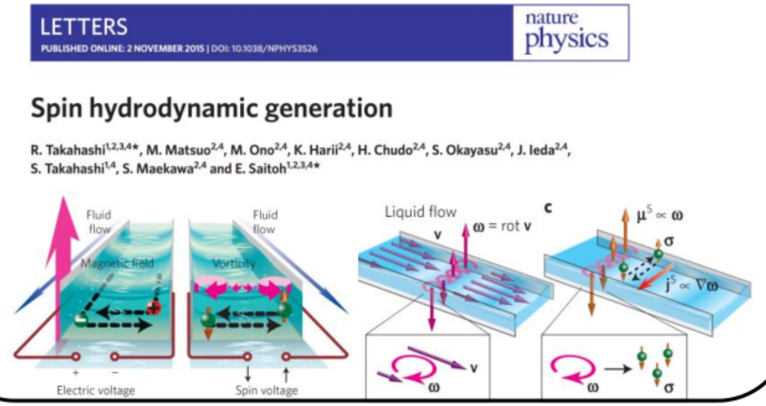
H. Chudo, et al, Applied Physics Express, 2015

Paramagnetic states



M. Ono, et al, Phys. Rev. B, 2015

Condensed matter



R. Takahashi, Nature Physics, 2016

Closely Connected with other fields

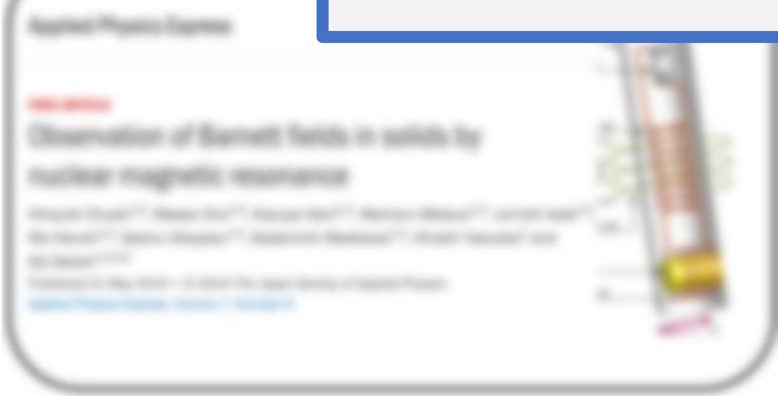
- Barnett effect: rotation → polarization

$\vec{J} \to \vec{s}$

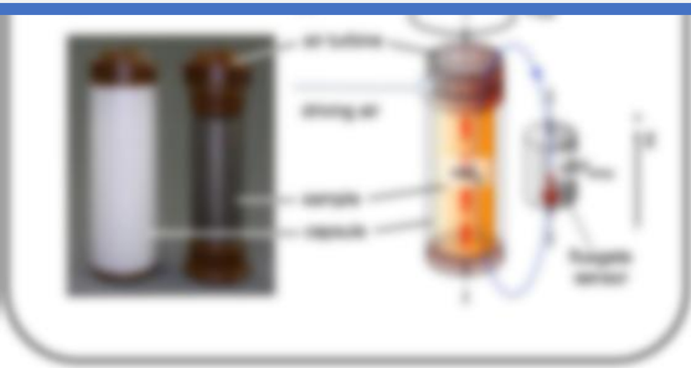
- Einstein-de Haas Effect: polarization → rotation

$\vec{s} \to \vec{J}$

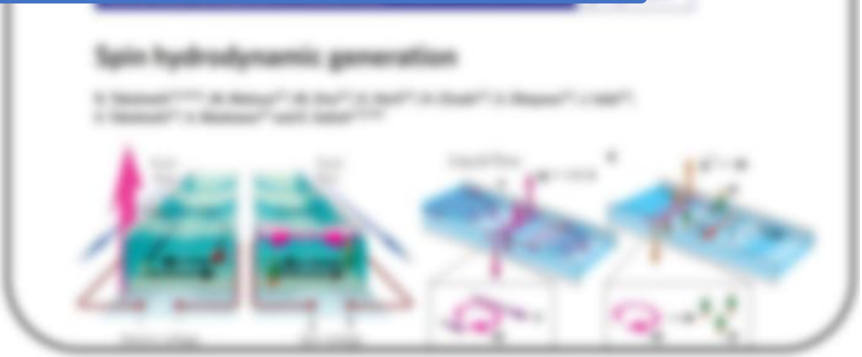
RHIC and LHC can study such effects at extreme conditions



H. Chudo, et al, Applied Physics Express, 2015



M. Ono, et al, Phys. Rev. B, 2015



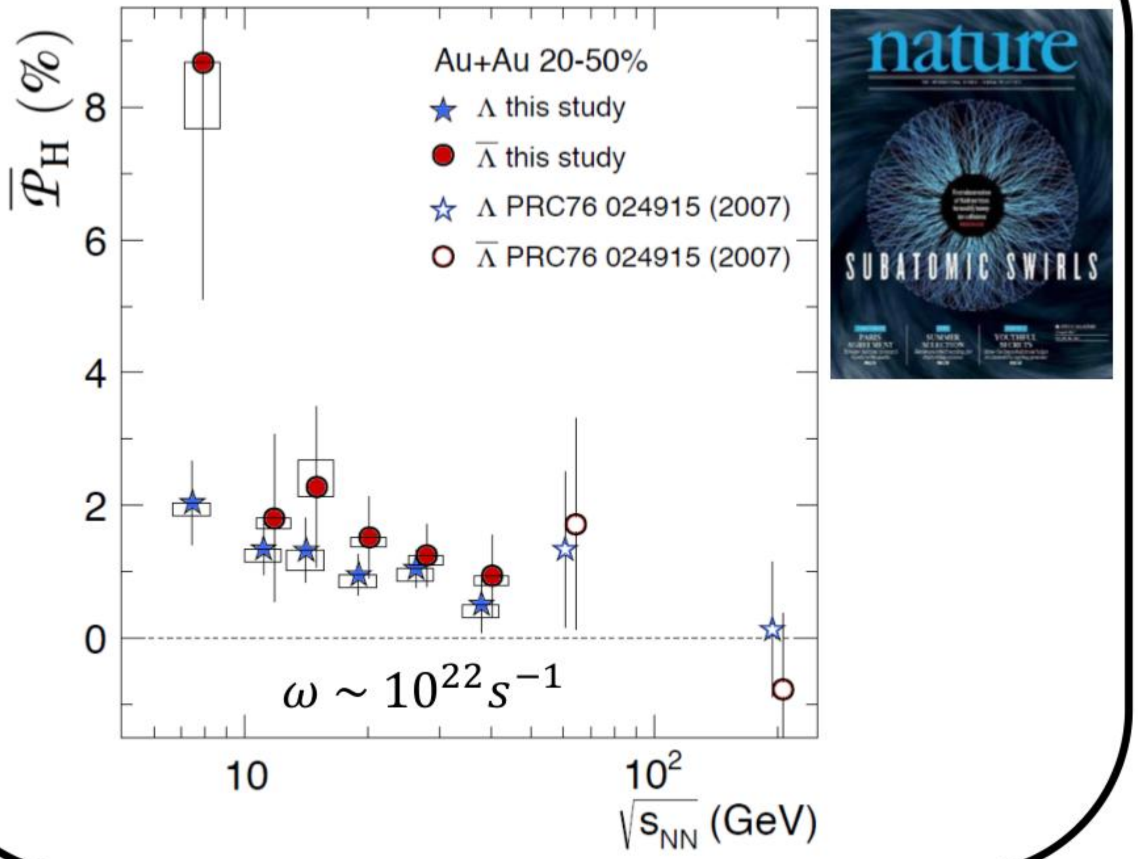
R. Takahashi, Nature Physics, 2016

Spin Polarization Measurements

26th International Symposium on Spin Physics
A Century of Spin

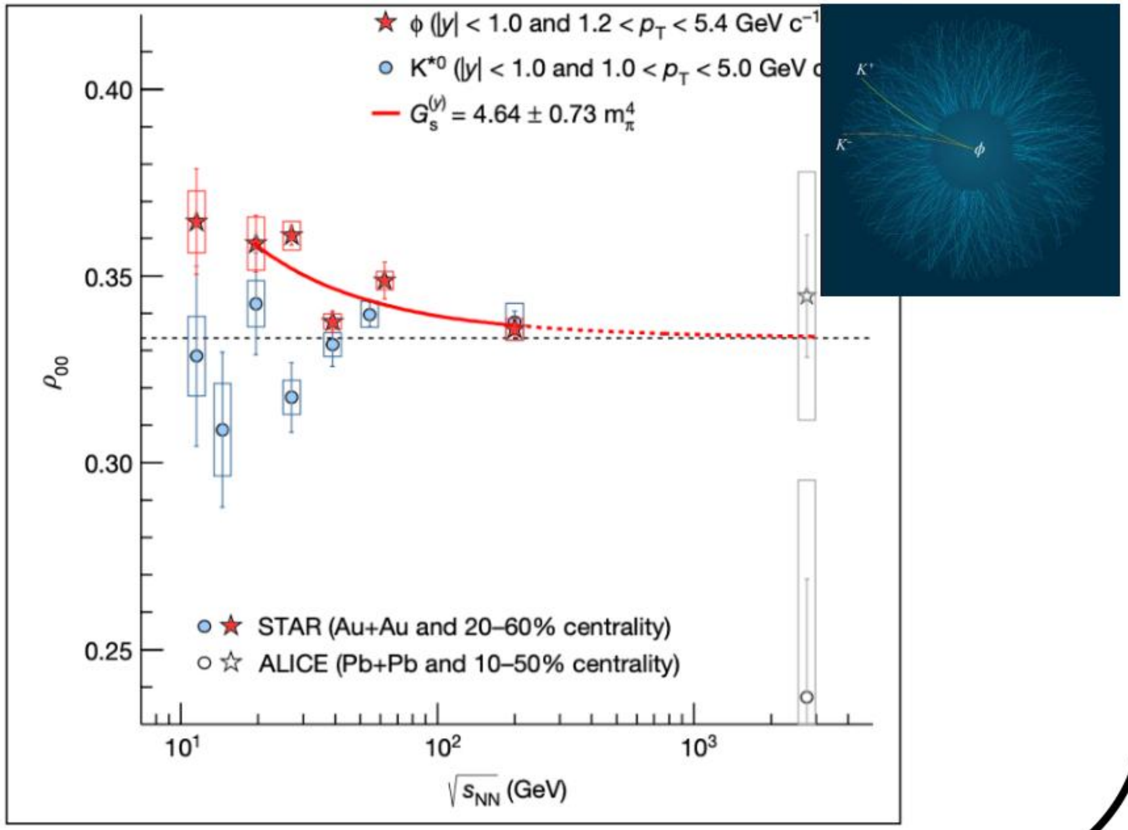
Most vortical fluid!

STAR Collaboration, Nature 548, 62 (2017)



Meson spin alignment

STAR Collaboration, Nature 614, 224 (2023)



Spin polarization: a new direction to probe the property of QGP

Spin Polarization in Hydrodynamics

Hydrodynamics

Heavy-Ion collision stages:

- Initial state + thermalization (< 1 fm)
- Hydrodynamics

$$\partial_\mu T^{\mu\nu} = 0, \qquad T^{\mu\nu} = e u^\mu u^\nu - P\Delta^{\mu\nu}$$
$$\partial_\mu N^\mu = 0, \qquad N^\mu = n u^\mu$$

EoS

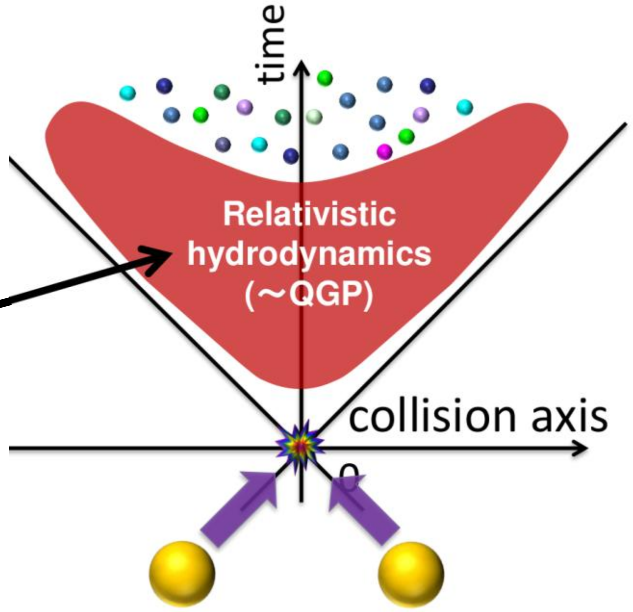
Hydro fields:

$u^\mu(x)$: flow velocity

$e(x)$: energy density

$n(x)$: (baryon) charge density

…



- Hadronization (Cooper-Frye)

$$E\frac{dN_i}{d^3p} = \frac{1}{(2\pi)^3}\int_\Sigma p\cdot d^3\sigma_\mu(x)\ f_i(x,p)$$

- Freeze-out & collected in detector

Hydrodynamics

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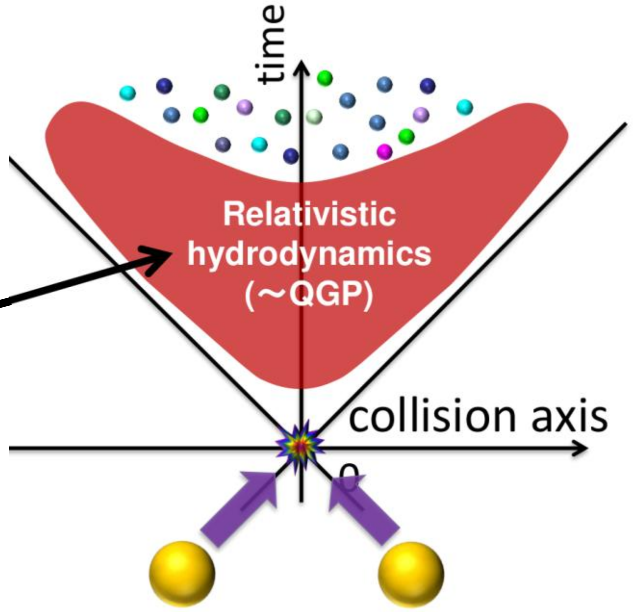

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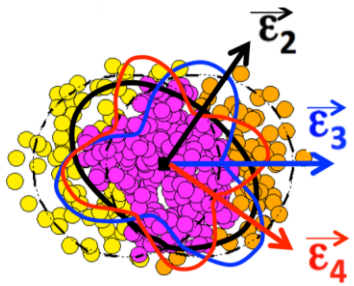
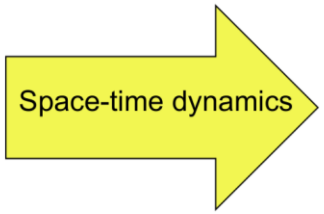
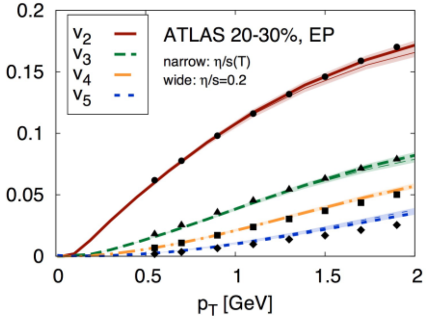
- Freeze-out & collected in detector

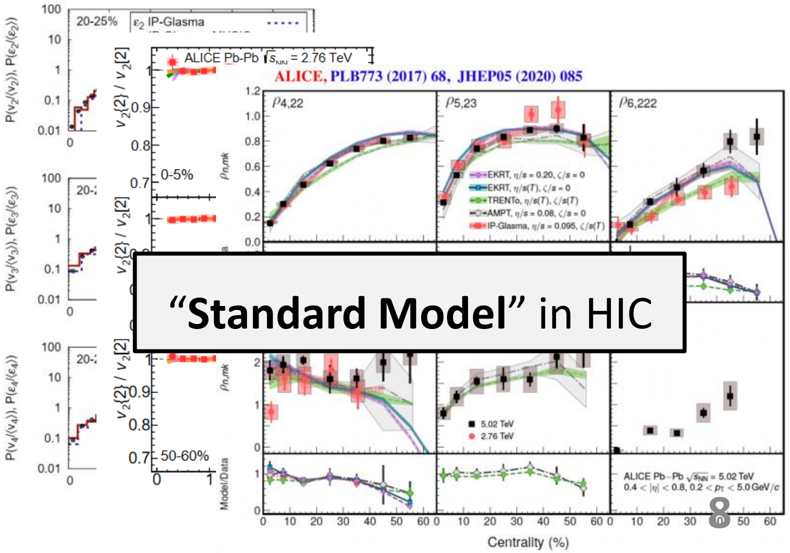
Hydrodynamics: transfer initial eccentricities into particle anisotropies



Hydro-response







"**Standard Model**" in HIC

Thermal Vorticity Induced Polarization

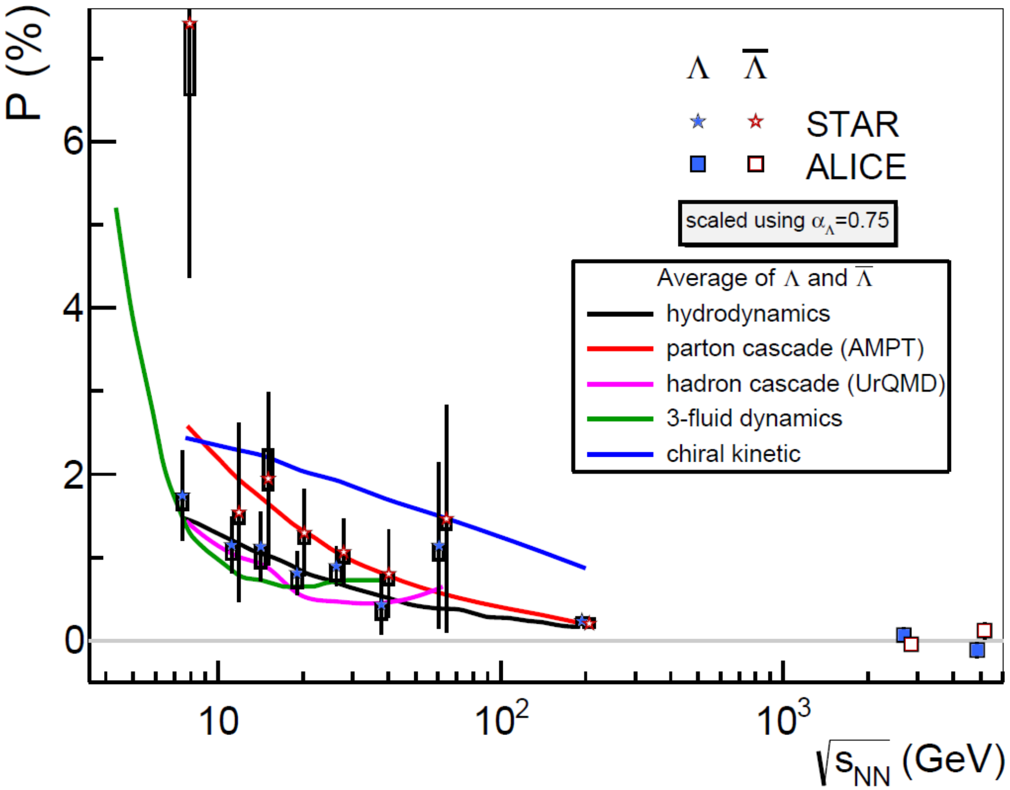
- Thermal vorticity effect in **global equilibrium**

$$S^{\mu}(x,p) = -\frac{1}{2m}\frac{S(S+1)}{3}[1-f(x,p)]\epsilon^{\mu\nu\rho\sigma}p_{\sigma}\varpi_{\nu\rho}$$

$\varpi_{\mu\nu}$: thermal vorticity, extracted from hydro

$$\varpi_{\mu\nu} = -\frac{1}{2}(\partial_{\mu}\beta_{\nu} - \partial_{\nu}\beta_{\mu}) \qquad \beta_{\mu} = u_{\mu}/T$$

- Successfully describe the global polarization by various hydrodynamics / transport models



P^{μ} = [thermal vorticity]

F. Becattini and M. Lisa, Ann.Rev.Nucl.Part.Sci. 70 (2020) 395-423

See also:

Karpenko I, Becattini F. Eur. Phys. J. C77:213 (2017)

Li H, Pang L-G, Wang Q, Xia XL. Phys. Rev. C96:054908 (2017)

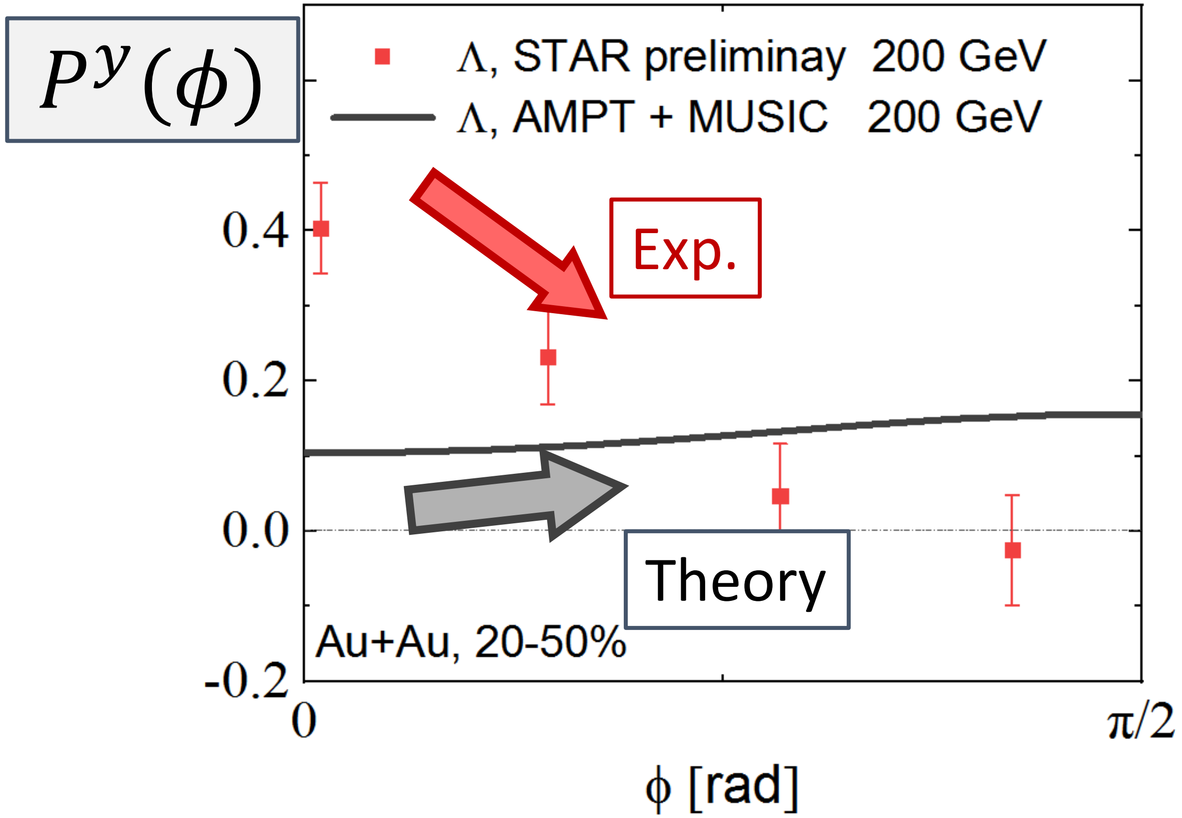
O. Vitiuk, L. Bravina and E. Zabrodin, Phys.Lett.B 803 (2020) 135298

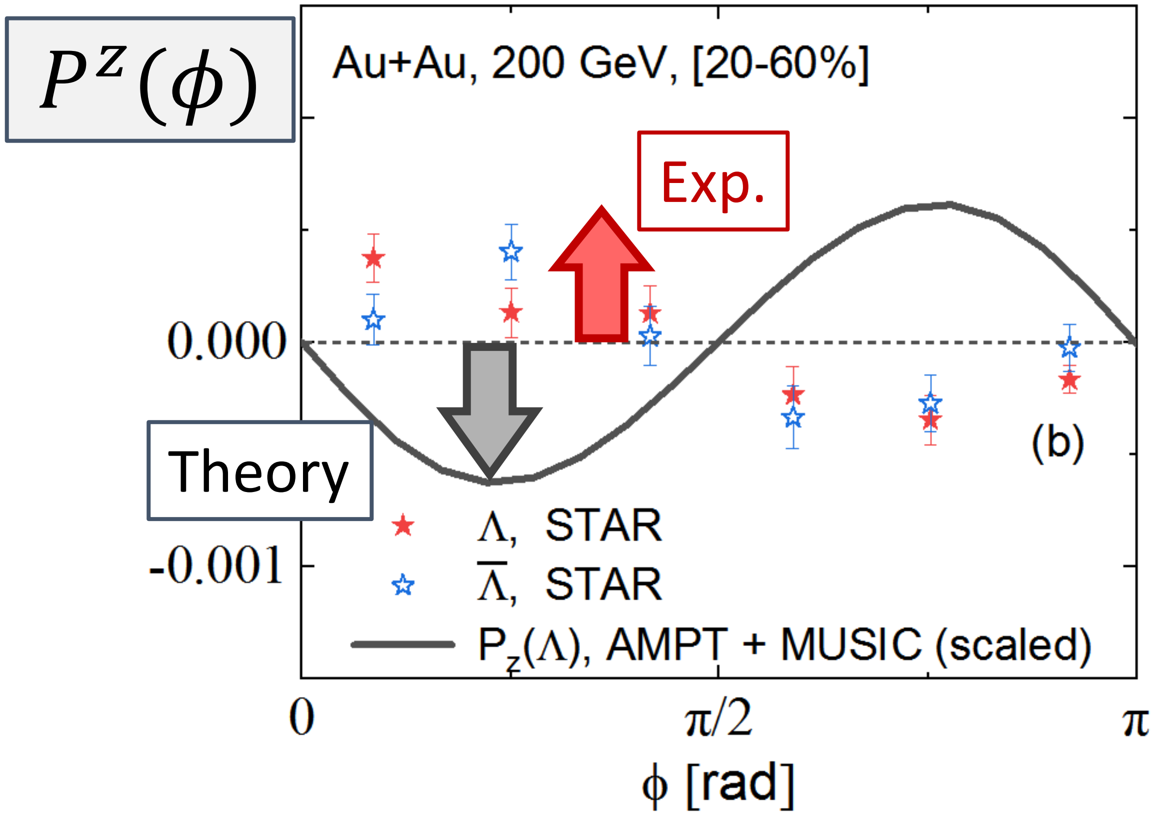
Ivanov YB, Toneev VD, Soldatov AA. Phys. Rev. C100:014908 (2019)

Sun Y, Ko CM. Phys. Rev. C96:024906 (2017)

Local Polarization Puzzle

BF, K. Xu, X-G, Huang, H. Song, PRC 103 (2021) 2, 024903





$$P^{\mu}(\phi) \neq \text{[thermal vorticity]}$$

Long exist in hydrodynamic and transport calculations, see also:

Karpenko and Becattini EPJC 17' PRL 18', X. Xia, PRC 18', D. Wei, et al PRC 19', X. Wu, et al PRR 19' ...

Shear Induced Polarization

- Global equilibrium may not valid for highly dynamical QGP evolution

Pics @ X. An

BF, S. Liu, LG. Pang, H. Song, Y. Yin, PRL 127 14, 142301(2021),
S. Liu and Y. Yin, JHEP 07 (2021) 188

- Axial Wigner function from CKT and linear response theory

$$\mathcal{A}^{\mu} = \frac{1}{2}\beta n_0(1-n_0)\left\{\epsilon^{\mu\nu\alpha\lambda}p_{\nu}\partial_{\alpha}^{\perp}u_{\lambda} + 2\epsilon^{\mu\nu\alpha\lambda}u_{\nu}p_{\alpha}\left[\beta^{-1}(\partial_{\lambda}\beta)\right] - 2\frac{p_{\perp}^{2}}{\varepsilon_0}\epsilon^{\mu\nu\alpha\rho}u_{\nu}Q_{\alpha}^{\ \lambda}\sigma_{\rho\lambda}\right\}$$

Thermal vorticity

(Anti-symmetric part of the u^{μ}/T gradients)

Shear-Induced Polarization

(Symmetric part of the u^{μ} or u^{μ}/T gradients)

$$Q^{\mu\nu} = -p_{\perp}^{\mu}p_{\perp}^{\nu}/p_{\perp}^{2} + \Delta^{\mu\nu}/3 \qquad \sigma^{\mu\nu} = \frac{1}{2}\left(\partial_{\perp}^{\mu}u^{\nu} + \partial_{\perp}^{\nu}u^{\mu}\right) - \frac{1}{3}\Delta^{\mu\nu}\partial_{\perp}\cdot u$$

Shear Induced Polarization

- Global equilibrium may not valid for highly dynamical QGP evolution

Pics @ X. An

BF, S. Liu, LG. Pang, H. Song, Y. Yin, PRL 127 14, 142301(2021), S. Liu and Y. Yin, JHEP 07 (2021) 188

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Thermal vorticity — Shear-Induced Polarization

- From global eq. to local eq., see also:
  - Statistical method (F. Becattini, et al., PLB 820 (2021) 136519)
  - Recent updates: Sheng @ Tues.

P^{μ} = [thermal vorticity] + [Shear]

$P^\mu(\phi)$ with Shear-Induced Polarization

P^μ = [thermal vorticity] + [Shear]

- S-quark scenario: large spin relaxation time
- **Qualitatively agrees with data!**

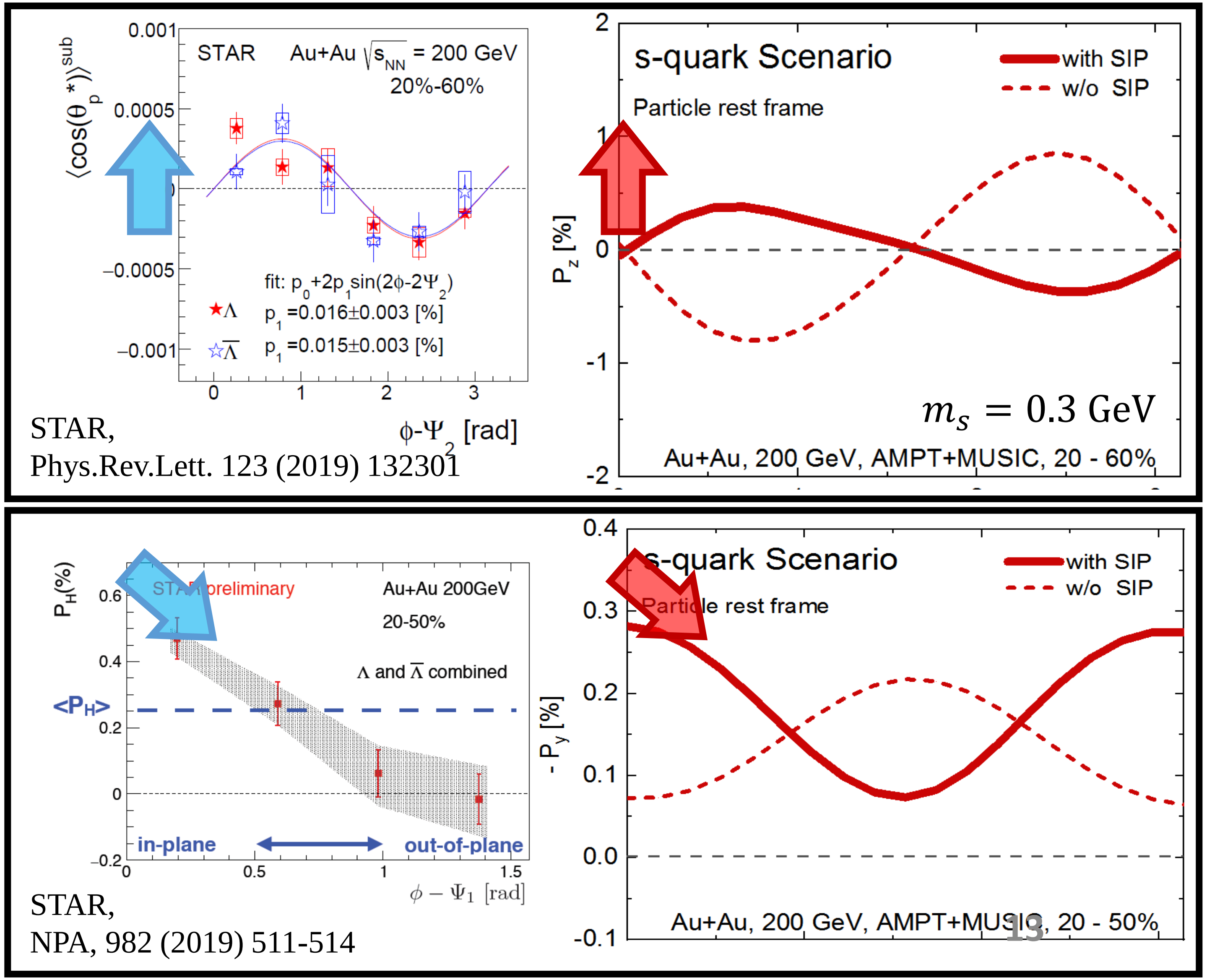
- Similar (thermal-)shear effect

  Hydrodynamics(vhlle with iso-thermal)
  F. Becattini, et al., PRL 127 (2021) 27, 272302

- Shear-induced polarization has also been confirmed by various model calculations

  Hydrodynamics(CLVisc)
  C. Yi, et al., Phys.Rev.C 104 (2021) 6, 064901
  UrQMD
  Y. Sun, et al, Phys.Rev.C 105 (2022) 3, 034911
  Blast-Wave
  W. Florkowski, et al., Phys.Rev.C 105 (2022) 6, 064901

BF, S. Liu, LG. Pang, H. Song, Y. Yin, PRL 127 14, 142301(2021)

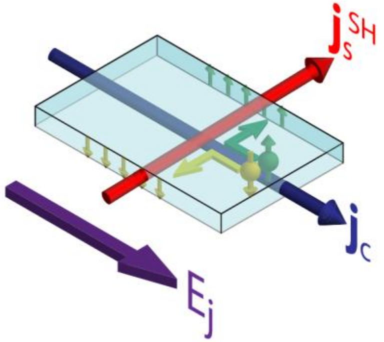


Probing the μ_B gradients – baryonic Spin Hall Effects

In condensed-matter

- Transverse spin current induced by spin-orbital coupling under external electric field

$$\vec{s} \propto \vec{p} \times \vec{E}$$



S. Meyer, et al., Nature Materials, 2017

J. Sinova, et al., Rev. Mod. Phys. 2015

In hot QCD matter

- Replacing electric field $\vec{E}$ to baryon chemical potential gradient $\vec{\nabla}\mu_B$

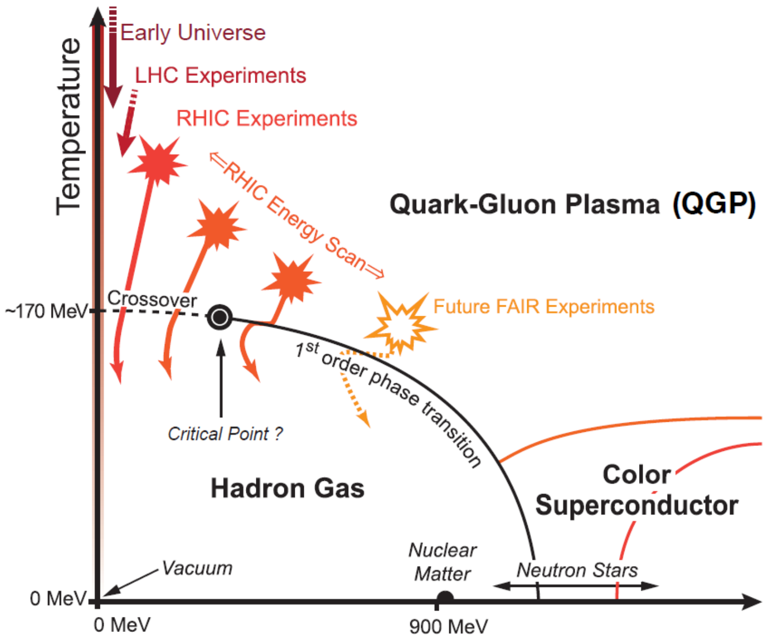
$$\vec{P}_\pm \propto \pm \vec{p} \times \vec{\nabla}\mu_B$$

Axial Wigner function $\mathcal{A}^\mu$ expansion with finite chemical potential: S. Liu and Y. Yin, PRD 104, 054043 (2021)

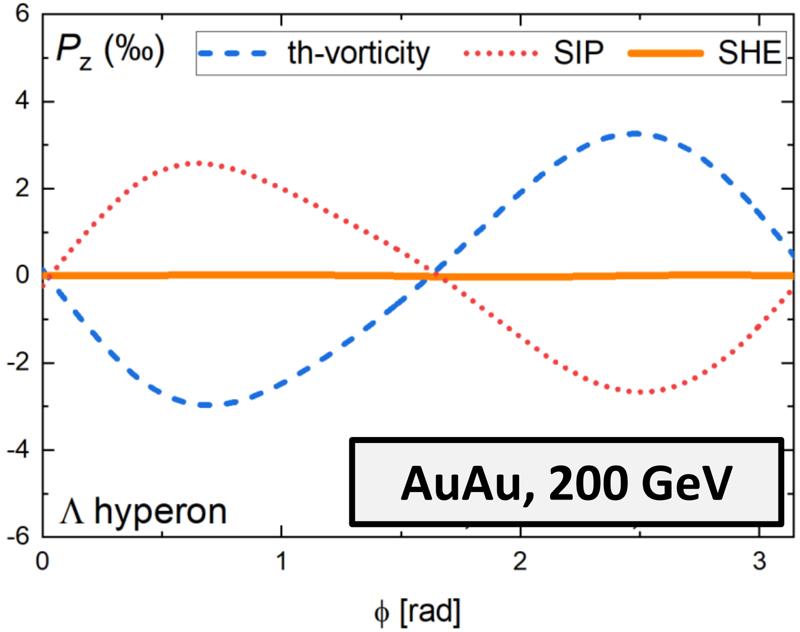
$$\mathcal{A}^\mu(x,p) = \beta f_0(x,p)(1-f_0(x,p))\varepsilon^{\mu\nu\alpha\rho} \times \left(\underbrace{\frac{1}{2}p_\nu \partial_\alpha^\perp u_\rho - \frac{1}{T}u_\nu p_\alpha \partial_\rho T}_{\text{thermal vorticity}} - \underbrace{\frac{p_\perp^2}{\varepsilon_0} u_\nu Q_\alpha^\lambda \sigma_{\rho\lambda}}_{\text{shear}} - \underbrace{\frac{q_B}{\varepsilon_0 \beta} u_\nu p_\alpha \partial_\rho(\beta\mu_B)}_{\text{baryonic SHE}} \right),$$

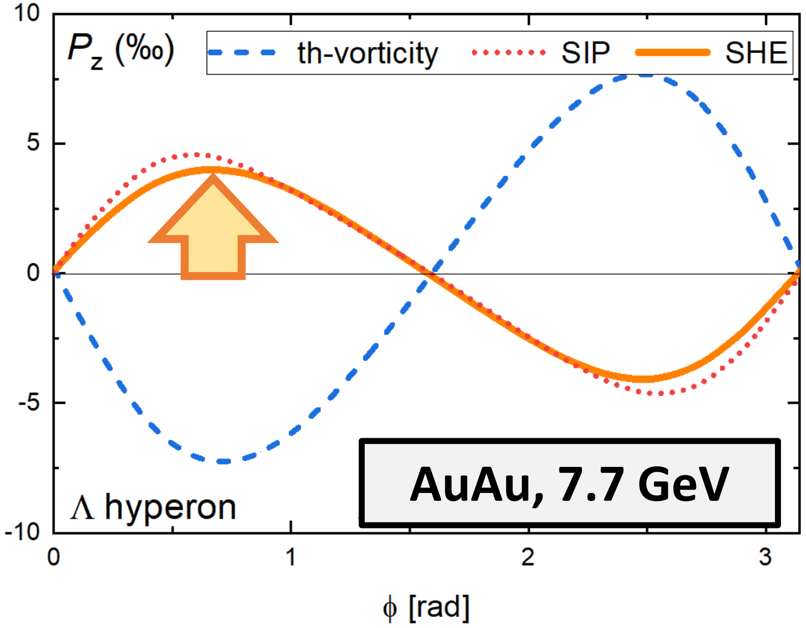
Baryonic Spin Hall Effects at RHIC-BES

- Decreasing collision energy → higher μ_B → Stronger baryonic SHE



B. Schenke@QM2015





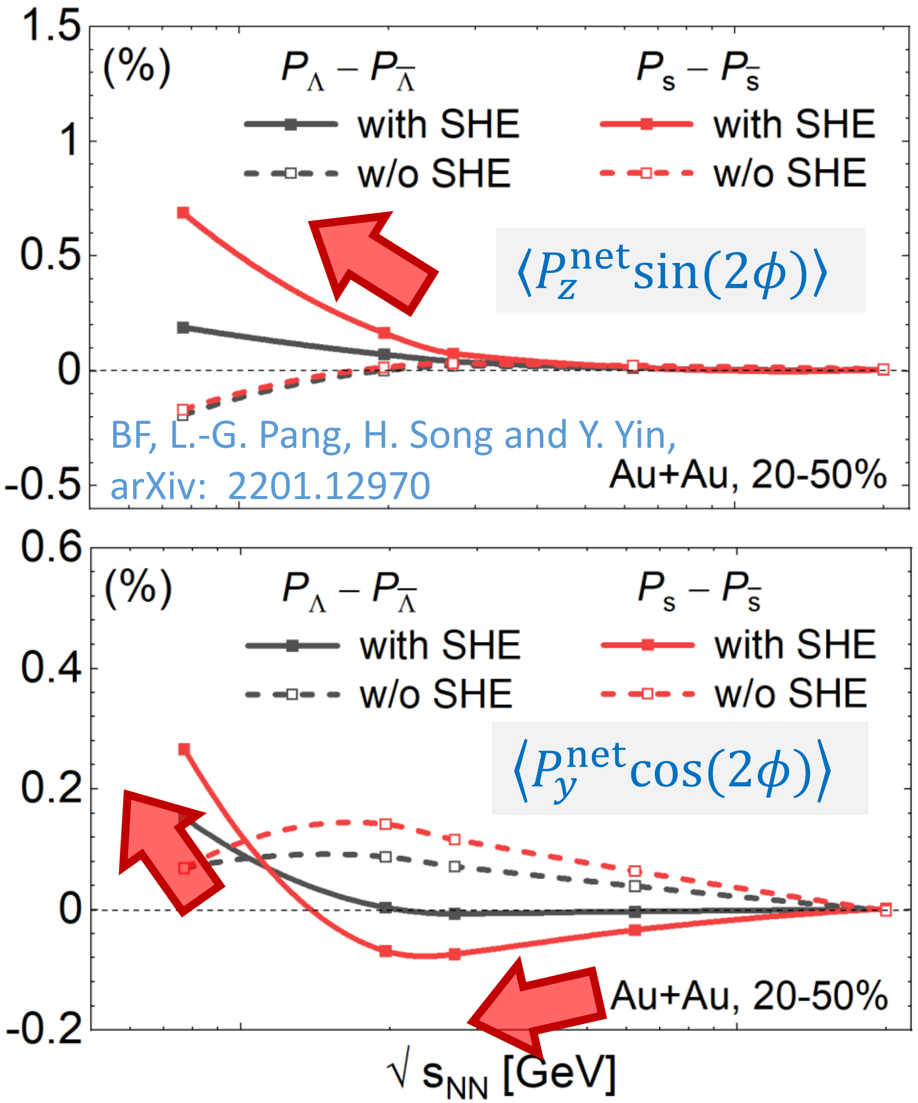
- $\Lambda - \overline{\Lambda}$ **polarization separation**: Opposite contribution for particles / anti-particles
- Extract SHE signal from net-polarization $(P_\Lambda - P_{\overline{\Lambda}})$

$$P^\mu_{SHE} \propto \frac{q_B}{\varepsilon_0 \beta} u_\nu p_\alpha \partial_\rho (\beta \mu_B)$$

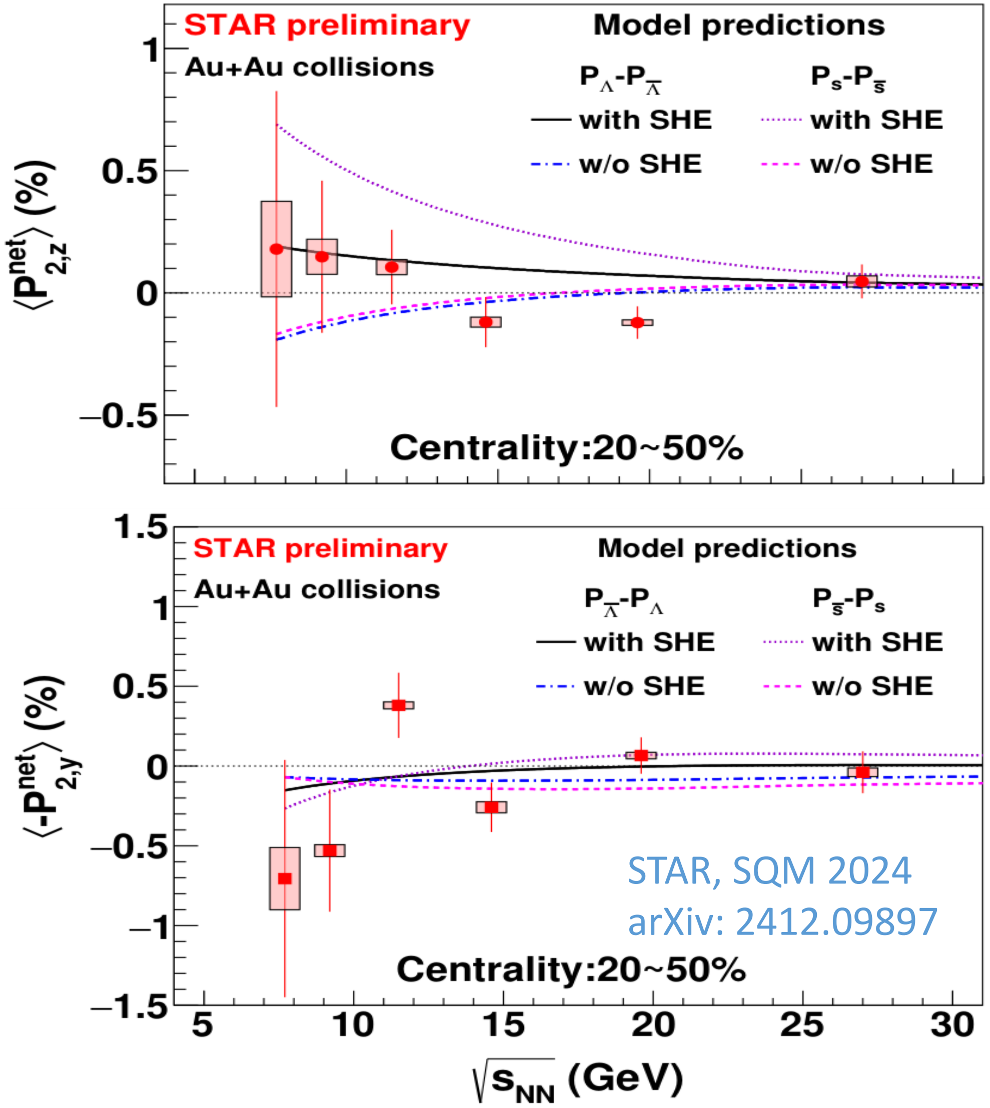
BF, L.-G. Pang, H. Song and Y. Yin, arXiv: 2201.12970

Baryonic Spin Hall Effects at RHIC-BES

- Increasing SHE signals by decreasing energy



- Qualitatively consistent with STAR measurements



Code Verification with WSU group

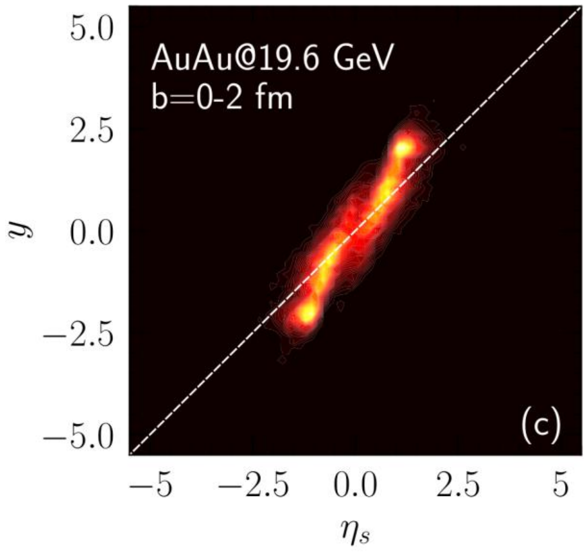
P^μ = [thermal vorticity] + [Shear] + [baryonic SHE]

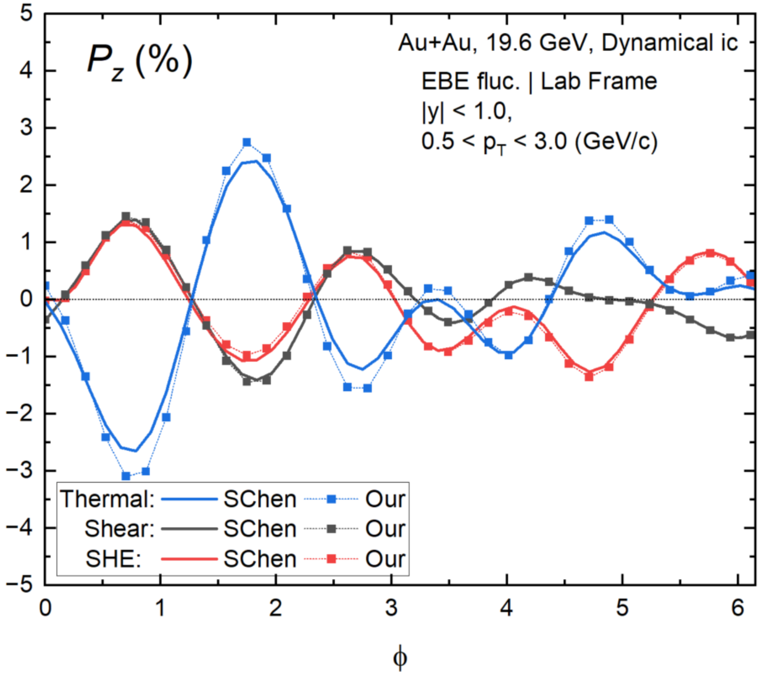
- Same oscillated initial condition and hydrodynamic model/parameters
- Independent gradient extraction and spin calculation codes
- **Consistent and stable results**
- Slight difference on "thermal vorticity" due to different dissipative definition

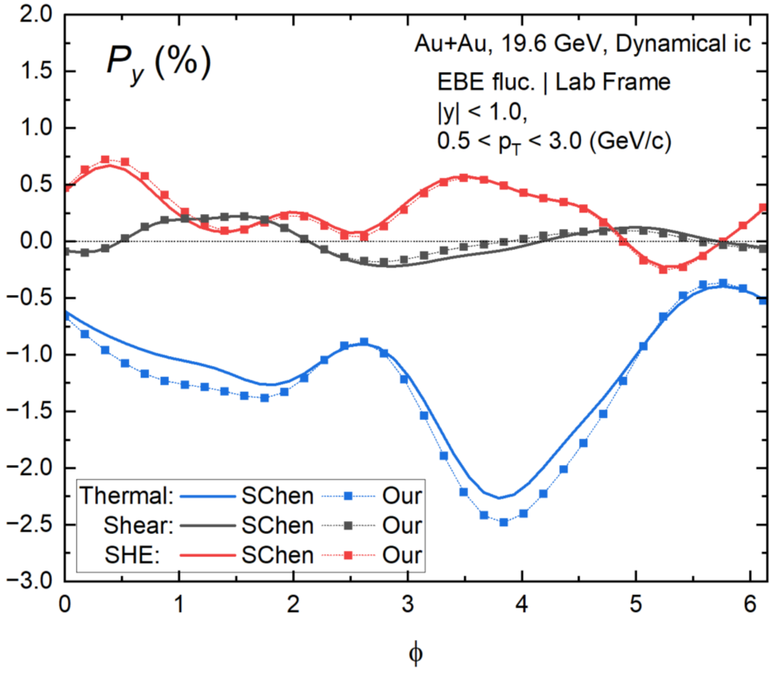
BF, L.-G. Pang, H. Song and Y. Yin, In progress

Dynamical MC-Glauber IC

C. Shen and B. Schenke, PRC 105,064905 (2022)





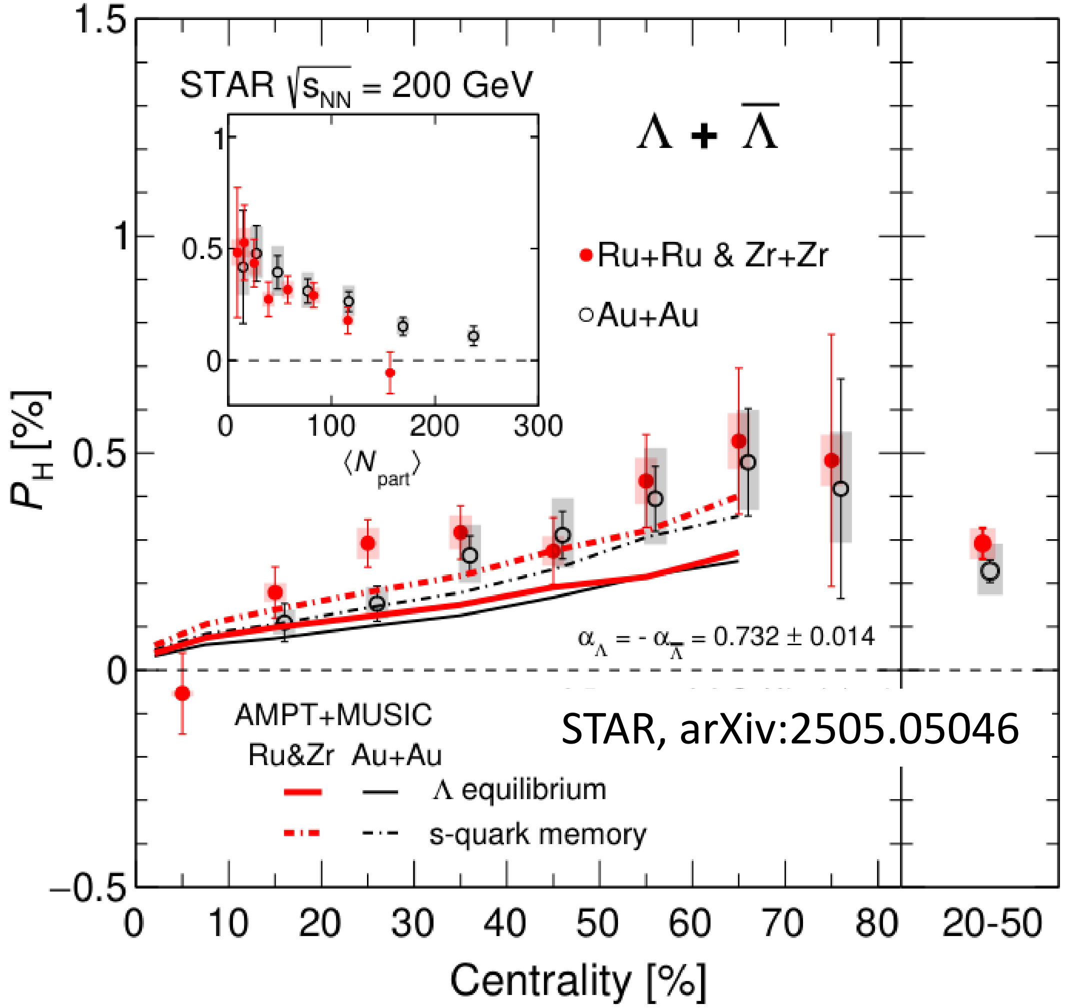


From qualitative toward quantitative descriptions

$\boldsymbol{P^{\mu}}$ = [thermal vorticity] + [Shear] + [baryonic SHE]

Global Polarization in Iso-bar Collisions

- Same hydrodynamic model (except the norm. factor) describes global polarization in AuAu / RuRu
- No obvious system size dependence and consistence with exp. data

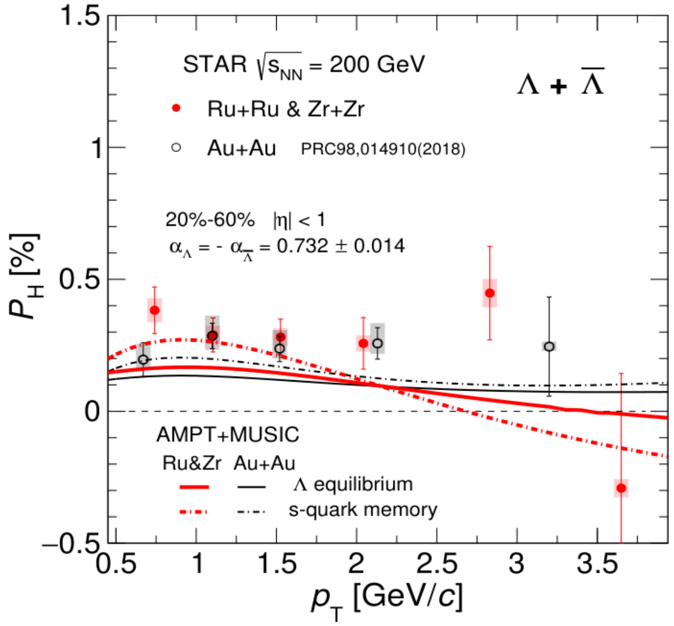


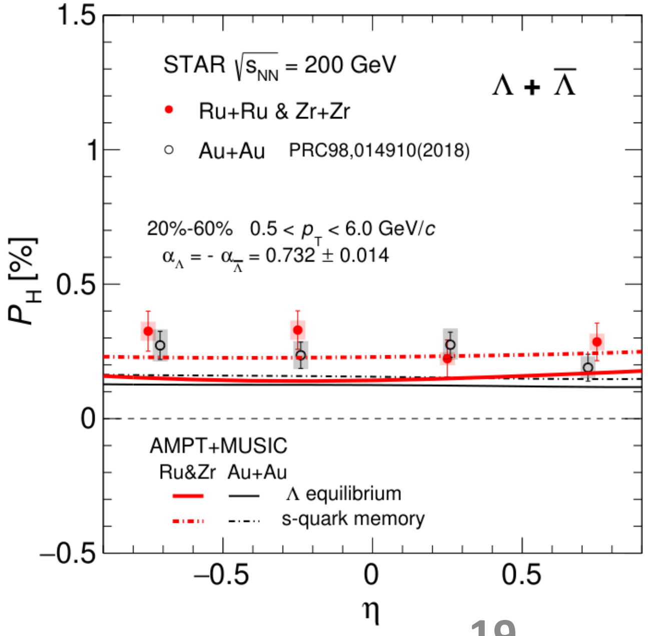
STAR, arXiv:2505.05046

P^μ = [thermal vorticity] + [Shear] + [baryonic SHE]

BF, L.-G. Pang, H. Song and Y. Yin, In preparation

- Also describes the differential distribution along p_T and η

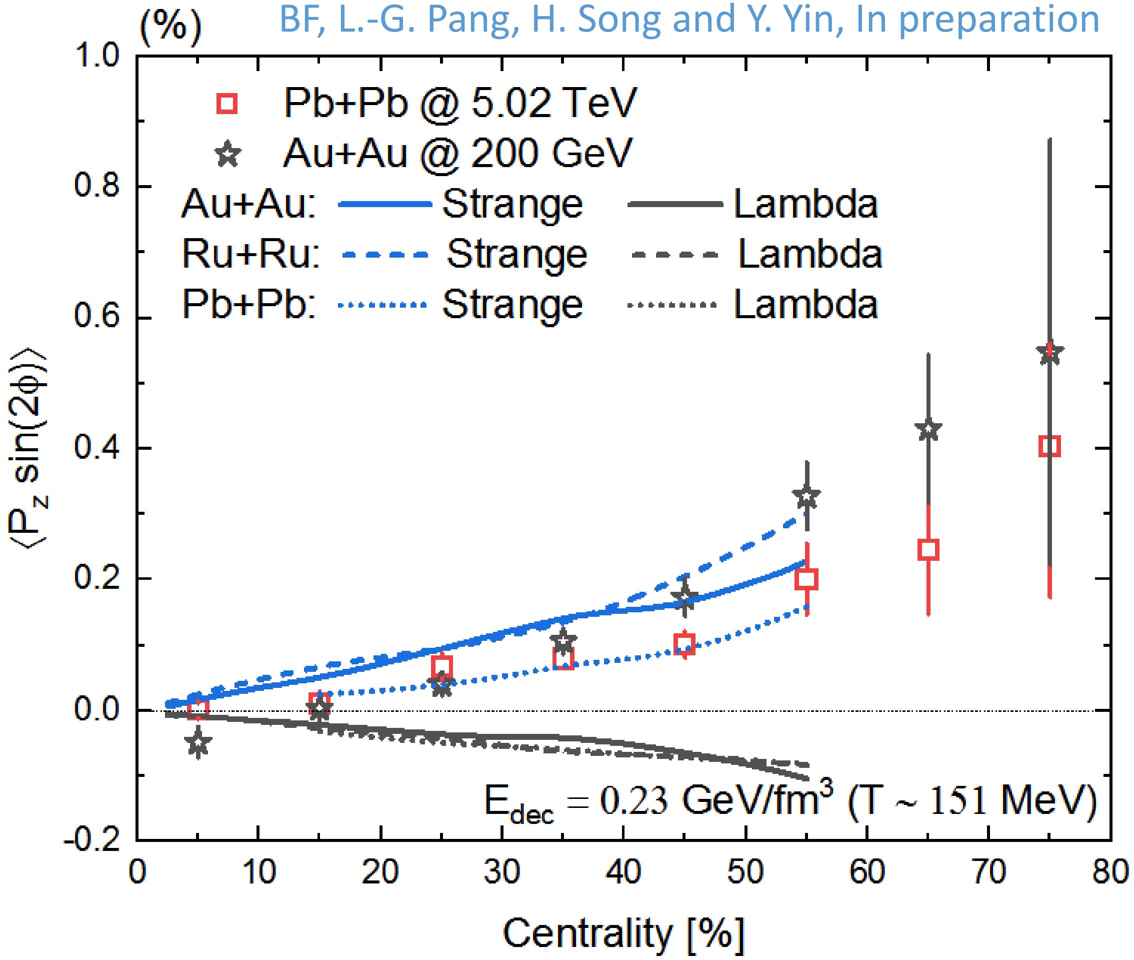


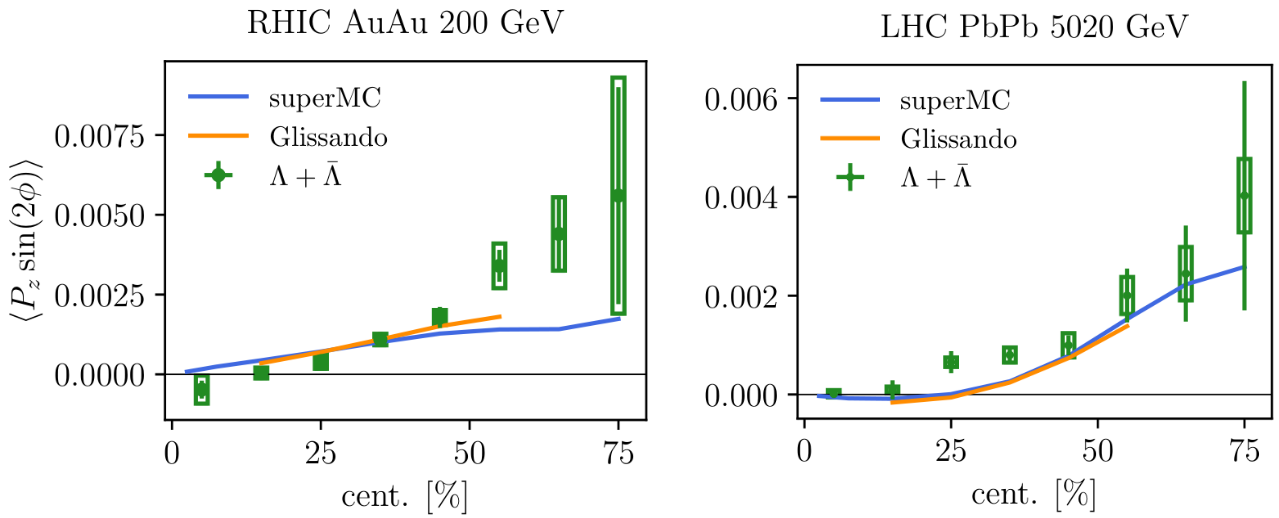


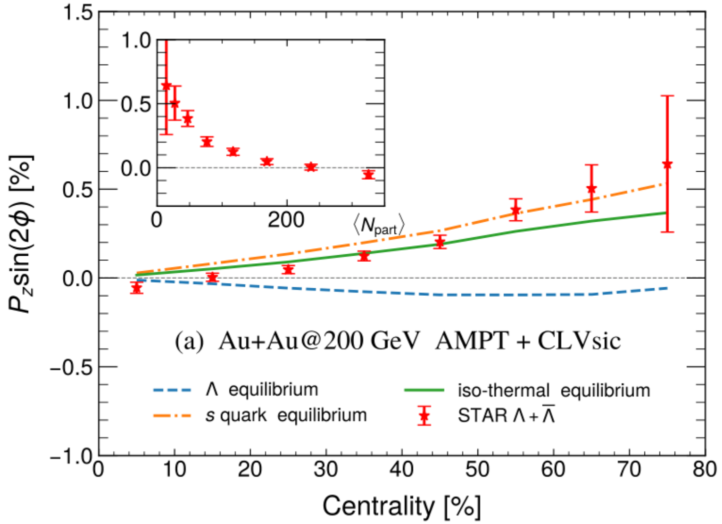
Local Polarization at RHIC and LHC

- Hydrodynamics (with same hydro parameter) reasonably describes the 2nd Fourier coefficient in RHIC and LHC systems

BF, L.-G. Pang, H. Song and Y. Yin, In preparation







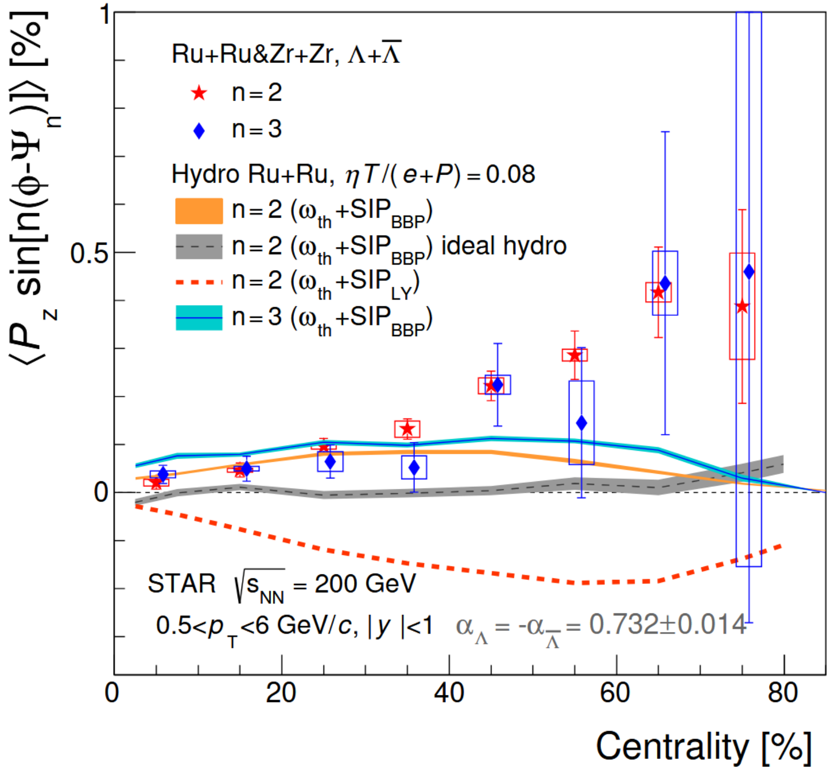
A. Palermo, et al., Eur.Phys.J.C 84 (2024) 9, 920

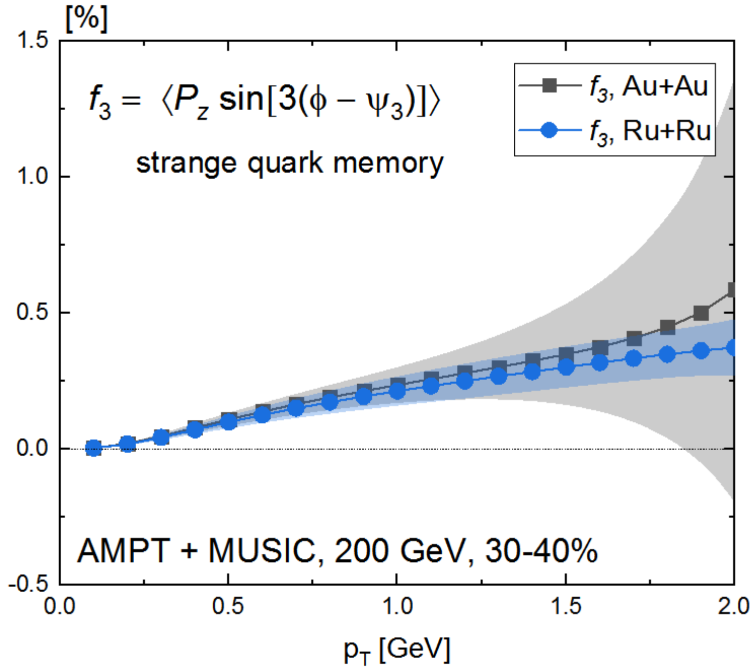
C. Yi, et al., arXiv: 2509.00377

Local Polarization at RHIC and LHC

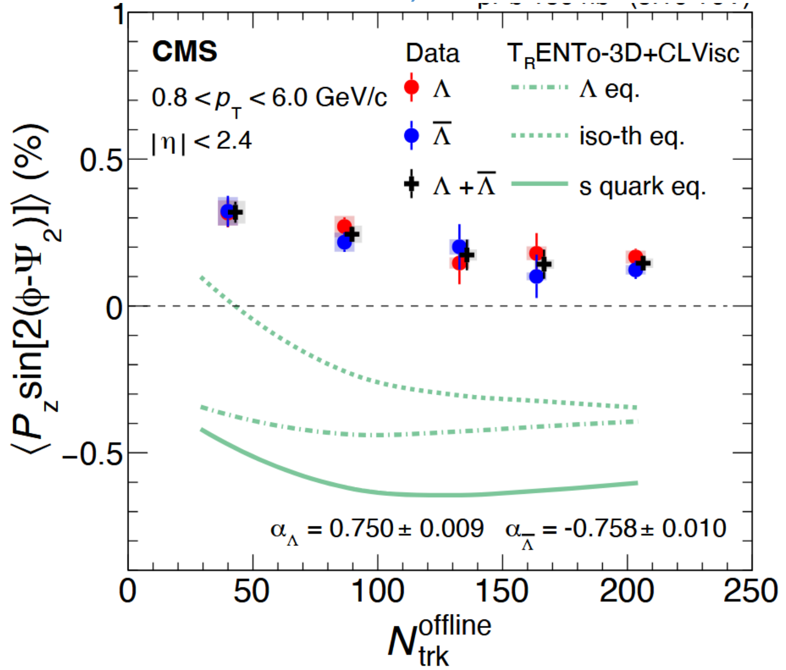
- Hydrodynamics (with same hydro parameter) reasonably describes the 2nd Fourier coefficient in RHIC and LHC systems
- Challenges in event-by-event simulation
- and small systems (talks by Cong, Chenyan, Di-Lun @ Tues.)

STAR, PRL 131 (2023) 20, 202301





CMS, arXiv: 2502.07898

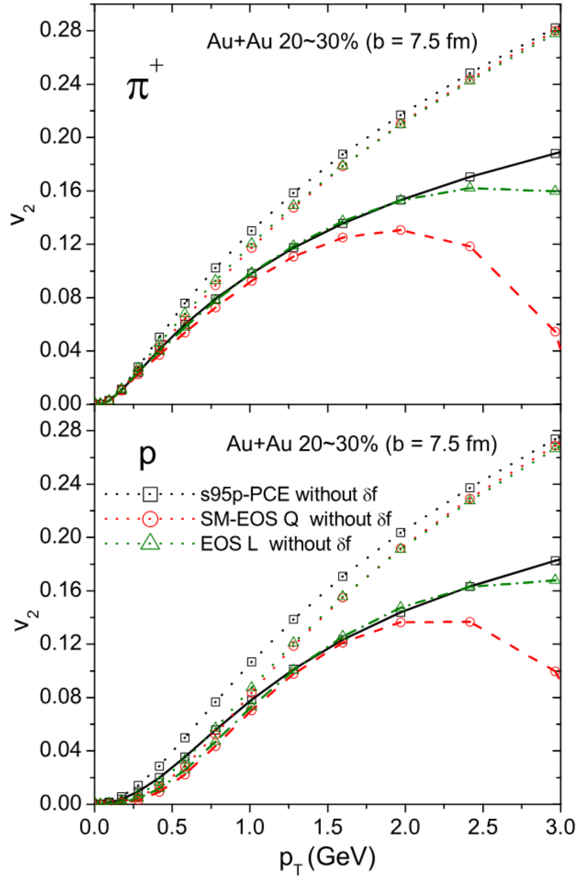


Probing the EoS through spin polarization

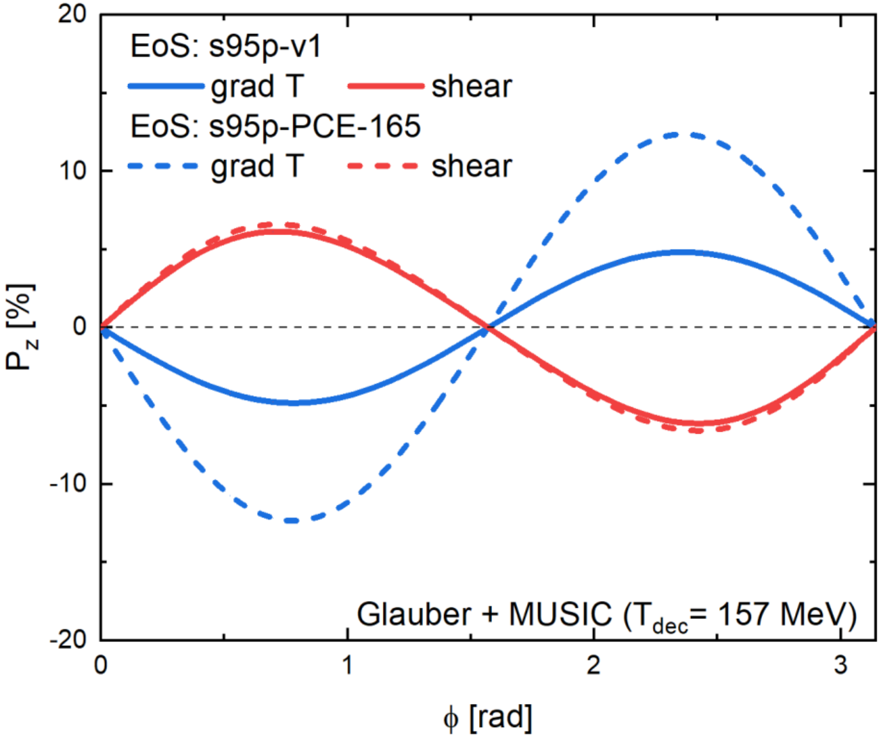
26th International Symposium on Spin Physics
A Century of Spin

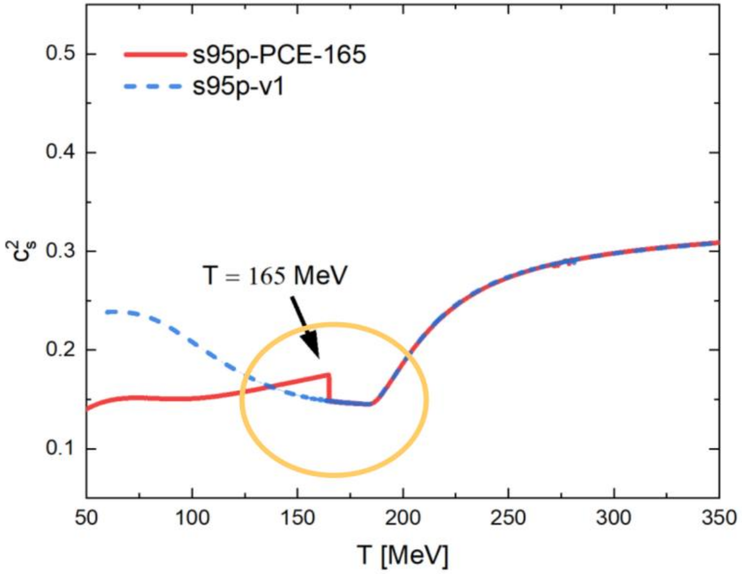
- Anisotropic flow is insensitive to different kinds of EoS
- Obviously EoS dependence of polarization (in particular for PCE)
- A jump of c_s and T in PCE-EOS → sensitivity on T gradients

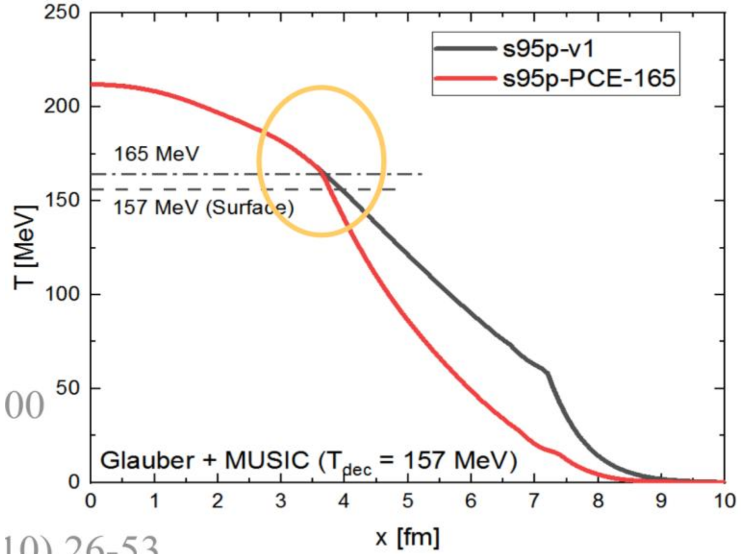
C. Shen, et al., PRC 82 (2010) 054904



BF, L.-G. Pang, H. Song and Y. Yin, In preparation





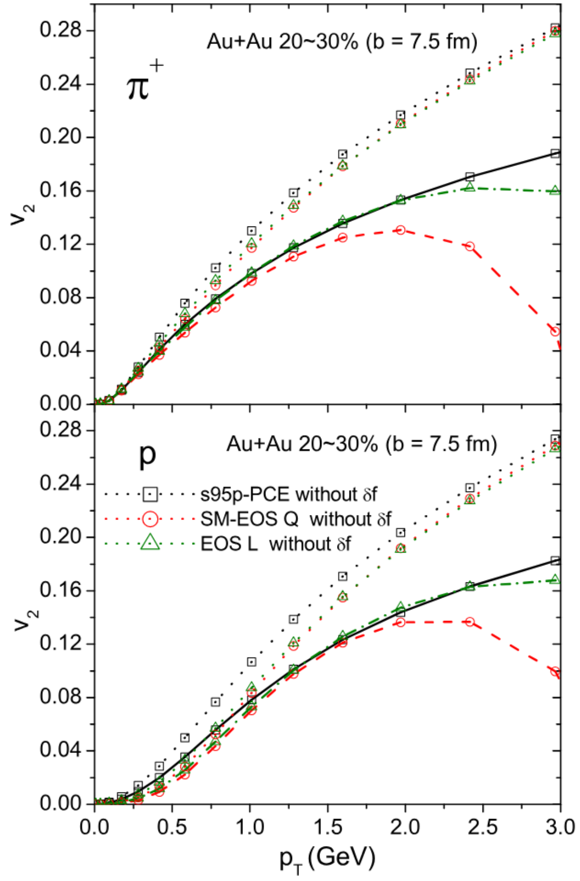


See also: C. Yi, S. Pu, D. Yang, PRC 104 (2021) 6, 064901

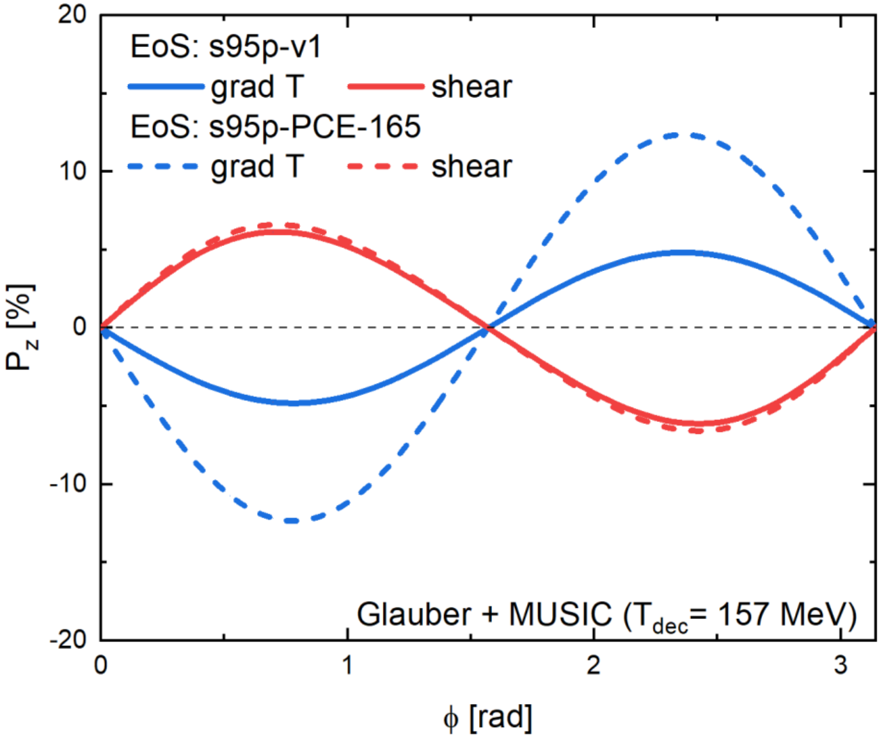
Probing the EoS through spin polarization

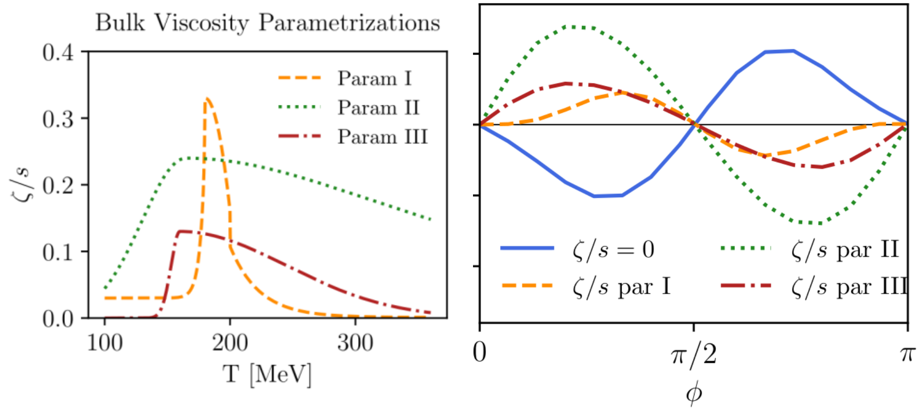
- Anisotropic flow is insensitive to different kinds of EoS
- Obviously EoS dependence of polarization (in particular for PCE)
- A jump of c_s and T in PCE-EOS → sensitivity on T gradients

C. Shen, et al., PRC 82 (2010) 054904

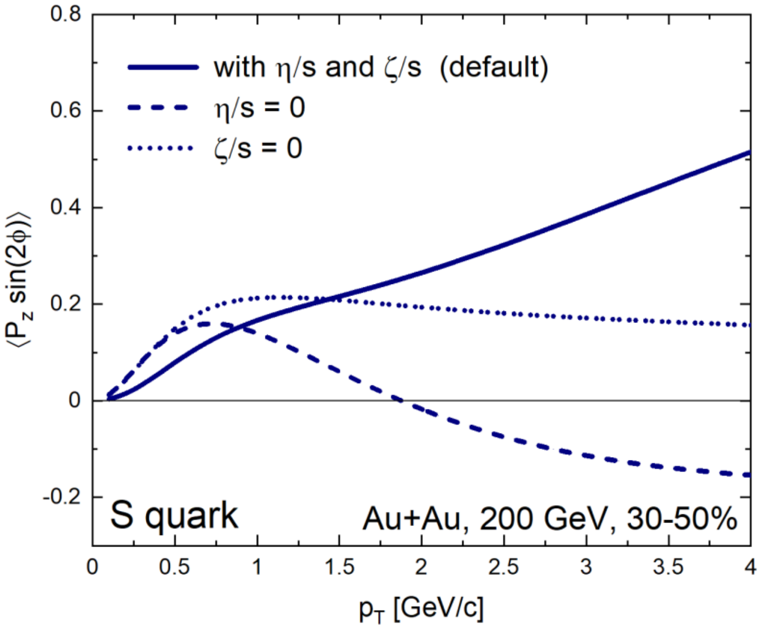


BF, L.-G. Pang, H. Song and Y. Yin, In preparation



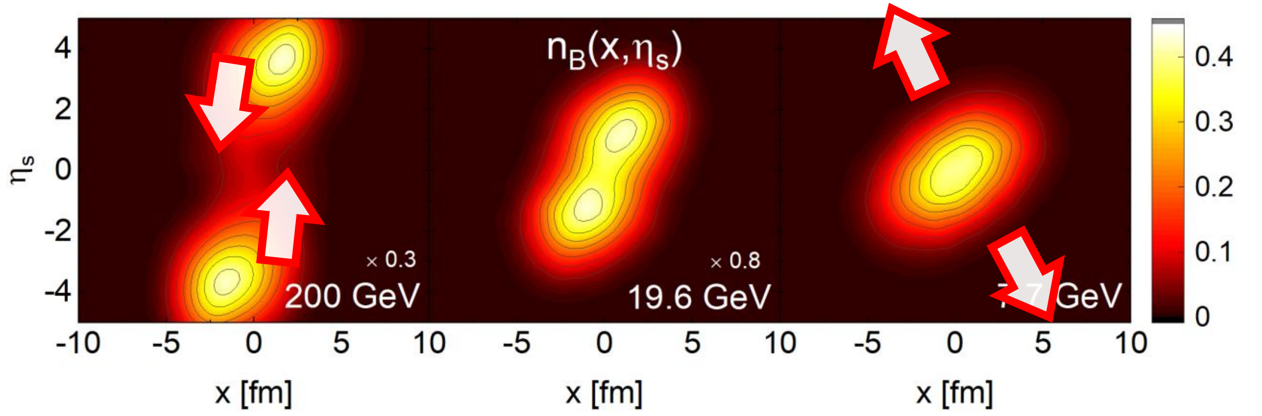


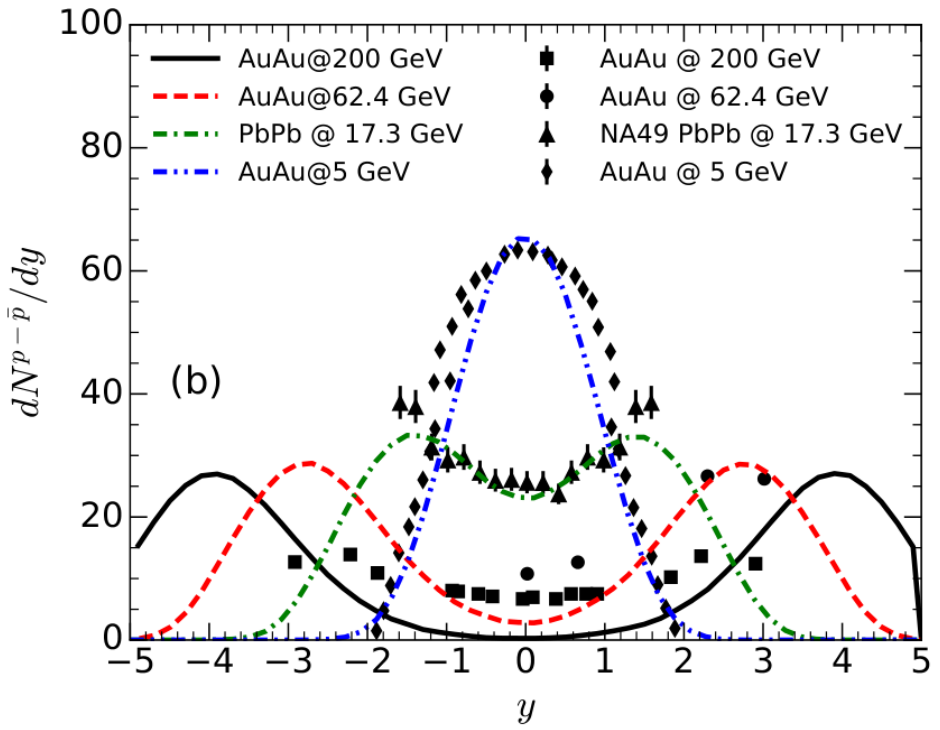
A. Palermo, et al., Eur.Phys.J.C 84 (2024) 9, 920

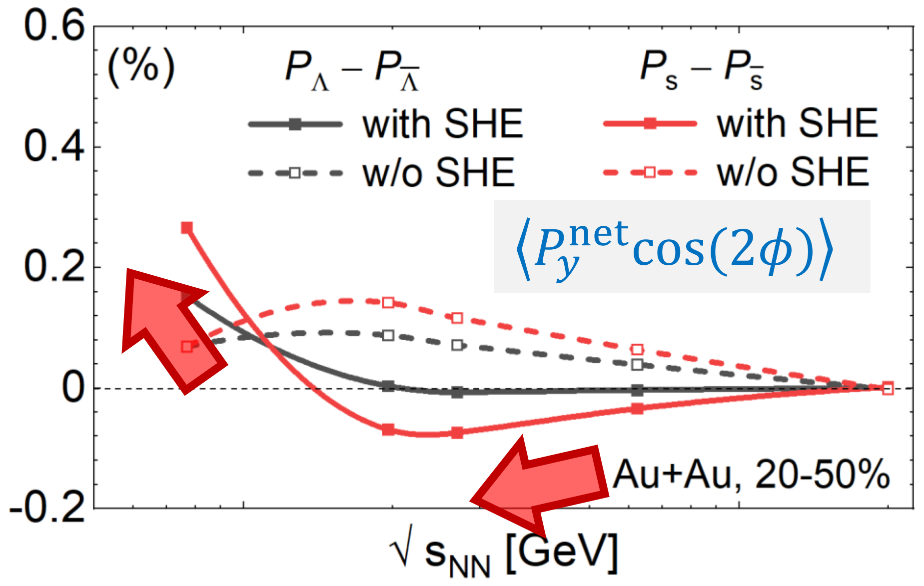


Probing the Initial Conditions

- Longitudinal baryon stopping
- AMPT IC: from "double peak" to "single peak"
- Non-monotonic energy dependence of $P_{y,SHE}$
- Probe and constrain initial condition models

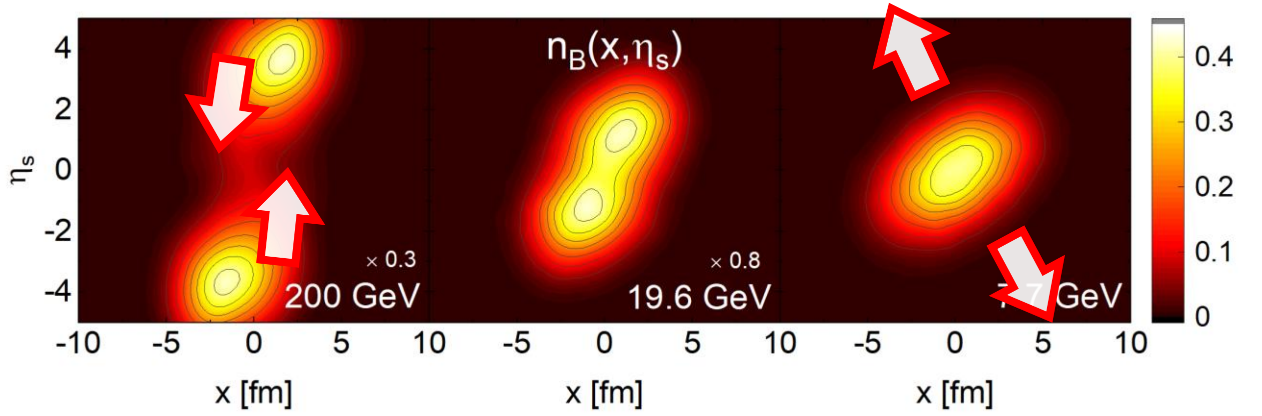




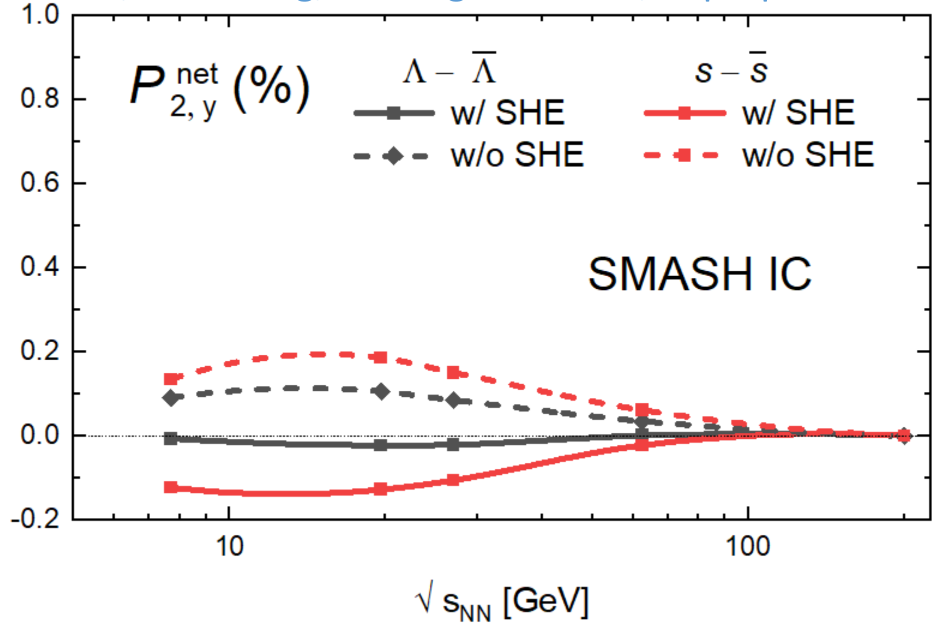


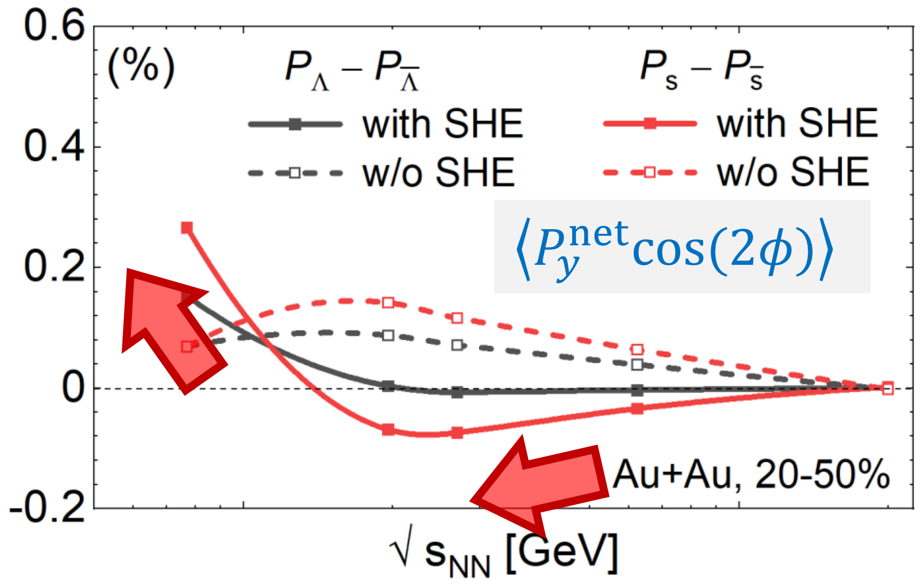
Probing the Initial Conditions

- Longitudinal baryon stopping
- AMPT IC: from “double peak” to “single peak”
- Non-monotonic energy dependence of $P_{y,SHE}$
- Probe and constrain initial condition models



BF, L.-G. Pang, H. Song and Y. Yin, In preparation





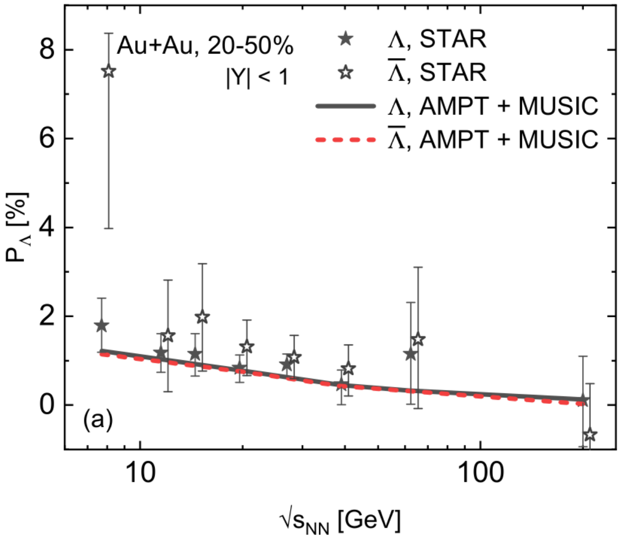
Summary

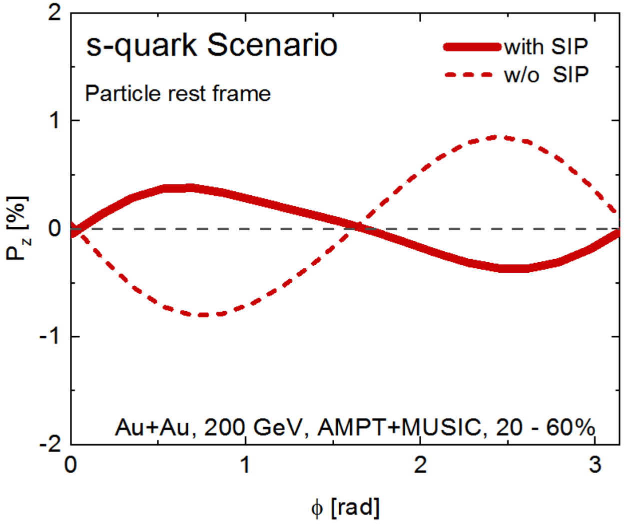
P^{μ} = [thermal vorticity] + [Shear] + [SHE]

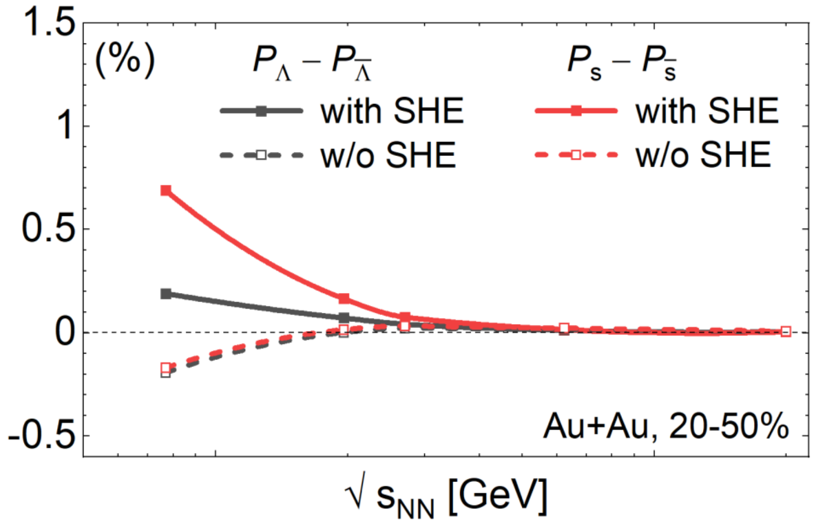
Global polarization

Essential for $P_z(\phi)$ puzzle

Spin generation by $\vec{\nabla}\mu_B$



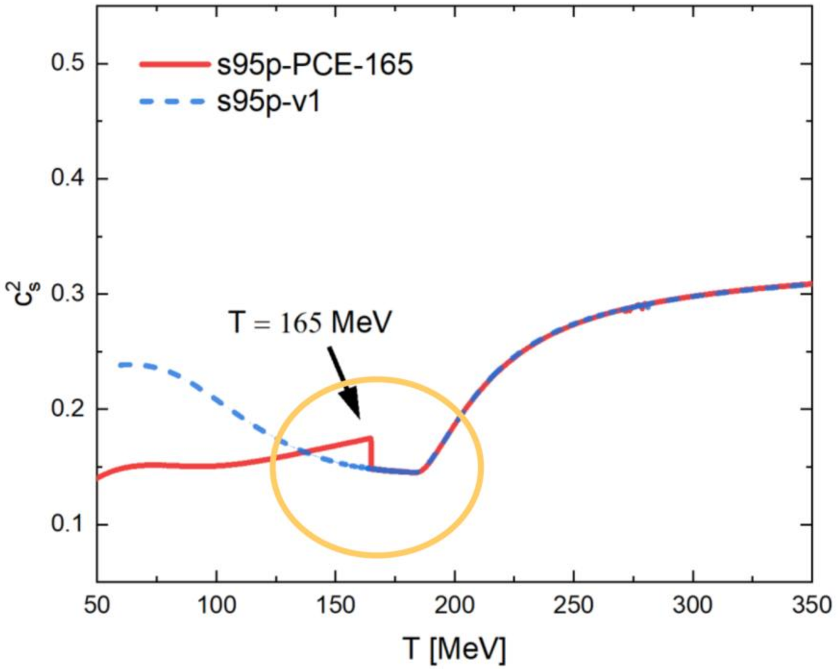


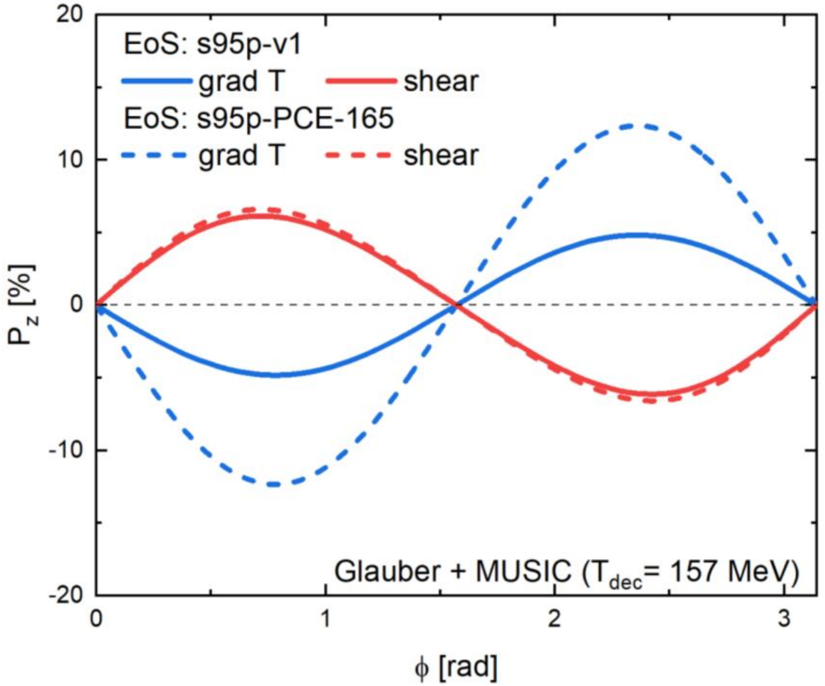


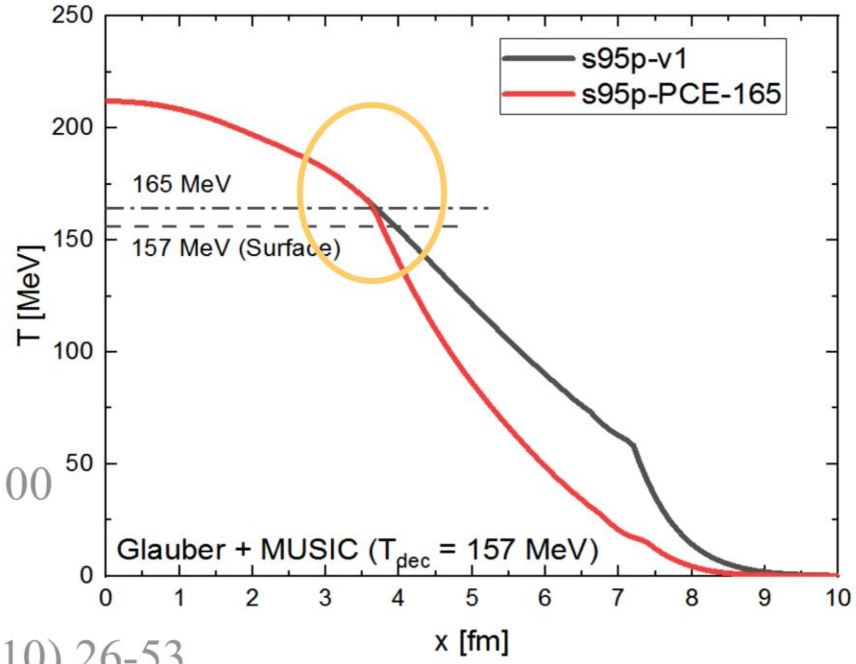
- Hydrodynamic model qualitatively / quantitatively describes local polarization (but still challenging!)
- Spin polarization as a powerful tool to probe EoS, transport coefficients, initial condition, …

Thanks!

Dependence on EoS







-Do not use EoS-s95p-PCE widely used in hydro calculations !

NEoS:

A. Monnai, B. Schenke, C. Shen, *Phys.Rev.C* 100

B. (2019) 2, 024907

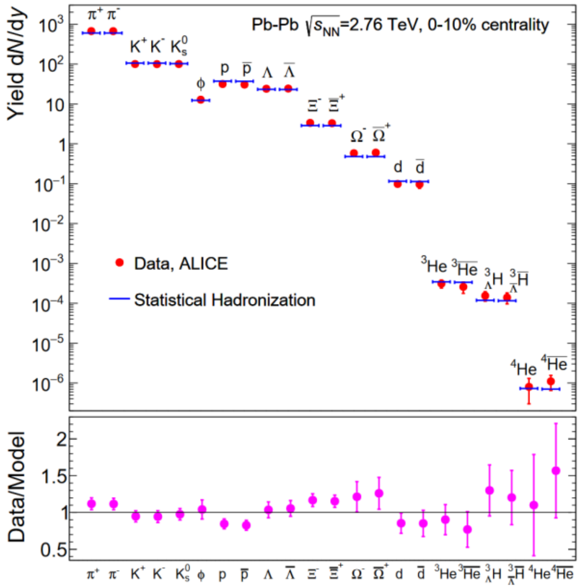
S95p-v1:

P. Huovinen, P. Petreczky, *Nucl.Phys.A* 837 (2010) 26-53

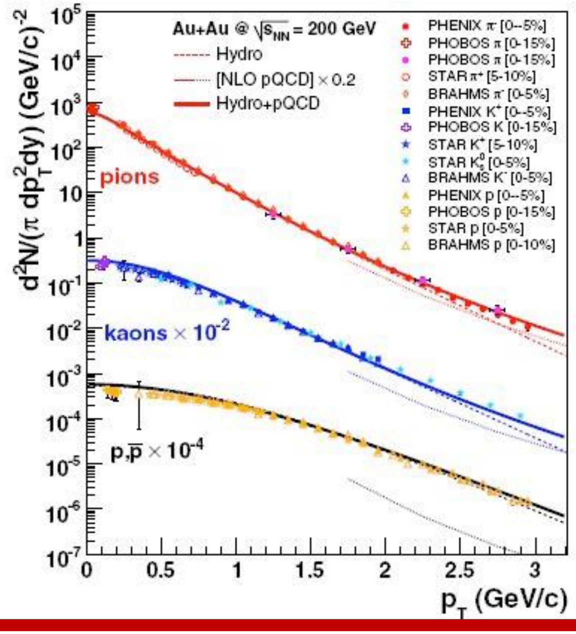
Explore QGP through soft probes ← spin polarization

Soft probes with finer details

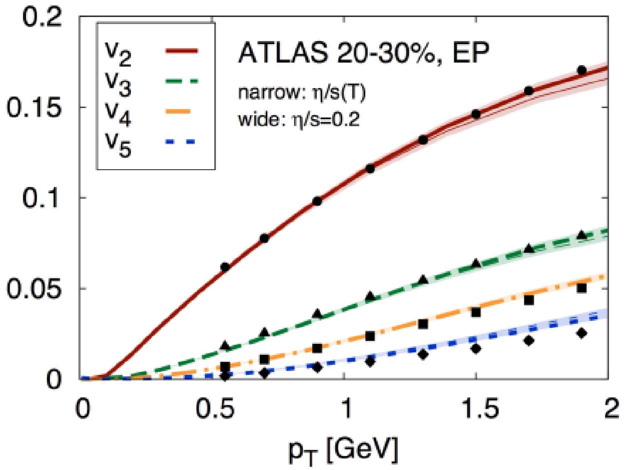
Particle Yields (T & μ_B)



p_T/y Spectra ($\langle u^\mu \rangle$)

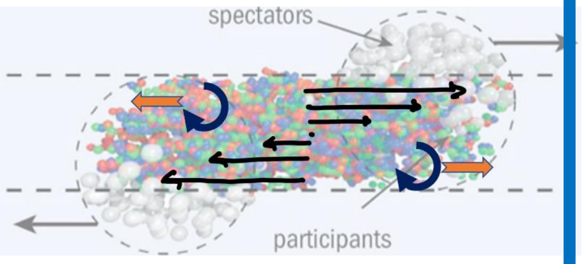


Anisotropic Flow ($u^\mu(x)$)

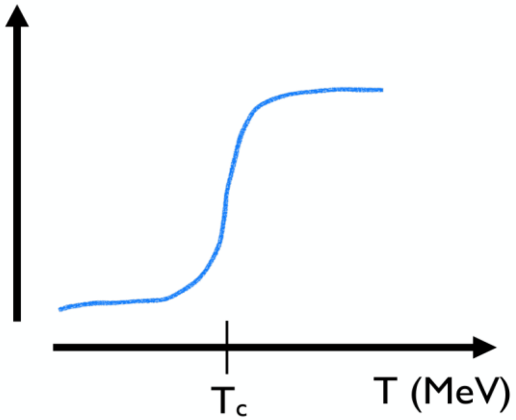


Spin Polarization

Gradients: $\partial_\nu u_\mu(x)$



$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \boldsymbol{v}$$



Sensitive probe of QCD phase transition

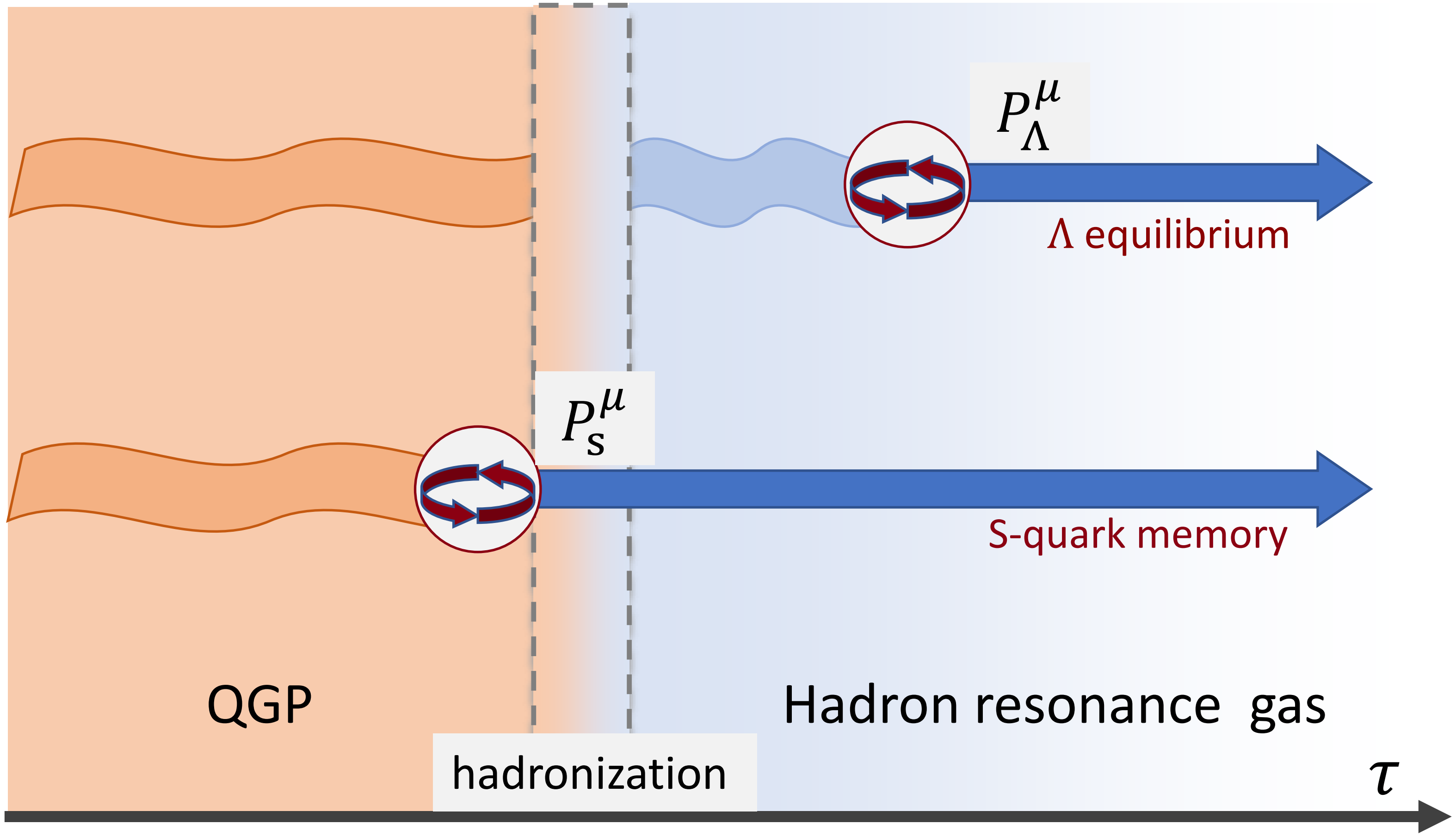
Exploring QGP through spin observables

Electronics (Flavortronics) Vs. **Spintronics**

Credit: M. Lisa, X. Huang

‘Λ equilibrium’ vs. ‘S-quark memory’

Spin Cooper-Frye: $$P^\mu(\boldsymbol{p}) = \frac{\int d\Sigma^\alpha p_\alpha \mathcal{A}^\mu(x,\boldsymbol{p};m)}{2m\int d\Sigma^\alpha p_\alpha n(\beta\varepsilon_0)}$$



Hydro evolution

BF, S. Liu, LG. Pang, H. Song, Y. Yin, Phys.Rev.Lett. 127 14, 142301(2021)

Two scenarios illustrate model uncertainties on spin relaxation time

‘Λ equilibrium’

$\tau_{\text{spin},\Lambda} \to 0$

Polarization of Λ-hyperon

$P^\mu_\Lambda(p)$

F. Becattini (2013)
and later hydrodynamic(transport) calculations

‘S-quark memory’

$\tau_{\text{spin},\Lambda} \to \infty$

Polarization of S-quark

$P^\mu_\Lambda(p) = P^\mu_s(p)$

Z.-T. Liang, X.-N. Wang, PRL 94 (2005) 102301