Vorticity and spin polarization in heavy-ion collisions

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September 15th , 2020 @ Webnar given at Sharif University of Technology, Tehran, Iran

Motivation of the talk

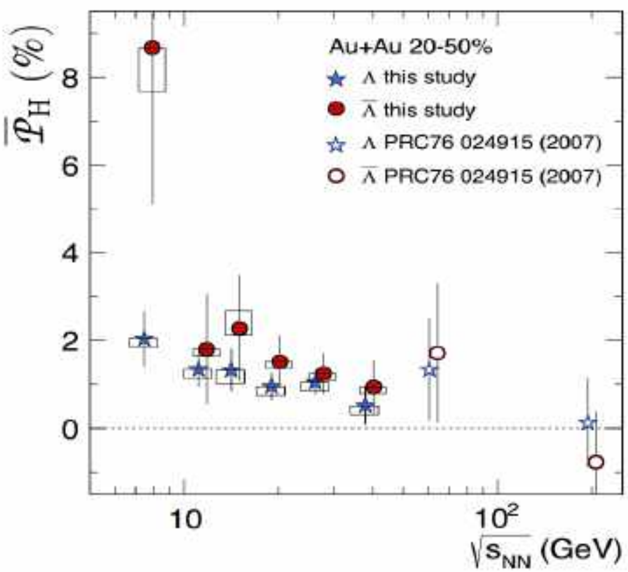
Quark-gluon plasma: "The most vortical fluid"

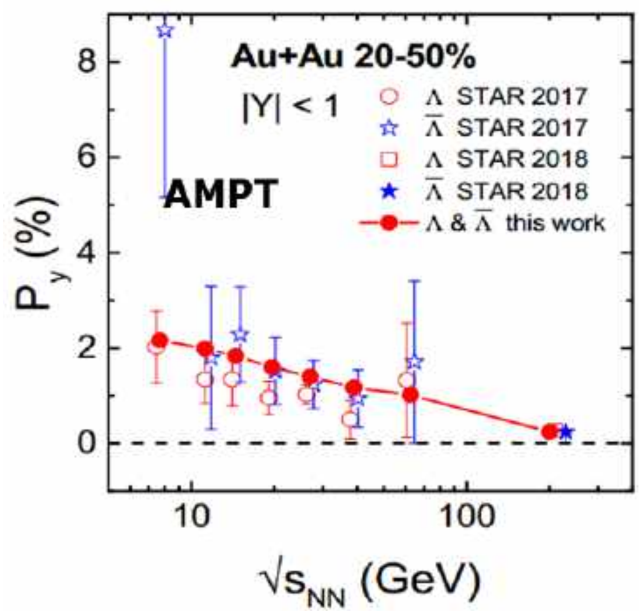
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*





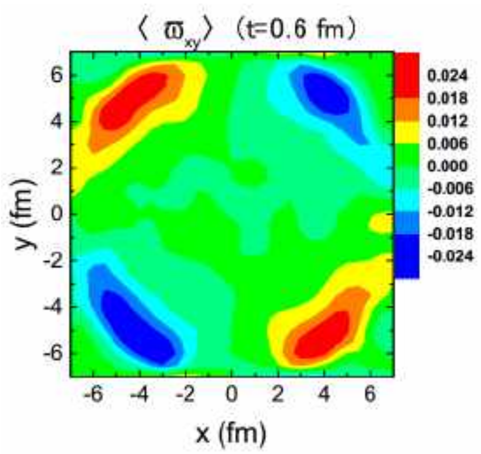
Experiment = Theory

Motivation of the talk

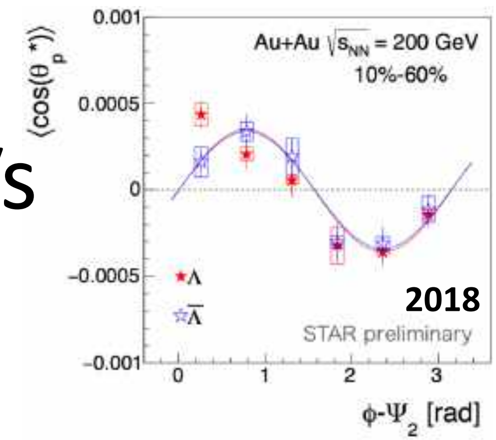
- **But: discrepancies exist between theory and experiments**

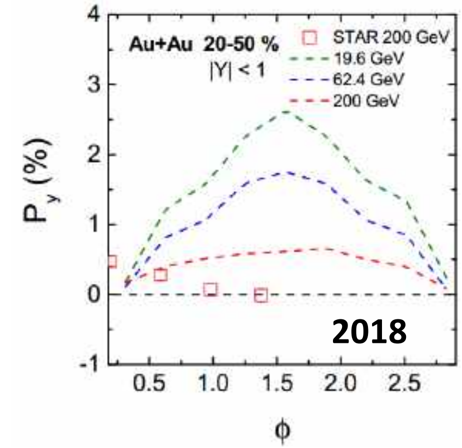
1) longitudinal polarization vs ϕ

2) Transverse polarization vs ϕ

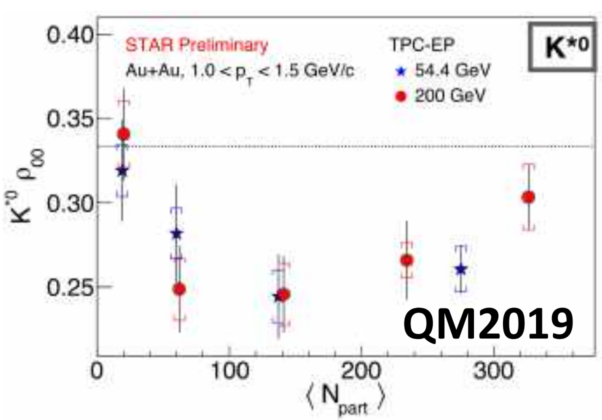


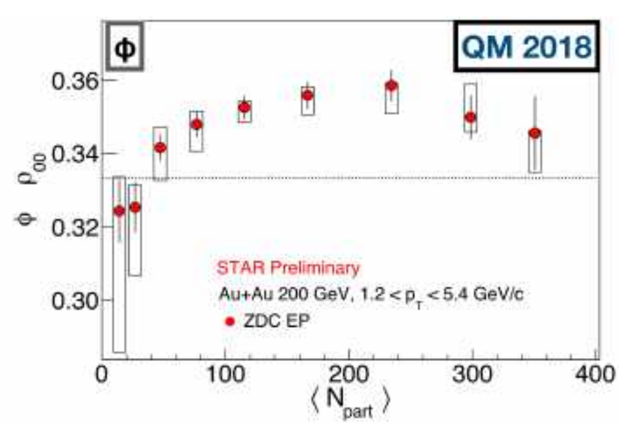
Vs





3) Vector meson spin alignment





Too big than expected!

Sign is not understood!

Outline

- Vorticity in heavy-ion collisions (HICs)
- From vorticity to spin polarization of hadrons
- Spin hydrodynamics
- Spin alignment and spin dependent hadron yields
- Summary

Vorticity in heavy-ion collisions

What is vorticity?

Vortex in a coffee cup

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

Fluid vorticity

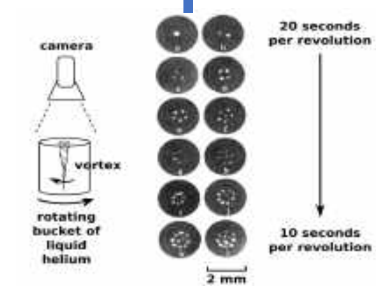
(Angular velocity of fluid cell)

What is vorticity?

- Vortices: common phenomena in fluids across a very broad hierarchy of scales

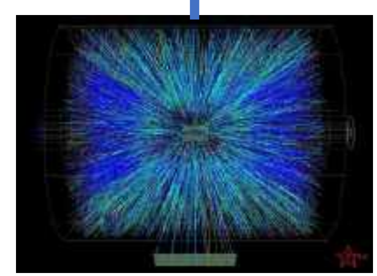
$10^{21}m$ | $10^{2}-10^{-2}m$ | $10^{-5}-10^{-8}m$ | $10^{-15}m$

Rotating galaxies



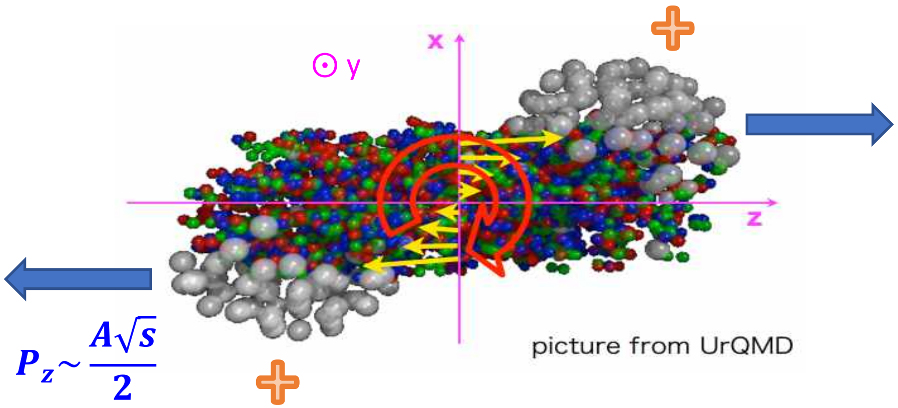
Superfluid helium

Tornados, ocean vortices, …



Quark gluon matter

Why fluid vorticity in HICs?



$P_z \sim \frac{A\sqrt{s}}{2}$

$$J_0 \sim \frac{Ab\sqrt{s}}{2} \sim 10^6 \hbar$$

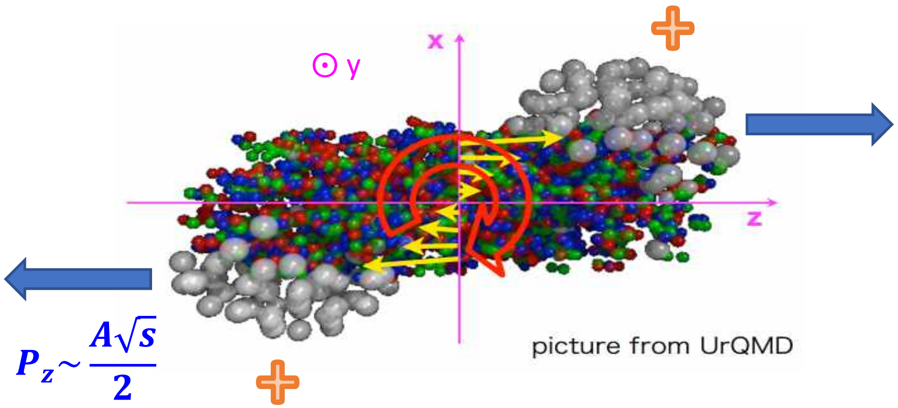
Global angular momentum

$$eB \sim \gamma \alpha_{\rm EM} \frac{Z}{b^2} \sim 10^{18}\ \mathrm{G}$$

Strong Magnetic field

(RHIC Au+Au 200 GeV, b=10 fm)

Why fluid vorticity in HICs?



$$P_z \sim \frac{A\sqrt{s}}{2}$$

$$J_0 \sim \frac{Ab\sqrt{s}}{2} \sim 10^6 \hbar$$

Global angular momentum

→

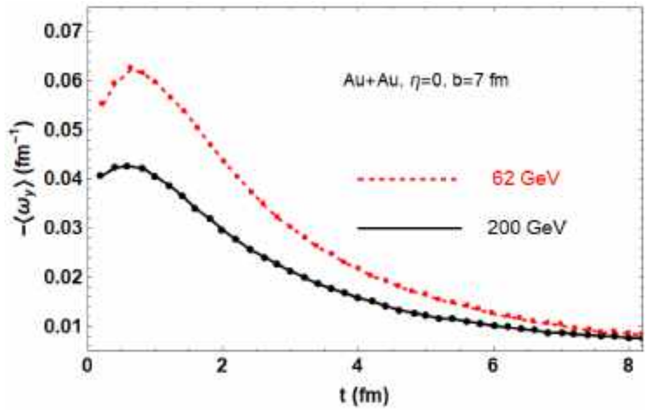
Local vorticity

$$\omega \sim ?$$

(RHIC Au+Au 200 GeV, b=10 fm)

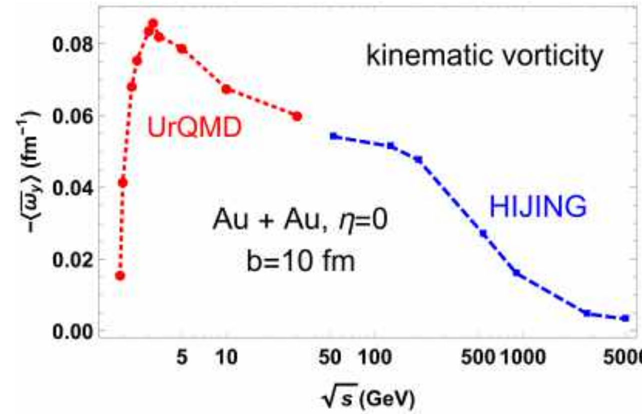
Vorticity by global angular momentum

Time dependence



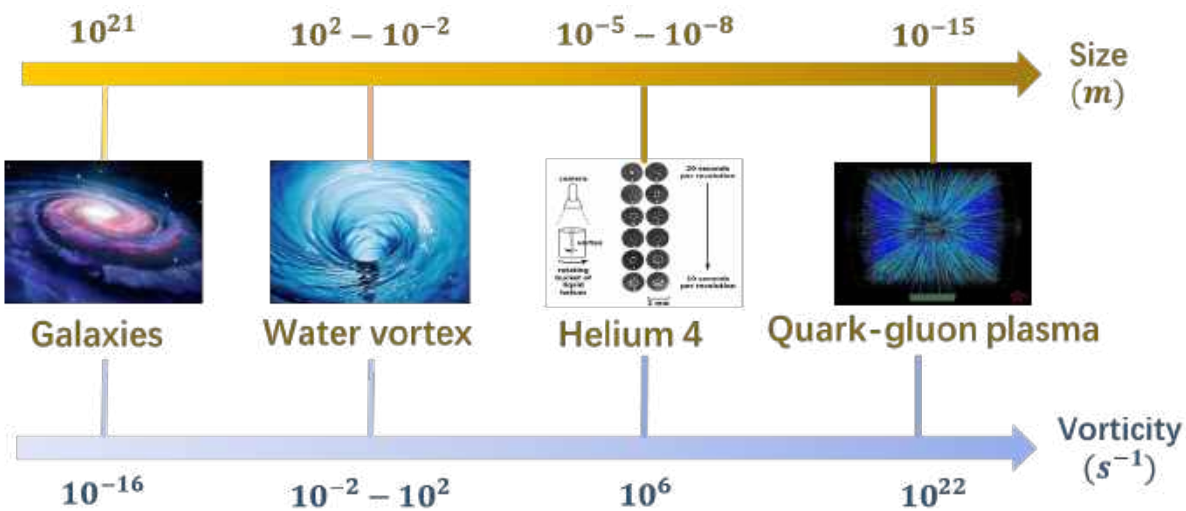
AMPT (Jiang-Lin-Liao 2016)

Energy dependence of initial vorticity



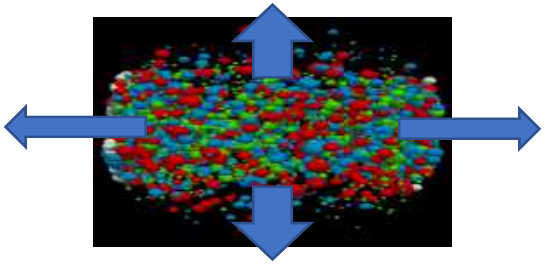
(Deng-XGH 2016; Deng-XGH-Ma-Zhang 2020)

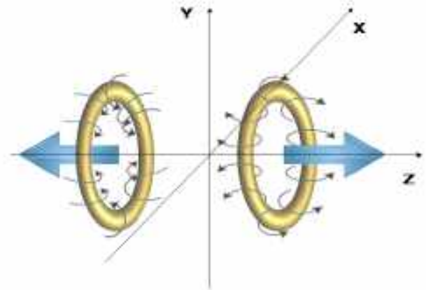
The most vortical fluid: Au+Au@RHIC at b=10 fm is $10^{20} - 10^{21}s^{-1}$

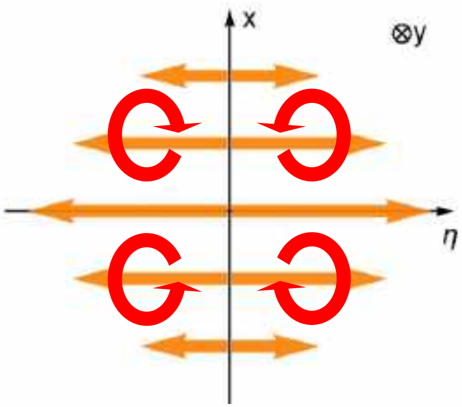


(See also: Becattini-Karpenko etal 2015,2016; Xie-Csernai etal 2014,2016,2019; Pang-Petersen-Wang-Wang 2016; Xia-Li-Wang 2017,2018; Sun-Ko 2017; Wei-Deng-XGH 2018; … …)

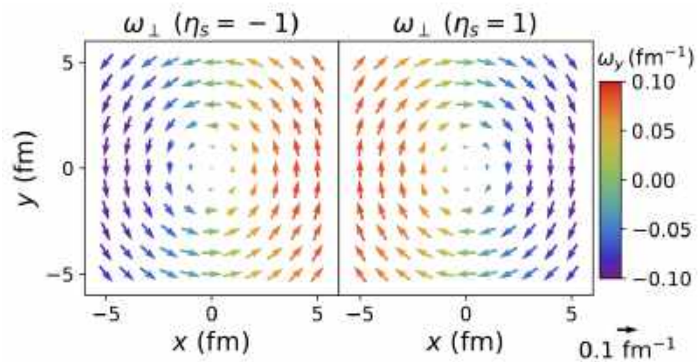
Vorticity by fireball expansion



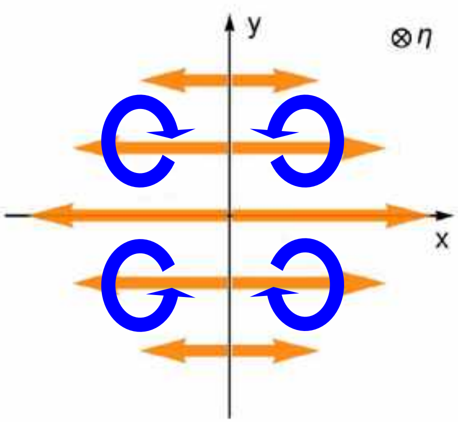




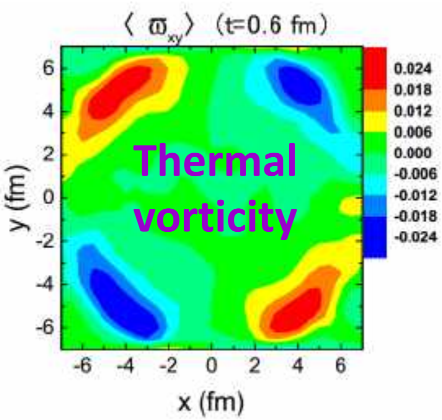
Transverse



(Xia-Li-Wang 2017)



Longitudinal

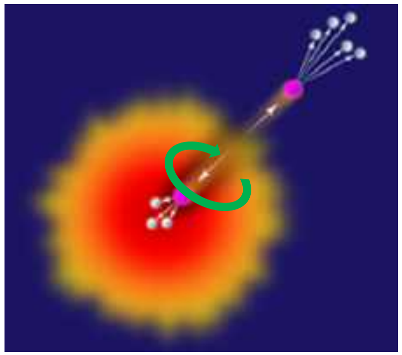


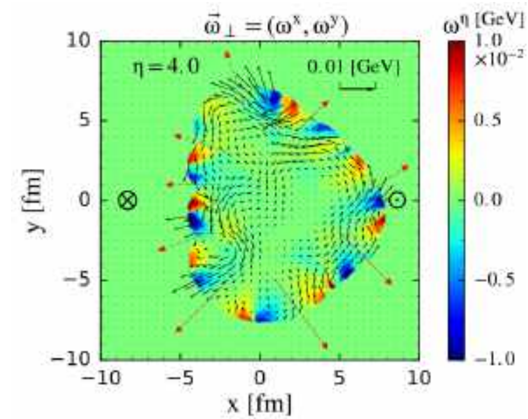
(Wei-Deng-XGH 2018)

(See also: Karpenko-Becattini 2017; Csernai etal 2014; Teryaev-Usubov 2015; Ivanov-Soldatov 2018; … …)

Other sources of vorticity

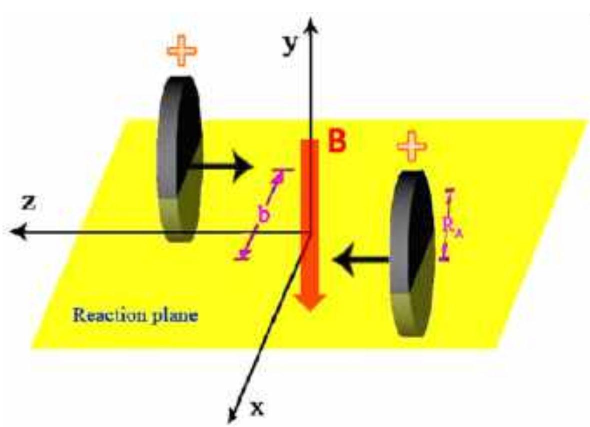
1) Jet

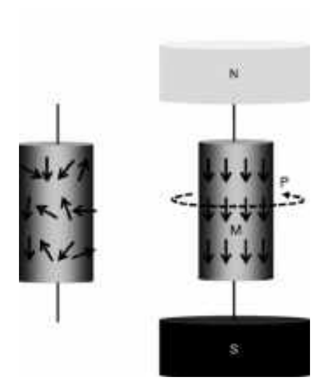




(Pang-Peterson-Wang-Wang 2016)

2) Magnetic field

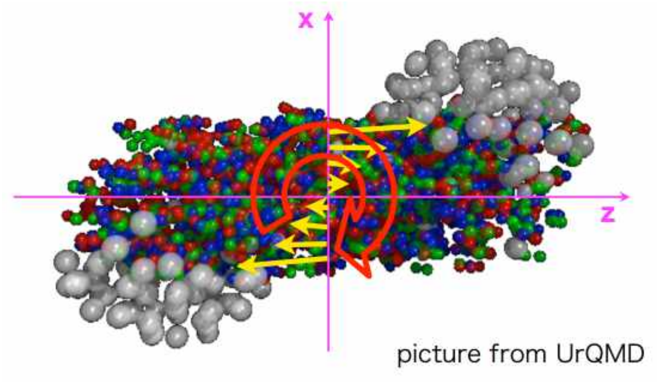




Einstein-de-Haas effect

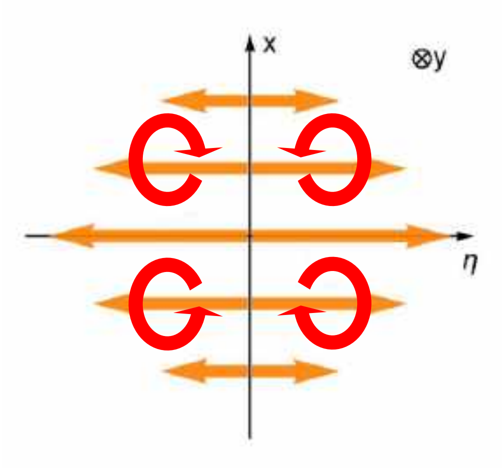
Main message:

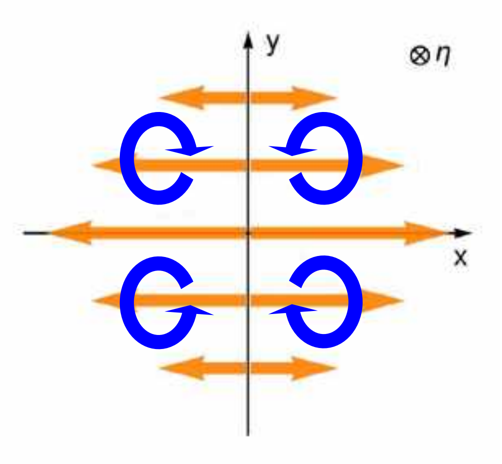
1. Global AM induces strong vorticity in HICs



: $\omega \approx 10^{21} - 10^{22}\ s^{-1}$

2. Fireball expansion: quadrupoles in both xy and xz planes





How to detect it experimentally? Spin polarization, Chiral vortical effects, … …

Spin polarization by vorticity

How vorticity polarizes spin?

Early idea: Liang-Wang PRL2005; Voloshin 2004

Vorticity interpretation (at thermal equilibrium)

$$H = H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S} \quad \Longrightarrow \quad \frac{dN}{d\boldsymbol{p}} \sim e^{-(H_0 - \boldsymbol{\omega}\cdot\boldsymbol{S})/T}$$

$$\Longrightarrow \quad \mathrm{P} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \sim \frac{\omega}{2T}$$

More rigorous derivation (Becattini etal 2013; Fang etal 2016; Liu-Mameda-XGH 2020)

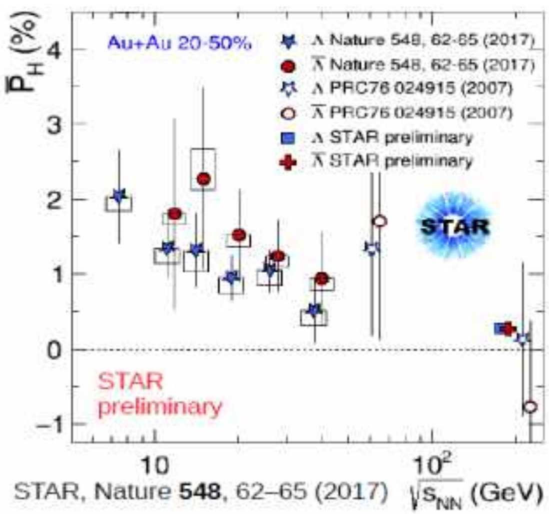
$$P^\mu(p) = \frac{1}{4m} \epsilon^{\mu\nu\rho\sigma} p_\nu \frac{\int d\Sigma_\lambda p^\lambda f'(x,p) \varpi_{\rho\sigma}(x)}{\int d\Sigma_\lambda p^\lambda f(x,p)} + O(\varpi^2)$$

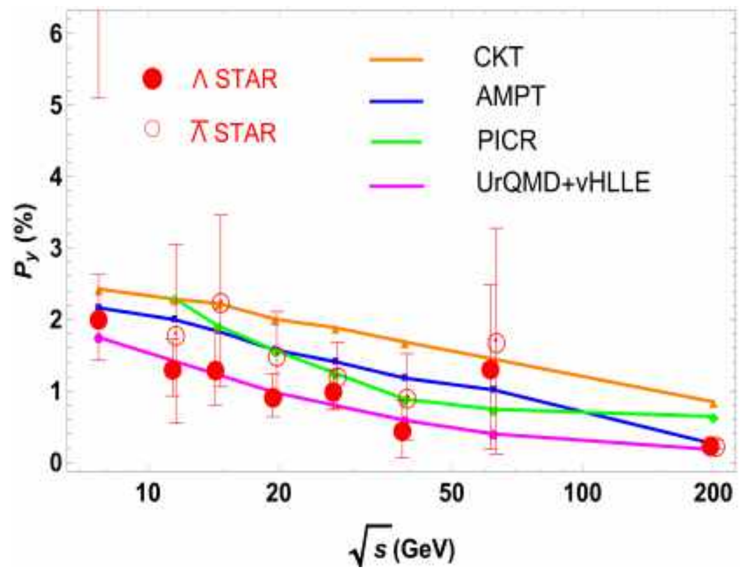
- Valid at global equilibrium. $f(x,p)$ is the distribution function (Fermi-Dirac)
- Thermal vorticity $\varpi_{\rho\sigma} = \left(\frac{1}{2}\right)\left(\partial_\sigma \beta_\rho - \partial_\rho \beta_\sigma\right)$
- Spin polarization is enslaved to thermal vorticity, not dynamical
- Friendly for numerical simulation (a spin Cooper-Frye type formula)

Global Λ spin polarization

The global polarization (i.e., integrated polarization over kinematics):

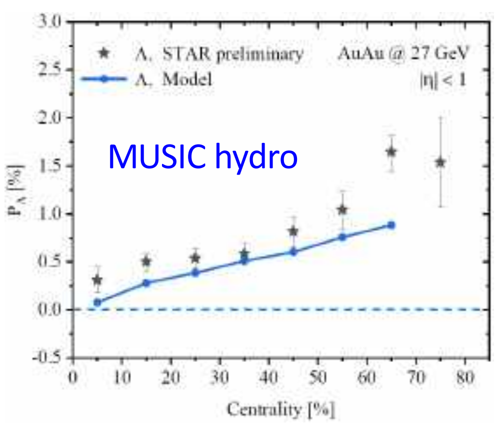
Experiment = Theory





Sun-Ko PRC2017; Wei-Deng-XGH PRC2019; Xie-Wang-Csernai PRC2017; Karpenko-Becattini EPJC2016

(Many similar results in literature)



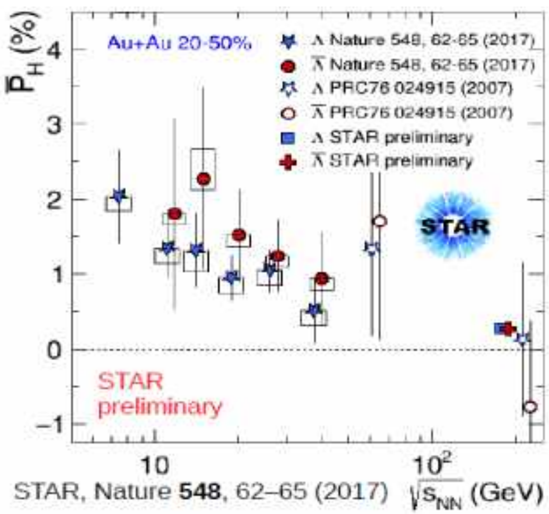
Fu-Xu-XGH-Song, to appear

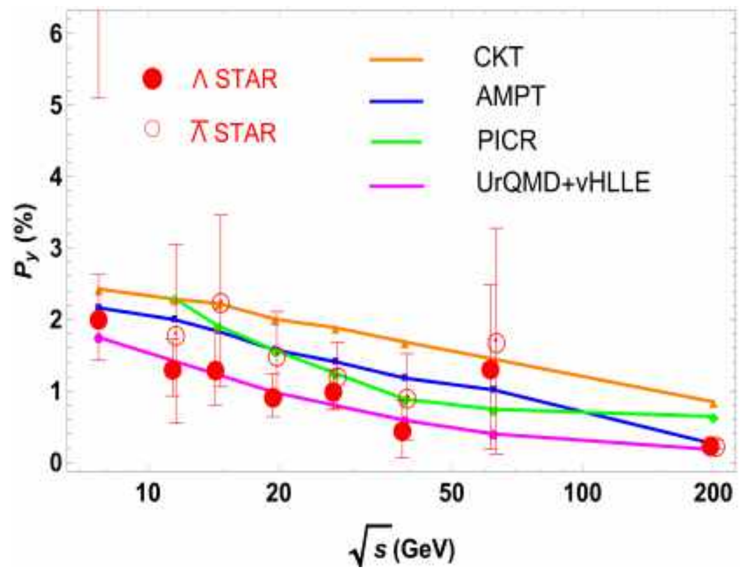
Vorticity interpretation of global Λ polarization works well!

Global Λ spin polarization

The global polarization (i.e., integrated polarization over kinematics):

Experiment = Theory





Sun-Ko PRC2017; Wei-Deng-XGH PRC2019; Xie-Wang-Csernai PRC2017; Karpenko-Becattini EPJC2016

(Many similar results in literature)

Though with big error bar, a difference between $P_y(\Lambda)$ and $P_y(\bar{\Lambda})$ is seen. Magnetic field?

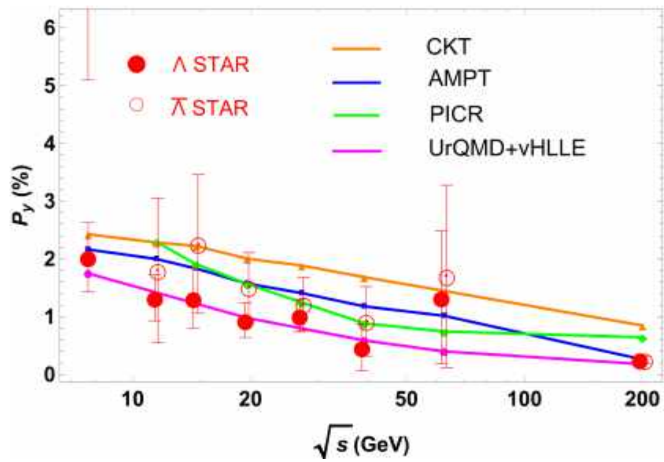
$$H = H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S} - \boldsymbol{m} \cdot \boldsymbol{B}$$

Vorticity interpretation of global Λ polarization works well!

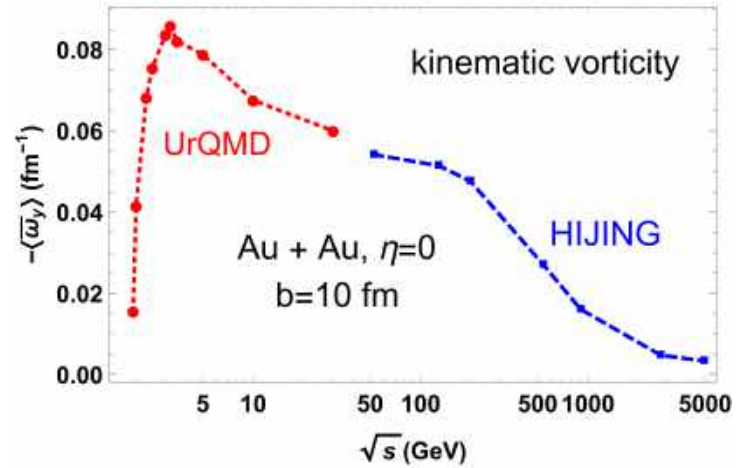
Global Λ spin polarization

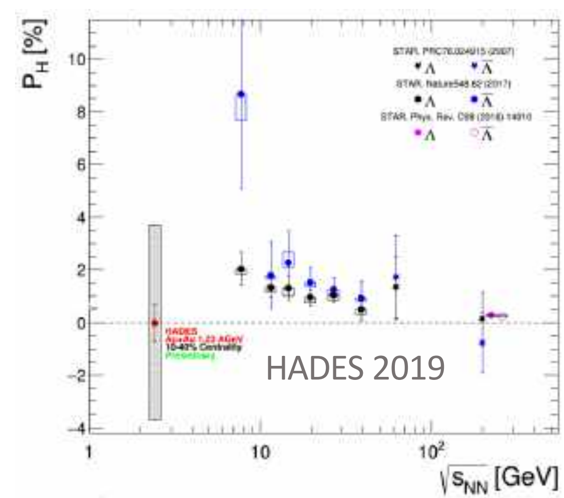
The global polarization: **Experiment = Theory**

(Deng-XGH 2016; Deng-XGH-Ma-Zhang 2020)



VS

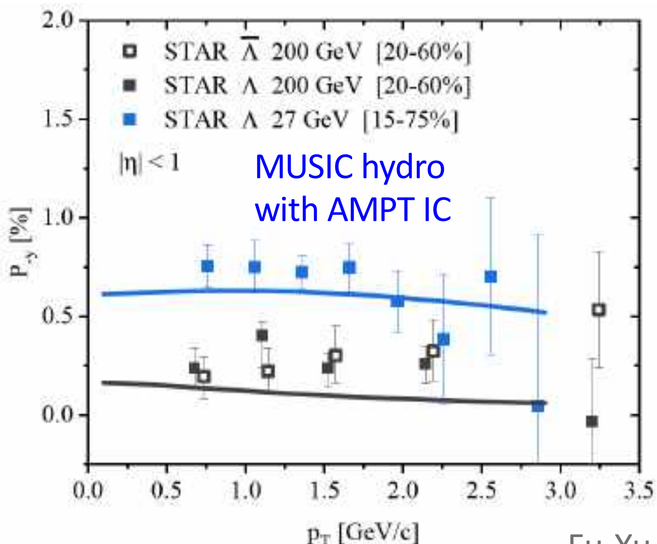


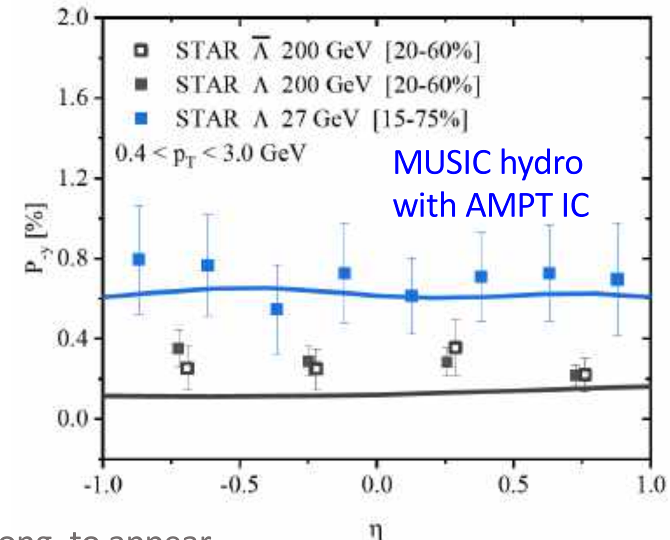


Need to study polarization at very low $\sqrt{s}$: NICA, FAIR, HIAF, BES II@RHIC?

Differential Λ spin polarization

The global Λ polarization reflects the total amount of angular momentum retained in the (-1,1) rapidity region. How is it distributed in e.g. p_T, η, and ϕ?

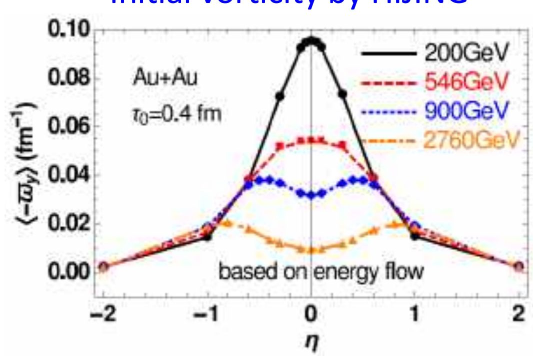




Fu-Xu-XGH-Song, to appear

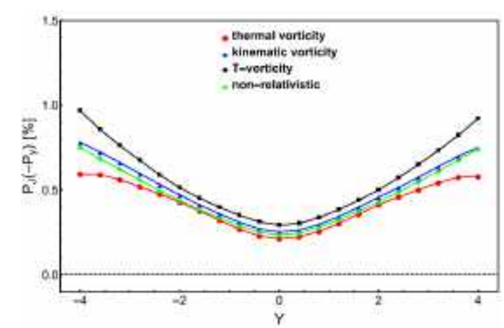
Would be interesting to look at very large rapidity?

Initial vorticity by HIJING



Deng-XGH PRC2016

Final polarization by hydro



Wu etal PRR2019

Differential Λ spin polarization

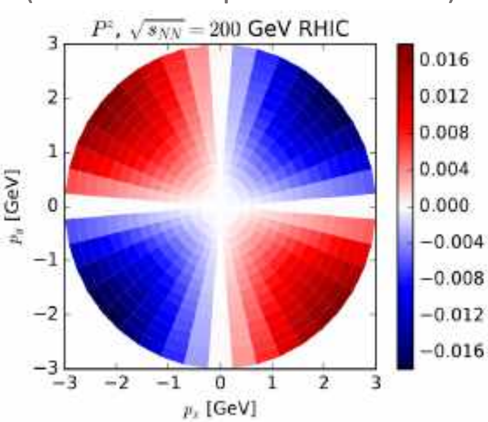
The global Λ polarization reflects the total amount of angular momentum retained in the (-1,1) rapidity region. How is it distributed in e.g. p_T, η, and ϕ?

- Spin harmonic flow: $$\frac{dP_{y,z}}{d\phi} \propto P_{y,z} + 2f_{2y,z}\sin(2\phi) + 2g_{2y,z}\cos(2\phi) + \cdots$$

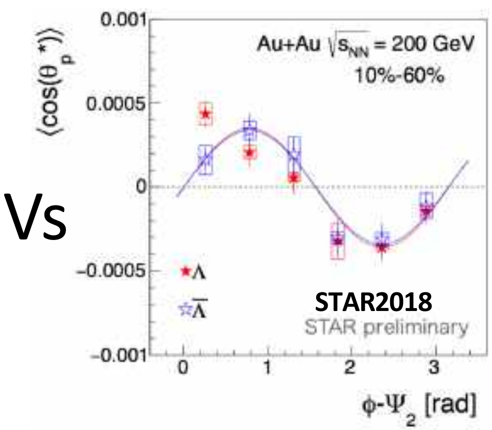
1) longitudinal polarization vs ϕ

2) Transverse polarization vs ϕ

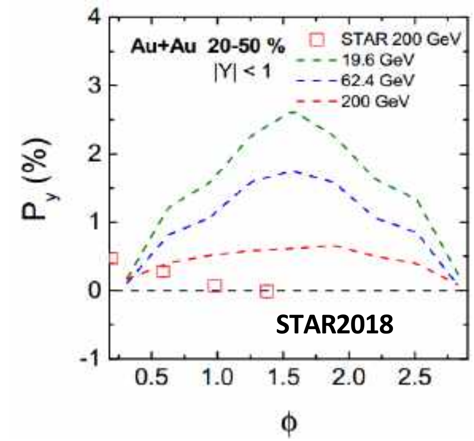
(Becattini-Karpenko PRL2018)



Vs



(Wei-Deng-XGH PRC2019)



$f_{2z}^{\text{ther}} < 0$ $\quad$ $f_{2z}^{\text{exp}} > 0$ $\quad$ $g_{2y}^{\text{ther}} < 0, g_{2y}^{\text{exp}} > 0$

We have a spin “sign problem”!

Differential Λ spin polarization

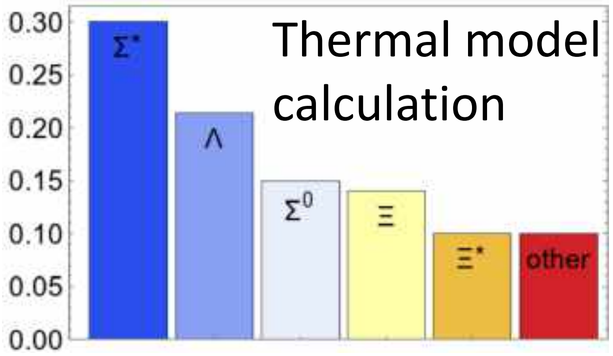
Attack the puzzles from theory side:

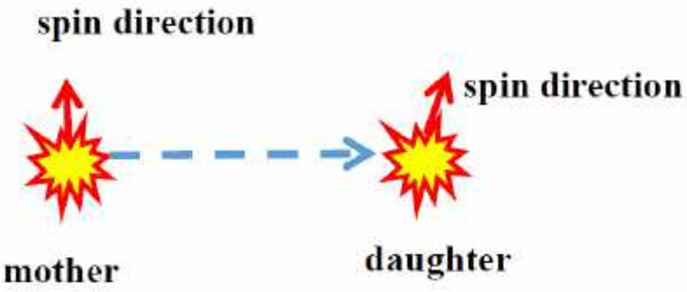
- Understand the vorticity (☺)
- Effect of feed-down decays (Xia-Li-XGH-Huang PRC2019, Becattini-Cao-Speranza EPJC2019)
  (Measured Λ may from decays of heavier particles)
- Go beyond equilibrium treatment (spin as a dynamic d.o.f)
  spin hydrodynamics
  spin kinetic theory
- Initial condition
  (Initial polarization, initial flow, … …)
- Other possibilities
  (chiral vortical effect (Liu-Sun-Ko 2019), mesonic mean-field(Csernai-Kapusta-Welle PRC2019), other spin chemical potential (Wu-Pang-XGH-Wang PRR2019, Florkowski etal2019), contribution from gluons, … …)
- Other observables for vorticity and spin polarization
  Vector meson spin alignment (Liang-Wang 2005; STAR and ALICE)
  Vorticity dependent hadron yield (ExHIC-P Collaboration 2002.10082)

Feed-down effect

One important contribution

- About 80% of Λ's are from decays of higher-lying particles





- Some decay channels can flip the spin, e.g., EM decay:

$$\Sigma^0 \to \Lambda + \gamma \qquad \left(\frac{1}{2}\right)^+ \to \left(\frac{1}{2}\right)^+ 1^-$$

- The angular momentum conservation, requires that if Σ is polarization along the vorticity, its daughter Λ must be polarized opposite to the vorticity

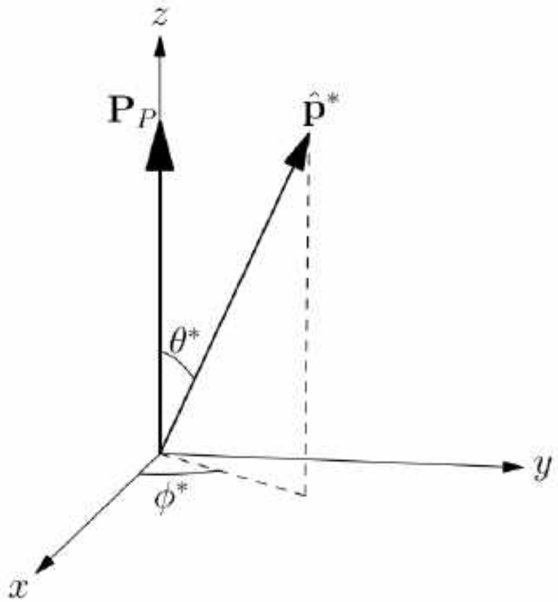
- Let us examine the decay contribution

Spin transfer

- Consider the decay process

$$P \to D + X$$

- The parent P is spin-polarized along z, the daughter D moves along p* in P's rest frame



Density matrix

$$\rho^f_{\lambda_D\lambda_X;\lambda'_D\lambda'_X}(\theta^*,\phi^*) = \sum_{M_P,M'_P} H_{\lambda_D\lambda_X;M_P}\rho^i_{M_P;M'_P}H^\dagger_{M'_P;\lambda'_D\lambda'_X}$$

$$|f\rangle = |\theta^*\phi^*\lambda_D\lambda_X\rangle \longleftarrow |i\rangle = |S_P M_P\rangle$$

The spin polarization of D:

$$\mathbf{P}_D = \mathrm{tr}_D\left(\widehat{\mathbf{P}}\rho^D_{\lambda_D;\lambda'_D}\right)/\mathrm{tr}_D\left(\rho^D_{\lambda_D;\lambda'_D}\right)$$

$$\rho^D_{\lambda_D;\lambda'_D} = \mathrm{tr}_X\left(\rho^f_{\lambda_D\lambda_X;\lambda'_D\lambda'_X}\right)$$

Spin transfer

- For example, consider the EM decay $1/2^{+} \to 1/2^{+}\,1^{-}$:

Initial density matrix:

$$\rho^{i}_{M_P;M'_P} = \mathrm{diag}\left(\frac{1+P_P}{2}, \frac{1-P_P}{2}\right)$$

$$\rho^{f}_{\lambda_D\lambda_X;\lambda'_D\lambda'_X} = \frac{1}{8\pi}\begin{pmatrix} 1+P_P\cos\theta^* & 0 & 0 & -P_P\sin\theta^* \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -P_P\sin\theta^* & 0 & 0 & 1-P_P\cos\theta^* \end{pmatrix}$$

$$\rho^{D}_{\lambda_D;\lambda'_D} = \frac{1}{8\pi}\begin{pmatrix} 1+P_P\cos\theta^* & 0 \\ 0 & 1-P_P\cos\theta^* \end{pmatrix}$$

$$\mathbf{P}_D = -(\mathbf{P}_P\cdot\hat{\mathbf{p}}^*)\,\hat{\mathbf{p}}^*$$

First derived by Gatto 1958

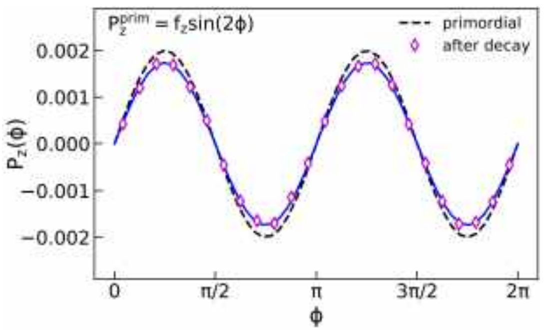
The feed-down correction

(Xia-Li-XGH-Huang PRC2019)

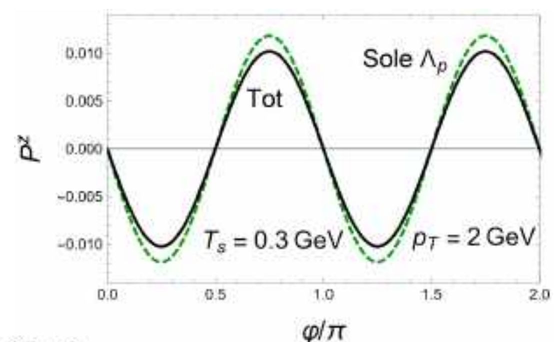
	spin and parity	$(1/N)dN/d\Omega^*$	$\mathbf{P}_D$	$\langle \mathbf{P}_D \rangle / \mathbf{P}_P$
strong decay	$1/2^+ \to 1/2^+ 0^-$	$1/(4\pi)$	$2(\mathbf{P}_P \cdot \hat{\mathbf{p}}^*)\hat{\mathbf{p}}^* - \mathbf{P}_P$	-1/3
strong decay	$1/2^- \to 1/2^+ 0^-$	$1/(4\pi)$	$\mathbf{P}_P$	1
strong decay	$3/2^+ \to 1/2^+ 0^-$	$3\left[1 - 2\Delta/3 - (1-2\Delta)\cos^2\theta^*\right]/(8\pi)$	Too long to be shown; see ref.	1
strong decay	$3/2^- \to 1/2^+ 0^-$	$3\left[1 - 2\Delta/3 - (1-2\Delta)\cos^2\theta^*\right]/(8\pi)$		-3/5
weak decay	$1/2 \quad \to 1/2 \;\; 0$	$(1 + \alpha P_P \cos\theta^*)/(4\pi)$		$(2\gamma+1)/3$
EM decay	$1/2^+ \to 1/2^+ 1^-$	$1/(4\pi)$	$-(\mathbf{P}_P \cdot \hat{\mathbf{p}}^*)\hat{\mathbf{p}}^*$	-1/3

- Longitudinal polarization $P_z = f_z \sin(2\phi)$

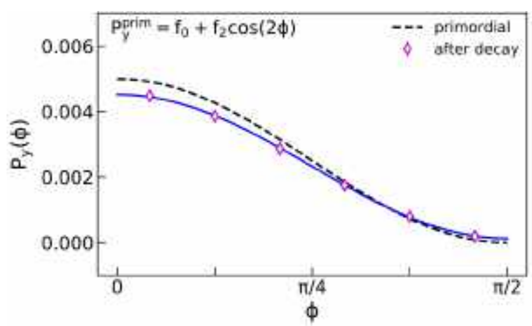
(Xia-Li-XGH-Huang PRC2019)



(Becattini-Cao-Speranza EPJC2019)



- Transverse polarization $P_y = f_0 + f_2\cos(2\phi)$



Conclusion:

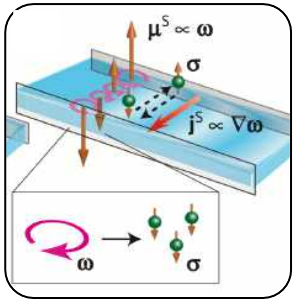
- Feed-down effects suppress ~10% Λ primordial spin polarization
- Do not solve the spin sign problem

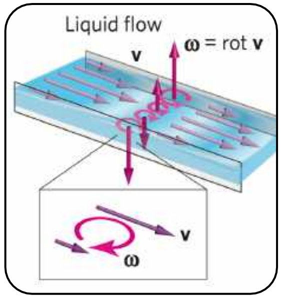
Spin hydrodynamics

Spin hydrodynamics

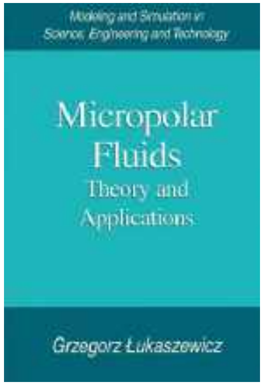
Framework for collective spin dynamics. Spin as a (quasi-)hydrodynamic variable

- Widely used in non-relativistic spintronics, micropolar fluid, … …





(Takahashi etal Nat.Phy.2016)



- Relativistic ideal spin hydrodynamics (Florkowski etal PRC2018)

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu}$$

$$\partial_\lambda S^{\lambda,\mu\nu} = 0 \qquad S^{\lambda,\mu\nu} = \frac{w u^\lambda}{4\zeta}\omega^{\mu\nu}$$

(See also: Florkowski etal PRD2018,PPNP2019; Motenegro etal PRD2017, PRD2017)

Spin hydrodynamics

Relativistic dissipative spin hydrodynamics (Hattori-Hongo-XGH-Matsuo-Taya PLB2019)

- **Identify (quasi-)hydrodynamic variables: T and u^μ (4 for translation), $\omega^{\mu\nu} = -\omega^{\nu\mu}$(spin chemical potential, 3 for rotation, 3 for boost).**
- **Derivative expansion. Apply 2nd law of thermodynamics.**
- **Constitutive relations up to $O(\partial)$**

$$T^{\mu\nu}_{(0)} = eu^\mu u^\nu + p(g^{\mu\nu} + u^\mu u^\nu)$$

heat current — shear viscosity — bulk viscosity

$$T^{\mu\nu}_{(1)} = -2\kappa\left(Du^{(\mu} + \beta\partial_\perp^{(\mu}\beta^{-1}\right)u^{\nu)} - 2\eta\partial_\perp^{<\mu}u^{\nu>} - \zeta(\partial_\mu u^\mu)\Delta^{\mu\nu}$$
$$-2\lambda\left(-Du^{[\mu} + \beta\partial_\perp^{[\mu}\beta^{-1} + 4u_\rho\omega^{\rho[\mu}\right)u^{\nu]} - 2\gamma\left(\partial_\perp^{[\mu}u^{\nu]} - 2\Delta^\mu_\rho\Delta^\nu_\lambda\omega^{\rho\lambda}\right)$$

boost heat current — rotational viscosity

- **Hydrodynamic equations**

$$\partial_\mu\left(T^{\mu\nu}_{(0)} + T^{\mu\nu}_{(1)} + O(\partial^2)\right) = 0$$

Energy-momentum conservation

$$\partial_\mu(u^\mu s^{\alpha\beta}) = T^{\beta\alpha}_{(1)} - T^{\alpha\beta}_{(1)} + O(\partial^2)$$

Angular momentum conservation

$$p = p(e, s^{\alpha\beta})$$

Equation of state

- **Israel-Stewart type theory**

$$\tau_\eta(D\sigma_\eta^{\mu\nu})_\perp + \sigma_\eta^{\mu\nu} = 2\eta\partial_\perp^{\langle\mu}u^{\nu\rangle},$$
$$\tau_\zeta(D\sigma_\zeta^{\mu\nu})_\perp + \sigma_\zeta^{\mu\nu} = \zeta\theta\Delta^{\mu\nu},$$
$$\tau_\lambda(Dq^\mu)_\perp + q^\mu = \lambda(Du^\mu + \beta\partial_\perp^\mu T - 4\Omega^{\mu\nu}u_\nu),$$
$$\tau_\gamma(D\phi^{\mu\nu})_\perp + \phi^{\mu\nu} = 2\gamma(\partial_\perp^{[\mu}u^{\nu]} + 2\Omega_\perp^{\mu\nu}),$$

(See also: Florkowski etal 2020; Shi-Gale-Jeon 2020)

Spin hydrodynamics

- Possible consequences: (1) New collective modes

$$\omega = -2iD_s,$$ ← **Longitudinal spin damping**

$$\omega = -2iD_b,$$ ← **Longitudinal boost damping**

$$\omega = \begin{cases} -2iD_s - i\gamma' k_z^2 + \mathcal{O}(k_z^4), \\ -i\gamma_\perp k_z^2 + O(k_z^4),, \end{cases}$$

← **Transverse spin damping**

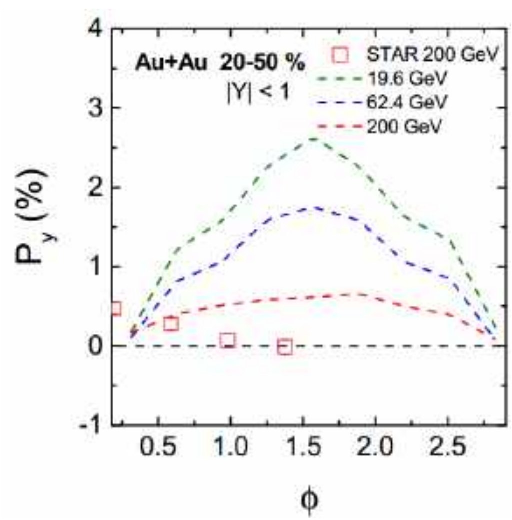
← **Shear viscous damping**

$$\omega = \begin{cases} \pm c_s k_z - i\frac{\gamma_{||}}{2} k_z^2 + \mathcal{O}(k_z^3), \\ -2iD_b - 2ic_s^2 \lambda' k_z^2 + \mathcal{O}(k_z^4). \end{cases}$$

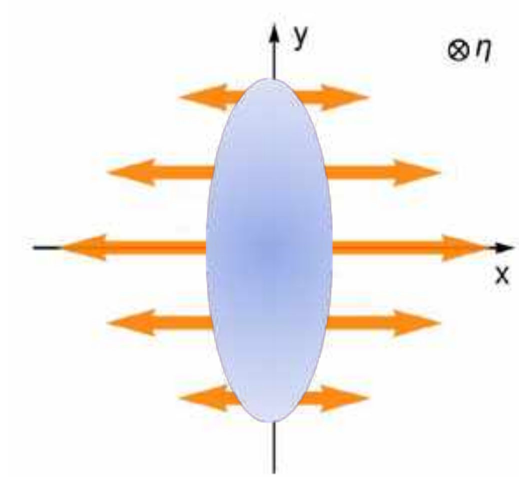
← **Sound and bulk viscous damping**

← **Transverse boost damping**

- (2) Polarization: azimuthal-dependence puzzle



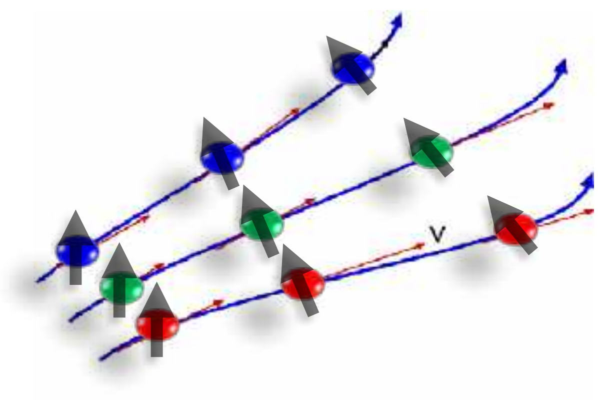
Spin elliptic flow? ←



Spin hydrodynamics

Future:

- Causal and stable (Israel-Stewart) 2^{nd} order spin hydrodynamics
- Flow frame choice and pseudo-gauge choice, especially for Belinfante gauge
- Calculation of rotational viscosity and boost heat conductivity (insight to QCD)
- Formulate spin hydrodynamics for large vorticity at $O(1)$ and with magnetic field
- Derive spin hydrodynamics from kinetic theory or holography
- Application: numerical spin hydrodynamics for <u>Λ polarization</u>



Other observables

ϕ-spin alignment

- Vorticity can also polarize spin of vector mesons, e.g. ϕ
- Consider recombination $q + \overline{q} \rightarrow \phi$, the density matrix of q:

$$\rho^q = \frac{1}{2}\begin{pmatrix} 1+P_q & 0 \\ 0 & 1-P_q \end{pmatrix}$$

- The density matrix of ϕ is obtained from $\rho^q \otimes \rho^{\overline{q}}$ in basis of |↑↑), |↑↓)- |↓↑), and |↓↓)

$$\rho^V = \begin{pmatrix} \frac{(1+P_q)(1+P_{\bar{q}})}{3+P_q P_q} & 0 & 0 \\ 0 & \frac{1-P_q P_q}{3+P_q P_q} & 0 \\ 0 & 0 & \frac{(1-P_q)(1-P_{\bar{q}})}{3+P_q P_{\bar{q}}} \end{pmatrix}$$

- Suppose $P_q = P_{\overline{q}}$,

$$\rho_{00}^{\rho(\mathrm{rec})} = \frac{1-P_q^2}{3+P_q^2}$$

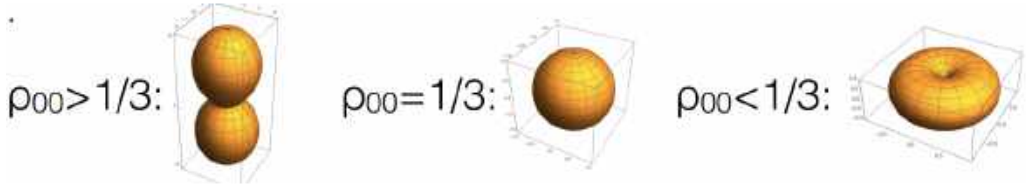
Liang-Wang 2005

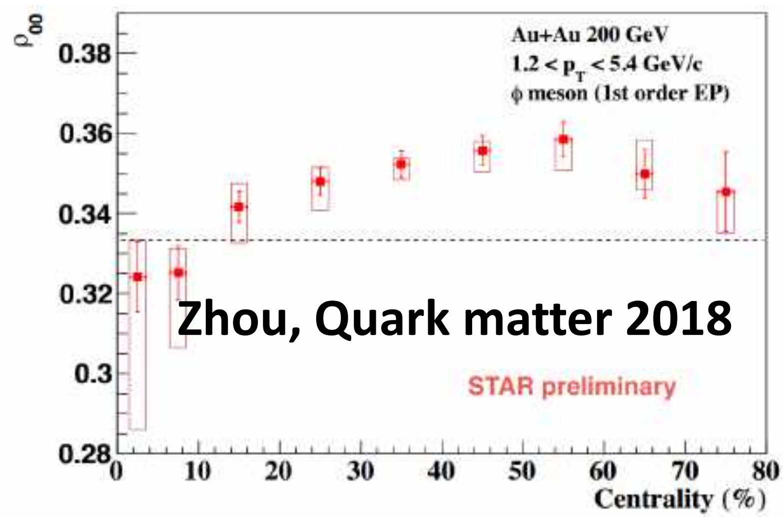
Smaller than 1/3

ϕ-spin alignment

- Φ decay via strong process, no parity violation, it is not easy to determine its spin polarization states, but

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* \right]$$





Puzzle: for most centrality, ρ_{00} is far above 1/3?

Magnetic field contribution?

Mesonic field (Sheng-Oliva-Wang 2019)?

Gluon contribution?

… …

ϕ-spin alignment

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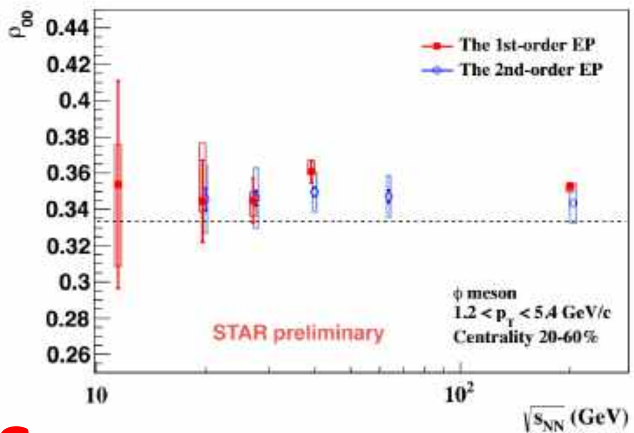
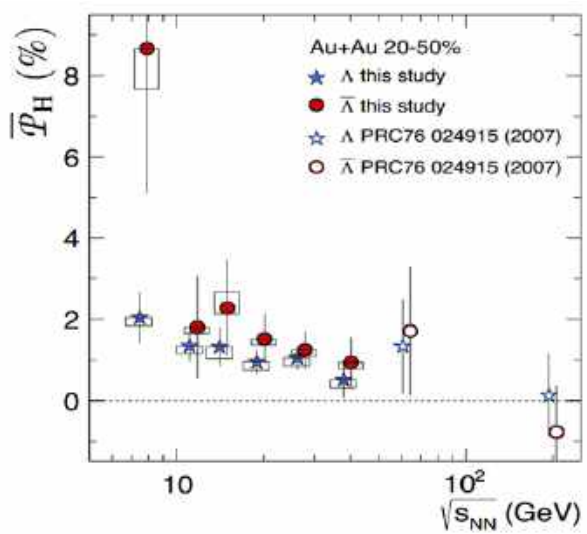
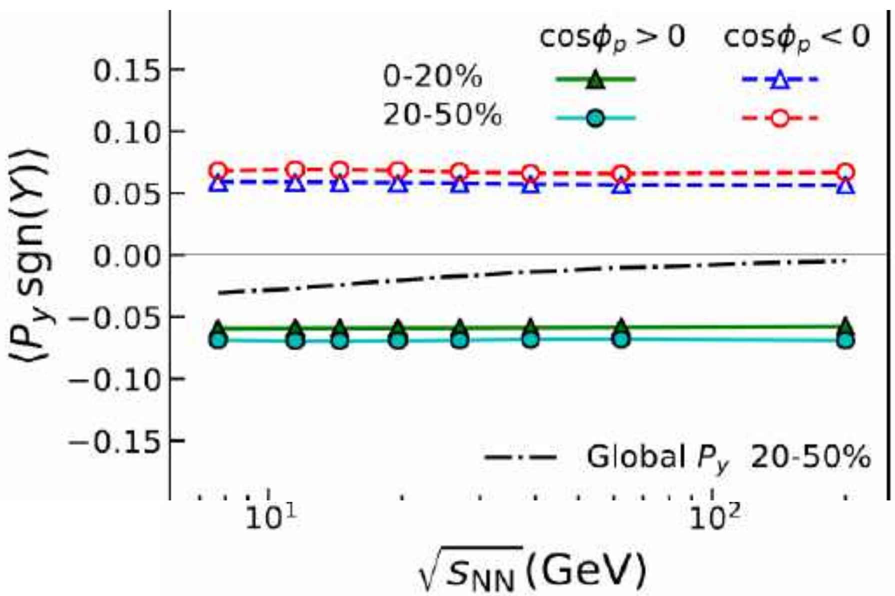


No significant energy dependence

May be understood. As ρ_{00} depends on P_q^2

Vs

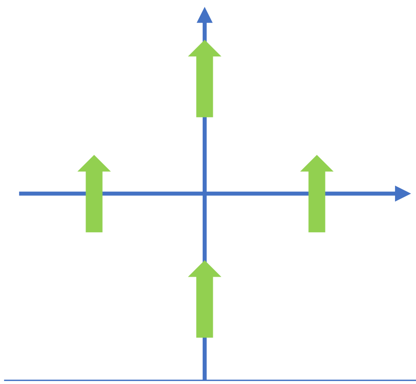




Xia-Li-Wang 2018

ϕ-spin alignment

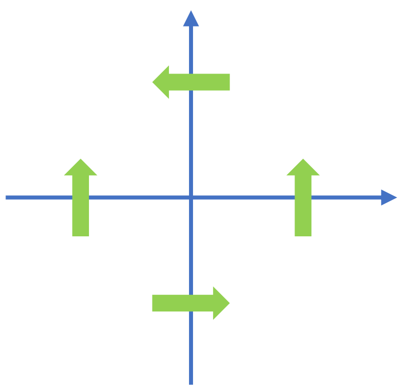
- **Spin configuration for vector mesons:**
  $\rho_{11} \sim |\uparrow\uparrow)\ (\uparrow\uparrow|$, $\rho_{-1-1} \sim |\downarrow\downarrow)\ (\downarrow\downarrow|$, $\rho_{00} \sim [|\uparrow\downarrow) - |\downarrow\uparrow)][(\uparrow\downarrow| - (\downarrow\uparrow|]$



$$\rho_{00} = \frac{1 - P_y^2}{3 + P_y^2}$$

Liang-Wang 2005

$$\rho_{00}^{V(rec)} < 1/3 \quad \text{for} \quad q^{\uparrow} + \bar{q}^{\uparrow} \to V$$

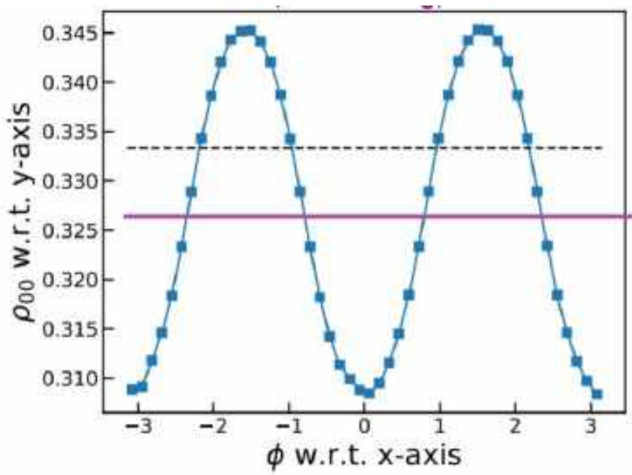


$$\rho_{00} = \frac{1 - P_y^2 + P_x^2 + P_z^2}{3 + P^2}$$

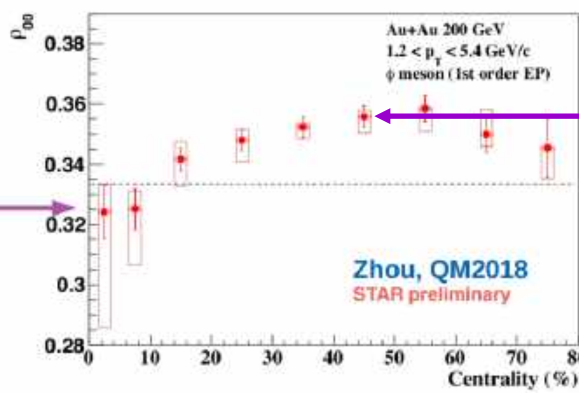
Xia-Li-XGH-Huang, to appear

ϕ-spin alignment

- **Predictions for central collisions:**



(Au+Au 200 GeV, b=0 fm, 1.2<pT<5.4 GeV)

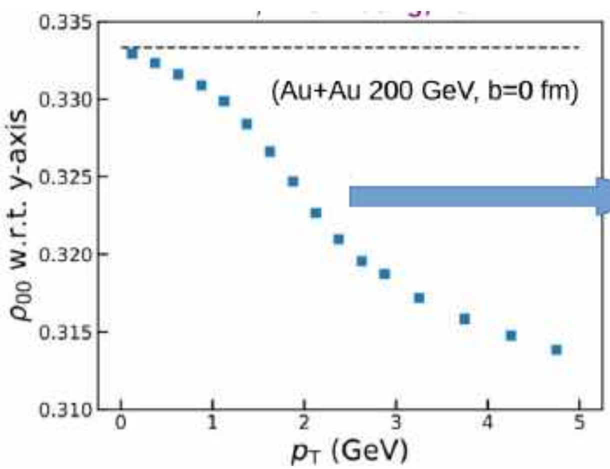


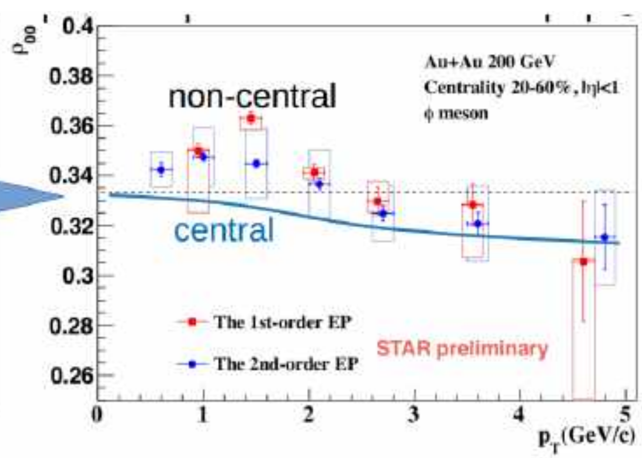
Noncentral collisions:
Magnetic field ?

$$\rho_{00}^{mag} = \frac{1 + P_y^2}{3 - P_y^2} > \frac{1}{3}$$

- EP is not needed in central case.
- Remove uncertainty caused by EP resolution.

$$\rho_{00}^{vor} = \frac{1 - P_y^2 + P_x^2 + P_z^2}{3 + P^2}$$





ϕ-spin alignment

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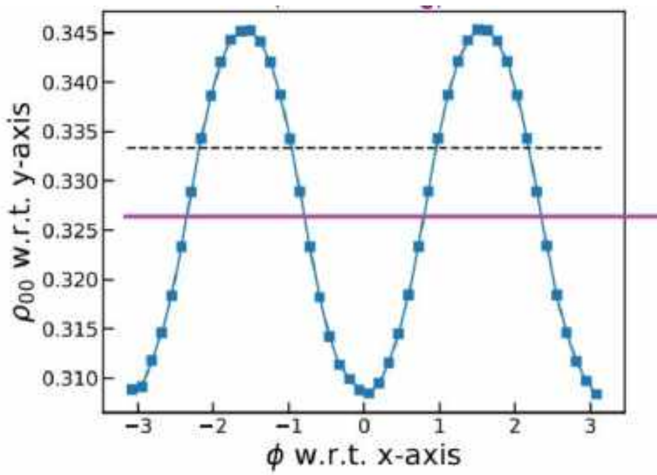

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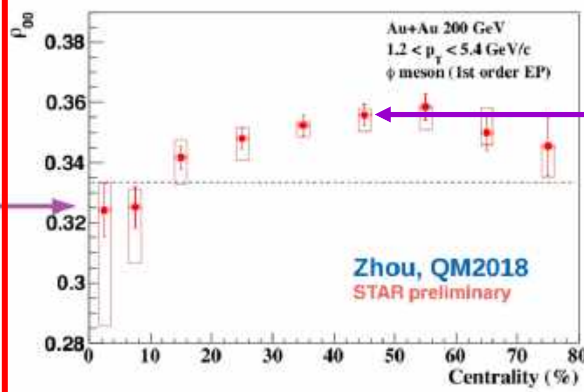

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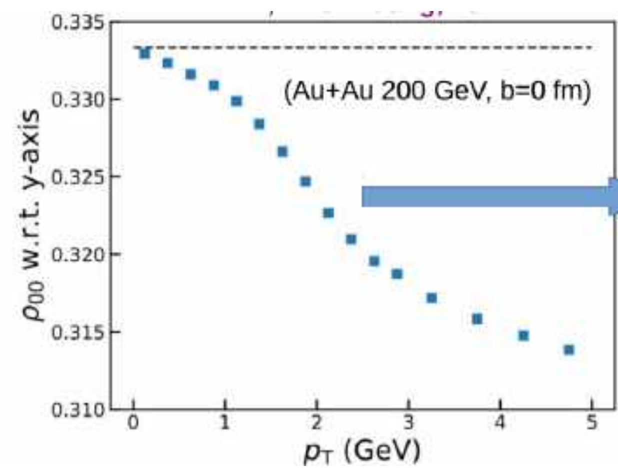
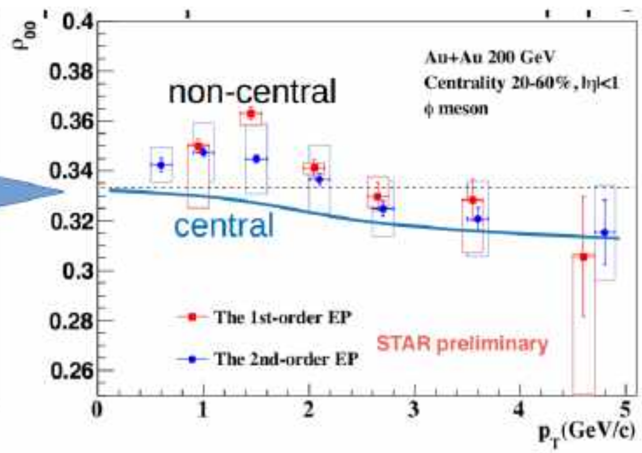




Well testable!
Evidence of circular vorticity

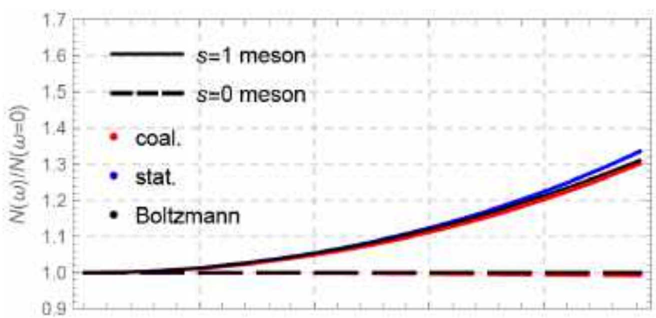
Spin dependent hadron yields

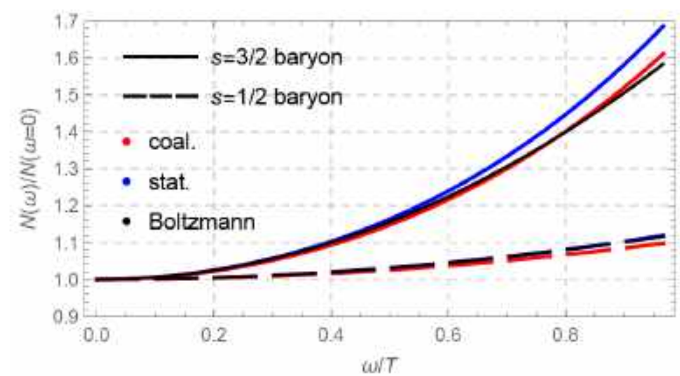
Vorticity is the "spin chemical potential" (ExHIC-P Collaboration 2002.10082)

$$E_{\rm h} = \sqrt{m_{\rm h}^2 + \boldsymbol{p}^2} - \boldsymbol{\mu}^{\rm ch} \cdot \boldsymbol{Q}_{\rm h} - \omega^{\rm ch} s_z$$

$$\frac{N^{\rm stat/coal}(\omega)}{N^{\rm stat/coal}(\omega = 0)} \sim 1 + \frac{s(1+s)}{6} \left(\frac{\omega}{T}\right)^2$$

Naively, it is the same order as ρ_{00}, could be cross-check of vector spin alignment





Observable: ratio of e.g. $\frac{N_{\phi}}{N_{K}}$ or $\frac{N_{\Omega}}{N_{\Xi}}$ as function of centrality and energy

Summary

Global angular momentum

Inhomogeneous expansion

⋮

→ Most vortical fluid →

Hyperon spin polarization | Vector meson spin alignment | …

Chiral vortical effects | Chiral vortical wave | …

Rotation dimension of QCD phase diagram

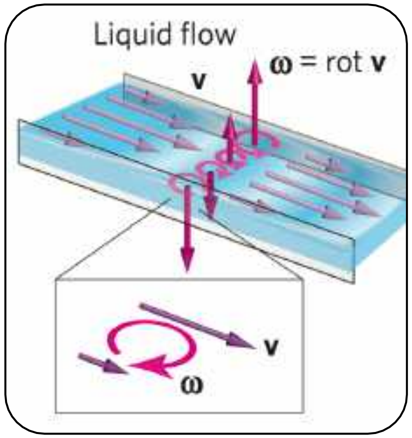
⋮

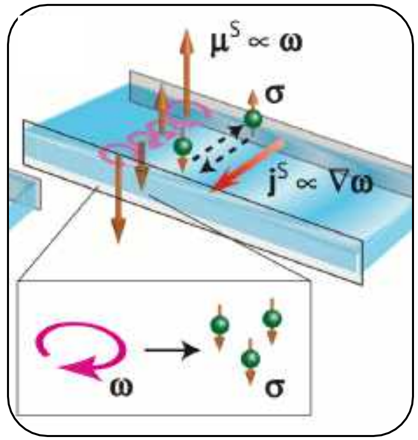
Heavy-ion physics: electronics era to spintronics era
Puzzles, challenges, but opportunities

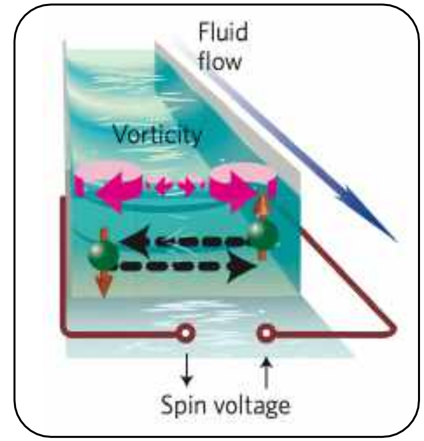
Thank you

Subatomic spintronics

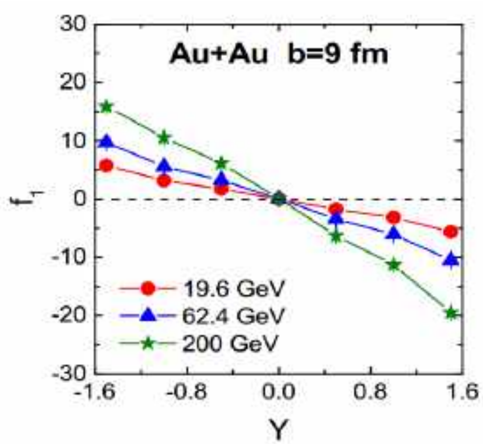
- **Spin hydrodynamic generation in Hg** (Takahashi, et al. Nat. Phys. (2016))

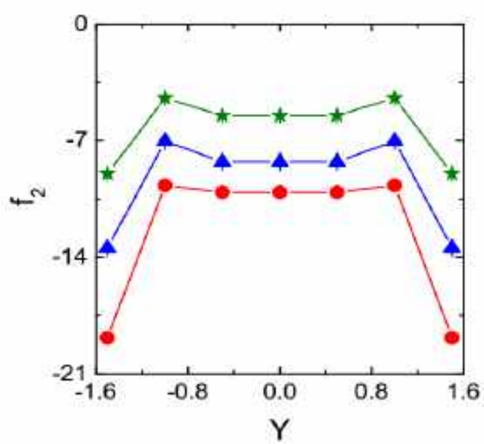


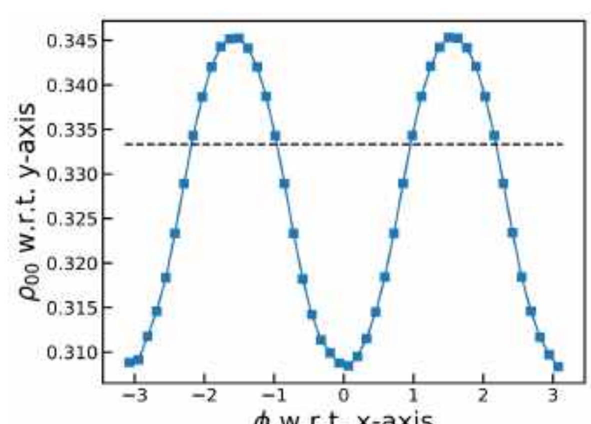




- **Subatomic spintronics in HIC: a new probe for QGP**







Angular momentum in HIC