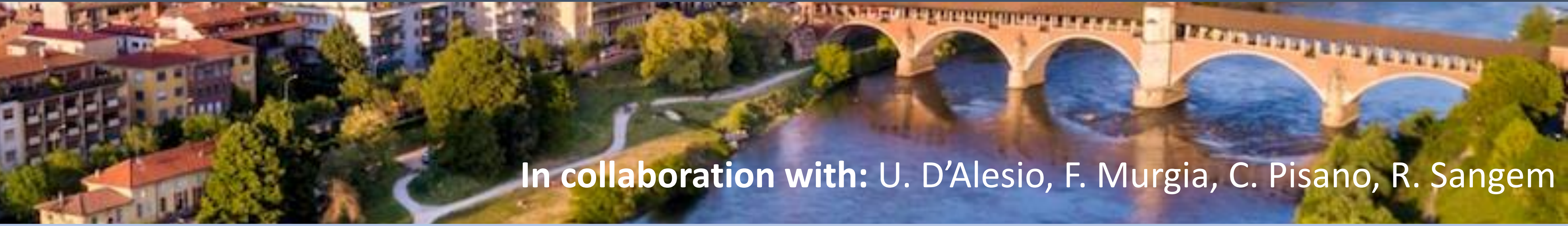
Transversity 2022

Pavia, 23-27 May 2022

Polarization phenomenology for quarkonium production in SIDIS



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Transversity 2022

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Istituto Nazionale di Fisica Nucleare

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QUARKONIUM PUZZLE

Quarkonium formation is described via different models

different ways to evaluate *short*- and *long*- distance scales

CSM

R. Baier & R. Ruckl (1983)
E.L. Berger & D.L. Jones (1981)

$$\sigma(\mathcal{Q}) = \hat{\sigma}(Q\bar{Q})|R(0)|^2$$

CEM

H. Fritzsch (1977)
F. Halzen (1977)

$$\sigma(\mathcal{Q}) = P_{\mathcal{Q}} \int_{2m_Q}^{M_T} \frac{\mathrm{d}\hat{\sigma}(m_{Q\bar{Q}})}{\mathrm{d}m_{Q\bar{Q}}} \mathrm{d}m_{Q\bar{Q}}$$

NRQCD

G.T. Bodwin, E. Braaten, G.P. Lepage (1997)
P. Cho & K. Leibovich (1996)

$$\sigma(\mathcal{Q}) = \sum_n \hat{\sigma}(Q\bar{Q}[n]) < \mathcal{O}[n] >$$

FF

G. C. Nayak, J. W. Qiu, G. Sterman (2005)
Z. B. Kang, J. W. Qiu, G. Sterman (2014)

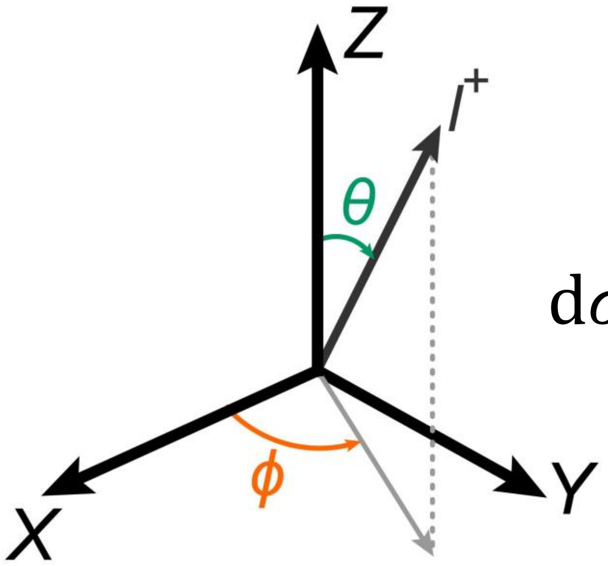
$$\sigma_{\mathcal{Q}}(p_T \gg m_{\mathcal{Q}}) = \mathrm{d}\hat{\sigma}_i(p_T/z) \otimes D_{i\to\mathcal{Q}}(z, m_{\mathcal{Q}}) + \mathrm{d}\sigma_{Q\bar{Q}[c]}(P_{Q\bar{Q}[c]} = p_T/z) \otimes D_{Q\bar{Q}[c]\to\mathcal{Q}}(z, m_{\mathcal{Q}})$$

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

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

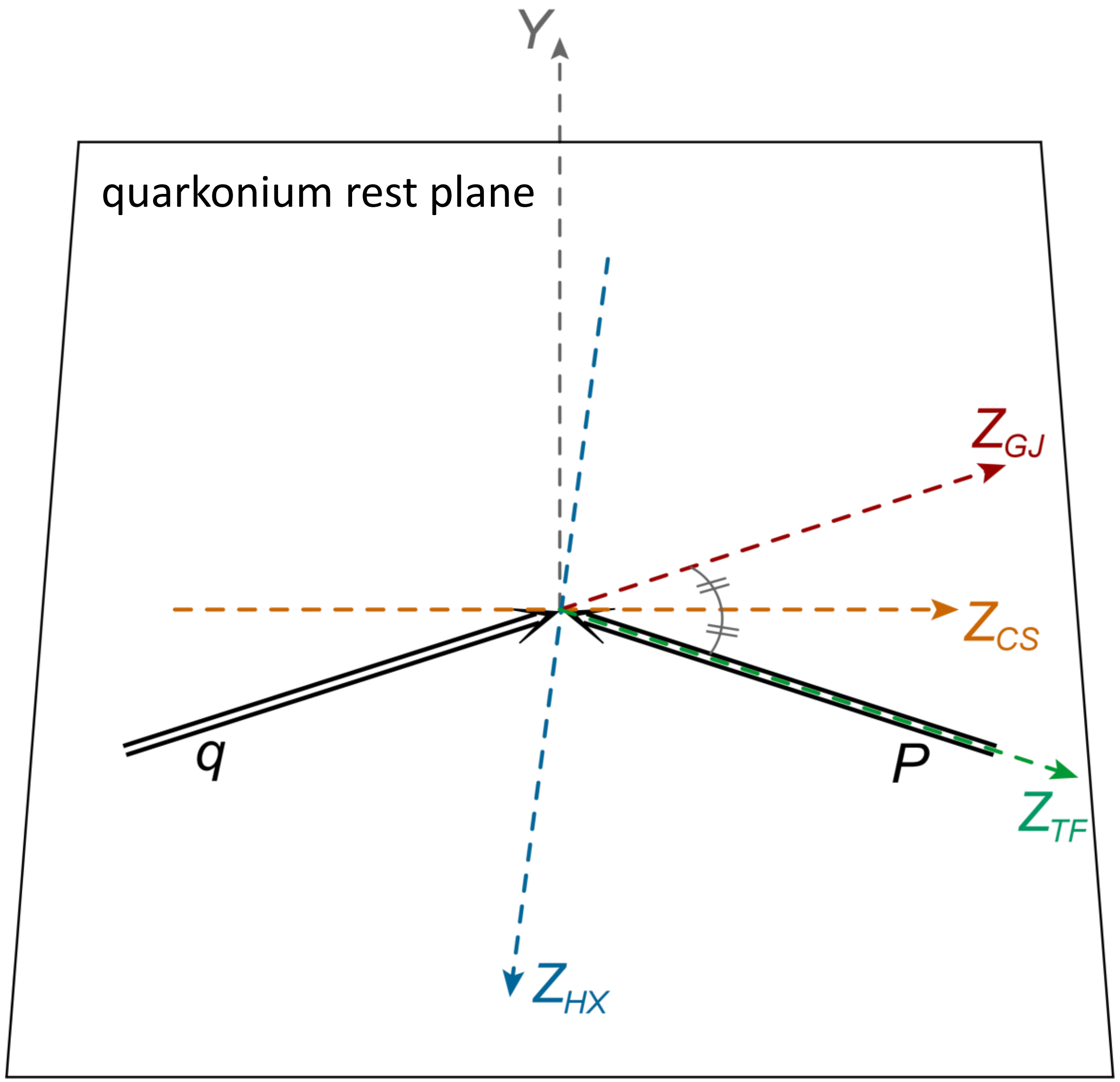
$$d\sigma \propto 1 + \lambda_\theta \cos^2\theta + \mu_{\theta\phi} \sin 2\theta \cos\phi + \nu_{\theta\phi} \sin^2\theta \cos 2\phi$$

Angular parameters are defined through ratio of polarized cross sections

This parameterization mimics the DY parameterization

Boer & Vogelsang, PRD 74 (2006)

SPIN-QUANTIZATION FRAME



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

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

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

COLLINEAR PHENOMENOLOGY

Typical experimental parameterization is usually adopted for $\mathrm{d}\sigma \equiv \dfrac{\mathrm{d}\sigma}{\mathrm{d}x_B \mathrm{d}y \mathrm{d}z \mathrm{d}^4 P_\psi \mathrm{d}\Omega}$

$$\mathrm{d}\sigma \propto 1 + \lambda_\theta \cos^2\theta + \mu_{\theta\phi} \sin 2\theta \cos\phi + \frac{\nu_{\theta\phi}}{2} \sin^2\theta \cos 2\phi$$

$$\lambda_\theta = \frac{\mathcal{W}_T - \mathcal{W}_L}{\mathcal{W}_T + \mathcal{W}_L} \qquad \mu_{\theta\phi} = \frac{\mathcal{W}_\Delta}{\mathcal{W}_T + \mathcal{W}_L} \qquad \nu_{\theta\phi} = \frac{2\mathcal{W}_{\Delta\Delta}}{\mathcal{W}_T + \mathcal{W}_L}$$

Next: predictions in CSM and NRQCD

different LDME choices

- C12 — Chao, Ma, Shao, Wang, Zhang, PRL 108 (2012) → includes polarization data
- G13 — Gong, Wan, Wang, Zhang, PRL 110 (2013) → tested on polarization data
- BK11 — Butenschoen & Kniehl, PRD 84 (2011) → includes low-P_T photoproduction data

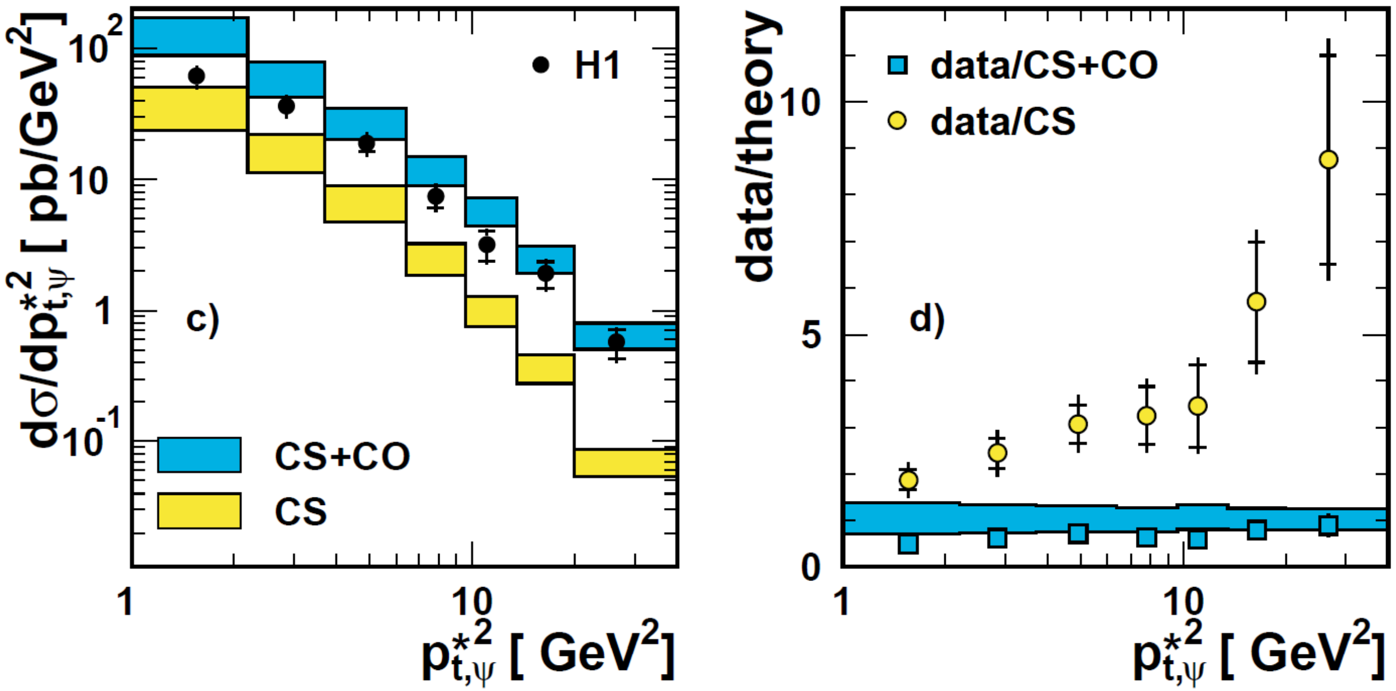
HERA UNPOLARIZED DATA

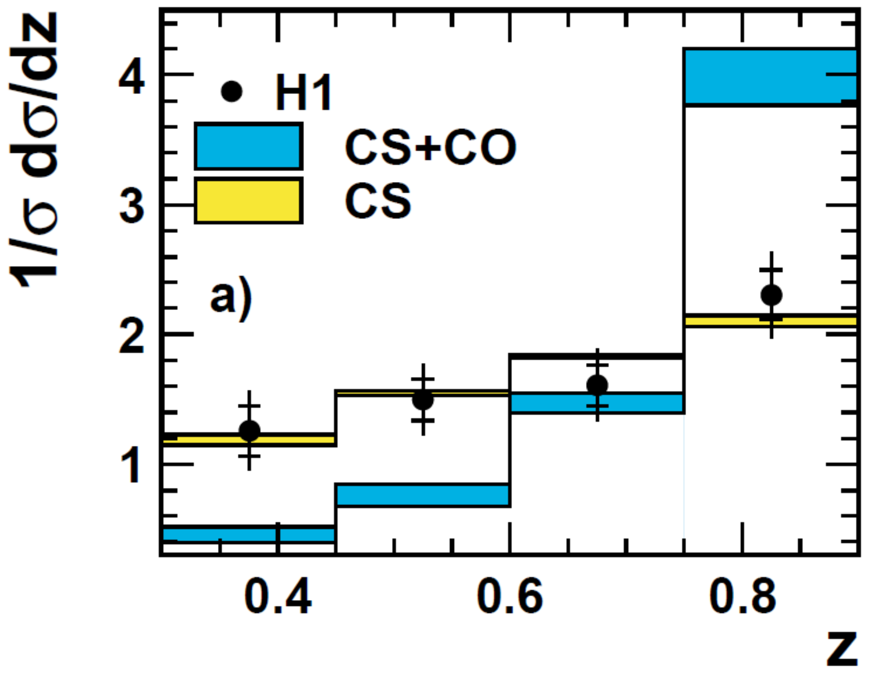
Adloff et al. (H1 Collaboration), EPJ C 25 (2002)

Kniehl & Zwirner, NPB 621 (2002)

Data from HERA collaboration

Theoretical predictions obtained by Kniehl-Zwirner





P_T data show a general better agreement with NRQCD predictions

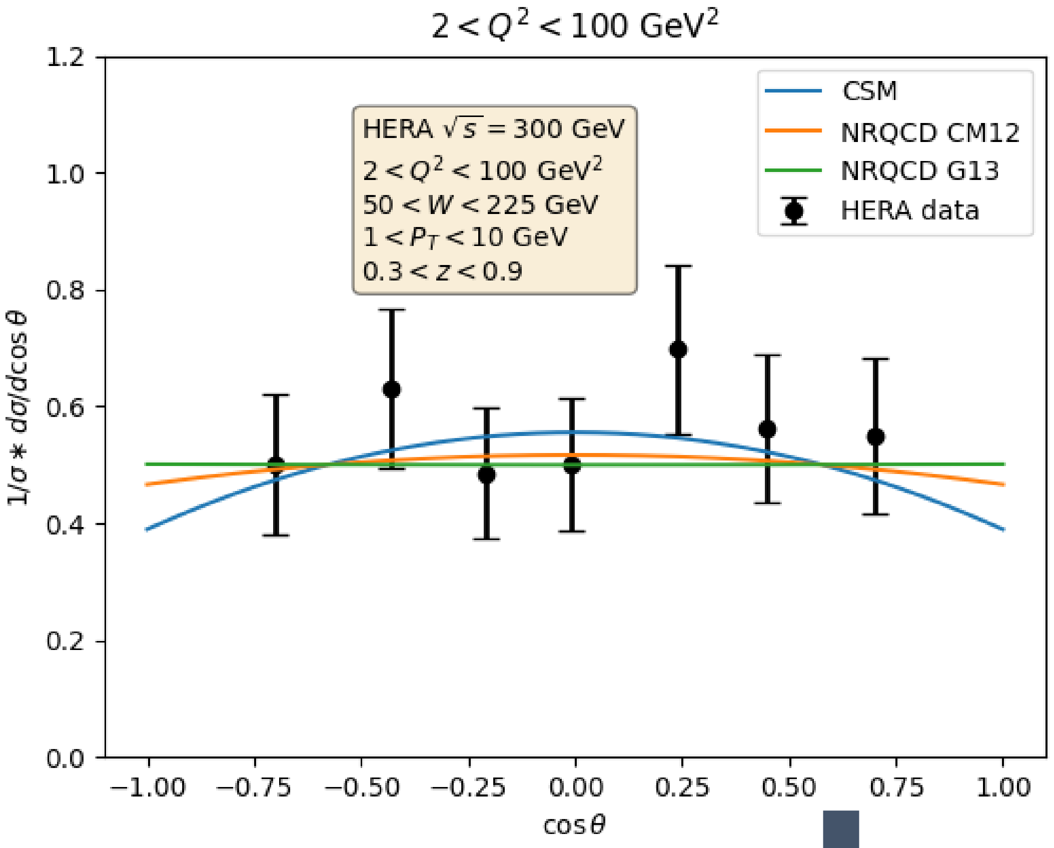
z (multiplicity) data show a general better agreement with CSM predictions

HERA POLARIZED DATA

Adloff et al. (H1 Collaboration), EPJ C 25 (2002)

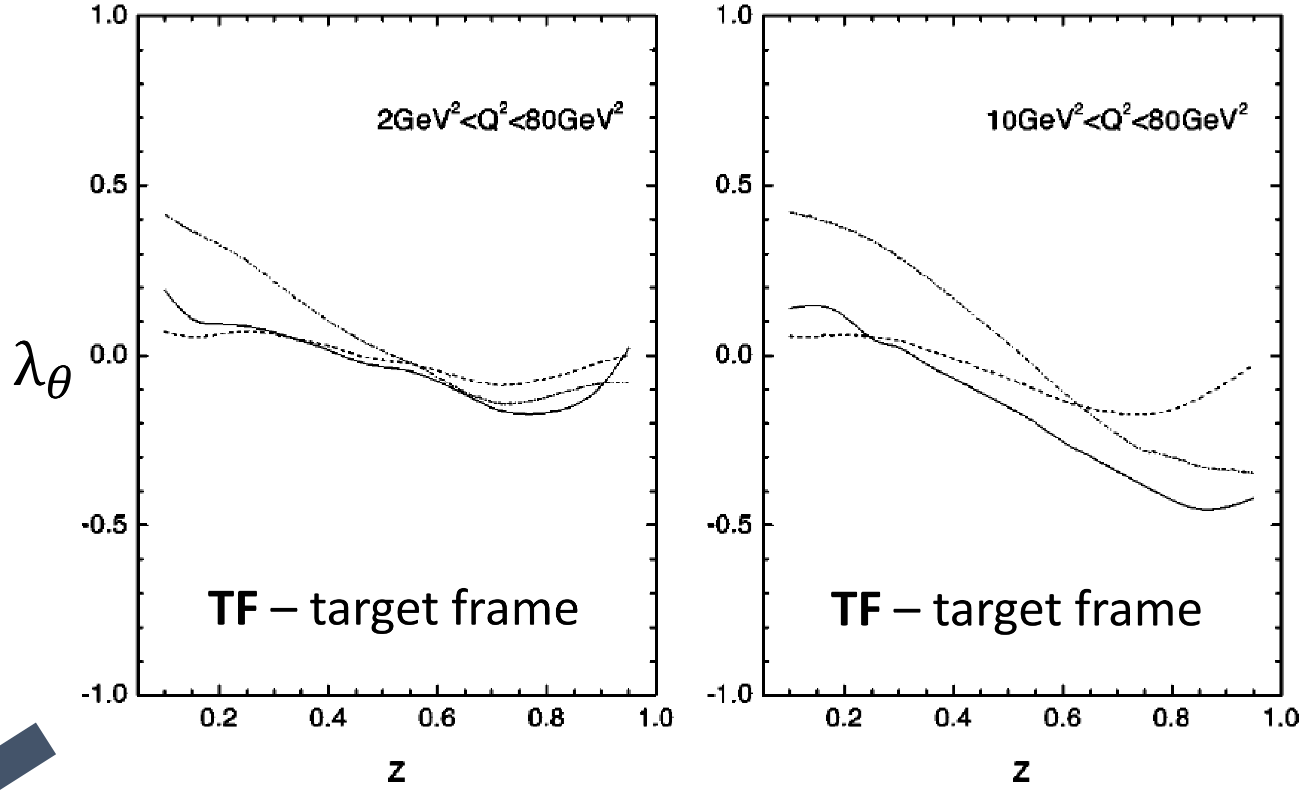
Yuan & Chao, PRD 63 (2001)

Data from HERA collaboration



From Yuan-Chao paper

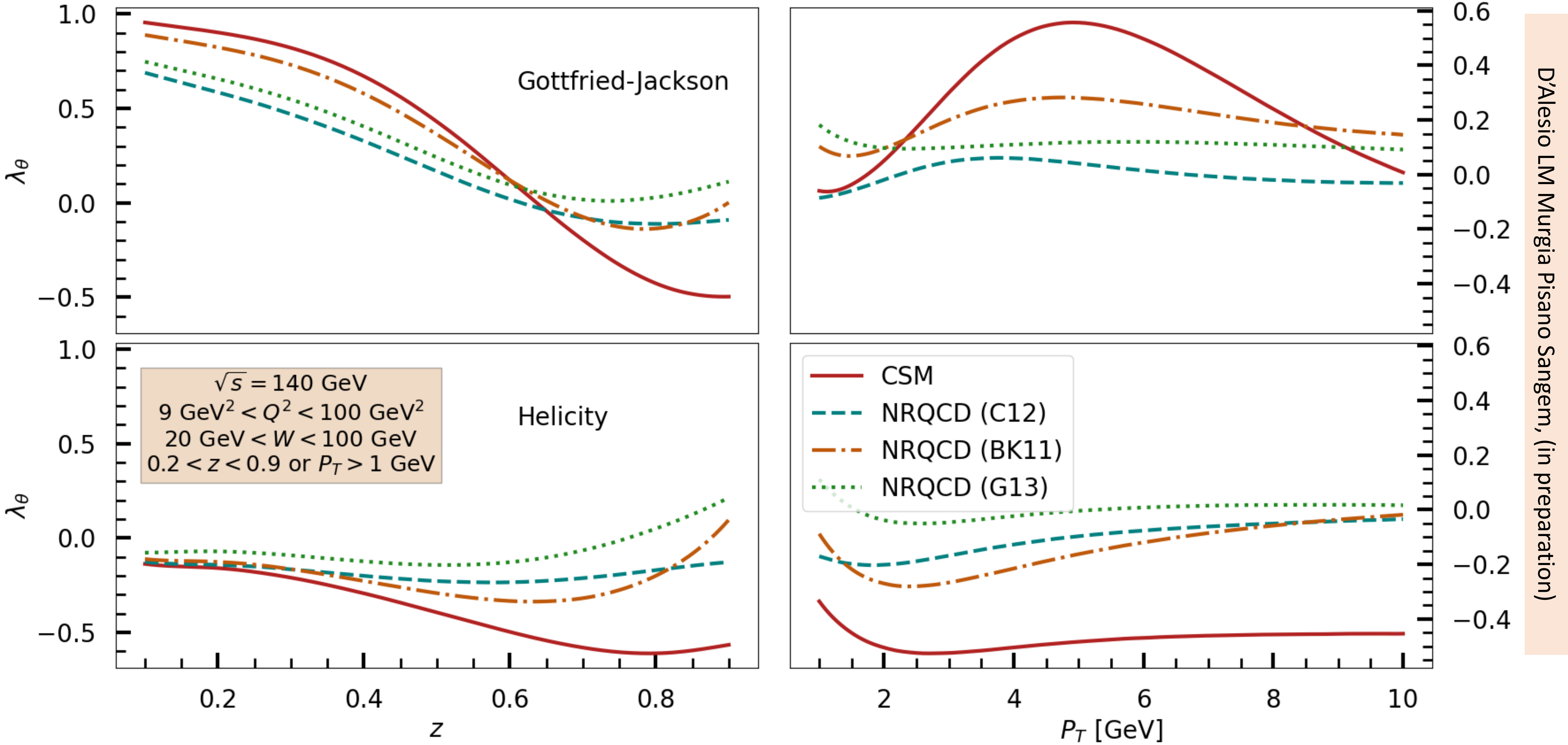
ep collisions (E_{ep}=300GeV, 40GeV<$W_{\gamma p}$<180GeV)



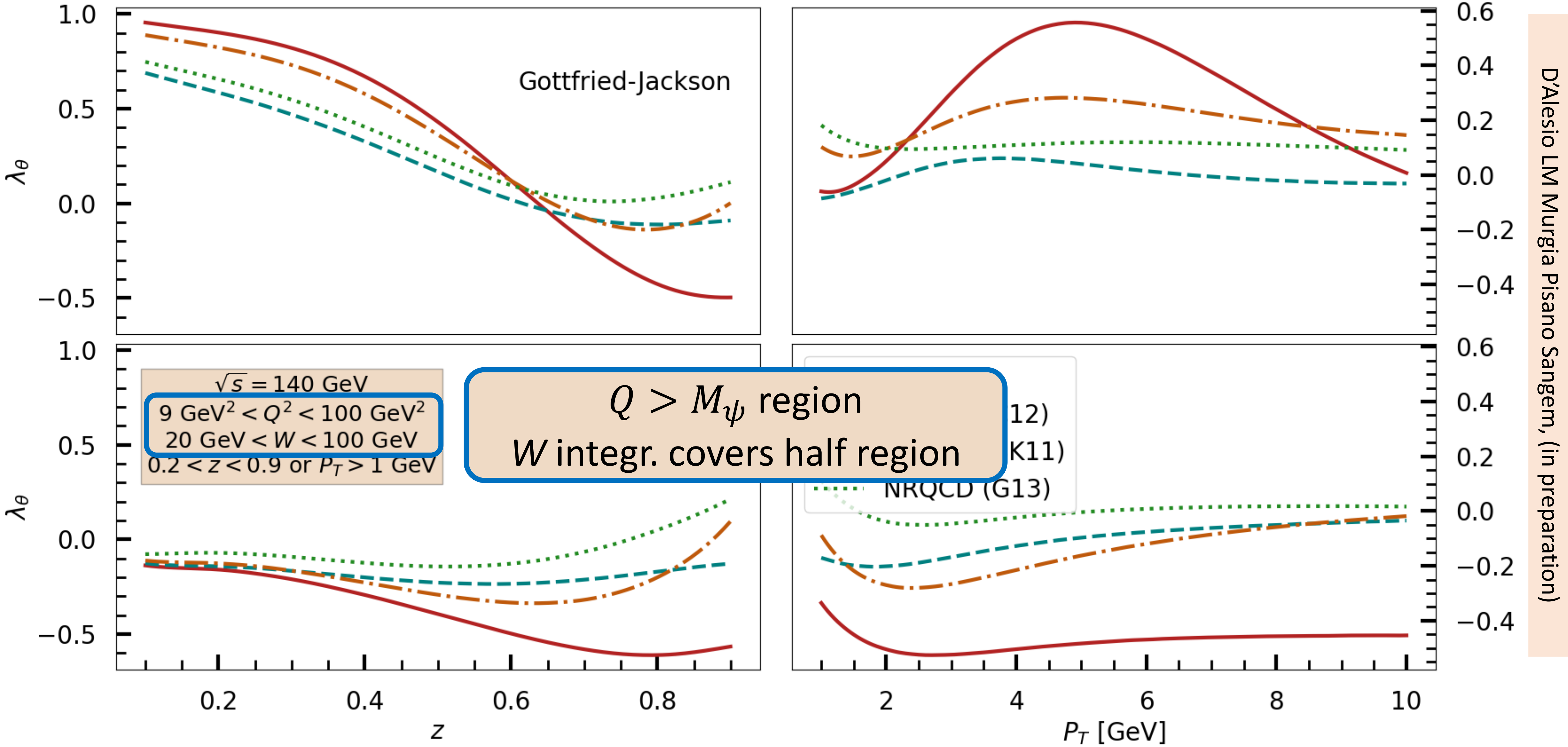
includes resolved photon contribution

Hard to extract information

Polarization at EIC (λ@140GeV)

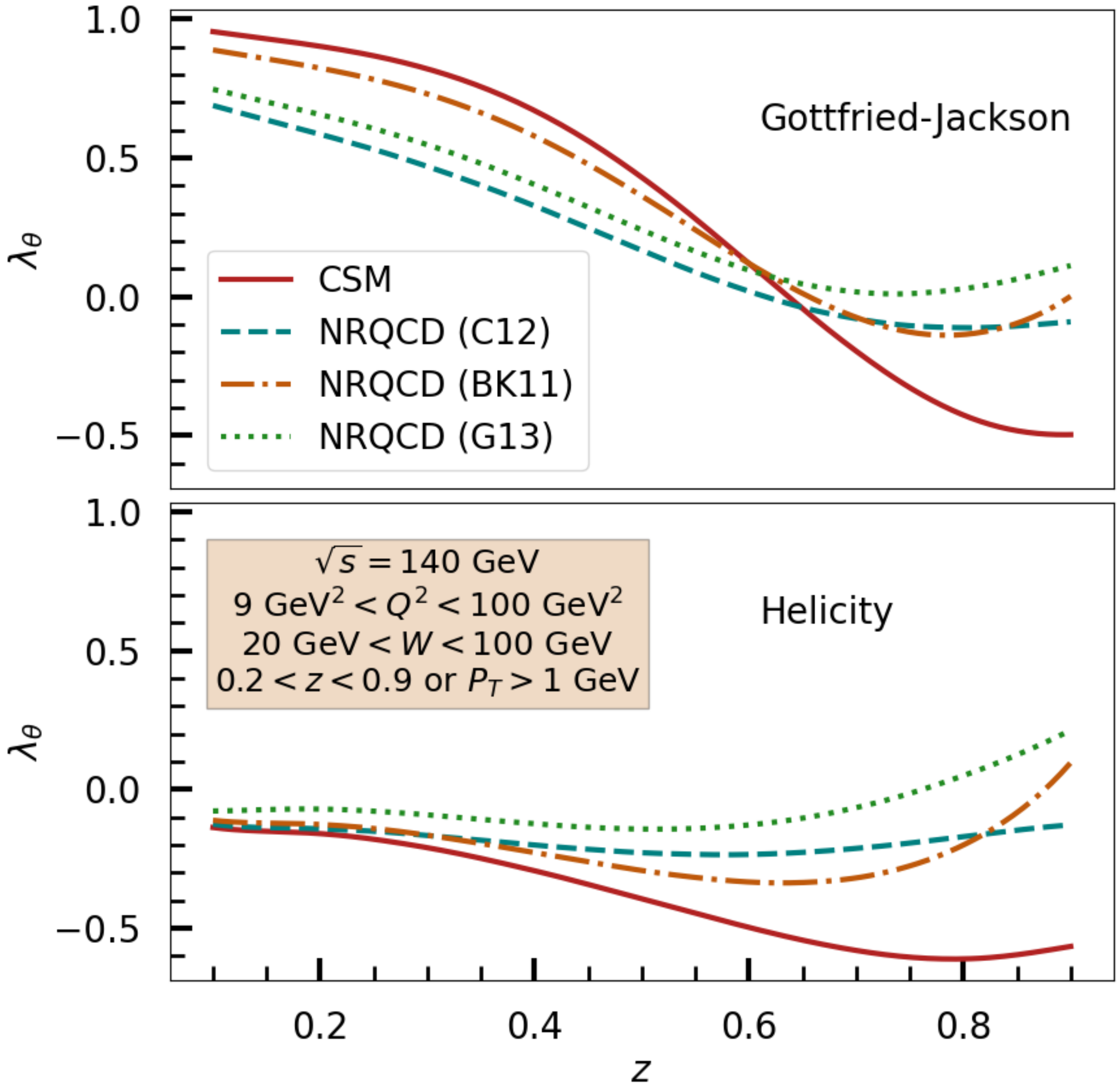


Polarization at EIC (λ@140GeV)



$Q > M_\psi$ region
W integr. covers half region

Polarization at EIC (λ@140GeV)



- Unpolarized cross section has a flat behaviour
- Relatively high values
- Not much difference between models and sets
- High-z behaviour interest

D'Alesio LM Murgia Pisano Sangem, (in preparation)

Polarization at EIC (λ@140GeV)

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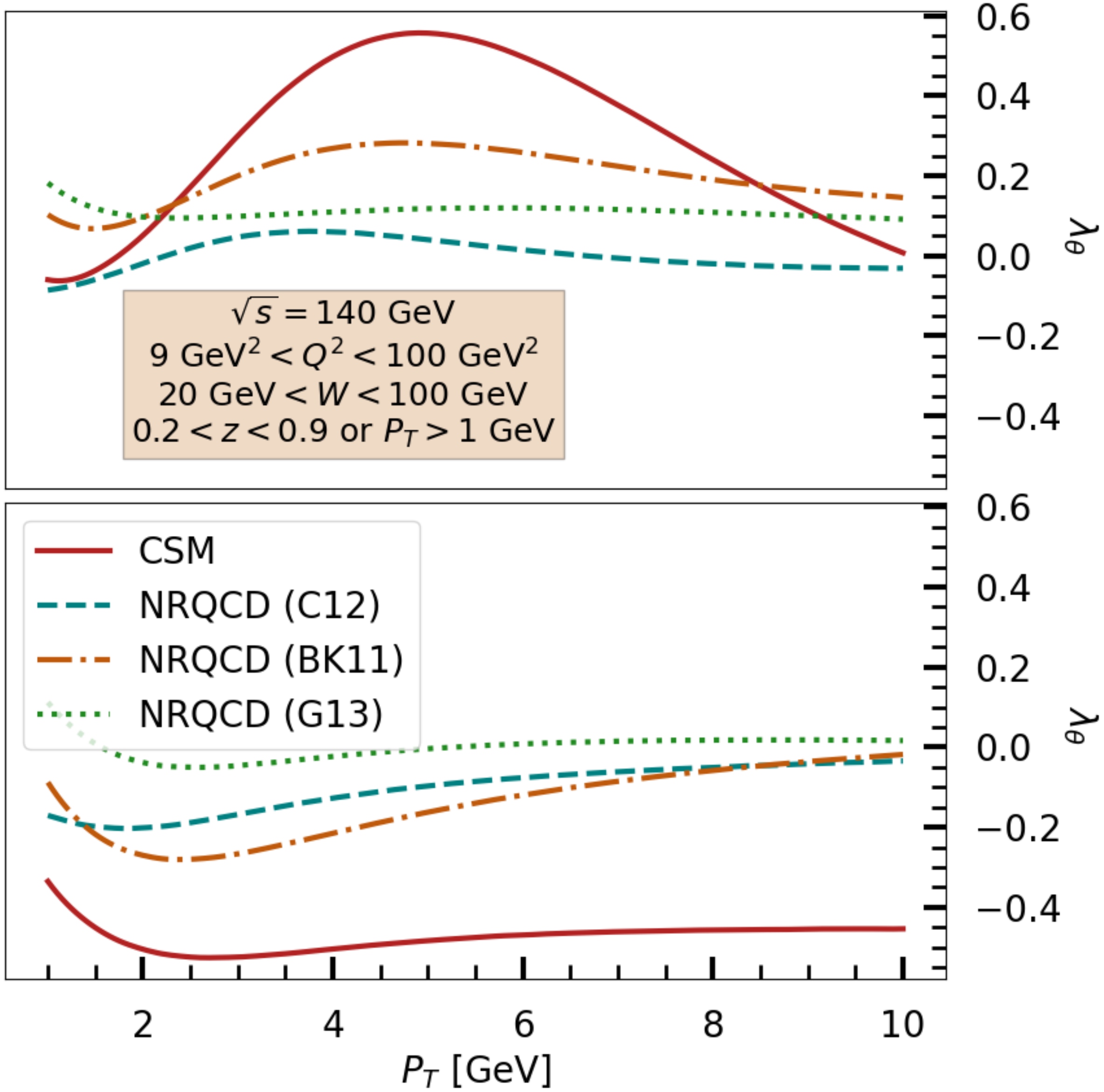
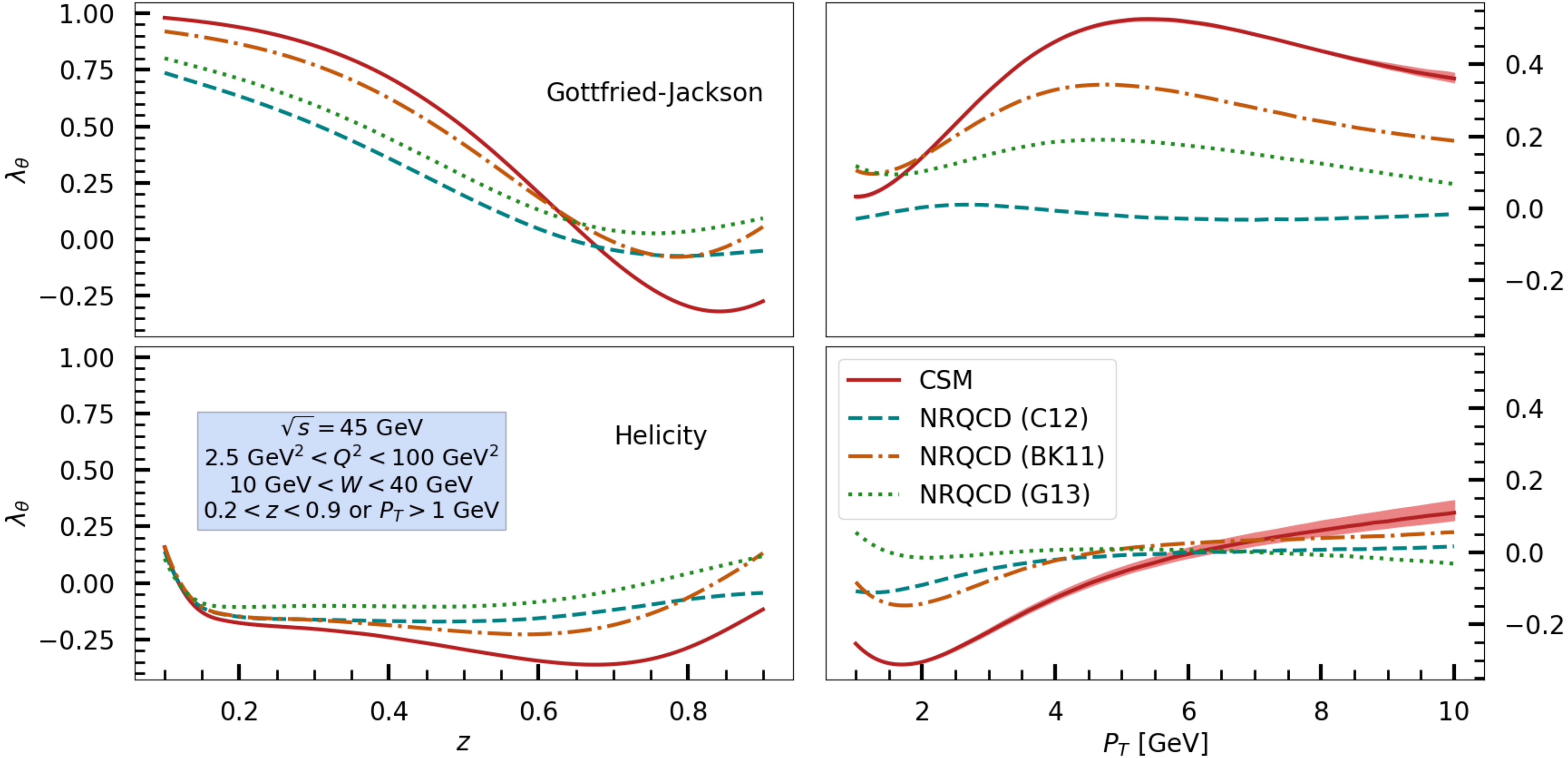
- Unpolarized cross section decrises with P_T
- Different behaviour between NRQCD and CSM predictions



Polarization at EIC (λ@45GeV)



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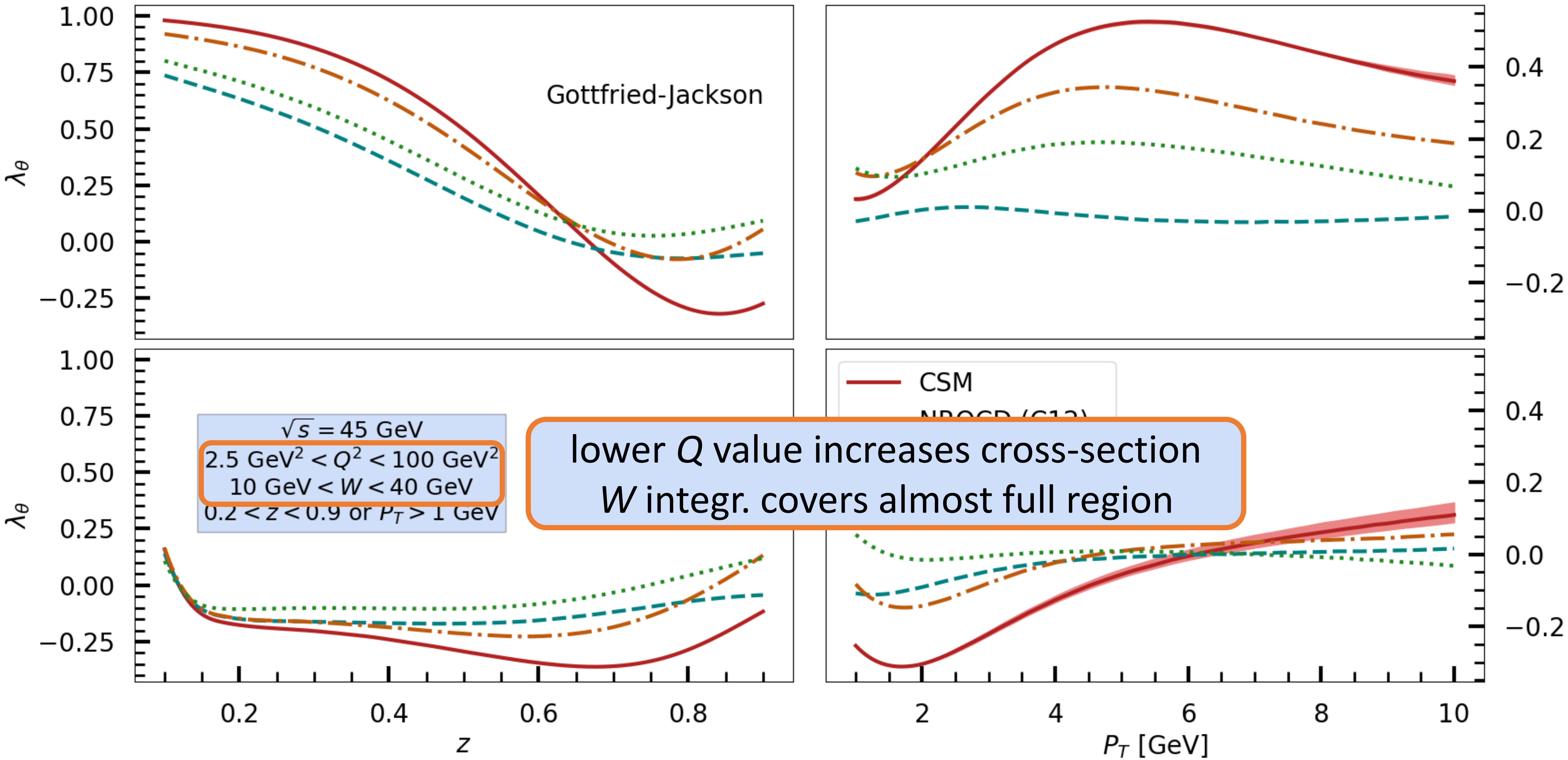
Polarization at EIC (λ@45GeV)



lower Q value increases cross-section
W integr. covers almost full region

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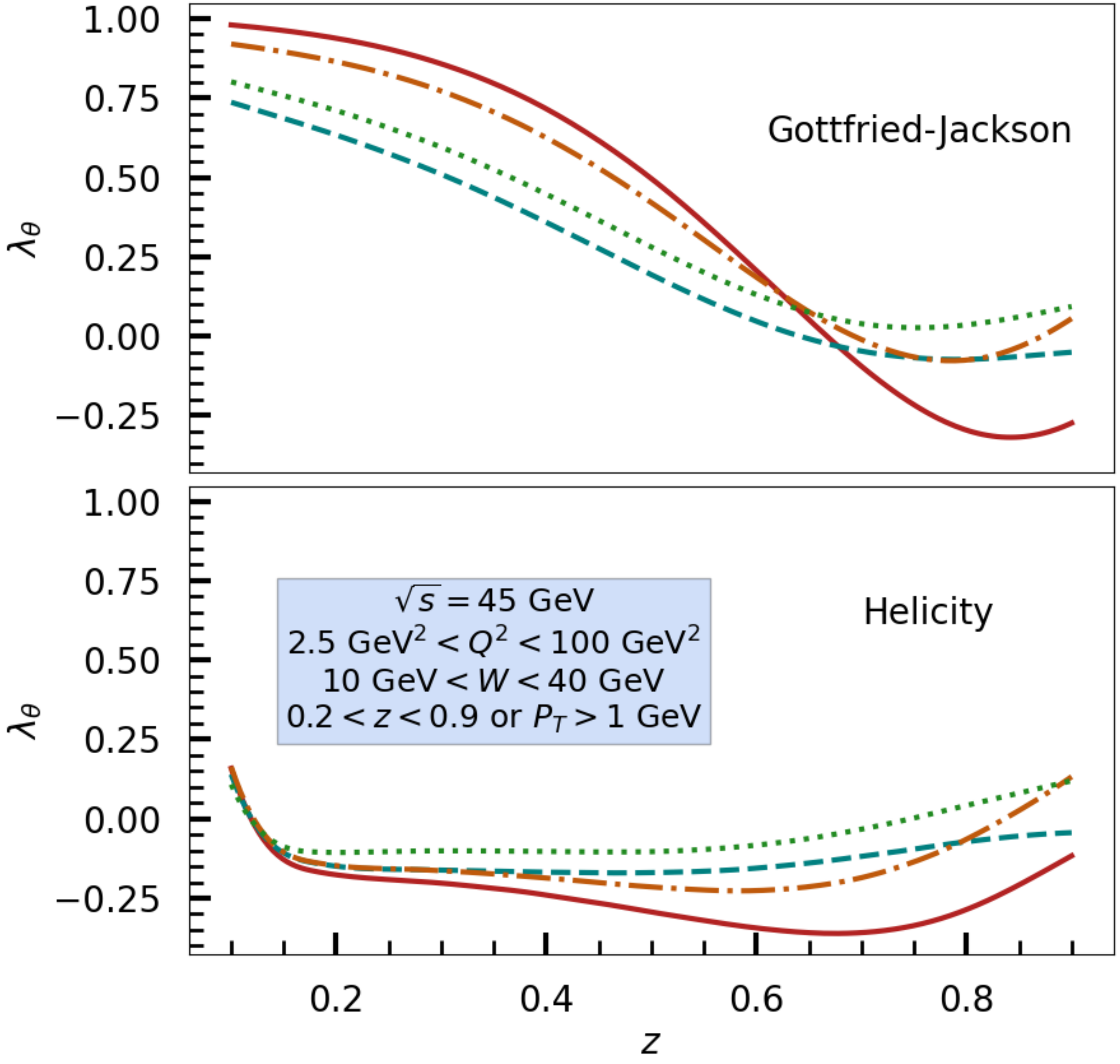
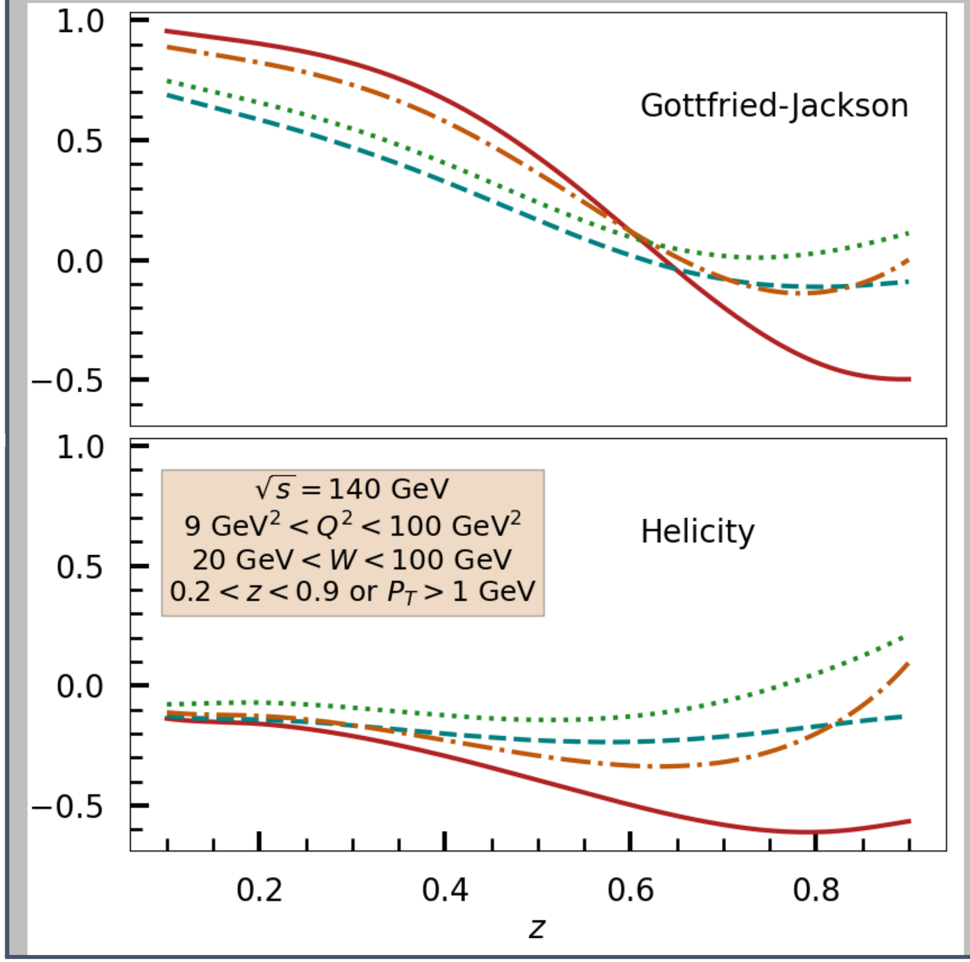
Polarization at EIC (λ@45GeV)



- low dependence on the energy:



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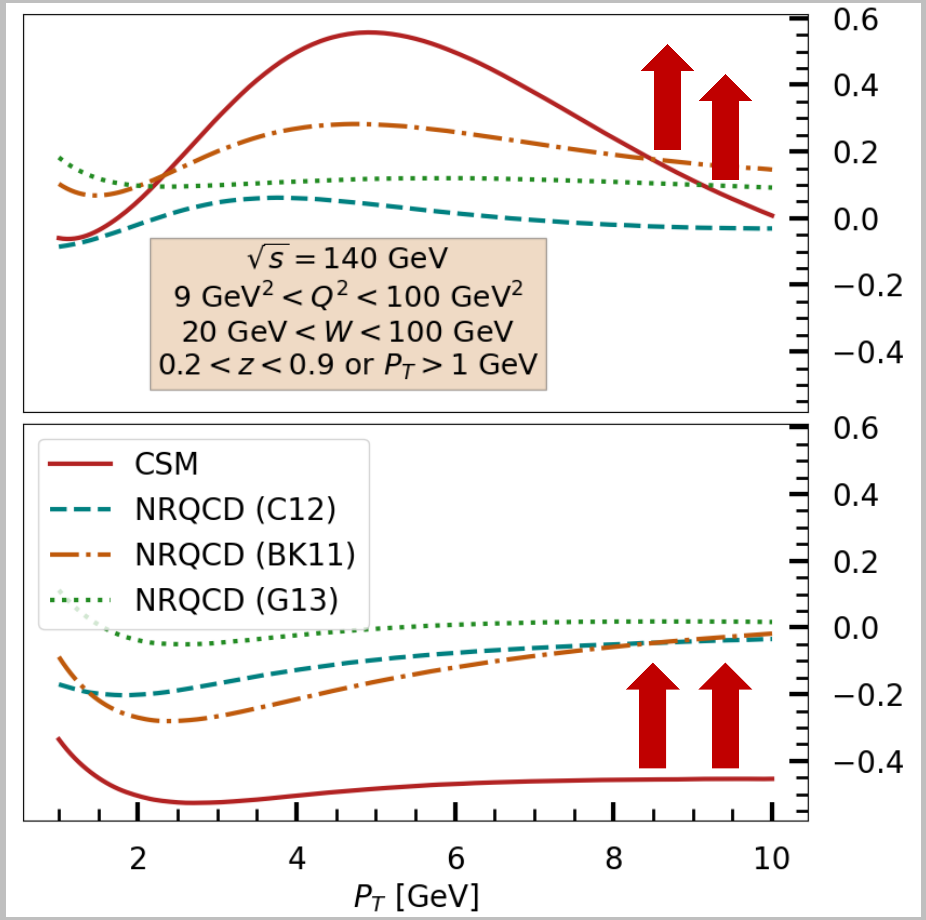
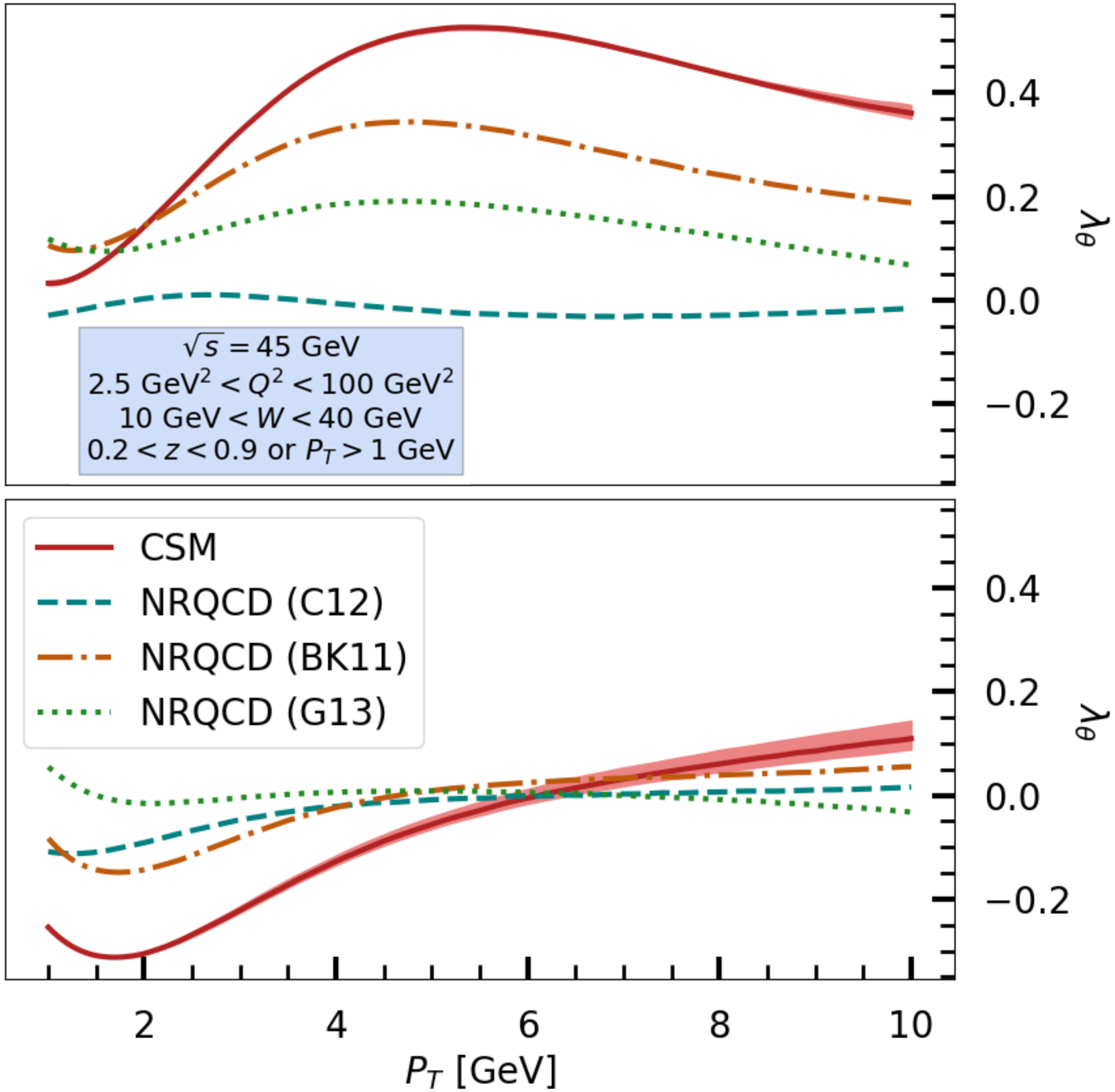
Polarization at EIC (λ@45GeV)

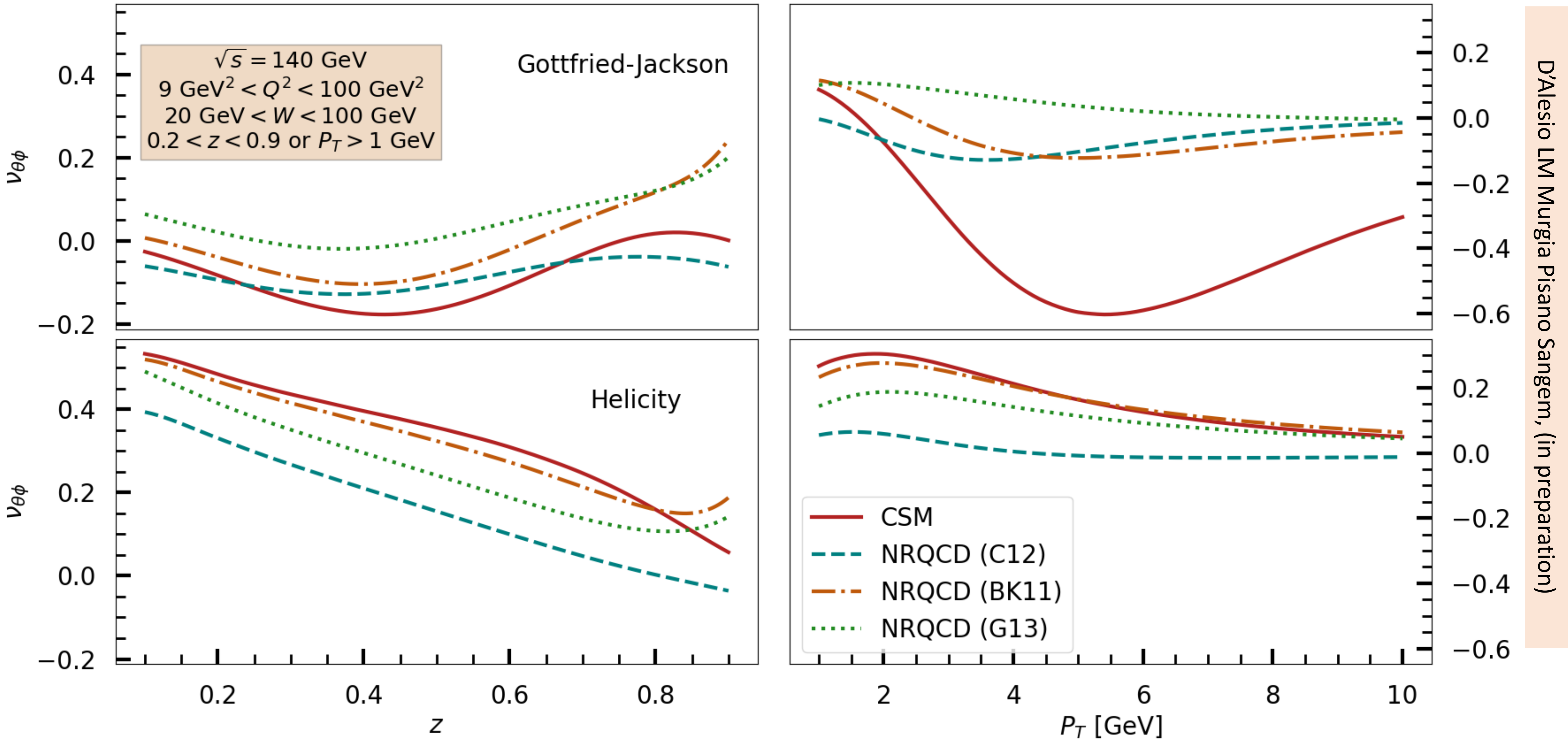
D'Alesio LM Murgia Pisano Sangem, (in preparation)

- visible dependence on the energy:





Polarization at EIC (ν@140GeV)



EIC ROTATIONAL INVARIANTS

Rotation around *Y*-axis from frame *A* to *B* mixes up the angular parameters

Like in Drell-Yan case, a rotational invariant approach can be a powerfull tool

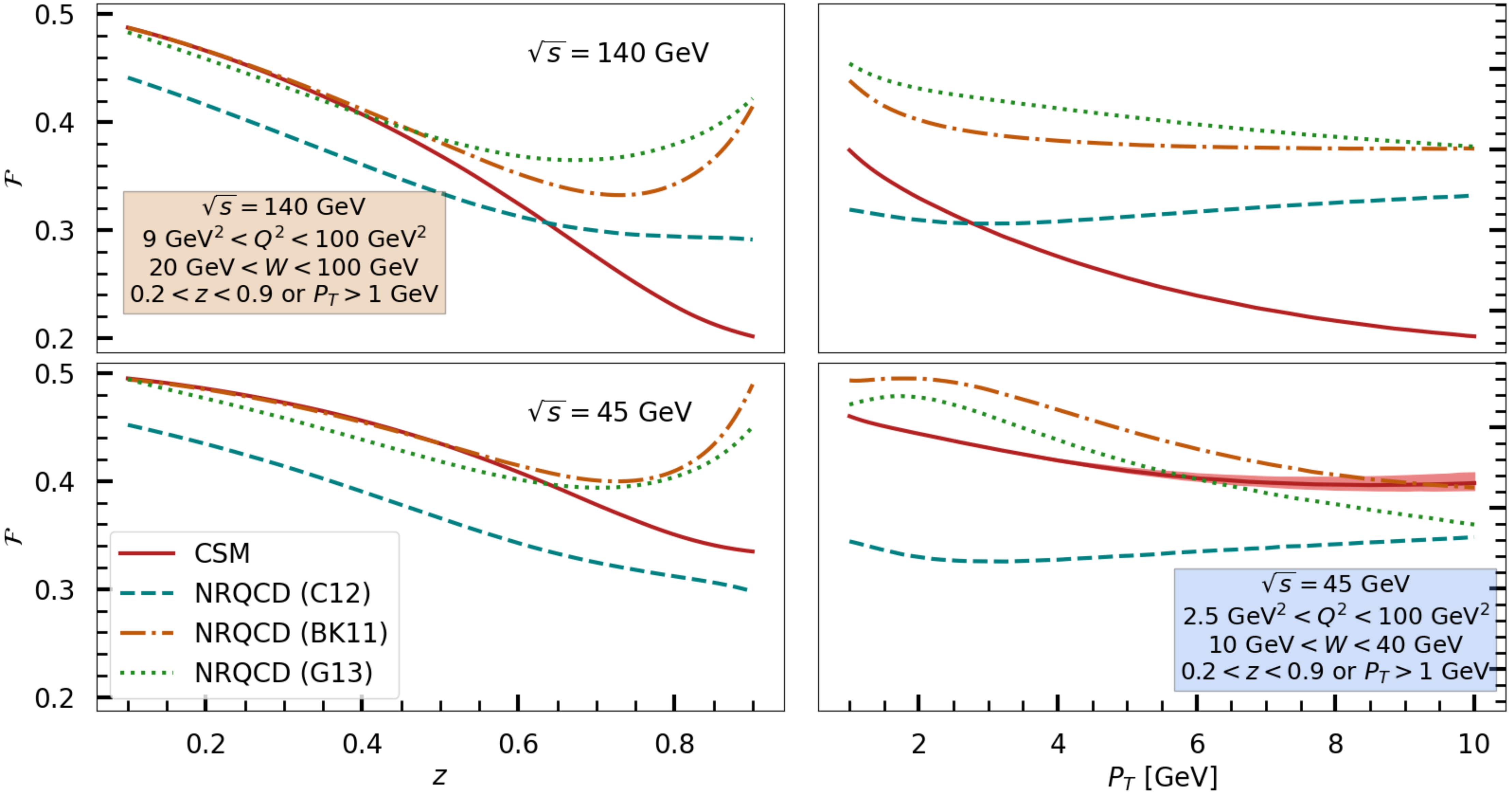
From λ_θ and $\nu_{\theta\phi}$ a family of invariant quantities can be identified, like

$$\mathcal{F} = \frac{1 + \lambda_\theta + \nu_{\theta\phi}}{3 + \lambda_\theta} \xrightarrow{\text{if Lam-Tung relation holds}} \mathcal{F} = \frac{1}{2}$$

All parameters $\lambda_\theta, \nu_{\theta\phi}, \mu_{\theta\phi}$ can identify another rotational invariant

$$\tilde{\lambda}' = \frac{(\lambda_\theta - \nu_{\theta\phi}/2)^2 + 4\mu_{\theta\phi}^2}{(3 + \lambda_\theta)^2}$$

EIC INVARIANTS PLOT (1)



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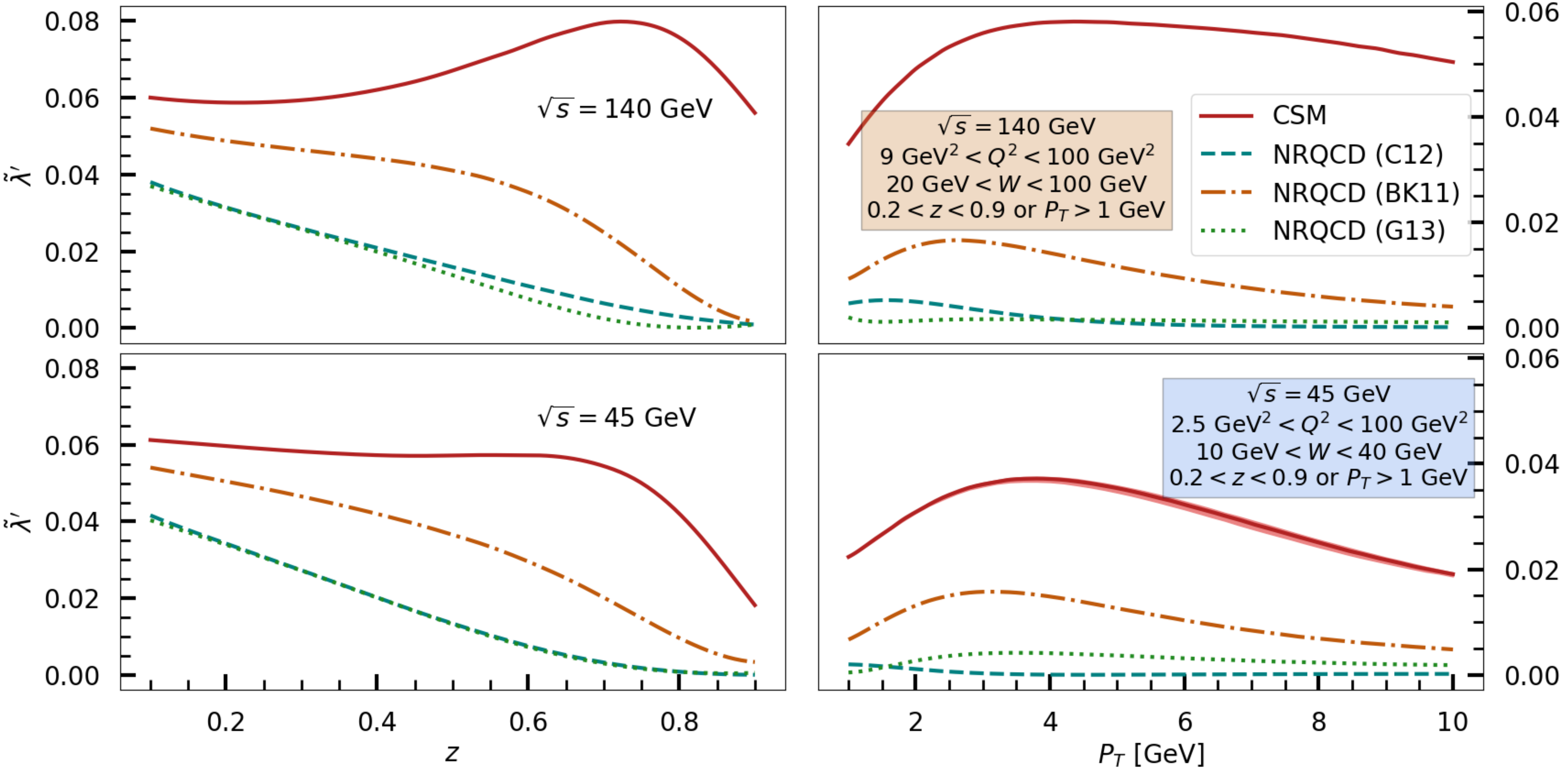
EIC INVARIANTS PLOT (2)



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TMD INTEREST

- Access to TMD shape function

Echevarria, JHEP 10 (2019)

Fleming, Makris, Mehen, JHEP 04 (2020)

- Access to TMD $h_1^{\perp g}$ linearly polarized gluon distribution

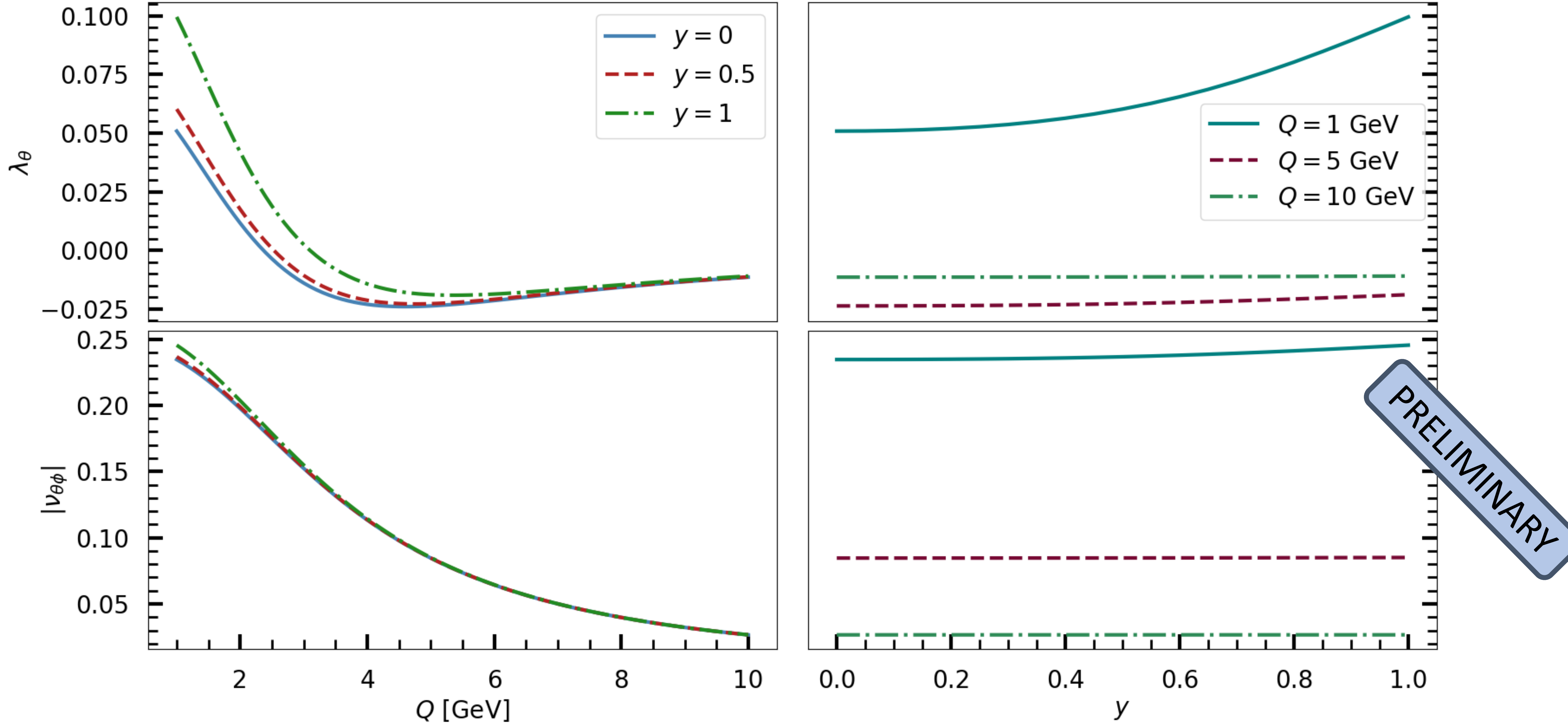
positivity bound $\frac{p_T^2}{2m_p^2}\left|h_1^{\perp g}\right| \leq f_1^g$

$$\mathcal{W}_T \propto \frac{1+(1-y)^2}{M_\psi(M_\psi^2+Q^2)}\left[\frac{1}{3}\mathcal{C}\left(f_1^g \Delta[^1S_0]\right)+\frac{4}{M_\psi^2}\frac{3M_\psi^4+Q^4}{(M_\psi^2+Q^2)^2}\mathcal{C}\left(f_1^g \Delta[^3P_0]\right)\right]$$

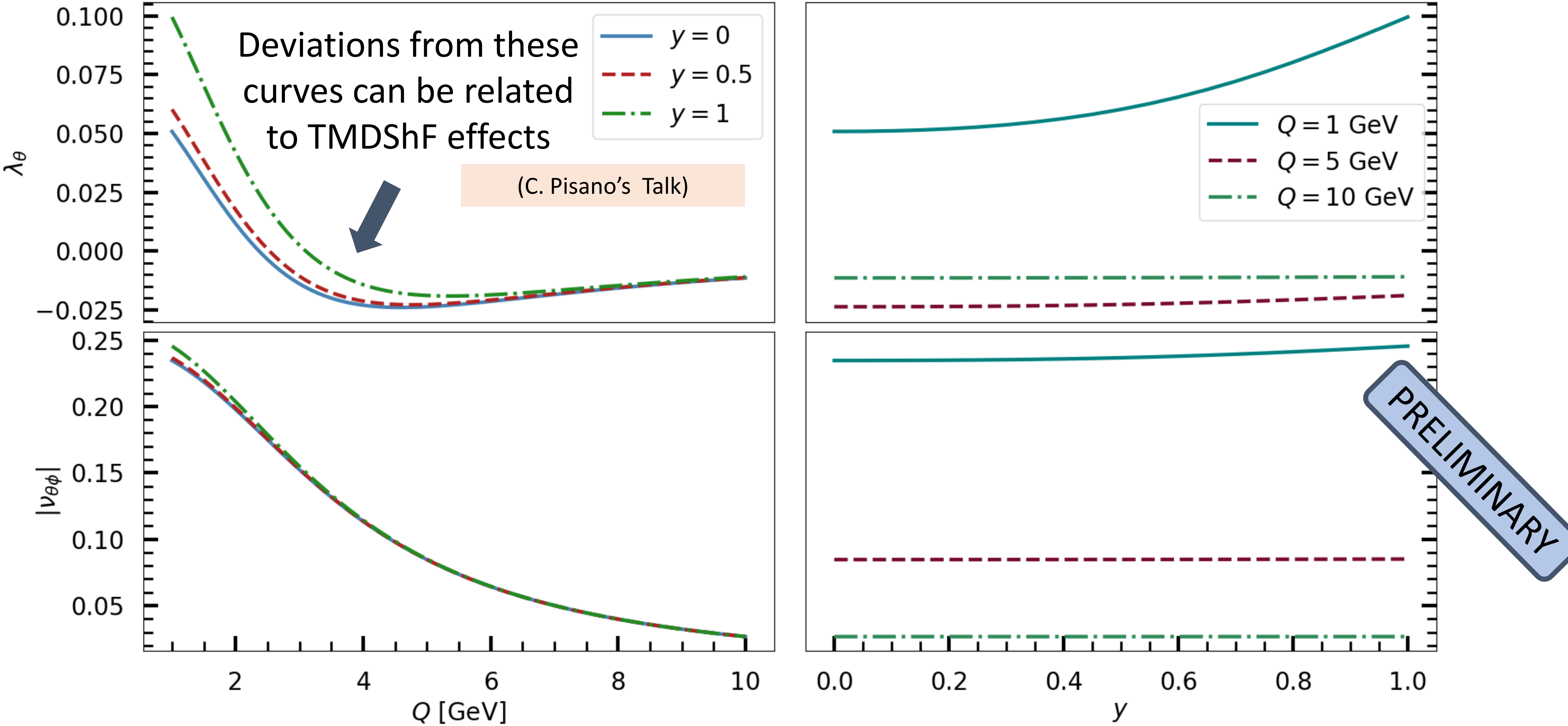
$$\mathcal{W}_L \propto \frac{1+(1-y)^2}{M_\psi(M_\psi^2+Q^2)}\left[\frac{1}{3}\mathcal{C}\left(f_1^g \Delta[^1S_0]\right)+\frac{4}{M_\psi^2}\mathcal{C}\left(f_1^g \Delta[^3P_0]\right)\right]+\frac{64Q^2(1-y)}{M_\psi(M_\psi^2+Q^2)^3}\mathcal{C}\left(f_1^g \Delta[^3P_0]\right)$$

$$\mathcal{W}_{\Delta\Delta} \propto -8\frac{1+(1-y)^2}{M_\psi(M_\psi^2+Q^2)^2}\mathcal{C}\left(w\, h_1^{\perp,g} \Delta[^3P_0]\right)$$

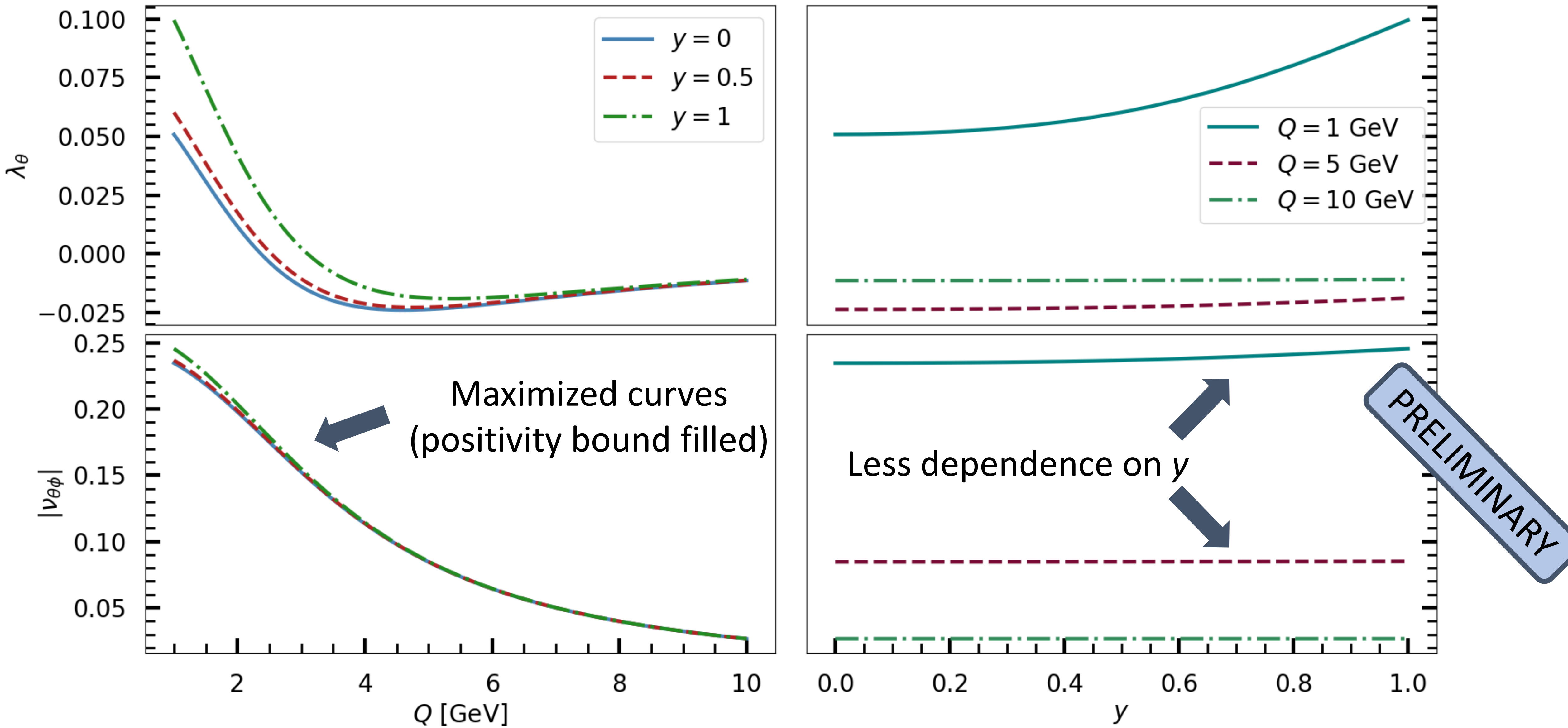
TMD PRELIMINARY PREDICTIONS



TMD PRELIMINARY PREDICTIONS



TMD PRELIMINARY PREDICTIONS



CONCLUSIONS

Importance of polarization J/ψ state analysis

Importance of full polarization measurements to achieve a complete picture

EIC luminosity could be useful in a P_T analysis

Studying the polarization behaviour at different energy/Q-binning

Rotational invariant quantities have a non-trival behaviour

Polarization data in the TMD region can disclose the role of TMDShF

Thanks for the attention