Global and local polarization of Λ hyperons across RHIC-BES energies

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Based on Phys.Rev.C 105 (2022) 6, 064909

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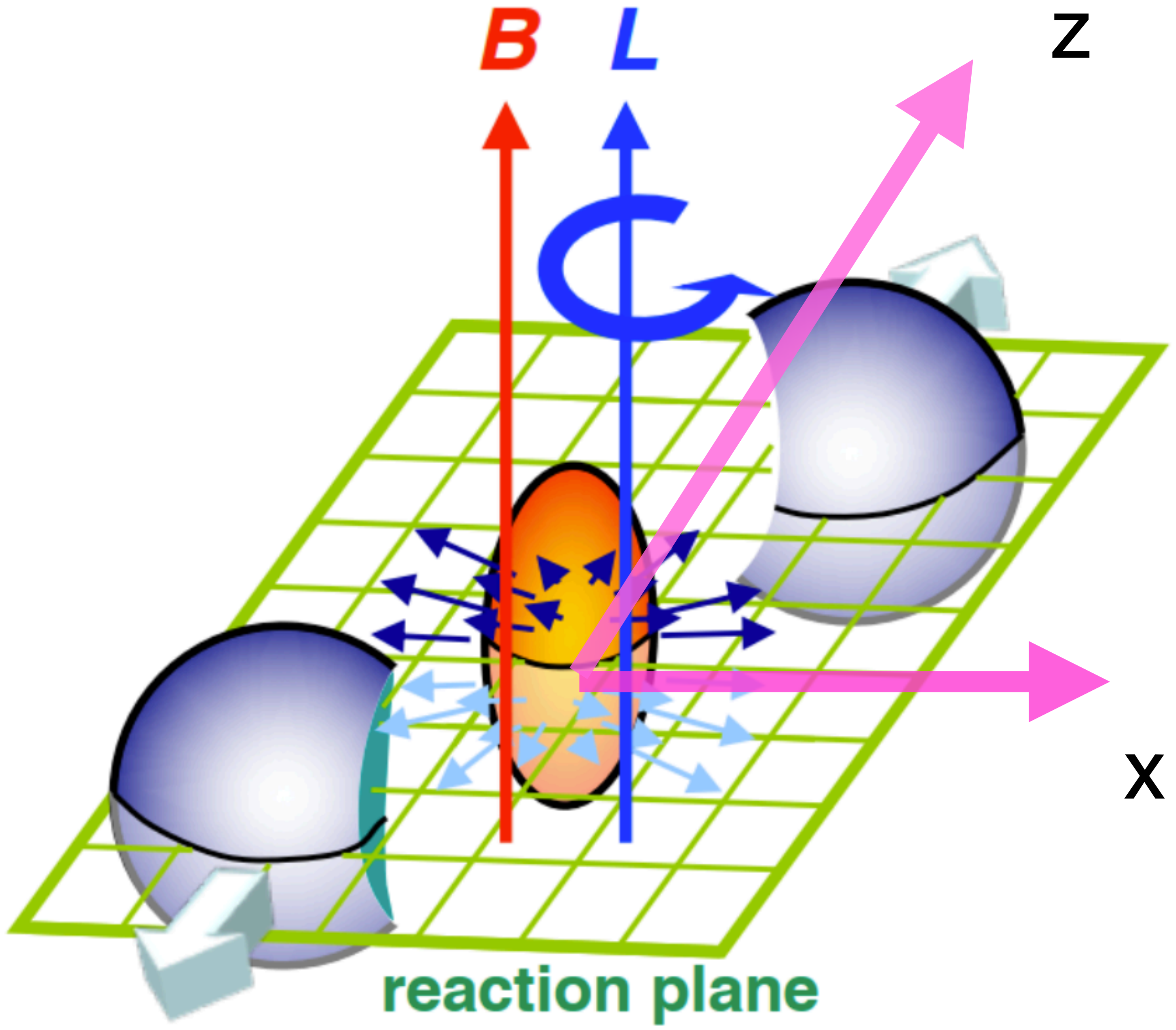
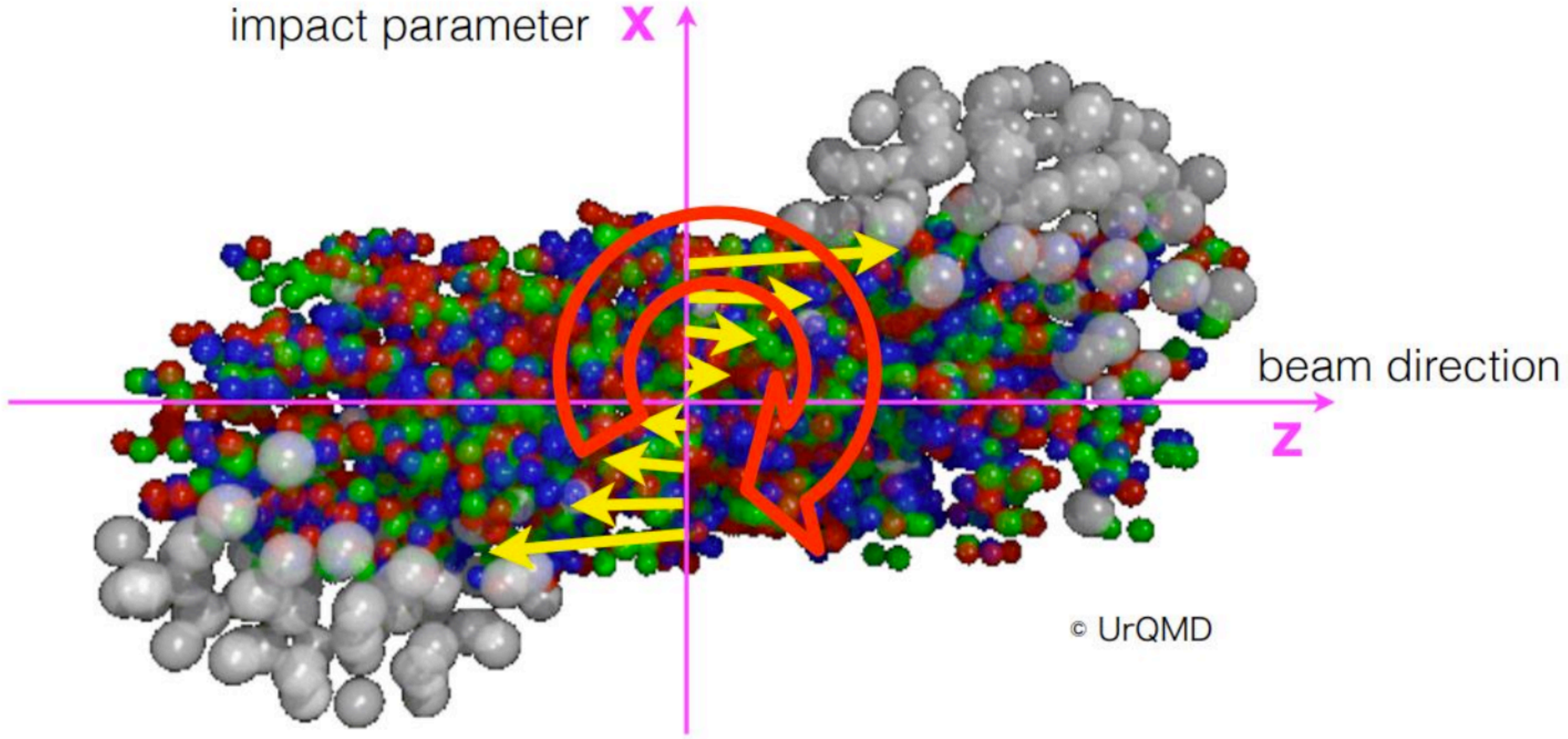
Outline

- Introduction
- $(3+1)$-D CLVisc hydrodynamics framework
  - AMPT and SMASH initial condition+hydro evolution + spin polarization
- Numerical results
  - Global and local polarization with spin hall effect (SHE), initial condition and baryon diffusion dependence
- Summary

Global polarization





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

Large angular momentum L ~ $10^5 - 10^7\hbar$

Strong magnetic filed B ~ $10^{13} - 10^{14}$ T

$\longrightarrow$ Polarization

Global polarization

Using screened potential model to calculate the global quark polarization:

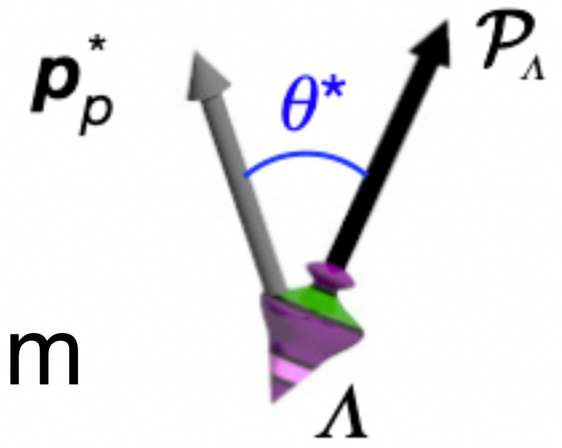
[Liang, Wang, Phys. Rev. Lett. 94 (2005) 102301]

$$P_q = -\frac{\pi \mu p}{4E\left(E + m_q\right)}$$

Λ and $\bar{\Lambda}$ hyperons are “self-analysing” $\boxed{\Lambda \to \mathrm{p} + \pi^-}$

the proton tends to be emitted along the spin direction of the parent Λ

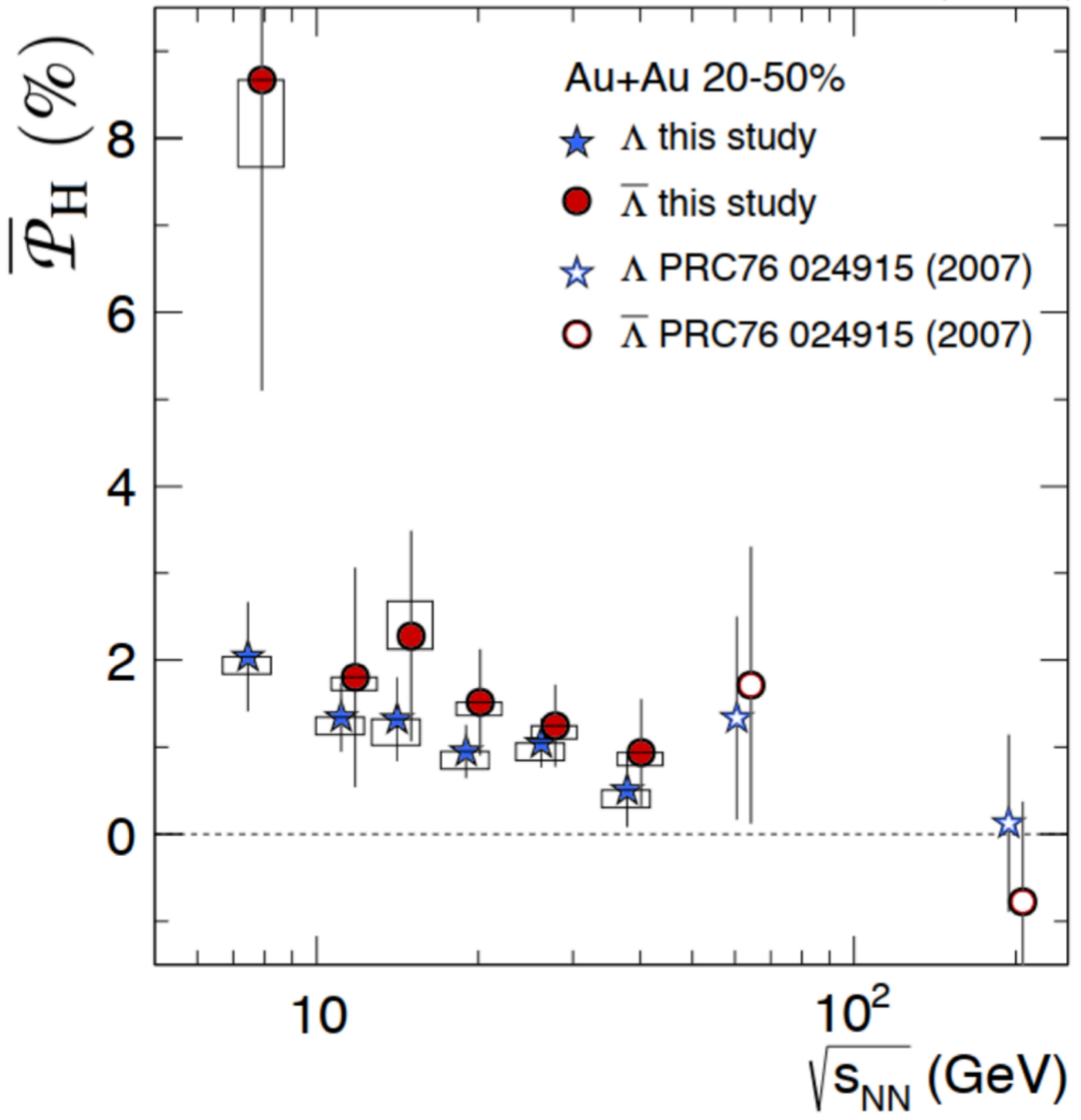
$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_{\mathrm{H}}\left|\mathscr{P}_{\mathrm{H}}\right|\cos\theta^*\right)$$



θ^*: the angle between proton momentum and Λ polarization vector $\mathscr{P}_{\mathrm{H}}$

α_{H}: the decay parameter

STAR, Nature 548, 62 (2017)



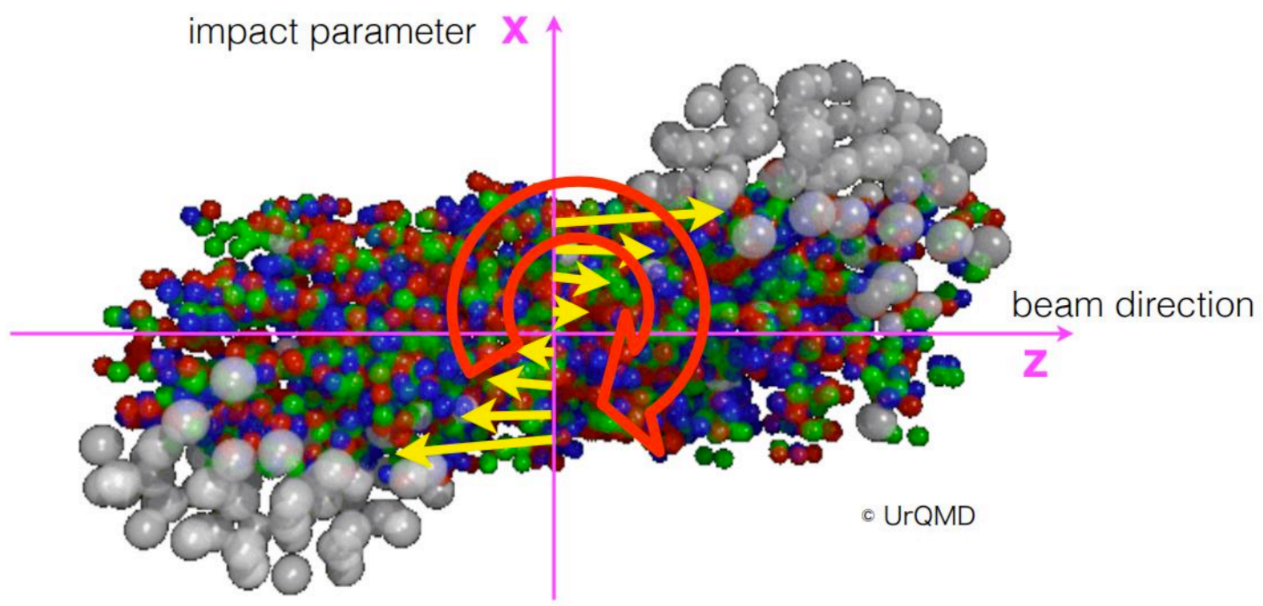
$$\omega \approx k_{\mathrm{B}} T\left(\overline{\mathscr{P}}_{\Lambda'} + \overline{\mathscr{P}}_{\bar{\Lambda}'}\right)/\hbar \sim 10^{22} s^{-1}$$

The fastest-rotating fluid so far!!!

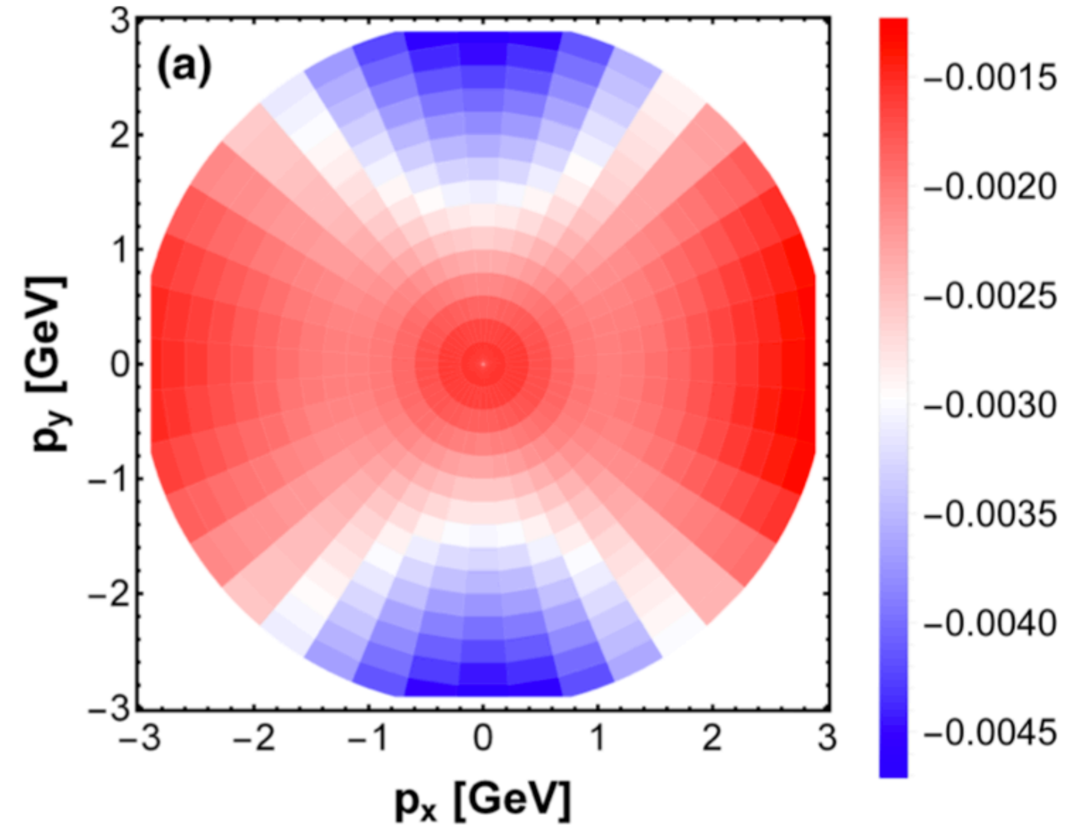
Local polarization

[Wu, Pang, Huang, and Wang, Phys. Rev. Research. 1, 033058 (2019)]
[Fu, Xu, Huang, and Song, Phys. Rev. C 103, 024903 (2021)]
[Xia, Li, Tang, and Wang, Phys. Rev. C 98, 024905 (2018)
[Becattini and Karpenko, Phys. Rev. Lett. 120, 012302 (2018)]
[Alzhrani, Ryu and Shen, Phys. Rev. C 106, 014905 (2022)]

Induced by angular momentum

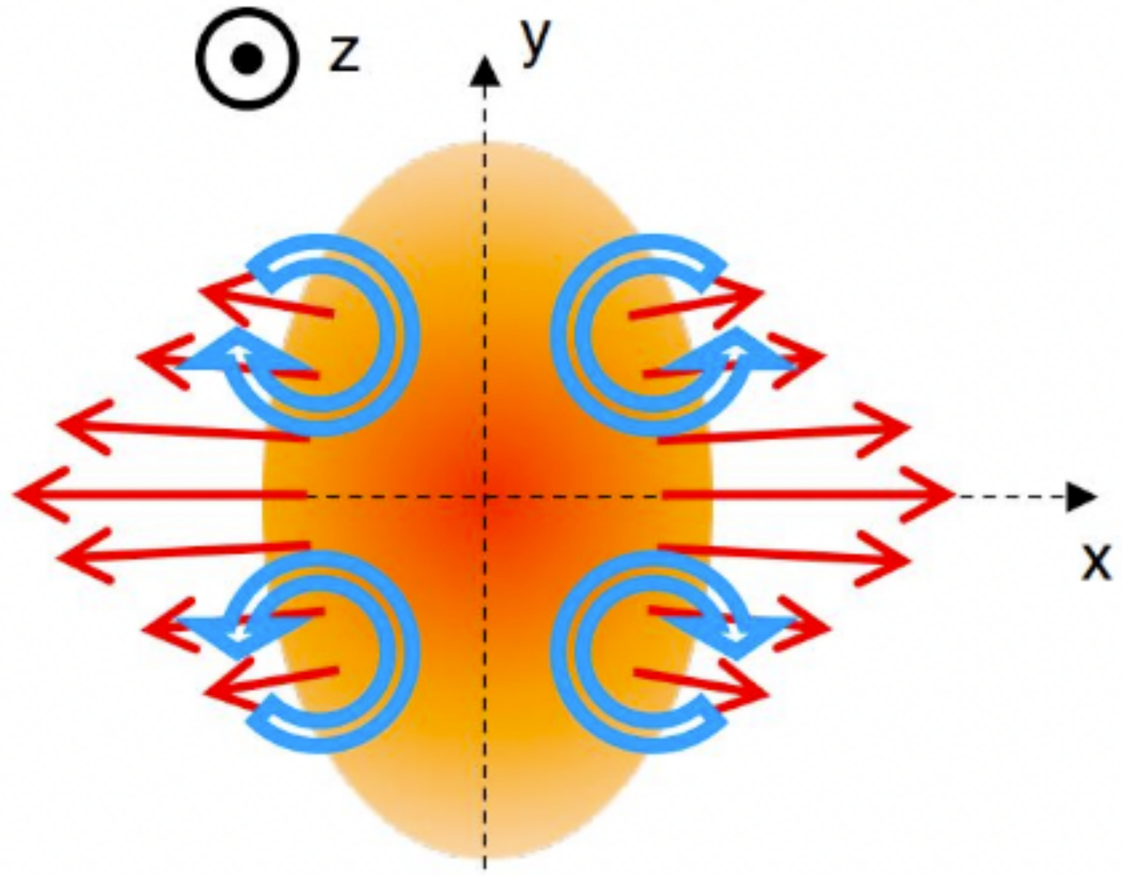


Transverse →

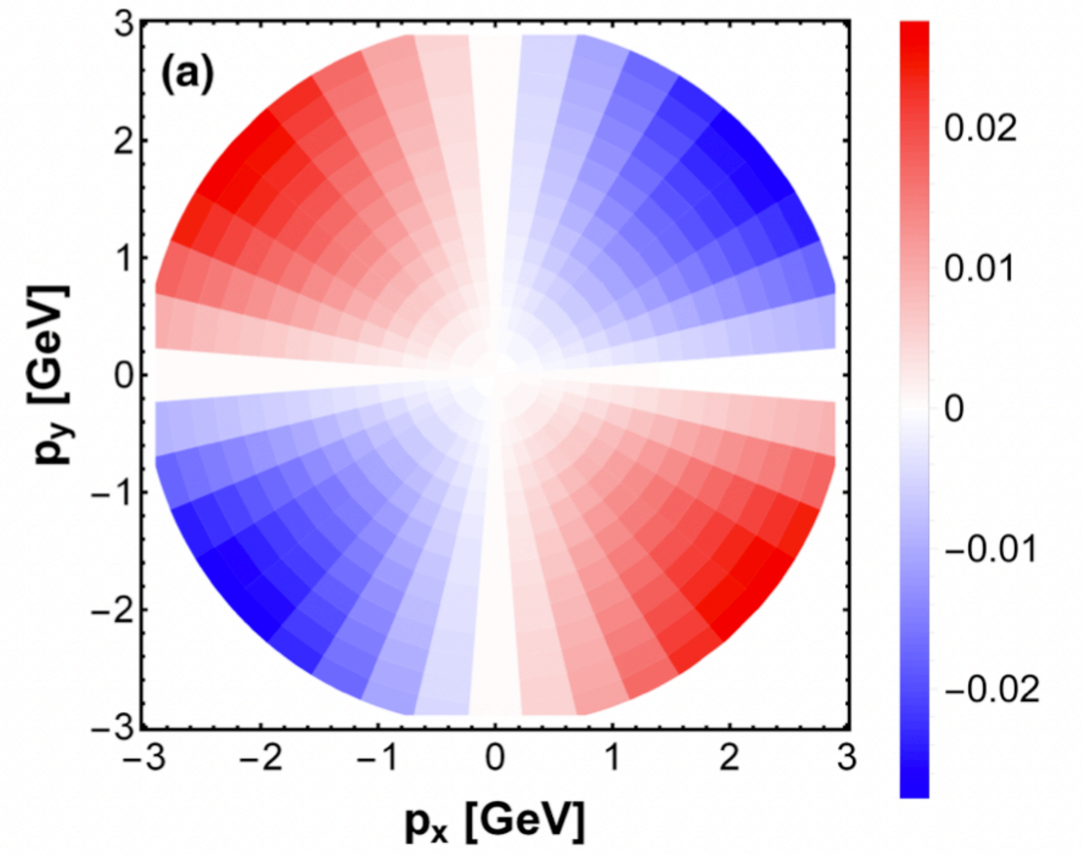


$P^y(\phi_p)$

Induced by inhomogeneous expansion



Longitudinal →



$P^z(\phi_p)$

[Lin, Ko, Li, Zhang and Pal,Phys. Rev. C72, 064901 (2005)]
[J. Weil et al., Phys. Rev. C 94, 054905 (2016), arXiv:1606.06642]

Initial condition

AMPT initial condition (Patron level)

- HIJING model : initial patrons via hard semi-hard scattering and excited strings
- ZPC model : the space-time evolution via elastic scattering

SMASH initial condition (Hadron level)

smash

- Effective solutions of $p^{\mu}\partial_{\mu}f + mF^{\mu}\partial_{p_{\mu}}(f) = C[f]$
- f(t, **x**, **p**) denotes one-particle distribution function
- C[f] includes elastic collisions, resonance formation and decays, string fragmentation
- mesons and baryons up to mass ≈ 2.35 GeV.

Initial condition

[Wu, Qin, Pang and Wang, Phys. Rev. C 105, 034909 (2022)]

At the initial proper time τ_0 , the initial energy momentum tensor $T^{\mu\nu}$ and the initial baryon current J^{μ} can be constructed at Melin coordinate via the local space-time information of patrons and hadrons,

$$T^{\mu\nu}\left(\tau_0, x, y, \eta_s\right) = K\sum_i \frac{p_i^{\mu} p_i^{\nu}}{p_i^{\tau}} G\left(\tau_0, x, y, \eta_s\right) \qquad J^{\mu}\left(\tau_0, x, y, \eta_s\right) = \sum_i Q_i \frac{p_i^{\mu}}{p_i^{\tau}} G\left(\tau_0, x, y, \eta_s\right)$$

where $G(\tau_0, x, y, \eta_s)$ denotes the Gaussian smearing

$$G\left(\tau_0, x, y, \eta_s\right) = \frac{1}{\mathcal{N}} \exp\left[-\frac{\left(x-x_i\right)^2 + \left(y-y_i\right)^2}{2\sigma_r^2} - \frac{\left(\eta_s - \eta_{si}\right)^2}{2\sigma_{\eta_s}^2}\right]$$

p^{μ} : the four-momentum of hadrons or patrons.

Q : the baryon charge for particles.

$\mathcal{N}$: the normalization factor to keep the net baryon number conservation.

$K, \sigma_r, \sigma_{\eta_s}$: free parameters to fit final charged hadrons yield.

Hydrodynamics evolution

[Wu, Qin, Pang and Wang, Phys. Rev. C 105, 034909 (2022)]

Energy-momentum conservation and net baryon current conservation:

$$\nabla_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = eU^\mu U^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\nabla_\mu J^\mu = 0 \qquad J^\mu = nU^\mu + V^\mu$$

Equation of motion of dissipative current:

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - \eta\sigma^{\mu\nu}\right) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha\langle}\sigma^{\mu\nu\rangle}_{\alpha} + \frac{9}{70}\frac{4}{e+P}\pi^{\langle\mu}_{\alpha}\pi^{\nu\rangle\alpha}$$

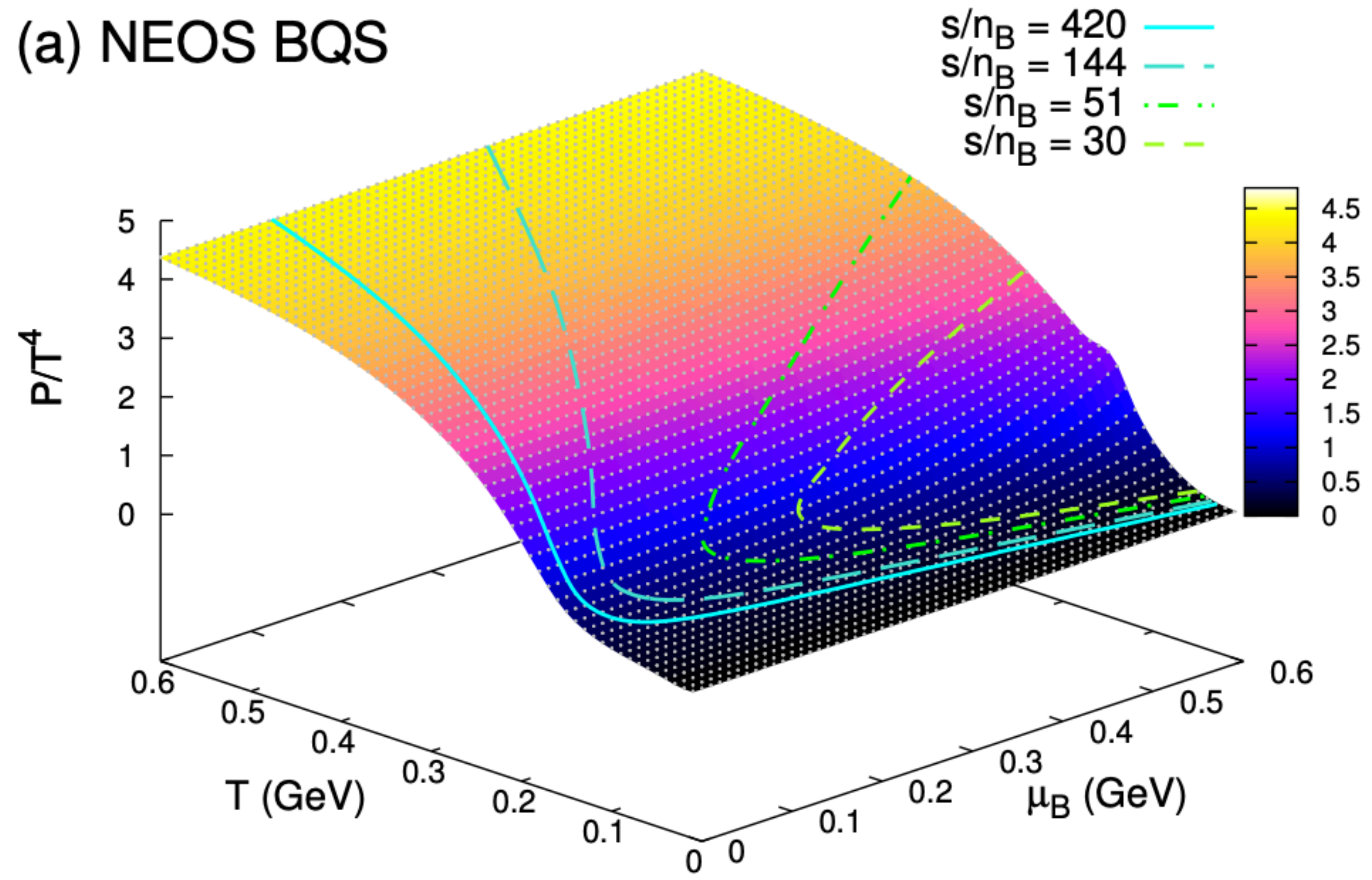
$$\Delta^{\mu\nu} DV_\mu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}$$

The shear viscosity $\eta = C_\eta \frac{e+p}{T}$

The baryon diffusion $\kappa_B = \frac{C_B}{T} n \left(\frac{1}{3}\cot\left(\frac{\mu_B}{T}\right) - \frac{nT}{e+P}\right)$

Equation of state

[Monnai, Schenke and Shen, Phys. Rev. C 100, 024907 (2019)]



High T: lattice QCD

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{\chi^{B,Q,S}_{l,m,n}}{l!m!n!} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^n$$

$\chi^{B,Q,S}_{l,m,n}$ is the (l+m+n)-th order susceptibility.

Low T: hadron gas model

$$P = \pm T \sum_i \int \frac{g_i d^3p}{(2\pi)^3} \ln\left[1 \pm e^{-(E_i - \mu_i)/T}\right]$$

$$= \sum_i \sum_k (\mp 1)^{k+1} \frac{1}{k^2} \frac{g_i}{2\pi^2} m_i^2 T^2 e^{k\mu_i/T} K_2\left(\frac{km_i}{T}\right)$$

Here i: particle species, g_i : degeneracy, m_i: particle's mass,

$K_2(x)$: the modified Bessel function of the second kind.

The complete nuclear equation of state:

$$\frac{P}{T^4} = \frac{1}{2}\left[1 - f\left(T, \mu_B, \mu_Q, \mu_S\right)\right] \frac{P_{\rm had}\left(T, \mu_B, \mu_Q, \mu_S\right)}{T^4}$$

$$+\frac{1}{2}\left[1 + f\left(T, \mu_B, \mu_Q, \mu_S\right)\right] \frac{P_{\rm lat}\left(T, \mu_B, \mu_Q, \mu_S\right)}{T^4}$$

The connecting function

$f \to 1$ at high T, $f \to -1$ at low T

Spin polarization

[Karpenko, F. Becattini, Eur. Phys. J. C 77 (2017) 213]
[Fang, Pang, Wang, Wang, Phys. Rev. C94, 024904 (2016)]
[Hidaka, Pu and Yang, Phys. Rev. D97, 016004 (2018)]

The modified Cooper-Frye formula for the polarization pseudo vector for spin-$\frac{1}{2}$ particles

$$\mathcal{S}^{\mu}(\mathbf{p}) = \frac{\int d\Sigma p \mathcal{J}_5^{\mu}(p, X)}{2m \int d\Sigma \mathcal{N}(p, X)}$$

where $\mathcal{J}_5$ and $\mathcal{N}$ are axial-charge current density and the number density of fermions.

For massless fermions, S(**p**) can be decomposed into different sources based on QKT

$$\mathcal{S}^{\mu}(\mathbf{p}) = \mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) + \mathcal{S}^{\mu}_{\text{shear}}(\mathbf{p}) + \mathcal{S}^{\mu}_{\text{accT}}(\mathbf{p}) + \mathcal{S}^{\mu}_{\text{chemical}}(\mathbf{p}) + \mathcal{S}^{\mu}_{\text{EB}}(\mathbf{p}),$$

Spin polarization

In the experiment, the polarization of Λ and $\bar{\Lambda}$ are measured in their own rest frames. Therefore, we express the polarization psudovector $\overrightarrow{P}*(\mathbf{p})$ in the rest frame by taking the Lorenz transformation,

$$\overrightarrow{P}*(\mathbf{p}) = \overrightarrow{P}(\mathbf{p}) - \frac{\overrightarrow{P}(\mathbf{p}) \cdot \vec{p}}{p^0\left(p^0 + m\right)}\vec{p} \qquad \text{where} \qquad P^\mu(\mathbf{p}) \equiv \frac{1}{s}\mathcal{S}^\mu(\mathbf{p})$$

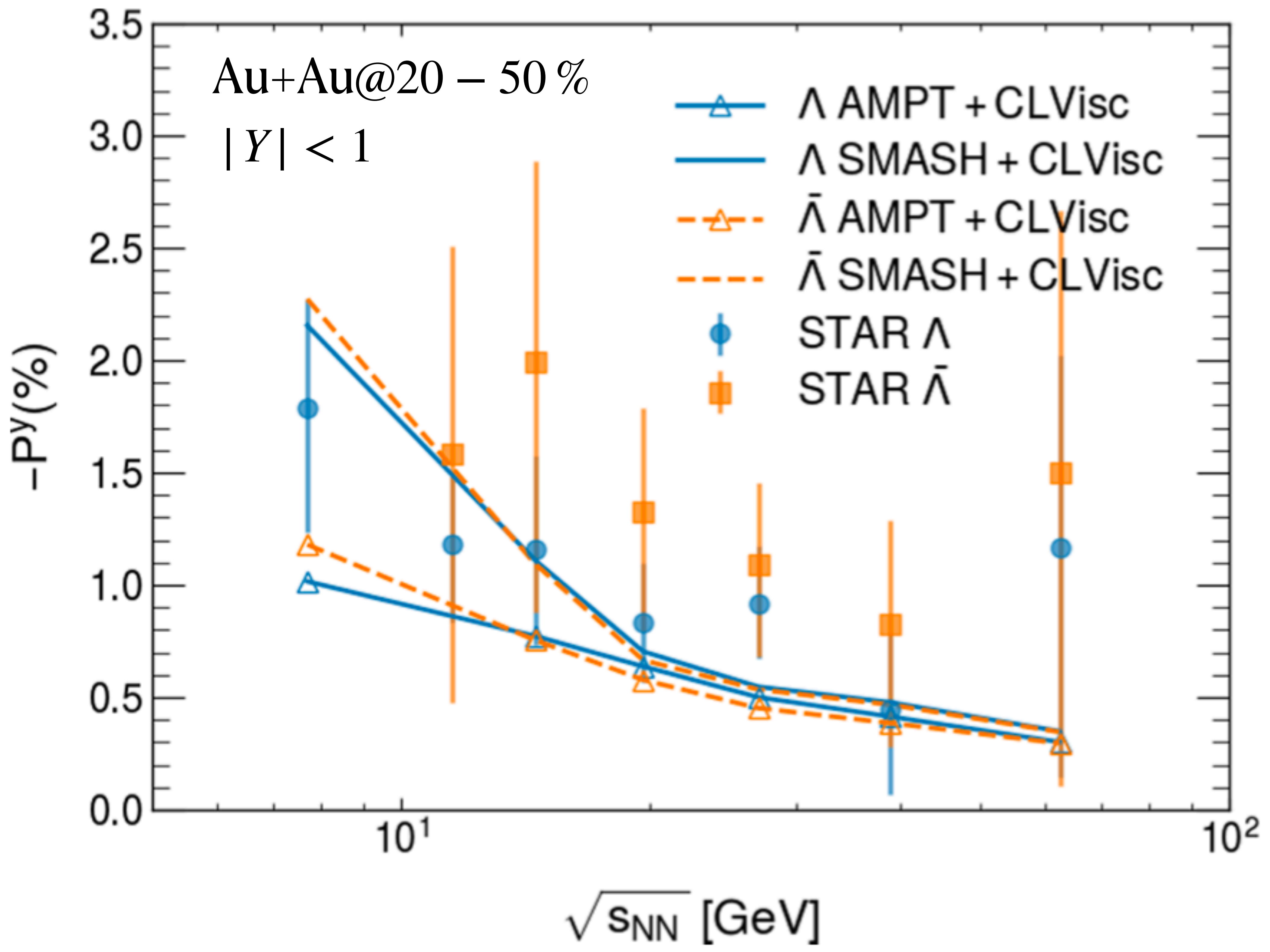
Finally, the local polarization is given by the averaging over momentum and rapidity.

$$\left\langle \overrightarrow{P}\left(\phi_p\right)\right\rangle = \frac{\int_{y_{\min}}^{y_{\max}} dy \int_{p_{T\,\min}}^{p_T\,\max} p_T dp_T \left[\Phi(\mathbf{p})\overrightarrow{P}*(\mathbf{p})\right]}{\int_{y_{\min}}^{y_{\max}} dy \int_{p_{T\,\max}}^{p_T\,\max} p_T dp_T \Phi(\mathbf{p})}$$

Global polarization

[H. Li, et al, PRC 96 (2017) 054908]

[Karpenko and Becattini , EPJC 77 (2017) 4, 213]



P_y increases when the collision energies decreases.

- the angular momentum scaled by total energy of fireball should decrease as the collisional energy increases.
- the time of evolution decreases.

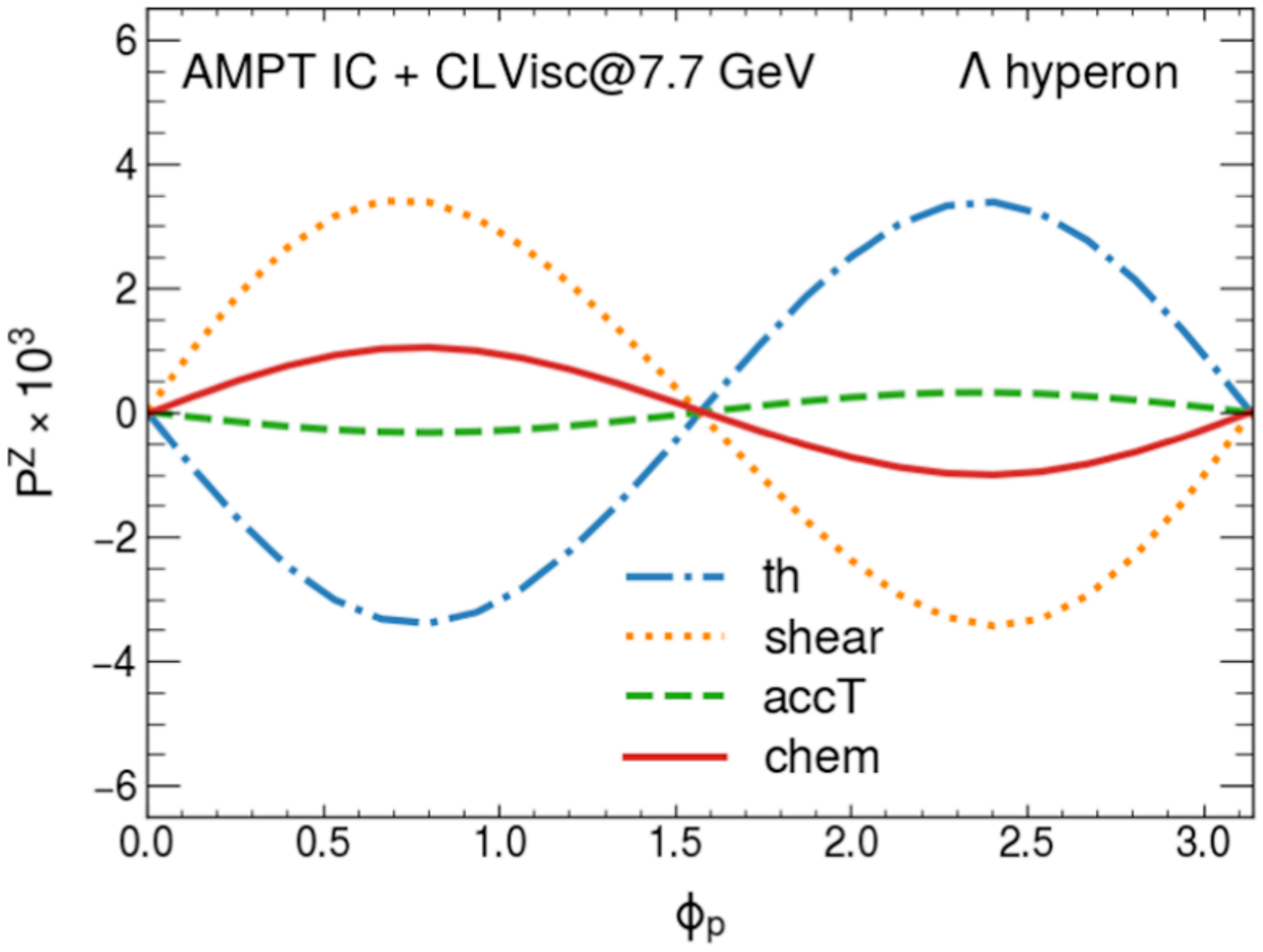
At the low-energy collision, the polarization from the SMASH initial condition is much larger than AMPT initial condition.

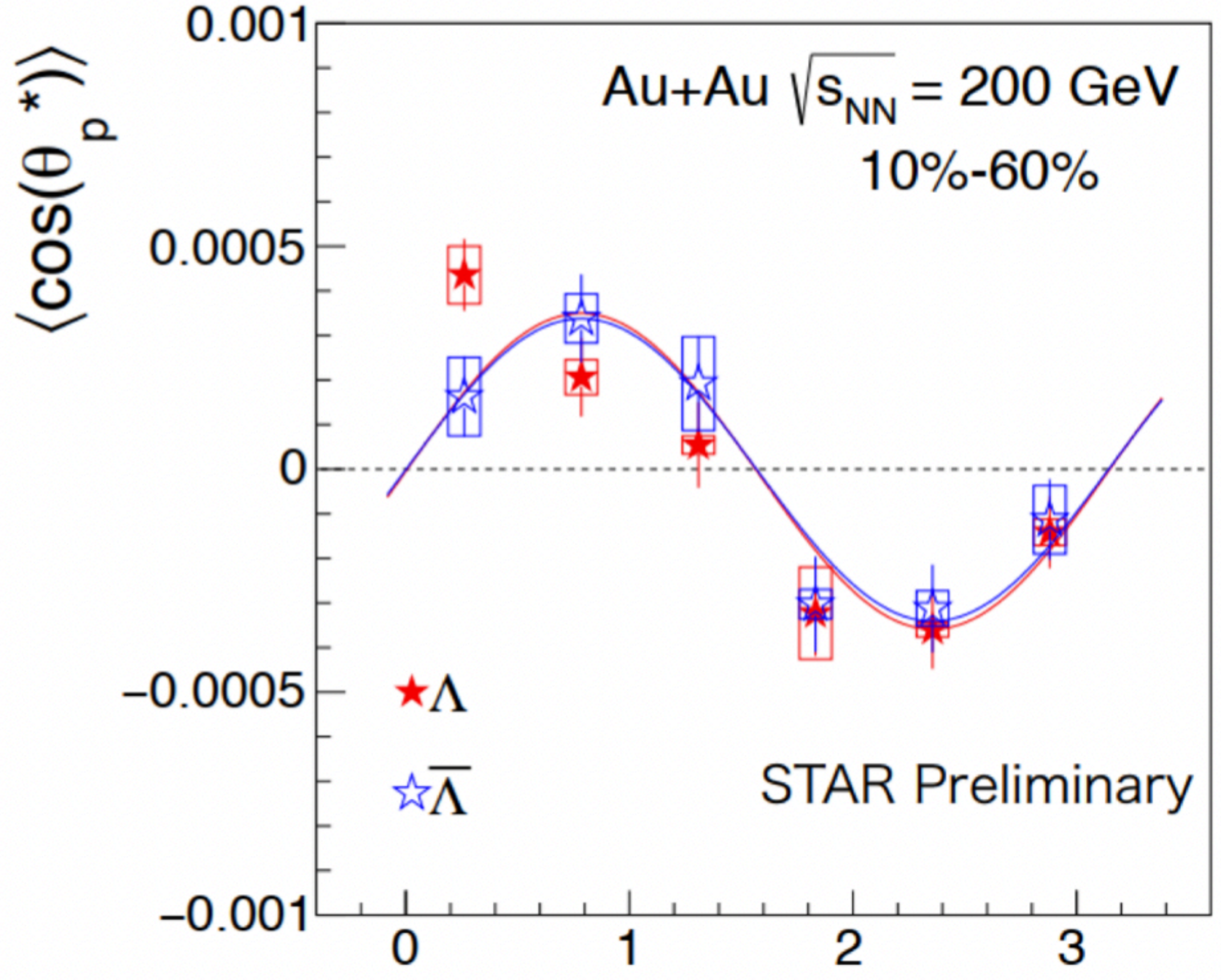
- the effect of finite nuclear thickness

The splitting between Λ and $\bar{\Lambda}$ can be neglected.

- the competitions between finite baryon density and the production time.

Local longitudinal polarization : different sources

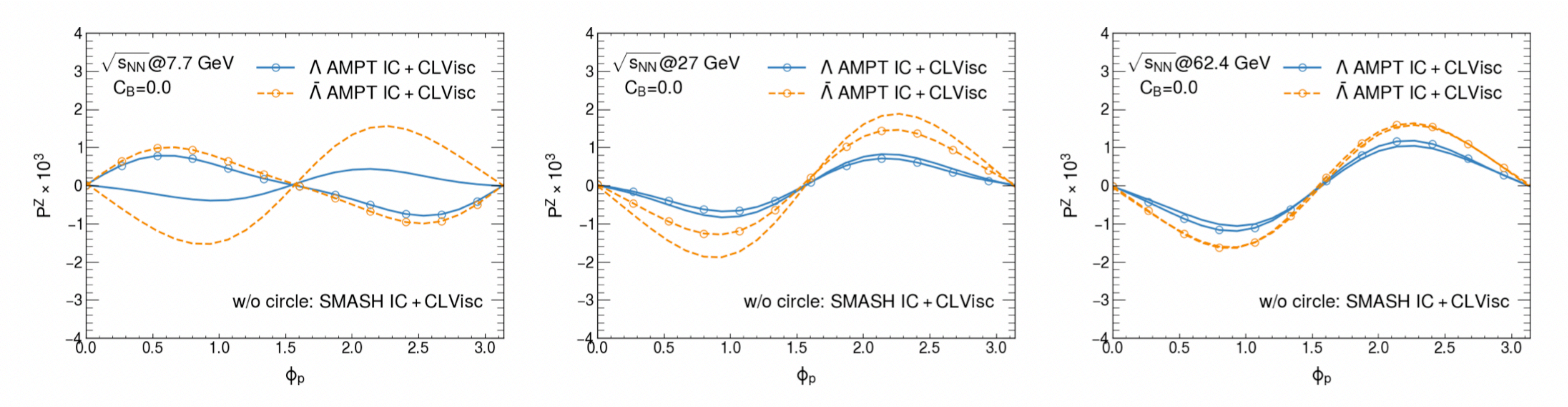




The polarization induced by the SHE P^z_{chem} and SIP P^z_{shear} provide the sine contribution to longitudinal polarization P_z .

The polarization from thermal vorticity P^z_{th} and fluid acceleration P^z_{accT} give the opposite contribution.

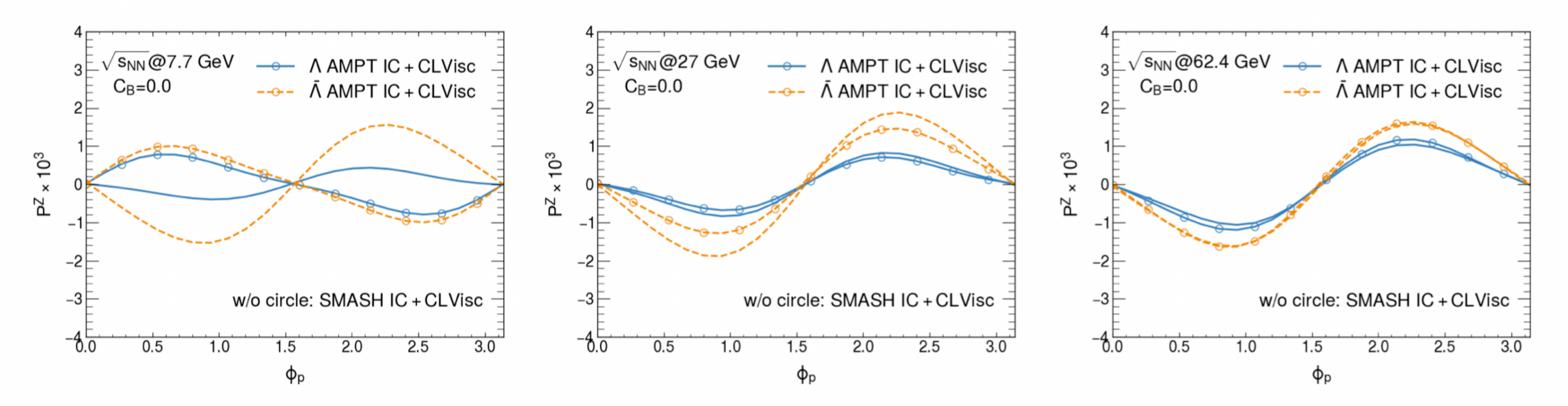
Total local longitudinal polarization: AMPT vs SMASH



At $\sqrt{s_{NN}} = 27,\ 62.4\mathrm{GeV}$, both AMPT and SMASH initial condition give the similar total local P^z.

At $\sqrt{s_{NN}} = 7.7\mathrm{GeV}$, the total local P^z from the AMPT initial conditions is significant different with the one from the SMASH initial conditions: opposite sign due to the contribution from P^z_{chem}.

Total local longitudinal polarization: Λ vs $\bar{\Lambda}$

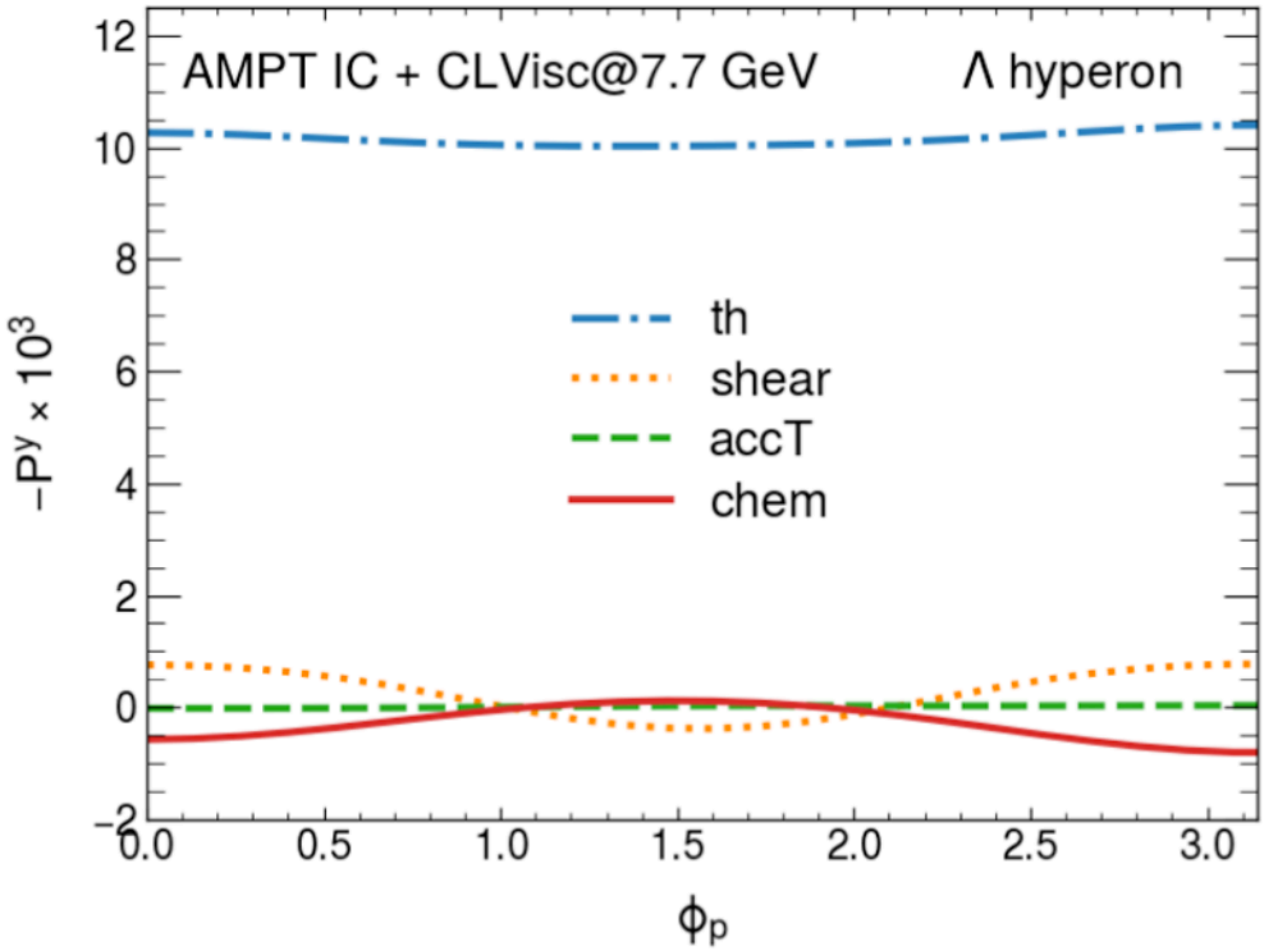


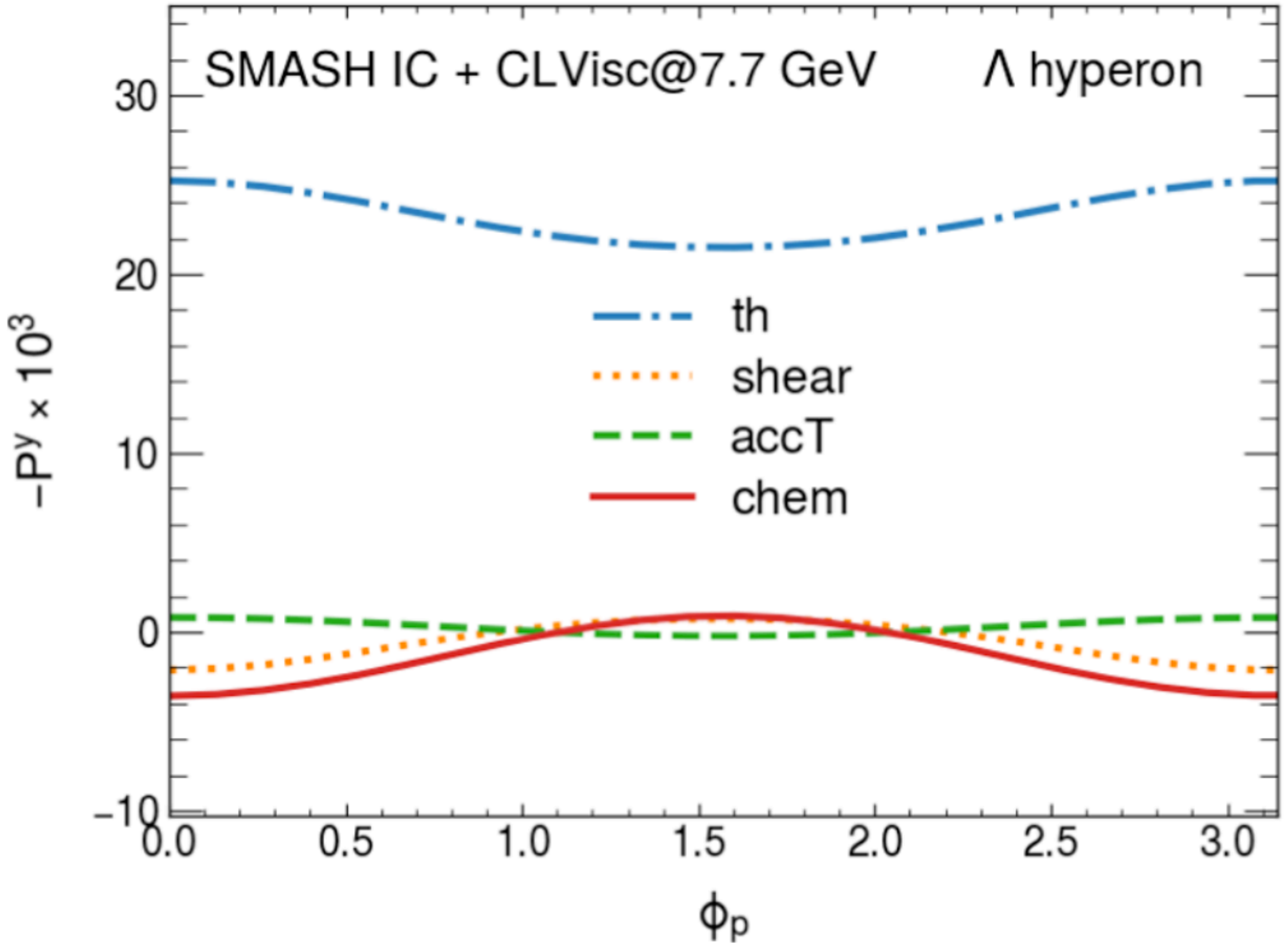
The longitudinal polarization for $\bar{\Lambda}$ has a larger magnitude than the one for Λ hyperons, especially 7.7 GeV.

The difference between Λ and $\bar{\Lambda}$ become smaller at the high collision energy.

It opens a window to probe the initial structure of QGP at the baryon-rich region through the local polarization of Λ and $\bar{\Lambda}$.

Local transverse polarization: different sources



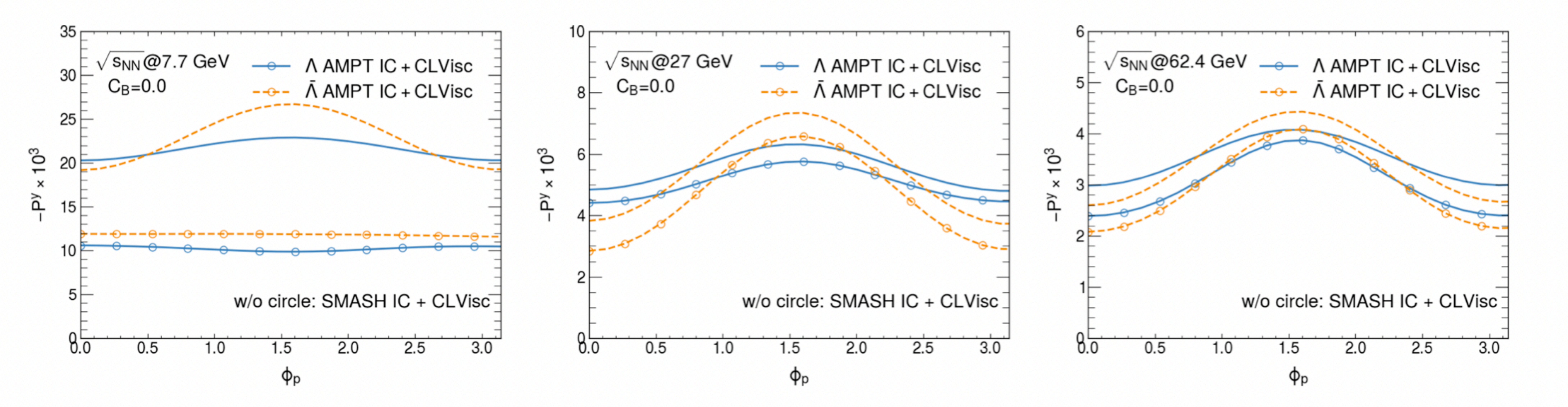


The contribution from $P^y_{\rm th}$ dominates over other sources for both the AMPT and the SMASH initial conditions.

The SMASH initial condition has a larger magnitude than the AMPT initial model, especially at 7.7 GeV.

The slope of $P^y_{\rm chem}$ seems to be opposite to that of $P^y_{\rm shear}$ in AMPT initial condition.

Total local transverse polarization: AMPT vs SMASH



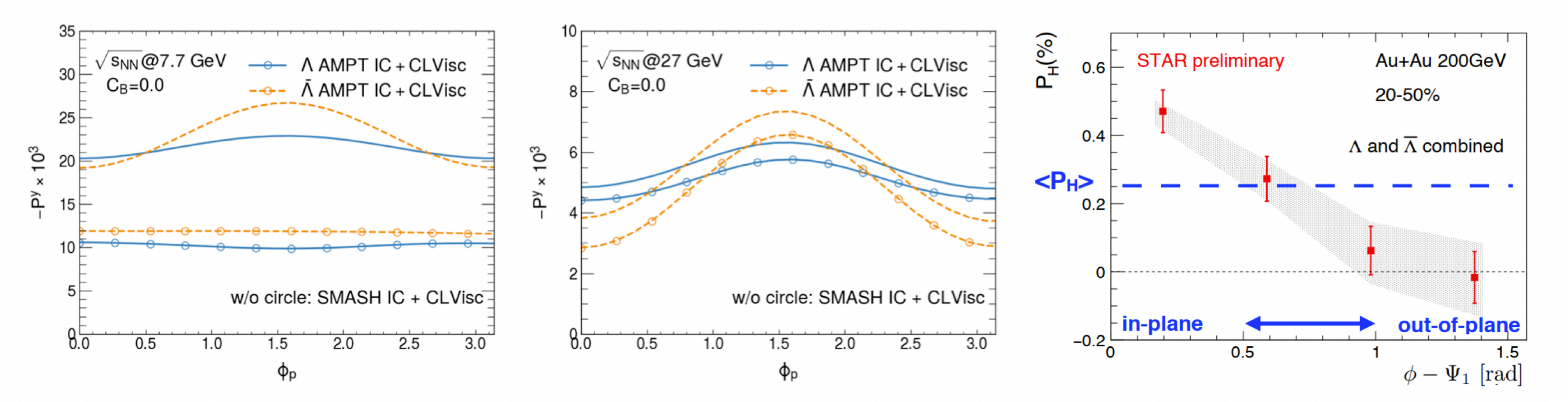
The magnitude of P^y increases with decreasing collision energies for both initial conditions.

P^y from the SMASH initial condition is larger than the one from the AMPT initial condition.

The polarization is smaller at the in-plane direction than at the out-of-plane direction.

(maybe sign puzzle at low energy?)

Total local transverse polarization: AMPT vs SMASH



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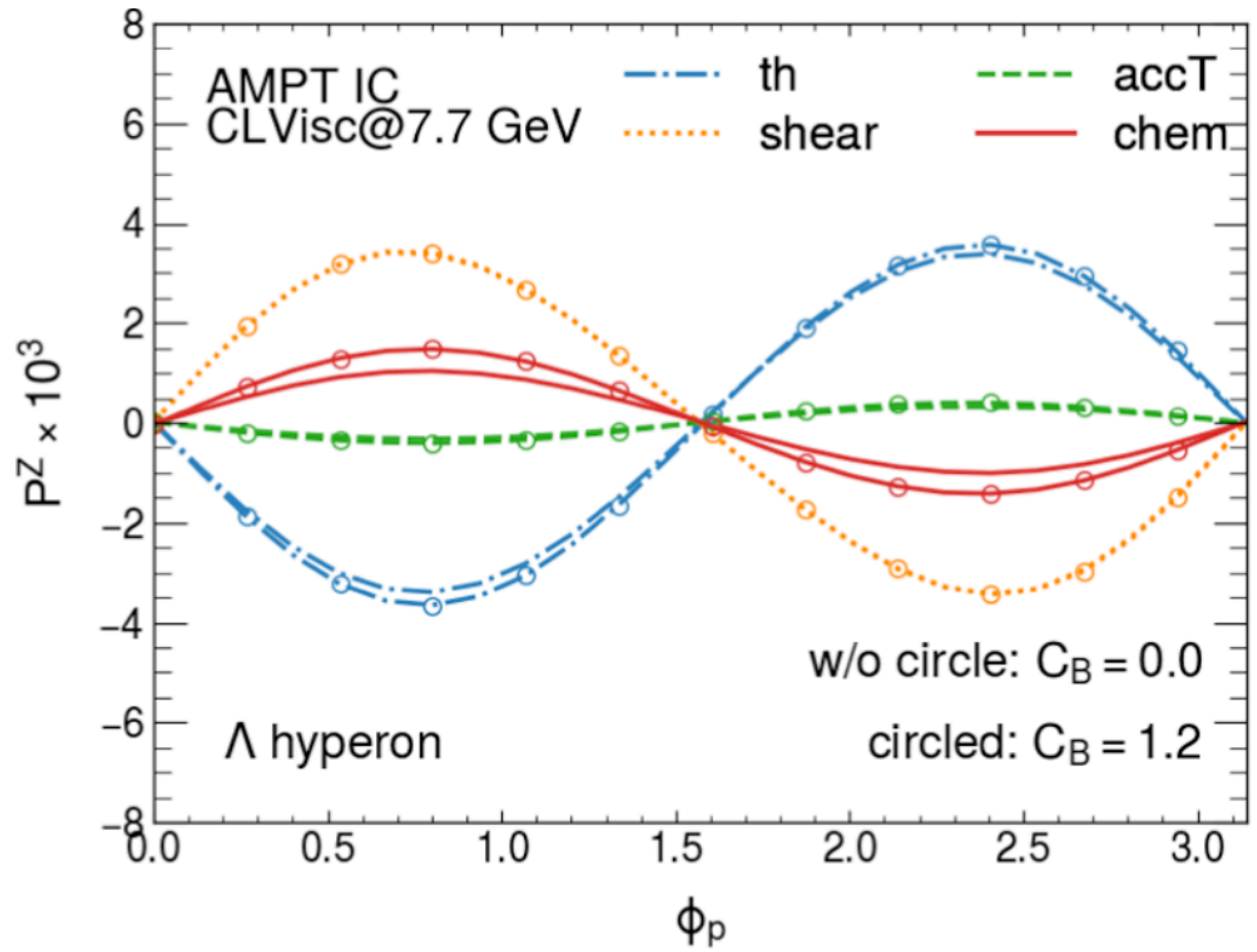
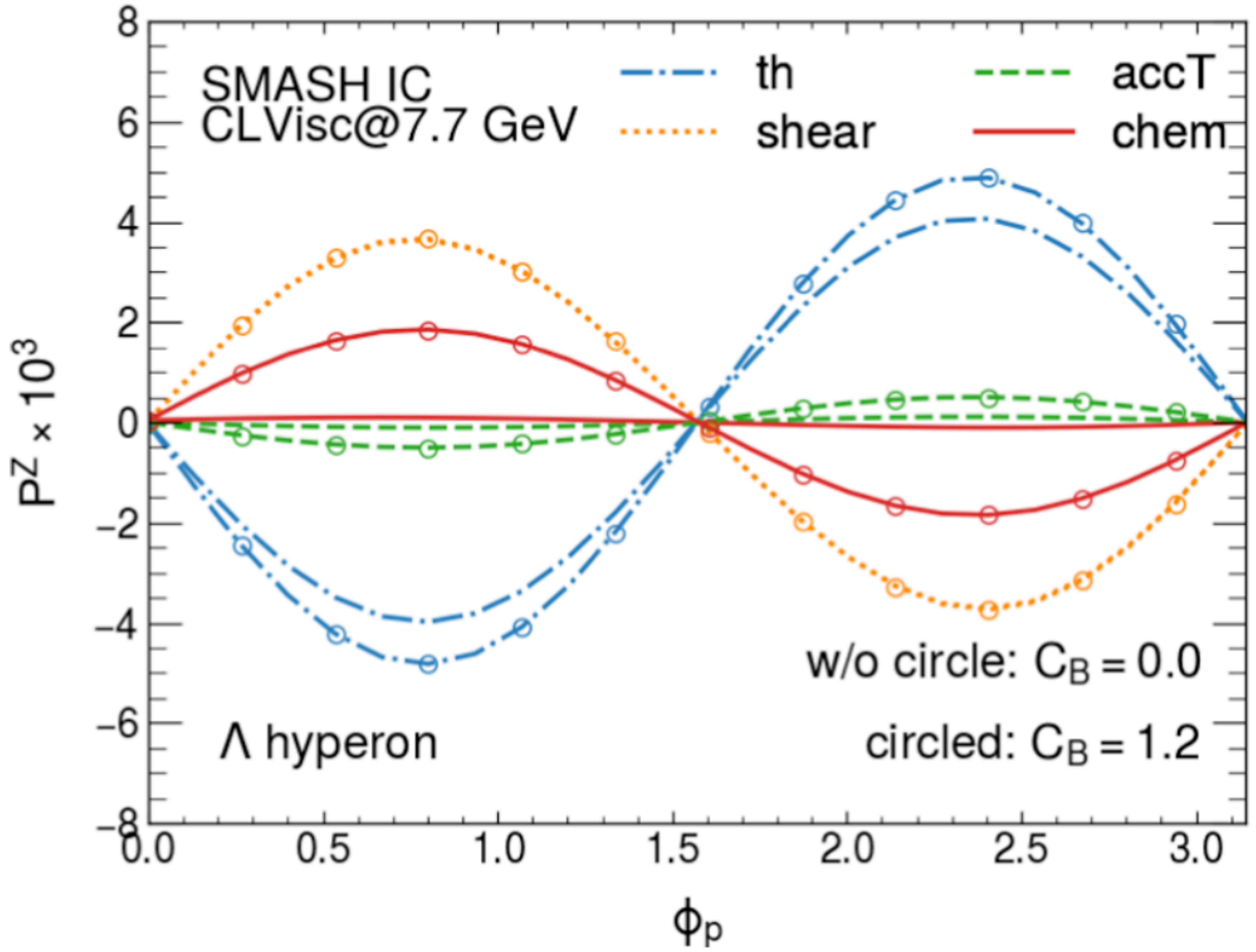
Baryon diffusion dependence

The baryon diffusion

$$\kappa_B = \frac{C_B}{T} n \left(\frac{1}{3} \cot\left(\frac{\mu_B}{T} \right) - \frac{nT}{e+P} \right)$$



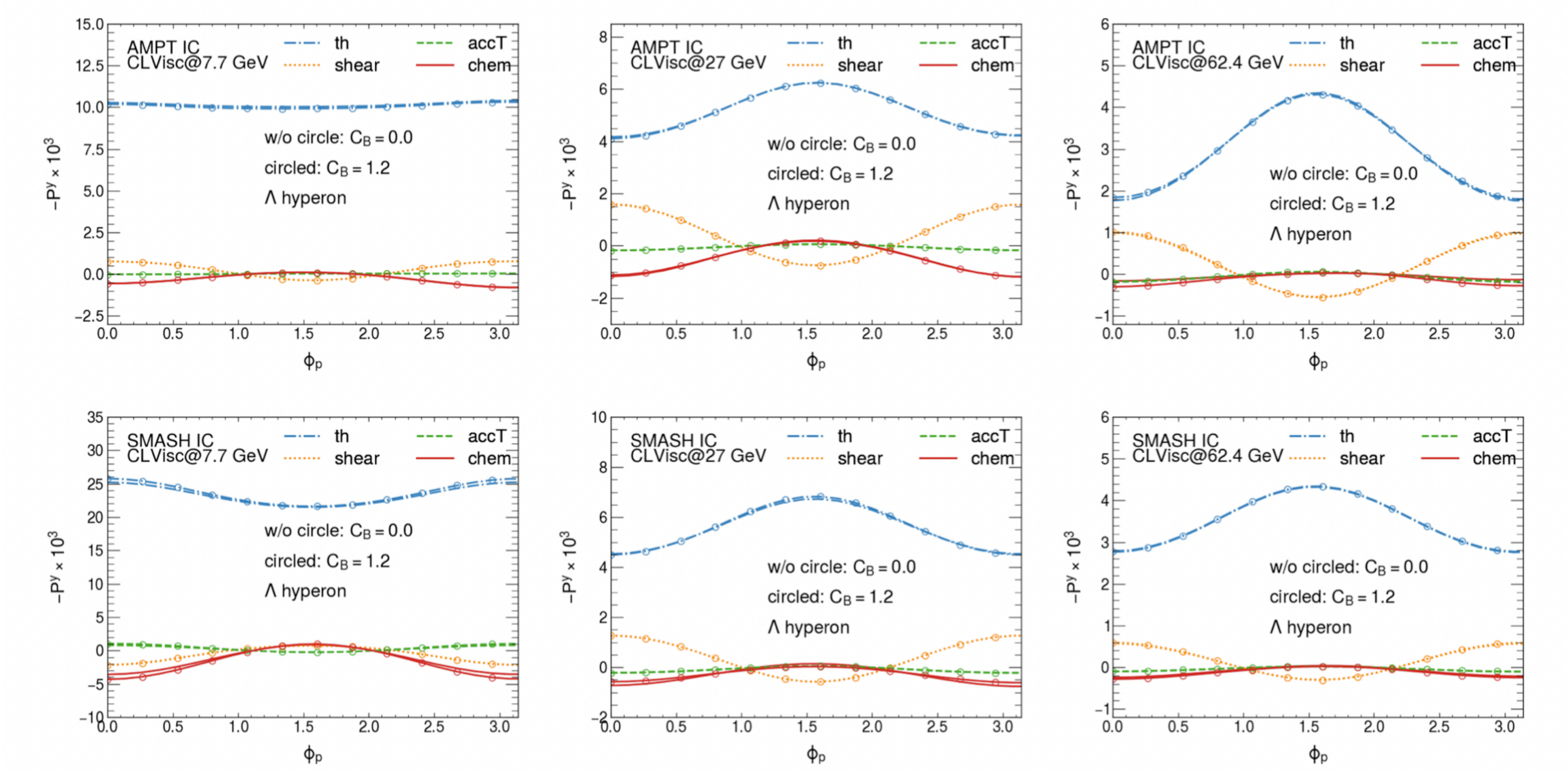


P^z_{shear} and P^z_{accT} are insensitive to baryon diffusion C_B.

P^z_{th} and P^z_{chem} are enhanced with baryon diffusion C_B increases.

The enhancement of P^z_{chem} is prominent at low energy and in SMASH initial model.

Local transverse polarization: baryon diffusion dependence



The baryon diffusion effect on P^y induced by different sources are negligible for AMPT and SMASH initial conditions.

The local transverse polarization of Λ is sensitive to initial conditions and a good observable to constrain the initial states of heavy ion collision.

Summary

- In this work, we discuss the effects of SHE, initial condition and baryon diffusion for global and local polarization at RHIC-BES energies

- The polarization induced by SHE P^z_{chem} gives a sizable contribution and even flip the sign of total polarization along beam direction with AMPT initial condition at 7.7 GeV.

- The polarization induced by SHE P^z_{chem} gives negligible contribution to the total polarization along beam direction with SMASH initial condition.

- The P^z_{th} and P^z_{chem} are sensitive to the baryon diffusion and total polarization P^z can flip the sign when $C_B = 1.2$ in SMASH initial condition.
- The effects of baryon diffusion to P^y are negligible for both initial conditions.

Backup

Spin polarization

[Hidaka, Pu and Yang, Phys. Rev. D97, 016004 (2018)]

[Yi, Pu, and Yang, Phys. Rev. C104.064901 (2021)]

$$\mathcal{S}^{\mu}_{\text{thermal}}(\mathbf{p}) = \int d\Sigma^{\sigma} F_{\sigma} \boxed{\epsilon^{\mu\nu\alpha\beta} p_{\nu} \partial_{\alpha} \frac{u_{\beta}}{T}}$$

Thermal vorticity

$$\mathcal{S}^{\mu}_{\text{shear}}(\mathbf{p}) = \int d\Sigma^{\sigma} F_{\sigma} \frac{\epsilon^{\mu\nu\alpha\beta} p_{\nu} u_{\beta}}{(up)T} p^{\rho} \boxed{\left(\partial_{\rho} u_{\alpha} + \partial_{\alpha} u_{\rho} - u_{\rho} D u_{\alpha}\right)}$$

Shear viscous tensor

$$\mathcal{S}^{\mu}_{\text{accT}}(\mathbf{p}) = -\int d\Sigma^{\sigma} F_{\sigma} \frac{\epsilon^{\mu\nu\alpha\beta} p_{\nu} u_{\alpha}}{T} \boxed{\left(D u_{\beta} - \frac{\partial_{\beta} T}{T}\right)}$$

Fluid acceleration

$$\mathcal{S}^{\mu}_{\text{chemical}}(\mathbf{p}) = 2\int d\Sigma^{\sigma} F_{\sigma} \frac{1}{(up)} \epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta} \boxed{\partial_{\nu} \frac{\mu}{T}}$$

Gradient of chemical potential
(Spin Hall Effect)

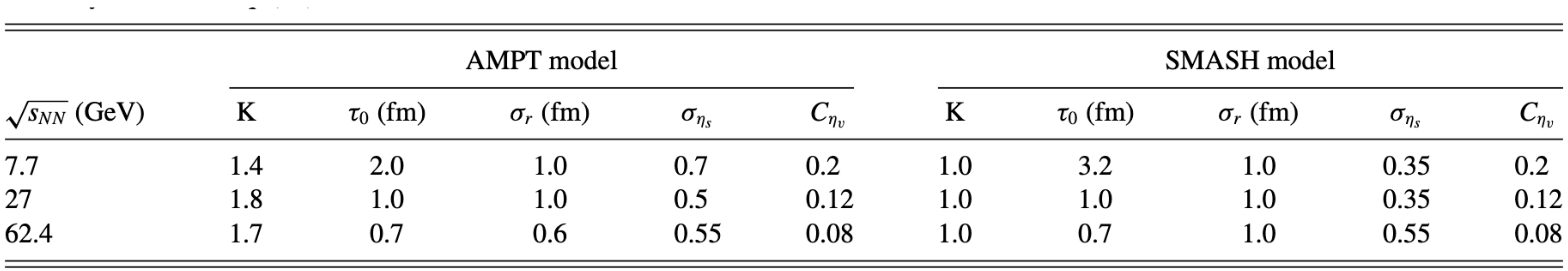
$$\mathcal{S}^{\mu}_{\text{EB}}(\mathbf{p}) = 2\int d\Sigma^{\sigma} F_{\sigma} \boxed{\left[\frac{\epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta} E_{\nu}}{(up)T} + \frac{B^{\mu}}{T}\right]}$$

Electromagnetic Fileds
(E= B = 0)

Here,

$$F^{\mu} = \frac{\hbar}{8m_{\Lambda}\Phi(\mathbf{p})} p^{\mu} f_{\text{eq}} \left(1 - f_{\text{eq}}\right) \qquad \Phi(\mathbf{p}) = \int d\Sigma^{\mu} p_{\mu} f_{\text{eq}}$$

Parameters

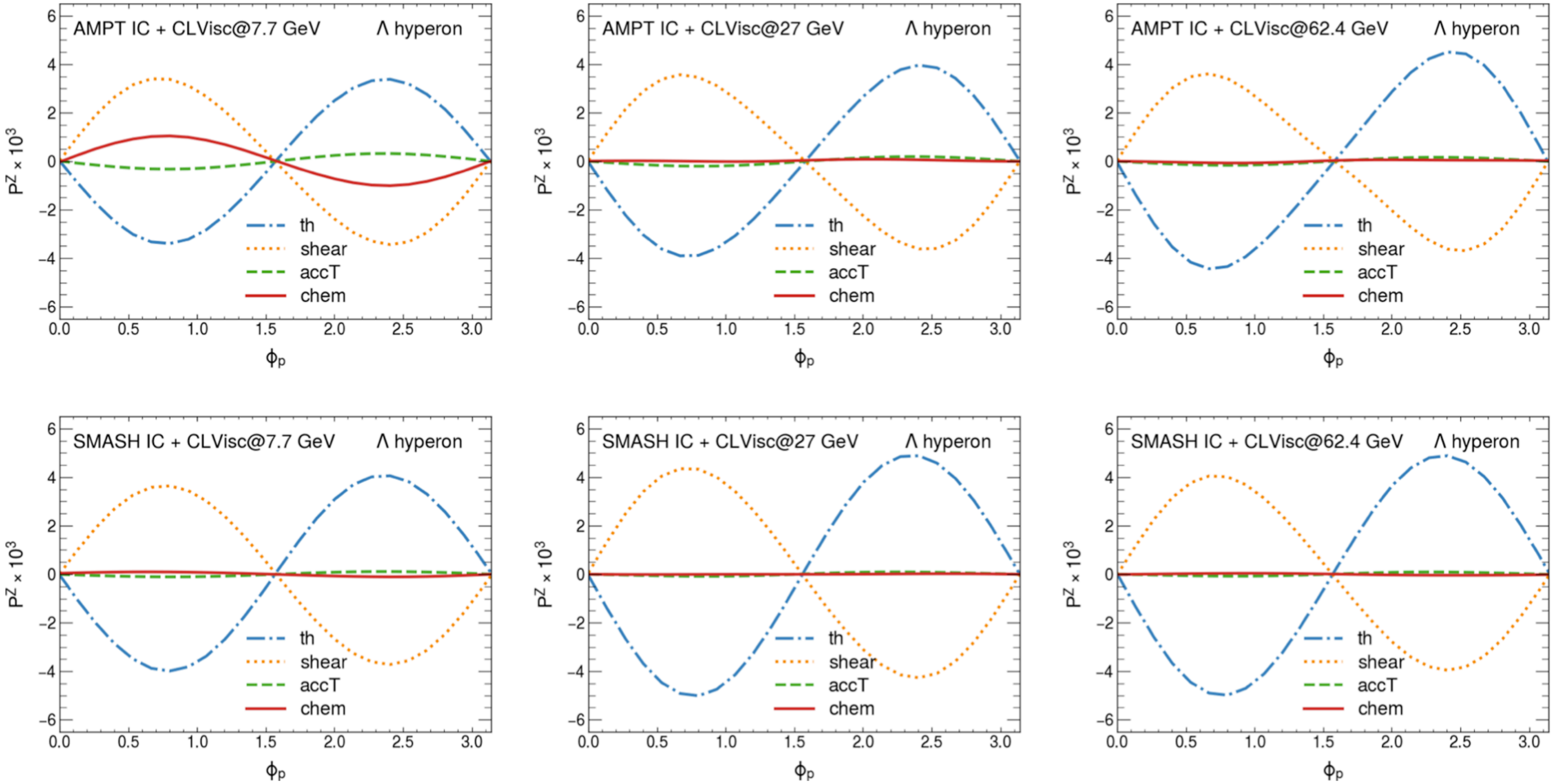


	AMPT model					SMASH model				
$\sqrt{s_{NN}}$ (GeV)	K	τ_0 (fm)	σ_r (fm)	σ_{η_s}	C_{η_v}	K	τ_0 (fm)	σ_r (fm)	σ_{η_s}	C_{η_v}
7.7	1.4	2.0	1.0	0.7	0.2	1.0	3.2	1.0	0.35	0.2
27	1.8	1.0	1.0	0.5	0.12	1.0	1.0	1.0	0.35	0.12
62.4	1.7	0.7	0.6	0.55	0.08	1.0	0.7	1.0	0.55	0.08

Local longitudinal polarization: AMPT vs SMASH

AMPT

SMSAH



SMASH initial conditions: (compared with AMPT initial condition)

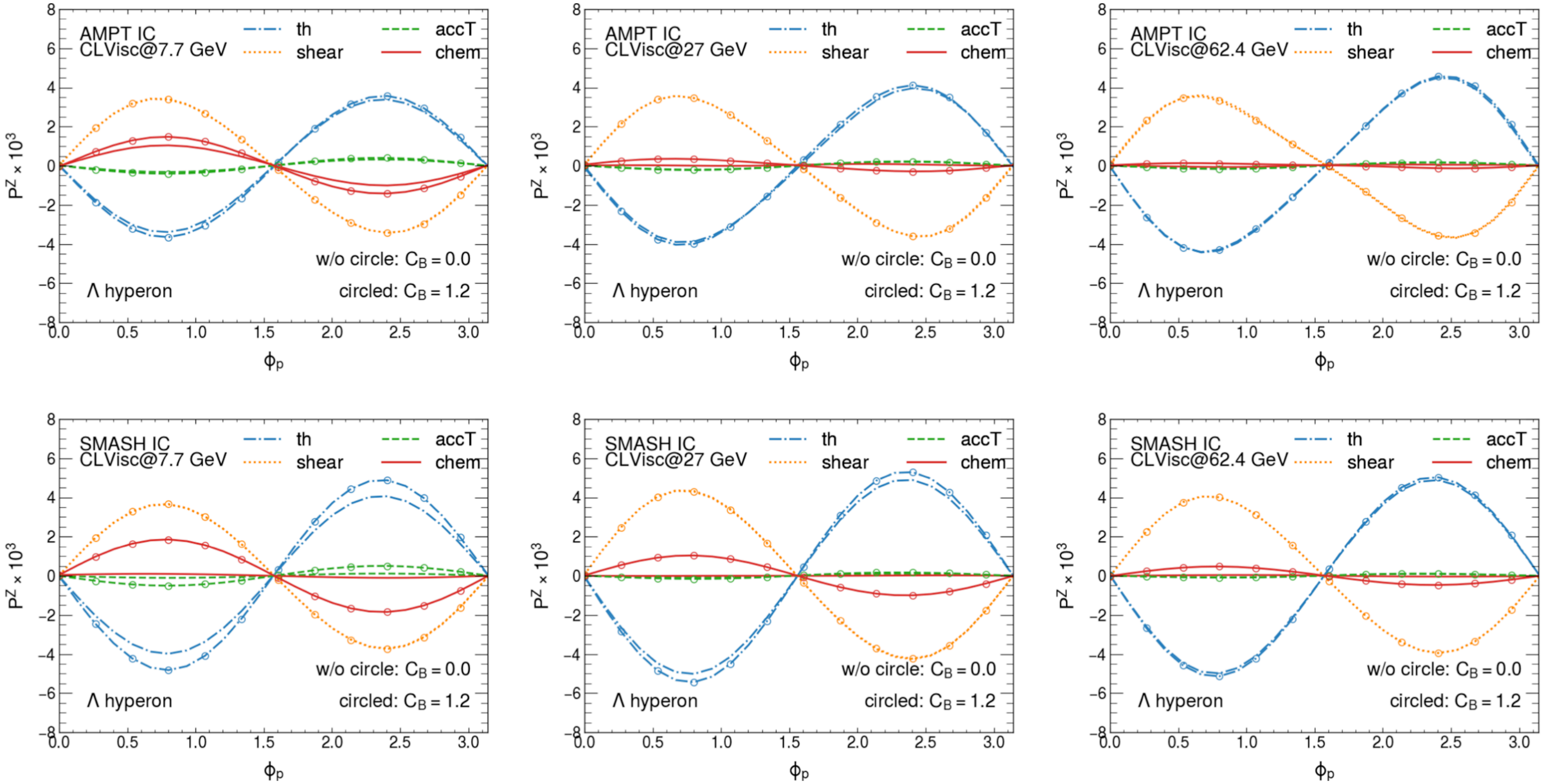
P^z_{th}, P^z_{shear} are same order for both model, similar radial flow

P^z_{accT} , P^z_{chem} is almost vanishing negligible and have a weak collision energies dependence

P^z_{chem} depends on initial conditions strongly.

Baryon diffusion dependence

$$\kappa_B = \frac{C_B}{T} n \left(\frac{1}{3} \cot\left(\frac{\mu_B}{T}\right) - \frac{nT}{e+P} \right)$$



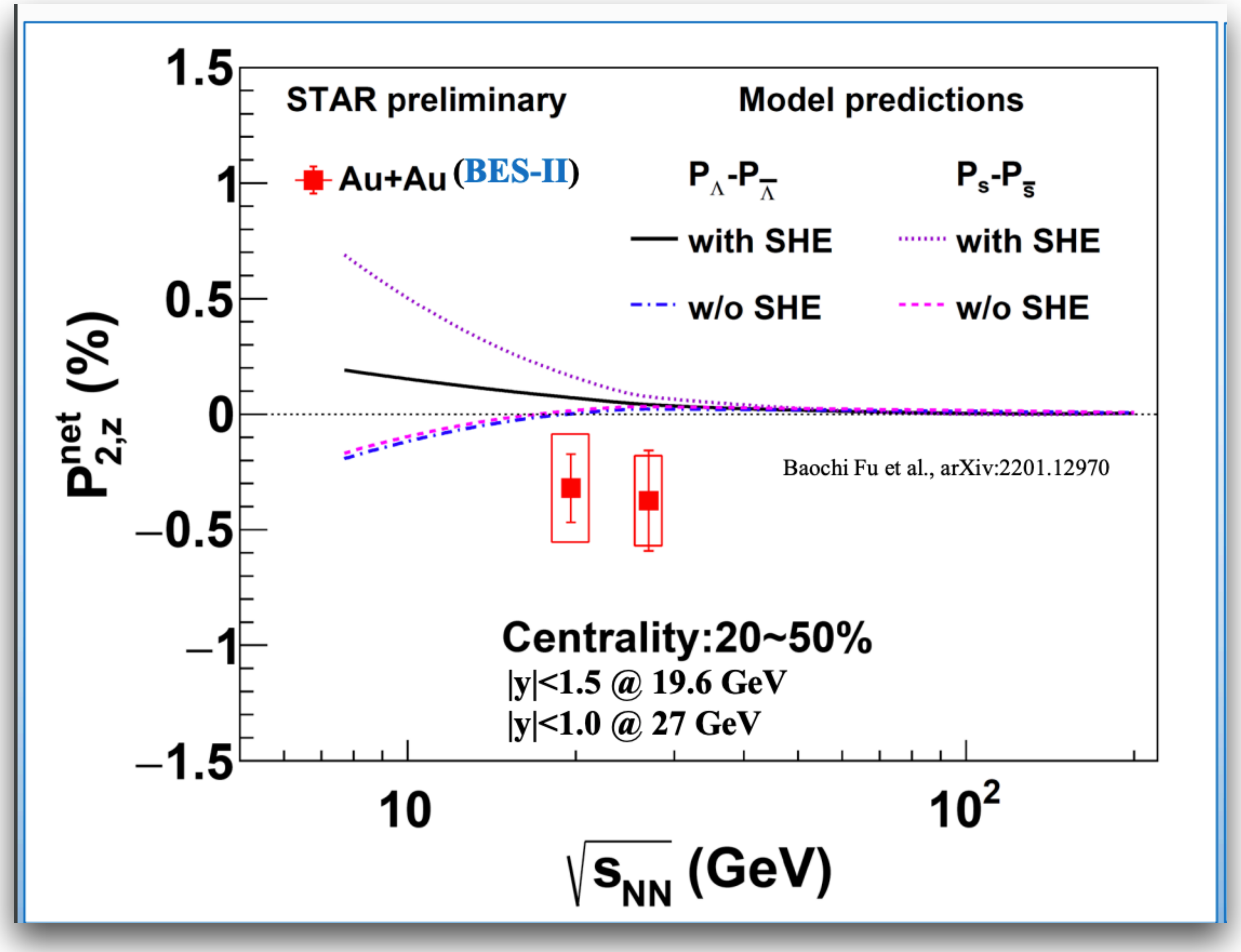
P^z_{shear} and P^z_{accT} are insensitive to baryon diffusion C_B.

P^z_{th} and P^z_{chem} are enhanced with baryon diffusion C_B increases.

The enhancement of P^z_{chem} is prominent at low energy and in SMASH model

Spin hall effect

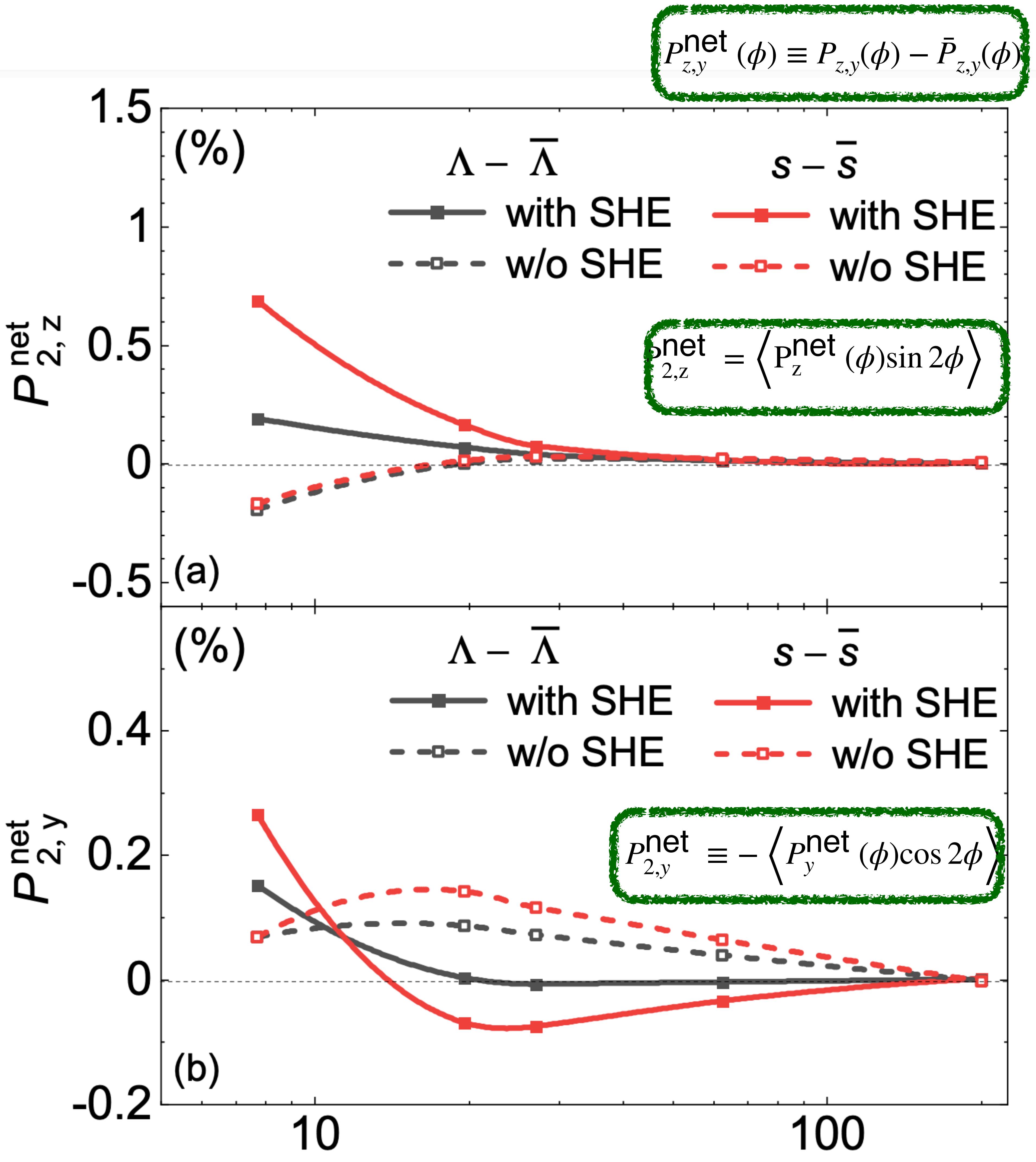
From Qiang Hu's Poster@SQM2022



Sign puzzle again???

[Fu, Liu,,Pang, Song and Yin, arXiv:2201.12970]

[S. Meyer et al., Nature Materials 16 (2017)]

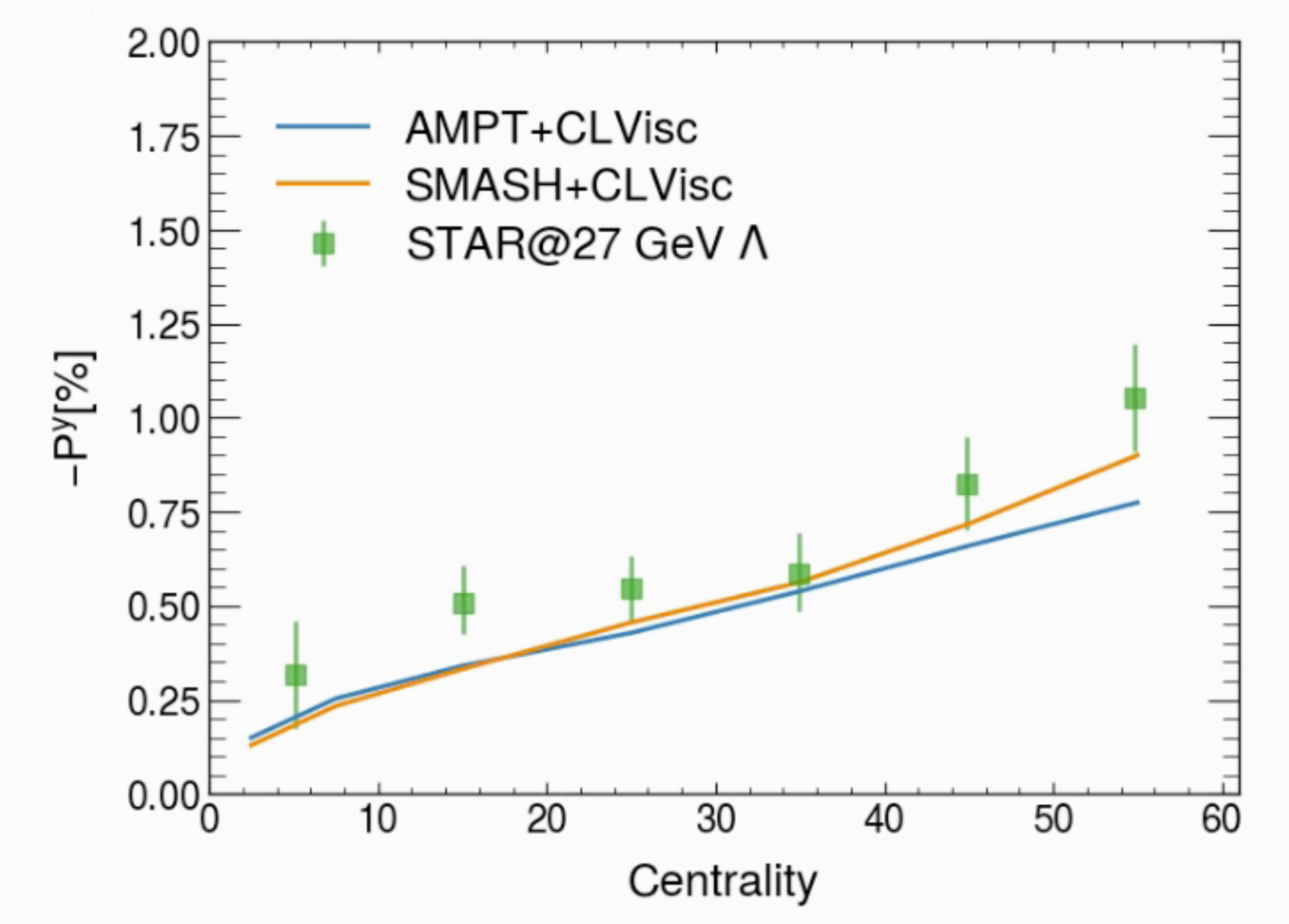


$P^{net}_{z,y}(\phi) \equiv P_{z,y}(\phi) - \bar{P}_{z,y}(\phi)$

$P^{net}_{2,z} = \left\langle P^{net}_{z}(\phi) \sin 2\phi \right\rangle$

$P^{net}_{2,y} \equiv -\left\langle P^{net}_{y}(\phi) \cos 2\phi \right\rangle$

Global Polarization



Global Polarization