Quark-gluon correlations in the twist-3 TMD using light-front wave functions

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In collaboration with:
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Based on arXiv:1806.10932

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Università di Pavia

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Mapping the proton in 3D

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* Twist-3: a particular TMD

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* Decomposition at twist-3 and singular terms

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* A particular model calculation

Twist-*3*, T-even, unpolarized, chiral odd

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$$\frac{M}{P^+} e(x, \boldsymbol{k}_\perp) = \int \frac{d\xi^- d\boldsymbol{\xi}_\perp}{2(2\pi)^3} e^{ik\cdot\xi} \, \langle P | \overline{\psi}(0) \mathcal{W}(0;\xi) \psi(\xi) | P \rangle \, |_{\xi^+=0}$$

Lorcé, Pasquini, Schweitzer JHEP01(2015)103

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$$\overline{\psi}(0)\mathcal{W}(0;\xi)\psi(\xi) = \overline{\psi}_+(0)\mathcal{W}(0;\xi)\psi_-(\xi) + \overline{\psi}_-(0)\mathcal{W}(0;\xi)\psi_+(\xi)$$

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$$\mathcal{W}(0;\xi)\,\psi_-(\xi))|_{\xi^+=0} = \mathcal{W}_1(0^-,\mathbf{0}_\perp;0^-,\boldsymbol{\xi}_\perp)\psi_-(0^+,0^-,\boldsymbol{\xi}_\perp)$$

$$-\,i\int_{0^-}^{\xi^-} d\zeta^-\mathcal{W}_1(0^-,\mathbf{0}_\perp;\zeta^-,\boldsymbol{\xi}_\perp)\frac{\gamma^+}{2}\left(i\boldsymbol{\gamma}_\perp \cdot \boldsymbol{D}_\perp + m\right)\psi_+(0^+,\zeta^-,\boldsymbol{\xi}_\perp)$$

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For the PDF: Efremov and Schweitzer JHEP 0308(2003)006

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$$e_{tw3} = -\frac{P^+}{M}\frac{g_s}{2}\int \frac{d\xi^- d\boldsymbol{\xi}_\perp}{2(2\pi)^3} e^{ik^+\xi^- - \boldsymbol{k}_\perp\cdot\boldsymbol{\xi}_\perp}$$

$$\times \left(\int_{0^-}^{\xi^-} d\zeta^- \int_{\infty^-}^{\zeta^-} d\eta^- \langle P|\overline{\psi}(0)\mathcal{W}_1(0^-,\mathbf{0}_\perp;\eta^-,\boldsymbol{\xi}_\perp)G^+{}_j(0^+,\eta^-,\boldsymbol{\xi}_\perp) \right.$$

$$\times\, \sigma^{j+}\mathcal{W}_1(\eta^-,\boldsymbol{\xi}_\perp;\zeta^-,\boldsymbol{\xi}_\perp)\psi(0^+,\zeta^-,\boldsymbol{\xi}_\perp)|P\rangle$$

$$+ \int_{0^-}^{\xi^-} d\zeta^- \int_{0^-}^{\infty^-} d\eta^- \langle P|\overline{\psi}(0)\mathcal{W}_1(0^-,\mathbf{0}_\perp;\eta^-,\mathbf{0}_\perp)G^+{}_j(0^+,\eta^-,\mathbf{0}_\perp)$$

$$\left. \times\, \sigma^{j+}\mathcal{W}_1(\eta^-,\mathbf{0}_\perp;\zeta^-,\boldsymbol{\xi}_\perp)\psi(0^+,\zeta^-,\boldsymbol{\xi}_\perp)|P\rangle \right)$$

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In light-cone gauge

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$$e(x, \boldsymbol{k}_\perp) = \frac{\delta(x)}{2M} \int \frac{d\boldsymbol{\xi}_\perp}{(2\pi)^2} e^{-i\boldsymbol{k}_\perp \cdot \boldsymbol{\xi}_\perp} \langle P|\overline{\psi}(0)\mathcal{W}(0; 0^+, 0^-, \boldsymbol{\xi}_\perp)\psi(0^+, 0^-, \boldsymbol{\xi}_\perp)|P\rangle$$
$$+ \tilde{e}(x, \boldsymbol{k}_\perp) + \frac{m}{xM} f_1(x, \boldsymbol{k}_\perp)$$
$$- \delta(x) \int_{-1}^{1} dy \left(\tilde{e}(y, \boldsymbol{k}_\perp) + \frac{m}{yM} f_1(y, \boldsymbol{k}_\perp)\right)$$

In light-cone gauge

Pure twist-3

$$
\begin{aligned}
e(x,\boldsymbol{k}_\perp) &= \frac{\delta(x)}{2M}\int \frac{d\boldsymbol{\xi}_\perp}{(2\pi)^2} e^{-i\boldsymbol{k}_\perp\cdot\boldsymbol{\xi}_\perp}\, \langle P|\overline{\psi}(0)\mathcal{W}(0;0^+,0^-,\boldsymbol{\xi}_\perp)\psi(0^+,0^-,\boldsymbol{\xi}_\perp)|P\rangle \\
&+ \tilde{e}(x,\boldsymbol{k}_\perp) + \frac{m}{xM} f_1(x,\boldsymbol{k}_\perp) \\
&- \delta(x)\int_{-1}^{1} dy\, \left(\tilde{e}(y,\boldsymbol{k}_\perp) + \frac{m}{yM} f_1(y,\boldsymbol{k}_\perp)\right)
\end{aligned}
$$

In light-cone gauge

Pure twist-3 Twist-2

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&+ \tilde{e}(x, \boldsymbol{k}_\perp) + \frac{m}{xM} f_1(x, \boldsymbol{k}_\perp) \\
&- \delta(x) \int_{-1}^{1} dy \left(\tilde{e}(y, \boldsymbol{k}_\perp) + \frac{m}{yM} f_1(y, \boldsymbol{k}_\perp) \right)
\end{aligned}
$$

In light-cone gauge

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$$+\,\tilde{e}(x,\boldsymbol{k}_\perp) + \frac{m}{xM} f_1(x,\boldsymbol{k}_\perp)$$
$$-\,\delta(x)\int_{-1}^{1} dy\,\left(\tilde{e}(y,\boldsymbol{k}_\perp) + \frac{m}{yM} f_1(y,\boldsymbol{k}_\perp)\right)$$

$$\int dx d\boldsymbol{k}_\perp\; e(x,\boldsymbol{k}_\perp) = \frac{1}{2M}\langle P|\overline{\psi}(0)\psi(0)|P\rangle$$

Trace of the **quark-gluon-quark** correlator

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$$\tilde{e}(x, \boldsymbol{k}_\perp) \propto \mathcal{F}.\mathcal{T}.\Big\{ \langle P|\overline{\psi}(0)\Big(A_{\perp,j}(\xi) - A_{\perp,j}(0)\Big)\sigma^{j+}\psi(\xi)|P\rangle \Big\}$$

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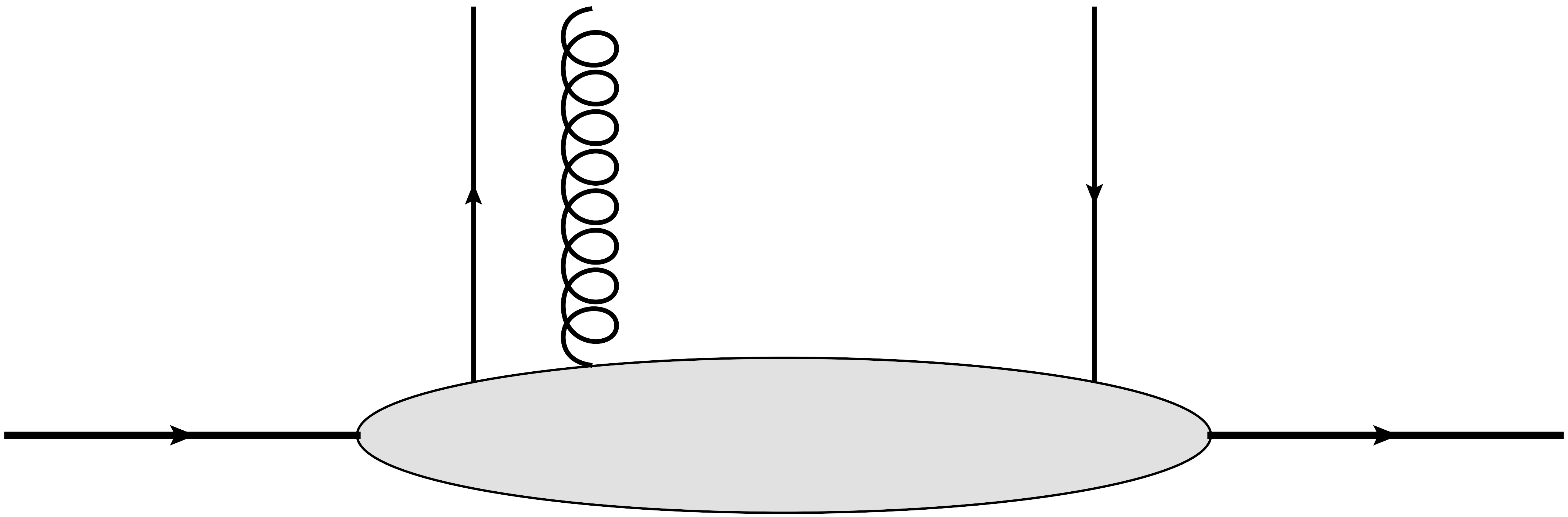

Light-front Fock expansion of the proton state

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$$|P, \Lambda\rangle = \Psi_{3q}^{\Lambda}|3q\rangle + \Psi_{3q+g}^{\Lambda}|3q+g\rangle + \cdots$$

Brodsky, Pauli Phys.Rept.301(1998)299

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Light-front wave functions: probabilities amplitudes

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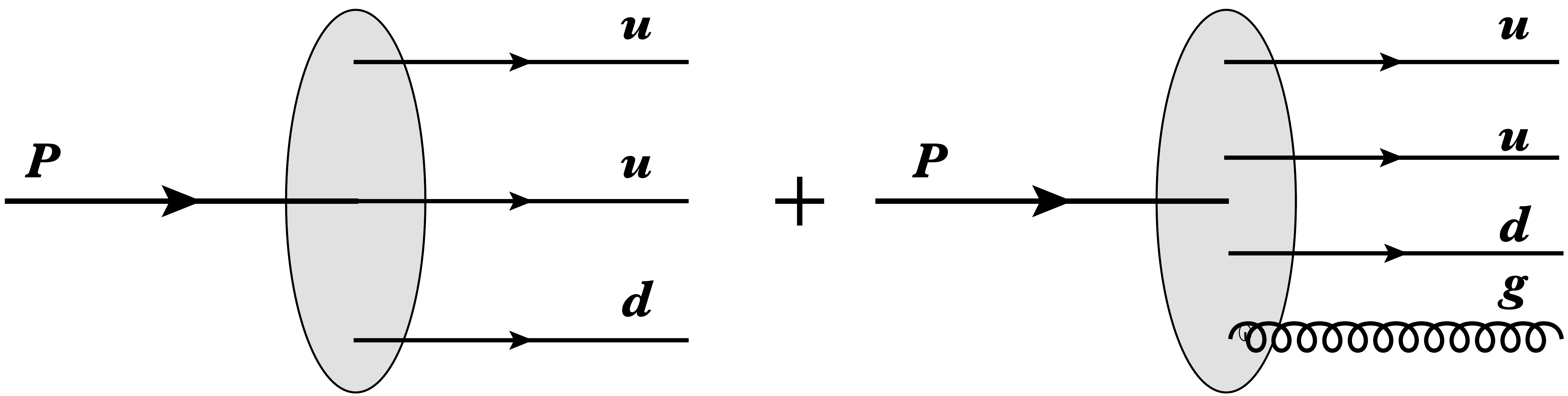

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Parametrize them in terms of functions
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Ji, Ma, Yuan NPB652(2003)383

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3 independent (& leading) LFWAs for L_z=0 of 3q+g

Braun et al. PRD83(2011)094023

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$$\Psi^{\downarrow}(1,2,3,4) \qquad \Psi^{1,\uparrow}(1,2,3,4) \qquad \Psi^{2,\uparrow}(1,2,3,4)$$

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Opposite polarization
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Braun et al. PRD83(2011)094023

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$$\begin{aligned}
\tilde{e}^u(x,k_\perp) = \frac{4g_s}{Mx\sqrt{3}} \int \frac{[dx]_{1234}[dk]_{1234}}{\sqrt{x_4}} \Re\Bigg\{ &-\delta(x-x_4-x_1)\delta^2(\boldsymbol{k}_\perp-\boldsymbol{k}_{\perp 4}-\boldsymbol{k}_{\perp 1}) \\
\times \Bigg[&\left(4\Psi^{(0)*}(-2-3,3,2) + 2\Psi^{(0)*}(2,3,-2-3)\right)\Psi^{1\uparrow}(1,2,3,4) \\
+ &\left(2\Psi^{(0)*}(-2-3,2,3) + \Psi^{(0)*}(3,2,-2-3)\right)\Psi^{2\uparrow}(1,2,3,4) \\
- &\,2\Psi^{(0)*}(2,-2-3,3)\Psi^{\downarrow}(1,2,3,4)\Bigg] + \delta(x-x_4-x_2)\delta^2(\boldsymbol{k}_\perp-\boldsymbol{k}_{\perp 4}-\boldsymbol{k}_{\perp 2}) \\
\times &\left[2\Psi^{(0)*}(-1-3,1,3)\Psi^{2\uparrow}(1,2,3,4) - \Psi^{(0)*}(1,-1-3,3)\Psi^{\downarrow}(1,2,3,4)\right] \\
+ &\,\delta(x-x_4-x_3)\delta^2(\boldsymbol{k}_\perp-\boldsymbol{k}_{\perp 4}-\boldsymbol{k}_{\perp 3})\,\Psi^{(0)*}(-1-2,1,2)\Psi^{1\uparrow}(1,2,3,4)\Bigg\}
\end{aligned}$$

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Fock state expansion up to the 3q+g state
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An explicit form for the LFWFs is required

$$\Psi_N^{L=0} = \phi(x_1, ..., x_N)\Omega_N\left(\{x_i\}, \{\boldsymbol{k}_{\perp,i}\}, \{a_i\}\right)$$

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$$\int [d\boldsymbol{k}_\perp]_{1,\dots,N}\ \Omega_N\left(\{x_i\}, \{\boldsymbol{k}_{\perp,i}\}, \{a_i\}\right) = 1$$

Leading twist distribution amplitudes

Braun et al, Phys.RevD83, 094023 (2011)

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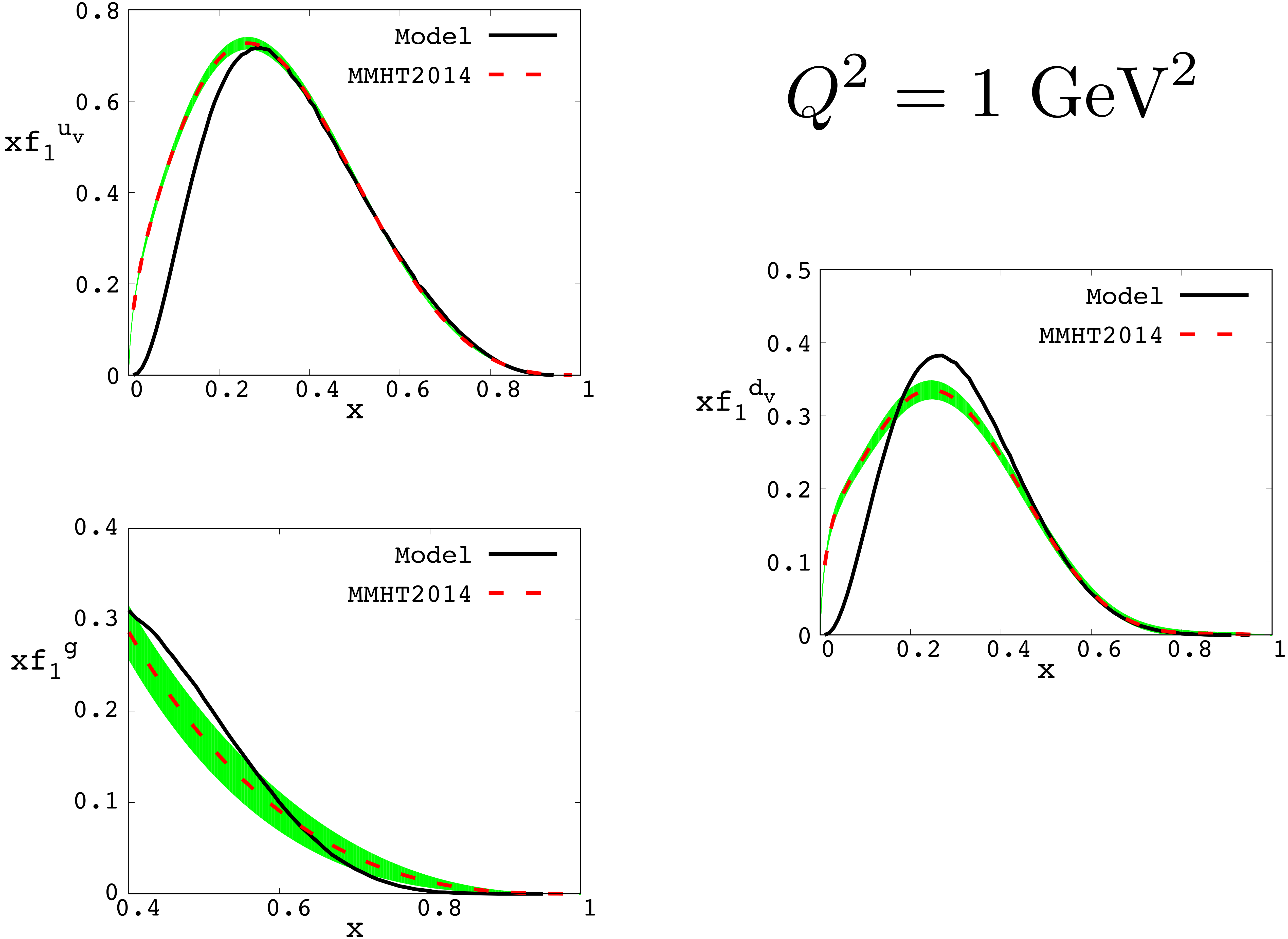
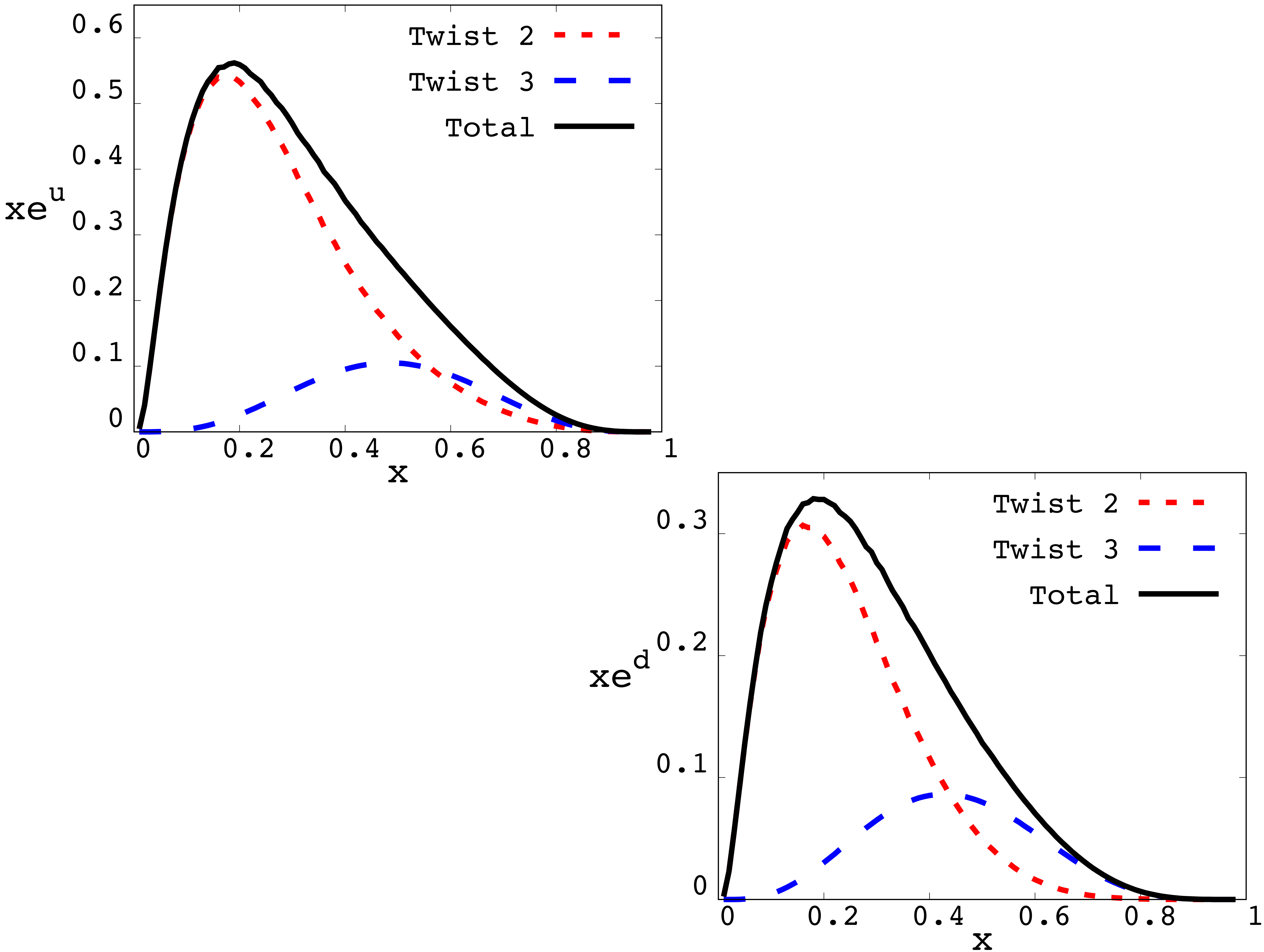
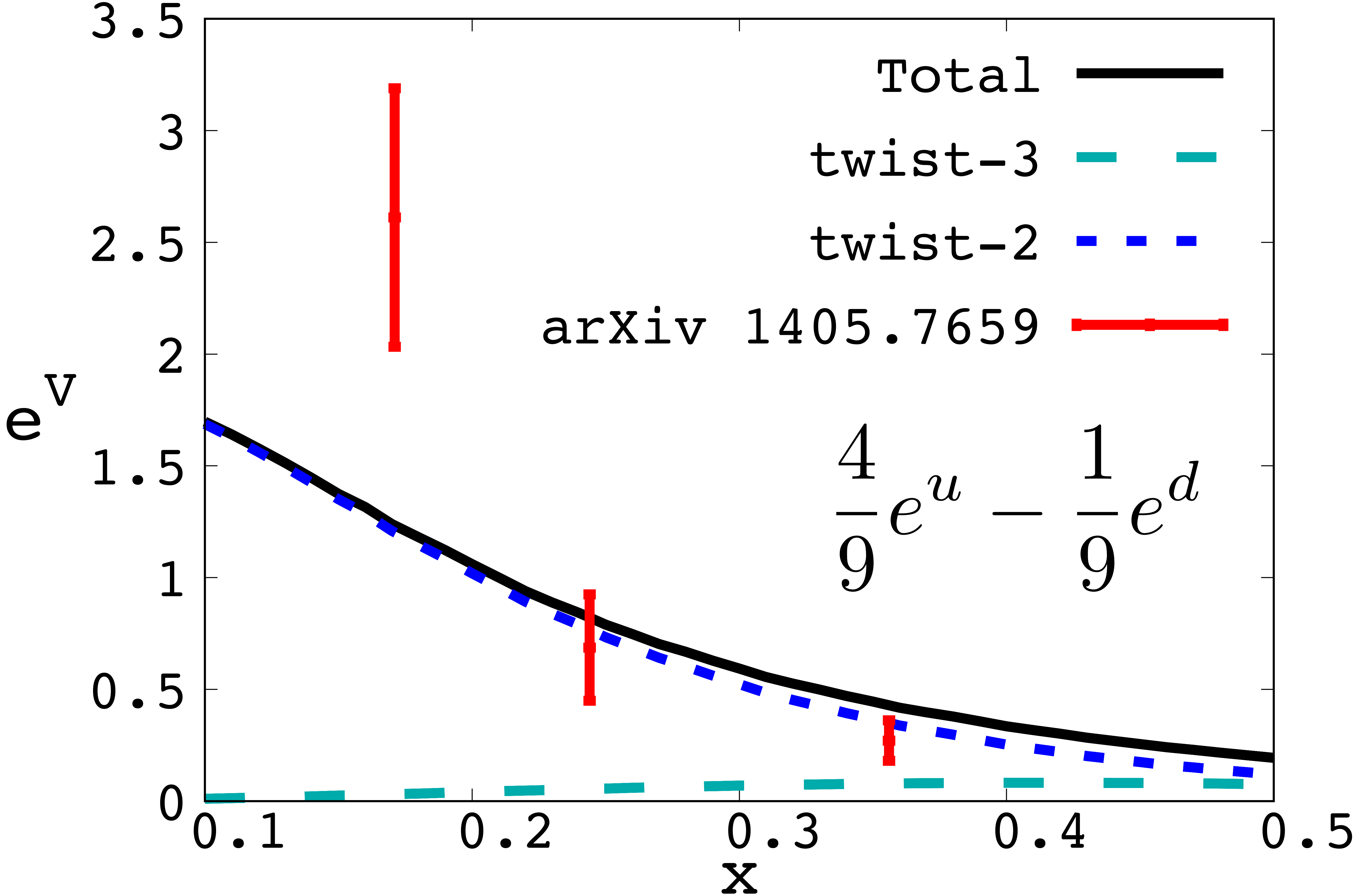
$$a_i = a_N \quad \forall i = 1, ..., N$$



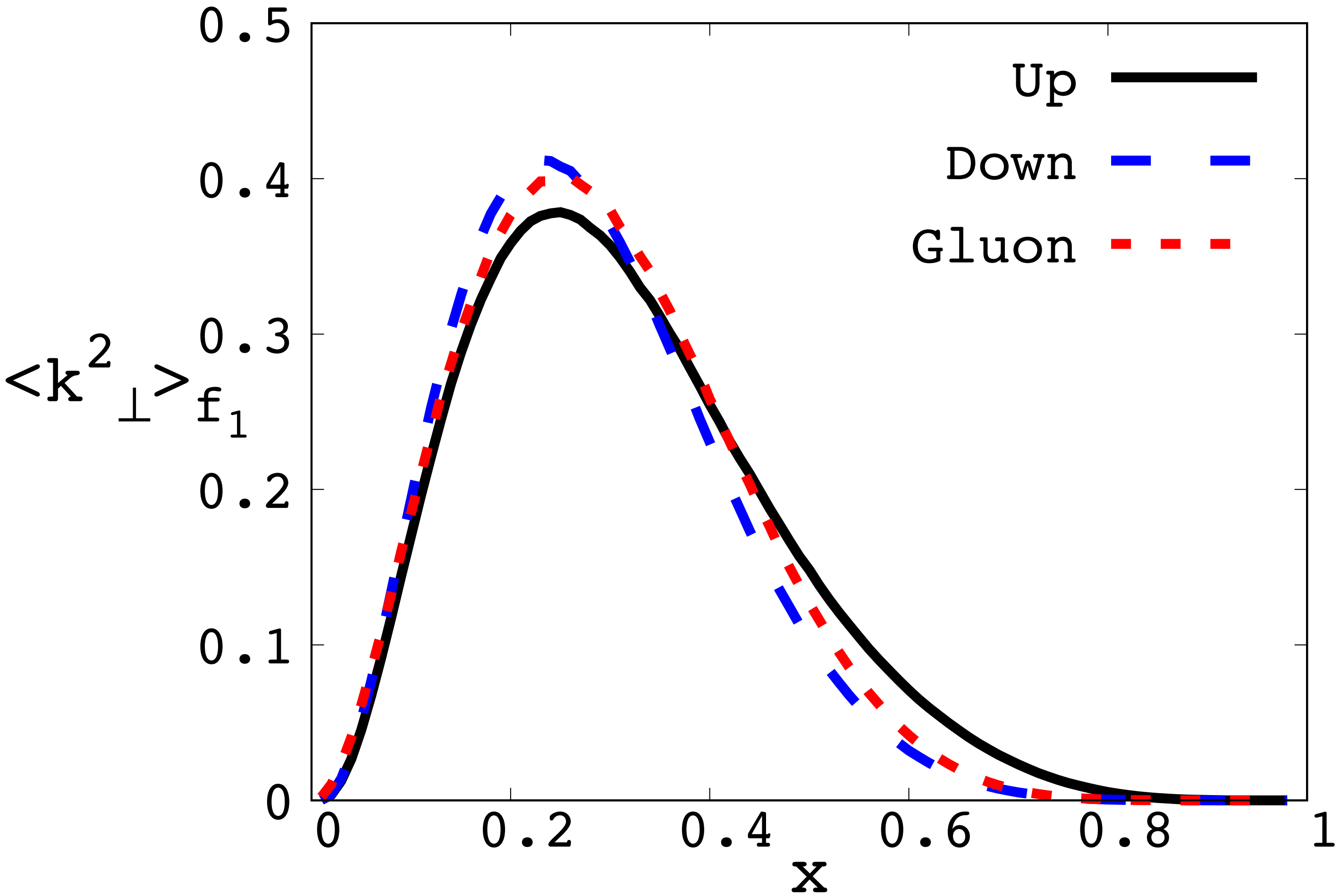
$Q^2 = 1\ \mathrm{GeV}^2$
Model
MMHT2014
$xf_1^{u_v}$
$xf_1^{d_v}$
xf_1^{g}
x
0
0.2
0.4
0.6
0.8
1
0.1
0.3
0.5

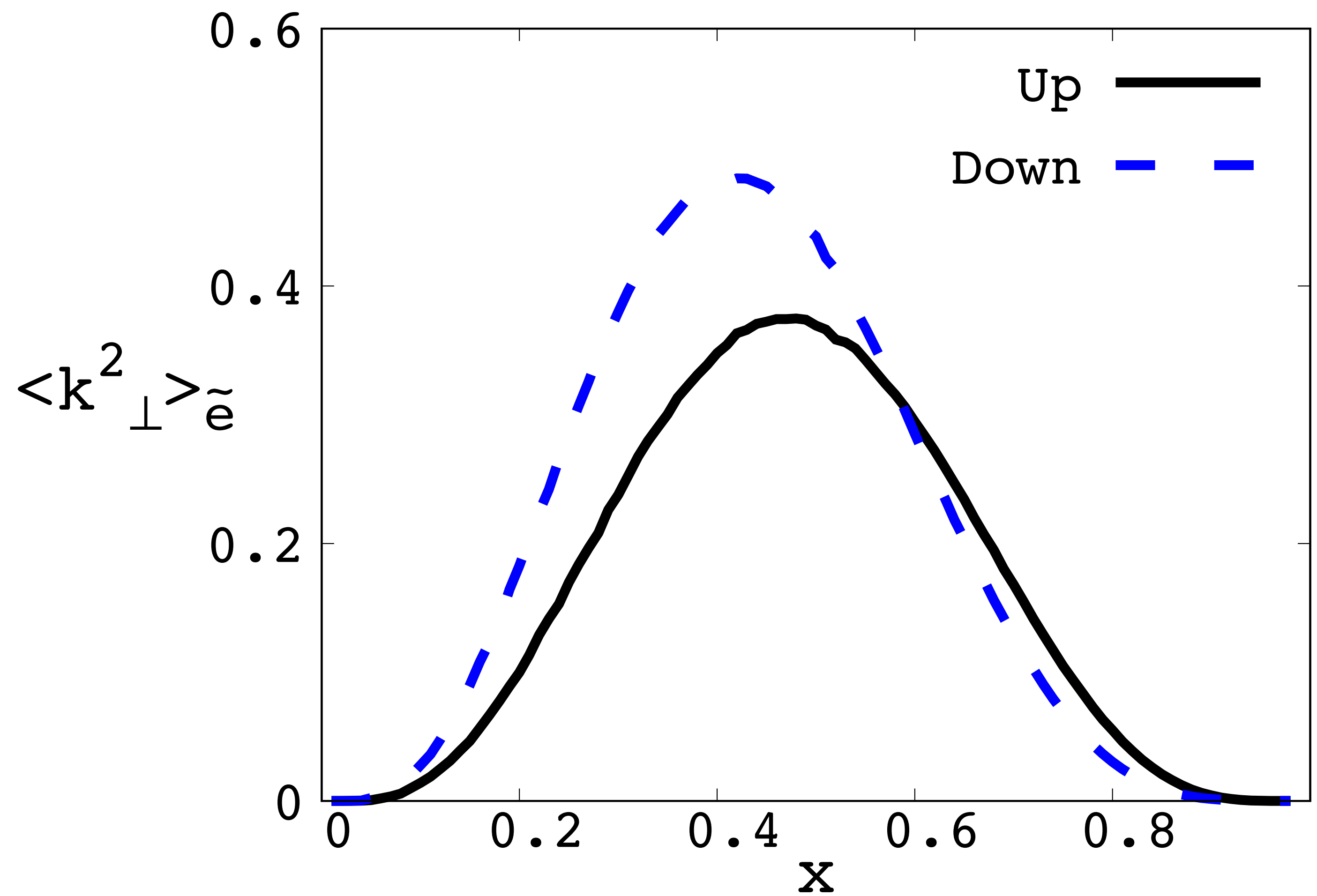


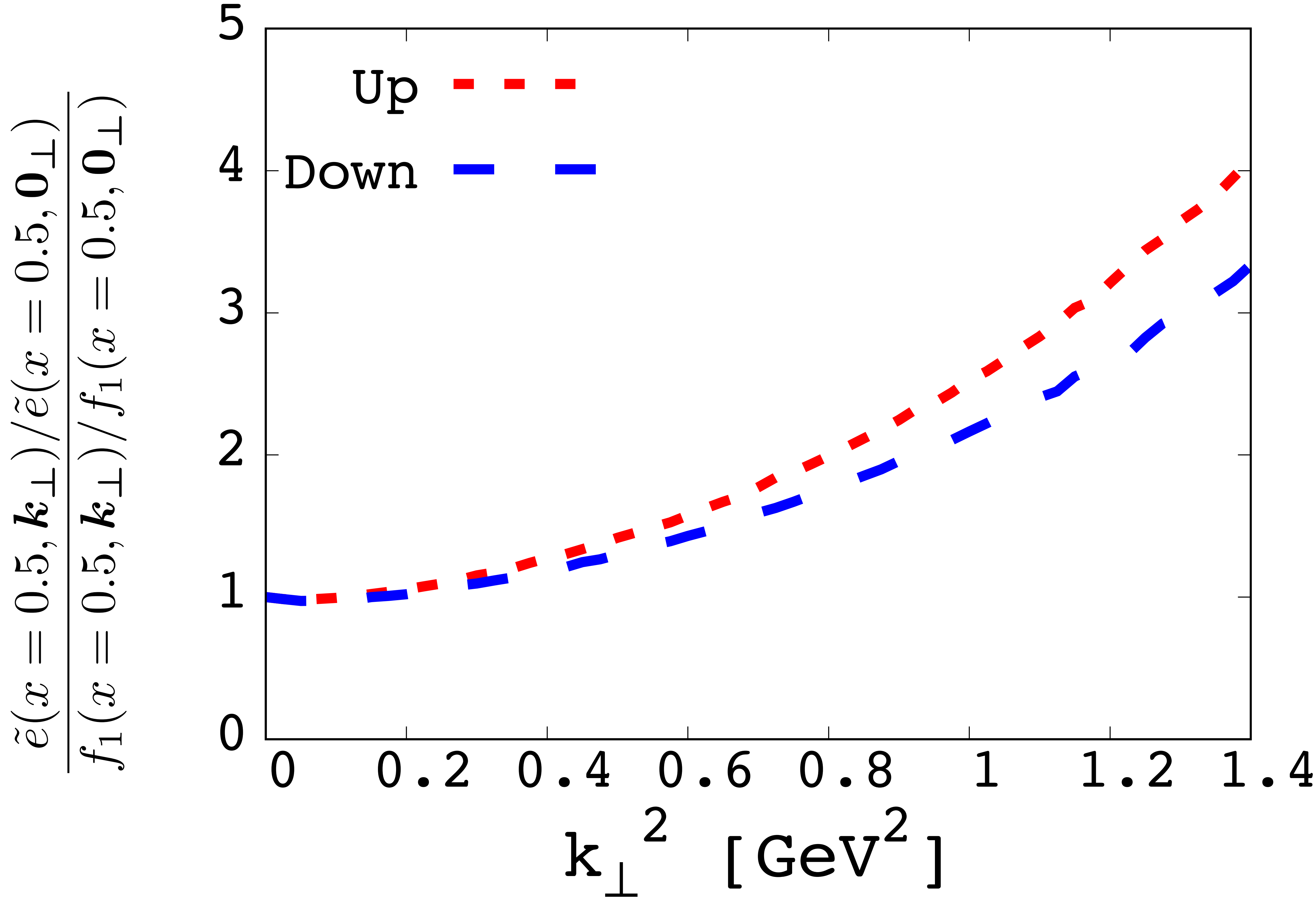
Twist 2
Twist 3
Total
xe^u
x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.2
0.4
0.6
0.8
1
Twist 2
Twist 3
Total
xe^d
x
0
0.1
0.2
0.3
0.2
0.4
0.6
0.8
1



Total
twist-3
twist-2
arXiv 1405.7659
$\frac{4}{9}e^u - \frac{1}{9}e^d$
e^V
x
3.5
3
2.5
2
1.5
1
0.5
0
0.1
0.2
0.3
0.4
0.5


0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
x
$<k^2_\perp>_{f_1}$
Up
Down
Gluon


0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
x
$<k^2_\perp>_{\tilde{e}}$
Up
Down



$\frac{\tilde{e}(x=0.5,\boldsymbol{k}_\perp)/\tilde{e}(x=0.5,\mathbf{0}_\perp)}{f_1(x=0.5,\boldsymbol{k}_\perp)/f_1(x=0.5,\mathbf{0}_\perp)}$
Up
Down
0
1
2
3
4
5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$k_\perp^2$ [GeV^2]

SUMMARY

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* The pure Twist-3 contribution is not-negligile, at least in the model

BACKUP

Model

$$\phi = 120 f_N x_1 x_2 x_3 \left(1 + A(x_1 - x_3) + B(x_1 + x_3 - 2x_2)\right)$$

$$\phi^{\downarrow} = -\frac{M}{96 g_s} \frac{8!}{2} \lambda_1^g x_1 x_2 x_3 x_4^2$$

$$\psi = -\frac{M}{96 g_s} \frac{8!}{4} \left(\lambda_2^g + \lambda_3^g\right) x_1 x_2 x_3 x_4^2$$

$$\theta = -\frac{M}{96 g_s} \frac{8!}{4} \left(\lambda_2^g - \lambda_3^g\right) x_1 x_2 x_3 x_4^2$$

PARAMETERS

$$f_N, \quad A, \quad B, \quad a_3,$$

$$\lambda_1, \quad \lambda_2, \quad \lambda_2, \quad \frac{a_4}{a_3}$$

$$m_q, \quad m_g,$$

$$F_{\mathrm{UU}}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left[\ldots - \frac{\boldsymbol{P}_h\cdot\boldsymbol{k}_\perp}{|\boldsymbol{P}_h|M}\left(xf^\perp D_1 + \frac{M_h}{M}h_1^\perp\frac{\tilde{H}}{z}\right)\right]$$

$$F_{\mathrm{LU}}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[\ldots - \frac{\boldsymbol{P}_h\cdot\boldsymbol{p}_\perp}{|\boldsymbol{P}_h|M}\left(xeH_1^\perp + \frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}\right)\right]$$

SIDIS