Collinear phenomenology of J/psi polarization at EIC

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EICUG Early Career Workshop 2022

Date: 26/05/2022

Istituto Nazionale di Fisica Nucleare

OUTLINE

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QUARKONIUM PUZZLE I

Quarkonium formation is described via different models

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

[1] Baier, Ruckl (1983)
[2] Berger, Jones (1981)

Color Singlet Model (CSM)

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

[2] Fritzsch (1977)
[3] Halzen (1977)

Color Evaporation Model (CEM)

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

[4] Bodwin, Braaten, Lepage (1997)
[5] Cho, Leibovich (1996)

Non-Relativistic QCD (NRQCD)

$$\sigma\left(\mathcal{Q}\right) = \sum_n \hat{\sigma}\left(Q\bar{Q}[n]\right)\langle 0|\mathcal{O}[n]|0\rangle$$

[6] Nayak, Qiu, Sterman (2005)
[7] Kang, Qiu, Sterman (2014)

Fragmentation Function approach (FF)

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

QUARKONIUM PUZZLE II

Quarkonium formation is described via different models

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

[1] Baier, Ruckl (1983)
[2] Berger, Jones (1981)

Color Singlet Model (CSM)

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

Quarkonium produced pertubatively as *color-neutral* $Q\bar{Q}$ couple

$|R(0)|$ from theoretical predictions

[4] Bodwin, Braaten, Lepage (1997)
[5] Cho, Leibovich (1996)

Non-Relativistic QCD (NRQCD)

$$\sigma\left(\mathcal{Q}\right) = \sum_n \hat{\sigma}\left(Q\bar{Q}[n]\right)\langle 0|\mathcal{O}[n]|0\rangle$$

$$[n] \equiv {}^{2S+1}L_J^{[c]}$$

Quarkonium produced pertubatively as *colored* $Q\bar{Q}$ couple that evolves non-pertubatively

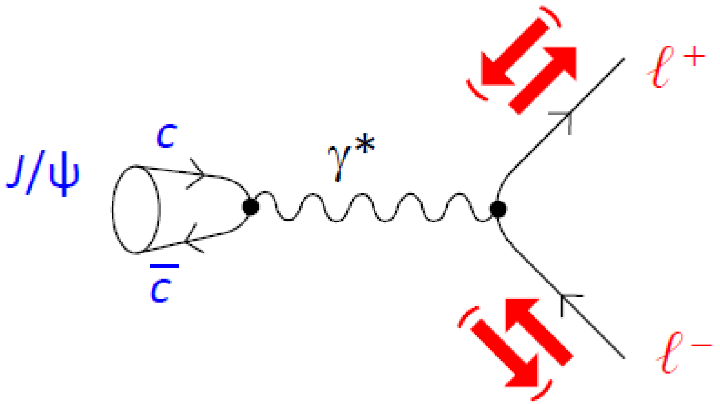
$\langle 0|\mathcal{O}[n]|0\rangle$ accessed via data fit

LDME

J/ψ DECAY PROPERTIES

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

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



Picture taken from Faccioli presentation for "Physics at LHC" 2022

[8] Faccioli, Lourenço, Seixas, Wöhri, EPJC 69 (2010)

Electroweak and strong forces preserve *helicity* (relativistic limit)

along l^+l^- quantization direction $m = 0$ is forbidden

$m_{J/\psi} = \pm 1, 0$

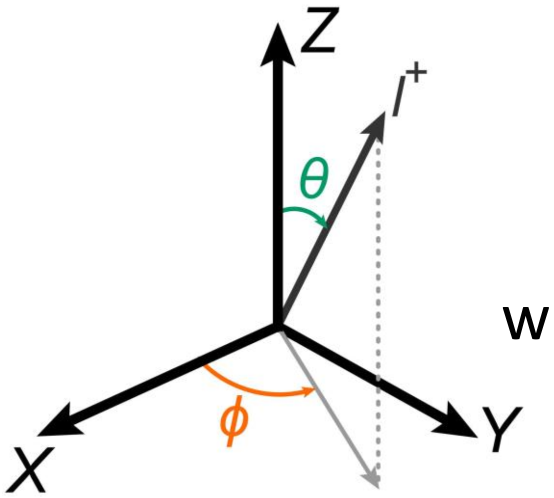
Wigner $D_{mm'}$-matrix

$m'_{l^+l^-} = \pm 1$

with parity conservation
(equal probability for m and $-m$)

ANGULAR STRUCTURE OF THE CROSS SECTION

Solid angle information enters the cross section via the following parameterization



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

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

$$\lambda_\theta = \frac{\mathrm{d}\sigma_{11} - \mathrm{d}\sigma_{00}}{\mathrm{d}\sigma_{11} + \mathrm{d}\sigma_{00}} \qquad \mu_{\theta\phi} = \frac{\sqrt{2}\,\mathrm{Re}[\mathrm{d}\sigma_{10}]}{\mathrm{d}\sigma_{11} + \mathrm{d}\sigma_{00}} \qquad \nu_\phi = \frac{2\mathrm{d}\sigma_{1\,-1}}{\mathrm{d}\sigma_{11} + \mathrm{d}\sigma_{00}}$$

→ polarized cross section $\mathrm{d}\sigma_{\lambda\lambda'}$

[9] Boer & Vogelsang, PRD 74 (2206)

This parameterization mimics the DY parameterization

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

${}^3P_J^{[8]}$ → $J = 0, 1, 2$

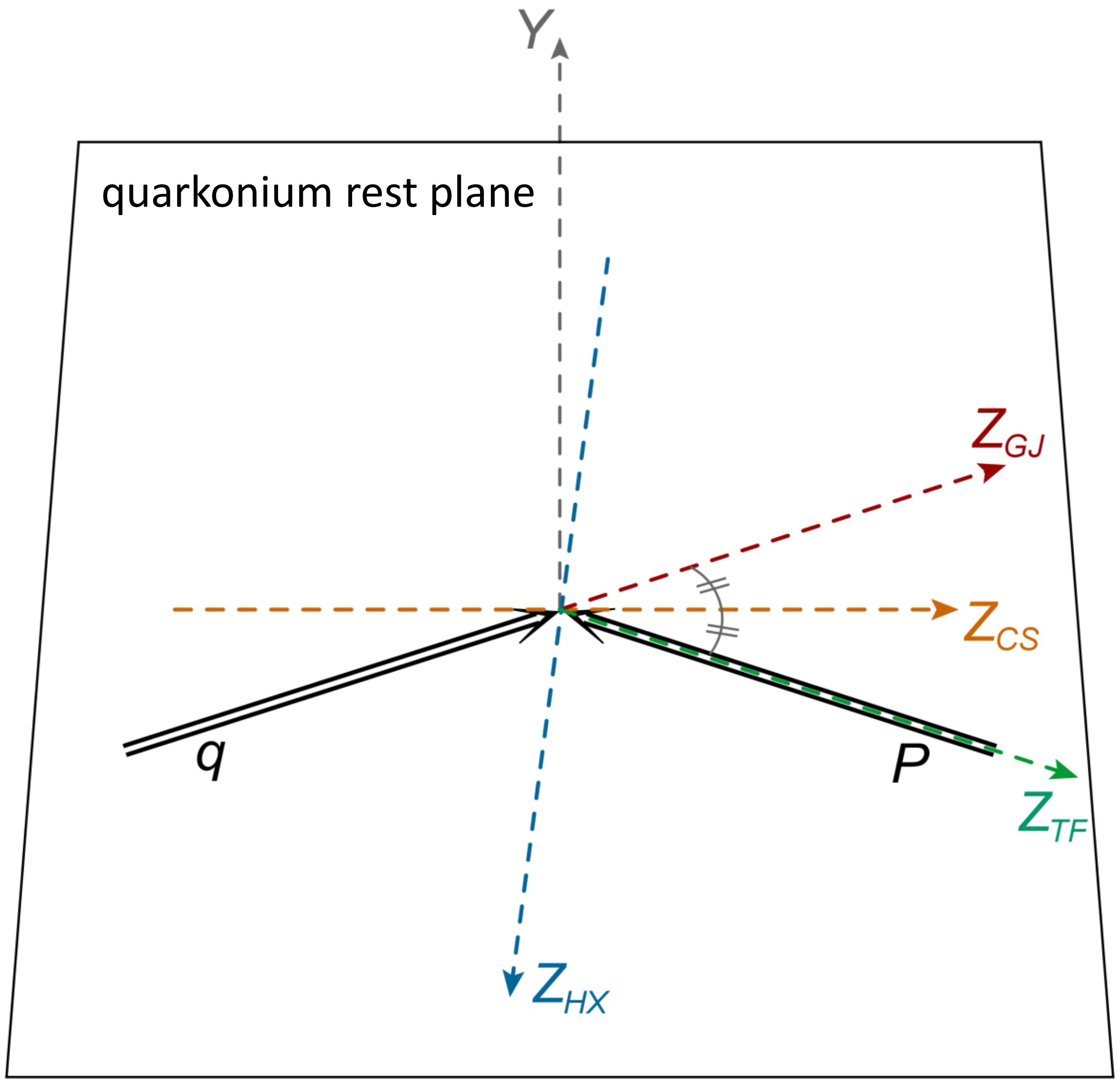
[10] Beneke, Krämer, Vänttinen, PRD 57 (1998)

NRQCD symmetries allow interference among states with same L and S

$$d\sigma_{\lambda\lambda'} = d\sigma_{\lambda\lambda'}({}^3S_1^{[1]}) + d\sigma_{\lambda\lambda'}({}^1S_0^{[8]}) + d\sigma_{\lambda\lambda'}({}^3S_1^{[8]}) + d\sigma_{\lambda\lambda'}(\{L=1, S=1\}^{[8]})$$

At high-q_T evaluated via partonic subprocess $\gamma^* + a \rightarrow c\bar{c}[n] + a$
(Collinear)

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

Experiments looks to the ratio of cross section

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \frac{3}{4\pi}\frac{1+\lambda_\theta\cos^2\theta + \mu_{\theta\phi}\sin 2\theta\cos\phi + \frac{\nu_\phi}{2}\sin^2\theta\cos 2\phi}{3+\lambda_\theta}$$

[11] Stebel, Watanabe, PRD 104 (2021)

angular parameter evaluated over a kinematic range, e.g. $\lambda_\theta = \frac{\int\left(\frac{\mathrm{d}\sigma_{11}}{\mathrm{d}PS} - \frac{\mathrm{d}\sigma_{00}}{\mathrm{d}PS}\right)\mathrm{d}PS}{\int\left(\frac{\mathrm{d}\sigma_{11}}{\mathrm{d}PS} + \frac{\mathrm{d}\sigma_{00}}{\mathrm{d}PS}\right)\mathrm{d}PS}$

Next: predictions in CSM and NRQCD

C12	[11] Chao, Ma, Shao, Wang, Zhang, PRL 108 (2012)	⟶ includes polarization data
G13	[12] Gong, Wan, Wang, Zhang, PRL 110 (2013)	⟶ tested on polarization data
BK11	[13] Butenschoen & Kniehl, PRD 84 (2011)	⟶ includes low-P_T photoproduction data

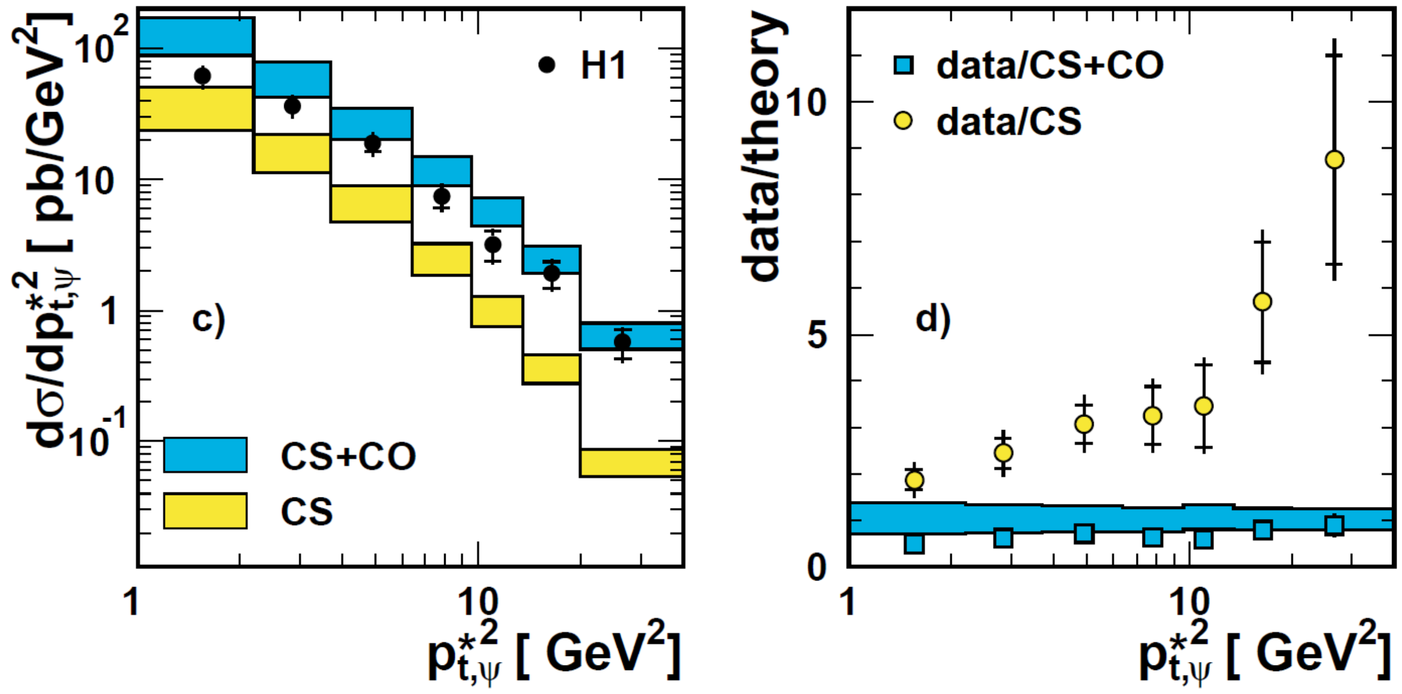
HERA UNPOLARIZED DATA

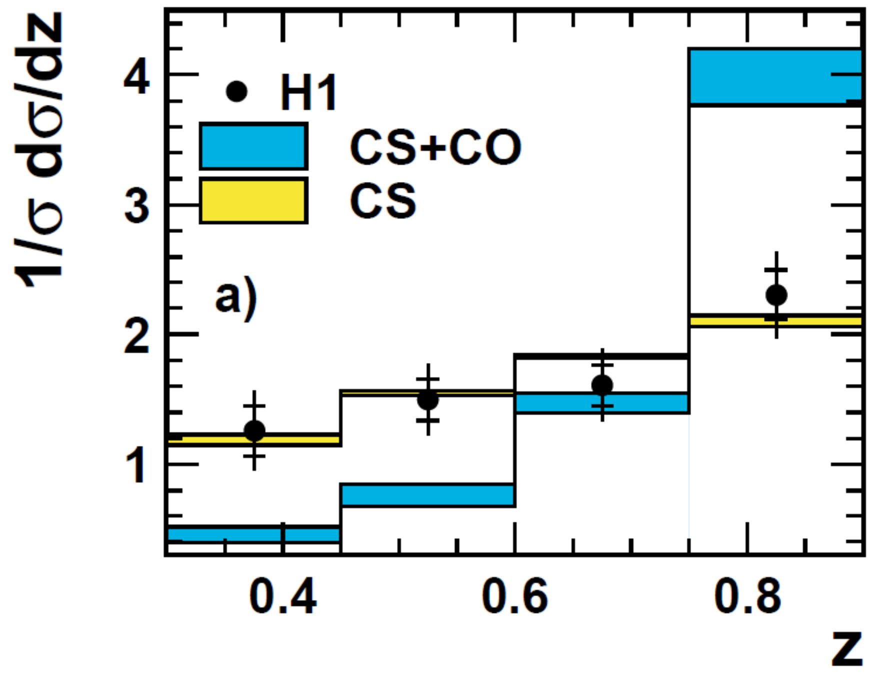
[14] Adloff et al. (H1 Collaboration), EPJ C 25 (2002)

[15] Kniehl & Zwirner, NPB 621 (2002)

Data from HERA collaboration

Theoretical predictions obtained by Kniehl-Zwirner





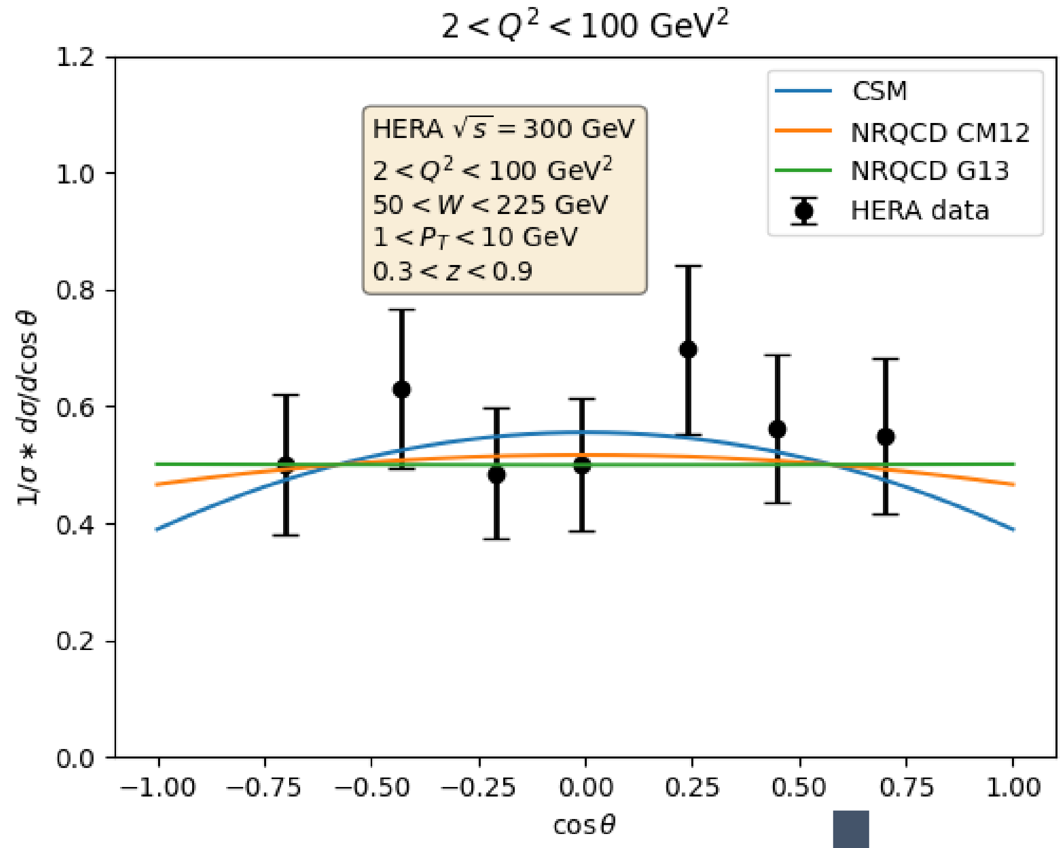
P_T data show a general better agreement with NRQCD predictions

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

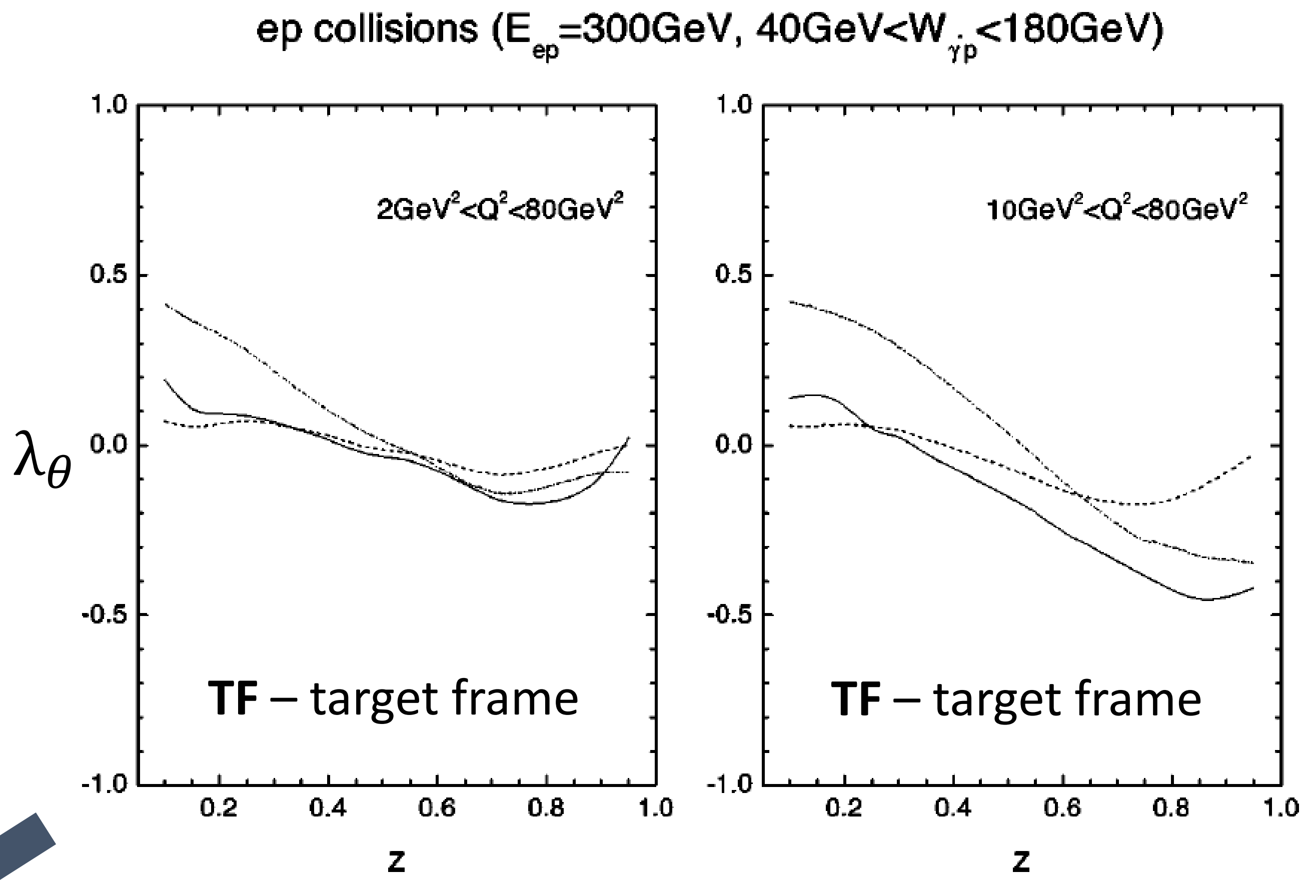
[14] Adloff et al. (H1 Collaboration), EPJ C 25 (2002)

[15] Yuan & Chao, PRD 63 (2001)

Data from HERA collaboration



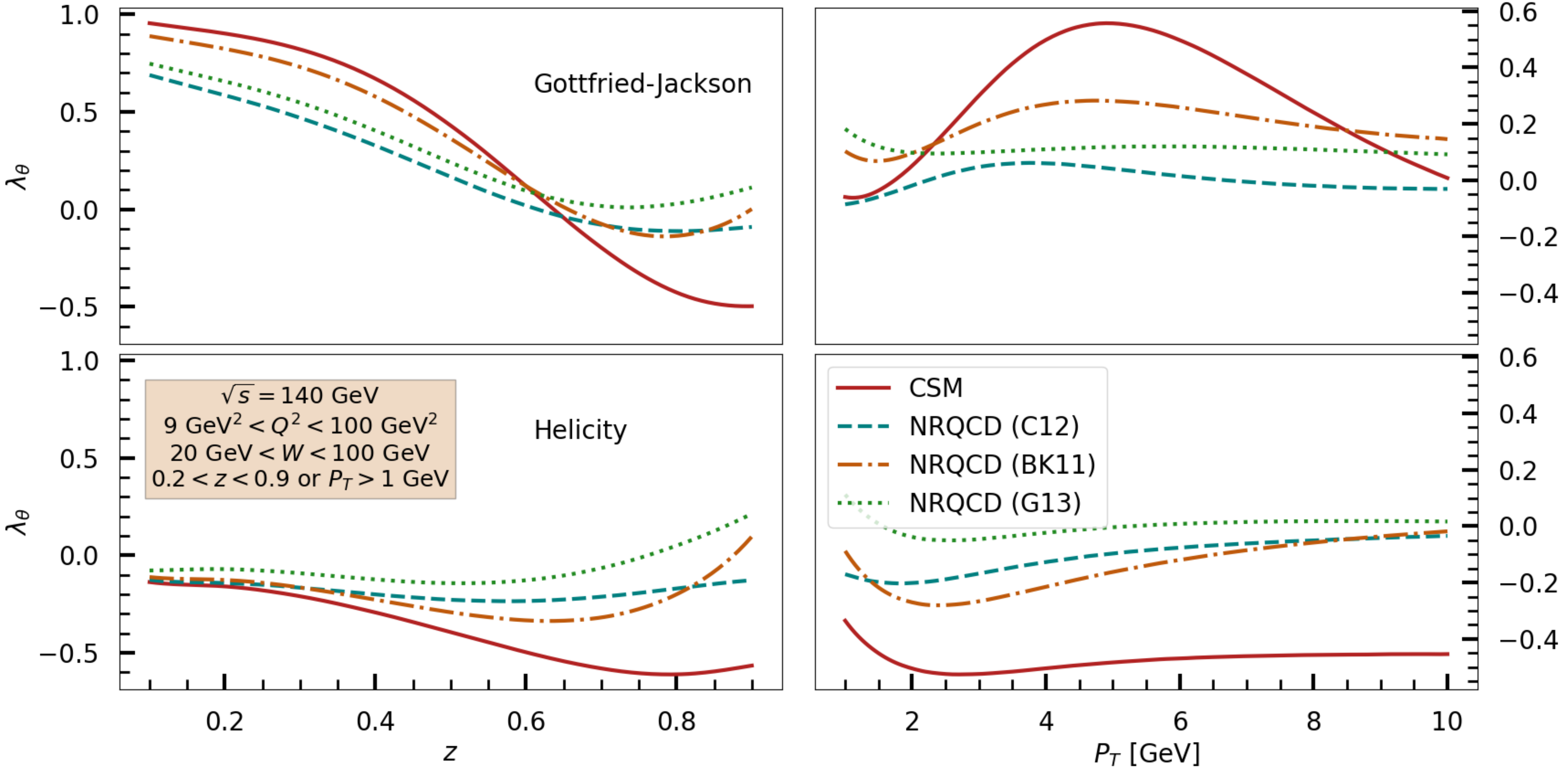
From Yuan-Chao paper



includes resolved photon contribution

Hard to extract information

Polarization at EIC (λ@140GeV)



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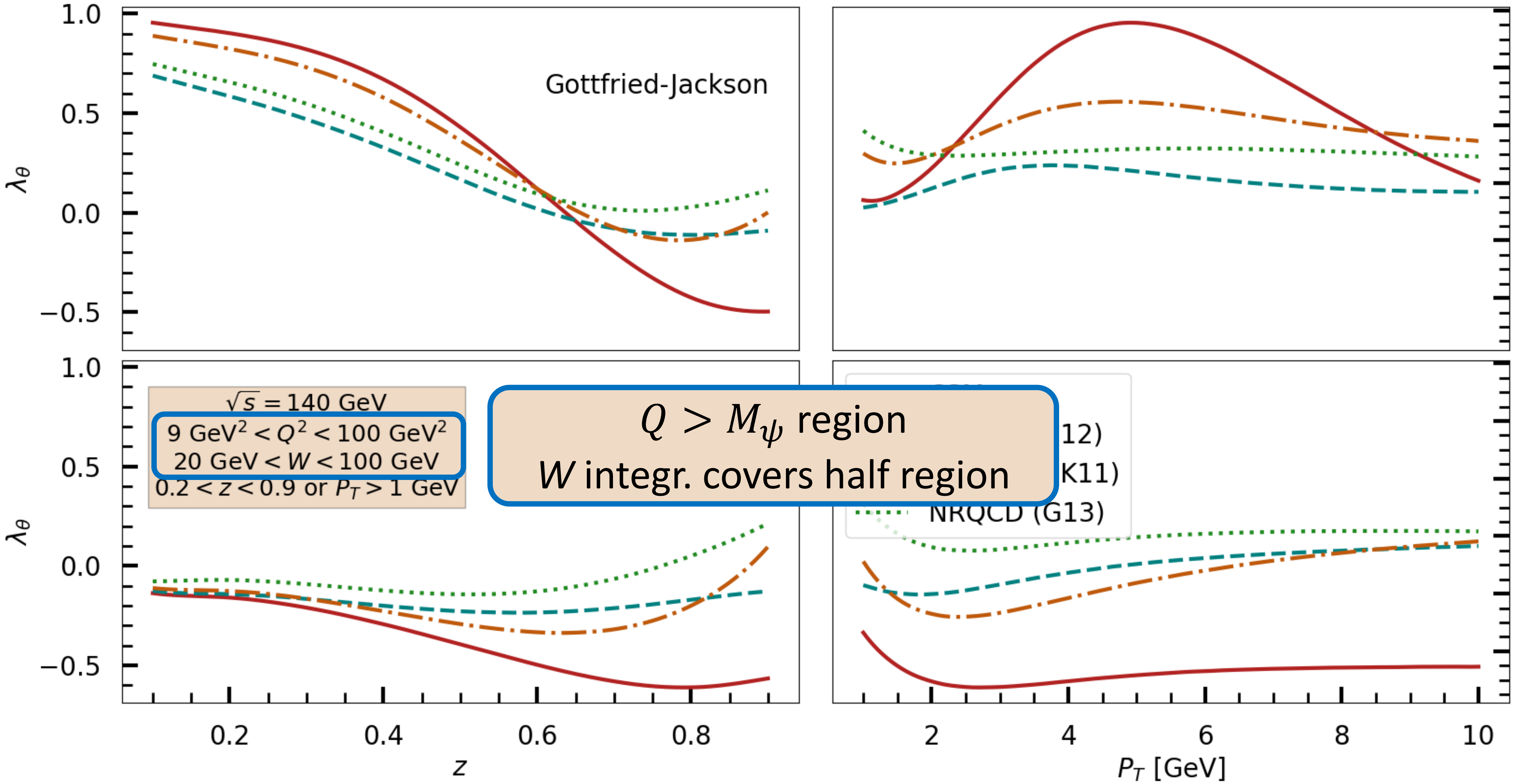
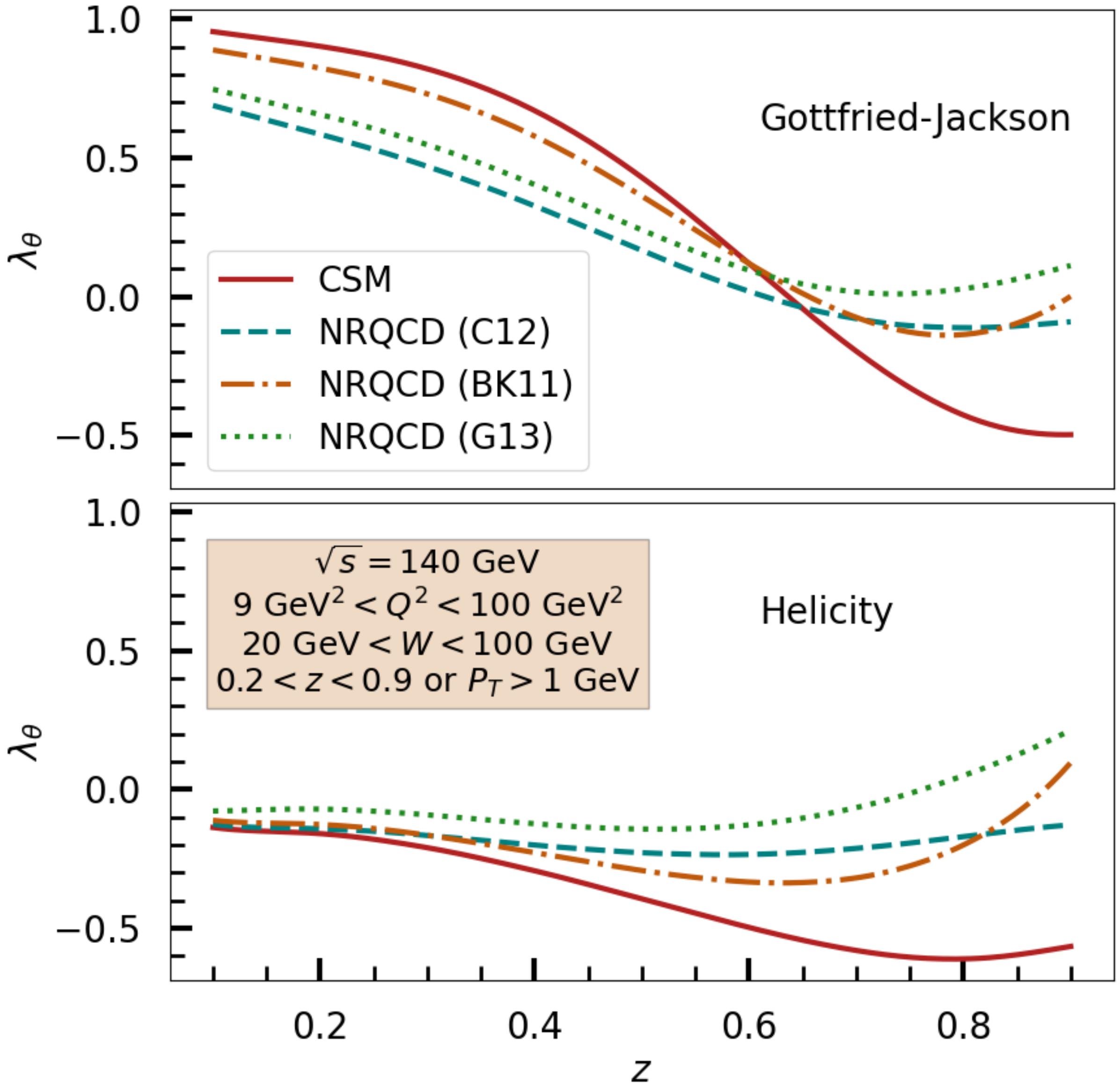
Polarization at EIC (λ@140GeV)



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

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

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

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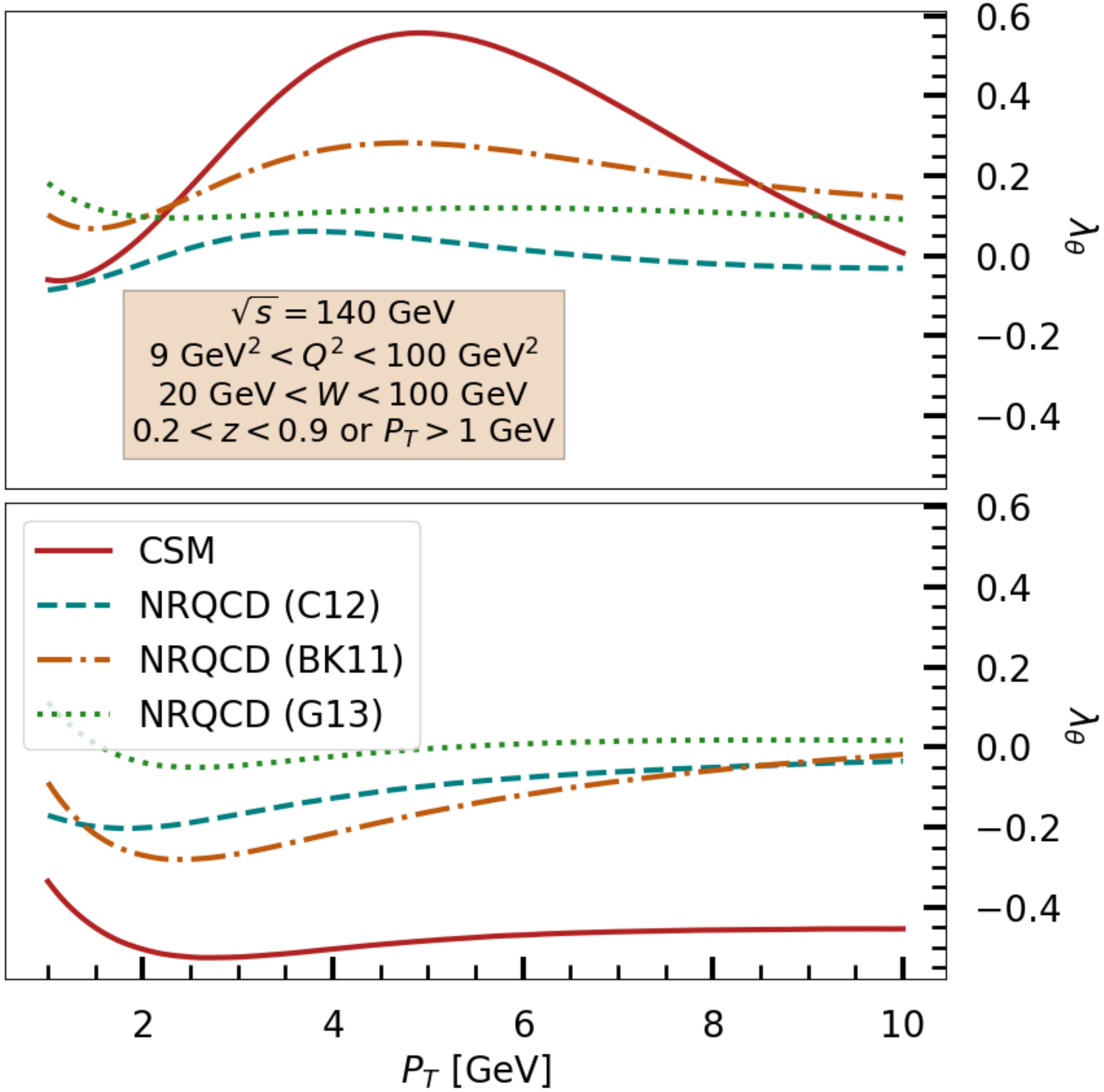
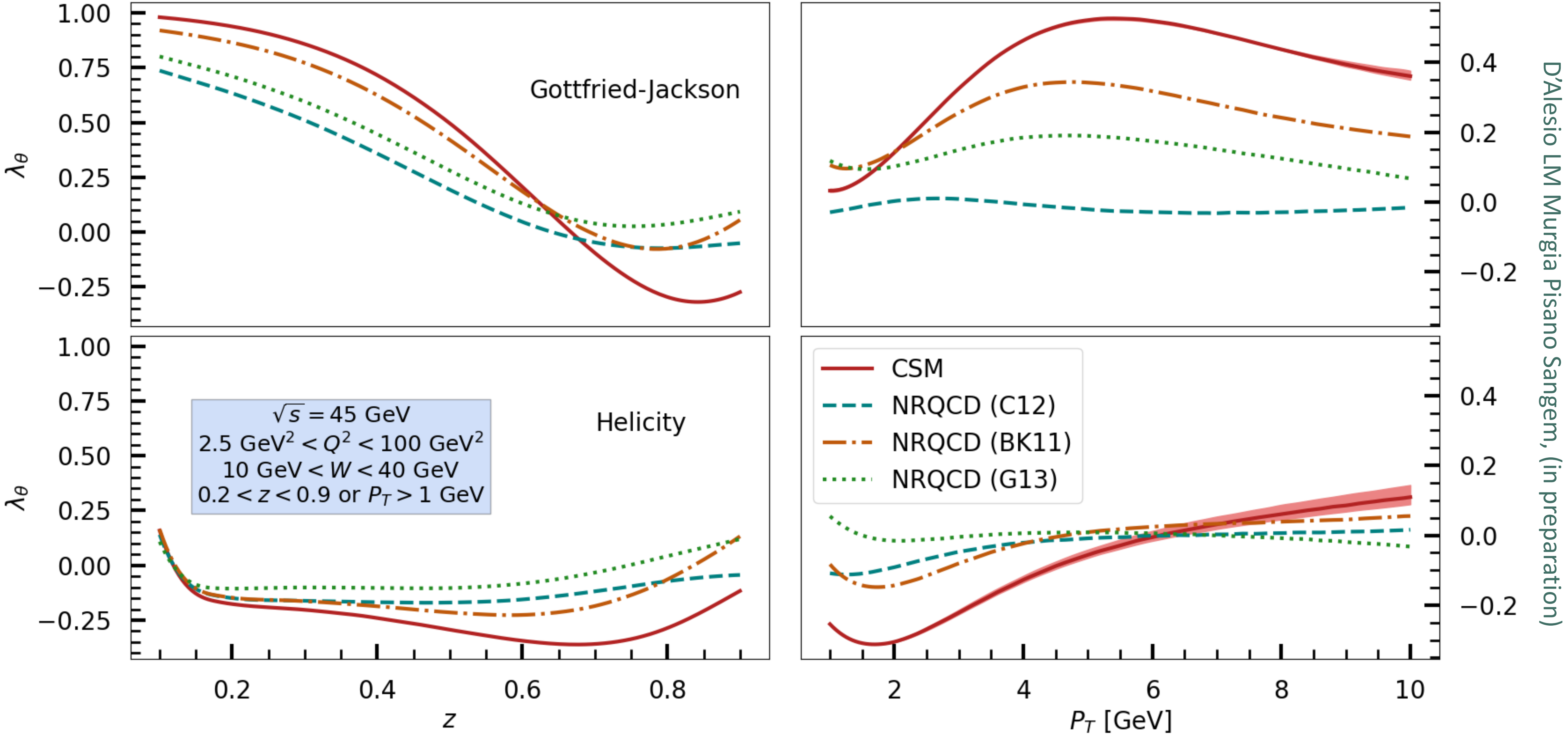
Polarization at EIC (λ@140GeV)

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

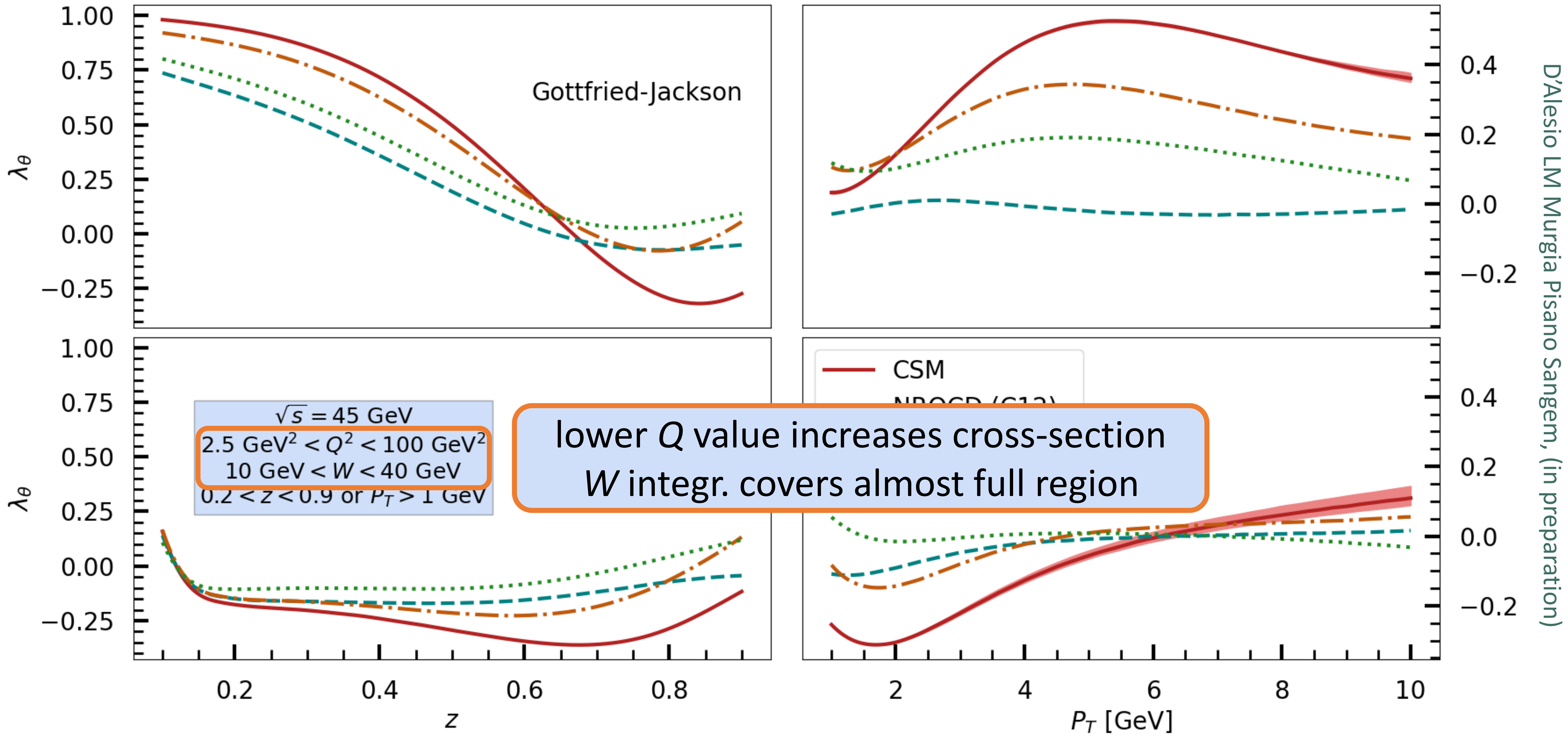
- Unpolarized cross section decrises with P_T
- Different behaviour between NRQCD and CSM predictions



Polarization at EIC (λ@45GeV)

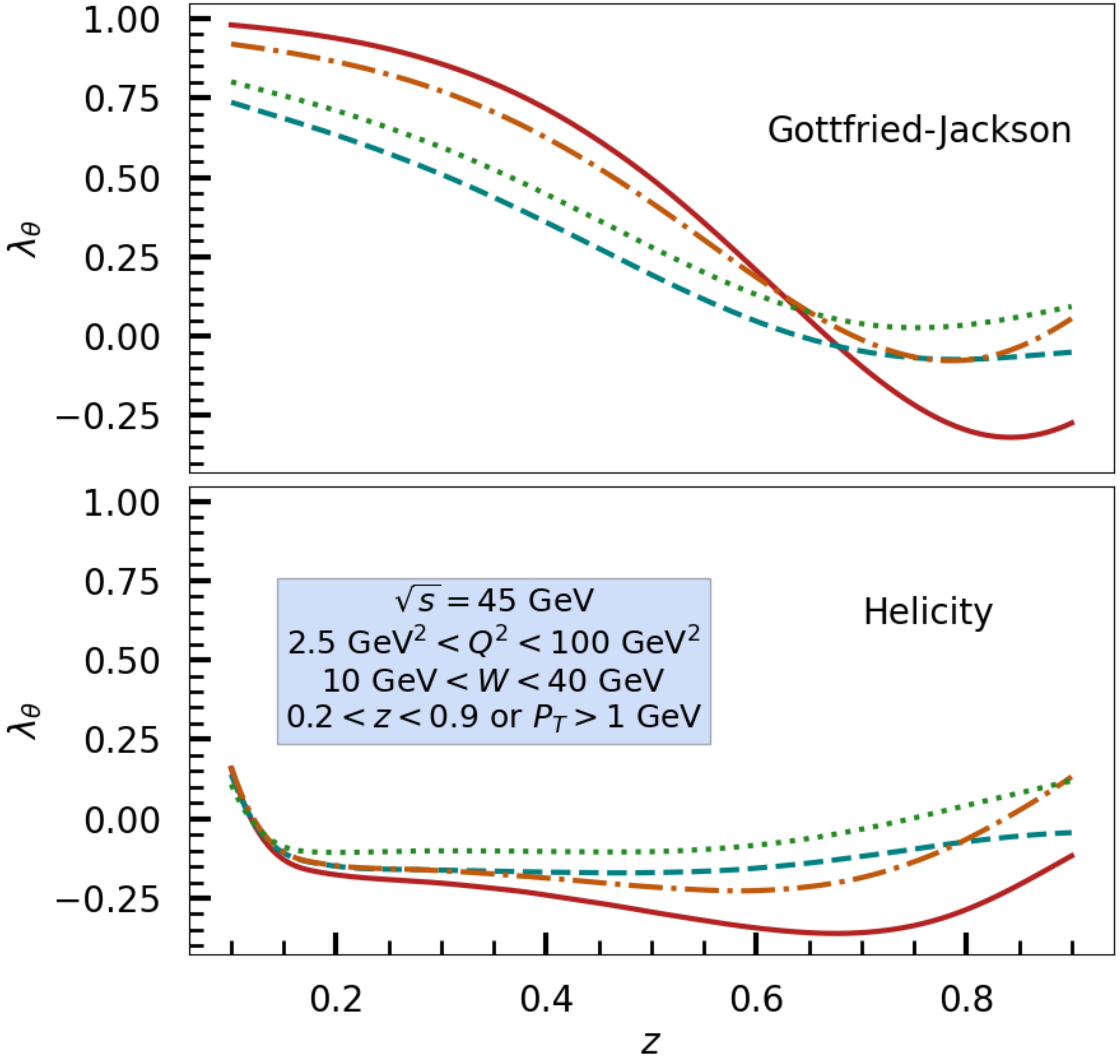


Polarization at EIC (λ@45GeV)

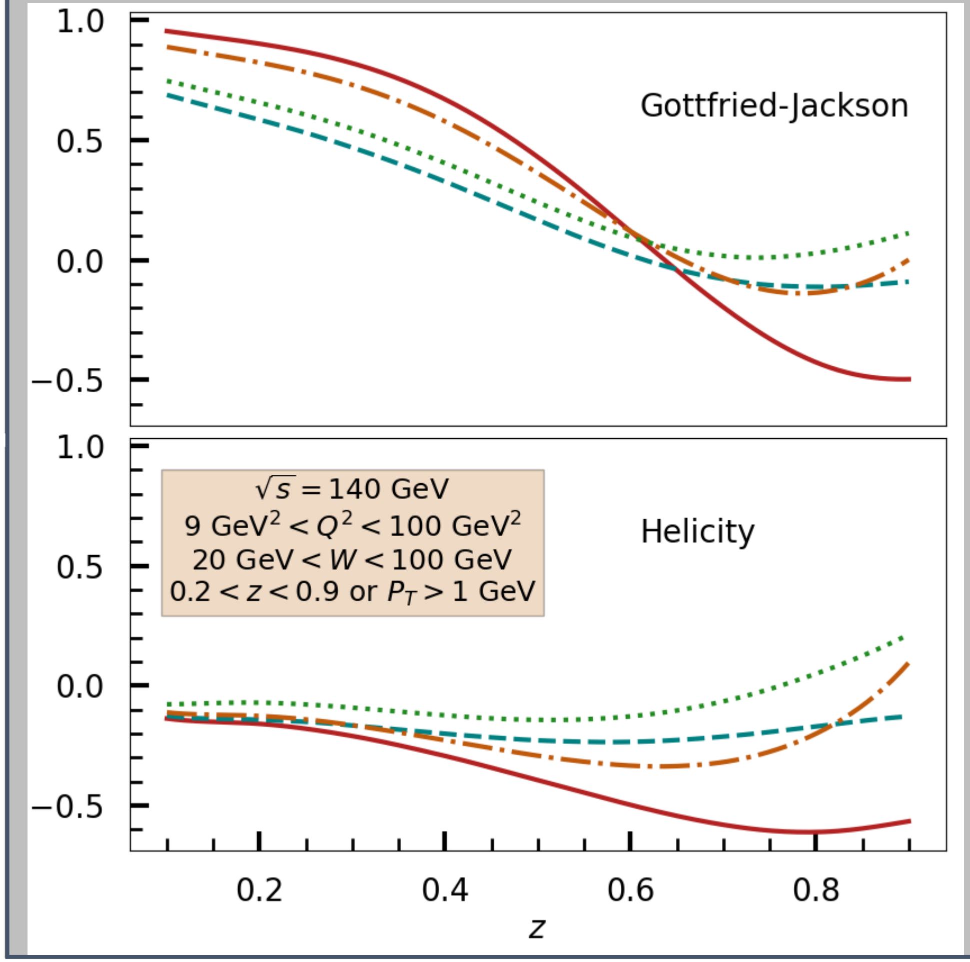


lower Q value increases cross-section
W integr. covers almost full region

Polarization at EIC (λ@45GeV)



- low dependence on the energy:

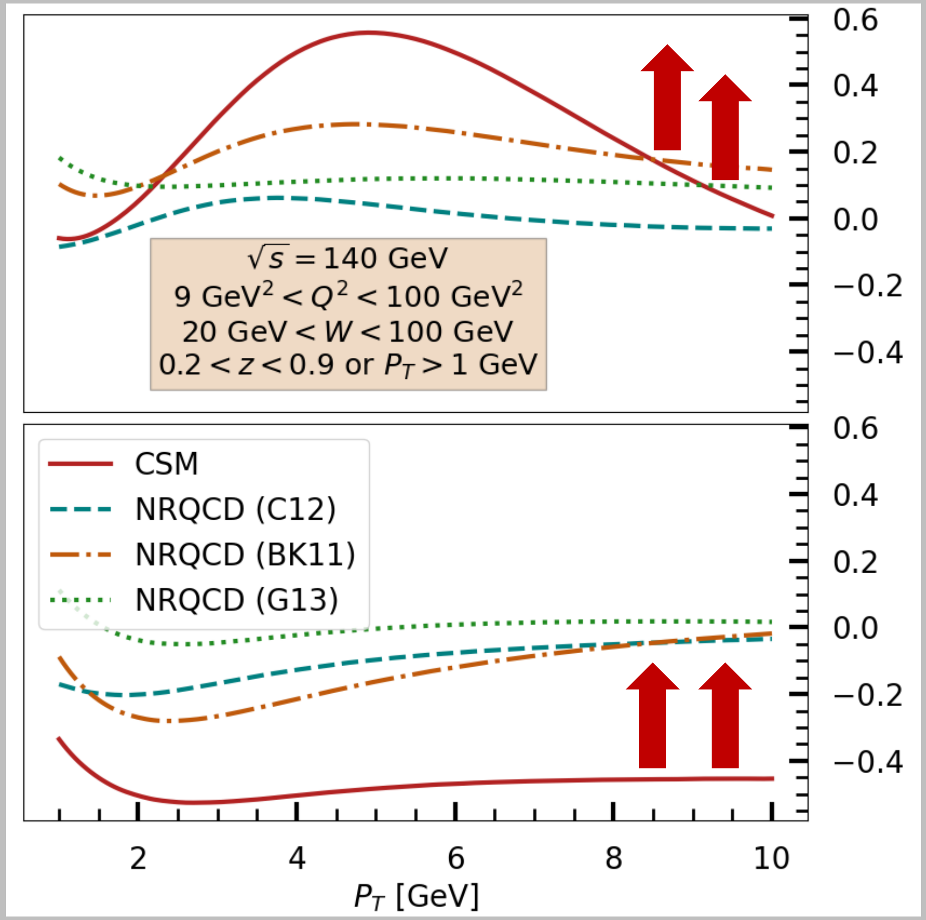


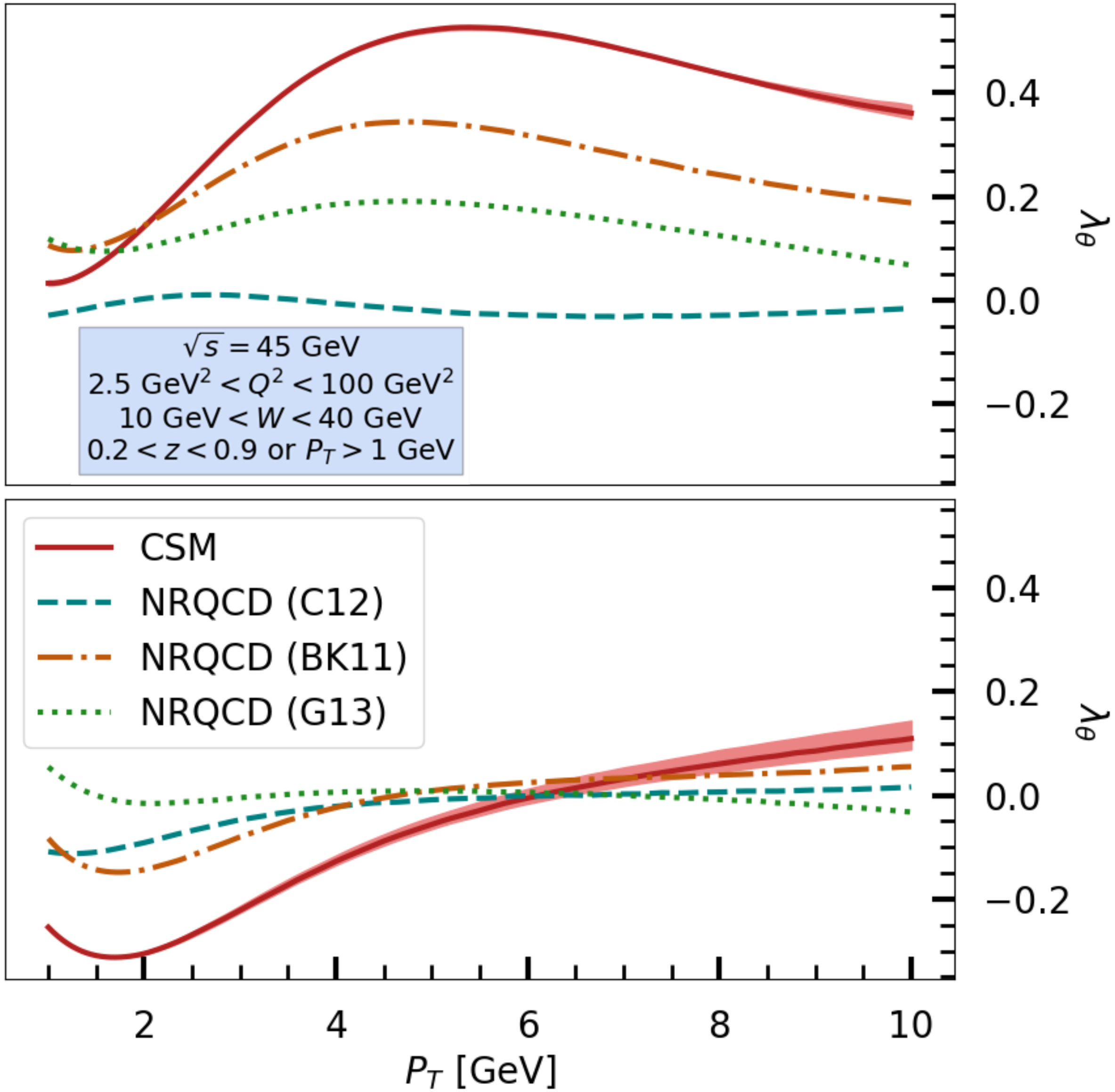
D'Alesio LM Murgia Pisano Sangem, (in preparation)

Polarization at EIC (λ@45GeV)

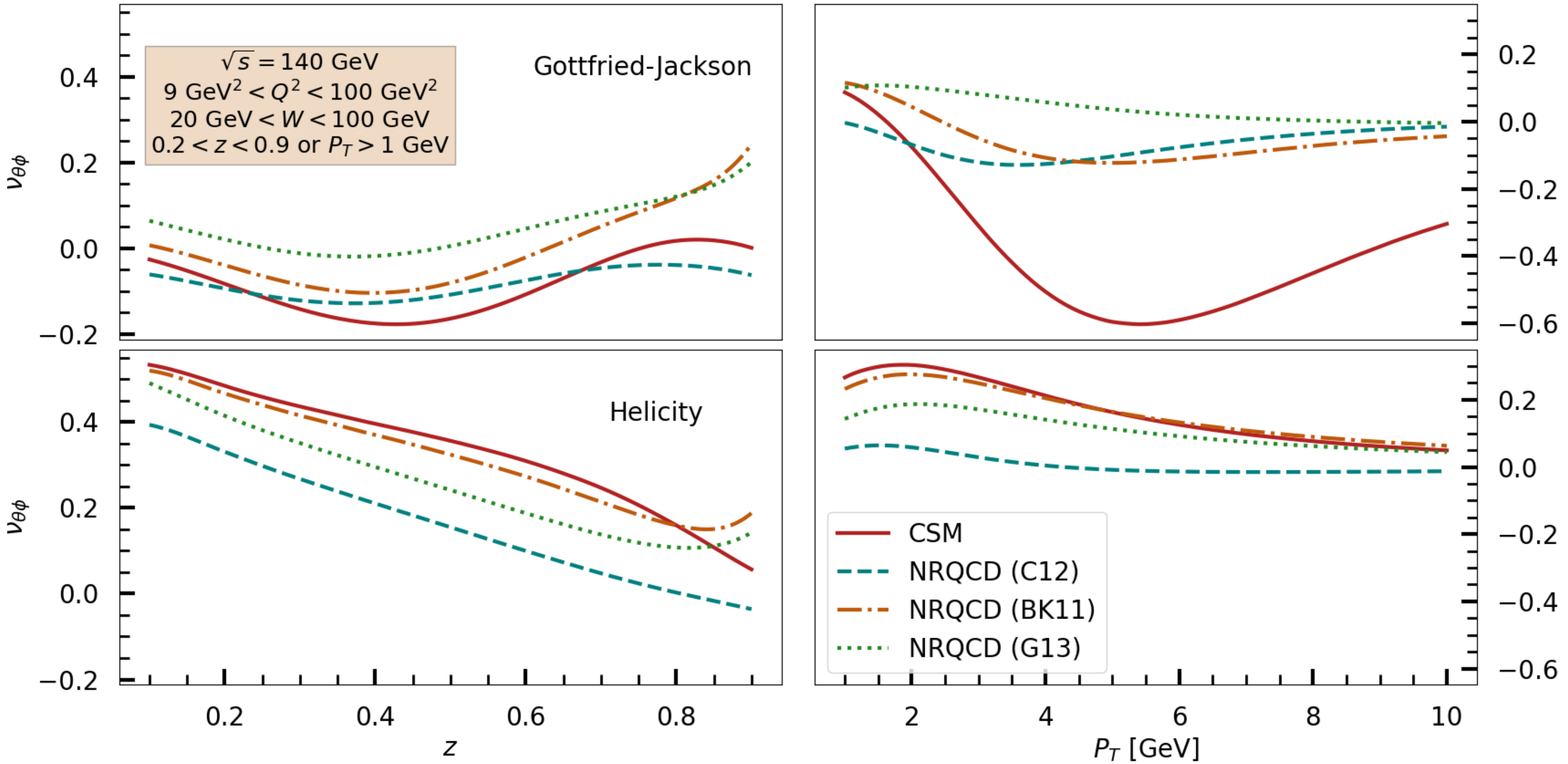
D'Alesio LM Murgia Pisano Sangem, (in preparation)

- visible dependence on the energy:





Polarization at EIC (ν@140GeV)



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EIC ROTATIONAL INVARIANTS I

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

Simpler invariants are linear in both λ_θ and $\nu_{\theta\phi}$

[8] Faccioli, Lourenço, Seixas, Wöhri, EPJC 69 (2010)

$$\mathcal{F} = \frac{1 + \lambda_\theta + \nu_{\theta\phi}}{3 + \lambda_\theta}$$

if Lam-Tung relation holds →

$$\mathcal{F} = \frac{1}{2}$$

[20] Lam, Tung, PRD 18 (1978)

$$\tilde{\lambda} = \frac{2\lambda + 3\nu}{2 - \nu}$$

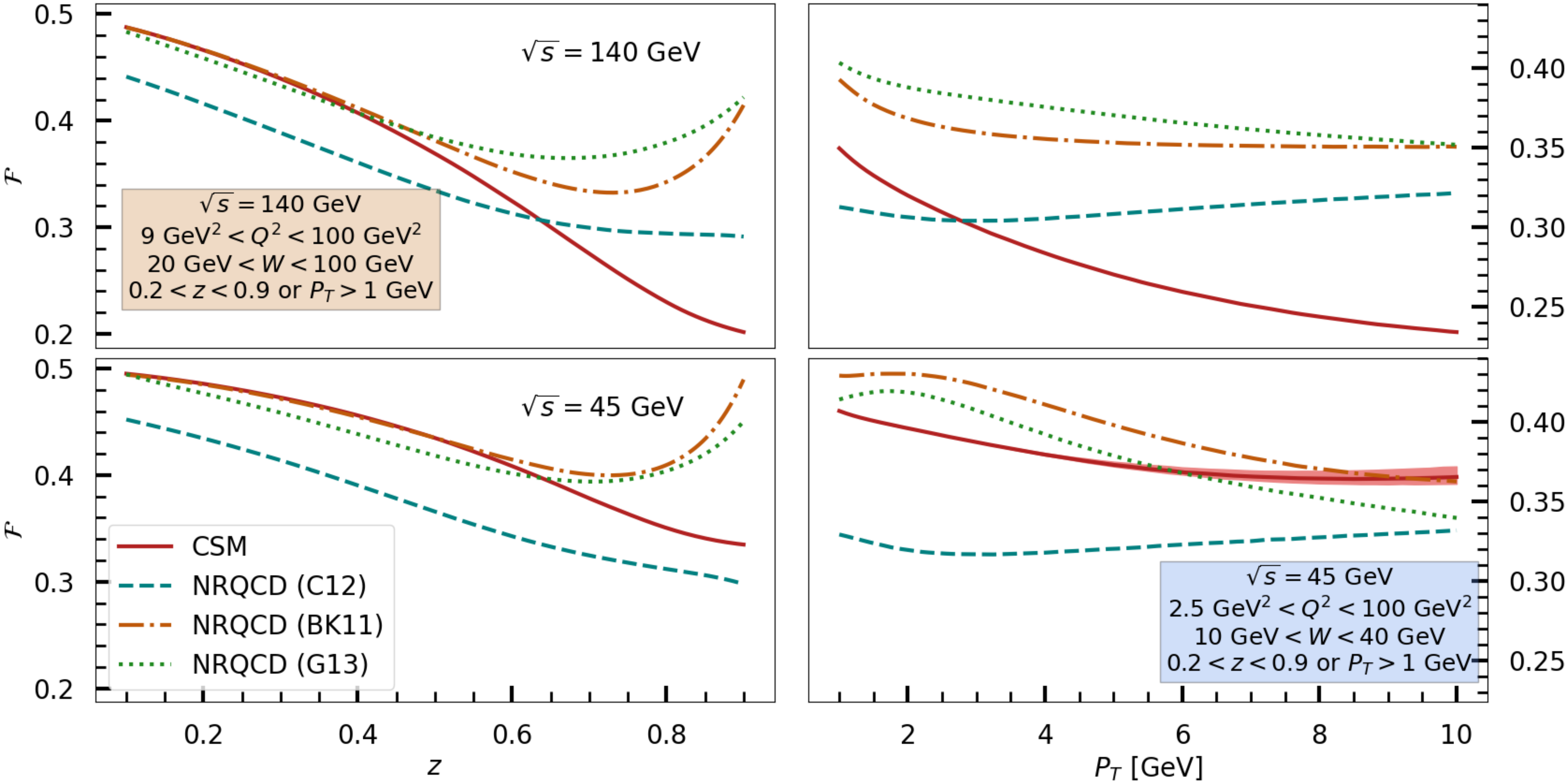
if Lam-Tung relation holds →

$$\tilde{\lambda} = +1$$

Notice that:
LT-rel. is a consequence of the qqV coupling

- Relevant theoretical tools
- Check for experimental consistence

EIC ROTATIONAL INVARIANT PLOT I



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

EIC ROTATIONAL INVARIANTS II

Combination of all parameters $\lambda_\theta, \nu_{\theta\phi}, \mu_{\theta\phi}$ [21] Palestini, PRD 83 (2011)

can identify other types of rotational invariant quantity

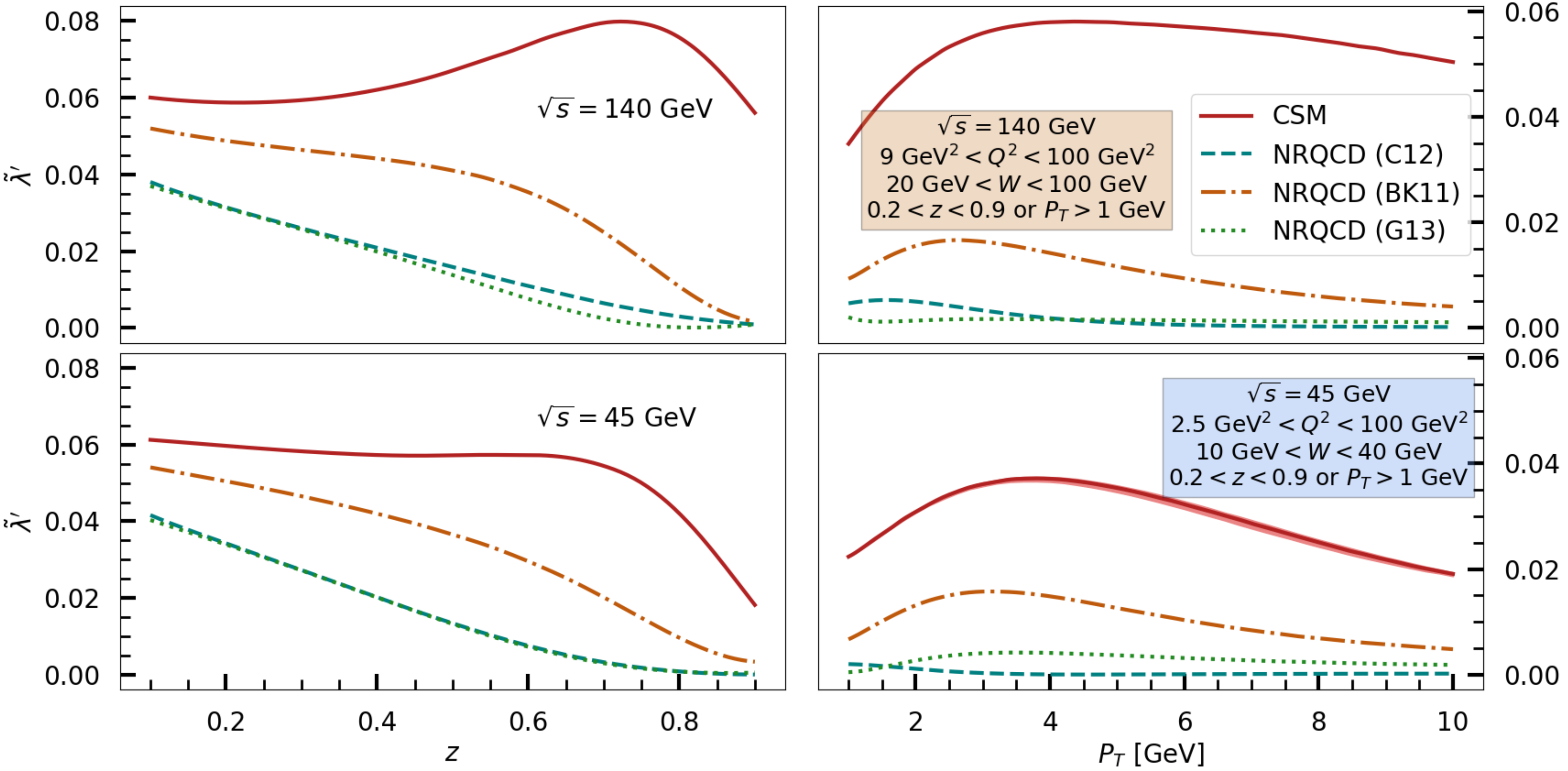
[22] Peng, Boer, Chang, McClellan, Teryaev, PhysLettB 789 (2019)

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

(hard to measure with precision)

Can provide additional constrains on both experimental and theoretical points of view

EIC ROTATIONAL INVARIANT PLOT II



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NEXT

Focus of the talk were the LO polarization prediction in the collinear framework

Polarized (and unpolarized) data at EIC for TMD studies

(see F. G. Celiberto talk on Thursday)

- Access to linearly polarized gluon distribution $h_1^{g\perp}$ via ν_ϕ parameter

[23] D'Alesio, LM, Murgia, Pisano, Sangem, JHEP 03 (2022)

- Impact of *TMD-shape functions*

[24] Echevarria, JHEP (2019)

[25] Fleming, Makris, Mehen, JHEP 04 (2020)

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

[23] D'Alesio, LM, Murgia, Pisano, Sangem, JHEP 03 (2022)

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

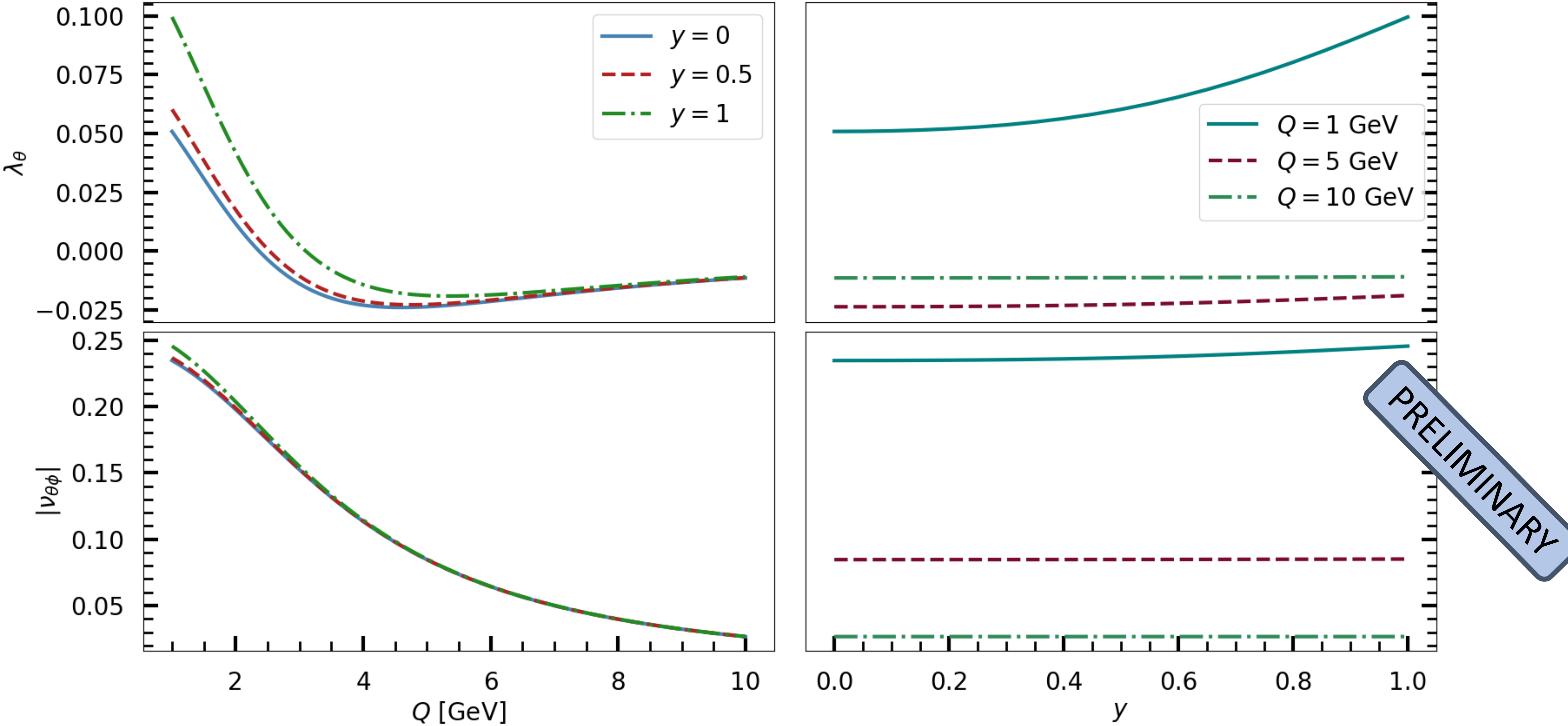
Studying polarization in different energy/Q-bins

Non-trival behaviour of rotational invariant quantities

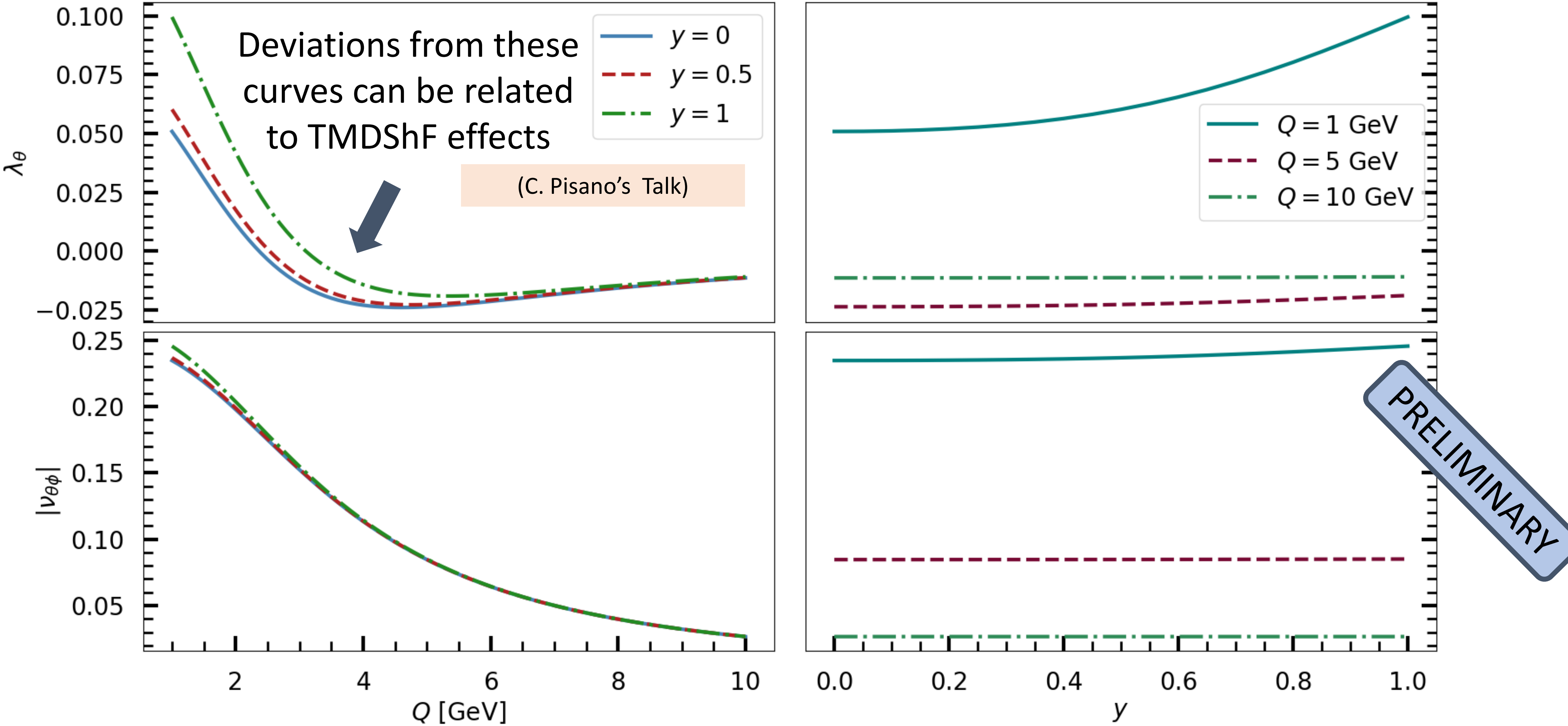
Polarization data in the TMD region can disclose the role of TMDShF

Thanks for the attention

TMD PRELIMINARY PREDICTIONS



TMD PRELIMINARY PREDICTIONS



TMD PRELIMINARY PREDICTIONS