

Sivers Asymmetry in inelastic J/Ψ leptonproduction at the EIC

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TMDs

Mulders and Rodrigues PRD 63 094021(2001)

Quark correlator

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

Quark field

Gluon correlator

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

Gluon field

Wilson line

quark pol.

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

nucleon pol.

gluon pol.

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

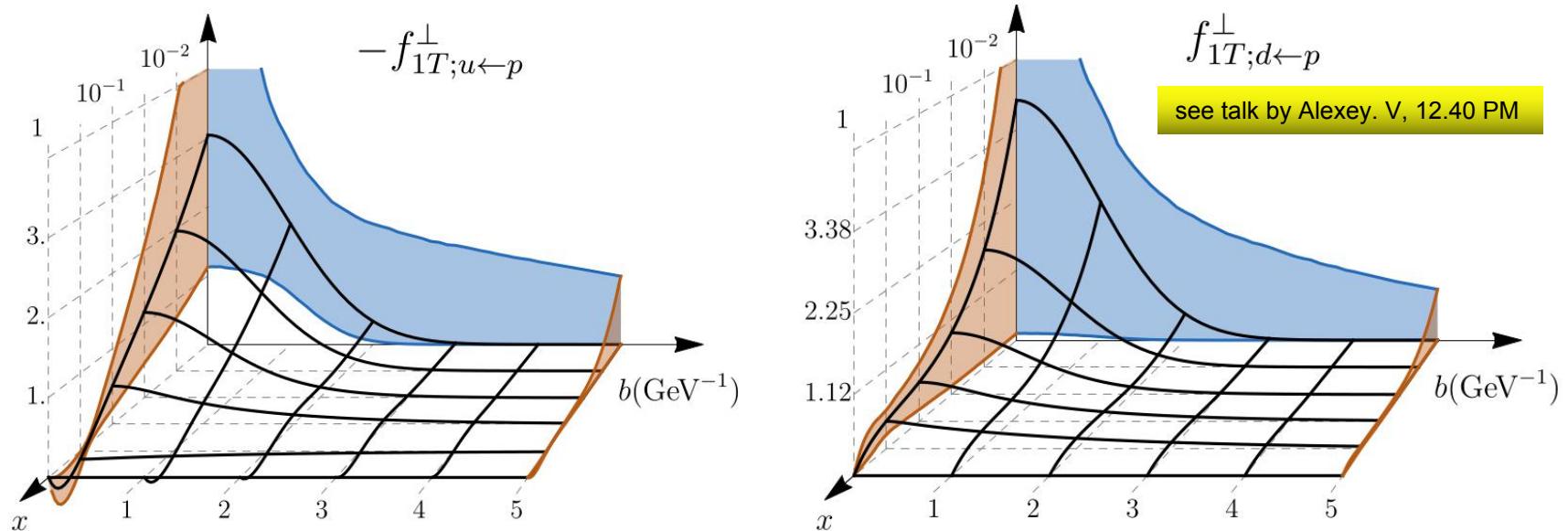
nucleon pol.

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

Quark Sivers TMDs

3D landscape of transversely polarized proton in terms of unp. quarks

- Quark Sivers TMDs have been extracted by using SIDIS, DY and $W^\pm$ /Z-boson data



M. Bury, A. Prokudin, A. Vladimirov, PRL 126, 112002 (2021), arXiv:2103.03270

- Another study (in GPM): Quark Sivers function 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 07 (2018) 148

see talk by Carlo. F, 12.58 PM

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

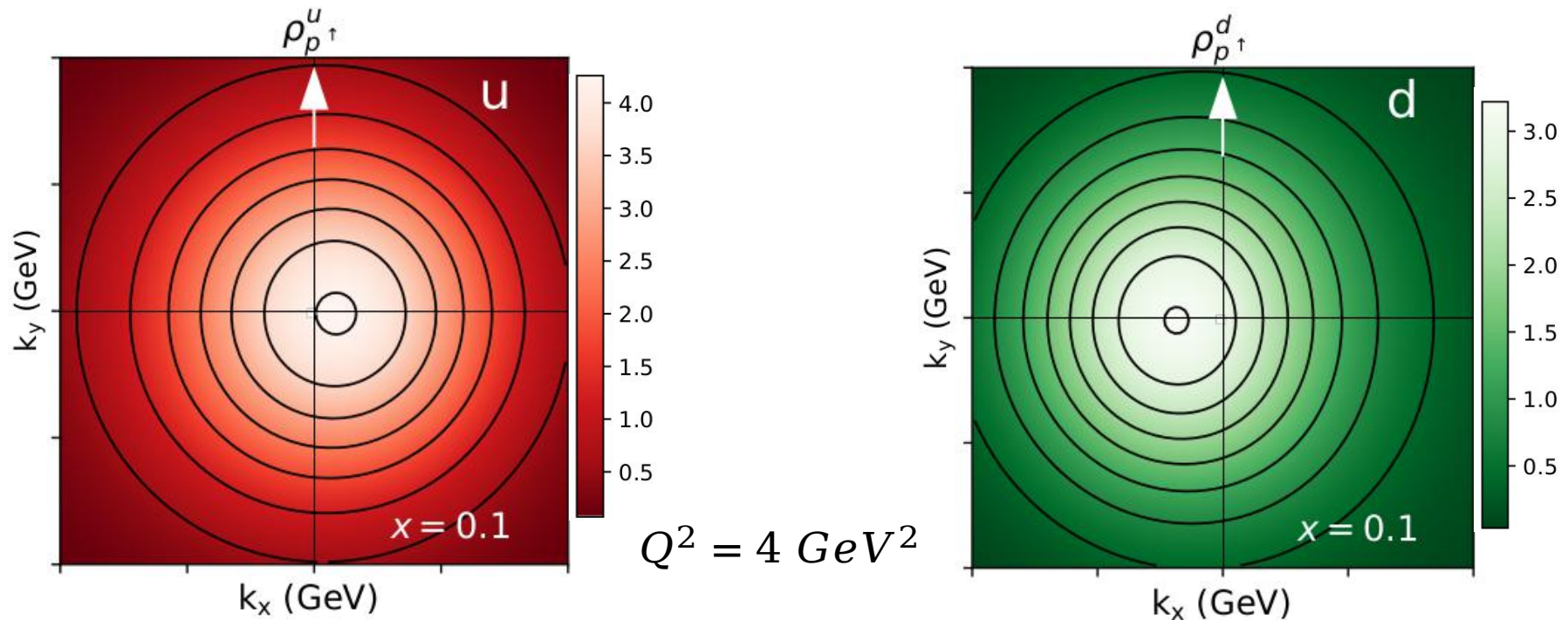
Quark Sivers TMDs

- Density of Unp. quarks inside a transversely polarized proton

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

$$\rho_{N\uparrow}^a(x, k_x, k_y; Q^2) = f_1^a(x, k_T^2; Q^2) - \frac{k_x}{M} f_{1T}^{\perp a}(x, k_T^2; Q^2)$$



- Using SIDIS data from COMPASS, HERMES and JLab

What about Gluon Sivers TMD?

- Gluon Sivers function (GSF) is not known fully

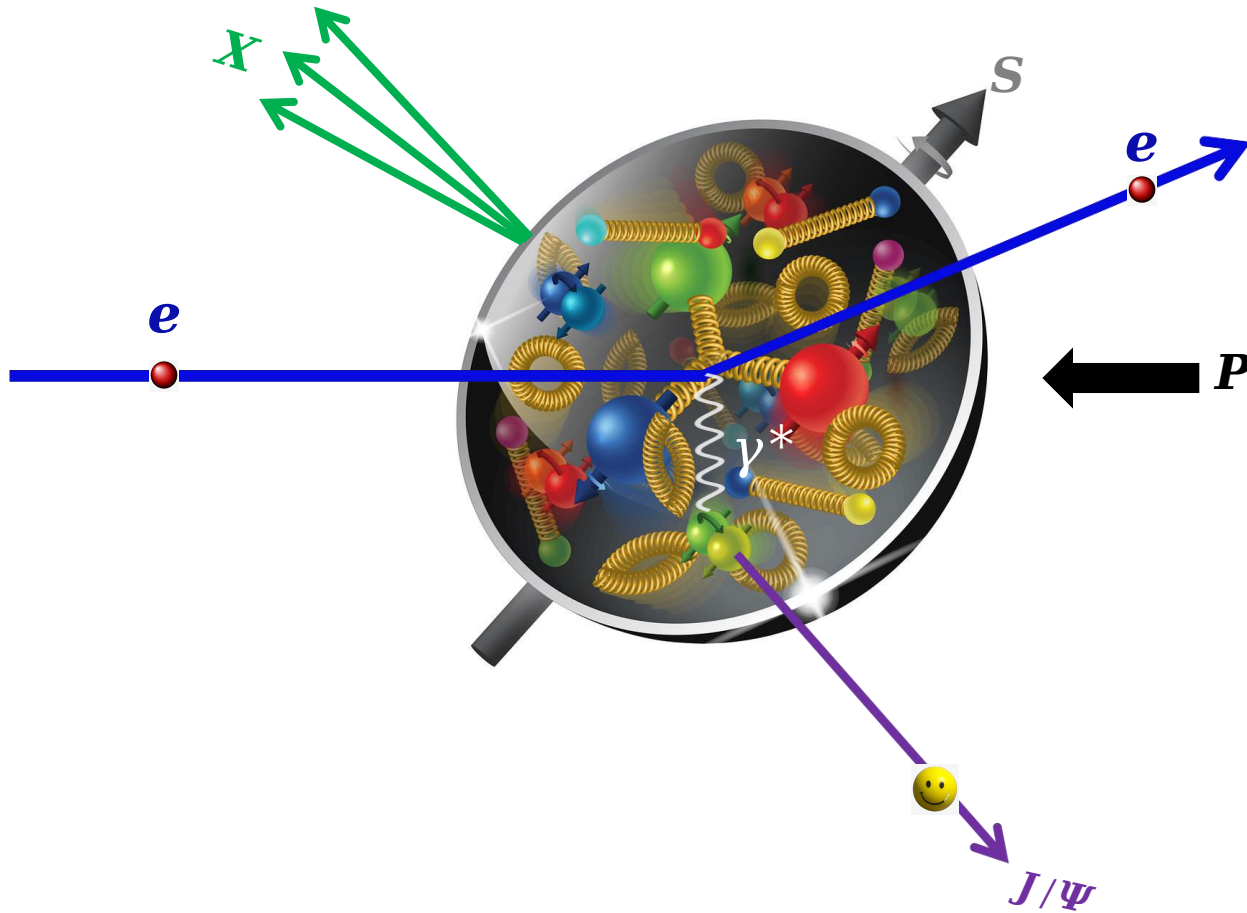
U. D'Alesio, F. Murgia, and C. Pisano, JHEP 09 (2015) 119

- GSF has been extracted from mid rapidity $pp^\uparrow \rightarrow \pi^0 + X$
- Upper values of first moment of the GSF has been extracted from 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. Tael, 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
- We propose the inelastic leptonproduction of J/ψ at EIC for probing the poorly known GSF

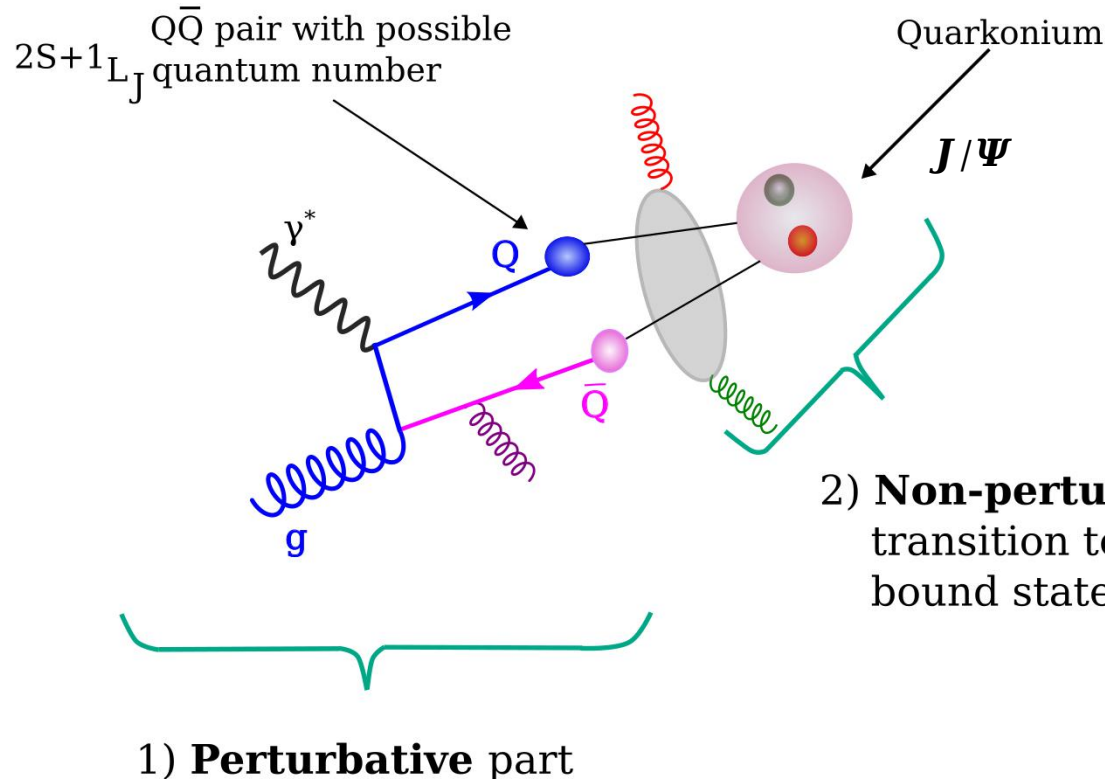
$$e + P^\uparrow \rightarrow e + J/\psi + X \text{ at EIC}$$



J/ψ as a probe for Gluon TMDs

- Color Singlet Model (CSM)

- Color Evaporation Model (CEM)

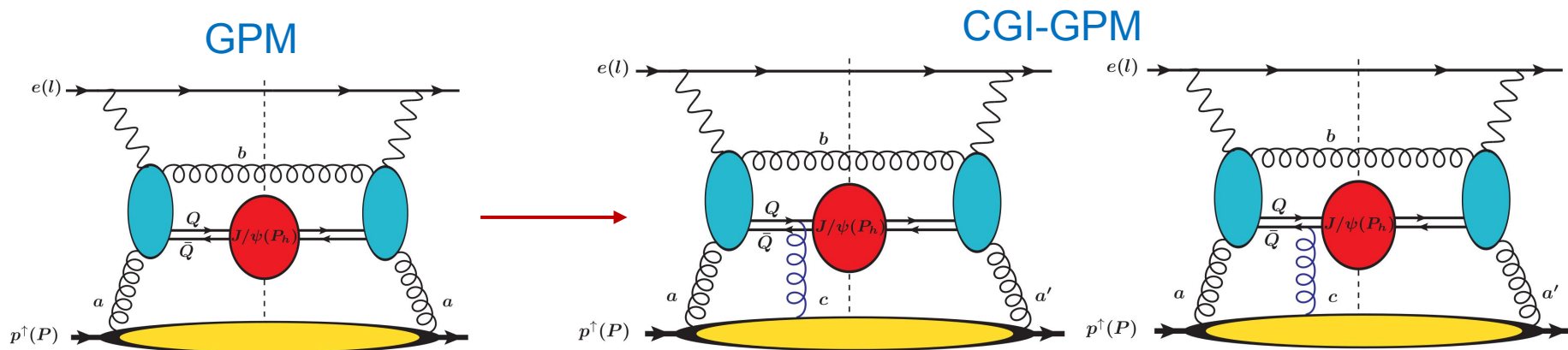


- Non-Relativistic QCD (NRQCD)

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

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

CGI-GPM



- 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

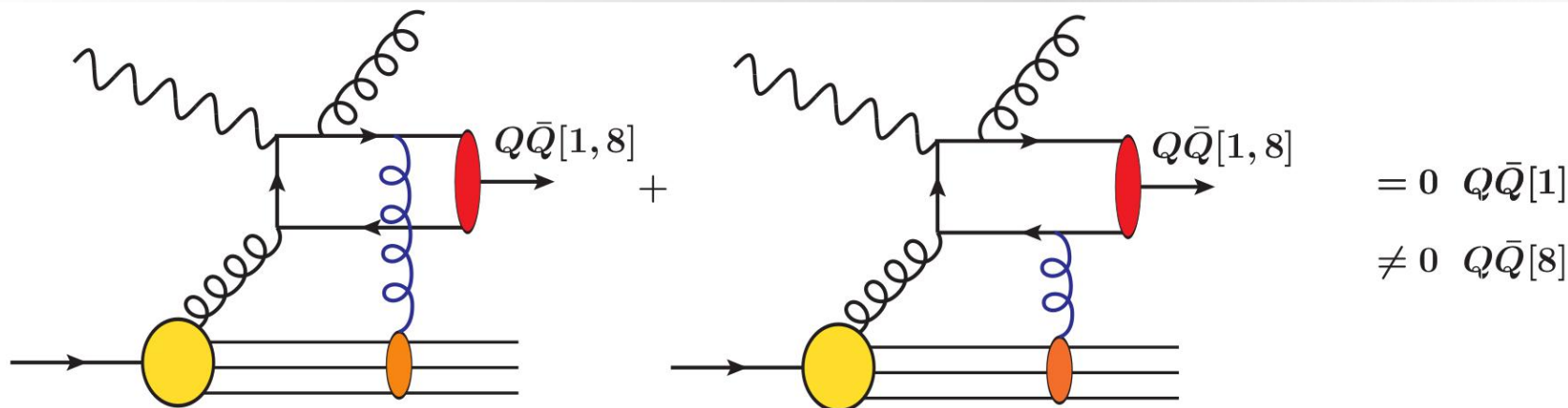
$$[\text{GPM}] f_{1T}^\perp H^U \longrightarrow f_{1T}^\perp{}^f H^{Inc(f)} + f_{1T}^\perp{}^d H^{Inc(d)} [\text{CGI-GPM}]$$

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 $C_I^{(f/d)} = 0$

CGI-GPM



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

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

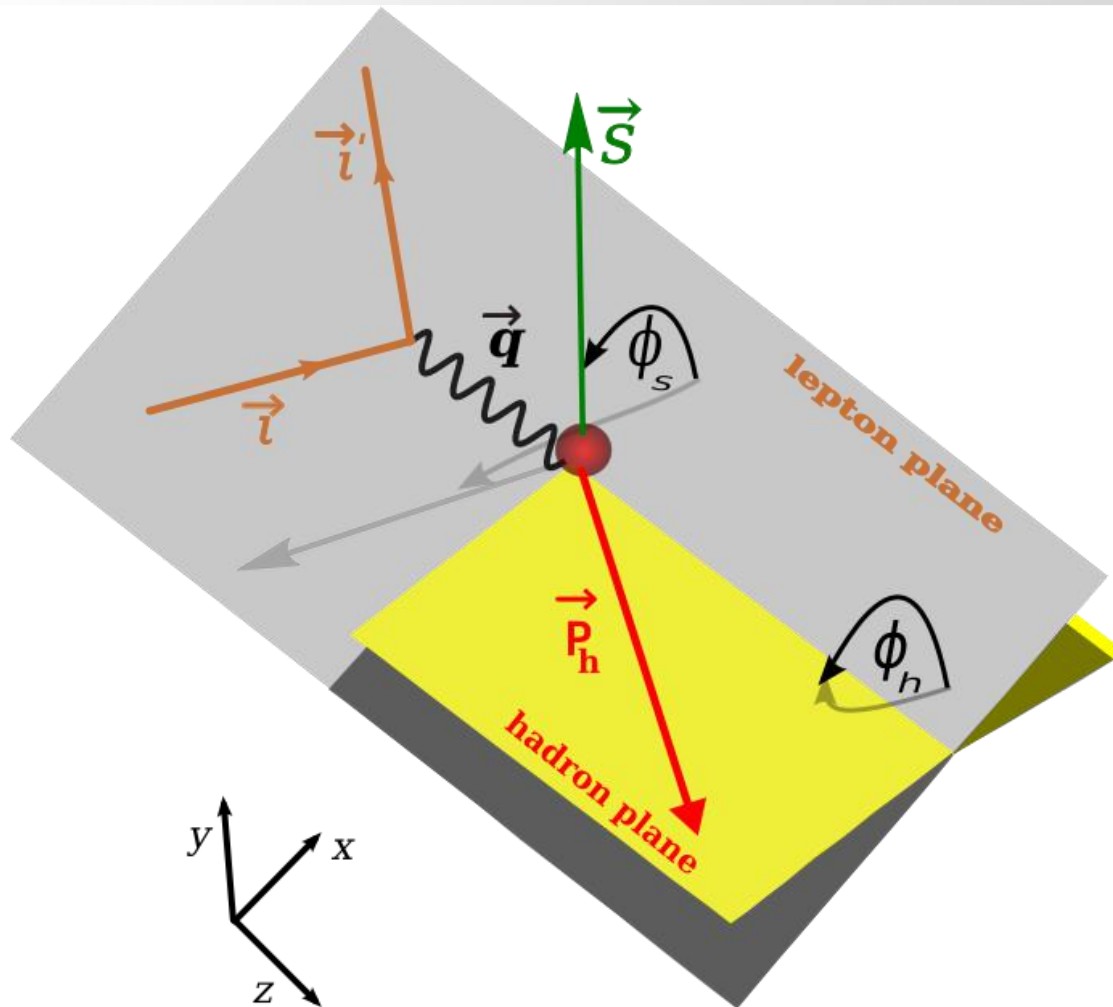
State	C_U	C_F	$\frac{C_F}{C_U}$
${}^3S_1^{(8)}, {}^1S_0^{(8)} \& {}^3P_J^{(8)}$	$\frac{N_c^2-1}{4N_c}$	$\frac{N_c}{4}$	$\frac{N_c^2}{N_c^2-1}$

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

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 $C_F^{(d)} = 0$

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



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

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

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

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

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

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

Sivers Asymmetry

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

Numerator of the Asymmetry

$$d\Delta\sigma = \frac{1}{2S} \frac{2}{(4\pi)^4 z} \sum_a \int \frac{dx_a}{x_a} d^2\mathbf{k}_{\perp a} \delta(\hat{s} + \hat{t} + \hat{u} - M^2 + Q^2) \\ \times \sum_n \frac{1}{Q^4} \Delta \hat{f}_{a/p^\uparrow}(x_a, \mathbf{k}_{\perp a}) L^{\mu\nu} H_{\mu\nu}^{a,U}[n] \langle 0 | \mathcal{O}^{J/\psi}(n) | 0 \rangle$$

Unp. differential cross section

$$\frac{d\sigma}{dQ^2 dy d^2\mathbf{P}_T dz} = \frac{1}{2S} \frac{2}{(4\pi)^4 z} \sum_a \int \frac{dx_a}{x_a} d^2\mathbf{k}_{\perp a} \delta(\hat{s} + \hat{t} + \hat{u} - M^2 + Q^2) \\ \times \sum_n \frac{1}{Q^4} f_{a/p}(x_a, k_{\perp a}) L^{\mu\nu} H_{\mu\nu}^{a,U}[n] \langle 0 | \mathcal{O}^{J/\psi}(n) | 0 \rangle,$$

Hard part

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

NRQCD

Leptonic tensor

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

- 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)

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

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

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

- For maximized asymmetry: Saturate the Sivers function

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

H1 Unp. dsigma

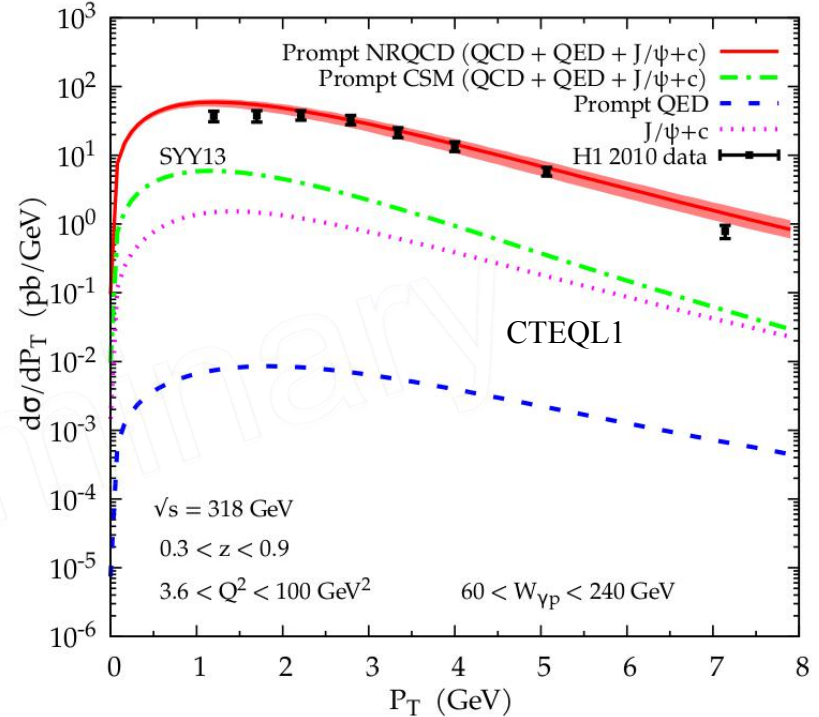
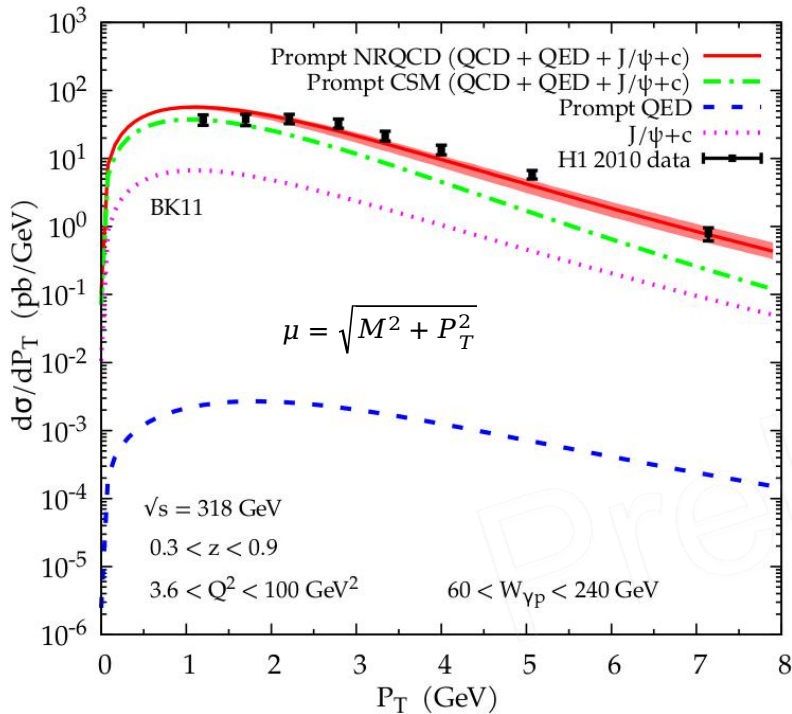
- Free parameters in our calculation are: Gaussian width and LDMEs

For Quarks: $\langle k_{\perp}^2 \rangle = 0.25 \text{ GeV}^2$

Gluons: $\langle k_{\perp}^2 \rangle = 1 \text{ GeV}^2$

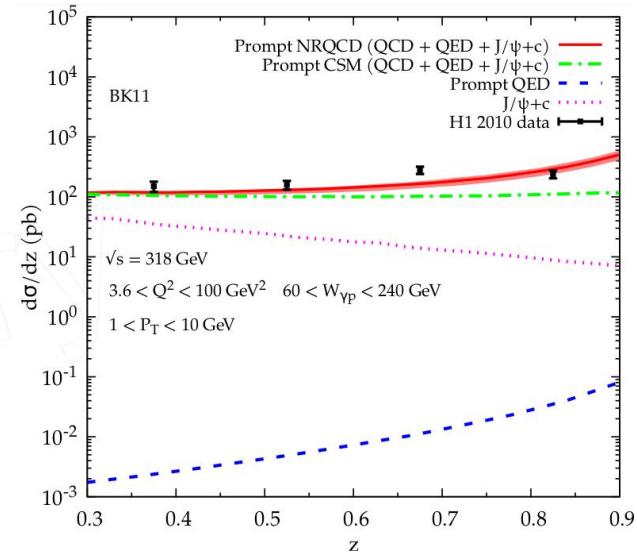
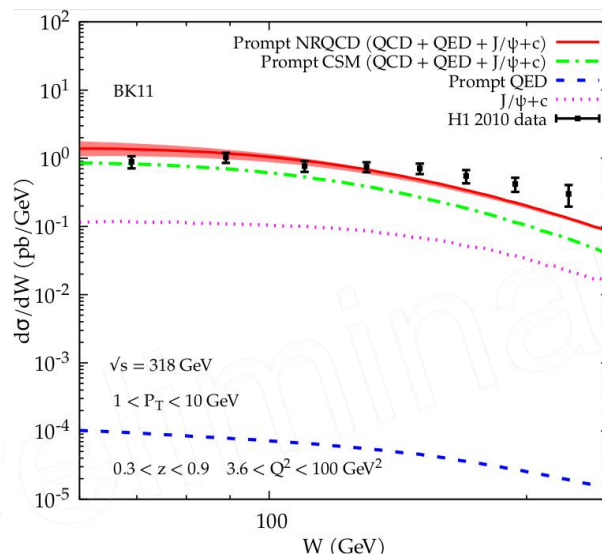
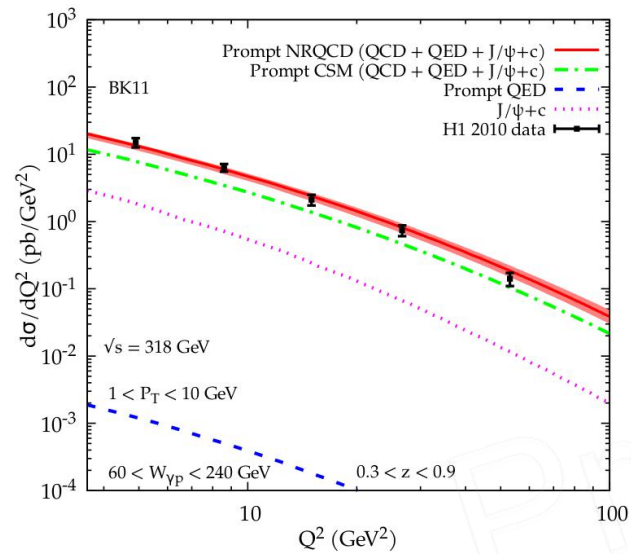
M. Anselmino, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia and A. Prokudin PRD 71 (2005) 074006

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



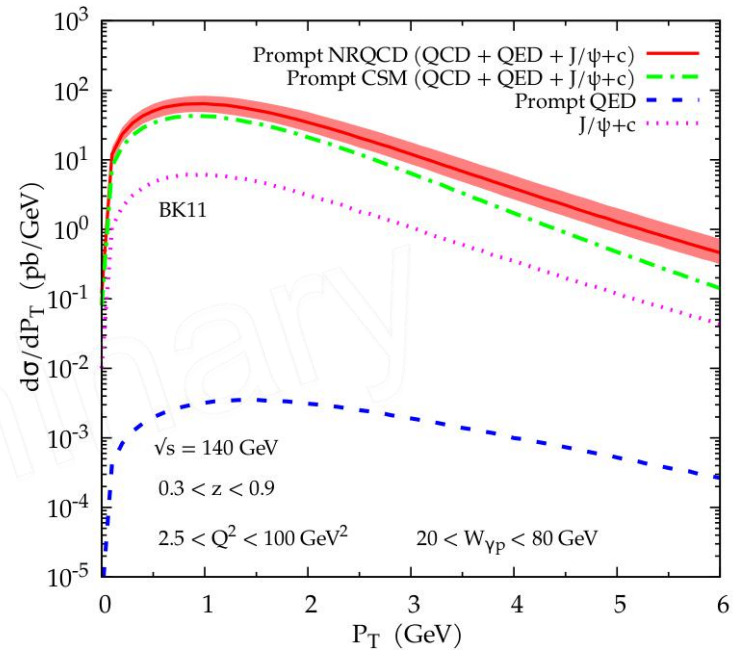
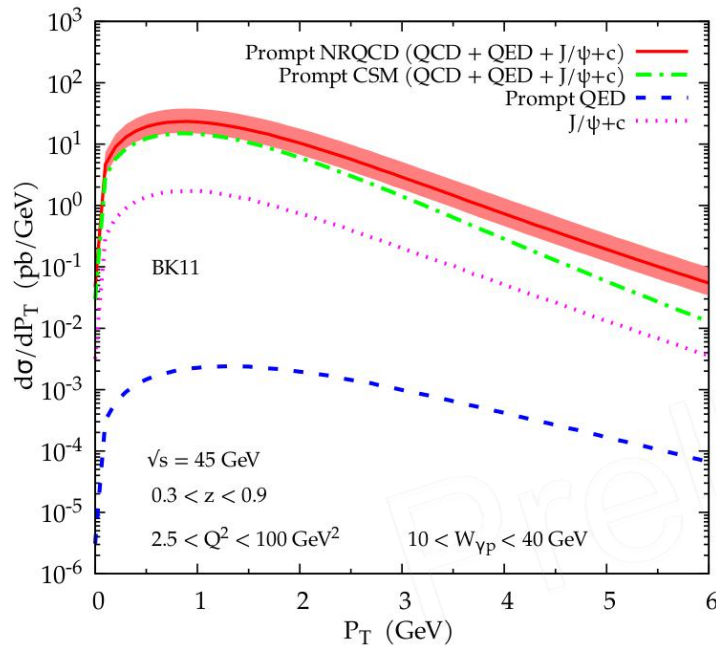
- Data from F.D. Aaron et al (H1), EPJC 68 (2010) 401
- Feed-down contribution: $\psi(2S)$ included, χ_c and b-quark are very small
- $\psi(2S)$ LDMEs are taken from R. Sharma and I. Vitev, PRC 87, 044905 (2013)

H1 Unp. dsigma

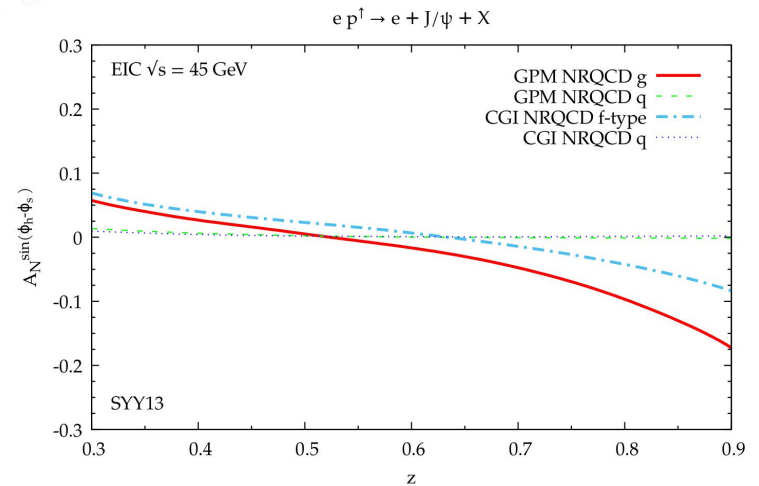
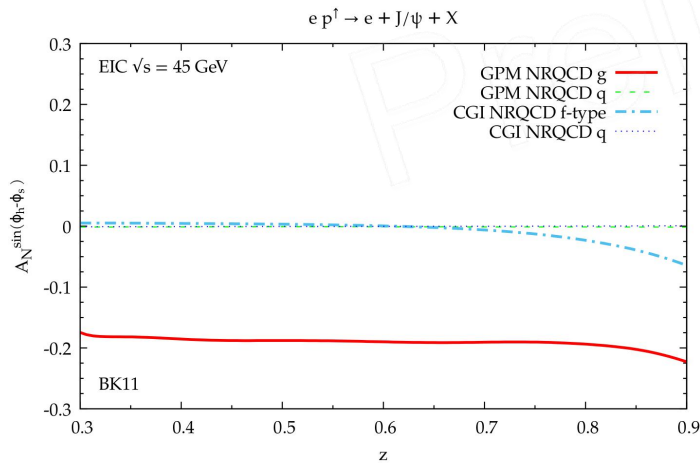
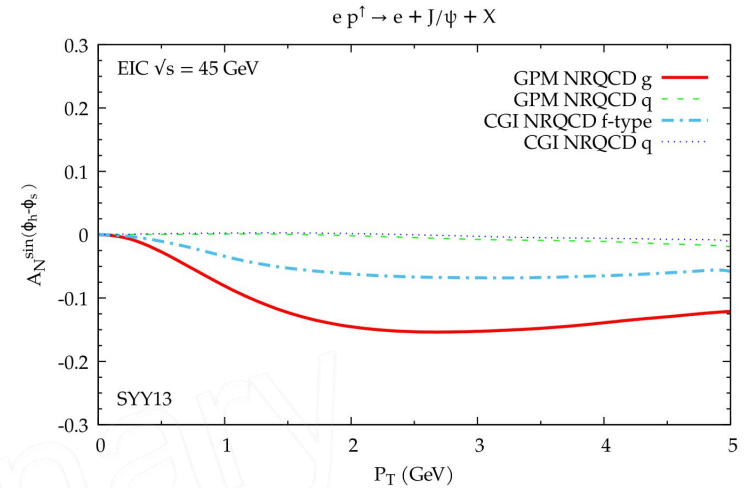
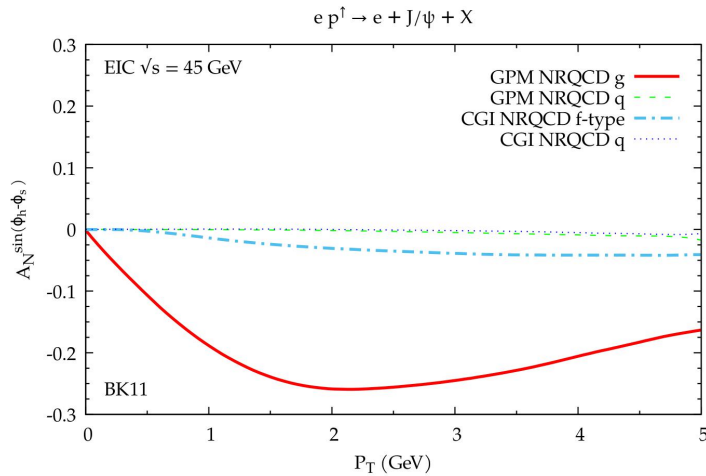


- Data from F.D. Aaron et al (H1), EPJC 68 (2010) 401

EIC Unp. dsigma

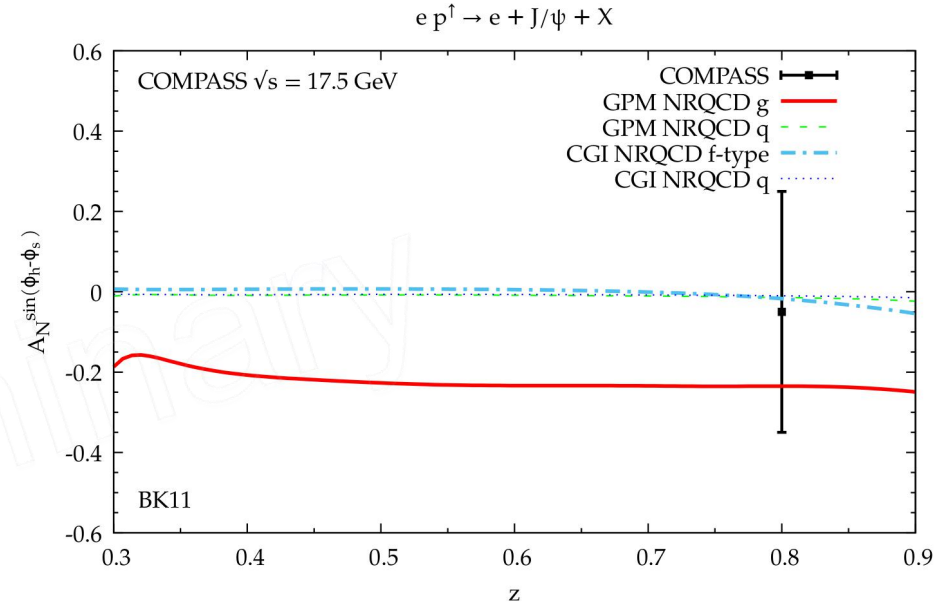
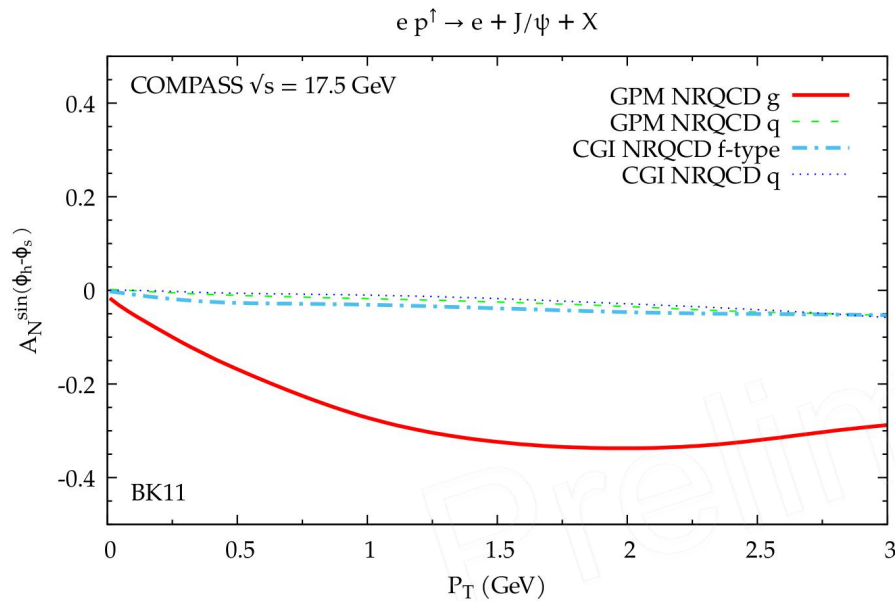


Sivers Asymmetry at EIC



$$\sqrt{s} = 45 \text{ GeV} \quad 0.3 < z < 0.9 \quad 2.5 < Q^2 < 100 \text{ GeV}^2 \quad 10 < W_{\gamma p} < 40 \text{ GeV} \quad 16$$

Sivers Asymmetry at COMPASS



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

- Data from J. Matoušek (COMPASS), J. Phys. Conf. Ser. 678, 012050 (2016)

Summary

- Siverts asymmetry in inelastic lepton production of J/ψ in ep collision is studied at EIC
- GPM predicts the sizable Siverts 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 region

Thank you for the attention