Spin polarization within perturbative calculations

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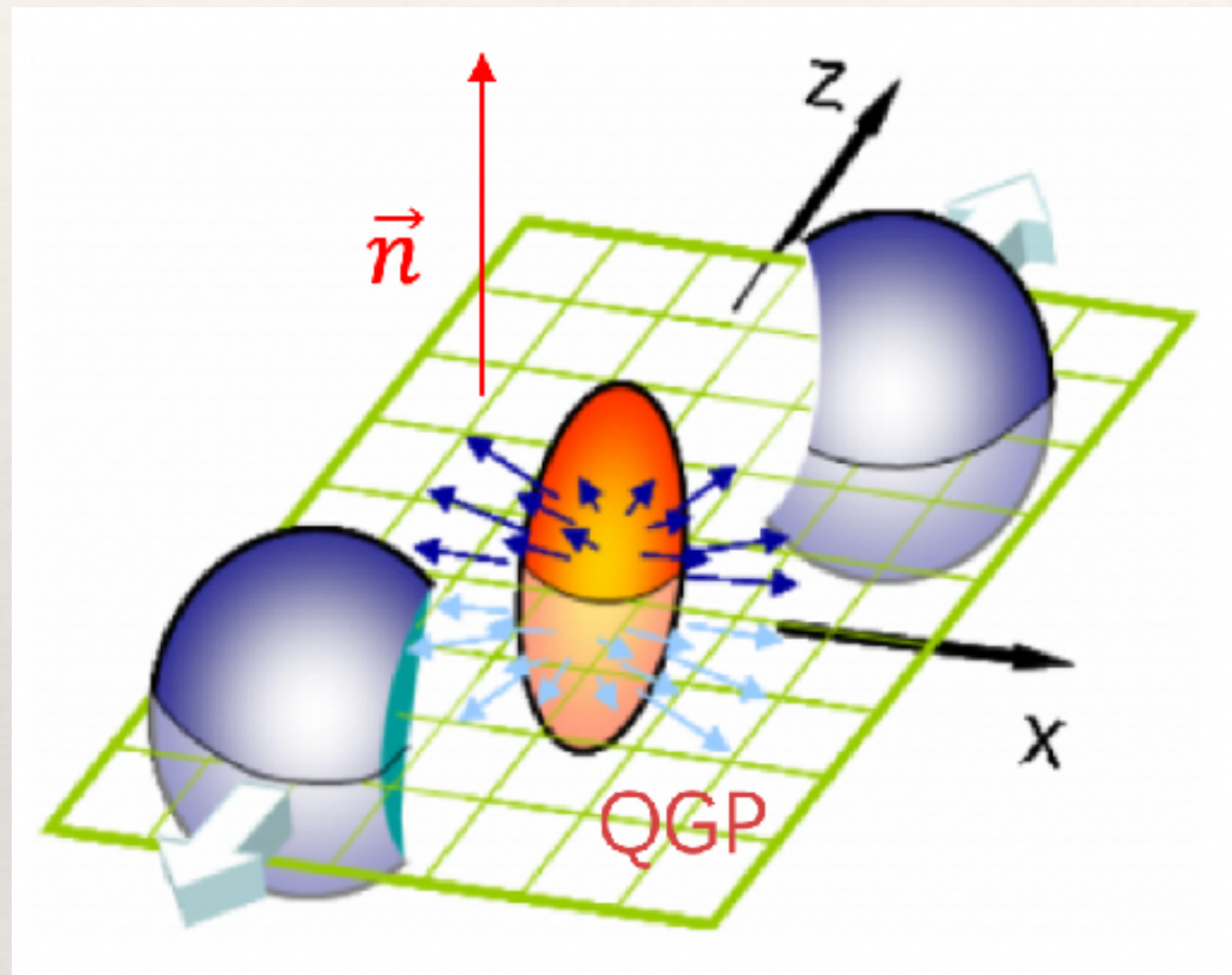
March 17, 2024 @ ExHIC-p Workshop

Outline

- **Introduction**

- **Production and evolution of the QGP global polarization**

  [X. Li, Z.-F. Jiang, SC, J. Deng, Eur. Phys. J. C 83 (2023) 1, 96]

- **Spin polarization from jet fragmentation**

  [X. Li, Z.-X. Chen, SC, S.-Y. Wei, Phys. Rev. D 109 (2024) 1, 014035]

- **Summary**

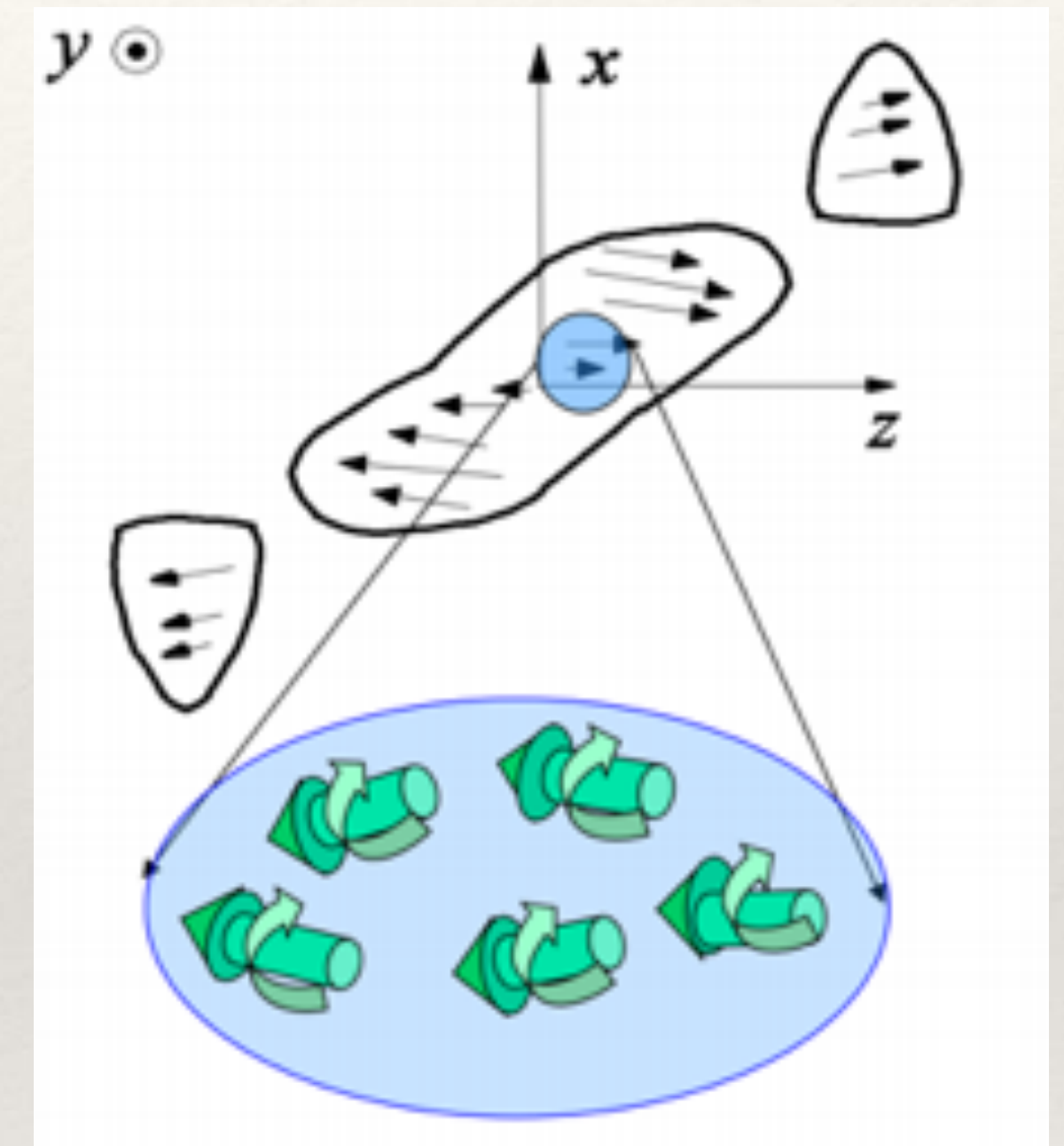# Spin-orbital coupling in a strongly interacting system

Non-central relativistic heavy-ion collisions

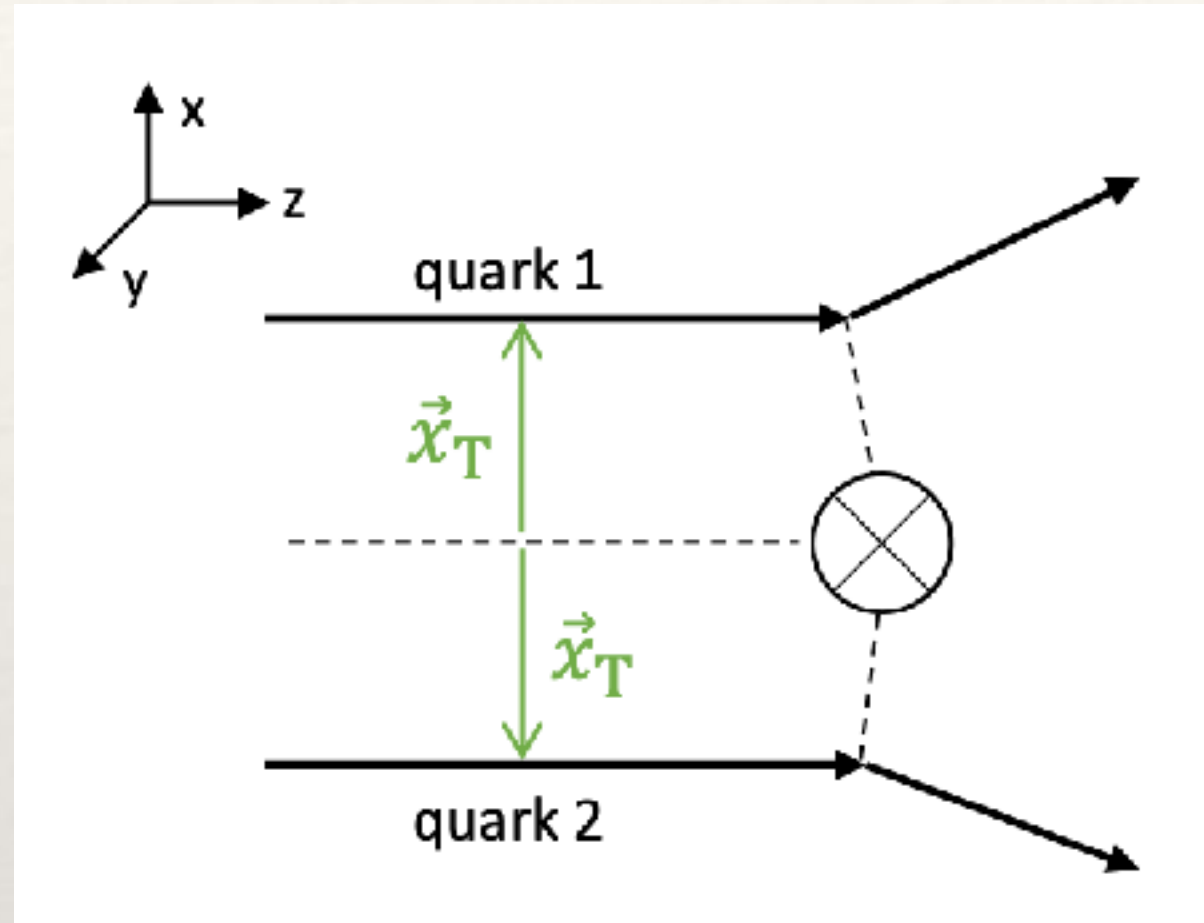Huge orbital angular momentum
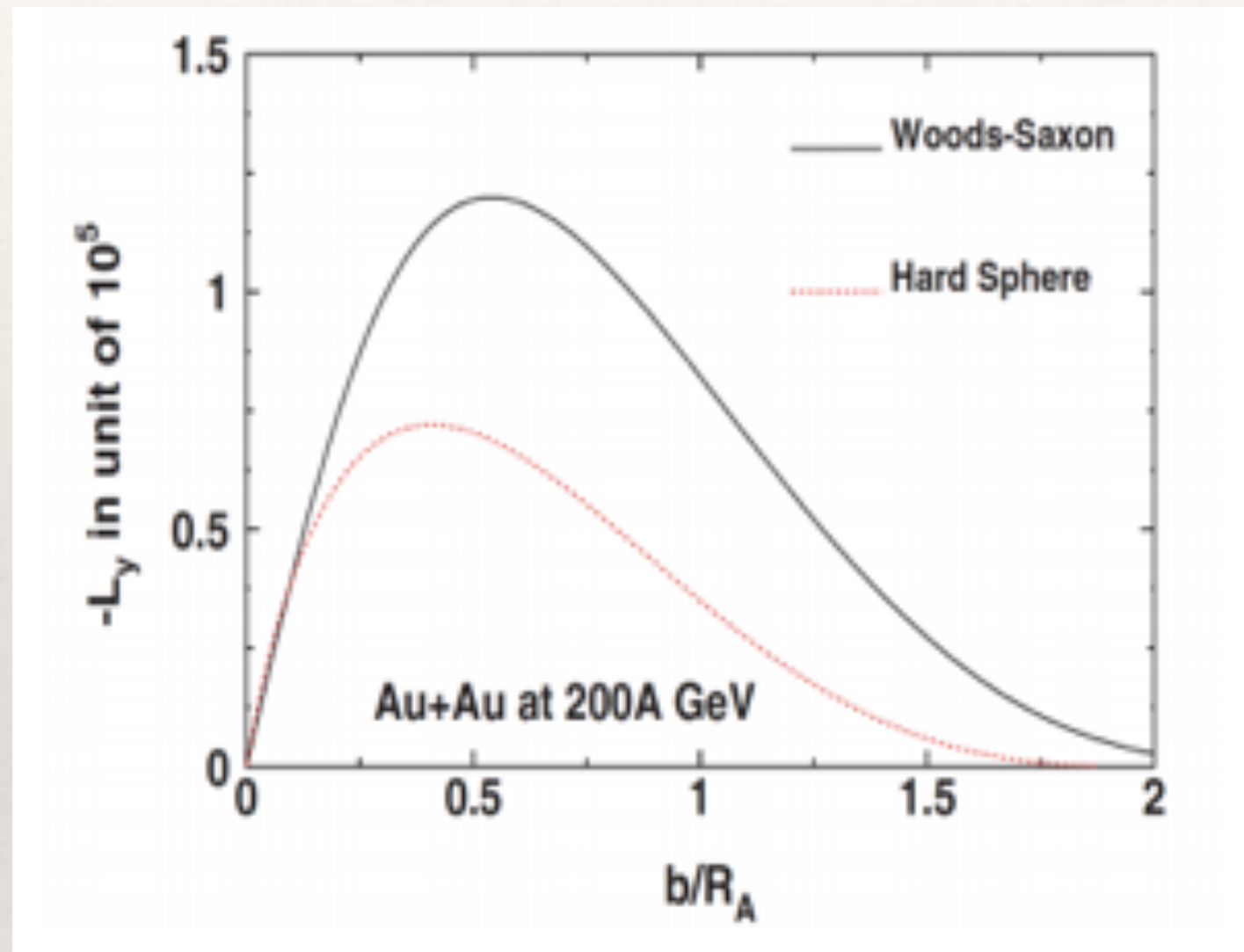
Global polarization

$$\hat{n} = \frac{\vec{b} \times \vec{P}}{\left| \vec{b} \times \vec{P} \right|} = -\hat{y}$$

J.-H. Gao, S.-W. Chen, W.-T. Deng, Z.-T. Liang, Q. Wang, X.-N. Wang, Phys. Rev. C 77 (2008) 044902

Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94 (2005) 102301

A brief review of the first calculation of global polarization

Quark-potential scattering model [Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94 (2005) 102301]

Consider a quark (quark 1) scattering with a potential

$$A_0(q_T) = g/(q_T^2 + \mu^2)$$

Initial momentum $(E, \vec{p})$, final spin $\lambda/2$ along $\hat{n}$ $(-\hat{y})$

Differential cross section w.r.t. $\vec{x}_T$:

$$\frac{d^2\sigma_\lambda}{d^2 x_T} = C_T \int \frac{d^2 q_T}{(2\pi)^2} \frac{d^2 k_T}{(2\pi)^2} e^{i(\vec{k}_T - \vec{q}_T)\cdot \vec{x}_T} \mathcal{I}_\lambda$$

(Fourier transform into the coordinate space)

$$\mathcal{I}_\lambda = \frac{g^2}{2(2E)^2} \bar{u}_\lambda(p_q) \slashed{A}(q_T)(\slashed{p}+m)\slashed{A}(k_T) u_\lambda(p_k)$$

(Final spin not summed)

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A brief review of the first calculation of global polarization

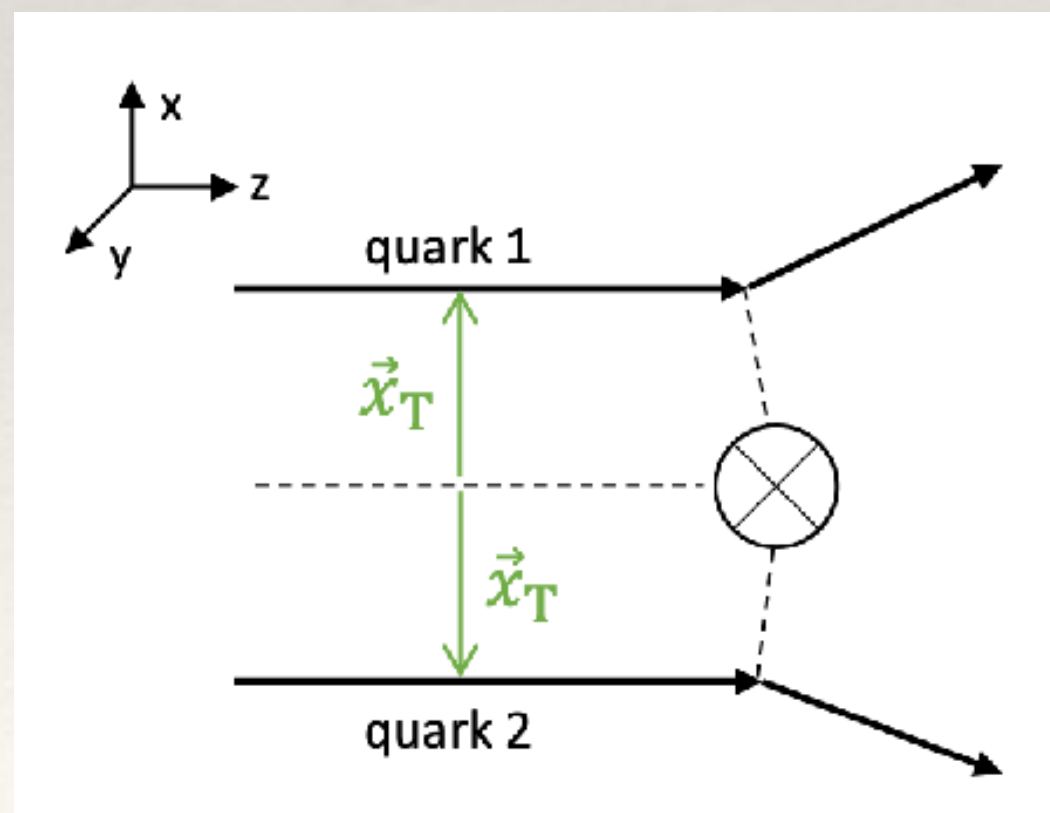With small angle approximation

Spin-independent cross section:
$$\frac{d\sigma}{d^2 x_T} = \frac{d\sigma_+}{d^2 x_T} + \frac{d\sigma_-}{d^2 x_T} = 4C_T \alpha_s^2 K_0^2(\mu x_T)$$

Spin-dependent cross section:
$$\frac{d\Delta\sigma}{d^2 x_T} = \frac{d\sigma_+}{d^2 x_T} - \frac{d\sigma_-}{d^2 x_T} = -4C_T \alpha_s^2 \mu \frac{\vec{p} \cdot (\hat{x}_T \times \hat{n})}{E(E+m)} K_0(\mu x_T) K_1(\mu x_T)$$

Polarization:
$$P = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\int_0^\infty dx \int_{-\infty}^\infty dy \frac{d\Delta\sigma}{dxdy}}{\int_0^\infty dx \int_{-\infty}^\infty dy \frac{d\sigma}{dxdy}} = -\frac{\pi\mu p}{2E(E+m)}$$
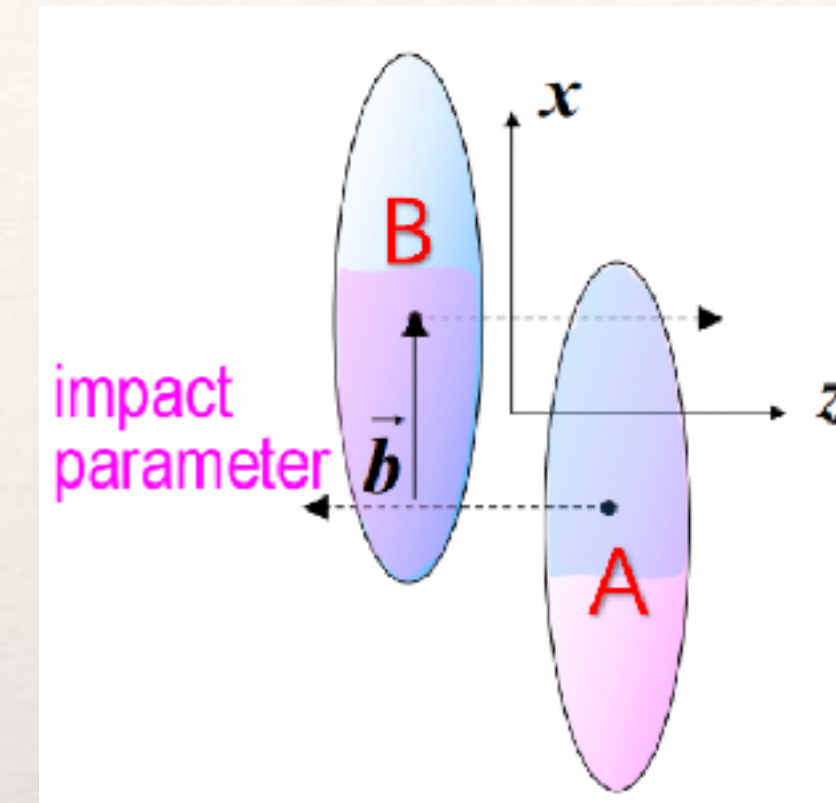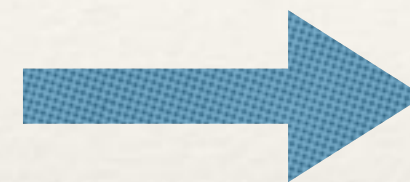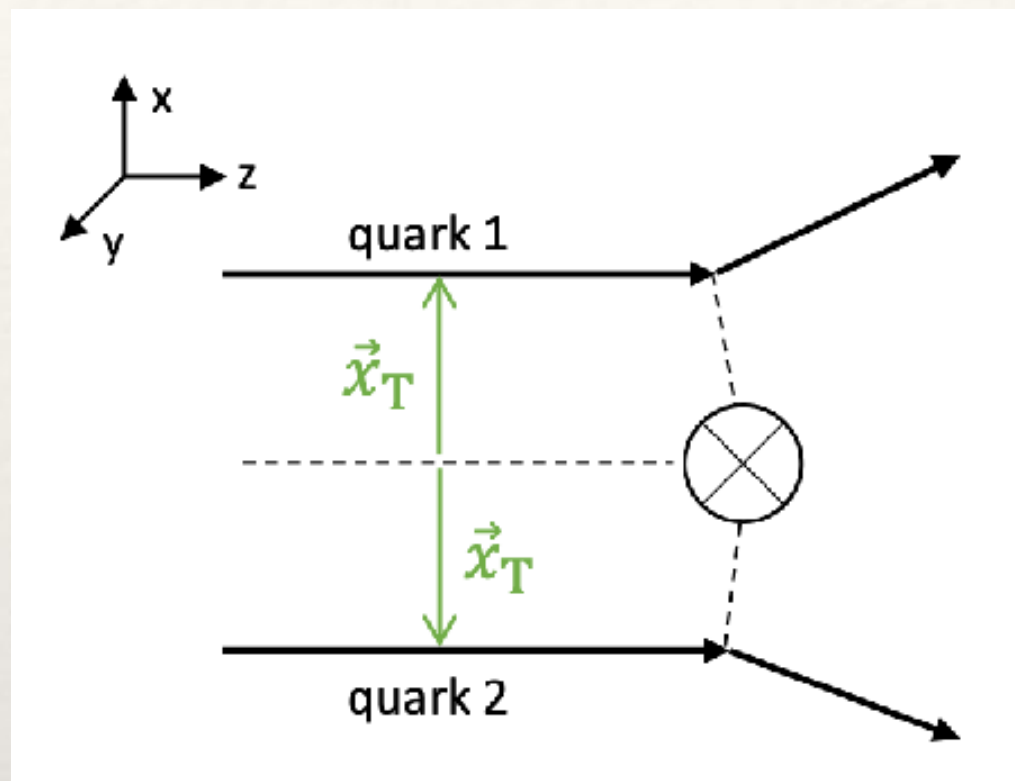

Caveats:

- Integration over only half plane (0 if over the whole plane)
- Approximating the whole nuclear matter with a single potential
- Only single scattering, no evolution

Model improvement

For a single quark from nucleus A scattering with the whole nucleus B

$T(x,y)$: participant number distribution in nucleus B (Glauber)

$$P = \frac{\Delta\sigma}{\sigma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\int_0^\infty dx \int_{-\infty}^\infty dy \frac{d\Delta\sigma}{dxdy}}{\int_0^\infty dx \int_{-\infty}^\infty dy \frac{d\sigma}{dxdy}}$$

$$P = \frac{\int T(x,y) \frac{d\Delta\sigma(x,y)}{d^2 x_T} d^2 x_T}{\int T(x,y) \frac{d\sigma(x,y)}{d^2 x_T} d^2 x_T}$$

Interact with one scattering center in a half plane

Interact with multiple scattering centers distributed according to nuclear density

Spatial distribution of quark polarization

Spin-independent probability for a quark from nucleus A

$$\mathcal{P}_A(x_A, y_A) = \int T_2(x_B, y_B) \frac{d\sigma(x_A, y_A, x_B, y_B)}{dx_B\, dy_B} dx_B\, dy_B$$

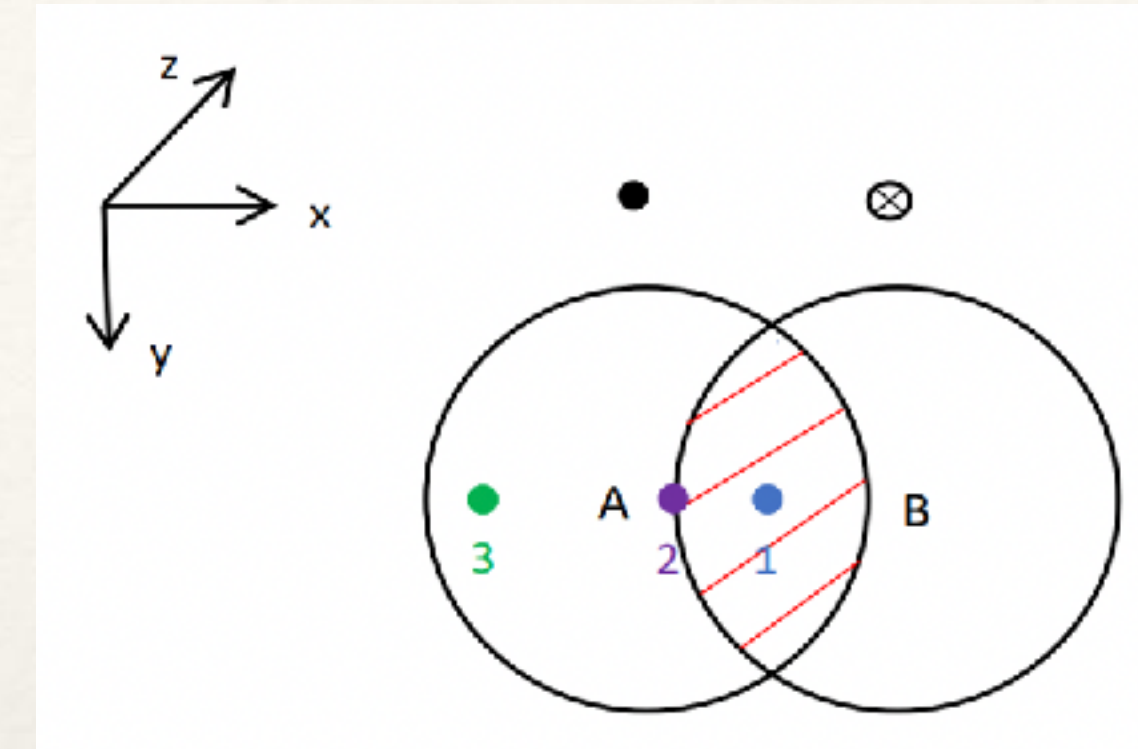Spin-dependent probability for a quark from nucleus A

$$\Delta\mathcal{P}_A(x_A, y_A) = \int T_2(x_B, y_B) \frac{d\Delta\sigma(x_A, y_A, x_B, y_B)}{dx_B\, dy_B} dx_B\, dy_B$$

Spatial distribution of quark polarization

$$P(x, y) = \frac{T_1(x,y)\Delta\mathcal{P}_A(x,y) + T_2(x,y)\Delta\mathcal{P}_B(x,y)}{T_1(x,y)\mathcal{P}_A(x,y) + T_2(x,y)\mathcal{P}_B(x,y)}$$
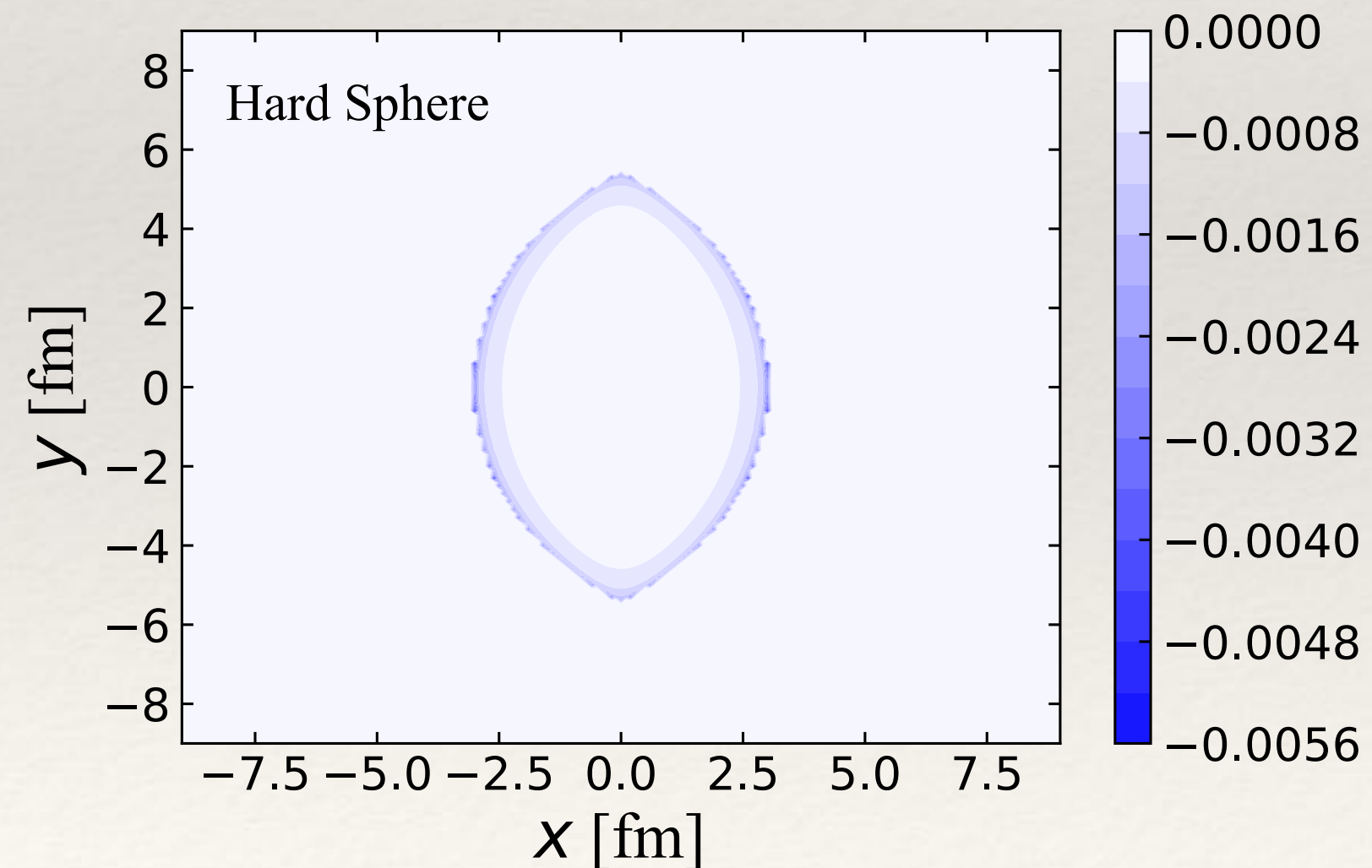
Spatial distribution of polarization from initial hard collisions

$$P(x,y) = \frac{T_1(x,y)\Delta\mathcal{P}_A(x,y) + T_2(x,y)\Delta\mathcal{P}_B(x,y)}{T_1(x,y)\mathcal{P}_A(x,y) + T_2(x,y)\mathcal{P}_B(x,y)}$$
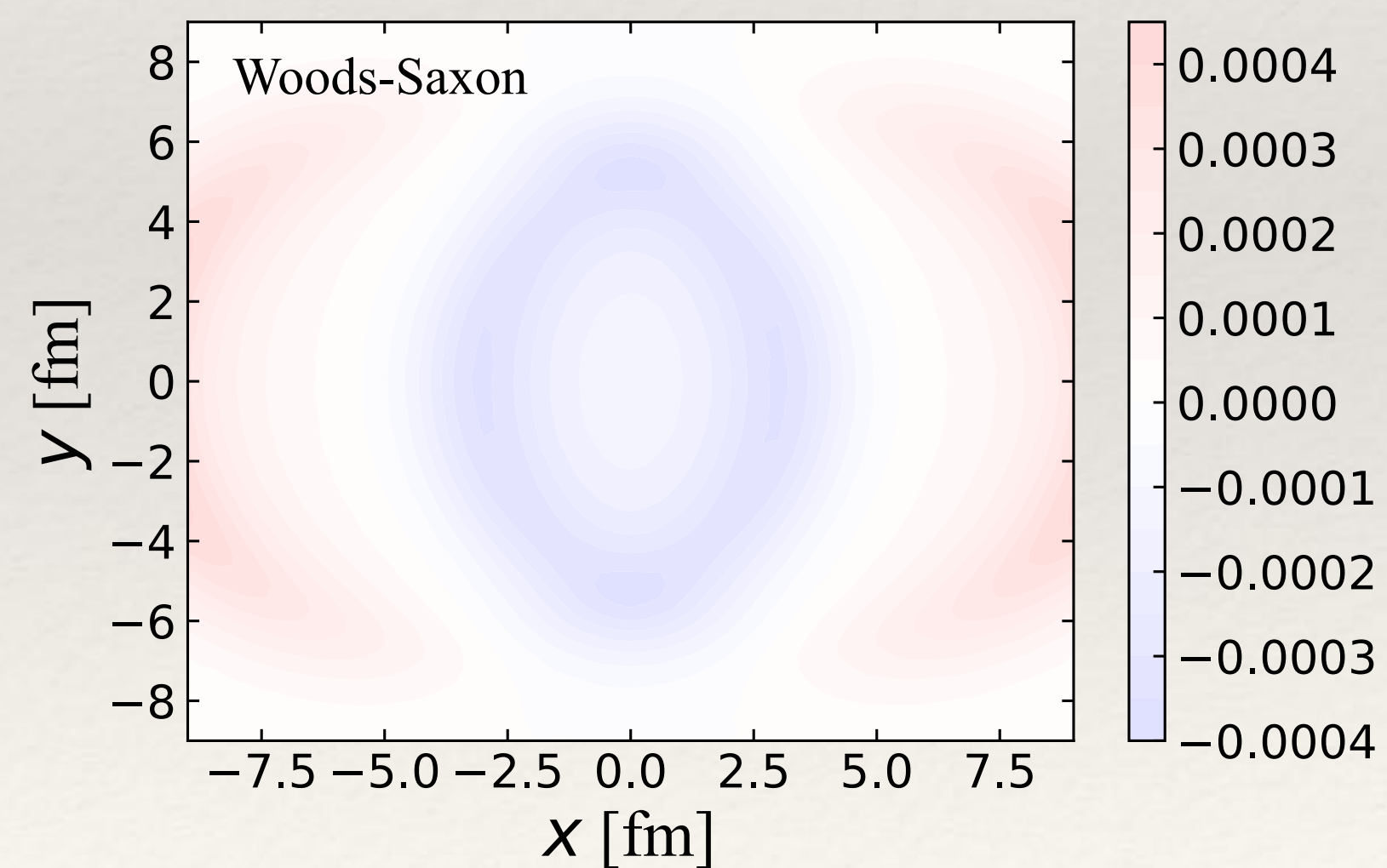
For 5-40% Au+Au @ 200 GeV
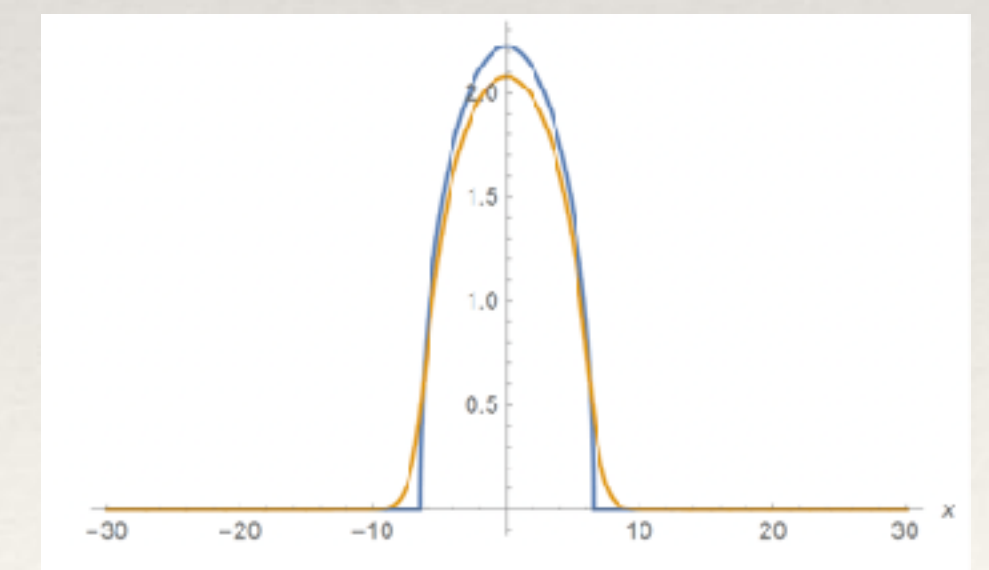
From Hard Sphere distribution
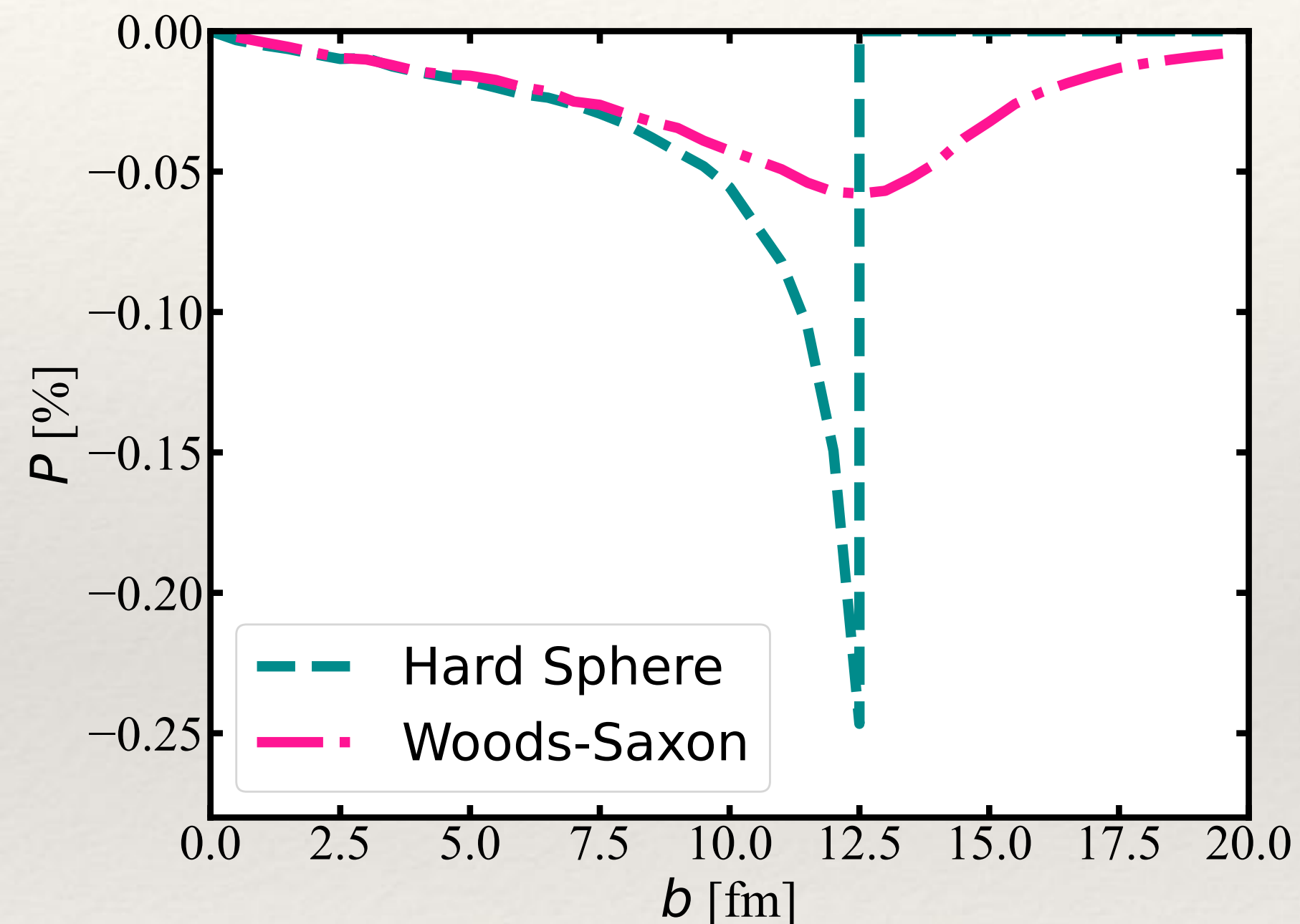
From Woods-Saxon distribution

Hard Sphere (HS)

Woods-Saxon (WS)

Transverse plane averaged polarization from initial collisions

$$\overline{P} = \frac{\int [T_1(x,y)\Delta\mathcal{P}_{\mathrm{A}}(x,y) + T_2(x,y)\Delta\mathcal{P}_{\mathrm{B}}(x,y)]dxdy}{\int [T_1(x,y)\mathcal{P}_{\mathrm{A}}(x,y) + T_2(x,y)\mathcal{P}_{\mathrm{B}}(x,y)]dxdy}$$

- Overall negative value of polarization (along $-\hat{y}$ direction)
- Noticeable difference between HS and WS calculations only at large impact parameter

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Multiple scatterings inside the QGP

For polarized initial quark state [X.-G. Huang, P. Huovinen, X.-N. Wang, Phys. Rev. C 84 (2011) 054910]

$$\frac{d\sigma_\lambda}{dx_T^2} = \frac{1}{2}g^4 C_T \left[\frac{1}{4\pi^2}(1+\lambda_f P_i)K_0^2(\mu x_T) - \frac{\mu}{4\pi^2}K_0(\mu x_T)K_1(\mu x_T)\frac{1}{E(E+m)}(\lambda_f + P_i)\,\vec{p}\cdot(\vec{n}\times\vec{x_T})\right]$$

Spin-independent cross section:

$$\frac{d\sigma}{d^2 x_T} = \frac{d\sigma_+}{d^2 x_T} + \frac{d\sigma_-}{d^2 x_T}$$

Spin-dependent cross section:

$$\frac{d\Delta\sigma}{d^2 x_T} = \frac{d\sigma_+}{d^2 x_T} - \frac{d\sigma_-}{d^2 x_T}$$

Polarization of final quark state:

$$P_f(x,y) = \frac{\int dx_1 dy_1\, s(x_1,y_1)\frac{d\Delta\sigma(x,y,x_1,y_1)}{dx_1 dy_1}}{\int dx_1 dy_1\, s(x_1,y_1)\frac{d\sigma(x,y,x_1,y_1)}{dx_1 dy_1}}$$
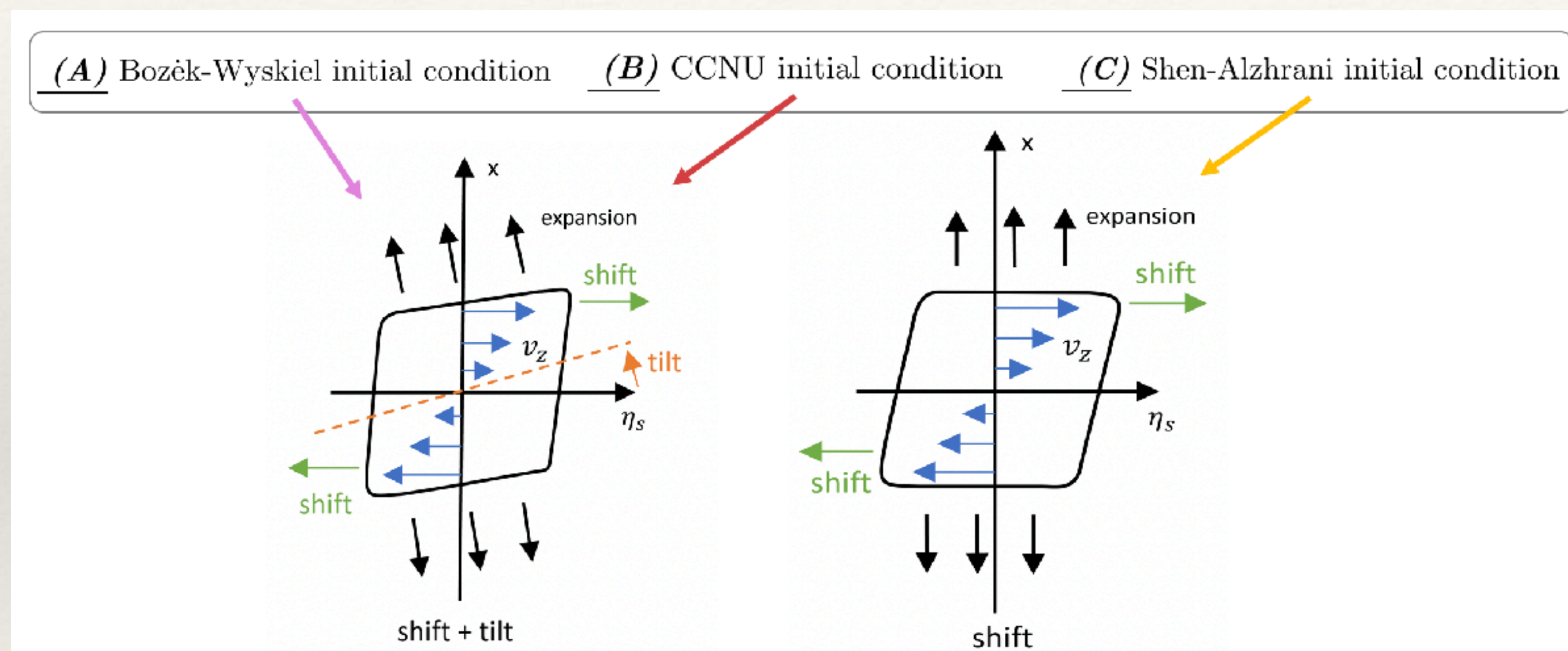
(*s*: entropy density of the QGP, from hydrodynamic model)

Time evolution of polarization:

$$\frac{dP(x,y)}{dt} = \frac{\Delta P(x,y)}{\tau_q} = \frac{4T\rho}{9s}\frac{s}{\eta_v}\Delta P(x,y)$$

$$(\Delta P = P_f - P_i)$$

Application of hydrodynamic model

- **(3+1)-D CLVisc hydrodynamic model** [L.-G. Pang, H. Petersen, X.-N. Wang, Phys. Rev. C 97 (2018) 064918; X.-Y. Wu, L.-G. Pang, G.-Y. Qin, X.-N. Wang, Phys. Rev. C 98 (2018) 024913]

- Compare three different initial geometries

(A) Bozèk-Wyskiel initial condition   (B) CCNU initial condition   (C) Shen-Alzhrani initial condition

(A) P. Bozek and I. Wyskiel, Phys. Rev. C 81 (2010) 054902

(B) Z.-F. Jiang, C.-B. Yang, Q. Peng, Phys. Rec. C 104 (2021) 064903

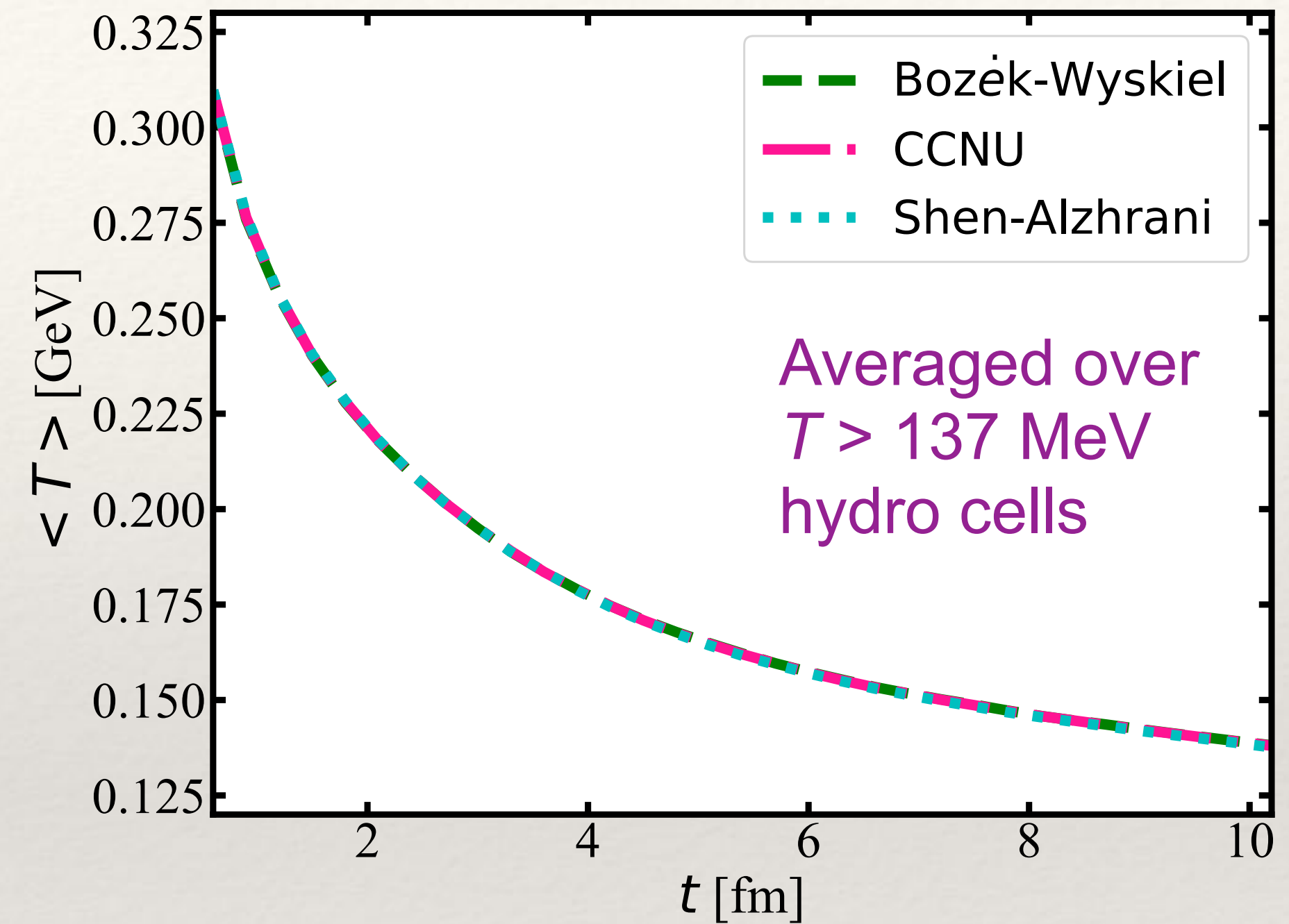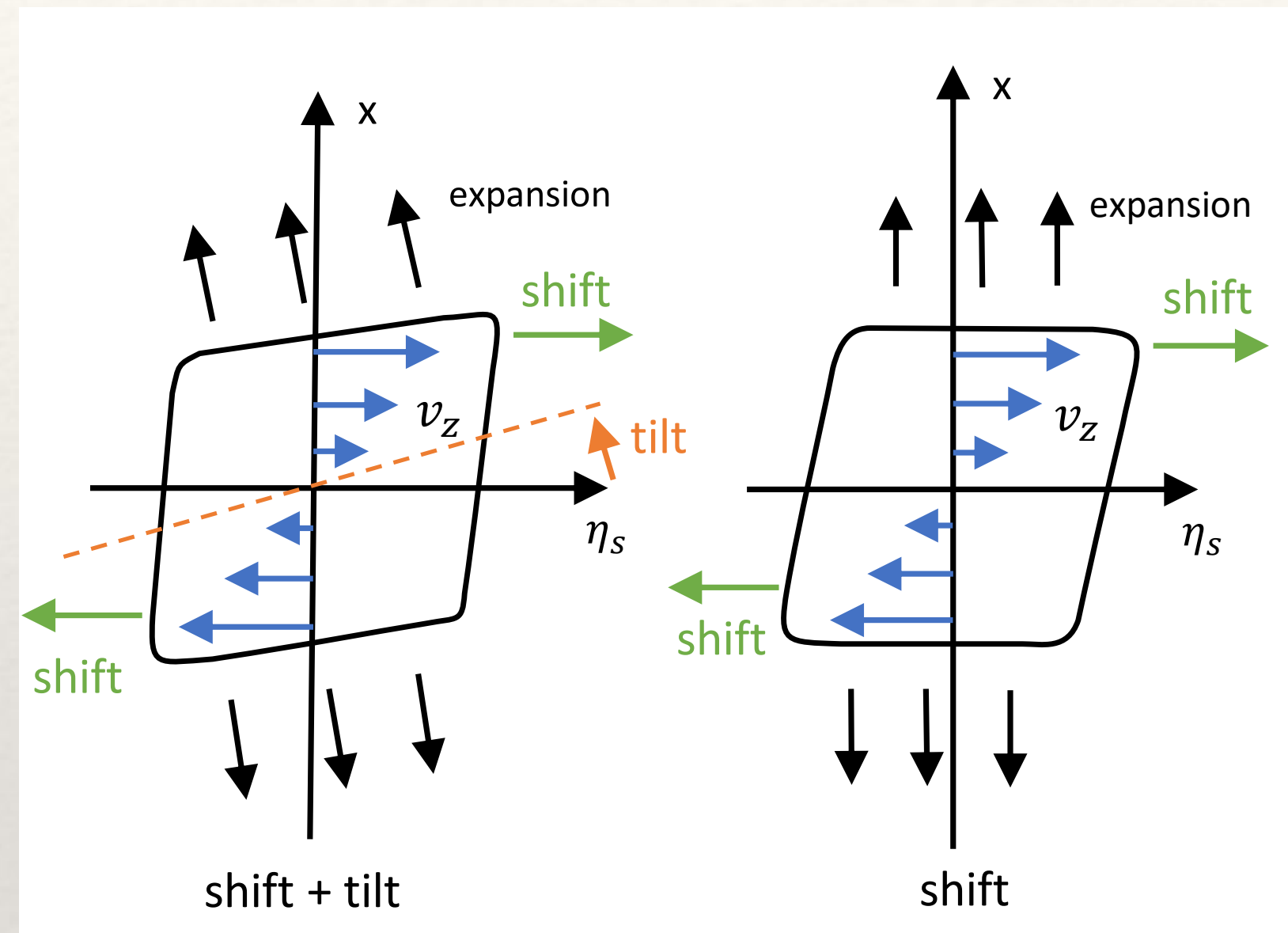(C) S. Ryu, V. Jupic, C. Shen, Phys. Rev. C 104 (2021) 054908

- Introduce initial longitudinal flow $\quad v_{\eta_s} = T^{\tau\eta}/T^{\tau\tau}$

$$T^{\tau\tau}(x, y, \eta_s) = \epsilon(x, y, \eta_s)\cosh(y_L) \qquad T^{\tau\eta}(x, y, \eta_s) = \frac{1}{\tau_0}\epsilon(x, y, \eta_s)\sinh(y_L)$$
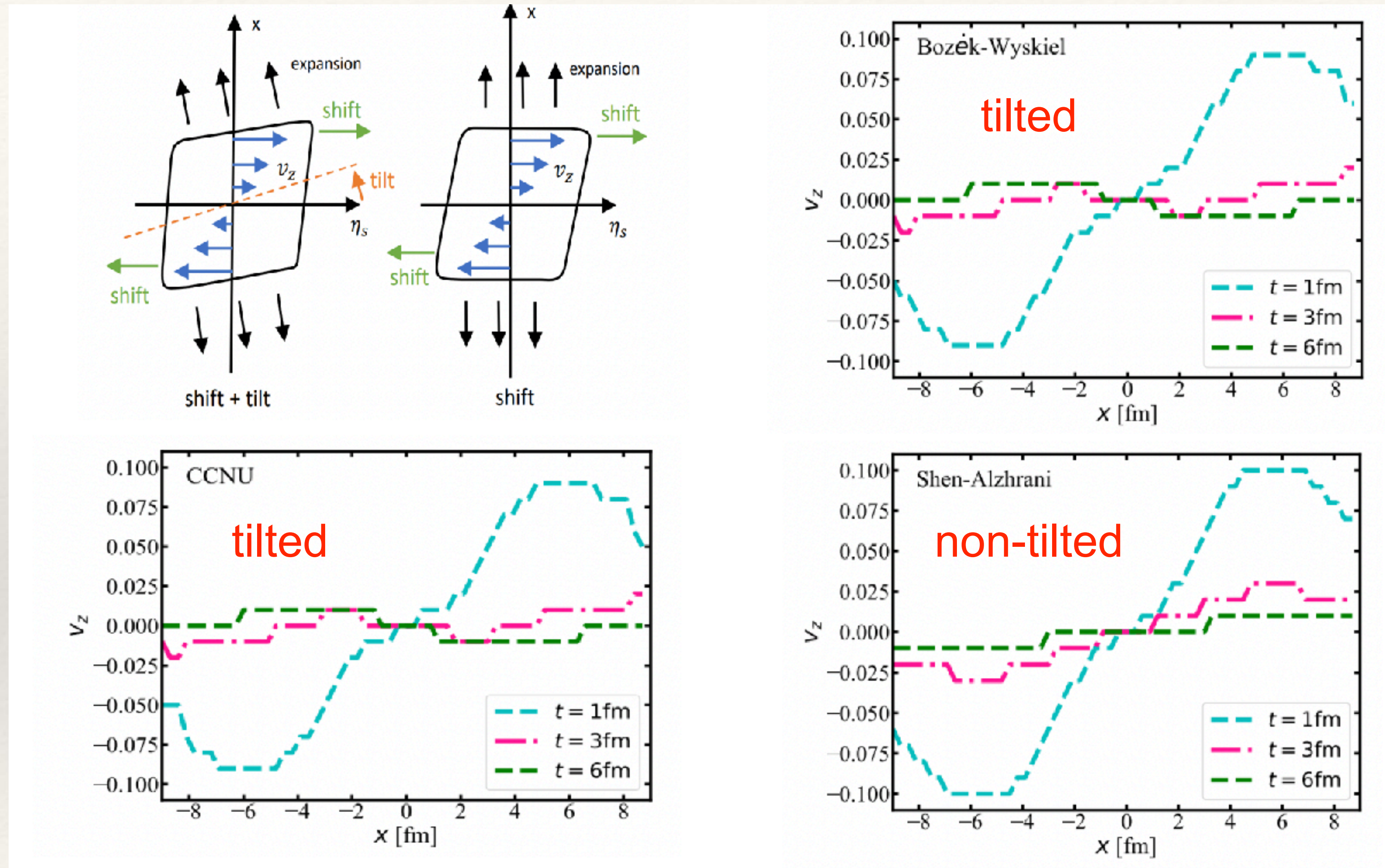
[S. Ryu, V. Jupic, C. Shen, Phys. Rev. C 104 (2021) 054908]

Evolution of average temperature

Averaged over
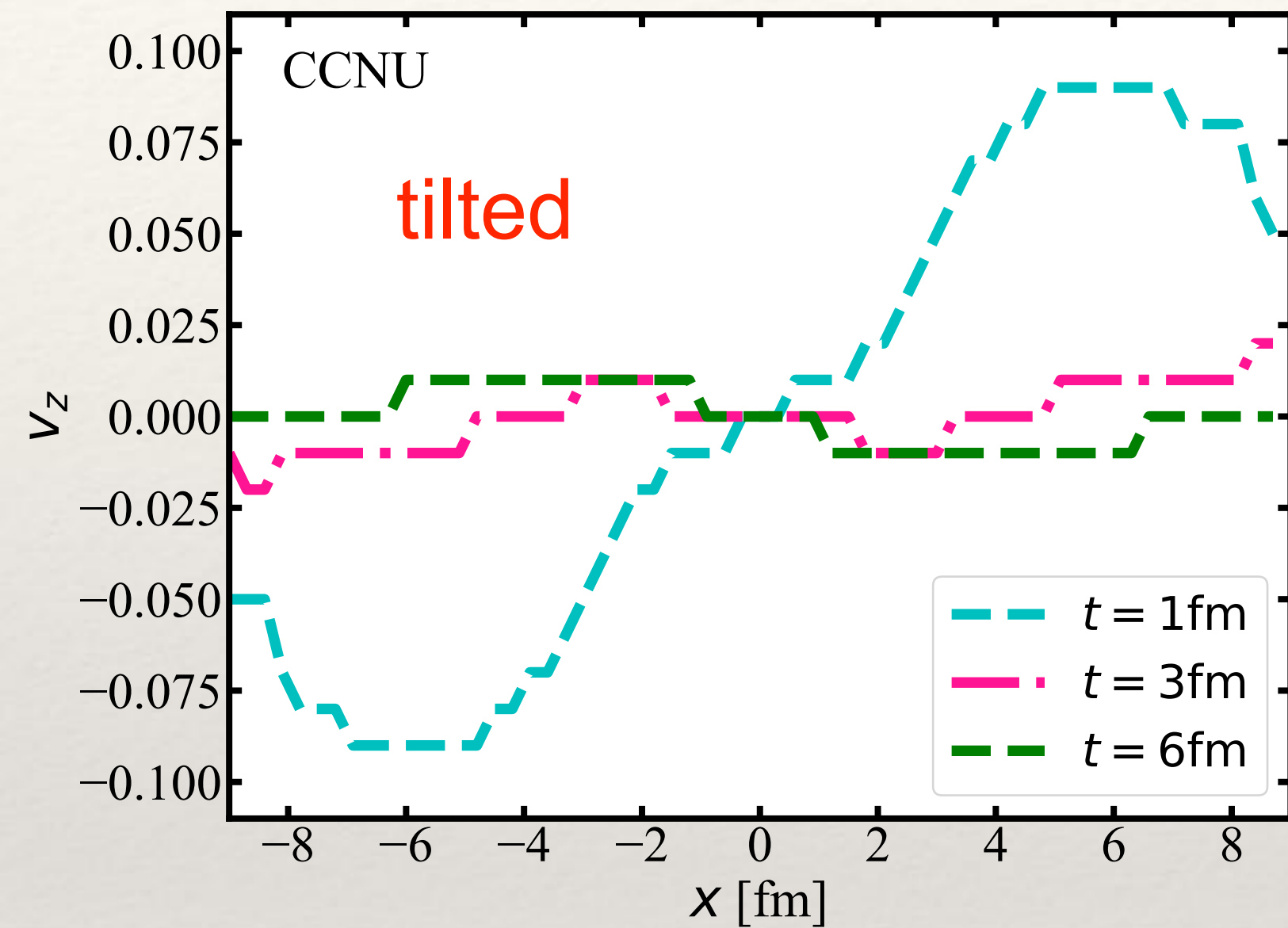$T > 137$ MeV
hydro cells

Consistent temperature evolution profiles between the three initial condition models

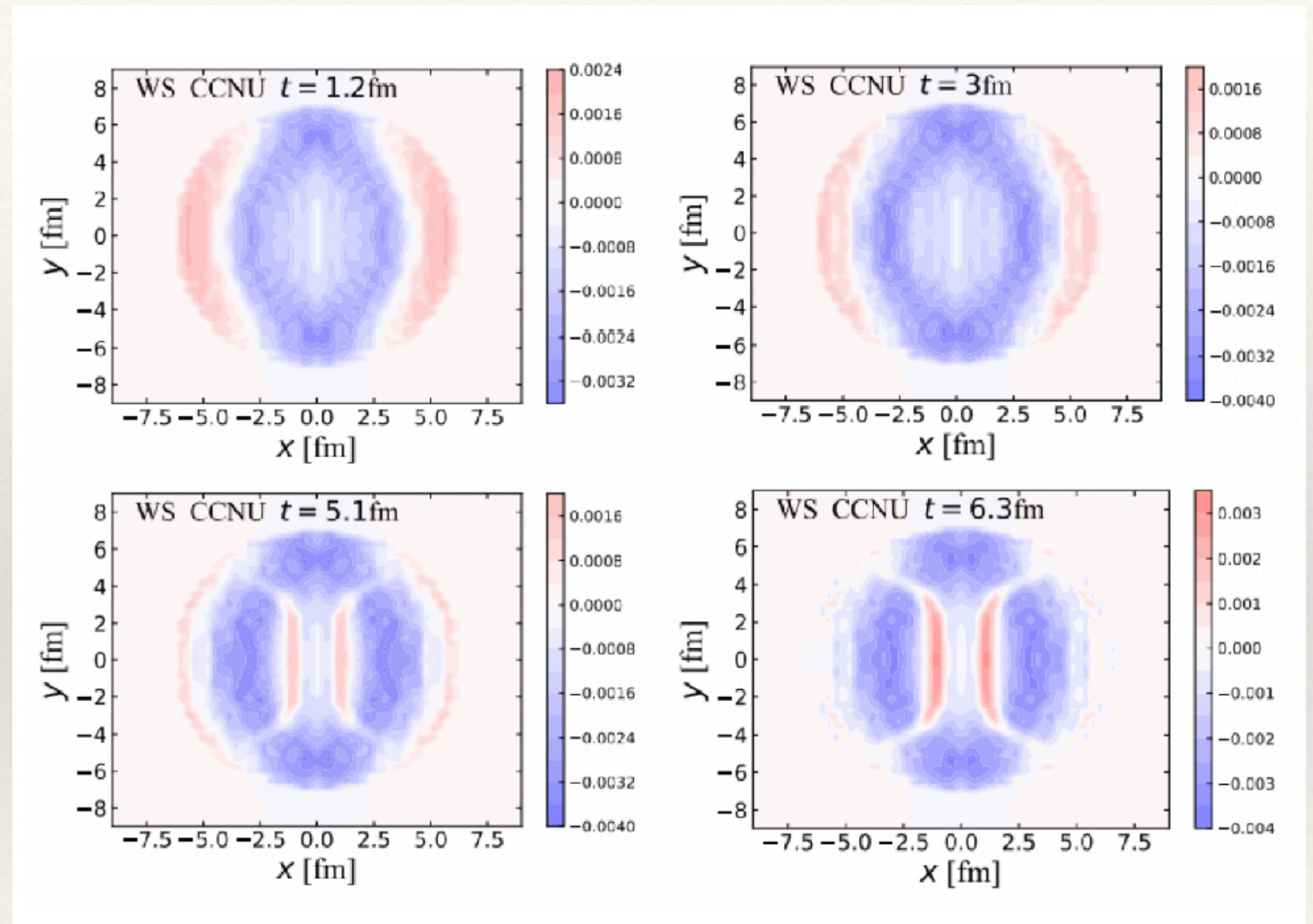# Evolution of longitudinal velocity at *z* = 0 plane

Sensitive to the initial geometry: tilted geometry reduces the longitudinal flow faster, even flip its sign
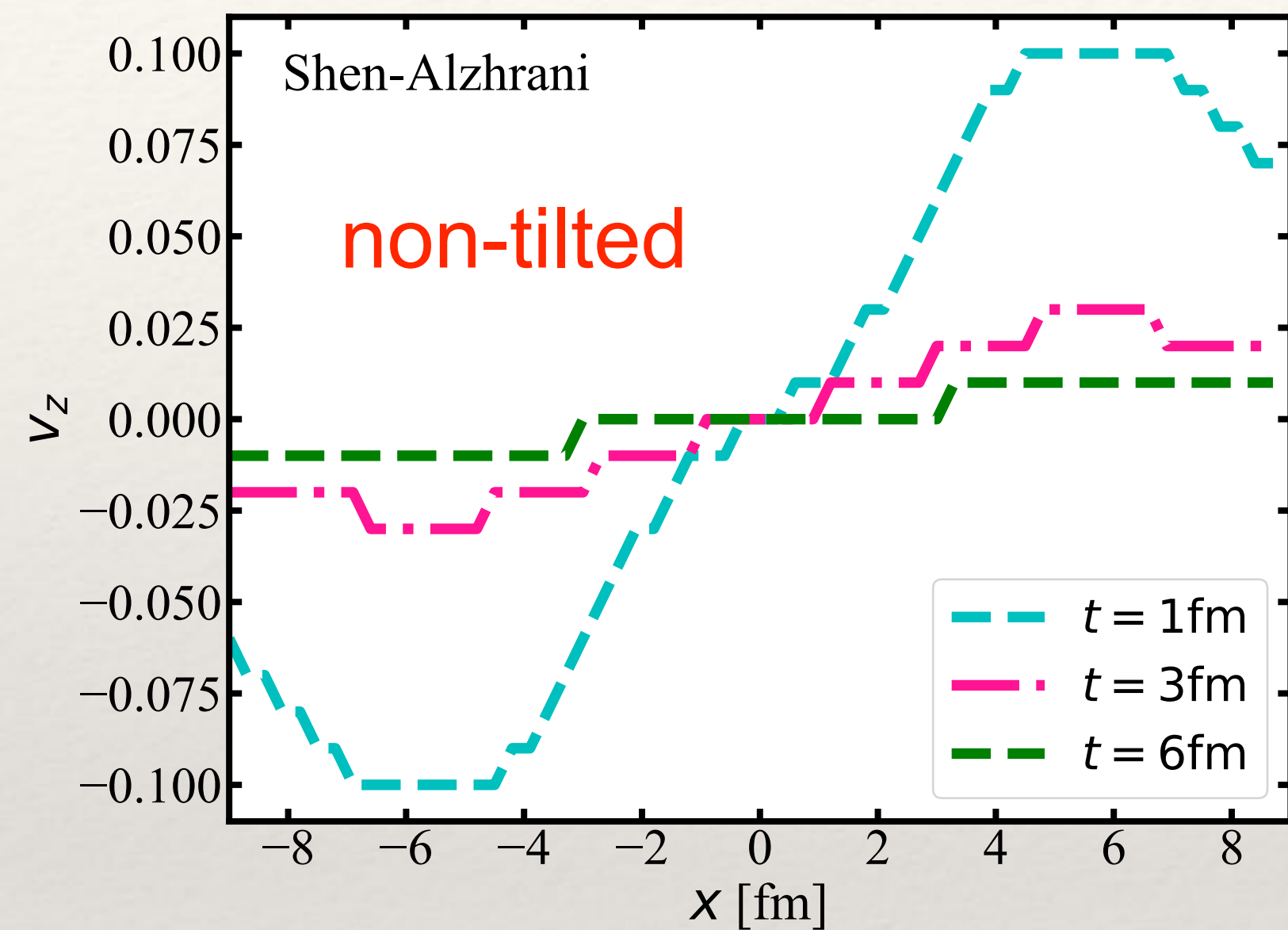
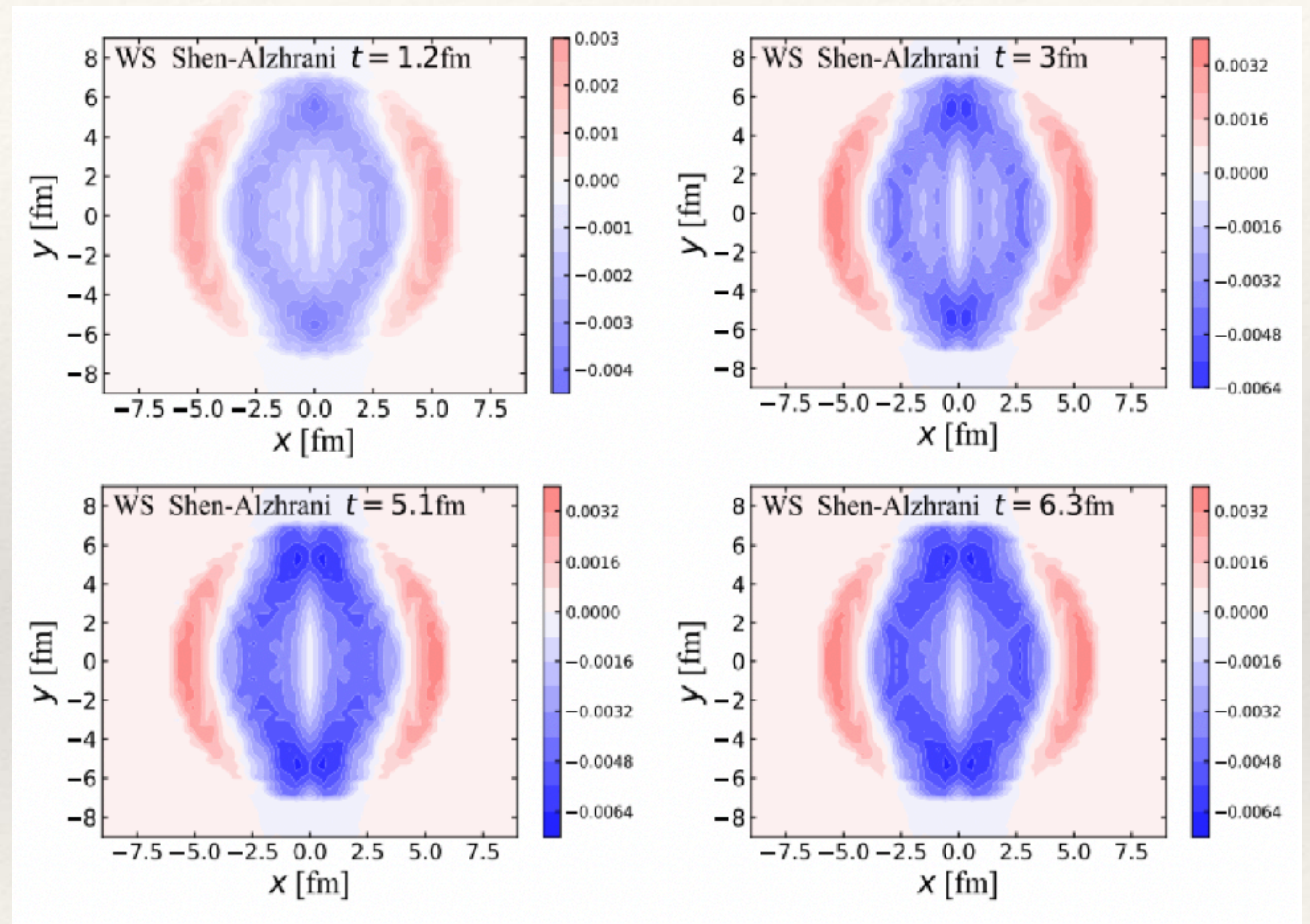# Spatial distribution of polarization with tilted initial geometry

- The velocity gradient is the main origin of polarization generated inside the QGP

Spatial distribution of polarization with non-tilted geometry

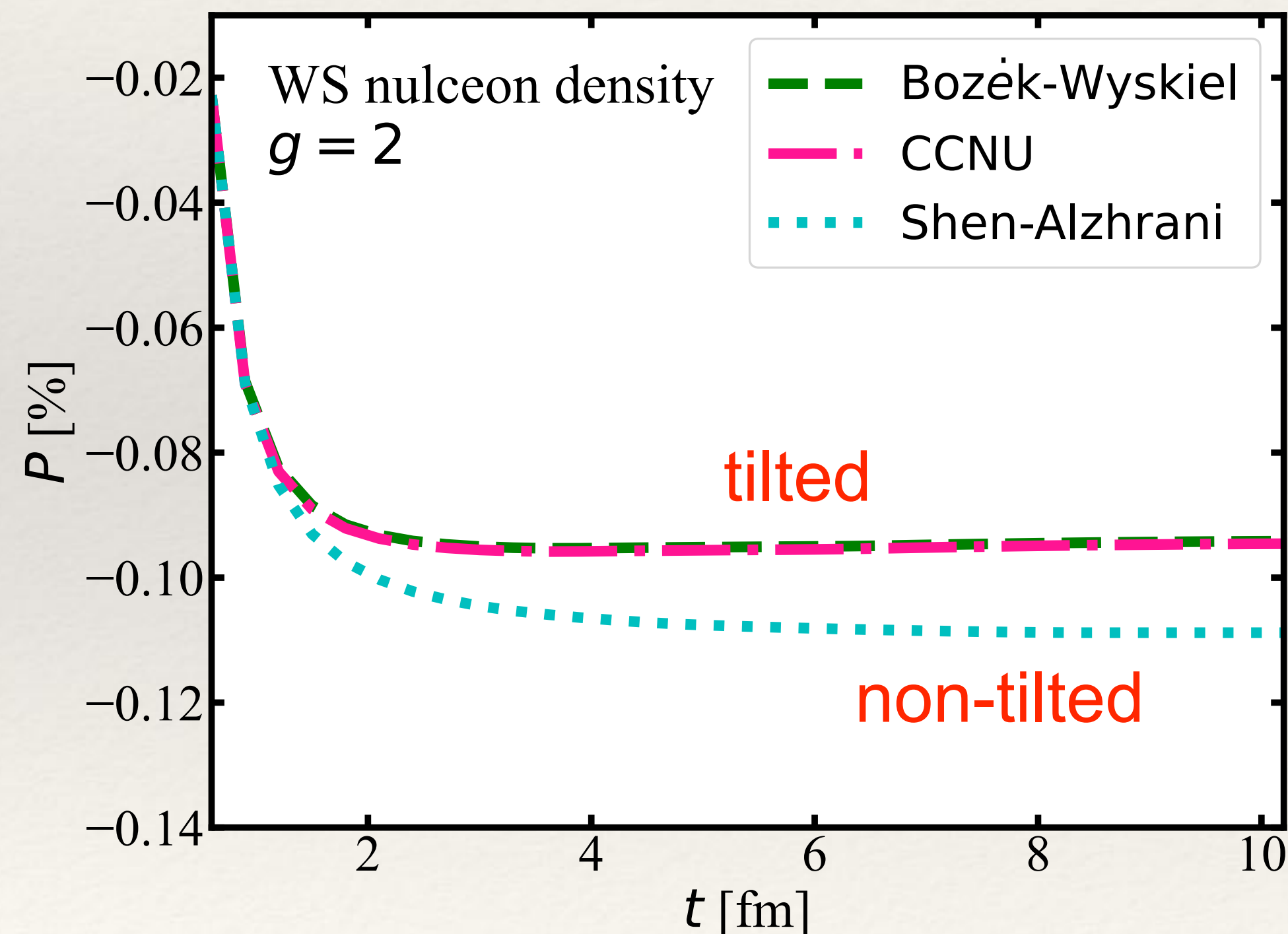- No sign flip for polarization with non-tilted initial geometry of QGP

Time evolution of the average global polarization

Increment of global polarization during one time step：

$$\overline{\Delta P}(t) = \frac{\int_{T > T_{\mathrm{frz}}} dx dy s(x,y,t) \Delta P(x,y,t)}{\int dx dy s(x,y,t)}$$
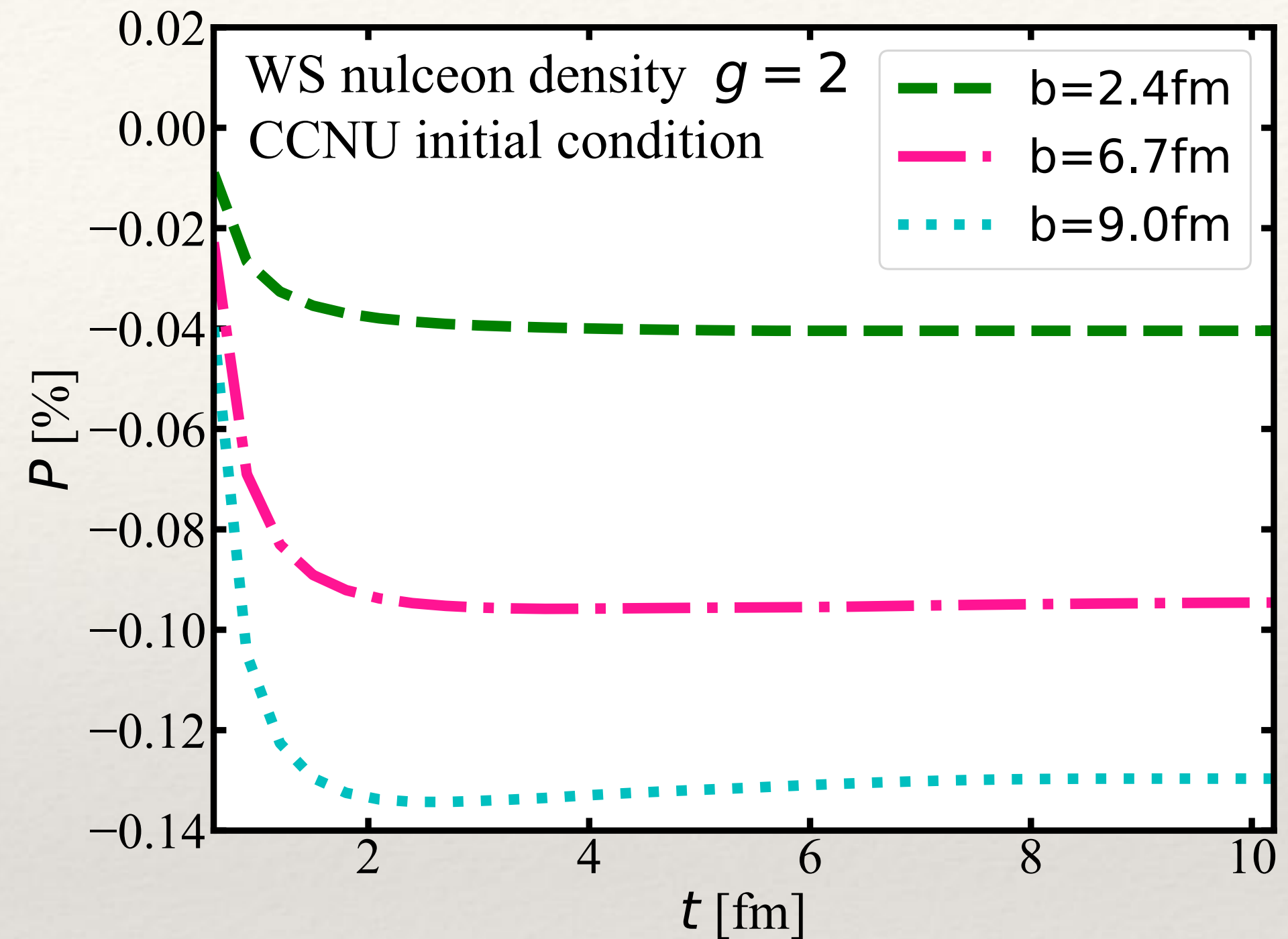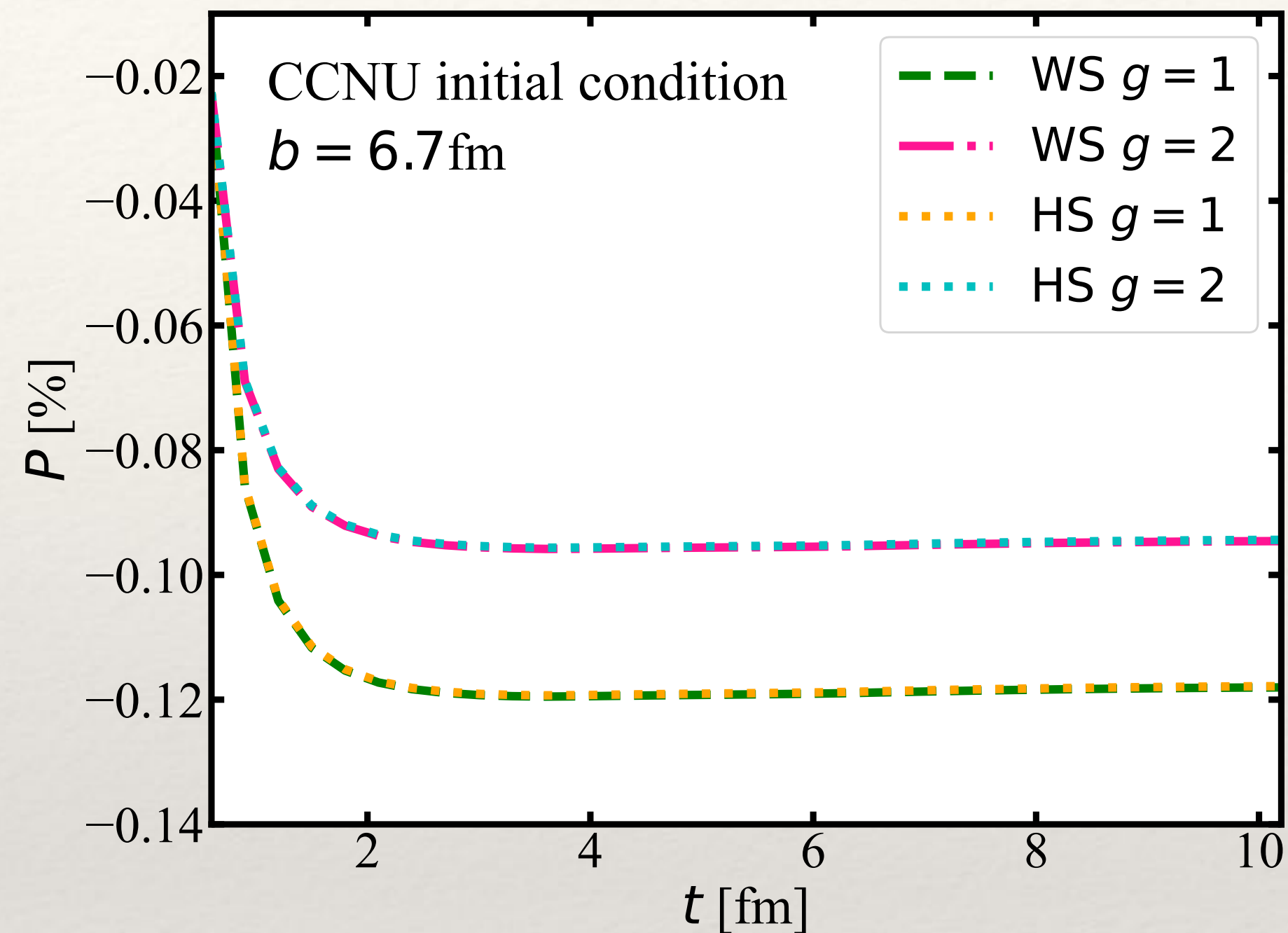
Update of polarization：

$$\overline{P}(t + \Delta t) = \overline{P}(t) + \overline{\Delta P}(t)$$

- Increase (in magnitude) of polarization from an initial value given by initial hard scatterings

- Evolution of polarization in QGP depends on the QGP initial condition

- About 15% difference in the final global polarization due to different initial condition

Time evolution of the average global polarization

- Negligible dependence on the nuclear density distribution for the average polarization

- Decrease of polarization with increase of the coupling strength (via μ_D)

- Significant increase of polarization with impact parameter

Another source of hadron polarization — jet fragmentation
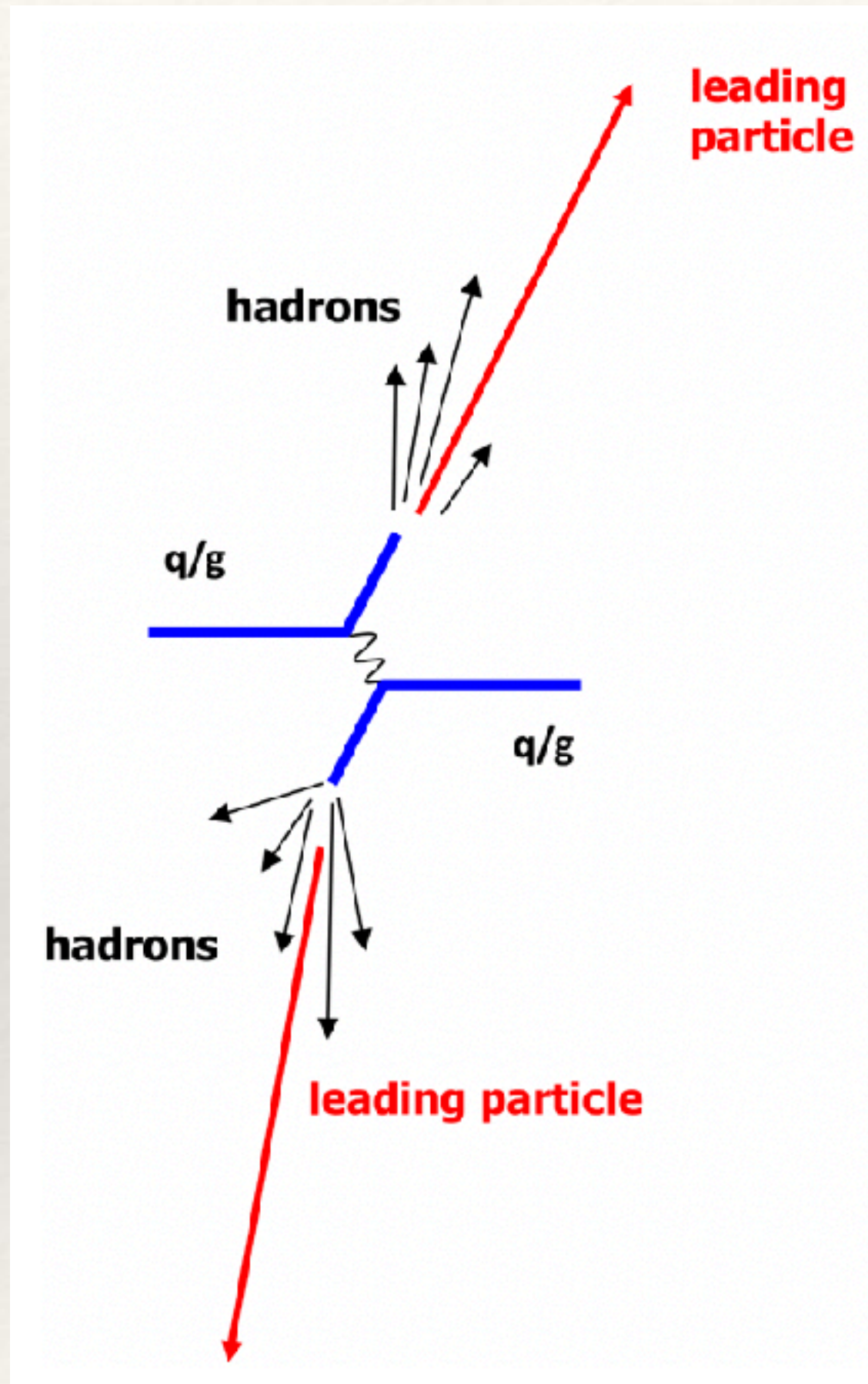
- In pp collisions:

$$d\sigma_h = \sum_{abjd} f_{a/p} \otimes f_{b/p} \otimes d\sigma_{ab \to jd} \otimes D_{h/j}$$

- In AA collisions (QGP modification of jet parton):

$$d\tilde{\sigma}_h = \sum_{abjdj'} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab \to jd} \otimes P_{j \to j'} \otimes D_{h/j'}$$

- Fragmentation function (FF):

$$D_{q \to h}(z, S, S_q) = D_1(z) + \lambda_q \lambda_h G_{1L}(z) + \vec{S}_{q\perp} \cdot \vec{S}_T H_{1T}(z)$$

unpolarized, polarized (longitudinal and transverse)

Constraints on longitudinal spin transfer

- Good constraints on unpolarized FFs, early stage for polarized FFs

- Example: DSV FFs to Λ hyperons [de Florian, Stratmann, Vogelsang, Phys. Rev. D 57 (1998) 5811]

Unpolarized parts: $\quad D_1^{u \to \Lambda} = D_1^{d \to \Lambda} = D_1^{s \to \Lambda}$

Polarized parts: $\quad G_{1L}^{u \to \Lambda} = G_{1L}^{d \to \Lambda} = \xi G_{1L}^{s \to \Lambda} \quad (G_{1L}^{g \to \Lambda} = G_{1L}^{c \to \Lambda} = 0$ at initial scale)

Scenario 1: $\xi = 0$;   Scenario 2: $\xi = -0.2$;   Scenario 3: $\xi = 1$

- Usual measurements of G_{1L} with polarized beams or weak-interaction-dominating reactions

- Proposal on constraining G_{1L} using the correlation of dihadron polarization (neither polarized beam nor weak interaction process) [H.-C. Zhang and S.-Y. Wei, Phys. Lett. B 839 (2023) 137821]

$$\mathscr{C}_{LL}(\eta_1, \eta_2) = \left(\frac{d\sigma_{\lambda_1 = \lambda_2}}{d\eta_1 d\eta_2} - \frac{d\sigma_{\lambda_1 = -\lambda_2}}{d\eta_1 d\eta_2} \right) \Bigg/ \left(\frac{d\sigma_{\lambda_1 = \lambda_2}}{d\eta_1 d\eta_2} + \frac{d\sigma_{\lambda_1 = -\lambda_2}}{d\eta_1 d\eta_2} \right)$$

Correlation of dihadron polarization in pp collisions
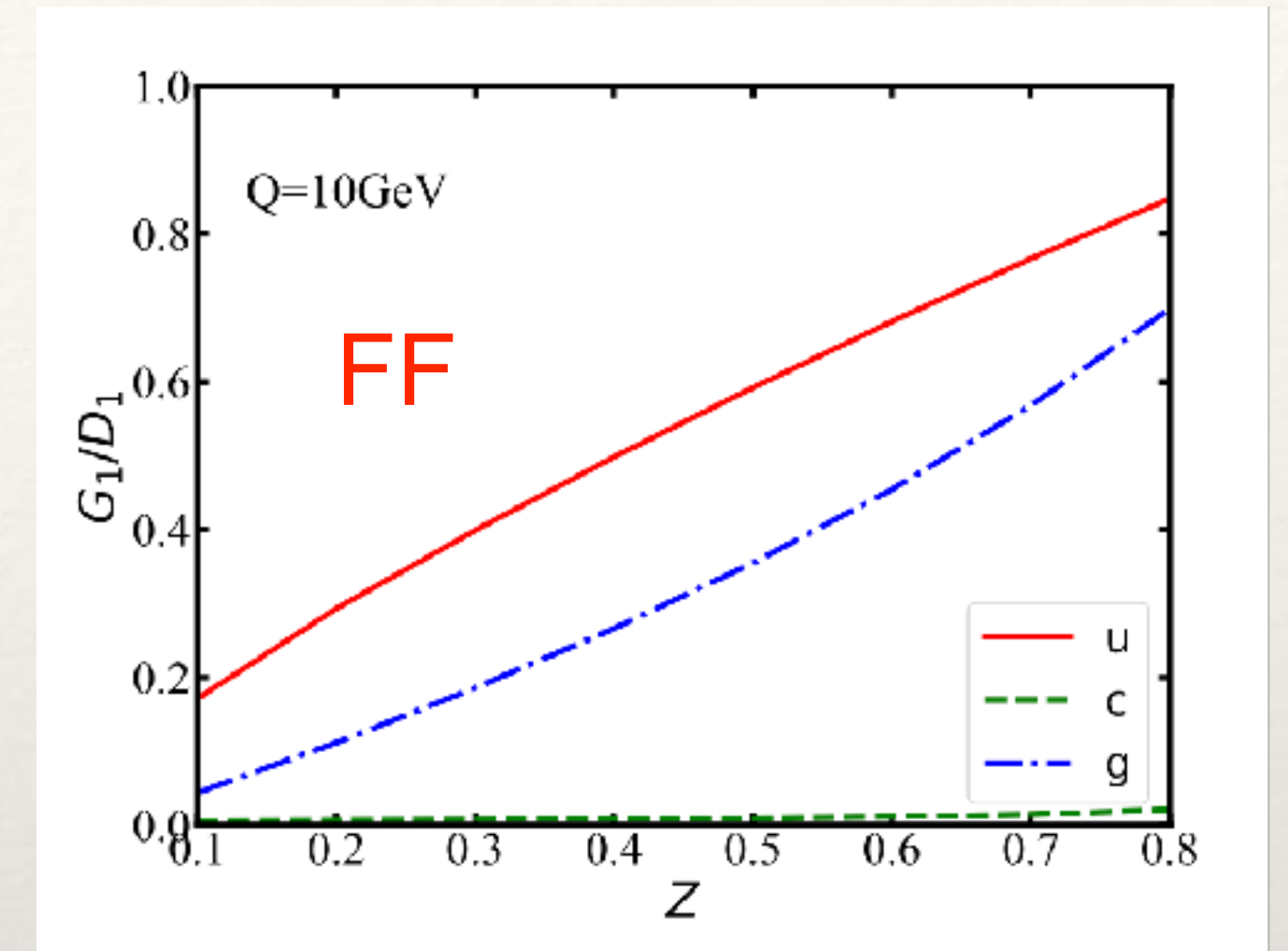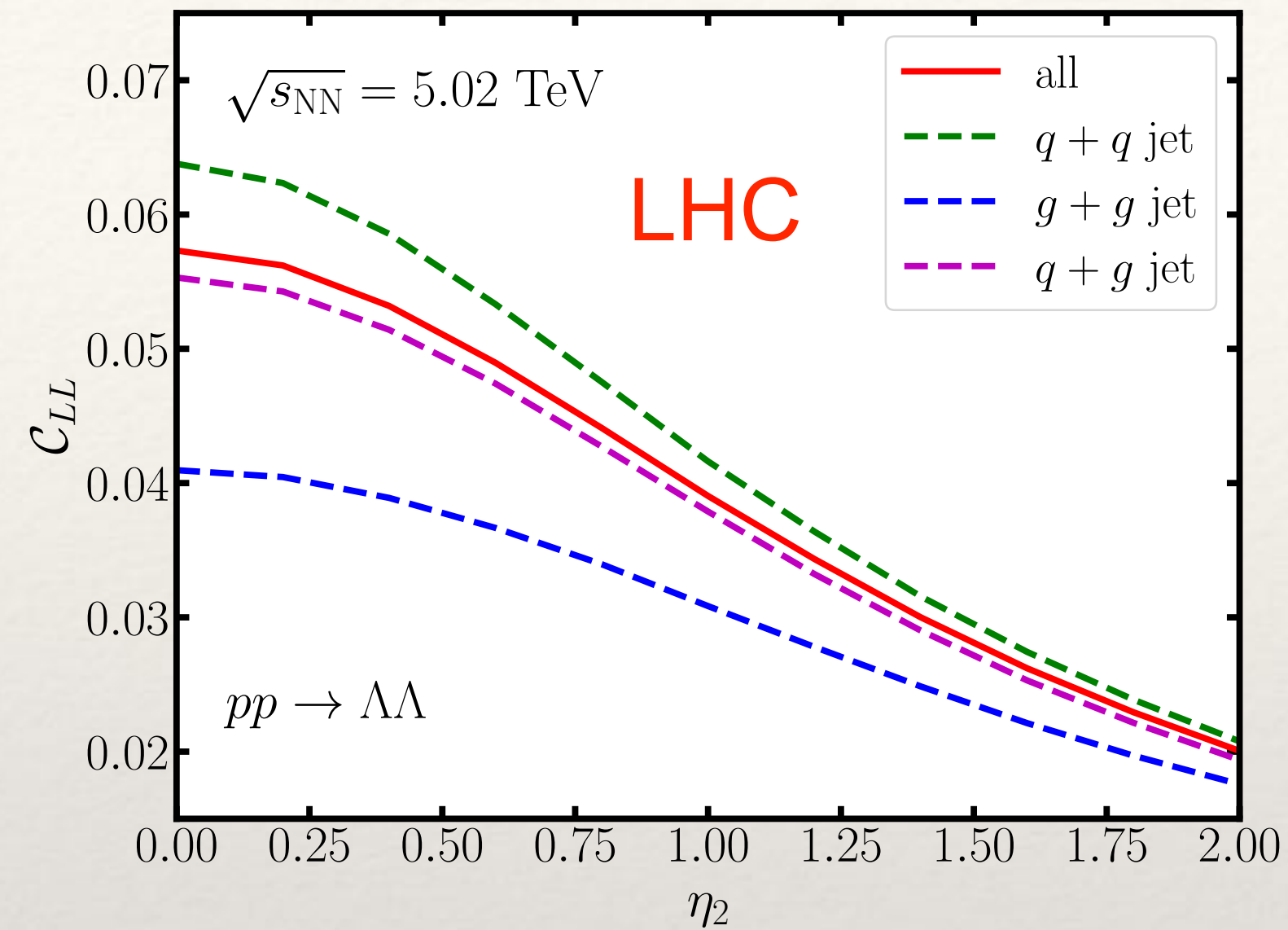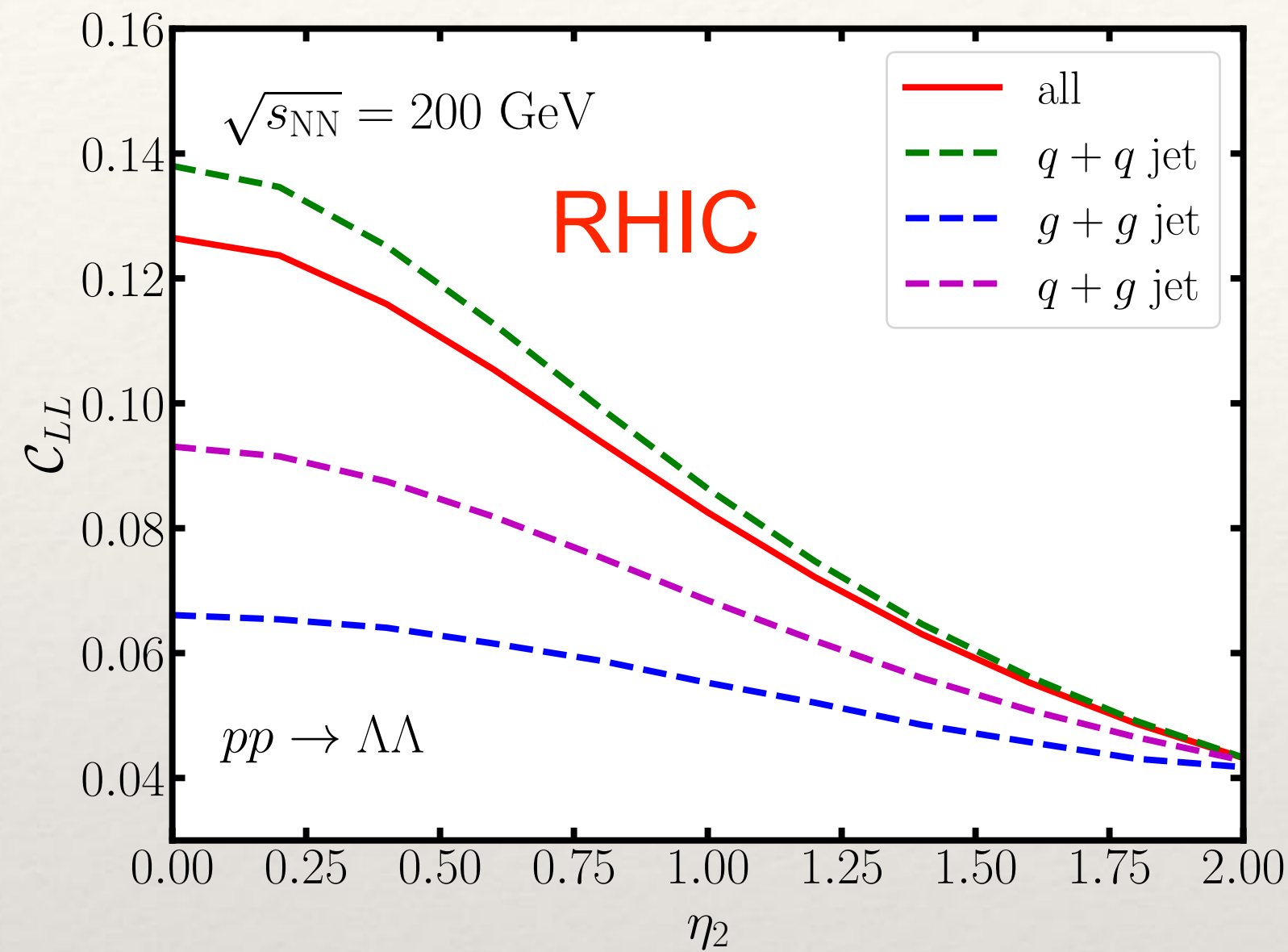
- $\Lambda\Lambda$ production: *t*-channel dominating, prefers same sign of partonic λ_1 and λ_2

- $\mathscr{C}_{LL}^{q+q} > \mathscr{C}_{LL}^{q+g} > \mathscr{C}_{LL}^{g+g}$: smaller longitudinal spin transfer from *g* than from *q* to Λ

- $\mathscr{C}_{LL}(\text{RHIC}) > \mathscr{C}_{LL}(\text{LHC})$: larger *z* probed at RHIC and smaller *g* contribution at RHIC

From pp to AA collisions

- Motivation: increase luminosity for experimental measurement

- Dihadron cross section in AA collisions at the leading order:

$$\frac{d\sigma^{AA}_{\lambda_1\lambda_2}}{d\eta_1 d^2\vec{p}_{T1} d\eta_2 d^2\vec{p}_{T2}} = \int dx dy \, T_A(x - \tilde{b}/2, y) T_A(x + \tilde{b}/2, y) \int \frac{dz_1}{z_1^2} \frac{dz_2}{z_2^2} \sum_{ab\to cd} \sum_{\lambda_c\lambda_d} \frac{1}{\pi} x_a f_{A,a}(x_a) x_b f_{A,b}(x_b)$$

$$\times \frac{d\hat{\sigma}^{ab\to cd}_{\lambda_c\lambda_d}}{dt} \mathcal{D}_c(z_1, \lambda_1; \lambda_c) \mathcal{D}_d(z_2, \lambda_2; \lambda_d) \delta^2 \left(\frac{\vec{p}_{T1}}{z_1} + \Delta\vec{p}_{T1} + \frac{\vec{p}_{T2}}{z_2} + \Delta\vec{p}_{T2} \right) + \{c \leftrightarrow d\}.$$

- Nuclear modification:

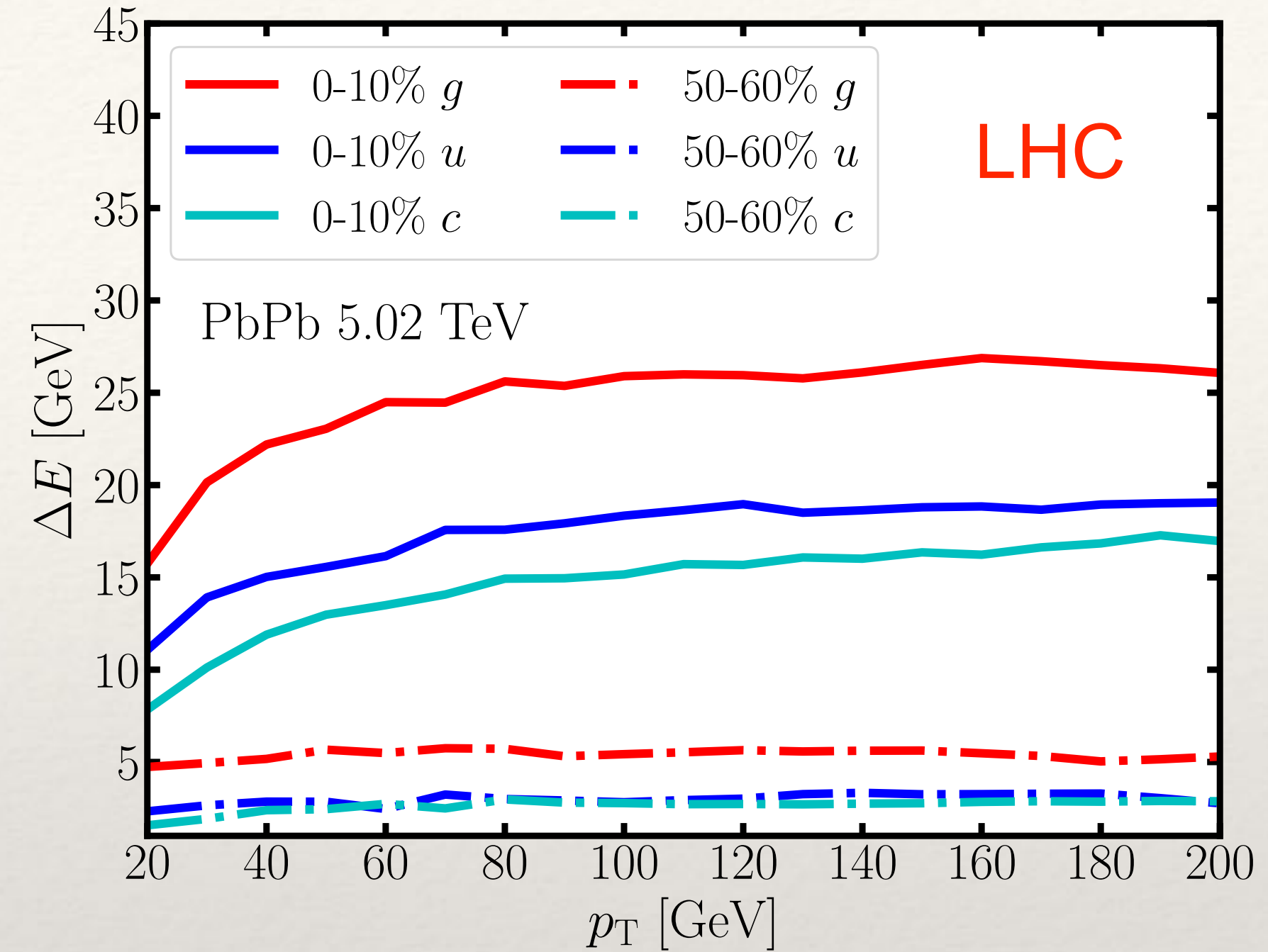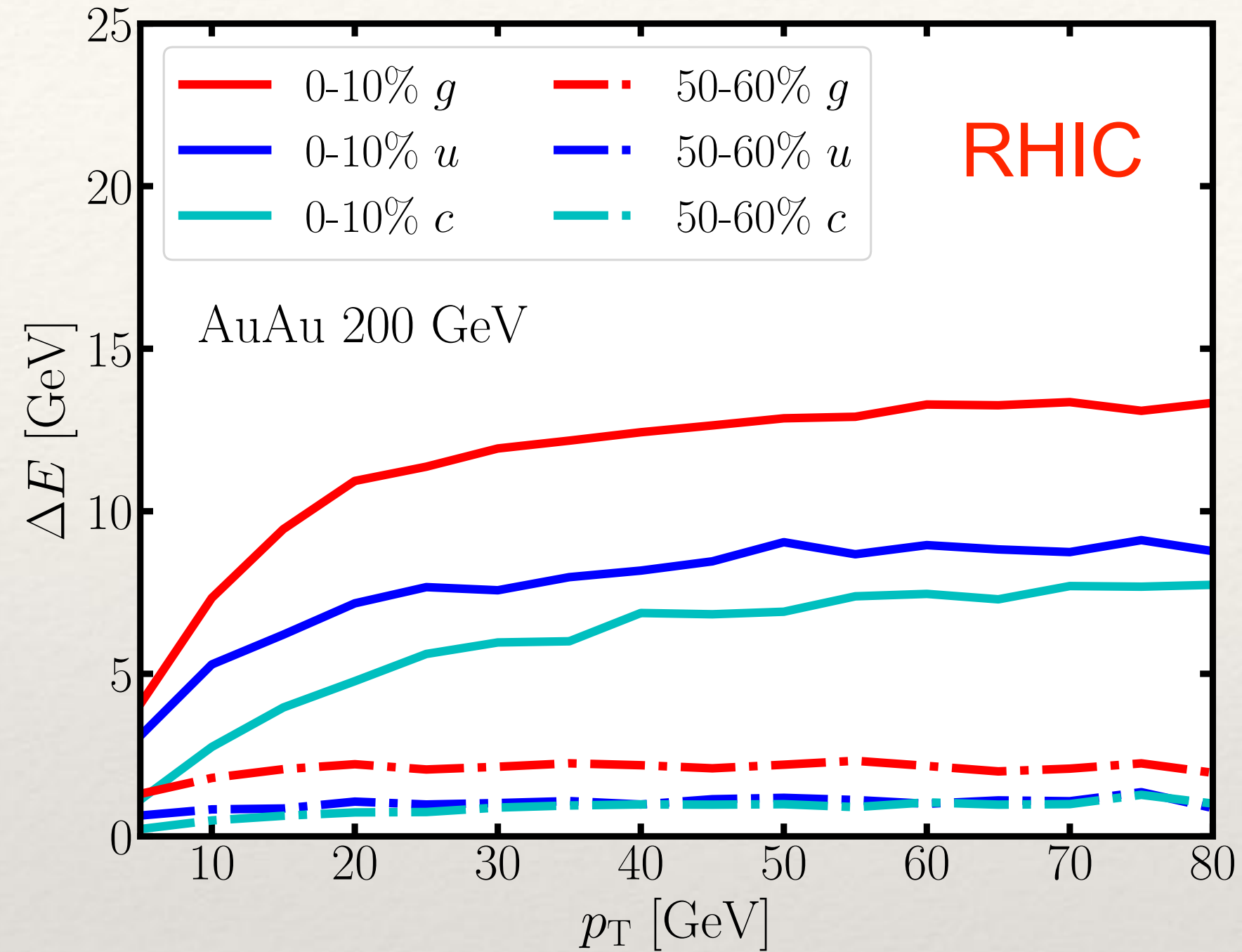 Nuclear modified PDF (cold nuclear matter effect) — CTEQ PDF + EPPS shadowing

  Parton energy loss in QGP: calculated using transport model (production location dependent)

  Production location — nuclear thickness function from Woods-Saxon distribution

- In the end:

$$\mathscr{C}_{LL}(\eta_1, \eta_2) = \left(\frac{d\sigma_{\lambda_1=\lambda_2}}{d\eta_1 d\eta_2} - \frac{d\sigma_{\lambda_1=-\lambda_2}}{d\eta_1 d\eta_2} \right) \Big/ \left(\frac{d\sigma_{\lambda_1=\lambda_2}}{d\eta_1 d\eta_2} + \frac{d\sigma_{\lambda_1=-\lambda_2}}{d\eta_1 d\eta_2} \right)$$

# Energy loss of different flavors of partons

- Calculated using linear Boltzmann transport (LBT) model + hydrodynamic model

  [SC, T. Luo, G.-Y. Qin, X.-N. Wang, Phys. Rev. C 94 (2016) 1, 014909]

- Flavor hierarchy of parton energy loss: $\Delta E_g > \Delta E_{u/d/s} > \Delta E_c$

- Stronger energy loss is more central collisions, and in more energetic collisions

# Correlation of dihadron polarization in pp *vs.* AA

pp
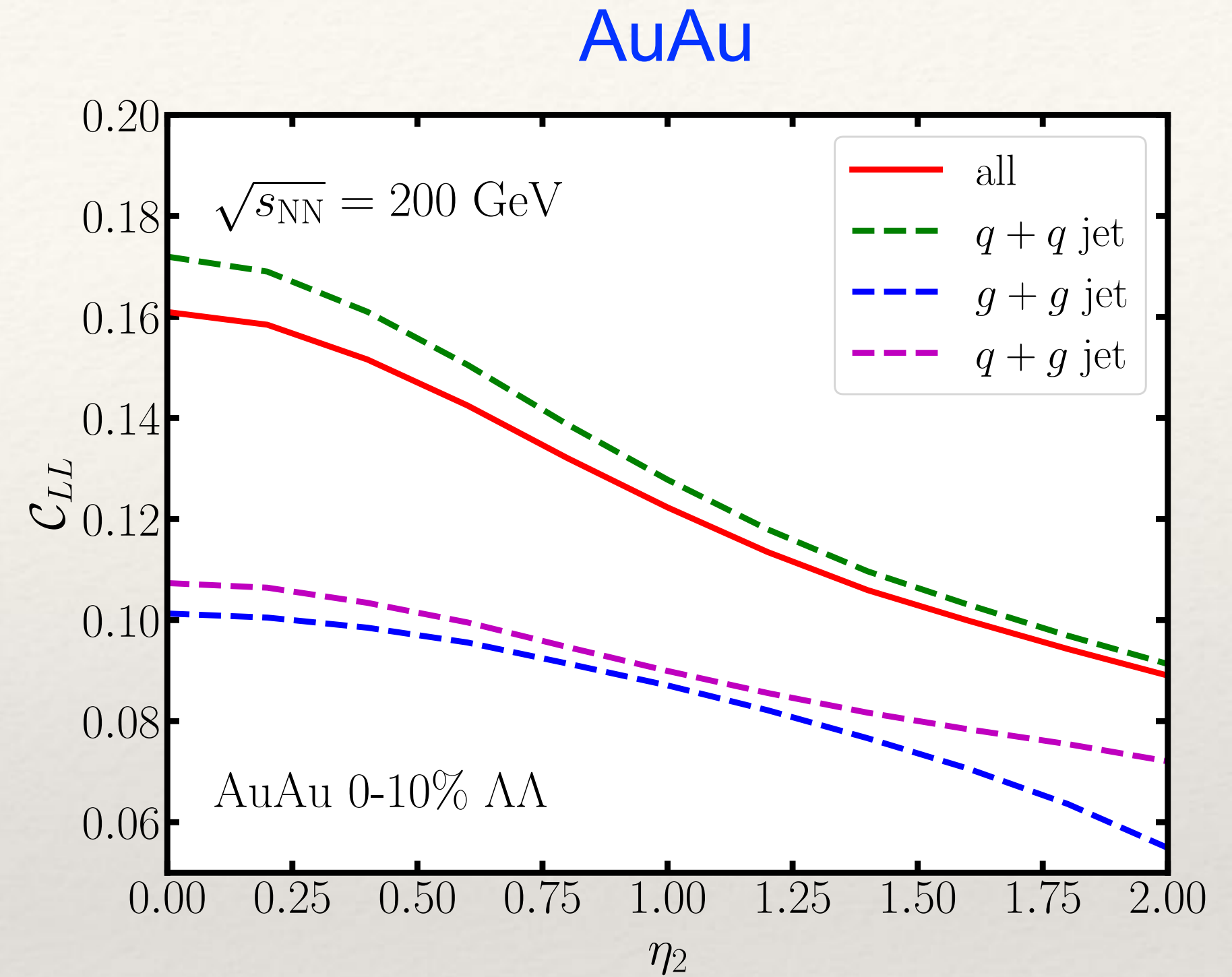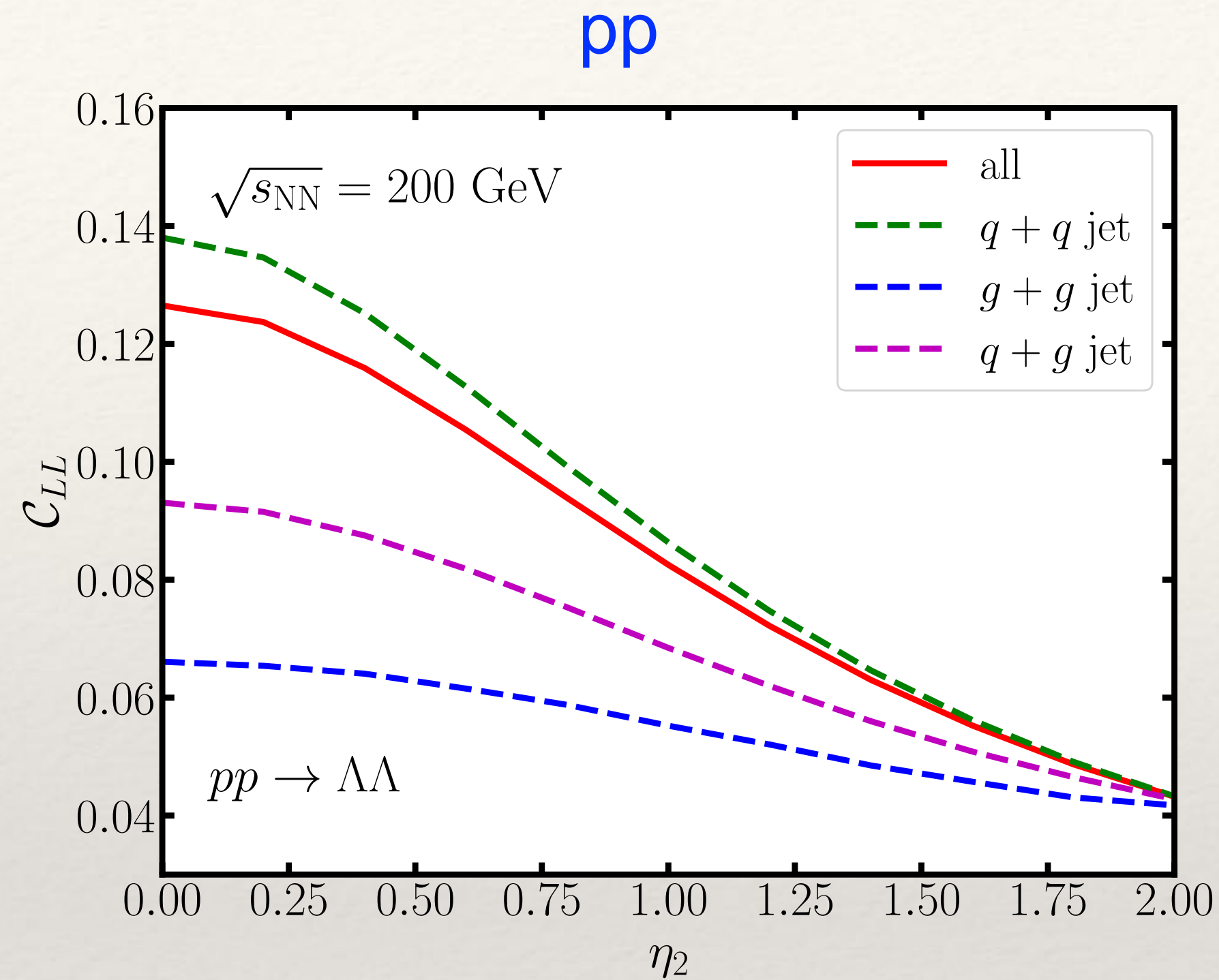
AuAu

- Stronger spin correlation in AuAu than in pp — parton energy loss, hadron with the same final p_T probes larger z region of FFs

- Stronger enhancement for gluons than for quarks

- At the same final p_T, energy loss increases quark *vs.* gluon fraction $\rightarrow$ enhance the total $\mathscr{C}_{LL}$

From pp to peripheral to central AA collisions

AuAu   PbPb
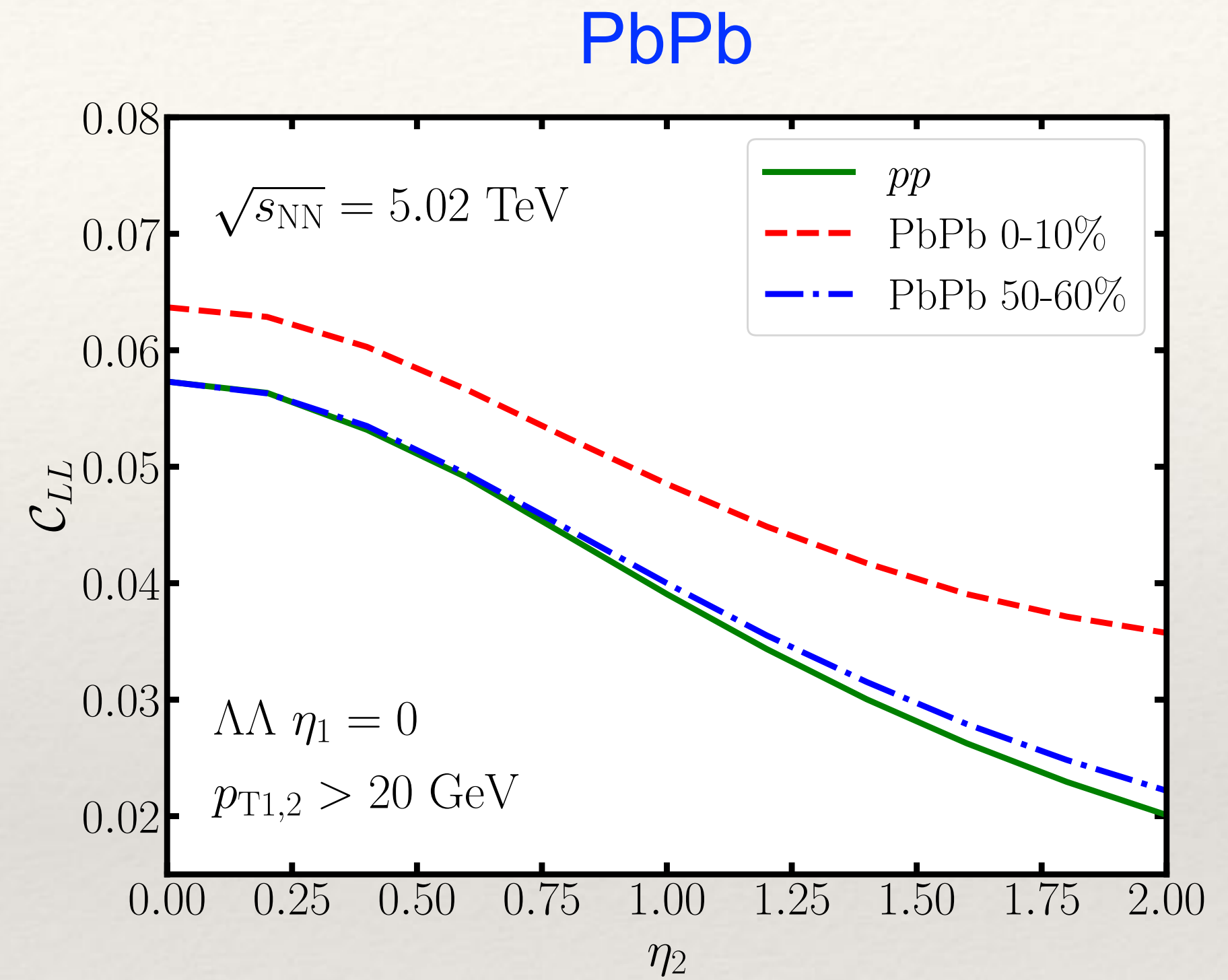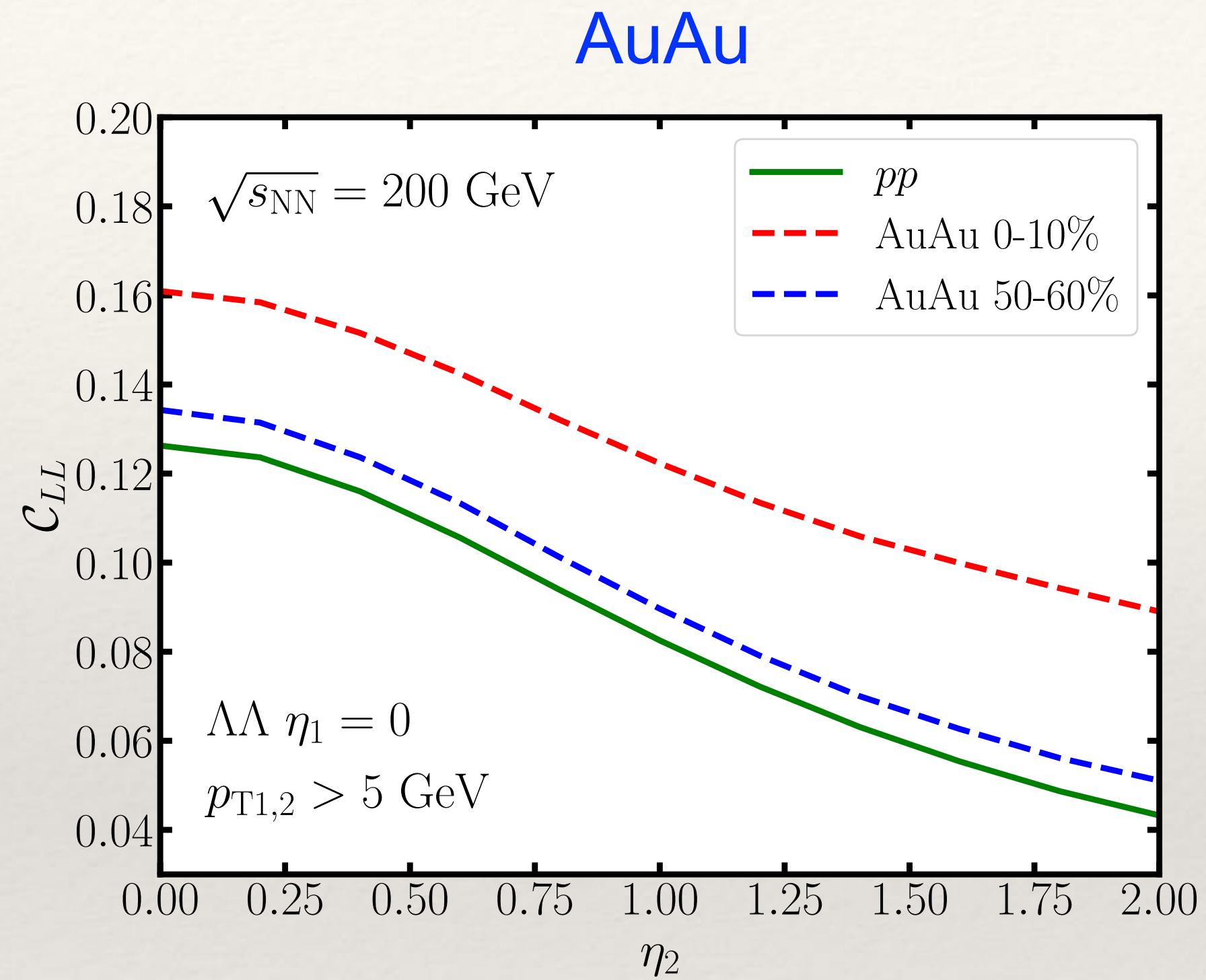
- Increase of $\mathscr{C}_{\mathrm{LL}}$ from pp to peripheral to central AA collisions

Constraint on the spin-dependent FFs

AuAu 0-10%

$\Lambda\Lambda$ $\eta_1 = 0$
$p_{T1,2} > 5$ GeV

- - - DSV Sce.1
-·- DSV Sce.2
—— DSV Sce.3
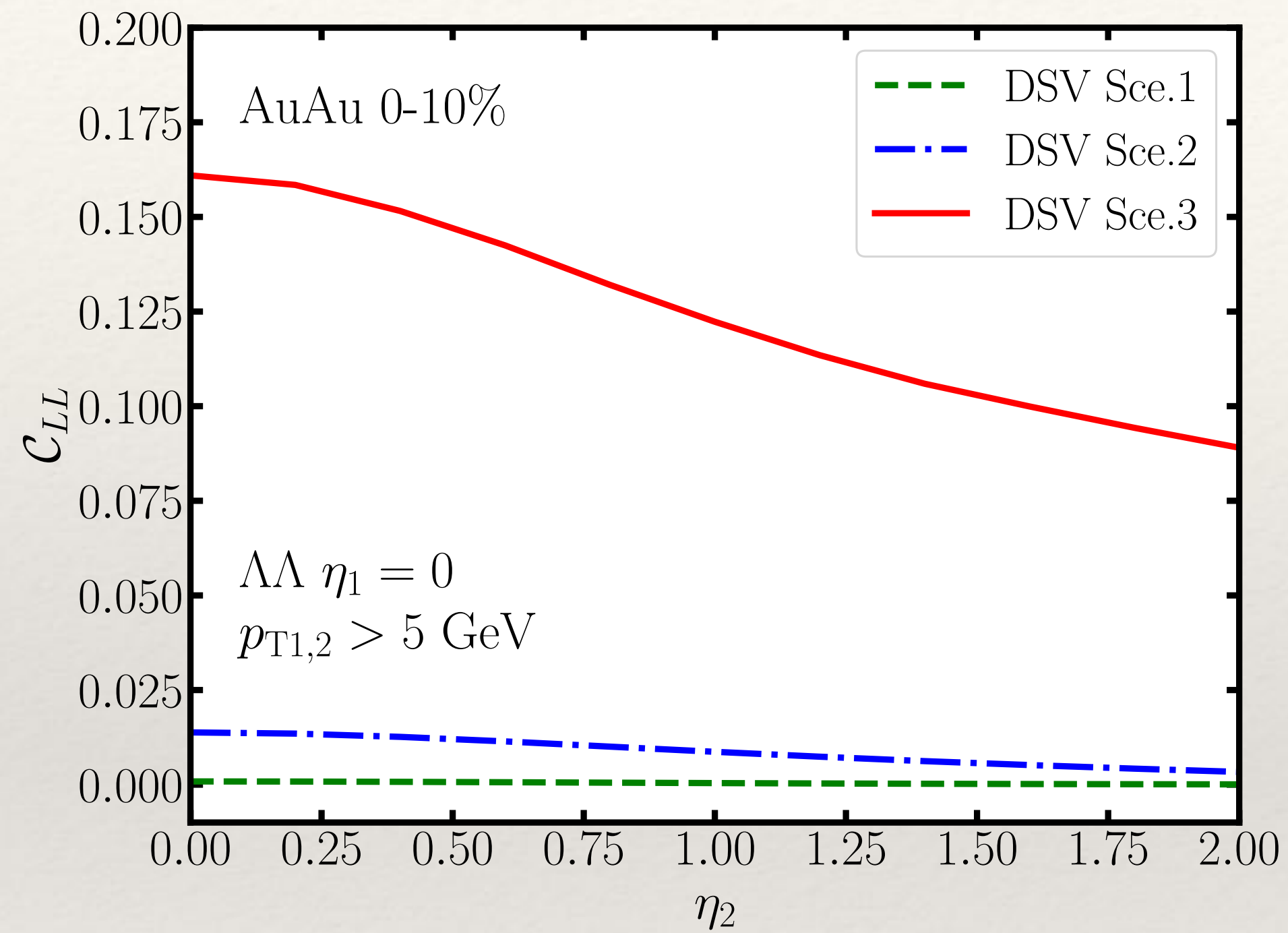
Comparison between 3 scenarios of DSV FFs (all tuned to spin-independent data)

- Scenario 1: only *s* transfers longitudinal spin to Λ

- Scenario 2: *s* has positive contribution, *u* and *d* have small negative contributions

- Scenario 3: *u*, *d*, *s* contribute equally to the polarized parts of FFs

$\mathscr{C}_{LL}$ **can be used to constrain the longitudinal spin transfer in FFs**

Comparison between $\Lambda\Lambda$ and $\Lambda\overline{\Lambda}$ correlations
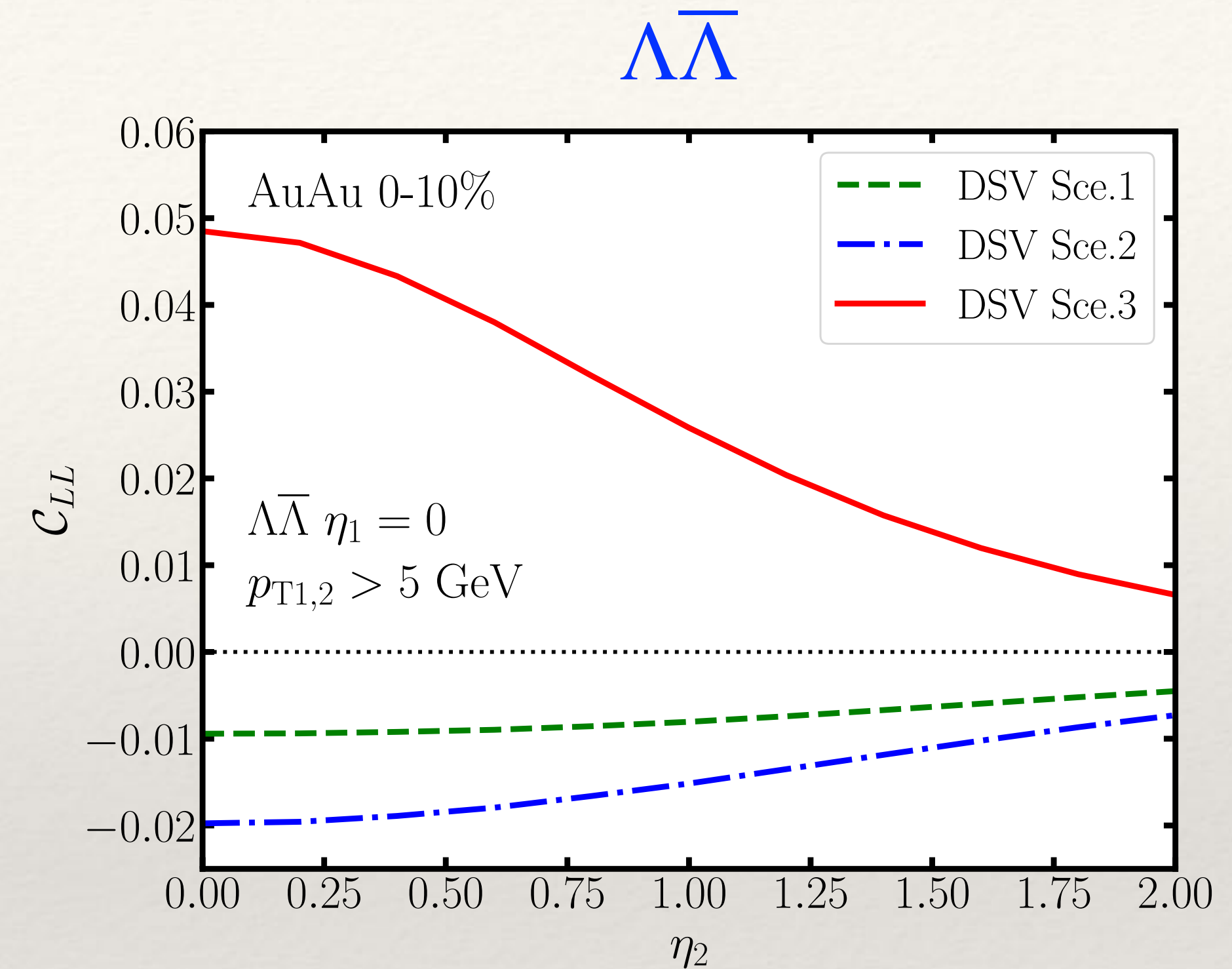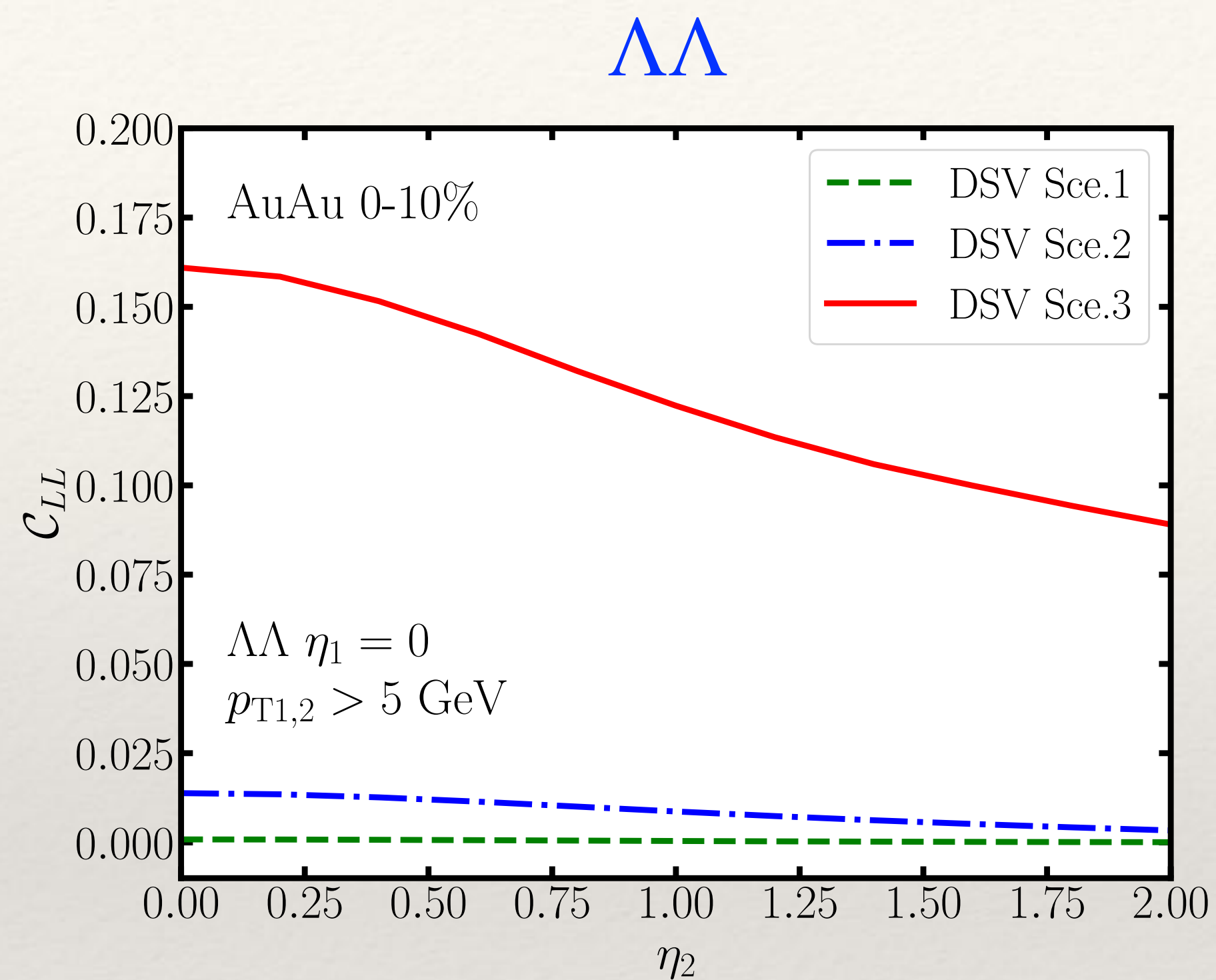
- Scenario 1 reflects contributions from s-channel $s\bar{s}$ production, negative $\mathscr{C}_{\mathrm{LL}}$

- $\mathscr{C}_{\mathrm{LL}}$ of $\Lambda\overline{\Lambda}$ is also sensitive to the selection of spin-dependent FFs

Correlation between charm quark and another parton
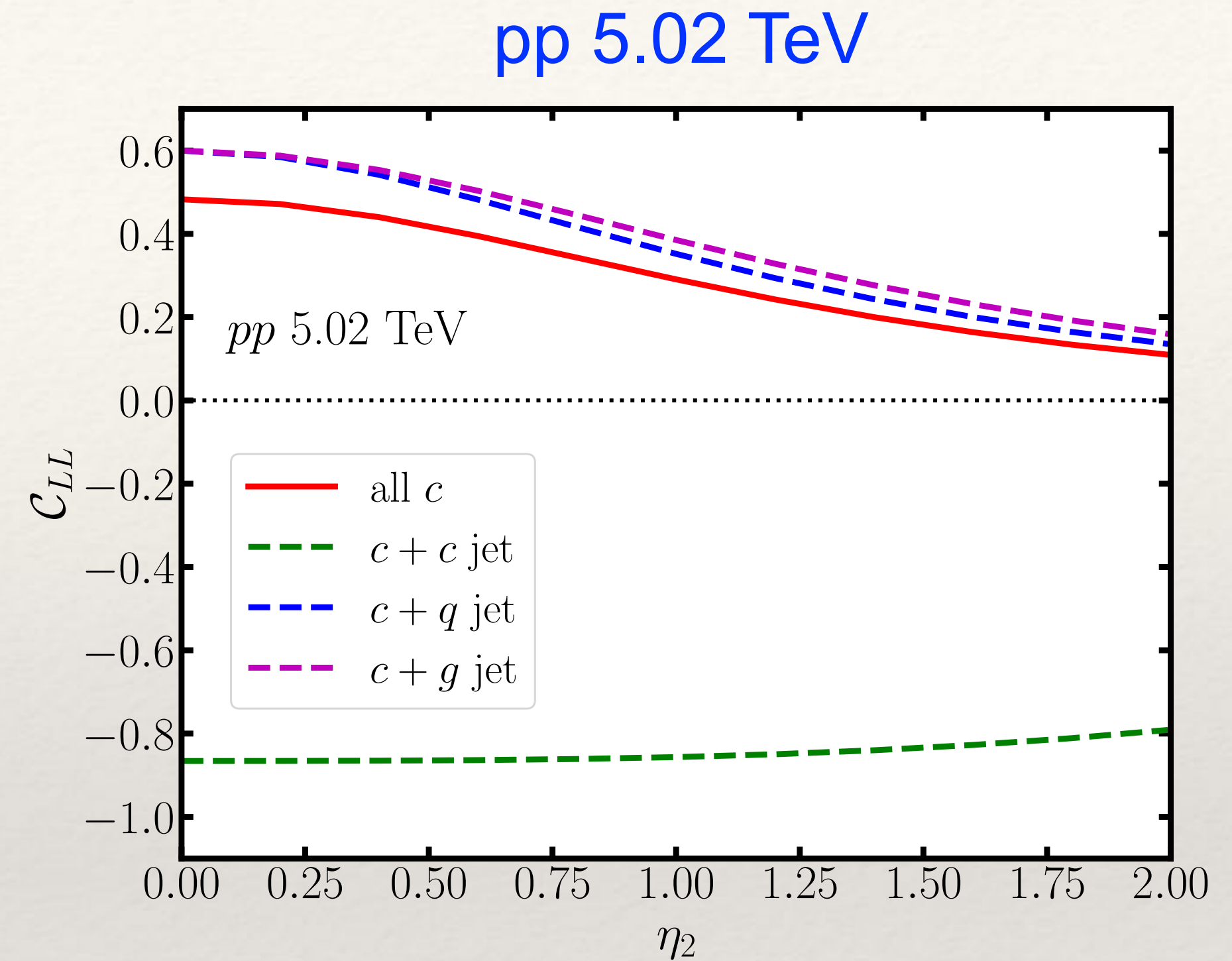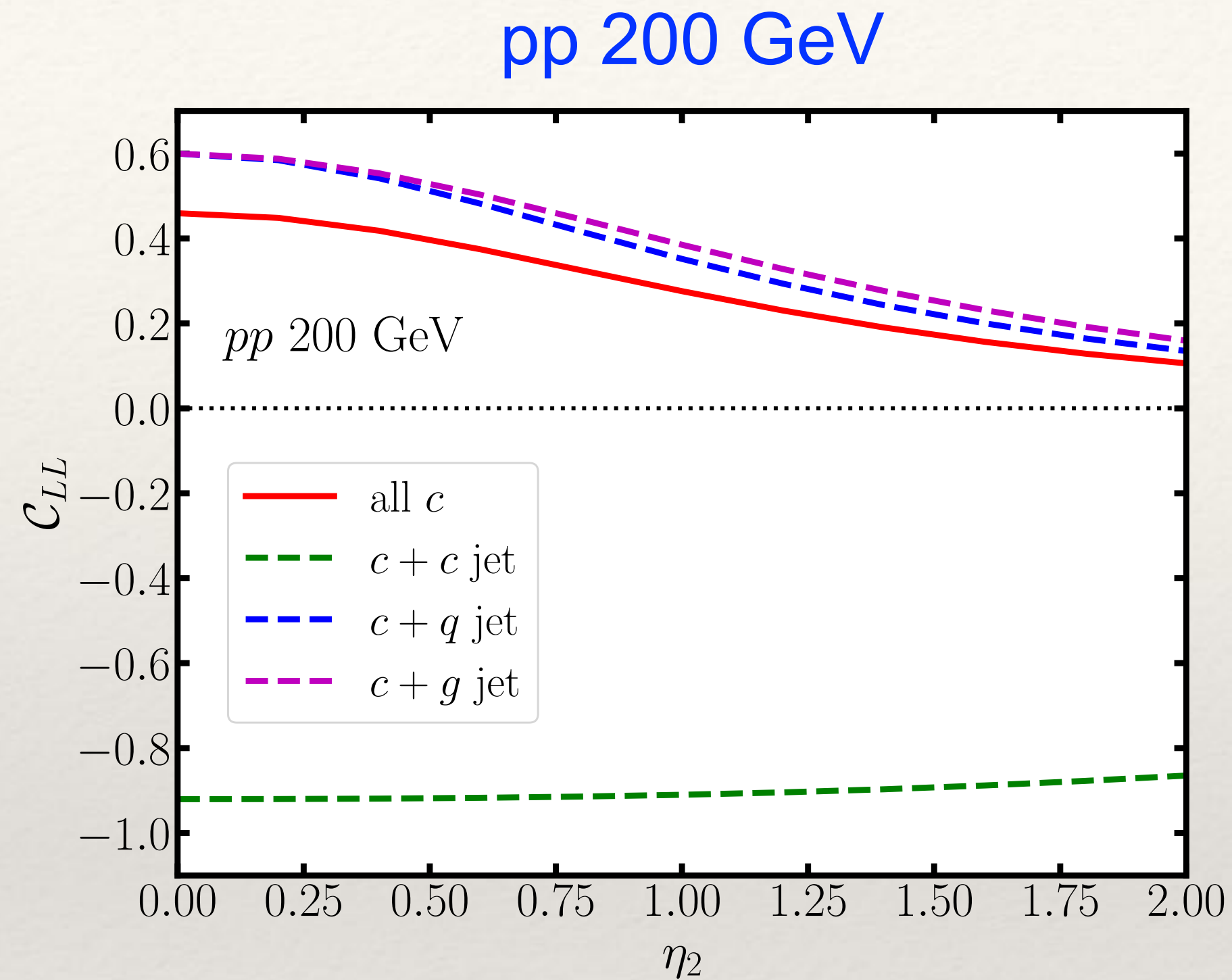
- Results at partonic level (lack of spin-dependent FFs for c)

- Different charm production mechanism (pair production, flavor excitation, gluon splitting)

- Strong negative $\mathscr{C}_{\mathrm{LL}}$ of back-to-back $c\bar{c}$ may help constrain FFs to Λ_c in the future

Summary

- Developed a perturbative approach for both initial production and spacetime evolution of quark polarization in relativistic heavy-ion collisions

- Found sensitivity of global polarization to the initial geometry of the QGP

- Studied the correlation of dihadron polarization ($\mathscr{C}_{\mathrm{LL}}$) from jet fragmentation

- Found enhancement of $\mathscr{C}_{\mathrm{LL}}$ from pp to peripheral AA and then to central AA collisions due to the increasing parton energy loss inside the QGP, and sensitivity of $\mathscr{C}_{\mathrm{LL}}$ to the longitudinal spin transfer in polarized FFs