"Precision QCD predictions for ep physics at the EIC (III): opportunities with a second IR

26/09/24

Quarkonium production at the Electron-Ion Collider

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Physics case for quarkonium studies at the EIC

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Abstract

The physics case for quarkonium-production studies accessible at the US Electron Ion Collider is described.

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- Talk based on our recent review* on quarkonium production at the EIC (arXiv:2409.03691 [hep-ph])
- ~80 pages covering variety of topics and sound physics cases for quarkonium studies @ the EIC by >40 authors worldwide
- Talk will motivate quarkonium production studies and summarise a selection of quarkonium physics cases at the EIC

*Followed our previous review on quarkonium physics for the HL-LHC (**Prog.Part.Nucl.Phys. 122 (2022) 103906, arXiv:2012.14161**) and emanated from the annual 'Quarkonia as Tools' workshops

Outline

Introduction to quarkonium

Tools for quarkonium

Legacy and future measurements at the EIC

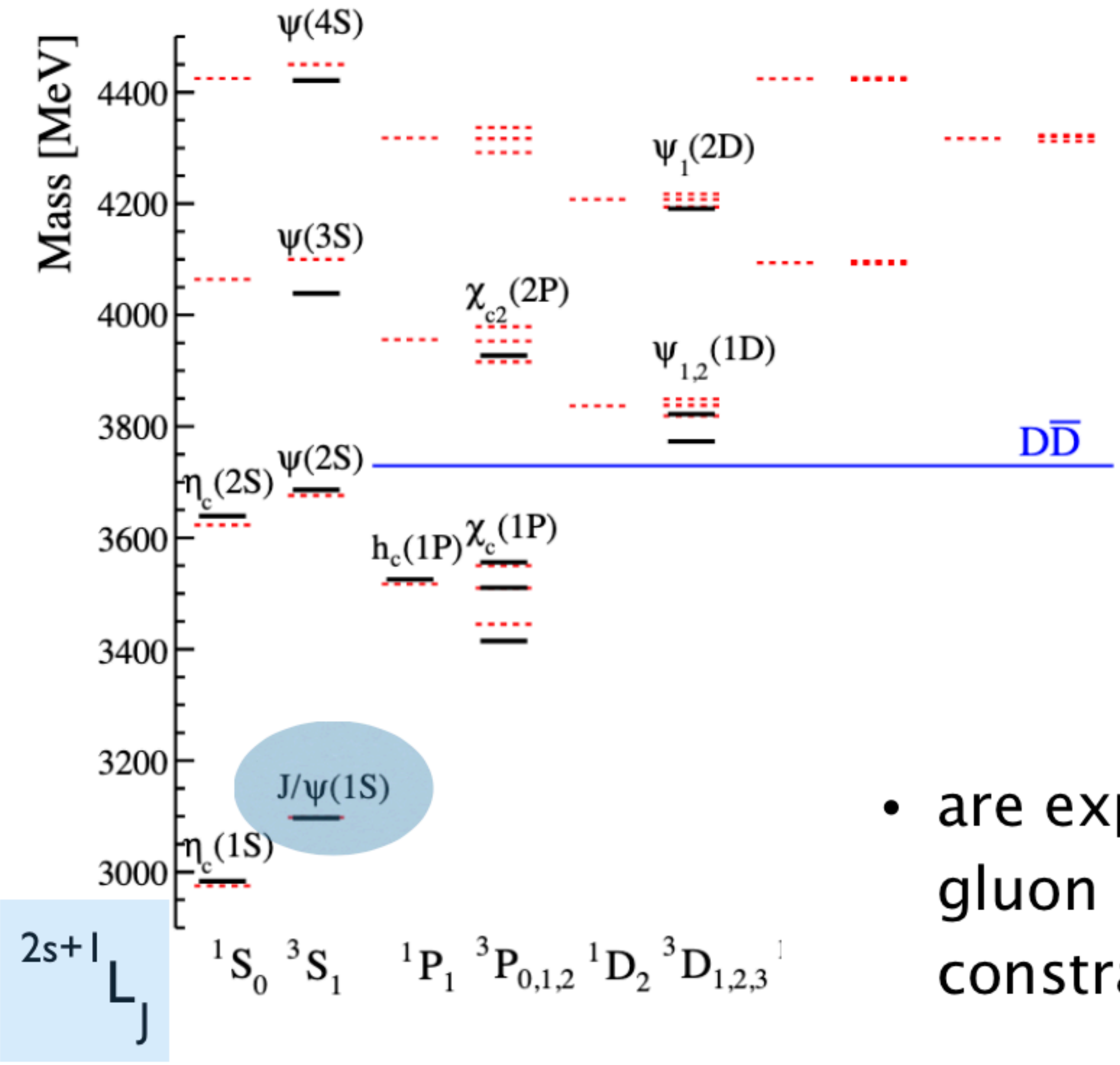
Quarkonia as tools

thanks to my co-editors for their various inputs to this presentation

Introduction

Charmonium hierarchy

Rev.Mod.Phys. 90 (2018) 1, 015003



Quarkonia: bound states of heavy c, b, quarks[1]

50 years since J/ψ discovery

In high-energy facilities, they

- offer complementary information on quarkonium production mechanisms and fundamentals of QCD
- are expected to underpin the search for gluon saturation at the EIC + provide constraints on QGP dynamics.

[1]bound states analogous to those of e^+e^- (positronium)

CEM, CSM models and NRQCD factorisation

- Colour Singlet Model (CSM)[1]

ccbar in physical colour singlet state
e.g. ccbar[3S11] for Jpsi

Non pert info in Jpsi w.f at origin can be deduced from potential models and/or decay widths

Not the whole story....

Application to P wave states such as chi_c => leftover IR divergences that cannot be cancelled => inconsistency

pheno problem on tevatron data for inclusive jpsi photoproduction, cross section at NLO falls 2 ord of mag. below data (shown later)

NNLO* alpha_s in CSM however goes in right direction (Lansberg,11)

CSM cannot describe inclusive hadroproduction PT spectra of charmonia and bottomonia at high PT also

- Colour Evaporation Model (CEM)

$$d\sigma^{\text{(N)LO, direct/prompt}}[Q+X] = \mathcal{P}_Q^{\text{direct/prompt}} \int_{2m_Q}^{2m_H} \frac{d\sigma^{\text{(N)LO}}[Q\bar{Q}+X]}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$$

$$\mathcal{P}_Q = 1/9 \times (2J_Q+1)/\sum_i (2J_i+1)$$

the quarkonium production cross section proportional to that of production of a QQ pair

in a small invariant-mass window where its hadronisation into a quarkonium is possible

No notion of $n = {}^{2s+1}L_J^{c}$

qualitative picture with nonetheless some phenomenological success...

see also (I(CEM Ma, Vogt 16'

[1]coincident with the LO term in the NRQCD expansion for S wave states

Quarkonium production à la NRQCD

NRQCD factorisation formula:

$$d\sigma_{J/\psi} = \sum_n d\sigma_{c\bar{c}[n]} \cdot \langle O^{J/\psi}[n] \rangle$$

$$n = {}^{2s+1}L_J^{\,c}$$

short-distance cross section (pert. QCD) for open quark pair in quantum state n

long-distance matrix element (LDME)

NRQCD: Phys. Rev. D 51 (1995). [Erratum: Phys.Rev.D 55, 5853 (1997)], pp. 1125-1171

expansion in relative velocity v of constituent heavy quarks allows one to systematically build up the quarkonium spectrum

$$|J/\psi\rangle = O(1)\left|c\bar{c}\left[{}^3S_1^{(1)}\right]\right\rangle + O(v)\left|c\bar{c}\left[{}^3P_J^{(8)}\right] + g\right\rangle + O(v^{3/2})\left|c\bar{c}\left[{}^1S_0^{(8)}\right] + g\right\rangle + O(v^2)\left|c\bar{c}\left[{}^3S_1^{(8)}\right] + gg\right\rangle + \ldots,$$

$$\mathcal{A}_{\mathrm{NRQCD}} = \langle J/\psi + X|\,\chi^\dagger(0)\kappa_n\psi(0)\,|0\rangle\,,$$

Different operators "couple" to different Fock states:

$$\chi^\dagger(0)\psi(0) \leftrightarrow \left|c\bar{c}\left[{}^1S_0^{(1)}\right]\right\rangle,\ \chi^\dagger(0)\sigma_i\psi(0) \leftrightarrow \left|c\bar{c}\left[{}^3S_1^{(1)}\right]\right\rangle,$$

$$\chi^\dagger(0)\sigma_i T^a\psi(0) \leftrightarrow \left|c\bar{c}\left[{}^3S_1^{(8)}\right]\right\rangle,\ \chi^\dagger(0)D_i\psi(0) \leftrightarrow \left|c\bar{c}\left[{}^1P_1^{(8)}\right]\right\rangle, \ldots$$

squared NRQCD amplitude (=LDME):

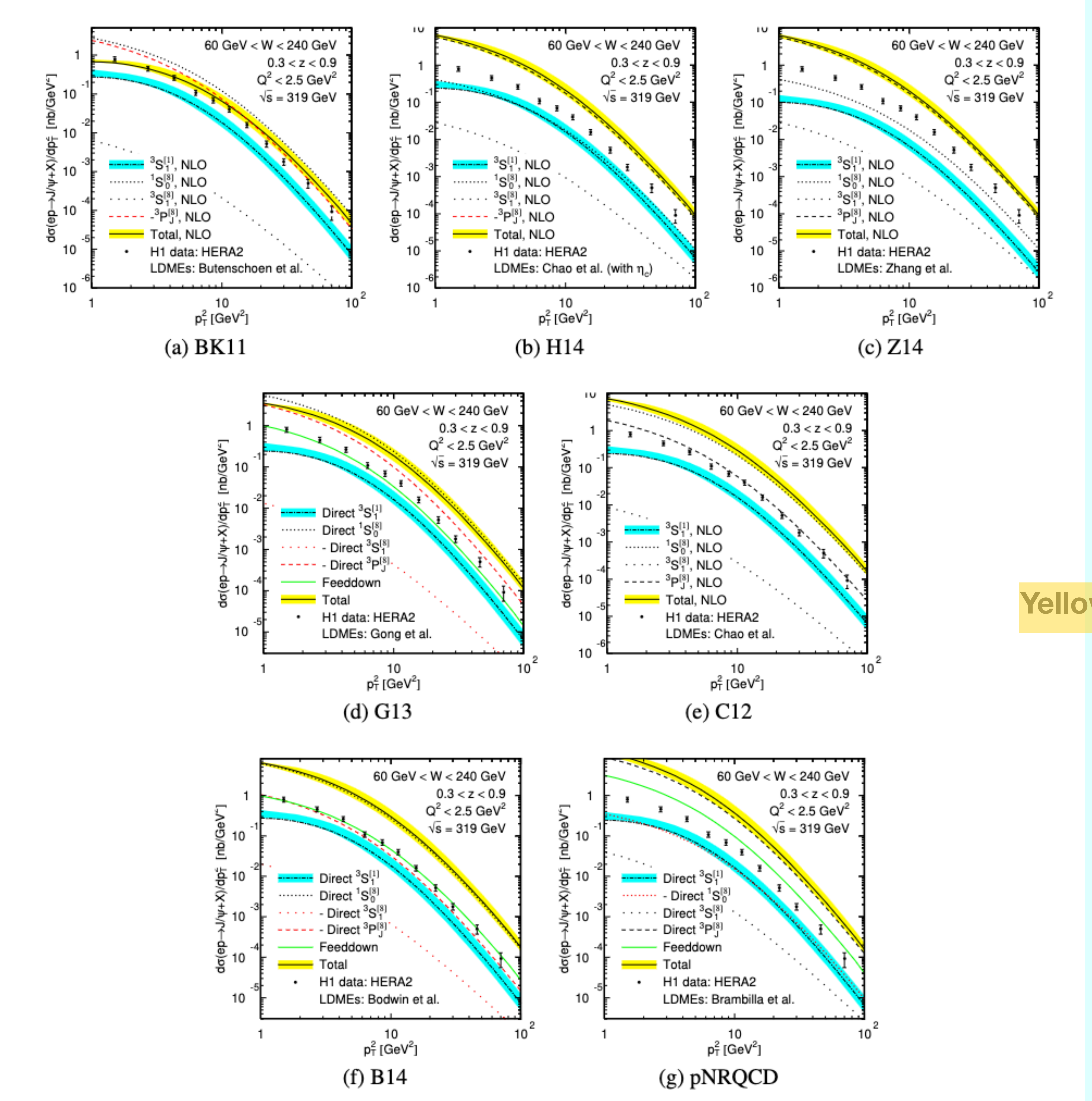
$$\sum_X |\mathcal{A}|^2 = \langle 0|\,\underbrace{\psi^\dagger\kappa_n^\dagger\chi a^\dagger_{J/\psi} a_{J/\psi}\chi^\dagger\kappa_n\psi}_{\mathcal{O}_n^{J/\psi}}\,|0\rangle = \left\langle \mathcal{O}_n^{J/\psi} \right\rangle,$$

- Leading term in v for S wave states is the CSM
- For P wave states, the CS and CO states have same velocity scaling therefore cancellation of singularities needs both.

Legacy and future measurements at the EIC

Status of LDME NRQCD fits I

pT spectra of inclusive **J/ψ** photoproduction, **ep -> J/ψ X,** at HERA, with LDMEs from various groups



Acronym	Reference	J/ψ hadropr.	J/ψ photopr. and e^+e^-	J/ψ polar. in hadropr.	η_c hadropr. ($P_T > 6.5$ GeV)
BK11	Butenschön et al. [104, 105, 106, 107]	✓($P_T > 3$ GeV)	✓	✗	✗
H14	Chao et al. + η_c [114]	✓($P_T > 6.5$ GeV)	✗	✓	✓
Z14	Zhang et al. [115]	✓($P_T > 6.5$ GeV)	✗	✓	✓
G13	Gong et al. [109]	✓($P_T > 7$ GeV)	✗	✓	✗
C12	Chao et al. [108]	✓($P_T > 7$ GeV)	✗	✓	✗
B14	Bodwin et al. [80]	✓($P_T > 10$ GeV)	✗	✓	✗
pNRQCD	Brambilla et al. [110, 116]	✓($P_T > 15$ GeV)	✗	✓	✗✓

- BK11 the only global fit, including **both** hadro- and photoproduction datasets while the others **only** hadroproduction
- BK11 describes well J/psi hadro- and photoproduction, but fails to describe charmonium polarisation observables in hadroproduction at large pT -> famous 'Polarisation puzzle'

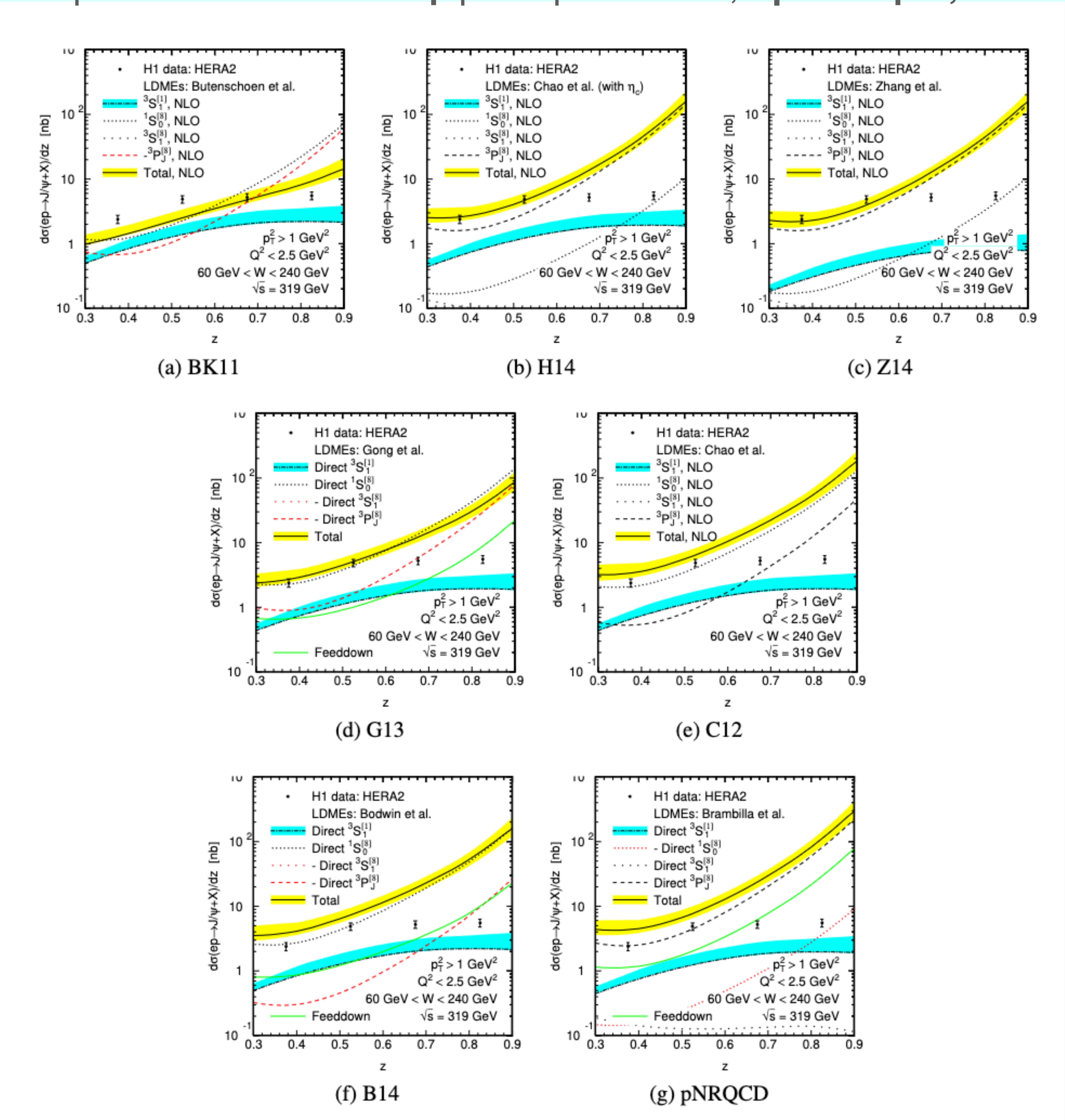
Yellow band: NRQCD up to O(v^4), means CSM + contribution of CO octet states.

Blue band: NLO CSM (leading term in NRQCD, falls below the data)

- H14 and Z14 describe well the J/psi polarisation and J/psi & eta_c hadroproduction but significantly overestimate the J/psi photoproduction (like the others, except BK11)
- Discrepancies in the yellow band amongst the groups for the presented observable show disagreement by factor of 2 at pT ~ 10 GeV while up to factor of 10 at low pT
- maximum reach in pT for this observable at EIC is 10 GeV, so any prediction including such CO contributions should be interpreted with care throughout the whole pT reach of the EIC

Status of LDME NRQCD fits II

z spectra of inclusive **J/ψ** photoproduction, **ep -> J/ψ X,** at HERA, with LDMEs from various groups



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Z14	Zhang et al. [115]	✓($P_T > 6.5$ GeV)	✗	✓	✓
G13	Gong et al. [109]	✓($P_T > 7$ GeV)	✗	✓	✗
C12	Chao et al. [108]	✓($P_T > 7$ GeV)	✗	✓	✗
B14	Bodwin et al. [80]	✓($P_T > 10$ GeV)	✗	✓	✗
pNRQCD	Brambilla et al. [110, 116]	✓($P_T > 15$ GeV)	✗	✓	✗✓

- Similar conclusions as just discussed hold for the z spectra

  (z = fraction of photon energy going to **J/ψ** in p rest frame)

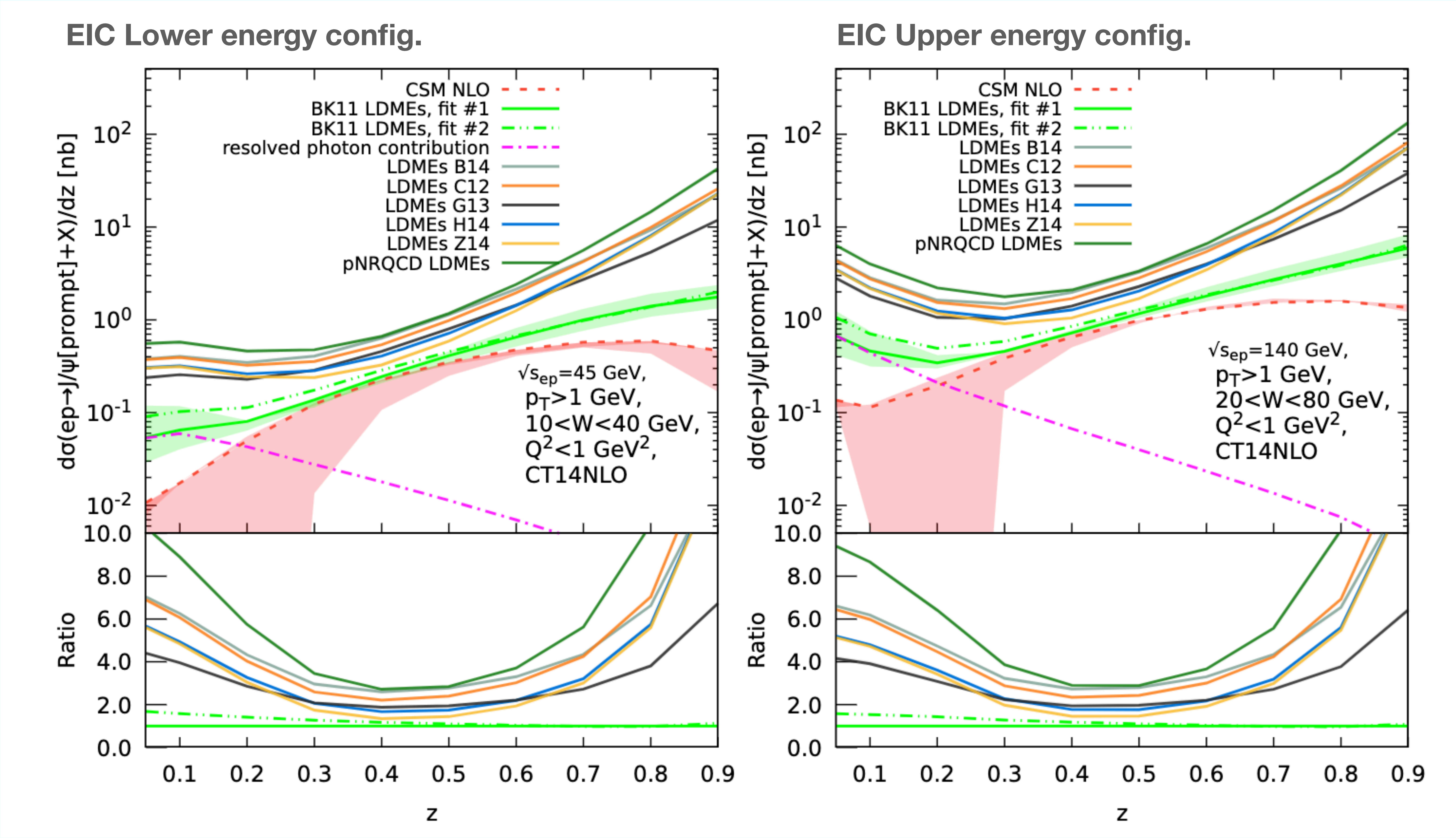
$$z = (p_{J/\psi}P)/(qP)$$

- Rapid increase of the spectrum towards z → 1 for all groups, except BK11

  (not reflected by the HERA data)

Predictions for the EIC kinematics

z spectra of inclusive **J/ψ** photoproduction, **ep -> J/ψ X,** at the EIC with LDMEs from various groups



- LDMEs extracted from photo- and hadroproduction data to be used in polarisation studies (leads to polarisation puzzle). Can check the scenario at EIC with measurements at a varied collision energy.
- Again, rapid increase of the spectrum towards z → 1 for all groups, except BK11
- Resolved photon contribution sizeable only for z<<1 (EIC data are therefore less sensitive to it so again process independence of LDMEs can be investigated in a cleaner environment in EIC photoproduction than at HERA)

$$z = (p_{J/\psi}P)/(qP)$$

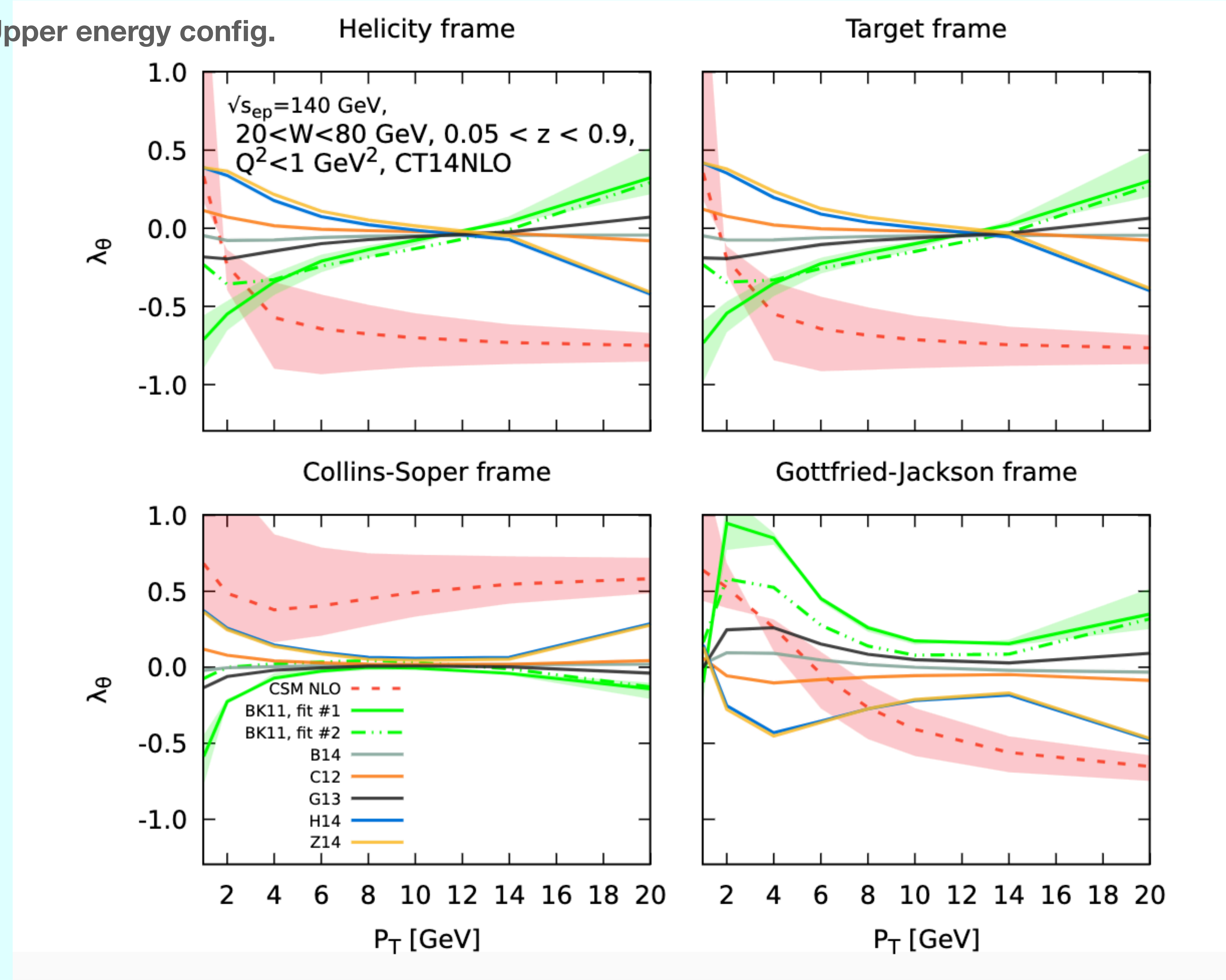
Prediction obtained using LDMEs and short-distance cross sections as before

Note: BK11 LDMEs, fit #2 obtained from same data as in #fit 1 (i.e. prompt photo- and hadroproduction data) but corrected for feed-down from heavier charmonium states

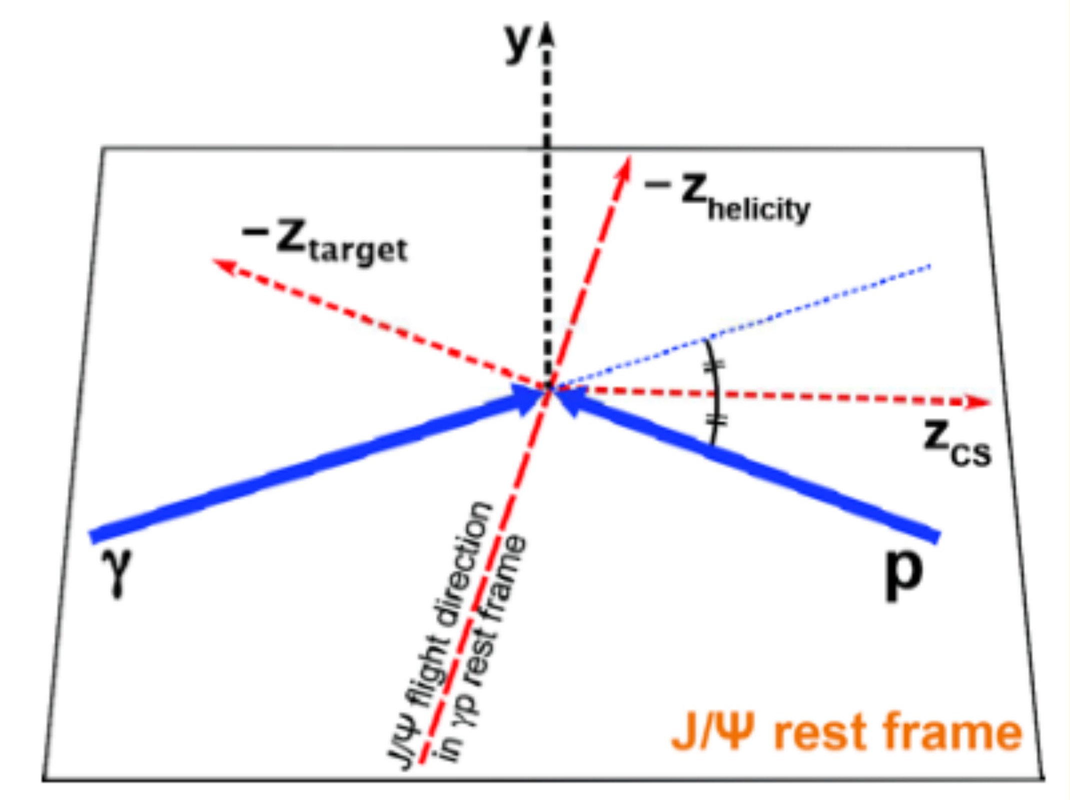
Polarisation at the EIC I

J/ψ transverse momentum (P_T) dependence of the λ_θ polarisation parameter in prompt J/ψ photoproduction (ep -> J/psi X, at the EIC with LDMEs from various groups

EIC Upper energy config.



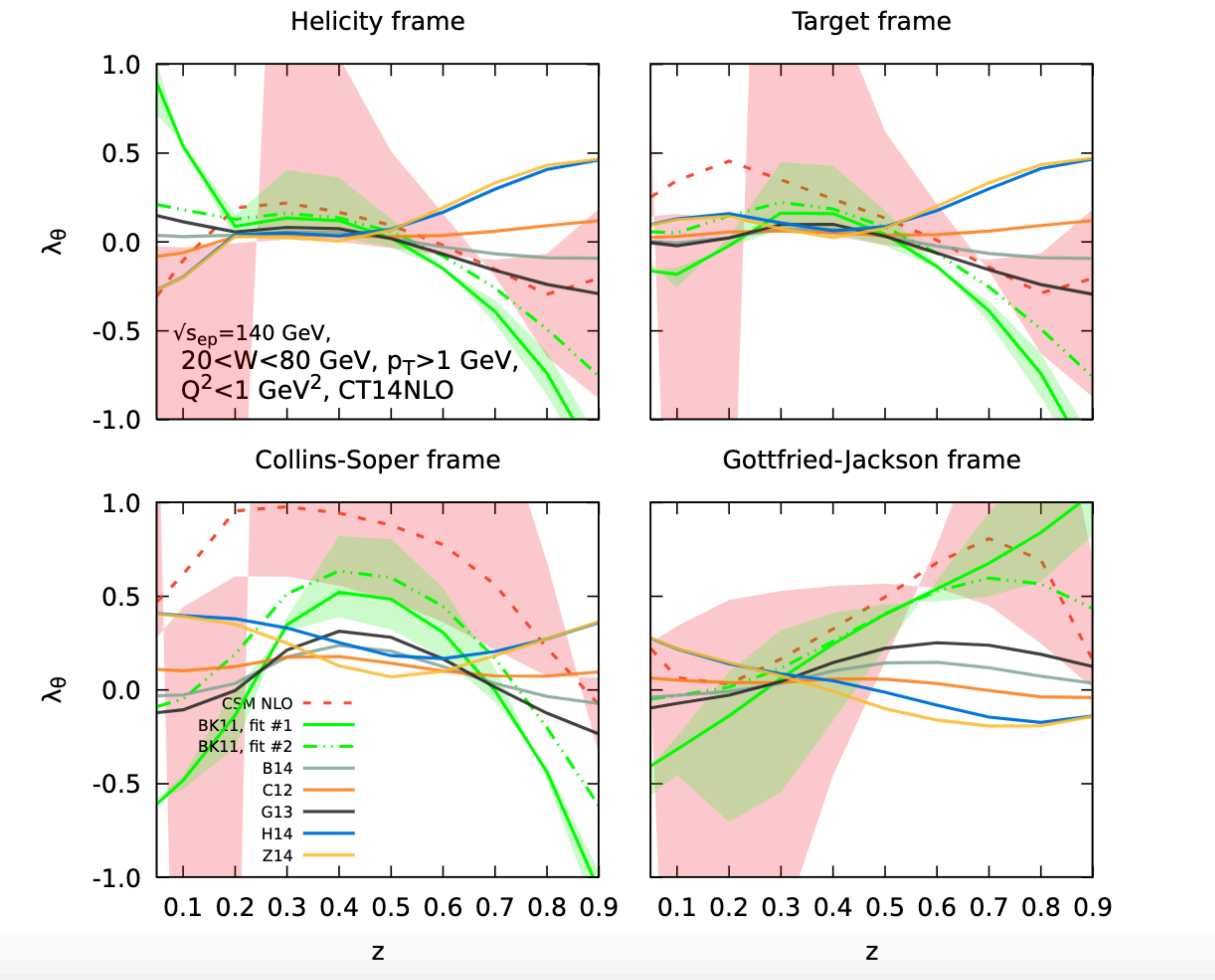
- NLO NRQCD predictions for all LDME sets roughly consistent with unpolarised production of **J/ψ** in all frames
- In contrast, NLO CSM predictions lead to significant polarisation
- BK11 different behaviour away from zero for high pT, recall doesn't describe polarisation in hadroproduction



Polarisation at the EIC II

J/ψ z dependence of the λ_θ polarisation parameter in prompt J/ψ photoproduction (ep -> J/psi X, at the EIC with LDMEs from various groups

EIC Upper energy config.



- NLO NRQCD predictions for all LDME sets roughly consistent with unpolarised production of **J/ψ** in all frames

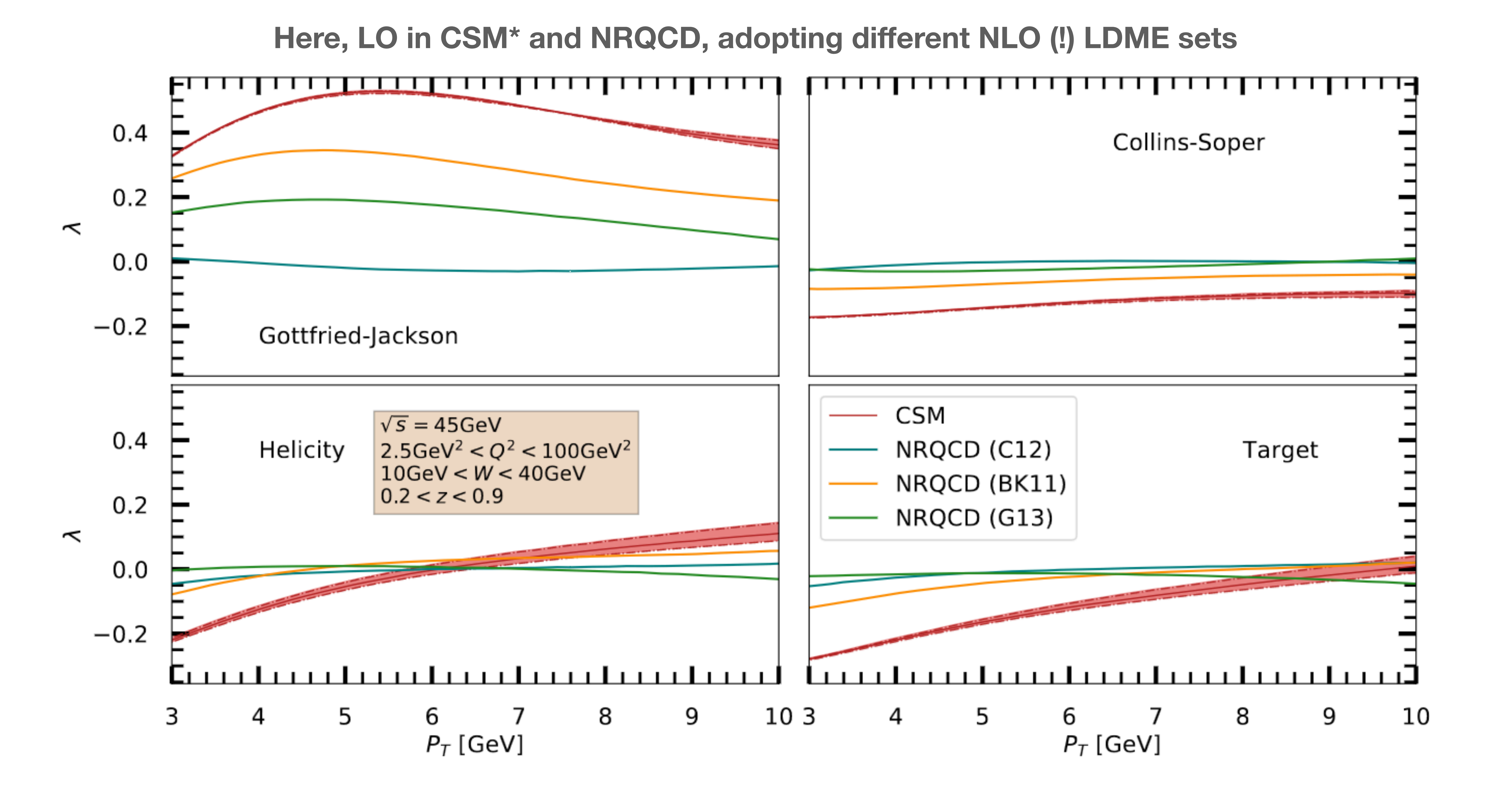
- Detailed behaviour of polarisation for different LDME sets is different for different frames -> important to constrain the theory.

- and allow one to favour/disfavour certain models or approaches

Polarisation at the EIC III - electroproduction

J/ψ PT dependence of the λ_θ polarisation parameter in prompt J/ψ electroproduction (ep -> J/psi X, at the EIC with LDMEs from various groups

EIC Lower energy config.



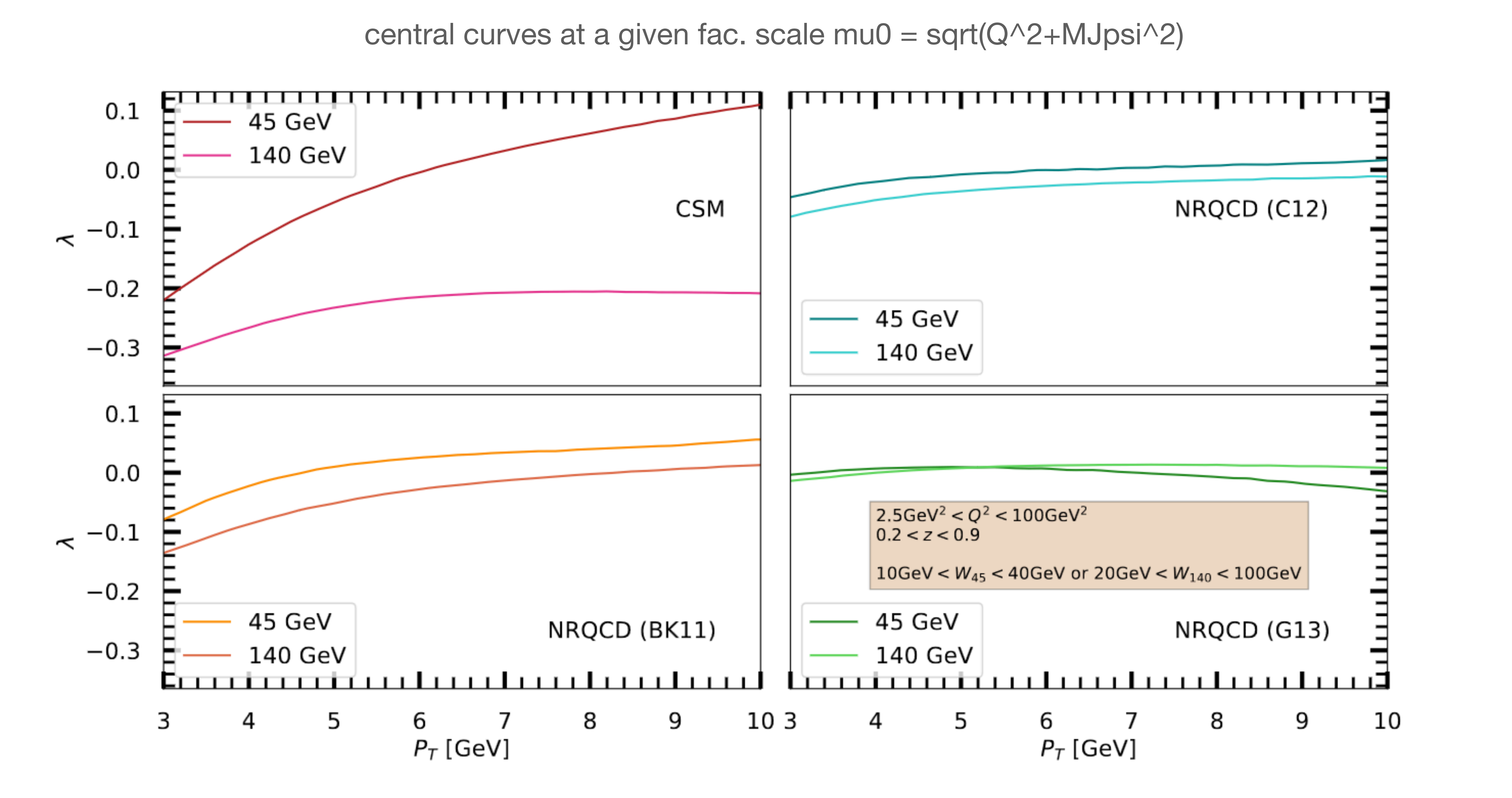
- HERA photoproduction measurements of polarisation exist but a) are not precise and b) were collected in region where different theory predictions agree well so theory constraining power low
- EIC electroproduction gives the handle on Q2 and will give highly precise data and allow for other/extended kinematical regions to be explored
- Polarisation different in different frames. The G-J frame gives largest separation between CSM and NRQCD predictions

*Theory state of the art is CSM NLO -> full NRQCD NLO analysis eagerly awaited.

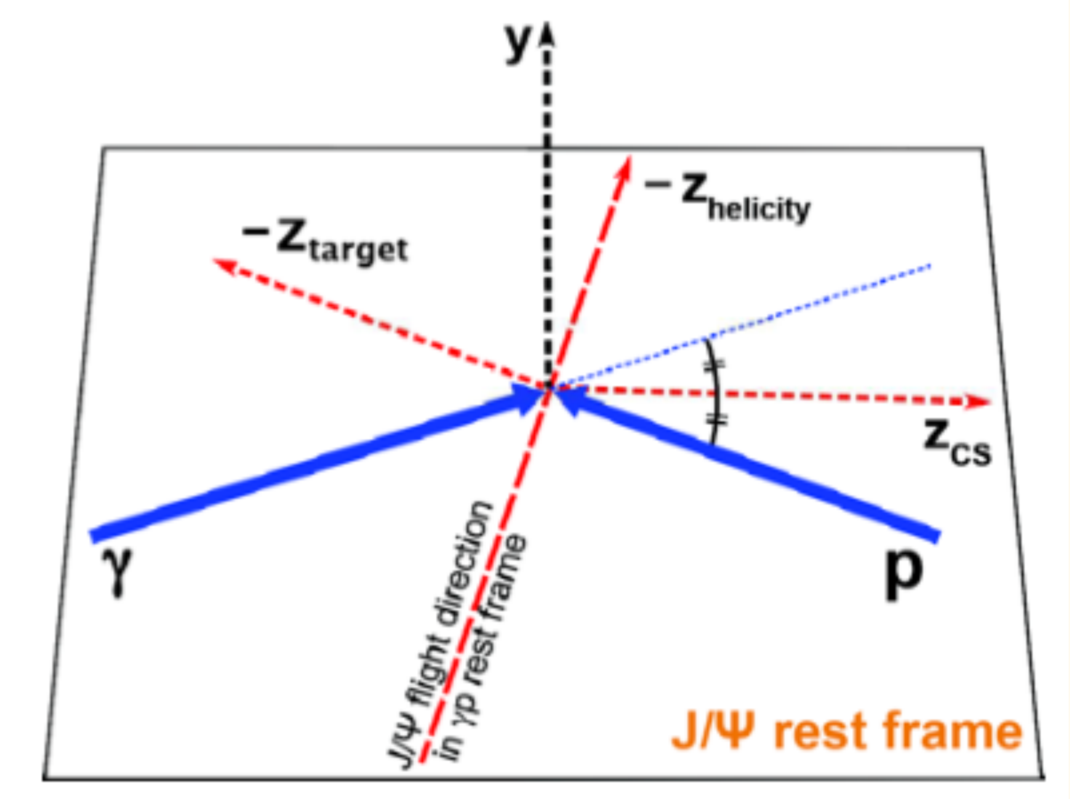
Polarisation at the EIC IV - electroproduction

J/ψ PT dependence of the λ_θ polarisation parameter in prompt J/ψ electroproduction (ep -> J/psi X, at the EIC with LDMEs from various groups

EIC energy config. variation



- Impact coming from variation of c.o.m energies at the EIC on the CSM and NRQCD predictions. Here, shown for helicity frame.
- CSM is more affected by the energy shift



Both (pT and z-)differential distributions at Q2 ≃ 0 and Q2 > 0 as well as polarisation observables should be measured to get a complete picture.

Other states at the EIC: χc

The χc-production has CS and CO contributions at the same order in v2, CO is unavoidable at NLO for χc. The NLO calculation for photoproduction **exists** and finite-Q2 production at NLO is within reach.

	$^1S_0^{(1)}$	$^3S_1^{(1)}$	$^1S_0^{(8)}$	$^3S_1^{(8)}$	$^1P_1^{(1)}$	$^3P_0^{(1)}$	$^3P_1^{(1)}$	$^3P_2^{(1)}$	$^1P_1^{(8)}$	$^3P_0^{(8)}$	$^3P_1^{(8)}$	$^3P_2^{(8)}$
η_c	1		v^4	v^3					v^4			
J/ψ		1	v^3	v^4						v^4	v^4	v^4
h_c			v^2		v^2							
χ_{c0}				v^2		v^2						
χ_{c1}				v^2			v^2					
χ_{c2}				v^2				v^2				

- Direct photoproduction at the LO in α_s:

$$\gamma^{(*)} + g \to c\bar{c}\left[{}^3P_{0,1,2}^{[1]}, {}^3S_1^{[8]}\right] + g,$$

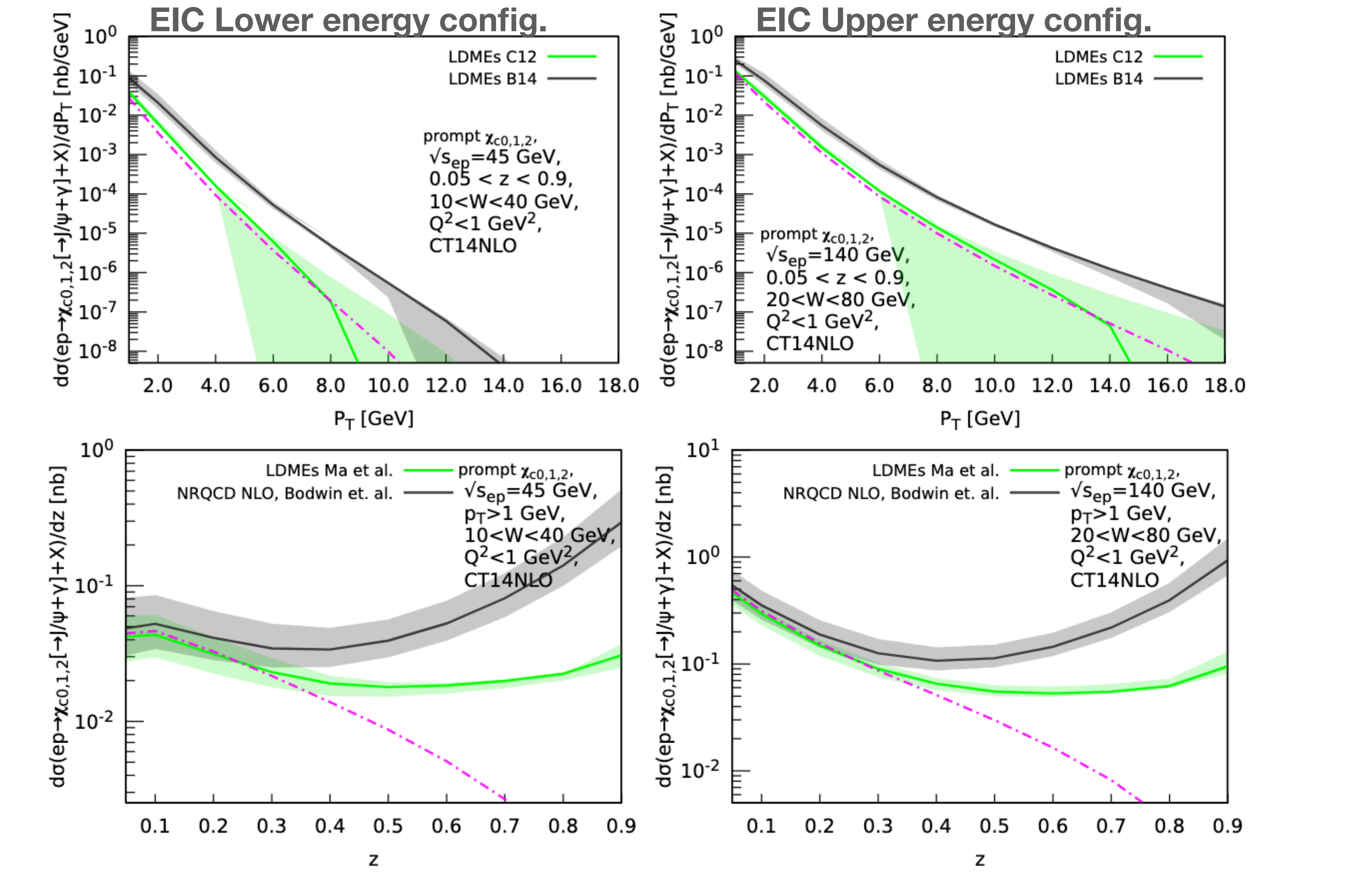
- Resolved-photon channels:

$$(\gamma \to) g/q + g \to c\bar{c}\left[{}^3P_{0,1,2}^{[1]}, {}^3S_1^{[8]}\right] + g/q,$$

- feeddown from $\psi(2S)$

pT

z



NLO NRQCD predictions for cross sections

Only LDMEs obtained by Chao et al. & Bodwin et al. lead to positive photoproduction cross sections.

The resolved-photon contribution for the LDME set of Chao et al. is shown by the dash-dotted line. The AGF [146] photon PDF set has been used.

The ψ(2S) → χc feed down has been included.

for P−wave production at NLO in NRQCD, one cannot make a clear distinction between CO and CS contributions as they directly depend on the NRQCD factorisation scale, μΛ

Interestingly, resolved photon contbn makes the χc cross sections positive at low z

Other states at the EIC: ηc

The ηc-production is a test of **HQSS relations** between LDMEs

- Direct-photon channels [H-F Zhang et. al, 2019] , LO in α_s

$$\boxed{\gamma + g \to c\bar{c}\left[{}^1S_0^{[1]}\right] + g + g,}$$

$$\gamma + g \to c\bar{c}\left[{}^1S_0^{[8]}\right] + g,$$

$$\gamma + q(\bar{q}) \to c\bar{c}\left[{}^1S_0^{[8]}\right] + q(\bar{q}),$$

$$\gamma + g \to c\bar{c}\left[{}^3S_1^{[8]}\right] + g,$$

$$\gamma + g \to c\bar{c}\left[{}^1P_1^{[8]}\right] + g,$$

$O(\alpha\alpha_s^3)$ ↓ expected to be negligible because of this power counting but resolved photon contbn brings up

- + resolved-photon channels

	${}^1S_0^{(1)}$	${}^3S_1^{(1)}$	${}^1S_0^{(8)}$	${}^3S_1^{(8)}$	${}^1P_1^{(1)}$	${}^3P_0^{(1)}$	${}^3P_1^{(1)}$	${}^3P_2^{(1)}$	${}^1P_1^{(8)}$	${}^3P_0^{(8)}$	${}^3P_1^{(8)}$	${}^3P_2^{(8)}$
η_c	1		v^4	v^3					v^4			
J/ψ		1	v^3	v^4						v^4	v^4	v^4
h_c			v^2		v^2							
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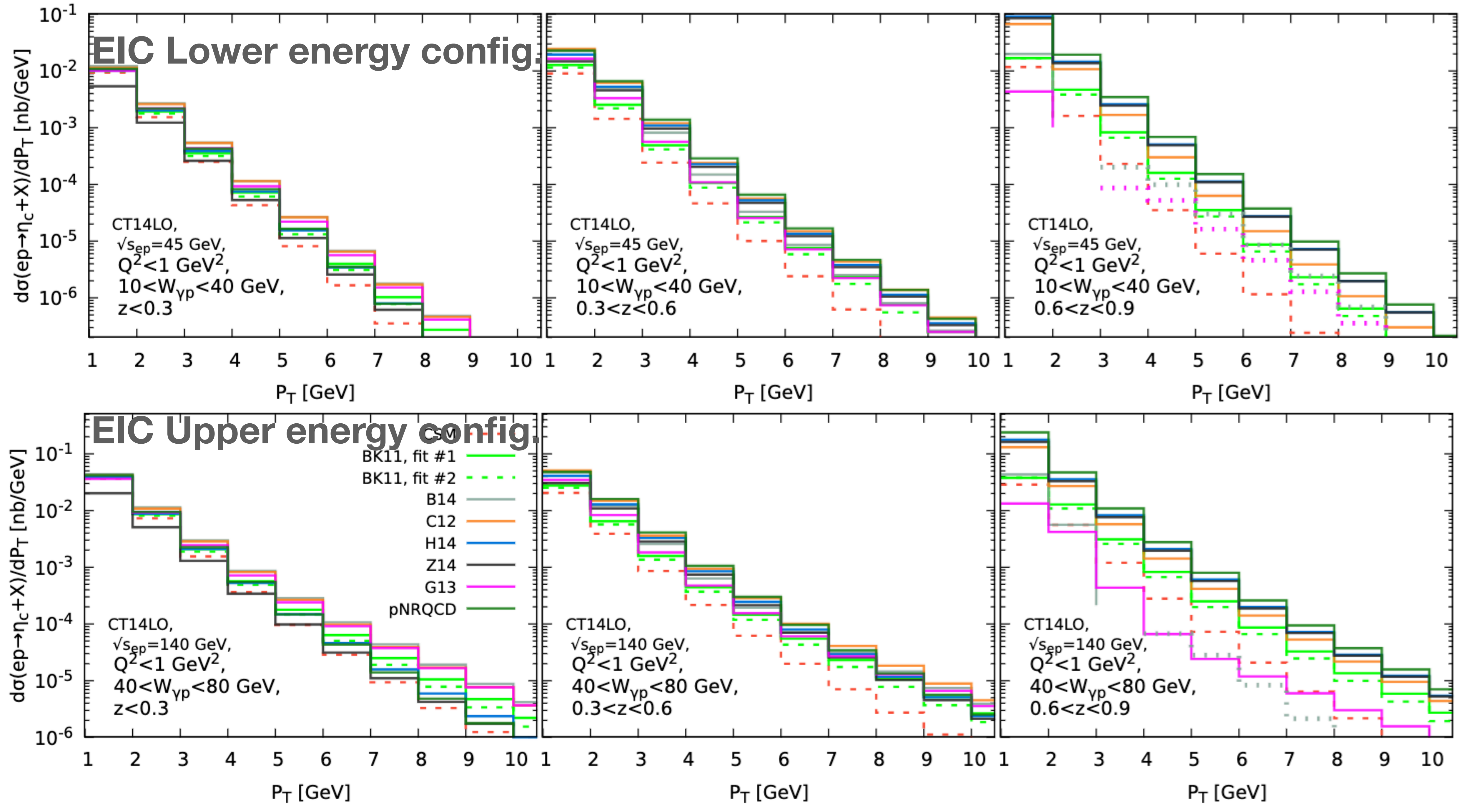

In recent works, ηc photo- and electroproduction cross sections were computed including all the CO and CS contributions at LO in αs

Plot uses NLO LDMEs

The CO contributions were computed by converting the J/ψ CO LDME sets to the ηc LDMEs through HQSS relations valid up v2 corrections (see table)

CO contributions are still important and the cross section at z > 0.5 strongly depends on the LDME choice

Other states at the EIC: ηc

The ηc-production is a test of **HQSS relations** between LDMEs

- Direct-photon channels [H-F Zhang et. al, 2019] , LO in α_s

$$\gamma + g \to c\bar{c}\left[{}^1S_0^{[1]}\right] + g + g,$$
$$\gamma + g \to c\bar{c}\left[{}^1S_0^{[8]}\right] + g,$$
$$\gamma + q(\bar{q}) \to c\bar{c}\left[{}^1S_0^{[8]}\right] + q(\bar{q}),$$
$$\gamma + g \to c\bar{c}\left[{}^3S_1^{[8]}\right] + g,$$
$$\gamma + g \to c\bar{c}\left[{}^1P_1^{[8]}\right] + g,$$

- + resolved-photon channels

$\mathcal{O}(\alpha\alpha_s^3)$

↓

expected to be negligible because of this power counting but resolved photon contbn brings up

	${}^1S_0^{(1)}$	${}^3S_1^{(1)}$	${}^1S_0^{(8)}$	${}^3S_1^{(8)}$	${}^1P_1^{(1)}$	${}^3P_0^{(1)}$	${}^3P_1^{(1)}$	${}^3P_2^{(1)}$	${}^1P_1^{(8)}$	${}^3P_0^{(8)}$	${}^3P_1^{(8)}$	${}^3P_2^{(8)}$
η_c	1		v^4	v^3					v^4			
J/ψ		1	v^3	v^4						v^4	v^4	v^4
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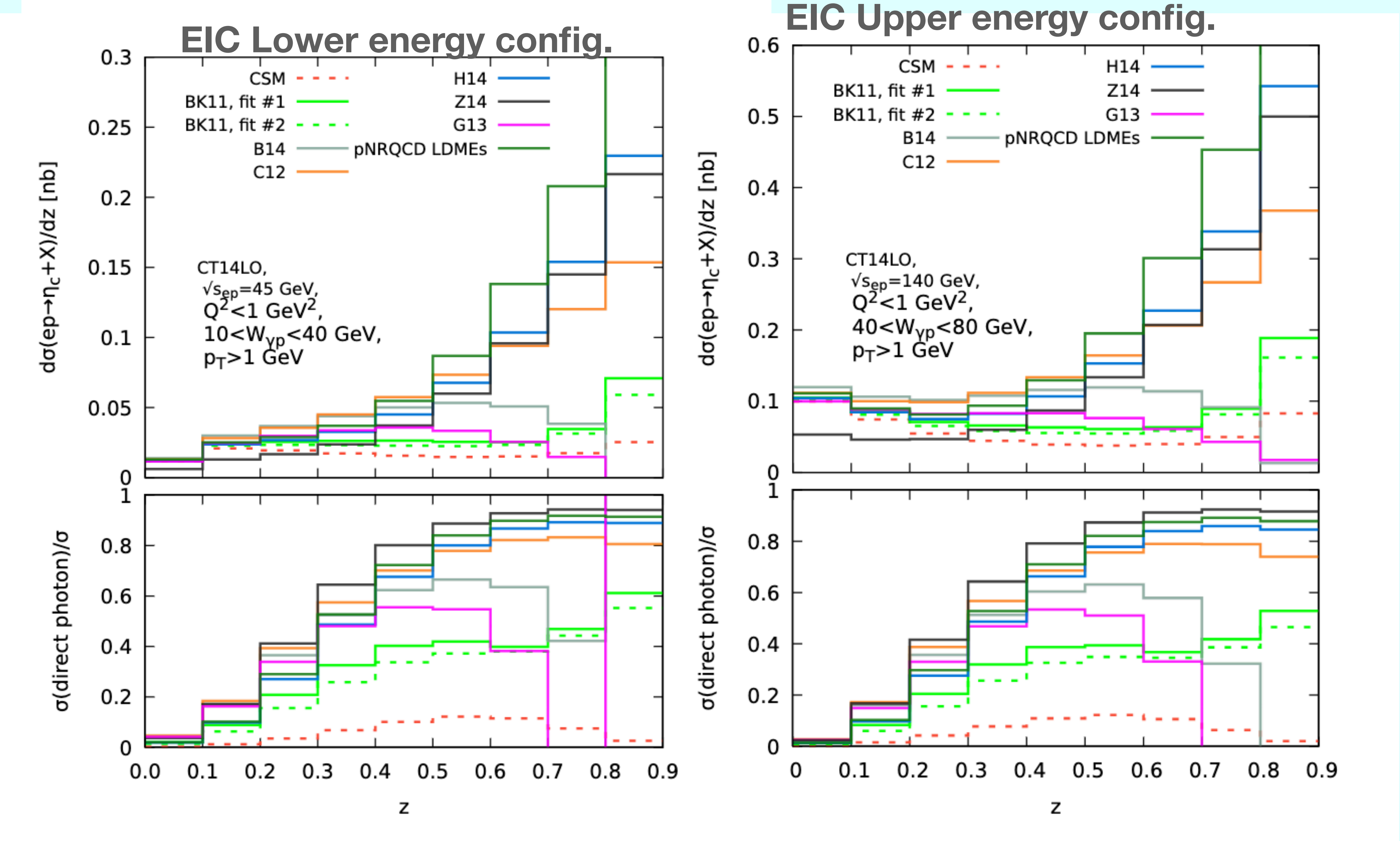

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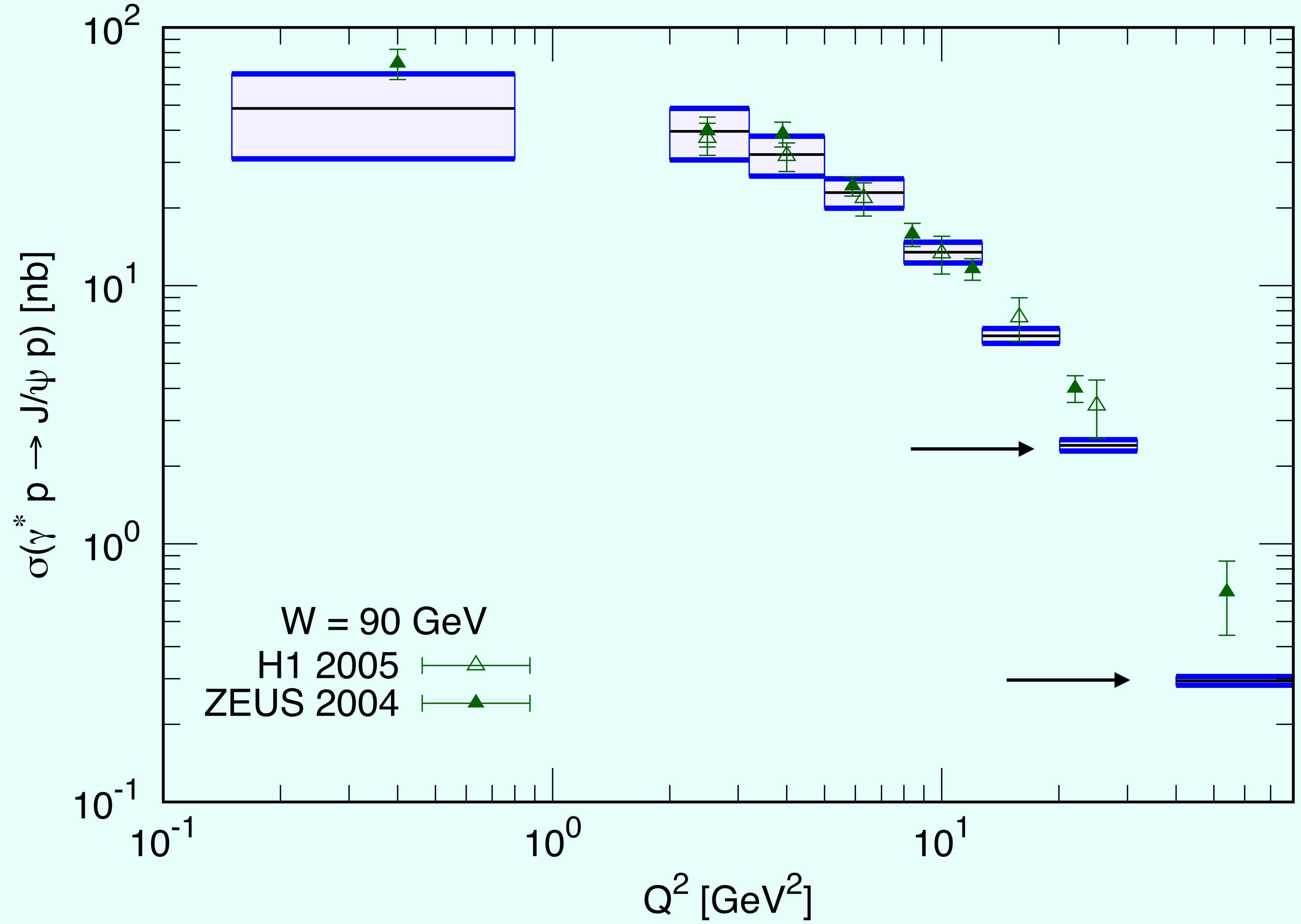
Plot uses NLO LDMEs

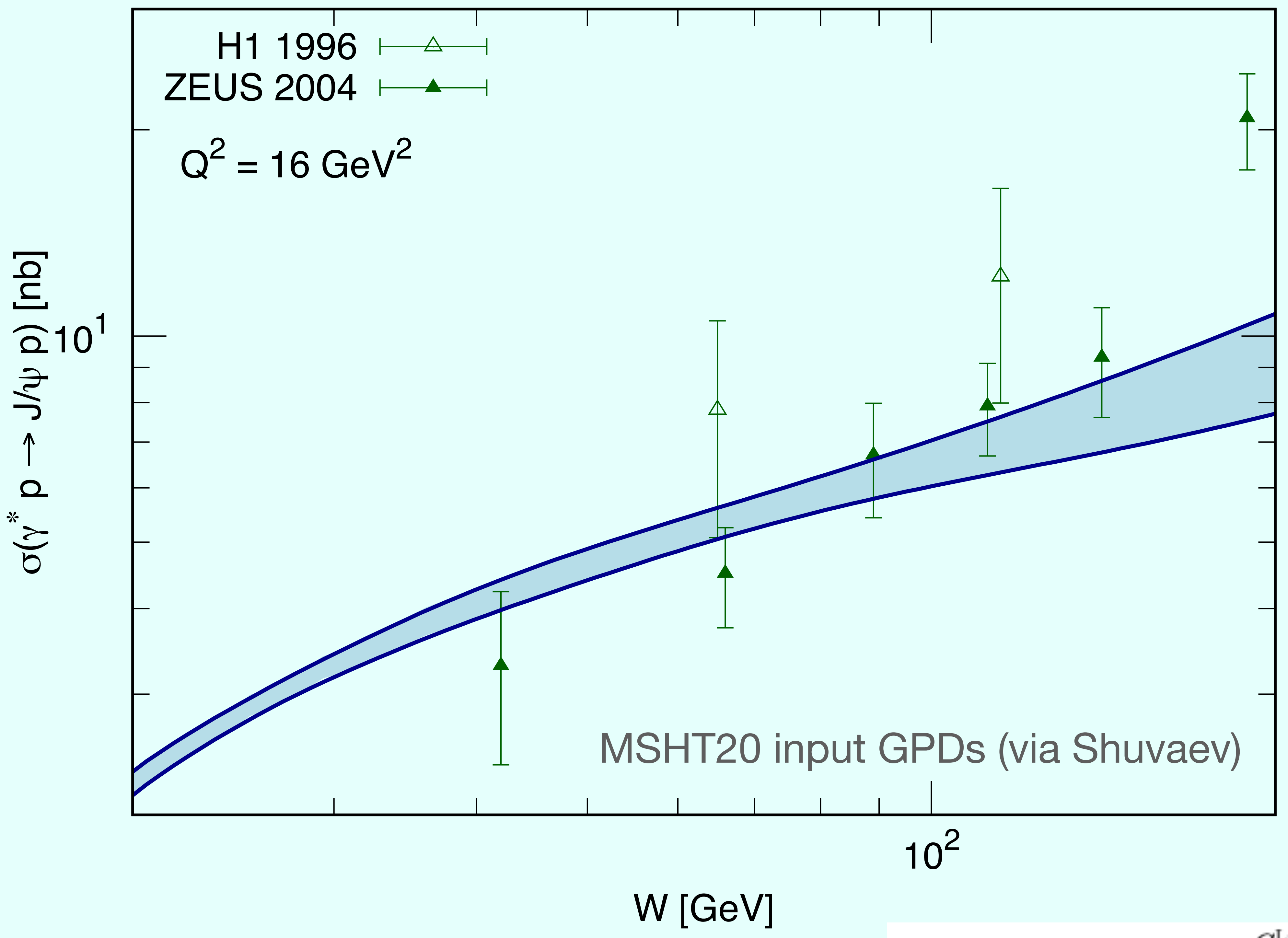
Most of LDME sets have z → 1 peak but some don't and are close to CSM prediction. Again, this is the LO computation with NLO LDMEs, be careful interpreting it!

The ψ(2S)-production is essentially free from feed-down from other charmonia, but has the same LDMEs as J/ψ so ψ(2S) is much "cleaner" phenomenologically than J/ψ

Quarkonia as Tools to study the parton content of **nucleons**

Exclusive heavy-vector meson production as probe of gluon PDF

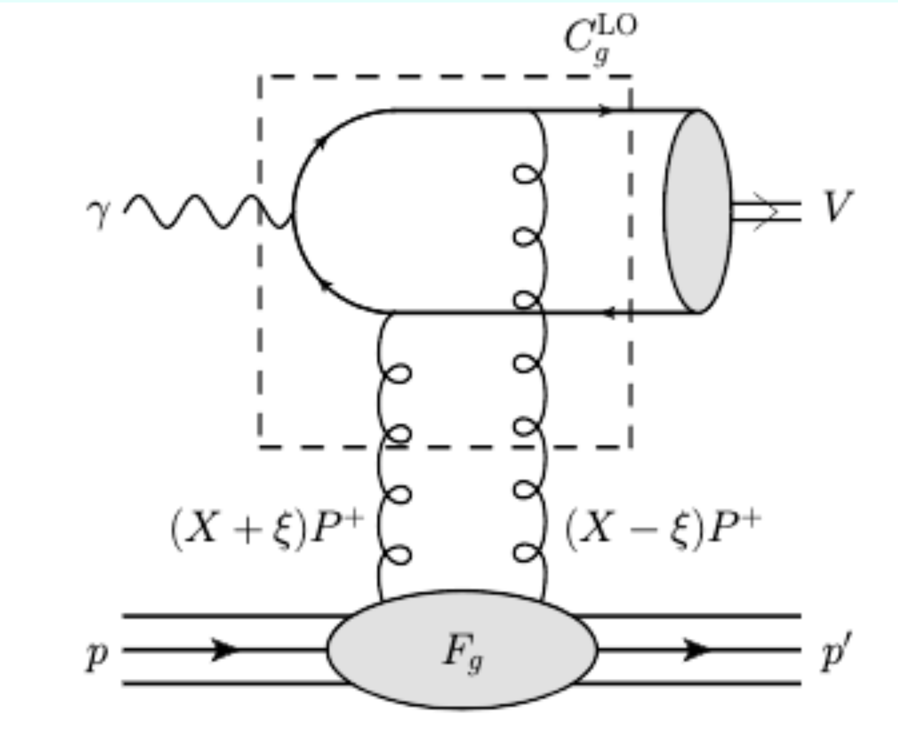




$$C_q^{(1)}|_{Q^2\to\infty} \sim \ln(Q^2/m^2)$$

$$C_g^{(1)}|_{Q^2\to\infty} \sim \ln(Q^2/m^2)^2$$

- Need for resummation evident in the data already?
- Errors shown are reflective of the PDF error only, factorisation scale dependency large at low Q^2 in conventional approach, alleviated through Q_0 subtraction or NLO CF + DLA HEF. At large scales, this dependency small.
- EIC will provide increased data coverage, complementing HERA and help resolve some discrepancies within current statistic-limited HERA data



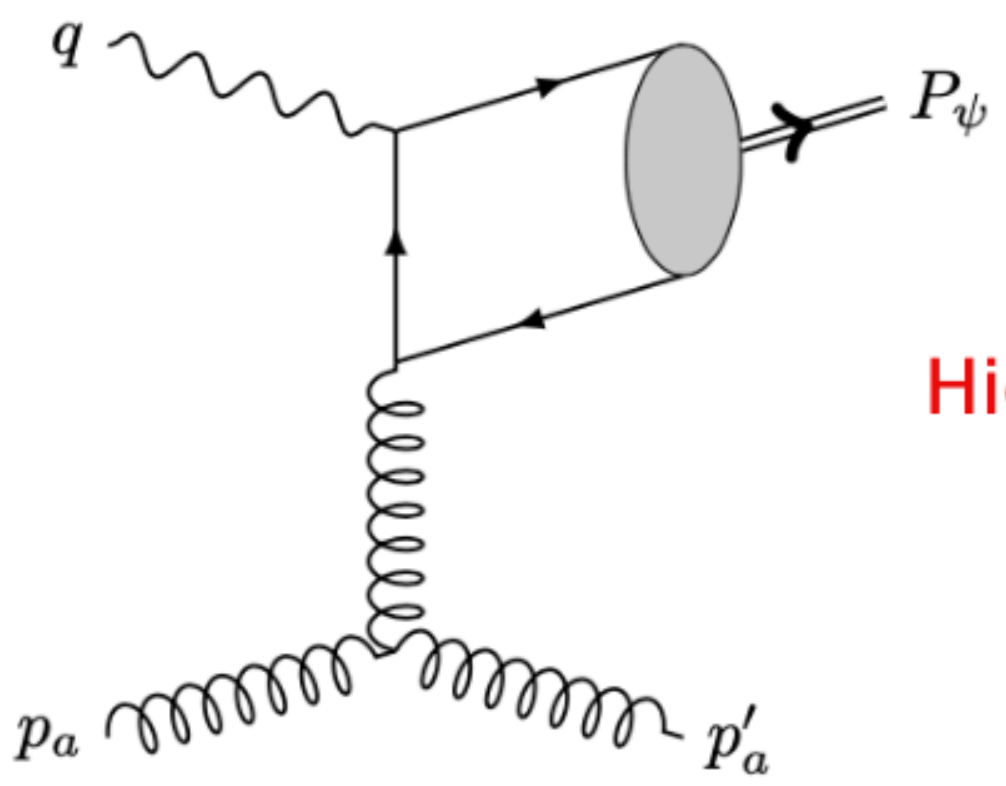
Quarkonia as Tools to learn about TMD observables

$e\,p \to e'\,J/\psi\,X$

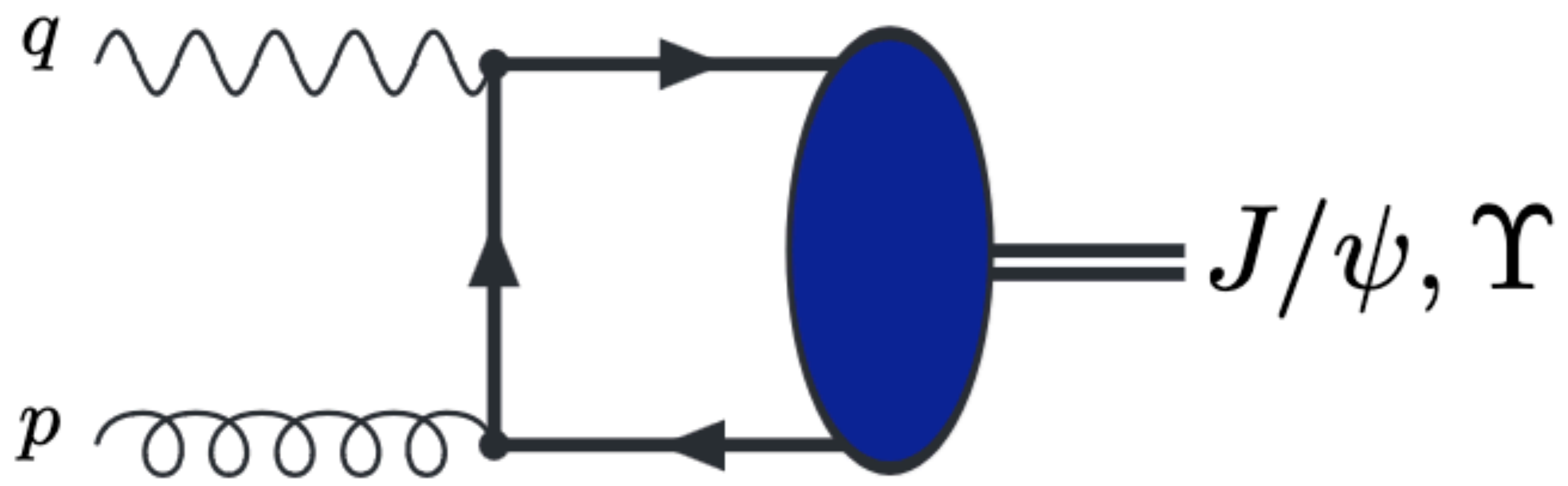
Using low p_T data to study NRQCD

SIDIS

and probe gluon TMDs

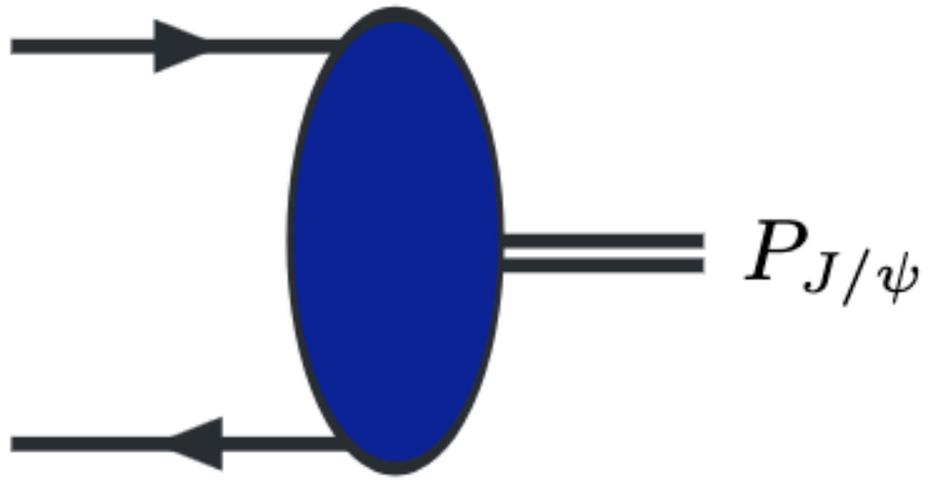


High p_T production: collinear factorization



Low p_T production: TMD factorization

At low p_T one becomes sensitive to the transverse momentum distribution of gluons inside the proton



Investigate gluon TMDs together with the LDMEs

Bacchetta, Boer, Pisano, Taels, 2018; Boer, Pisano, Taels, 2021

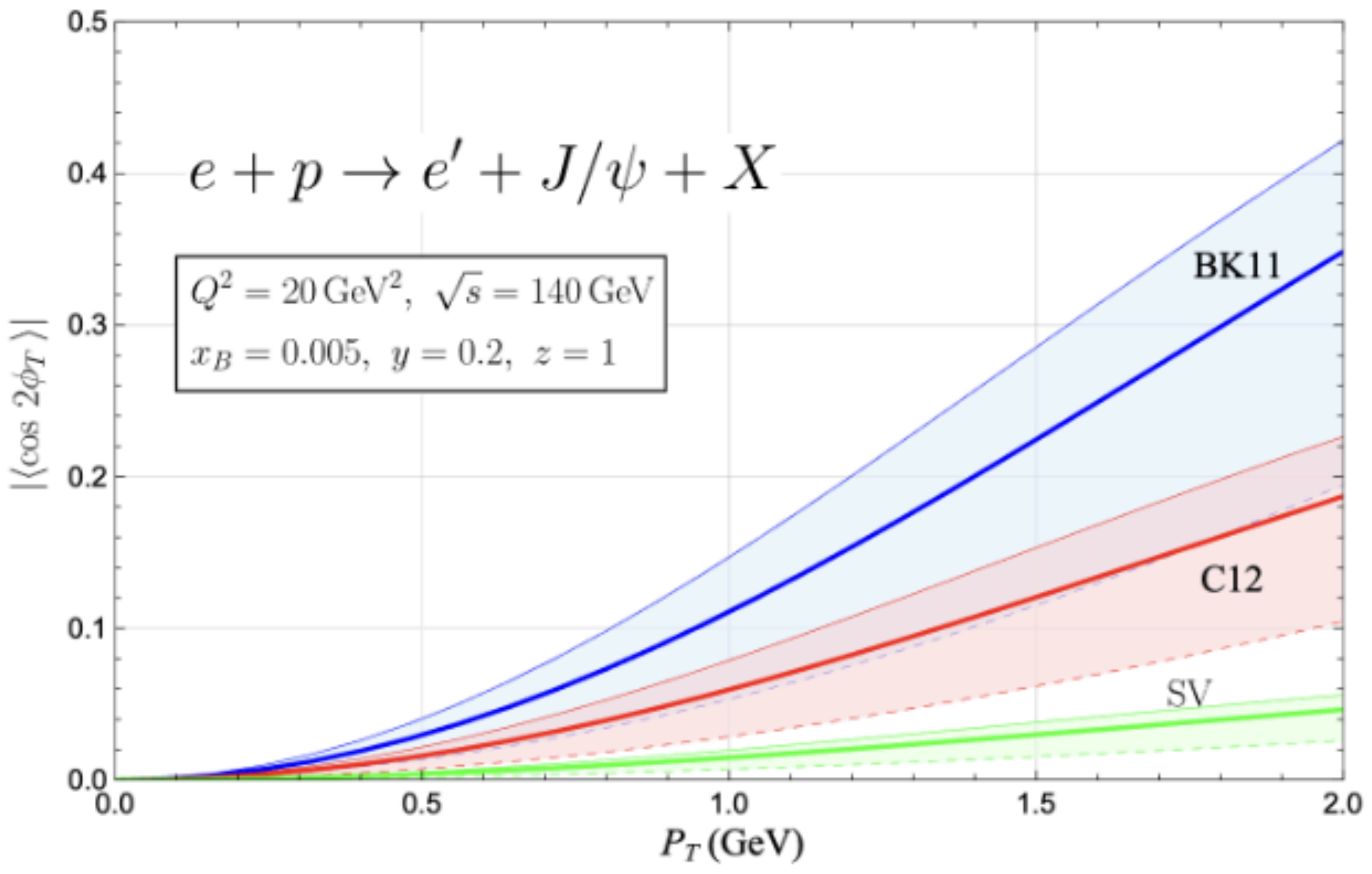
Angular modulations in the p_T distribution

linearly polarised gluon TMD

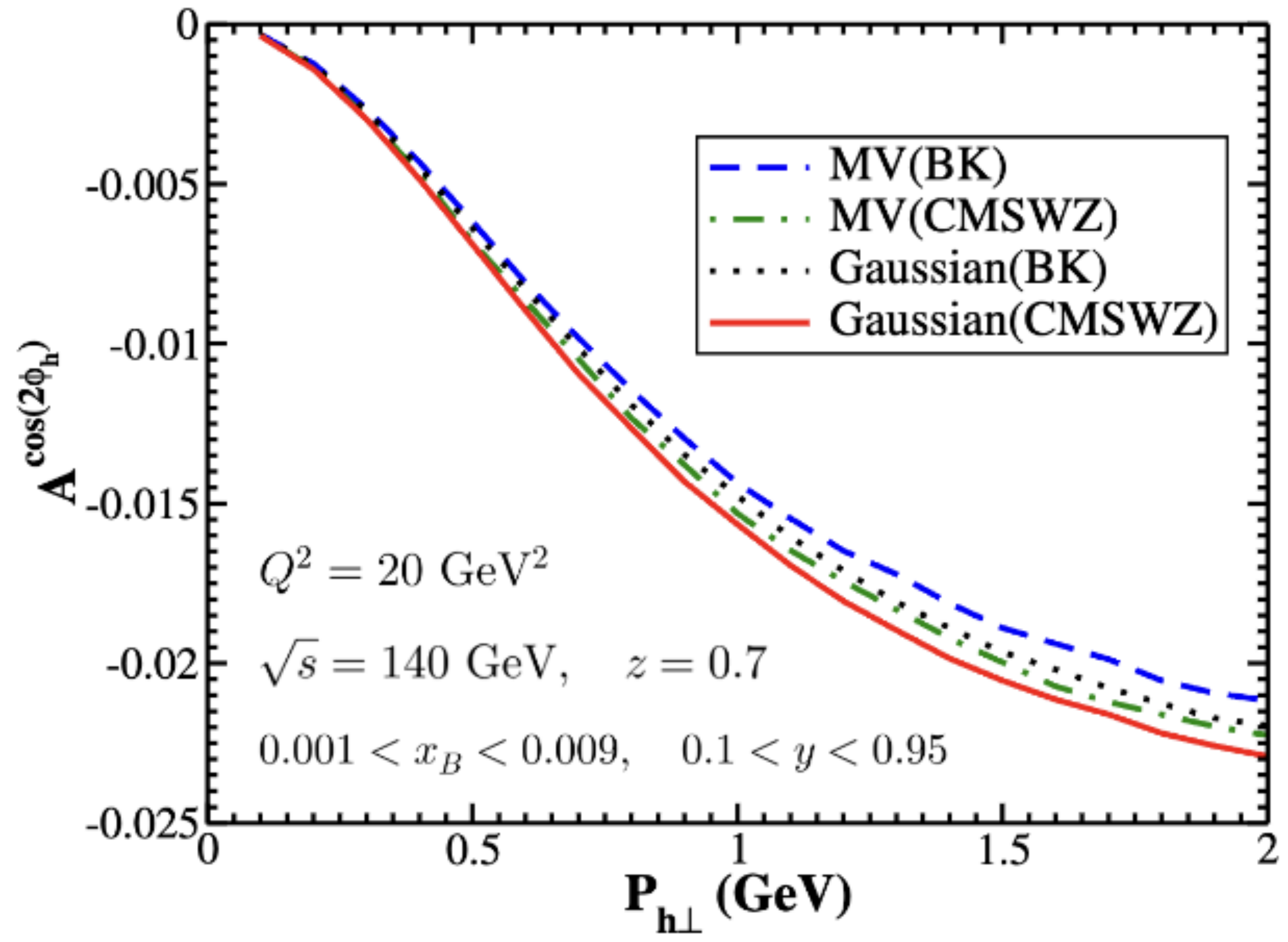
LDMEs encoded in TMD ShF

$$\frac{d\sigma^{UP}}{dy\,dx_B\,d^2\boldsymbol{P}_T^*} = \mathcal{N}\left[\sum_n A_{UP}^{[n]}\, \mathcal{C}\left[f_1^g\, \Delta^{[n]}\right] + \sum_n B_{UP}^{[n]}\, \mathcal{C}\left[w h_1^{\perp g}\, \Delta_h^{[n]}\right] \cos 2\phi_T^*\right]$$

TMD predictions (left) including TMD evolution show that a sizable $\cos 2\phi_T$ modulation due to linearly polarized gluons is possible, but there are large uncertainties due to poorly known CO LDMEs



Bor, Boer, 2022; EIC onium review, 2024



Kishore, Mukherjee, Pawar, Siddiqah, 2022

$$\langle \cos 2\phi_T^* \rangle \equiv \frac{\int d\phi_T^* \cos 2\phi_T^* \frac{d\sigma^{UU}}{dy\,dx_B\,d^2\boldsymbol{P}_T^*}}{\int d\phi_T^* \frac{d\sigma^{UU}}{dy\,dx_B\,d^2\boldsymbol{P}_T^*}} = \frac{1}{2}\,\frac{\sum_n B_{UU}^{[n]}\, \mathcal{C}\left[w h_1^{\perp g}\, \Delta_h^{[n]}\right]}{\sum_n A_{UU}^{[n]}\, \mathcal{C}\left[f_1^g\, \Delta^{[n]}\right]}$$

Another approach (right) -a generalized parton model with gluon radiation- predicts much smaller $\cos 2\phi_T$ modulation, and much less dependence on the CO LDMEs

Knowledge of cos phiT distribution gives handle on 1S08 and 3P08 LDMEs

Can be clarified at EIC

Polarized quarkonia at EIC

Will the quarkonium state be produced polarized at EIC?

In $e\,p \to \mathcal{Q}\,X$ (untagged e', dominated by $Q^2 \approx 0$) in collinear factorization at high p_T the ${}^1S_0^{8}$ state dominates ≈ unpolarized

Qiu, Wang, Qing, 2020

$$\frac{\int d\phi_T^* \frac{d\sigma^{UP}}{dy\,dx_B\,d^2\boldsymbol{P}_T^*}}{\int d\phi_T^* \frac{d\sigma^{UU}}{dy\,dx_B\,d^2\boldsymbol{P}_T^*}} = \frac{\sum_n A_{UP}^{[n]}\, C\left[f_1^g\,\Delta^{[n]}\right]}{\sum_n A_{UU}^{[n]}\, C\left[f_1^g\,\Delta^{[n]}\right]} = \frac{A_{UP}}{A_{UU}}$$

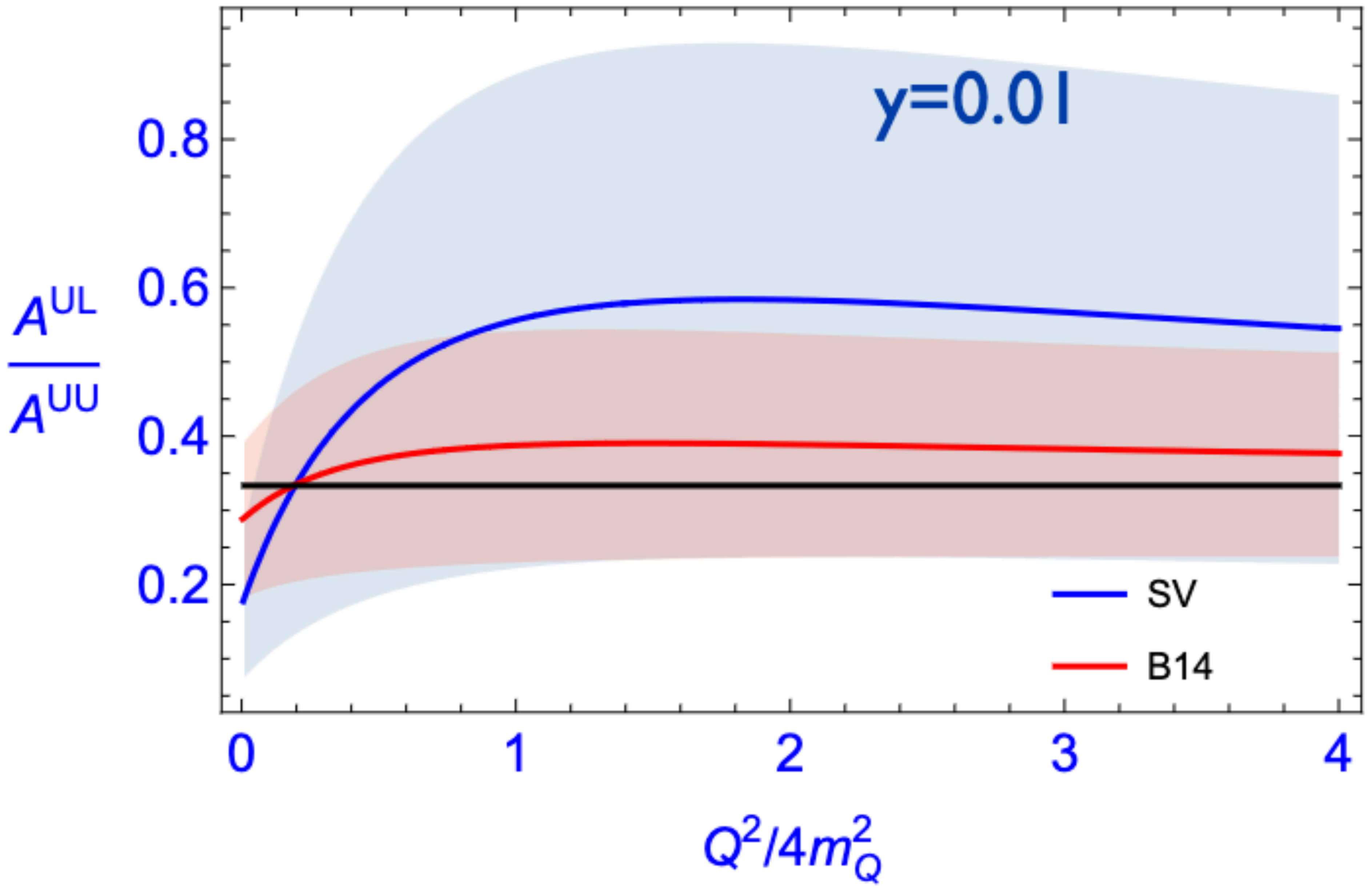
*if shape function polarisation independent

LO epxressions known only

NLO expressions desirable

In the TMD regime the ratio A^{UL}/A^{UU} (fraction of longitudinally polarized to unpolarized J/ψ's) is compatible with 1/3, but with large uncertainties

$$\left.\frac{A_{UL}}{A_{UU}}\right|_{\mathcal{O}_8^P \ll \mathcal{O}_8^S} \approx \frac{1}{3}$$



Boer, Pisano, Taels, 2021

Deviations from 1/3 would indicate the relevance of ${}^3P_0$

Gluon Sivers effect at the EIC (I)

D. Boer, C.A. Flett, C. Flore, D. Kikoła, J.-P. Lansberg, M. Nefedov, C. Van Hulse *et al.*, arxiv:2409.03691 [hep-ph]

Access polarised nucleon TMDs (e.g. the Sivers function), through the **Single Transverse Spin Asymmetries** (STSA), denoted AN, or AUT.

- Single Transverse Spin Asymmetries (STSA) are a key player to access the gluon Sivers effect
- experimentally defined as:

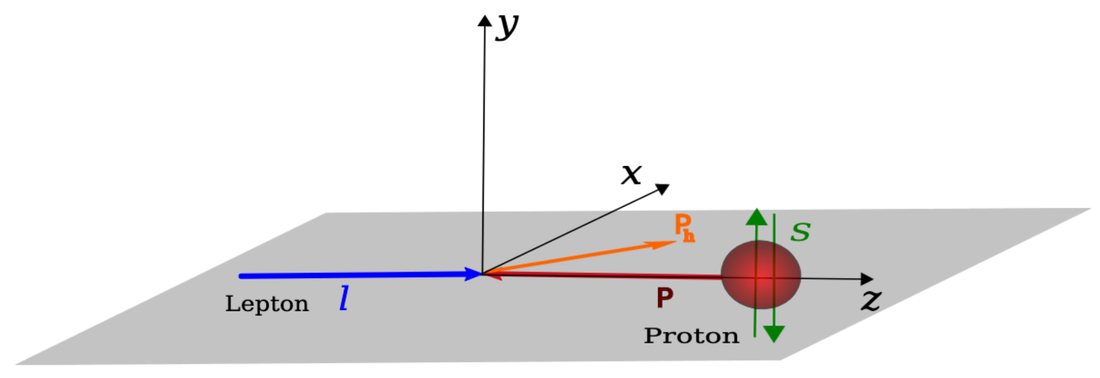
$$A_N = \frac{1}{\mathcal{P}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

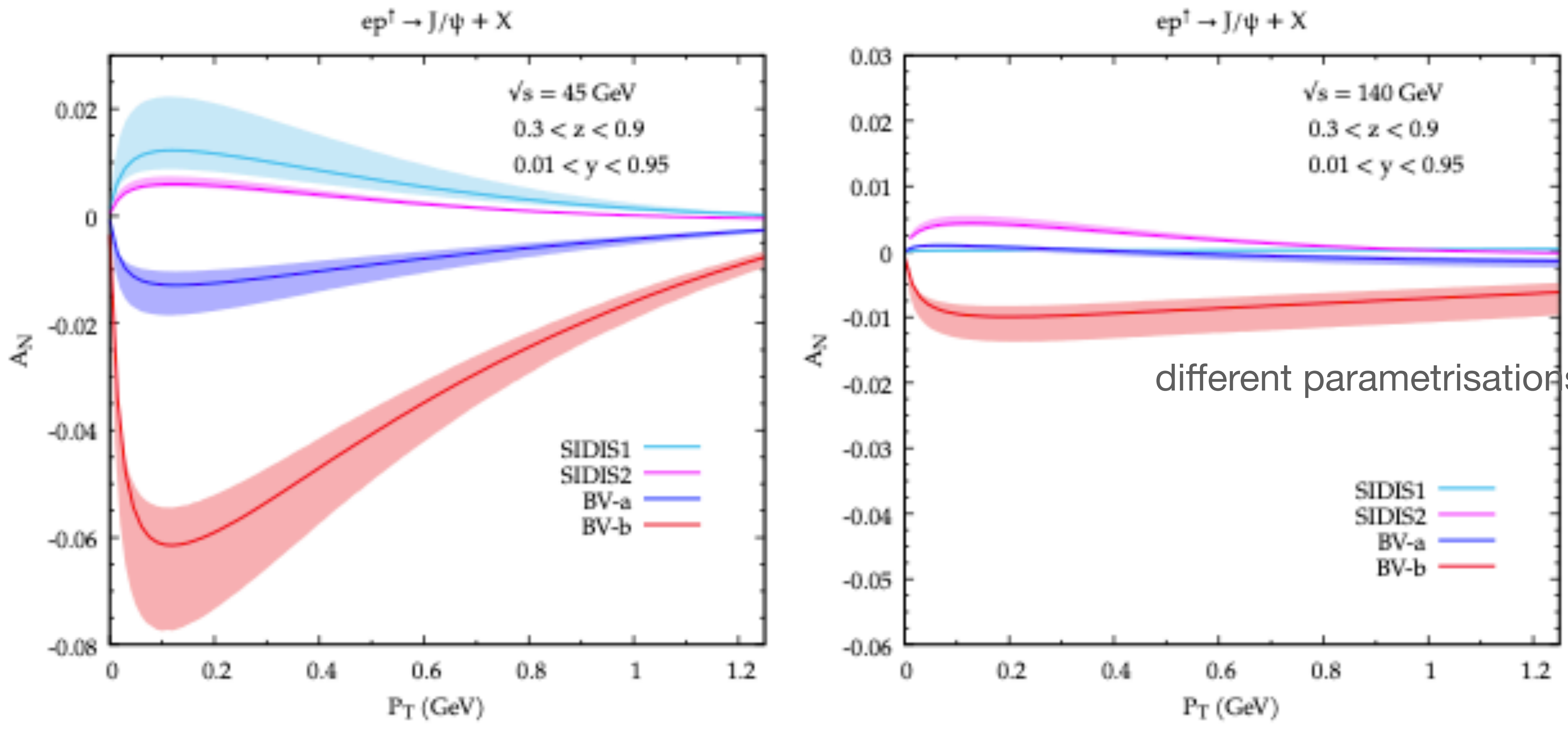
cross section of particles produced with the target nucleon spin orientation upwards or downwards

- GPM predictions for A_N in inclusive J/ψ photoproduction at the EIC

[S. Rajesh, R. Kishore, A. Mukherjee, PRD 98 (1) (2018) 014007]

$$E_Q \frac{d\sigma}{d^3 \boldsymbol{P}_Q} = \frac{1}{2(2\pi)^2} \int dx_\gamma dx_g d^2\boldsymbol{k}_{\perp g} f_{\gamma/e}(x_\gamma) f_{g/p}(x_g, \boldsymbol{k}_{\perp g}) \delta(\hat{s} + \hat{t} + \hat{u} - M_Q{}^2) \times \frac{1}{2\hat{s}} |\mathcal{M}_{\gamma+g\to Q+g}|^2.$$





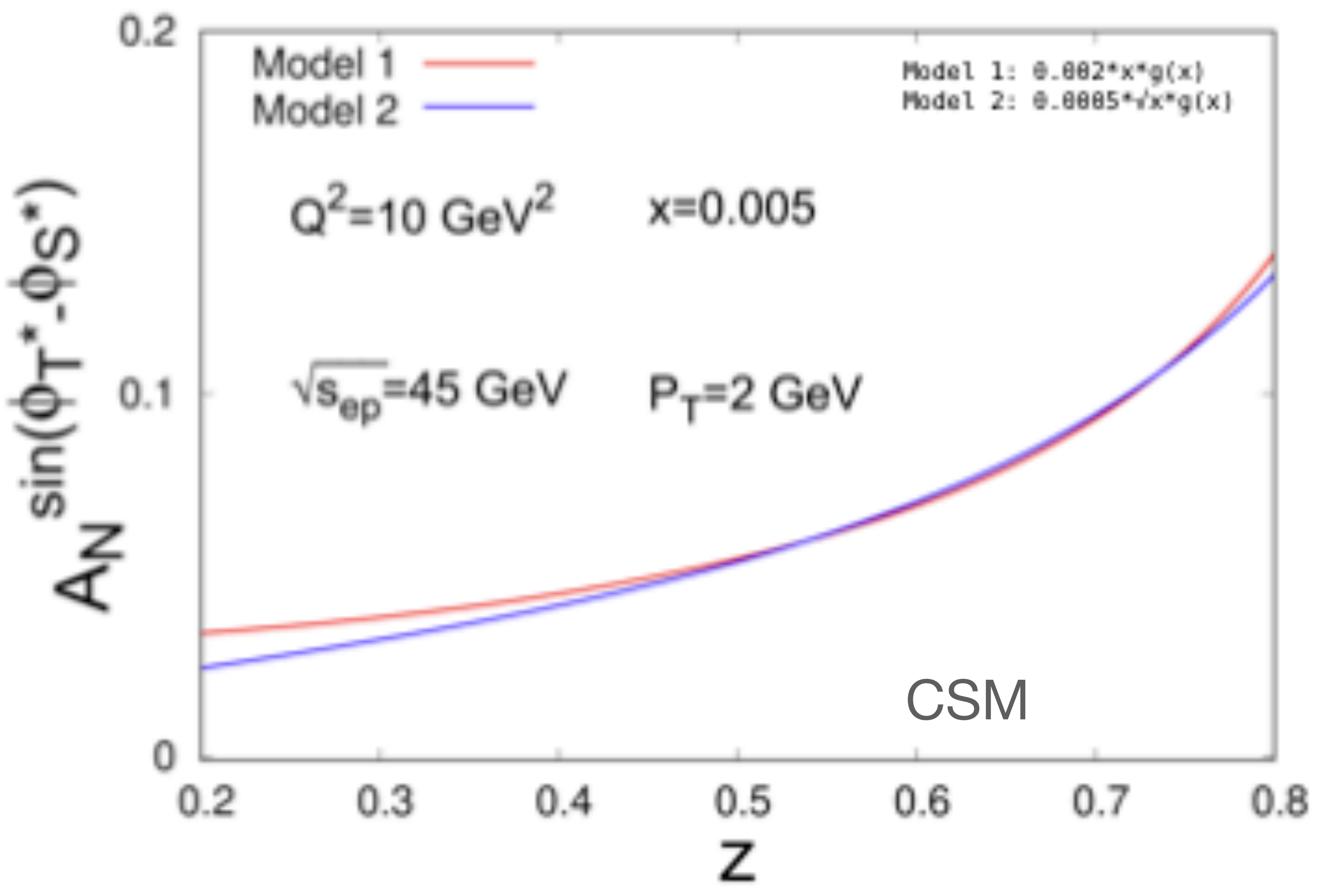
different parametrisations of GSF here

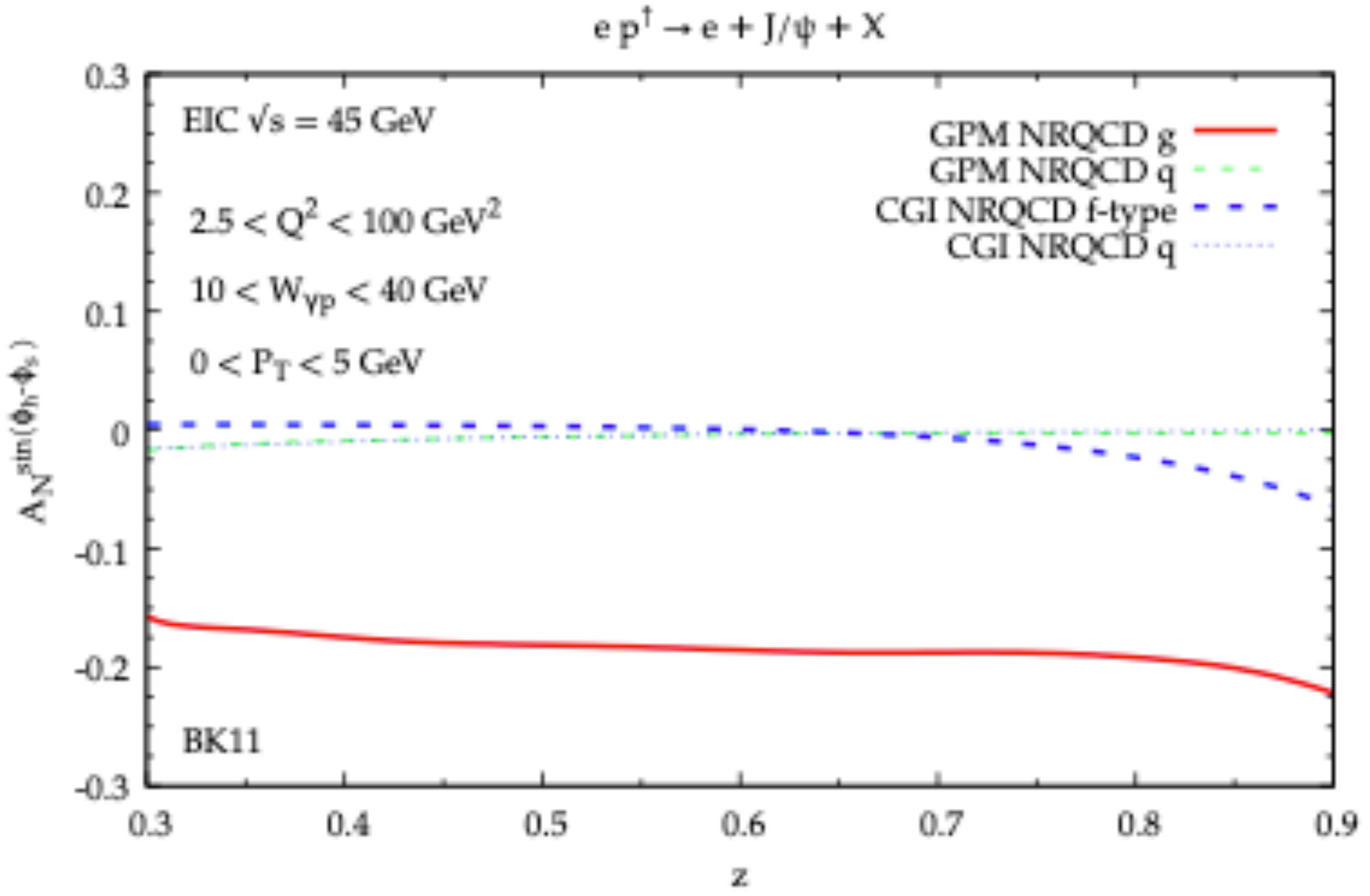
sizeable GS effect predicted, short of 15% at z=0.8

ratio so not dependent on LDME

Gluon Sivers effect at the EIC (II)

D. Boer, C.A. Flett, C. Flore, D. Kikoła, J.-P. Lansberg, M. Nefedov, C. Van Hulse *et al.*, arxiv:2409.03691 [hep-ph]





- aziumuthal modulations in polarised SIDIS give access to gluon Sivers function (GSF):

$$A_N^{\sin(\phi_T^*-\phi_S^*)} \equiv 2\frac{\int d\phi_S^* d\phi_T^* \sin(\phi_T^*-\phi_S^*)(d\sigma^\uparrow - d\sigma^\downarrow)}{\int d\phi_S^* d\phi_T^* (d\sigma^\uparrow + d\sigma^\downarrow)}$$

- collinear twist-3 based computations (left) and maximised predictions in the (CGI-)GPM formalism (right)
- non-zero asymmetry expected: a promising tool to access GSF at the EIC

Quarkonia as Tools to study the parton content of **nuclei**

Nuclear Parton Distribution Functions

- Nuclear modification factor R_{eA} to study modification of a given PDF in a nucleus.

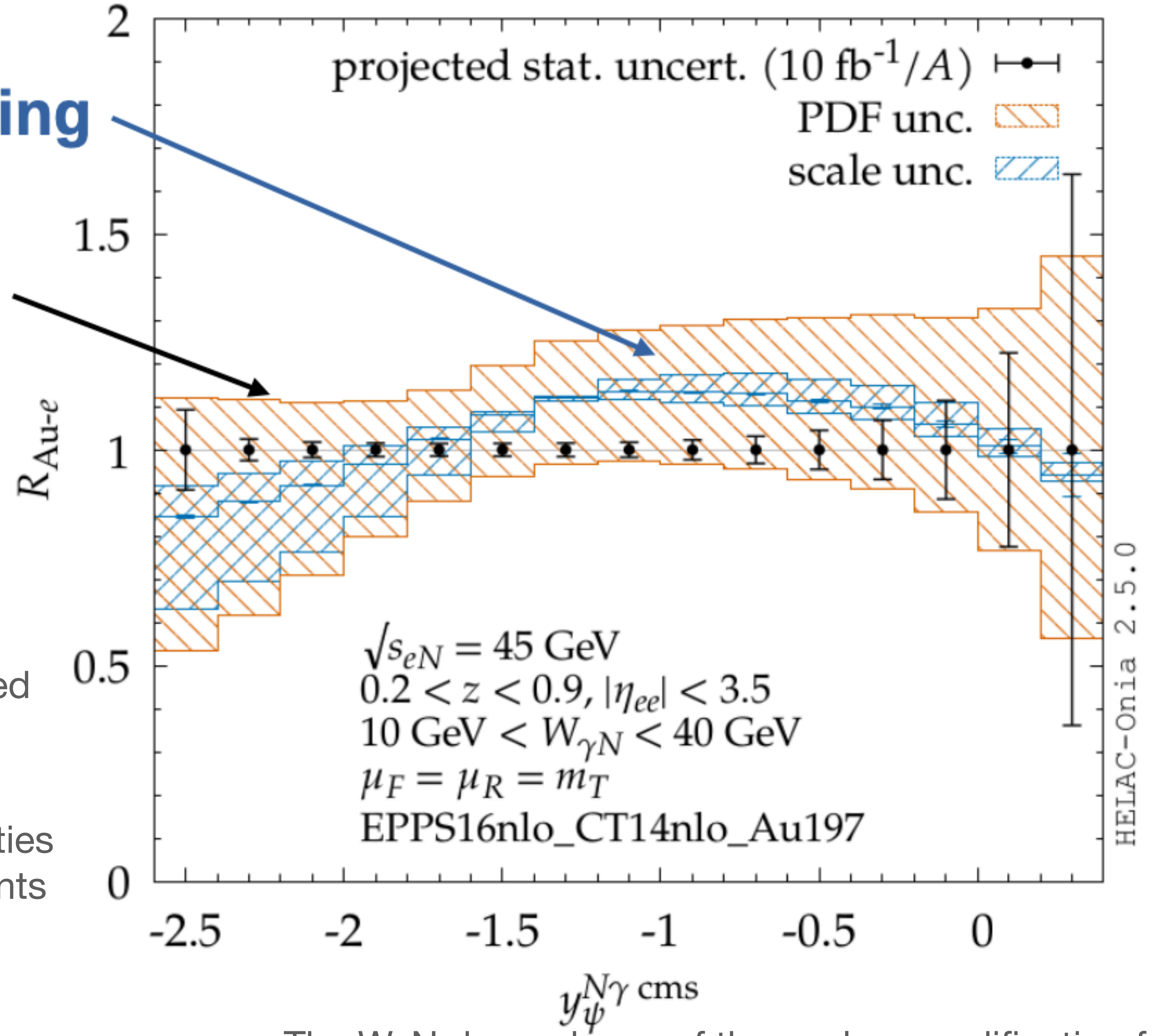
$$R_{eA} = \frac{1}{A}\frac{(d)\sigma_{eA}}{(d)\sigma_{ep}}$$

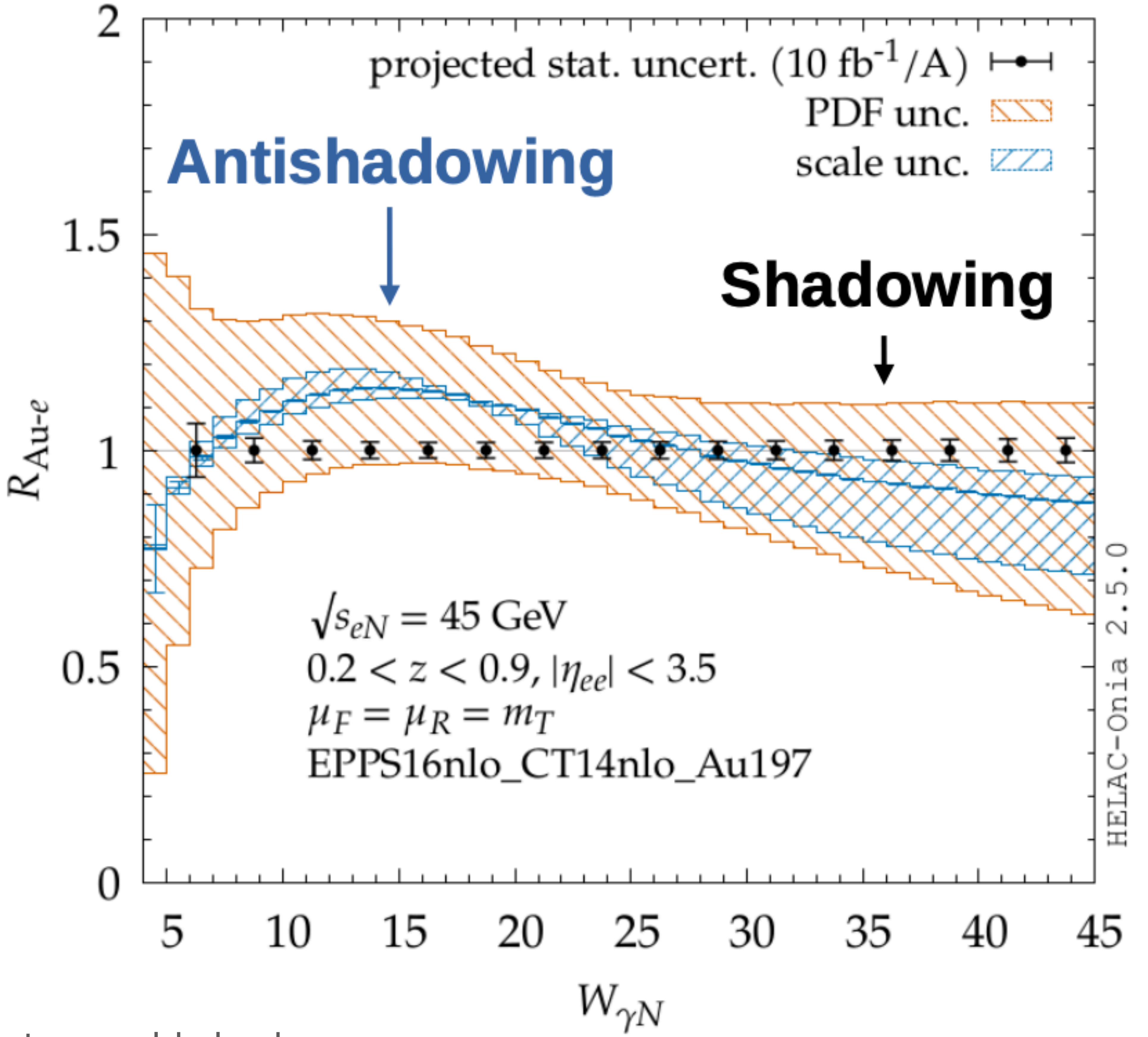
$R_{eA} = 1 \rightarrow$ no modification of parton distribution

- Quarkonium: access to gluon nPDF

Quarkonia as tool to study Nuclear PDFs

LO CSM predictions with projected statistical uncerainty





R_{eAu} measured in inclusive J/psi production in eA

$\gamma + g \rightarrow J/\psi + g$

J/ψ is expected to be mostly produced in the backward region

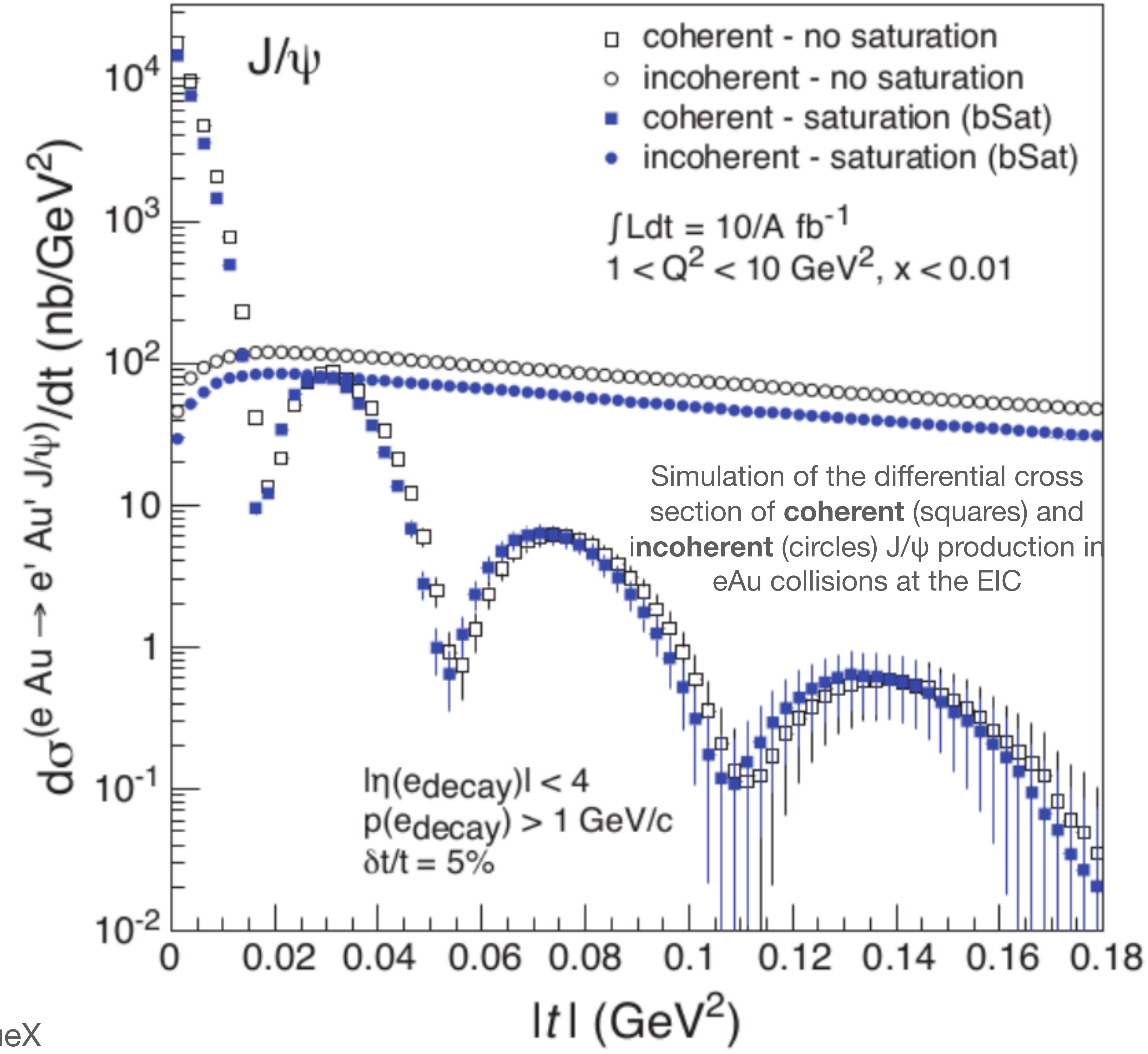
smallest stat unc at large negative rapdities -> shadowing region -> largest constraints on gluon nPDF

The WγN dependence of the nuclear modification factor would also be a very interesting tool to probe gluon nPDFs

Shadowing and **antishadowing** can be probed via J/ψ photoproduction with good precision at the EIC; good constraining power for the gluon nPDFs parametrization

Nuclear Generalized Parton Distributions

- Diffractive J/ψ production → access to the **spatial distribution of gluons** inside the nucleus (Generalized Parton Distributions)
- Experimental challenges:
  - determining momentum transfer **t** with high precision
  - distinguishing coherent from incoherent events



Simulation of the differential cross section of **coherent** (squares) and **incoherent** (circles) J/ψ production in eAu collisions at the EIC

T. Toll, T. Ullrich, PRC 87, 024913 (2013)

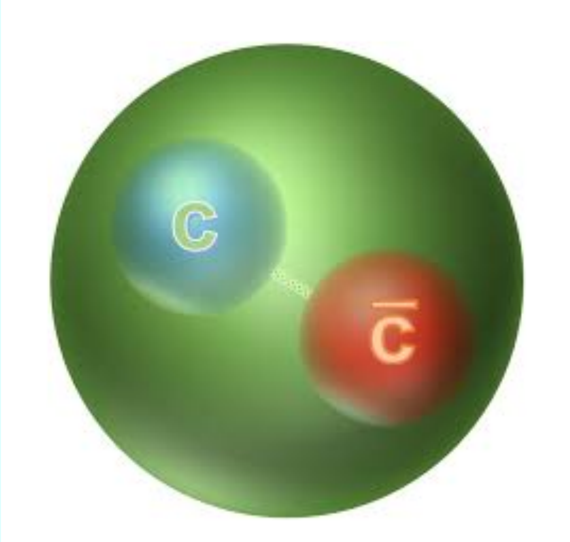
Existing measurements off nuclei lack statistical precision and cannot disentangle coherent and incoherent productions

Multiple measurements from HERA, LHC, Tevatron, RHIC

threshold measurements from GlueX

Summary

- Quarkonium is an extremely useful tool to probe the internal structure of matter, namely one of the main goals of the Electron Ion Collider.



- Studies of quarkonium production in (polarised) electron-proton and electron-nucleus collisions can produce unprecedented insights into the 3D structure of the nucleon and into the partonic content of the nuclei as well as help to settle the long-lasting debate on how quarkonia form.

- Quarkonium production at large transverse momenta in proton-proton and electron-proton collisions has been studied extensively within the frameworks of NRQCD and collinear factorisation.

- Remains a challenge to obtain a simultaneous description of all HERA, LHC and Tevatron data for J/ψ photo- and hadroproduction, η_c hadroproduction, J/ψ polarisation as well as inclusive production in e^+e^- annihilation at B factories.

- Further data from the EIC can help but its p_T reach is limited to 10-15 GeV for charmonia and much less for bottomonia. The focus would then be on low-p_T data $\longrightarrow$ TMDs and shape functions

- The EIC will provide new data to further unravel the quarkonium production mechanism, while at the same time offer new ways to employ quarkonium production as a tool to study TMDs and other parton distributions, particularly the gluon TMD, about which little is known
  - Analogous studies can be performed in electron-nucleus collisions