Exploring twist-3 PDFs

$g_T(x) \quad e(x) \quad h_L(x)$

in lattice QCD using Quasi-PDF approach

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Outline

- Brief Overview of twist-3 PDFs
- Quasi-PDF approach
- Matching for the twist-3 PDFs
- BC-type sum rules for light-cone & quasi-PDFs
- Summary

Brief Overview of twist-3 PDFs

Twist-2 PDFs

Order of contribution: $\mathcal{O}(1)$

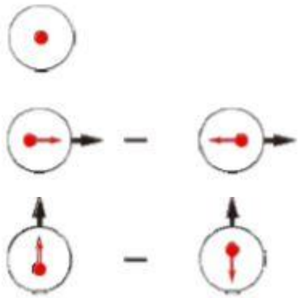
PDFs	Dirac structure
$f_1(x)$	$\Gamma = \gamma^+$
$g_1(x)$	$\Gamma = \gamma^+\gamma_5$
$h_1(x)$	$\Gamma = i\sigma^{i+}\gamma_5$

Density interpretation:

$f_1(x)$

$g_1(x)$

$h_1(x)$



Twist-3 PDFs

Order of contribution: $\mathcal{O}(1/\mathrm{Q})$

Jaffe, Ji (PRL 67, 552)/ Jaffe, Ji (Nucl. Phys. B 375, 527)

PDFs	Dirac structure
$e(x)$	$\Gamma = 1$
$g_T(x)$	$\Gamma = \gamma_\perp^i\gamma_5$
$h_L(x)$	$\Gamma = i\sigma^{+-}\gamma_5$

No density interpretation:

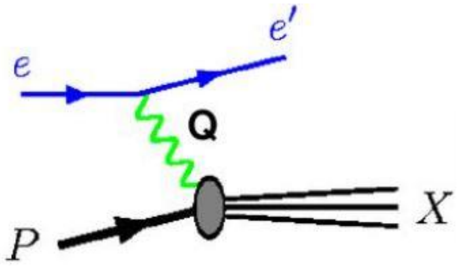
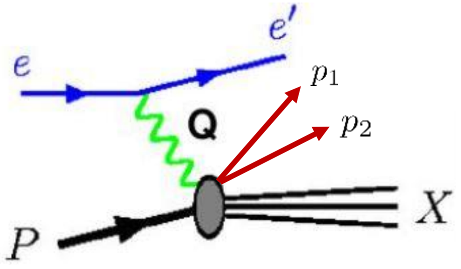
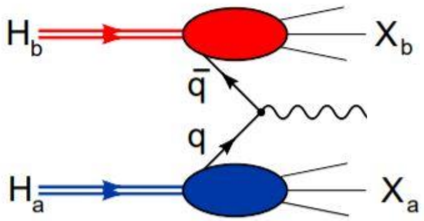
Burkardt (arXiv: 0810.3589)

$\int dx\, x^2 g_T(x) \rightarrow \perp$ **force**

$\int dx\, x^2 e(x) \rightarrow \perp$ **force**

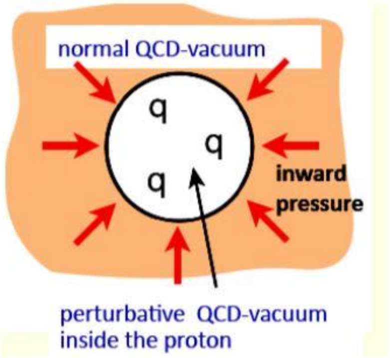
Brief Overview of twist-3 PDFs

Processes sensitive to twist-3 PDFs

PDFs	Processes	Data
$g_T(x)$		**For instance:** **Hall A, 2016/** **Hall C, 2018**
$e(x)$		**For instance:** **Preliminary CLAS data (2014)**
$h_L(x)$		**None**

Brief Overview of twist-3 PDFs

Some model studies of twist-3 PDFs (not exhaustive)

PDFs	Model & $\delta(x)$?		
$e(x)\;\; h_L(x)$	 $\cancel{\delta(x)}$ **Jaffe, Ji, 1991**	χ**QSM** $\delta(x)\quad (e(x))$ **Ohnishi, Wakamatsu, 2003**	 $\cancel{\delta(x)}$ **Jakob, et. al, 1997** $\delta(x)$ **Burkardt, Aslan, 2018**
$g_T(x)$			$\cancel{\delta(x)}$ **Jakob, et. al, 1997** $\delta(x)$ **Burkardt, Aslan, 2018**

Quasi-PDF approach

Light-cone (standard) correlator

$$F^{[\Gamma]}(x) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ik\cdot z} \times \langle p|\bar{\psi}(-\tfrac{z}{2})\,\Gamma\,\mathcal{W}(-\tfrac{z}{2},\tfrac{z}{2})\psi(\tfrac{z}{2})|p\rangle\Big|_{z^+=\vec{z}_\perp=0}$$

- **Time dependence :** $z^0 = \frac{1}{\sqrt{2}}(z^+ + z^-) = \frac{1}{\sqrt{2}}z^-$
- **Cannot be computed on Euclidean lattice**

Quasi-PDF approach

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Correlator for quasi-PDFs (Ji, 2013)

$$F_{\mathrm{Q}}^{[\Gamma]}(x;P^3) = \frac{1}{2}\int \frac{dz^3}{2\pi} e^{ik\cdot z} \times \langle p|\bar{\psi}(-\tfrac{z}{2})\,\Gamma\,\mathcal{W}_{\mathrm{Q}}(-\tfrac{z}{2},\tfrac{z}{2})\psi(\tfrac{z}{2})|p\rangle\Big|_{z^0=\vec{z}_\perp=0}$$

- **Non-local correlator depending on position** z^3
- **Can be computed on Euclidean lattice**

- **Quasi-PDF approach made it possible to directly extract light-cone PDFs from lattice QCD**

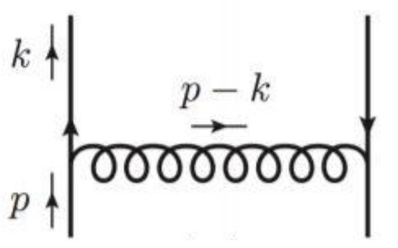
<u>Quasi-PDF approach</u>

Light-cone (standard) correlator	**Correlator for quasi-PDFs (Ji, 2013)**
$$F^{[\Gamma]}(x) = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ik\cdot z} \times \langle p\vert\bar{\psi}(-\tfrac{z}{2})\,\Gamma\,\mathcal{W}(-\tfrac{z}{2},\tfrac{z}{2})\psi(\tfrac{z}{2})\vert p\rangle\Big\vert_{z^+=\vec{z}_\perp=0}$$	$$F_{\mathrm{Q}}^{[\Gamma]}(x;P^3) = \frac{1}{2}\int \frac{dz^3}{2\pi} e^{ik\cdot z} \times \langle p\vert\bar{\psi}(-\tfrac{z}{2})\,\Gamma\,\mathcal{W}_{\mathrm{Q}}(-\tfrac{z}{2},\tfrac{z}{2})\psi(\tfrac{z}{2})\vert p\rangle\Big\vert_{z^0=\vec{z}_\perp=0}$$
• **Time dependence :** $z^0 = \frac{1}{\sqrt{2}}(z^+ + z^-) = \frac{1}{\sqrt{2}} z^-$ • **<u>Cannot</u> be computed on Euclidean lattice**	• **Non-local correlator depending on position** z^3 • **<u>Can</u> be computed on Euclidean lattice**

- **Quasi-PDF approach made it possible to directly extract light-cone PDFs from lattice QCD**
- **By now, enormous progress has taken place: Extraction of twist-2 PDFs, twist-2 GPDs, …**
- **Other Euclidean approaches: Pseudo-PDF (Radyushkin, 2017), current-current correlators (Ma, Qiu, 2014) …**

Quasi-PDF approach

Sample calculations for twist-2 PDF f_1 in Quark Target Model (QTM)



Quasi-PDF approach

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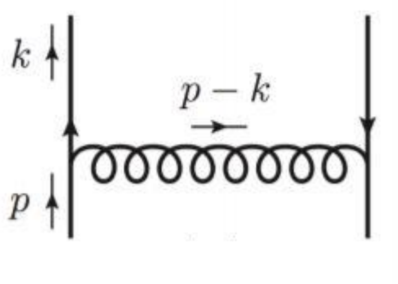

$$f_1(x) = -\frac{ig^2 C_F \mu^{2\epsilon} g_{\mu\nu}}{4} \int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\overline{u}\,\gamma^\nu\,(\not{k}+m_q)\,\gamma^+\,(\not{k}+m_q)\,\gamma^\mu\right]}{(k^2 - m_q^2 + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)}\,\delta\left(x - \frac{k^+}{p^+}\right)\frac{1}{p^+}$$

Quasi-PDF approach

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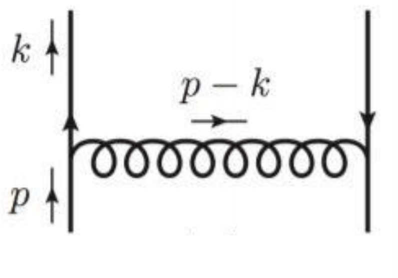

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Quasi-PDF approach

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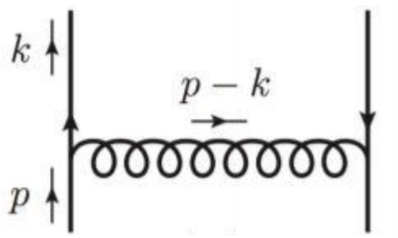

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Quasi-PDF approach

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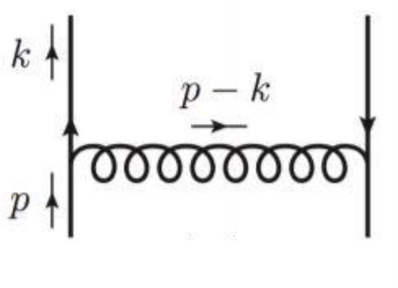

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- $\int dk^- \rightarrow$ Residue theorem
- Perform $\int d^2 k_\perp$

$$\boxed{f_1(x) = \frac{\alpha_s C_F}{2\pi}(1-x)\left(\mathcal{P}_{\mathrm{UV}} + \ln\frac{\mu^2}{x m_g^2} - 2\right)}$$

$$\mathcal{P}_{\mathrm{UV}} = \frac{1}{\epsilon_{\mathrm{UV}}} + \ln 4\pi - \gamma_E$$

$$\int_0^\infty dk_\perp$$

Quasi-PDF approach

Sample calculations for twist-2 PDF f_1 in Quark Target Model (QTM)

What if I calculate f_1 , with, a completely spatial correlator & with γ^3 in the Infinite Momentum Frame (IMF)?

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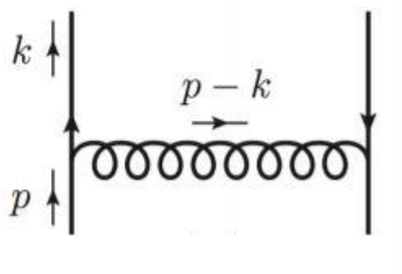

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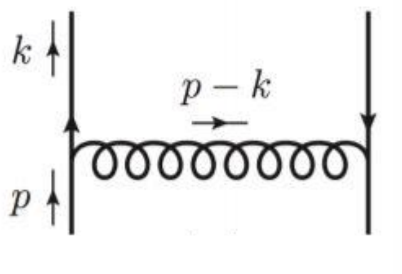

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- $k \to (k^0,\, k_\perp,\, k^3)$

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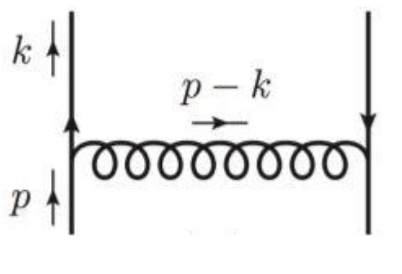

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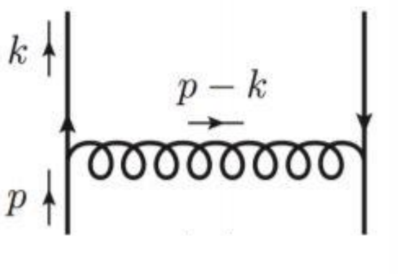

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- $\int dk^0 \to$ Residue theorem
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Quasi-PDF approach

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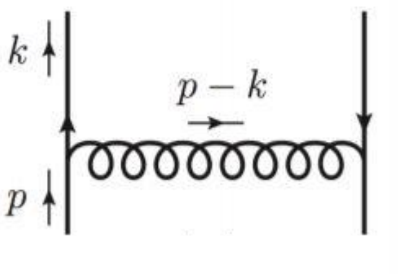

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$$\int_0^\infty dk_\perp$$

$$\boxed{f_1(x) = \frac{\alpha_s C_F}{2\pi}(1-x)\left(\mathcal{P}_{\mathrm{UV}} + \ln\frac{\mu^2}{x\boldsymbol{m_g^2}} - 2\right)}$$

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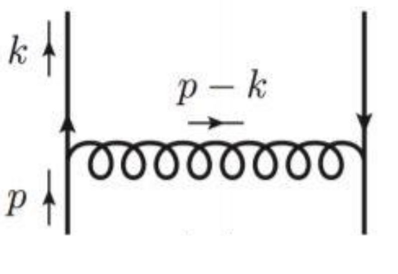

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Unfortunately, this cannot be calculated on lattice

Quasi-PDF approach

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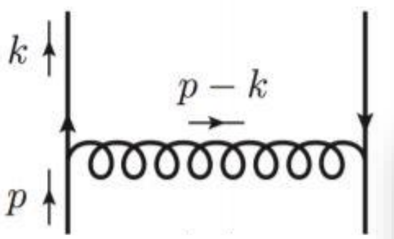

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What if I keep p^3 finite & repeat this calculation?

- $\int dk^0 \to$ Residue theorem
- Take $p^3 \to \infty$
- Perform $\int d^2 k_\perp$

$\int_{\mathbf{0}}^{\boldsymbol{\infty}} dk_\perp$

$$\boxed{f_1(x) = \frac{\alpha_s C_F}{2\pi}(1-x)\left(\mathcal{P}_{\mathrm{UV}} + \ln\frac{\mu^2}{x\boldsymbol{m_g^2}} - 2\right)}$$

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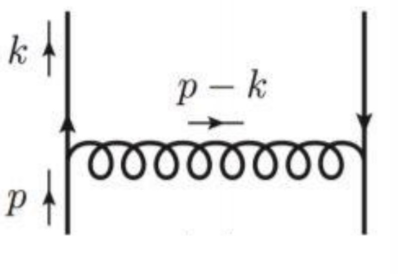
What if I calculate f_1 , with, a completely spatial correlator & with γ^3 & keeping p^3 finite?



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- Keeping p^3 finite, perform $\int d^2k_\perp$

$$f_1(x,p^3) = \frac{\alpha_s C_F}{2\pi}\begin{cases} (1-x)\,\ln\dfrac{x}{x-1}+1 & x>1 \\ (1-x)\,\ln\dfrac{4(1-x)p_3^2}{m_g^2}+x & 0<x<1 \\ (1-x)\,\ln\dfrac{x-1}{x}-1 & x<0 \end{cases}$$

Quasi-PDF approach

Sample calculations for twist-2 PDF f_1 in Quark Target Model (QTM)

What if I calculate f_1, with, a completely spatial correlator & with γ^3 & keeping p^3 finite?

Support outside "physical" region $0 < x < 1$

$$\int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\bar{u}\,\gamma^\nu\,(\not{k}+\cancel{m_q})\,\gamma^3\,(\not{k}+\cancel{m_q})\,\gamma^\mu\right]}{(k^2-\cancel{m_q^2}+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}\,\delta\!\left(x-\frac{\boldsymbol{k^3}}{\boldsymbol{p^3}}\right)\frac{1}{\boldsymbol{p^3}}$$

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$\int_{0}^{\infty} dk_\perp$

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Support outside "physical" region $0 < x < 1$

$$\int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\bar{u}\,\gamma^\nu\,(\not{k} + \cancel{m_q})\,\gamma^3\,(\not{k} + \cancel{m_q})\,\gamma^\mu\right]}{(k^2 - \cancel{m_q^2} + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)}\,\delta\!\left(x - \frac{k^3}{p^3}\right)\frac{1}{p^3}$$

- Keeping p^3 finite, perform $\int d^2 k_\perp$

$$f_1(x) = \frac{\alpha_s C_F}{2\pi}(1-x)\left(\mathcal{P}_{\mathrm{UV}} + \ln\frac{\mu^2}{x m_g^2} - 2\right)$$

$$f_1(x, p^3) = \frac{\alpha_s C_F}{2\pi}\begin{cases} (1-x)\,\ln\dfrac{x}{x-1} + 1 & x > 1 \\ (1-x)\,\ln\dfrac{4(1-x)p_3^2}{m_g^2} + x & 0 < x < 1 \\ (1-x)\,\ln\dfrac{x-1}{x} - 1 & x < 0 \end{cases}$$

$\int_0^\infty dk_\perp$

Quasi-PDF approach

Sample calculations for twist-2 PDF f_1 in Quark Target Model (QTM)

What if I calculate f_1, with, a completely spatial correlator & with γ^3 & keeping p^3 finite?

Support outside "physical" region $0 < x < 1$

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UV-finite!

$$\int_0^\infty dk_\perp$$

Quasi-PDF approach

Sample calculations for twist-2 PDF f_1 in Quark Target Model (QTM)

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Divergences will manifest after we integrate over x

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$$\int_{\boldsymbol{0}}^{\boldsymbol{\infty}} dk_\perp$$

Quasi-PDF approach

IR singularities of quasi-PDFs & light-cone PDFs are same

What if I calculate f_1, with, a completely spatial correlator & with γ^3 & keeping p^3 finite?

Support outside "physical" region $0 < x < 1$

$$\int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\bar{u}\,\gamma^\nu\,(\not{k} + \cancel{m_q})\,\gamma^3\,(\not{k} + \cancel{m_q})\,\gamma^\mu\right]}{(k^2 - \cancel{m_q^2} + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)}\,\delta\!\left(x - \frac{k^3}{p^3}\right)\frac{1}{p^3}$$

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$\int_0^\infty dk_\perp$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

- **Matching formula**

$$q_{\mathrm{Q}}(x;P^3) = \int_{-1}^{+1} \frac{d\,y}{|y|} C\left(\frac{x}{y}\right) q(y) + \mathcal{O}\left(\frac{M^2}{(P^3)^2}\right)$$

(Scale dependence omitted)

(Xiong, Ji, Zhang, Zhao, 2013/ Stewart, Zhao, 2017/ Izubuchi, Ji, Jin, Stewart, Zhao, 2018/ Ma, Qiu (2018)/ Chen, Wang, Zhu (2020)/ Li, Ma, Qiu (2020))

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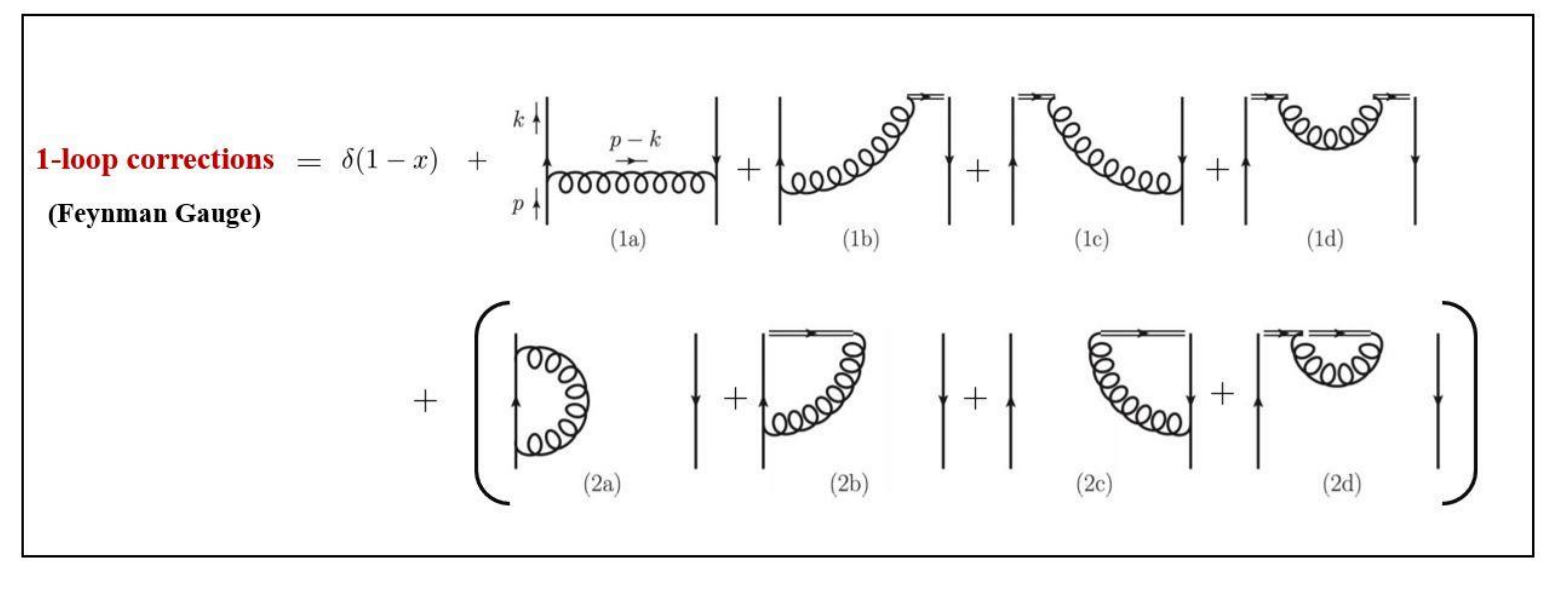
- **One-loop matching coefficient**

$$C(x; P^3) = \delta(1-x) + \frac{\alpha_s C_F}{2\pi} \left[q_{\mathrm{Q}}(x; P^3) - q(x) \right]$$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

- **Matc**



, 2017/

- **One-**

- **Set up for our calculation**

i. **Feynman Gauge**

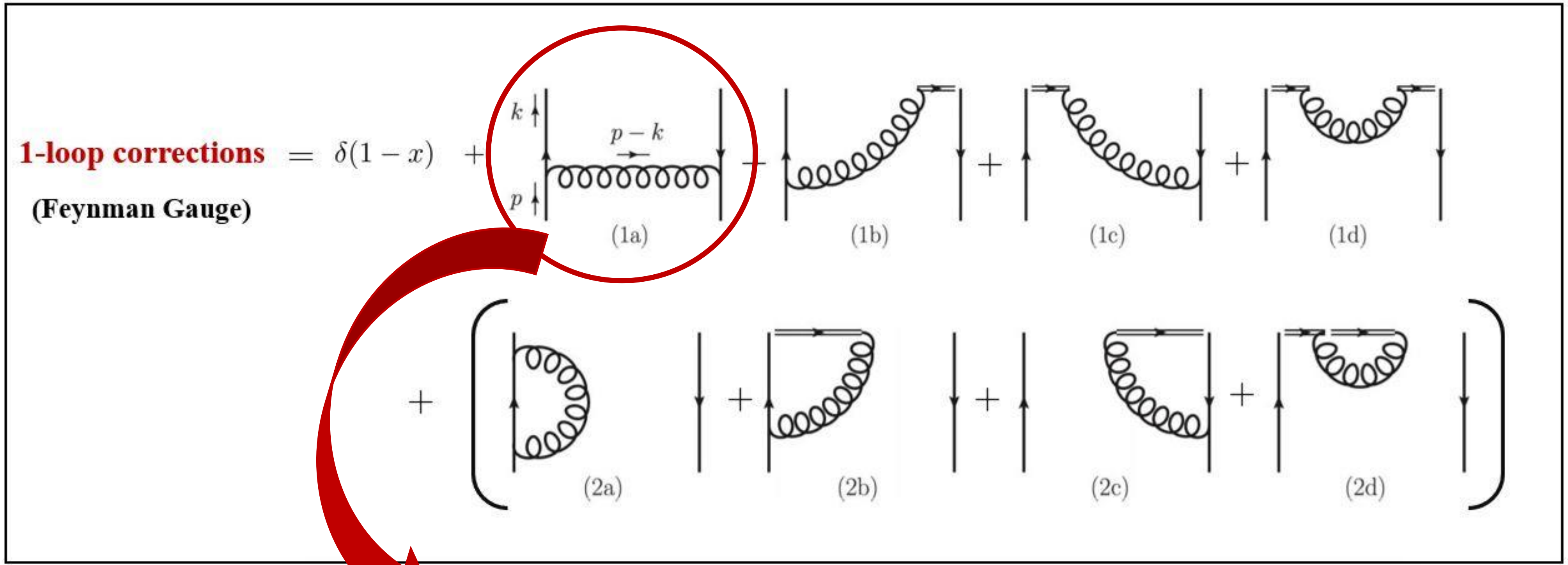
ii. **UV :** $\int^{\infty} d^2k_\perp \longrightarrow \epsilon_{\rm UV}$

iii. **IR :** $\int_0 d^2k_\perp \longrightarrow \begin{cases} m_q \neq 0 \\ \epsilon_{\rm IR} \\ m_g \neq 0 \end{cases}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

- Matc



, 2017/

- One-

Ladder diagram: Origin of new features at twist-3

- Set up for our calculatio

i. Feynman Gauge

ii. UV : $\int^{\infty} d^2k_\perp \longrightarrow \epsilon_{\text{UV}}$

iii. IR : $\int_0 d^2k_\perp \longrightarrow \begin{cases} m_q \neq 0 \\ \epsilon_{\text{IR}} \\ m_g \neq 0 \end{cases}$

<u>Case 1</u>: g_T & $g_{T,\mathbf{Q}}$

Matching for twist-3 PDF $g_T(x)$

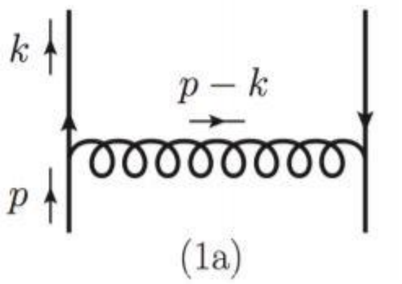
SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_T(x)$

Definition: $$\frac{M}{P^+} S_\perp^i \, g_T(x) = \Phi^{[\gamma^i \gamma_5]}$$

Hadron attributes: $(M,\, S_\perp^i,\, P^+)$

Quark Target Model (QTM)



$$\boxed{\frac{m_q}{p^+} s_\perp^i \, g_T^{(1a)}(x) = -\frac{ig^2 C_F \mu^{2\epsilon} g_{\mu\nu}}{4} \int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\bar{u}\,\gamma^\nu\,(\not{k}+m_q)\,\gamma^i\gamma_5\,(\not{k}+m_q)\,\gamma^\mu\right]}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}\,\delta\!\left(x-\frac{k^+}{p^+}\right)\frac{1}{p^+}}$$

- **One <u>cannot</u> set** m_q **to zero at the start in QTM calculations**
- **Extract linear terms in** m_q **& then set** $m_q = 0$ **, unless it is used as the IR regulator**

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_T(x)$

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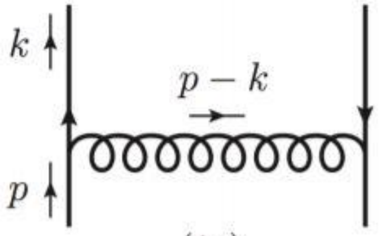
$\downarrow$ **Quark Target Model (QTM)**



(1a)

$$\boxed{\frac{m_q}{p^+} s_\perp^i \, g_T^{(1a)}(x) = -\frac{ig^2 C_F \mu^{2\epsilon} g_{\mu\nu}}{4} \int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\bar{u}\,\gamma^\nu\,(\not{k} + m_q)\,\gamma^i \gamma_5\,(\not{k} + m_q)\,\gamma^\mu\right]}{(k^2 - m_q^2 + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)}\,\delta\!\left(x - \frac{k^+}{p^+}\right)\frac{1}{p^+}}$$

$\downarrow$ **Trace algebra** $\Big|_{n=4-2\epsilon}$

$$g_T^{(1a)}(x) = -\frac{ig^2 C_F \mu^{2\epsilon}}{(2\pi)^n} p^+ \int_{-\infty}^{\infty} d^{n-2}k_\perp dk^- dk^+ \frac{2p^+k^- + \ldots}{(k^2 - m_q^2 + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)}\,\delta\!\left(x - \frac{k^+}{p^+}\right)\frac{1}{p^+}$$

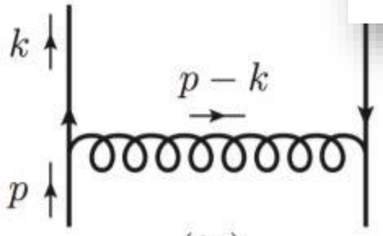
Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_T(x)$

Definition:

Twist-2	Twist-3
Numerator independent of k^-	Numerator has one power of k^-



(1a)

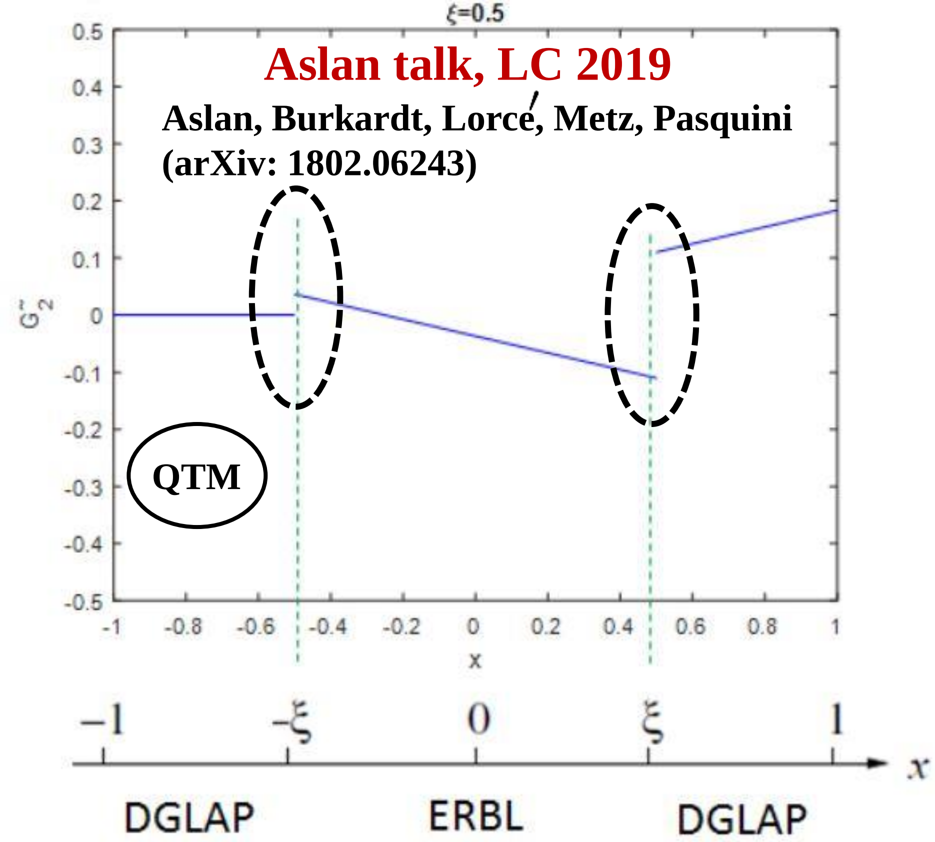
$$\boxed{\frac{m_q}{p^+}\, s_\perp^i\, g_T^{(1a)}(x) = -\frac{ig^2 C_F \mu^{2\epsilon} g_{\mu\nu}}{4} \int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\bar{u}\,\gamma^\nu\,(\not{k}+m_q)\,\gamma^i\gamma_5\,(\not{k}+m_q)\,\gamma^\mu\right]}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}\,\delta\!\left(x-\frac{k^+}{p^+}\right)\frac{1}{p^+}}$$

Trace algebra $\Big|_{n=4-2\epsilon}$

$$g_T^{(1a)}(x) = -\frac{ig^2 C_F \mu^{2\epsilon}}{(2\pi)^n}\, p^+ \int_{-\infty}^{\infty} d^{n-2}k_\perp\, dk^-\, dk^+ \,\frac{2p^+k^- + \ldots}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}\,\delta\!\left(x-\frac{k^+}{p^+}\right)\frac{1}{p^+}$$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)



...	Twist-3
...ent of k^-	Numerator has one power of k^-

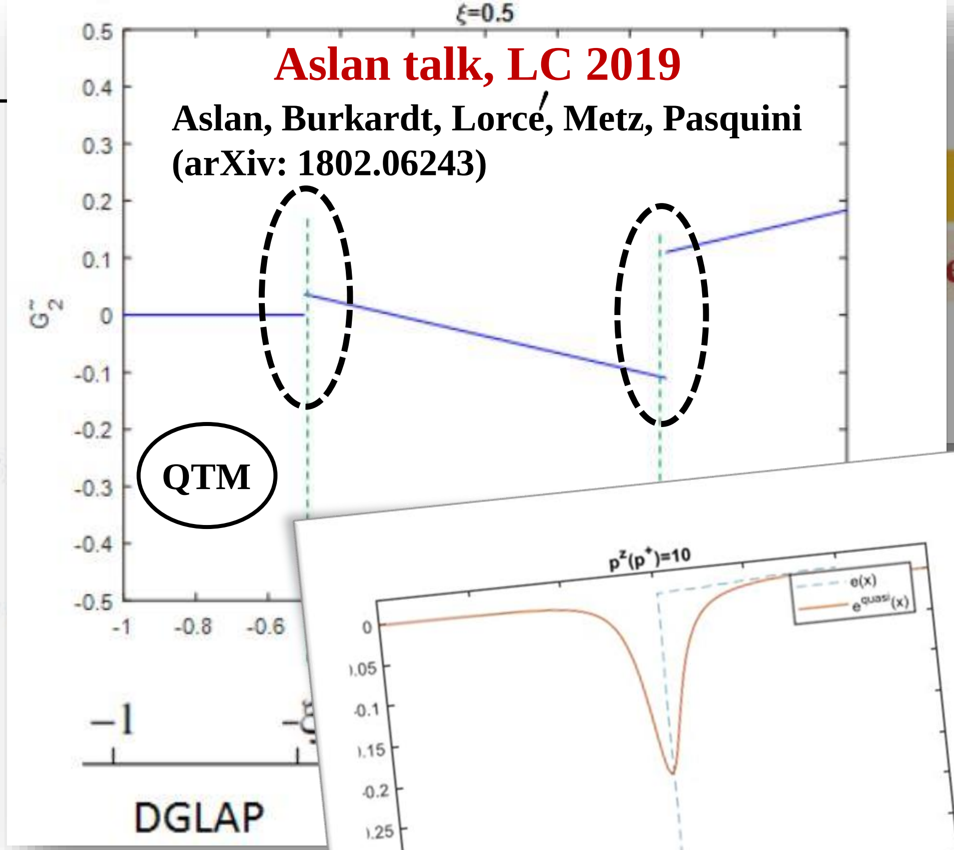
$$\ldots_F\,\mu^{2\epsilon} g_{\mu\nu} \over 4 \int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\bar{u}\,\gamma^{\nu}\,(\not{k}+m_q)\,\gamma^{i}\gamma_5\,(\not{k}+m_q)\,\gamma^{\mu}\right]}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}\,\delta\!\left(x-\frac{k^+}{p^+}\right)\frac{1}{p^+}$$

$$\ldots n=4-2\epsilon$$

$$g_T^{(1a)}(x) = -\frac{ig^2 C_F \mu^{2\epsilon}}{(2\pi)^n} p^+ \int_{-\infty}^{\infty} d^{n-2}k_\perp dk^- dk^+ \frac{2p^+k^- + \ldots}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}\,\delta\!\left(x-\frac{k^+}{p^+}\right)\frac{1}{p^+}$$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)



	Twist-3
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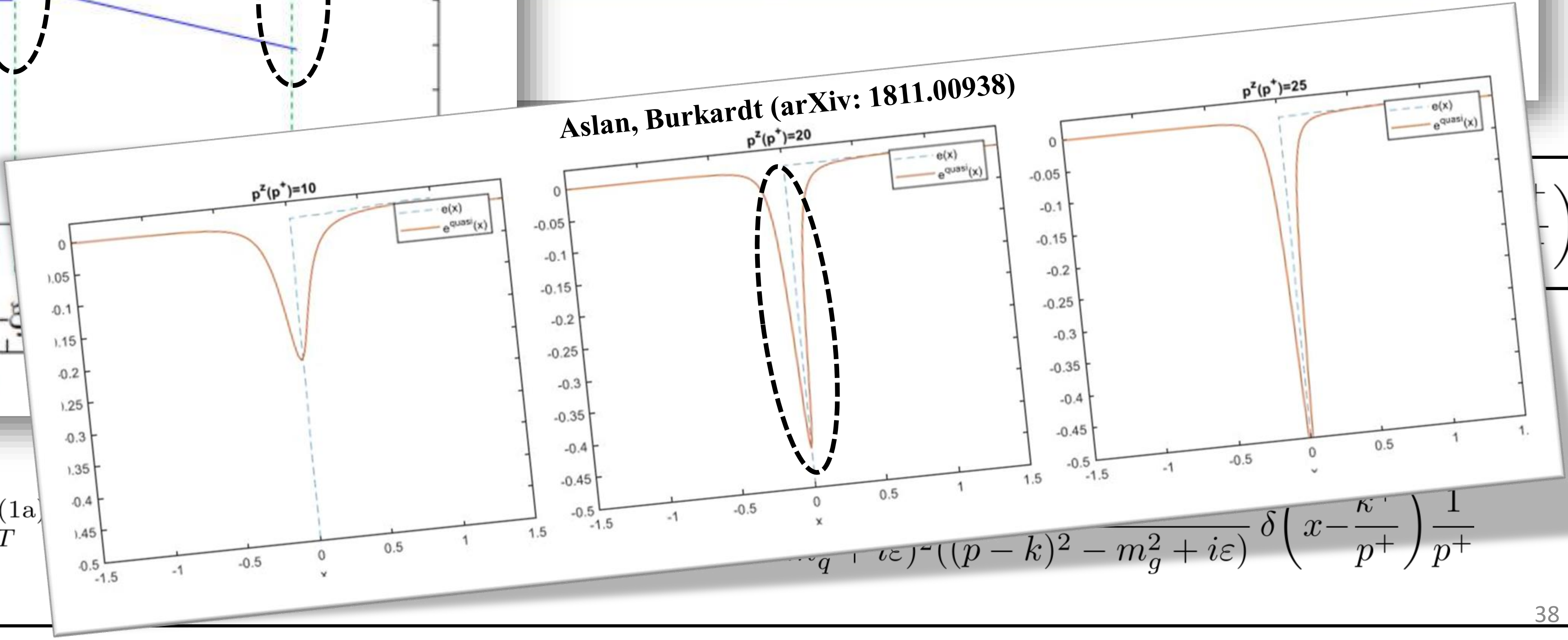

$$g_T^{(1a)} \ldots ((p-k)^2 - m_g^2 + i\varepsilon)} \delta\left(x - \frac{k^+}{p^+}\right) \frac{1}{p^+}$$

Close look …

Term: $$\frac{2p^+k^-}{(k^2 - m_q^2 + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)}$$

i. Cancellation of gluon propagator:

$$\frac{2p^+k^-}{(k^2 - m_q^2 + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)} \xrightarrow{k^- = -\frac{(p-k)^2 - m_g^2}{2(1-x)p^+} - \frac{(k_\perp^2 + m_g^2)}{2(1-x)p^+} + \frac{m_q^2}{2p^+}}$$

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Singular term

$$+$$

$$\frac{1}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}$$

Canonical term

Close look …

Term: $$\frac{2p^+k^-}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}$$

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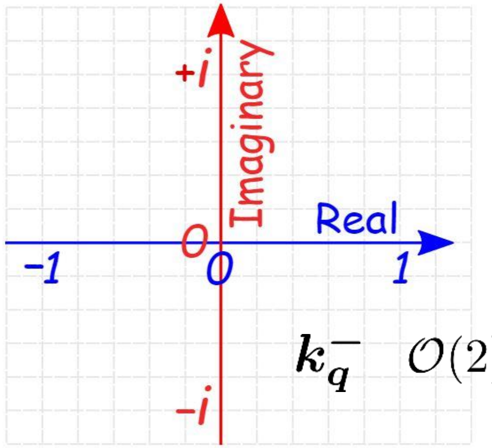
Singular term

ii. Result after $\int dk^-$: Yan (Phys. Rev. D 7, 1780)/ Burkardt (arXiv: 9505226)/ Aslan, Burkardt (arXiv: 1811.00938) …



k_q^- $\mathcal{O}(2)$

Close look …

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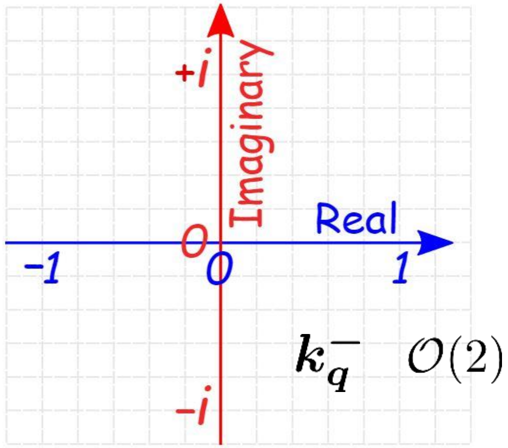

$$\int_{-\infty}^{\infty} \frac{dk^-}{(k^2-m_q^2+i\varepsilon)^2}$$

Close look …

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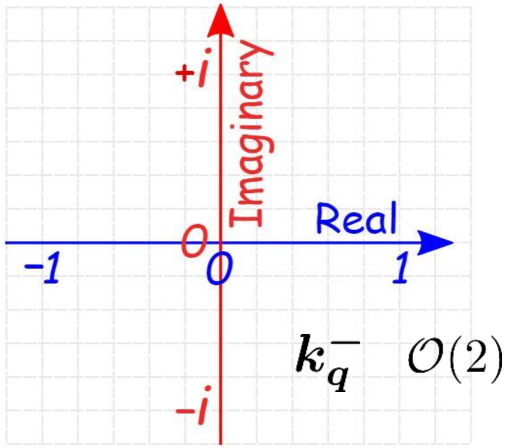

$$\int_{-\infty}^{\infty} \frac{dk^-}{(k^2-m_q^2+i\varepsilon)^2} = \begin{cases} \boldsymbol{k^+ \neq 0} : \quad \int_{-\infty}^{\infty} \frac{dk^-}{(2k^+k^- - k_\perp^2 - m_q^2 + i\varepsilon)^2} = 0 \\ \\ \end{cases}$$

Close look …

Term: $$\frac{2p^+k^-}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}$$

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Singular term

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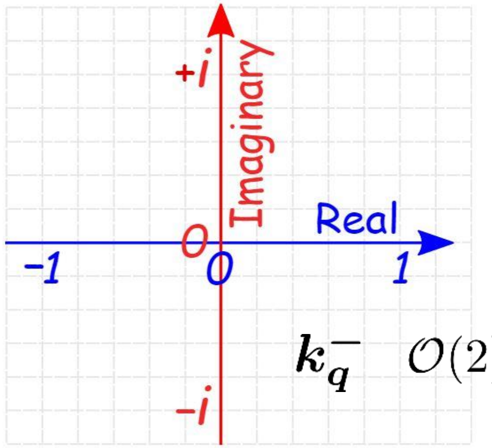

$\boldsymbol{k_q^-}$ $\quad\mathcal{O}(2)$

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Close look …

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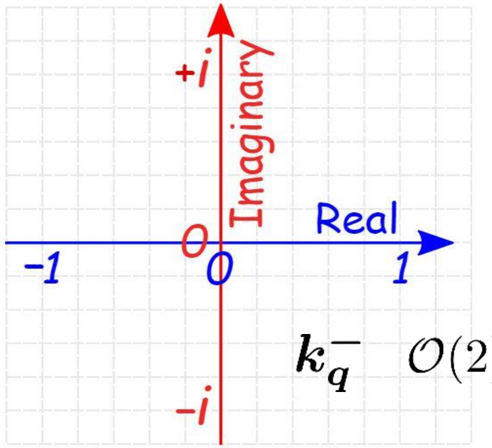

k_q^- $\mathcal{O}(2)$

$$\int_{-\infty}^{\infty} \frac{dk^-}{(k^2-m_q^2+i\varepsilon)^2} = \begin{cases} \boldsymbol{k^+ \neq 0}: & \int_{-\infty}^{\infty} \frac{dk^-}{(2k^+k^- - k_\perp^2 - m_q^2+i\varepsilon)^2} = 0 \\ \boldsymbol{k^+ = 0}: & \int_{-\infty}^{\infty} \frac{dk^-}{(k_\perp^2+m_q^2-i\varepsilon)^2} \to \text{linear divergence} \end{cases}$$

$$\boxed{\therefore \quad \int_{-\infty}^{\infty} \frac{dk^-}{(k^2-m_q^2+i\varepsilon)^2} = \frac{i\pi}{k_\perp^2+m_q^2}\,\delta(k^+)}$$

Zero modes

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Close look at singular term

Result after $\int d^{\,n-2}k_\perp$ **:** $g_{T(\mathrm{s})}^{(1a)}(x) = -\alpha_s C_F \delta(x)\,(4-n)\,\mu^{2\epsilon} \int \frac{d^{\,n-2}k_\perp}{(2\pi)^{n-2}} \frac{1}{(k_\perp^2 + m_q^2)}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

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i. $m_q \neq 0$

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Result after $\int d^{n-2}k_\perp$ **:** $g_{T(\mathrm{s})}^{(1a)}(x) = -\alpha_s C_F \delta(x) \underbrace{(4-n)}_{\propto\, \epsilon_{\mathrm{UV}}} \mu^{2\epsilon} \underbrace{\int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \frac{1}{(k_\perp^2 + m_q^2)}}_{\propto\, \frac{1}{\epsilon_{\mathrm{UV}}}}$

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i. $m_q \neq 0$	$g_{T(\mathrm{s})}^{(1a)}\big\vert_{m_q\neq 0} = -\frac{\alpha_s C_F}{2\pi}\delta(x)$

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i. $m_q \neq 0$	$g_{T(\mathrm{s})}^{(1a)}\big\vert_{m_q\neq 0} = -\frac{\alpha_s C_F}{2\pi}\delta(x)$
ii. ϵ_{IR}	

Matching for twist-3 PDF $g_T(x)$

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$$\delta(x)\,\epsilon_{\mathrm{UV}}\,\frac{1}{\epsilon_{\mathrm{UV}}} - \delta(x)\,\epsilon_{\mathrm{IR}}\,\frac{1}{\epsilon_{\mathrm{IR}}}$$

i. $m_q \neq 0$	$g_{T(\mathrm{s})}^{(1a)}\big\vert_{m_q \neq 0} = -\frac{\alpha_s C_F}{2\pi}\delta(x)$
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i. $m_q \neq 0$	$g_{T(\mathrm{s})}^{(1a)}\big\vert_{m_q\neq 0} = -\frac{\alpha_s C_F}{2\pi}\delta(x)$
ii. ϵ_{IR}	$g_{T(\mathrm{s})}^{(1a)}\big\vert_{\epsilon_{\mathrm{IR}}} = 0$

- **IR dependence of zero modes**

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Close look at singular term

Result after $\int d^{n-2}k_\perp$ **:** $g_{T(\mathrm{s})}^{(1a)}(x) = -\alpha_s C_F \delta(x)\,(4-n)\,\mu^{2\epsilon}\int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}}\frac{1}{(k_\perp^2+m_q^2)}$

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- **IR dependence of zero modes**

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iii. $m_g \neq 0$	

- **IR dependence of zero modes**
- **Working with $m_g \neq 0$ is an issue at twist-3:** **IR divergence unattended for the singular term! First time at twist-3!**

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Close look at singular term

Result after $\int d^{n-2}k_\perp$ **:** $g_{T(\mathrm{s})}^{(1a)}(x) = -\alpha_s C_F \delta(x)\,(4-n)\,\mu^{2\epsilon}\int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}}\frac{1}{(k_\perp^2+m_q^2)}$

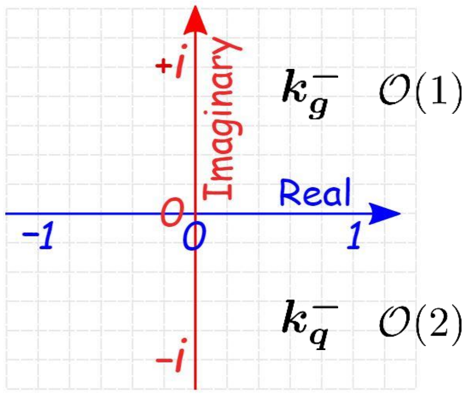
i. $m_q \neq 0$	$g_{T(\mathrm{s})}^{(1a)}\big\vert_{m_q\neq 0} = -\frac{\alpha_s C_F}{2\pi}\delta(x)$
ii. ϵ_{IR}	$g_{T(\mathrm{s})}^{(1a)}\big\vert_{\epsilon_{\mathrm{IR}}} = 0$
iii. $m_g \neq 0$	$g_{T(\mathrm{s})}^{(1a)}(x) = \begin{cases} g_{T(\mathrm{s})}^{(1a)}(x)\big\vert_{m_q\neq 0} = -\frac{\alpha_s C_F}{2\pi}\delta(x) \\ g_{T(\mathrm{s})}^{(1a)}(x)\big\vert_{\epsilon_{\mathrm{IR}}} = 0 \end{cases}$

- **IR dependence of zero modes**
- **Working with** $m_g \neq 0$ **is an issue at twist-3:** **IR divergence unattended for the singular term! First time at twist-3!**
- **Consider two practical options:**
  1. **Retain** m_q **in** $g_{T(\mathrm{s})}$
  2. **Do DR for** $\int_0 d^{n-2}k_\perp$ **in** $g_{T(\mathrm{s})}$

  However, work with $m_g \neq 0$ **for** $g_{T(\mathrm{c})}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)



Results for canonical part:

$$g_{T(\mathrm{c})}(x) \approx \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \int \frac{dk^-}{2\pi} \frac{2k^2 + 2k_\perp^2 + 2m_q^2 - (4-n)m_g^2}{(k^2 - m_q^2 + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)}$$

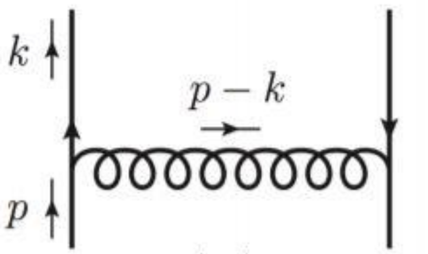
i. $m_q \neq 0$	$g_{T(\mathrm{c})}^{(1\mathrm{a})}(x)\Big\vert_{m_q} = \frac{\alpha_s C_F}{2\pi}\left(x\,\mathcal{P}_{\mathrm{UV}} + x\ln\frac{\mu_{\mathrm{UV}}^2}{(1-x)^2 m_q^2} + \frac{x^2-2x-1}{1-x}\right)$
ii. $m_g \neq 0$	$g_{T(\mathrm{c})}^{(1\mathrm{a})}(x)\Big\vert_{m_g} = \frac{\alpha_s C_F}{2\pi}\left(x\,\mathcal{P}_{\mathrm{UV}} + x\ln\frac{\mu_{\mathrm{UV}}^2}{x m_g^2} + (1-x)\right)$
iii. ϵ_{IR}	$g_{T(\mathrm{c})}^{(1\mathrm{a})}(x)\Big\vert_{\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi}\left(x\,(\mathcal{P}_{\mathrm{UV}} - \mathcal{P}_{\mathrm{IR}}) + x\ln\frac{\mu_{\mathrm{UV}}^2}{\mu_{\mathrm{IR}}^2}\right)$

$$\mathcal{P}_{\mathrm{UV/IR}} = \frac{1}{\epsilon_{\mathrm{UV/IR}}} + \ln 4\pi - \gamma_E$$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

General structure for the ladder-diagram result: LC $g_T(x)$



(1a)

$$g_T^{(1a)} = g_{T(\mathrm{s})}^{(1a)} + g_{T(\mathrm{c})}^{(1a)}$$

Singular term $\propto \delta(x)$

Canonical term

Matching for twist-3 PDF $g_T(x)$

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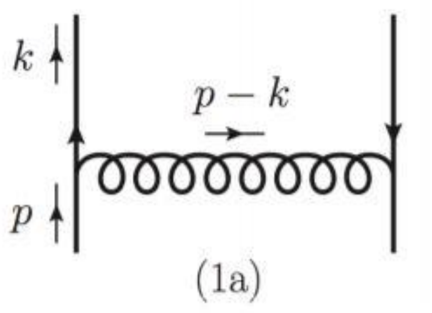


$$g_T^{(1a)} = g_{T(\mathrm{s})}^{(1a)} + g_{T(\mathrm{c})}^{(1a)}$$

Singular term $\propto \delta(x)$ **(IR scheme-dependent)**

Canonical term

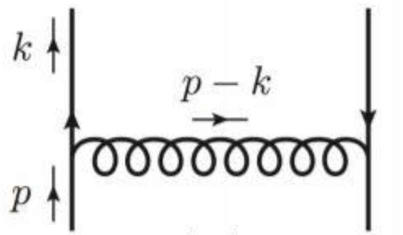
IR regulator	$\delta(x)$?
$m_q \neq 0$	✓
ϵ_{IR}	✗

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Definition: $\frac{M}{P^3} S_\perp^i \, g_{T,\mathrm{Q}}(x) = \Phi^{[\gamma^i \gamma_5]}$



(1a)

$$\boxed{\frac{m_q}{p^3} g_{T,\mathrm{Q}}^{(1a)}(x) = -\frac{ig^2 C_F \mu^{2\epsilon} g_{\mu\nu}}{4} \int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\overline{u}\,\gamma^\nu\,(\not{k}+m_q)\,\gamma^i\gamma_5\,(\not{k}+m_q)\,\gamma^\mu\right]}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}\,\delta\left(x-\frac{k^3}{p^3}\right)\frac{1}{p^3}}$$

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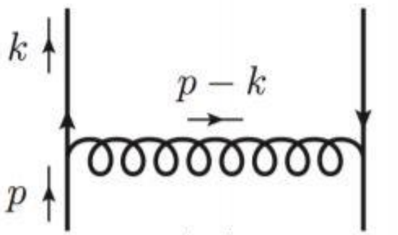


(1a)

$$\boxed{\frac{m_q}{\boldsymbol{p^3}} g_{T,\mathrm{Q}}^{(1a)}(x) = -\frac{ig^2 C_F \mu^{2\epsilon} g_{\mu\nu}}{4} \int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\overline{u}\,\gamma^\nu \,(\not{k} + m_q)\,\gamma^i\gamma_5\,(\not{k} + m_q)\,\gamma^\mu\right]}{(k^2 - m_q^2 + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)} \,\delta\!\left(x - \frac{\boldsymbol{k^3}}{\boldsymbol{p^3}}\right) \frac{1}{\boldsymbol{p^3}}}$$

$g_{T,\mathrm{Q(s)}}^{(1a)}$

Split into singular & canonical parts

$g_{T,\mathrm{Q(c)}}^{(1a)}$

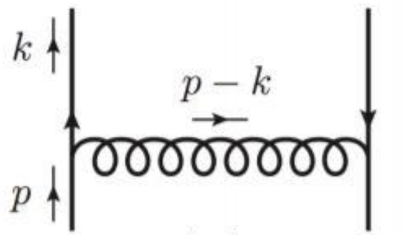
$$\boxed{g_{T,\mathrm{Q}} \approx \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \int \frac{dk^0}{2\pi} \frac{(4-n)}{(k^2 - m_q^2 + i\varepsilon)^2}} + \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \int \frac{dk^0}{2\pi} \frac{2k^2 + 2k_\perp^2 + 2m_q^2 - (4-n)m_g^2}{(k^2 - m_q^2 + i\varepsilon)^2((p-k)^2 - m_g^2 + i\varepsilon)}$$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Definition: $\frac{M}{P^3} S_\perp^i \, g_{T,\mathrm{Q}}(x) = \Phi^{[\gamma^i\gamma_5]}$



(1a)

$$\frac{m_q}{p^3} g_{T,\mathrm{Q}}^{(1a)}(x) = -\frac{ig^2 C_F \mu^{2\epsilon} g_{\mu\nu}}{4} \int_{-\infty}^{\infty} \frac{d^n k}{(2\pi)^n} \frac{\mathrm{Tr}\left[u\,\bar{u}\,\gamma^\nu\,(\not{k}+m_q)\,\gamma^i\gamma_5\,(\not{k}+m_q)\,\gamma^\mu\right]}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)} \delta\left(x-\frac{k^3}{p^3}\right)\frac{1}{p^3}$$

Split into singular & canonical parts

$g_{T,\mathrm{Q(s)}}^{(1a)}$ $g_{T,\mathrm{Q(c)}}^{(1a)}$

$$g_{T,\mathrm{Q}} \approx \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \int \frac{dk^0}{2\pi} \frac{(4-n)}{(k^2-m_q^2+i\varepsilon)^2} + \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \int \frac{dk^0}{2\pi} \frac{2k^2+2k_\perp^2+2m_q^2-(4-n)m_g^2}{(k^2-m_q^2+i\varepsilon)^2((p-k)^2-m_g^2+i\varepsilon)}$$

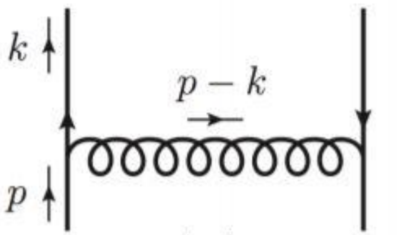
Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Close look at singular term

$$g^{(1a)}_{T,\mathrm{Q(s)}} \approx \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \underbrace{\int \frac{dk^0}{2\pi} \frac{(4-n)}{(k^2 - m_q^2 + i\varepsilon)^2}}_{\displaystyle \frac{(4-n)}{(k_\perp^2 + x^2 p_3^2 + m_q^2)^{3/2}}}$$



(1a)

Matching for twist-3 PDF $g_T(x)$

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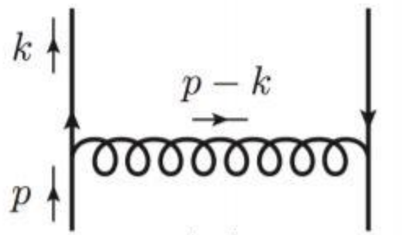

(1a)

i. $m_q \neq 0$

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Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Close look at singular term

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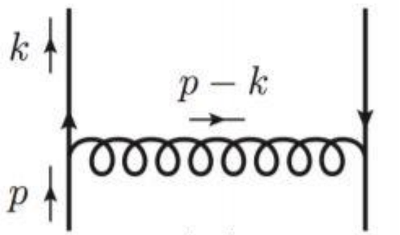
$$\frac{(4-n)}{(k_\perp^2 + x^2 p_3^2 + m_q^2)^{3/2}} \propto \epsilon$$



(1a)

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Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Close look at singular term

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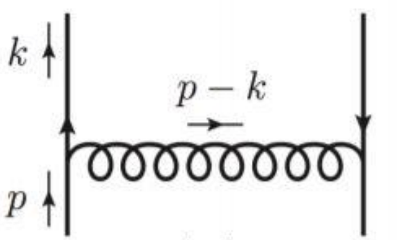


(1a)

i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\vert_{m_q\neq 0} = 0$

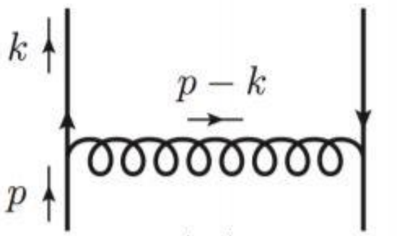
Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Close look at singular term

$$g^{(1a)}_{T,\mathrm{Q(s)}} \approx \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{\,n-2}k_\perp}{(2\pi)^{n-2}} \underbrace{\int \frac{dk^0}{2\pi}\, \frac{(4-n)}{(k^2 - m_q^2 + i\varepsilon)^2}}_{\dfrac{(4-n)}{(k_\perp^2 + x^2 p_3^2 + \cancel{m_q^2})^{3/2}}}$$



(1a)

i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\vert_{m_q\neq 0} = 0$
ii. ϵ_{IR}	

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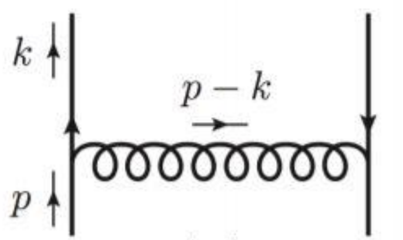
- **UV-finite**



(1a)

i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\vert_{m_q \neq 0} = 0$
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Matching for twist-3 PDF $g_T(x)$

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Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Close look at singular term

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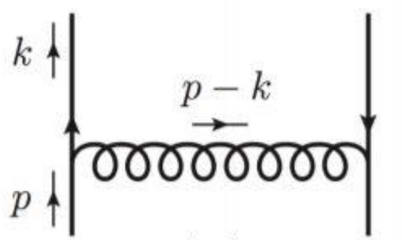


(1a)

- **UV-finite**
- **IR-finite except at** $x=0$

i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\|_{m_q\neq 0} = 0$
ii. ϵ_{IR}	

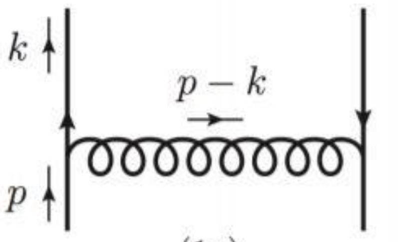
Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Close look at singular term

$$g^{(1a)}_{T,\mathrm{Q(s)}} \approx \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \underbrace{\int \frac{dk^0}{2\pi} \frac{(4-n)}{(k^2 - m_q^2 + i\varepsilon)^2}}_{\frac{(4-n)}{(k_\perp^2 + x^2 p_3^2 + \cancel{m_q^2})^{3/2}}}$$



- **UV-finite**
- **IR-finite except at $x = 0$**

i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\vert_{m_q \neq 0} = 0$
ii. ϵ_{IR}	

$$\int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \frac{(4-n)}{(k_\perp^2 + x^2 p_3^2)^{3/2}} = \frac{2^{-1+2\epsilon_{\mathrm{IR}}} \pi^{-3/2+\epsilon_{\mathrm{IR}}} \Gamma(1/2 + \epsilon_{\mathrm{IR}})}{(p^3)^{1+2\epsilon_{\mathrm{IR}}}} \frac{1}{|x|^{1+2\epsilon_{\mathrm{IR}}}}$$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

We derive:

$$\frac{1}{|x|^{1+2\,\epsilon_{\mathrm{IR}}}} = -\frac{\delta(x)}{\epsilon_{\mathrm{IR}}} + \left[\frac{1}{|x|}\right]_{+(0)} + \mathcal{O}(\epsilon_{\mathrm{IR}}) \qquad -1 < x < 1$$

$\epsilon_{\mathrm{IR}} < 0$

(See also Izubuchi et. al., arXiv: 1801.0391)

$$\underbrace{\int \frac{dk^0}{2\pi} \frac{(4-n)}{(k^2 - m_q^2 + i\varepsilon)^2}}_{\frac{(4-n)}{(k_\perp^2 + x^2 p_3^2 + \cancel{m_q^2})^{3/2}}}$$

- **UV-finite**
- **IR-finite except at** $x = 0$

i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\vert_{m_q \neq 0} = 0$
ii. ϵ_{IR}	

$$\int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \frac{(4-n)}{(k_\perp^2 + x^2 p_3^2)^{3/2}} = \frac{2^{-1+2\epsilon_{\mathrm{IR}}} \pi^{-3/2+\epsilon_{\mathrm{IR}}}\, \Gamma(1/2+\epsilon_{\mathrm{IR}})}{(p^3)^{1+2\epsilon_{\mathrm{IR}}}} \frac{1}{|x|^{1+2\epsilon_{\mathrm{IR}}}}$$

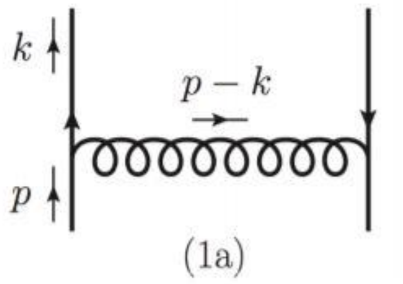
Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Close look at singular term

$$g^{(1a)}_{T,\mathrm{Q(s)}} \approx \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \underbrace{\int \frac{dk^0}{2\pi} \frac{(4-n)}{(k^2 - m_q^2 + i\varepsilon)^2}}_{\frac{(4-n)}{(k_\perp^2 + x^2 p_3^2 + m_q^2)^{3/2}}}$$



i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\rvert_{m_q \neq 0} = 0$
ii. ϵ_{IR}	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\rvert_{\epsilon_{\mathrm{IR}}} = \dfrac{\alpha_s C_F}{2\pi}\delta(x)$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

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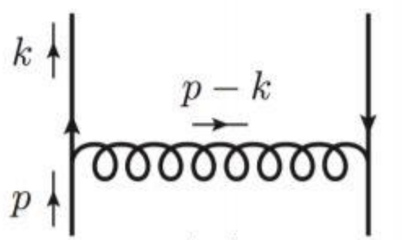


(1a)

i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\vert_{m_q \neq 0} = 0$
ii. ϵ_{IR}	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\vert_{\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi} \delta(x)$

- **Just as in LC case, existence of zero modes in quasi-PDF is IR scheme-dependent**

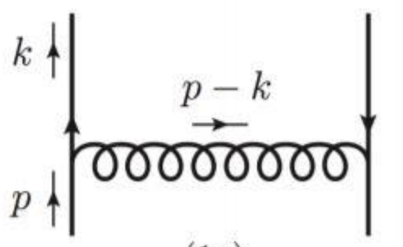
Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Calculation of ladder diagram for $g_{T,\mathrm{Q}}(x)$

Close look at singular term

$$g^{(1a)}_{T,\mathrm{Q(s)}} \approx \alpha_s C_F \mu^{2\epsilon} \int \frac{d^{n-2}k_\perp}{(2\pi)^{n-2}} \underbrace{\int \frac{dk^0}{2\pi} \frac{(4-n)}{(k^2 - m_q^2 + i\varepsilon)^2}}_{\dfrac{(4-n)}{(k_\perp^2 + x^2 p_3^2 + m_q^2)^{3/2}}}$$



(1a)

i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\vert_{m_q\neq 0} = 0$
ii. ϵ_{IR}	$g^{(1a)}_{T,\mathrm{Q(s)}}\big\vert_{\epsilon_{\mathrm{IR}}} = \dfrac{\alpha_s C_F}{2\pi}\delta(x)$

- **Just as in LC case, existence of zero modes in quasi-PDF is IR scheme-dependent**
- **Again, 2 (qualitatively) different results if we work with** $m_g \neq 0$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Results for canonical part:

i. $m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(c)}}(x)\Big\vert_{m_q} = \frac{\alpha_s C_F}{2\pi} \begin{cases} x\,\ln\frac{x}{x-1} - 1 & x>1 \\ x\,\ln\frac{p_3^2}{m_q^2} + x\ln\frac{4x}{1-x} + 1 - 2x + \frac{2}{x-1} & 0<x<1 \\ x\,\ln\frac{x-1}{x} + 1 & x<0 \end{cases}$
ii. $m_g \neq 0$	$g^{(1a)}_{T,\mathrm{Q(c)}}(x)\Big\vert_{m_g} = \frac{\alpha_s C_F}{2\pi} \begin{cases} x\,\ln\frac{x}{x-1} - 1 & x>1 \\ x\,\ln\frac{p_3^2}{m_g^2} + x\ln 4(1-x) + 1 - 2x & 0<x<1 \\ x\,\ln\frac{x-1}{x} + 1 & x<0 \end{cases}$
iii. ϵ_{IR}	$g^{(1a)}_{T,\mathrm{Q(c)}}(x)\Big\vert_{\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi} \begin{cases} x\,\ln\frac{x}{x-1} - 1 & x>1 \\ -x\,\mathcal{P}_{\mathrm{IR}} + x\,\ln\frac{4x(1-x)p_3^2}{\mu_{\mathrm{IR}}^2} - x & 0<x<1 \\ x\,\ln\frac{x-1}{x} + 1 & x<0 \end{cases}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, M... D 102 (2020)

Results f...

IR singularities present in the "physical region" $0 < x < 1$ only

i. $m_q \neq 0$	$$g_{T,\mathrm{Q(c)}}^{(1a)}(x)\Big|_{m_q} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\ln\frac{x}{x-1} - 1 & x>1 \\ x\ln\frac{p_3^2}{m_q^2} + x\ln\frac{4x}{1-x} + 1 - 2x + \frac{2}{x-1} & 0<x<1 \\ x\ln\frac{x-1}{x} + 1 & x<0 \end{cases}$$	
ii. $m_g \neq 0$	$$g_{T,\mathrm{Q(c)}}^{(1a)}(x)\Big|_{m_g} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\ln\frac{x}{x-1} - 1 & x>1 \\ x\ln\frac{p_3^2}{m_g^2} + x\ln 4(1-x) + 1 - 2x & 0<x<1 \\ x\ln\frac{x-1}{x} + 1 & x<0 \end{cases}$$	
iii. ϵ_{IR}	$$g_{T,\mathrm{Q(c)}}^{(1a)}(x)\Big|_{\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\ln\frac{x}{x-1} - 1 & x>1 \\ -x\,\mathcal{P}_{\mathrm{IR}} + x\ln\frac{4x(1-x)p_3^2}{\mu_{\mathrm{IR}}^2} - x & 0<x<1 \\ x\ln\frac{x-1}{x} + 1 & x<0 \end{cases}$$	

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantin... M... ...lato, Steffens/ PRD 102 (2020)

Result... f...

Finite terms in $0 < x < 1$ look very different

i.	$m_q \neq 0$	$g^{(1a)}_{T,\mathrm{Q(c)}}(x)\Big\|_{m_q} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\ln\frac{x}{x-1}-1 & x>1 \\ x\ln\frac{p_3^2}{m_q^2}+\underbrace{x\ln\frac{4x}{1-x}+1-2x+\frac{2}{x-1}} & 0<x<1 \\ x\ln\frac{x-1}{x}+1 & x<0 \end{cases}$
ii.	$m_g \neq 0$	$g^{(1a)}_{T,\mathrm{Q(c)}}(x)\Big\|_{m_g} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\ln\frac{x}{x-1}-1 & x>1 \\ x\ln\frac{p_3^2}{m_g^2}+\underbrace{x\ln 4(1-x)+1-2x} & 0<x<1 \\ x\ln\frac{x-1}{x}+1 & x<0 \end{cases}$
iii.	ϵ_{IR}	$g^{(1a)}_{T,\mathrm{Q(c)}}(x)\Big\|_{\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\ln\frac{x}{x-1}-1 & x>1 \\ -x\mathcal{P}_{\mathrm{IR}}+\underbrace{x\ln\frac{4x(1-x)p_3^2}{\mu_{\mathrm{IR}}^2}-x} & 0<x<1 \\ x\ln\frac{x-1}{x}+1 & x<0 \end{cases}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, M... 102 (2020)

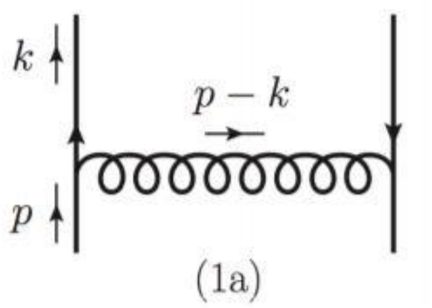
Results for the "unphysical regions" $x > 1\,,\, x < 0$ are the same

i. $m_q \neq 0$	$$g^{(1a)}_{T,\mathrm{Q(c)}}(x)\Big|_{m_q} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\,\ln\frac{x}{x-1} - 1 & x > 1 \\ x\,\ln\frac{p_3^2}{m_q^2} + x\ln\frac{4x}{1-x} + 1 - 2x + \frac{2}{x-1} & 0 < x < 1 \\ x\,\ln\frac{x-1}{x} + 1 & x < 0 \end{cases}$$
ii. $m_g \neq 0$	$$g^{(1a)}_{T,\mathrm{Q(c)}}(x)\Big|_{m_g} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\,\ln\frac{x}{x-1} - 1 & x > 1 \\ x\,\ln\frac{p_3^2}{m_g^2} + x\ln 4(1-x) + 1 - 2x & 0 < x < 1 \\ x\,\ln\frac{x-1}{x} + 1 & x < 0 \end{cases}$$
iii. ϵ_{IR}	$$g^{(1a)}_{T,\mathrm{Q(c)}}(x)\Big|_{\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\,\ln\frac{x}{x-1} - 1 & x > 1 \\ -x\,\mathcal{P}_{\mathrm{IR}} + x\,\ln\frac{4x(1-x)p_3^2}{\mu_{\mathrm{IR}}^2} - x & 0 < x < 1 \\ x\,\ln\frac{x-1}{x} + 1 & x < 0 \end{cases}$$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

General structure for the ladder-diagram result: Quasi $g_{T,\mathrm{Q}}(x)$



$$g_{T,\mathrm{Q}}^{(1a)} = g_{T,\mathrm{Q(s)}}^{(1a)} + g_{T,\mathrm{Q(c)}}^{(1a)}$$

Singular term $\propto \delta(x)$

(IR scheme-dependent)

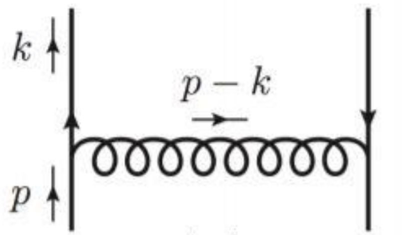
Canonical term

IR regulator	$\delta(x)$?
$m_q \neq 0$	✗
ϵ_{IR}	✓

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Agreement of the IR singularities between light-cone PDF & quasi-PDF



(1a)

Matching for twist-3 PDF $g_T(x)$

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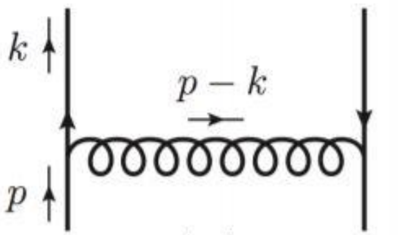


(1a)

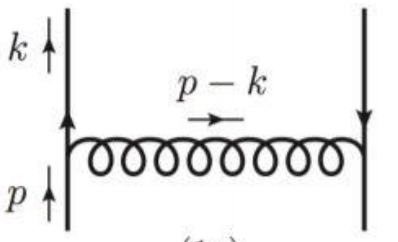
- **Singular terms:** Coefficient of singular terms are IR finite

Light-cone PDF	Quasi-PDF
$g_{T(\mathrm{s})}^{(1a)}(x) = \begin{cases} g_{T(\mathrm{s})}^{(1a)}(x)\big\rvert_{m_q\neq 0} = -\dfrac{\alpha_s C_F}{2\pi}\delta(x) \\ g_{T(\mathrm{s})}^{(1a)}(x)\big\rvert_{\epsilon_{\mathrm{IR}}} = 0 \end{cases}$	$g_{T,\mathrm{Q(s)}}^{(1a)}(x) = \begin{cases} g_{T,\mathrm{Q(s)}}^{(1a)}(x)\big\rvert_{m_q\neq 0} = 0 \\ g_{T,\mathrm{Q(s)}}^{(1a)}(x)\big\rvert_{\epsilon_{\mathrm{IR}}} = \dfrac{\alpha_s C_F}{2\pi}\delta(x) \end{cases}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Agreement of the IR singularities between light-cone PDF & quasi-PDF



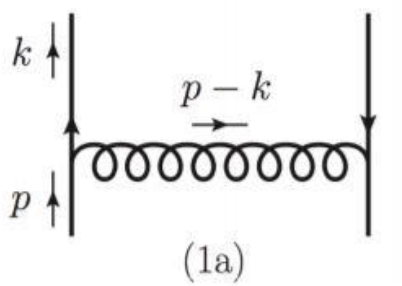
(1a)

- **Singular terms:** **Coefficient of singular terms are IR finite**
- **Canonical terms:**

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Agreement of the IR singularities between light-cone PDF & quasi-PDF



- **Singular terms:** Coefficient of singular terms are IR finite
- **Canonical terms:**

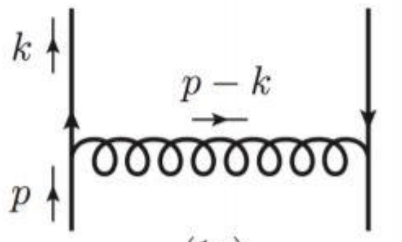
Quark mass

Light-cone PDF	$g_{T(\mathrm{c})}^{(1\mathrm{a})}(x)\Big\|_{m_q} = \frac{\alpha_s C_F}{2\pi}\left(x\ln\frac{\mu_{\mathrm{UV}}^2}{m_q^2} + x\ln\frac{1}{(1-x)^2} + x\,\mathcal{P}_{\mathrm{UV}} + \frac{x^2-2x-1}{1-x}\right)$
Quasi-PDF	$g_{T,\mathrm{Q(c)}}^{(1\mathrm{a})}(x)\Big\|_{m_q} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\ \ln\frac{x}{x-1} - 1 & x>1 \\ x\ \ln\frac{p_3^2}{m_q^2} + x\ln\frac{4x}{1-x} + 1 - 2x + \frac{2}{x-1} & 0<x<1 \\ x\ \ln\frac{x-1}{x} + 1 & x<0 \end{cases}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Agreement of the IR singularities between light-cone PDF & quasi-PDF



(1a)

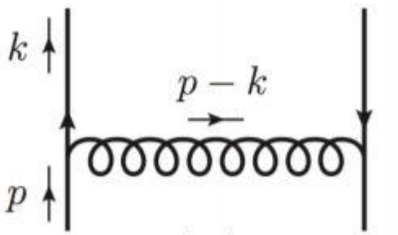
- **Singular terms:** **Coefficient of singular terms are IR finite**
- **Canonical terms:**

Quark mass	**Light-cone PDF**	$g^{(1\mathrm{a})}_{T(\mathrm{c})}(x)\Big\vert_{m_q} = \dfrac{\alpha_s C_F}{2\pi}\left(x\ln\dfrac{\mu^2_{\mathrm{UV}}}{m_q^2} + x\ln\dfrac{1}{(1-x)^2} + x\,\mathcal{P}_{\mathrm{UV}} + \dfrac{x^2-2x-1}{1-x} \right)$
	Quasi-PDF	$g^{(1\mathrm{a})}_{T,\mathrm{Q(c)}}(x)\Big\vert_{m_q} = \dfrac{\alpha_s C_F}{2\pi}\begin{cases} x\ \ln\frac{x}{x-1} - 1 & x>1 \\ x\ \ln\frac{p_3^2}{m_q^2} + x\ln\frac{4x}{1-x} + 1 - 2x + \frac{2}{x-1} & 0<x<1 \\ x\ \ln\frac{x-1}{x} + 1 & x<0 \end{cases}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Agreement of the IR singularities between light-cone PDF & quasi-PDF



(1a)

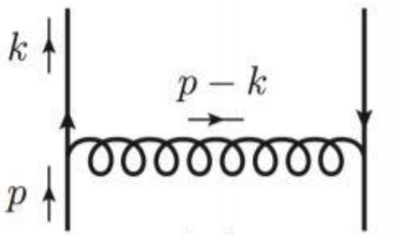
- **Singular terms:** **Coefficient of singular terms are IR finite**
- **Canonical terms:**

Gluon mass	**Light-cone PDF**	$g_{T(\mathrm{c})}^{(1\mathrm{a})}(x)\Big\vert_{m_g} = \frac{\alpha_s C_F}{2\pi}\left(x\ln\frac{\mu_{\mathrm{UV}}^2}{m_g^2} + x\ln\frac{1}{x} + x\,\mathcal{P}_{\mathrm{UV}} + (1-x)\right)$
	Quasi-PDF	$g_{T,\mathrm{Q(c)}}^{(1\mathrm{a})}(x)\Big\vert_{m_g} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\ln\frac{x}{x-1} - 1 & x>1 \\ x\ln\frac{p_3^2}{m_g^2} + x\ln 4(1-x) + 1 - 2x & 0<x<1 \\ x\ln\frac{x-1}{x} + 1 & x<0 \end{cases}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Agreement of the IR singularities between light-cone PDF & quasi-PDF



(1a)

- **Singular terms:** **Coefficient of singular terms are IR finite**
- **Canonical terms:**

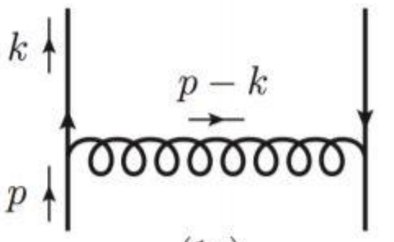
DR for IR

Light-cone PDF	$g_{T(\mathrm{c})}^{(1\mathrm{a})}(x)\Big\vert_{\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi}\left(-x\,\mathcal{P}_{\mathrm{IR}} + x\,\mathcal{P}_{\mathrm{UV}} + x\ln\frac{\mu_{\mathrm{UV}}^2}{\mu_{\mathrm{IR}}^2}\right)$
Quasi-PDF	$g_{T,\mathrm{Q(c)}}^{(1\mathrm{a})}(x)\Big\vert_{\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\ln\frac{x}{x-1} - 1 & x>1 \\ -x\,\mathcal{P}_{\mathrm{IR}} + x\ln\frac{4x(1-x)p_3^2}{\mu_{\mathrm{IR}}^2} - x & 0<x<1 \\ x\ln\frac{x-1}{x} + 1 & x<0 \end{cases}$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Agreement of the IR singularities between light-cone PDF & quasi-PDF



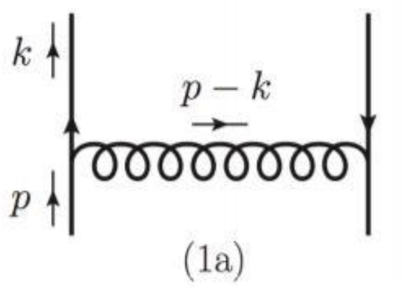
(1a)

- **Singular terms:** **Coefficient of singular terms are IR finite**
- **Canonical terms:** **IR singularities agree for all 3 regulators**

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Agreement of the IR singularities between light-cone PDF & quasi-PDF



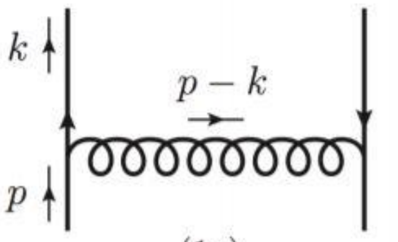
- **Singular terms:** **Coefficient of singular terms are IR finite**
- **Canonical terms:** **IR singularities agree for all 3 regulators**

- **Other diagrams can be calculated just like in the twist-2 case**

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Agreement of the IR singularities between light-cone PDF & quasi-PDF



(1a)

- **Singular terms:** **Coefficient of singular terms are IR finite**
- **Canonical terms:** **IR singularities agree for all 3 regulators**

- **Other diagrams can be calculated just like in the twist-2 case**
- **Diagram by diagram the IR singularities agree, which is at the heart of quasi-PDF approach**
- **Matching is possible for $g_T(x)$**

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Matching

- **Matching coefficient can be extracted diagram by diagram**

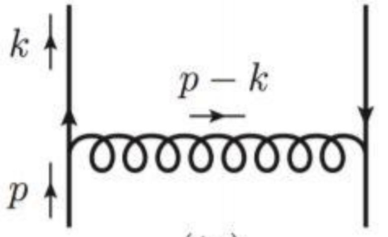
Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Matching

- **Matching coefficient can be extracted diagram by diagram**

Example:



(1a)

$$\boxed{\begin{aligned} C^{(1a)}(x) &= \delta(1-x) + \tilde{q}^{(1a)}(x) - q^{(1a)}(x) \\ &= \delta(1-x) + C^{(1a)}_{(\mathrm{s})}(x) + C^{(1a)}_{(\mathrm{c})}(x) \end{aligned}}$$

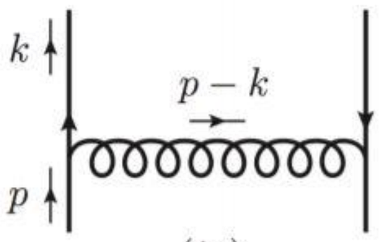
Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Matching

- **Matching coefficient can be extracted diagram by diagram**

Example:



(1a)

$$
\begin{aligned}
C^{(1a)}(x) &= \delta(1-x) + \tilde{q}^{(1a)}(x) - q^{(1a)}(x) \\
&= \delta(1-x) + C^{(1a)}_{(\mathrm{s})}(x) + C^{(1a)}_{(\mathrm{c})}(x)
\end{aligned}
$$

Singular part of matching coefficient

$$
C^{(1a)}_{(\mathrm{s})}(x)\Big|_{m_q,\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi}\delta(x)
$$

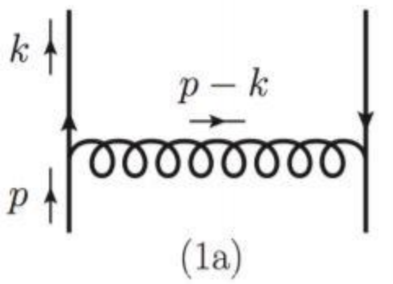
Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Matching

- **Matching coefficient can be extracted diagram by diagram**

Example:



$$\begin{aligned} C^{(1a)}(x) &= \delta(1-x) + \tilde{q}^{(1a)}(x) - q^{(1a)}(x) \\ &= \delta(1-x) + C^{(1a)}_{(\mathrm{s})}(x) + C^{(1a)}_{(\mathrm{c})}(x) \end{aligned}$$

Singular part of matching coefficient

$$C^{(1a)}_{(\mathrm{s})}(x)\Big|_{m_q,\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi}\delta(x)$$

Canonical part of matching coefficient

$$C^{(1a)}_{(\mathrm{c})}(x)\Big|_{m_q,m_g,\epsilon_{\mathrm{IR}}} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\,\ln\frac{x}{x-1} - 1 & x > 1 \\ x\,\ln\frac{4x(1-x)p_3^2}{\mu^2} - x & 0 < x < 1 \\ x\,\ln\frac{x-1}{x} + 1 & x < 0 \end{cases}$$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Matching

- **Matching coefficient can be extracted diagram by diagram**

Example:

(1a)

Matching coefficient for $g_T(x)$ is independent of IR scheme

Singular part of matching coefficient

$$C_{\rm (s)}^{(1a)}(x)\Big|_{m_q,\epsilon_{\rm IR}} = \frac{\alpha_s C_F}{2\pi}\delta(x)$$

Canonical part of matching coefficient

$$C_{\rm (c)}^{(1a)}(x)\Big|_{m_q,m_g,\epsilon_{\rm IR}} = \frac{\alpha_s C_F}{2\pi}\begin{cases} x\,\ln\frac{x}{x-1} - 1 & x>1 \\ x\,\ln\frac{4x(1-x)p_3^2}{\mu^2} - x & 0<x<1 \\ x\,\ln\frac{x-1}{x} + 1 & x<0 \end{cases}$$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Matching in $\overline{\text{MS}}$ scheme

$$
C^{(1)}_{\overline{\text{MS}}}\left(\xi, \frac{\mu^2}{p_3^2}\right) = \frac{\alpha_s C_F}{2\pi}\begin{cases} 0 & \xi > 1 \\ \delta(\xi) & 0 < \xi < 1 \\ 0 & \xi < 0 \end{cases} + \frac{\alpha_s C_F}{2\pi}\begin{cases} \left[\frac{-\xi^2 + 2\xi + 1}{1-\xi}\ln\frac{\xi}{\xi - 1} + \frac{\xi}{1-\xi} + \frac{3}{2\xi}\right]_+ - \frac{3}{2\xi} & \xi > 1 \\ \left[\frac{-\xi^2 + 2\xi + 1}{1-\xi}\ln\frac{4\xi(1-\xi)p_3^2}{\mu^2} + \frac{\xi^2 - \xi - 1}{1-\xi}\right]_+ & 0 < \xi < 1 \\ \left[\frac{-\xi^2 + 2\xi + 1}{1-\xi}\ln\frac{\xi - 1}{\xi} - \frac{\xi}{1-\xi} + \frac{3}{2(1-\xi)}\right]_+ - \frac{3}{2(1-\xi)} & \xi < 0 \end{cases}
$$

$$
+ \frac{\alpha_s C_F}{2\pi}\delta(1-\xi)\left(-\frac{1}{2} + \frac{3}{2}\ln\frac{\mu^2}{4p_3^2}\right)
$$

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- **Convolution integrals** $q(x) = \int_{-\infty}^{\infty}\frac{d\xi}{|\xi|}C(\xi)\tilde{q}\left(\frac{x}{\xi}\right)$

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Matching in $\overline{\text{MS}}$ scheme

$$\approx \frac{3}{2}\ln\xi$$

$$C^{(1)}_{\overline{\text{MS}}}\left(\xi,\frac{\mu^2}{p_3^2}\right) = \frac{\alpha_s C_F}{2\pi}\begin{cases} 0 & \xi>1 \\ \delta(\xi) & 0<\xi<1 \\ 0 & \xi<0 \end{cases} + \frac{\alpha_s C_F}{2\pi}\begin{cases} \left[\frac{-\xi^2+2\xi+1}{1-\xi}\ln\frac{\xi}{\xi-1}+\frac{\xi}{1-\xi}+\frac{3}{2\xi}\right]_+ - \frac{3}{2\xi} & \xi>1 \\ \left[\frac{-\xi^2+2\xi+1}{1-\xi}\ln\frac{4\xi(1-\xi)p_3^2}{\mu^2}+\frac{\xi^2-\xi-1}{1-\xi}\right]_+ & 0<\xi<1 \\ \left[\frac{-\xi^2+2\xi+1}{1-\xi}\ln\frac{\xi-1}{\xi}-\frac{\xi}{1-\xi}+\frac{3}{2(1-\xi)}\right]_+ - \frac{3}{2(1-\xi)} & \xi<0 \end{cases}$$

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$$\approx \frac{3}{2}\ln\xi$$

Problems with $\overline{\text{MS}}$

- **Convolution integrals** $q(x) = \int_{-\infty}^{\infty}\frac{d\xi}{|\xi|}C(\xi)\tilde{q}\left(\frac{x}{\xi}\right)$
- **Mismatch in norm:** $\int_{-\infty}^{\infty} dx\, \tilde{q}^{\overline{\text{MS}}}(x,\mu,p^3) \neq \int_0^1 dx\, q^{\overline{\text{MS}}}(x,\mu)$

Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

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Introduce $\mathrm{M\overline{MS}}$ **(Alexandrou et. al., arXiv: 1902.00587)**

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Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

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Matching for twist-3 PDF $g_T(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

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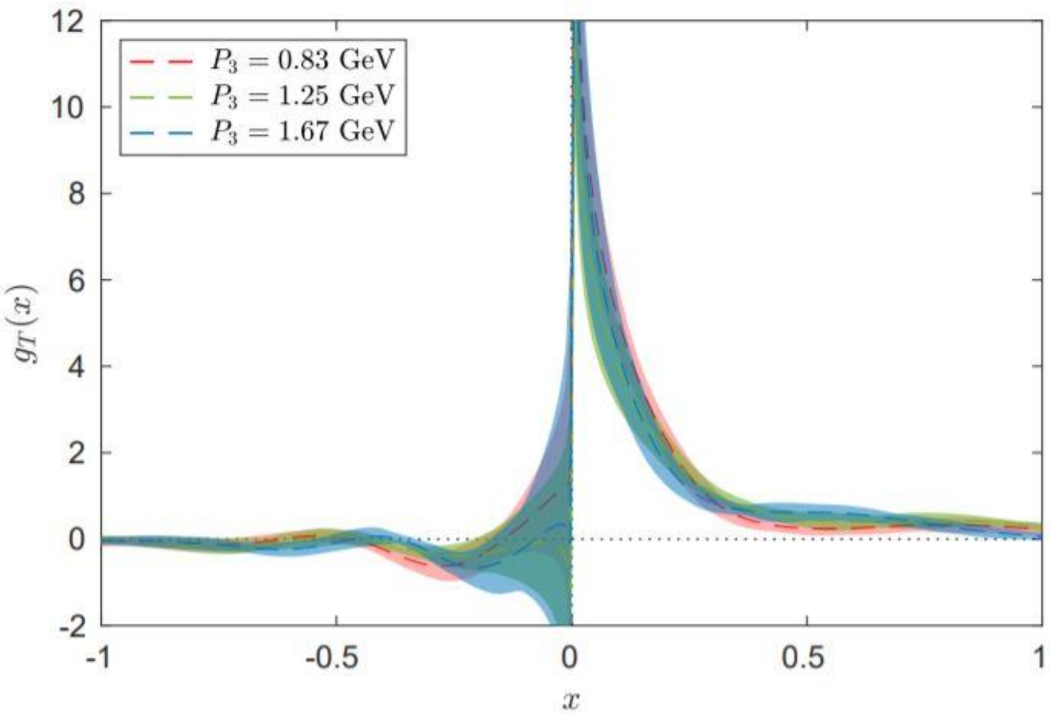
Lattice QCD results for $g_T^{\mathrm{u-d}}(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD Rapid 102 (2020)

Ensemble: $a = 0.093$ fm, $L \approx 3$ fm



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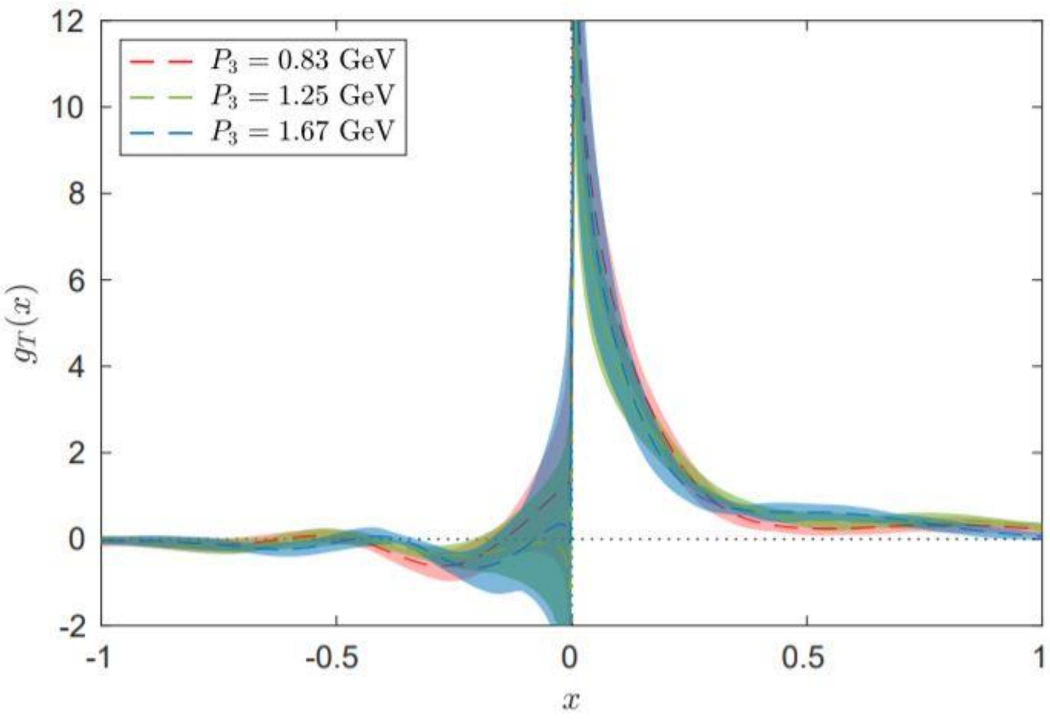
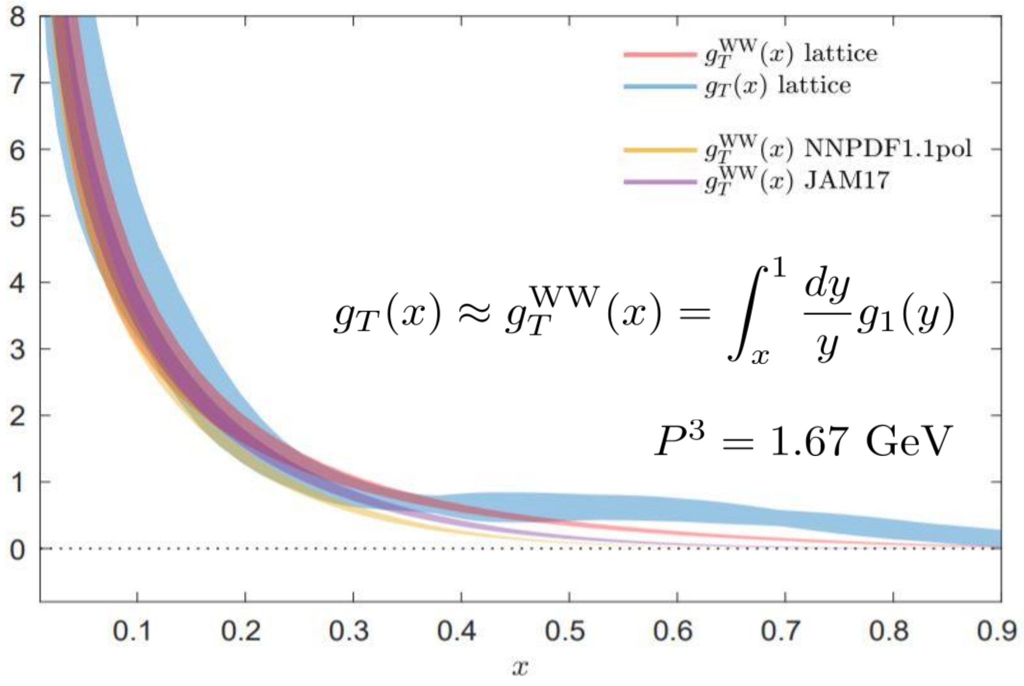
Extended Twisted Mass Collaboration

Ensemble: $a = 0.093$ fm, $L \approx 3$ fm





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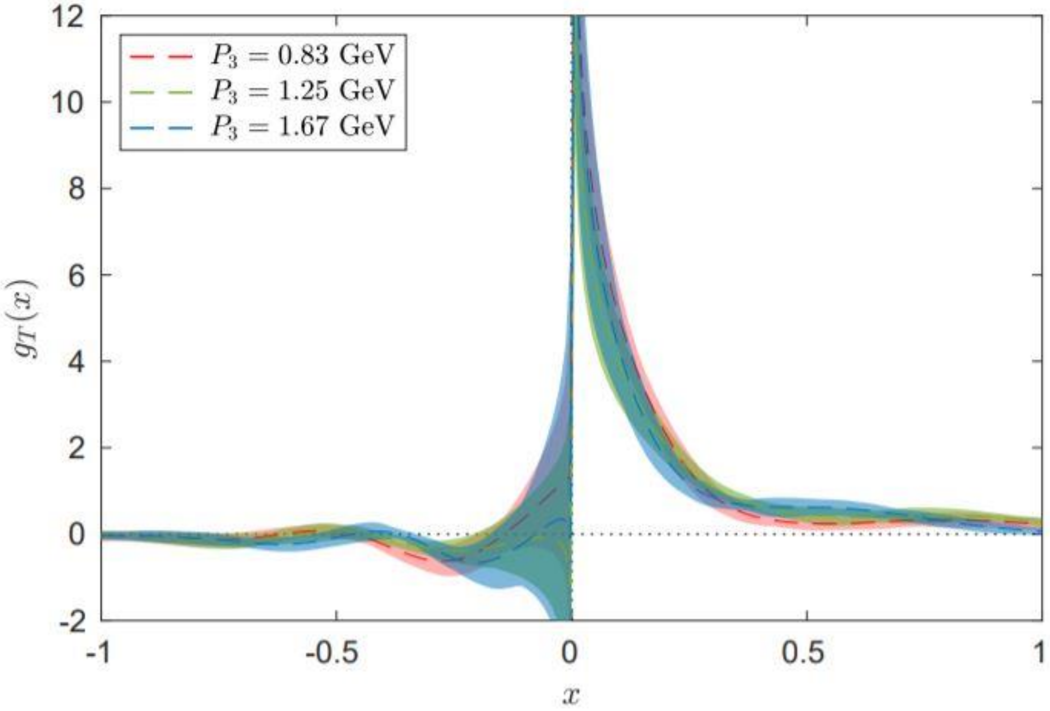

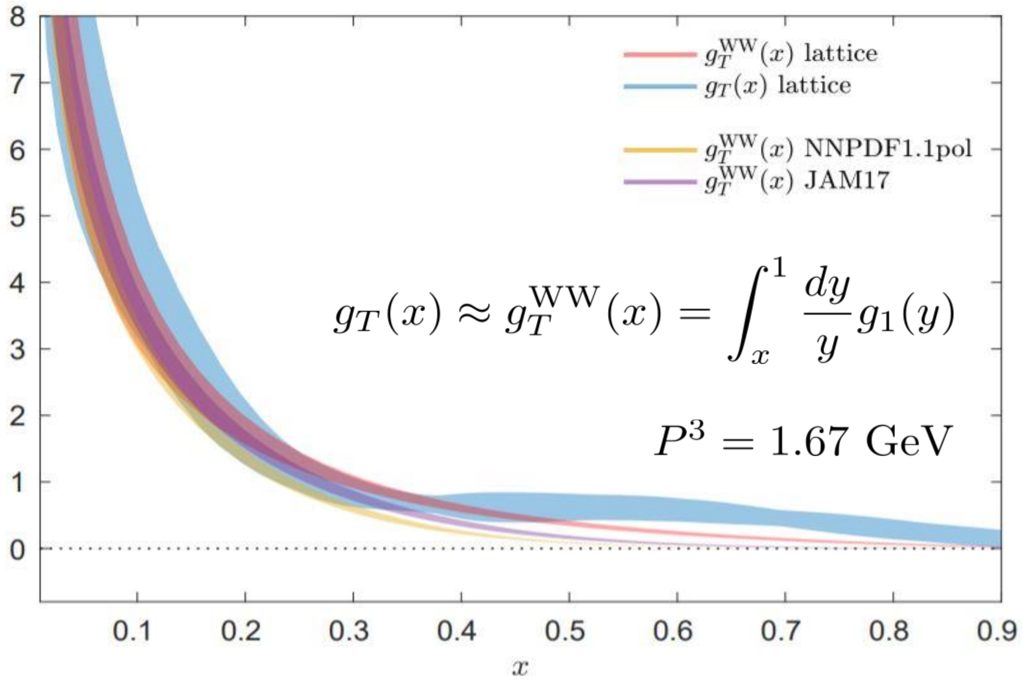

$$g_T(x) \approx g_T^{\mathrm{WW}}(x) = \int_x^1 \frac{dy}{y} g_1(y)$$

$P^3 = 1.67$ GeV

Good agreement between $g_T(x)$ **&** $g_T^{\mathrm{WW}}(x)$

Lattice QCD results for $g_T^{\mathrm{u-d}}(x)$

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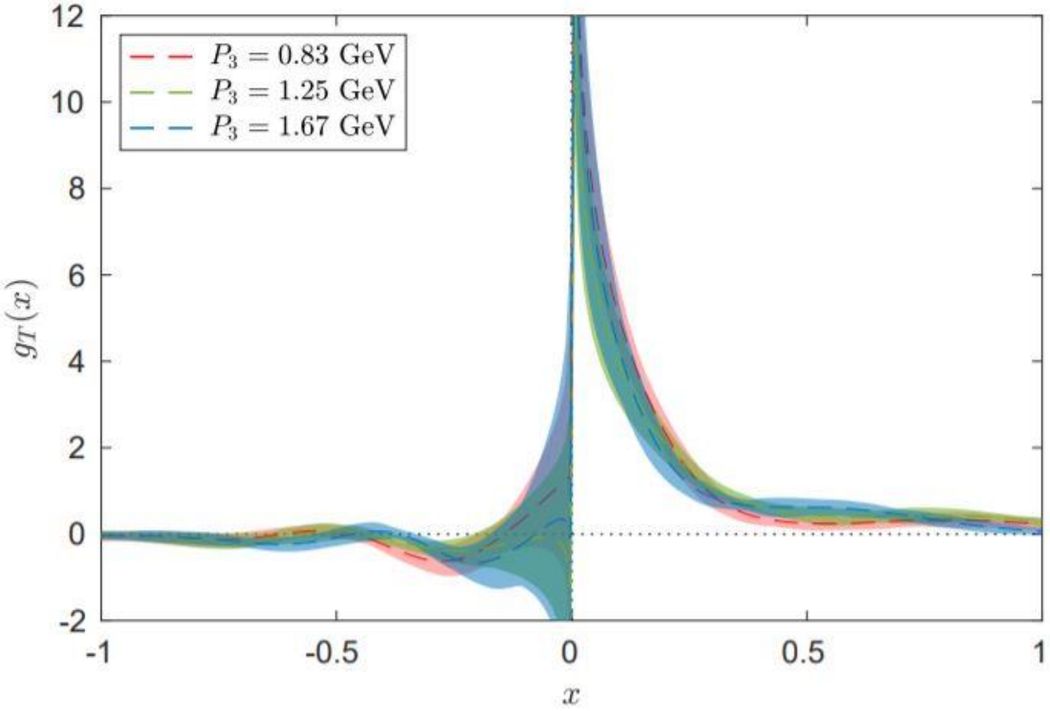

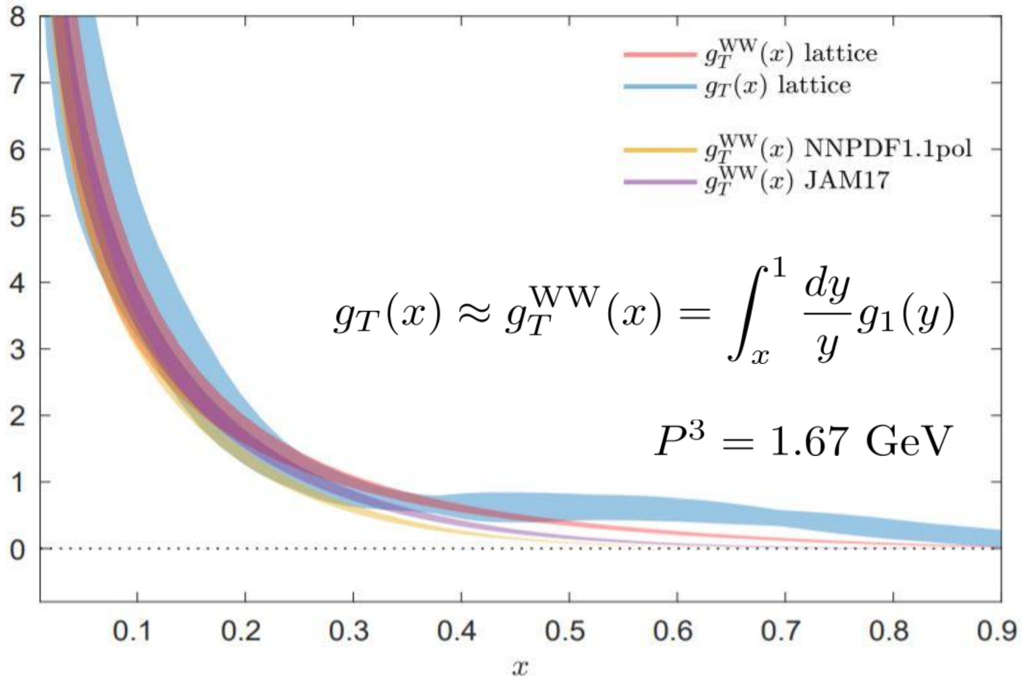

Good agreement between $g_T(x)$ **&** $g_T^{\mathrm{WW}}(x)$

Still, possible violation of up to $30\% - 40\%$ **perceivable**

Case 2:

$$\begin{cases} e \\ h_L \end{cases} \quad \& \quad \begin{cases} e_{\mathbf{Q}} \\ h_{L,\mathbf{Q}} \end{cases}$$

Non-trivial role of zero-modes in matching for $e(x)$ & $h_L(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Light-cone PDF	Features
Example: $$h_{L(\mathrm{s})}^{(1a)}(x)\big\vert_{m_q} = -\frac{\alpha_s C_F}{2\pi}\,\boldsymbol{\delta(x)}\left(\mathcal{P}_{\mathrm{UV}} + \ln\frac{\mu_{\mathrm{UV}}^2}{m_q^2} - 1\right)$$	• **Zero modes are unavoidable**

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Quasi-PDF	**Features**
Example: $h^{(1a)}_{L,{\rm Q(s)}}(x)\Big\vert_{m_q} = -\frac{\alpha_s C_F}{2\pi}\frac{p^3}{\sqrt{x^2 p_3^2 + m_q^2}}$	• **Seemingly different looking IR pole structure**

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SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Light-cone PDF	Features
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Quasi-PDF	Features
Example: $h^{(1a)}_{L,\mathrm{Q(s)}}(x)\big\vert_{m_q} = -\frac{\alpha_s C_F}{2\pi}\frac{p^3}{\sqrt{x^2 p_3^2 + m_q^2}}$	• **Seemingly different looking IR pole structure** • **Do quasi-PDFs and LC PDFs share same IR physics?**

Non-trivial role of zero-modes in matching for $e(x)$ & $h_L(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Treatment of IR singularity for quasi-PDFs (non-zero quark mass)
$h^{(1a)}_{L,\mathrm{Q(s)}}(x)\Big\|_{m_q} = -\frac{\alpha_s C_F}{2\pi}\frac{1}{\sqrt{x^2+\eta^2}}$ where, $\eta^2 = \frac{m_q^2}{p_3^2}$ $\quad -1 < x < 1$

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$$h^{(1a)}_{L,\mathrm{Q(s)}}(x) \approx -\frac{\alpha_s C_F}{2\pi}\frac{1}{x}$$

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Recall:

$$h^{(1a)}_{L(\mathrm{s})}(x)\big|_{m_q} = -\frac{\alpha_s C_F}{2\pi}\boldsymbol{\delta(x)}\left(\mathcal{P}_{\mathrm{UV}} + \ln\frac{\boldsymbol{\mu^2_{\mathrm{UV}}}}{\boldsymbol{m_q^2}} - 1\right)$$

$$h^{(1a)}_{L,\mathrm{Q(s)}}(x) \approx -\frac{\alpha_s C_F}{2\pi}\frac{1}{x}$$

- **Doing a twist-expansion before we calculate the matching coefficient gives rise to an <u>incorrect conclusion</u> of mismatch in the IR between quasi & LC PDFs!**

Non-trivial role of zero-modes in matching for $e(x)$ & $h_L(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Treatment of IR singularity for quasi-PDFs (non-zero quark mass)

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Incorrect approach	Correct approach
$h^{(1a)}_{L,\mathrm{Q(s)}}(x) \approx -\frac{\alpha_s C_F}{2\pi}\frac{1}{x}$	$\int_{-1}^{1} dx\, \frac{f(x)}{\sqrt{x^2+\eta^2}} = \int_{-1}^{1} dx\, f(x)\,\delta(x)\left(\ln\frac{4}{\eta^2}\right) + \int_{-1}^{1} dx\, f(x)\left[\frac{1}{\lvert x\rvert}\right]_{+[0]} + \mathcal{O}(\eta^2)$
• **Doing a twist-expansion before we calculate the matching coefficient gives rise to an <u>incorrect conclusion</u> of mismatch in the IR between quasi & LC PDFs!**	• **By convoluting with a well-behaved test-function, it is possible to isolate singularity at** $x=0$ • **Agreement in the IR poles between quasi & LC PDFs: Matching possible for** $e(x)$, $h_L(x)$

Non-trivial role of zero-modes in matching for $e(x)$ & $h_L(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens/ PRD 102 (2020)

Treatment of IR singularity for quasi-PDFs (non-zero quark mass)

Point $x = 0$ is extremely delicate for quasi-PDFs!

Incorrect approach	Correct approach
$h^{(1a)}_{L,\mathrm{Q(s)}}(x) \approx -\frac{\alpha_s C_F}{2\pi} \frac{1}{x}$	$\int_{-1}^{1} dx \, \frac{f(x)}{\sqrt{x^2+\eta^2}} = \int_{-1}^{1} dx \, f(x) \delta(x) \left(\ln \frac{4}{\eta^2} \right) + \int_{-1}^{1} dx \, f(x) \left[\frac{1}{\lvert x \rvert} \right]_{+[0]} + \mathcal{O}(\eta^2)$
• **Doing a twist-expansion before we calculate the matching coefficient gives rise to an <u>incorrect conclusion</u> of mismatch in the IR between quasi & LC PDFs!**	• **By convoluting with a well-behaved test-function, it is possible to isolate singularity at $x = 0$** • **Agreement in the IR poles between quasi & LC PDFs: Matching possible for $e(x)$, $h_L(x)$**

Matching for twist-3 PDF $h_L(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens (in preparation)

Matching in $\mathrm{M\overline{MS}}$ scheme

Singular part of matching coefficient

$$C^{(\mathrm{s})}_{\mathrm{M\overline{MS}}}\left(\xi, \frac{\mu^2}{p_3^2}\right) = \frac{\alpha_s C_F}{2\pi} \begin{cases} \delta(1-\xi)\left(\frac{1}{2} - \frac{1}{2}\ln\frac{\mu^2}{4p_3^2}\right) & \xi > 1 \\ -\delta(\xi)\left(\ln\frac{4p_3^2}{\mu^2} + 1\right) - \mathrm{R}_0(|\xi|) & 0 < \xi < 1 \\ \delta(1+\xi)\left(\frac{1}{2} - \frac{1}{2}\ln\frac{\mu^2}{4p_3^2}\right) & \xi < 0 \end{cases}$$

$$R_0(|\xi|) = \left[\frac{1}{|\xi|}\right]_{+[0]} =$$

$$\theta(|\xi|)\,\theta(1-|\xi|)\lim_{\beta\to 0}\left[\frac{\theta(|\xi|-\beta)}{|\xi|} + \delta(|\xi|-\beta)\ln\beta\right]$$

Canonical part of matching coefficient

$$C^{(\mathrm{c})}_{\mathrm{M\overline{MS}}}\left(\xi, \frac{\mu^2}{p_3^2}\right) = \frac{\alpha_s C_F}{2\pi} \begin{cases} \left[\frac{2}{1-\xi}\ln\frac{\xi}{\xi-1} + \frac{1}{1-\xi} + \frac{1}{\xi}\right]_+ & \xi > 1 \\ \left[\frac{2}{1-\xi}\ln\frac{4\xi(1-\xi)p_3^2}{\mu^2} + 2(1-\xi) - \frac{1}{1-\xi}\right]_+ & 0 < \xi < 1 \\ \left[\frac{2}{1-\xi}\ln\frac{\xi-1}{\xi} - \frac{1}{1-\xi} + \frac{1}{1-\xi}\right]_+ & \xi < 0 \end{cases}$$

Matching for twist-3 PDF $h_L(x)$

SB, Cichy, Constantinou, Metz, Scapellato, Steffens (in preparation)

Matching in $\mathrm{M\overline{MS}}$ scheme

Singular part of matching coefficient

$$\delta(1-\xi)\left(\frac{1}{2}-\frac{1}{2}\ln\frac{\mu^2}{4p_3^2}\right) \qquad \xi > 1$$

Matching coefficient for $h_L(x)$ (as well as for $e(x)$) is independent of IR scheme

Canonical part of matching coefficient

$$C^{(\mathrm{c})}_{\mathrm{M\overline{MS}}}\left(\xi,\frac{\mu^2}{p_3^2}\right) = \frac{\alpha_s C_F}{2\pi}\begin{cases}\left[\frac{2}{1-\xi}\ln\frac{\xi}{\xi-1}+\frac{1}{1-\xi}+\frac{1}{\xi}\right]_+ & \xi > 1\\ \left[\frac{2}{1-\xi}\ln\frac{4\xi(1-\xi)p_3^2}{\mu^2}+2(1-\xi)-\frac{1}{1-\xi}\right]_+ & 0<\xi<1\\ \left[\frac{2}{1-\xi}\ln\frac{\xi-1}{\xi}-\frac{1}{1-\xi}+\frac{1}{1-\xi}\right]_+ & \xi<0\end{cases}$$

Burkhardt-Cottingham type sum rules

for

Light-cone & Quasi-PDFs

See also: Burkhardt, Cottingham, 1970/ Mulders, Tangerman, 1994/ Burkardt, 1995

Burkhardt-Cottingham type sum rules for light-cone & quasi-PDFs

SB & Metz (in preparation)

Sum rules in perturbative QCD models
BC sum rule $\int_0^1 dx\, g_1(x) \quad = \quad \int_0^1 dx\, g_T(x)$
h-sum rule $\int_0^1 dx\, h_1(x) \quad = \quad \int_0^1 dx\, h_L(x)$

Burkhardt-Cottingham type sum rules for light-cone & quasi-PDFs

SB & Metz (in preparation)

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BC sum rule $$\int_0^1 dx\, g_1(x) \;=\; \int_0^1 dx\, g_T(x)$$
h-sum rule $$\int_0^1 dx\, h_1(x) \;=\; \int_0^1 dx\, h_L(x)$$

- **Analytically & numerically checked the BC and h sum rules, by going beyond the UV-divergent parts**

Burkhardt-Cottingham type sum rules for light-cone & quasi-PDFs

SB & Metz (in preparation)

Sum rules in perturbative QCD models

BC sum rule

$$\int_0^1 dx\, g_1(x) = \int_0^1 dx\, g_T(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off		

h-sum rule

$$\int_0^1 dx\, h_1(x) = \int_0^1 dx\, h_L(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off		

- **Analytically & numerically checked the BC and h sum rules, by going beyond the UV-divergent parts**
- **Sum rules are valid in DR scheme**

Burkhardt-Cottingham type sum rules for light-cone & quasi-PDFs

SB & Metz (in preparation)

Sum rules in perturbative QCD models

BC sum rule

$$\int_0^1 dx\, g_1(x) = \int_0^1 dx\, g_T(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off	✗	✗

h-sum rule

$$\int_0^1 dx\, h_1(x) = \int_0^1 dx\, h_L(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off		

- **Analytically & numerically checked the BC and h sum rules, by going beyond the UV-divergent parts**
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Burkhardt-Cottingham type sum rules for light-cone & quasi-PDFs

SB & Metz (in preparation)

Sum rules in perturbative QCD models

BC sum rule

$$\int_0^1 dx\, g_1(x) = \int_0^1 dx\, g_T(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off	✗	✗

h-sum rule

$$\int_0^1 dx\, h_1(x) = \int_0^1 dx\, h_L(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off	✓	✗

- Analytically & numerically checked the BC and h sum rules, by going beyond the UV-divergent parts
- Sum rules are valid in DR scheme

Burkhardt-Cottingham type sum rules for ligh… …si-PDFs

The h-sum rule holds "accidentally" in QTM when cut-off is applied

$$\int_0 dx\, g_1(x) = \int_0^1 dx\, g_T(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off	✗	✗

h-sum rule

$$\int_0^1 dx\, h_1(x) = \int_0^1 dx\, h_L(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off	✓	✗

- **Analytically & numerically checked the BC and h sum rules, by going beyond the UV-divergent parts**
- **Sum rules are valid in DR scheme**

Burkhardt-Cottingham type sum rules for light-cone & quasi-PDFs

SB & Metz (in preparation)

Sum rules in perturbative QCD models

BC sum rule

$$\int_0^1 dx\, g_1(x) = \int_0^1 dx\, g_T(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off	✕	✕

h-sum rule

$$\int_0^1 dx\, h_1(x) = \int_0^1 dx\, h_L(x)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off	✓	✕

- Analytically & numerically checked the BC and h sum rules, by going beyond the UV-divergent parts
- Sum rules are valid in DR scheme
- Sum rules may not hold in cut-off scheme ⟶ Breaking of rotational invariance (basis of existence of sum rules)

Usually, what one does: $\int^{\Lambda} dk_\perp$

Burkhardt-Cottingham type sum rules for light-cone & quasi-PDFs

SB & Metz (in preparation)

Sum rules hold for quasi-PDFs in models, with the same caveat

BC sum rule

$$\int_0^1 dx\, g_1(x) = \int_0^1 dx\, g_T(x)$$

$$\int_{-\infty}^{\infty} dx\, g_{1,\mathrm{Q}}(x;p^3) = \int_{-\infty}^{\infty} dx\, g_{T,\mathrm{Q}}(x;p^3)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off	✗	✗

h-sum rule

$$\int_0^1 dx\, h_1(x) = \int_0^1 dx\, h_L(x)$$

$$\int_{-\infty}^{\infty} dx\, h_{1,\mathrm{Q}}(x;p^3) = \int_{-\infty}^{\infty} dx\, h_{L,\mathrm{Q}}(x;p^3)$$

UV	Quark Target Model	Yukawa Model
DR	✓	✓
Cut-off	✓	✗

- Analytically & numerically checked the BC and h sum rules, by going beyond the UV-divergent parts
- Sum rules are valid in DR scheme
- Sum rules may not hold in cut-off scheme $\longrightarrow$ Breaking of rotational invariance (basis of existence of sum rules)

Burkhardt-Cottingham type sum rules for light-cone & quasi-PDFs

SB & Metz (in preparation)

Sum rules in perturbative QCD models
What if we apply cut-off in a rotationally invariant manner (QFT textbook-like calculations)? • **This technique directly gives us the integral of the PDFs** • **Sum rules hold**

Burkhardt-Cottingham type sum rules for light-cone & quasi-PDFs

SB & Metz (in preparation)

Sum rules in perturbative QCD models

Mass sum rule:

$$\boxed{\int dx\, e(x) = \frac{\partial m}{\partial m_q}}$$

Regulated mass of target

- **Derived regulated mass in QTM & YM, by going beyond UV-divergent terms**
- **Mass sum rules hold with the same caveat for cut-off, as discussed in the context of BC-type sum rules**

Summary

- **Quasi-PDF approach has made it possible to directly access PDFs from lattice QCD**
- **Extracted matching coefficient for** $g_T(x)$, $h_L(x)$ **(&** $e(x)$**) for the first time**
- **Presence of singular zero-modes in perturbative results makes the extraction of matching coefficient non-trivial**
- **We laid the necessary theoretical foundation to deal with zero-modes in matching**
- **First-ever results for** $g_T(x)$ **is now available from lattice QCD**
- **Gearing up for the first lattice QCD extraction of** $h_L(x)$ **&** $e(x)$
- **Profound impact of quasi-PDF approach for quantities that are difficult to access in experiments**