Shear-induced spin polarization and "strange memory" in heavy-ion collisions

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In collaboration: Baochi Fu, Longgang Pang, Huichao Song, Yi Yin

Strangeness in Quark Matter, Online, May 19, 2021

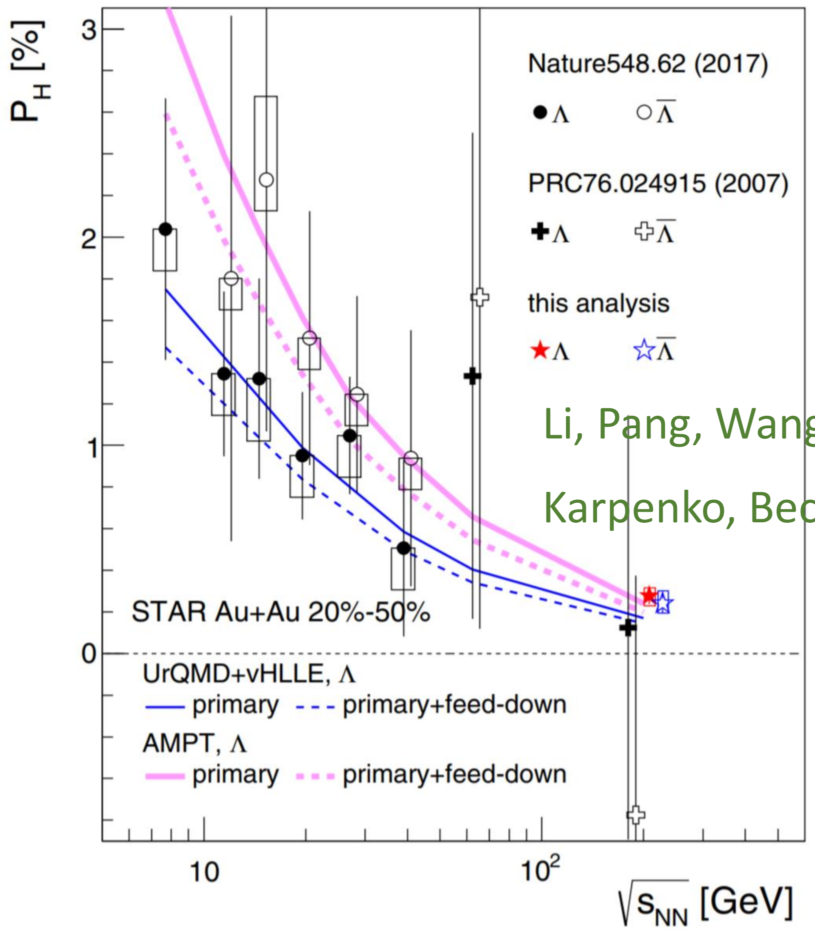
Based on work: Fu, Liu, Pang, Song, Yin arXiv:2103.10403; Liu, Yin, arXiv:2103.09200

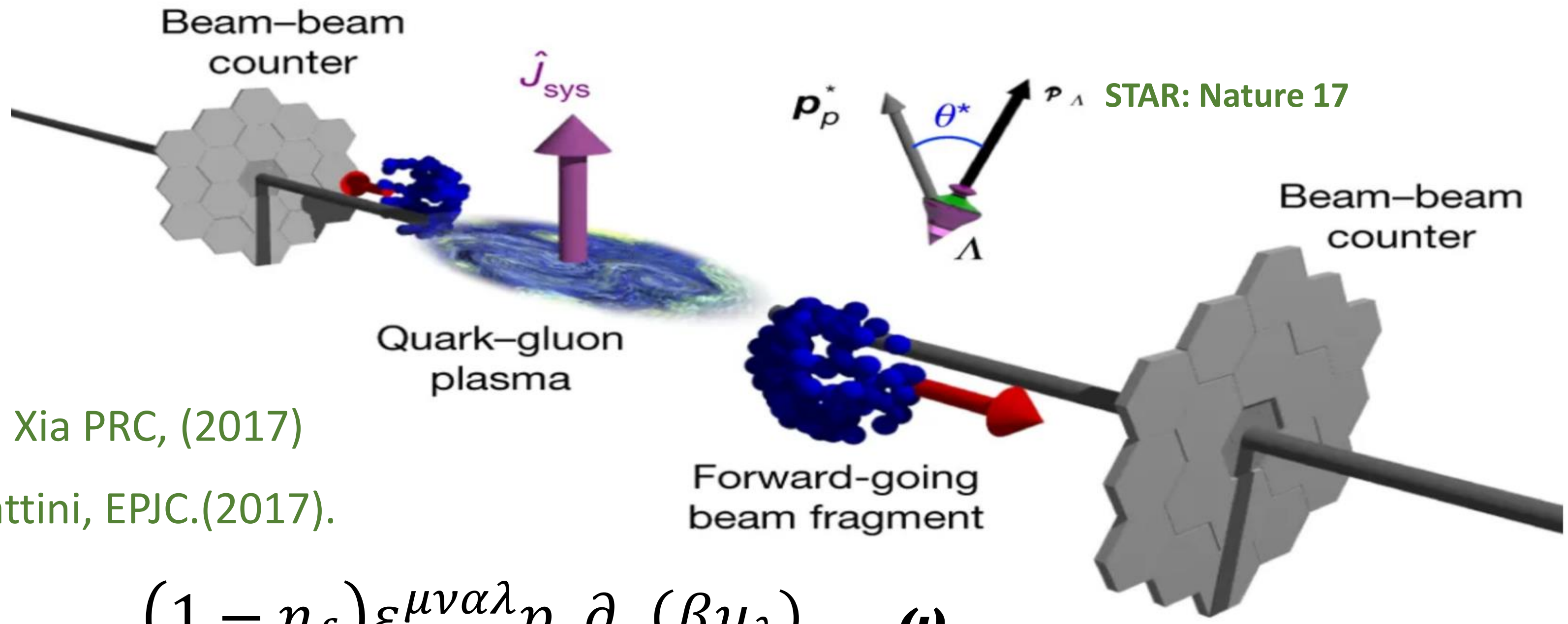
Outline

1) Background and motivation
2) Theoretical formalism
3) Phenomenology consequence
4) Conclusion and prospective

Vorticity Induced Polarization

STAR PRC 2018



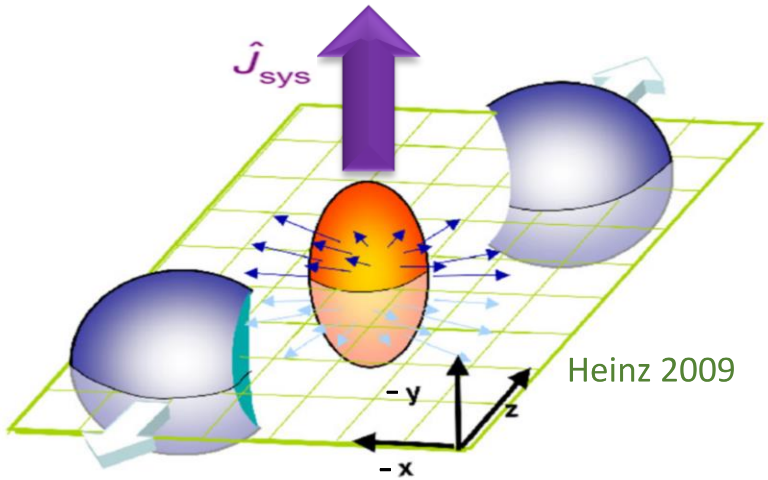


STAR: Nature 17

Li, Pang, Wang, Xia PRC, (2017)

Karpenko, Becattini, EPJC.(2017).

$$\boldsymbol{\mathcal{P}} = \frac{(1-n_f)\varepsilon^{\mu\nu\alpha\lambda}p_\nu\partial_\alpha(\beta u_\lambda)}{4m} \approx \frac{\boldsymbol{\omega}}{2T}$$



Heinz 2009

- ❖Rotation, vorticity, most vortical fluid
- ❖Vorticities can lead to polarization

T-gradient Induced Polarization

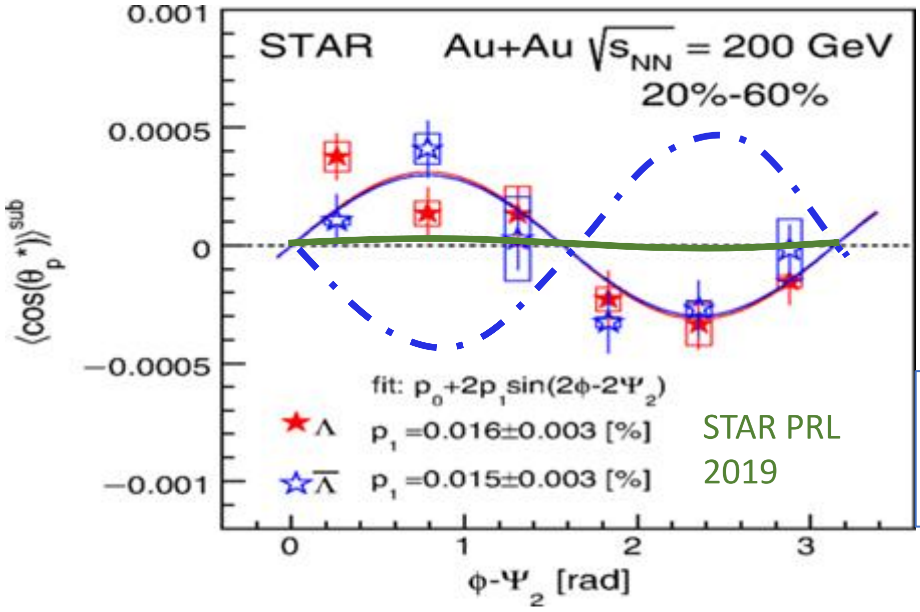
$$\mathcal{P} = \frac{(1-n_f)\epsilon^{\mu\nu\alpha\lambda}p_\nu\partial_\alpha(\beta u_\lambda)}{4m} \qquad \beta = 1/T$$

$$= \frac{(1-n_f)}{2m}\{\beta[-(p\cdot\omega)u^\mu + (p\cdot u)\omega^\mu] - \varepsilon^{\mu\lambda\nu\alpha}u_\lambda p_\nu \partial_\alpha \beta\}$$

Spin Nernst Effect

$$\mathcal{P}_z = \langle\cos(\theta)\rangle/[\alpha_H\langle\cos^2(\theta)\rangle]$$

Polarization along the beam direction



Sketches of theoretical curves

Voloshin, EPJ 2018
Becattini, Karpenko, PRL 2018

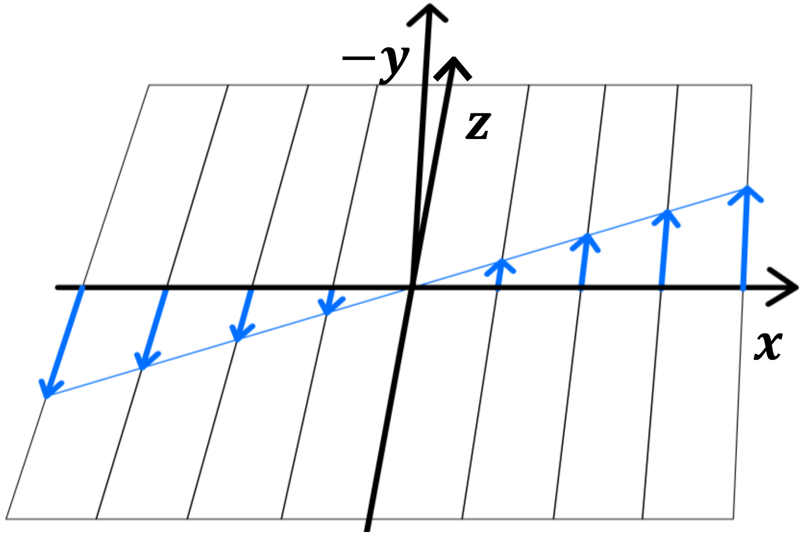
- ❖Local vorticity induced polarization , **neglectable** (using hydro)
- ❖T-gradient induced Polarization dominate, but **opposite sign**
- ❖"Spin puzzles"? What is missing?

Other Hydrodynamic Gradients

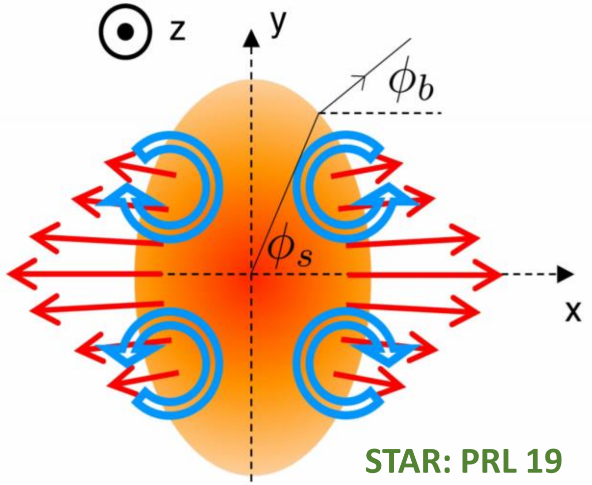
$$\sigma_{xz} = \frac{1}{2}(\partial_x u_z + \partial_z u_x) \sim \omega_y = \frac{1}{2}(\partial_z u_x - \partial_x u_z) \neq 0$$

- $\partial_\alpha \beta$, $\omega^\mu = \frac{1}{2}\varepsilon^{\mu\nu\alpha\lambda} u_\nu \partial_\alpha^\perp u_\lambda$, ?
- General flow gradients

$$\partial_\mu^\perp u_\nu = \underbrace{\frac{1}{2}\left(\partial_\mu^\perp u_\nu - \partial_\nu^\perp u_\mu\right)}_{\text{Vorticity}} + \underbrace{\frac{1}{2}\left(\partial_\mu^\perp u_\nu + \partial_\nu^\perp u_\mu\right)}_{\text{Shear } \sigma_{\mu\nu}}$$



- Both the vorticity and shear are sizable in heavy-ion collisions



- Could shear induce polarization?

Spin Induced by Hydrodynamic Gradients

- Chiral kinetic theory in local equilibrium $n(\beta(\varepsilon_0 - \Delta\varepsilon_\lambda))$

Chen, Son, Stephanov PRL 2015

$$\mathcal{A}^\mu = \sum_\lambda \left(\lambda p^\mu f_\lambda + \frac{1}{2} \frac{\epsilon^{\mu\nu\alpha\rho} p_\nu u_\alpha \partial_\rho f_\lambda}{p \cdot u} \right)$$

Closely related to polarization

$$\varepsilon_0 = p \cdot u$$
$$\Delta\varepsilon_\lambda = -(1/2)\lambda\omega \cdot p/\varepsilon_0$$
$$\Delta^{\mu\nu} = \eta^{\mu\nu} - u^\mu u^\nu$$
$$V_\perp^\mu = \Delta^{\mu\nu} V_\nu$$
$$\omega^\mu = (1/2)\epsilon^{\mu\nu\alpha\lambda} u_\nu \partial_\alpha^\perp u_\lambda$$
$$Q^{\mu\nu} = -p_\perp^\mu p_\perp^\nu / p_\perp^2 + \Delta^{\mu\nu}/3,$$
$$\sigma^{\mu\nu} = \partial_\perp^{(\mu} u^{\nu)} - \Delta^{\mu\nu} \partial_\perp \cdot u/3$$

- Gradient expansion at leading order

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

Fu, Liu, Pang, Song, Yin arXiv:2103.10403

- Vorticity + *T*-Gradient + Shear induced polarization

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$$\boxed{\epsilon^{\mu\nu\alpha\lambda} p_\nu \partial_\alpha (\beta u)_\lambda}$$

$$\varepsilon_0 = p \cdot u$$

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Fu, Liu, Pang, Song, Yin arXiv:2103.10403

❖Vorticity + *T*-Gradient + Shear induced polarization

New discovery

Spin Induced by Hydrodynamic Gradients

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Fu, Liu, Pang, Song, Yin arXiv:2103.10403

❖Vorticity + T-Gradient + Shear induced polarization

Identical results can be obtained based on QFT at arbitrary mass using linear response

Liu, Yin, arXiv:2103.09200

$$\mathcal{A}^\mu = \langle J_5^\mu(t,\boldsymbol{x},\boldsymbol{p})\rangle = \langle \varepsilon_p \int d^3\boldsymbol{y}\ \bar{\psi}\left(t, \boldsymbol{x}-\frac{\boldsymbol{y}}{2}\right)\gamma^\mu\gamma^5\psi\left(t,\boldsymbol{x}+\frac{\boldsymbol{y}}{2}\right)e^{-ip\boldsymbol{y}}\rangle$$

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Same result (set $\hat{t}_\nu = u_\nu$) obtained latter independently by Becattini, Buzzegoli, Palermo, arXiv: 2103.10917

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$$\begin{aligned}
\varepsilon_0 &= p \cdot u \\
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\end{aligned}$$

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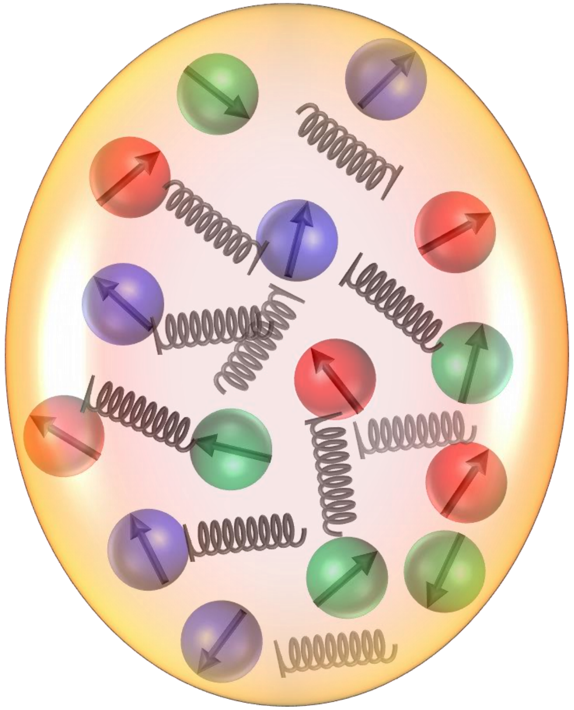
- Vorticity + *T*-Gradient + Shear induced polarization

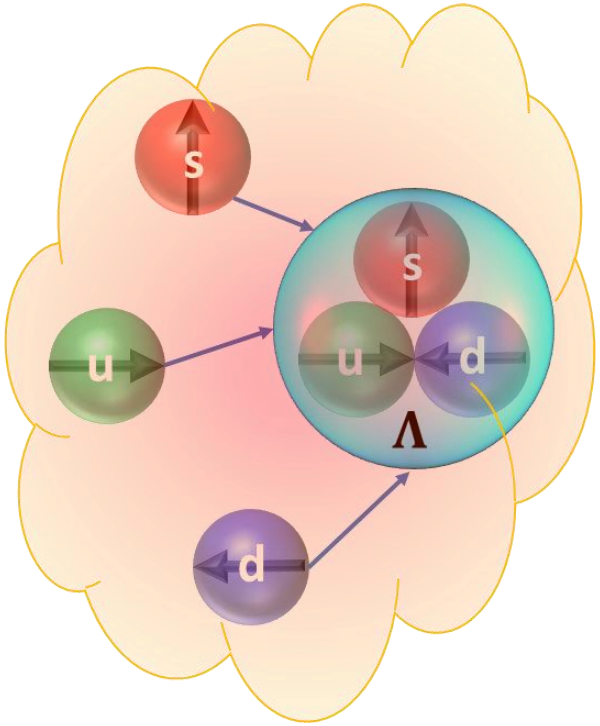
- Freezeout for the polarization

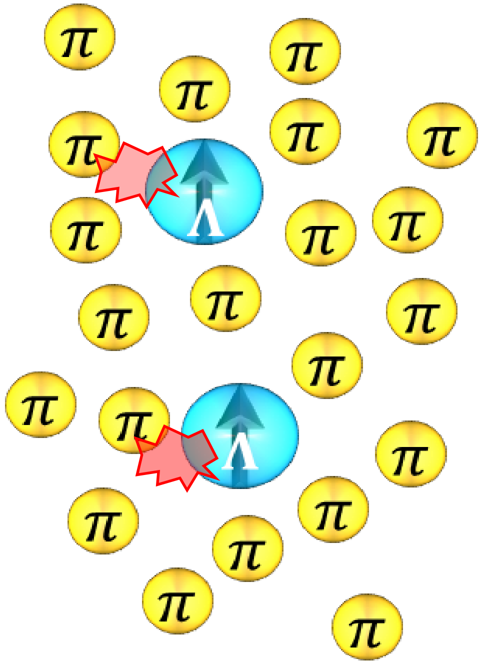
$$P^\mu(\boldsymbol{p}) = \frac{\int d\Sigma^\alpha p_\alpha \mathcal{A}^\mu(x, \boldsymbol{p}; m)}{2m \int d\Sigma^\alpha p_\alpha n(\beta\varepsilon_0)}$$

Becattini, Chandra, Zanna, Grossi, *Annals Phys* (2013)

The Evolution of the Spin in Heavy-ion Collisions

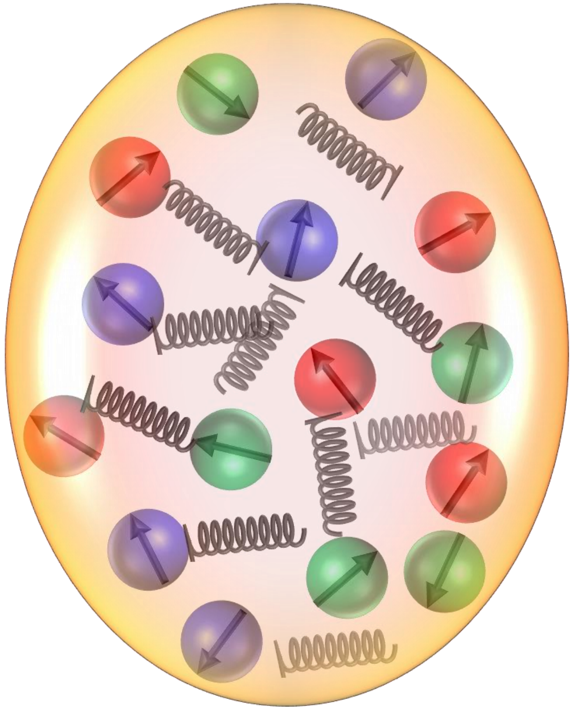


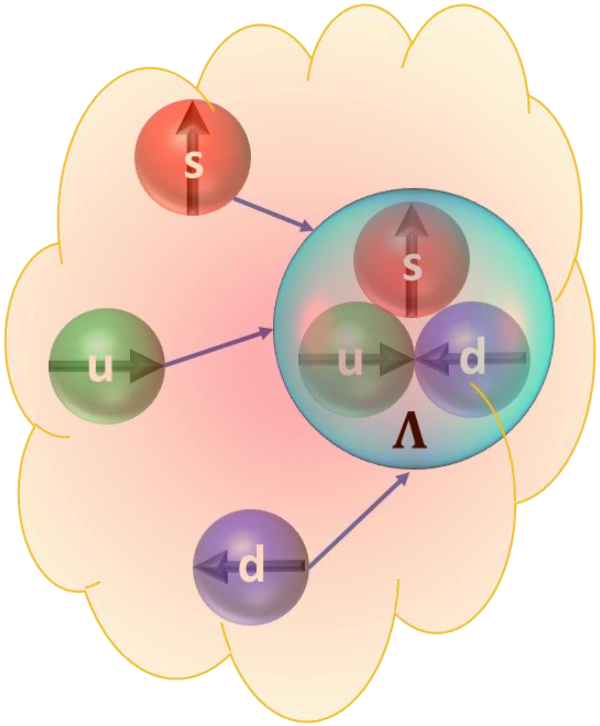


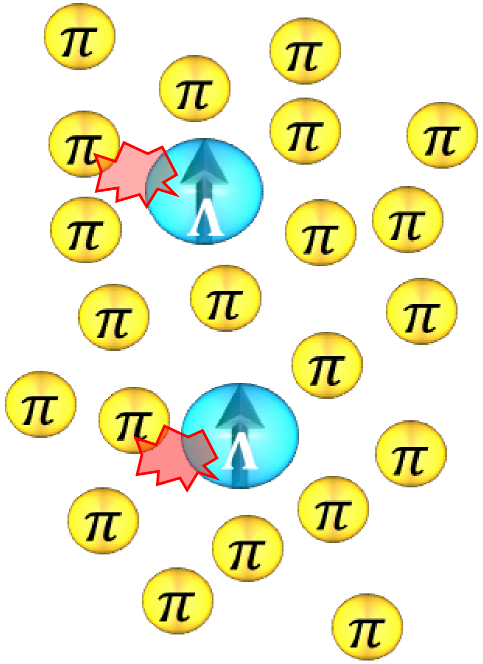


- ❖Spin in hydrodynamic QGP medium
- ❖Hadronization with spin
- ❖Hadronic evolution of the spin

The Evolution of the Spin in Heavy-ion Collisions







- ❖Spin in hydrodynamic QGP medium
- ❖Hadronization with spin
- ❖Hadronic evolution of the spin

Hard problem in general!
Continue with well motivated assumptions
Study two limiting scenarios

Two Scenarios: for Hadronization & Hadronic Evolution

- **Lambda equilibrium scenario:**
  - Assuming P_Λ is in full equilibrium, which is commonly assumed (statistical hadronization)

$$P^\mu(\boldsymbol{p}) = \frac{\int d\Sigma^\alpha p_\alpha \, \mathcal{A}^\mu(x, \boldsymbol{p}; m_\Lambda)}{2m_\Lambda \int d\Sigma^\alpha p_\alpha n(\beta\varepsilon_0)} .$$

- **Strange memory scenario:** ($P_\Lambda \approx P_s$, Λ spin has full memory of s quark spin)
  - Assuming $P_\Lambda \approx P_s$ at the hadronization since ud form a spin singlet (quark recombination)
  - Assuming P_Λ does not evolve significantly in hadronic phase

Liang, Wang, PRL 2004

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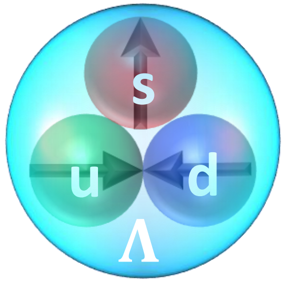
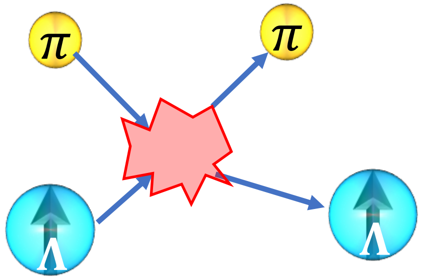
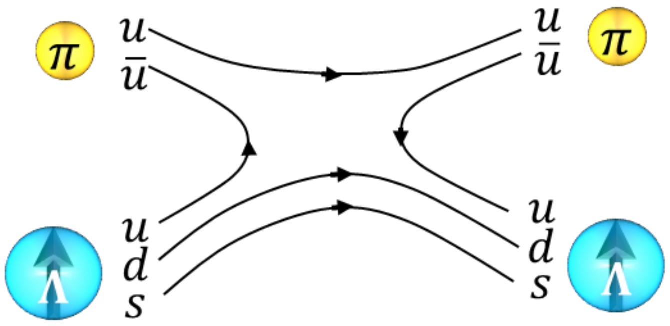


$$(\uparrow_u \downarrow_d - \downarrow_u \uparrow_d) \uparrow_s$$





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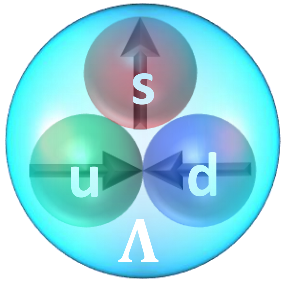
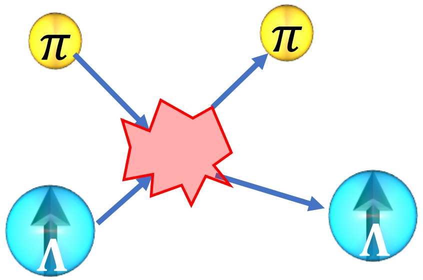
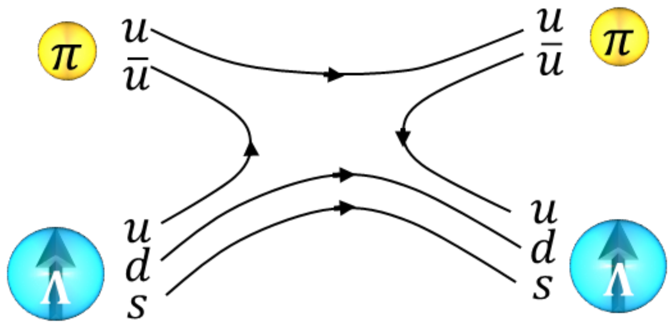


$$(\uparrow_u \downarrow_d - \downarrow_u \uparrow_d)\ \uparrow_s$$





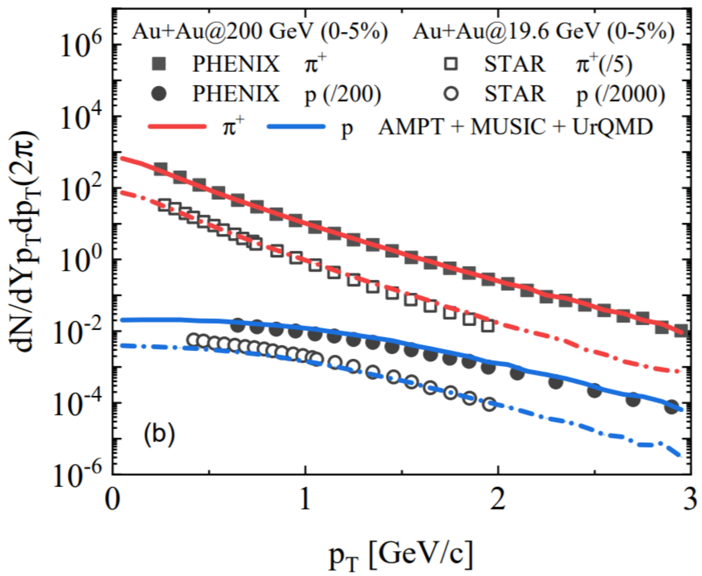
Hydrodynamic Framework

- ❖AMPT initial condition + MUSIC+ UrQMD
- ❖Tuned to reproduce the soft hardon observables

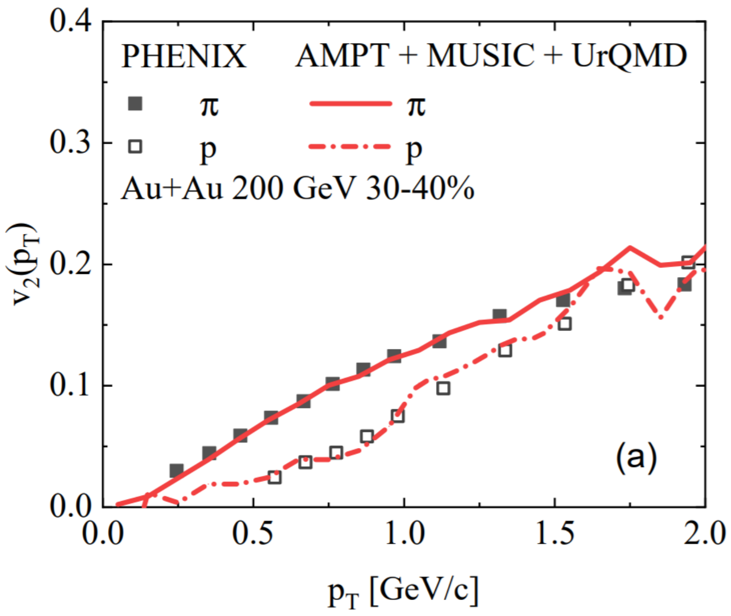
Fu, Xu ,Huang, Song, PRC 2021

Only used in calibration with soft observables, not used in polarization

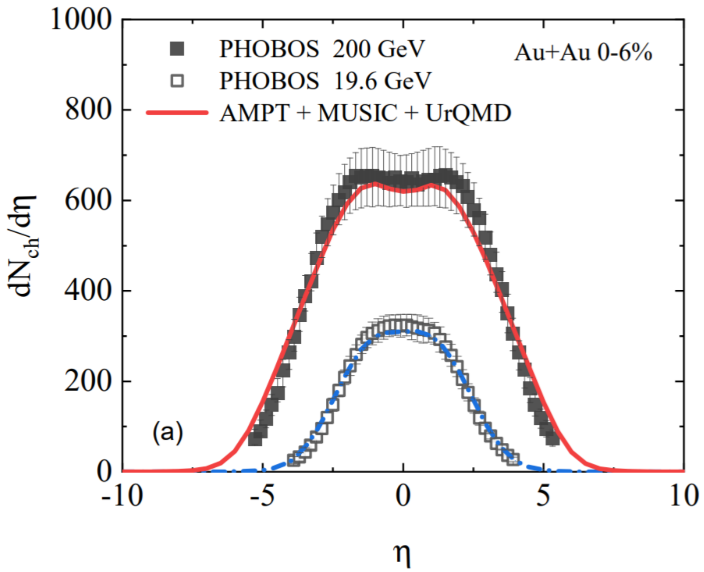
Transverse momentum spectra



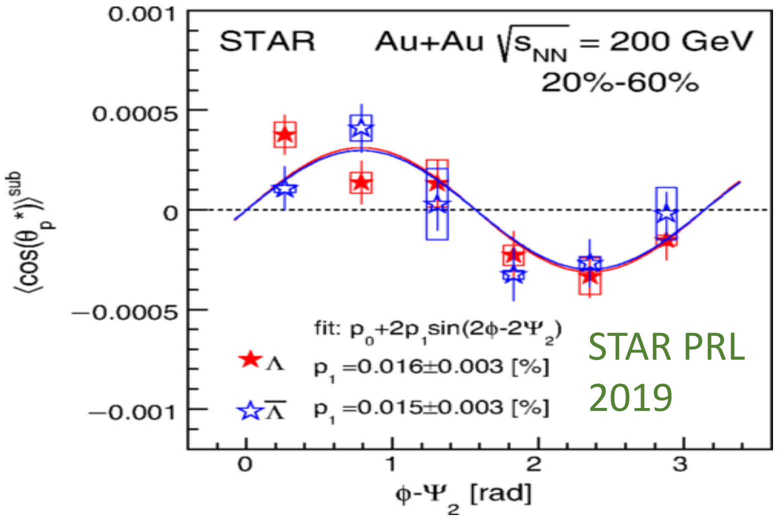
$v_2(p_T)$



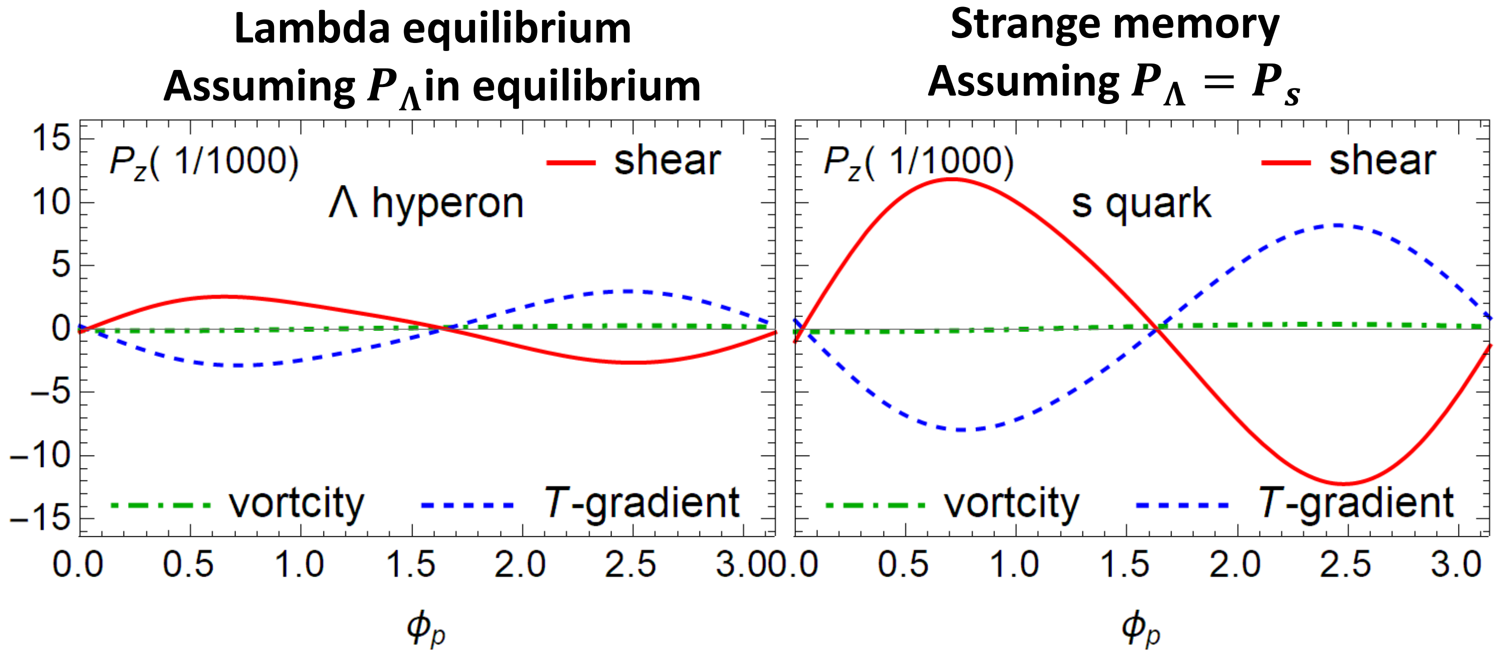
$dN/d\eta$



Results for the Local Spin Polarization at z Direction



STAR PRL 2019



- Vorticity + T-gradient + Shear:

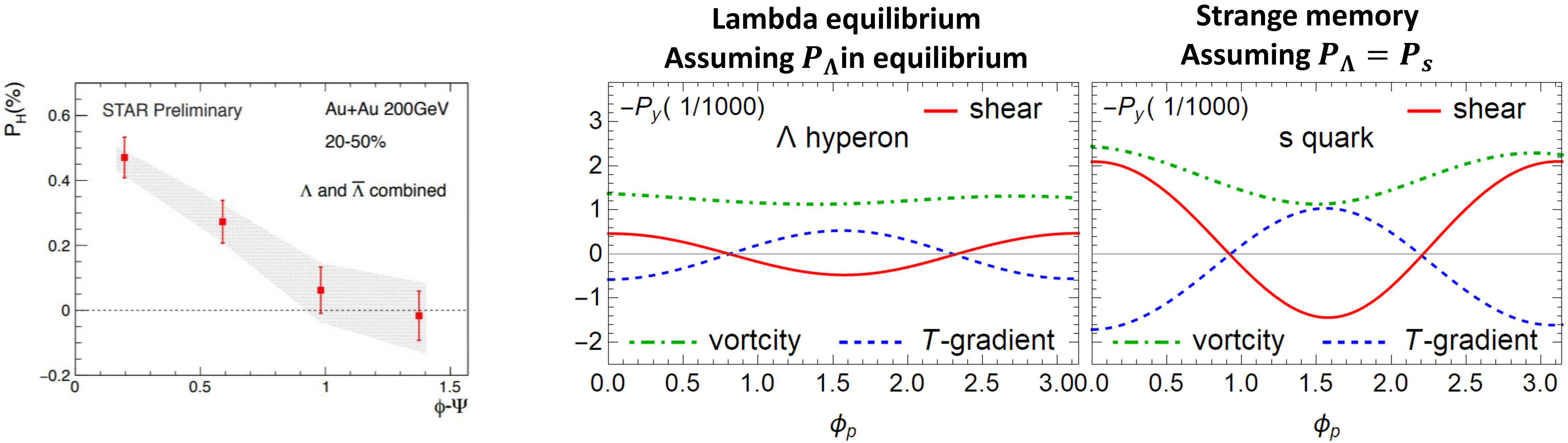
$$\mathcal{A}^\mu = \frac{1}{2}\beta n_0(1-n_0)\left\{\boxed{\epsilon^{\mu\nu\alpha\lambda}p_\nu\partial_\alpha^\perp u_\lambda} + \boxed{2\epsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha\left[\beta^{-1}(\partial_\lambda\beta)\right]} - \boxed{2\frac{p_\perp^2}{\varepsilon_0}\epsilon^{\mu\nu\alpha\rho}u_\nu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

- T-gradient has the "**opposite sign**" comparing to experiments
- Shear has the **"same sign"**
- Shear and T-gradient are competing

Details see our work:
Fu, Liu, Pang, Song, Yin arXiv:2103.10403

Similar results latter independently obtained by:
Becattini, Buzzegoli, Palermo, Inghirami, Karpenko, arXiv: 2103.14621

Results for the Local Spin Polarization at y Direction



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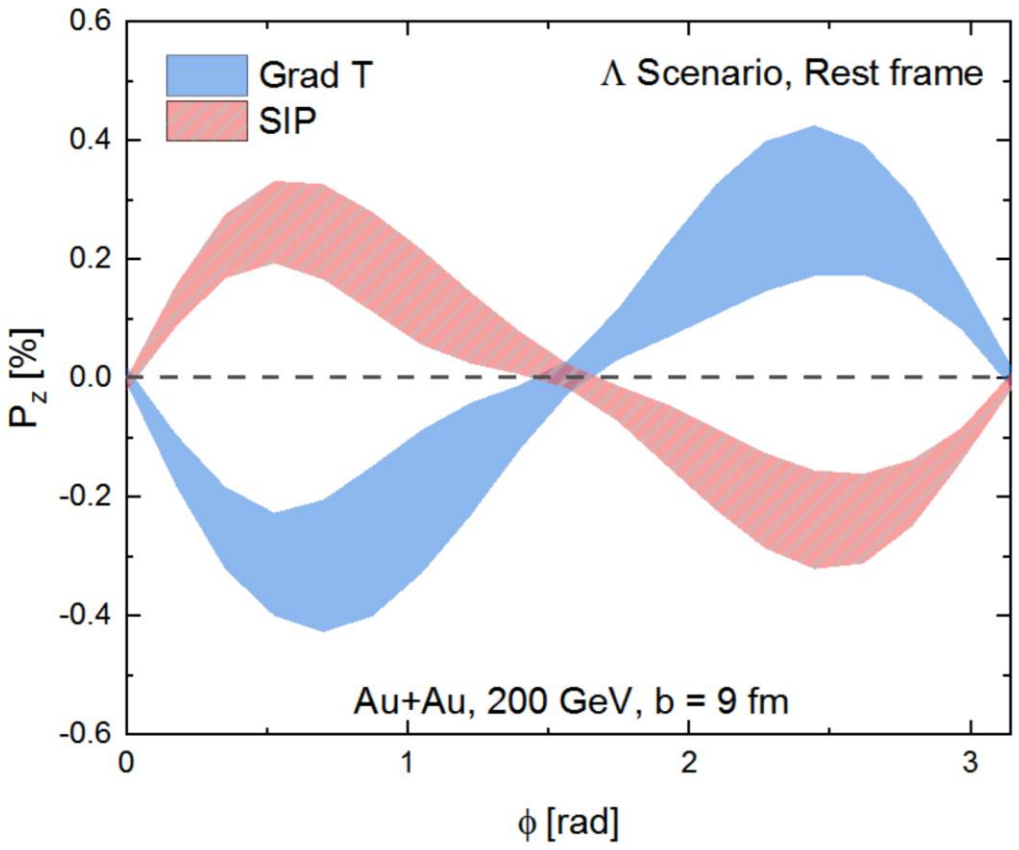
❖T-gradient has the "**opposite sign**" comparing to experiments

❖Shear has the "**same sign**"

❖Shear and T-gradient are competing

Robustness

- The tests performed
  - Initial flow: on → off
  - Initial condition: AMPT → Glauber
  - Shear viscosity: 0.08 → off
  - Bulk viscosity: ζ/s → off
  - Freeze-out temperature: 167 MeV → 157 MeV
- Remarks
  - Signs of SIP and Grad-T are robust
  - They are competing



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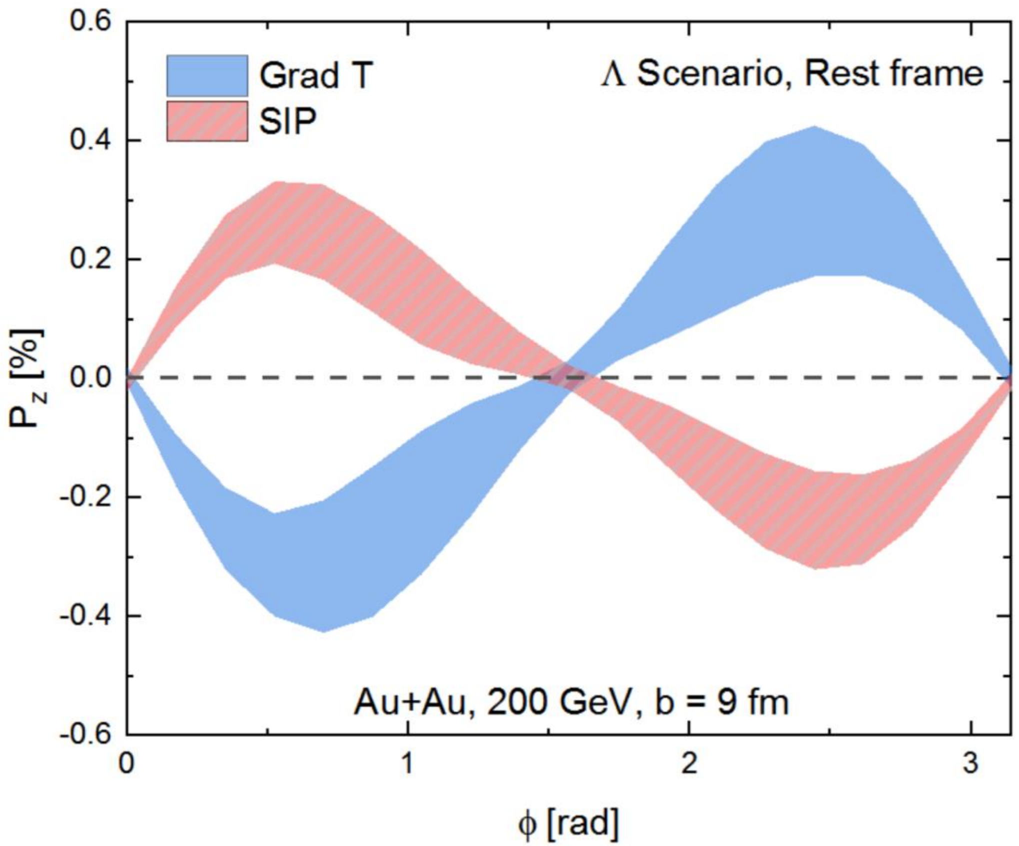
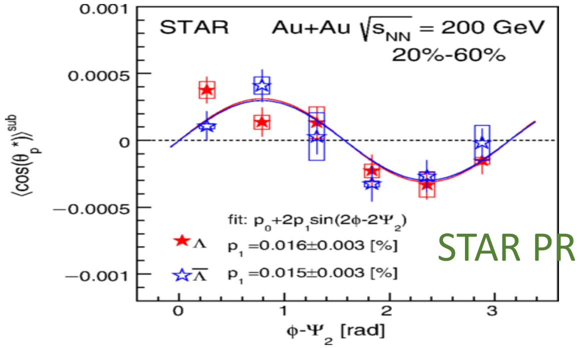
- Remarks
  - SIP always **same sign**
  - Grad-T always **opposite sign**
  - They are competing





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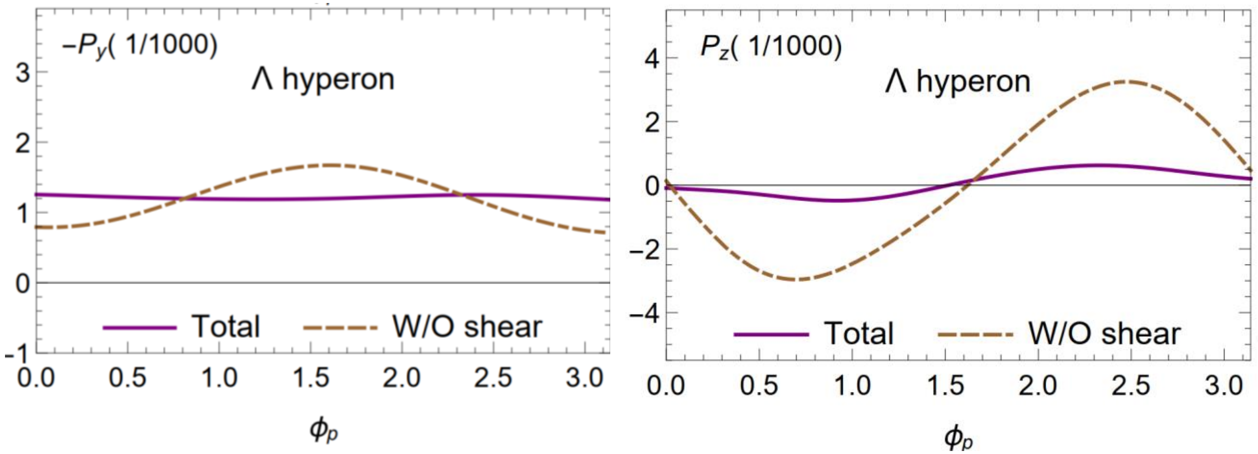
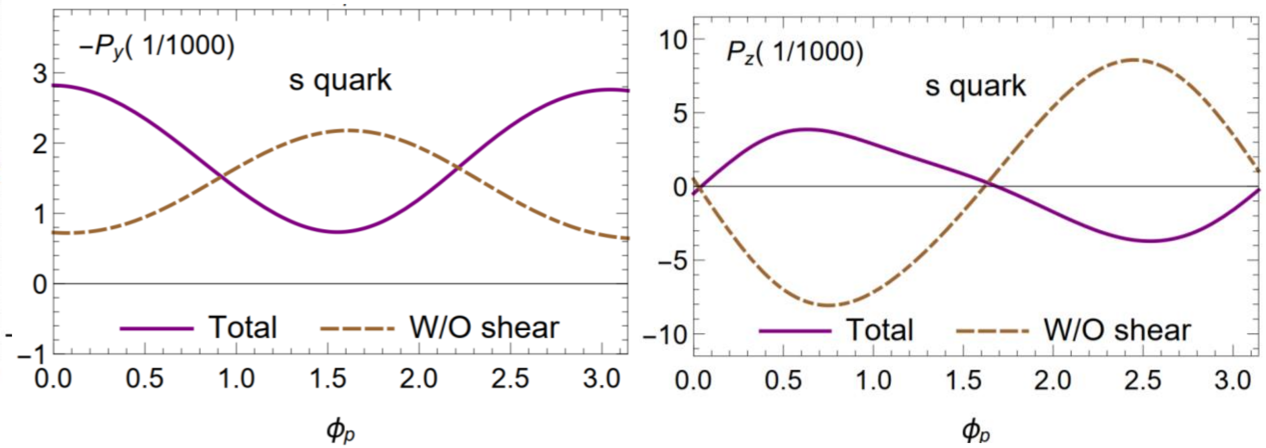
Total Polarization and Total Polarization W/O Shear

Lambda equilibrium, assuming P_Λ in equilibrium



Strange memory, assuming $P_\Lambda = P_s$



❖Thermal Vorticity + Thermal Shear:

$$\mathcal{A}^\mu = \boxed{\boxed{\frac{1}{2} n_0(1-n_0)\, \epsilon^{\mu\nu\alpha\lambda} p_\nu \partial_\alpha (\beta u)_\lambda} - n_0(1-n_0) \frac{1}{\varepsilon_0} \epsilon^{\mu\nu\alpha\rho} u_\nu\, p_\rho p^\lambda \partial_{(\alpha}(\beta u)_{\lambda)}}$$

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

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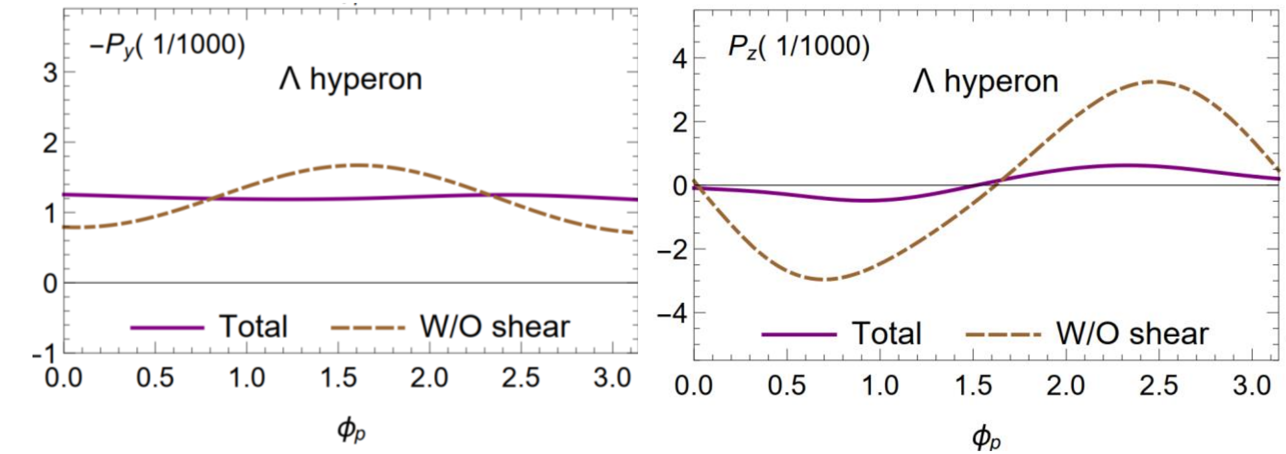

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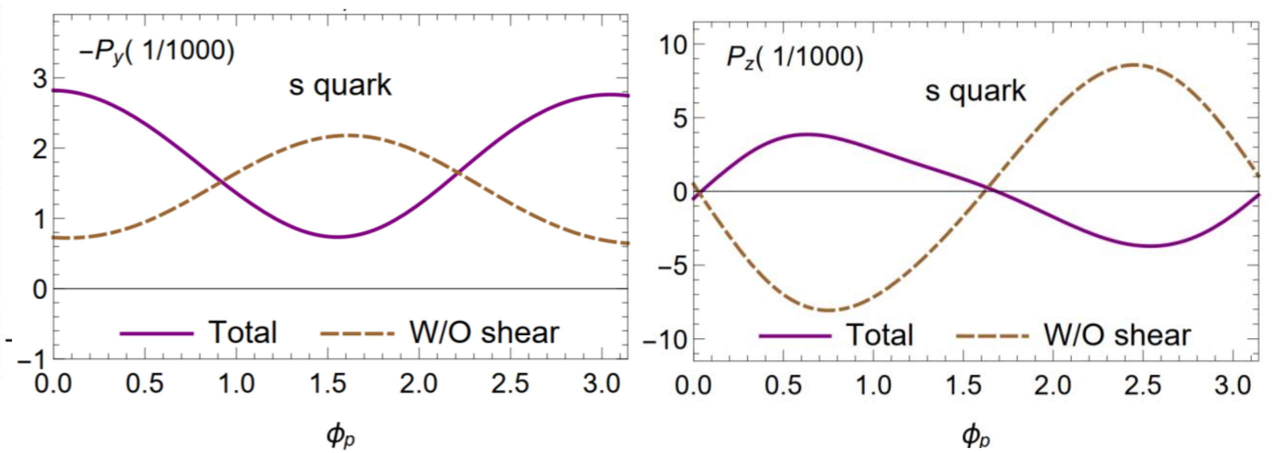
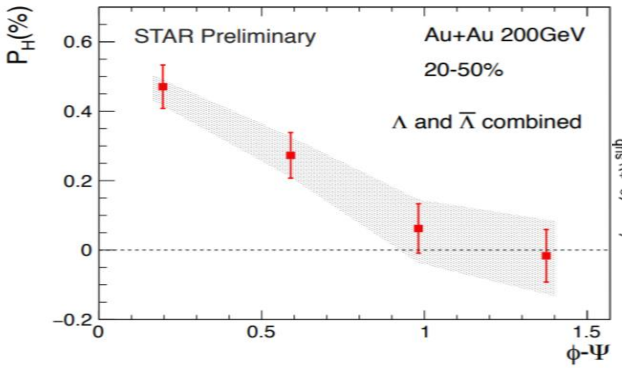
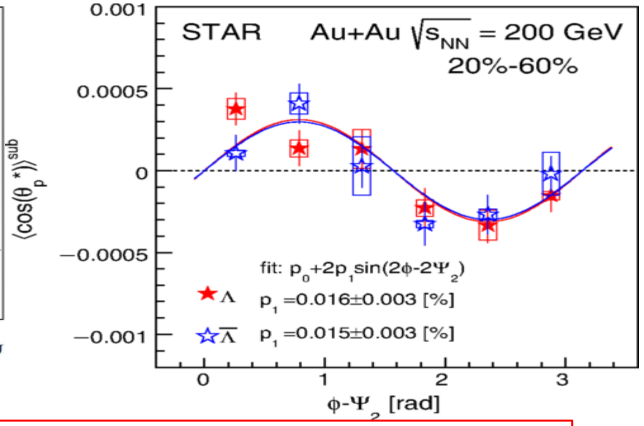




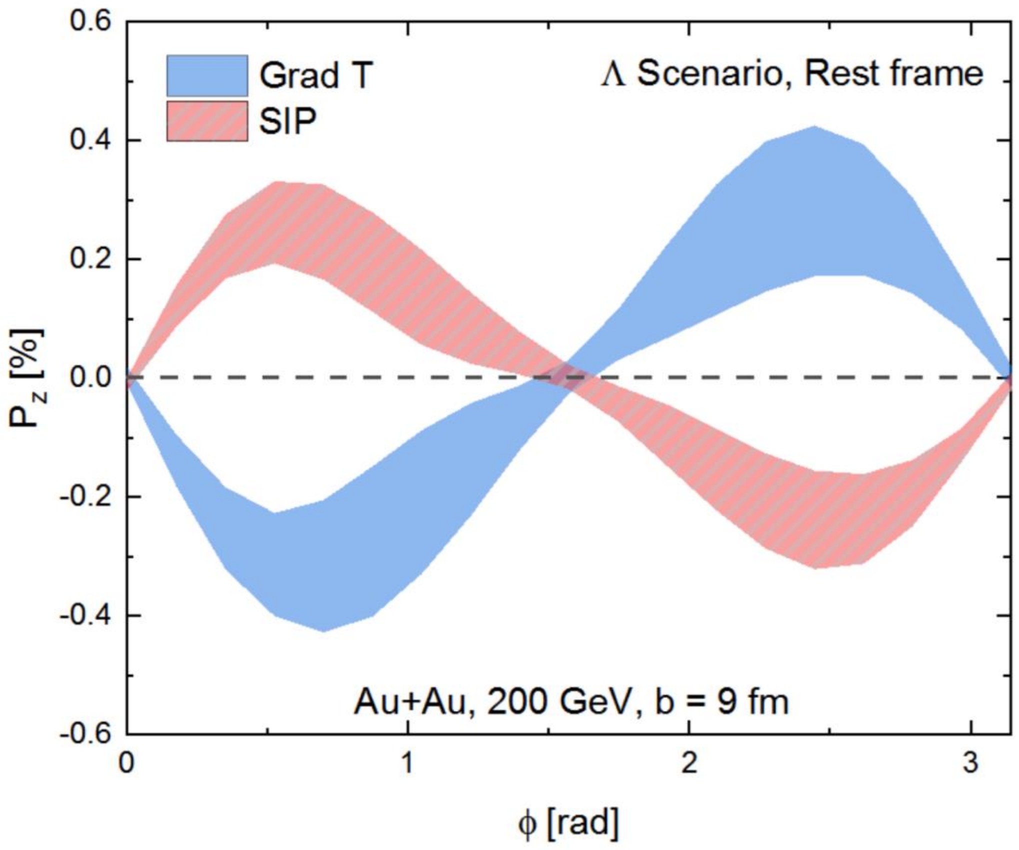


Lambda equilibrium is disfavored by experiment

Robustness

❖ The tests performed
- Initial flow: on → off
- Initial condition: AMPT → Glauber
- Shear viscosity: 0.08 → off
- Bulk viscosity: ζ/s → off
- Freeze-out temperature: 167 MeV → 157 MeV

❖ Remarks
- SIP always **same sign**
- Grad-T always **opposite sign**
- They are competing



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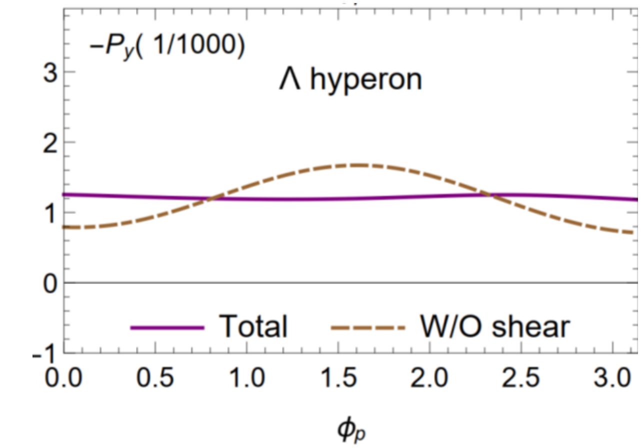

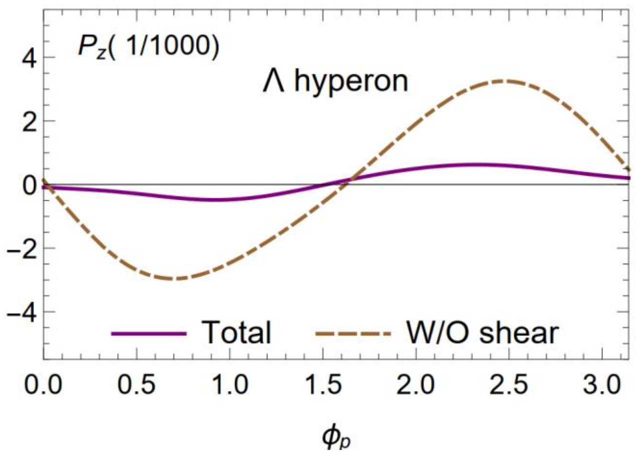

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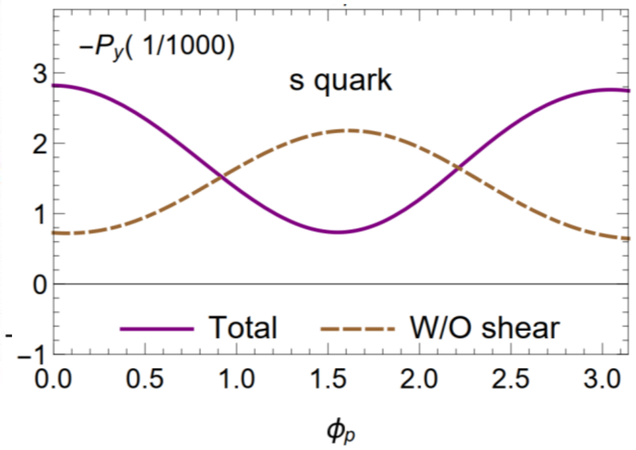

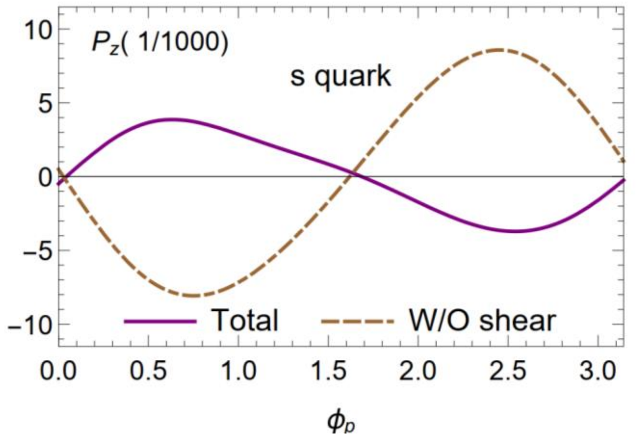

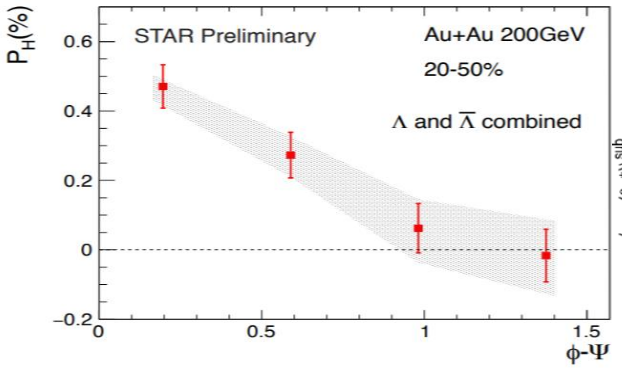

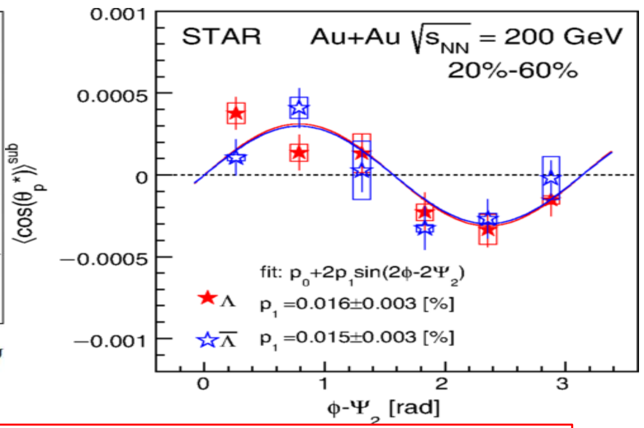

Even in robustness test, no case is found to qualitatively agree with data

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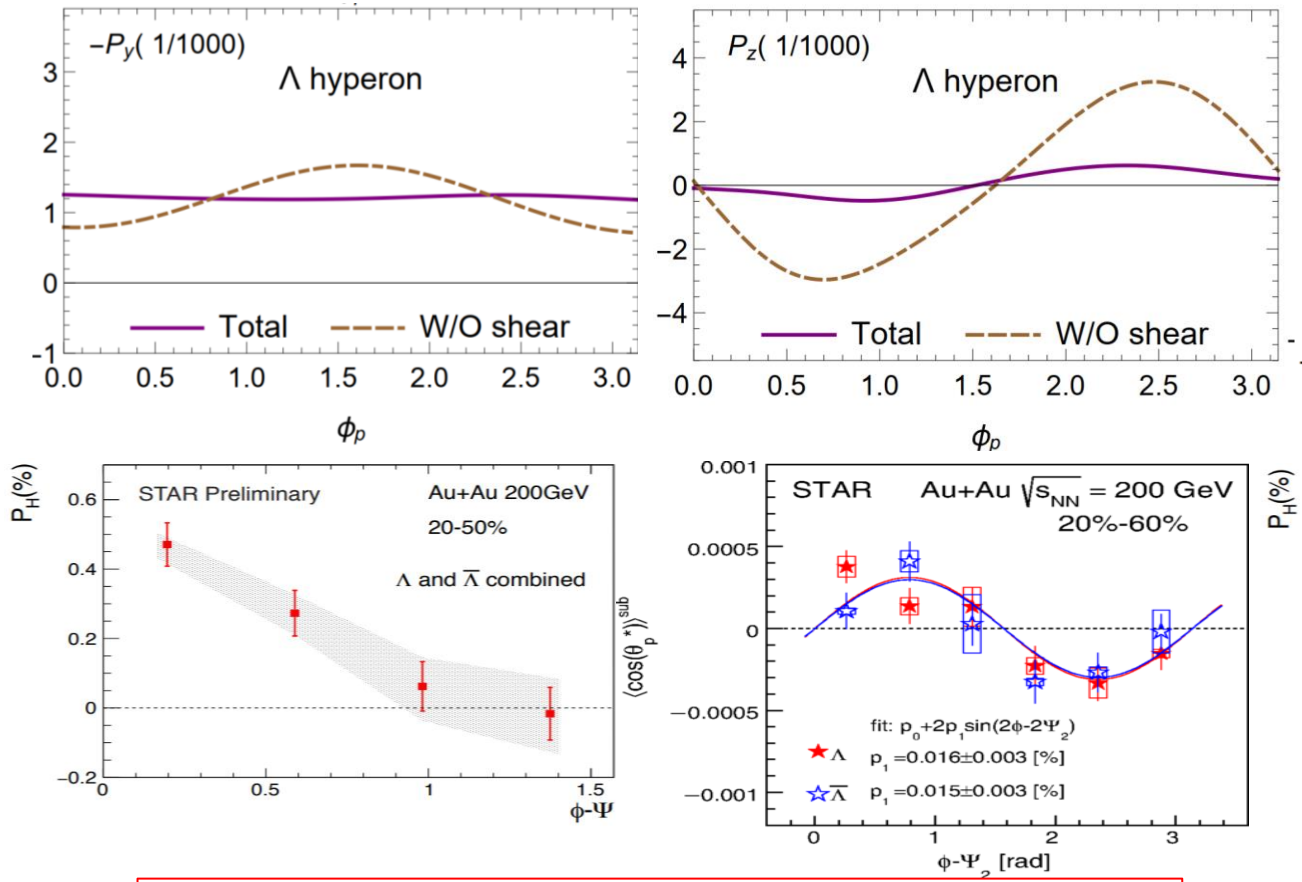
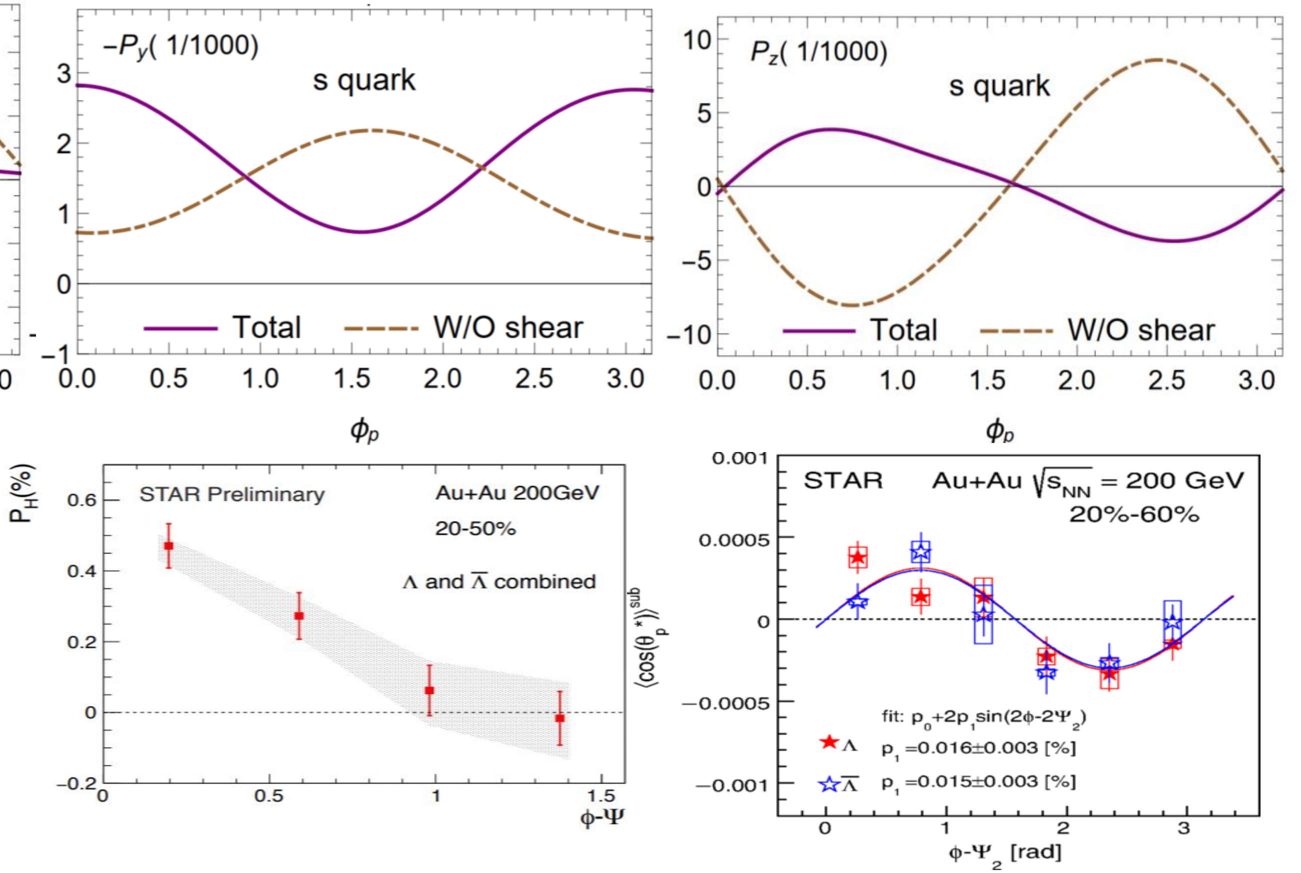


Lambda equilibrium is disfavored by experiment

Strange memory, assuming $P_\Lambda = P_s$



Strange memory is preferred by experiment

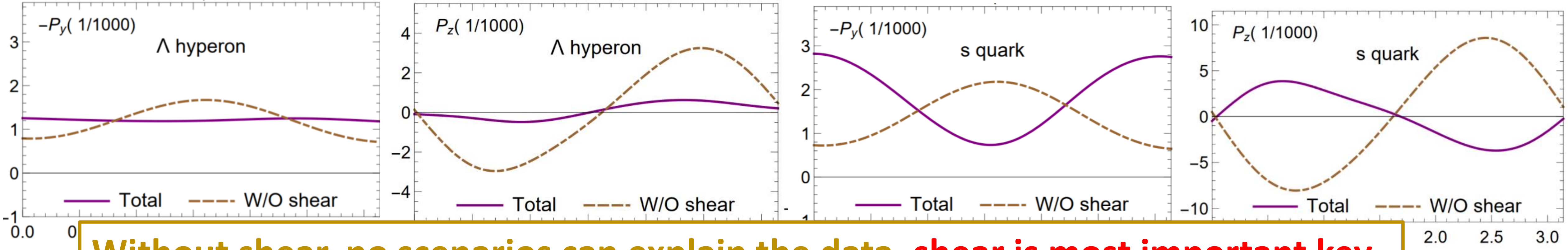
- ❖Go beyond conventional statistical hadronization in spin physics?
- ❖**Strange memory (quark recombination)**, modified statistical hadronization, … ?

Fu, Liu, Pang, Song, Yin arXiv:2103.10403

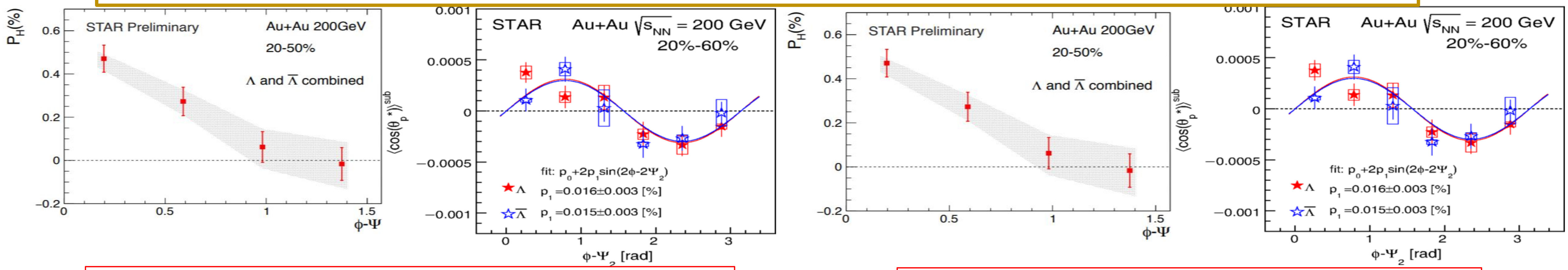
Becattini, Buzzegoli, Palermo, Inghirami, Karpenko, arXiv: 2103.14621

Total Polarization and Total Polarization W/O Shear

Lambda equilibrium, assuming P_Λ in equilibrium **Strange memory, assuming $P_\Lambda = P_s$**



Without shear, no scenarios can explain the data, shear is most important key



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Results: Competitions between SIP and Other Effects

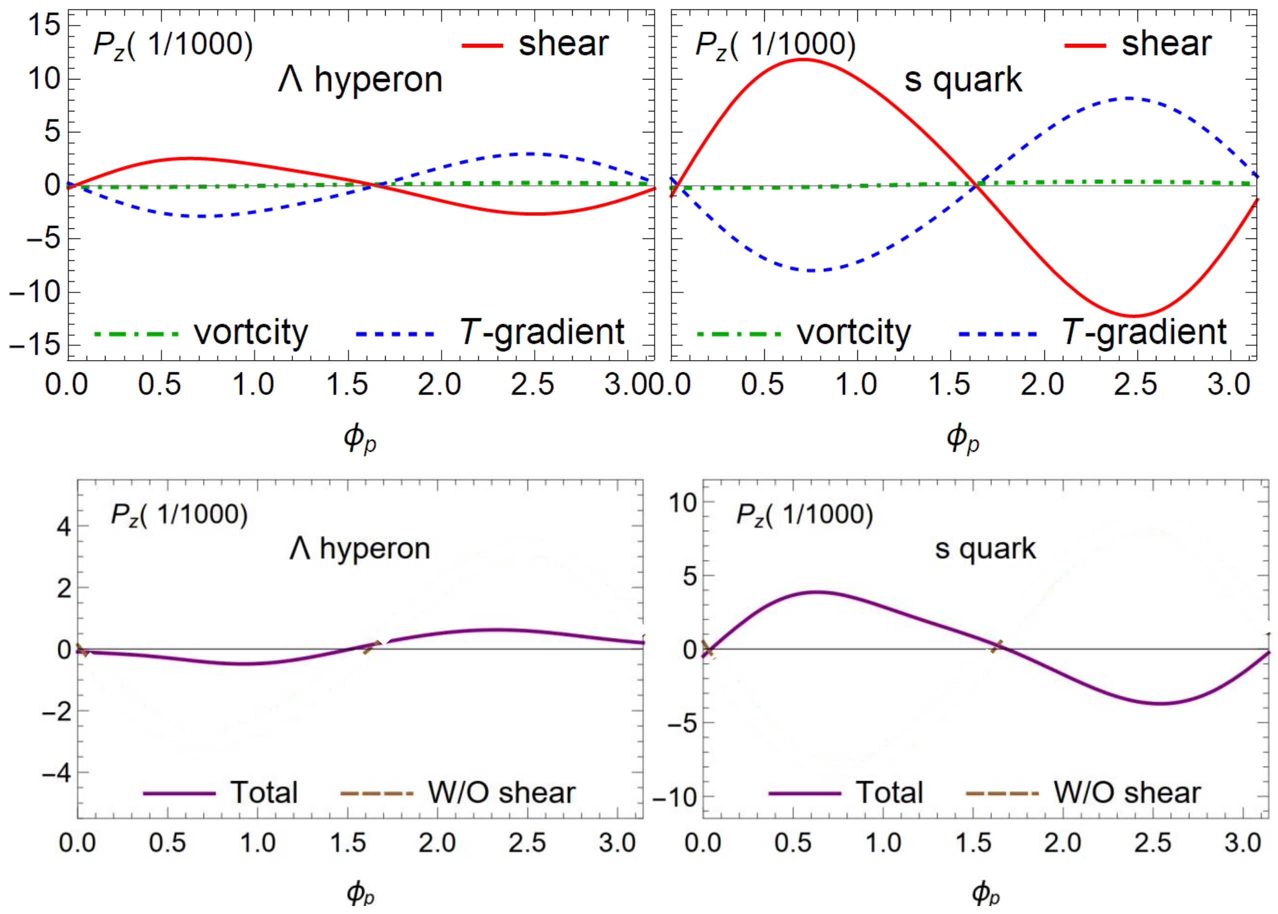
- Competition between

$$\boxed{\epsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha[\beta^{-1}\partial_\lambda\beta]} - \boxed{\epsilon^{\mu\nu\alpha\rho}u_\nu p_\rho(p^\lambda/\varepsilon_0)\partial_{(\alpha}u_{\lambda)}}$$

- Additional factor $p/\varepsilon \sim p/m$, enhance in smaller mass
- Smaller mass allows the Shear to win the T-gradient

Lambda equilibrium
Assuming P_Λ in equilibrium

Strange memory
Assuming $P_\Lambda = P_s$



Results: Competitions between SIP and Other Effects

- Competition between

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$$-\boxed{\epsilon^{\mu\nu\alpha\rho}u_\nu p_\rho\left(p^\lambda/\varepsilon_0\right)\partial_{(\alpha}u_{\lambda)}}$$

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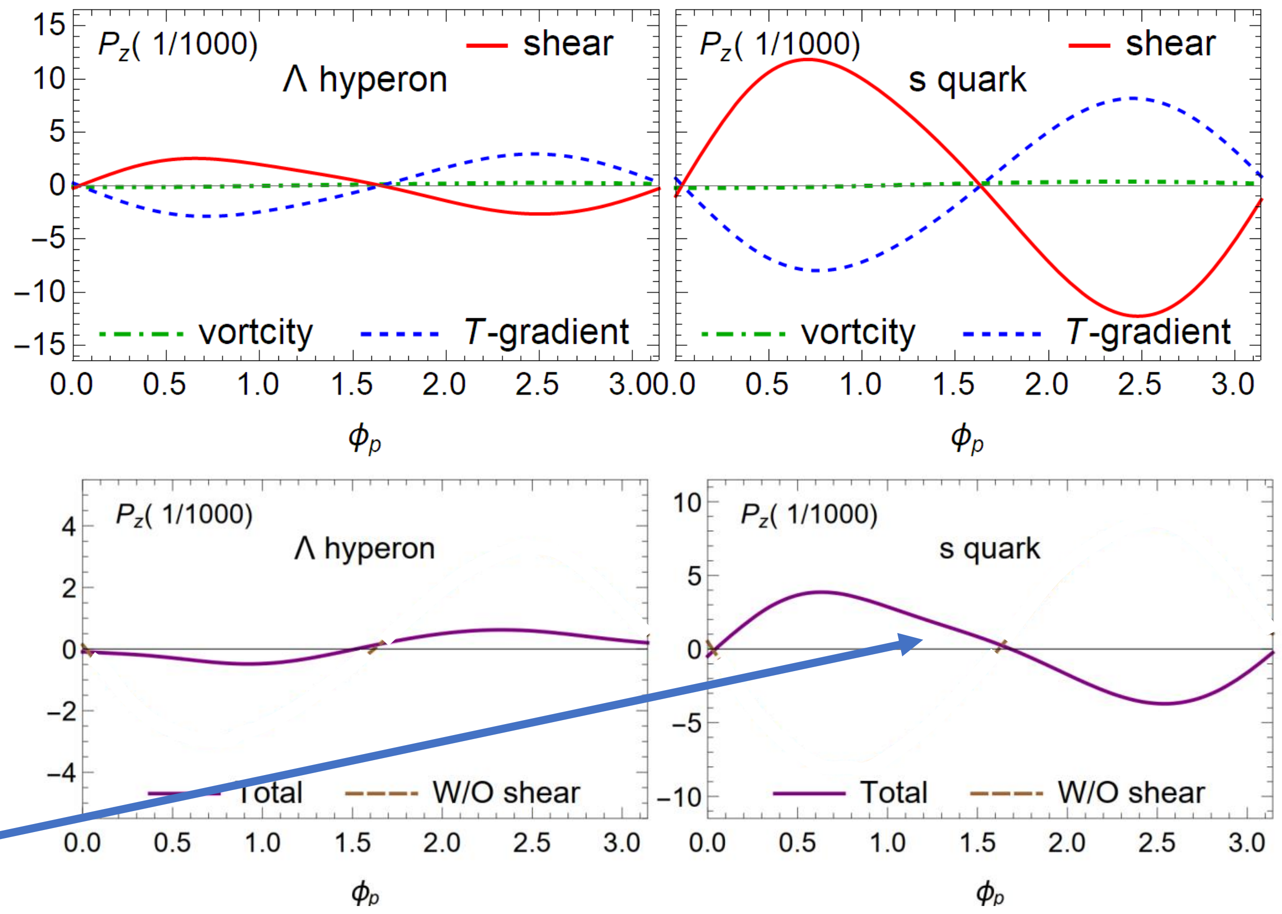

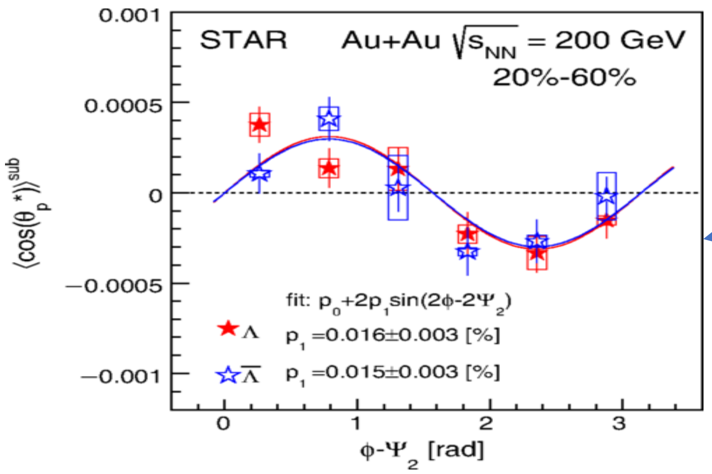

Summary

❖ Conclusions

- First time discover the Shear Induced Polarization (SIP)
- SIP has the “SAME SIGN” as those in experiments and it is one of the major contributions to local polarization
- Insights on the hadronization mechanism. In **strange memory** scenario, the total also has a sign agree with experiments.

❖ Future works

- Hadronization and hadronic evolution are required for quantitative studies
- Other puzzling phenomena in spin physics of heavy-ion collisions
- Non-perturbative effects