From Collinear to TMD Distributions in the Large-x Regime

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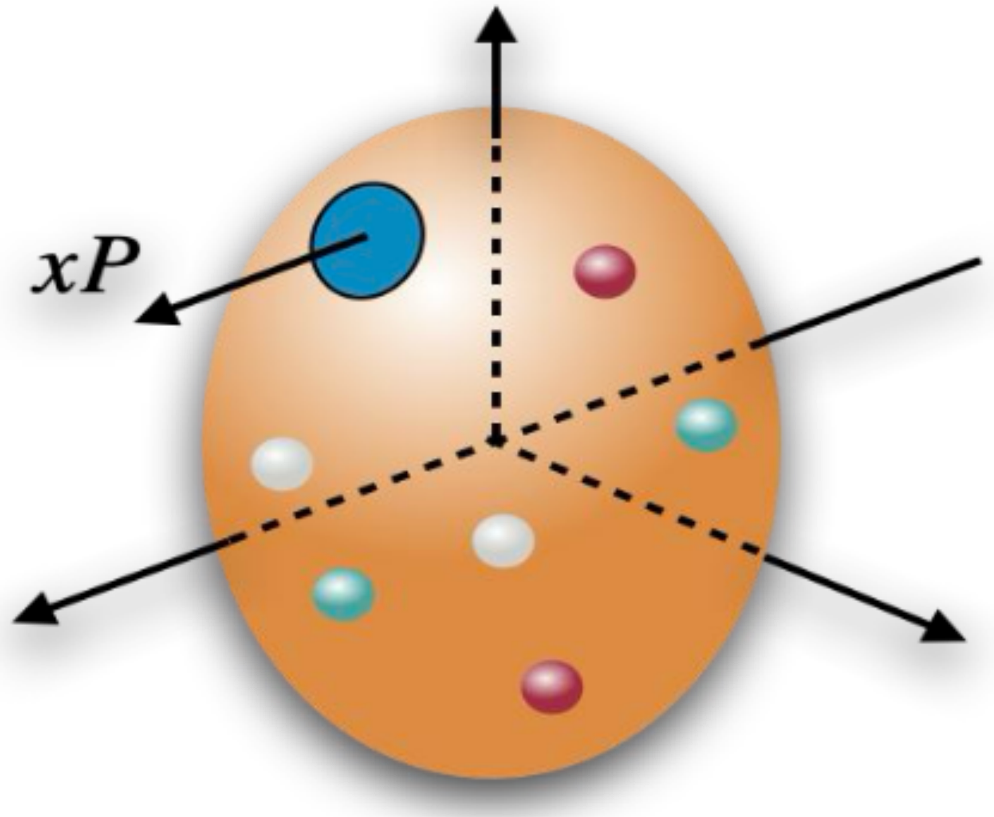
Distribution Functions for Partons

- Twist-2 quark **PDF** operator definition

Twist ≡ Dimension − Spin = 2

$$f^{[\Gamma]}(x) = \int \frac{db^+}{2\pi} e^{-ib^+(xP^-)} \langle P,S \,|\, \bar{q}(b^+)\ [b^+,0] \Gamma q(0) \,|\, P,S \rangle$$



PDF

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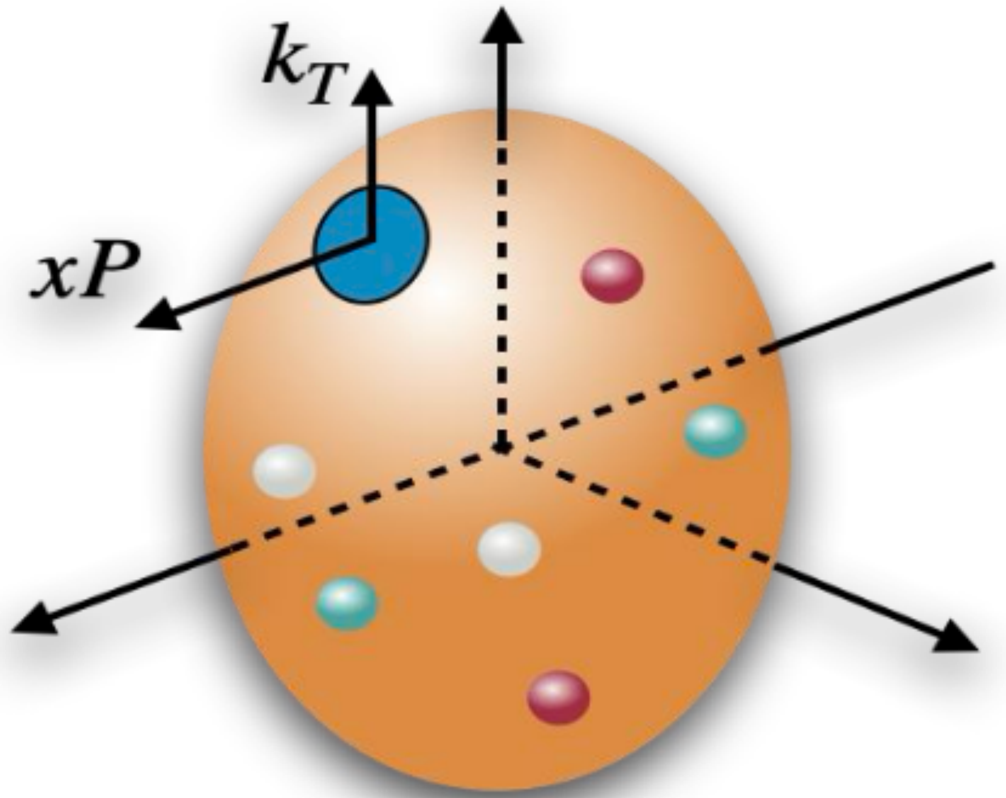
$$F^{[\Gamma]}(x, b_T) = \int \frac{db^+}{2\pi} e^{-ib^+(xP^-)} \langle P,S \,|\, \bar{q}(b)\ [b, b+s\infty][b+s\infty, s\infty][s\infty,0] \Gamma q(0) \,|\, P,S \rangle$$



TMD

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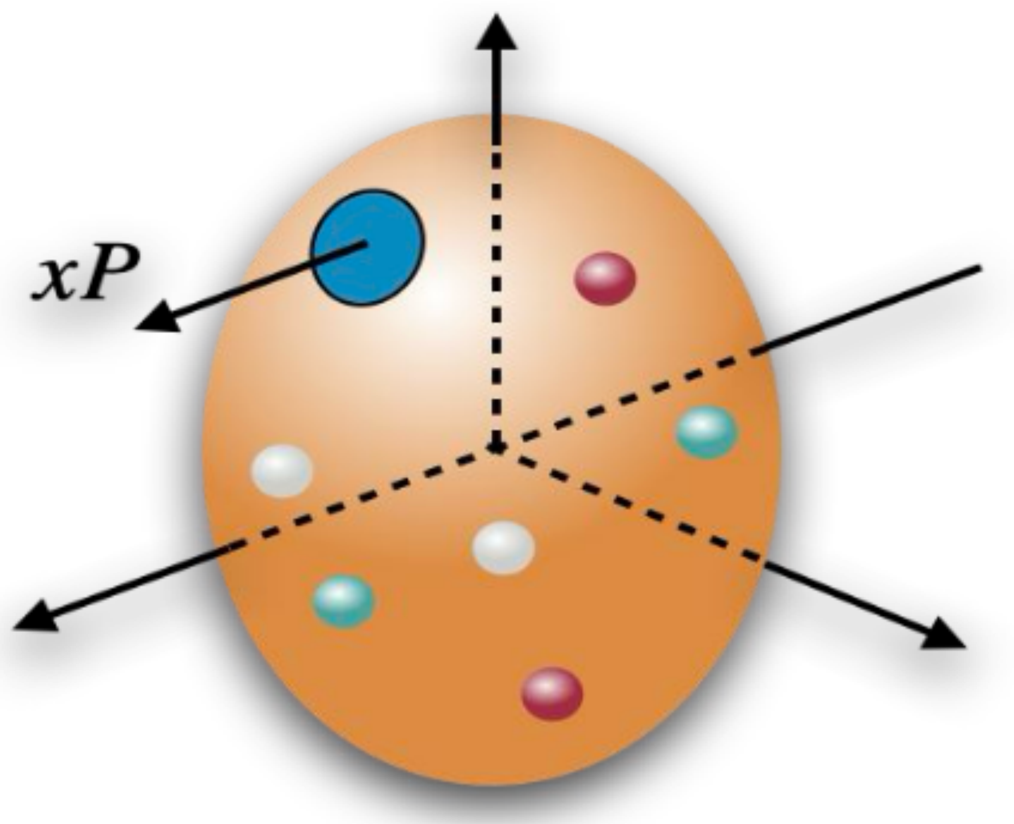

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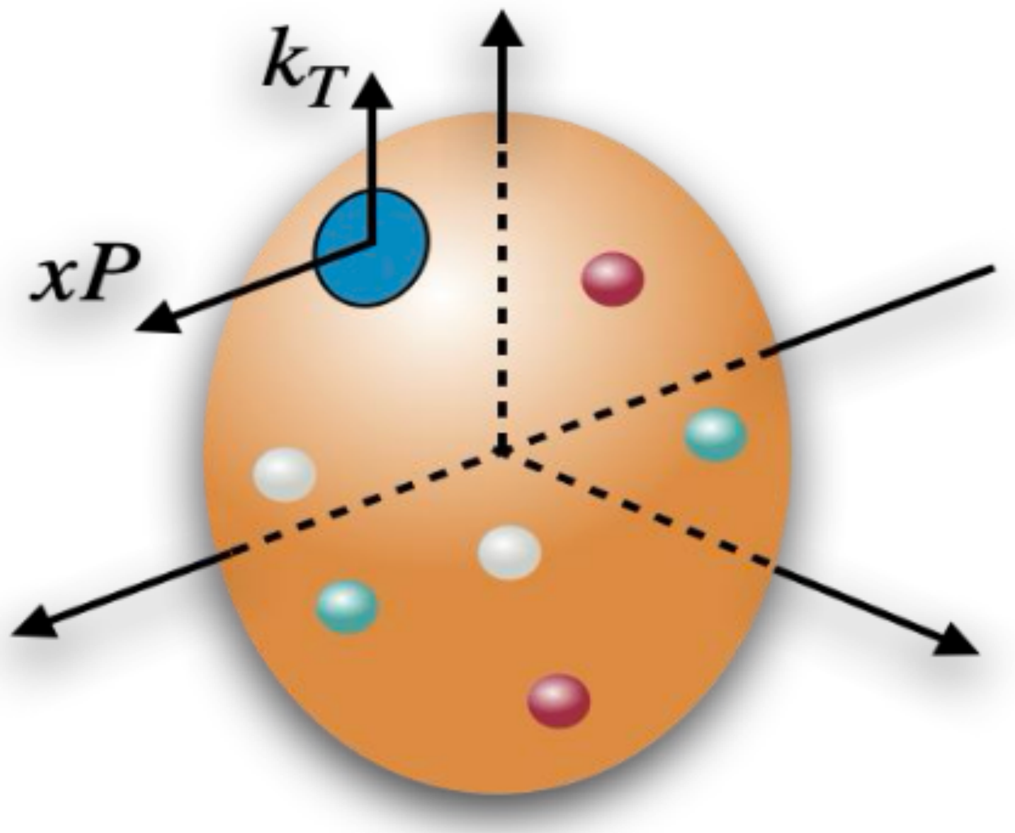
- Higher twist operators involve more fields:

$$\left.\begin{array}{l} \langle P, S \,|\, \bar{q}(b_1^+)[b_1^+, b_2^+]\; \Gamma\; F^{\mu +}(b_2^+)[b_2^+, b_3^+] q(b_3^+) \,|\, P, S \rangle \\ \langle P, S \,|\, F^{\mu +}(b_1^+)[b_1^+, b_2^+]\; \Gamma\; F^{\nu +}(b_2^+)[b_2^+, b_3^+] F^{\rho +}(b_3^+) \,|\, P, S \rangle \end{array}\right\}$$

Twist = 3



TMD

Distribution Functions for Partons

- Three independent twist-2 quark PDFs:

$\Gamma = \gamma^+$	$\Gamma = \gamma^+\gamma^5$	$\Gamma = i\sigma^{\nu+}\gamma^5$
$f_1(x)$ Unpolarized	$g_1(x)$ Helicity	$h_1(x)$ Transversity

- Eight independent twist-2 quark TMDPDFs:

$\Gamma = \gamma^+$	$\Gamma = \gamma^+\gamma^5$	$\Gamma = i\sigma^{\nu+}\gamma^5$	
$f_1(x, b_T)$ Unpolarized	$g_1(x, b_T)$ Helicity	$h_1(x, b_T)$ Transversity	$h_1^\perp(x, b_T)$ Boer-Mulders
$f_{1T}^\perp(x, b_T)$ Sivers	$g_{1T}^\perp(x, b_T)$ Worm-gear-T	$h_{1L}^\perp(x, b_T)$ Worm-gear-L	$h_{1T}^\perp(x, b_T)$ Pretzelosity

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- Twist-3 PDFs

(arxiv: 2209.00962)

- $\bar{q} F^{\mu+} q \longrightarrow$ $T(x_1, x_2, x_3)$ $\Delta T(x_1, x_2, x_3)$ $E(x_1, x_2, x_3)$ $H(x_1, x_2, x_3)$
- $F^{\mu+} \times 3 \longrightarrow$ $G_\pm(x_1, x_2, x_3)$ $Y_\pm(x_1, x_2, x_3)$

Matching Coefficient Function

- Related by **Operator Product Expansion** in small b_T regime

$$F_i(x, b_T) = \underbrace{C_{ij}^F(x, b_T)}_{\text{Twist-2 Match. Coeff.}} \otimes f_j(x) + \sum_t \underbrace{C_{t,ij}^F(x, x_1, x_2, x_3, b_T)}_{\text{Twist-3 Matching Coefficient}} \otimes t_j(x_1, x_2, x_3) + \mathcal{O}(b_T^2)$$

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TMDPDF	Leading Matching PDFs	Order Matching Coeff.
Unpolarized $f_1(x,b_T)$	$f_1(x)$	N^3LO
Helicity $g_1(x,b_T)$	$g_1(x)$	NLO
Transversity $h_1(x,b_T)$	$h_1(x)$	N^2LO

Twist-2

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Transversity $h_1(x,b_T)$	$h_1(x)$	N^{2}LO
Worm-gear-L $h_{1L}^{\perp}(x,b_T)$	h_1 , E , H	NLO
Worm-gear-T $g_{1T}^{\perp}(x,b_T)$	g_1 , T , ΔT , $G_{\pm}$, $Y_{\pm}$	NLO

Twist-2

Twist-2&3

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Worm-gear-L $h_{1L}^{\perp}(x, b_T)$	Wandzura-Wilczek h_1 E, H	NLO	Twist-2&3
Worm-gear-T $g_{1T}^{\perp}(x, b_T)$	Contributions g_1 T, ΔT, $G_{\pm}$, $Y_{\pm}$	NLO	

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Worm-gear-L $h_{1L}^{\perp}(x, b_T)$	Wandzura-Wilczek Contributions h_1 E, H	NLO	Twist-2&3
Worm-gear-T $g_{1T}^{\perp}(x, b_T)$	Wandzura-Wilczek Contributions g_1 T, ΔT, $G_\pm$, $Y_\pm$	NLO	Twist-2&3
Sivers $f_{1T}^{\perp}(x, b_T)$	T, ΔT, $G_\pm$, $Y_\pm$	NLO	Twist-3
Boer-Mulders $h_1^{\perp}(x, b_T)$	$E(x_1, x_2, x_3)$	NLO	Twist-3
Pretzelosity $h_{1T}^{\perp}(x, b_T)$	$-$	-	Twist-4

Matching Coefficient Function at Large-x

- Three type of contributions to $C^F(x, b_T)$:
  - Harmonic Polylogarithms → $H(a_1, \ldots, a_n, x)$
  - Delta Distribution → $L_0(x) = \delta(1-x)$
  - Plus Distributions → $L_1(x) = \dfrac{1}{(1-x)_+}$,..., $L_m(x) = \left(\dfrac{\ln^{m-1}(1-x)}{1-x}\right)_+$

Singular $x \to 1$
(Dominate at large-x)

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- Expansion in loops (α_s^n) and in L_m

$$
\begin{aligned}
C^F = \sum_{n,m} \alpha_s^n \left[L_m C^F_{n,m} + \Delta C^F_n\right] = \; & \boxed{L_0 C^F_{0,0} \qquad \text{LO}} \\
& \boxed{+\alpha_s L_1 C^F_{1,1} + \alpha_s L_0 C^F_{1,0} \qquad +\alpha_s \Delta C^F_1 \quad \text{NLO}} \\
& \boxed{+\alpha_s^2 L_2 C^F_{2,2} + \alpha_s^2 L_1 C^F_{2,1} + \alpha_s^2 L_0 C^F_{2,0} \qquad +\alpha_s^2 \Delta C^F_2 \quad \text{N}^2\text{LO}} \\
& + \ldots \qquad \vdots
\end{aligned}
$$

Matching Coefficient Function at Large-x

- Three type of contributions to $C^F(x, b_T)$:
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$$C^F = \sum_{n,m} \alpha_s^n \left[L_m C^F_{n,m} + \Delta C^F_n\right] = \begin{array}{llll} L_0 C^F_{0,0} & & & \\ +\alpha_s L_1 C^F_{1,1} & +\alpha_s L_0 C^F_{1,0} & & +\alpha_s \Delta C^F_1 \\ +\alpha_s^2 L_2 C^F_{2,2} & +\alpha_s^2 L_1 C^F_{2,1} & +\alpha_s^2 L_0 C^F_{2,0} & +\alpha_s^2 \Delta C^F_2 \\ \mathrm{LL}_x & \mathrm{NLL}_x & \mathrm{N^2LL}_x & \cdots \end{array}$$

Matching Coefficient Function in Mellin Space

- Mellin transformation

$$\mathbf{M}_N[C^F] = \int_0^1 \mathrm{d}x\, x^{N-1} C^F(x, b_T)$$

- Large-x asymptotics correspond to large-N dominant terms in Mellin space

$$\lim_{N\to\infty} \mathbf{M}_N[H] = 0 \qquad \lim_{N\to\infty} \mathbf{M}_N[L_0] = 1 \qquad \lim_{N\to\infty} \mathbf{M}_N[L_m] \sim \ln^m N$$

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- Transforming $\alpha_s^n \ln^m N$-terms up to N^{3}LO for unpolarized TMDPDF and TMDFF

$$\lim_{N\to\infty} \mathbf{M}_N\left[C_{ij}^{f_1}\right] = \delta_{ij} \exp\left[2D_i(b_T)\ln \bar{N} + E_i(b_T)\right]$$

Exponentiation!

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Exponentiation!

Perturbative Collins-Soper Kernel

Renormalized Soft Function

(2006.05329)

Resummed Matching Coefficient Function

- General to all orders and for all pure twist-2 matchings

Collinear-Soft Function

Joint Resummation (2211.08341)

$$\lim_{N\to\infty} \mathbf{M}_N\left[C^F_{ij}\right] = \delta_{ij}\exp\left[2D_i(b_T)\ln\bar{N}+E_i(b_T)\right] = \delta_{ij}\,S^c_i(b_T)$$

- At large-N, C^F_{ij} dominated by soft-gluon radiation

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$\boxed{\mathrm{N^3LO}} + \boxed{\mathrm{N^2LO}} \Rightarrow \boxed{\mathrm{N^3LL}_x \text{ Resummation}}$

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N^{3}LO + N^{2}LO → N^{3}LL$_x$ Resummation

(2006.05329)

- Transforming back to x-space

No $L_m(x)$-terms

$$C_{ij}^F(x,b_T) = \underbrace{\delta_{ij}\left[\delta(1-x) - \frac{2D_i(b_T)}{(1-x)_+^{1+2D_i(b_T)}}\right]\exp\left[E_i(b_T) - \sum_{k=2}^{\infty}\frac{\zeta_k}{k}\left(2D_i(b_T)\right)^k\right]}_{= V_i(x,b_T)} + \Delta C_{ij}^F(x,b_T)$$

(Unpolarized Beam Function Matching - 1909.00811)

Wandzura-Wilczek Contribution

- Matching for Worm-gear distributions mix twist-2 and twist-3 PDFs

$$g_{1T}^{\perp,i}(x,b_T) = C_{ij}^{g_{1T}^{\perp}}(x,b_T) \otimes g_1^j(x) + \sum_t C_{t,ij}^{g_{1T}^{\perp}}(x,x_1,x_2,x_3,b_T) \otimes t_j(x_1,x_2,x_3) + \mathcal{O}(b_T^2)$$

$$h_{1L}^{\perp,i}(x,b_T) = C_{ij}^{h_{1L}^{\perp}}(x,b_T) \otimes h_1^j(x) + \sum_t C_{t,ij}^{h_{1L}^{\perp}}(x,x_1,x_2,x_3,b_T) \otimes \bar{t}_j(x_1,x_2,x_3) + \mathcal{O}(b_T^2)$$

Wandzura-Wilczek (WW)

- At tree-level:

$$g_{1T}^{\perp,\text{WW-tree}}(x,b_T) = x\int_x^1 \frac{dy}{y}\, g_1(y) \qquad h_{1L}^{\perp,\text{WW-tree}}(x,b_T) = -\,x^2\int_x^1 \frac{dy}{y^2}\, h_1(y)$$

Resummed Wandzura-Wilczek Contribution

- Same large-x asymptotic behavior as the leading contribution

$$F_i^{\mathrm{WW}}(x, b_T) = \int_x^1 \frac{dy}{y}\left[V_i(y, b)\, F_i^{\mathrm{WW\text{-}tree}}\left(\frac{x}{y}, b_T\right) + \sum_j \Delta C_{ij}^{WW}(y, b_T)\, f_j\left(\frac{x}{y}\right)\right]$$

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- After performing tree-level integral

$$C_{ij}^{WW}(x, b_T) = \overbrace{\frac{\delta_{ij}}{(1-x)^{2D_i(b_T)}} \exp\left[E_i(b_T) - \sum_{k=2}^{\infty} \frac{\zeta_k}{k} \left(2D_i(b_T)\right)^k \right]}^{V_i^{WW}(x, b_T)} + \Delta C_{ij}^{WW}(x, b_T)$$

(Universal Resummation term for WW terms)

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- NLO remainder terms vanish as $x \to 1$:

$$\Delta C_{qq}^{g_{1T}^{\perp}}(x,b_T) = 2a_s C_F\,(\mathbf{L}_\mu - 1)\big(\ln(x) + (1-x)\big) + \mathcal{O}(a_s^2)$$

$$\Delta C_{qq}^{h_{1L}^{\perp}}(x,b_T) = 4a_s C_F\,\mathbf{L}_\mu \ln(x) + \mathcal{O}(a_s^2)$$

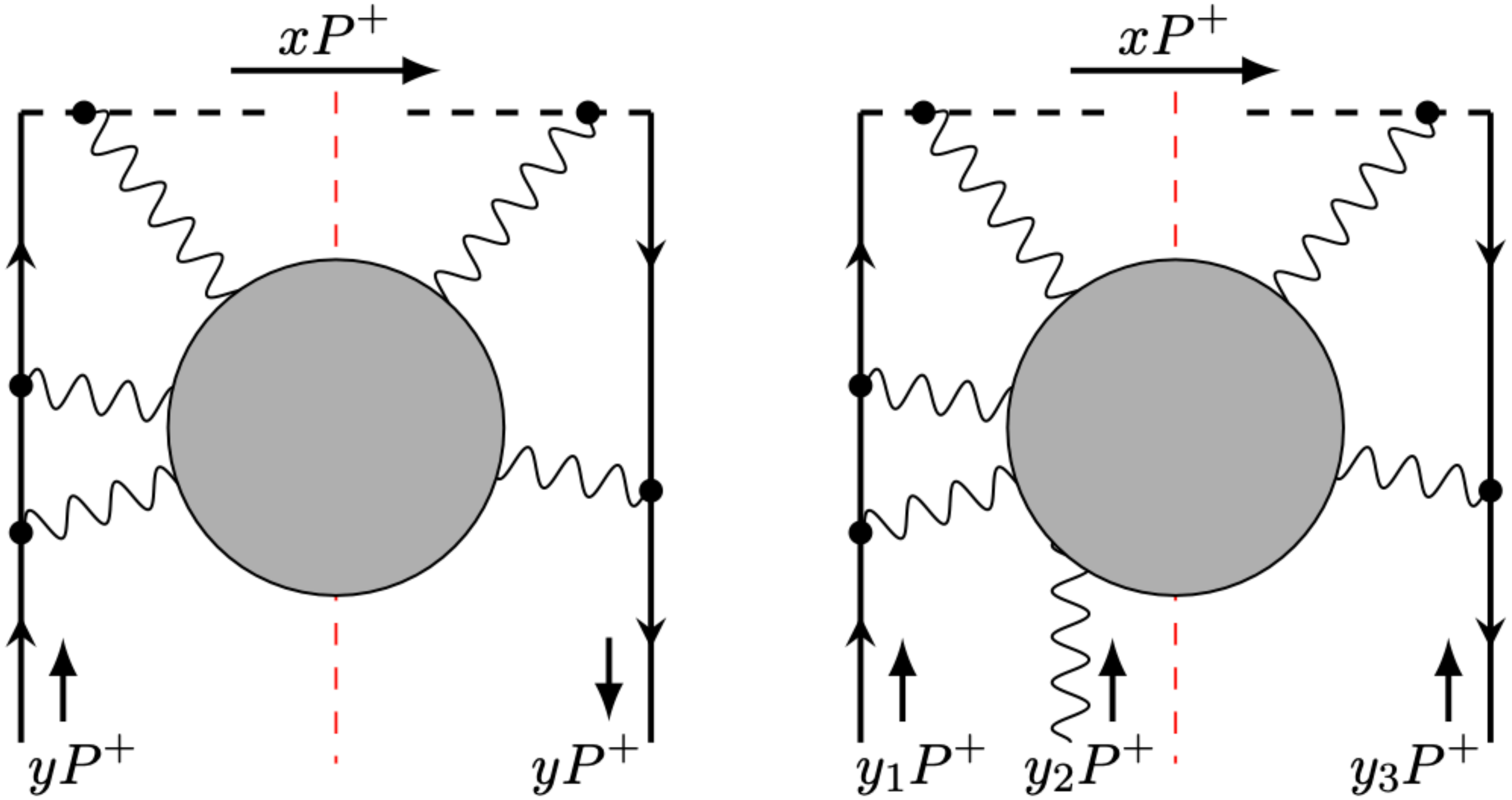
$\mathbf{LL}_x$ and $\mathbf{NLL}_x$ successfully resummed!

Twist-3 Contributions

$$F_i(x,b_T) = C^F_{ij}(x,b_T)\otimes f_j(x) + \boxed{\sum_t C^F_{t,ij}(x,x_1,x_2,x_3,b_T)\otimes t_j(x_1,x_2,x_3)} + \mathcal{O}(b_T^2)$$

Twist-3 Matching

- For twist-3 matching, only resummation to LL_x



Resummed Twist-3 Contributions

- Sivers and Boer-Mulders are simplest

$$f_{1T,q}^{\perp}(x,b_T) = \pm\frac{\pi\, e^{a_s E_q^{(1)}(b_T)}}{(1-x)^{2a_s D_q^{(1)}(b_T)}}\, T_q(-x,0,x) + \sum_t \Delta C_{t,ij}^{f_{1T}^{\perp}}(x,x_1,x_2,x_3,b_T) \otimes \hat{t}_j(x_1,x_2,x_3) + \mathcal{O}(b_T^2)$$

$$h_{1,q}^{\perp}(x,b_T) = \mp\frac{\pi\, e^{a_s E_q^{(1)}(b_T)}}{(1-x)^{2a_s D_q^{(1)}(b_T)}}\, E_q(-x,0,x) + \sum_t \Delta C_{t,ij}^{h_1^{\perp}}(x,x_1,x_2,x_3,b_T) \otimes \tilde{t}_j(x_1,x_2,x_3) + \mathcal{O}(b_T^2)$$

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LL_x+ some NLL_x

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$$f_{1T,q}^{\perp}(x,b_T) = \boxed{\pm\frac{\pi\, e^{a_s E_q^{(1)}(b_T)}}{(1-x)^{2a_s D_q^{(1)}(b_T)}} T_q(-x,0,x)} + \sum_t \Delta C_{t,ij}^{f_{1T}^{\perp}}(x,x_1,x_2,x_3,b_T) \otimes \hat{t}_j(x_1,x_2,x_3) + \mathcal{O}(b_T^2)$$

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LL_x+ some NLL_x

- Reminder terms do not vanish in the large-x limit $\longrightarrow$ Subleading NLL_x contributions

$$\left[\Delta C_{T,qq}^{f_{1T}^{\perp}} \otimes T_q\right](x,b_T) = a_s\left(2\mathbf{L}_\mu\left(2C_F - \frac{C_A}{2}\right)T_q(-x,0,x) + \cdots\right)$$

$$\left[\Delta C_{E,qq}^{h_1^{\perp}} \otimes E_q\right](x,b_T) = a_s\left(-2\mathbf{L}_\mu\left(\frac{3C_F}{2} - \frac{C_A}{2}\right)E_q(-x,0,x) + \cdots\right)$$

Large-x Resummation Implications

- Phenomenological fitting ansatz for TMDs

$$F_i(x, b_T) = C_{ij}^F\big(x, b^*(b_T); \mu_{OPE}\big) \otimes f_j(x; \mu_{OPE}) \cdot f_{NP}(x, b_T)$$

Non-perturbative models

- Resummation at large-x restricts our models $\longrightarrow$ $\boxed{2D_i\big(b^*(b_T); \mu_{OPE}\big) < 1}$

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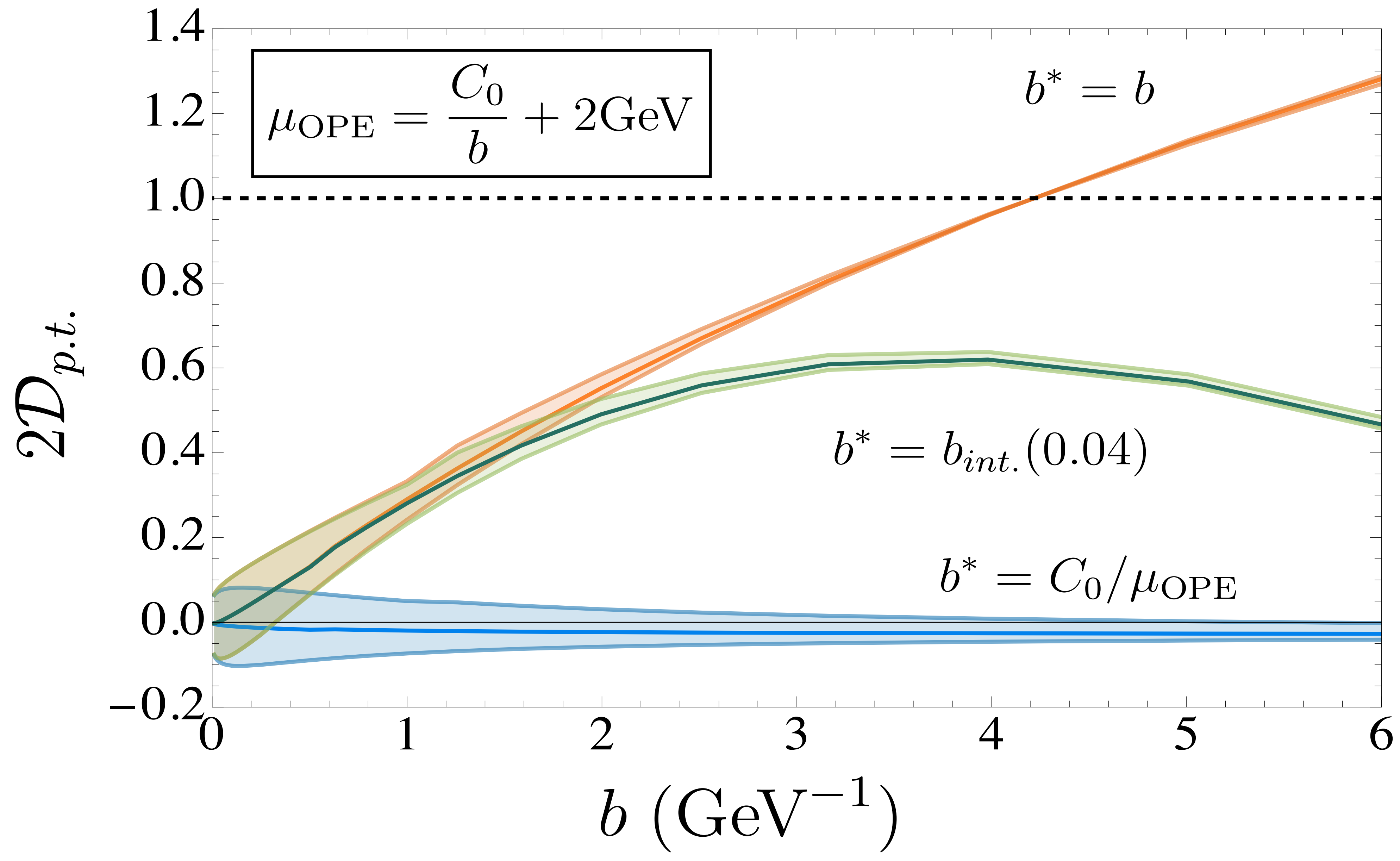


- ART23 linear b^*-model breaks this constraint

(ART23: 2305.07473)

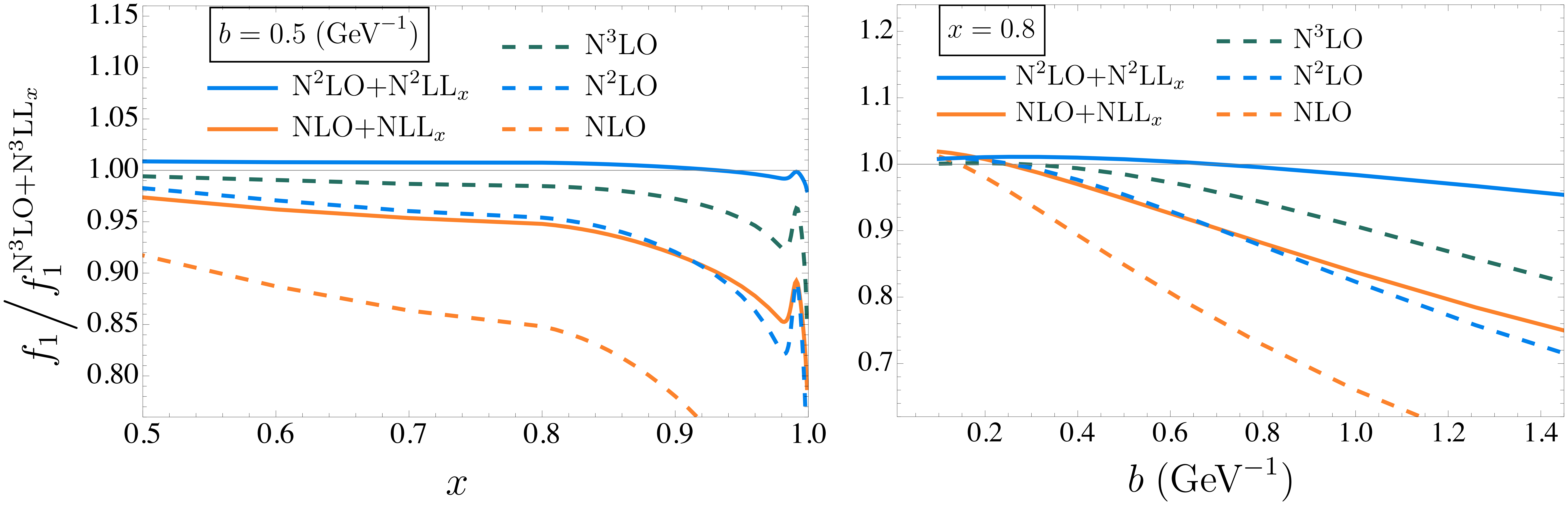
- In ART25 resummation is used with new model:

$$b^*_{int.}(a, b) = be^{-ab^2} + \frac{2e^{-\gamma_E}}{\mu_{OPE}(b)}\left(1 - e^{-ab^2}\right)$$

(ART25: 2503.11201)

Large-x Resummation Impact

- Unpolarized TMDPDF (u-quark)



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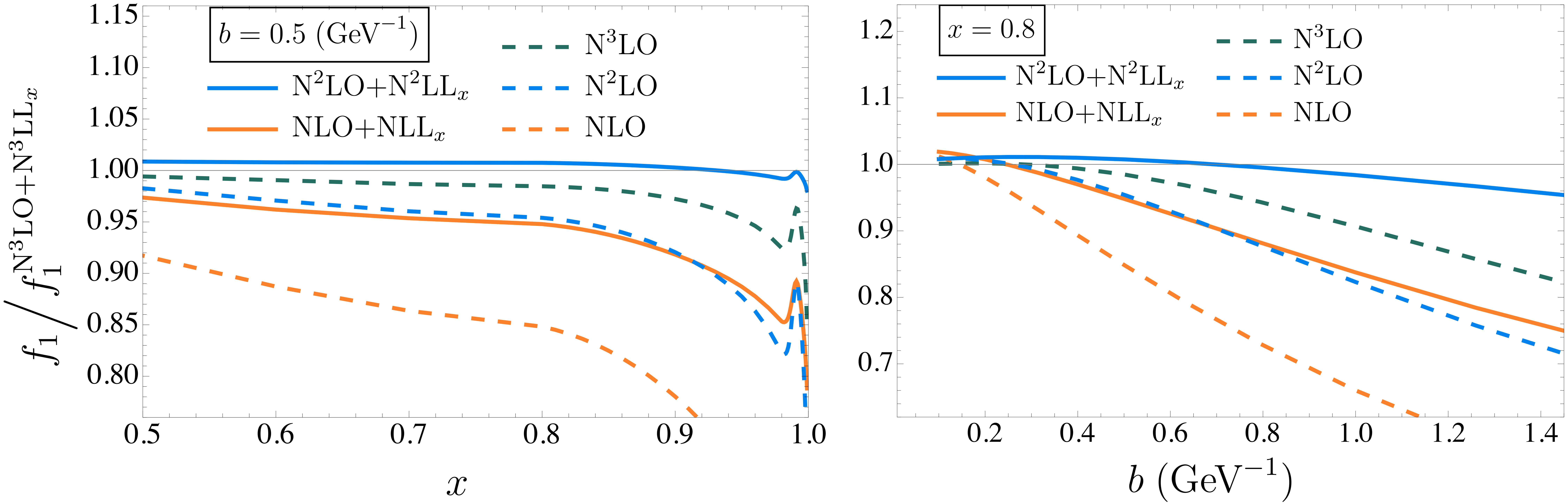


Large-x Resummation

Bigger differences for $x \gtrsim 0.5$ and $b_T \gtrsim 0.3\,\text{GeV}^{-1}$

Faster convergence (approximate higher orders)

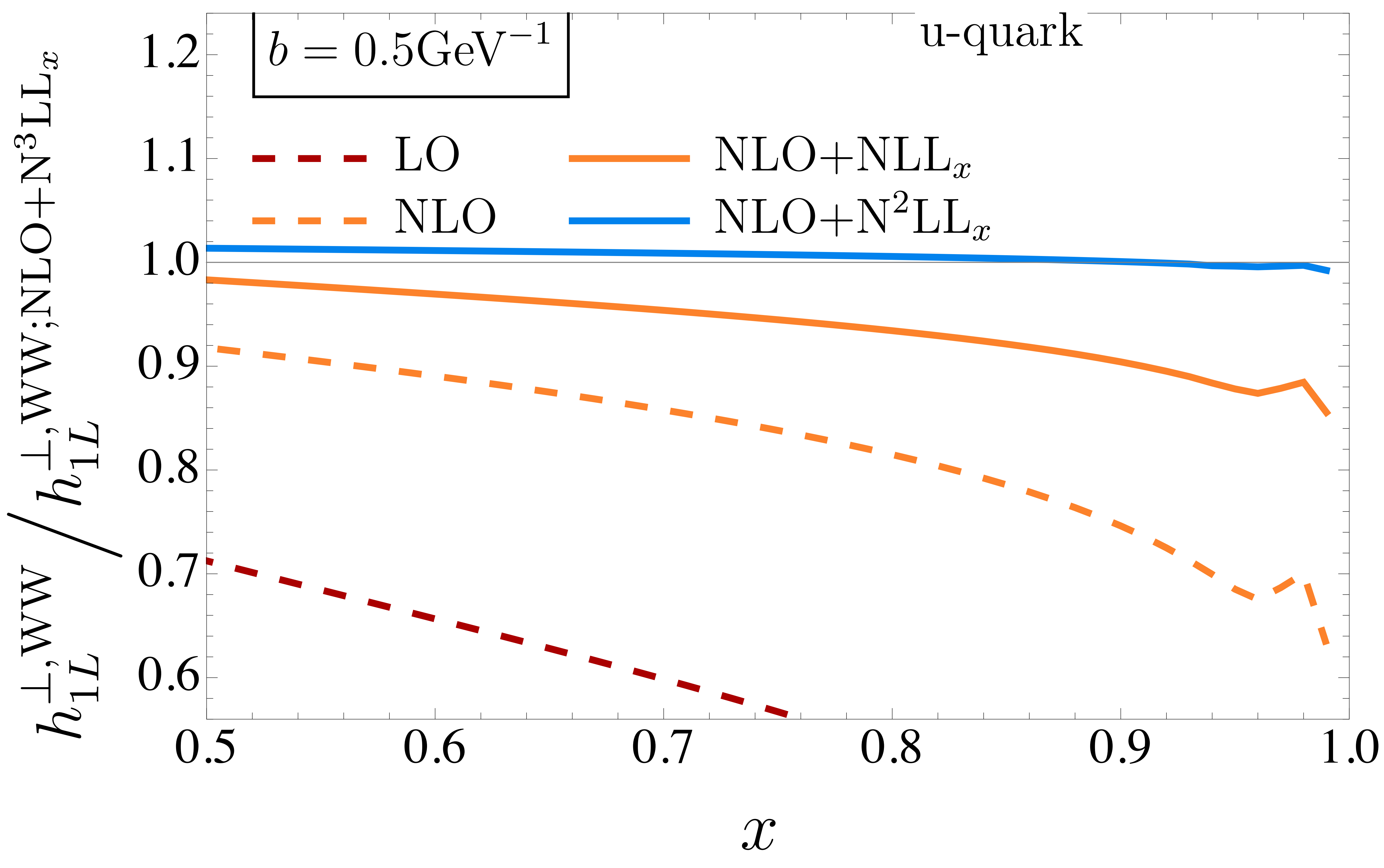
Large-x Resummation Impact

- WW-contribution to Worm-gear-L

Only NLO coefficient available

Greater impact of N^{3}LL$_x$ resummation

(Similarly for helicity and Worm-gear-T distributions)



Conclusions

- Large-x resummation directly within TMDs
  - Process-independent and universal
  - Valid for all leading TMDPDFs (except for pretzelosity) and TMDFFs
- First results for large-x asymptotics of higher twist matchings
  - Wandzura-Wilczek contribution valid to all log-orders
  - Twist-3 contribution valid to LL_x
- Resummation significantly improves extraction of many TMDs

Thank you for your attention!

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