Spin alignment in quarkonium production in SIDIS

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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. Bodwi, 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)

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

POLARIZATION AS A KEY OBSERVABLE

Polarization is less dependent from theoretical uncertainties

(factorization scale, heavy quark masses, LDME, …)

(for spin-1)

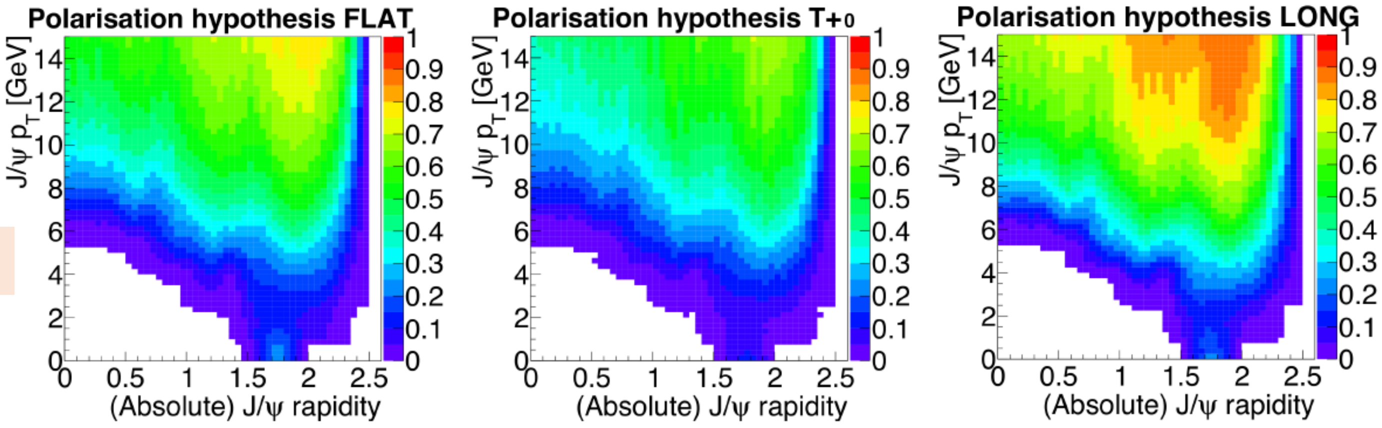
$$d\sigma \sim 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$

Angular parameters are defined through ratio of polarized cross sections

Complete analysis of quarkonium polarization requires measurement of both polar and azimuthal angles

Impact on detector acceptance:

Aad et al. (ATLAS Collaboration), NuclPhysB 850 (2011)



OUTLINE

Matching procedure (in NRQCD)

Section A

HERA recap

Section B

EIC preliminary results for the collinear region

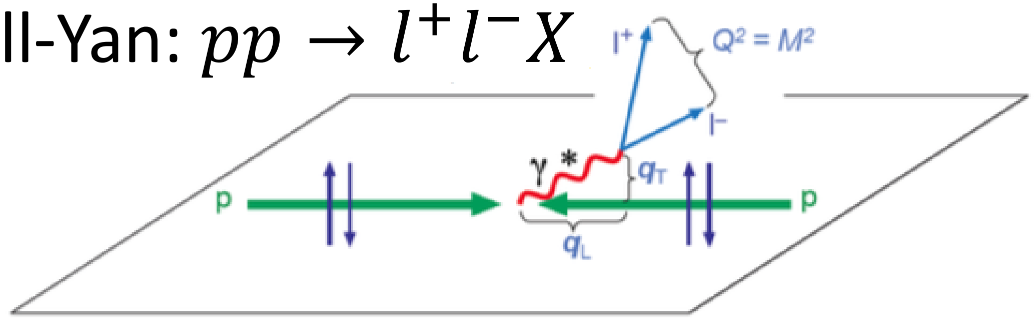
Section C

TMD factorization is formally proven only for few processes

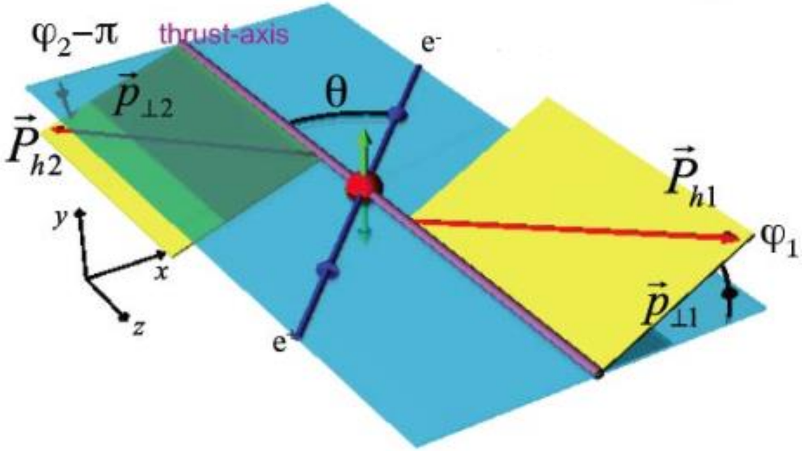
Collins, Cambridge University Press (2011)

Echevarría Idibi Scimemi, JHEP 07 (2012)

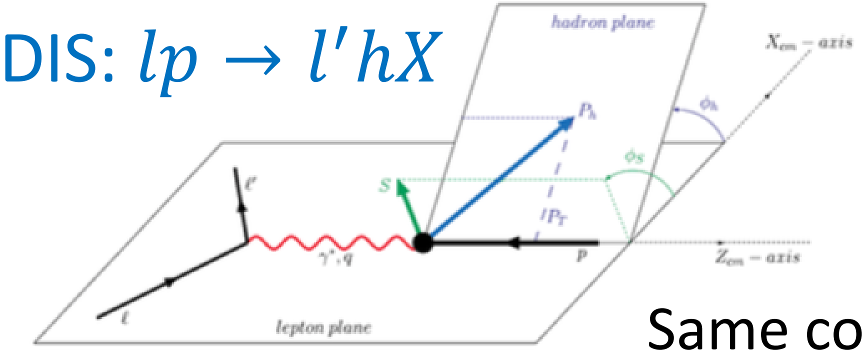
Drell-Yan: $pp \to l^+ l^- X$



lepton annihilation: $e^+ e^- \to \pi\pi X$



SIDIS: $lp \to l' h X$



Same color flow for quarkonium production

➡ No factorization breaking expected

ANGULAR STRUCTURE OF THE CROSS SECTION

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

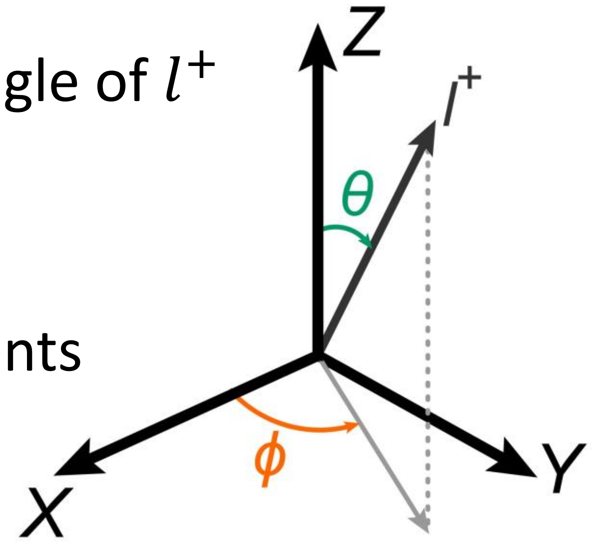
$$J/\psi \to l^+ l^-$$

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^+

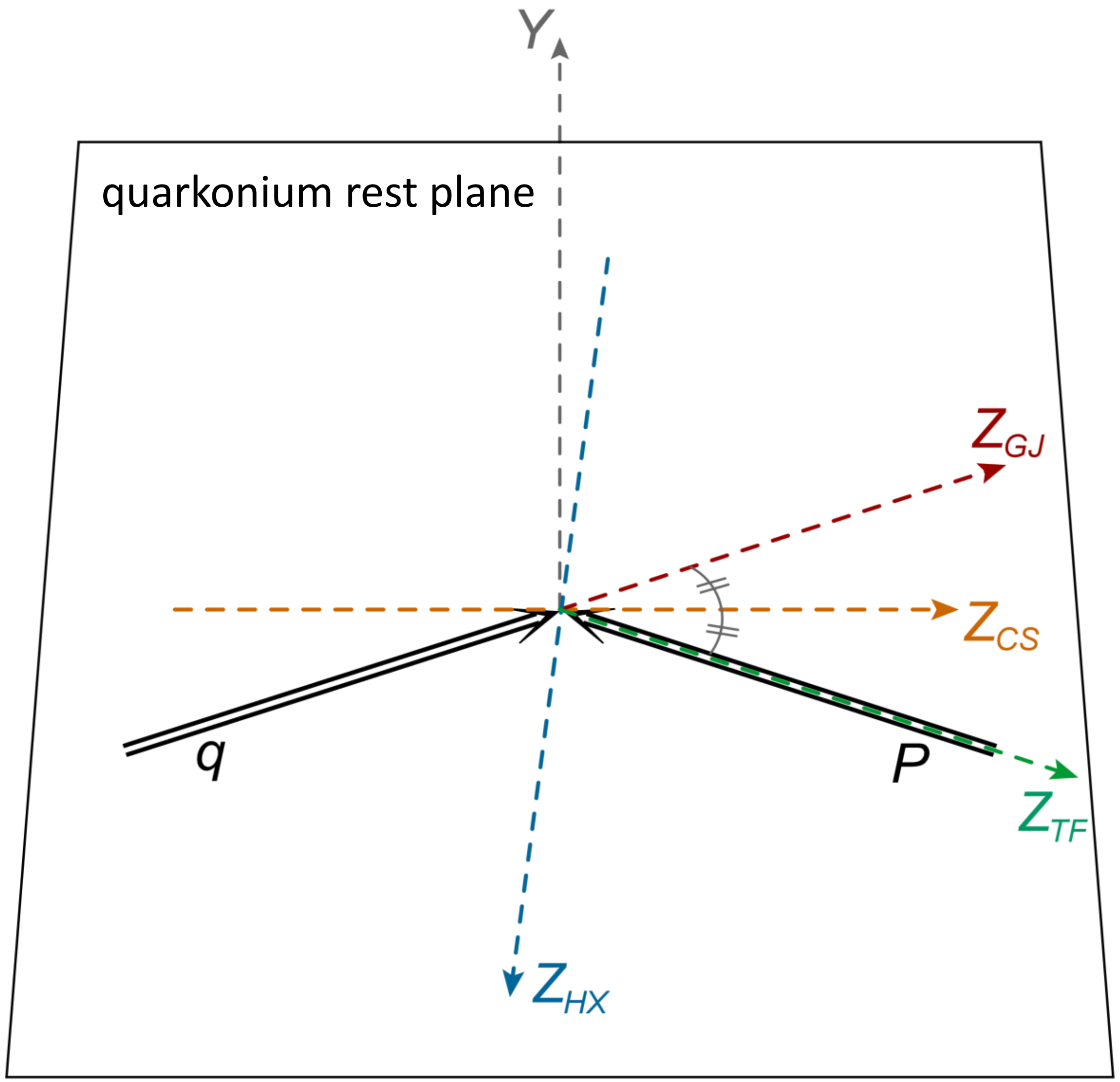


Boer & Vogelsang, PRD 74 (2006)

The parameterization could be obtained from model independent arguments

Hermiticity   Parity conservation   Gauge invariance

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

J/ψ POLARIZATION IN **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)

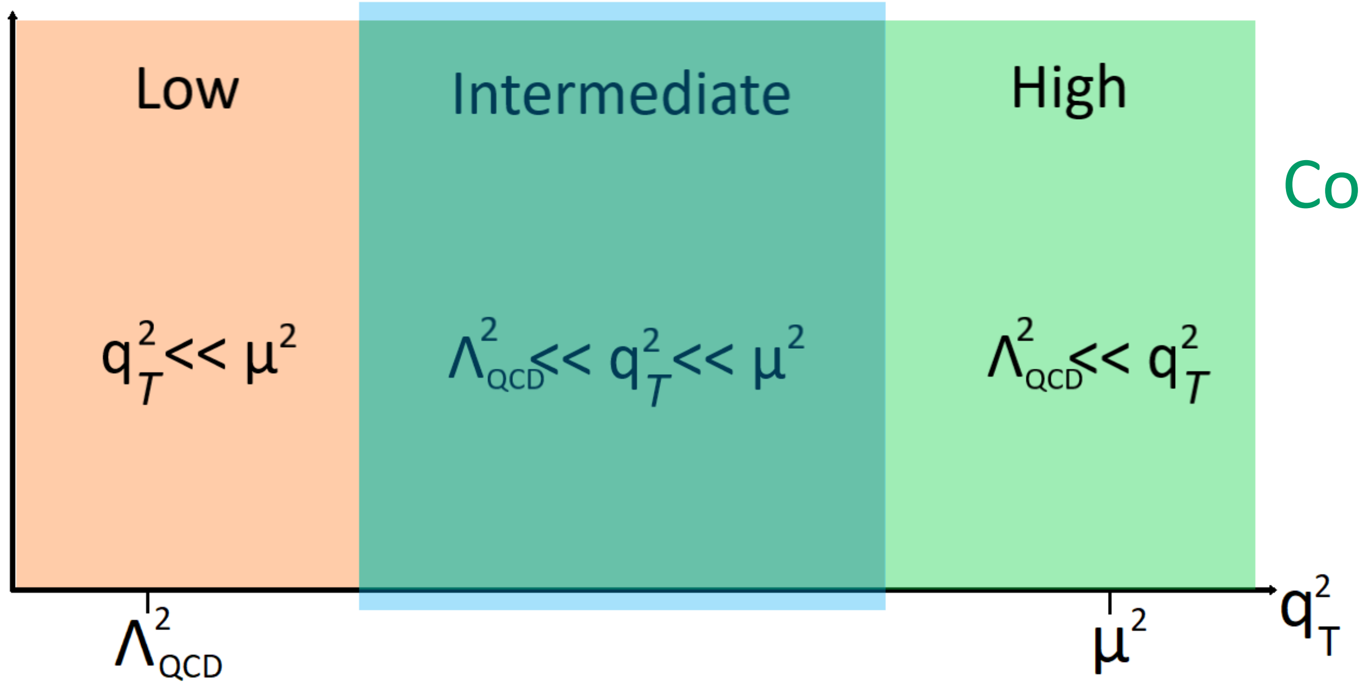
FACTORIZATION SCHEME

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

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

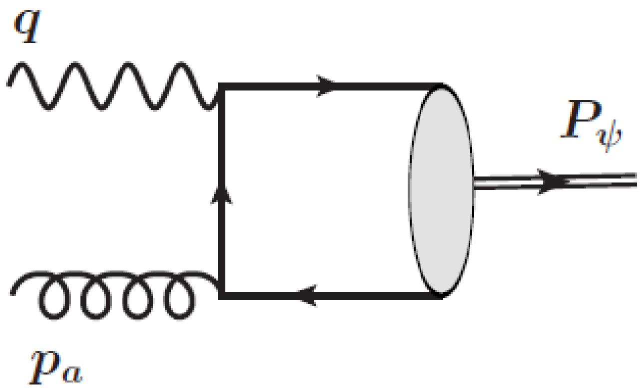
Description of same dynamics? Need to be matched!

Bacchetta, Boer, Diehl, Mulders, JHEP 08 (2008)

J/ψ POLARIZATION AT SMALL q_T

Partonic subprocesses at order $\alpha\alpha_s$

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



described by
polarized partonic cross section $\widetilde{w}_\Lambda^P$

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

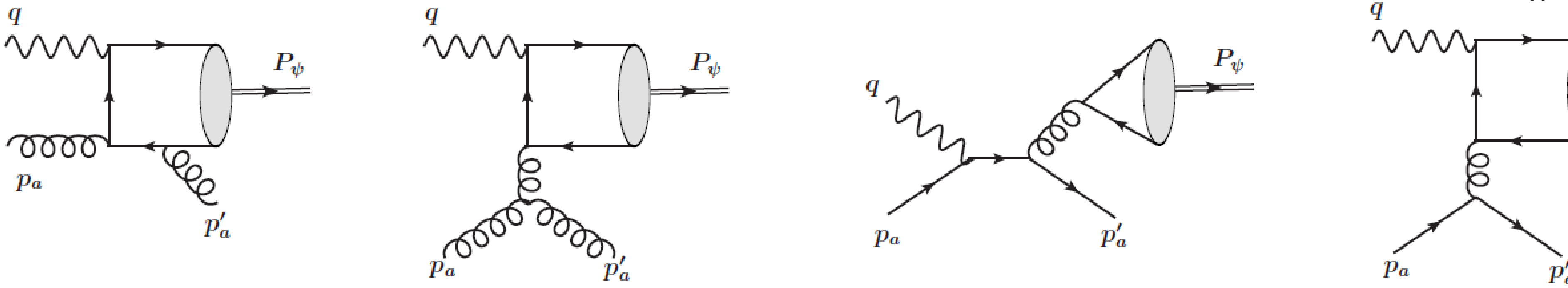
D'Alesio, LM, Murgia, Pisano, Sangem, under review

J/ψ POLARIZATION AT HIGH q_T

Partonic subprocesses at order $\alpha\alpha_s^2$

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

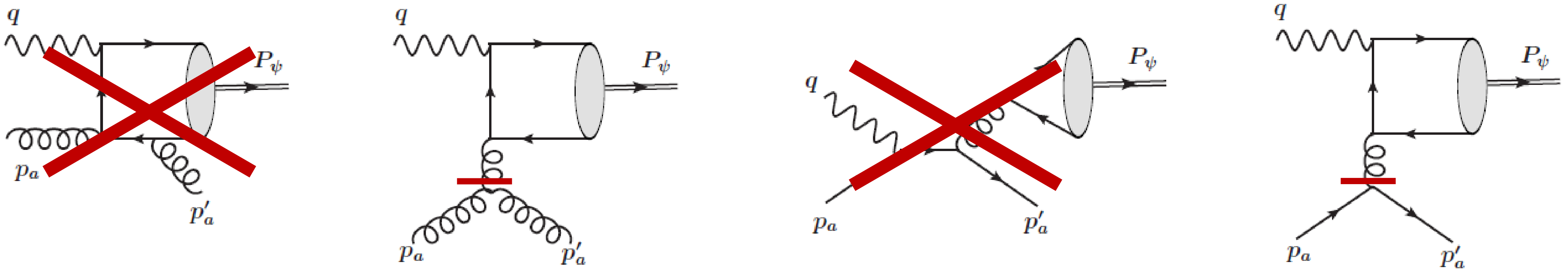
$a = q, \bar{q}, g$



in total:
12 diagrams

Full $\mathcal{W}_\Lambda^P$ evaluated for all $q_T \gg \Lambda_{\rm QCD}$

For small q_T limit divergences are related to $\alpha\alpha_s$ $\gamma^* g$ subprocesses



MATCHING AND SMEARING EFFECT

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

$$(\Lambda, \mathcal{P}) = (L, \perp),\ (T, \perp),\ (L, \|)$$

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

(P. Taels talk)

→ 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

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

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

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

D'Alesio, LM, Murgia, Pisano, Sangem, under review

COLLINEAR PHENOMENOLOGY

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

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

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

where $\lambda = +1$ → transverse, $\lambda = -1$ → longitudinal

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

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)	→ tested on polarization data
BK11	Butenschoen & Kniehl, PRD 84 (2011)	→ include low-P_T and photoproduction unpolarized data

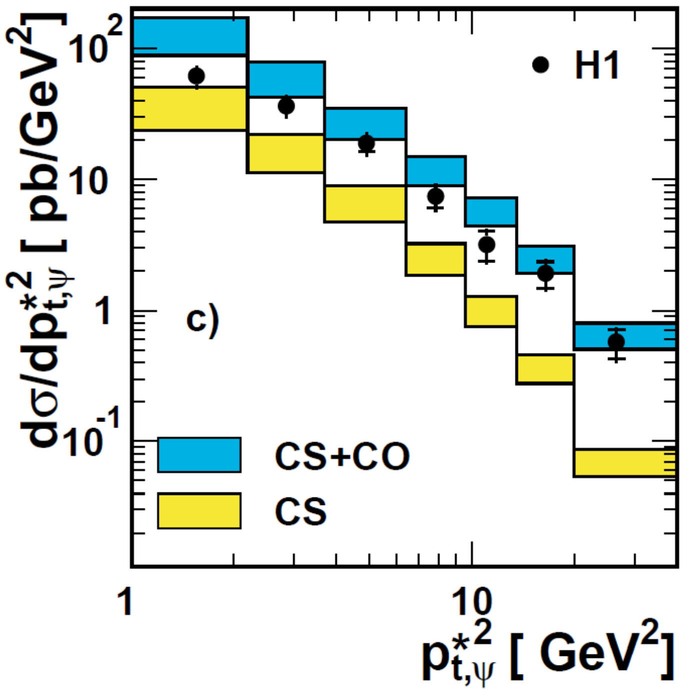
HERA UNPOLARIZED DATA

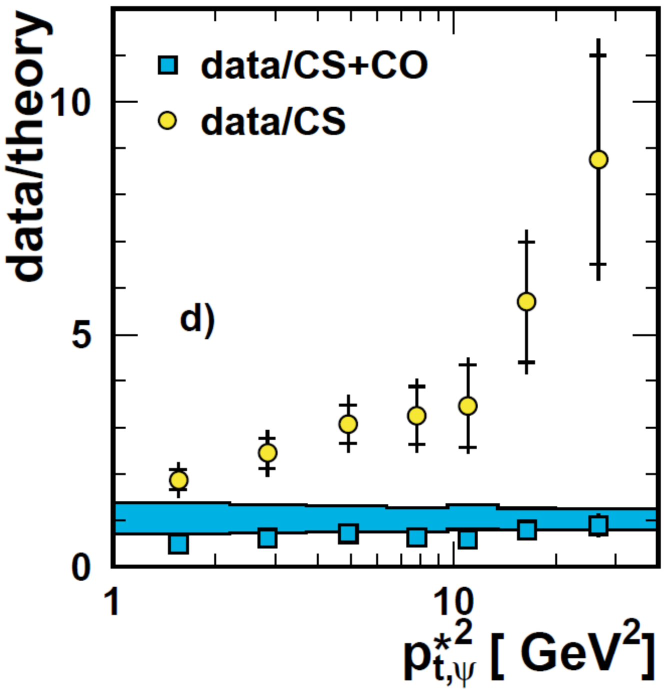
Adloff et al. (H1 Collaboration), EPJ C 25 (2002)

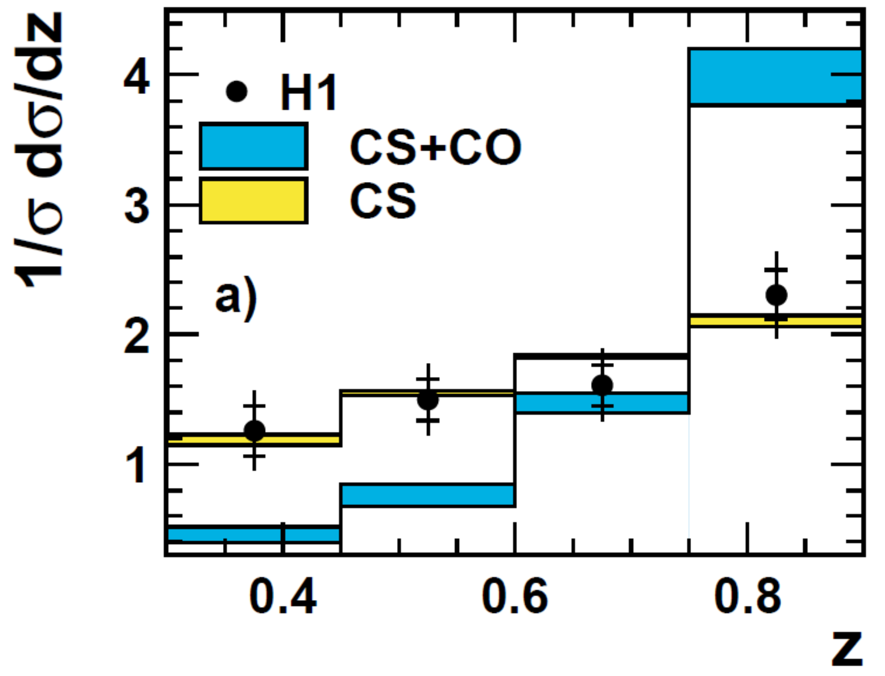
Knieh & Zwirner, NPB 621 (2002)

Data from HERA collaboration

Theoretical prediction obtained by Kniehl-Zwirner







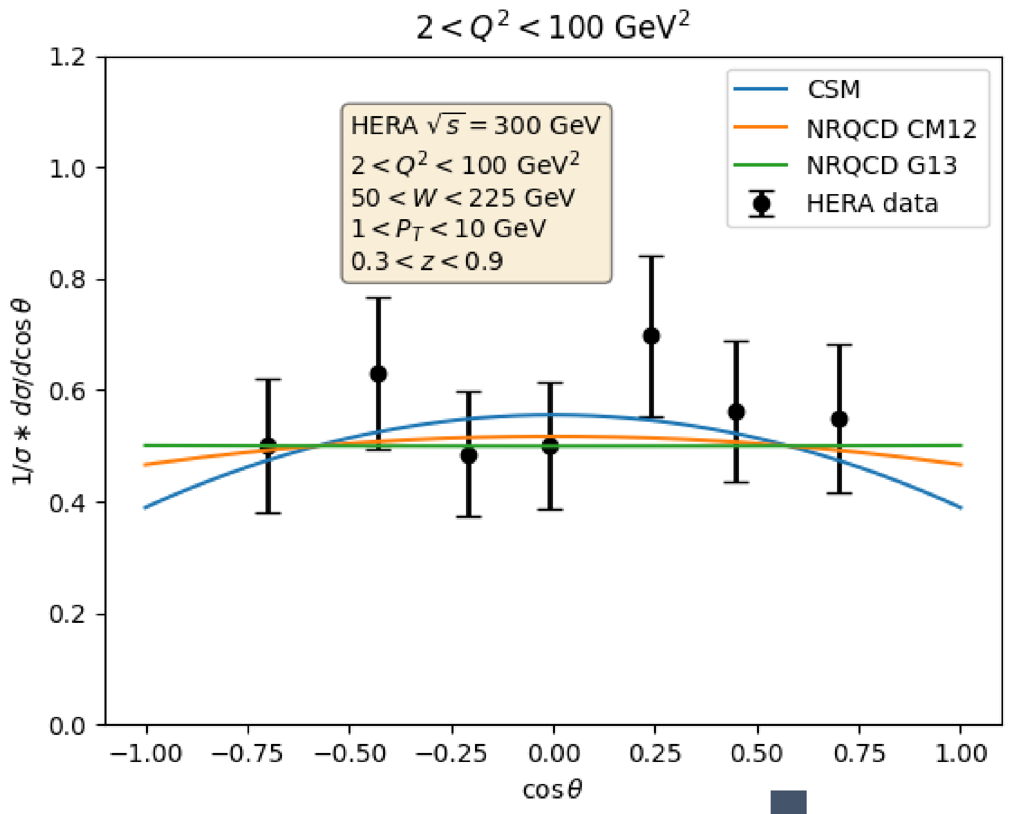
P_T data show a general better agreement with NRQCD predictions

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

HERA POLARIZED DATA

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

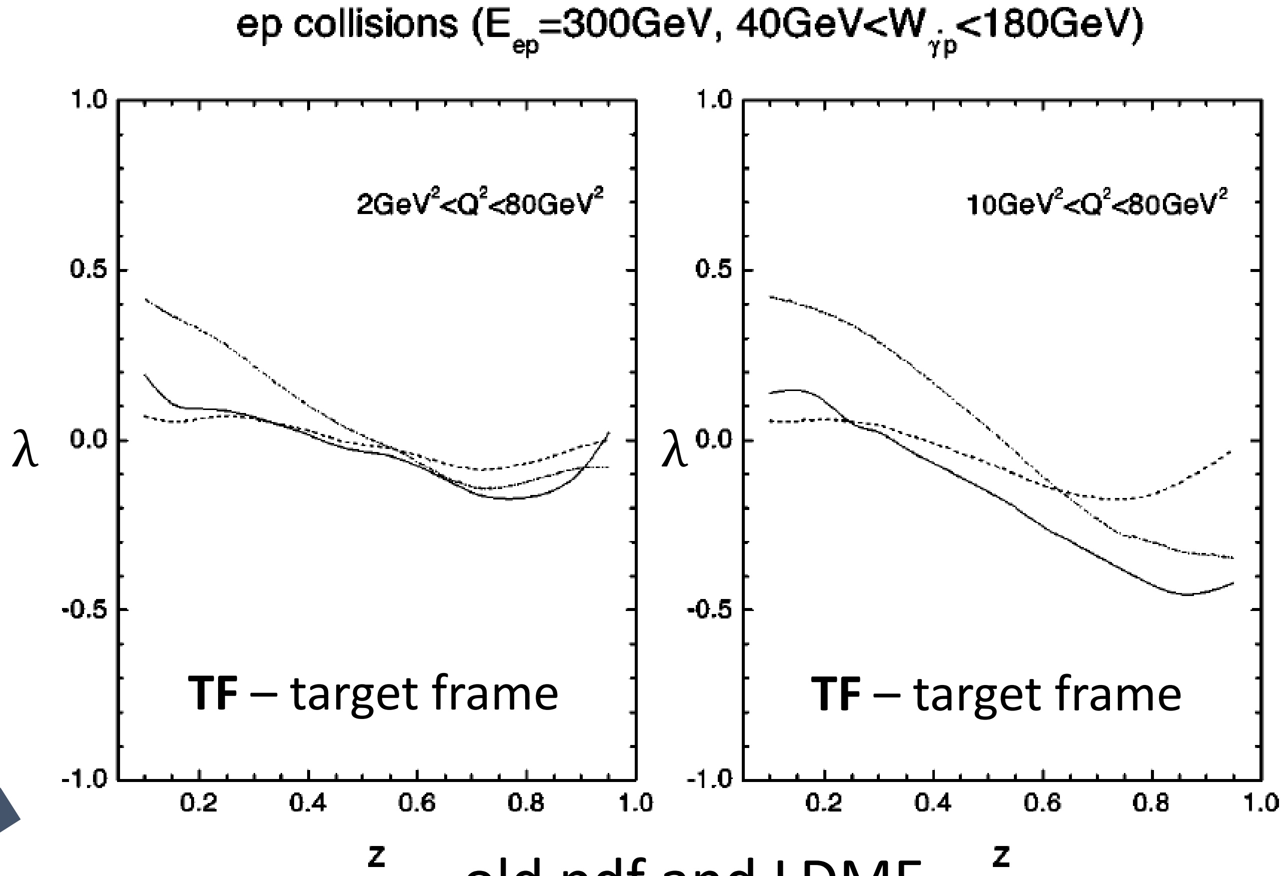
Data from HERA collaboration



Hard to extract information

Yuan & Chao, PRD 63 (2001)

From Yuan-Chao paper



old pdf and LDME

includes resolved photon contribution

CEM at HERA

No result yet regarding polarization in SIDIS within CEM

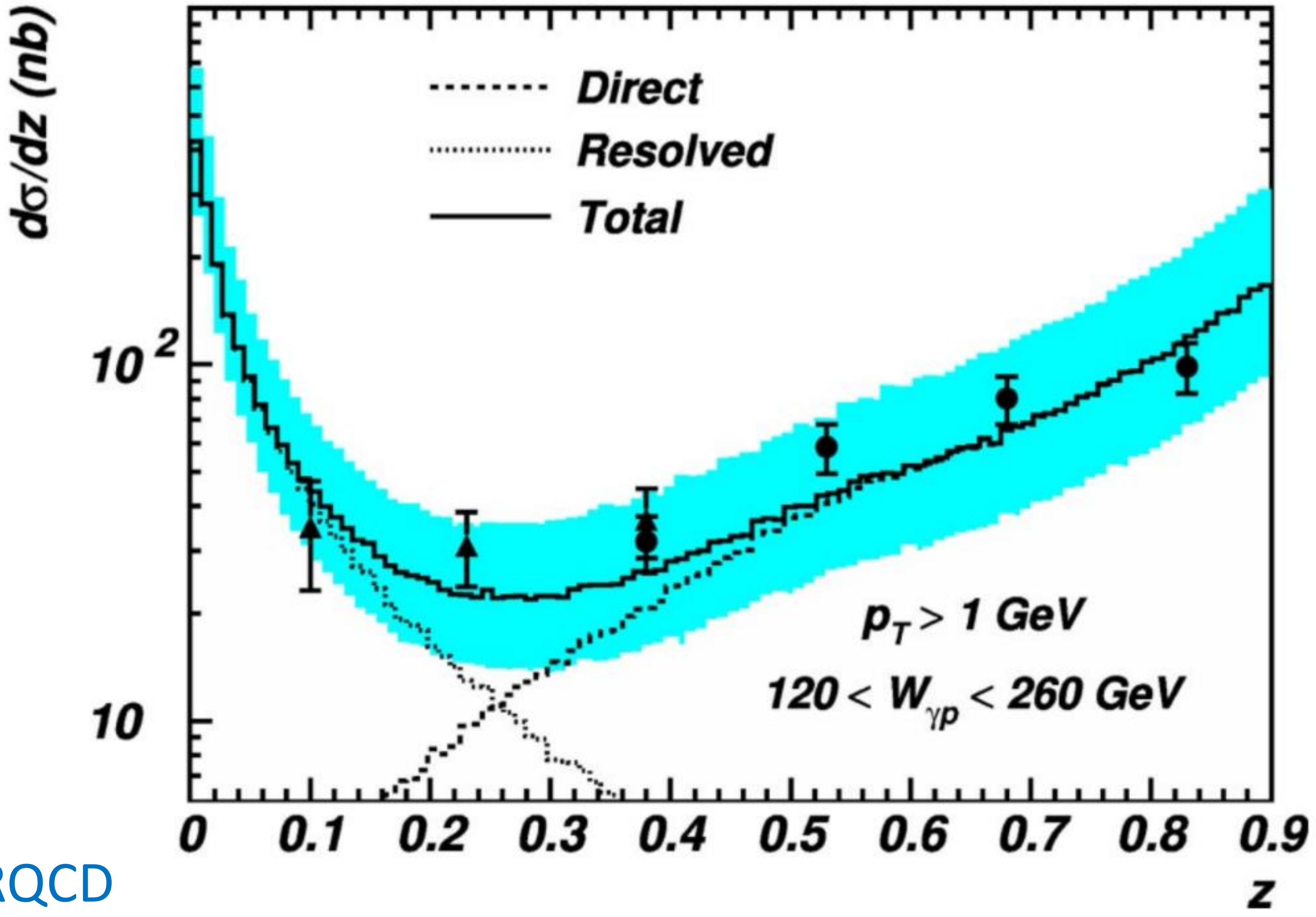
CEM predictions respect to photoproduction are promising for future SIDIS polarization result

Data from HERA collaboration

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

Prediction from

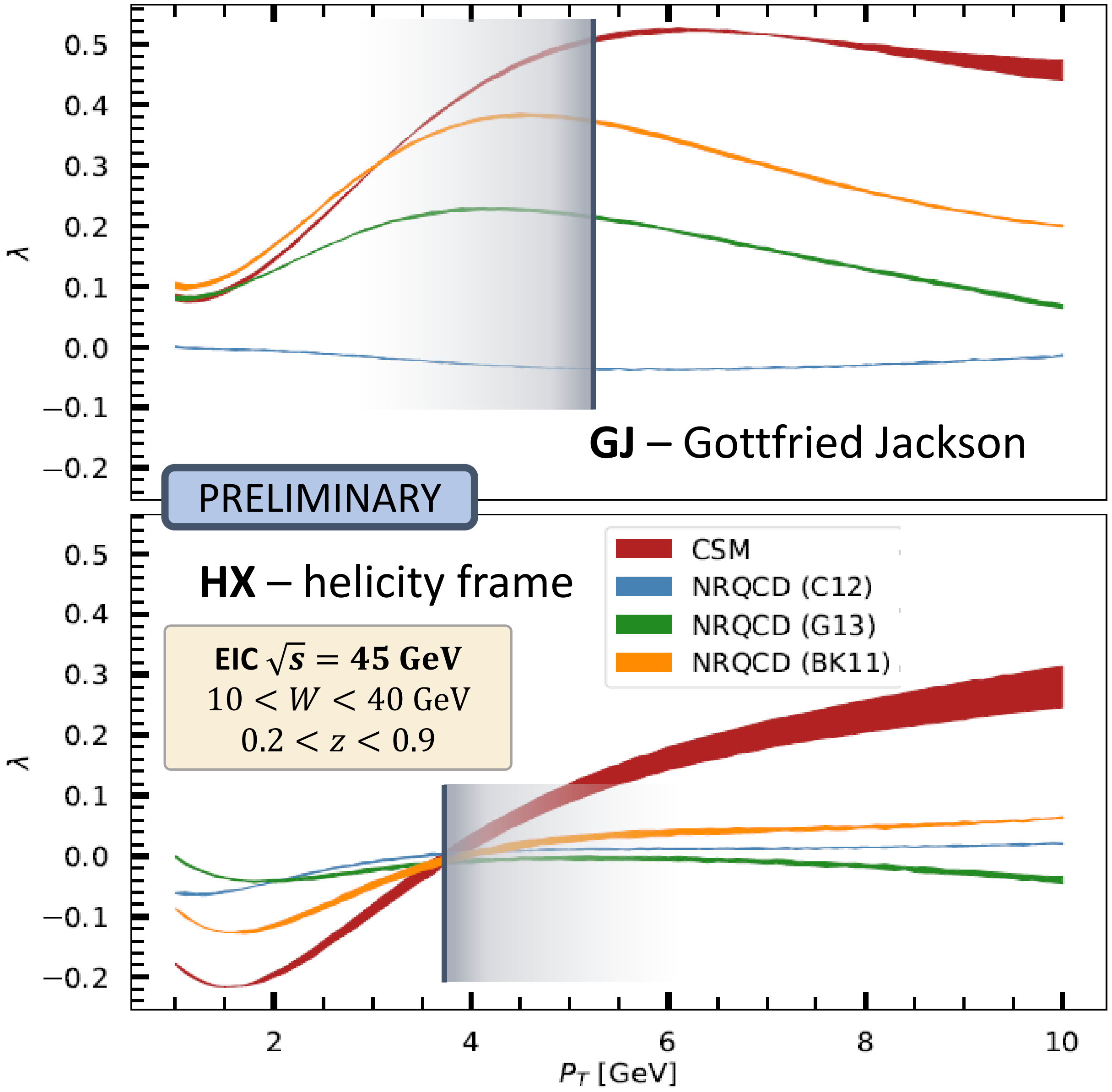
Eboli, Gregores, Halzen, PRD 67 (2003)



Corresponding prediction for CSM and NRQCD in photoproduction in

Butenschoen, Kniehl, PRL 107 (2011)

POLARIZATION AT *EIC*

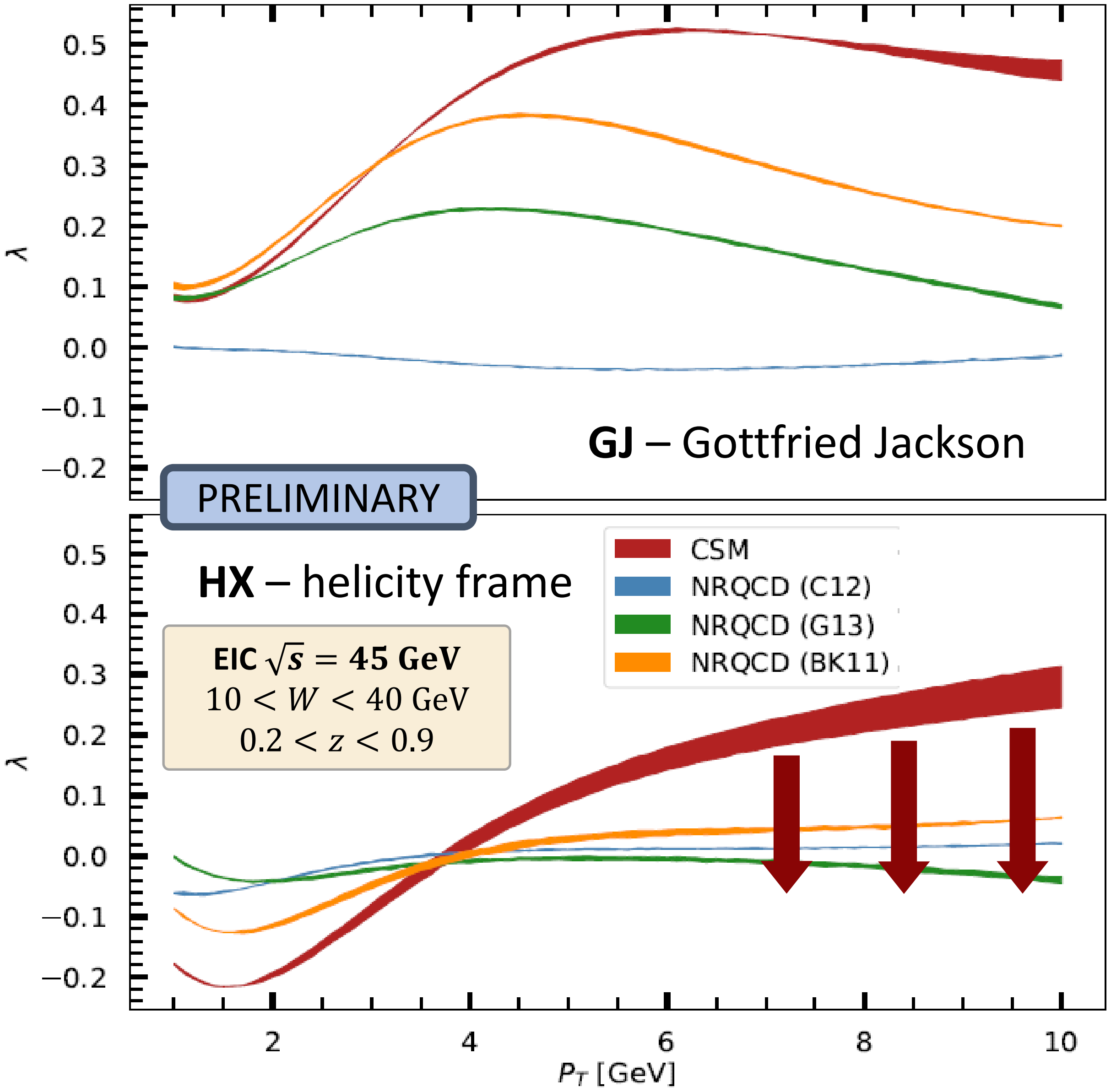


EIC collinear predictions for λ vs P_T

Analysis for different frames and energies allows for a more complete picture

(resolved photon not included)

POLARIZATION AT *EIC*



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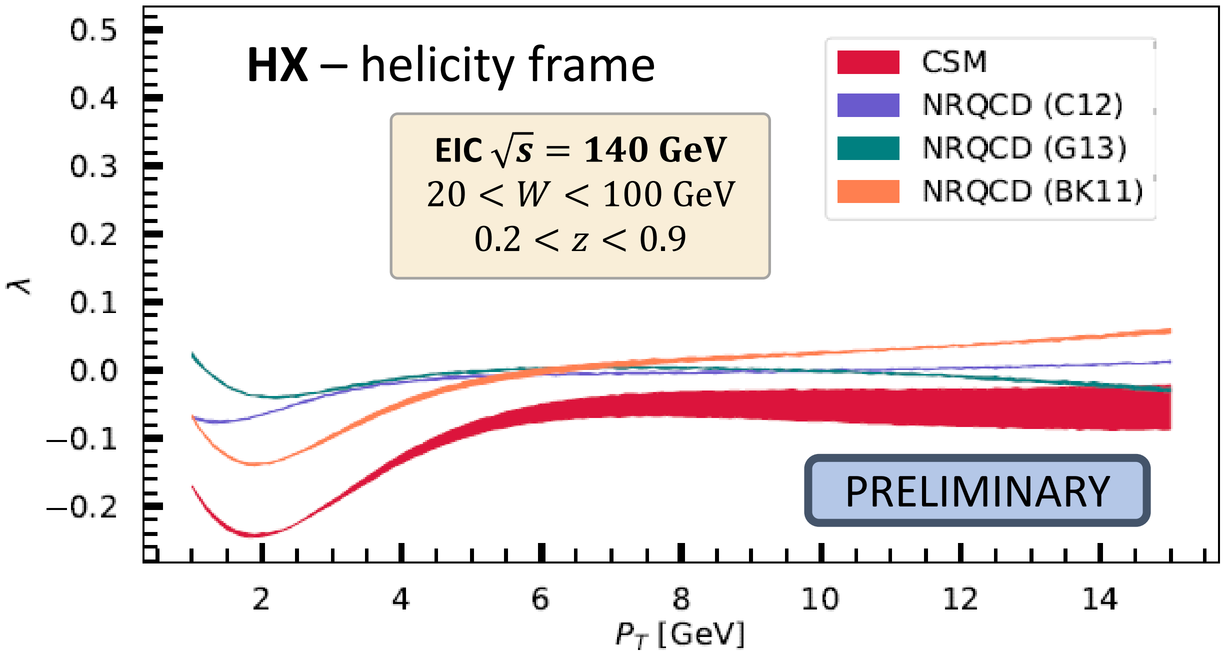


EIC INVARIANTS

Upon rotation around Y-axis from *a* to *b* λ, μ, ν mix up

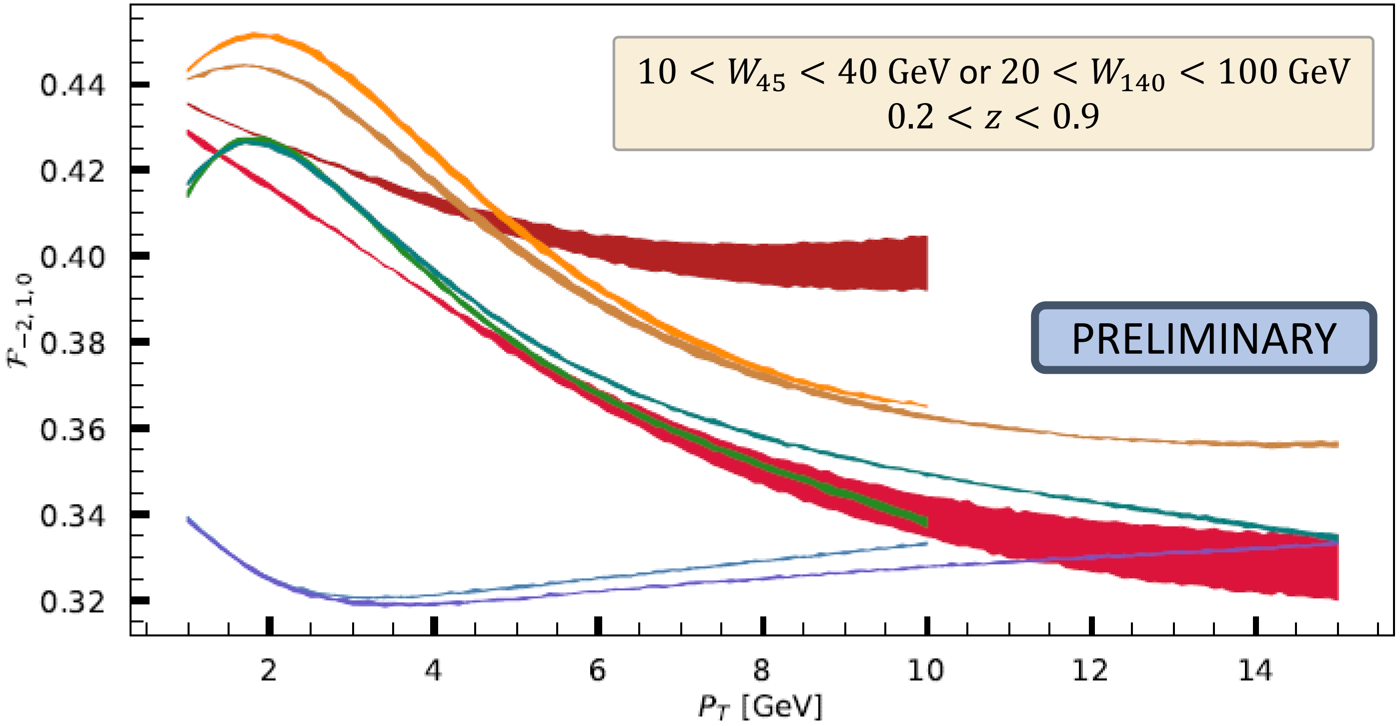
$$\begin{pmatrix} \lambda^b \\ \mu^b \\ \nu^b \end{pmatrix} = \frac{1}{1+\Delta} \begin{pmatrix} 1 - \frac{3}{2}\sin^2\theta_{ab} & -\frac{3}{2}\sin 2\theta_{ab} & \frac{3}{4}\sin^2\theta_{ab} \\ \frac{1}{2}\sin 2\theta_{ab} & \cos 2\theta_{ab} & -\frac{1}{4}\sin 2\theta_{ab} \\ \sin^2\theta_{ab} & \sin 2\theta_{ab} & 1 - \frac{1}{2}\sin^2\theta_{ab} \end{pmatrix} \begin{pmatrix} \lambda^a \\ \mu^a \\ \nu^a \end{pmatrix}$$

with $\Delta = \frac{\sin^2\theta_{ab}}{2}\left(\lambda - \frac{\nu}{2}\right) + \frac{\sin 2\theta_{ab}}{2}\mu$

One can identify a family of functions which are invariant under this rotation

$$\mathcal{F}_{c_1,c_2,c_3} = \frac{(3+\lambda) + c_1(1-\nu/2)}{c_2(3+\lambda) + c_3(1-\nu/2)}$$

EIC INVARIANTS



One can define variables invariant upon rotation around Y-axis

$$\mathcal{F}_{-2,1,0} = \frac{1+\lambda+\nu}{3+\lambda}$$

Color legend reminder:

$\sqrt{s} = 45\text{GeV}$

- CSM
- NRQCD (C12)
- NRQCD (G13)
- NRQCD (BK11)

$\sqrt{s} = 140\text{GeV}$

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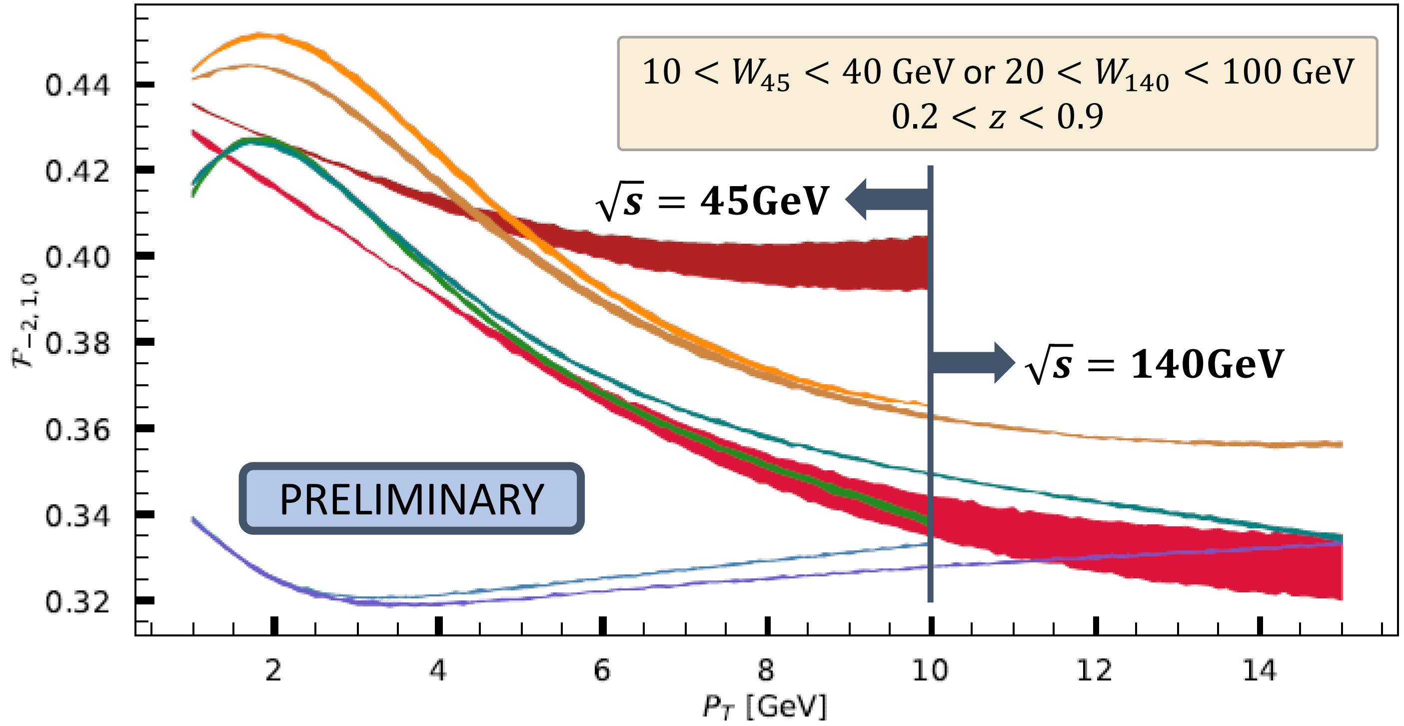

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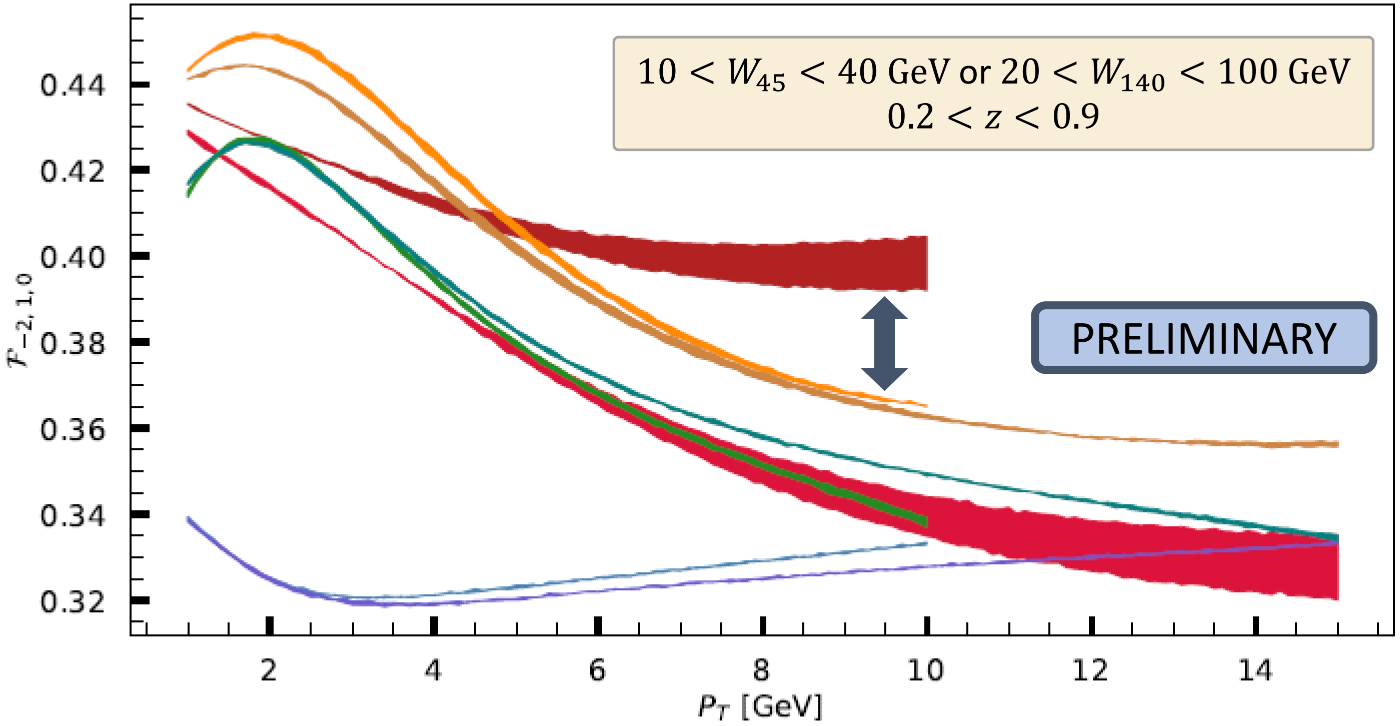

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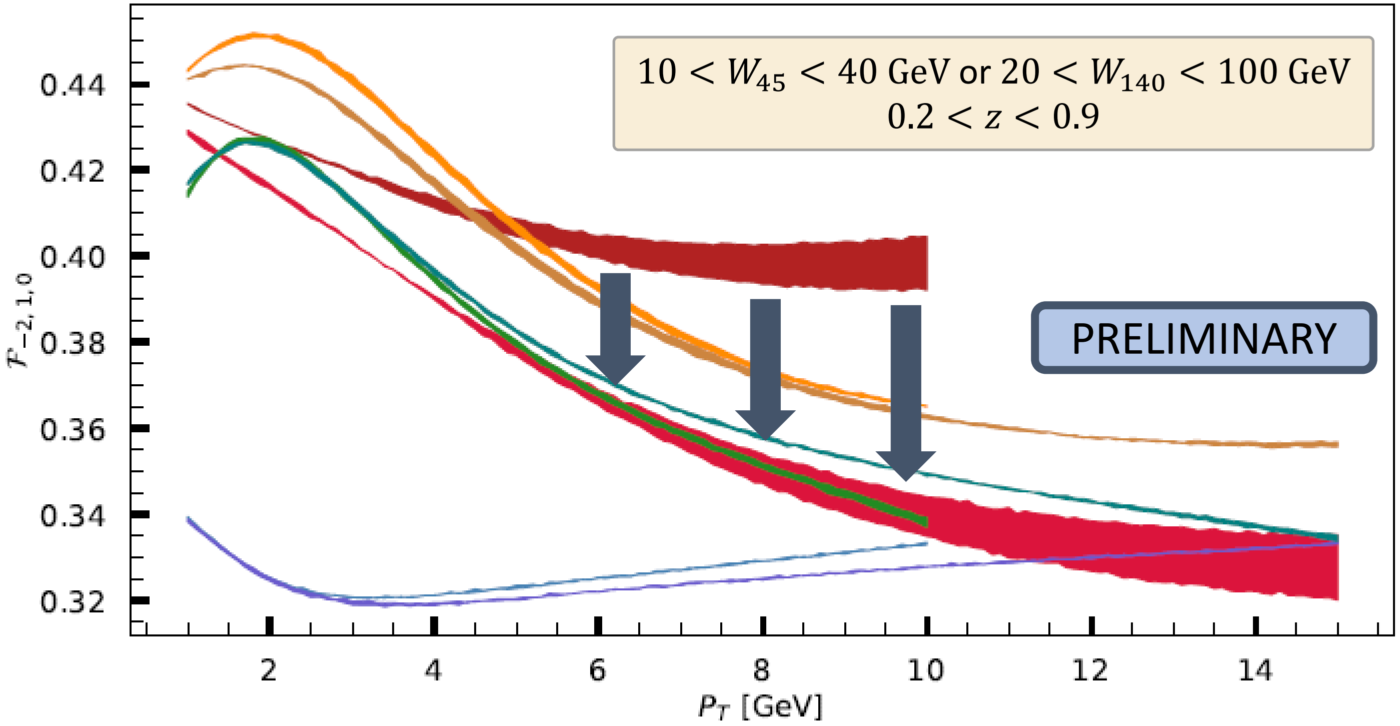

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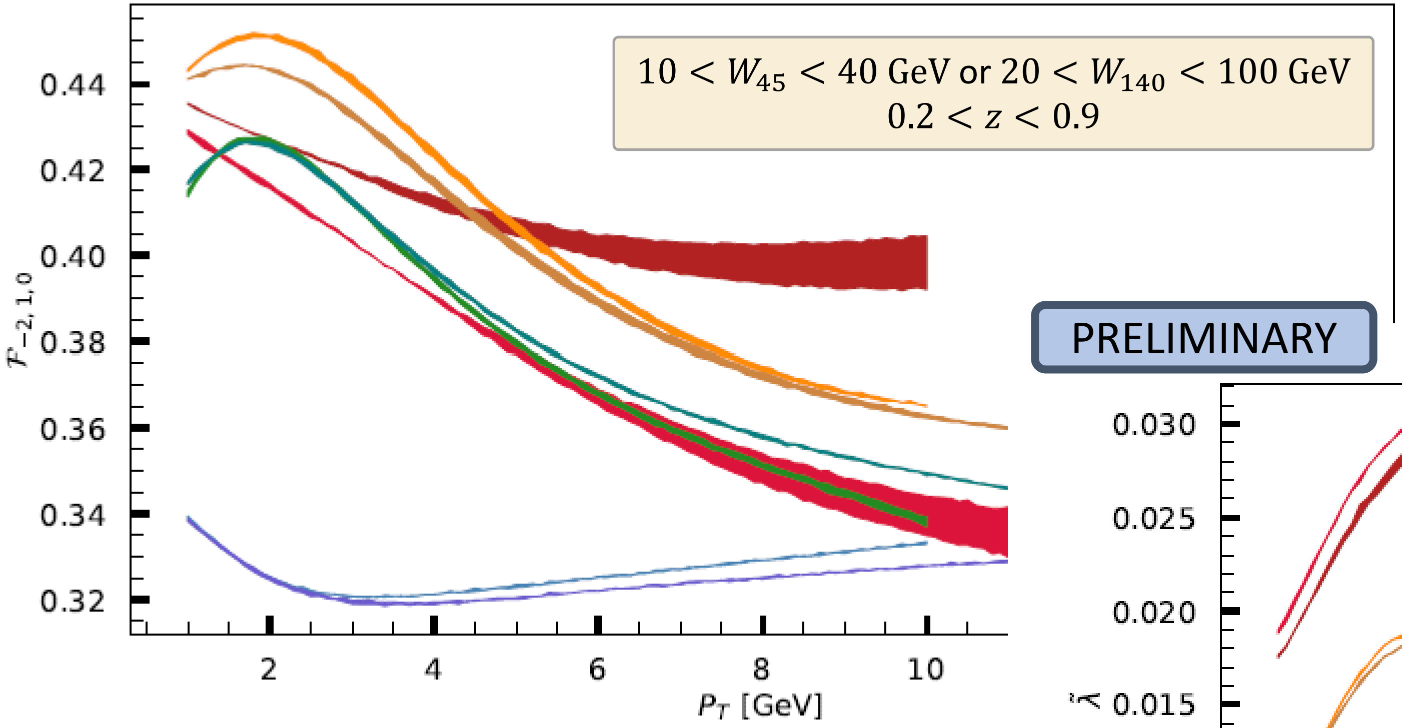

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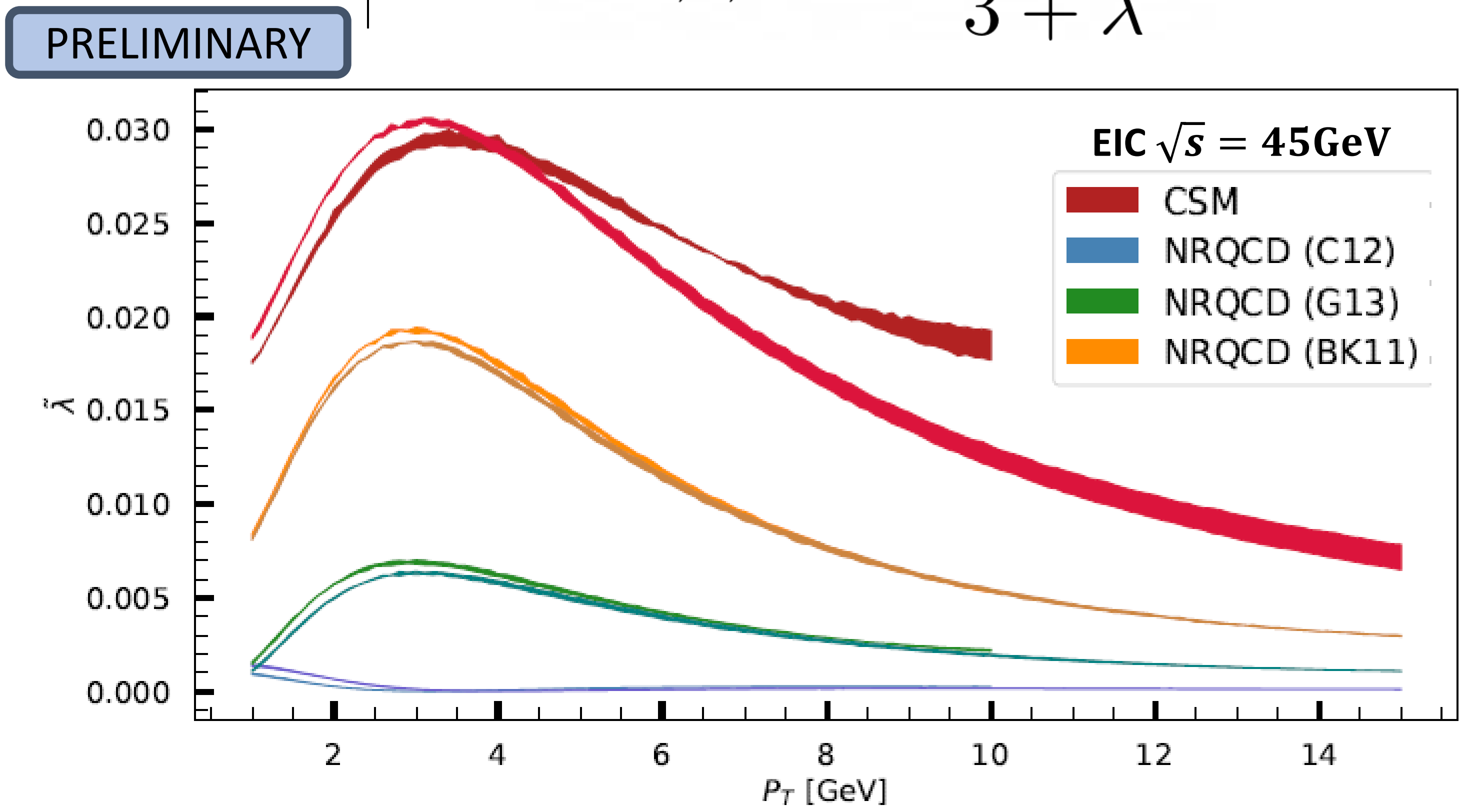
$$\tilde{\lambda} = \frac{(\lambda-\nu/2)^2+4\mu^2}{(3+\lambda)^2}$$



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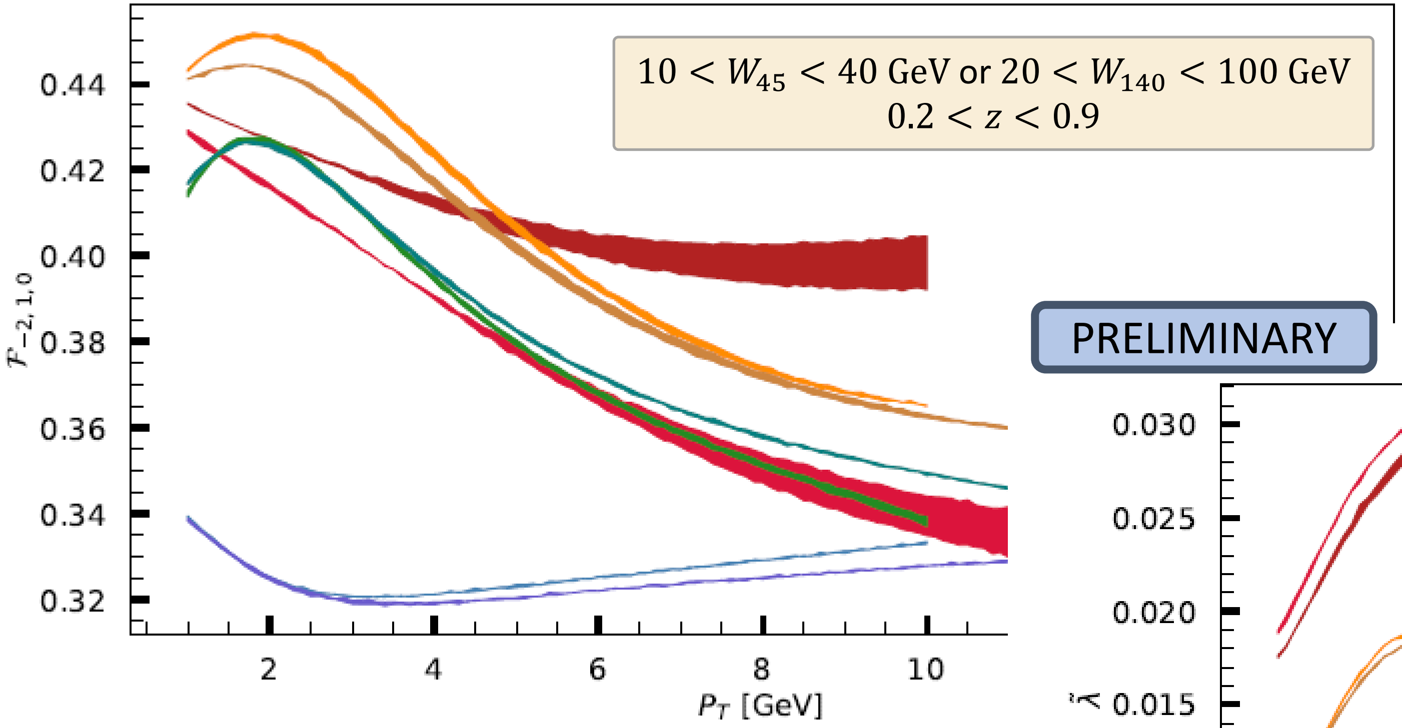

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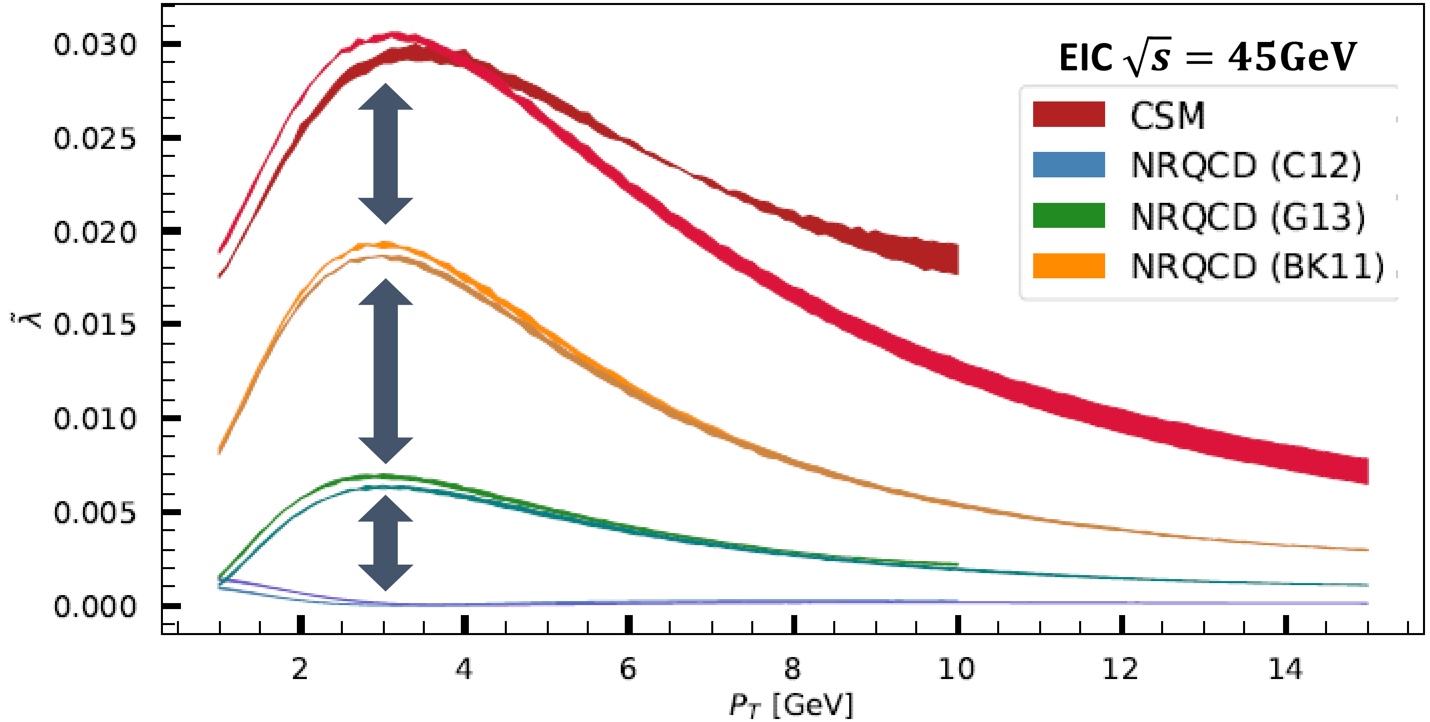
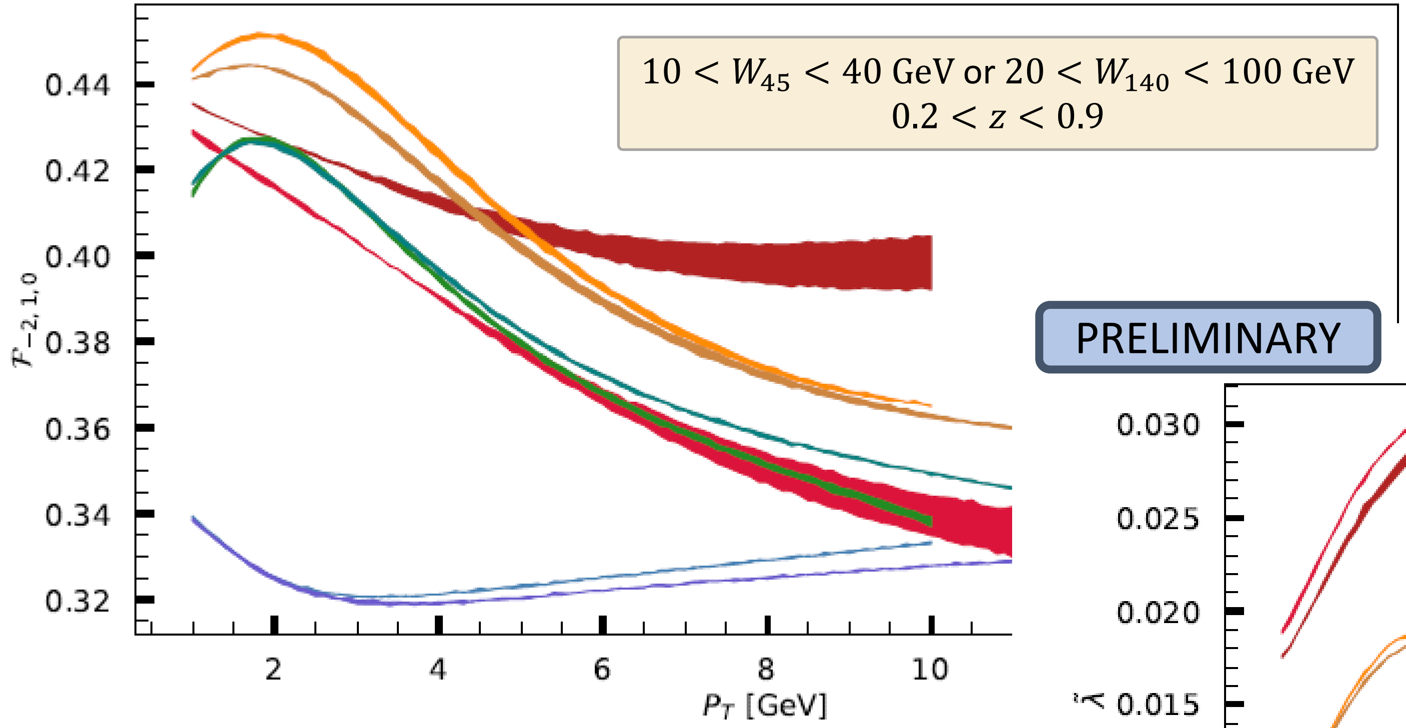
PRELIMINARY



EIC INVARIANTS



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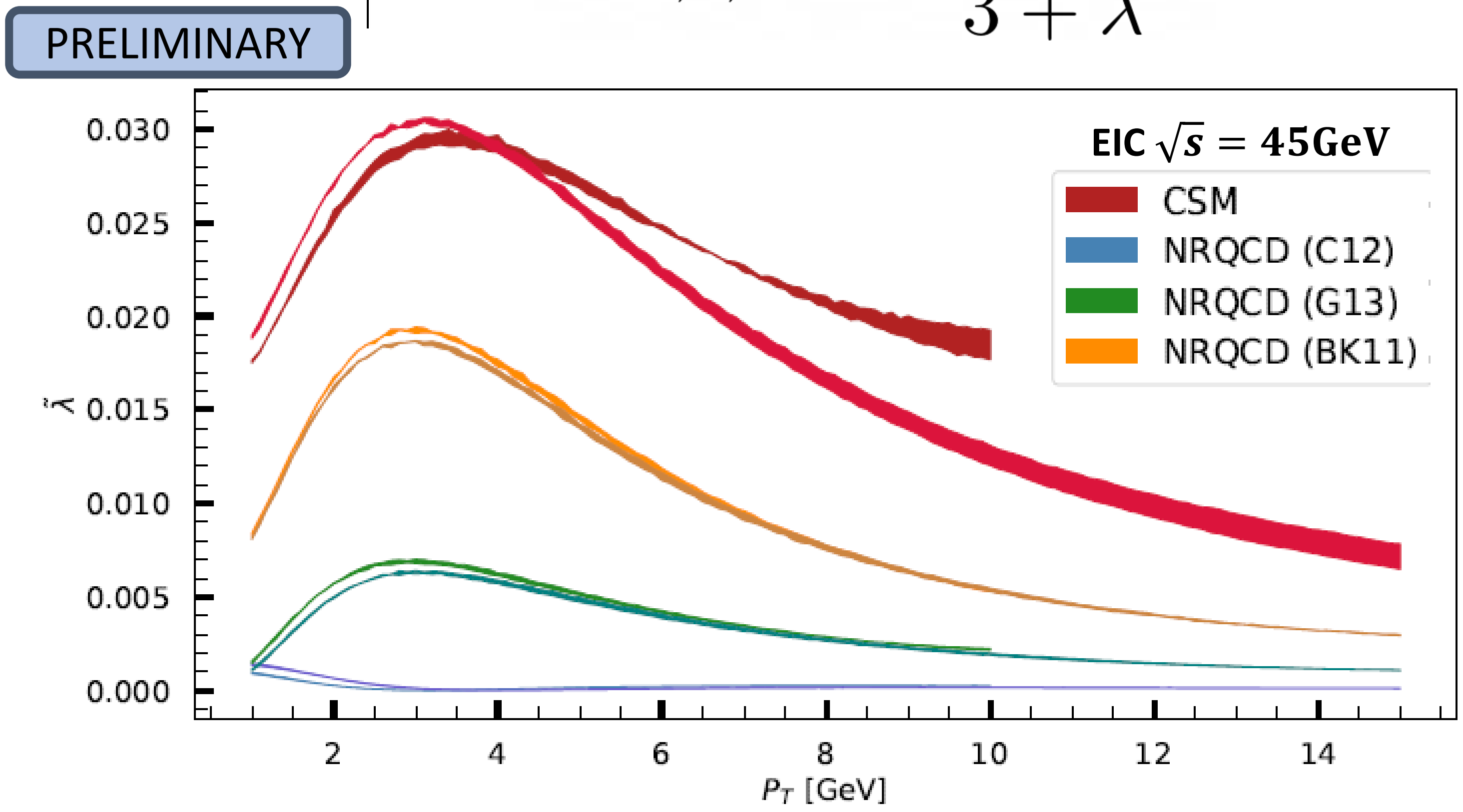

More information encoded!

CONCLUSIONS

Importance of polarization states analysis

Access to gluon TMD PDFs

In TMD region $\mathcal{W}_{\Delta\Delta}^{\perp}$ is related to the linearly polarized gluon distribution $h_1^{\perp}$

Proper shape functions are necessary to provide correct expressions in the intermediate q_T region

Comparison between HERA and EIC predictions shows the importance of full polarization measurement to achieve a complete picture

Thanks for the attention