Hadronic effects on Lambda polarization

Che-Ming Ko
Texas A&M University

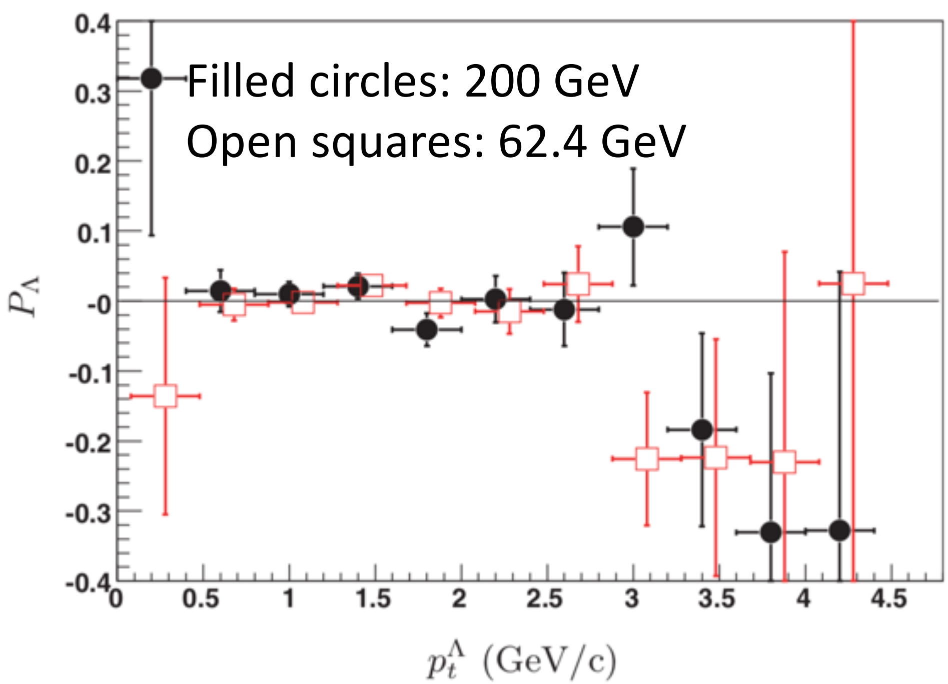
- ❑ Introduction
- ❑ Temperature dependence of Lambda spin polarization
- ❑ Hadronic effects on Lambda spin polarization
- ❑ Summary

In collaboration with Haesom Sung and Su Houng Lee

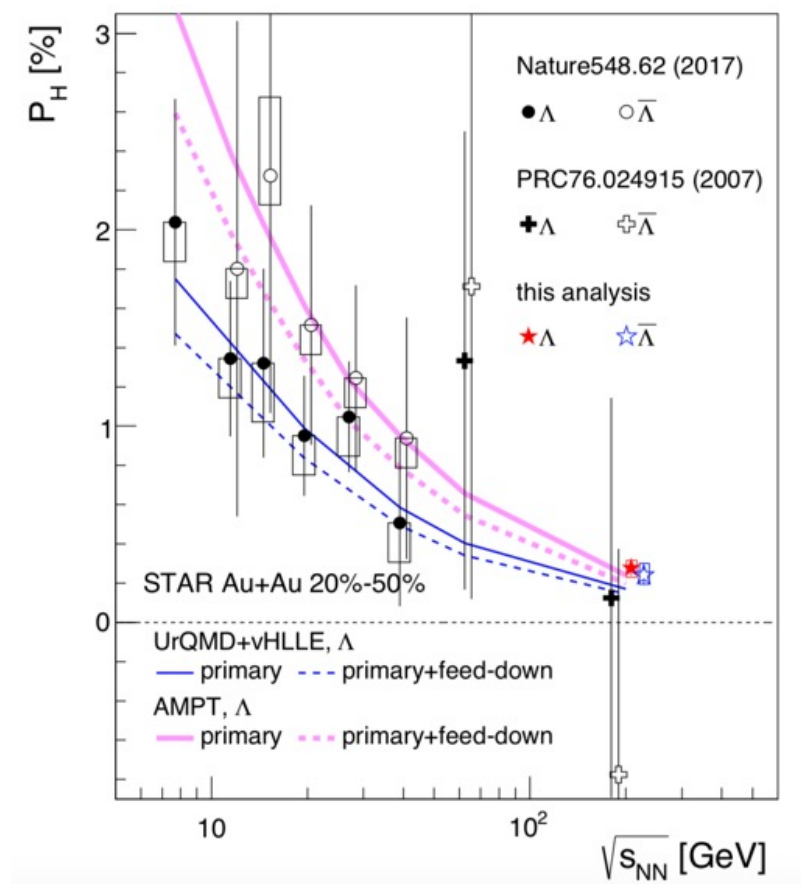
Λ polarization in relativistic heavy ion collisions

- First suggested by Z. T. Liang & X. N. Wang, PRL 94, 102301 (2005)

Abelev (STAR), PRC 76, 024915 (2007)



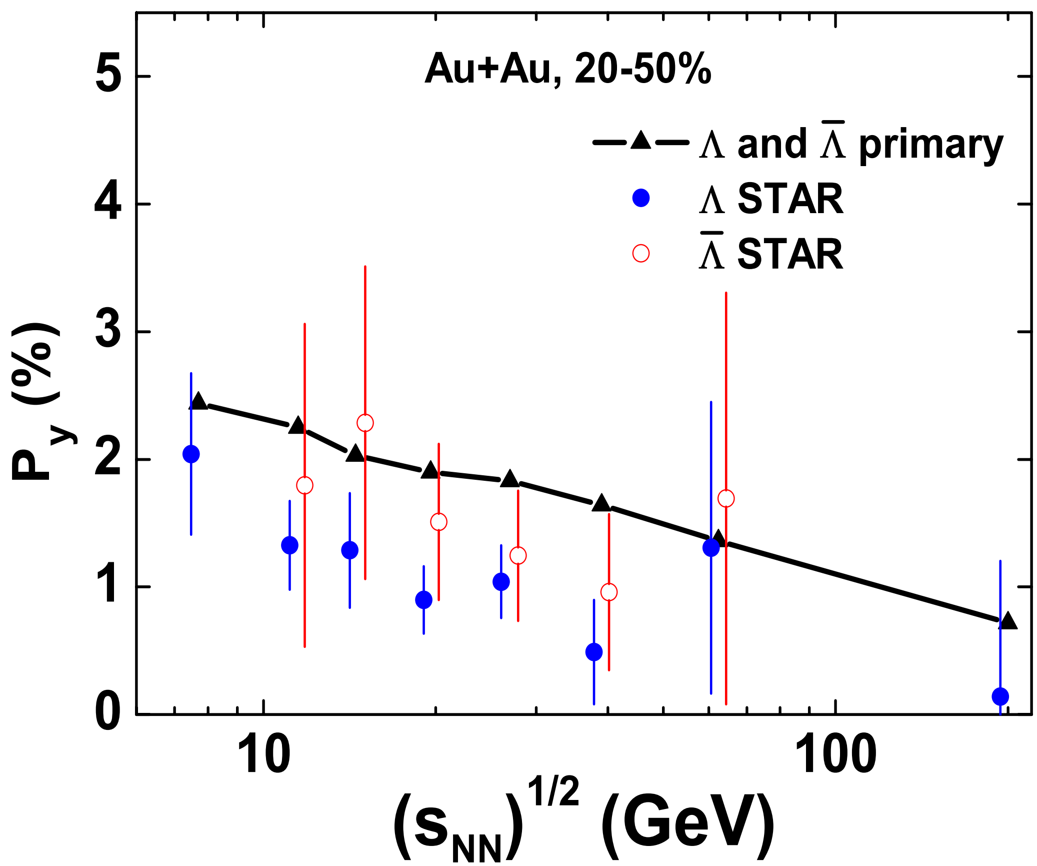
Adam (STAR), PRC 98, 14910 (2018)



- Studies based on fluid dynamics [Cernai, Becatiini, Karpenko, Voloshin] and transport models [Wang et al.] assuming Λ in thermal equilibrium in the rotating fireball at chemical freeze out of HIC both predict Λ polarizations comparable to the STAR data.

Λ polarization from chiral kinetic approach

Sun & Ko, PRC 96, 024906 (2017)



$$\frac{d\mathbf{x}}{dt} = \frac{\hat{\mathbf{p}} + 2\lambda|\mathbf{p}|(\hat{\mathbf{p}}\cdot\mathbf{b})\boldsymbol{\omega}}{1 + 6\lambda|\mathbf{p}|(\mathbf{b}\cdot\boldsymbol{\omega})}$$

$$\Lambda = \pm 1 = \text{helicity}$$

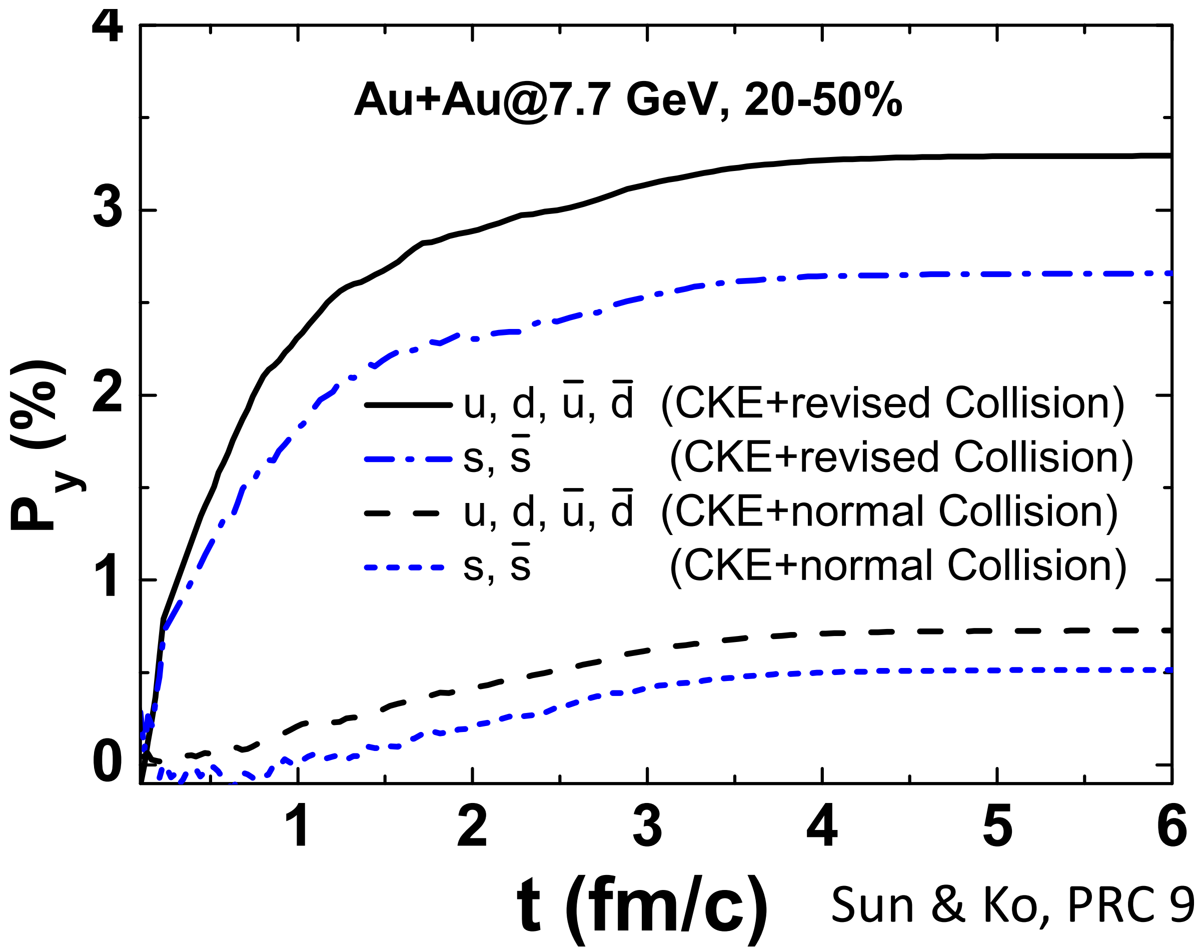
$$\mathbf{b} = \frac{\hat{\mathbf{p}}}{2|\mathbf{p}|^2} = \text{Berry curvature}$$

$$\frac{d\mathbf{p}}{dt} = 0$$

Including scattering that ensures the equilibrium distribution $\sqrt{G}f$ with $\sqrt{G} = 1 + 6\lambda|\mathbf{p}|(\mathbf{b}\cdot\boldsymbol{\omega})$.

- Consistent with data that Λ polarization decreases with collision energy due to decreasing vorticity field with increasing energy.

Global quark polarization from chiral kinetic approach



Sun & Ko, PRC 96, 024906 (2017)

- Quark polarization of about 2.5% is generated early in time due to large vorticity field, which decreases with time.
- Modified quark scattering due to change of phase-space measure enhances global quark polarization.

Color and spin statistical factors for polarized Λ

- Statistical factor for 3 colored quarks or antiquarks to form a colorless Λ or anti-Λ: g_C=1/27

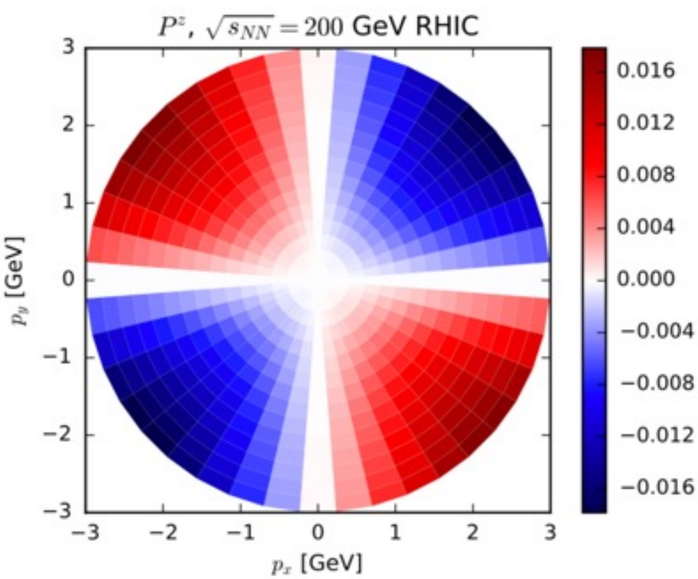
- Statistic factor for 3 spin-1/2 quarks to form a polarized spin ½ Λ: Λ spin is determined by the spin of s-quark, so u and d quarks form a spin singlet

$$
\begin{aligned}
g_S &= |(1/\sqrt{2})(\langle\uparrow\downarrow| - \langle\downarrow\uparrow|)[\cos(\theta_1/2)\cos(\theta_2/2)|\uparrow\uparrow\rangle \\
&\quad + \cos(\theta_1/2)\sin(\theta_2/2)e^{i\phi_2}|\uparrow\downarrow\rangle \\
&\quad + \sin(\theta_1/2)\cos(\theta_2/2)e^{i\phi_1}|\downarrow\uparrow\rangle \\
&\quad + \sin(\theta_1/2)\sin(\theta_2/2)e^{i(\phi_1+\phi_2)}|\downarrow\downarrow\rangle]|^2 \\
&= \frac{1}{4}(1 - \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2\cos(\phi_1 - \phi_2)) \\
&= \frac{1}{4}(1 - \lambda_1\lambda_2\hat{\mathbf{p}}_1 \cdot \hat{\mathbf{p}}_2)
\end{aligned}
$$

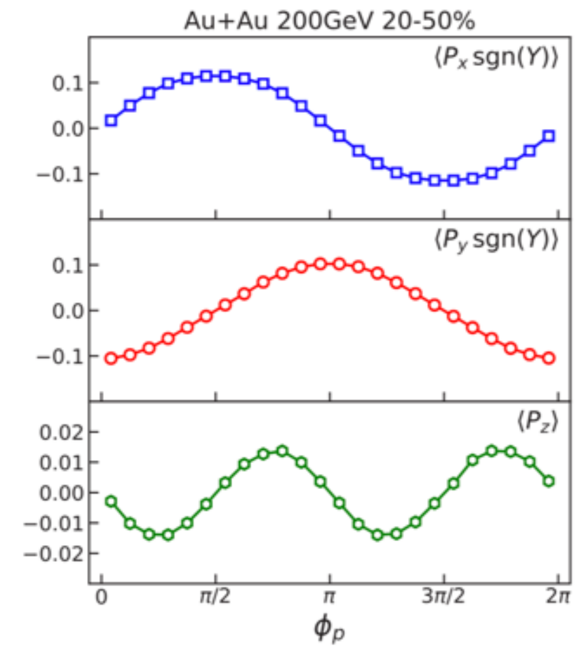
where $\theta_1(\theta_2)$ and $\phi_1(\phi_2)$ are polar angles of u(d) quark spin direction.

Longitudinal spin polarization

Becattini & Karpeno, PRL 120, 012302 (2018)



Xia, Li, Tang & Wang, PRC 98, 024905 (2018)

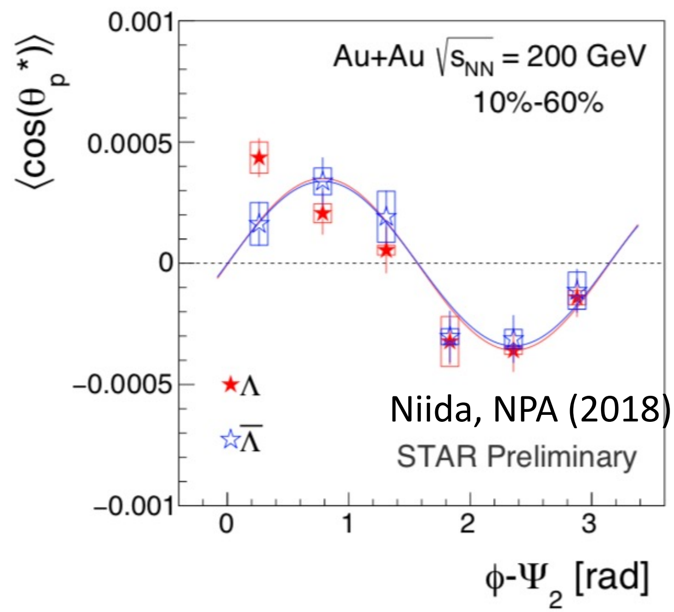


In terms of thermal vorticity

$$\bar{\omega}_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu), \quad \beta = \frac{u}{T}$$

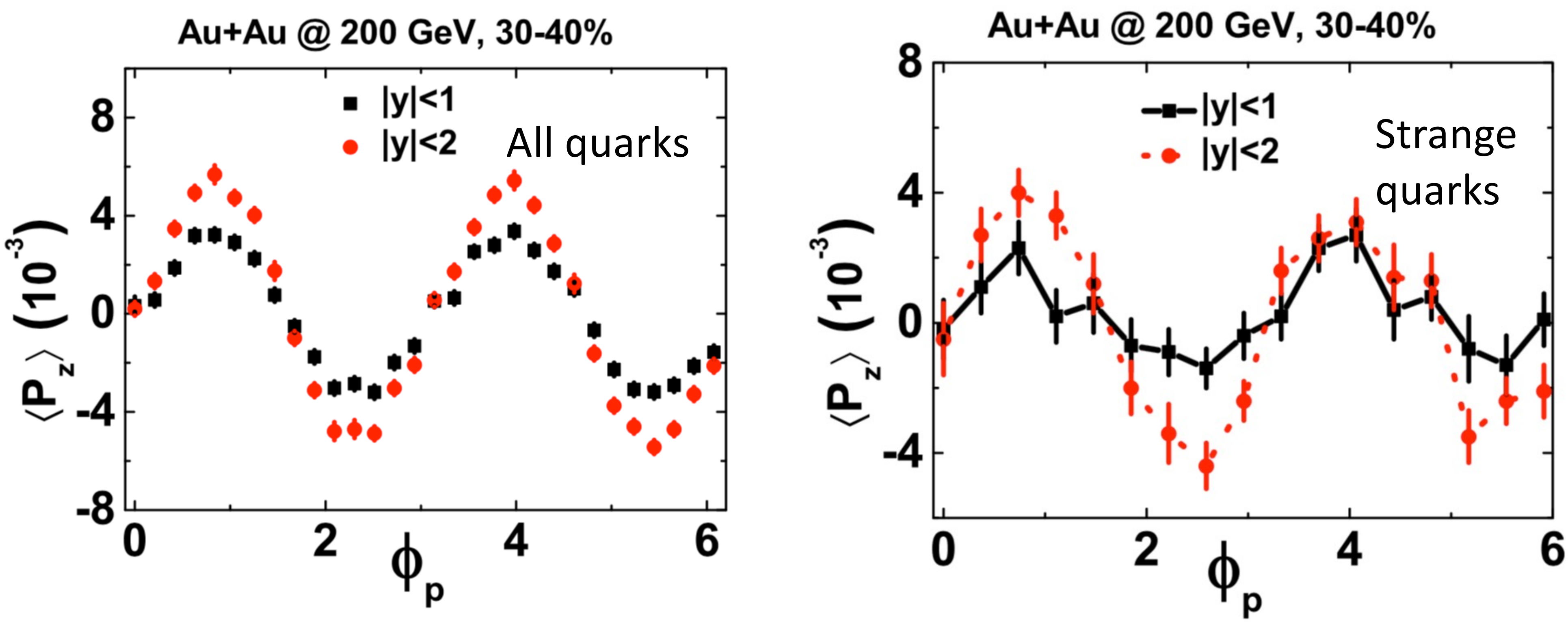
$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau} p_\tau \times \frac{\int_\Sigma d\Sigma_\lambda p^\lambda \bar{\omega}_{\rho\sigma} n_F (1 - n_F)}{\int_\Sigma d\Sigma_\lambda p^\lambda n_F}$$

$$S^z(\mathbf{p}_T, y = 0) \approx \frac{dT}{d\tau}\frac{1}{mT} v_2(p_T) \sin 2\phi$$



leads to opposite sign in the azimuthal-angle dependence of p_z compared to STAR data.

- Azimuthal angle dependence of longitudinal spin polarization in chiral kinetic approach

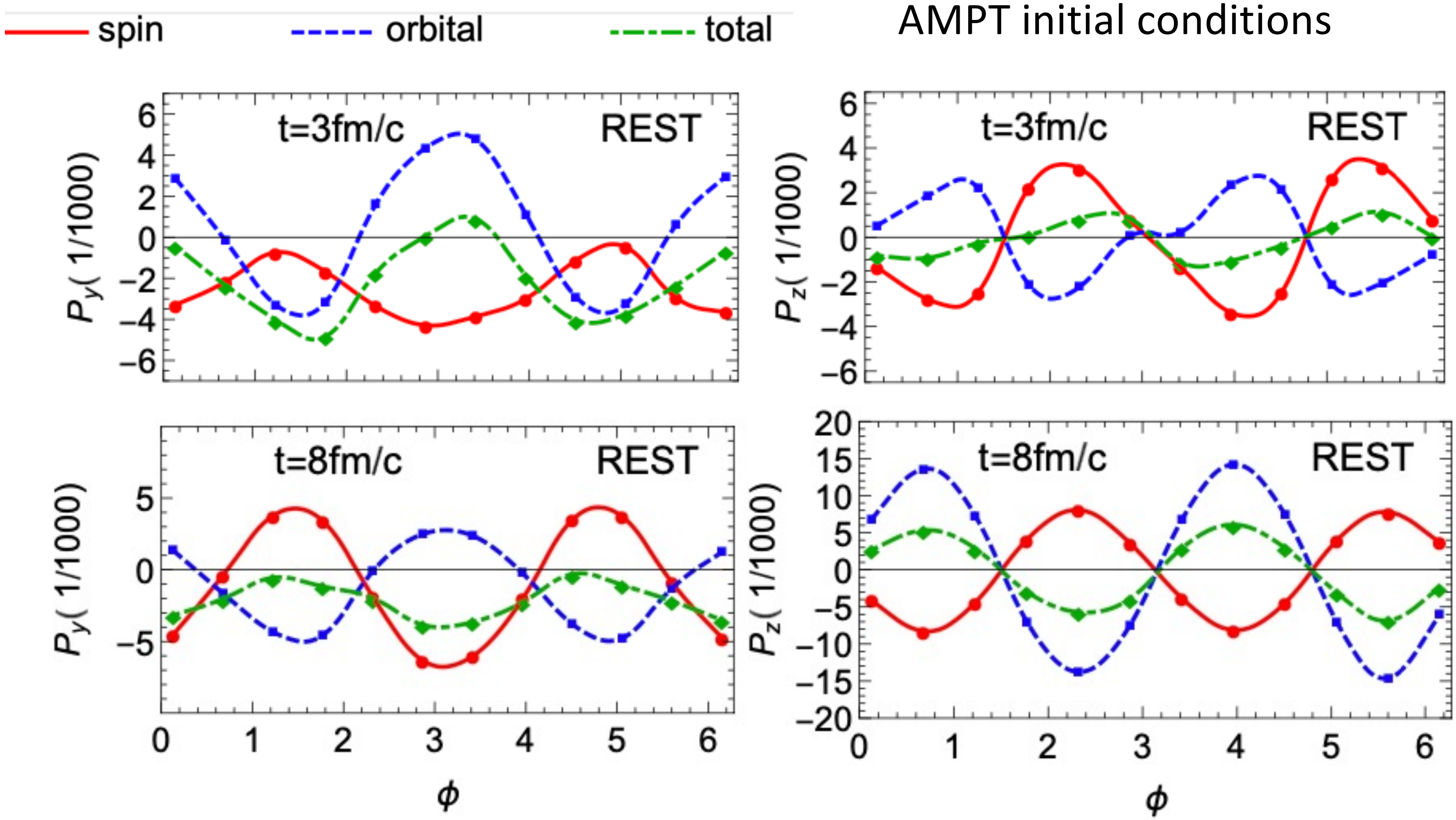


- Similar to that from preliminary STAR data [Niida, NPA (2018)].
- Opposite sign from those based on thermal-vorticity [Becattini & Karpenko, PRL 120, 012302 (2018); Xia et al., PRC 98, 024905 (2018)].

Local spin polarizations in an angular momentum conserved chiral transport model

Shuai Liu, Yifeng Sun & Ko, PRL 127, 142301 (2022)

AMPT initial conditions



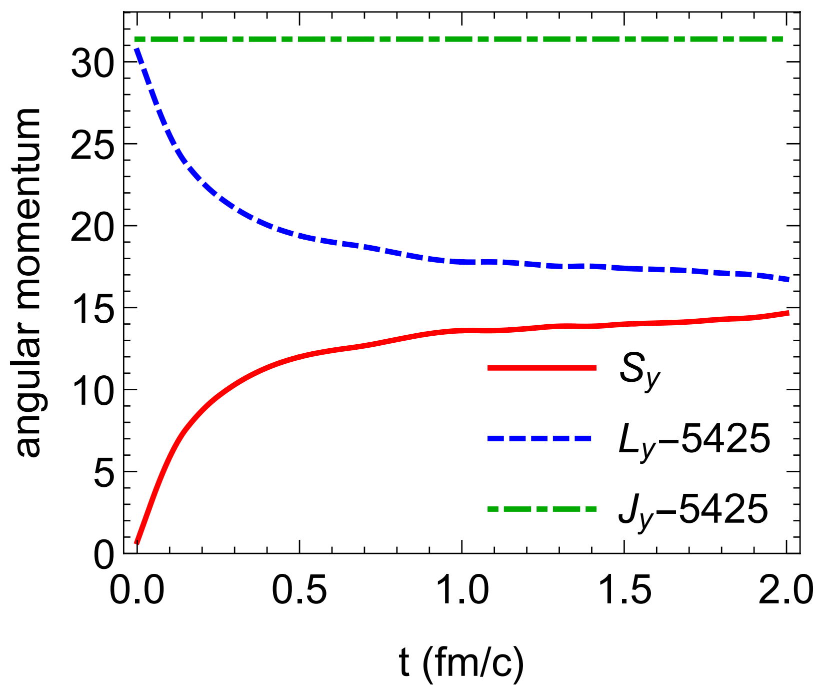
- P_y is dominated initially by the orbital contribution and finally by the spin contribution, which is reversed for P_z.
- Both P_y and P_z have similar azimuthal angle dependence as in STAR data.

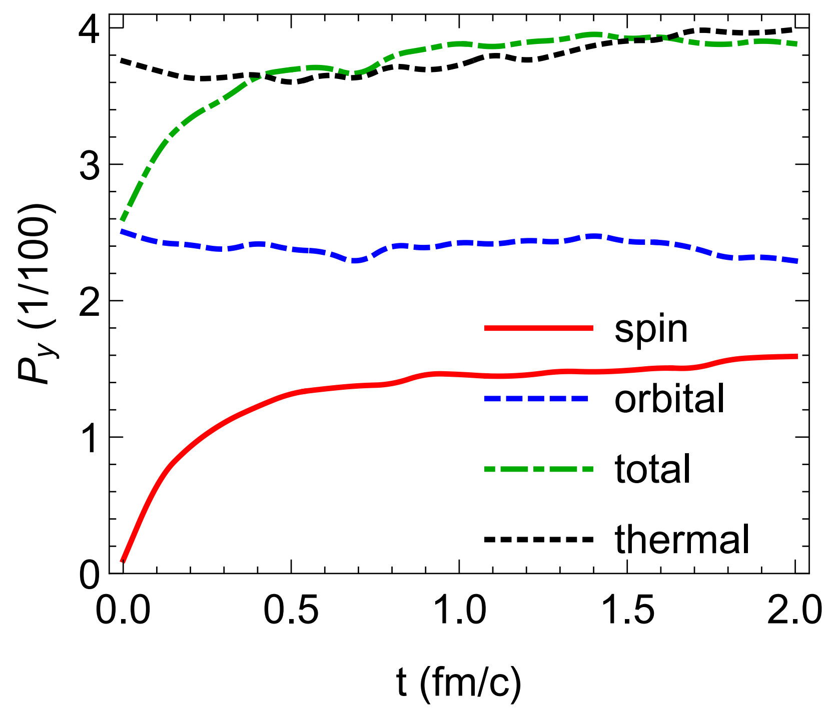
Expanding quark matter

Shuai Liu, Yifeng Sun & CMK, PRL 127, 142301 (2021)

$$\text{Conserved current} \quad j^{\mu}_{R/L} \approx \int \frac{d^3\mathbf{p}}{(2\pi)^3 p}(\underbrace{p^{\mu} f_{R/L}}_{\text{spin}} + \underbrace{S^{\mu\nu}\partial_{\nu} f_{R/L}}_{\text{orbital}})$$

$$\text{Spin polarization} \quad \mathcal{P}_y = \frac{\int d^3\mathbf{x} j_{5y}(\mathbf{x})}{\int d^3\mathbf{x}\, n(\mathbf{x})}$$





- Initial conditions: Sizes: 5×5×5 fm^3; Temp. : 300 MeV; Flow profile: $\gamma\boldsymbol{v} = 2\boldsymbol{\omega}(x,0,0)$ with $\boldsymbol{\omega} = (0,0.12,0)$ (fm/c)$^{-1}$; $L_y = 5425\ \hbar,\ S_y = 0$; isotropic quark scattering cross section of 10 mb.

- Total angular momentum $J_y = L_y + S_y$ is conserved.
- Total polarization increases with time and approaches the thermal value ω/T.

Spin polarization vector of a fermion

- Shuai Liu & Yi Yin, JHEP 07, 188 (2021)
- F. Becattini, M. Buzzegoli & A. Palermo, PLB 820, 136519 (2021)
- Cong Yi, Shi Pu & Di-Lun Yang, PRC 104, 064901 (2021)

$$S^\mu(x,p) = -\frac{1}{8m}(1-n_F)\epsilon^{\mu\nu\rho\sigma}p_v\varpi_{\rho\sigma}(x) - \frac{1}{4m}(1-n_F)\epsilon^{\mu\nu\rho\sigma}p_v\frac{n_\rho p^\lambda \xi_{\lambda\sigma}(x)}{n\cdot p}$$

where *p* is the 4-momentum of the fermion, n_F is the Fermi-Dirac distribution function, *n* is a unit four vector that specifies the frame of reference, and

$$\text{thermal vorticity } \varpi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma\beta_\rho - \partial_\rho\beta_\sigma)$$

$$\text{thermal shear } \xi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma\beta_\rho + \partial_\rho\beta_\sigma)$$

where $\beta = {}^u/_T$ with *u* being the flow field.

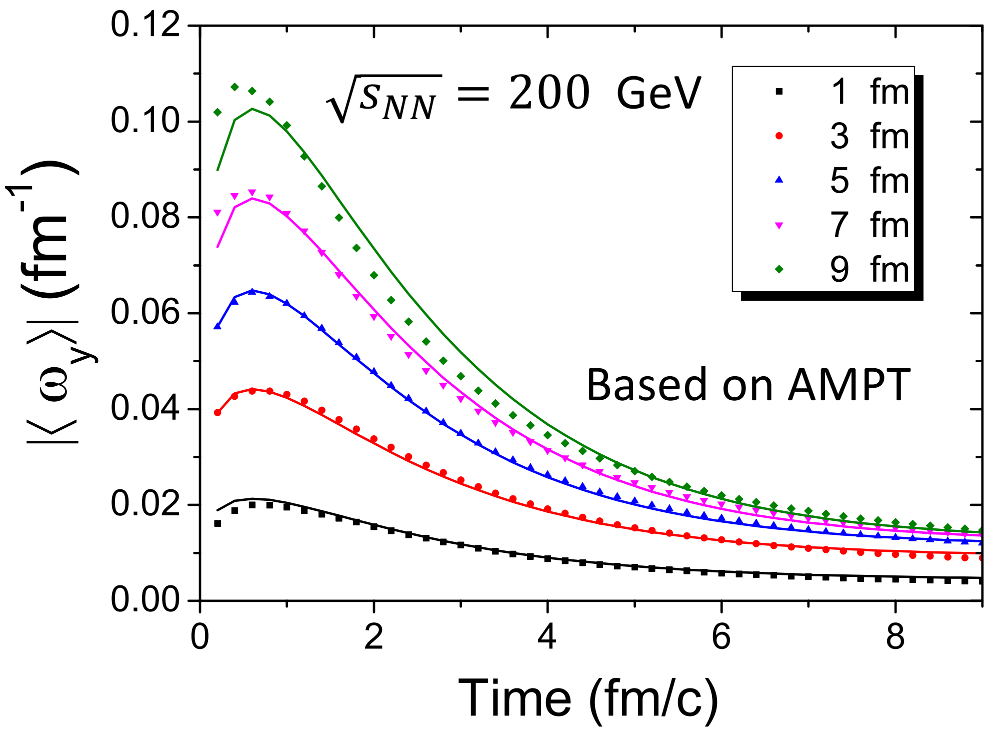
- Thermal shear is needed to describe the azimuthal angle dependence of Lambda local polarization in hydro and coarse-grained transport approaches but is naturally included in the chiral kinetic approach.

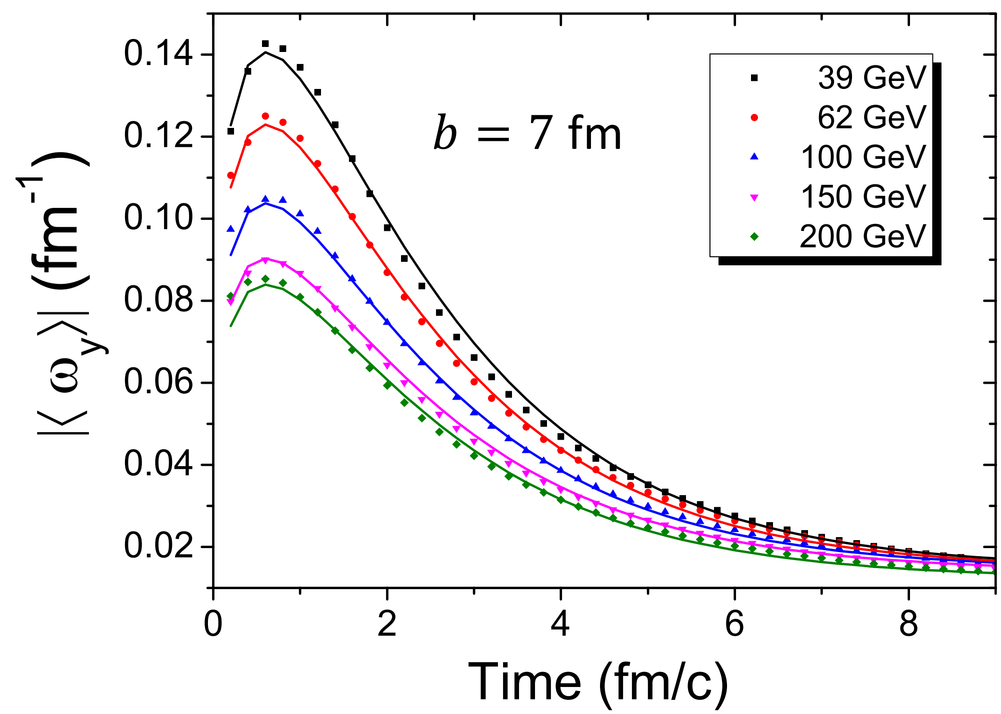
Vorticity in relativistic heavy ion collisions

Jiang, Lin & Liao,
PRC 94, 044910 (2016)

$$\boldsymbol{\omega} = \frac{1}{2}\boldsymbol{\nabla} \times \mathbf{v}, \quad \langle \omega_y \rangle = \frac{\int d^3\mathbf{r}\ [\mathcal{W}(\mathbf{r})]\, \omega_y(\mathbf{r})}{\int d^3\mathbf{r}\ [\mathcal{W}(\mathbf{r})]}, \quad \mathcal{W}(\mathbf{r}) = \rho^2 \epsilon(\mathbf{r})$$

ρ: distance from y-axis
$\epsilon(\boldsymbol{r})$: energy density



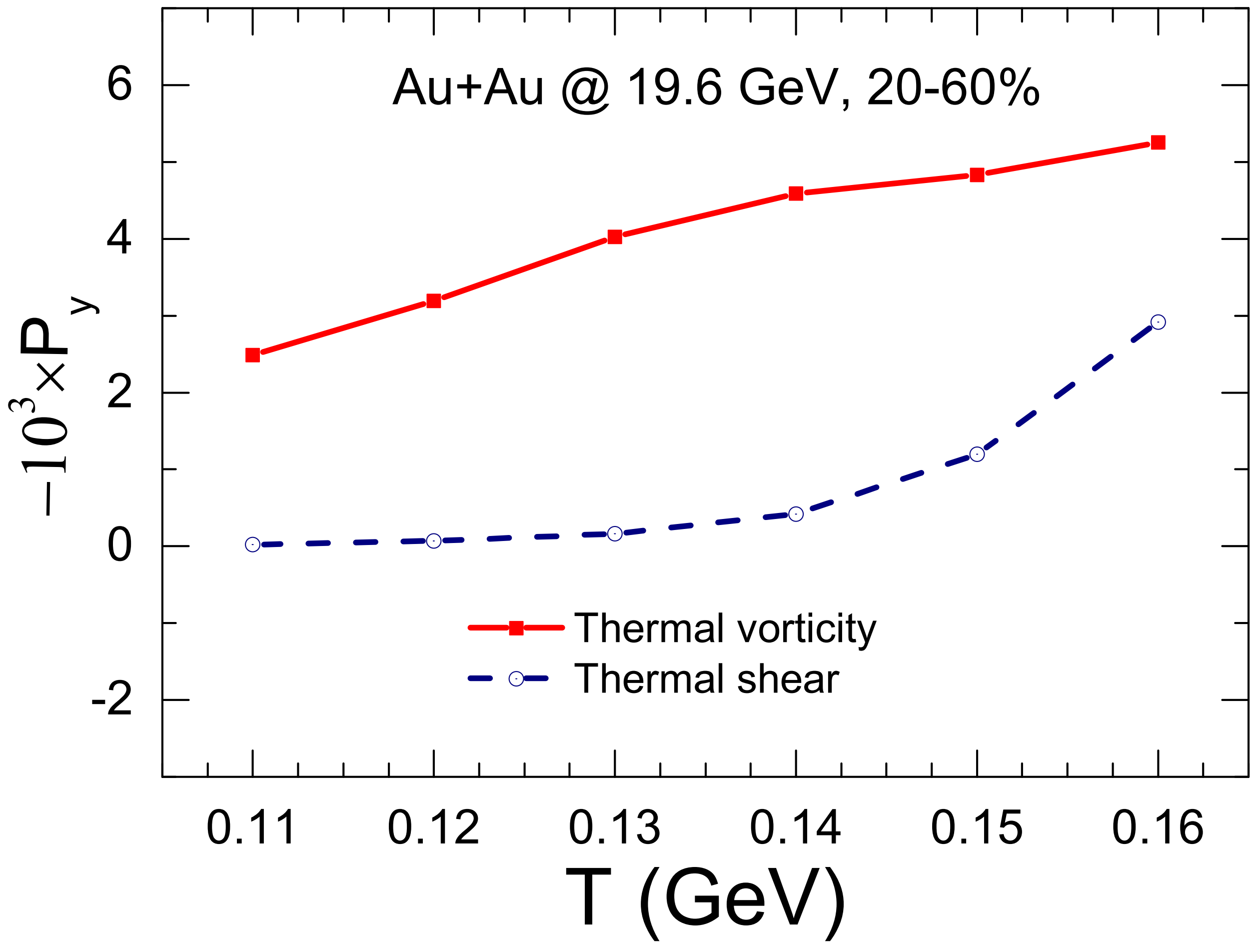


- Average vorticity decreases with time, decreasing impact parameter, and increasing collision energy. The lifetime is much longer than that of electromagnetic field.
- Can lead to chiral vortical effect and vortical separation effect

$$\mathbf{J}^V = \frac{\mu\mu_5}{\pi^2}\boldsymbol{\omega} \quad \text{and} \quad \mathbf{J}^A = \left(\frac{T^2}{6} + \frac{\mu^2 + \mu_5^2}{2\pi^2}\right)\boldsymbol{\omega}$$

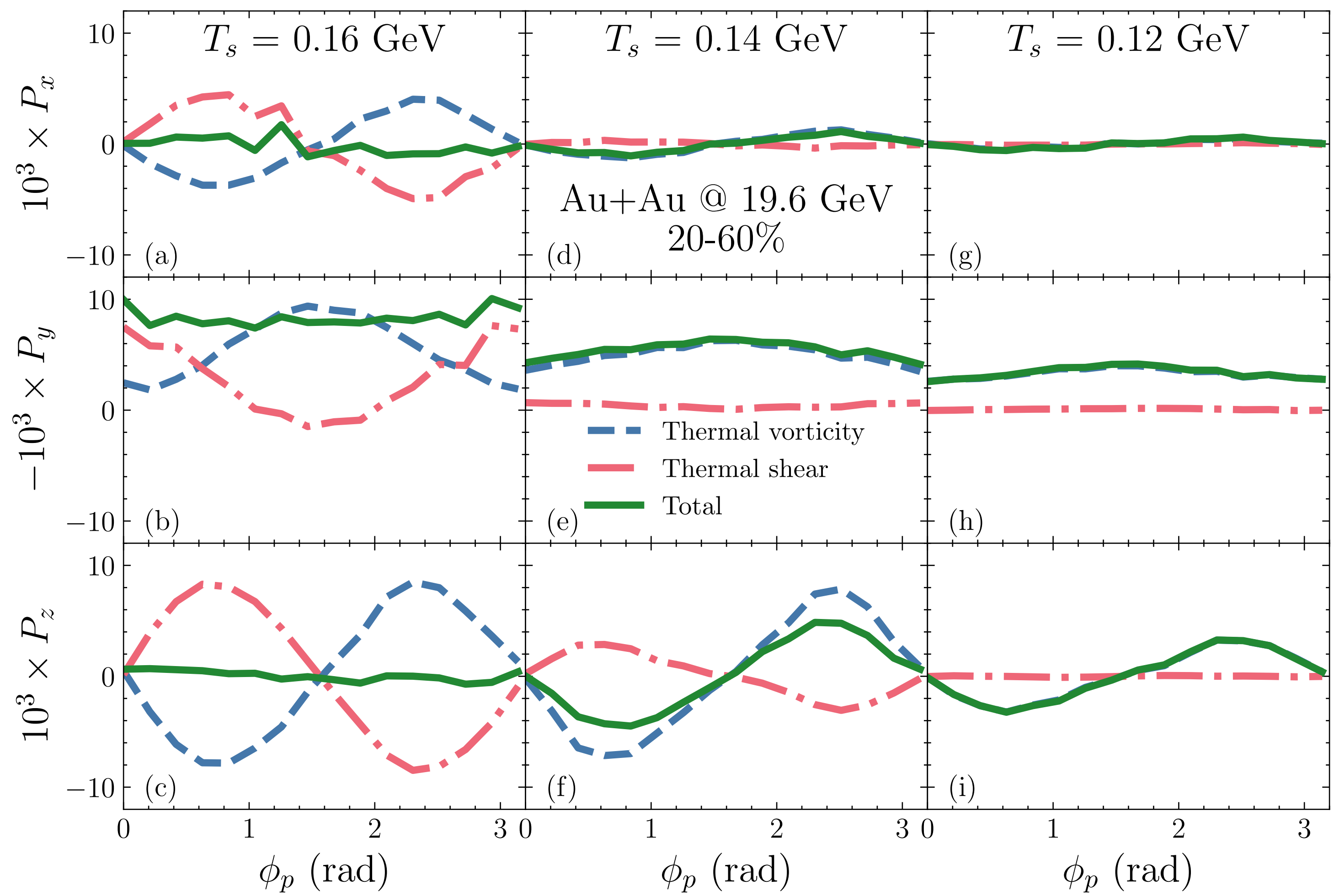
Evolution of Λ global polarization during hadronic expansion

Yifeng Sun, Zhen Zhang, Wenbin Zhao & Ko, PRC 105, 034911 (2022)



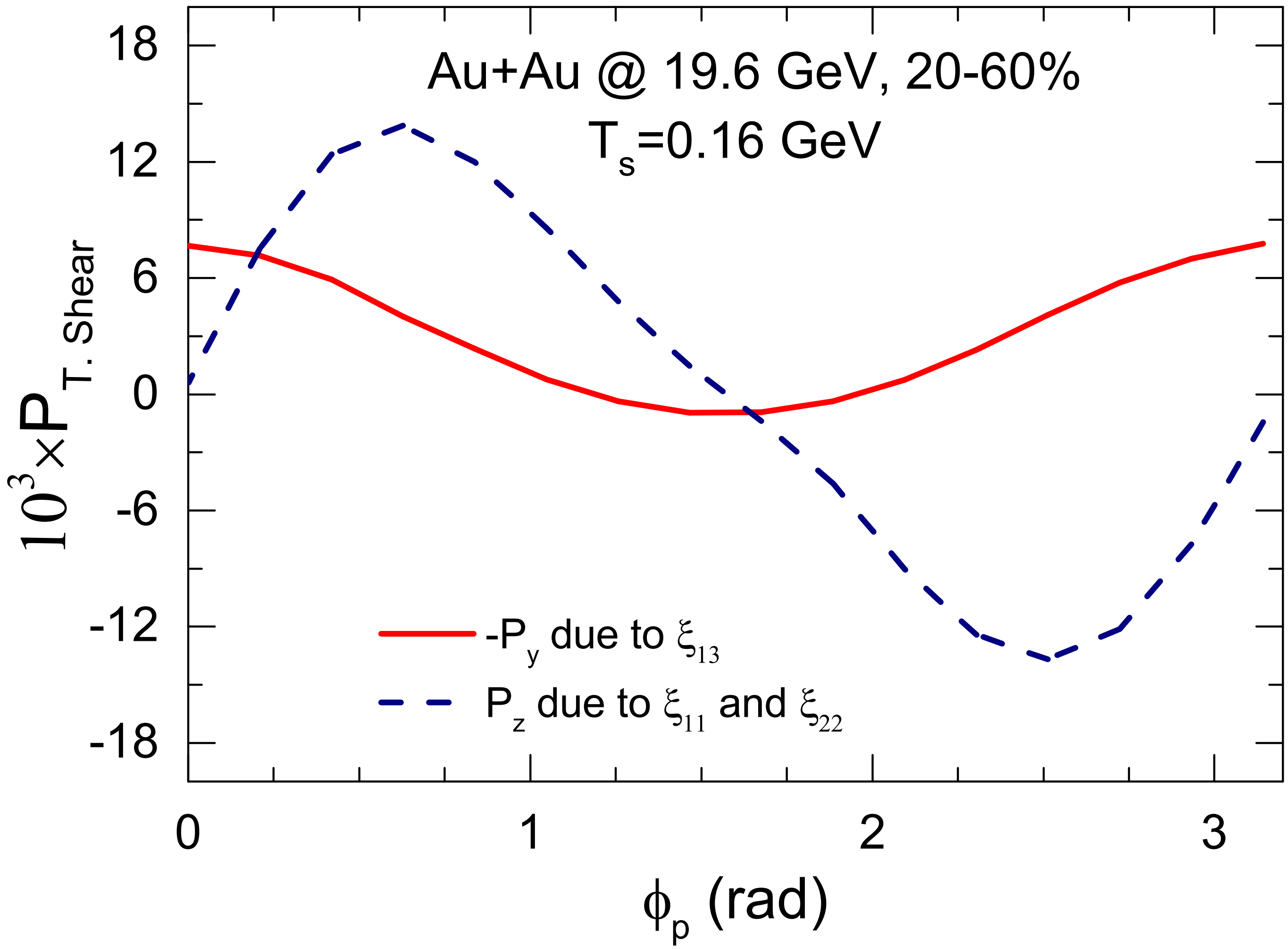
MUSIC+UrQMD: Thermal vorticity contributes to Λ global polarization more than that from thermal shear, and both contributions decrease with decreasing temperature.

Temperature dependence of thermal vorticity and thermal shear to Λ local spin polarization



Thermal vorticity and thermal shear give opposite azimuthal angle dependence of Λ local polarization, and both contributions decrease with temperature.

Contribution of thermal shear components to Λ polarization



Transverse components of thermal shear give Λ polarization a similar azimuthal angle dependence as seen in experiments.

EPJ Web of Conferences **276**, 06001 (2023) https://doi.org/10.1051/epjconf/202327606001
SQM 2022

Hadron production from heavy ion collisions

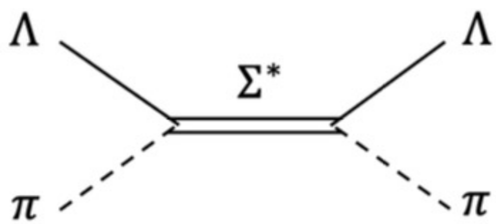
Che Ming Ko[1,*]

[1]Cyclotron Institute and Department of Physic and Astronomy, Texas A&M University, College Station, Texas 77843-3366, USA

Abstract. A brief review of some topics in hadron production from heavy ion collisions is given. They include charged pion ratio as a probe of nuclear symmetry energy, in-medium effects on pion production, enhanced Λ_c/D^0 ratio, Λ local polarization, and $X(3872)$ production.

of 150 MeV [48]. Both Λ global and local spin polarizations decrease, however, with temperature as the hadronic matter cools [49]. The fact that the experimental data is consistent with Λ spin polarizations at the hadronization temperature indicates that they freeze out or decouple early from the hadronic matter. This would be the case if the $\Lambda - \pi$ scattering is through the spin $3/2$, parity positive $\Sigma^*(1358)$ resonance since the ratio of Λ spin non-flip to flip probabilities in this scattering is 3.5.

S-channel $\Lambda - \pi$ scattering



$$\bar{\sigma}(s) = \frac{8\pi}{k^2}\frac{s\Gamma^2(s)}{(s - m_{\Sigma^*}^2)^2 + s\Gamma^2(s)}$$

$$M_{\Sigma^*} = 1358\ \text{MeV}, \quad \Gamma(M_{\Sigma^*}) = 39.4\ \text{MeV}$$

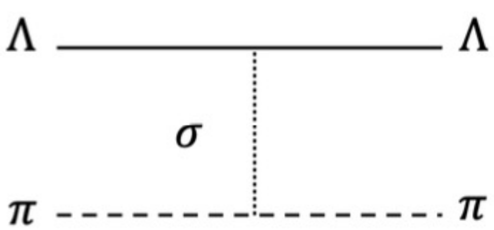
$$k = \sqrt{\frac{[s - (m_\Lambda + m_\pi)^2][s - (m_\Lambda - m_\pi)^2]}{4s}}$$

$$\sigma_{++} = \frac{1}{3}\bar{\sigma}\sum_{m,M}\left|\left\langle \frac{1}{2}\frac{1}{2}1m\middle|\frac{3}{2}M\right\rangle\right|^4 = \frac{14}{27}\bar{\sigma}$$

$$\sigma_{+-} = \sigma\frac{1}{3}\sum_{m,M}\left|\left\langle \frac{1}{2} - \frac{1}{2}1m\middle|\frac{3}{2}M\right\rangle\left\langle \frac{3}{2}M\middle|\frac{1}{2}\frac{1}{2}1m\right\rangle\right|^2 = \frac{4}{27}\bar{\sigma}$$

Ratio of spin flip to Non-flip cross sections: $R = \frac{\sigma_{+-}}{\sigma_{++}} \approx 0.3$

t-channel $\Lambda - \pi$ scattering



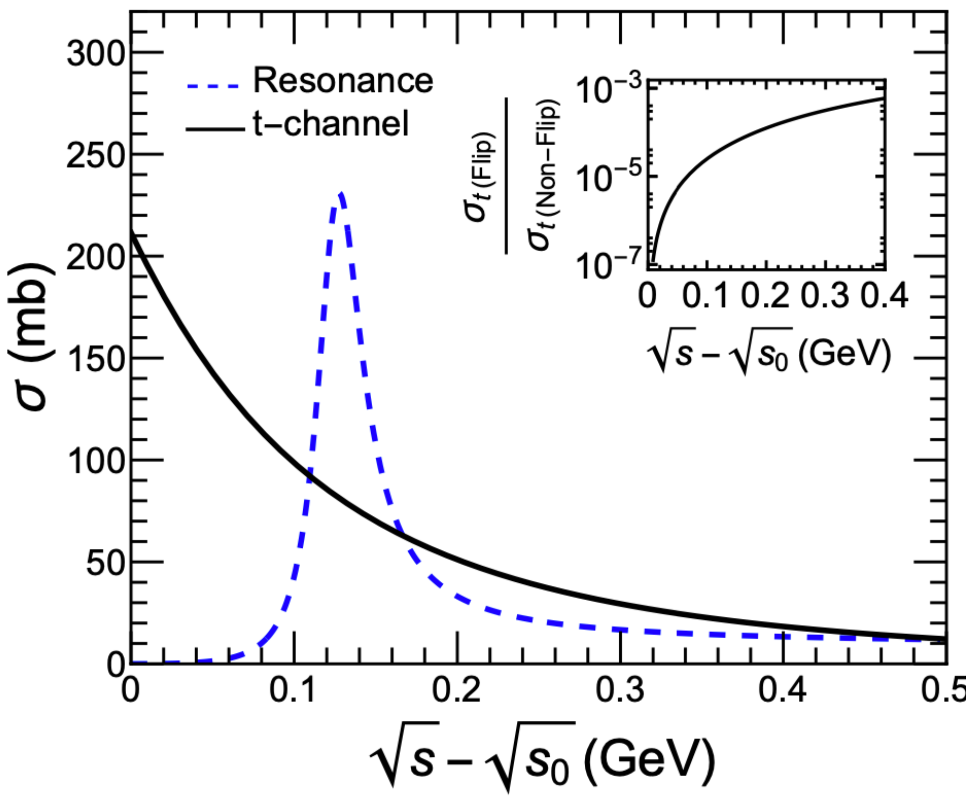
$$\mathcal{L} = g_{\sigma\Lambda\Lambda}\bar{\Lambda}\Lambda\sigma,\ \ \mathcal{L} = g_{\sigma\pi\pi}\sigma\pi\pi$$
$$m_\sigma = 400 - 550\ \mathrm{MeV},\ \ \Gamma_\sigma(m_\sigma) = 200 - 350\ \mathrm{MeV}$$
$$g_{\sigma\Lambda\Lambda} = 7.07,\ \ g_{\sigma\pi\pi} = 2.37\ \mathrm{GeV}$$

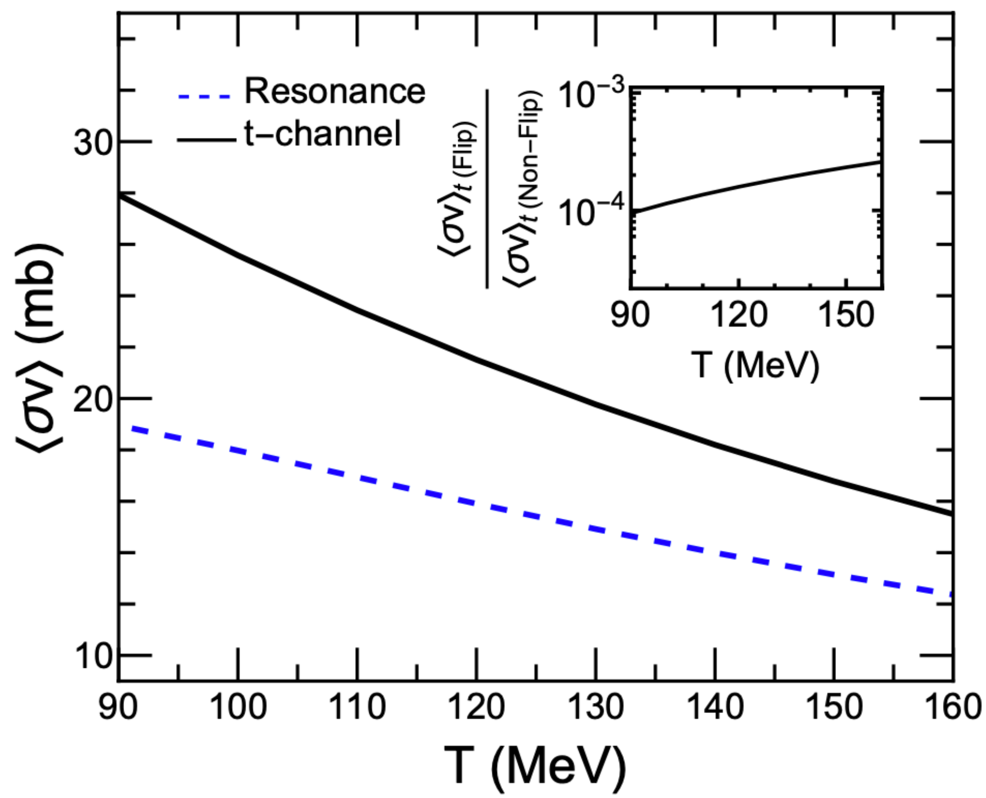
$$|\mathcal{M}_{t++}|^2 = \frac{g^2_{\Lambda\Lambda\sigma}g^2_{\sigma\pi\pi}F^2(t)}{(t-m_\sigma^2)^2 + m_\sigma^2\Gamma_\sigma(s)^2} \times (E_\Lambda + m_\Lambda)^2\left[1 - \frac{p^2\cos\theta}{(E_\Lambda + m_\Lambda)^2}\right]^2$$
$$|\mathcal{M}_{t+-}|^2 = \frac{g^2_{\Lambda\Lambda\sigma}g^2_{\sigma\pi\pi}F^2(t)}{(t-m_\sigma^2)^2 + m_\sigma^2\Gamma_\sigma(s)^2}\,\frac{p^4\sin^2\theta}{(E_\Lambda + m_\Lambda)^2}$$

$$F(t) = \frac{\Lambda^2 + m_\sigma^2}{\Lambda^2 + t},\ \ \Lambda = 1.8\ \mathrm{GeV}$$

Spin flip is a relativistic effect.

$\Lambda - \pi$ scattering cross sections and their thermal average





- t-channel cross section at $\sqrt{s} < m_{\Sigma^*}$ is larger than s-channel one.
- t-channel has a larger thermal averaged cross section than s-channel one at all temperature.
- Lambda spin flip cross section is 1/3.5 in s-channel and negligible in t-channel.

Kinetic equations for Lambda spin evolution

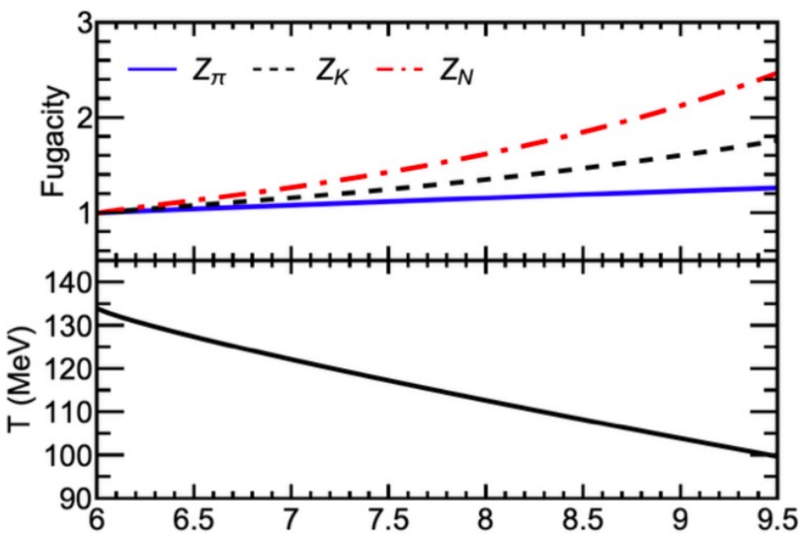
$$\frac{dN_{\Lambda_+}}{d\tau} = -\langle\sigma_{\Lambda_+\pi\to\Lambda_-\pi}v\rangle z_\pi n_\pi N_{\Lambda_+} + \langle\sigma_{\Lambda_-\pi\to\Lambda_+\pi}v\rangle z_\pi n_\pi N_{\Lambda_-}$$

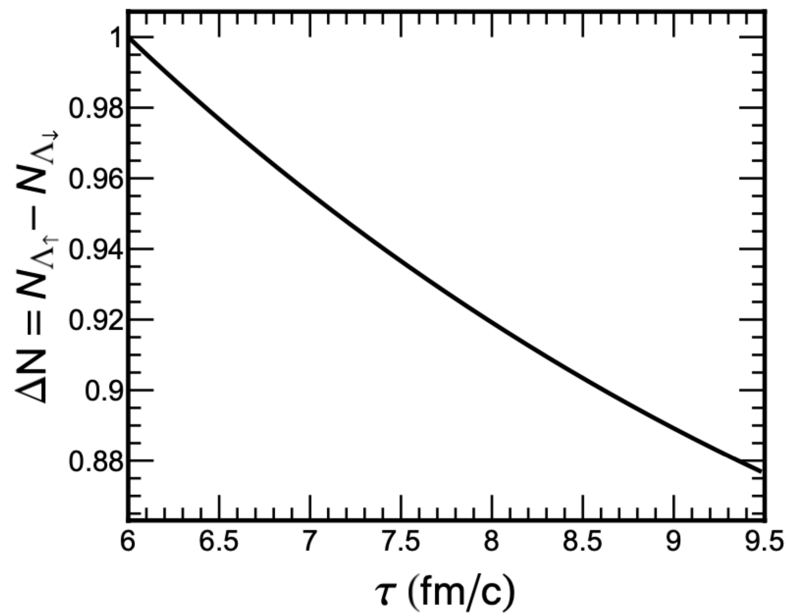
$$\frac{dN_{\Lambda_-}}{d\tau} = \langle\sigma_{\Lambda_+\pi\to\Lambda_-\pi}v\rangle z_\pi n_\pi N_{\Lambda_+} - \langle\sigma_{\Lambda_-\pi\to\Lambda_+\pi}v\rangle z_\pi N_{\Lambda_-}$$

$$\langle\sigma_{\Lambda_+\pi\to\Lambda_-\pi}v\rangle = \langle\sigma_{\Lambda_-\pi\to\Lambda_+\pi}v\rangle \equiv \langle\sigma v\rangle \longrightarrow \frac{d\Delta N}{d\tau} = -2\langle\sigma v\rangle z_\pi n_\pi \Delta N$$

$$T(\tau) = T_{\rm ch} - (T_{\rm ch} - T_{\rm k})\left(\frac{\tau - \tau_{\rm ch}}{\tau_{\rm k} - \tau_{\rm ch}}\right)^{0.85}$$

$\sqrt{s_{NN}}$ (GeV)	$T_{\rm ch}$ (MeV)	$T_{\rm k}$ (MeV)	$\tau_{\rm ch}$ (fm/c)	$\tau_{\rm k}$ (fm/c)
7.7	144	110	5.96	9.47





- Lambda polarization is reduced by only 11% from chemical to kinetic freeze out.

Summary

- Small Lambda spin flip than non-flip cross sections justifies the neglect of hadronic scattering effect on Lambda spin polarization.
- Need however to include effects due to Lambda-pion scattering via the omega meson exchange and also effects due to Lambda-nucleon scattering.