Gluon TMDs in Quarkonium Production in SIDIS

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TMDs

Mulders and Rodrigues PRD 63 094021(2001)

Quark correlator

Quark field

$$\Phi_{ij}(x,k) = \int \frac{d^4\xi}{(2\pi)^4} e^{ik.\xi}\langle P \mid \overline{\Psi}_j(0)W[0,\xi]\Psi_i(\xi) \mid P\rangle$$

Gluon correlator

Gluon field

$$\Phi_g^{\mu\nu;\rho\sigma}(x,k) = \int \frac{d^4\xi}{(2\pi)^4} e^{ik.\xi}\langle P|\mathrm{Tr}[F^{\mu\nu}(\xi)W[\xi,0]F^{\rho\sigma}(0)W[0,\xi]]|P\rangle$$

Wilson line

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

		gluon pol.		
		U	Circularly	Linearly
nucleon pol.	U	f_1^g		$h_1^{\perp g}$
	L		g_{1L}^g	$h_{1L}^{\perp g}$
	T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

U: Unpolarized, **L**: Longitudinally, **T**: Transverse

Quark Sivers TMDs

- GPM : Quark Sivers function (QSF) extracted using latest SIDIS data from HERMES, COMPASS and JLab experiments in pion and kaon production

M. Anselmino, M. Boglione, U. D'Alesio, F. Murgia and A. Prokudin, JHEP 04 (2017) 046

M. Boglione, U. D'Alesio, C. Flore and G. Hernandez, JHEP 2018

M. Boglione, U. D'Alesio, C. Flore, G. Hernandez, F. Murgia and A. Prokudin, PLB 815(2021)

see talk by Carlo. F

- TMD Evolution: QSF has been extracted by using SIDIS, DY and $W^{\pm}$ /Z-boson data

Global fit @ NNLL: M.G. Echevarria, Z.B. Kang and J.Terry JHEP01(2021)126

Global fit @ NNNLO: M. Bury, A. Prokudin, A. Vladimirov JHEP 05 (2021) 151, PRL 126, 112002 (2021)

Global fit @ NLL: A. Bacchetta, F.Delcarro, C.Pisano, M.Radici and A. Signori JHEP06 (2017) 081

A.Bacchetta, F.Delcarro, C.Pisano and M.Radici arXiv:2004.14278

QSF is established very well but not the gluon Sivers function

What about Gluon Sivers TMD?

- Gluon Sivers function (GSF) is not known fully

U. D'Alesio, F. Murgia, and C. Pisano, JHEP 09 (2015) 119

- GSF has been extracted from mid rapidity $pp^{\uparrow} \rightarrow \pi^0 + X$

- First moment of the GSF has been extracted using mid rapidity $pp^{\uparrow} \rightarrow \pi^0 + X$ and $pp^{\uparrow} \rightarrow D^0 + X$ data at RHIC

U. D'Alesio, C. Flore, F. Murgia, C. Pisano and P. Taels, PRD 99 (2019) 036013

- Due to the limited data, GSF could not be constrained over the wide range in x and $K_{\perp}$

- EIC could play vital role in shaping the GSF

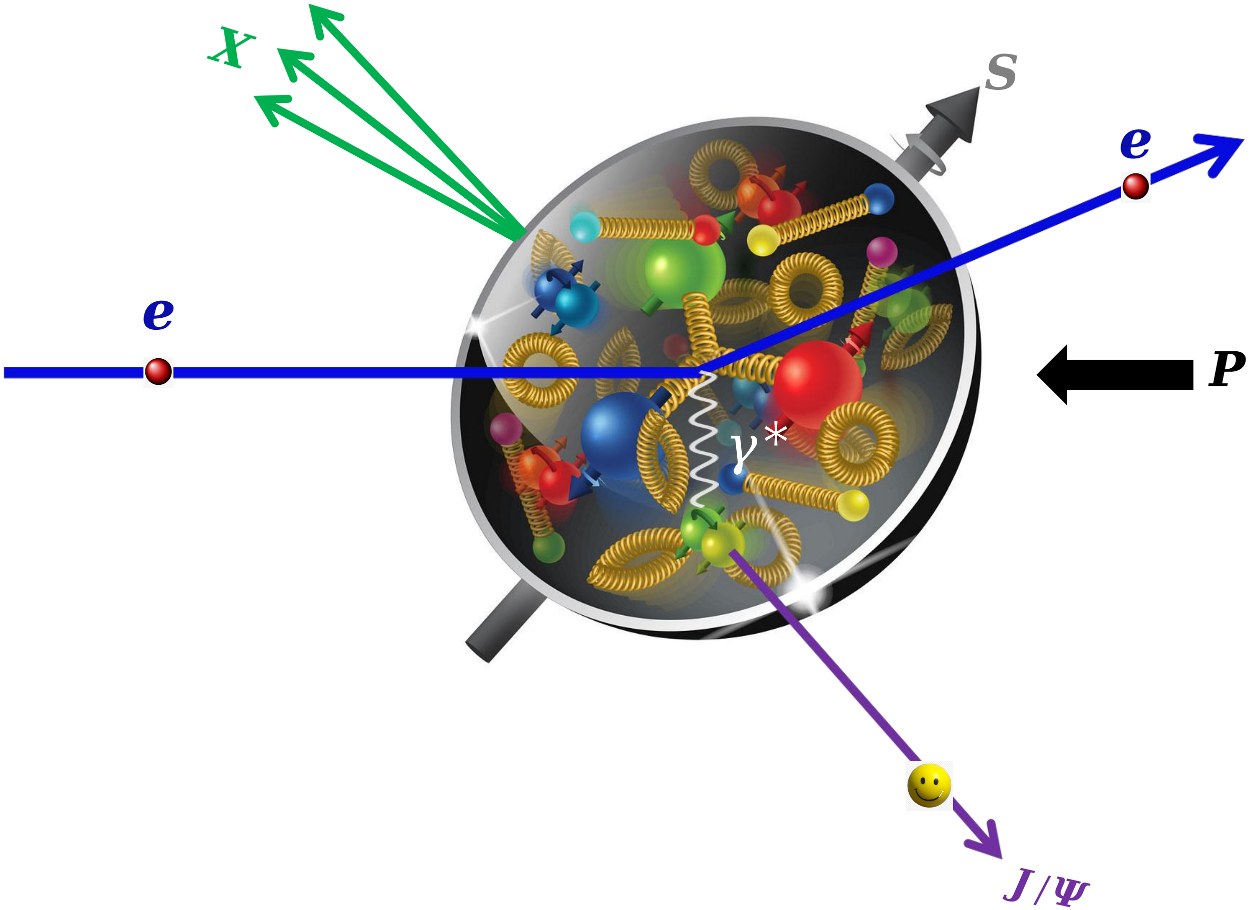
- The $ep^{\uparrow} \rightarrow e + J/\Psi + X$ process has been studied at $z = 1$

A. Mukherjee and SR EPJC 77 (2017) 12, 854

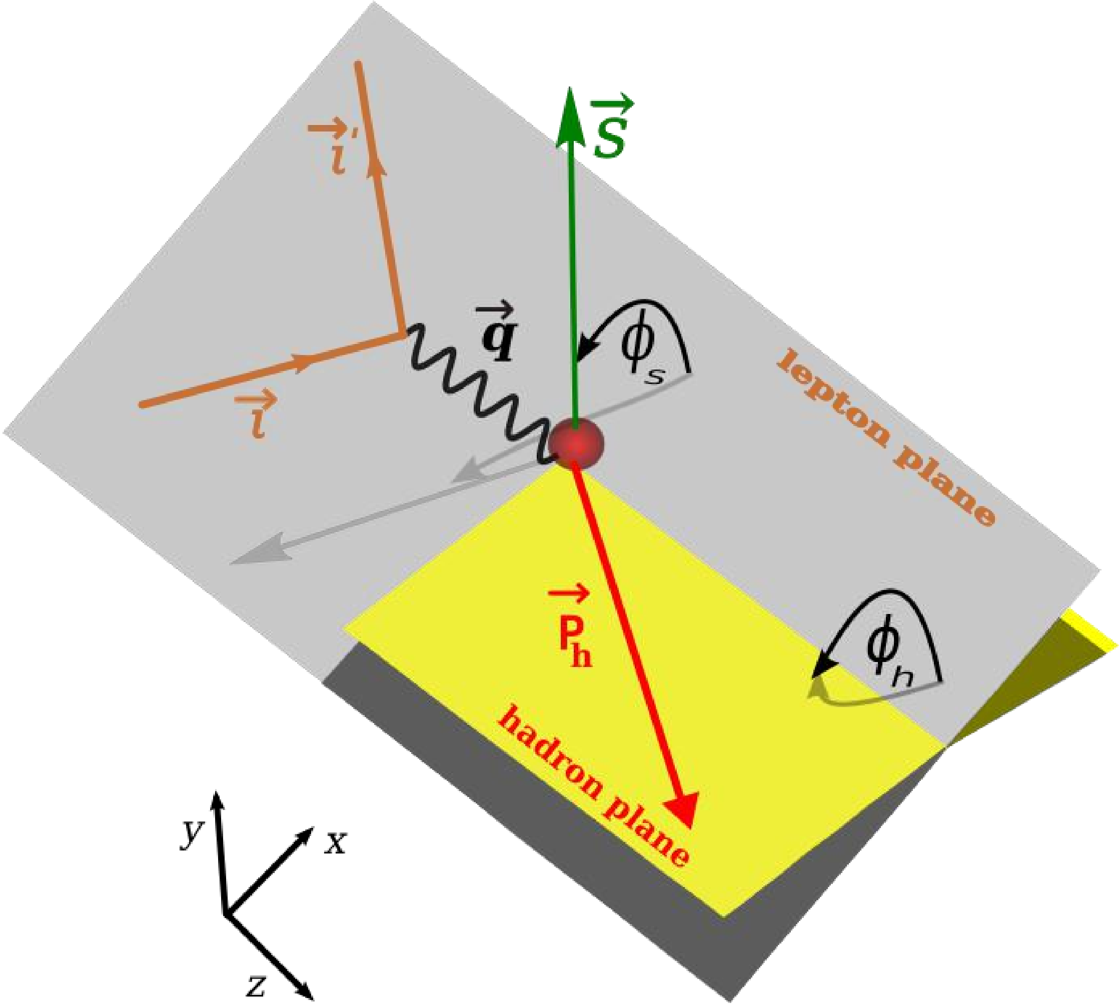
A. Bacchetta, D. Boer, C. Pisano and P. Taels EPJC 80 (2020) 1, 72

- We propose the inelastic leptoproduction of J/ψ at EIC for probing the poorly known GSF in the region $z < 1$

$e + P^{\uparrow} \rightarrow e + J/\psi + X$ at EIC



$e + P^{\uparrow} \rightarrow e + J/\psi + X$



$$s = (P + l)^2 = 2P.l$$

$$-q^2 = Q^2$$

$$x_B = \frac{Q^2}{2P.q}$$

$$y = \frac{P.q}{P.l}$$

$$z = P.P_h/P.q$$

- We consider a frame in which the proton and virtual photon are moving along -z and +z axes respectively

J/ψ as a probe for Gluon TMDs

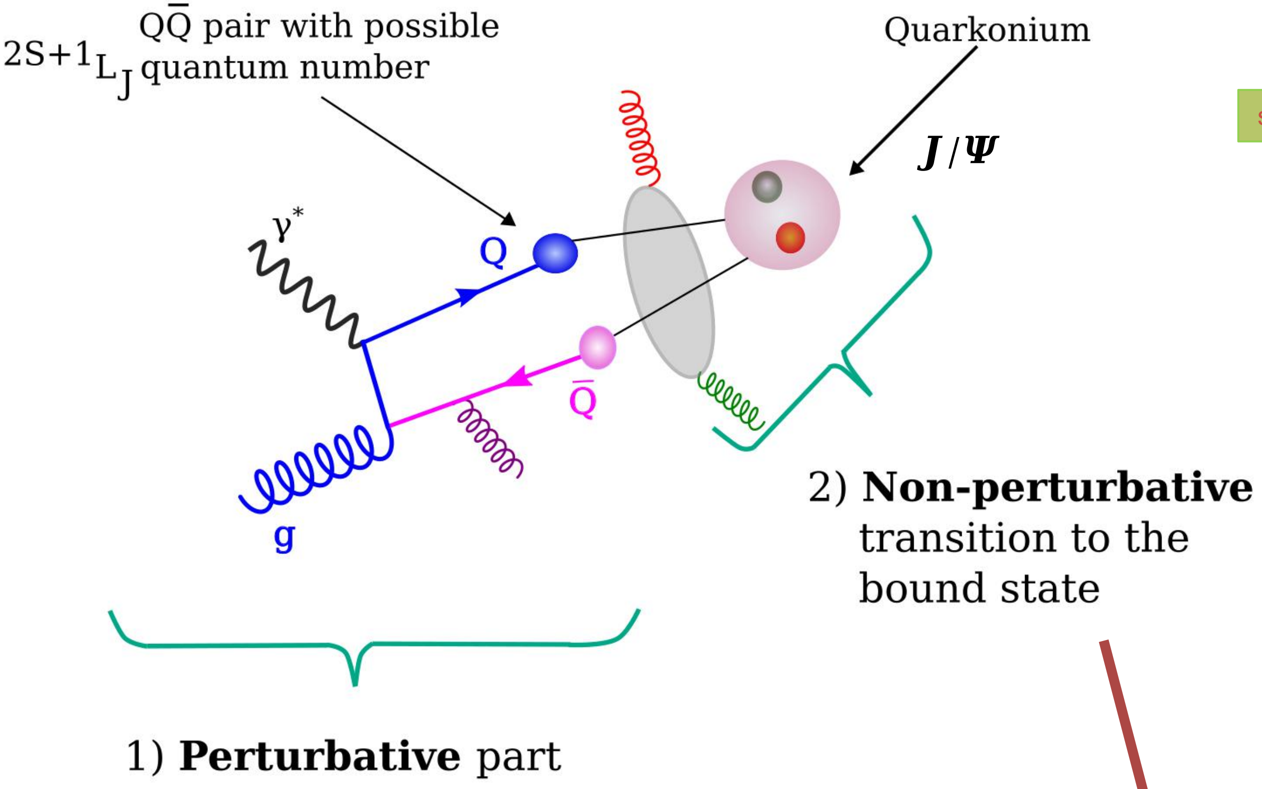
- Color Singlet Model (CSM)

  Baier and R. Ruckl, Z.Phys.C 19 (1983) 251

- Color Evaporation Model (CEM)

  H. Fritzsch, PL 67B (1977) 217-221

see talk by Jean-Philippe. L



$Q\bar{Q}$ pair with possible $^{2S+1}L_J$ quantum number

Quarkonium

1) **Perturbative** part

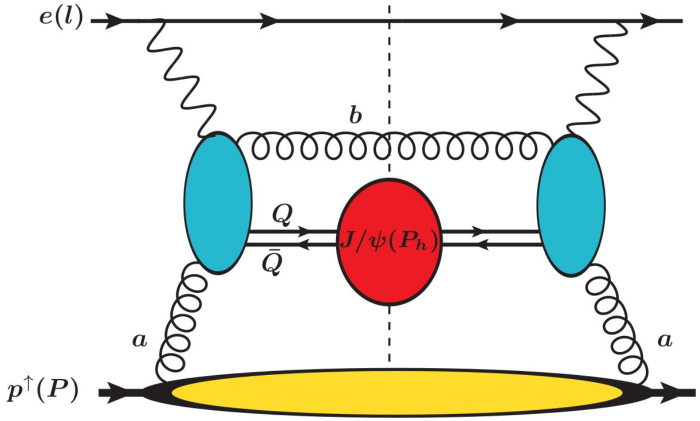
2) **Non-perturbative** transition to the bound state

- Non-Relativistic QCD (NRQCD)

$$d\sigma^{ab\to J/\psi} = \sum_n d\hat{\sigma}_n[ab \to c\bar{c}(n)]\langle 0 \mid \mathcal{O}_n^{J/\psi} \mid 0\rangle$$

G. T. Bodwin et al, PRD51 (1995)

Generalized Parton Model(GPM)



- Inclusion of intrinsic transverse momentum and spin effects in a natural way
- Assumed TMD factorization
- Gaussian ansatz for TMD parametrization

Unpolarized cross section: $ep \to e + J/\Psi + X$ in GPM

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\,\mathrm{d}y\,\mathrm{d}^2\boldsymbol{P}_T\,\mathrm{d}z} = \frac{1}{2S}\frac{2}{(4\pi)^4 z}\sum_a\int\frac{\mathrm{d}x_a}{x_a}\,\mathrm{d}^2\boldsymbol{k}_{\perp a}\,\delta\left(\hat{s}+\hat{t}+\hat{u}-M^2+Q^2\right)$$

$$\times\sum_n\frac{1}{Q^4}f_{a/p}(x_a,k_{\perp a})L^{\mu\nu}H^{a,U}_{\mu\nu}[n]\langle 0\mid\mathcal{O}^{J/\psi}(n)\mid 0\rangle\ ,$$

Leptonic tensor

$$L^{\mu\nu} = 8\pi\alpha Q^2\left(-g^{\mu\nu}+\frac{2}{Q^2}(l^\mu l'^\nu + l^\nu l'^\mu)\right)$$

$$= 8\pi\alpha Q^2\left(-g^{\mu\nu}+\frac{(2-y)^2}{y^2}\frac{4x_{_B}^2}{Q^2}P^\mu P^\nu+\frac{(2-y)\sqrt{1-y}}{y^2}\frac{8x_{_B}}{Q}\frac{P^\mu\hat{l}_\perp^\nu+P^\nu\hat{l}_\perp^\mu}{2}+4\frac{1-y}{y^2}\hat{l}_\perp^\mu\hat{l}_\perp^\nu\right)$$

Hard part

$$q^\mu H^{a,U}_{\mu\nu}[n] = 0$$

NRQCD

unpolarized dsigma

- Two sets of LDMEs are considered

  M. Butenschoen and B. Kniehl, PRD84 (2008) 051501 (BK11)
  P. Sun, C. Yuan and F. Yuan PRD88 (2013) 054008 (SYY13)

Partonic channels @ $\alpha\alpha_s^2$

$$\gamma^* + g \rightarrow J/\Psi + g \qquad \gamma^* + q(\overline{q}) \rightarrow J/\Psi + q(\overline{q})$$

- Intrinsic charm-quark $\gamma^* + c(\overline{c}) \rightarrow J/\Psi + c(\overline{c})$ is also considered
- QED diagrams contribution is also included $@\alpha^3$
- Feed-down contribution: $\psi(2S)$ included, χ_c and b-quark are very small
- $\psi(2S)$ LDMEs are taken from R. Sharma and I. Vitev, PRC 87, 044905 (2013)

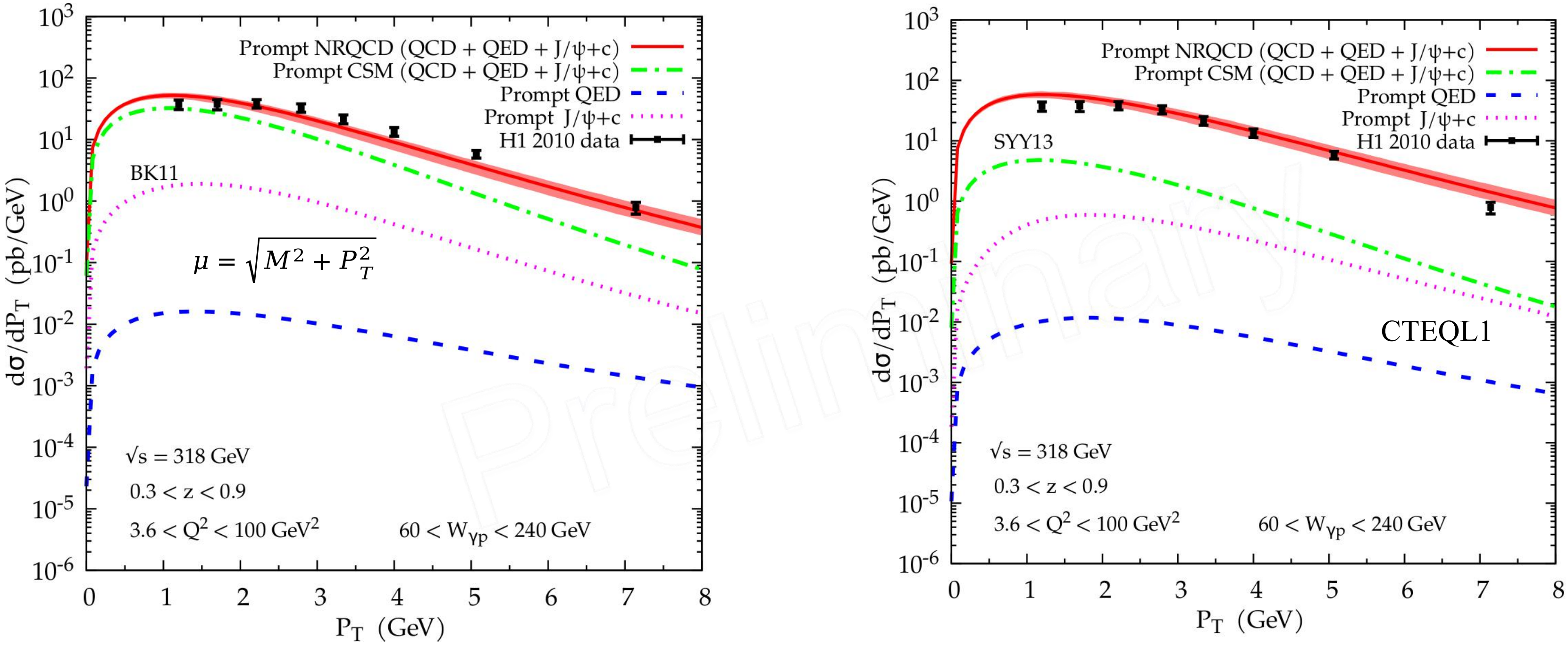
H1 Unp. dsigma

- Free parameters in our calculation are: Gaussian width and LDMEs

For Quarks: $< k_\perp^2 >= 0.25\ GeV^2$ Gluons: $< k_\perp^2 >=\ 1\ GeV^2$

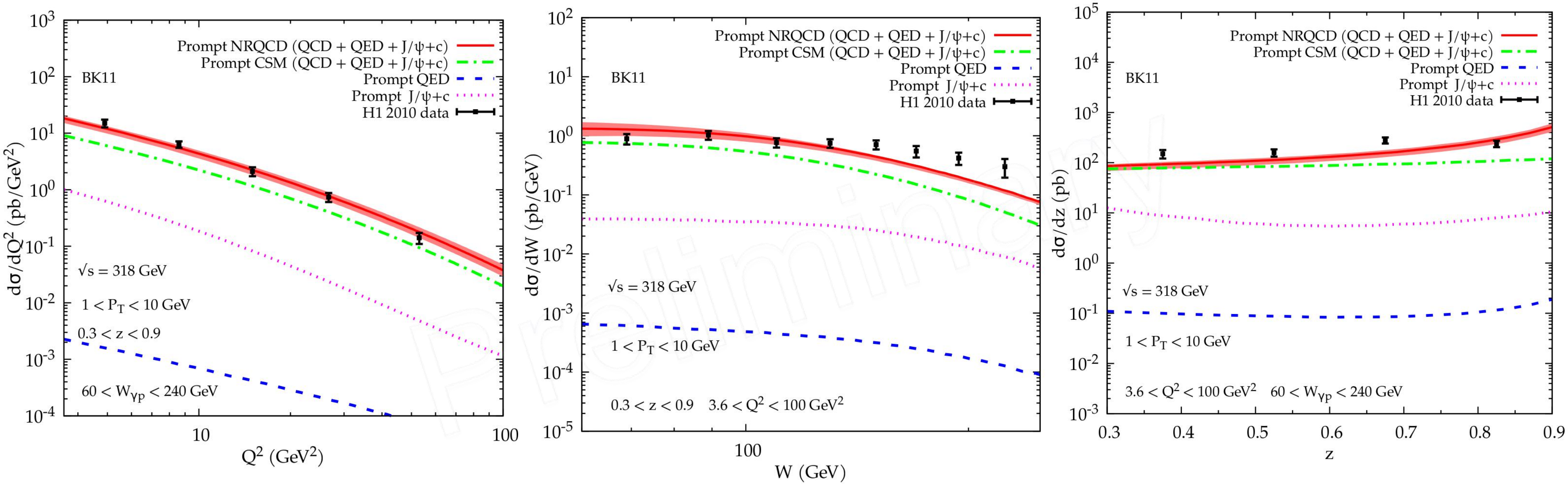
M. Anselmino, M. Boglione, U. D’Alesio, A. Kotzinian, F. Murgia and A. Prokudin PRD 71 (2005) 074006

U. D’Alesio, F. Murgia, C.Pisano and SR, EPJC 79 (2019) 12, 1029



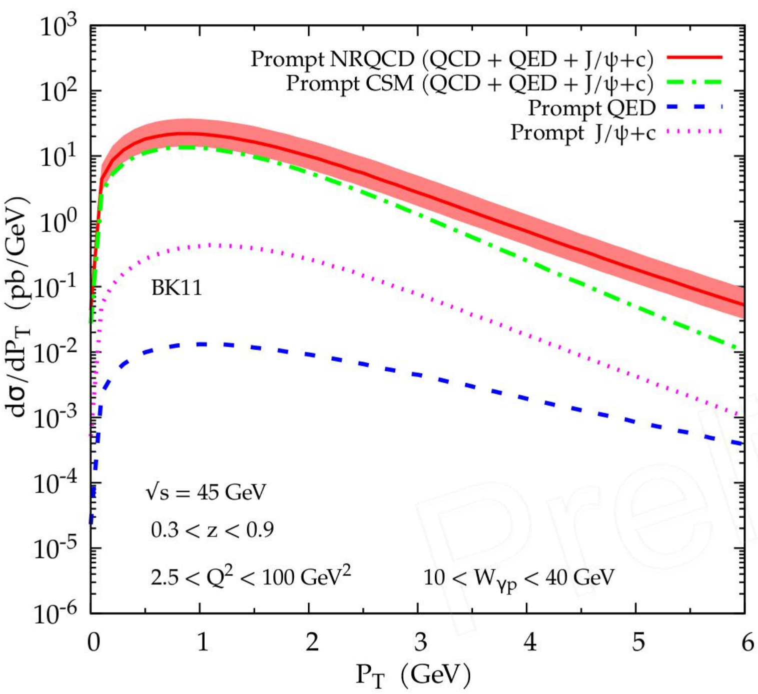
- Data from F.D. Aaron et al (H1), EPJC 68 (2010) 401

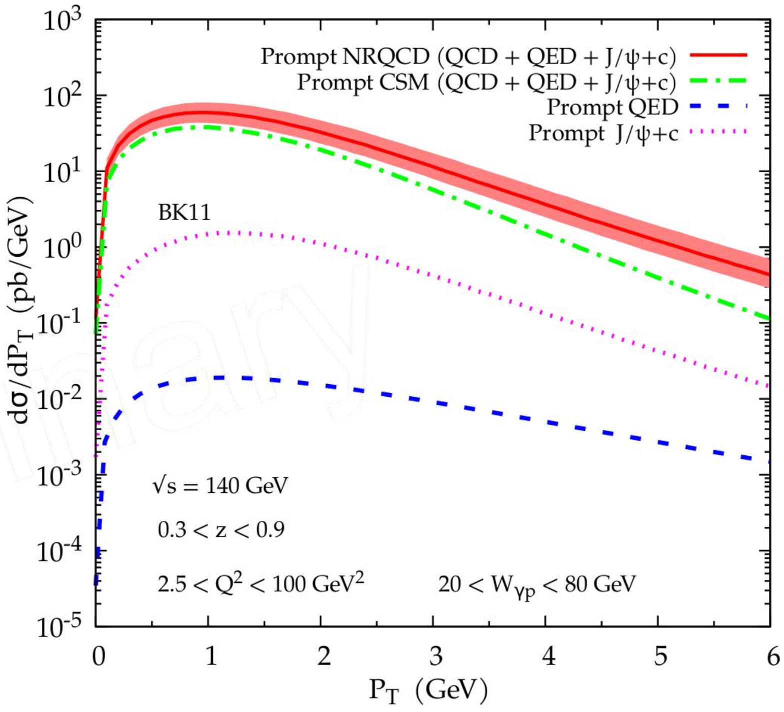
H1 Unp. dsigma



- Data from F.D. Aaron et al (H1), EPJC 68 (2010) 401

EIC Unp. dsigma





Sivers Asymmetry

$$A_N^{\sin(\phi_h-\phi_s)} \equiv 2\frac{\int \mathrm{d}\phi_s \mathrm{d}\phi_h \sin(\phi_h-\phi_s)(\mathrm{d}\sigma^{\uparrow}-\mathrm{d}\sigma^{\downarrow})}{\int \mathrm{d}\phi_s \mathrm{d}\phi_h (\mathrm{d}\sigma^{\uparrow}+\mathrm{d}\sigma^{\downarrow})} \equiv 2\frac{\int \mathrm{d}\phi_s \mathrm{d}\phi_h \sin(\phi_h-\phi_s)\mathrm{d}\Delta\sigma(\phi_s,\phi_h)}{\int \mathrm{d}\phi_s \mathrm{d}\phi_h 2\mathrm{d}\sigma}$$

- The denominator is twise the unpolarized differential cross section

  - The numerator of the asymmetry is sensitive to the Sivers function

$$\begin{aligned}\mathrm{d}\Delta\sigma^{\mathrm{GPM}} &= \frac{1}{2S}\frac{2}{(4\pi)^4 z}\sum_a \int \frac{\mathrm{d}x_a}{x_a}\,\mathrm{d}^2\boldsymbol{k}_{\perp a}\,\delta\left(\hat{s}+\hat{t}+\hat{u}-M^2+Q^2\right)\left(-2\,\frac{k_{\perp a}}{M_p}\right)\sin(\phi_s-\phi_a)\\ &\times \sum_n \frac{1}{Q^4}\, f_{1T}^{\perp a}(x_a,k_{\perp a})\, L^{\mu\nu} H_{\mu\nu}^{a,U}[n]\,\langle 0 \mid \mathcal{O}^{J/\psi}(n) \mid 0\rangle\,.\end{aligned}$$

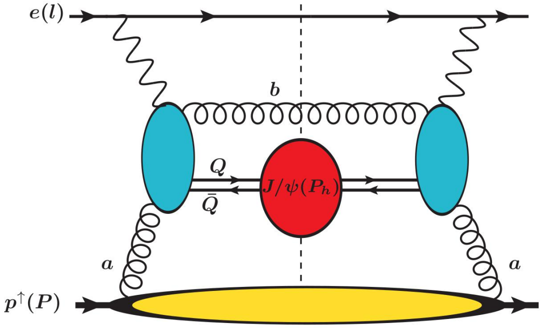
- In GPM: 1 QSF and 1 GSF (universal, process independent)

- In CGI-GPM: 1 QSF and 2 GSFs (universal but process dependent)

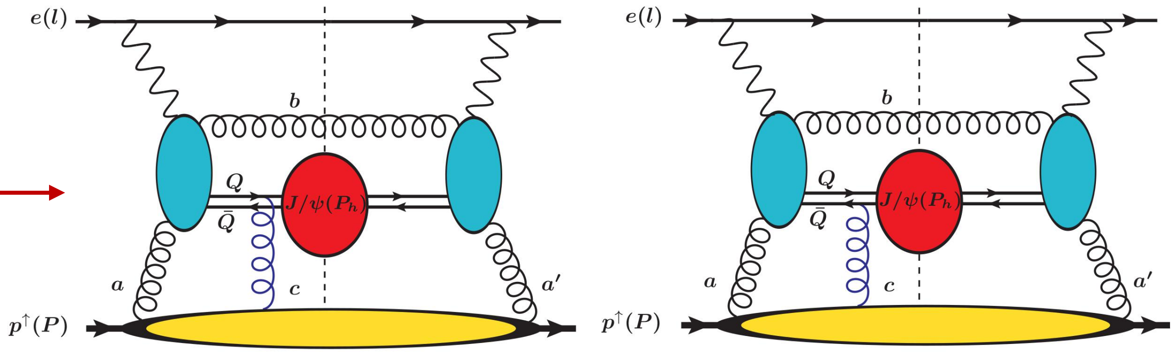
$$\begin{aligned}\mathrm{d}\Delta\sigma^{\mathrm{CGI-GPM}} &= \frac{1}{2S}\frac{2}{(4\pi)^4 z}\int \frac{\mathrm{d}x_a}{x_a}\,\mathrm{d}^2\boldsymbol{k}_{\perp a}\,\delta\left(\hat{s}+\hat{t}+\hat{u}-M^2+Q^2\right)\left(-2\,\frac{k_{\perp a}}{M_p}\right)\sin(\phi_s-\phi_a)\\ &\times \sum_n \frac{1}{Q^4} L^{\mu\nu}\Big\{\sum_q f_{1T}^{\perp q}(x_a,k_{\perp a})\, H_{\mu\nu}^{q,\mathrm{Inc}}[n] + \sum_{m=f,d} f_{1T}^{\perp g}(x_a,k_{\perp a})\, H_{\mu\nu}^{g,\mathrm{Inc(m)}}[n]\Big\}\,\langle 0 \mid \mathcal{O}^{J/\psi}(n) \mid 0\rangle\end{aligned}$$

CGI-GPM

GPM



CGI-GPM



C_U $\qquad$ $C_F^{(f/d)}$ $\qquad$ [color factors]

- The new color factors are shifted to hard part

$$H^{Inc(f/d)} \equiv \frac{C_I^{(f/d)} + C_F^{(f/d)}}{C_U} H^U$$

- Two independent $f_{1T}^{\perp\,(f/d)}$ which are process dependent

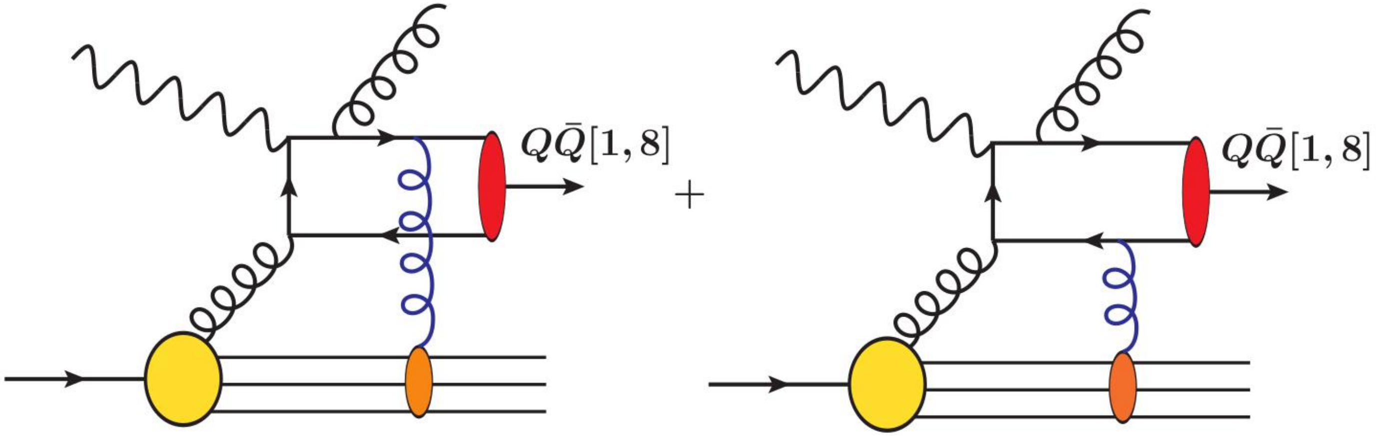
$$\text{[GPM] } f_{1T}^{\perp} H^U \longrightarrow f_{1T}^{\perp\,f} H^{Inc(f)} + f_{1T}^{\perp\,d} H^{Inc(d)} \text{ [CGI-GPM]}$$

L. Gamberg and Z. B. Kang, PLB 696 (2011)

U. D'Alesio, L. Maxia, F. Murgia, C.Pisano and SR, PRD 102 (2020)

- No initial state interactions due to colorless photon $\quad C_I^{(f/d)} = 0$

CGI-GPM



$= 0 \quad Q\bar{Q}[1]$

$\neq 0 \quad Q\bar{Q}[8]$

- CS state does not contribute to asymmetry
- Only CO states contribute to asymmetry

$$\gamma^* q(\bar{q}) \to Q\bar{Q}\left[{}^{2S+1}L_J^{(1,8)}\right] + q(\bar{q})$$

State	C_U	C_F	$\frac{C_F}{C_U}$
${}^3S_1^{(8)}$, ${}^1S_0^{(8)}$ & ${}^3P_J^{(8)}$	$\frac{N_c^2-1}{4N_c}$	$\frac{N_c}{4}$	$\frac{N_c^2}{N_c^2-1}$

$$\gamma^* g \to Q\bar{Q}\left[{}^{2S+1}L_J^{(1,8)}\right] + g$$

State	C_U	$C_F^{(f)}$	$C_F^{(d)}$	$\frac{C_F^{(f)}}{C_U}$	$\frac{C_F^{(d)}}{C_U}$
${}^1S_0^{(8)}$& ${}^3P_J^{(8)}$	$\frac{N_c}{2}$	$\frac{N_c}{4}$	0	$\frac{1}{2}$	0
${}^3S_1^{(8)}$	$\frac{N_c^2-4}{2N_c}$	$\frac{N_c^2-4}{4N_c}$	0	$\frac{1}{2}$	0
${}^3S_1^{(1)}$	$\frac{1}{4N_c}$	0	0	0	0

- d-type GSF is zero due to $C_F^{(d)} = 0$

TMDs Parametrization

- Parametrization of TMDs within GPM: Gaussian ansatz

- Unp. TMD $$f(x_a, \mathbf{k}_{\perp a}^2, \mu) = f(x_a, \mu) \frac{1}{\pi \langle k_{\perp a}^2 \rangle} e^{-\mathbf{k}_{\perp a}^2 / \langle k_{\perp a}^2 \rangle}$$

- Sivers TMD $$\Delta^N f_{a/p^\uparrow}(x_a, k_{\perp a}, \mu) = 2\mathcal{N}_a(x_a) f_{a/p}(x_a, \mu) \frac{\sqrt{2e}}{\pi} \sqrt{\frac{1-\rho}{\rho}} k_{\perp g} \frac{e^{-k_{\perp a}^2/\rho \langle k_{\perp a}^2 \rangle}}{\langle k_{\perp a}^2 \rangle^{3/2}}$$

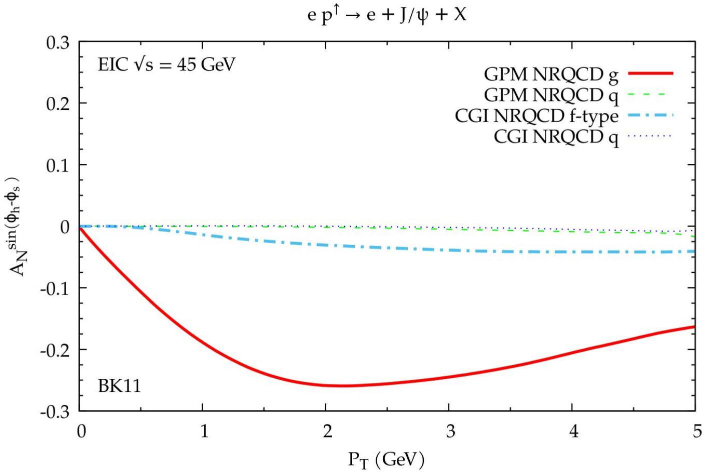
$$\mathcal{N}_a(x_a) = N_a x_a^\alpha (1-x_a)^\beta \frac{(\alpha+\beta)^{(\alpha+\beta)}}{\alpha^\alpha \beta^\beta}$$

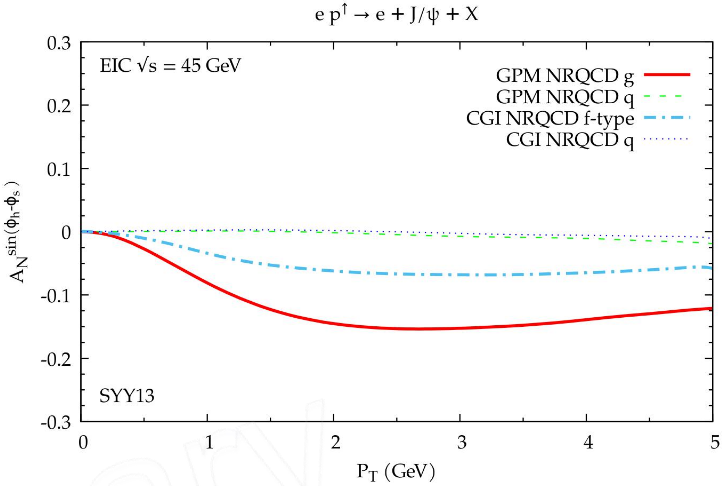
U. D'Alesio, C. Flore, F. Murgia, C. Pisano and P. Taels, PRD 99 (2019) 036013

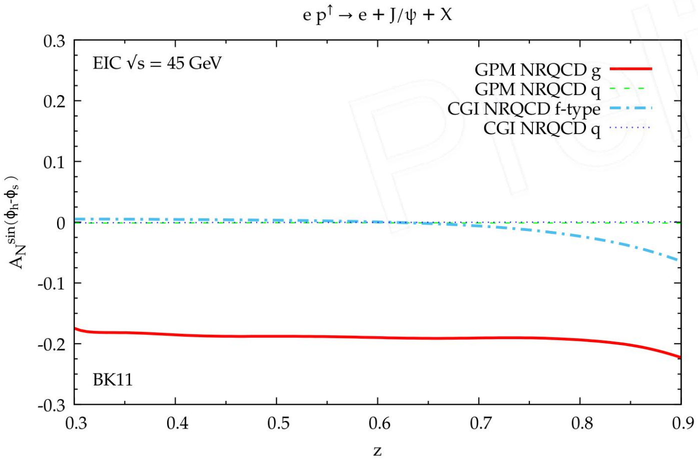
- For maximized asymmetry: Saturate the Sivers function

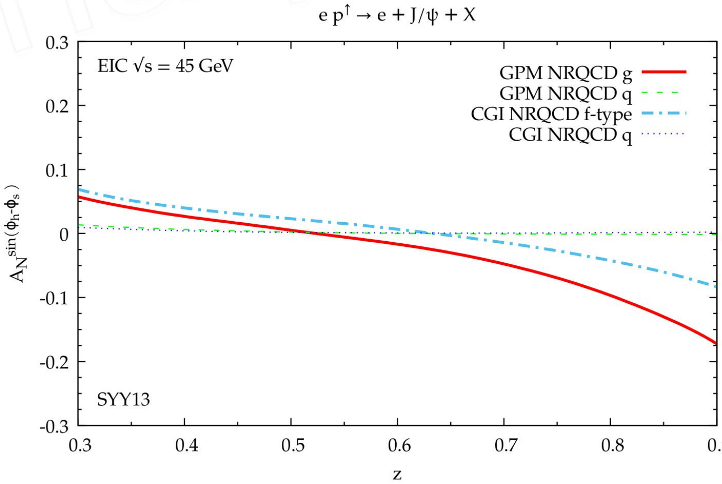
$$\rho = 2/3,\ \mathcal{N}_a(x_a) = +1\ \&\ \mathcal{N}_g^{(f,d)}(x_g) = +1$$

Sivers Asymmetry at EIC



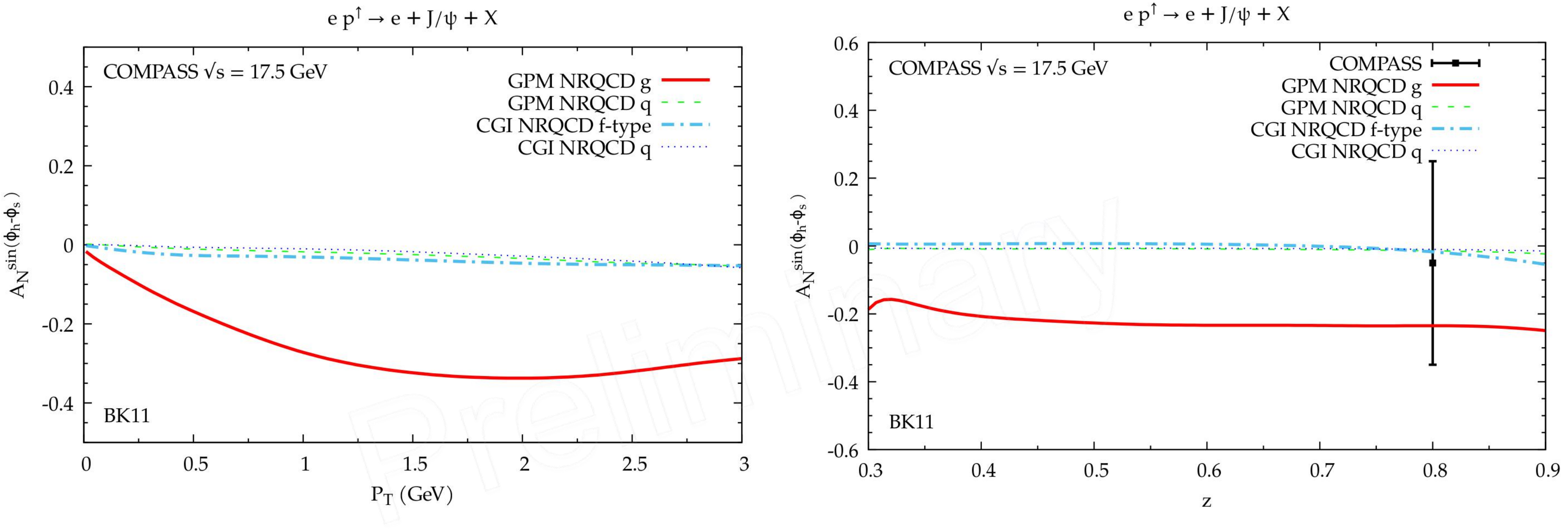






$\sqrt{s} = 45\ GeV$ $0.3 < z < 0.9$ $2.5 < Q^2 < 100\ GeV^2$ $10 < W_{\gamma p} < 40\ GeV$

Sivers Asymmetry at COMPASS



$\sqrt{s} = 17.5\ GeV$ 0.3 < $z < 0.9$ 0.03 < $Q^2 < 20\ GeV^2$ 0.003 < $X_B < 0.1$

- Data from J. Matoušek (COMPASS), J. Phys. Conf. Ser. 678, 012050 (2016)
- Negative GSF has been reported by COMPASS using Monte Carlo simulation

PLB 772 (2017) 854–864

Summary

- Sivers asymmetry in inelastic leptoproduction of J/ψ in ep collision is studyied at EIC

- GPM predicts the sizable Sivers asymmetry, while it is drastically reduced in CGI-GPM

- Hence, quarkonium production in ep collision is a promising channel to probe the unknown GSF

- Process dependence of GSF: $ep^{\uparrow} \rightarrow e + J/\psi + X$ at EIC could be used to probe the f −type GSF

- Unpolarized cross-section estimation is in good agreement with HERA data in the low P_T regioin

Thank you for the attention