Role of the twist-3 gluon effect on the single transverse-spin asymmetry in the semi-inclusive J/ψ production

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Hongxi Xing(SCNU)

Phys. Rev. D108 (2023)

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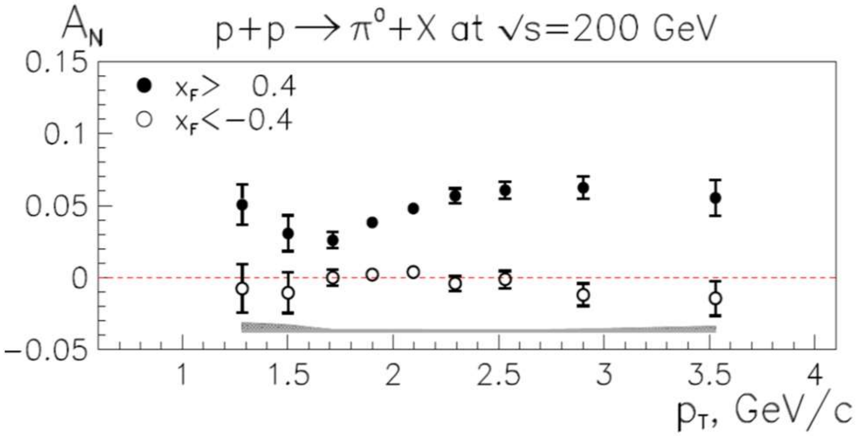
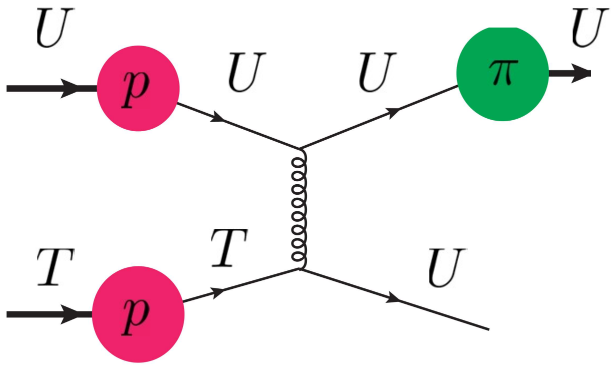
New era in the nucleon structure

- Single Transverse-Spin Asymmetry





$$A_N \sim \alpha_s \frac{m_q}{P_T} \quad \text{negligible}$$

Conventional picture does not work

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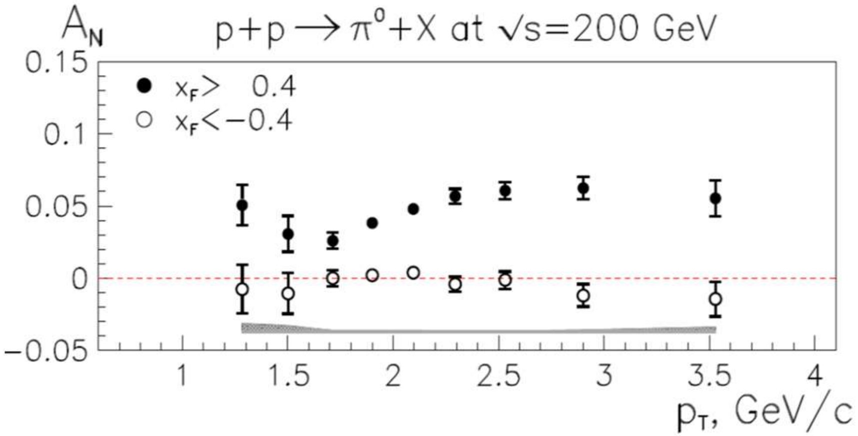

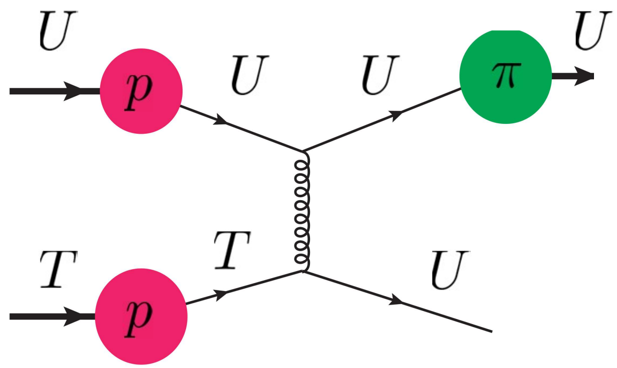

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Conventional picture does not work

$$\mathcal{F}.\mathcal{T}.\langle PS_\perp|\bar{\psi}(0)\gamma^\mu\psi(x^-, x_T)|PS_\perp\rangle = 2f(x, k_T)p^\mu + \frac{2}{M_N}\epsilon^{\mu\nu\rho\sigma}P_\nu k_{T\rho}S_{\perp\sigma}f_{1T}^\perp(x, k_T)\cdots$$

New era in the nucleon structure

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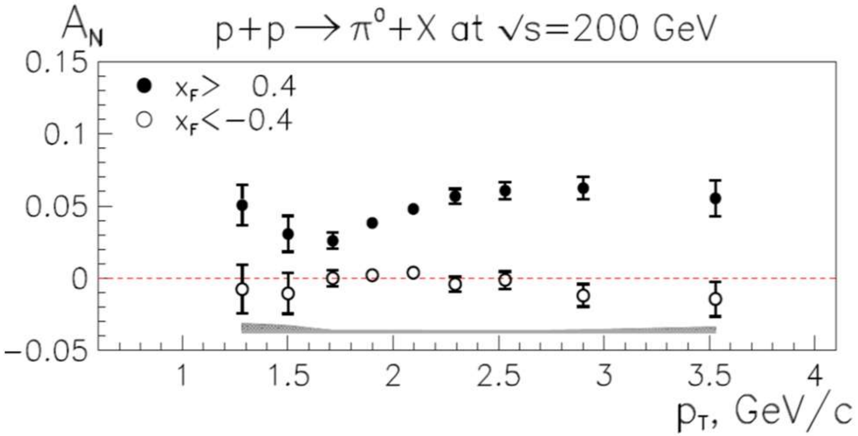
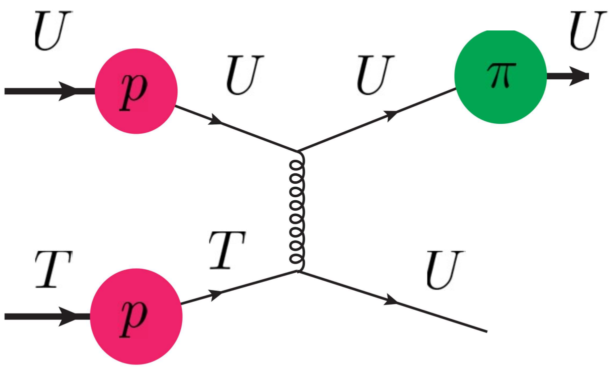




$A_N \sim \alpha_s \frac{m_q}{P_T}$ negligible

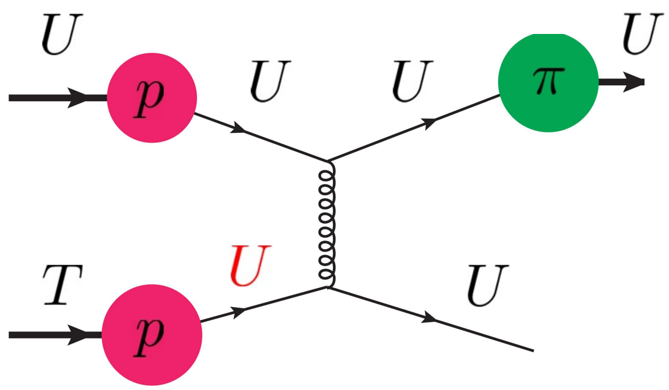
Conventional picture does not work

$$\mathcal{F}.\mathcal{T}.\langle PS_\perp|\bar{\psi}(0)\gamma^\mu\psi(x^-,x_T)|PS_\perp\rangle = 2f(x,k_T)p^\mu + \frac{2}{M_N}\epsilon^{\mu\nu\rho\sigma}P_\nu k_{T\rho}S_{\perp\sigma}f_{1T}^\perp(x,k_T)\cdots$$

quark pol. / nucleon pol.

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Twist-2 TMDs

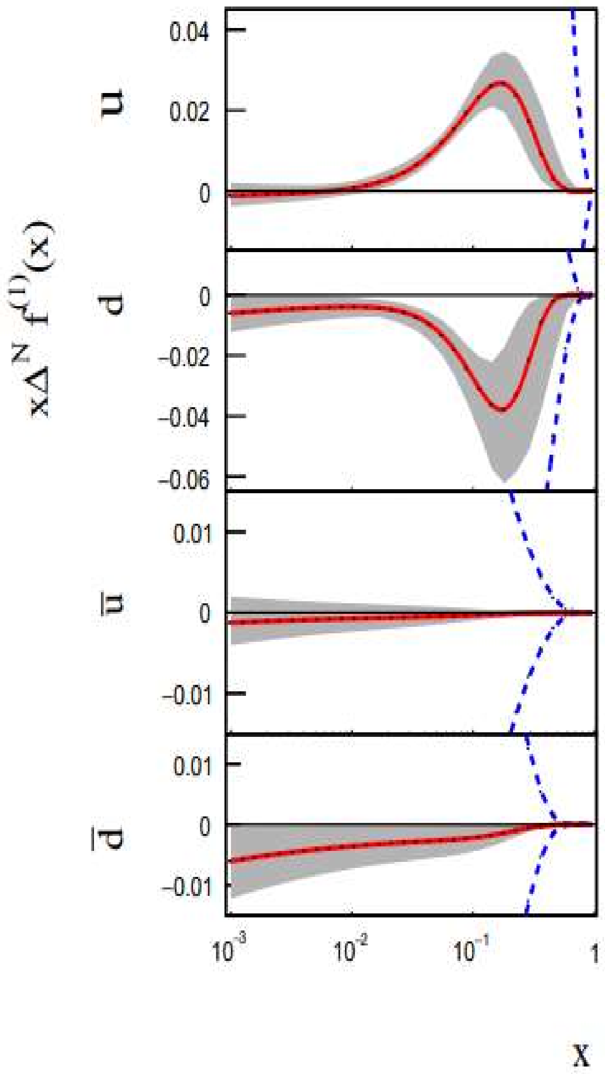


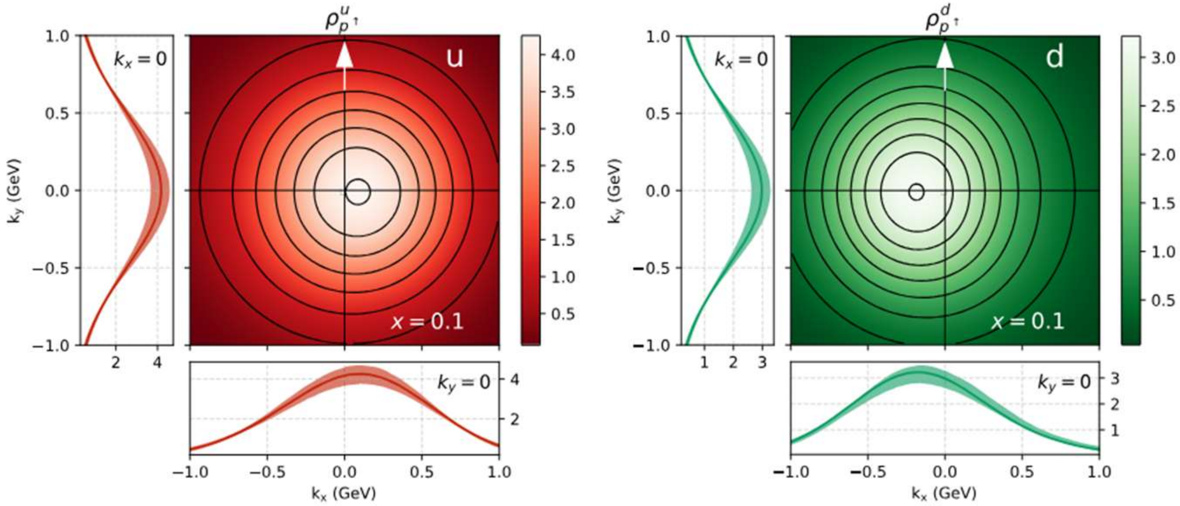
Understanding of the 3D structure and nontrivial polarization effects are tasks of future experiments

Quark Sivers effect

well determined in the past couple of decades

TMD Handbook, arXiv:2304.03302





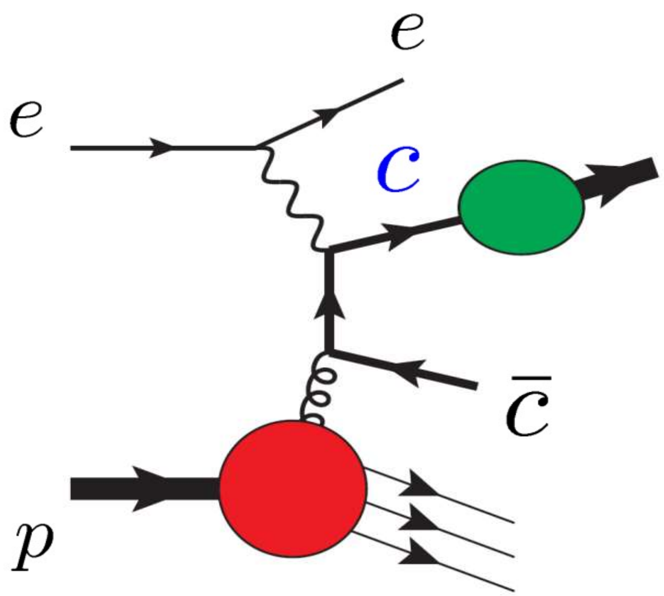
Proceed with precision tests

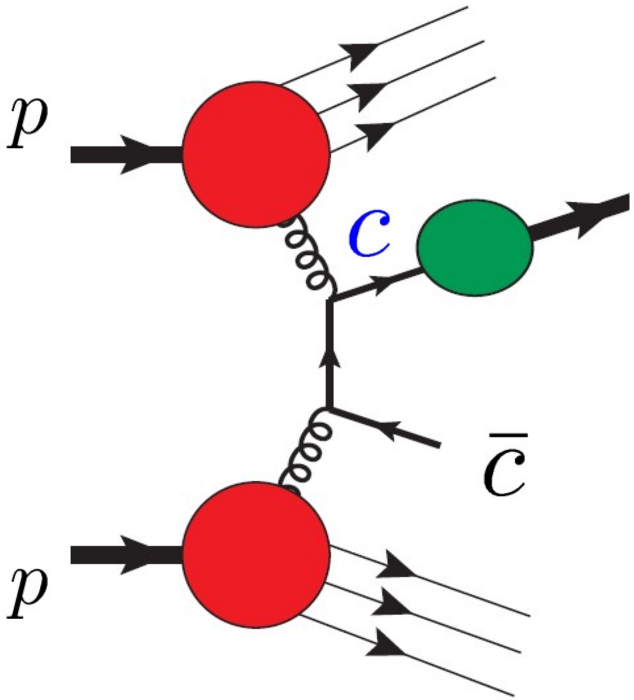
- Sea distributions
- Role of scale evolution
- Confirmation of the sign change

M. Anselmino, M. Boglione, U. D'Alesio, F. Murgia and A. Prokudin, JHEP 04 (2017)

Heavy quark production

Heavy quarks are mainly produced by the gluon fusion.





Heavy meson productions like $D,\ J/\psi, \cdots$ are ideal observables to investigate gluon distribution functions

Gluon Sivers effect

A lot of work have been done on the gluon TMD Sivers effect

· D-meson production

PRD 70, 074025 (2004) PRD 94, 114022 (2016) PRD 96, 036011 (2017)

PRD 97, 076001 (2018) PRD 99, 036013 (2019)

· J/ψ production

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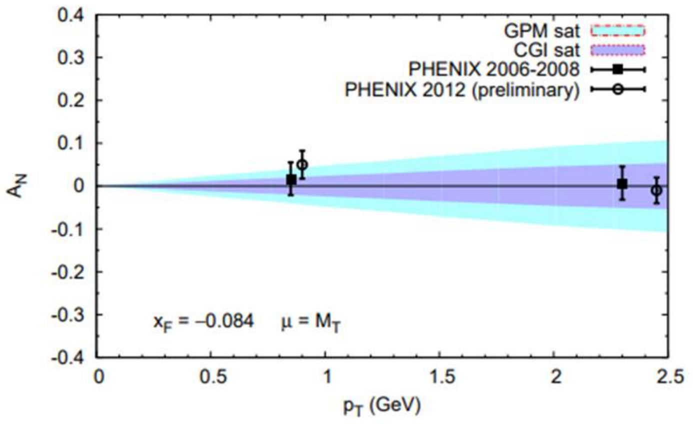
PRD 101, 054003 (2020) EPJC 79, 1029 (2019) PRD 102, 094011 (2020)

However...



Only a few data points are available

A. Adare et al. [PHENIX Collaboration], Phys. Rev. D 82 (2010) 112008

little information on the gluon TMD Sivers function even at the tree-level

Gluon Sivers in twist-3

Two independent functions

H. Beppu, Y. Koike, K. Tanaka and SY, Phys. Rev. D82 (2010)

C-odd function: $O(x_1, x_2)$ C-even function: $N(x_1, x_2)$

Separation of them is always a problem

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· D-meson production in ep Z. B. Kang and J. W. Qiu, Phys. Rev. D78 (2008)
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in pp Z. B. Kang, J. W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. D78 (2008)
Y. Koike and SY, Phys. Rev. D84 (2011)

No results for J/ψ production

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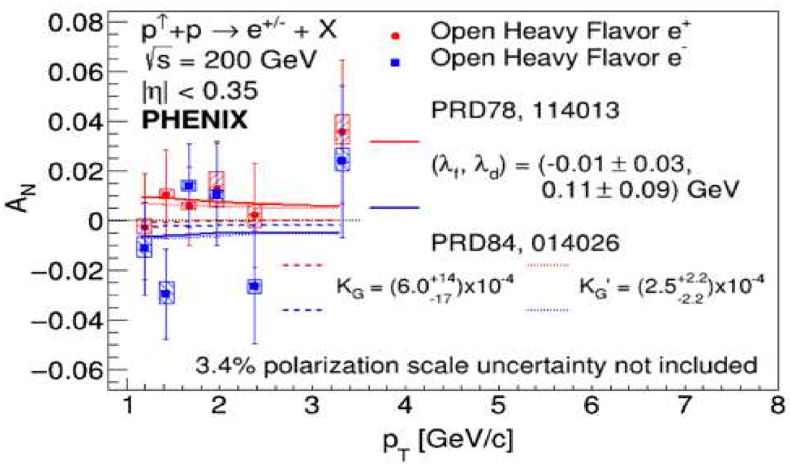


N. J. Abdulameer et al. [PHENIX], Phys. Rev. D107 (2023)

$$O(x,x) = N(x,x) = K_G G(x) \qquad K_G = (6.0^{+14}_{-17}) \times 10^{-4}$$

Upper bound of the functions

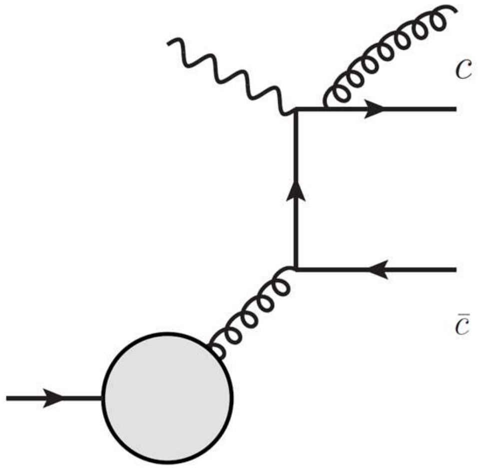
Collinear twist-3 + NRQCD

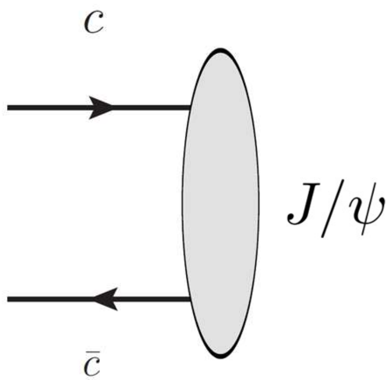
We adopt non-relativistic QCD framework for the hadronization into J/ψ

- The charm quark pair is produced through a hard scattering

$$\gamma^* + g \to \sum_n c\bar{c}[n] + g \qquad n\text{: possible Fock state} \quad {}^3S_1^{[1]}, {}^1S_0^{[8]}, {}^3S_1^{[8]}, \cdots$$

- Haronization happens nonperturbatively





$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]}) \rangle$

Long distance matrix element

(LDME)

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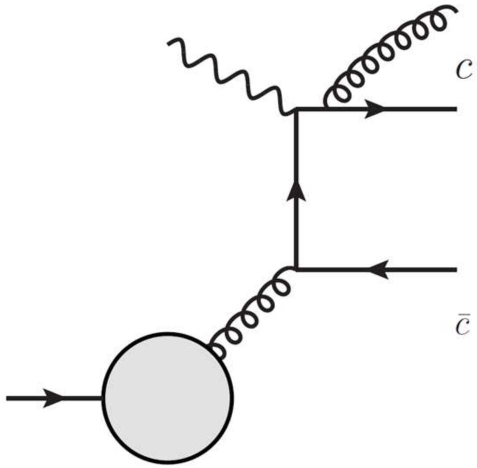

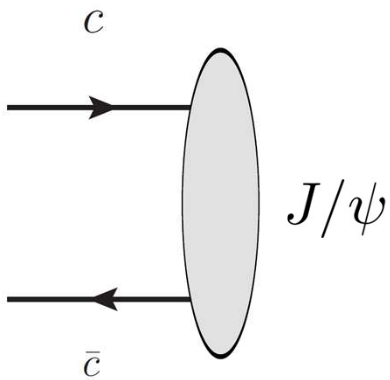

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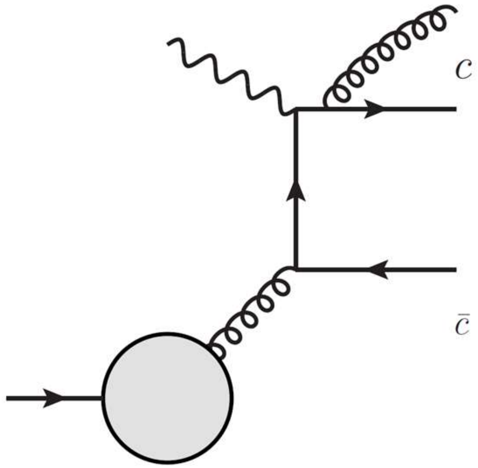
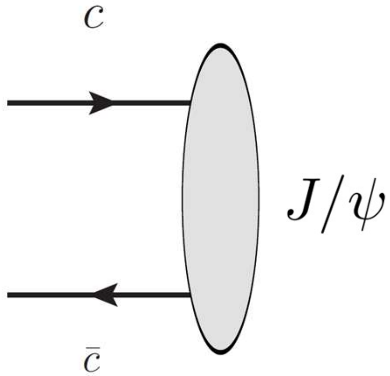
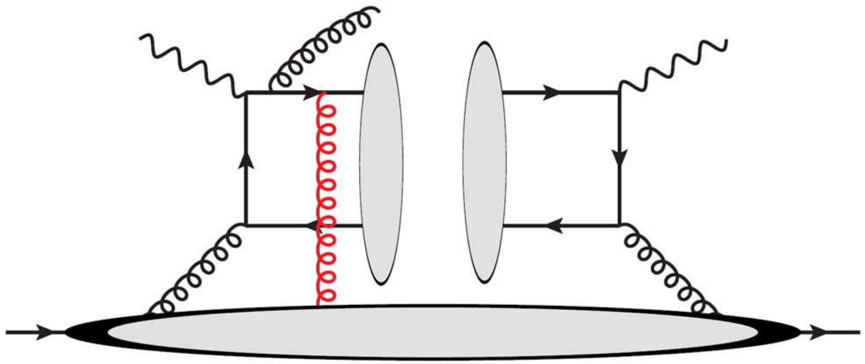


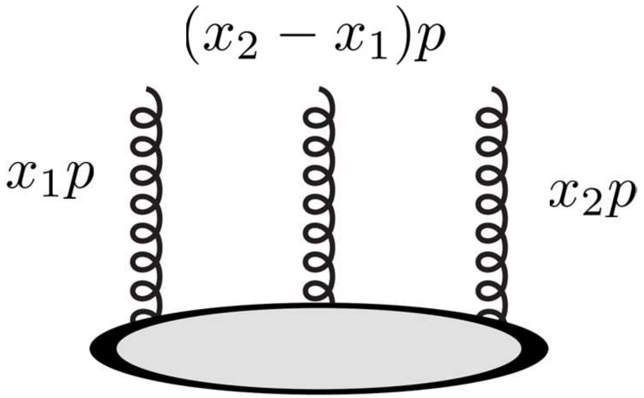


$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]}) \rangle$

Long distance matrix element (LDME)

- Twist-3 contribution requires one more gluon line





H. Beppu, Y. Koike, K. Tanaka and SY, Phys. Rev. D82 (2010)

$$\int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle PS_\perp | \left\{ \begin{array}{c} d_{bca} \\ if_{bca} \end{array} \right\} (-i) F_b^{\beta n}(0)[0,\mu n] iF_c^{\gamma n}(\mu n)[\mu n, \lambda n] iF_a^{\alpha n}(\lambda n) | PS_\perp \rangle$$

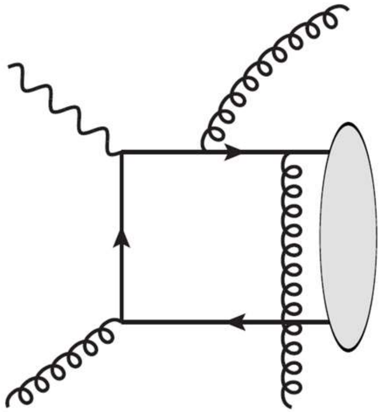
$$= 2iM_N [g^{\alpha\beta} \epsilon^{\gamma p n S} \left\{ \begin{array}{c} O(x_1, x_2) \\ N(x_1, x_2) \end{array} \right\} + g^{\beta\gamma} \epsilon^{\alpha p n S} \left\{ \begin{array}{c} O(x_2, x_2 - x_1) \\ N(x_2, x_2 - x_1) \end{array} \right\} + g^{\gamma\alpha} \epsilon^{\beta p n S} \left\{ \begin{array}{c} O(x_1, x_1 - x_2) \\ N(x_1, x_1 - x_2) \end{array} \right\}$$

Two independent correlation functions

Pole contributions

Sivers effect arises from pole contributions in the twist-3 calculation

There are two types of poles in J/ψ production



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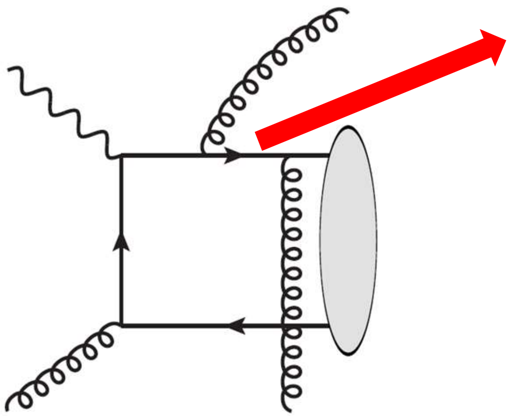

$$\frac{1}{(\frac{P_{J/\psi}}{2}-(x_2-x_1)p)^2-\frac{m_{J/\psi}^2}{4}+i\epsilon}$$

$$P\frac{1}{(\frac{P_{J/\psi}}{2}-(x_2-x_1)p)^2-\frac{m_{J/\psi}^2}{4}}-i\pi\delta\Big((\frac{P_{J/\psi}}{2}-(x_2-x_1)p)^2-\frac{m_{J/\psi}^2}{4}\Big)$$

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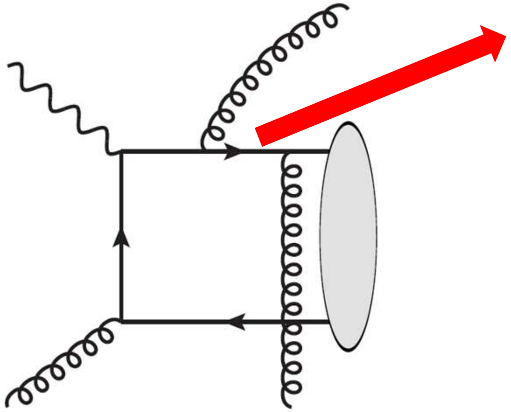

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Soft-gluon-pole(SGP) $-i\pi\frac{1}{P_{J/\psi}\cdot p}\delta(x_2-x_1)$

$$O(x,x),\ O(x,0),\ N(x,x),\ N(x,0)$$

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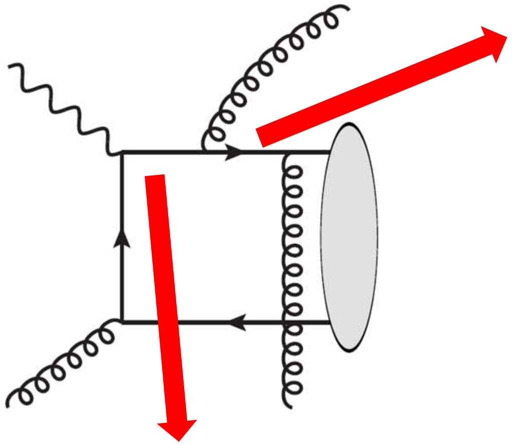

$$\frac{1}{(\frac{P_{J/\psi}}{2}-(x_2-x_1)p)^2-\frac{m^2_{J/\psi}}{4}+i\epsilon}$$

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$$\frac{1}{(x_1p+q-\frac{P_{J/\psi}}{2})^2-\frac{m^2_{J/\psi}}{4}+i\epsilon}$$

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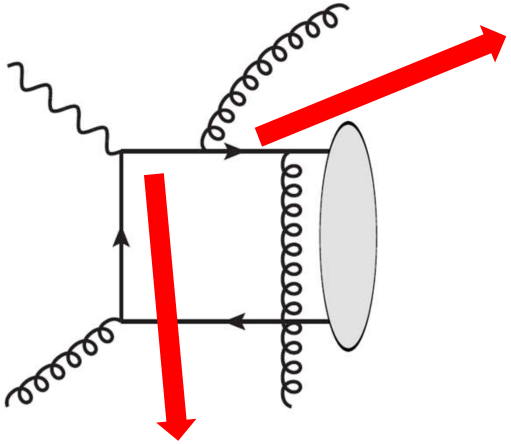


$$\frac{1}{(\frac{P_{J/\psi}}{2}-(x_2-x_1)p)^2-\frac{m_{J/\psi}^2}{4}+i\epsilon}$$

$$P\frac{1}{(\frac{P_{J/\psi}}{2}-(x_2-x_1)p)^2-\frac{m_{J/\psi}^2}{4}} - i\pi\delta\Big((\frac{P_{J/\psi}}{2}-(x_2-x_1)p)^2-\frac{m_{J/\psi}^2}{4}\Big)$$

Soft-gluon-pole(SGP) $-i\pi\frac{1}{P_{J/\psi}\cdot p}\delta(x_2-x_1)$

$$O(x,x),\ O(x,0),\ N(x,x),\ N(x,0)$$

$$\frac{1}{(x_1p+q-\frac{P_{J/\psi}}{2})^2-\frac{m_{J/\psi}^2}{4}+i\epsilon}$$

Hard-pole(HP) $-i\pi\frac{1}{2p\cdot(q-\frac{P_{J/\psi}}{2})}\delta\Big(x_1-Ax\Big)$ $A\neq 0$

$$O(x,Ax),\ O(x,(1-A)x),\ O(Ax,-(1-A)x)$$

$$N(x,Ax),\ N(x,(1-A)x),\ N(Ax,-(1-A)x)$$

Cross section formula

$$\text{SIDIS } e^-(\ell) + p^\uparrow(p) \to e^-(\ell') + J/\psi(P_{J/\psi}) + X$$

$$S_{ep} = (p+\ell)^2 \qquad x_B = \frac{Q^2}{2p\cdot q} \qquad Q^2 = -(\ell-\ell')^2 \qquad z_f = \frac{p\cdot P_{J/\psi}}{p\cdot q}$$

$$\frac{d^6\Delta\sigma}{dx_B dQ^2 dz_f dP_T^2 d\phi d\chi} = \frac{\alpha_{em}^2\alpha_s^2 e_c^2(2\pi M_N)}{4\pi S_{ep}^2 x_B^2 Q^2}\left(\mathcal{N}\langle\mathcal{O}^{J/\psi}({}^3S_1^{[1]})\rangle\right)\sum_{i=1,\ldots,4,8,9}\mathcal{A}_i(\phi-\chi)\mathcal{S}_i(\Phi_S-\chi)$$
$$\times\int\frac{dx}{x^2}\delta\left[\frac{P_T^2}{Q^2}-\left(1-\frac{1}{\hat{x}}+\frac{m_{J/\psi}^2}{z_f Q^2}\right)\left(1-\frac{1}{z_f}\right)\right]\left[N(x,x)\sigma_i^{N1}+N(x,0)\sigma_i^{N2}+N(x,Ax)\sigma_i^{N3}\right.$$
$$\left.+N(x,(1-A)x)\sigma_i^{N4}+N(Ax,-(1-A)x)\sigma_i^{N5}\right]$$

- C-odd function is canceled $O(x_1, x_2)$
- Derivative terms $\frac{d}{dx}N(x,x)$, $\frac{d}{dx}N(x,0)$ are canceled,

  but nonderivative functions $N(x,x), N(x,0)$ survive

Feng Yuan, Phys. Rev. D78 (2008)

- Hard-pole contribution exist in J/ψ production

A. Schafer and J. Zhou, Phys. Rev. D88 (2013)

The cross section has five types azimuthal dependences

$$\frac{d^6\Delta\sigma}{dx_B dQ^2 dz_f dP_T^2 d\phi d\chi} = \sin(\phi_h - \phi_S)(\mathcal{F}_1 + \mathcal{F}_2 \cos\phi_h + \mathcal{F}_3 \cos 2\phi_h) + \cos(\phi_h - \phi_S)(\mathcal{F}_4 \sin\phi_h + \mathcal{F}_5 \sin 2\phi_h)$$

We perform numerical calculations for five normalized structure functions

$$\frac{\mathcal{F}_1}{\sigma_1^{\rm U}}, \quad \frac{\mathcal{F}_2}{2\sigma_1^{\rm U}}, \quad \frac{\mathcal{F}_3}{2\sigma_1^{\rm U}}, \quad \frac{\mathcal{F}_4}{2\sigma_1^{\rm U}}, \quad \frac{\mathcal{F}_5}{2\sigma_1^{\rm U}}$$

$\sigma_1^{\rm U}$: unpolarized cross section

$$\frac{\mathcal{F}_1}{\sigma_1^{\rm U}} = \frac{2\pi M_N}{[\frac{4}{y^2}(1-y+\frac{y^2}{2})\hat{\sigma}_1 - 2\hat{\sigma}_2]\bar{x}G(\bar{x})}\Big[\frac{4}{y^2}(1-y+\frac{y^2}{2})\Big(\sum_{i=1}^{5} N^i(\bar{x})\sigma_1^{Ni}\Big) - 2\Big(\sum_{i=1}^{5} N^i(\bar{x})\sigma_2^{Ni}\Big)\Big] \qquad y = \frac{Q^2}{x_B S_{ep}}$$

LDME is canceled in the ratio

$$N^{1,2,3,4,5}(x) = \{N(x,x),\ N(x,0),\ N(x,Ax),\ N(x,(1-A)x),\ N(Ax,-(1-A)x)\}$$

We use two models

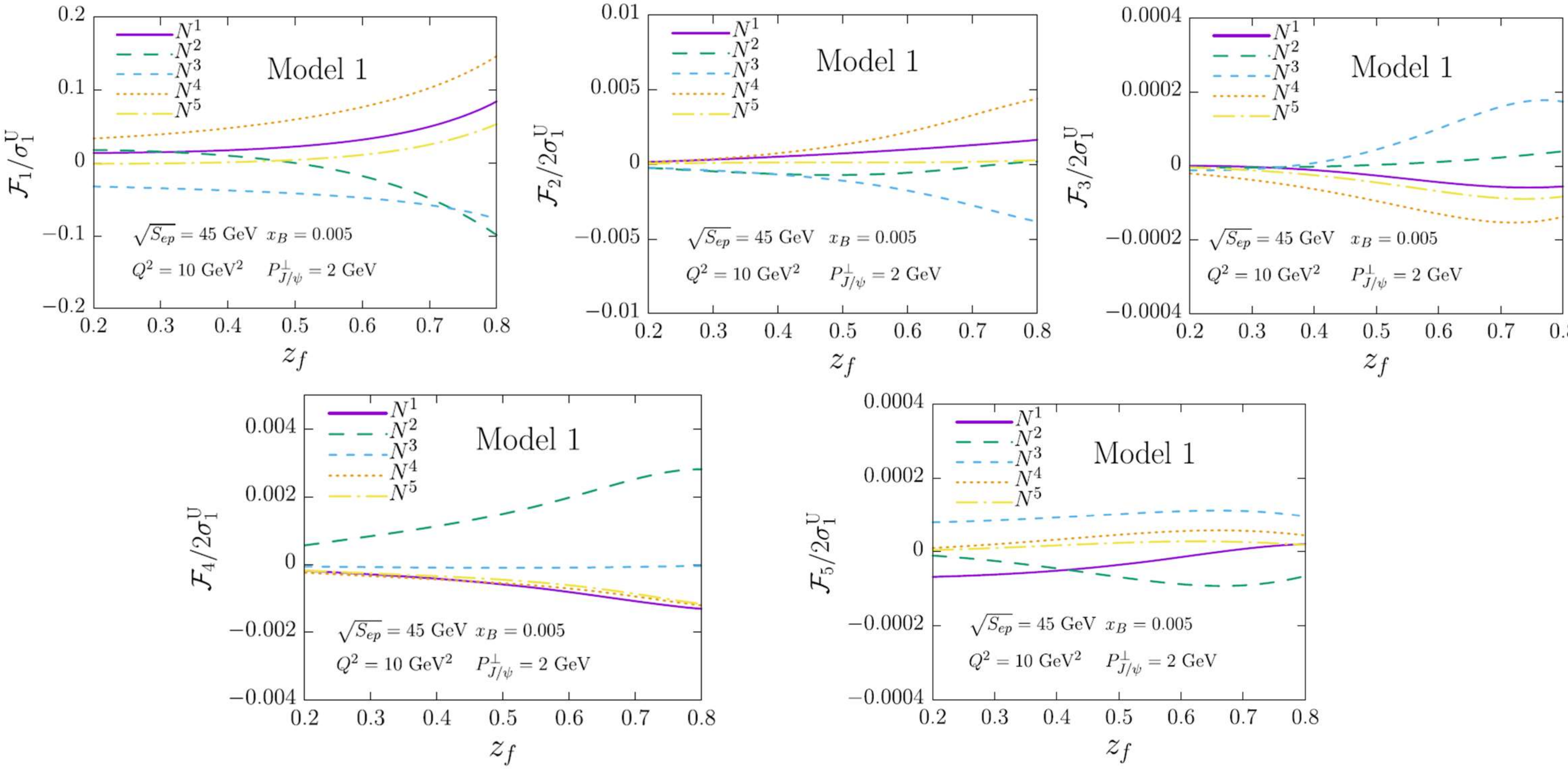
$$N(x,x) = 0.002xG(x)$$

$$N(x,x) = 0.0005x^{\frac{1}{2}}G(x)$$

Upper bound of the experimental data

Z. B. Kang, J. W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. D78 (2008)
Y. Koike and SY, Phys. Rev. D84 (2011)

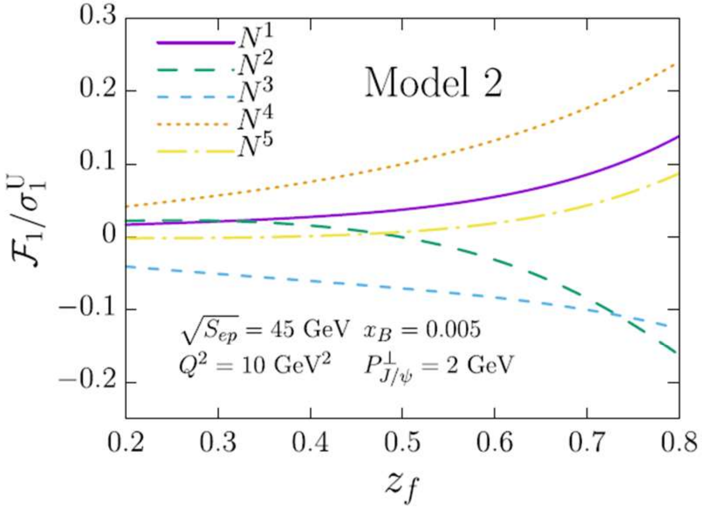
Numerical simlation(model1)

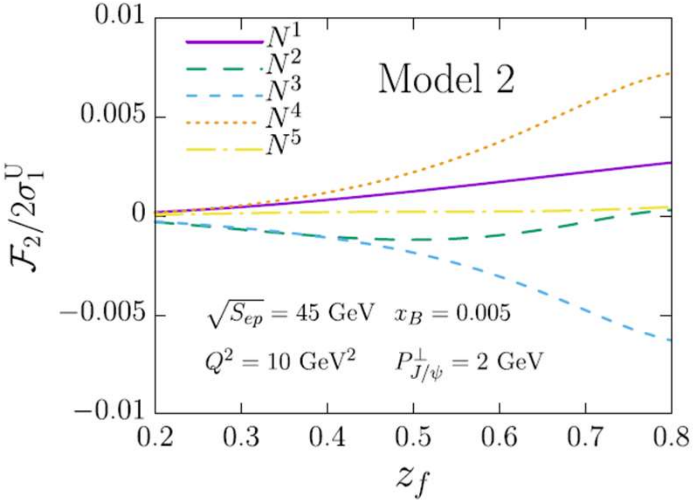


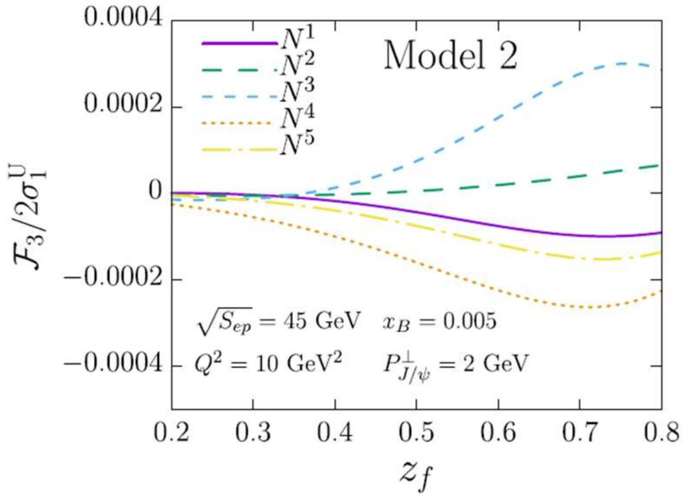
$$N^{1,2,3,4,5} = \{N(x,x),\ N(x,0),\ N(x,Ax),\ N(x,(1-A)x),\ N(Ax,-(1-A)x)\} = \ 0.002xG(x)$$

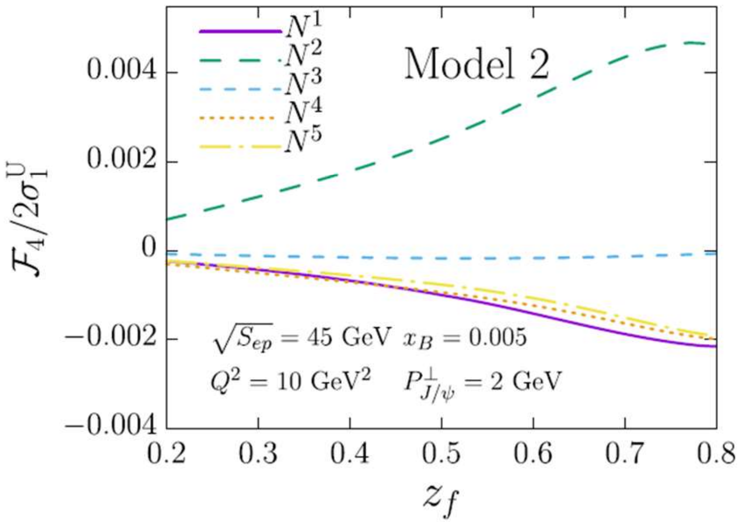
EIC energy: $\sqrt{S_{ep}} = 45$ GeV $\quad x_B = 0.005 \quad Q^2 = 10$ GeV^2 $\quad P_{J/\psi}^{\perp} = 2$ GeV

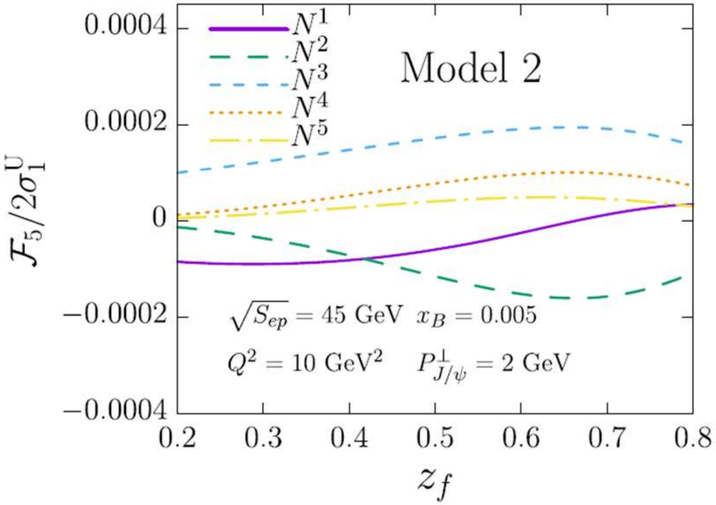
Numerical simlation(model2)











$$N^{1,2,3,4,5} = \{N(x,x),\ N(x,0),\ N(x,Ax),\ N(x,(1-A)x),\ N(Ax,-(1-A)x)\} = \ 0.0005x^{\frac{1}{2}}G(x)$$

Summary

- We calculated the twist-3 gluon contribution to the SSA in the J/ψ production

- The C-odd function $O(x_1, x_2)$ is canceled and the LDME is also canceled in the ratio if the color singlet contribution is dominant

$\longrightarrow$ Ideal observable to measure $N(x_1, x_2)$

Relation with TMD (analogy with $f_{1T}^{\perp(1)}(x) = \pi F_{FT}(x, x)$)

$$G_T^{(1)}(x) = -4\pi(N(x,x) - N(x,0)) \qquad \Delta H_T^{(1)}(x) = 8\pi N(x,0)$$

- The SSA could be sizable in the EIC energy

○ Future work

- Calculation for pp collision

- Calculation for color-octet channels

- Matching between TMD and the collinear twist-3