Matching relations for gluon TMDs up to one-loop accuracy

Alessio Carmelo Alvaro

In collaboration with N. Kato, B. Pasquini, C. Pisano, S. Rodini

Bridging TMD frameworks: intersections, tensions and applications

ECT*, Trento, 9-13 March 2026

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Outline

1) Introduction

2) Tree-level computation

3) One-loop computation

4) Conclusions

Introduction

Matching relations

In the small-b regime:

$$f_i(x,b) = \sum_n \alpha_s^n \sum_j \left[C_{ij}^{(n)} \otimes f_j \right](x) + O(b^2)$$

TMD

Matching Coefficient

PDF

Matching relations

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$$b \to 0 \leftrightarrow \int dp_T$$

Collinear Kinematic $\leftrightarrow$ Integration over p_T TMD kinematic

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Constraints on TMD functional form $\rightarrow$ Parameterization $f_i(x,b) \propto \sum_j \left(C_{ij} \otimes f_j \right)(x)$

Predictions for TMD observables

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Known Examples (Quark TMDs)

$$g_1(x,b) = \int_0^1 du \int dy\, \delta(x-uy)\, \delta(1-u)\, g_1(y) = g_1(x)$$

Helicity TMD | Mellin Convolution | Matching coefficient | Helicity PDF

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$$g_1(x,b) = \int_0^1 du \int dy\, \delta(x-uy)\, \delta(1-u)\, g_1(y) = g_1(x)$$

$$g_1(x,b) = 4a_s C_F \Gamma(-\epsilon)\left(\mu^2 \boldsymbol{b}^2\right)^{\epsilon} \int_0^1 du \int dy\, \delta(x-uy) \left(\frac{2}{(1-u)_+} - 1 - u + (1-u)\epsilon \right) g_1(y)$$

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$$g_{1T}(x,b) = \int_0^1 du \int dy\, \delta(x-uy)\, u\left(y g_1(y) + y \mathcal{T}_g(y)\right)$$

Worm-gear T TMD

WW approximation

Twist-3 part

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$$f_{1T}^{\perp}(x,b) = \pm \int_0^1 du \int dy\, \delta(x-uy)\, \delta(1-u)\, \pi\, T(-y,0,y) = \pm\, \pi\, T(-x,0,x)$$

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Actual Status of Matching Relations

Quark TMDs

Distribution	Tw2	Tw3	Accuracy
f_1	$f_1\,, f_g$	-	$\mathrm{N^3LO}$
g_1	$g_1\,, \Delta f_g$	-	$\mathrm{N^3LO}$
g_{1T}	$g_1\,, \Delta f_g$	$\mathcal{T}_g\,, \mathcal{G}$	NLO
h_1	h_1	-	$\mathrm{N^3LO}$
h_{1L}	h_1	$\mathcal{T}_h$	NLO
$h_{1T}^{\perp}$	-	$\mathcal{T}_h$	NLO
$f_{1T}^{\perp}$	-	$T\,, \mathcal{G}$	NLO
$h_1^{\perp}$	-	E	NLO

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h_1	h_1	-	$\mathrm{N^3LO}$
h_{1L}	h_1	$\mathcal{T}_h$	NLO
$h_{1T}^{\perp}$	-	$\mathcal{T}_h$	NLO
$f_{1T}^{\perp}$	-	$T\,, \mathcal{G}$	NLO
$h_1^{\perp}$	-	E	NLO

Gluon TMDs

Distribution	Tw2	Tw3	Accuracy
f_1^g	$f_g\,, f_1$	-	$\mathrm{N^3LO}$
$h_1^{\perp g}$	$f_g\,, f_1$	-	$\mathrm{N^3LO}$
g_{1L}^g	$\Delta f_g\,, g_1$		$\mathrm{N^3LO}$
g_{1T}^g			
$f_{1T}^{\perp g}$	-		
h_{1T}^g	-		
$h_{1L}^{\perp g}$			
$h_{1T}^{\perp g}$			

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Gluon TMDs

hadron \ gluon	unpolarized	circular	linear
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g, h_{1T}^{\perp g}$

Light blue: T-Even Pink: T-Odd

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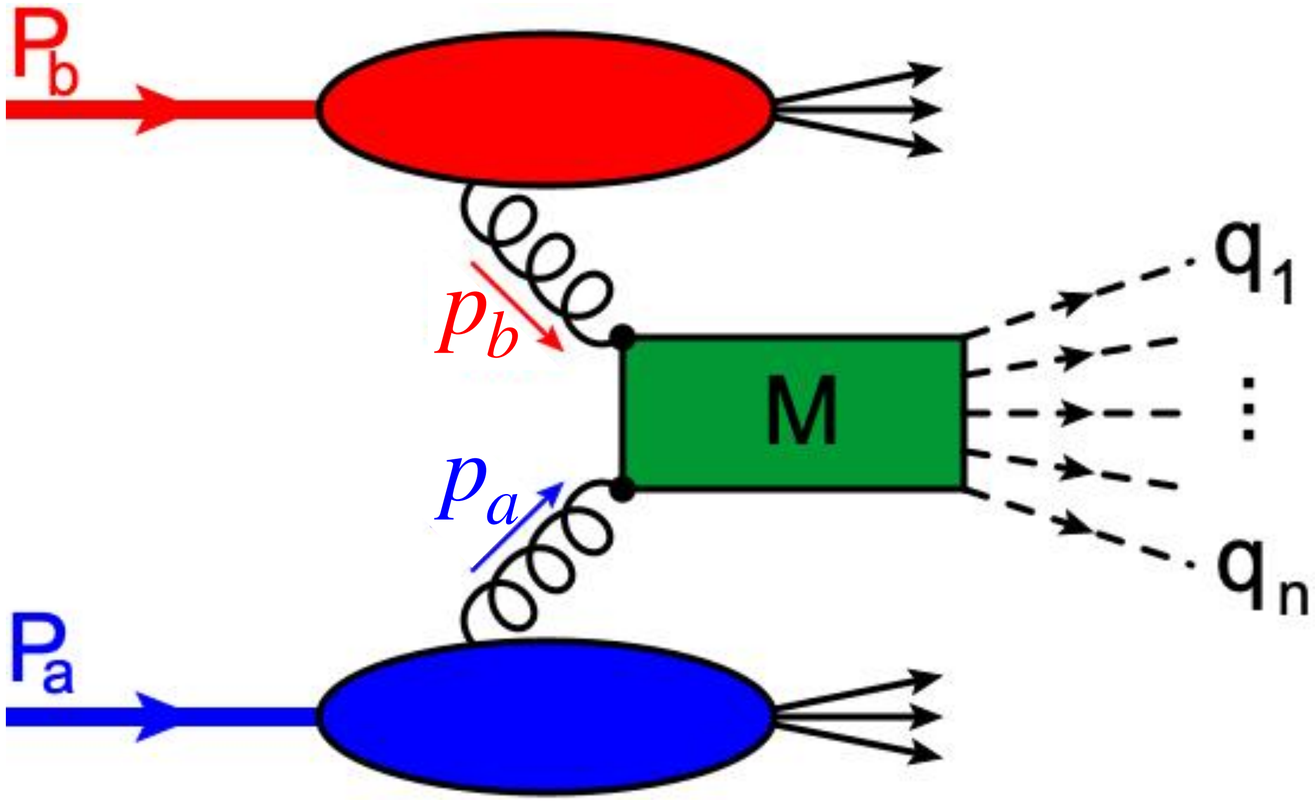
Processes for gluon TMDs



Hadron-hadron collisions

Different final states:
two photons, Higgs
color singlet hadrons

Unpolarized hadrons $\rightarrow f_1^g \, , h_1^{\perp,g}$

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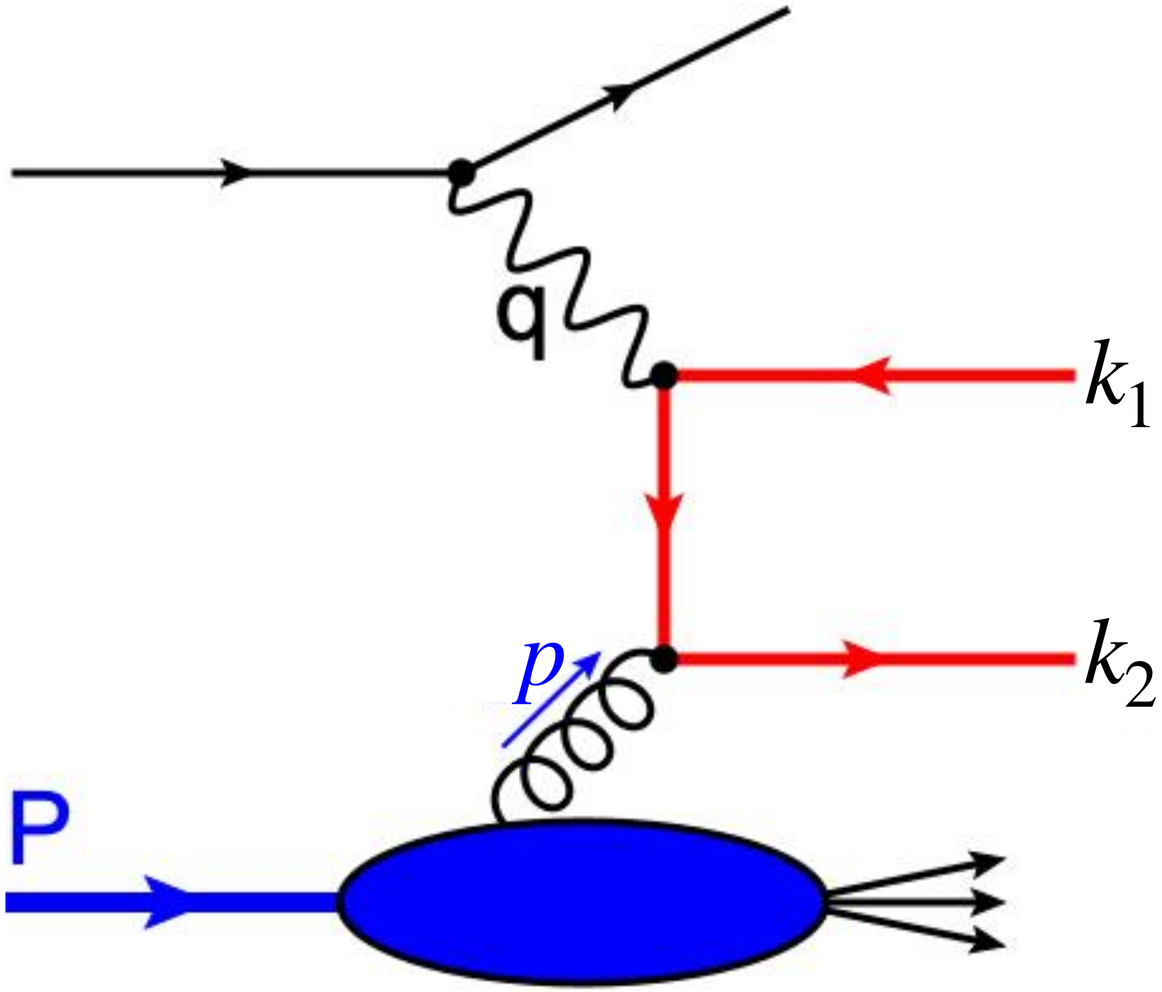
Processes for gluon TMDs



Lepton-hadron collisions

Heavy-quarks dijet

Polarized gluon distributions
Sivers: *2603.00375*

Questions and motivations

1) Distributions matching onto HT (higher twist) operators

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2) T-odd distributions

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3) Corrections $O(b^2M^2)$

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3) Corrections $O(b^2M^2)$

$\Longrightarrow$ Analysis of HT operators

Tree-level computation

Tree level computation

$$G^{\mu\nu}(x,b) = \sum_{n=0}^{\infty} \frac{1}{n!} b_{\mu_1} \dots b_{\mu_n} \left[\partial^{\mu_1} \dots \partial^{\mu_n} G^{\mu\nu}(x,b) \right]_{|b=0}$$

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Each term is a sum of operators with geometrical twist $2 \leq k \leq n+2$

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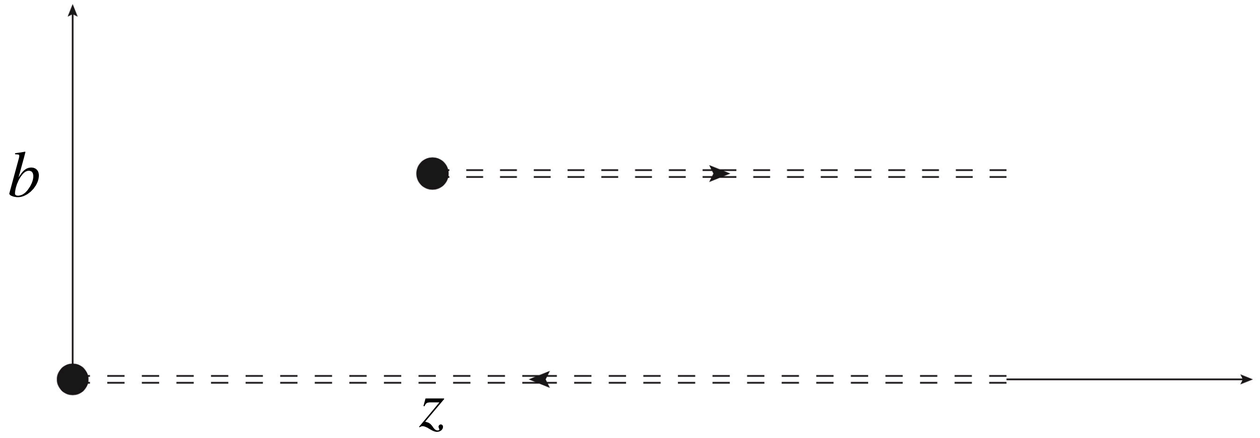
Does a unified treatment exist?
Moos, Vladimirov, JHEP 12 (2020) 145
Rodini, Alvaro, Pasquini, PLB 845 (2023) 138163

Tree level computation



$$F^{\mu+}(zn+b)\,[zn+b\,,\infty n+b]$$
$$[\infty n+b\,,\infty n]\,[\infty n\,,0]\,F^{\nu+}(0)$$

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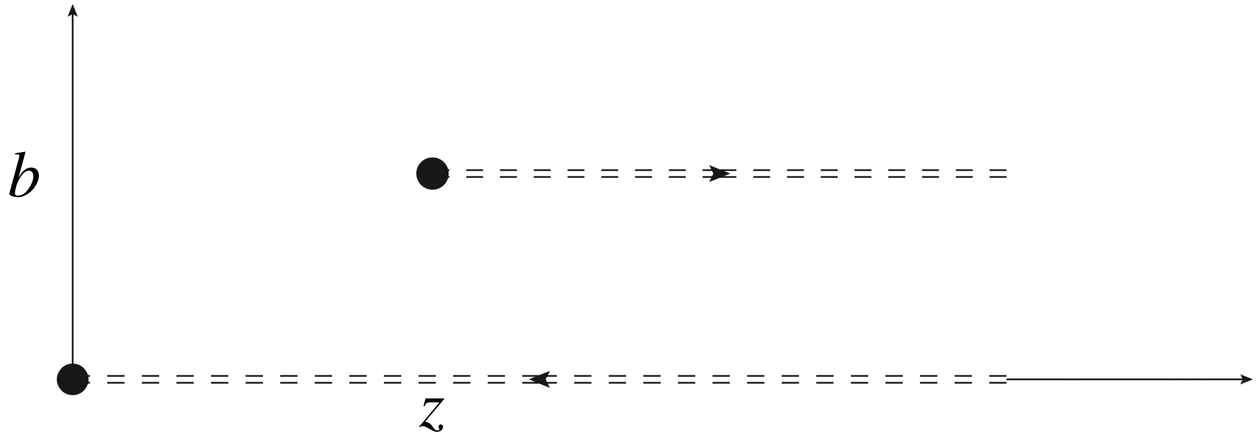
Tree level computation



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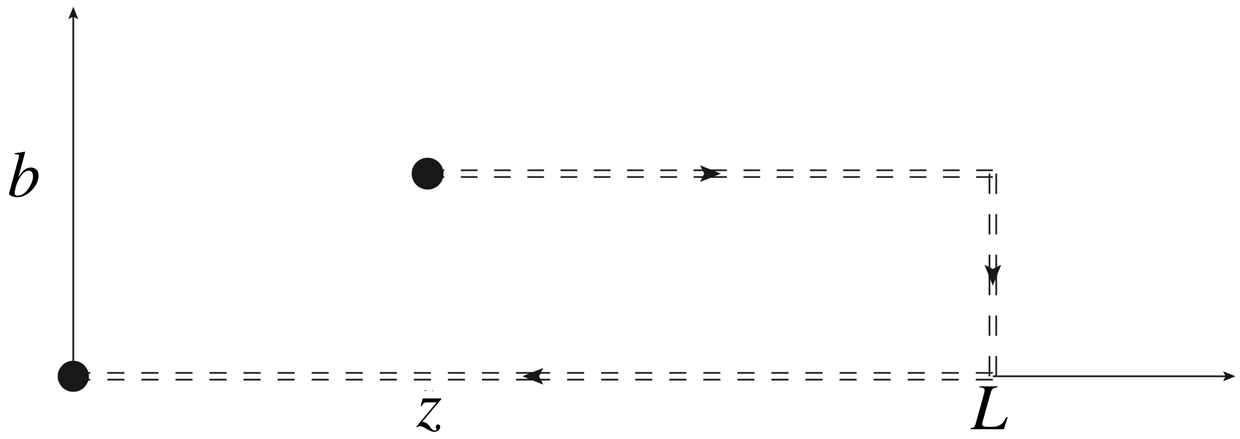

$$F^{\mu+}(zn+b)\,[zn+b\,,Ln+b]$$
$$[Ln+b\,,Ln]\,[Ln\,,0]\,F^{\nu+}(0)$$

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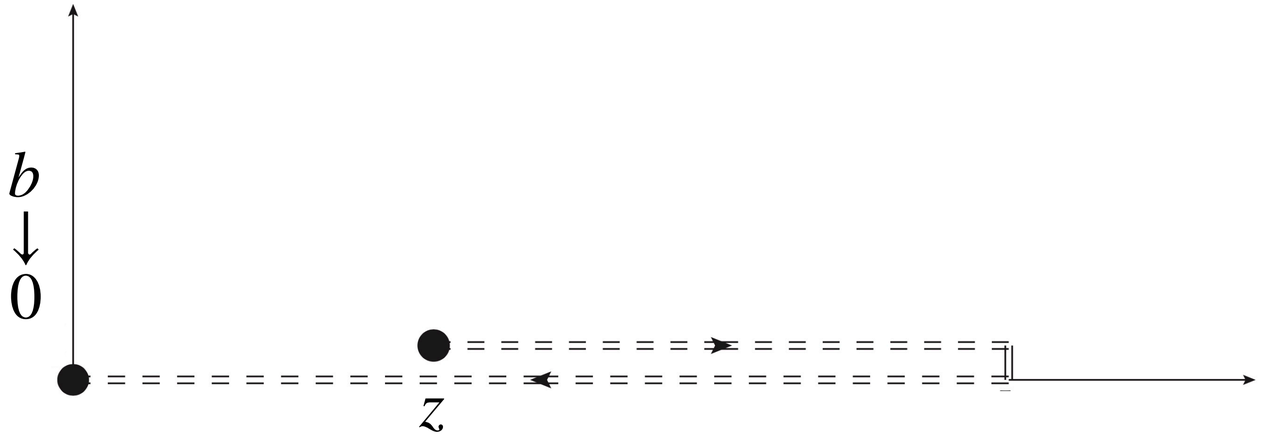
Tree level computation



$$\sum_{n=0}^{\infty} \frac{1}{n!} \left(F^{\mu+}(zn) \, [zn \, , Ln] \right) \left(b \cdot \overleftarrow{D} \right)^{n} [Ln \, , 0] \, F^{\nu+}(0)$$

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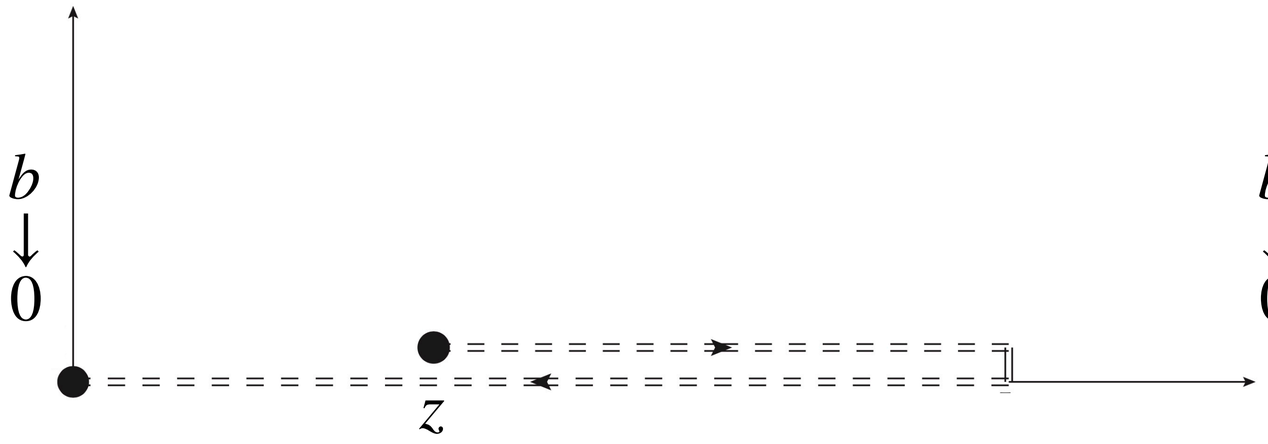
Tree level computation



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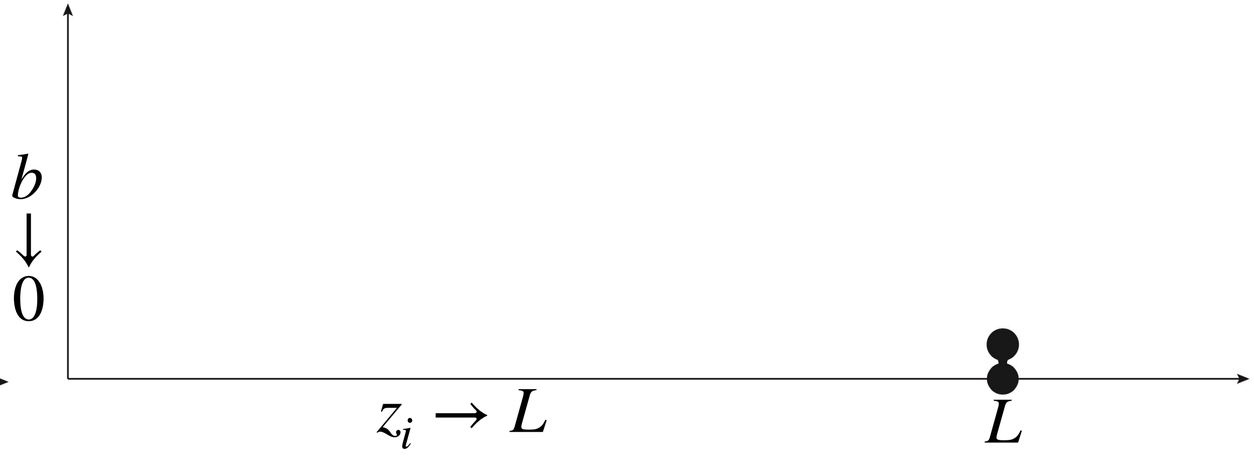

$$\sum_{n=0}^{\infty} \frac{1}{n!} \sum_{s,t=0}^{\infty} \frac{(z-L)^s (-L)^t}{s!\,t!} F^{\mu+} \overleftarrow{D}_+^s \left(b \cdot \overleftarrow{D} \right)^n D_+^t \, F^{\nu+}$$

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Tree level computation

Spinor Formalism: $x_\mu \rightarrow x_{\alpha\dot{\alpha}} = x_\mu \sigma^\mu_{\alpha\dot{\alpha}}$

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Twist decomposition $\rightarrow$ (anti)symmetrization of spinor indeces

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Hadronic matrix element

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$$L \rightarrow \mp \infty$$

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$$L \rightarrow \mp \infty$$

Fourier transform to x-space

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Example of results: unpolarized

$$f_1^g(x,b) = f_g(x)$$

$$+\sum_{k=1}^{\infty} \frac{1}{k!(k-1)!}\left(\frac{x^2M^2b^2}{4}\right)^k \int_0^1 du \int dy\, \delta(x-uy)\left(\frac{\bar{u}}{u}\right)^{k-1} f_g(y)$$

Leading Term

Mass series

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Example of results: Sivers

$$f_{1T}^{\perp,g}(x,b) = \mp\frac{2\pi}{x}\left(2F_2^+ + F_4^+\right)(-x,0,x)$$

$$\mp\sum_{k=1}^{\infty}\frac{1}{(k-1)!(k+1)!}\left(\frac{x^2M^2b^2}{4}\right)^k\int_0^1 du\int dy\,\delta(x-uy)\,G_k(u)\,\frac{2\pi}{y}\left(2F_2^+ + F_4^+\right)(-y,0,y)$$

Leading Term

Mass series

T-oddness

Example of results: worm-gear T

$$g_{1T}^{\perp,g}(x,b) = -\int_0^1 du \int dy\, \delta(x-uy)\, u \left(y\Delta f_g(y) + 2\frac{\mathcal{G}_g(y)}{y} - 2\frac{\mathcal{G}_q(y)}{y} \right)$$

WW approximation

Twist 3 gluon PDF

Twist 3 quark PDF

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Summary tree-level

6 TMDs match at tree-level up to twist 3 PDFs

$$\left\{f_1^g, g_{1L}^g\right\}, \left\{g_{1T}^{\perp,g}\right\}, \left\{f_{1T}^{\perp,g}, h_{1T}^g\right\}, \left\{h_{1L}^{\perp,g}\right\}$$

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$h_1^{\perp,g}$: NLO matching

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$h_1^{\perp,g}$: NLO matching

$h_{1T}^{\perp,g}$: twist 4 and 5 PDFs

One-loop computation

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Parton-in-parton method:

✔ Easy to implement

✘ Only leading-twist

One-loop computation

Parton-in-parton method:

- ✓ Easy to implement
- ✗ Only leading-twist

Position space:

- ✓ Higher-twist contributions
- ✗ More difficult implementation

Parton-in-parton

$$\Phi_i^{(n)}(x,b) = a_s^n \int_0^1 du \int dy\, \delta(x-uy) \sum_j C_{ij}^{(n)}(u)\, \Phi_j(y)$$

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Parton-in-parton

$$\Phi_i^{(n)}(x,b) = a_s^n \int_0^1 du \int dy\, \delta(x-uy) \sum_j C_{ij}^{(n)}(u)\, \Phi_j(y)$$

$$C_{ij}^{(n)} \Longleftrightarrow \langle p_j\,, s_j \,|\, F^{\mu+}\, \Gamma^i_{\mu\nu}\, F^{\nu+} \,|\, p_j\,, s_j \rangle$$

$\Gamma_{\mu\nu}$ proper projector

$p_j\,, s_j$ gluon/quark final state

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Main idea

Question: can we extend to higher-twist? and how?

$$p_j^\mu = (p^+ , 0 , \mathbf{0}) \Longrightarrow p_j^\mu = (p^+ , \frac{\boldsymbol{p_T^2}}{2p^+} , \boldsymbol{p_T})$$

$\left(\boldsymbol{b} \cdot \boldsymbol{p_T}\right)^n$ associated to higher-twist terms

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Hint: quark worm-gears (tree-level)

$$C_q^{L/L}(u) = e^{ib\cdot p_T}\,\delta(1-u) = (1 + ib\cdot p_T)\,\delta(1-u)$$

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Guess: replacements

$$1 \to s_L\, g_1(y)$$

$$i(b\cdot p_T) \to iM(b\cdot S)\, y\, g_T^q(y)$$

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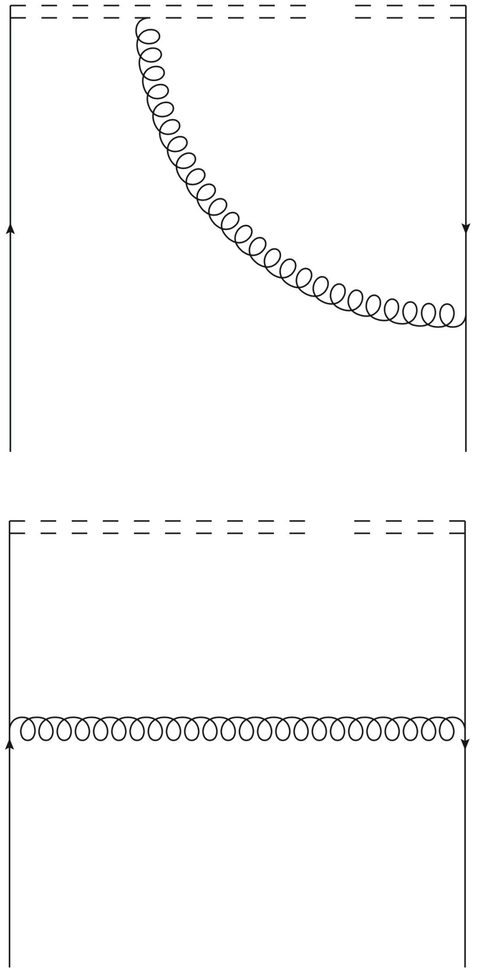
Same for $C_q^{T/T}(u)$

Validation: quark worm-gears (one-loop)

Comparison with position-space computation
(Feynman gauge)



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Comparison with position-space computation
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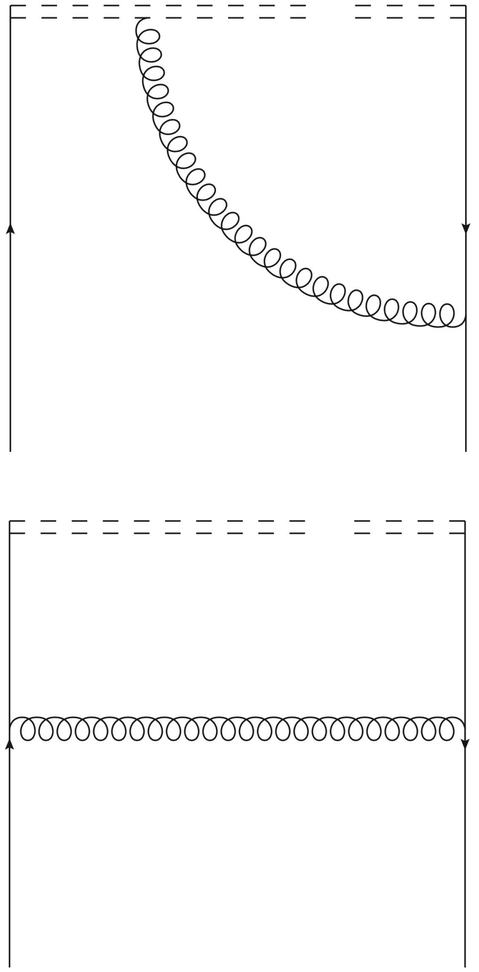
For each diagram:

LT $\rightarrow$ LP + NLP

NLT $\rightarrow$ LP

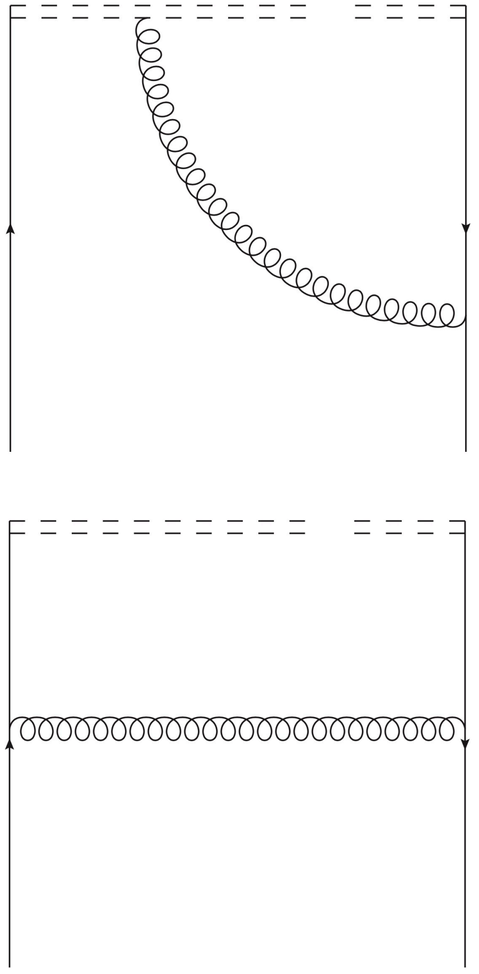


Validation: quark worm-gears (one-loop)

Position space:

$$\text{LT} \rightarrow \gamma^+\gamma^5 + (b\partial)\gamma^+\gamma^5 + \ldots \sim O(b^0) + O(b^1) + \ldots$$

$$\text{NLT} \rightarrow \gamma_T^\mu\gamma^5 \sim O(b^1) + \ldots$$



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Parton-in-parton:

Global phase $e^{iub\cdot p_T} = 1 + iub \cdot p_T + \ldots$

Projector $\gamma^5\gamma^\alpha P_\alpha = \gamma^5\gamma^- p^+ + \gamma^5\gamma_T^\alpha p_{T,\alpha} + \gamma^5\gamma^+ p^-$

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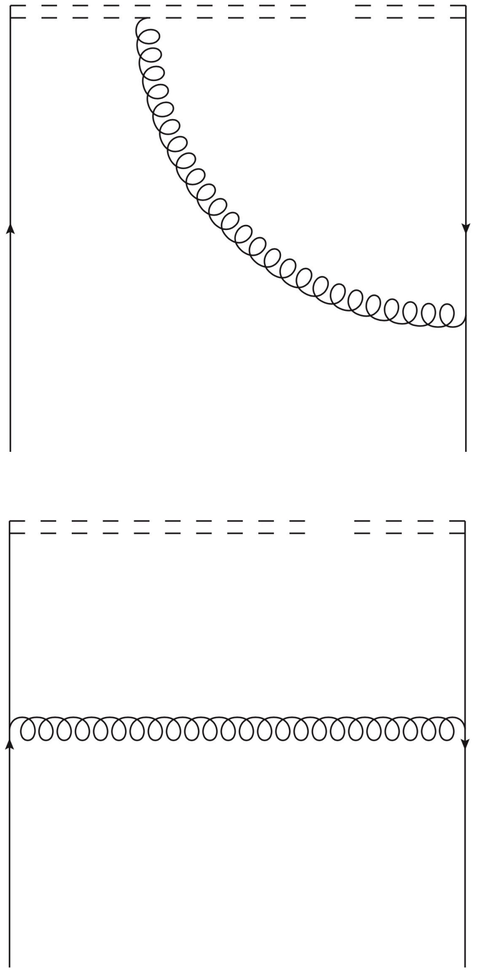

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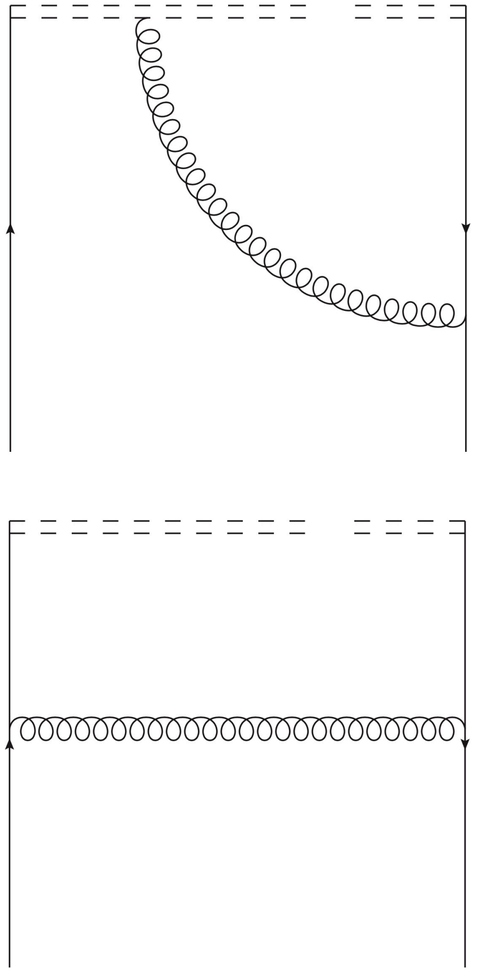
$$\text{LT} \rightarrow O(b^0) + O(b^1) + \ldots$$

$$\text{NLT} \rightarrow O(b^1) + \ldots$$

$$O(b^0) \sim tw2 \rightarrow g_1$$

$$O(b^1) \sim tw2 + tw3 \rightarrow g_{1T}$$



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Validation: quark worm-gears (one-loop)

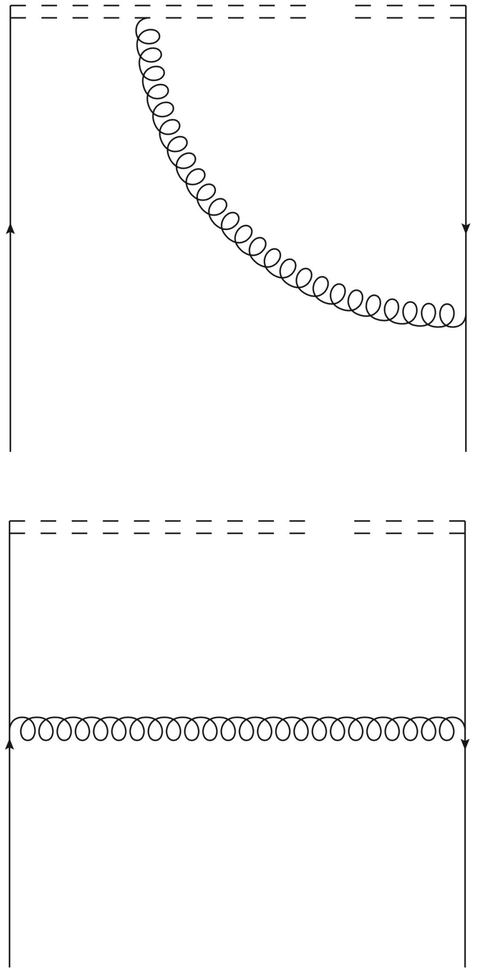
Comparison with position-space computation
(Feynman gauge)

For each diagram:

LT $\rightarrow$ LP + NLP

NLT $\rightarrow$ LP

Exact correspondence!



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Formalization

Guess: $i\,p_T^\mu \rightarrow$ tree-level matching

Formalization

Guess: $i\,p_T^\mu \to$ tree-level matching

$$p_T^\mu \to -\,i\,\partial_T^\mu(0) \Longrightarrow e^{ib\cdot p_T} \to e^{b\cdot\partial_T(0)}$$

$$\Phi_i(x,b) = \int_0^1 du \int dy\,\delta(x-uy)\,\sum\nolimits_j C_{ij}(u)\,\left(e^{b\cdot\partial_T(0)}\,\Phi_j(y,b)\right)$$

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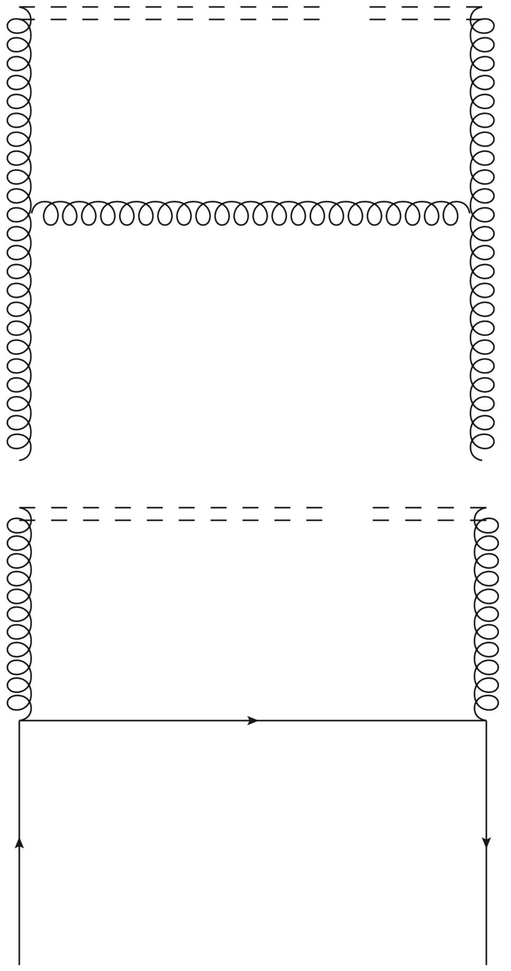
Gluon results

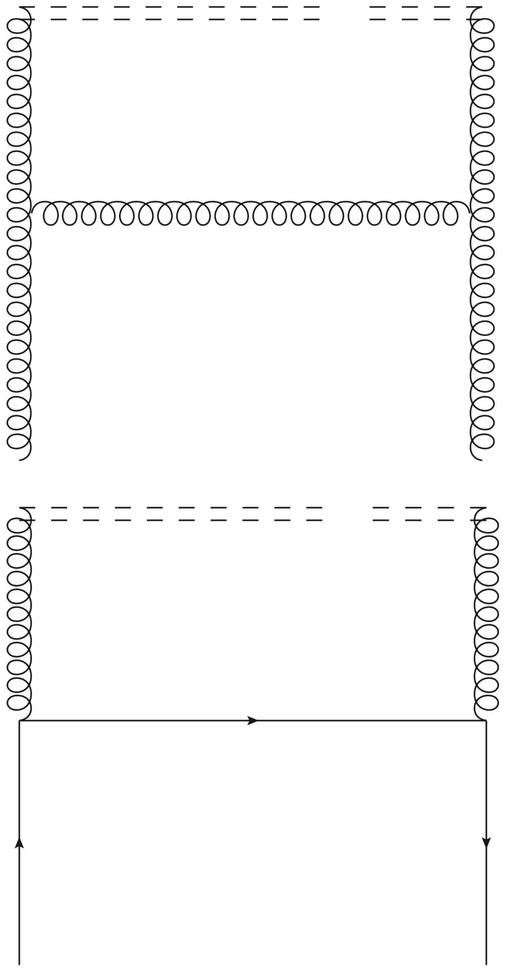
Light-cone gauge



Gluon results

Light-cone gauge

Recover known results



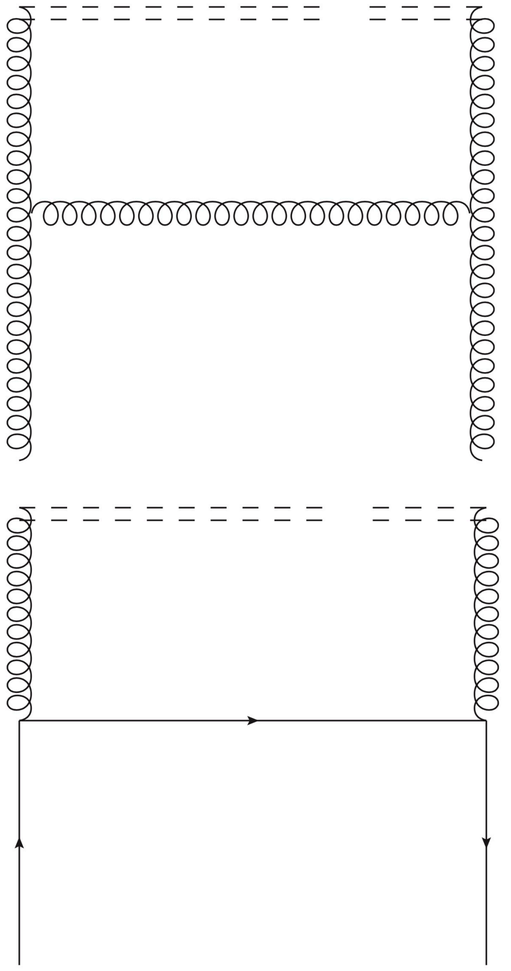
Gluon results

Light-cone gauge

Recover known results

Wandzura-Wilczek for the $g_{1T}^{\perp,g}$:

$$g_{1T}^{\perp,g}(x,b) = \int_0^1 du \int dy\, \delta(x-uy)$$
$$\times \left\{ 4\, C_{gg}(\mu^2, b^2, \epsilon)\, u \left(\Delta p_{gg} + 2\epsilon(1-u) \right) \left(-y g_T^g(y) \right) \right.$$
$$\left. +2\, C_{gq}(\mu^2, b^2, \epsilon)\, u \left(\Delta p_{gq} + 2\epsilon(1-u) \right) \left(y g_T^q(y) \right) \right\}$$



Results and simple extensions

Parton-in-parton method for higher twist

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Results and simple extensions

Parton-in-parton method for higher twist

Extension to higher-loops

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Results and simple extensions

Parton-in-parton method for higher twist

Extension to higher-loops

Extension to GTMDs

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Conclusions

Summary

Distribution	Tw2	Tw3	Accuracy
f_1^g	$f_g\,, f_1$	-	$\mathrm{N^3LO}$
$h_1^{\perp g}$	$f_g\,, f_1$	-	$\mathrm{N^3LO}$
g_{1L}^g	$\Delta f_g\,, g_1$	-	$\mathrm{N^3LO}$
g_{1T}^g	$\Delta f_g\,, g_1$	$\mathcal{G}_g\,, \mathcal{G}_q$	NLO/LO
$f_{1T}^{\perp g}$	-	$2F_2^+ + F_4^+$	LO
h_{1T}^g	-	$2F_2^+ - 2F_4^+$	LO
$h_{1L}^{\perp g}$	-	$2F_2^+ - 2F_4^+$	LO
$h_{1T}^{\perp g}$	-	-	LO

Outlook

Inclusion of higher-twist PDFs

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Outlook

Inclusion of higher-twist PDFs

Inclusion of T-odd effects

Outlook

Inclusion of higher-twist PDFs

Inclusion of T-odd effects

Inclusion of mass corrections

Outlook

Inclusion of higher-twist PDFs

Inclusion of T-odd effects

Inclusion of mass corrections

Extension of higher-twist TMDs