Sivers effect on the single transverse-spin asymmetries in J/ψ production in the collinear pQCD approach

Shinsuke Yoshida

(South China Normal University)

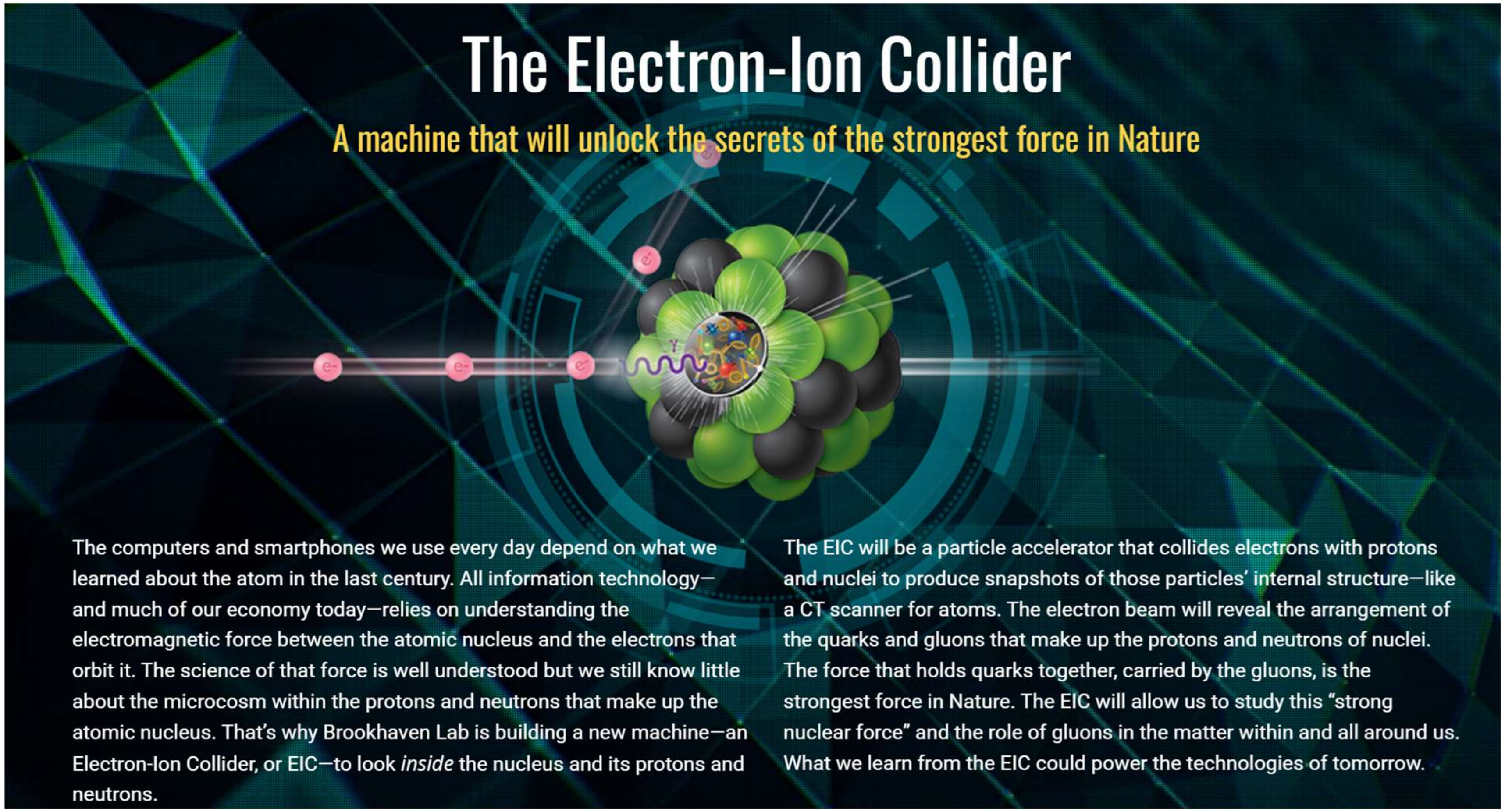
in collaboration with: Longjie Chen(IFJ PAN)
Hongxi Xing(SCNU)

Phys. Rev. D108 (2023), arXiv:2605.19300

Meson2026@Krakow, June 25-30

Next generation experiment

https://www.bnl.gov/eic/



Next generation experiment

https://www.bnl.gov/eic/

The Electron-Ion Collider

A machine that will unlock the secrets of the strongest force in Nature

3D structure of protons and nuclei

The EIC will bring high-energy electrons into head-on collisions with high-energy protons or atomic nuclei to produce “freeze-frame” snapshots of those particles’ inner structure, creating the first-ever tomographic 3D images of the “ocean” of gluons within. These images will tell scientists how gluons and quarks bind each other to form the particles within and around us.

More

Gluon saturation and the color glass condensate

Recent experiments and advances in theory suggest that protons, neutrons, and nuclei appear as dense “walls” of gluons at high energies, creating what may be among the strongest force fields in nature. Discovering and studying this form of matter, the “color glass condensate,” will provide deeper insight into why matter in this subatomic realm is stable.

More

Solving the mystery of proton spin

The EIC will be the world’s first polarized electron-proton collider—meaning the “spins” of both colliding particles can be aligned in a controlled way. This will make it possible to experimentally solve the outstanding mystery of how the teeming quarks and gluons inside the proton combine their spins to generate the overall spin carried by the proton.

More

Next generation experiment

https://www.bnl.gov/eic/

The Electron-Ion Collider

A machine that will unlock the secrets of the strongest force in Nature

3D structure of protons and nuclei

The EIC will bring high-energy electrons into head-on collisions with high-energy protons or atomic nuclei to produce “freeze-frame” snapshots of those particles’ inner structure, creating the first-ever tomographic 3D images of the “ocean” of gluons within. These images will tell scientists how gluons and quarks bind each other to form the particles within and around us.

More

Gluon saturation and the color glass condensate

Recent experiments and advances in theory suggest that protons, neutrons, and nuclei appear as dense “walls” of gluons at high energies, creating what may be among the strongest force fields in nature. Discovering and studying this form of matter, the “color glass condensate,” will provide deeper insight into why matter in this subatomic realm is stable.

More

Solving the mystery of proton spin

The EIC will be the world’s first polarized electron-proton collider—meaning the “spins” of both colliding particles can be aligned in a controlled way. This will make it possible to experimentally solve the outstanding mystery of how the teeming quarks and gluons inside the proton combine their spins to generate the overall spin carried by the proton.

More

Why 3D?

It has been confirmed in experiments that quark's and gluon's spin contributions are not sufficient

How can we access the orbital angular momenta ?

· Canonical OAM

C. Lorce and B. Pasquini, Phys. Rev. D84, 014015 (2011)

Y. Hatta, Phys. Lett. B708 (2012)

classical ⟶ quantum

$$L_z = (\vec{r}_\perp \times \vec{p}_\perp)_z \qquad\qquad L_q^z = \int dx \int d^2 b_T \int d^2 k_T \, (\vec{b}_T \times \vec{k}_T)_z f_q(x, \vec{k}_T, \vec{b}_T)$$

$f_q(x, \vec{k}_T, \vec{b}_T)$: Wigner distribution

· Mechanical OAM

$$J^q = \frac{1}{2}\int_0^1 dx x\Big(H^q(x,0,0) + E^q(x,0,0)\Big)$$

model relation

M. Burkardt, PRD 66(2002) S. Meissner, A. Metz and K. Goeke, PRD76(2007)

$f_{1T}^{\perp(0)q}(x) = -L(x)E^q(x,0,0)$ $L(x)$: model function

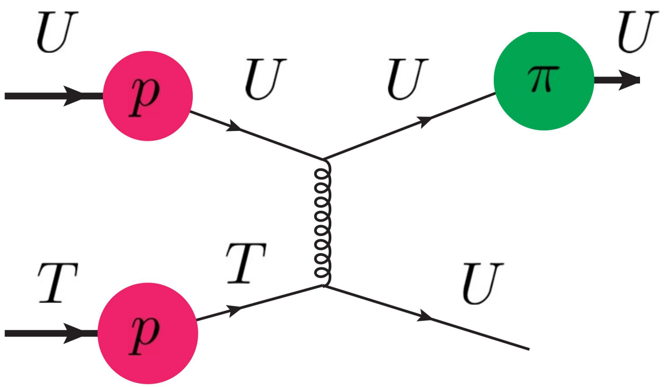
k_T-moment of Sivers TMD function $f_{1T}^{\perp q}(x, k_T)$

Understanding the transverse degrees of freedom is a central task in modern nucleon structure physics

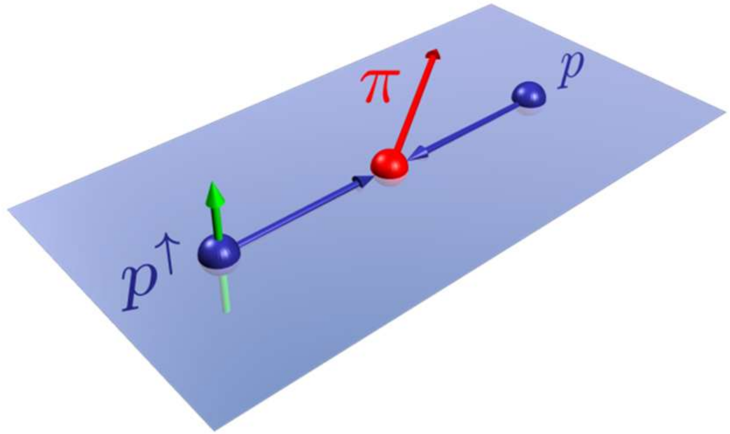
Large single spin asymmetry

Single Spin Asymmetry (SSA)

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



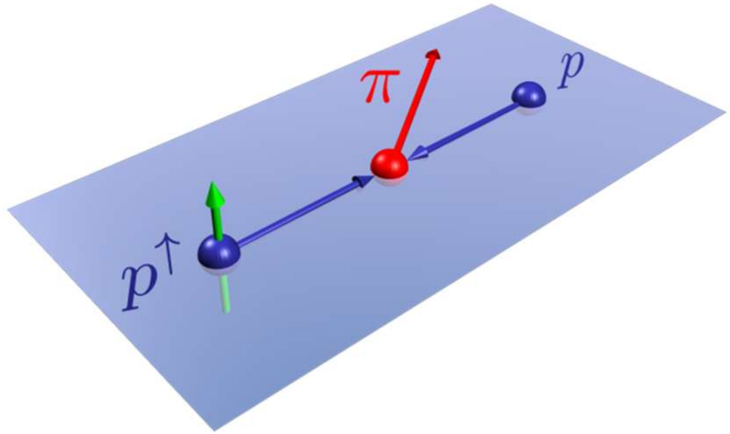
$\sim \frac{m_q}{P_T}$ negligible

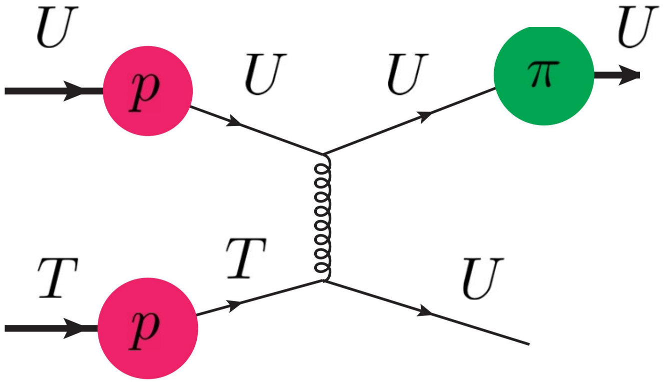


Large single spin asymmetry

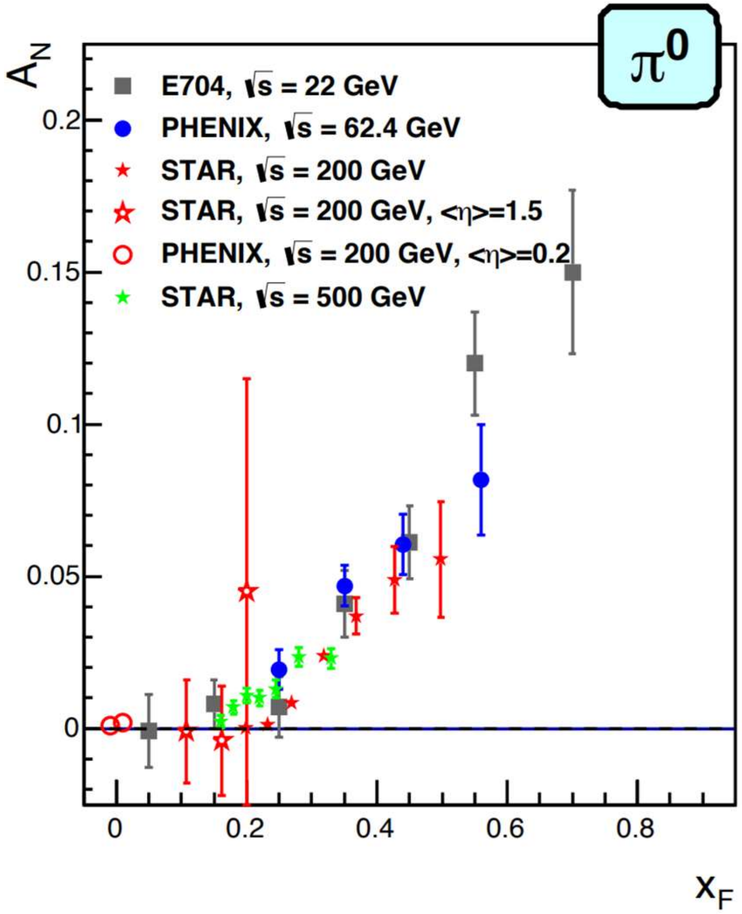
Single Spin Asymmetry (SSA)

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$





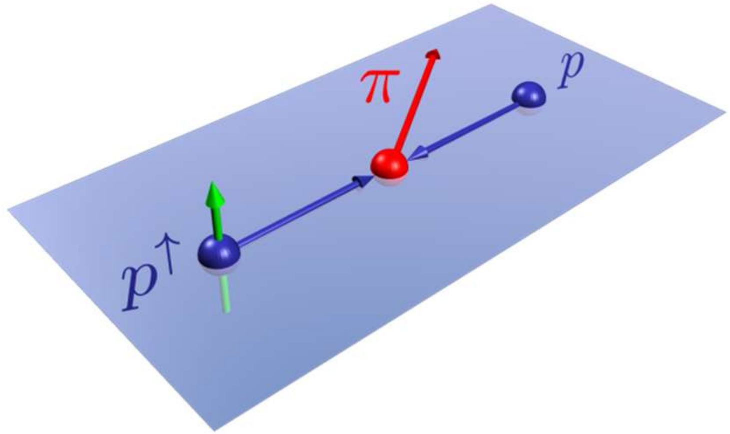
$$\sim \frac{m_q}{P_T}$$ negligible

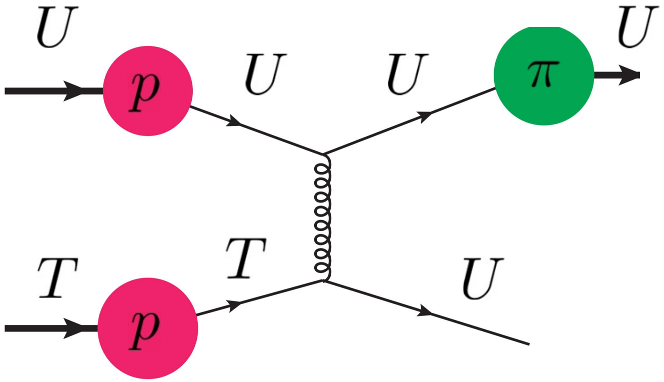


Large single spin asymmetry

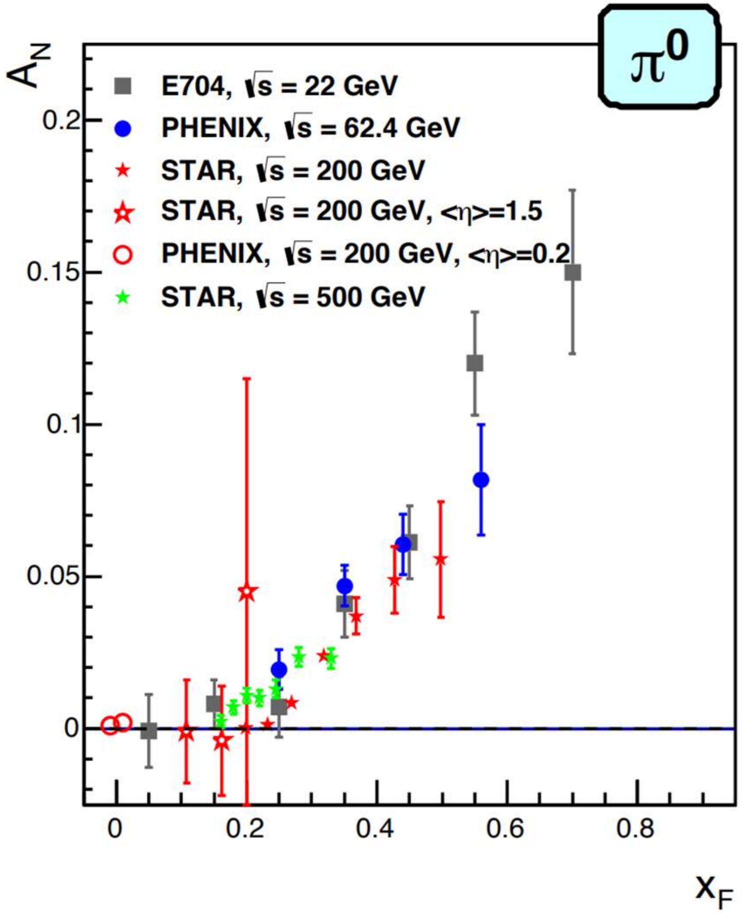
Single Spin Asymmetry (SSA)

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$





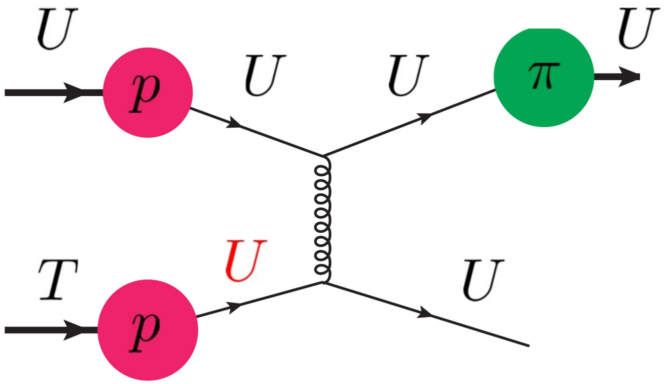
$\sim \dfrac{m_q}{P_T}$ negligible



Sivers effect D. W. Sivers, Phys. Rev. D41 (1990)

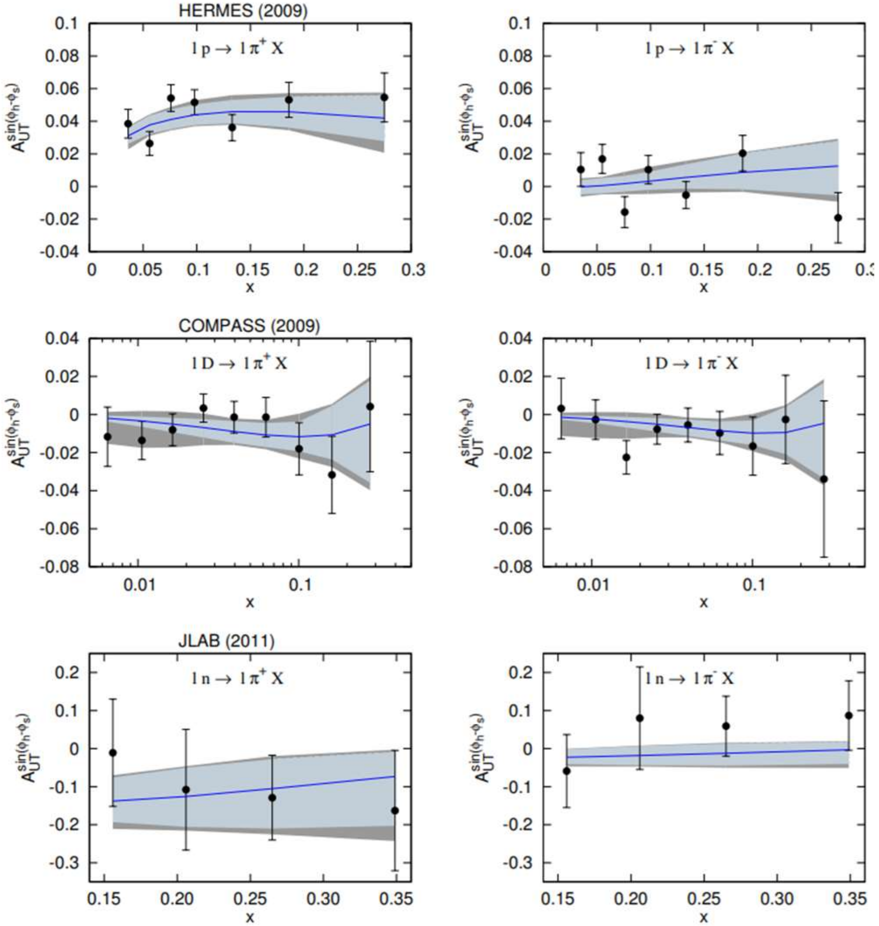
$$\mathcal{F}.\,\mathcal{T}.\ \langle pS_{\perp}|\bar{\psi}(0)\gamma^{+}\psi(\lambda n, \vec{x}_T)|pS_{\perp}\rangle \sim \epsilon^{+\alpha\beta\gamma} p_{\alpha} k_{T\beta} S_{\perp\gamma} f_{1T}^{\perp q}(x, k_T)$$

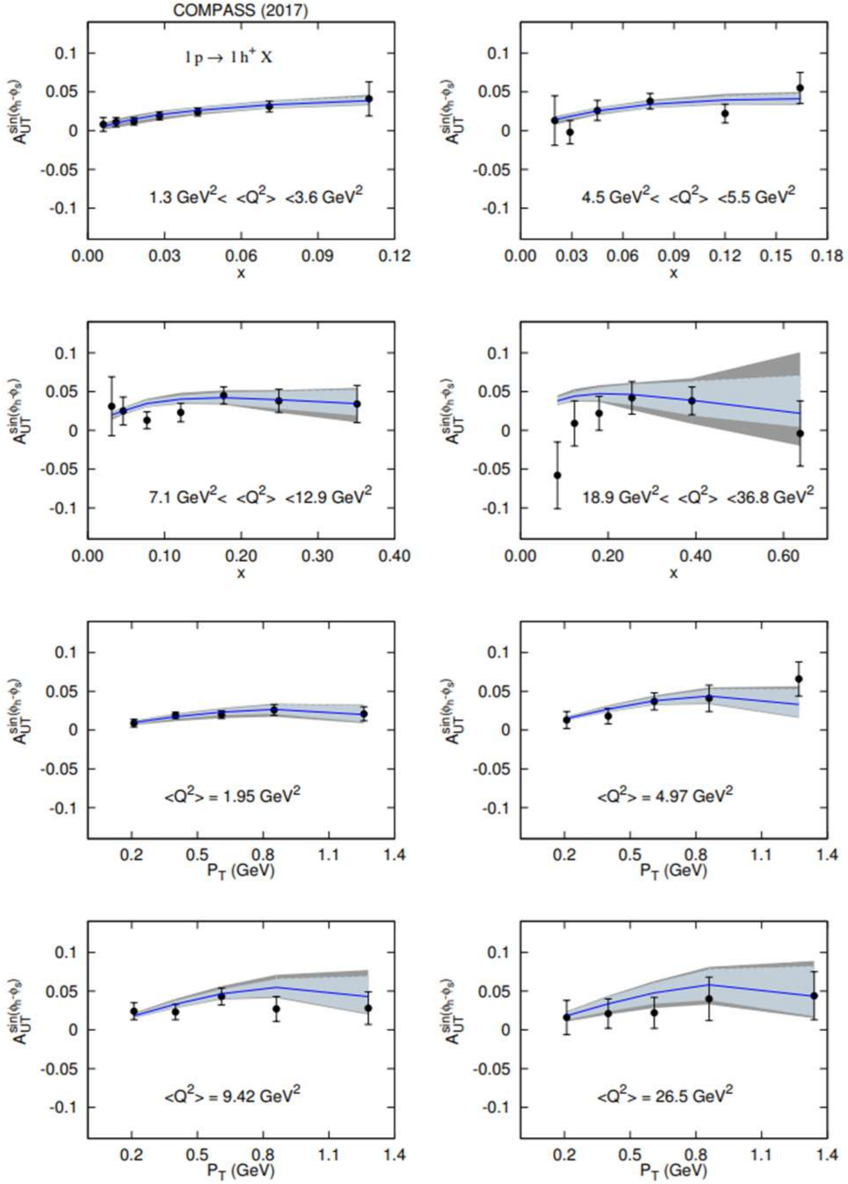
chiral-even needs parton's transverse momentum



Successes of TMD

SSA data in SIDIS has been reported in the past couple of decades



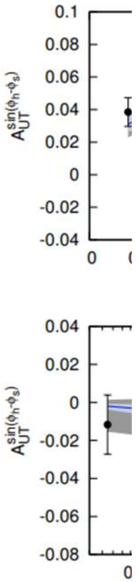


Reasonable description of the existing data

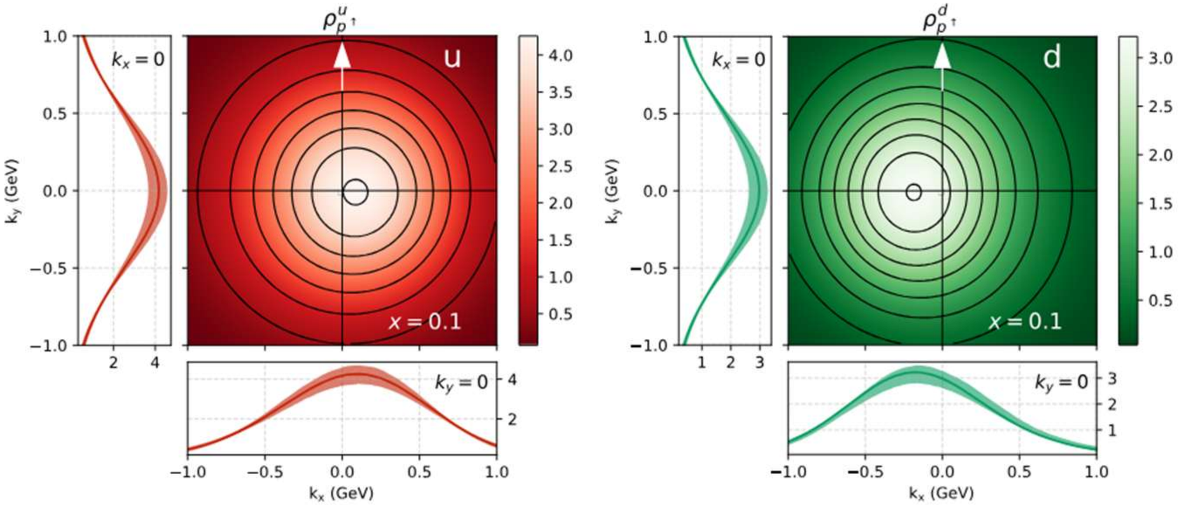
M. Boglione, U. D'Alesio, C. Flore
and J. O. Gonzalez-Hernandez, JHEP07 (2018)

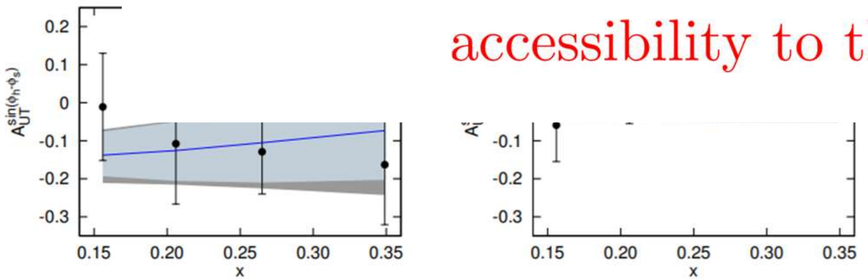
Successes of TMD

SSA data in SIDIS has been reported in the past couple of decades

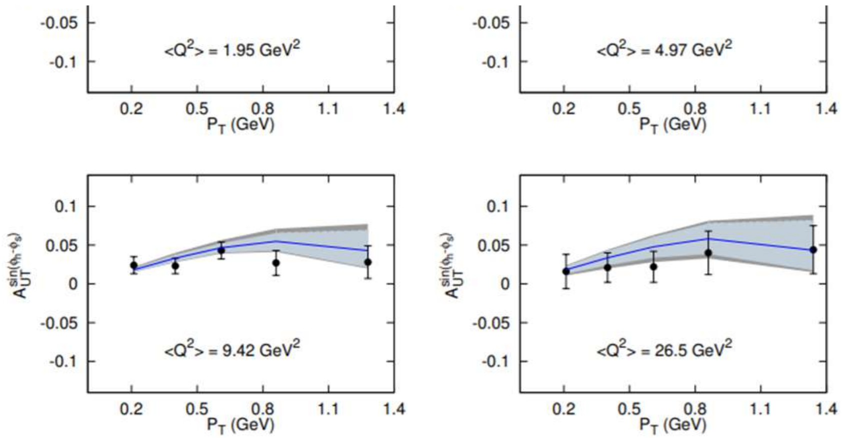


TMD Handbook, arXiv:2304.03302





accessibility to the transverse structure



Reasonable description of the existing data

M. Boglione, U. D'Alesio, C. Flore
and J. O. Gonzalez-Hernandez, JHEP07 (2018)

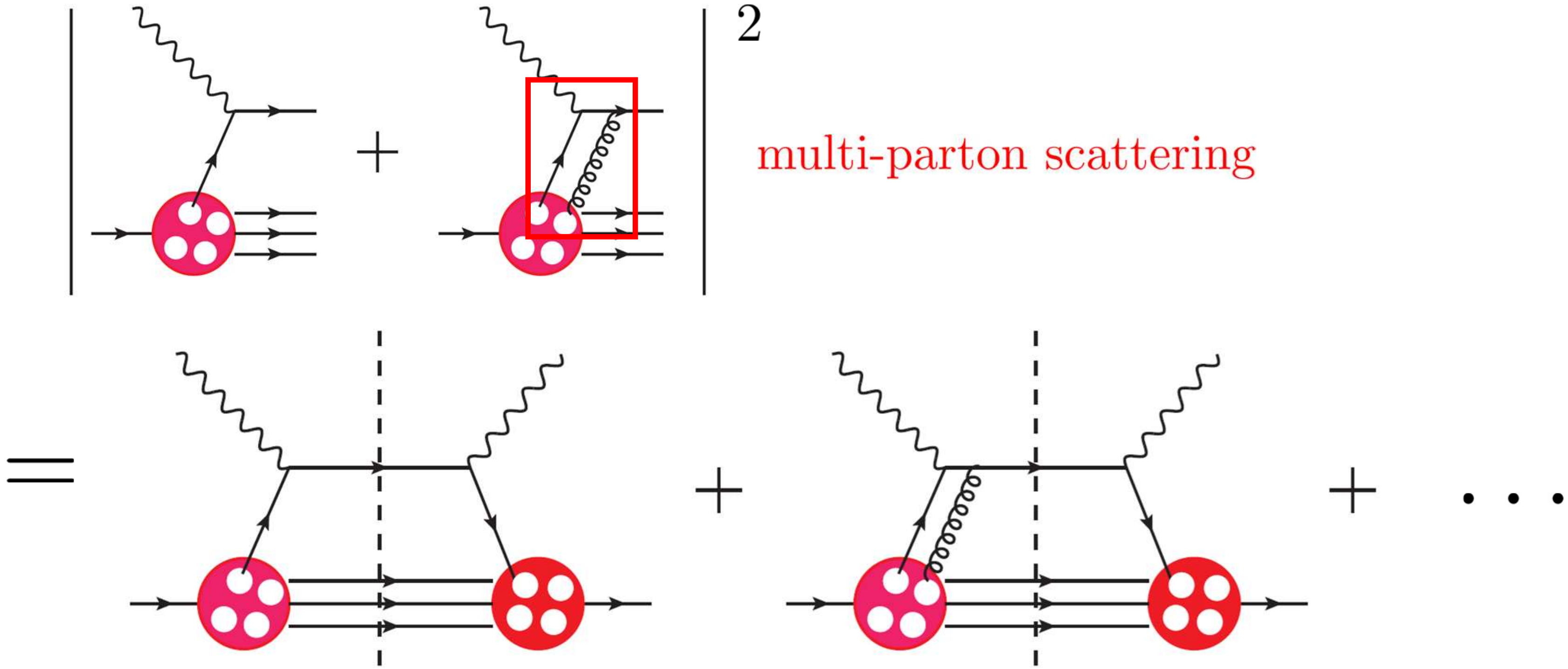
Collinear twist-3 framework

TMD framework requires small transverse momentum of the observed particle P_T relavant to small parton momentum k_T, and large scale Q for a perturbative treatment

○ SIDIS, Drell-Yan, e^+e^--annihilation

✖ $pp \to hX$

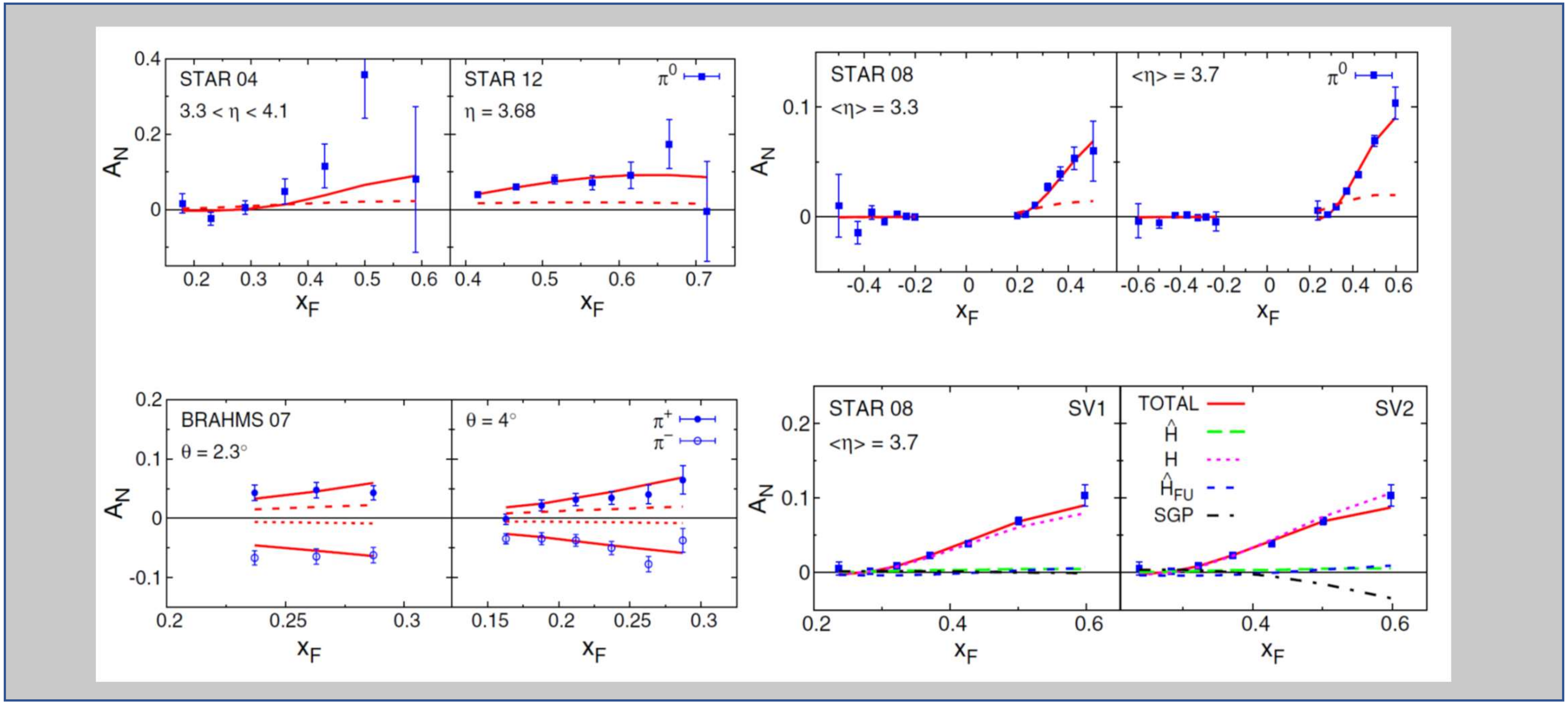
Higher twist framework has been developed to describe single-scale processes



$$\mathcal{F}.\mathcal{T}.\langle PS_\perp|\bar{\psi}_j(0)gF^{\alpha+}(x_2^-)\psi_i(x_1^-)|PS_\perp\rangle$$
$$= -\frac{M_N}{2}\epsilon^{\alpha\beta-+}(\not{P})_{ij}S_{\perp\beta}F_{FT}(x_1,x_2) + \cdots$$

Twist-3 phenomenology

K. Kanazawa, Y. Koike, A. Metz and D. Pitonyak, Phys. Rev. D 89(2014)



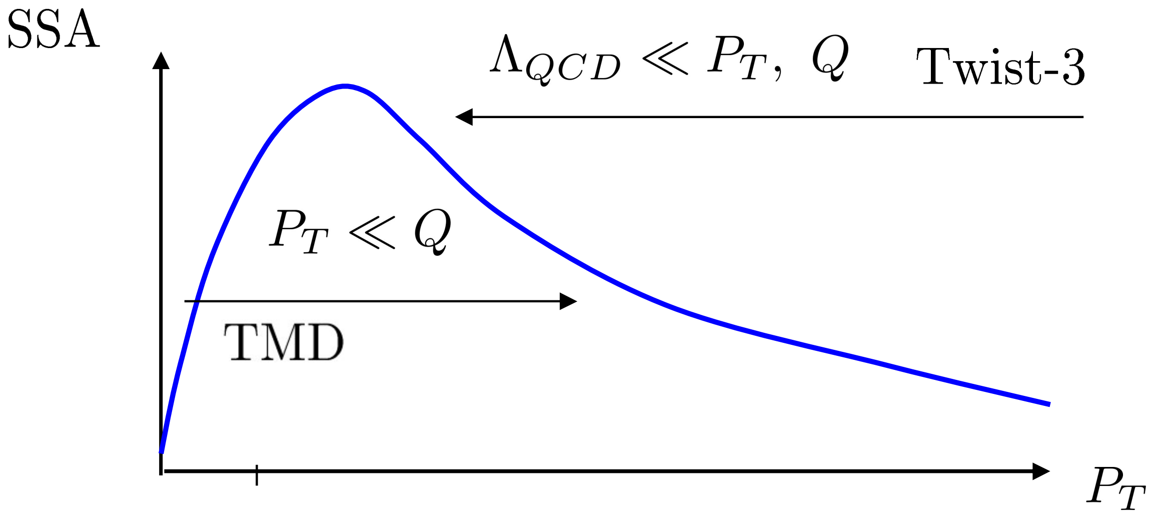
The twist-3 framework gives a resonable description to exiting RHIC data

Relationship between TMD and twist-3

TMD and the collinear twist-3 are equivalent in intermediate P_T region

X. Ji, J.-W. Qiu, W.Vogelsang and F. Yuan, PRD73(2006)

PLB638(2006)



$$\pi F_{FT}(x,x) = f_{1T}^{\perp q(1)}(x) \quad \left(f_{1T}^{\perp q(n)}(x) = \int d^2k_T \left(\frac{k_T^2}{2M_N}\right)^n f_{1T}^{\perp q}(x,k_T) \right)$$

twist-3 QS-function $\qquad$ k_T-moment of Sivers

twist-3 function gives indirect information about the transverse momentum

SSAs in heavy quark production

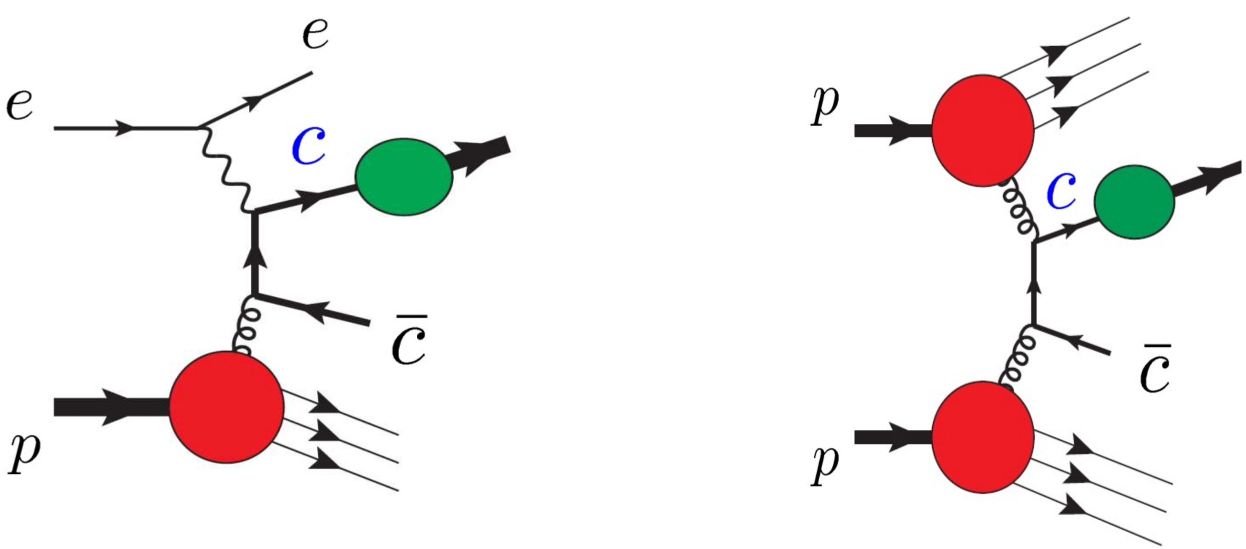
We discuss SSAs in

$$\text{SIDIS: } e^- + p^\uparrow \to e^- + J/\psi + X$$

$$p^\uparrow + p \to J/\psi + X$$

Understanding the gluon Sivers effect is a task of future experiments

Heavy quarks are mainly produced by gluon fusion.



Heavy meson production such as D, $J/\psi, \cdots$ are ideal observables to investigate gluon distribution functions

Gluon Sivers effect in TMD

A lot of papers have been published on the gluon TMD Sivers effect

- *D*-meson production

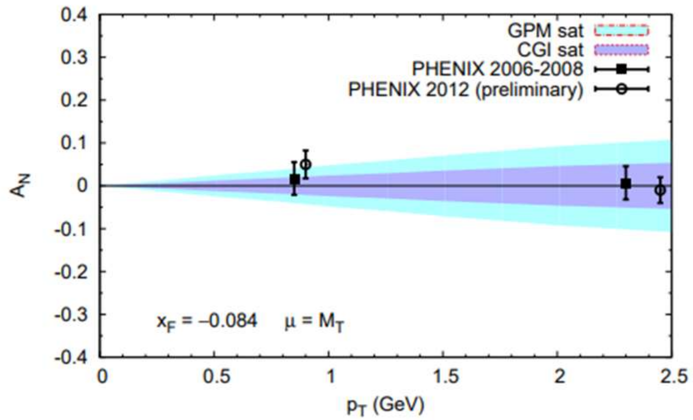
  PRD 70, 074025 (2004) PRD 94, 114022 (2016) PRD 96, 036011 (2017)
  PRD 97, 076001 (2018) PRD 99, 036013 (2019)

- J/ψ production

  PRD 96, 036011 (2017) PRD 99, 036013 (2019) PRD 91, 014005 (2015) EPJC 77, 854 (2017)
  PRD 98, 014007 (2018) PRD 100, 014007 (2019) PRD 100, 094016 (2019)
  PRD 101, 054003 (2020) EPJC 79, 1029 (2019) PRD 102, 094011 (2020) PRD 107, 014008 (2023)

CGI-GPM model is used for *pp* collision

However...



Only four data points are available

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

little information on the gluon TMD Sivers function

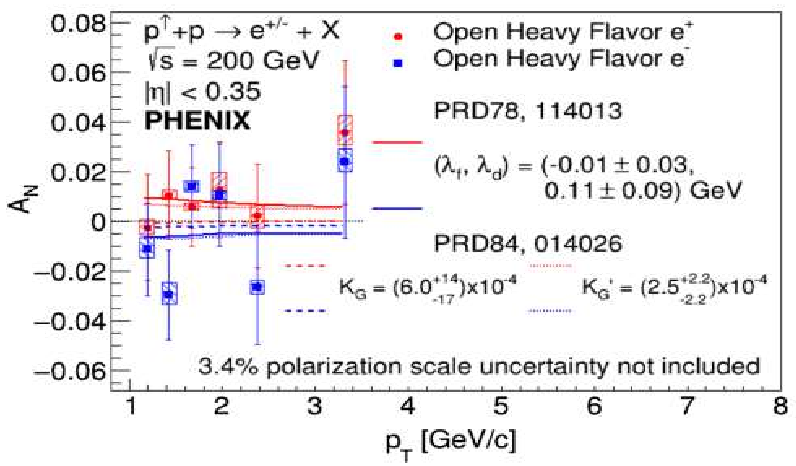
Gluon Sivers effect in twist-3

· D-meson production

PRD 78, 034005 (2008) PRD 78, 114013 (2008) PRD 82, 054005 (2010) PRD 84, 014026 (2011)

· J/ψ production

Phys. Rev. D108 (2023), arXiv:2605.19300 this talk



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

Two independent functions

$$O(x_1, x_2) \qquad N(x_1, x_2)$$

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

Upper bound of the functions

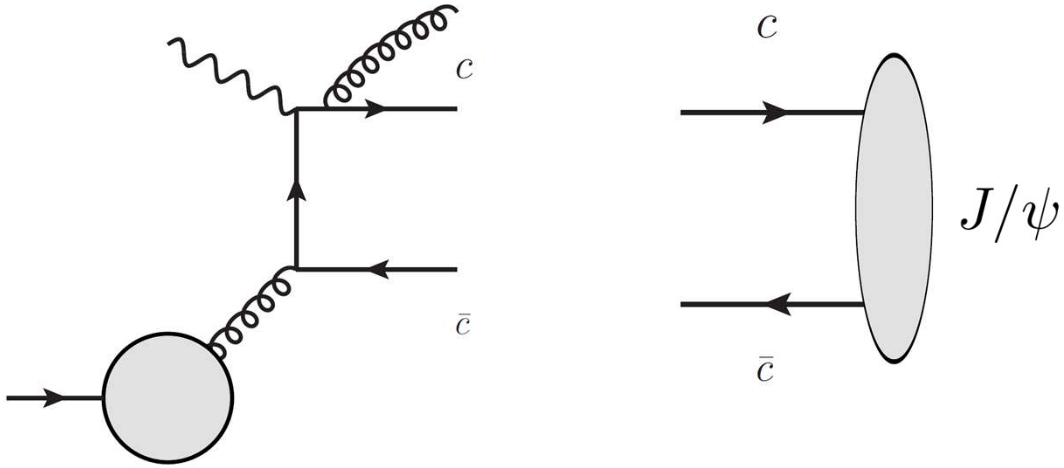
Collinear twist-3 + NRQCD

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

- The charm quark pair is produced through a hard scattering

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

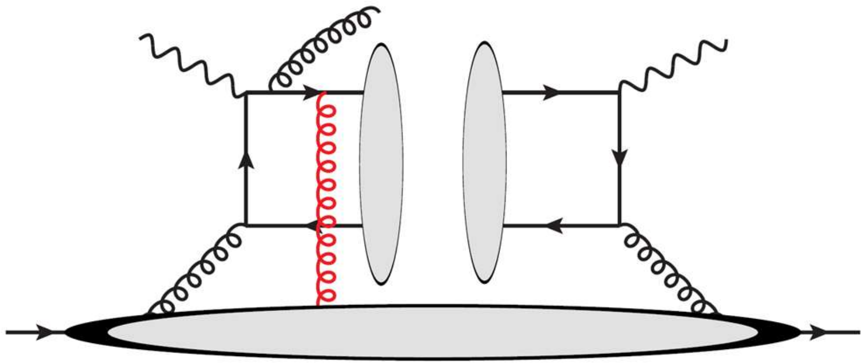
- Haronization happens nonperturbatively

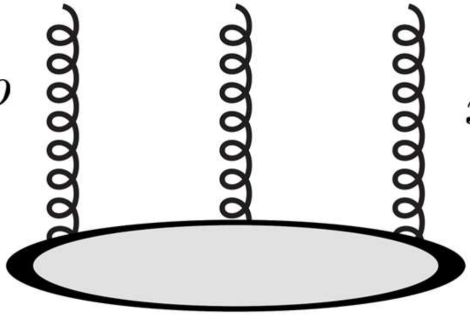


$\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]}) \rangle$

Long distance matrix element (LDME)

- Twist-3 contribution requires one more gluon line





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

$$\int \frac{d\lambda}{2\pi}\int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle PS_\perp | \left\{ \begin{array}{c} d_{bca} \\ i f_{bca} \end{array} \right\} F_e^{\beta n}(0)[0,\mu n]_{eb} F_c^{\gamma n}(\mu n)[\mu n, \lambda n]_{ad} F_d^{\alpha n}(\lambda n) | PS_\perp \rangle$$

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

Two independent twist-3 functions

C-even function is related to gluon TMDs

Y. Koike, K. Yabe and SY, Phys. Rev. D101(2020)

$$G_T^{(1)}(x) = 4\pi \Big(N(x,x) - N(x,0) \Big)$$

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

Cross section in SIDIS

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

kinematical variables

$$S_{ep} = (p+\ell)^2 \qquad x_B = \frac{Q^2}{2p\cdot q}$$

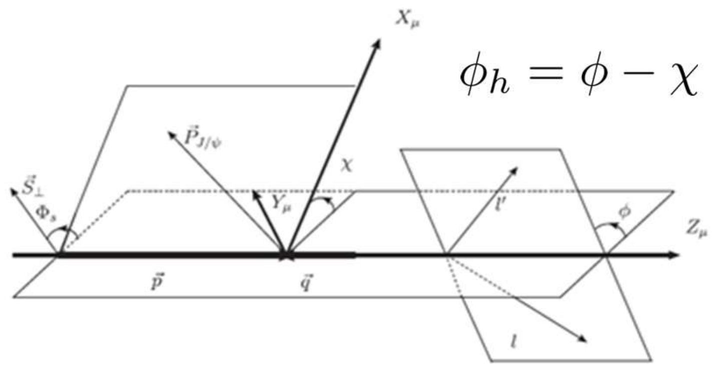
$$Q^2 = -(\ell-\ell')^2 \qquad z_f = \frac{p\cdot P_{J/\psi}}{p\cdot q}$$

Phys. Rev. D108 (2023)

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

$$= \sin(\phi_h-\phi_S)(\mathcal{F}_1+\mathcal{F}_2\cos\phi_h+\mathcal{F}_3\cos 2\phi_h)$$
$$+\cos(\phi_h-\phi_S)(\mathcal{F}_4\sin\phi_h+\mathcal{F}_5\sin 2\phi_h)$$

$$\phi_h = \phi - \chi$$



- C-odd function $O(x_1,x_2)$ is canceled $\leftrightarrow$ D-meson production

We perform numerical calculations for five normalized structure functions

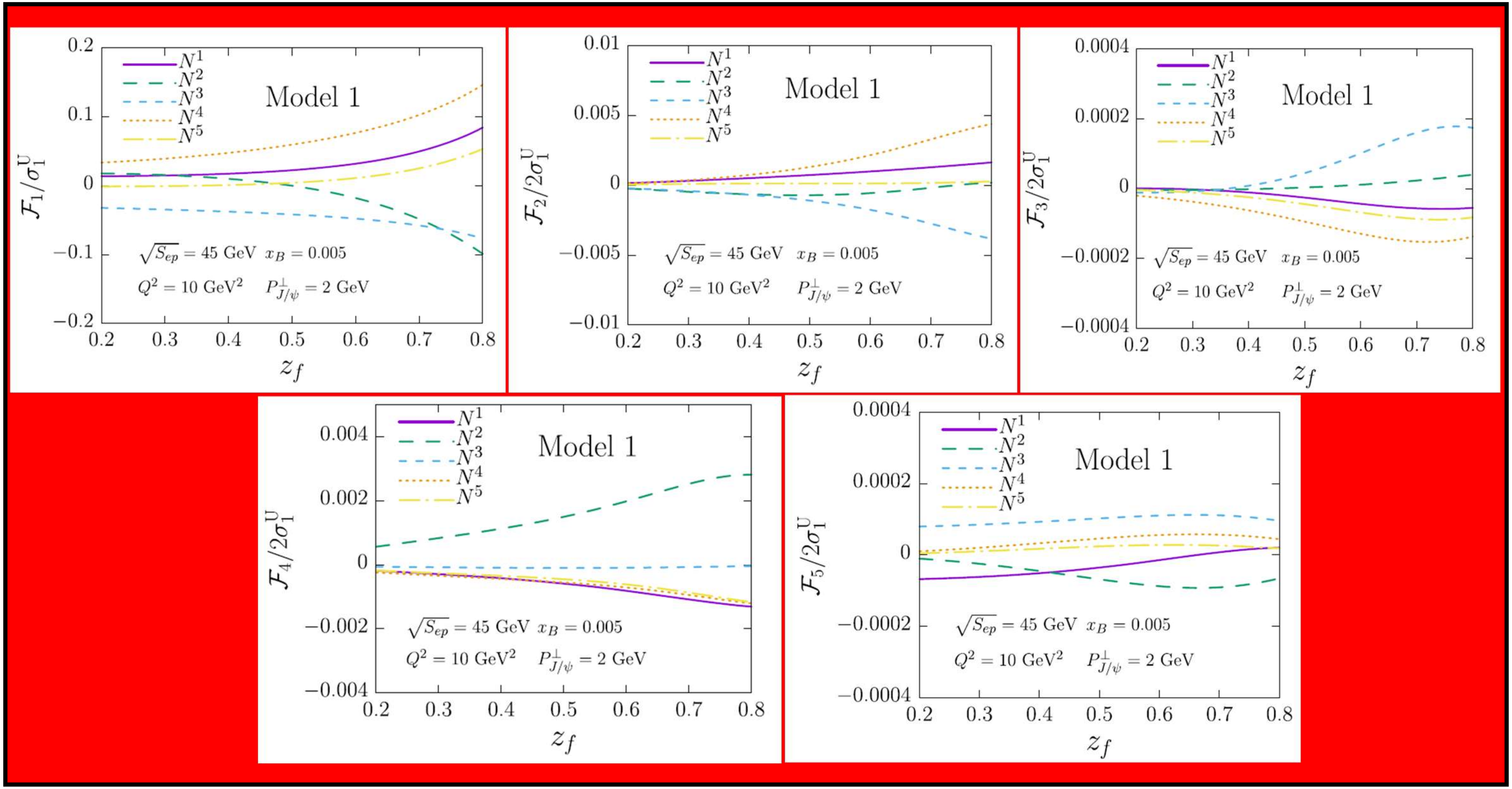
$$\frac{\mathcal{F}_1}{\sigma_1^{\mathrm{U}}},\quad \frac{\mathcal{F}_2}{2\sigma_1^{\mathrm{U}}},\quad \frac{\mathcal{F}_3}{2\sigma_1^{\mathrm{U}}},\quad \frac{\mathcal{F}_4}{2\sigma_1^{\mathrm{U}}},\quad \frac{\mathcal{F}_5}{2\sigma_1^{\mathrm{U}}}$$

σ_1^{U} : unpolarized cross section

LDME is canceled in the ratio

Numerical simlation

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



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

TMD related functions

Cross section in pp

$$p^\uparrow(p) + p(p') \to J/\psi(P_{J/\psi}) + X$$

Mandelstam variables

$$\hat{s} = (xp + x'p')^2 \quad \hat{t} = (xp - P_J)^2 \quad \hat{u} = (x'p' - P_J)^2$$

arXiv:2605.19300

$$\begin{aligned} & P_J^0 \frac{d\Delta\sigma}{d^3P_J} \\ = \; & \frac{4\pi\alpha_s^3(-\pi M_N)}{S}\left(\mathcal{N}\langle O^{J/\psi}[^3S_1^{(1)}]\rangle\right)\int\frac{dx}{x'}G(x')\int\frac{dx}{x^2}\delta(\hat{s}+\hat{t}+\hat{u}-m_J^2) \\ & \times\left(\hat{s}\epsilon^{P_J pnS_\perp} - (\hat{t}-m_J^2)x'\epsilon^{npp'S_\perp}\right)\left(-\frac{1}{N_c^2C_F}+\frac{1}{4C_F}\right)\Big[x\frac{d}{dx}N(x,x)\left(-\frac{4}{\hat{s}\hat{u}}\hat{\sigma}^U\right)+x\frac{d}{dx}N(x,0)\hat{\sigma}_D \\ & +N(x,x)\hat{\sigma}_{ND1}+N(x,0)\hat{\sigma}_{ND2}+N(x,Hx)\hat{\sigma}_{H1}+N(x-Hx,x)\hat{\sigma}_{H2}+N(Hx,Hx-x)\hat{\sigma}_{H3}\Big], \end{aligned}$$

- C-odd function $O(x_1, x_2)$ is canceled

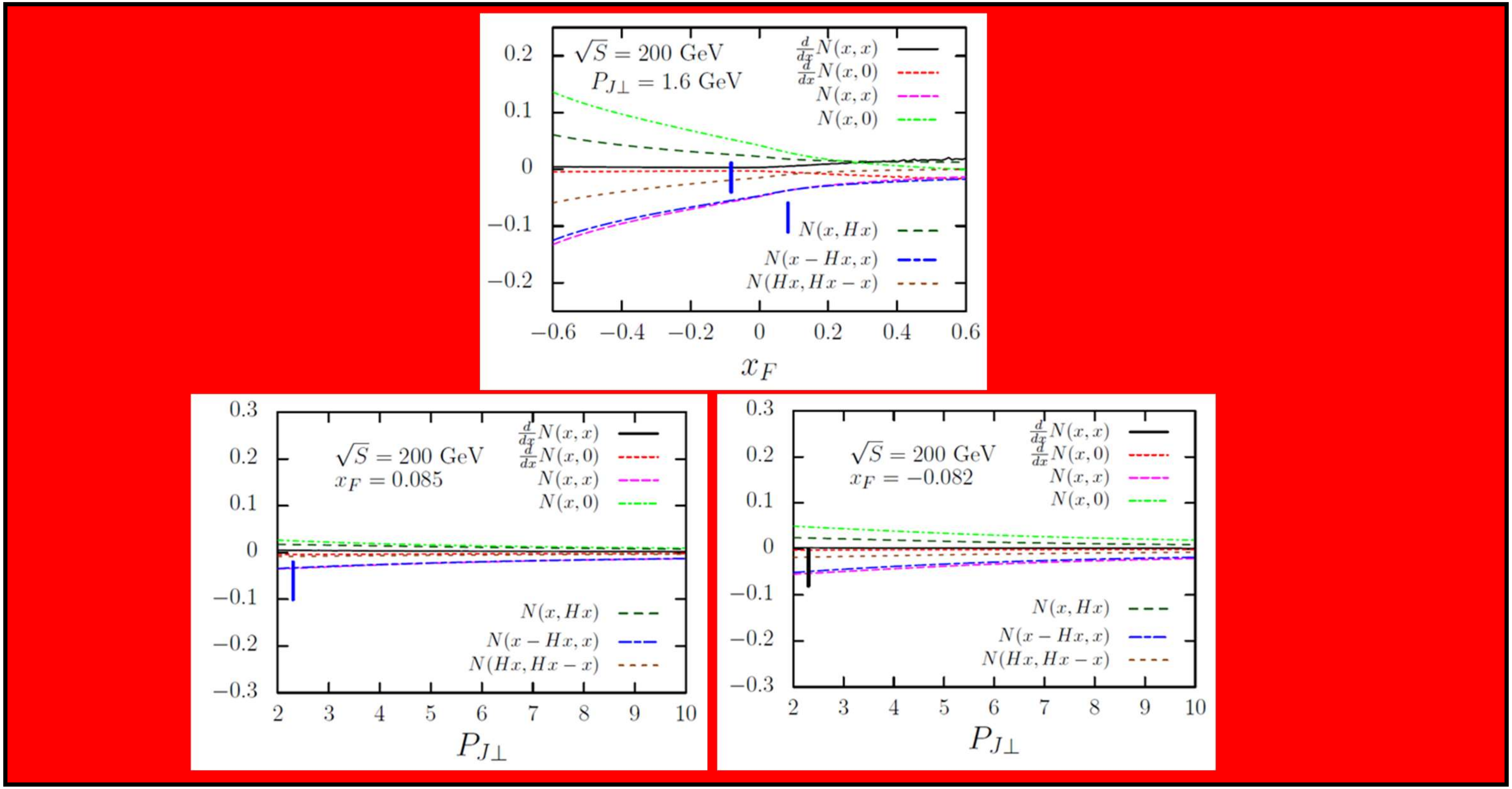
- 5 types of functions

$$N(x,x),\; N(x,0),\; N(x,Hx),\; N(x-Hx,x),\; N(Hx,Hx-x)$$

$$H = -\frac{\hat{u}-m_J^2}{\hat{s}-\hat{u}}$$

Numerical simlation

RHIC energy: $\sqrt{S} = 200$ GeV



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

TMD related functions

Summary

· Sivers effect is a key for understanding transverse momenta of partons

· Understanding of gluon Sivers effect is a challenging task in future experiments

A lot of studies within TMD, but insufficient within the collinear twist-3

· We have derived the cross section formula for the SSA in $ep \to J/\psi X$

in $pp \to J/\psi X$

Our results give a theoretical basis to analyses at RHIC, EIC, LHCspin

○ Future work

· Calculation for color-octet channels

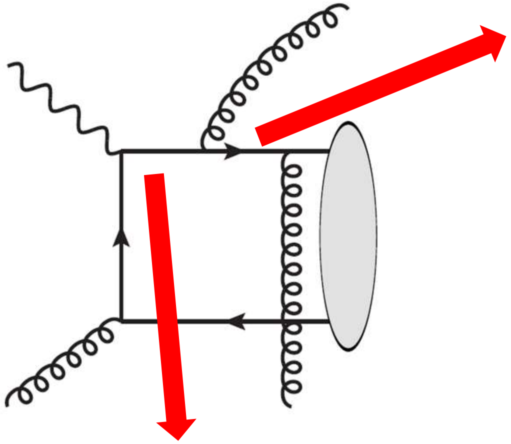
· Matching between TMD and the collinear twist-3 on gluon Sivers

Backup

Pole contributions

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

There are two types of poles in J/ψ production



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

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

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

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

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

Evolution equations of the twist-3 gluon distributions

V. M. Braun, A. N. Manashov and B. Pirnay, Phys. Rev. D80 (2009)

$$\mu\frac{d}{d\mu}T_F^{\pm}(x,x) = \frac{\alpha_s N_c}{\pi}\Bigg(-T_F^{\pm}(x,x) + \int_x^1 \frac{d\xi}{\xi}\Bigg\{2\bar{P}_{gg}(z)T_F^{\pm}(\xi,\xi) + \frac{z}{1-z}\left[T_F^{\pm}(\xi,x) - T_F^{\pm}(\xi,\xi)\right]$$

$$-(1-z)\left(z+\frac{1}{z}\right)T_F^{\pm}(\xi,\xi) + \frac{1+z}{2}\Big[T_F^{\pm}(x,\xi) - \Delta T_F^{\pm}(x,\xi)\Big]$$

$$\mp\frac{1}{2}(1-z)\Big[T_F^{\pm}(x,x-\xi) - \Delta T_F^{\pm}(x,x-\xi)\Big] + \frac{1}{2}A^{\pm}\bigg(\bar{P}_{gq}(z)\Big[\mathcal{T}_{q,F}(\xi,\xi) \pm \mathcal{T}_{q,F}(-\xi,-\xi)\Big]$$

$$-\frac{2-z}{z}\Big[\mathcal{T}_{q,F}(x-\xi,-\xi) \pm \mathcal{T}_{q,F}(\xi,\xi-x)\Big] + \Big[\Delta\mathcal{T}_{q,F}(x-\xi,-\xi) \mp \Delta\mathcal{T}_{q,F}(\xi,\xi-x)\Big]\bigg)\Bigg\}\Bigg),$$

$$T_F^{+} = N,\ T_F^{-} = O$$