J/ψ polarization at EIC within the NRCD approach and matching issue

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OUTLINE

- Quarkonium polarization within NRQCD

  introduction

  parameterization of the cross section

  TMD factorization and matching issue

- EIC preliminary prediction in the collinear region

TRANSVERSE MOMENTUM DISTRIBUTIONs (TMDs)

Gluon TMDs are still poorly known

Different processes could be use to probe gluon TMD

quarkonium production

D production (open charm)

pions at mid y

di-jet production

gluon polar. / proton polar.	Unpolarized	Circular	Linear
Unpolarized	f_1		$h_1^{\perp}$
Longitudinal		g_{1L}	$h_{1L}^{\perp}$
Transverse	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$

Leading twist TMDs

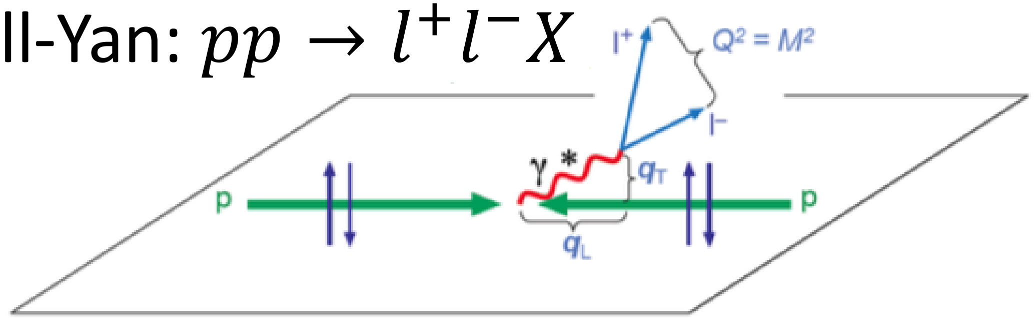
Mulders Rodriguez, PRD 63 (2001)

TMD FACTORIZATION

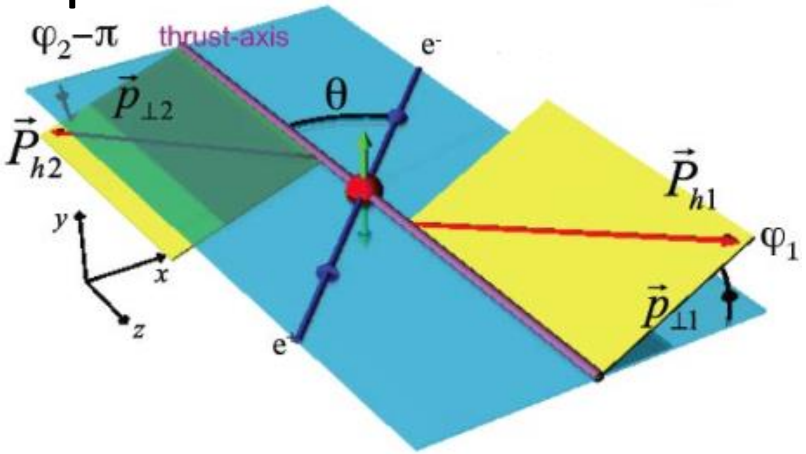
TMD factorization is formally proven only for few processes

Collins, Cambridge University Press (2011)

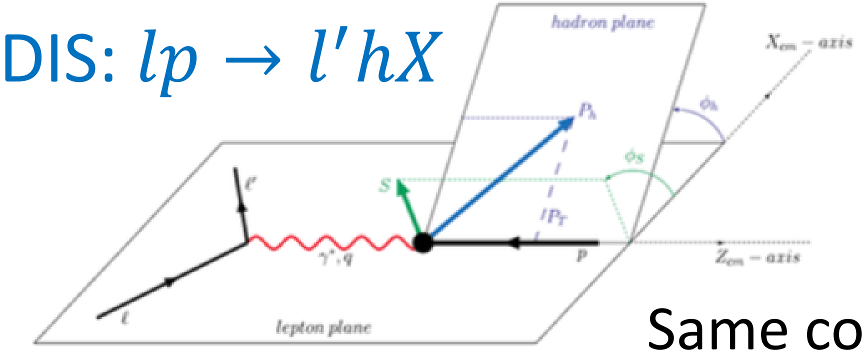
Drell-Yan: $pp \to l^+ l^- X$



leptoproduction: $e^+ e^- \to \pi\pi X$



SIDIS: $lp \to l' h X$



Same color flow for quarkonium production

➡ No factorization breaking expected

QUARKONIUM POLARIZATION

By measuring the polarization we can understand the angular momentum state in which the particle is produced

Test of hadronization models (CSM vs NRQCD vs …?)

Color Singlet Model (CSM) → **Non-relativistic QCD approach (NRQCD)**

Quarkonium produced perturbatively as *color-neutral* $Q\bar{Q}$-pair

Baier Ruckl, Z.Phys.C 19 (1983)

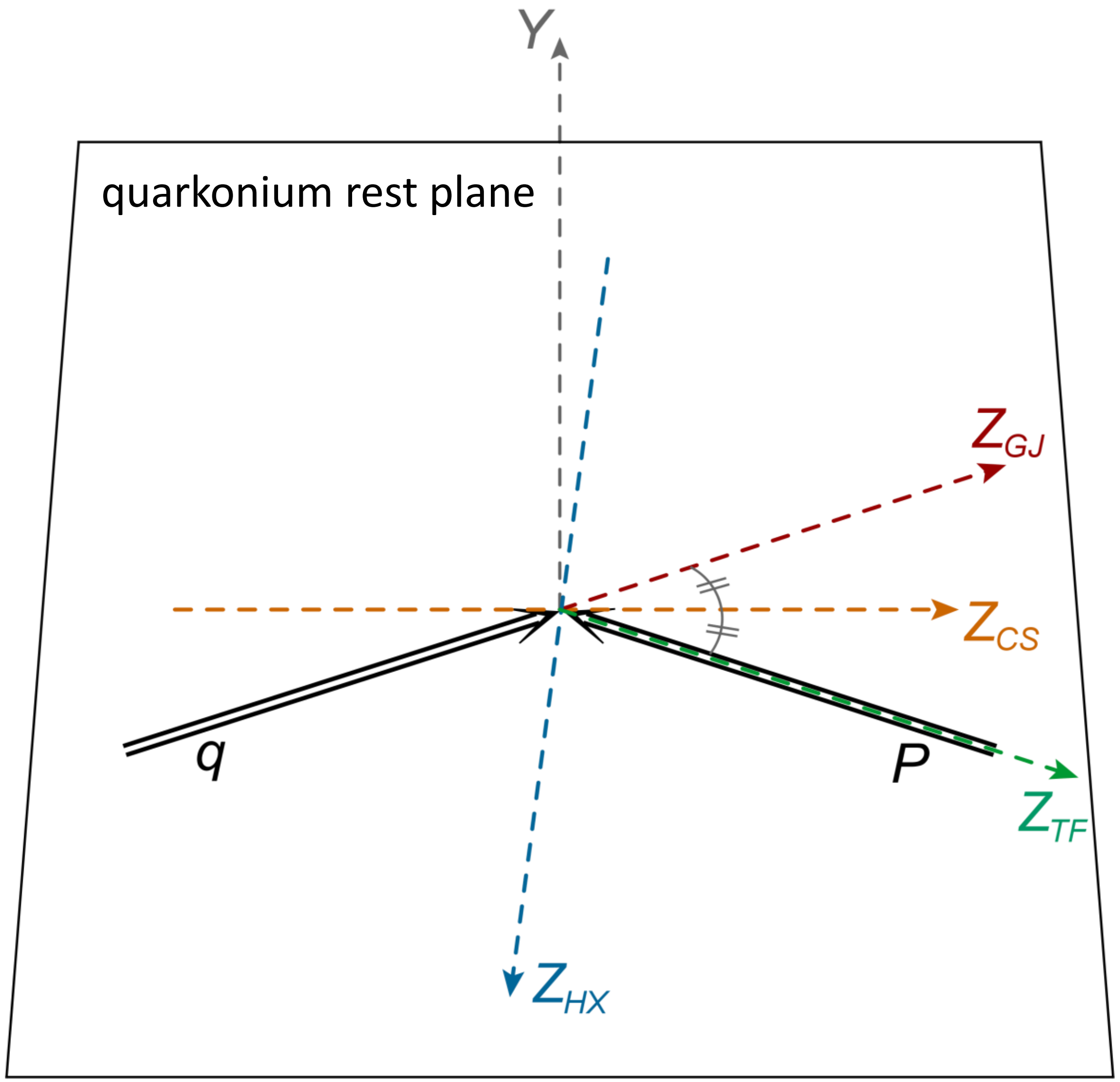
Berger Jones, PRD 23 (1981)

Quarkonium produced through *colored* $Q\bar{Q}$-pair that evolves non-pertubatively → LDME

Bodwin Braaten Lepage, PRD 55 (1997)

Cho Leibovich, PRD 53 (1996)

QUARKONIUM POLARIZATION IN *SIDIS*



J/ψ polarization is studied in the *quarkonium rest frame*

$$\gamma^*(q) + p(P) \to J/\psi(P_\psi) + X$$

Different choices for the reference frame

GJ	*Gottfried-Jackson* frame
CS	*Collins-Soper* frame
HX	*Helicity* frame
TF	*Target* frame

Frames are related by a rotation around *Y*-axis

ANGULAR STRUCTURE OF THE CROSS SECTION

J/ψ polarization is accessed by the angular distribution of its decay products

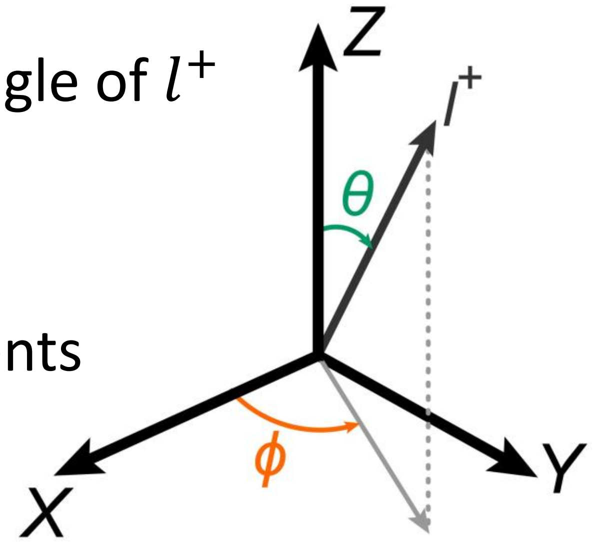
$$J/\psi \to l^+ l^-$$

Faccioli Lourenço Seixas Wöhri, EPJC 69 (2010)

SIDIS cross section is parameterized as

$$d\sigma \propto \mathcal{W}_T(1+\cos^2\theta) + \mathcal{W}_L(1-\cos^2\theta) + \mathcal{W}_\Delta \sin 2\theta \cos\phi + \mathcal{W}_{\Delta\Delta}\sin^2\theta\cos 2\phi$$

with $\Omega(\theta, \phi)$ solid angle of l^+



Boer Vogelsang, PRD 74 (2006)

The parameterization could be obtained from model independent arguments

Hermiticity   Parity conservation   Gauge invariance

J/ψ POLARIZATION WITHIN *NRQCD*

In the NRQCD approach there is a double expansion: α_s and v

up to v^4 order $\quad {}^3S_1^{[1]}, \quad {}^1S_0^{[8]}, \quad {}^3S_1^{[8]}, \quad {}^3P_J^{[8]}$

${}^1S_0^{[8]}$ → unpolarized

${}^3P_J^{[8]}$ → $J = 0, 1, 2$

NRQCD symmetries allow interference among states with same L and S

$$\mathcal{W}_\Lambda^{\mathcal{P}} = \mathcal{W}_\Lambda^{\mathcal{P}}\left[{}^3S_1^{(1)}\right] + \mathcal{W}_\Lambda^{\mathcal{P}}\left[{}^1S_0^{(8)}\right] + \mathcal{W}_\Lambda^{\mathcal{P}}\left[{}^3S_1^{(8)}\right] + \mathcal{W}_\Lambda^{\mathcal{P}}\left[\{L=1, S=1\}^{(8)}\right]$$

→ $\Lambda = T, L, \Delta, \Delta\Delta$ J/ψ helicity

$\mathcal{P} = T, L$ γ^* polarization

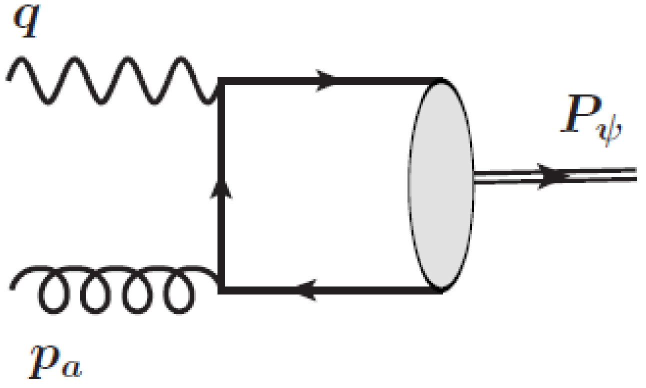
Beneke Krämer Vänttinen, PRD 57 (1998)

J/ψ POLARIZATION AT SMALL q_T

Partonic subprocesses at $\alpha\alpha_s$

$$\gamma^*(q) + g(p_a) \to c\bar{c}[n](P_\psi)$$

described by pol. part. c.s. $\widetilde{w}_\Lambda^P$



4 frame independent $\mathcal{W}$ helicity structure functions survive

Neglecting smearing effects:

$$\mathcal{W}_T^\perp = \widetilde{w}_T^\perp f_1(x, \boldsymbol{q}_T^2) \qquad \mathcal{W}_L^\perp = \widetilde{w}_L^\perp f_1(x, \boldsymbol{q}_T^2)$$

$$\mathcal{W}_L^\parallel = \widetilde{w}_L^\parallel f_1(x, \boldsymbol{q}_T^2) \qquad \mathcal{W}_{\Delta\Delta}^\perp = \widetilde{w}_{\Delta\Delta}^\perp h_1^\perp(x, \boldsymbol{q}_T^2)$$

proportional to $< \mathcal{O}_8[^3P_0] >$

access to

D'Alesio LM Murgia Pisano Sangem, arXiv:2110.07529

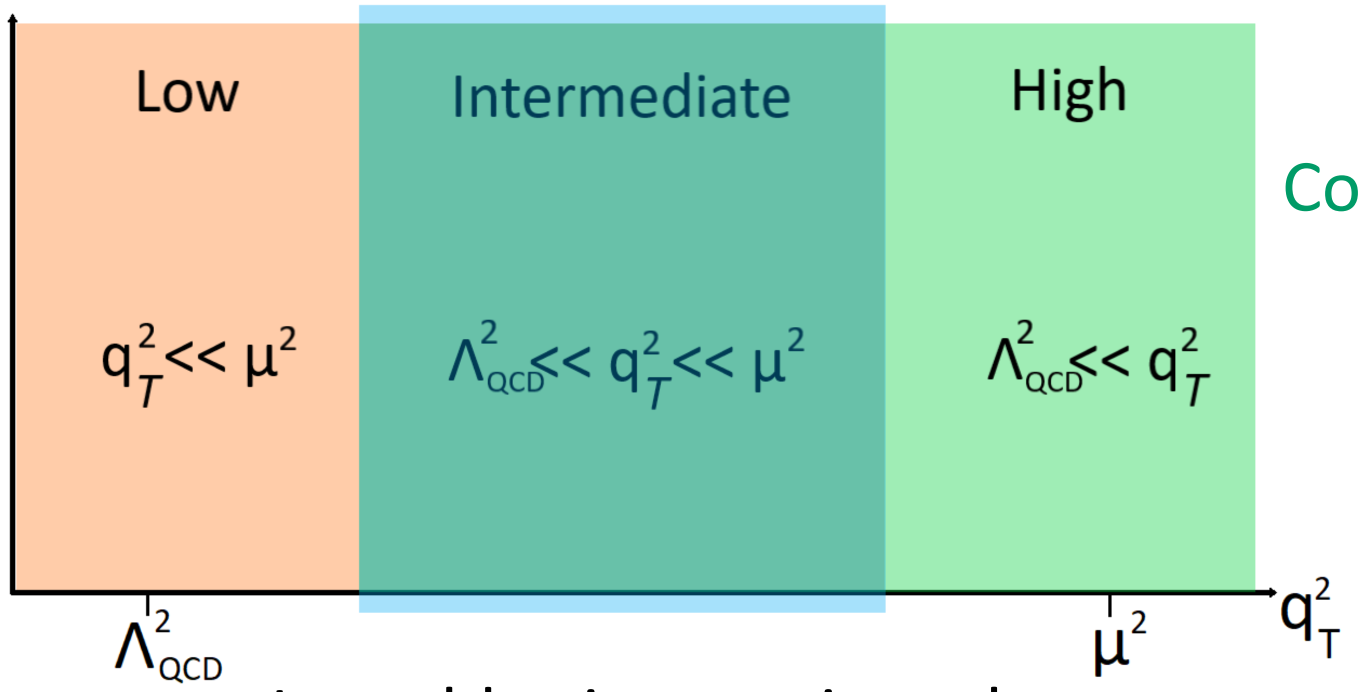
FACTORIZATION SCHEMES

In the J/ψ rest frame the virtual photon has a transverse momentum (TM) $\boldsymbol{q_T}$

TMD factorization

small transverse momentum

$q_T^2 \ll \mu^2$



Collinear factorization

high transverse momentum

$q_T^2 \gg \Lambda_{QCD}^2$

It could exist a region where both schemes are valid

$\Lambda_{QCD}^2 \ll q_T^2 \ll \mu^2$

Description of same dynamics? Need to be matched!

Bacchetta Boer Diehl Mulders, JHEP 08 (2008)

MATCHING AND SMEARING EFFECTS

In the $\Lambda_{QCD} \ll q_T \ll Q$ region

$$(\Lambda, P) = (L, \perp), (T, \perp), (L, \parallel)$$

$$\mathcal{W}^{\perp}_{\Delta\Delta}\Big|_{coll.} - \mathcal{W}^{\perp}_{\Delta\Delta}\Big|_{TMD} = 0 \qquad \mathcal{W}^{P}_{\Lambda}\Big|_{coll.} - \mathcal{W}^{P}_{\Lambda}\Big|_{TMD} \neq 0$$

→ matching requires *shape functions*

Echevarria, JHEP 10 (2019)

Fleming Makris Mehen, JHEP 04 (2020)

Shape function $\Delta^{[n]}$ is a TMD generalization of NRQCD LDME

$$f_1^g \longrightarrow \mathcal{C}\left[f_1^g \Delta^{[n]}\right] \longrightarrow \Delta^{[n]}(\boldsymbol{k}_T^2, \mu^2) = \frac{\alpha_s}{2\pi^2 \boldsymbol{k}_T^2} C_A < \mathcal{O}_8[n] > \ln \frac{\mu^2}{\boldsymbol{k}_T^2} \qquad k_T^2 \gg m_p^2$$

$$h_1^{\perp g} \longrightarrow \mathcal{C}\left[w h_1^{\perp g} \Delta^{[n]}\right] \longrightarrow$$ $\Delta^{[n]}(\boldsymbol{k}_T^2, \mu^2)$ not observable at this α_s order

Boer D'Alesio Murgia Pisano Taels, JHEP 09 (2020)

D'Alesio LM Murgia Pisano Sangem, arXiv:2110.07529

EIC: COLLINEAR REGION PRELIMINARY RESULTS

Experimentally a different parameterization is usually adopted for $\mathrm{d}\sigma \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}x_B \mathrm{d}y \mathrm{d}z \mathrm{d}^4 P_\psi \mathrm{d}\Omega}$

$$\mathrm{d}\sigma \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

$$\lambda = \frac{\mathcal{W}_T - \mathcal{W}_L}{\mathcal{W}_T + \mathcal{W}_L} \qquad \mu = \frac{\mathcal{W}_\Delta}{\mathcal{W}_T + \mathcal{W}_L} \qquad \nu = \frac{2\mathcal{W}_{\Delta\Delta}}{\mathcal{W}_T + \mathcal{W}_L}$$

where $\lambda = +1$ → transverse

$\lambda = -1$ → longitudinal

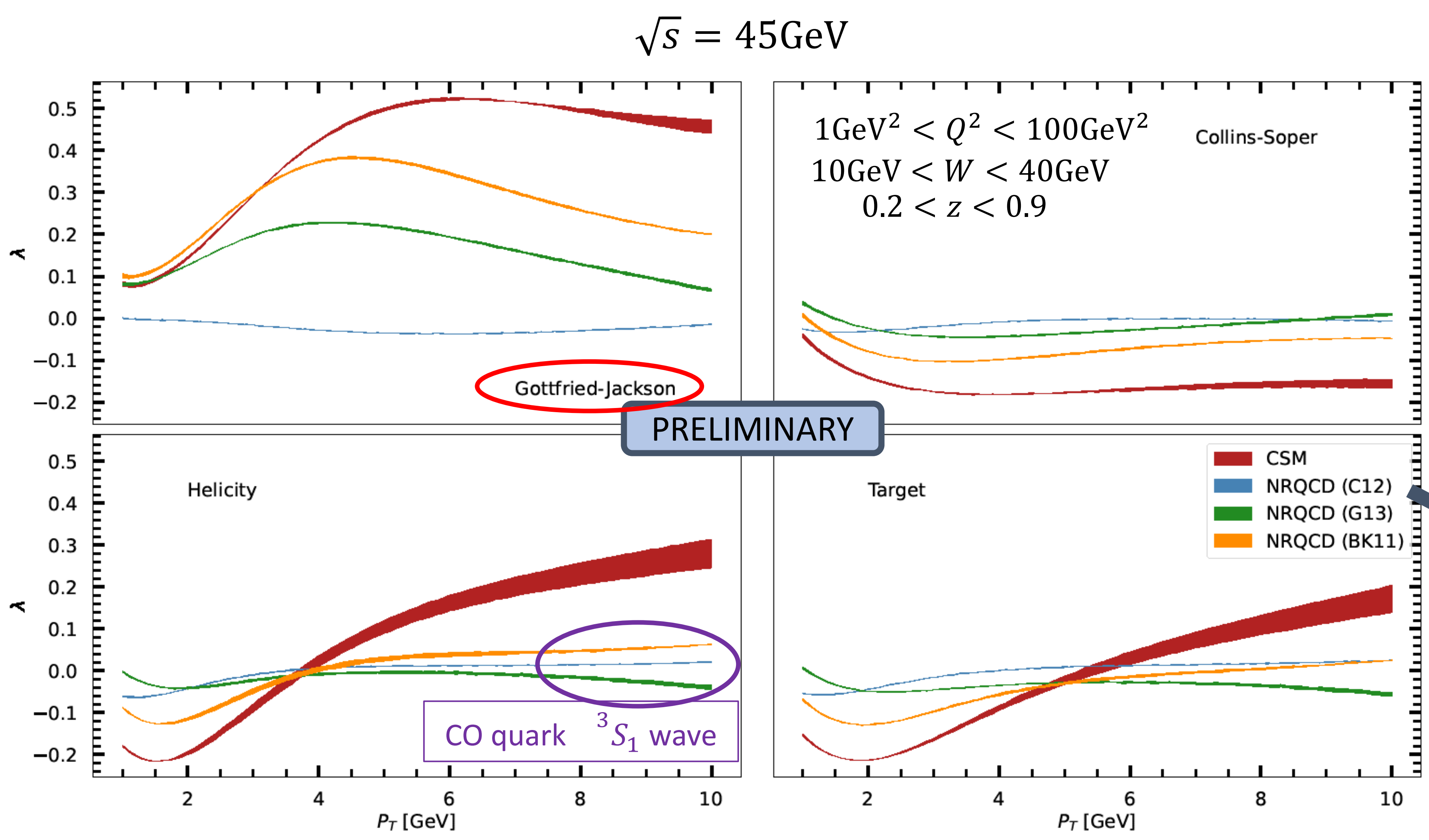
→ easier to access

Next: focus on λ in CSM and NRQCD at scale $\mu_0/2 < \mu < 2\mu_0$ $\quad \mu_0 = \sqrt{M_\psi^2 + Q^2}$

NRQCD with different LDME choices

C12	Chao Ma Shao Wang Zhang, PRL 108 (2012)	→ include polarization data
G13	Gong Wan Wang Zhang, PRL 110 (2013)	→ include polarization data
BK11	Butenschoen Kniehl, PRD 84 (2011)	→ include low P_T unpolarized data

PREDICTIONS FOR *EIC*



CSM vs NRQCD

GJ frame to probe λ

CSM

- dependence on scale μ

NRQCD

- dependence on LDME choices

C12
almost unpol. prod.

Access to $^3S_1$ CO parameter through quark contribution

CONCLUSIONS

- Study of J/ψ polarization states in different frames at EIC
- Access to gluon TMD PDFs
- In TMD region $\mathcal{W}_{\Delta\Delta}^{\perp}$ is related to the linearly polarized gluon distribution
- Proper shape functions are necessary to provide correct expressions in the intermediate q_T region
- Preliminary predictions for EIC in the collinear approach already highlight the importance of precise polarization data

Thanks for the attention