# Gluon TMDs and inelastic $J/\psi$ leptoproduction at the EIC

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# Overview

- Quarkonium as a Lab for Gluon TMDs and the gluon Sivers function
- $J/\psi$ leptoproduction at small-intermediate transverse momentum
- Interplay TMD [CGI-GPM] and NRQCD approaches: Challenging but intriguing!
- Comparison with H1 (unp. cross sect.) and COMPASS (Sivers asymmetry) data
- Estimates for EIC kinematics and concluding remarks

# Gluon TMDs at leading twist

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

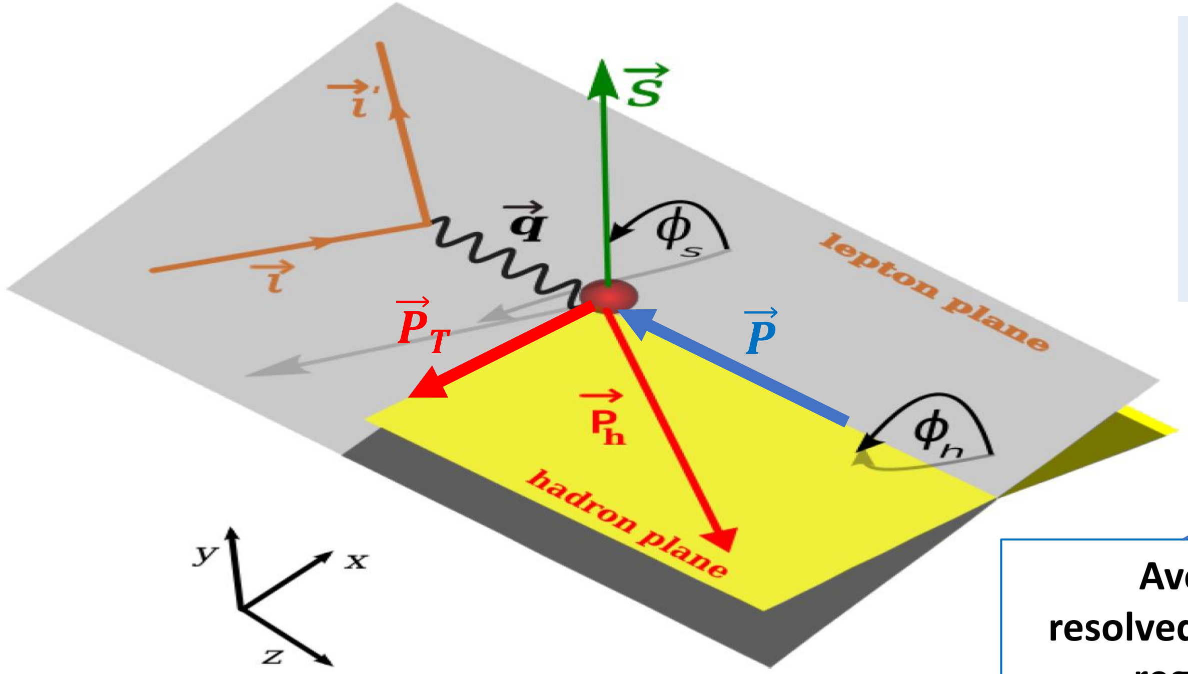
$f_{1T}^{\perp g(d)}$ $f_{1T}^{\perp g(f)}$

Mulders & Rodrigues PRD 63 094021 (2001)

- Eight LT Gluon TMDS for spin ½ hadrons
- Analogous to quarks but linear vs transverse pol.
- More complicate gauge link structure
- Two independent gluon Sivers functions
- Different properties and features
- Different relevance in different processes
- Phenomenology needs accurate fits of as much as possible observables

Boer, Lorcé, Pisano, Zhou
Adv. High Energy Phys. 2015 371396 (2015)

# Quarkonium leptoproduction: $\ell p^{\uparrow} \to \ell' J/\psi + X$




$$s = (\ell + P)^2 \qquad W^2_{\gamma p} = (q + P)^2 \qquad Q^2 = -q^2$$

$$x_B = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot \ell} \qquad z = \frac{P\cdot P_h}{P\cdot q}$$

$$0.3 < z < 0.9 \qquad P_T \leq 8 \text{ GeV}$$

Avoid resolved-photon region

Avoid collinear divergences at $z$=1

$P_T \lesssim$ few GeV: TMD regime
$P_T$ up to 8 GeV: Matches LO collinear scheme

$$\hat{s} = (k_a + q)^2 = x_a y S - Q^2\left(1 + \frac{\boldsymbol{k}^2_{\perp a}}{x_a y S}\right),$$

$$\hat{t} = (q - P_h)^2 = (z-1)Q^2 + M^2 - \frac{M^2 + \boldsymbol{P}_T^2}{z},$$

$$\hat{u} = (k_a - P_h)^2 = M^2 - x_a y z S - \frac{\boldsymbol{k}^2_{\perp a}}{x_a y S}\frac{M^2 + \boldsymbol{P}_T^2}{z} + 2k_{\perp a}P_T\cos(\phi_a - \phi_h)$$

For $\ell p^{\uparrow} \to \ell' J/\psi + X$ at $z = 1$ see:
A. Mukherjee & S. Rajesh EPJC 77 854 (2017)
A. Bacchetta, Boer, Pisano, Taels EPJC 80 72 (2020)

# Unpolarized cross section in a TMD GPM + NRQCD scheme

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

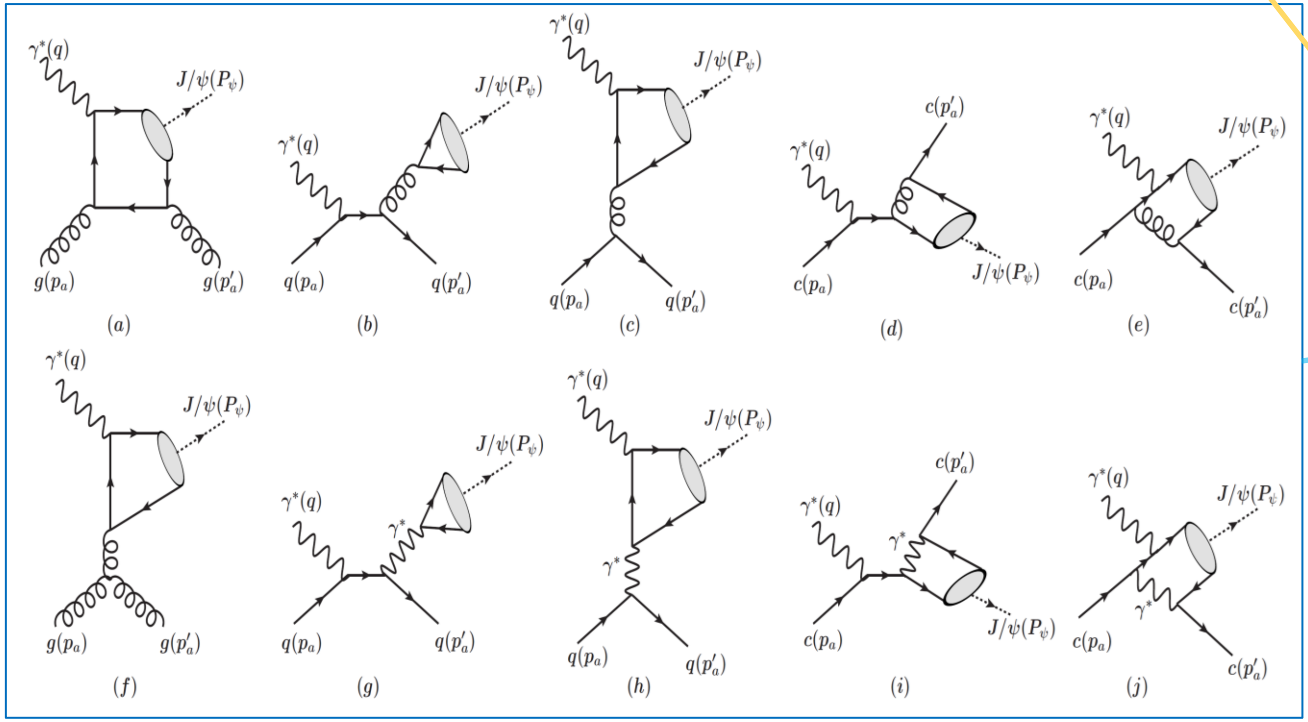
TMD PDFs

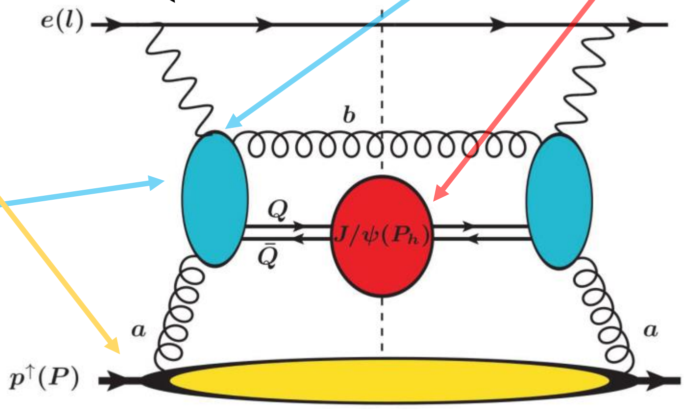
Leptonic tensor

Hard scattering contribution

NRQCD LDMEs

QCD @$\alpha\alpha_s^2$ + QED @$\alpha^3$ + intrinsic charm




$n = {}^3S_1^{(1,8)},\ {}^1S_0^{(8)},\ {}^3P_J^{(8)}, J = 0,1,2$

Bodwin, Braaten, Lepage PRD 51 1125 (1995)

# Unpolarized cross section in a TMD GPM + NRQCD scheme

- We consider two sets of LDMEs:
  - Butenschoen & Kniehl PRD 84 051501 (2011) [BK11]
  - Sun, Yuan & Yuan PRD 88 054008 (2013) [SYY13] [ no CS]

TABLE III: Numerical values of LDMEs for $J/\psi$.

| | $\langle\mathcal{O}_1^{J/\psi}(^3S_1)\rangle$ GeV$^3$ | $\langle\mathcal{O}_8^{J/\psi}(^3S_1)\rangle$ $\times\,10^{-2}$GeV$^3$ | $\langle\mathcal{O}_8^{J/\psi}(^1S_0)\rangle$ $\times\,10^{-2}$GeV$^3$ | $\langle\mathcal{O}_8^{J/\psi}(^3P_0)\rangle$ $\times\,10^{-2}$GeV$^5$ |
|---|---|---|---|---|
| BK11 [5] | 1.32 | $+0.224$ | $+4.97$ | $-1.61$ |
| SYY13 [6] | | $-0.93$ | $+14.23$ | $-1.75\,m_c^2$ |

- All partonic channels $@\alpha\alpha_s^2$: $\gamma^* + g \to J/\psi + g,\ \ \gamma^* + q(\bar{q}) \to J/\psi + q(\overline{q})$ [including intrinsic charm]
- Direct $c(\bar{c})$ fragmentation into $J/\psi$ negligible in the low $P_T$ region

- QED contributions $@\alpha^3$ also included

- Feed-down contributions:
  - $\psi(2S)$ included; LDME set: Sharma & Vitev PRC 87 044905 (2013)
  - $\chi_c$ and $b$-quark contributions negligible in the low $P_T$ region

TABLE IV: Numerical values of LDMEs for $\psi(2S)$.

| | $\langle\mathcal{O}_1^{\psi(2S)}(^3S_1)\rangle$ GeV$^3$ | $\langle\mathcal{O}_8^{\psi(2S)}(^3S_1)\rangle$ $\times\,10^{-2}$GeV$^3$ | $\langle\mathcal{O}_8^{\psi(2S)}(^1S_0)\rangle$ $\times\,10^{-2}$GeV$^3$ | $\langle\mathcal{O}_8^{\psi(2S)}(^3P_0)\rangle$ $\times\,10^{-2}$GeV$^5$ |
|---|---|---|---|---|
| Ref.[7] | 0.76 | $+0.33$ | $+0.8$ | $+0.8\,m_c^2$ |

Quarkonium overviews:
J.P. Lansberg Phys. Rep. 889 1 (2020)
N. Brambilla et al EPJC 71 1534 (2011)

# Unpolarized cross section in a TMD GPM + NRQCD scheme

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

$\langle k_{\perp q}^2 \rangle = 0.25\ \mathrm{GeV}^2$ $\langle k_{\perp g}^2 \rangle = 1.0\ \mathrm{GeV}^2$ $\mu^2 = M^2 + P_T^2$ **collinear PDFs CTEQ-L1**

**Anselmino, Boglione, D'Alesio Kotzinian, FM, Prokudin PRD 71 074006 (2005)**

**U. D'Alesio, FM, C. Pisano, S. Rajesh EPJC 79 12 (2019)**

## NRQCD LDMEs

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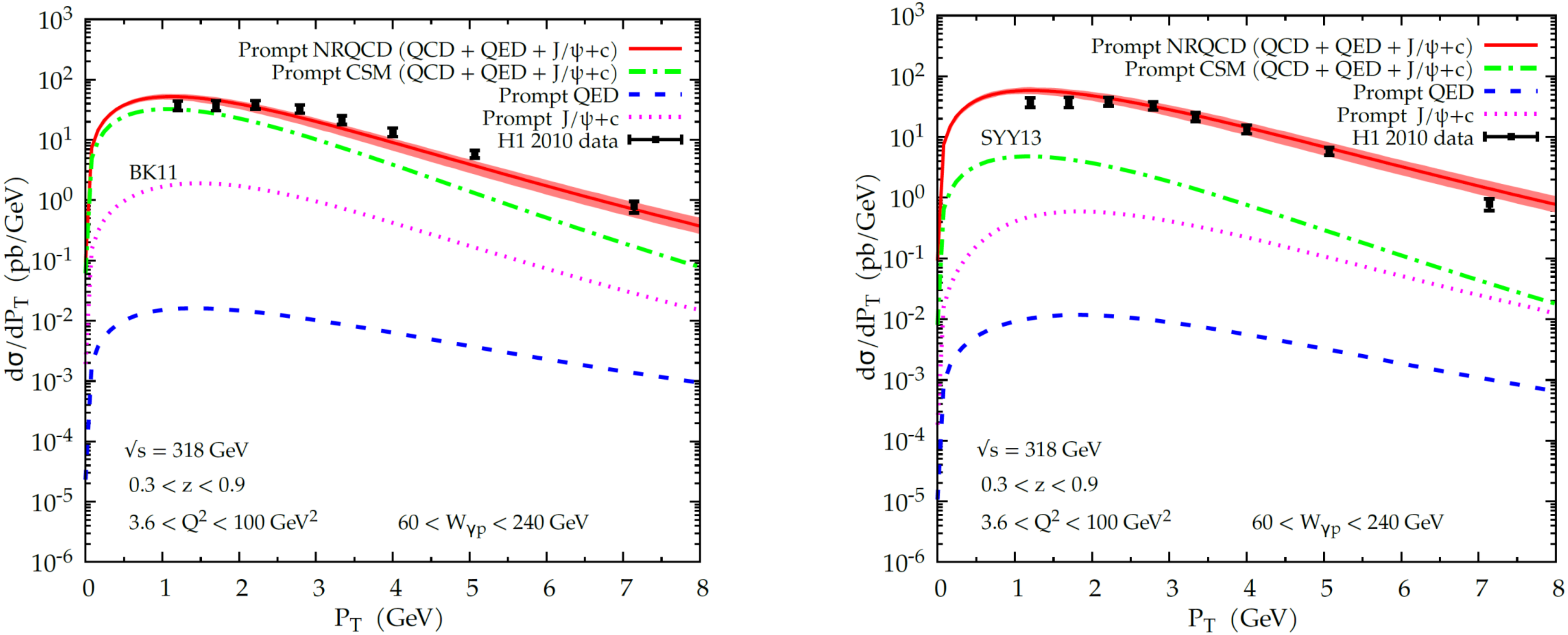
**Sharma & Vitev PRC 87 044905 (2013)**

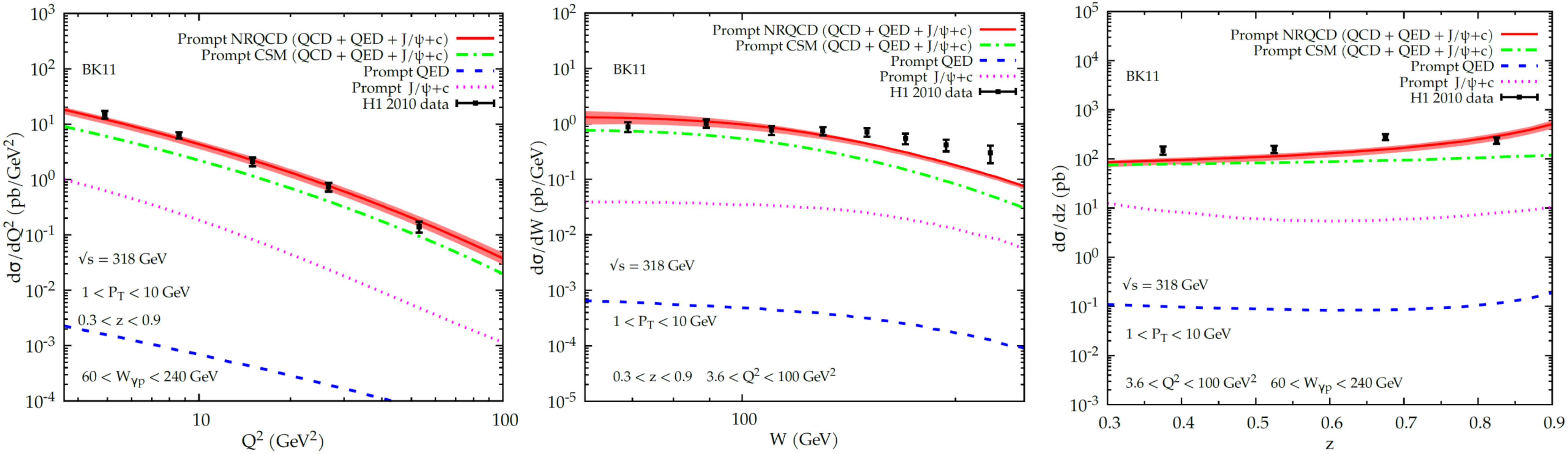
# Unpolarized cross section in a TMD GPM + NRQCD scheme vs. H1 data




$\mu^2 = M^2 + P_T^2$ collinear PDFs CTEQ-L1 Data: H1 Collab. EPJC 68 401 (2010)

**Uncertainty bands: only scale dependence $\in [\mu/2 \div 2\mu]$**

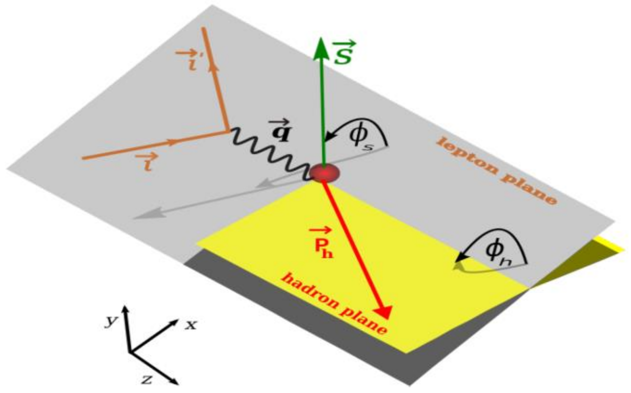
# Unpolarized cross section in a TMD GPM + NRQCD scheme vs. H1 data




$\mu^2 = M^2 + P_T^2$ **collinear PDFs CTEQ-L1** **Data: H1 Collab. EPJC 68 401 (2010)**

**Uncertainty bands: only scale dependence $\in [\mu/2 \div 2\mu]$**

# Sivers Asymmetry in $J/\psi$ leptoproduction




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

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

**GPM: TMDs hypotethically UNIVERSAL one single GSF**

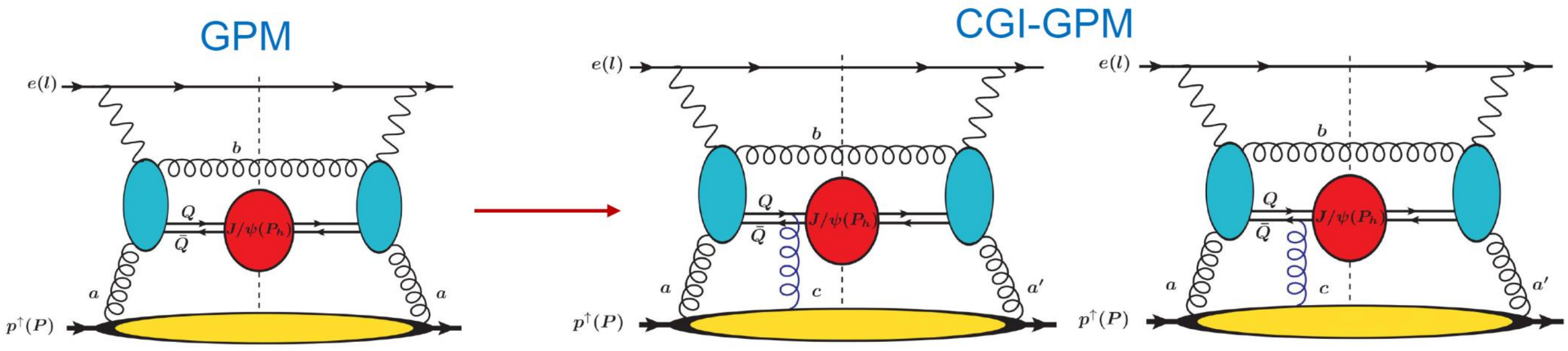
$$\mathrm{d}\Delta\sigma^{\mathrm{CGI-GPM}} = \frac{1}{2S}\frac{2}{(4\pi)^4 z}\int \frac{\mathrm{d}x_a}{x_a}\,\mathrm{d}^2\boldsymbol{k}_{\perp a}\,\delta\left(\hat{s}+\hat{t}+\hat{u}-M^2+Q^2\right)\left(-2\frac{k_{\perp a}}{M_p}\right)\sin(\phi_s-\phi_a) \times \sum_n \frac{1}{Q^4} L^{\mu\nu}\left\{\sum_q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

**CGI-GPM: TMDs process dependent via ISIs and FSIs Two (*f*- and *d*-type) GSFs**

$$H_{\mu\nu}^{a,\mathrm{Inc}}[n] = \frac{C^{\mathrm{Inc}}}{C_U} H_{\mu\nu}^{a,U}[n] = \frac{C_I + C_F}{C_U} H_{\mu\nu}^{a,U}[n]$$

**Process-dependent color factors can be absorbed into modified hard cross sections Two universal GSFs**

# Sivers Asymmetry in $J/\psi$ leptoproduction




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

No ISIs (colorless photon) $\Longrightarrow$ $C_I^{(f/d)} = 0$

$C_F^{(f/d)} = 0$ for CS state, only CO states contribute

$C_F^{(d)} = 0 \Longrightarrow$ only $f$-type GSF contributes to the SSA

More details in:
Gamberg & Kang PLB 696 109 (2011)
U. D'Alesio, L. Maxia, FM, C. Pisano, S. Rajesh PRD 102 094011 (2020)

# Sivers Asymmetry in $J/\psi$ leptoproduction

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

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

$$\rho = \frac{\langle k_\perp^2\rangle_S}{\langle k_\perp^2\rangle + \langle k_\perp^2\rangle_S}$$

**Maximizing the Asymmetry:** $\mathcal{N}_q(x) = +1,\quad \mathcal{N}_g^{(f/d)}(x) = +1,\quad \rho = 2/3$

**Cancellations among different partonic contributions are still possible due to relative signs of NRQCD LDMEs**

TABLE III: Numerical values of LDMEs for $J/\psi$.

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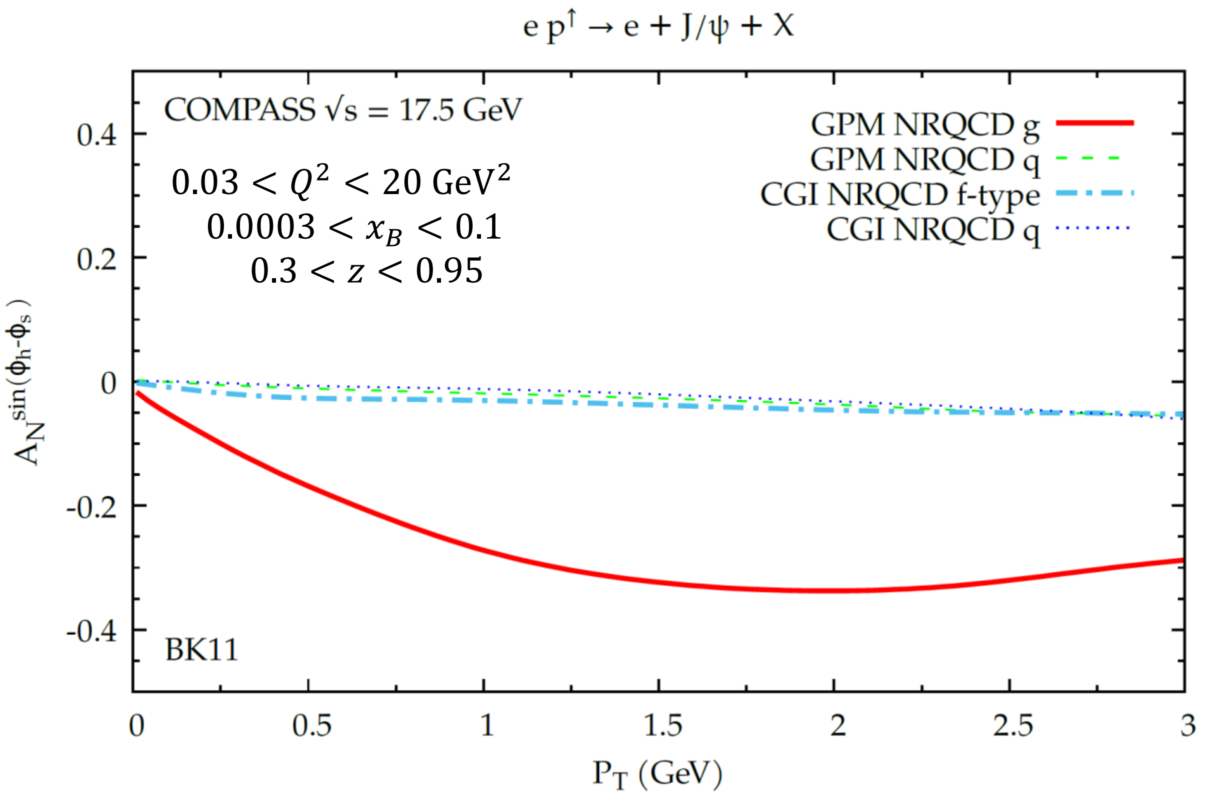
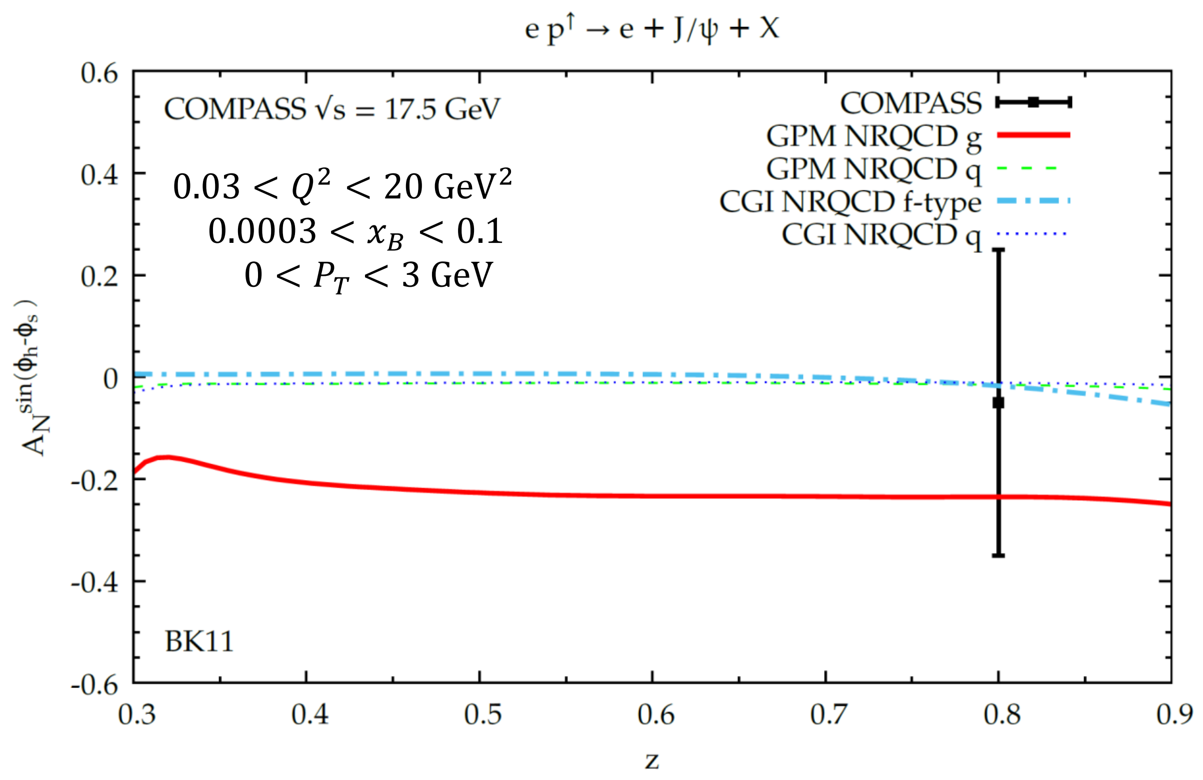
# Maximized Sivers Asymmetry @ COMPASS



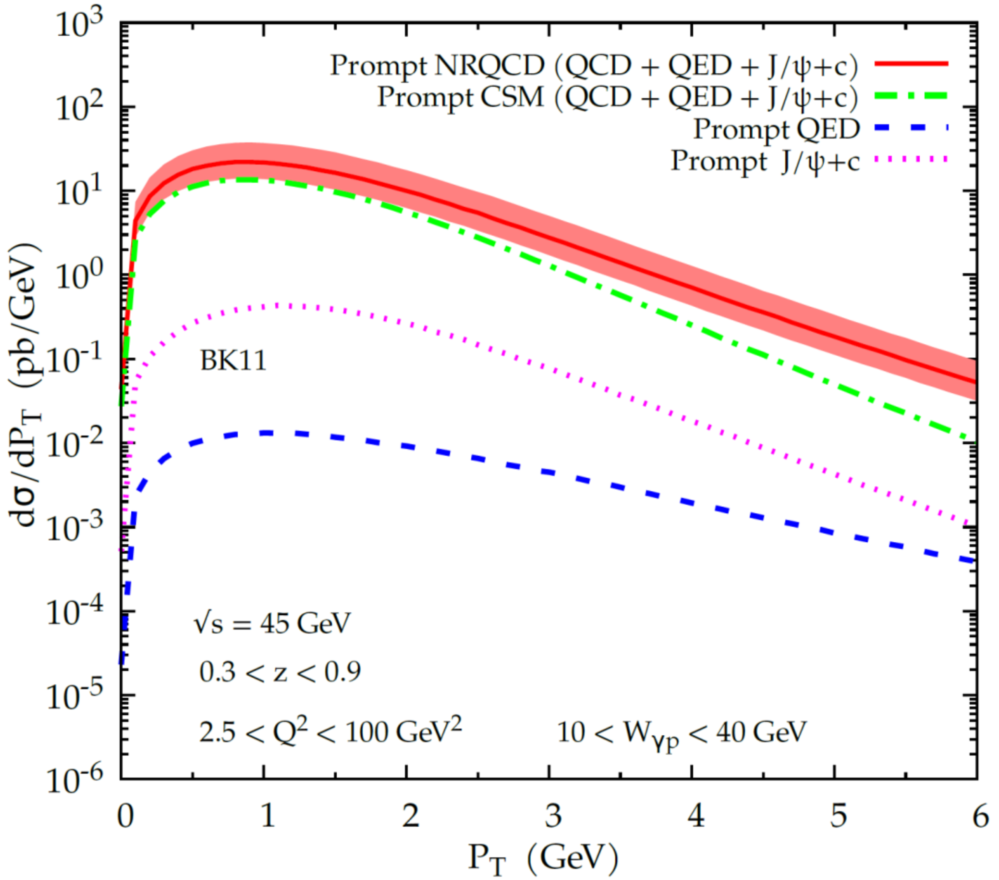

**SSA Data point: COMPASS Collab. J. Phys. Conf. Ser. 678 012050 (2017)**

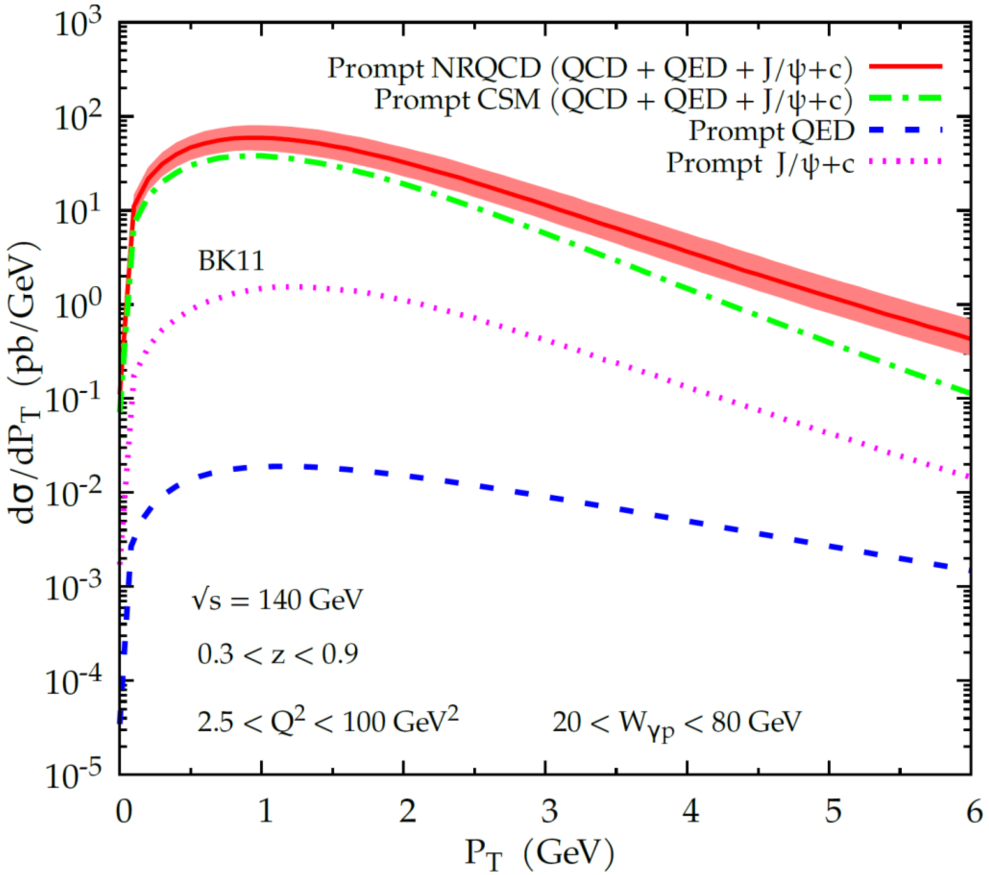
**Negative gluon Sivers asymmetry measured by COMPASS**
**Monte Carlo analysis with enhanced photon-gluon contribution**
**COMPASS Collab. PLB 772 854 (2017)**

| Subprocess | Deuteron data | | | Proton data | | |
|---|---|---|---|---|---|---|
| | Asymmetry | Statistical error | Systematic uncertainty | Asymmetry | Statistical error | Systen uncert |
| PGF | –0.14 | 0.15 | 0.10 | –0.26 | 0.09 | 0.06 |

# Estimates for $J/\psi$ leptoproduction at the EIC

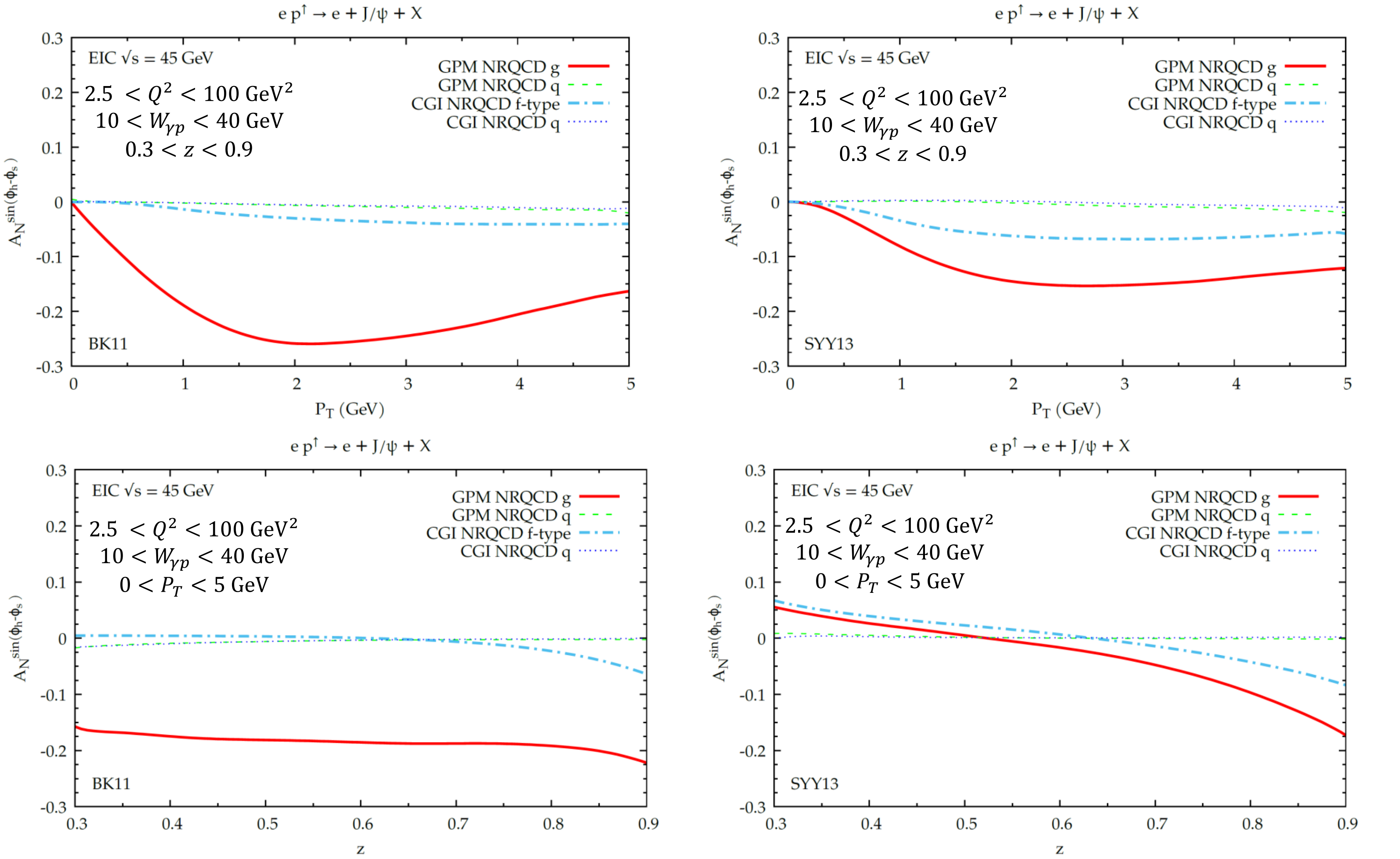
## Unpolarized cross section at $\sqrt{s} = 45$ GeV [left] and $\sqrt{s} = 140$ GeV [right]



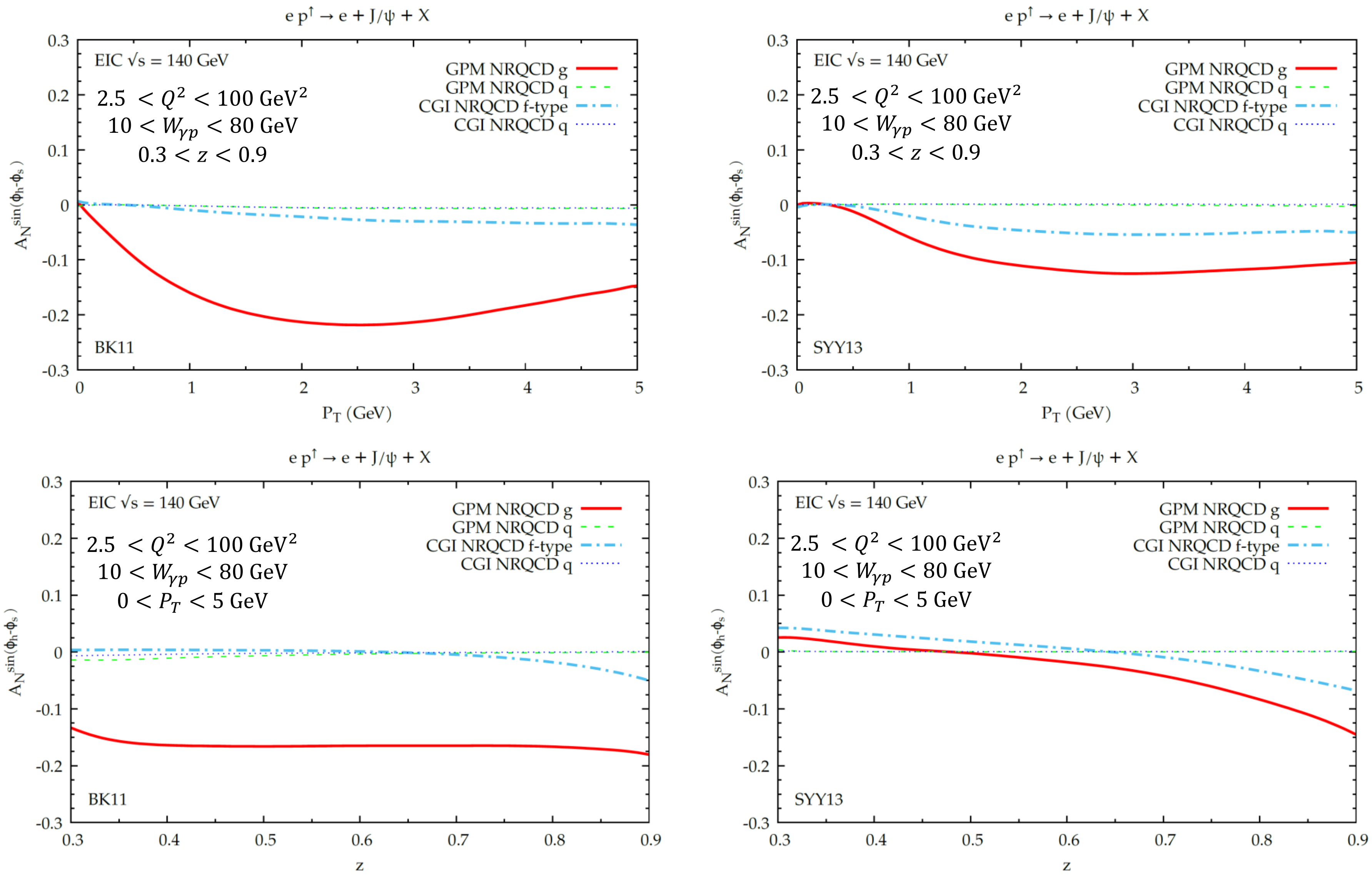
# Estimates for $J/\psi$ leptoproduction at the EIC

## Maximized Sivers Asymmetry at $\sqrt{s} = 45$ GeV for BK11 [left] and SYY13 [right] sets, vs. $P_T$ [top] and $z$ [bottom]



# Estimates for $J/\psi$ leptoproduction at the EIC

## Maximized Sivers Asymmetry at $\sqrt{s} = 140$ GeV for BK11 [left] and SYY13 [right] sets, vs. $P_T$ [top] and $z$ [bottom]



# Summary

- Inelastic $J/\psi$ electroproduction at EIC as a tool for studying gluon TMDs and the Sivers asymmetry
- (Color-gauge-invariant) generalized parton model + NRQCD simultaneously at work
- Dependence on NRQCD LDMEs investigated by adopting two availabe sets for the $P_T$ range considered
- Reasonable agreement with H1 unpolarized cross sections in the small-intermediate $P_T$ region
- Only color-octet FSIs and $f$-type GSF are at work for Sivers SSA in $\ell p^{\uparrow} \to \ell' + J/\psi + X$ useful for phenomenology
- Estimates for cross sections and maximized Sivers asymmetry at EIC and COMPASS kinematics

# Thanks for your attention!