Quarkonium@EIC

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Supported by the FELLINI project and the European Commission

Trace anomaly	Threshold production
GPDs and Wigner functions	Exclusive production
gluon TMDs/production mechanisms	Inelastic production at small $p_T/p_T^{\star}$
Hadronization of heavy quarks	Inelastic production at moderate and large $p_T/p_T^{\star}$
Interactions of heavy quarks with nuclear medium	In eA at moderate $p_T/p_T^{\star}$
Gluon distributions of nuclei	Coherent photoproduction

Trace anomaly	Threshold production
GPDs and Wigner functions	Exclusive production

In this talk

gluon TMDs/production mechanisms	Inelastic production at small $p_T/p_T^\star$
Hadronization of heavy quarks	Inelastic production at moderate and large $p_T/p_T^\star$
Interactions of heavy quarks with nuclear medium	In eA at moderate $p_T/p_T^\star$

Gluon distributions of nuclei	Coherent photoproduction

Production in DIS

Photo-production

$Q \lesssim 1\ \mathrm{GeV}$

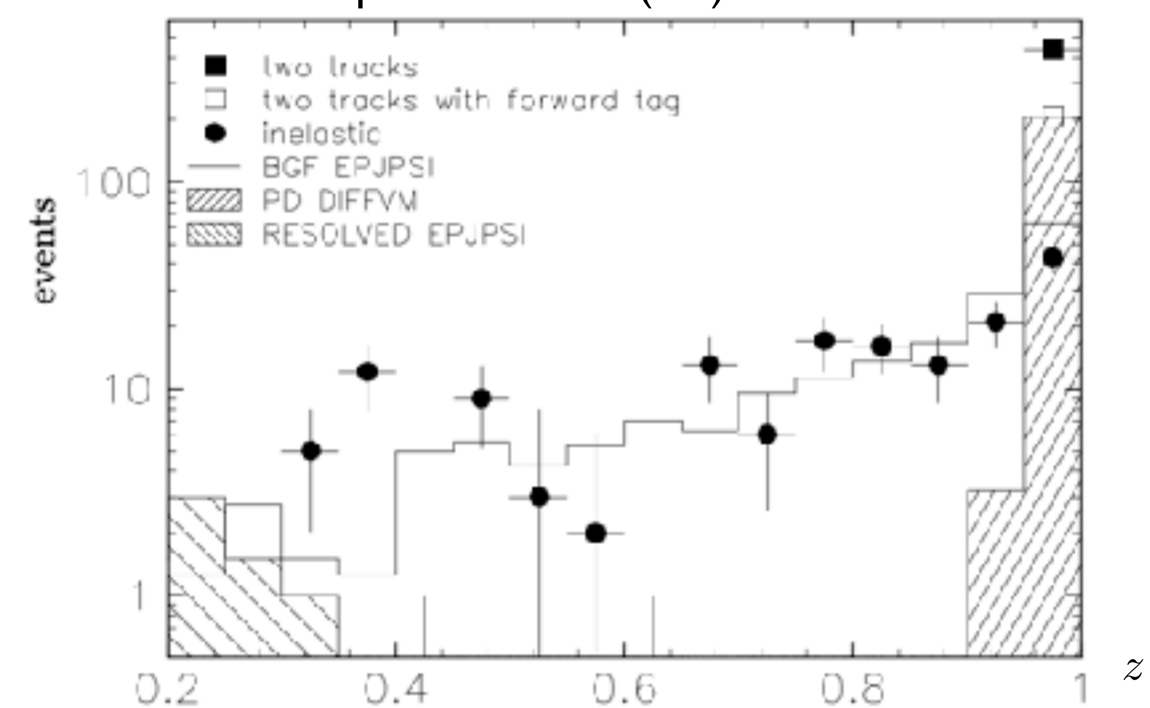
Lepto-production

$Q > 2\ \mathrm{GeV}$

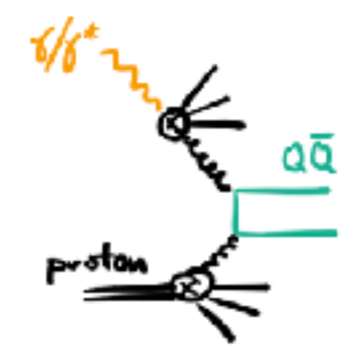
Multi-differential measurements available although large binning is used

Reduced statistics

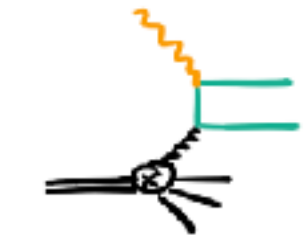
arXiv: hep-ex/9603005 (H1)



Resolved



Photon-gluon fusion



Diffractive

Observables:

$$z = \frac{P \cdot p_\psi}{P \cdot p_\gamma}$$ Energy fraction

$p_T / p_T^\star$ Transverse momentum w.r.t. traget-hadron (Laboratory and γ^*-p CM frames)

NRQCD and NRQCD factorization conjecture

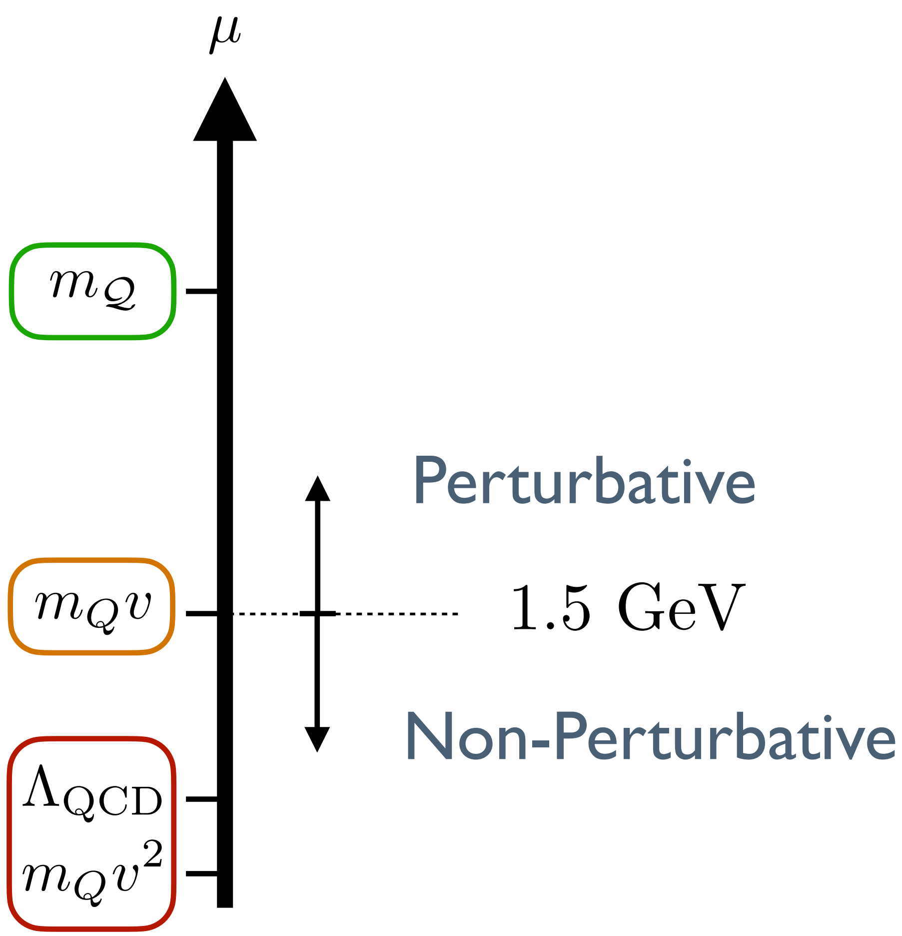
Large-moderate $p_T/p_T^\star$ puzzle

The small $p_T/p_T^\star$ puzzle

Interaction with nuclear medium

NRQCD degrees of freedom

NRQCD = Non-Relativistic QCD



$b\bar{b}: \quad v^2 \sim 0.1$ bottomonium

$c\bar{c}: \quad v^2 \sim 0.3$ charmonium

Relative velocity of the heavy quark and antiquark in the quarkonium

typical momentum of heavy quark: $|\mathbf{p}_Q| \sim m_Q v$ (soft)

typical kinetic energy of heavy quark: $K_Q \sim m_Q v^2$ (ultra-soft)

The Lagrangian

arXiv:hep-ph/9910209 (M. E. Luke, A.V. Manohar, I. Z. Rothstein)

soft: $p_s^\mu \sim m_Q v(1,1,1,1)$

ultra-soft: $p_{us}^\mu \sim m_Q v^2(1,1,1,1)$

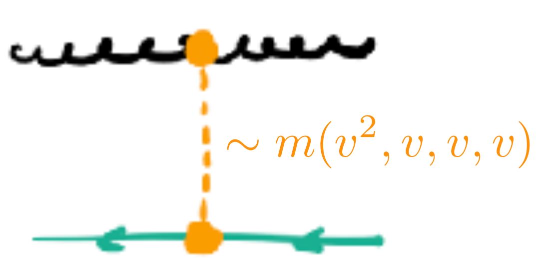
ultra-soft

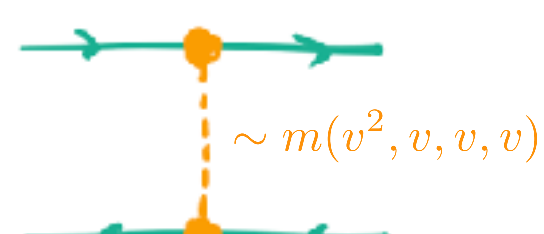
subleading

$$\mathcal{L} = \sum_{\mathbf{p}} \psi_{\mathbf{p}}^\dagger \left\{ iD^0 - \frac{(\mathbf{p} - i\mathbf{D})^2}{2m} \right\} \psi_{\mathbf{p}}$$

$$-4\pi\alpha_s \sum_{q,q'\mathbf{p},\mathbf{p}'} \left\{ \frac{1}{q^0} \psi_{\mathbf{p}'}^\dagger \left[A_{q'}^0, A_q^0\right] \psi_{\mathbf{p}} + \frac{g^{\nu 0}(q'-p+p')^\mu - g^{\mu 0}(q-p+p')^\nu + g^{\mu\nu}(q-q')^0}{(\mathbf{p}'-\mathbf{p})^2} \psi_{\mathbf{p}'}^\dagger \left[A_{q'}^\nu, A_q^\mu\right] \psi_{\mathbf{p}} \right\}$$

soft





$$+ \sum_{\mathbf{p},\mathbf{q}} \frac{4\pi\alpha_s}{(\mathbf{p}-\mathbf{q})^2} \psi_{\mathbf{q}}^\dagger T^A \psi_{\mathbf{p}} \chi_{-\mathbf{q}}^\dagger T^A \chi_{-\mathbf{p}} + \ldots$$

Factorization conjecture and LDMEs

arXiv: hep-ph/9407339 (G.T. Bodwin, E. Braaten, G.P. Lepage)

$$Q\bar{Q}(n) \xrightarrow{\langle \mathcal{O}_n^{\mathcal{Q}} \rangle} \mathcal{Q}$$

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

LDME: Long Distance Matrix Elements

$$d\sigma(a+b \to \mathcal{Q} + X) = \sum_n d\sigma(a+b \to Q\overline{Q}(n) + X)\langle \mathcal{O}_n^{\mathcal{Q}} \rangle$$

$$d\sigma_0(1 + \alpha_s C_1 + \alpha_s^2 C_2 + \ldots) \quad \langle \mathcal{O}({}^{2S+1}L_J^{[1,8]}) \rangle \sim v^{3+2L+2E+4M}$$

For ${}^3S_1$: (J/ψ and Υ) :

$$\langle \mathcal{O}({}^3S_1^{(1)}) \rangle \sim v^3$$

$$\langle \mathcal{O}({}^3S_1^{(8)}) \rangle \sim v^7 \qquad \langle \mathcal{O}({}^1S_0^{(8)}) \rangle \sim v^7$$

$$\langle \mathcal{O}({}^3P_J^{(8)}) \rangle \sim v^7$$

$$\mathcal{O}_n^{\mathcal{Q}} = \mathcal{O}_2^{n\dagger} \left(\sum_X |X + \mathcal{Q}\rangle\langle X + \mathcal{Q}| \right) \mathcal{O}_2^n$$

$$\mathcal{O}_2^n = \psi^\dagger \mathcal{K}^n \chi$$

ultra-soft + soft

Factorization conjecture and LDMEs

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LDME: Long Distance Matrix Elements

$$d\sigma(a+b\to\mathcal{Q}+X) = \sum_n d\sigma(a+b\to Q\overline{Q}(n)+X)\langle\mathcal{O}_n^{\mathcal{Q}}\rangle$$

Perturbative expansion in the strong coupling.

NRQCD Scaling Rules

$$d\sigma_0(1+\alpha_s C_1+\alpha_s^2 C_2+\ldots) \qquad \langle\mathcal{O}({}^{2S+1}L_J^{[1,8]})\rangle \sim v^{3+2L+2E+4M}$$

For ${}^3S_1$: $(J/\psi$ and $\Upsilon)$:

$$\langle\mathcal{O}({}^3S_1^{(1)})\rangle \sim v^3$$

$$\langle\mathcal{O}({}^3S_1^{(8)})\rangle \sim v^7 \qquad \langle\mathcal{O}({}^1S_0^{(8)})\rangle \sim v^7$$

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Perturbative expansion in the strong coupling.

NRQCD Scaling Rules

$$d\sigma_0(1 + \alpha_s C_1 + \alpha_s^2 C_2 + \dots) \quad \langle \mathcal{O}({}^{2S+1}L_J^{[1,8]}) \rangle \sim v^{3+2L+2E+4M}$$

For ${}^3S_1$: (J/ψ and Υ) :

$\langle \mathcal{O}({}^3S_1^{(1)}) \rangle \sim v^3$ Leading

$\langle \mathcal{O}({}^3S_1^{(8)}) \rangle \sim v^7$ $\langle \mathcal{O}({}^1S_0^{(8)}) \rangle \sim v^7$

$\langle \mathcal{O}({}^3P_J^{(8)}) \rangle \sim v^7$ First subheading

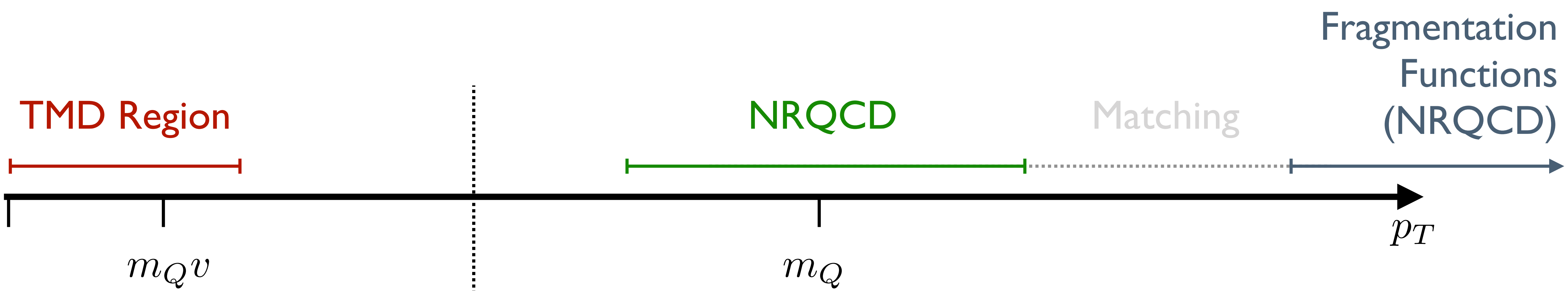
$$\mathcal{O}_n^{\mathcal{Q}} = \mathcal{O}_2^{n\dagger} \left(\sum_X |X + \mathcal{Q}\rangle\langle X + \mathcal{Q}| \right) \mathcal{O}_2^n$$

$$\mathcal{O}_2^n = \psi^\dagger \mathcal{K}^n \chi$$

ultra-soft + soft

Transverse momentum spectrum

Quarkonium spectrum vs EFT regions



Expansion in v and in λ

$\lambda = q_\perp / M$

will properly incorporate quarkonium recoiling against soft radiation

Expansion in the relative velocity

Note: it is possible to probe TMDs in this region as well but the additional measurement introduces a new soft scale which changes the factorization: e.g., TMD fragmentation

NRQCD and NRQCD factorization conjecture

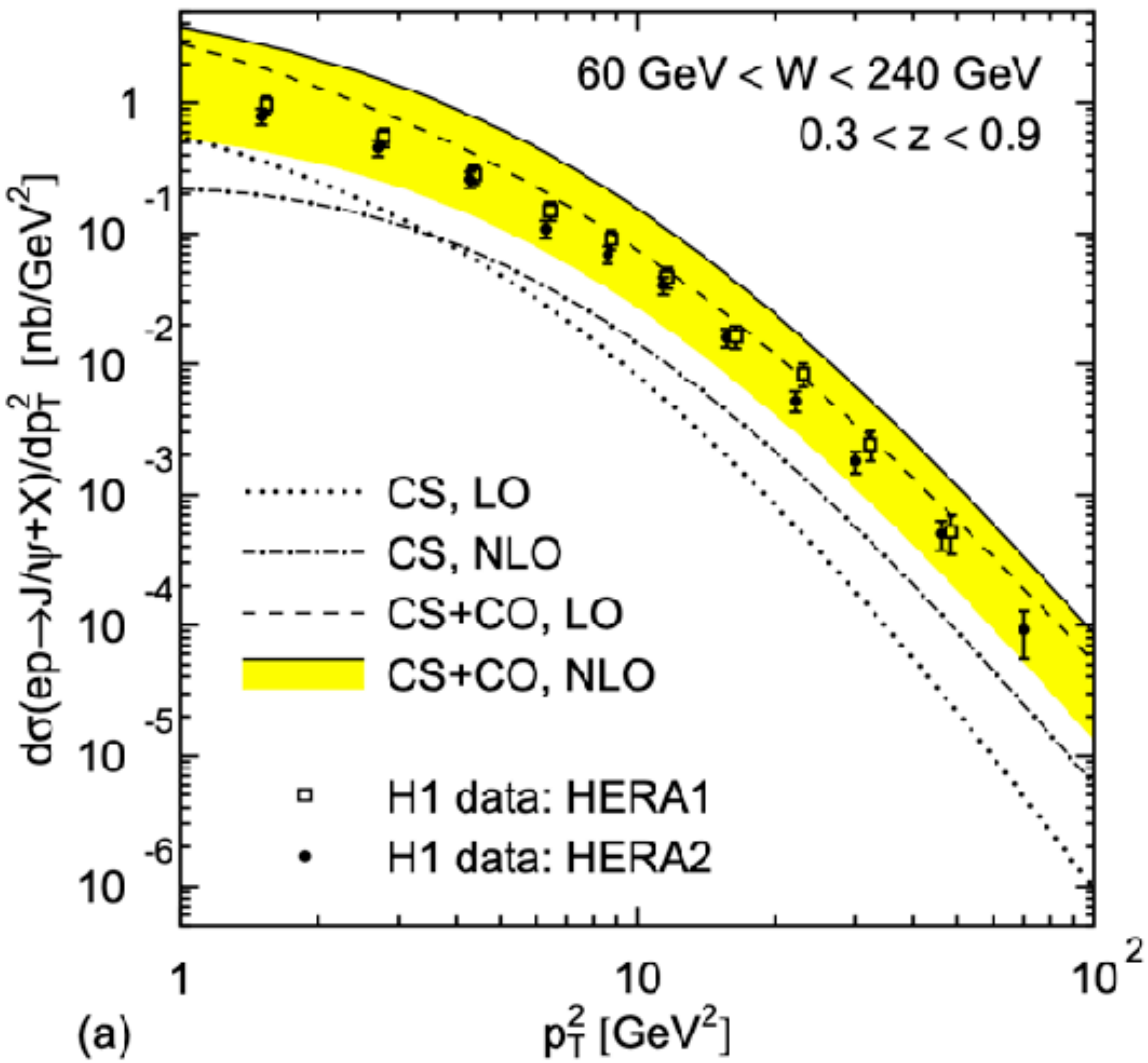
Large-moderate $p_T/p_T^\star$ puzzle

The small $p_T/p_T^\star$ puzzle

Interaction with nuclear medium

Production at HERA

arXiv:0909.2798 (M. Butenschoen, B.A. Kniehl)



For J/ψ : $\langle\mathcal{O}(^3S_1^{(1)})\rangle \sim v^3$

$\langle\mathcal{O}(^3S_1^{(8)})\rangle \sim v^7$

$\langle\mathcal{O}(^1S_0^{(8)})\rangle \sim v^7$

$\langle\mathcal{O}(^3P_J^{(8)})\rangle \sim v^7$

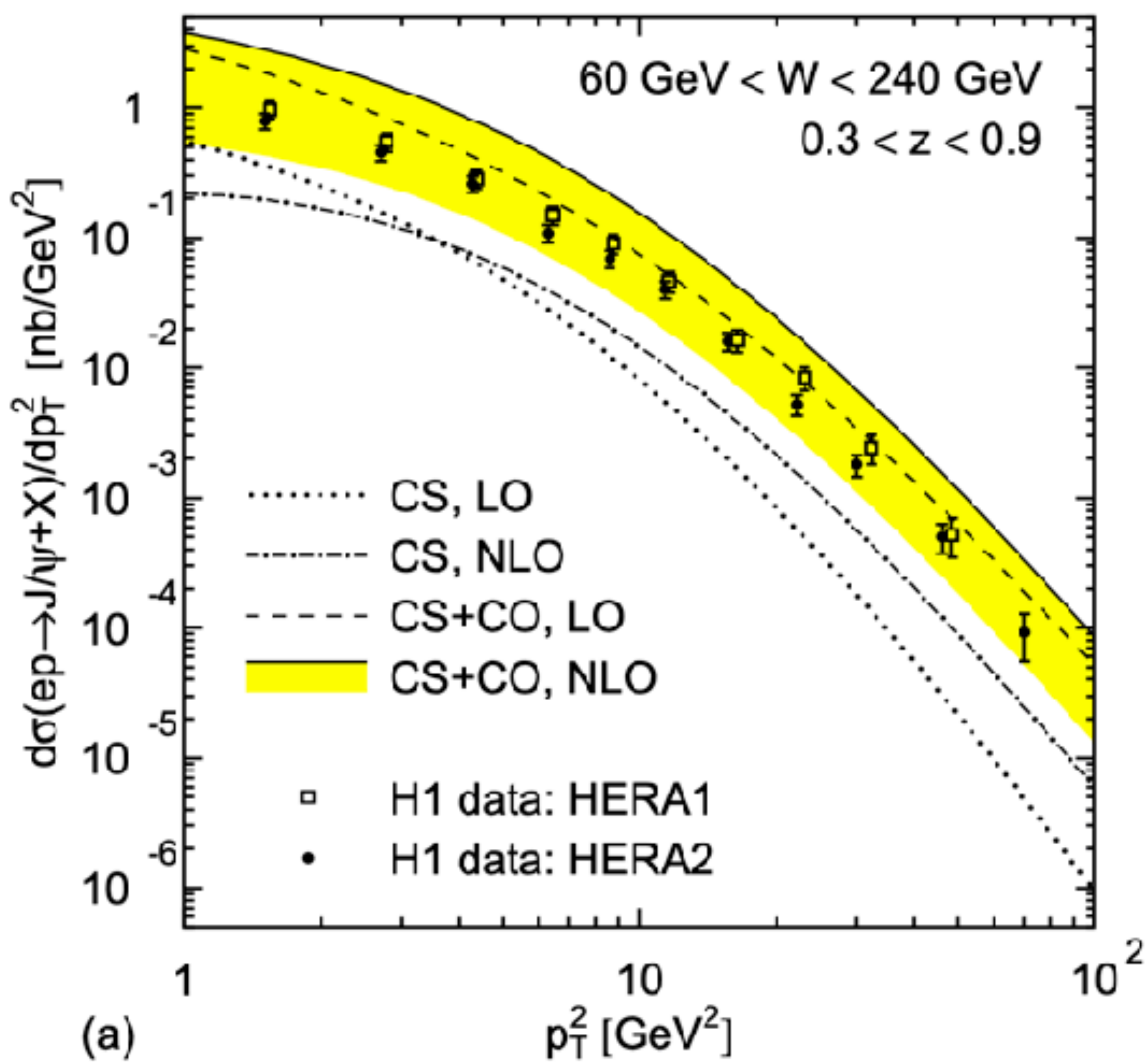
CS-LO contribution under-predicts the data

CS-NLO enhances the contribution but still not there yet

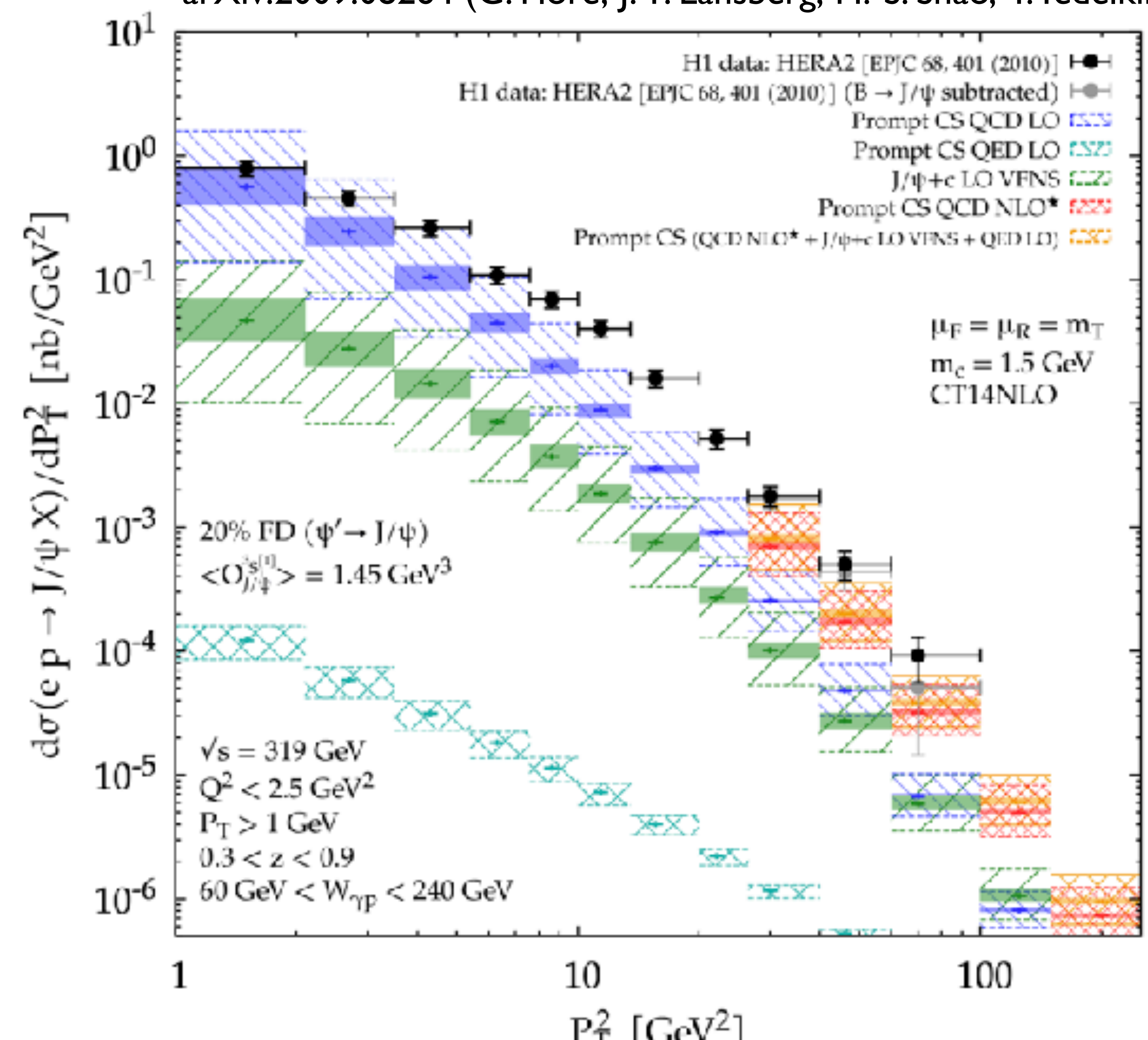
NRQCD-NLO overshoots the data (within the theory error)

Production at HERA (revisit)

arXiv:0909.2798 (M. Butenschoen, B.A. Kniehl)

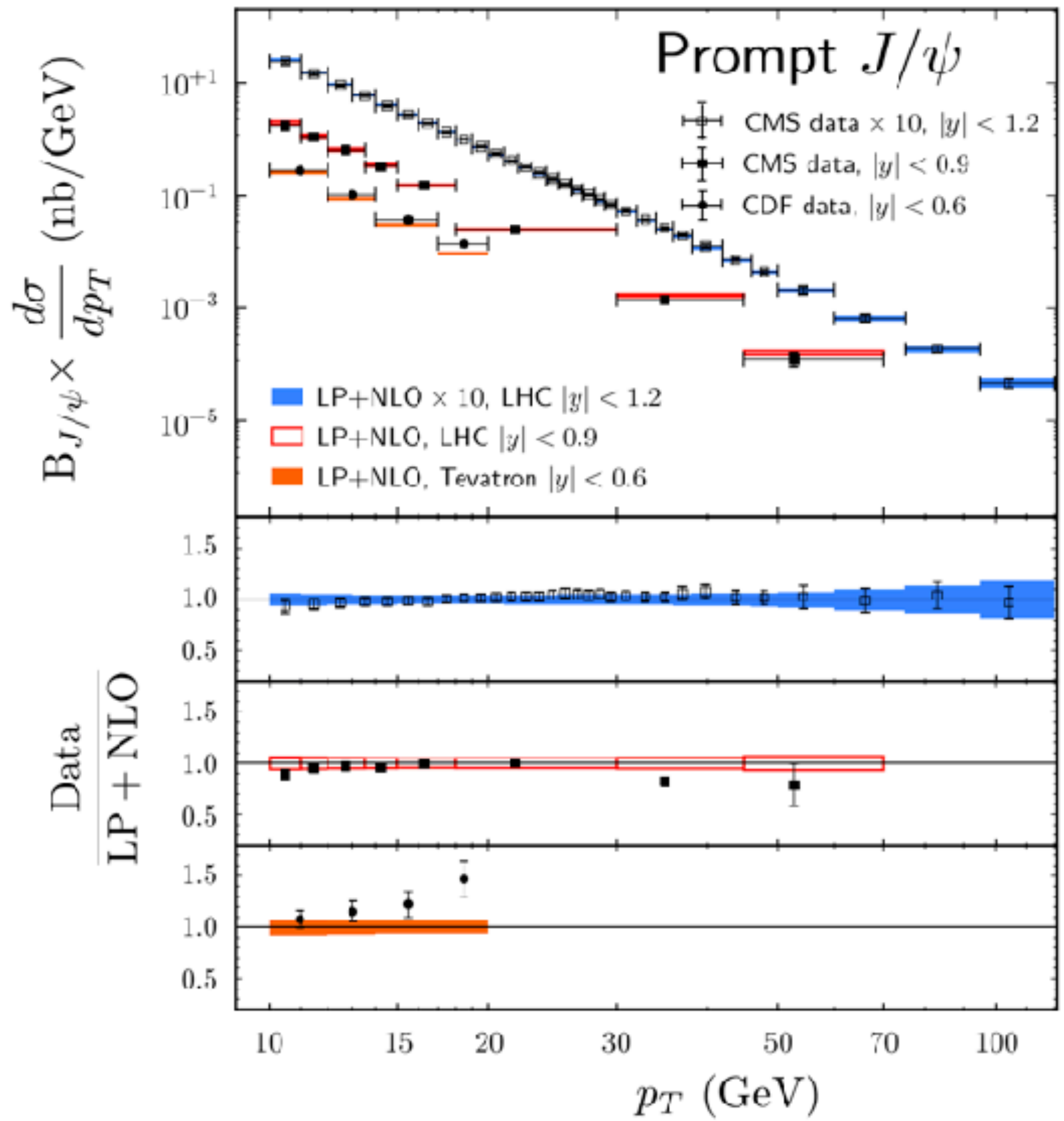


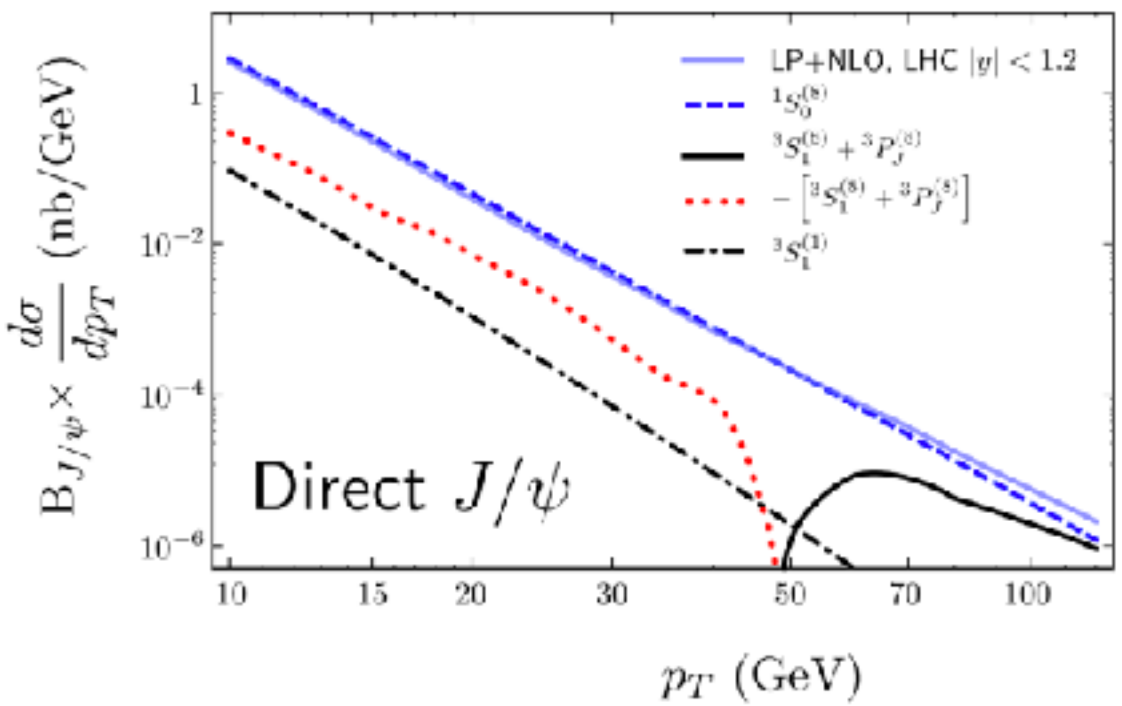
arXiv:2009.08264 (C. Flore, J.-P. Lansberg, H.-S. Shao, Y.Yedelkina)

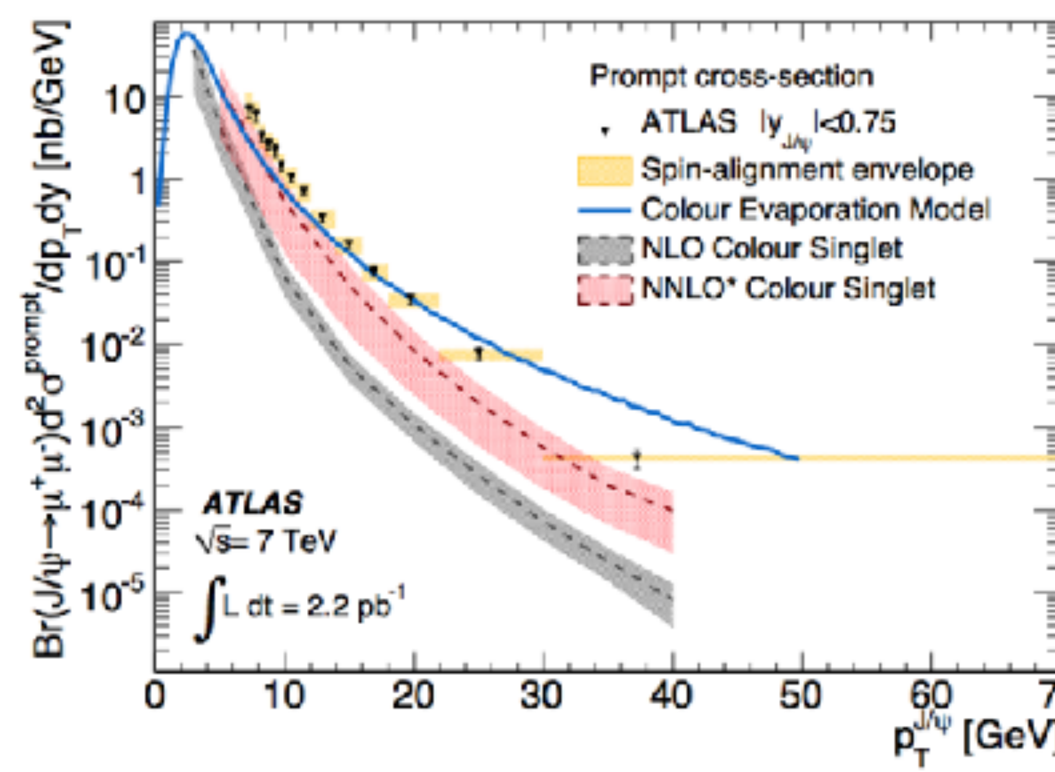


Universality of LDMEs

arXiv:1509.07904 (G.T. Bodwin, K.-T. Chao, H.S. Chung, U-R. Kim, J. Lee, and Y.-Q. Ma)



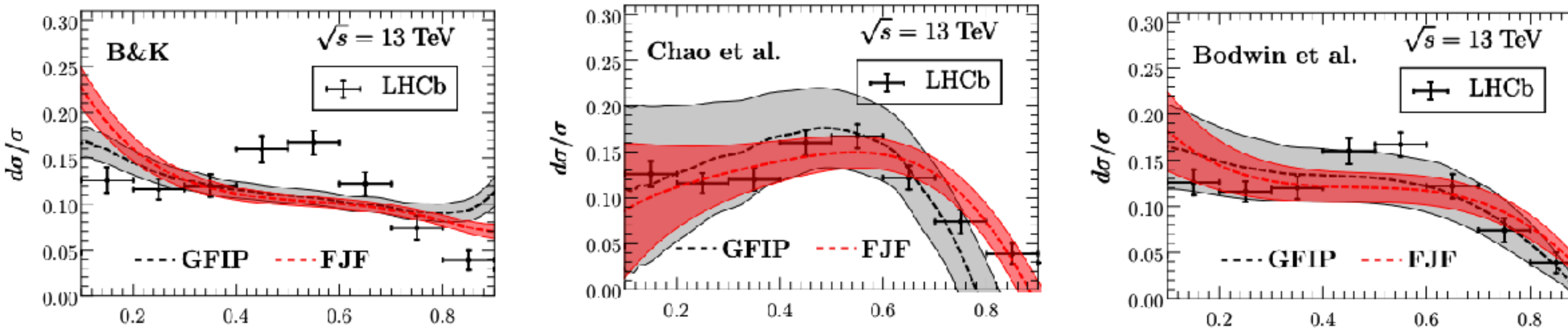




arXiv:1104.3038 (ATLAS)

New observables (In-jet quarkonia)

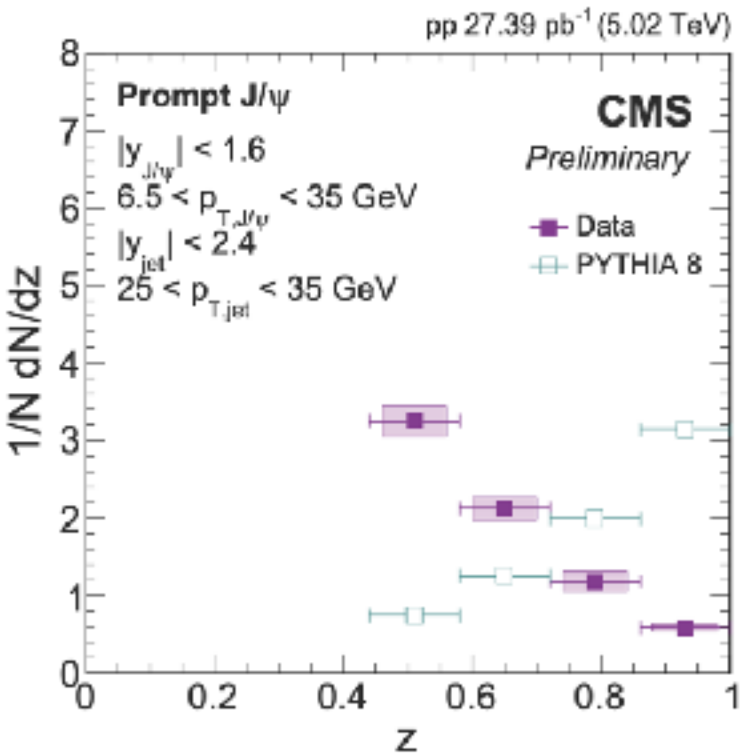
arXiv:1702.05525 (R. Bain, Y. Makris, T. Mehen, L. Dai and A.K. Leibovich)

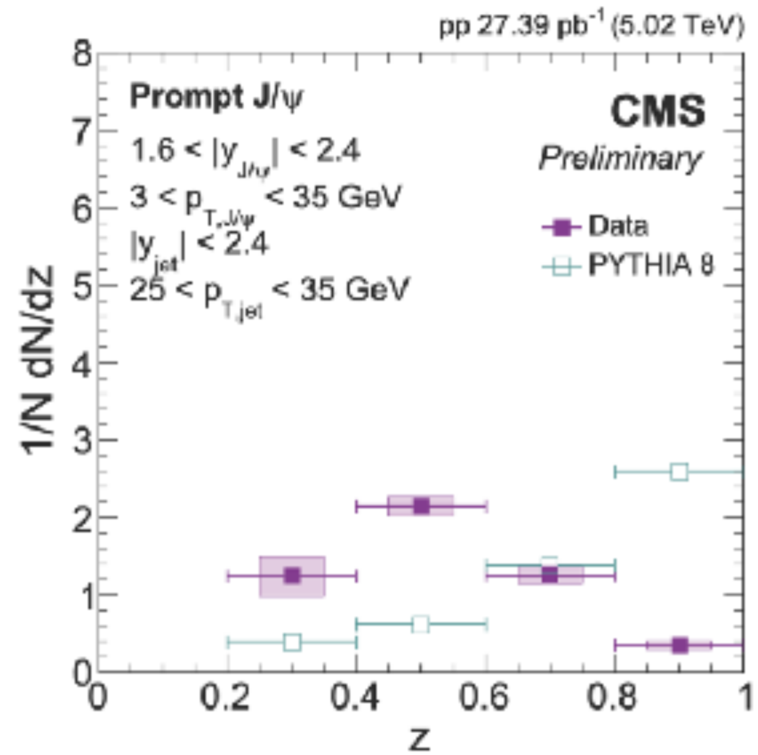


$$z = \frac{p_T^{\psi}}{p_T^{\text{jet}}}$$

	χ_{cJ}		$J/\psi(1S)/\psi(2S)$	
Initiating parton / Mechanism	${}^3P_J^{[1]}$	${}^3S_1^{[8]}$	${}^3P_J^{[8]}/{}^1S_0^{[8]}$	${}^3S_1^{[1]}$
g	α_s^2	α_s	α_s^2	α_s^3
Q	α_s^2	α_s^2	α_s^3	α_s^2
q	α_s^3	α_s^2	α_s^3	α_s^4

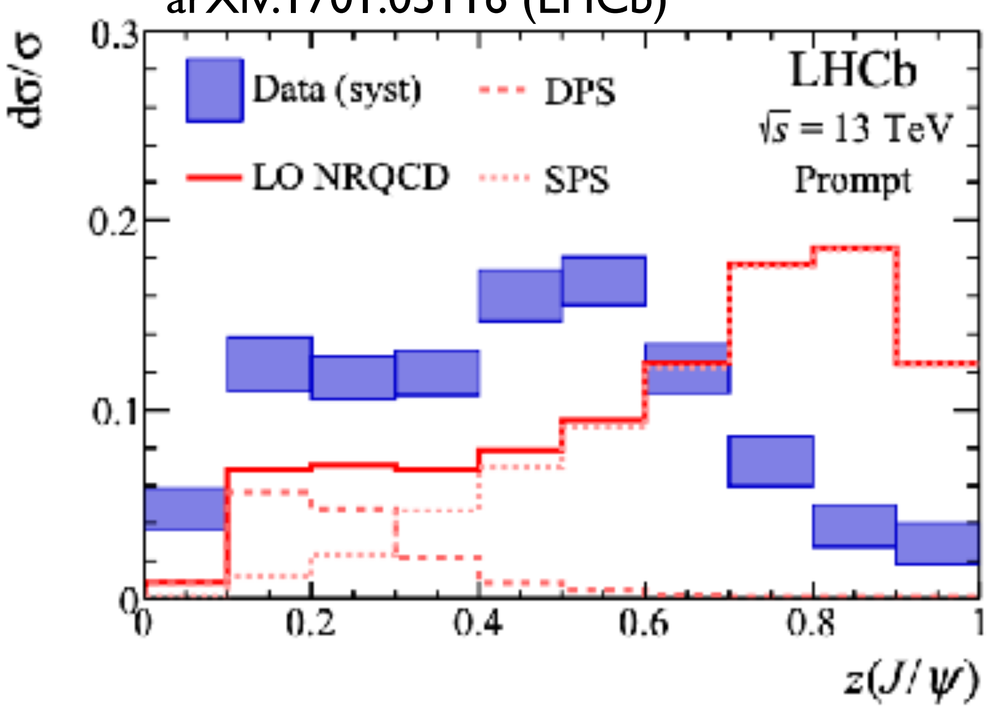
New observables (In-jet quarkonia)





Nucl.Phys. A982 (2019) 186-188 (CMS)

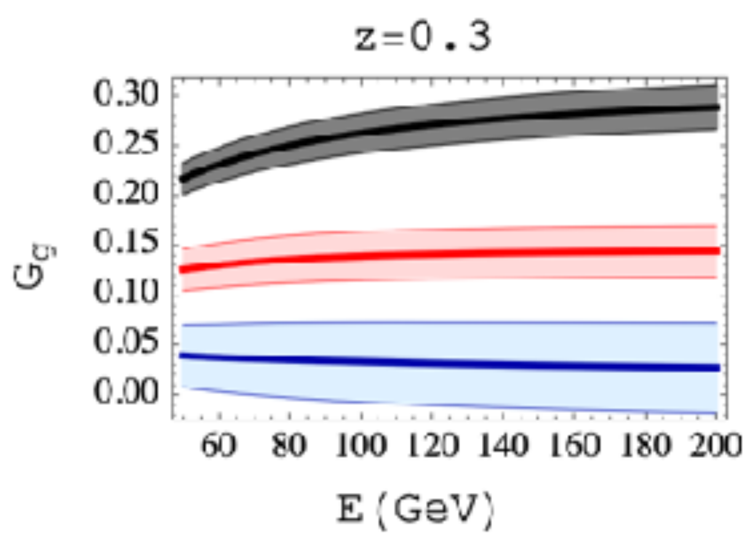
arXiv:1701.05116 (LHCb)



Simulations under-estimate the effect of evolution both in color singlet and color octet mechanisms.

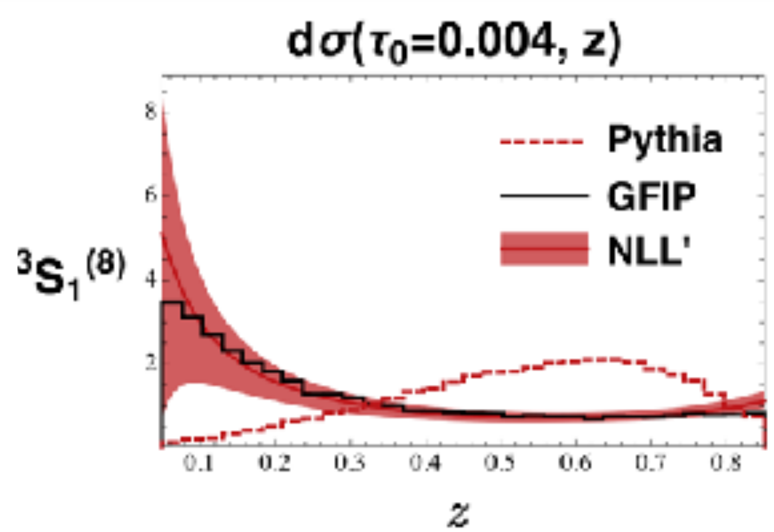
New tools ?

New observables (In-jet quarkonia)



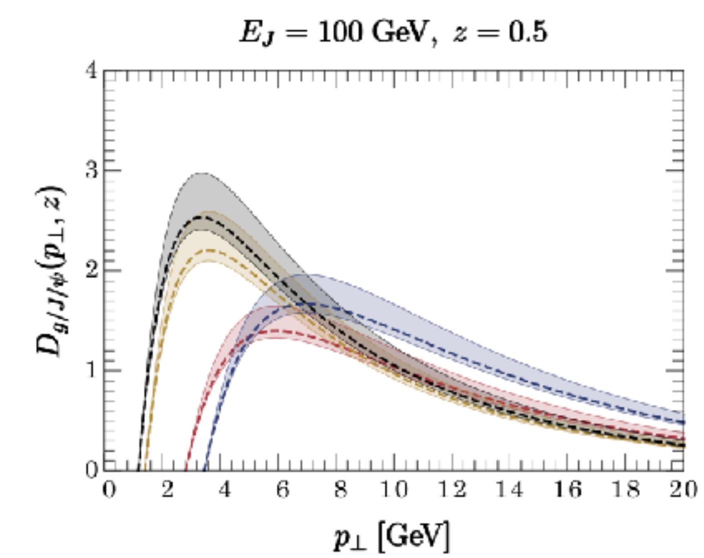
Jet energy, energy fraction

arXiv:1406.2295 (M. Baumgarta , A. K. Leibovichb , T. Mehenc , and I.Z. Rothsteind)



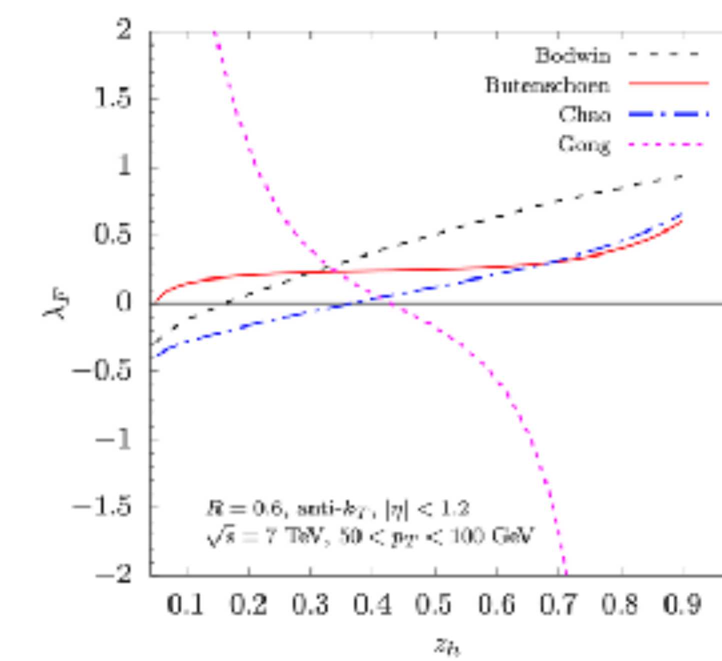
Angularities, energy fraction

arXiv:1603.06981 (R. Bain, L. Dai, A. Hornig, A.K. Leibovich, Y. Makris, and T. Mehen)



transverse momentum, energy fraction

arXiv:1610.06508 (R. Bain, Y. Makris, and T. Mehen)



Polarization, energy fraction

arXiv:1702.03287 (Z.-B Kang, J.-W. Qiu, F. Ringer, H. Xing, and H. Zhang)

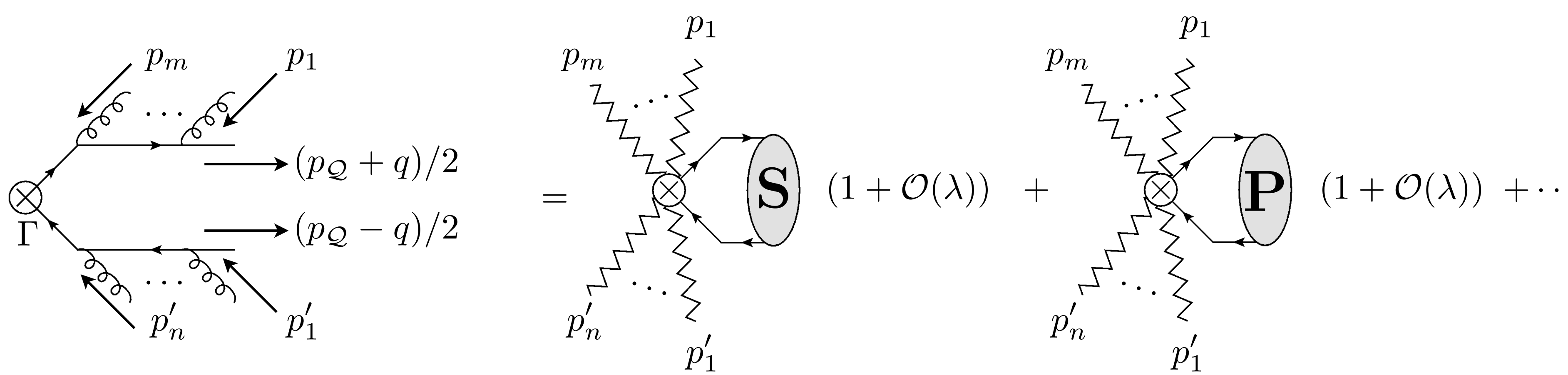
NRQCD and NRQCD factorization conjecture

Large-moderate $p_T/p_T^\star$ puzzle

The small $p_T/p_T^\star$ puzzle

Interaction with nuclear medium

Color-octet photon-gluon fusion



$$d_\Gamma(m,n) \quad = \quad d_\Gamma^{(0)}(m,n)\ (1+\mathcal{O}(\lambda)) \quad + \ d_\Gamma^{(1)}(m,n)\ (1+\mathcal{O}(\lambda)) \quad + \cdots$$

S-wave octet: ${}^1S_0^{(8)}$

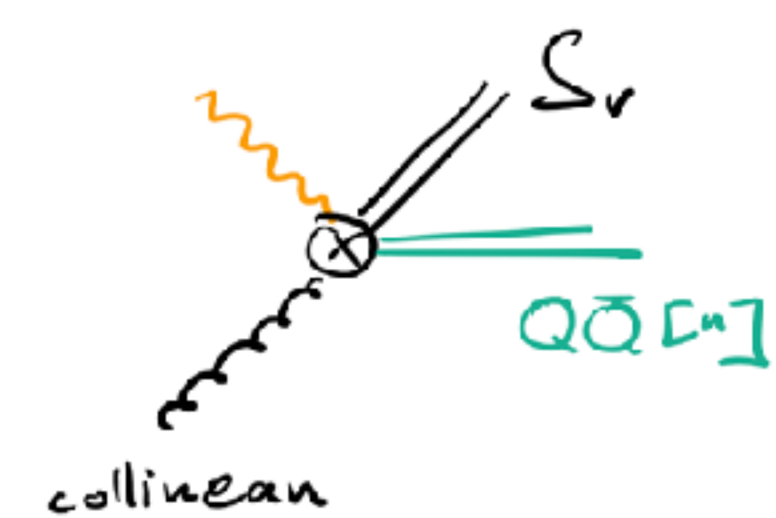
$$(\psi^\dagger T^a \chi)\mathcal{S}_v^{ba} B_{n\perp}^{c,i} S_n^{cb} \epsilon_\perp^k$$

P-wave octet: ${}^3P_{0/2}^{(8)}$

$$(\psi^\dagger \frac{\sigma^j \overleftrightarrow{\mathcal{P}}^m}{2} T^a \chi)\mathcal{S}_v^{ba} B_{n\perp}^{c,i} S_n^{cb} \epsilon_\perp^k$$

$$S_v = \sum_n \sum_{\text{perms}} \frac{g^n}{n!} \prod_{s=1}^{n} \left[\frac{A^0_{n+1-s}}{p^0_l(s)} \right]$$

$$S_v(x,-\infty) = \mathrm{P}\left[\exp\left(-ig\int_{-\infty}^{0} d\tau\, v\cdot A_{soft}(x^\mu + v^\mu\tau)\right)\right]$$



Factorization and the shape-functions

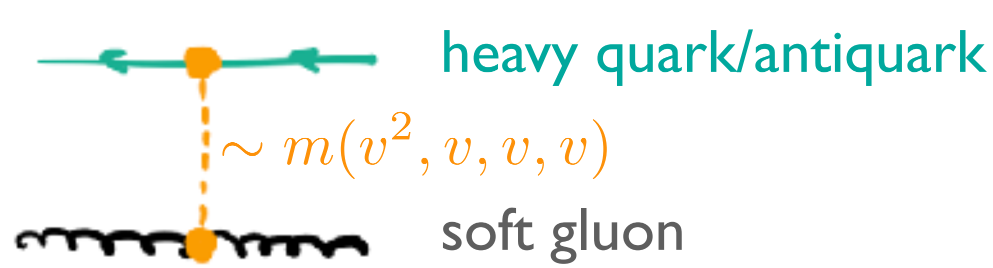
$$d\sigma \sim f^{\perp}_{g/H}(x,\boldsymbol{b}) \sum_n H_n \times S^{\perp}_n(\boldsymbol{b})$$

- Half the rapidity divergences
- CO associated logarithms
- No operator mixing at NLL
- No LDMEs

The shape functions

$$S_{Q\bar{Q}[n]\to\mathcal{Q}} \sim \sum_X \left\langle O_2^{[n]} \mathcal{S}_v^{ba} \mathcal{S}_n^{bc} \middle| \mathcal{Q}+X \right\rangle \left\langle \mathcal{Q}+X \middle| \mathcal{S}_n^{cd} \mathcal{S}_v^{ed} O_2^{[n]\dagger} \right\rangle$$

Quarkonium TMD-shape functions* encode both soft and non-perturbative quarkonium related effects. Further factorization is not possible due to Coulomb-like interactions:



*See:
arXiv:1907.06494 (M. Echevarria)
arXiv:1910.03586 (S. Fleming, Y. Makris, T. Mehen)

Shape-functions@NLO

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The shape functions

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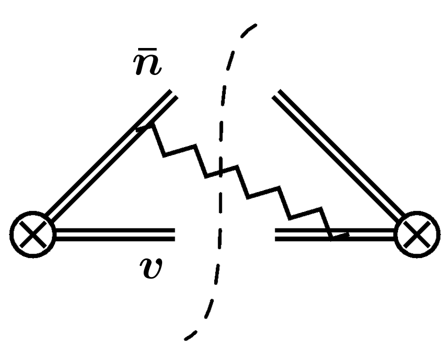
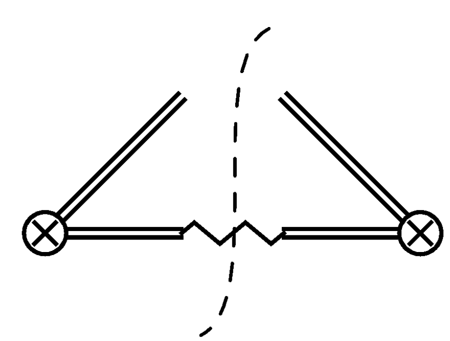
$$= \langle O_n^{\mathcal{Q}} \rangle_{\mathrm{LO}} \left(\delta^{(2)}(\boldsymbol{q}_\perp) + \frac{\alpha_s^2 C_A}{2\pi} \left\{ 4\ln\left(\frac{\nu}{\mu}\right) \mathcal{L}_0(q_\perp^2,\mu^2) - 2\mathcal{L}_1(q_\perp^2,\mu^2) - 2\mathcal{L}_0(q_\perp^2,\mu^2) - \frac{\pi}{12}\delta^{(2)}(\boldsymbol{q}_\perp) \right\} \right) + \mathcal{O}(\alpha_s^2)$$



(a) (+ mirror diagram)



(b)

$$O_2^{[n]}(x) \sim \psi^\dagger \mathcal{K}^{[n]} \psi(x)$$

$$\mathcal{L}_n(q_\perp^2,\mu^2) = \frac{1}{(2\pi)^2\mu^2} \left[\frac{\mu^2}{q_\perp^2} \ln(q_{\perp^2}/\mu^2) \right]_+$$

Consistency check

$$d\sigma \sim f^{\perp}_{g/H}(x,\boldsymbol{b}) \sum_n H_n \times S^{\perp}_n(\boldsymbol{b})$$

- Half the rapidity divergences
- CO associated logarithms
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The shape functions

$$S_{Q\bar{Q}[n]\to\mathcal{Q}} \sim \sum_X \left\langle O_2^{[n]} \mathcal{S}_v^{ba} \mathcal{S}_n^{bc} \middle| \mathcal{Q}+X \right\rangle \left\langle \mathcal{Q}+X \middle| \mathcal{S}_n^{cd} \mathcal{S}_v^{ed} O_2^{[n]\dagger} \right\rangle$$

$$= \langle O_n^{\mathcal{Q}} \rangle_{\rm LO} \Big(\delta^{(2)}(\boldsymbol{q}_\perp) + \frac{\alpha_s^2 C_A}{2\pi} \Big\{ 4 \ln\left(\frac{\nu}{\mu}\right) \mathcal{L}_0(q_\perp^2,\mu^2) - 2\mathcal{L}_1(q_\perp^2,\mu^2) - 2\mathcal{L}_0(q_\perp^2,\mu^2) - \frac{\pi}{12}\delta^{(2)}(\boldsymbol{q}_\perp) \Big\} \Big) + \mathcal{O}(\alpha_s^2)$$

The hard functions

$$H_n = 1 + \frac{\alpha_s C_A}{2\pi} \Big\{ 2D(n) - \frac{\pi^2}{12} - \ln\left(\frac{\mu^2}{s}\right) - \frac{\beta_0}{2C_A} \ln\left(\frac{\mu^2}{s}\right) - \frac{1}{2}\ln^2\left(\frac{\mu^2}{s}\right) \Big\} + \mathcal{O}(\alpha_s^2)$$

arXiv:hep-ph/9708349 (F. Maltoni, M. L. Mangano, and A. Petrelli)

Color-singlet: multiple operators

S-wave singlet: ${}^3S_1^{(1)}$

$$O^{jk\ell}_{\text{cc-1}}(\omega,\bar\omega;{}^3S_1^{[1]}) = g^2\left[\delta(\omega - n\cdot\mathcal{P})\boldsymbol{B}^{j,a}_{\bar n\perp}\,\delta(\bar\omega - \overleftrightarrow{\mathcal{P}})\,\boldsymbol{B}^{k,a}_{\bar n\perp}\right](\psi\,\boldsymbol{\sigma}^\ell\chi)$$

collinear-collinear arXiv:hep-ph/0211303 (S. Fleming and A. K. Leibovich)

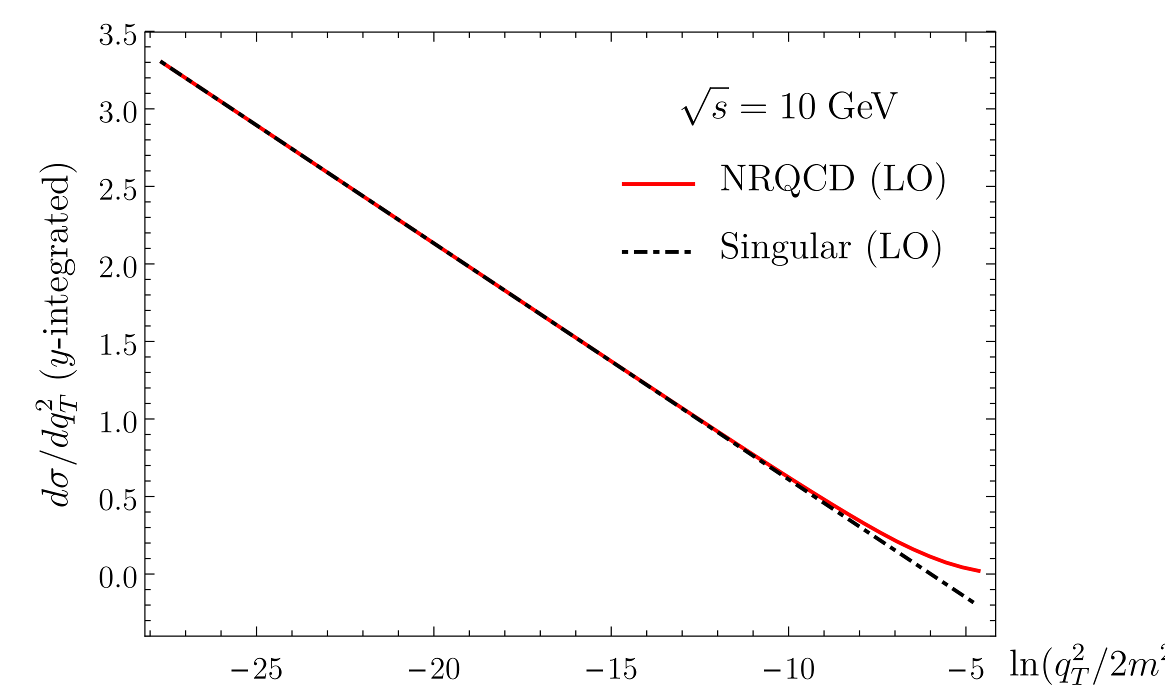
$$O^{jk\ell}_{\text{cs-1}}(\omega;{}^3S_1^{[1]}) = g^2\boldsymbol{B}^{j,a}_{s}\left[\delta(\omega - n\cdot\mathcal{P})\boldsymbol{B}^{k,a}_{\bar n\perp}\right](\psi\,\boldsymbol{\sigma}^\ell\chi)$$

$$O^{jk\ell}_{\text{cs-2}}(\omega;{}^3S_1^{[1]}) = g^2\left[\frac{(\boldsymbol{\mathcal{P}}\times\boldsymbol{B}^a_s)^j}{v\cdot\mathcal{P}}\right]\left[\delta(\omega - n\cdot\mathcal{P})\boldsymbol{B}^{k,a}_{\bar n\perp}\right](\psi\,\boldsymbol{\sigma}^\ell\chi)$$

collinear-soft presented here for the first time

The color singlet operators are suppressed in the λ power counting but enhanced in the relative velocity, v.

$$\left.\frac{d\sigma^{\text{LO}}({}^3S_1^{[1]})}{dq_T^2}\right|_{q_T\to 0} \sim A\log q_T + B$$



In progress: (S. Fleming, Y. Makris, T. Mehen, and J. Lieffers)

The color-singlet "factorized" cross section

$$d\sigma(\text{cc-1}) \sim H_{\mu\nu\rho\sigma}(M,\mu) \otimes \mathcal{B}_\perp^{\mu\nu\rho\sigma}(z,\boldsymbol{b},M,\mu) \times \langle {}^3S_1^{[1]} \rangle$$

$$d\sigma({}^3S_1^{[1]}) = d\sigma(\text{cc-1}) + d\sigma(\text{cs-1}) + d\sigma(\text{cs-2})$$

$$z = \frac{P\cdot P_\psi}{P\cdot P_\gamma} \sim 1$$

$$\mathcal{B}_\perp^{\mu\nu\rho\sigma} \sim \text{Im}\Big[\langle P|T[B_{n\perp}^{\mu a} B_{n\perp}^{\nu a}(x^+,0^-,x^\perp) B_{n\perp}^{\rho a} B_{n\perp}^{\sigma a}(0)]|P\rangle\Big]$$

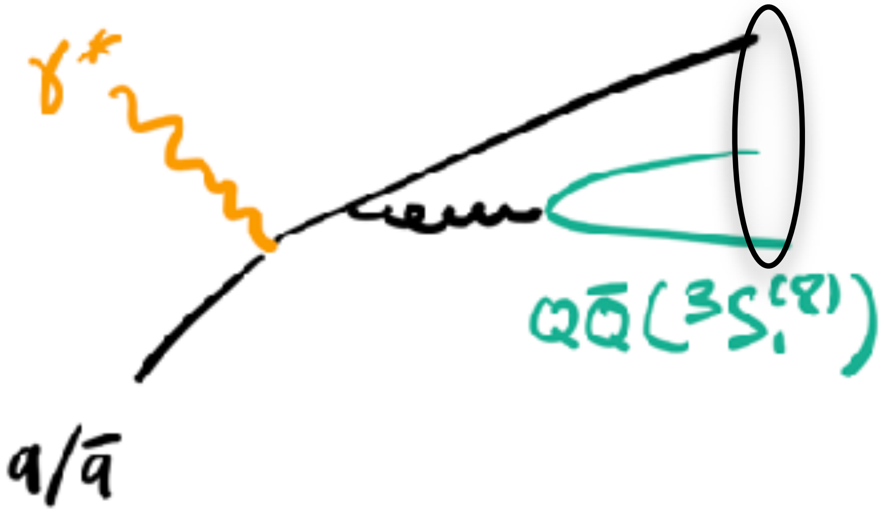
For perturbative values of transverse momentum we can match onto the collinear PDF.

$$\mathcal{B}_\perp(z,M,\mu) = \int_0^{1-z} dy\; C_\perp^{(1)}(y,z,x) \otimes f_{g/P}(x,\mu)$$

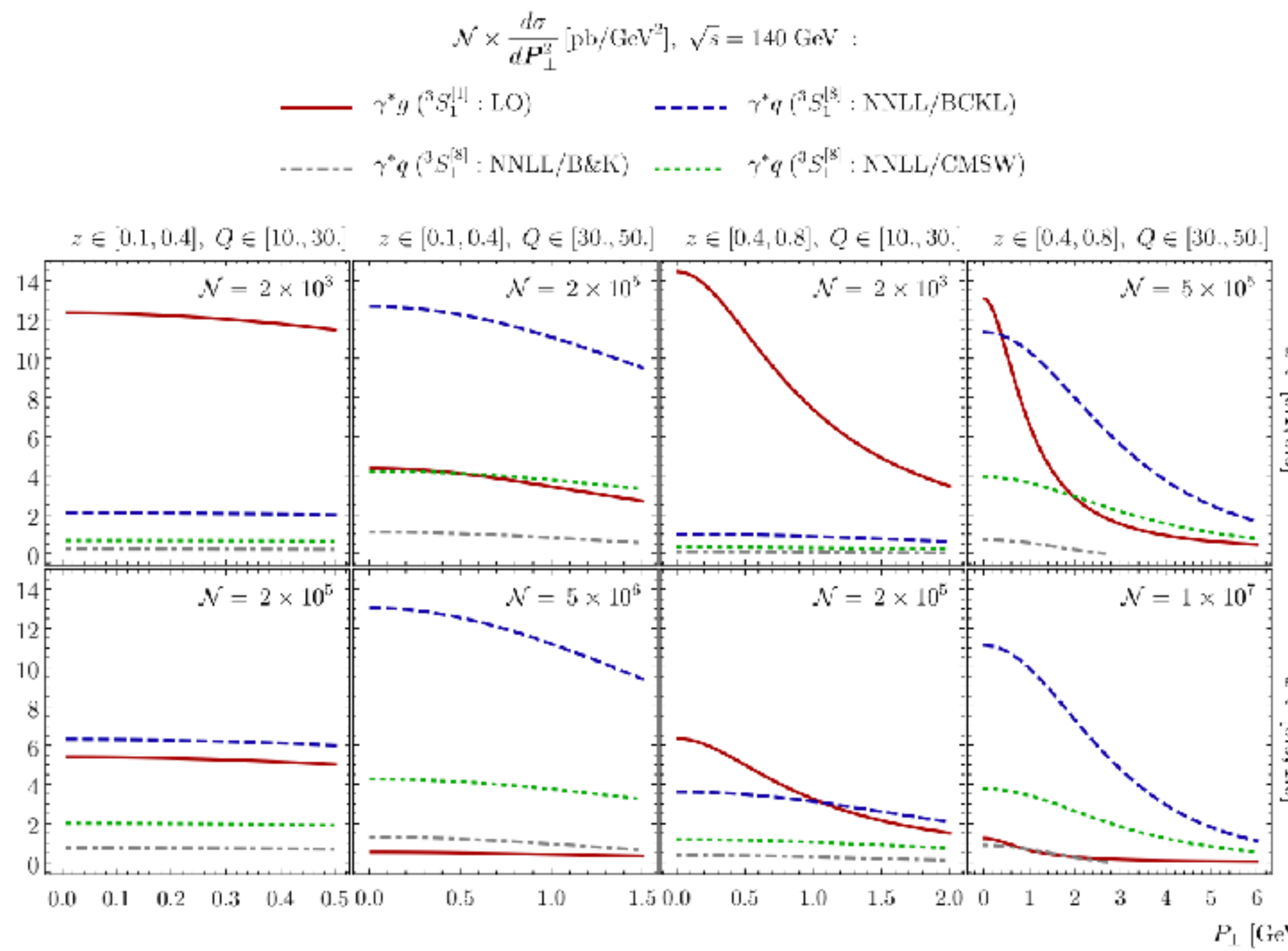
Leading order
contributions suffer from rapidity divergences which cancel in the sum of all operators

Note: the factorization for the cc-1 term does not involve any shape or soft function, only the standard quarkonium LDME.

Quarkonium TMD fragmentation: $Q \gg m_H$



arXiv: 2007.05547 (M.G. Echevarria, Y. Makris, I. Scimemi)



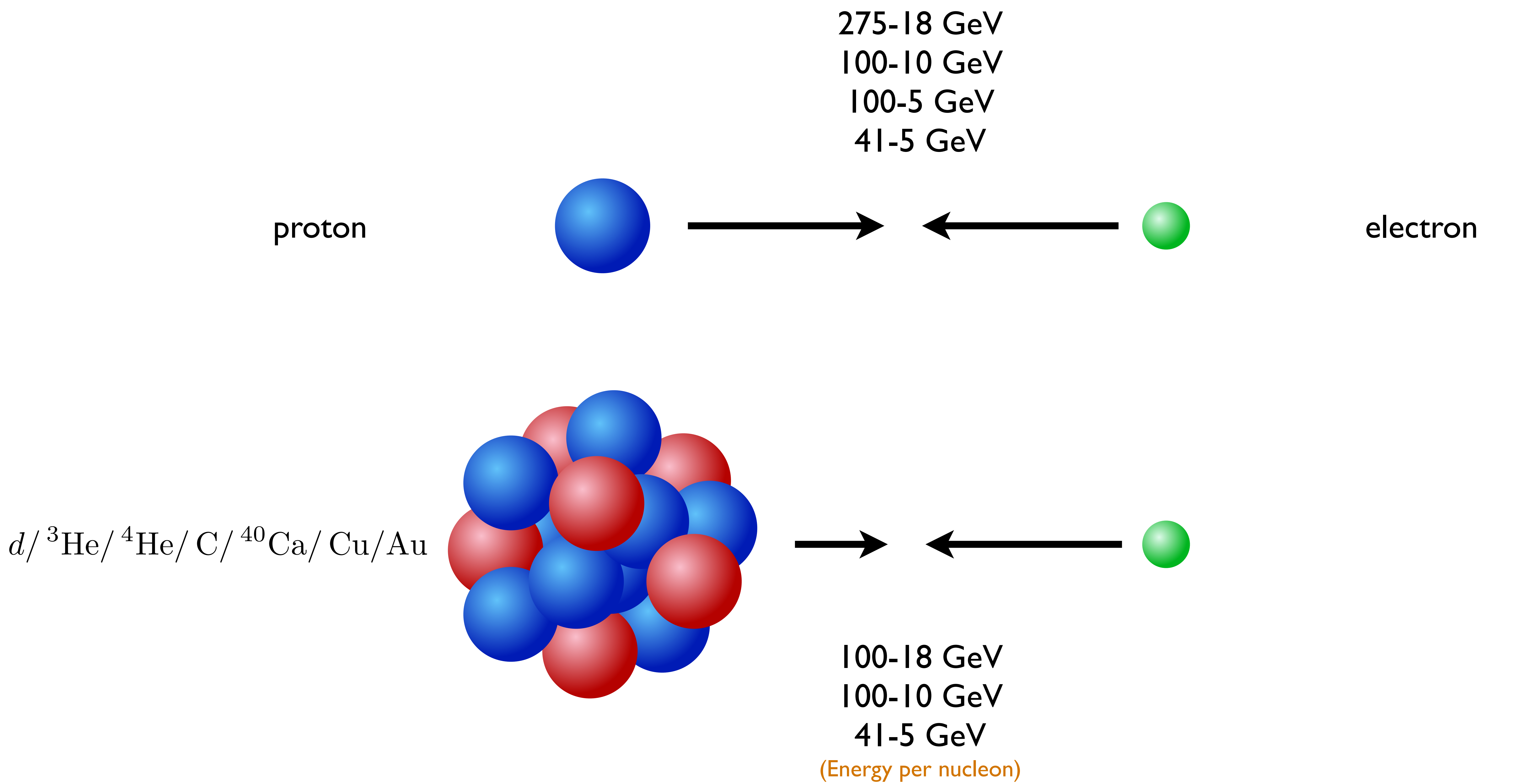
NRQCD and NRQCD factorization conjecture

Large-moderate $p_T/p_T^\star$ puzzle

The small $p_T/p_T^\star$ puzzle

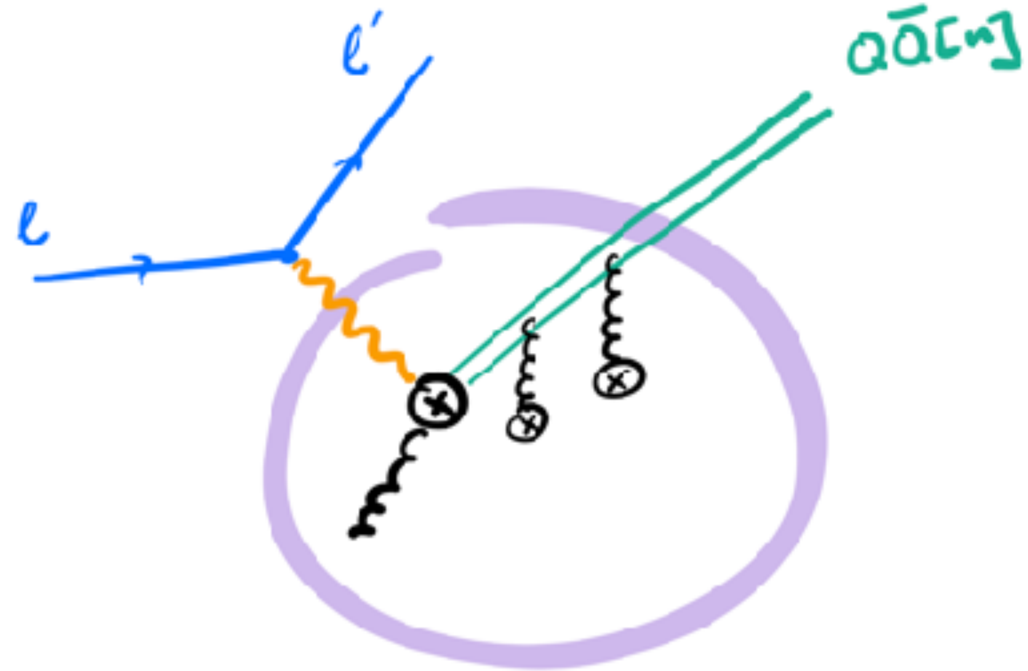
Interaction with nuclear medium

$eA \to J/\psi + X$ @EIC



Interactions with nuclear matter

arXiv:1906.04186 (Y. Makris, I. Vitev)



Leading contributions

$$\mathcal{L}^{(0)}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) = \sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\left(-gA^0_{G/C}\right)\psi_{\mathbf{p}} \quad (collinear/static/soft)$$

First sub-leading contributions

$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_{G}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\left(\frac{2A^{\mathbf{n}}_G(\mathbf{n}\cdot\boldsymbol{\mathcal{P}}) - i\left[(\boldsymbol{\mathcal{P}}_\perp\times\mathbf{n})A^{\mathbf{n}}_G\right]\cdot\boldsymbol{\sigma}}{2m}\right)\psi_{\mathbf{p}} \quad (collinear)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = 0 \quad (static)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\left(\frac{2\mathbf{A}_C\cdot\boldsymbol{\mathcal{P}} + [\boldsymbol{\mathcal{P}}\cdot\mathbf{A}_C] - i\left[\boldsymbol{\mathcal{P}}\times\mathbf{A}_C\right]\cdot\boldsymbol{\sigma}}{2m}\right)\psi_{\mathbf{p}} \quad (soft)$$

Interactions can be incorporated into the NRQCD Lagrangian

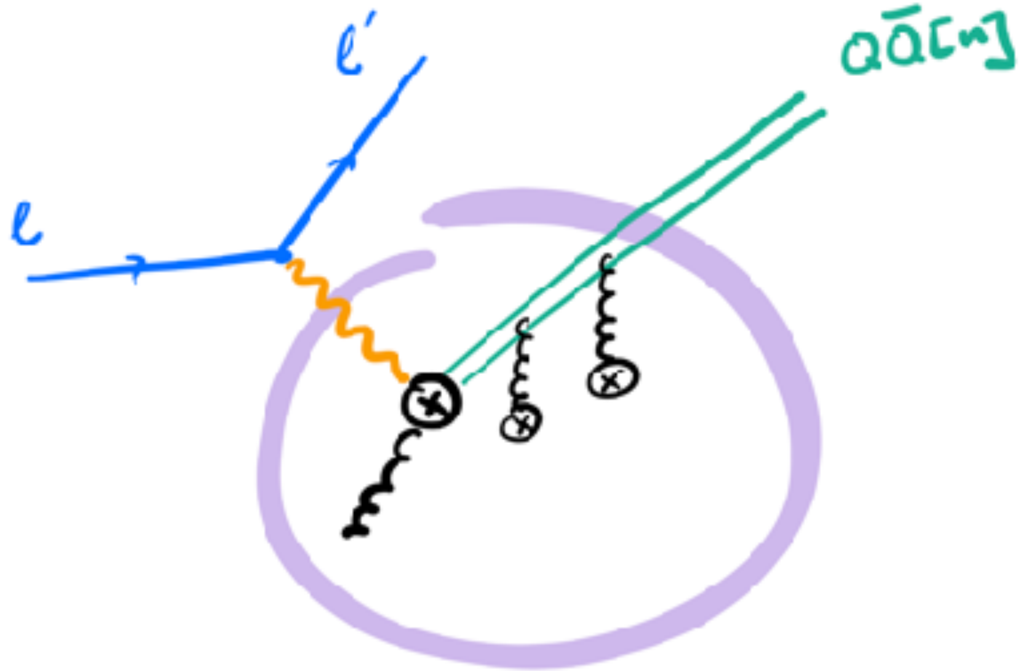
$$\mathcal{L}_{\mathrm{NRQCD}} \to \mathcal{L}_{\mathrm{NRQCD}} + \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \cdots$$

This approach has been successfully applied for jet in-medium propagation (SCET-G):

arXiv:1103.1074 (G. Ovanesyan and I. Vitev)

arXiv:1405.4293 (Y.-T. Chien and I. Vitev)

Interactions with nuclear matter



arXiv:1906.04186 (Y. Makris, I. Vitev)

Leading contributions

$$\mathcal{L}^{(0)}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) = \sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(-gA^0_{G/C}\Big)\psi_{\mathbf{p}} \quad (collinear/static/soft)$$

First sub-leading contributions

$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_{G}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2A^{\mathbf{n}}_G(\mathbf{n}\cdot\mathcal{P}) - i\big[(\mathcal{P}_\perp\times\mathbf{n})A^{\mathbf{n}}_G\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \quad (collinear)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = 0 \quad (static)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2\mathbf{A}_C\cdot\mathcal{P} + [\mathcal{P}\cdot\mathbf{A}_C] - i\big[\mathcal{P}\times\mathbf{A}_C\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \quad (soft)$$

Interactions can be incorporated into the NRQCD Lagrangian

$$\mathcal{L}_{\rm NRQCD} \to \mathcal{L}_{\rm NRQCD} + \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \cdots$$

Open quantum systems: In principle adaptable to cold nuclear matter
- No adaptations (currently) for EIC

arXiv:2009.10559, arXiv:1403.5783 (Y. Akamatsu)
arXiv:1711.04515 (N. Brambilla, M.A. Escobedo, J. Soto, and A. Vairo)
arXiv:1811.07027, arXiv:2009.02408 (X. Yao and T. Mehen)

Closing comments

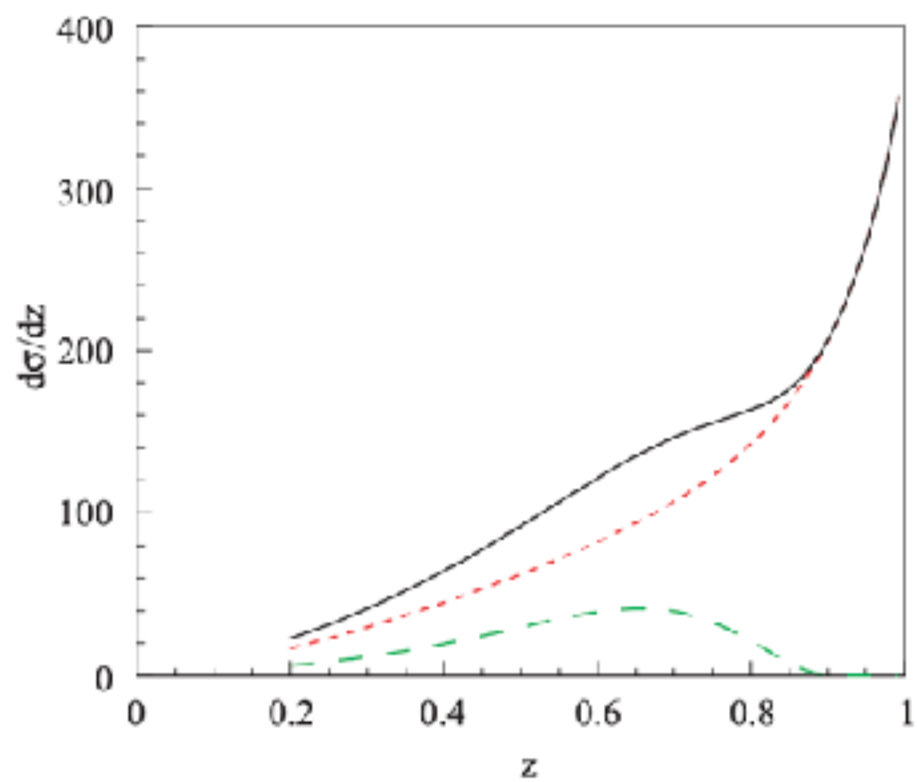
Lepton-nucleon/nucleus collisions constitute an excellent laboratory for the studies of quarkonium production (it is simplified and cleaner environment compared to hadronic colliders, yet far richer than in the electron-positron annihilation)

The various production channels can be disentangled by considering different kinematic regimes, establishing this way DIS as a prime framework for the study quarkonium production channels.

The study of nuclear effects in quarkonium production it’s an emerging field of nuclear physics where EIC measurements are expected to play a major role in our understudying of these effects.

Energy fraction spectrum

SCET resummed spectrum: $p_T > 0$



arXiv: hep-ph/0607121 (S. Fleming, A.K. Leibovich, T. Mehen)