QUARK MATTER KRAKÓW 2022

Probing early-time longitudinal dynamics with the Λ hyperon's spin polarization in relativistic heavy-ion collisions

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in collaboration with

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S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)

S. Ryu, V. Jupic, and C. Shen (arXiv:2106.08125)

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Model : spin polarization in E-by-E hydrodynamics

initial energy-momentum conservation

$$\frac{d^2}{d^2\mathbf{x}_\perp}\left\{\begin{array}{c} E \\ p^z \end{array}\right\} = m_N \left\{\begin{array}{c} [T_A(\mathbf{x}_\perp) + T_B(\mathbf{x}_\perp)]\cosh y_{\rm beam} \\ [T_A(\mathbf{x}_\perp) - T_B(\mathbf{x}_\perp)]\sinh y_{\rm beam} \end{array}\right\} \equiv M(\mathbf{x}_\perp)\left\{\begin{array}{c} \cosh y_{\rm CM} \\ \sinh y_{\rm CM} \end{array}\right\}$$

energy-momentum tensor : $T^{\tau\tau}(\tau_0, \mathbf{x}_\perp, \eta_s) = e(\mathbf{x}_\perp, \eta_s)\cosh(f y_{\rm CM})$

$$T^{\tau\eta}(\tau_0, \mathbf{x}_\perp, \eta_s) = \frac{e(\mathbf{x}_\perp, \eta_s)}{\tau_0}\sinh(f y_{\rm CM})$$

C. Shen and S. Alzhrani (2020)

S. Ryu, V. Jupic, and C. Shen (2021)

spin polarization vector

$$S^\mu(p) = \frac{1}{4m}\frac{\int p\cdot d^3\Sigma\, n_0(1-n_0)\,\mathcal{A}^\mu}{\int p\cdot d^3\Sigma\, n_0}$$

$$\left(P^\mu_{\rm lab} = \frac{1}{S}S^\mu(p)\right)$$

axial vector

$$\mathcal{A}^\mu_{\rm BBP} = -\epsilon^{\mu\rho\sigma\tau}\left(\frac{1}{2}\omega_{\rho\sigma}p_\tau + \frac{1}{E}\hat{t}_\rho\xi_{\sigma\lambda}p^\lambda p_\tau\right) \qquad \hat{t}^\mu = (1,0,0,0)$$

F. Becattini, M. Buzzegoli, and A. Palermo (2021)

$$\mathcal{A}^\mu_{\rm LY} = -\varepsilon^{\mu\rho\sigma\tau}\left[\frac{1}{2}\omega_{\rho\sigma}p_\tau + \frac{1}{E}u_\rho\xi_{\sigma\lambda}p^\lambda_\perp p_\tau + \frac{b_i}{\beta E}u_\rho p^\perp_\sigma\partial^\perp_\tau(\beta\mu_B)\right]$$

$$p^\mu_\perp = p^\mu - (p\cdot u)\,u^\mu$$

S. Y. F. Liu and Y. Yin (2021)

C. Yi, S. Pu, and D. Yang (2021)

thermal **vorticity**

$$\omega^{\mu\nu} \equiv -\frac{1}{2}\left[\partial^\mu\left(\frac{u^\nu}{T}\right) - \partial^\nu\left(\frac{u^\mu}{T}\right)\right]$$

and **shear**

$$\xi^{\mu\nu} \equiv \frac{1}{2}\left[\partial^\mu\left(\frac{u^\nu}{T}\right) + \partial^\nu\left(\frac{u^\mu}{T}\right)\right]$$

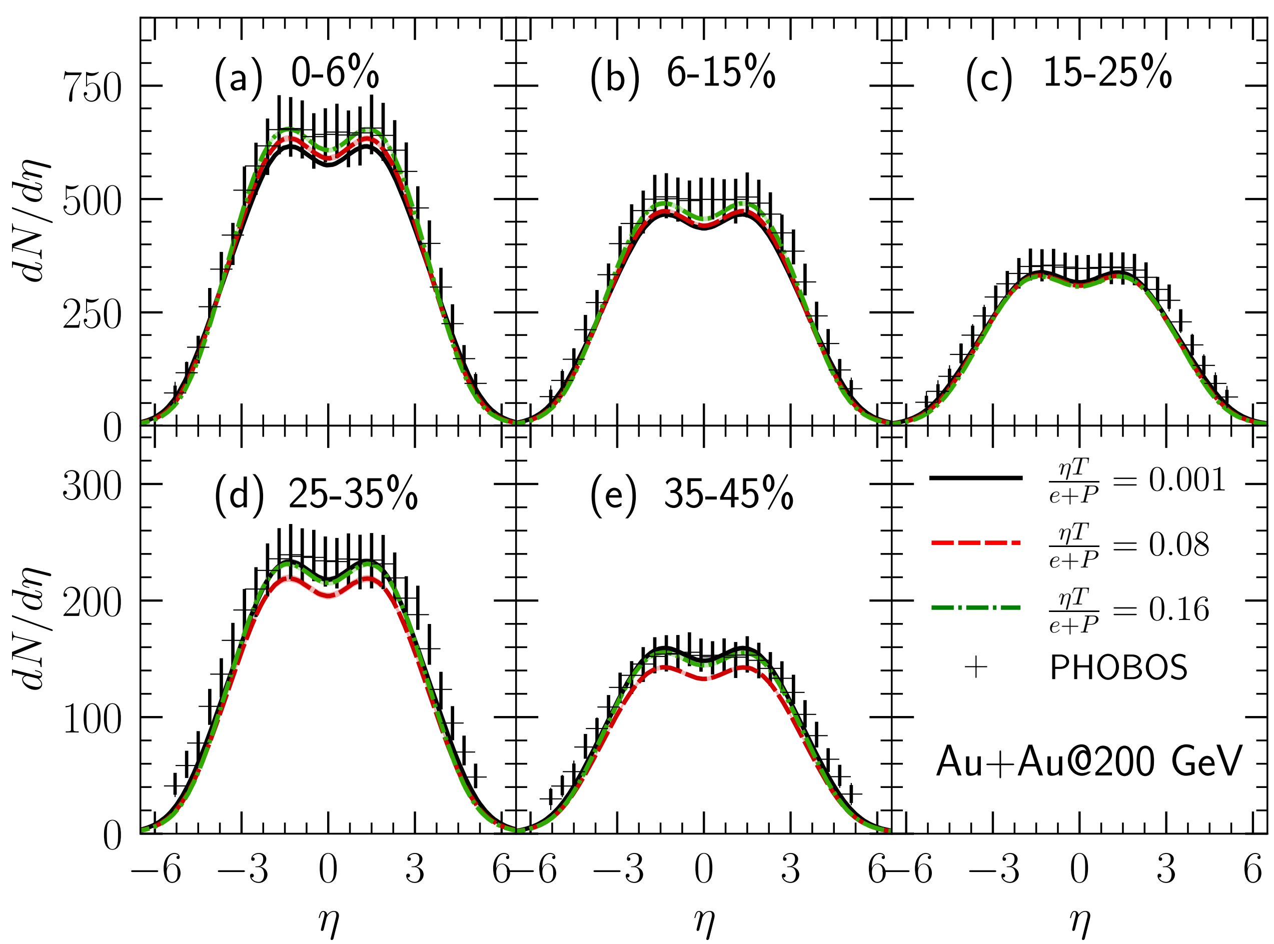
Result : charged hadron yield and anisotropic flow

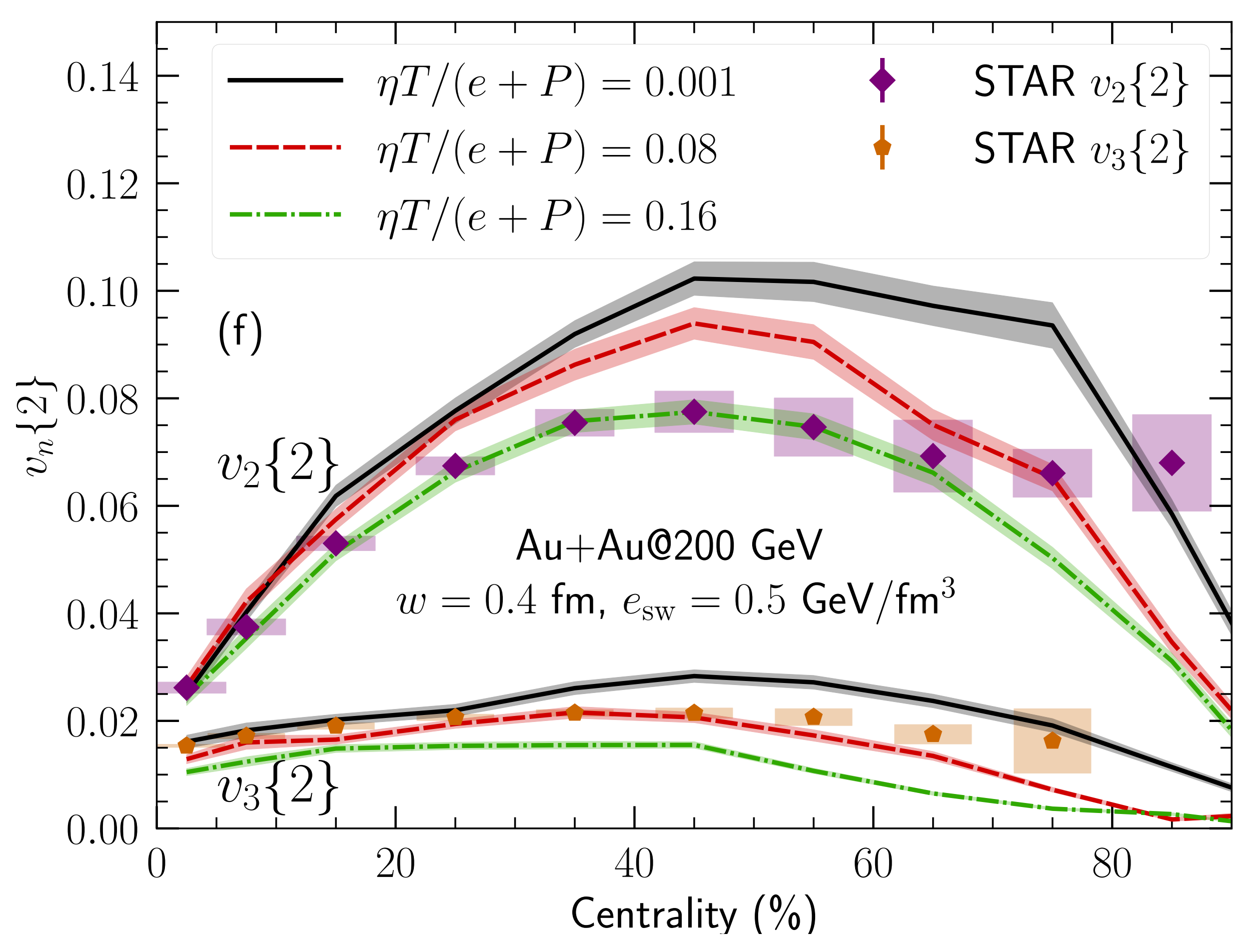
S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)

- Our framework provides reasonable descriptions of hadron yield and anisotropic (elliptic and triangular) flow coefficents.

- Experimental data favor $\frac{\eta T}{\epsilon + P} \sim 0.08 - 0.16$ and hot spot width $w = 0.4 - 0.8\,\mathrm{fm}$.

(see backup slide for w-dependence.)



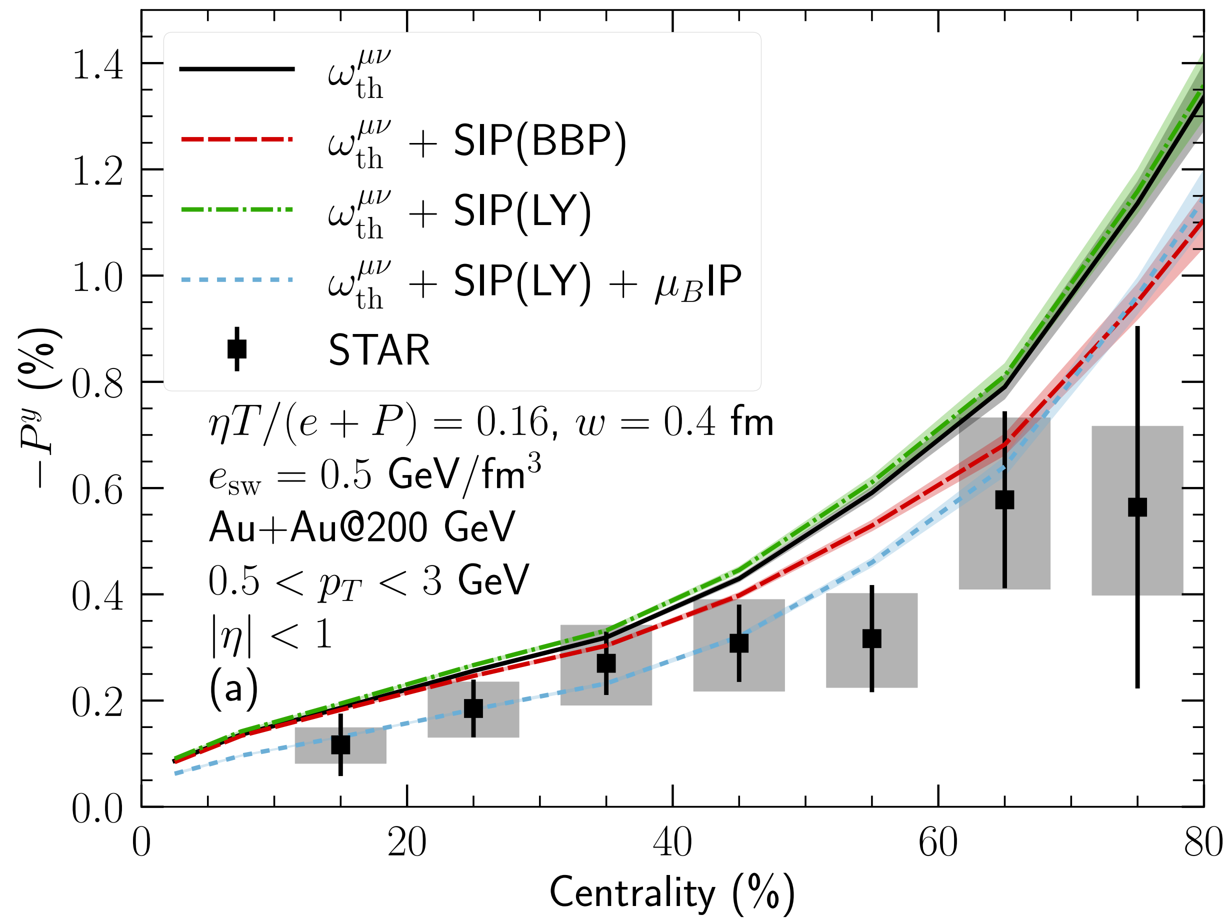


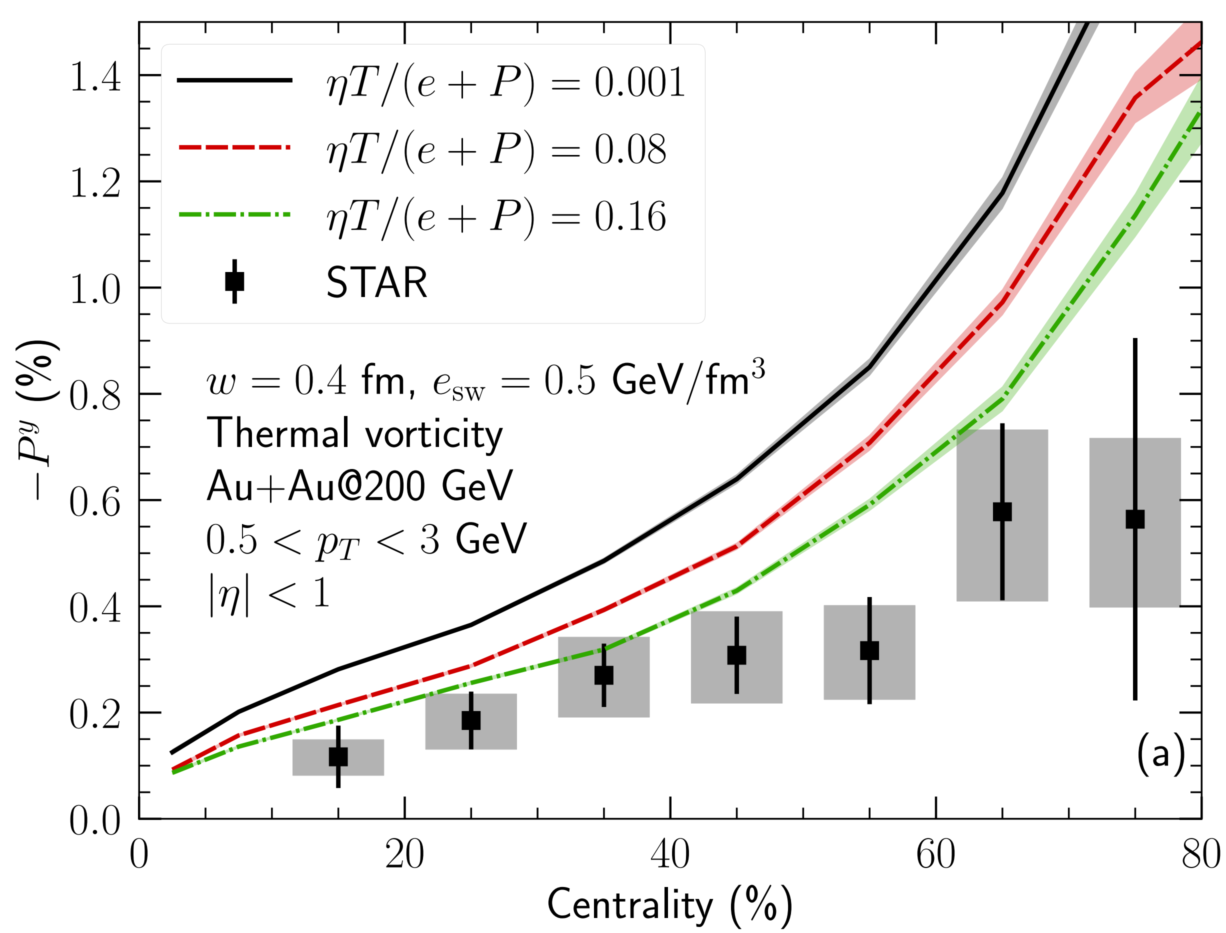
Result : Λ hyperon polarization
the global polarization

S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)

- Global polarization is strongly sensitive to the shear viscosity, because the vortical movement is smeared faster in the presense of viscosity.
- Global polarization is dominated by system's thermal vorticity.

$$S^y_{\mathrm{global}} = \frac{1}{4m} \frac{\int dy \int d^2\mathbf{p}_\perp \int p \cdot d^3\Sigma\, n_0(1-n_0)\, \mathcal{A}^y}{\int dy \int d^2\mathbf{p}_\perp \int p \cdot d^3\Sigma\, n_0}$$





Result : Λ hyperon polarization

longitudinal polarization

centrality and azimuthal dependence

S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)

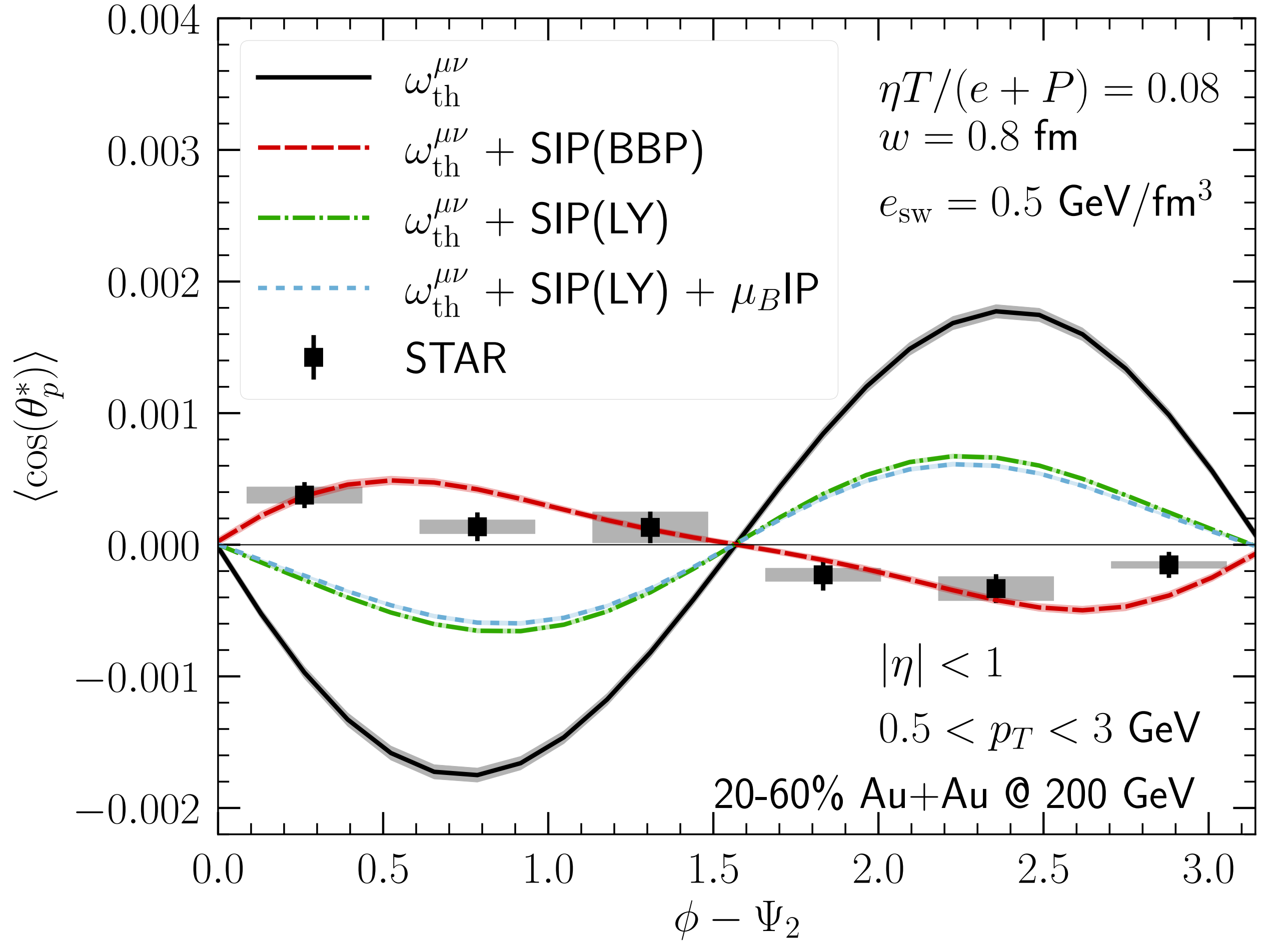
- The shear-induced polarization is substantial for azimuthal dependence of the longitudinal polarization.

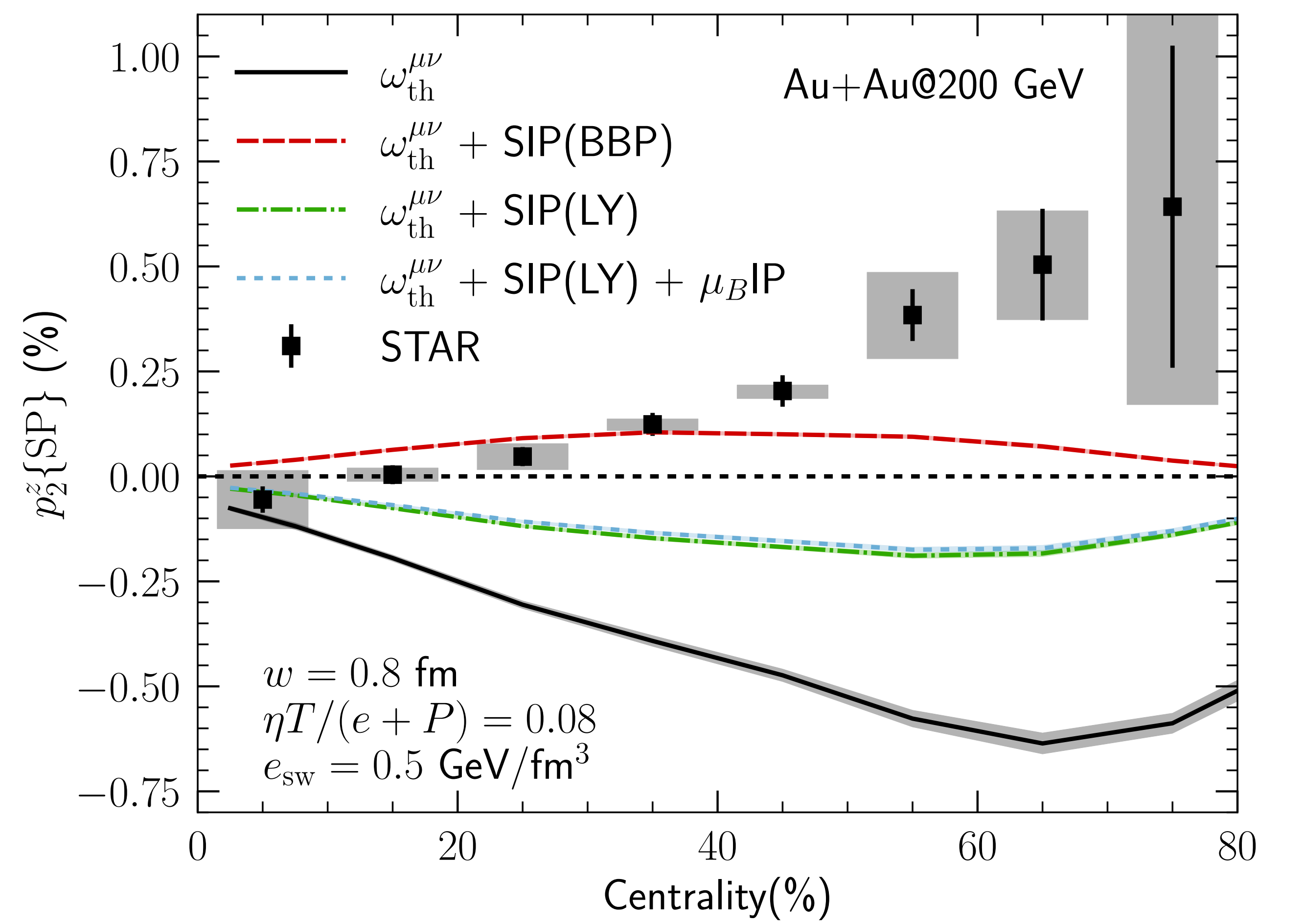
$$\mathcal{A}^{\mu}_{\text{SIP-BBP}} = -\epsilon^{\mu\rho\sigma\tau}\frac{1}{E}\hat{t}_{\rho}\xi_{\sigma\lambda}p^{\lambda}p_{\tau} \text{ and } \mathcal{A}^{\mu}_{\text{SIP-LY}} = -\varepsilon^{\mu\rho\sigma\tau}\frac{1}{E}u_{\rho}\xi_{\sigma\lambda}p^{\lambda}_{\perp}p_{\tau}$$

$$\langle\cos\theta^*_{\mathbf{p}}\rangle(\phi_{\mathbf{p}}) = \langle\cos^2\theta^*_{\mathbf{p}}\rangle\alpha_\Lambda P^z(\phi_{\mathbf{p}}) = \frac{\alpha_\Lambda}{3}P^z(\phi_{\mathbf{p}})$$

$$\mathcal{P}^z_n \equiv \int_0^{2\pi}\frac{d\phi}{2\pi}P^z(\phi)\,e^{in\phi}$$

$$p^z_n\{\text{SP}\} \equiv \frac{\langle\text{Im}\,\mathcal{P}^z_n\mathcal{Q}^*_{n,A}\rangle_{\text{ev}}}{\sqrt{\langle\text{Re}\,\mathcal{Q}_{n,A}\mathcal{Q}^*_{n,B}\rangle_{\text{ev}}}}$$





Result : Λ hyperon polarization

longitudinal polarization

S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)

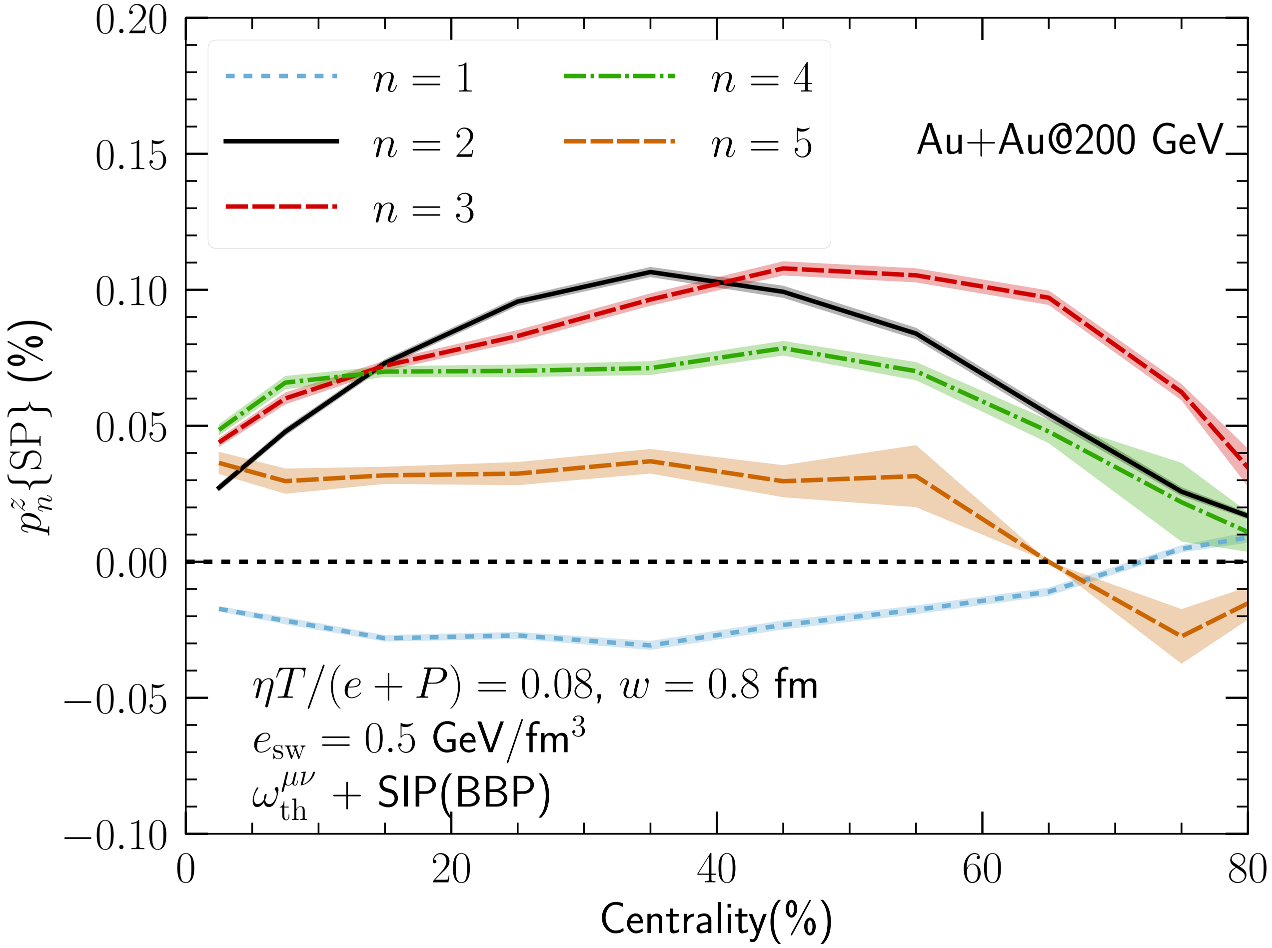
correlation with anisotropic flow coefficient v_n

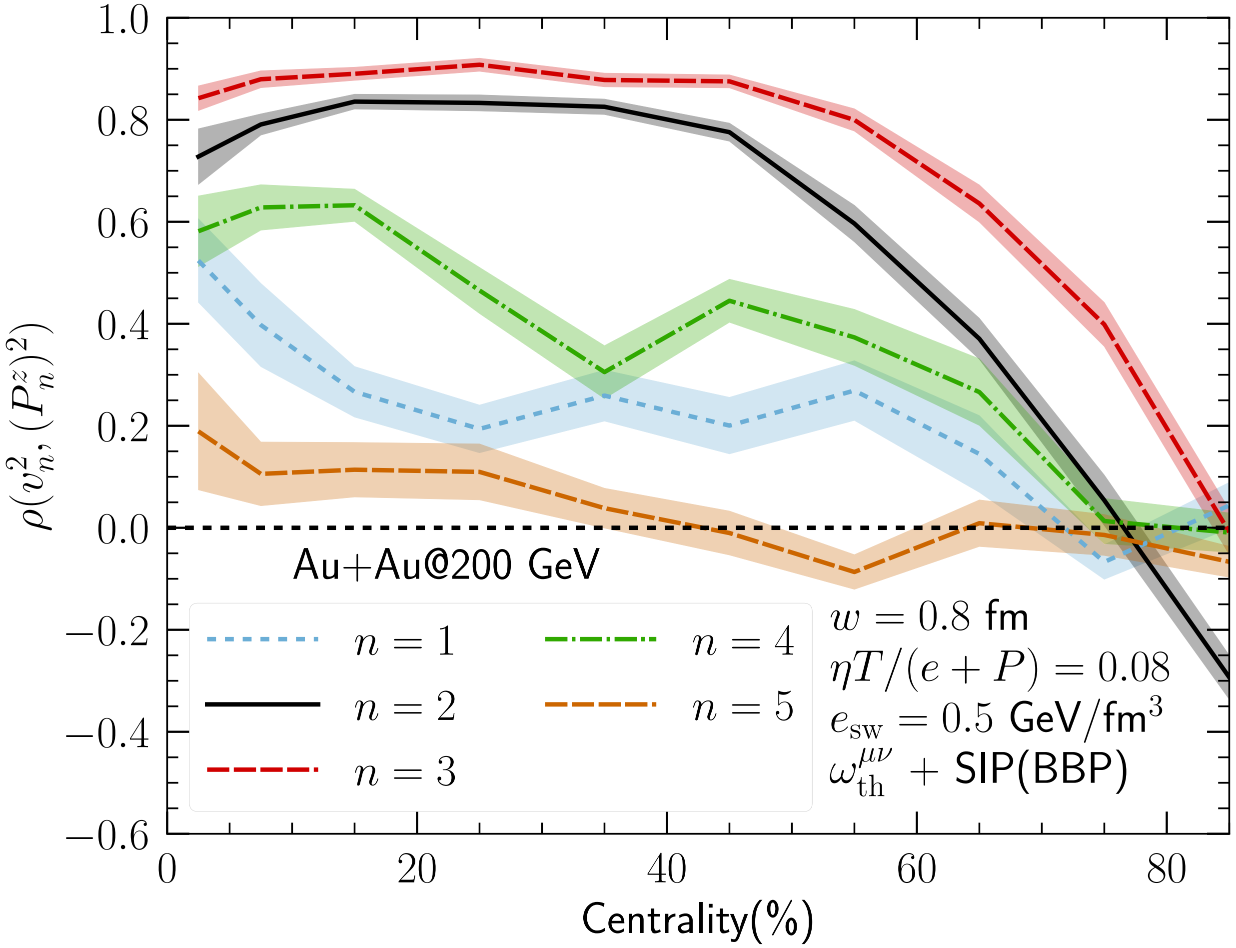
- longitudinal polarization is positively correlated with the anisotropic flow.
- Predictions for the n-th Fourier coefficients of $P^z(\phi_{\mathbf{p}})$:
  $p_3^z\{\mathrm{SP}\}$ and $p_4^z\{\mathrm{SP}\}$ are comparable to $p_2^z\{\mathrm{SP}\}$.

$$\rho\,(v_n^2, (P_n^z)^2) = \frac{\langle \hat{\delta} v_n^2 \hat{\delta}(P_n^z)^2\rangle_{\mathrm{ev}}}{\sqrt{\langle[\hat{\delta} v_n^2]^2\rangle_{\mathrm{ev}}\langle[\hat{\delta}(P_n^z)^2]^2\rangle_{\mathrm{ev}}}}$$

$$\left(\hat{\delta}\mathcal{O} \equiv \delta\mathcal{O} - \frac{\langle\delta\mathcal{O}\,\delta N_{\mathrm{ch}}\rangle_{\mathrm{ev}}}{\langle(\delta N_{\mathrm{ch}})^2\rangle_{\mathrm{ev}}}\delta N_{\mathrm{ch}}\right)$$

$$p_n^z\{\mathrm{SP}\} \equiv \frac{\langle \mathrm{Im}\,\mathcal{P}_n^z \mathcal{Q}_{n,A}^*\rangle_{\mathrm{ev}}}{\sqrt{\langle \mathrm{Re}\,\mathcal{Q}_{n,A}\mathcal{Q}_{n,B}^*\rangle_{\mathrm{ev}}}}$$



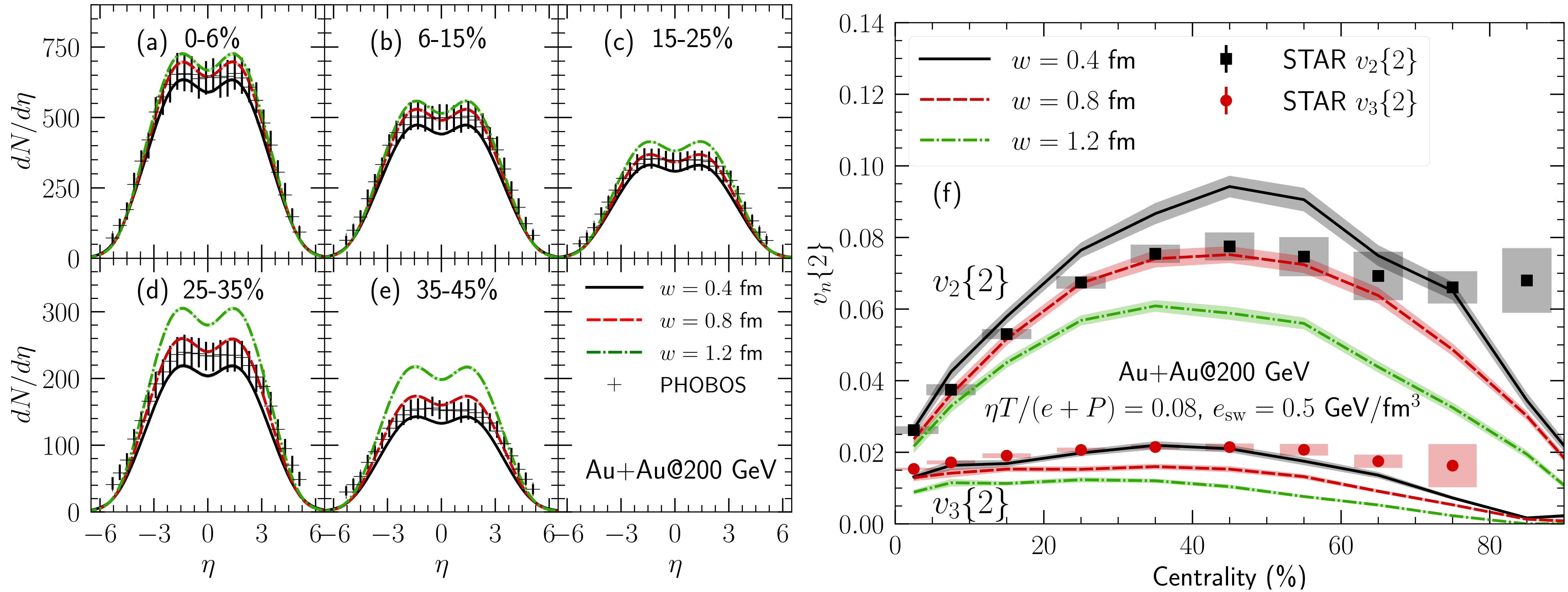


Backup

Result : sensitivity to width of energy deposit

S. Alzhrani, S. Ryu and C. Shen (arXiv:2203.15718)

charged hadron production and anisotropic flow



Result : sensitivity to width of energy deposit

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global and longitudinal polarization