Transverse-momentum-dependent gluon distribution in a spectator model

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in collaboration with
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HAS QCD
HADRONIC STRUCTURE AND
QUANTUM CHROMODYNAMICS

Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

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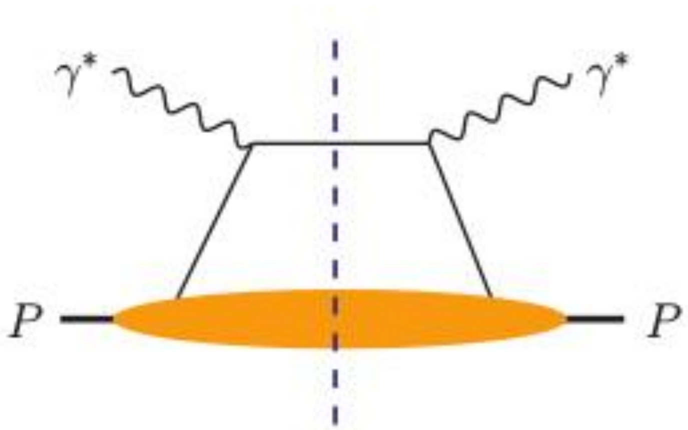
Parton densities: an overview

p_T - integrated

Collinear PDFs

- Inclusive processes
- p_T ~ hardest scale



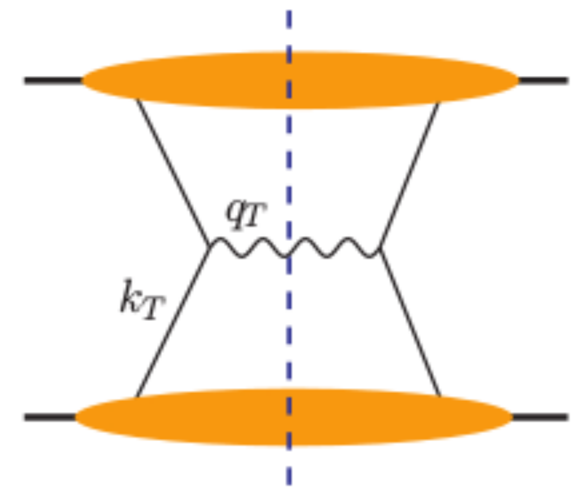
GPDs

- Exclusive processes
- *Skewness* effects

p_T - unintegrated

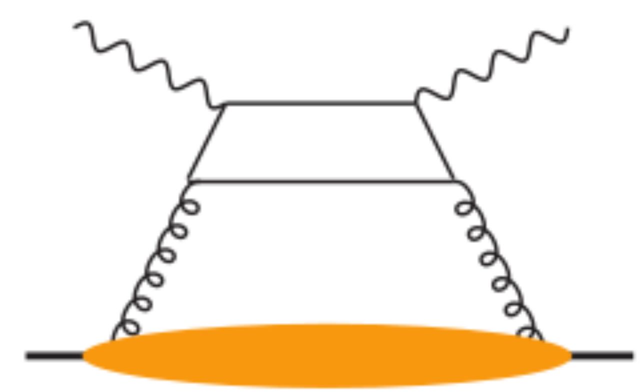
TMDs

- (Semi-)inclusive processes
- p_T << hardest scale



UGDs

- *High-energy factorization* (**BFKL**)
- Small x, large p_T



Gluon TMDs at twist-2

gluon pol.

nucleon pol.

	U	circ.	lin.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

T-even

T-odd

Gluon TMDs at twist-2

unpolarized TMD

Boer-Mulders

nucleon pol. \ gluon pol.	U	circ.	lin.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

T-even

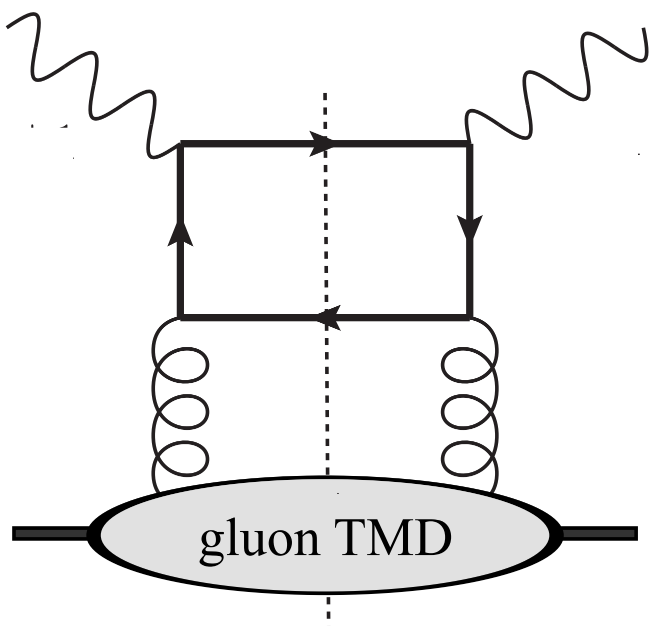
T-odd

helicity TMD

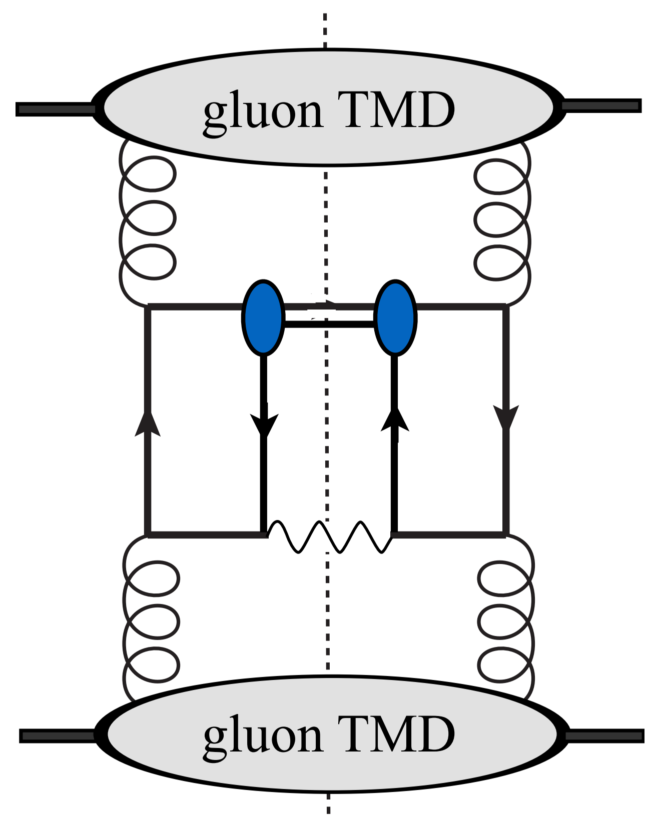
worm-gear

Gluon TMDs:
a largely unexplored territory

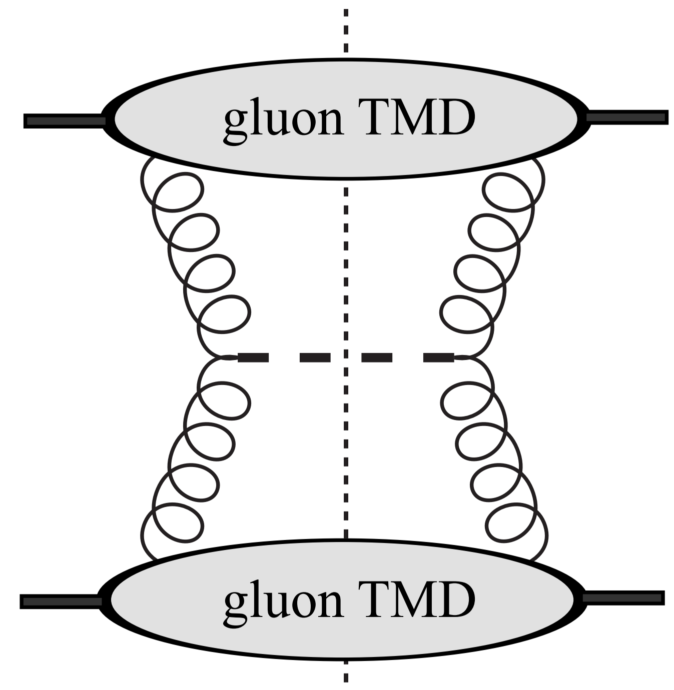
$ep \to e + \text{jet} + \text{jet} + X$



$pp \to J/\Psi + \gamma + X$



$pp \to H(\eta_c) + X$

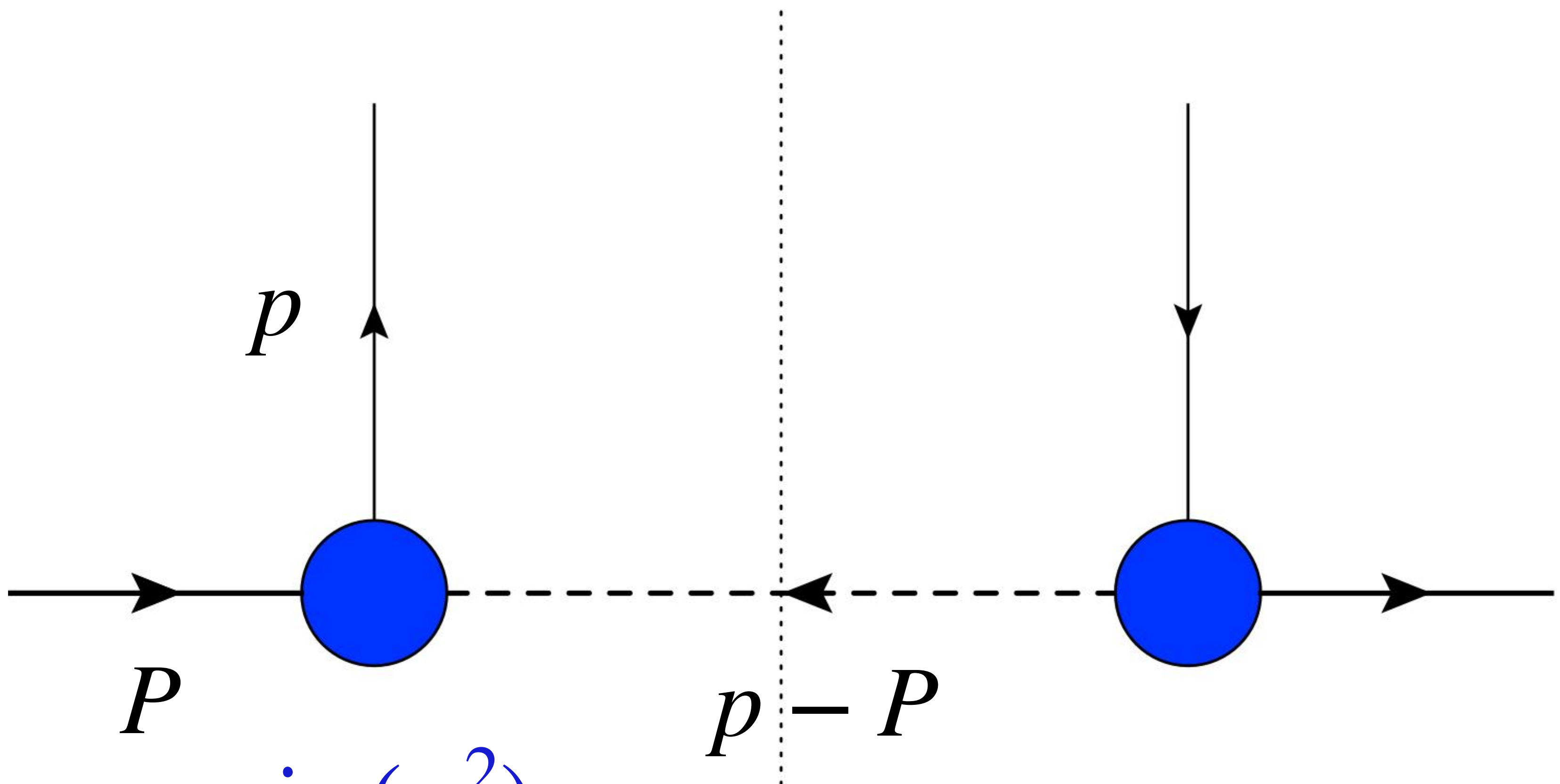


[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang, *Phys. Rev. Lett.* **108** (2012) 032002]
[W.J. den Dunnen, J.P. Lansberg, C. Pisano, M. Schlegel, *Phys. Rev. Lett.* **112** (2014) 21200]
[J.P. Lansberg, C. Pisano, F. Scarpa, M. Schlegel, *Phys. Lett. B* **784** (2018) 217]
[A. Bacchetta, D. Boer, C. Pisano, P. Taels, arXiv:1809.02056 [hep-ph]]
[U. D'Alesio, C. Flore, F. Murgia, C. Pisano, P. Taels, arXiv:1811.02970 [hep-ph]]

Motivation

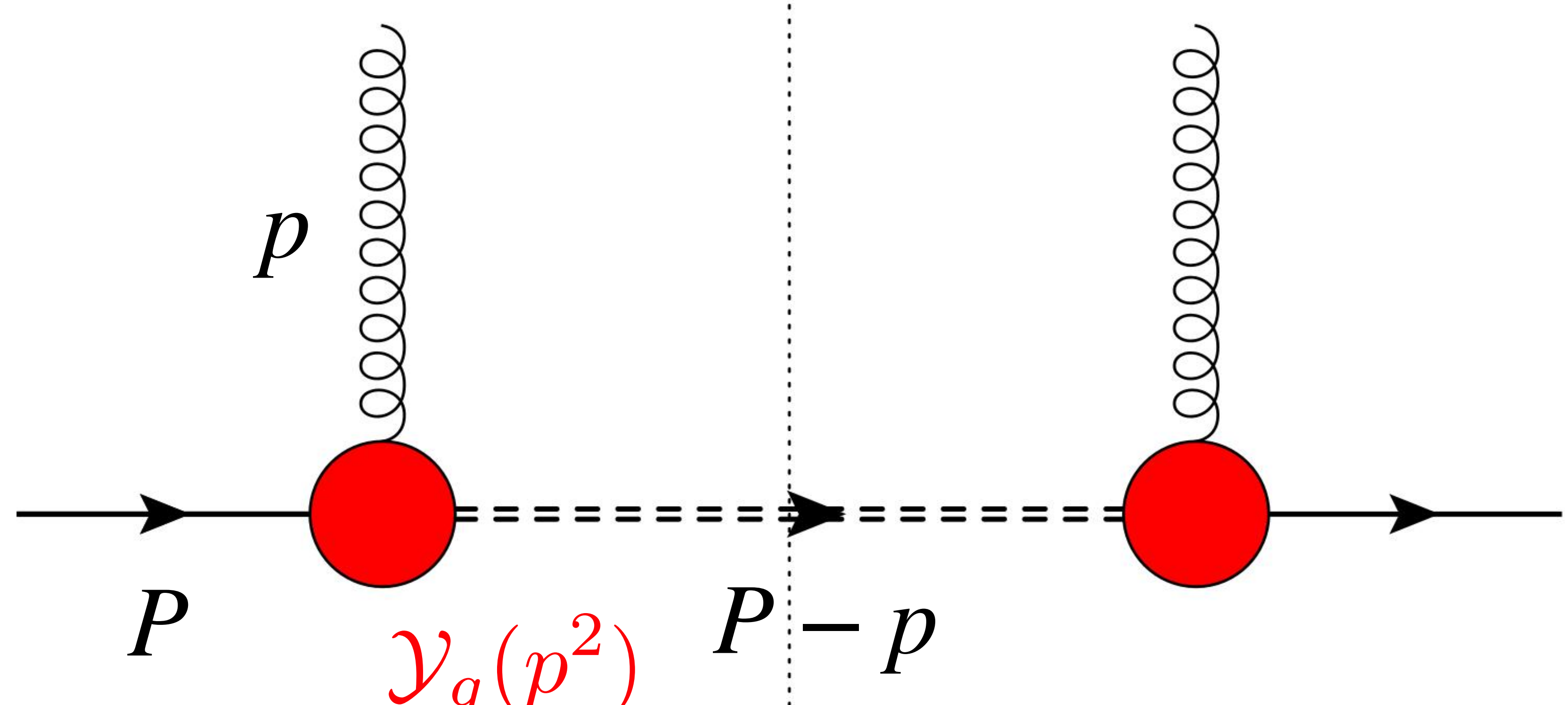
- Need for a flexible model, suited to phenomenology
- Concurrent enhancement of quark-TMD description
- Consistent framework for all parton TMDs

Effective vertices



$$ig_s(p^2)$$

$$i\frac{g_a(p^2)}{\sqrt{2}}\gamma^\mu\gamma^5$$



Quark and gluon correlators

Scalar-diquark spectator

$$\Phi_s = \frac{1}{2(2\pi)^3(1-x)P^+}\frac{g_s^2}{(p^2-m_q^2)^2}(\not{p}+m_q)\frac{1+\gamma^5\not{S}}{2}(\not{P}+M_H)(\not{p}+m_q)$$

Axial-vector-diquark spectator

$$\Phi_a = \frac{1}{2(2\pi)^3(1-x)P^+}\frac{g_a^2}{(p^2-m_q^2)^2}(\not{p}+m_q)\frac{\gamma^5\gamma_\mu}{\sqrt{2}}\frac{1+\gamma^5\not{S}}{2}(\not{P}+M_H)\frac{\gamma^5\gamma_\nu}{\sqrt{2}}(\not{p}+m_q)d_T^{\mu\nu}(P-p)$$

Spin-1/2 spectator (gluon)

$$\Phi_g = \frac{1}{2(2\pi)^3(1-x)P^+}Tr\left[(\not{P}+M_H)\frac{1+\gamma^5\not{S}}{2}G^*_{\mu\rho}(p)G^{\nu\sigma}(p)\mathcal{Y}_g^{\rho *}\mathcal{Y}_{g\sigma}(\not{P}-\not{p}+M_X)\right]$$

$$\mathcal{Y}_g^\mu = g_1(p^2)\gamma^\mu + i\frac{g_2(p^2)}{2M_H}\sigma^{\mu\nu}p_\nu$$

Quark and gluon correlators

Scalar-diquark spectator

$$\Phi_s = \frac{1}{2(2\pi)^3(1-x)P^+}\frac{g_s^2}{(p^2-m_q^2)^2}(\not{p}+m_q)\frac{1+\gamma^5\not{S}}{2}(\not{P}+M_H)(\not{p}+m_q)$$

Axial-vector-diquark spectator

$$\Phi_a = \frac{1}{2(2\pi)^3(1-x)P^+}\frac{g_a^2}{(p^2-m_q^2)^2}(\not{p}+m_q)\frac{\gamma^5\gamma_\mu}{\sqrt{2}}\frac{1+\gamma^5\not{S}}{2}(\not{P}+M_H)\frac{\gamma^5\gamma_\nu}{\sqrt{2}}(\not{p}+m_q)d_T^{\mu\nu}(P-p)$$

Spin-1/2 spectator (gluon)

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$$\mathcal{Y}_g^\mu = g_1(p^2)\gamma^\mu + i\frac{g_2(p^2)}{2M_H}\sigma^{\mu\nu}p_\nu$$

Selection out of 12 Dirac structures

State of the art

- First calculation of leading-twist T-even quark TMDs with scalar and axial-vector di-quarks

  [R. Jakob, P. J. Mulders, and J. Rodrigues, Nucl. Phys. **A626**, 937 (1997)]

- Gluon TMD PDFs and FFs

  [P.J. Mulders, J. Rodrigues, Phys. Rev. **D63** (2001) 094021]
  [J. Rodrigues, PhD thesis (2001)]

- Complete calculation of all the leading-twist TMDs with scalar di-quarks

  [S. Meissner, A. Metz, and K. Goeke, Phys. Rev. **D76**, 034002 (2007)]

- Inclusion of different axial-vector di-quark polarization states and nucleon-parton-spectator form factors

  (fit to PDF parametrizations) [A. Bacchetta, F. Conti, M. Radici, Phys. Rev. **D78** (2008) 074010]
  (application on azimuthal asymmetries) [A. Bacchetta, M. Radici, F. Conti, M. Guagnelli, Eur. Phys. J. **A45** (2010) 373-388]

How to improve the description?

Spectator-system spectral-mass function

spectral-mass function

$$F(x, \boldsymbol{p}_T^2) = \int \mathrm{d}M_X \, \rho_X(M_X) \, \hat{F}(x, \boldsymbol{p}_T^2; M_X)$$

spectator-model TMD

(inspiring idea) [G.R. Goldstein, J.O.G. Hernandez, S. Liuti, Phys.Rev. **D84** (2011) 034007]

$$\rho_X\left(M_X; \{X^{(\mathrm{pars})}\} \equiv \{A, B, b, c, C, M_D, \sigma\}\right) = \mu^{2b}\left[\frac{A}{B+\mu^{2c}} + \frac{C}{\pi\sigma} e^{-\frac{(M_X - M_D)^2}{\sigma^2}}\right]$$

low-x (high-μ^2) tail $\propto (b - c)$

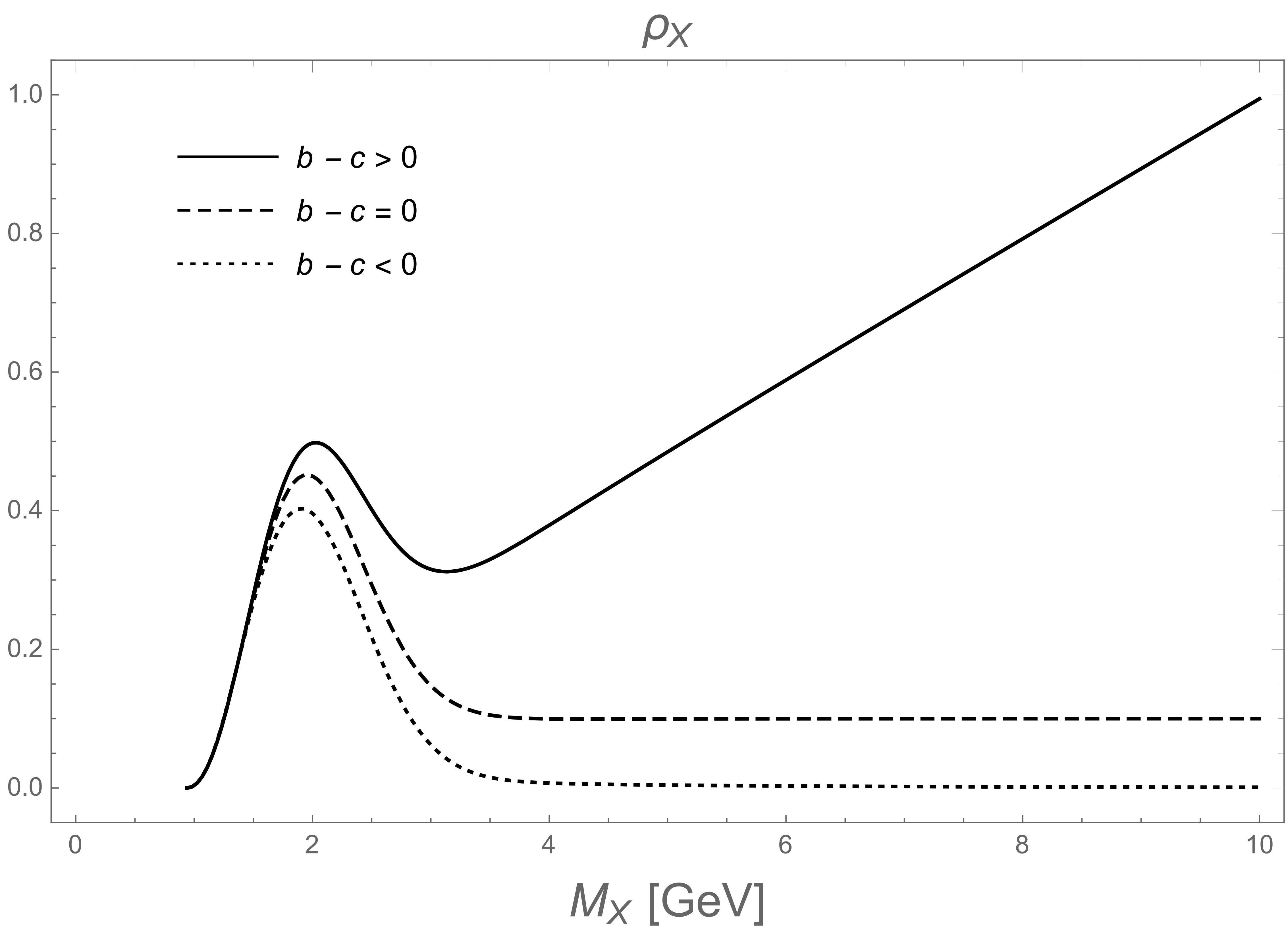
2N-quark contribution

$$\mu^2 = M_X^2 - (M_H - m_{q/g})^2$$

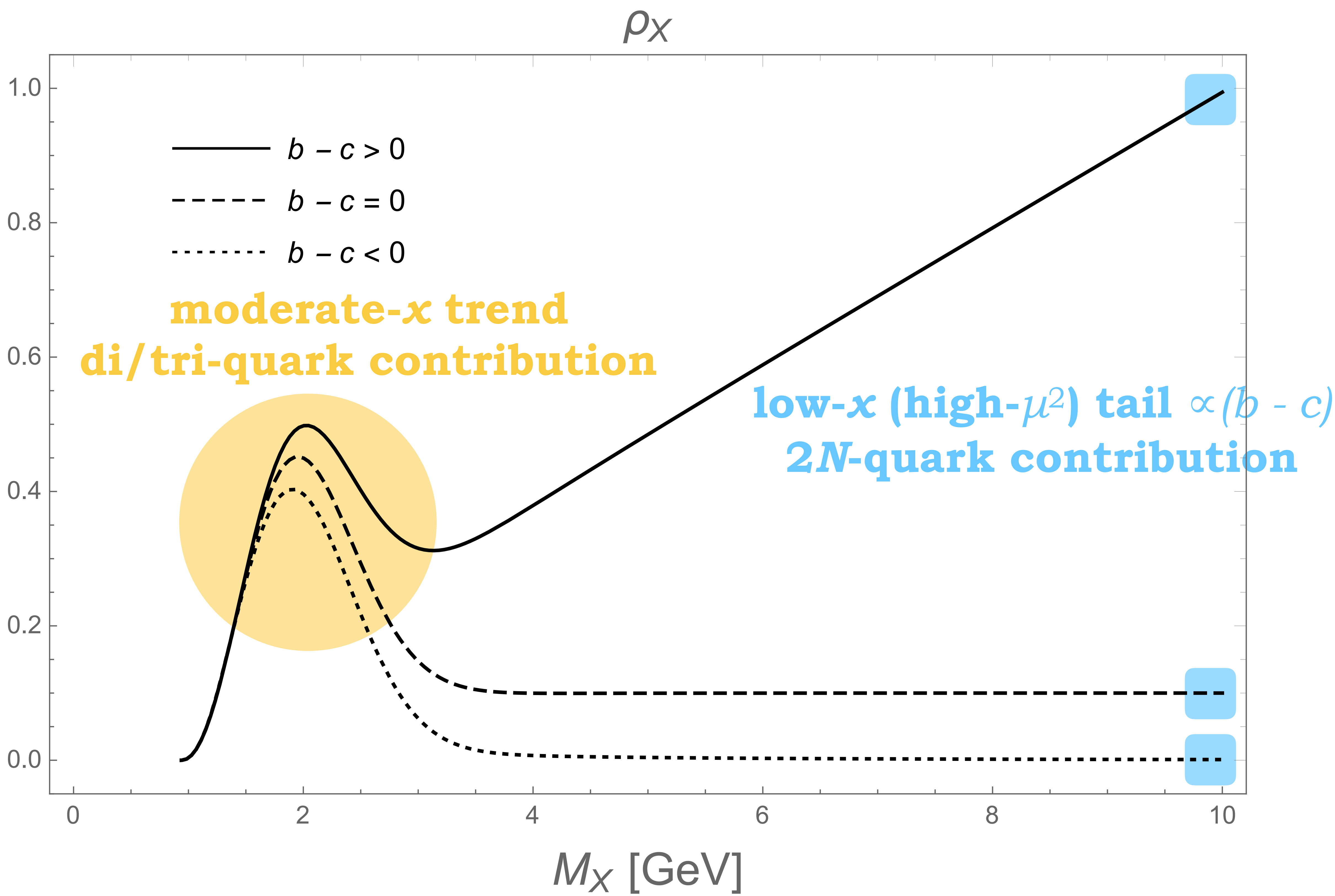
moderate-x trend

di/tri-quark contribution

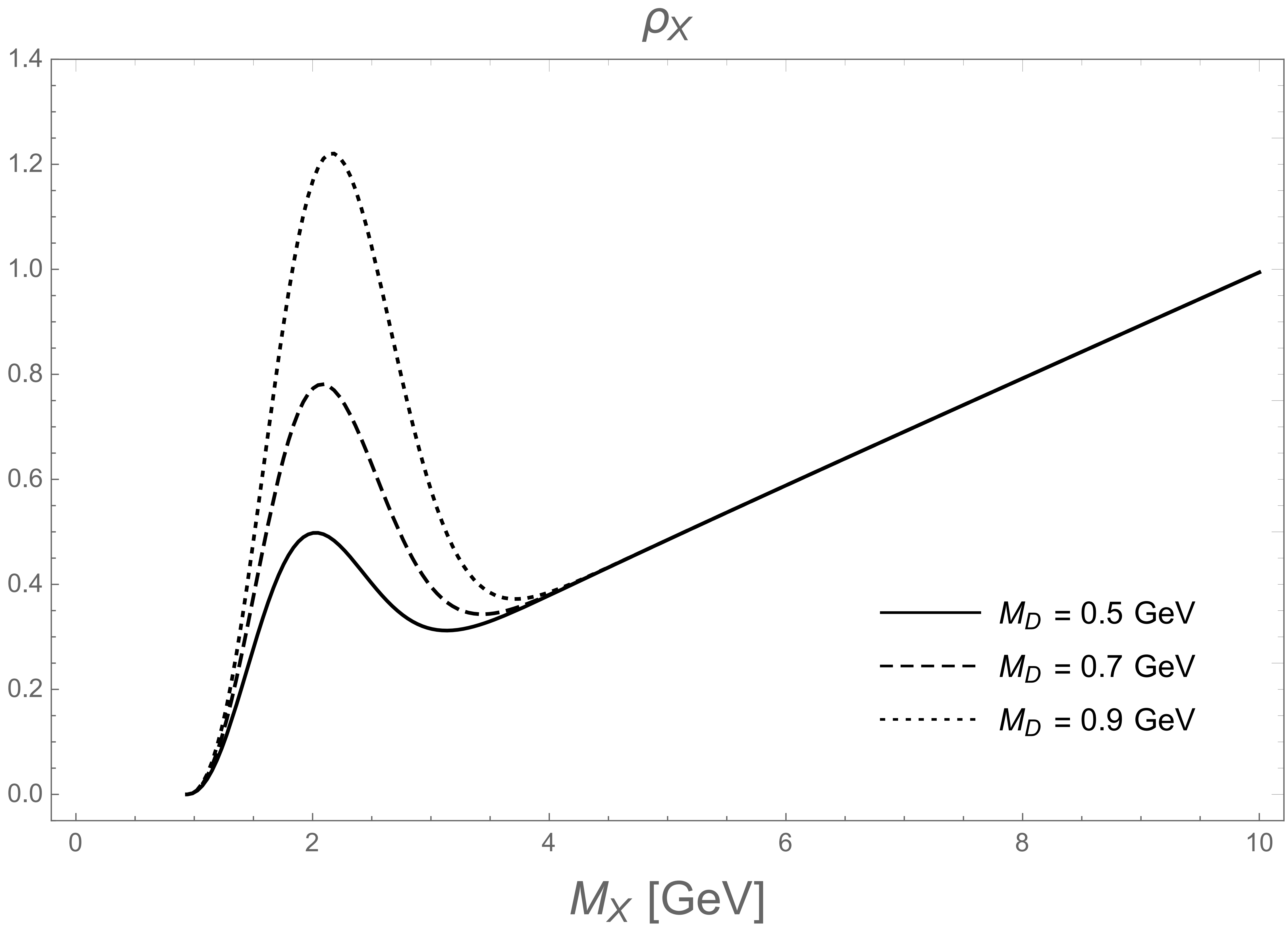
Spectral function vs *(b - c)*



Spectral function vs *(b - c)*



Spectral function vs M_D



Metodology

- Calculate TMDs from parton correlators
- Weight TMDs over M_X via spectral function
- Integrate over parton p_T to get PDFs
- Perform a first explorative analysis:
  - ☑ **Guess-fit** of unpolarized PDFs
  - ☑ **Prediction** for helicity PDFs

Our parametrization

$$F^{u_v}(x,\boldsymbol{p}_T^2) = \int \mathrm{d}M_s^{u_v}\rho_s\left(M_s^{u_v}\right)\hat{F}_s^{u_v}(x,\boldsymbol{p}_T^2) + \int \mathrm{d}M_a^{u_v}\rho_a\left(M_a^{u_v}\right)\hat{F}_a^{u_v}(x,\boldsymbol{p}_T^2)$$

$$F^{d_v}(x,\boldsymbol{p}_T^2) = \int \mathrm{d}M_a^{d_v}\rho_a\left(M_a^{d_v}\right)\hat{F}_a^{d_v}(x,\boldsymbol{p}_T^2)$$

$$F^{\,\mathrm{sea}}(x,\boldsymbol{p}_T^2) = \int \mathrm{d}M_s^{\mathrm{sea}}\rho_s\left(M_s^{\mathrm{sea}}\right)\hat{F}_s^{\,\mathrm{sea}}(x,\boldsymbol{p}_T^2)$$

$$F^{g}(x,\boldsymbol{p}_T^2) = \int \mathrm{d}M^{g}\rho_g\left(M^{g}\right)\hat{F}^{g}(x,\boldsymbol{p}_T^2)$$

Our parametrization

$$F^{u_v}(x,\boldsymbol{p}_T^2) = \int \mathrm{d}M_s^{u_v}\,\rho_s\,(M_s^{u_v})\,\hat{F}_s^{u_v}(x,\boldsymbol{p}_T^2) + \int \mathrm{d}M_a^{u_v}\,\rho_a\,(M_a^{u_v})\,\hat{F}_a^{u_v}(x,\boldsymbol{p}_T^2)$$

$$F^{d_v}(x,\boldsymbol{p}_T^2) = \int \mathrm{d}M_a^{d_v}\,\rho_a\,\left(M_a^{d_v}\right)\,\hat{F}_a^{d_v}(x,\boldsymbol{p}_T^2)$$

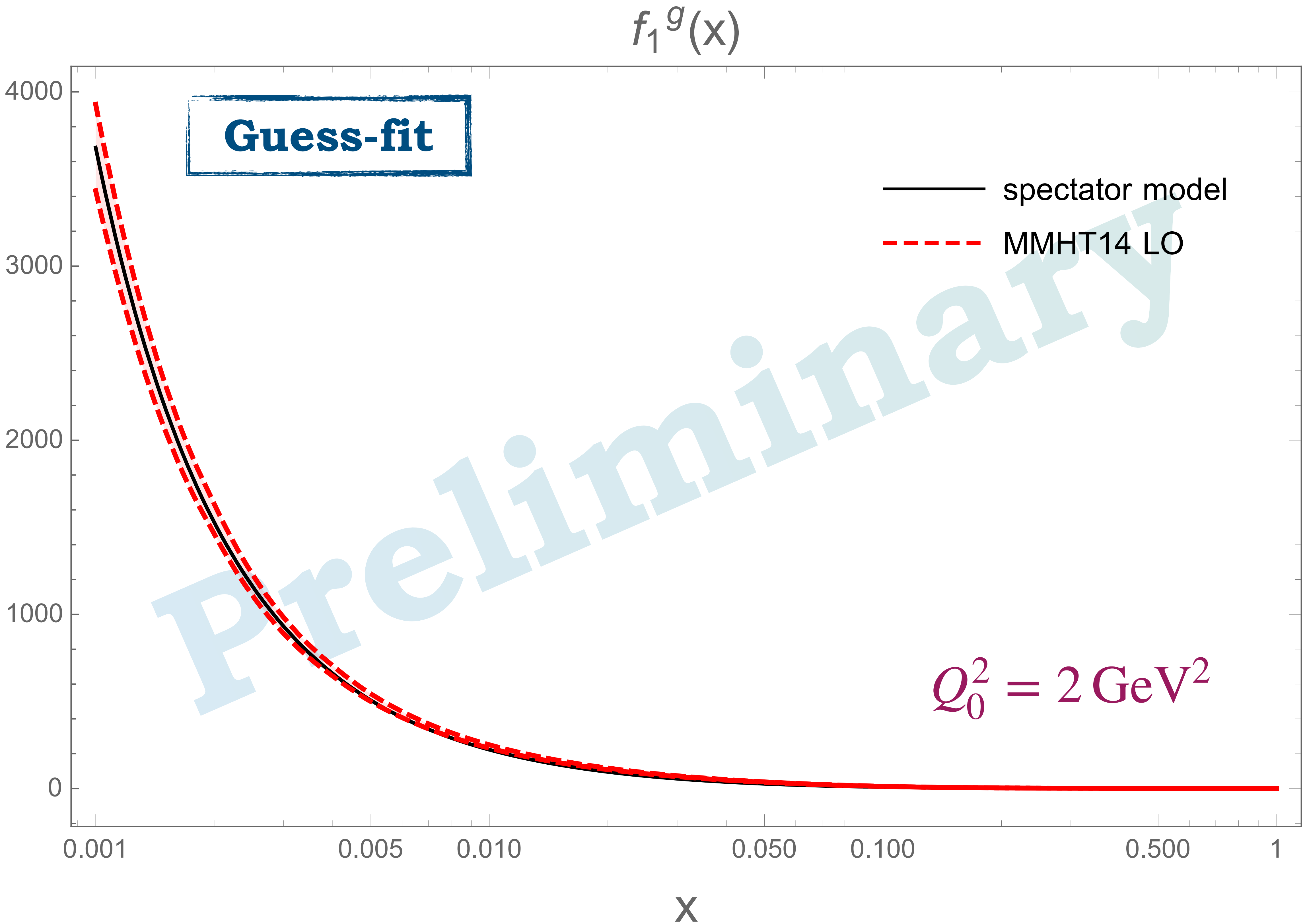
$$F^{\,\mathrm{sea}}(x,\boldsymbol{p}_T^2) = \int \mathrm{d}M_s^{\mathrm{sea}}\,\rho_s\,(M_s^{\mathrm{sea}})\,\hat{F}_s^{\,\mathrm{sea}}(x,\boldsymbol{p}_T^2)$$

$$F^{g}(x,\boldsymbol{p}_T^2) = \int \mathrm{d}M^{g}\,\rho_g\,(M^{g})\,\hat{F}^{g}(x,\boldsymbol{p}_T^2)$$

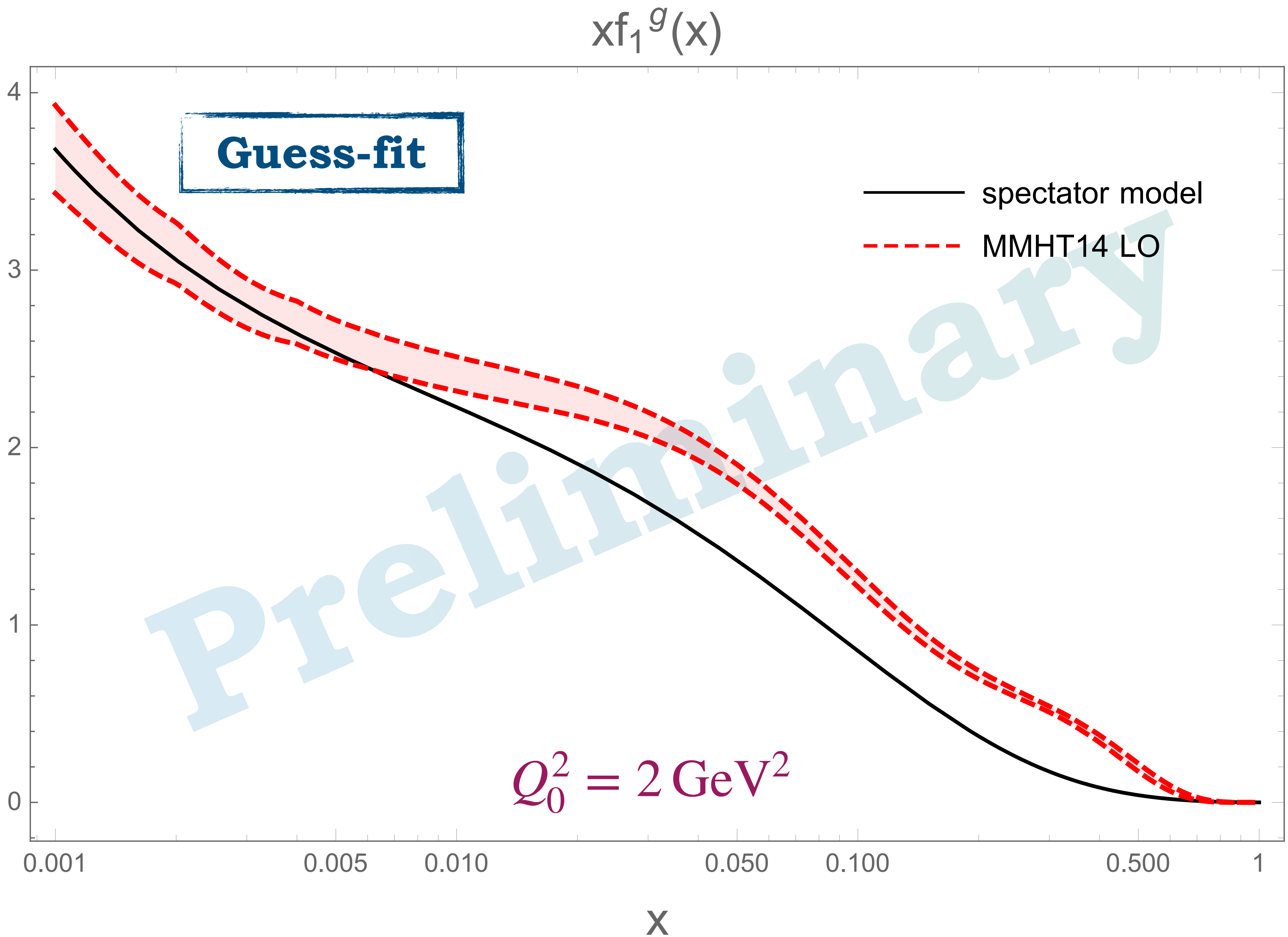
scalar di-quark **axial-vector di-quark**

spin-1/2

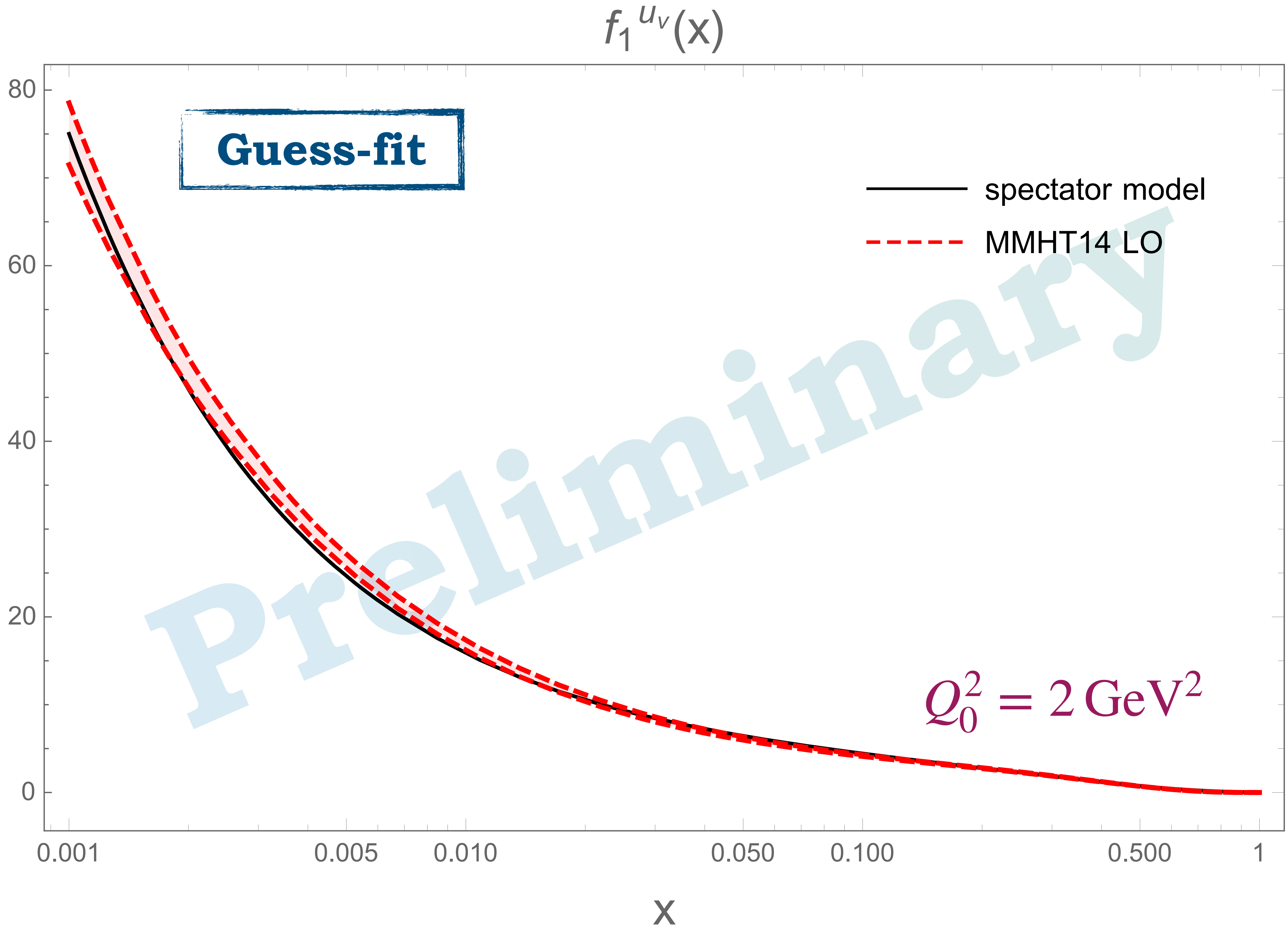
Unpolarized gluon PDF



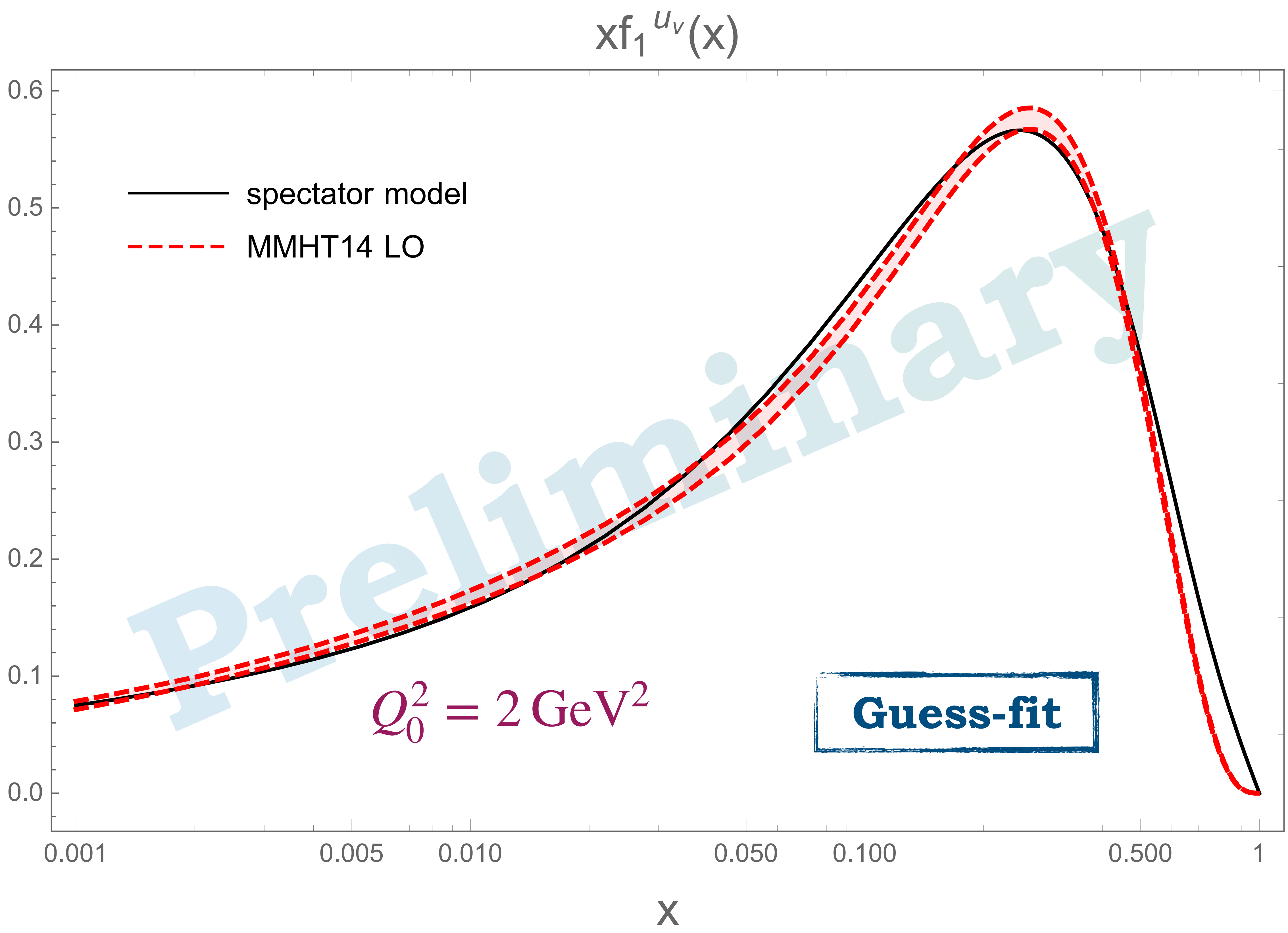
Unpolarized gluon PDF



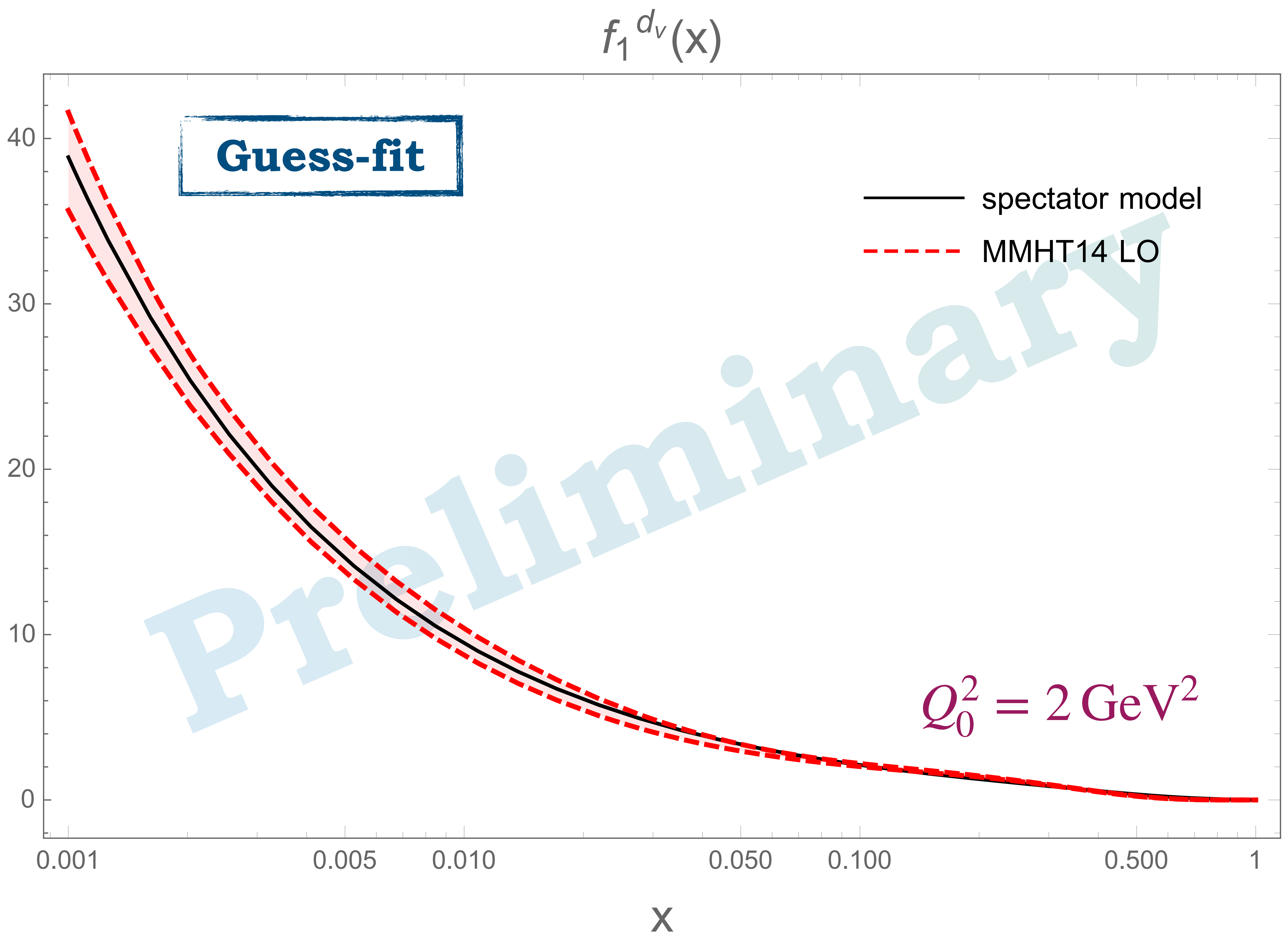
Unpolarized valence-up PDF



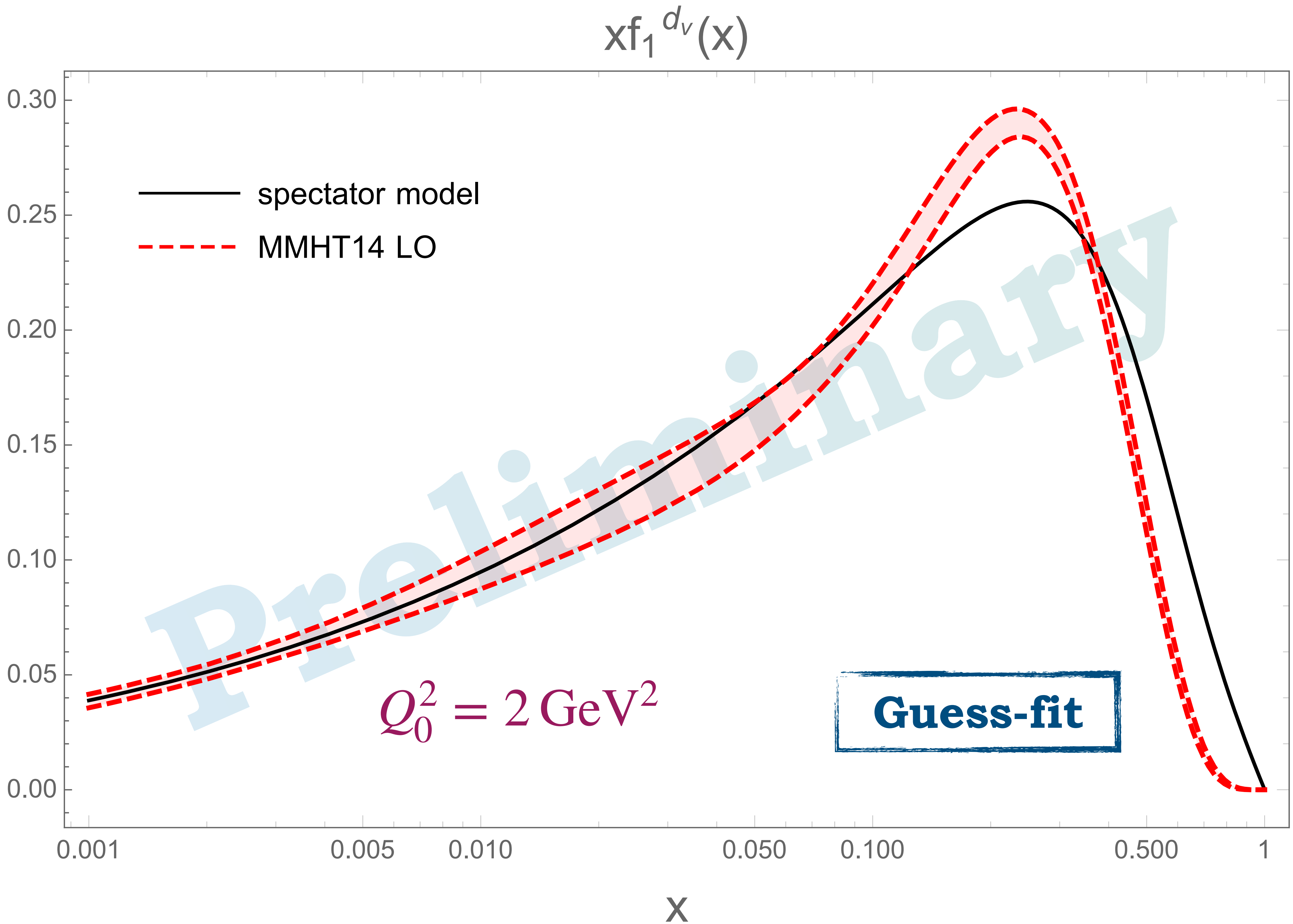
Unpolarized valence-up PDF



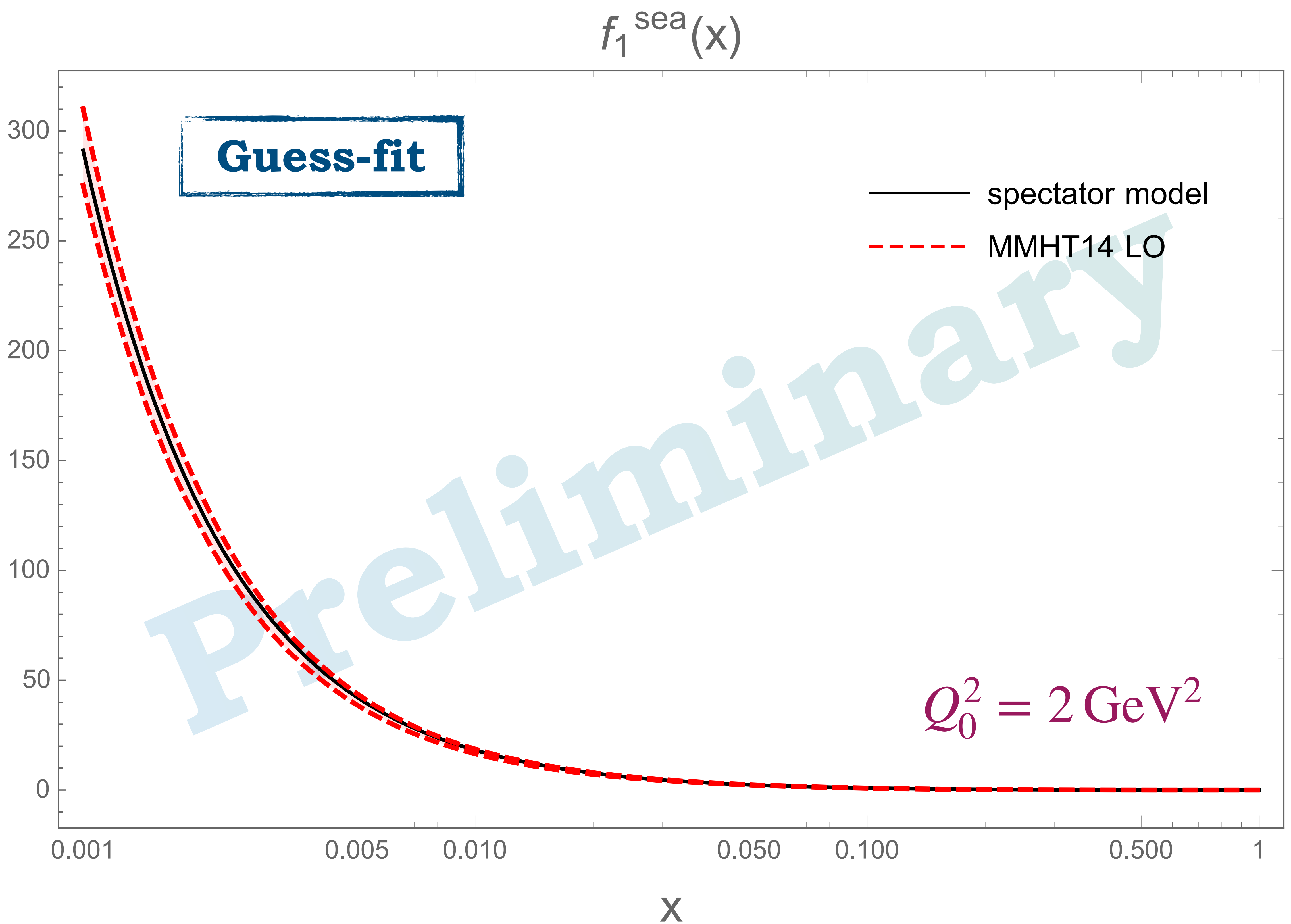
Unpolarized valence-down PDF



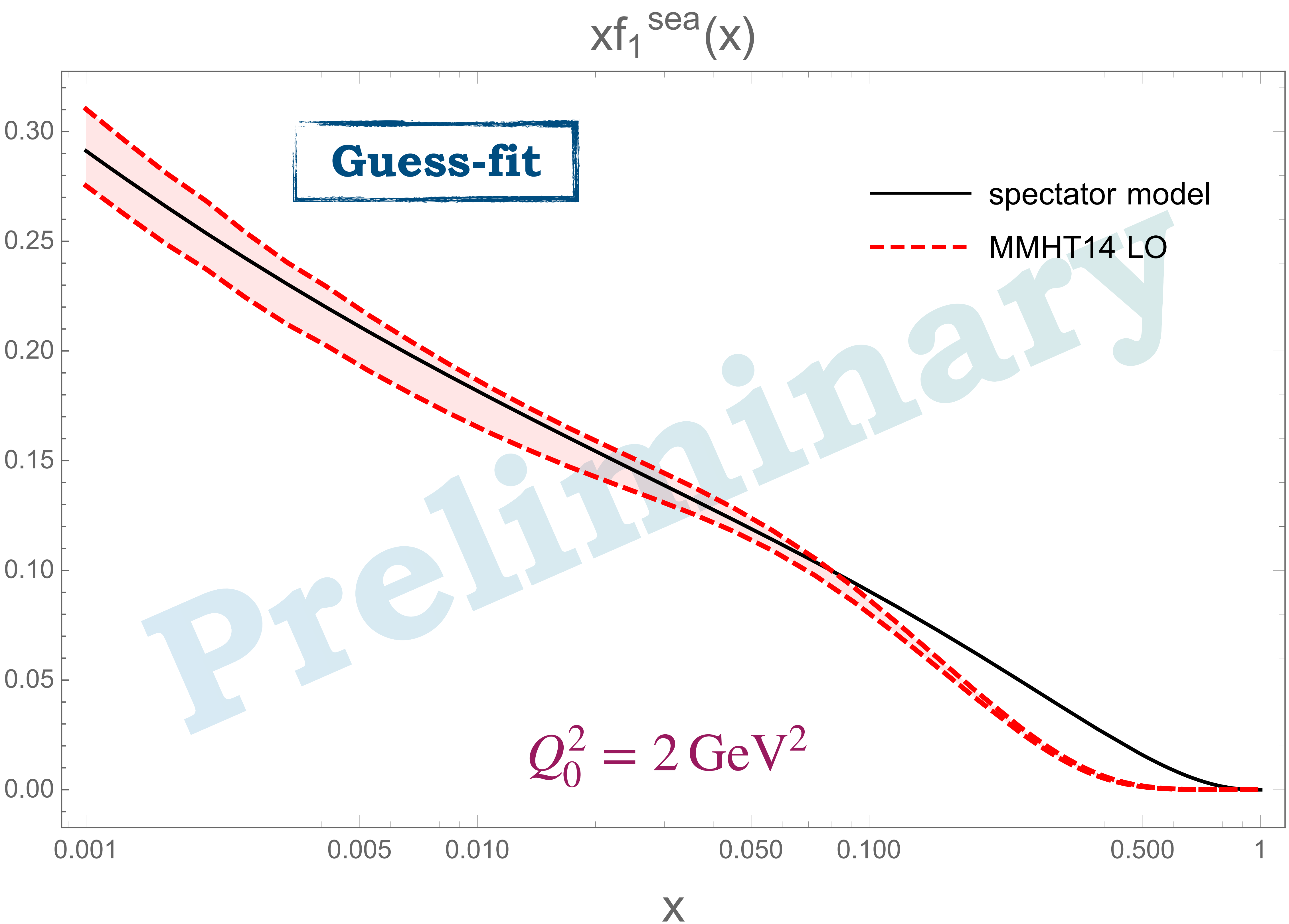
Unpolarized valence-down PDF



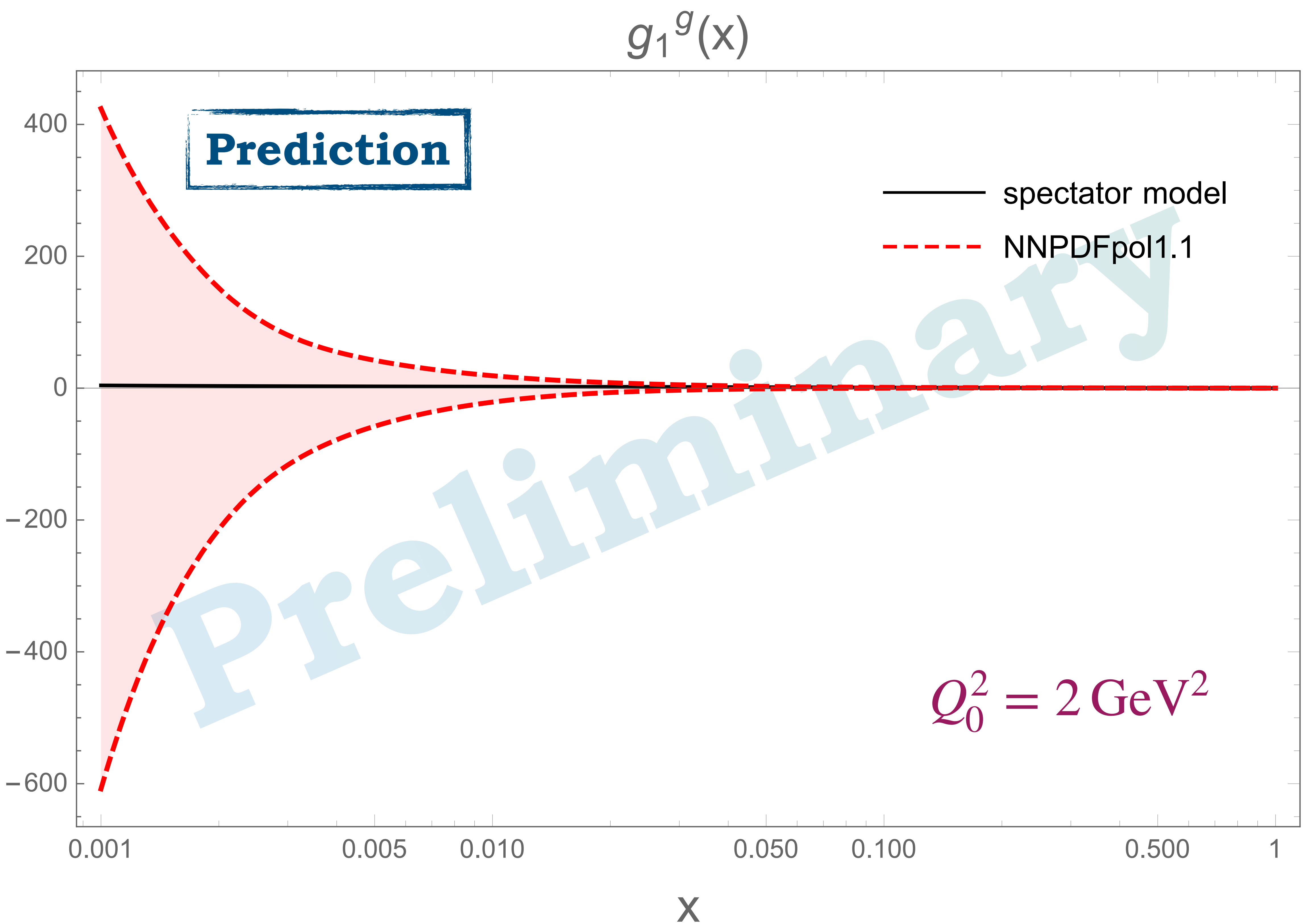
Unpolarized sea PDF



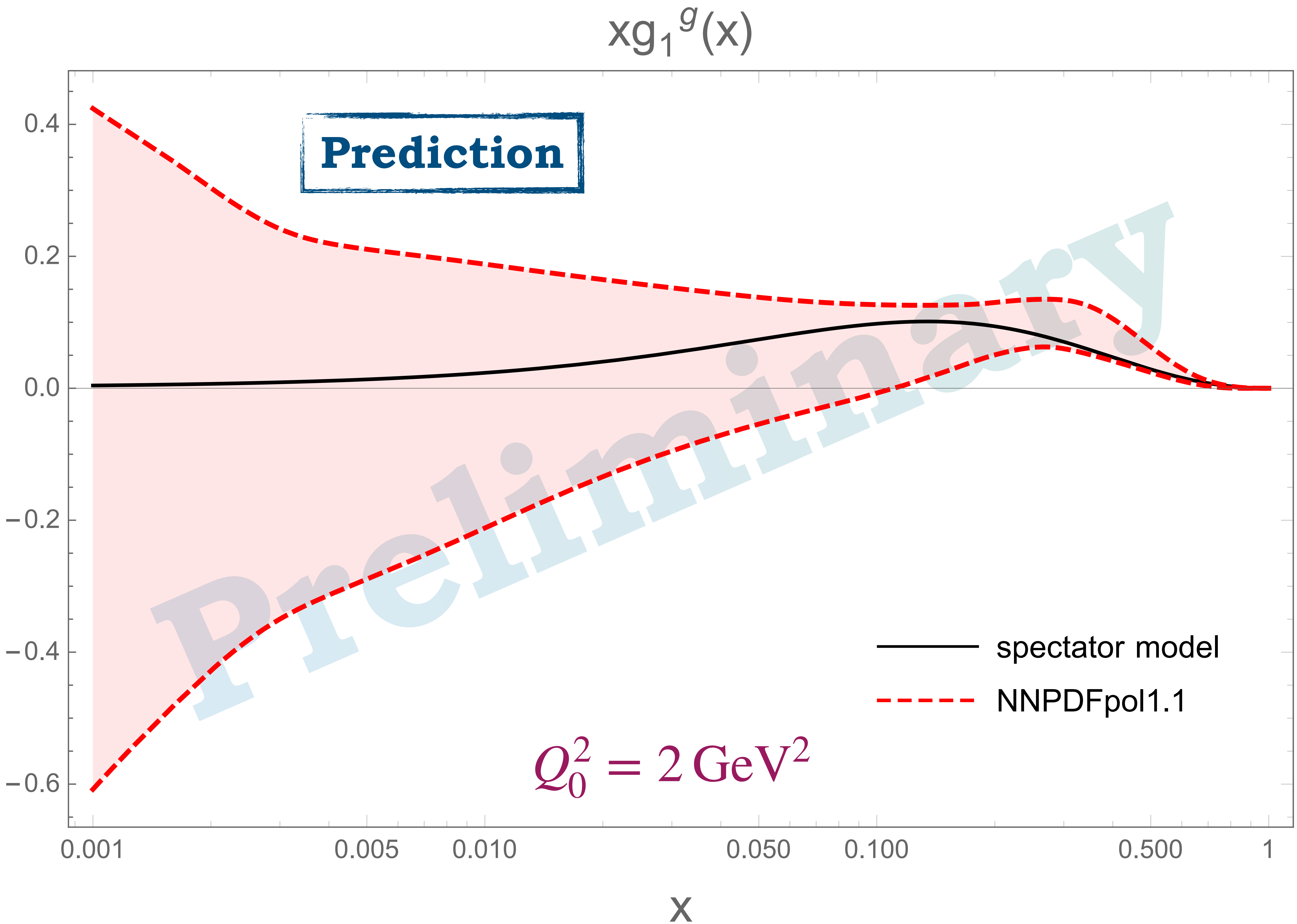
Unpolarized sea PDF



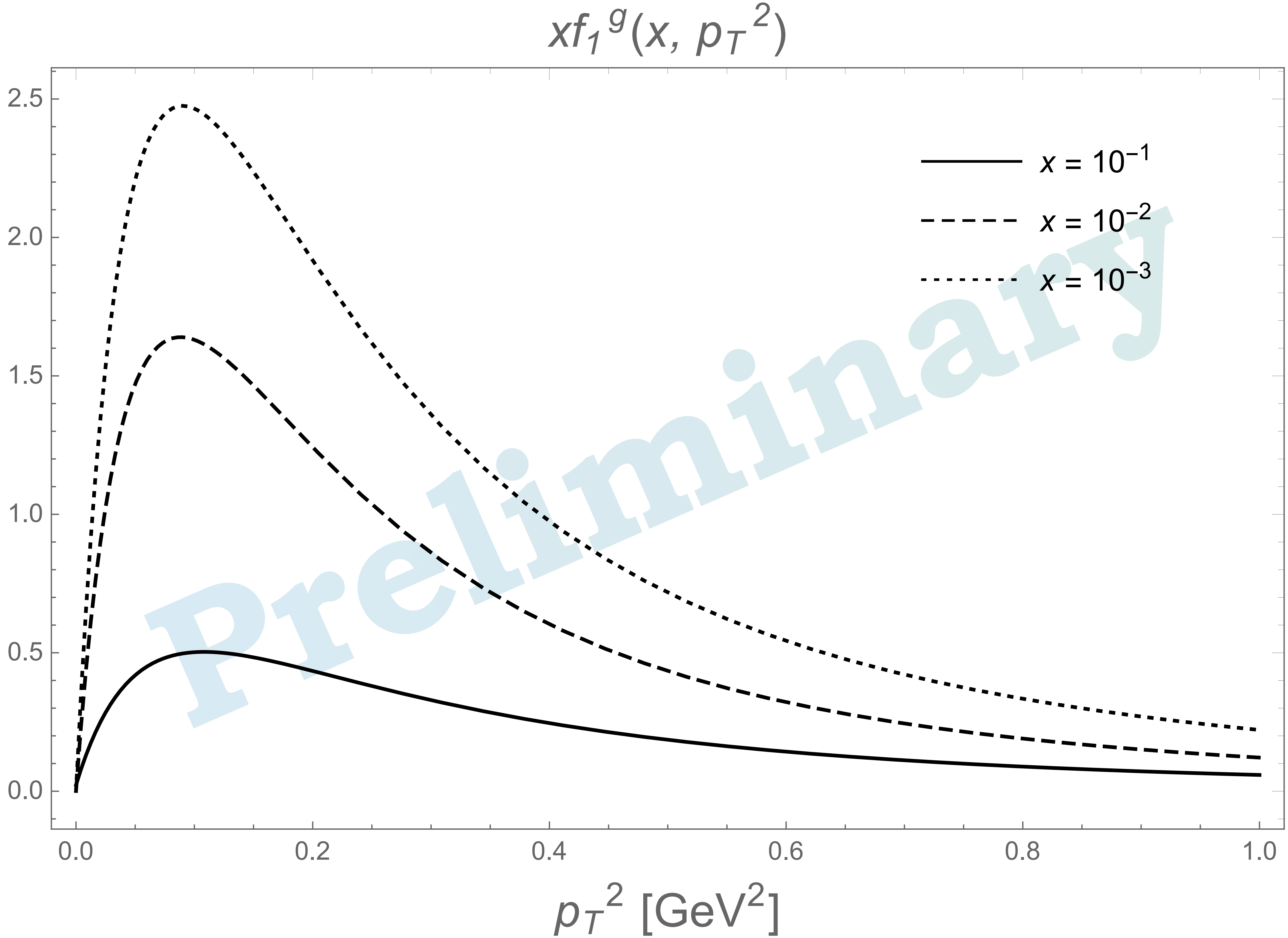
Helicity gluon PDF



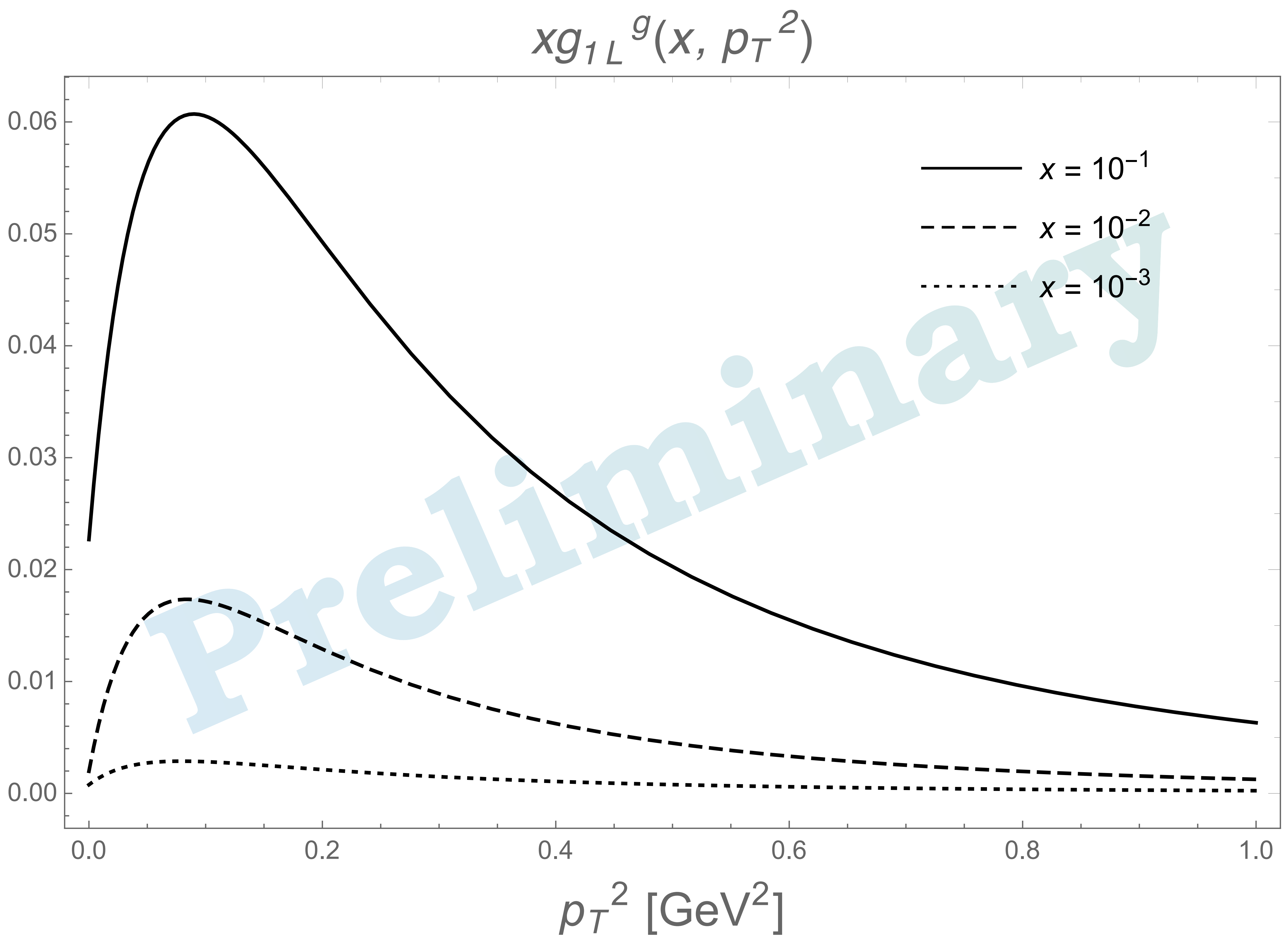
Helicity gluon PDF



Unpolarized gluon TMD



Helicity gluon TMD



Conclusions & Outlook

- ☑ Systematic calculation of all twist-2 T-even parton TMDs
- ☑ Spectral mass to catch small- and moderate-x effects
- ☑ Encouraging results from **guess-fit** of f_1 + **prediction** for g_1
- ☐ **Simultaneous fit** of f_1 and g_1 with **BFKL** input on small-x tail
- ☐ Effect of collinear evolution to be gauged
- ☐ T-odd TMDs with one-gluon exchange in eikonal approximation
- ☐ Extraction of gluon TMDs from *golden channels*

...grazie! 🙃

Backup slides

Spectator-model gluon TMDs (1)

$$\hat{f}_1^g(x,\boldsymbol{p}_T^2) = \big[4g_1^2 M_H^2 (x^2(M_X - M_H(1-x))^2 + \boldsymbol{p}_T^2((x-2)x+2))$$
$$- 4g_1 g_2 M_H x^2 (M_H + M_X)((M_X - M_H(1-x))^2 + \boldsymbol{p}_T^2)$$
$$+ g_2^2(\boldsymbol{p}_T^2 x(M_H^2(3x-2) + 2M_H M_X x + M_X^2(x+2))$$
$$+ x^2(M_H + M_X)^2(M_X - M_H(1-x))^2 + 2(\boldsymbol{p}_T^2)^2)\big]$$
$$/4(2\pi)^3 M_H^2 x(L_g^2(m_g^2) + \boldsymbol{p}_T^2)^2$$

$$\hat{g}_{1L}^g(x,\boldsymbol{p}_T^2) = \big[(2g_1 M_H - g_2(M_H + M_X))(2g_1 M_H(x(M_X - M_H(1-x))^2 - \boldsymbol{p}_T^2(x-2))$$
$$+ g_2(-M_H^2 x^3(M_H + M_X) + \boldsymbol{p}_T^2 x(M_X - 3M_H) + 2\boldsymbol{p}_T^2(M_H - M_X)$$
$$+ 2M_H x^2(M_H - M_X)(M_H + M_X) - x(M_H - M_X)^2(M_H + M_X)))\big]$$
$$/4(2\pi)^3 M_H^2(L_g^2(m_g^2) + \boldsymbol{p}_T^2)^2$$

$$L_X^2(m^2) = xM_X^2 + (1-x)m^2 - x(1-x)M_H^2$$

Spectator-model gluon TMDs (2)

$$g_{1T}^{g}(x,\boldsymbol{p}_T^2) = \big[((2g_1 M_H - g_2(M_H + M_X))((M_X - M_H(1-x)) \\ (-2g_1 M_H(1-x) - g_2 M_X x) - g_2 \boldsymbol{p}_T^2))\big] \\ /(2(2\pi)^3 M_H (L_X^2(m_g^2) + \boldsymbol{p}_T^2)^2)$$

$$h_1^{\perp g}(x,\boldsymbol{p}_T^2) = \big[(4g_1^2 M_H^2(1-x) + g_2^2(x(M_X^2 - M_H^2(1-x)) + \boldsymbol{p}_T^2))\big] \\ /((2\pi)^3 x (L_X^2(m_g^2) + \boldsymbol{p}_T^2)^2)$$

$$L_X^2(m^2) = x M_X^2 + (1-x)m^2 - x(1-x)M_H^2$$

Spectator-model quark TMDs scalar di-quark (1)

$$f_1^{q(s)}(x, \boldsymbol{p}_T^2) = \frac{g_s^2}{(2\pi)^3} \frac{\left[(m + xM)^2 + \boldsymbol{p}_T^2\right](1-x)}{2\left[\boldsymbol{p}_T^2 + L_s^2(m^2)\right]^2}$$

$$g_{1L}^{q(s)}(x, \boldsymbol{p}_T^2) = \frac{g_s^2}{(2\pi)^3} \frac{\left[(m + xM)^2 - \boldsymbol{p}_T^2\right](1-x)}{2\left[\boldsymbol{p}_T^2 + L_s^2(m^2)\right]^2}$$

$$g_{1T}^{q(s)}(x, \boldsymbol{p}_T^2) = \frac{g_s^2}{(2\pi)^3} \frac{M\,(m + xM)\,(1-x)}{\left[\boldsymbol{p}_T^2 + L_s^2(m^2)\right]^2}$$

$$h_{1L}^{\perp\, q(s)}(x, \boldsymbol{p}_T^2) = -g_{1T}^{q(s)}(x, \boldsymbol{p}_T^2)$$

$$L_X^2(m^2) = xM_X^2 + (1-x)m^2 - x(1-x)M_H^2$$

Spectator-model quark TMDs scalar di-quark (2)

$$h_{1T}^{q(s)}(x, \boldsymbol{p}_T^2) = f_1^{q(s)}(x, \boldsymbol{p}_T^2)$$

$$h_{1T}^{\perp\, q(s)}(x, \boldsymbol{p}_T^2) = -\frac{g_s^2}{(2\pi)^3} \frac{M^2\,(1-x)}{[\boldsymbol{p}_T^2 + L_s^2(m^2)]^2}$$

$$h_1^{q(s)}(x, \boldsymbol{p}_T^2) = h_{1T}^{q(s)}(x, \boldsymbol{p}_T^2) + \frac{\boldsymbol{p}_T^2}{2M^2}\, h_{1T}^{\perp\, q(s)}(x, \boldsymbol{p}_T^2)$$

$$= \frac{g_s^2}{(2\pi)^3} \frac{(m + xM)^2\,(1-x)}{2\,[\boldsymbol{p}_T^2 + L_s^2(m^2)]^2} = \frac{1}{2}\,\left(f_1^{q(s)}(x, \boldsymbol{p}_T^2) + g_1^{q(s)}(x, \boldsymbol{p}_T^2)\right)$$

$$L_X^2(m^2) = xM_X^2 + (1-x)m^2 - x(1-x)M_H^2$$

Spectator-model quark TMDs axial-vector di-quark (1)

$$f_1^{q(a)}(x, \boldsymbol{p}_T^2) = \frac{g_a^2}{(2\pi)^3} \frac{\boldsymbol{p}_T^2 \, (1 + x^2) + (m + xM)^2 \, (1 - x)^2}{2 \, [\boldsymbol{p}_T^2 + L_a^2(m^2)]^2 \, (1 - x)}$$

$$g_{1L}^{q(a)}(x, \boldsymbol{p}_T^2) = \frac{g_a^2}{(2\pi)^3} \frac{\boldsymbol{p}_T^2 \, (1 + x^2) - (m + xM)^2 \, (1 - x)^2}{2 \, [\boldsymbol{p}_T^2 + L_a^2(m^2)]^2 \, (1 - x)}$$

$$g_{1T}^{q(a)}(x, \boldsymbol{p}_T^2) = \frac{g_a^2}{(2\pi)^3} \frac{M \, x \, (m + xM)}{[\boldsymbol{p}_T^2 + L_a^2(m^2)]^2}$$

$$L_X^2(m^2) = xM_X^2 + (1 - x)m^2 - x(1 - x)M_H^2$$

Spectator-model quark TMDs axial-vector di-quark (2)

$$h_{1L}^{\perp\, q(a)}(x, \boldsymbol{p}_T^2) = g_{1T}^{q(a)}(x, \boldsymbol{p}_T^2)/x \ ,$$

$$h_{1T}^{q(a)}(x, \boldsymbol{p}_T^2) = -\frac{g_a^2}{(2\pi)^3} \frac{x\, \boldsymbol{p}_T^2}{[\boldsymbol{p}_T^2 + L_a^2(m^2)]^2\, (1-x)}$$

$$h_{1T}^{\perp\, q(a)}(x, \boldsymbol{p}_T^2) = 0$$

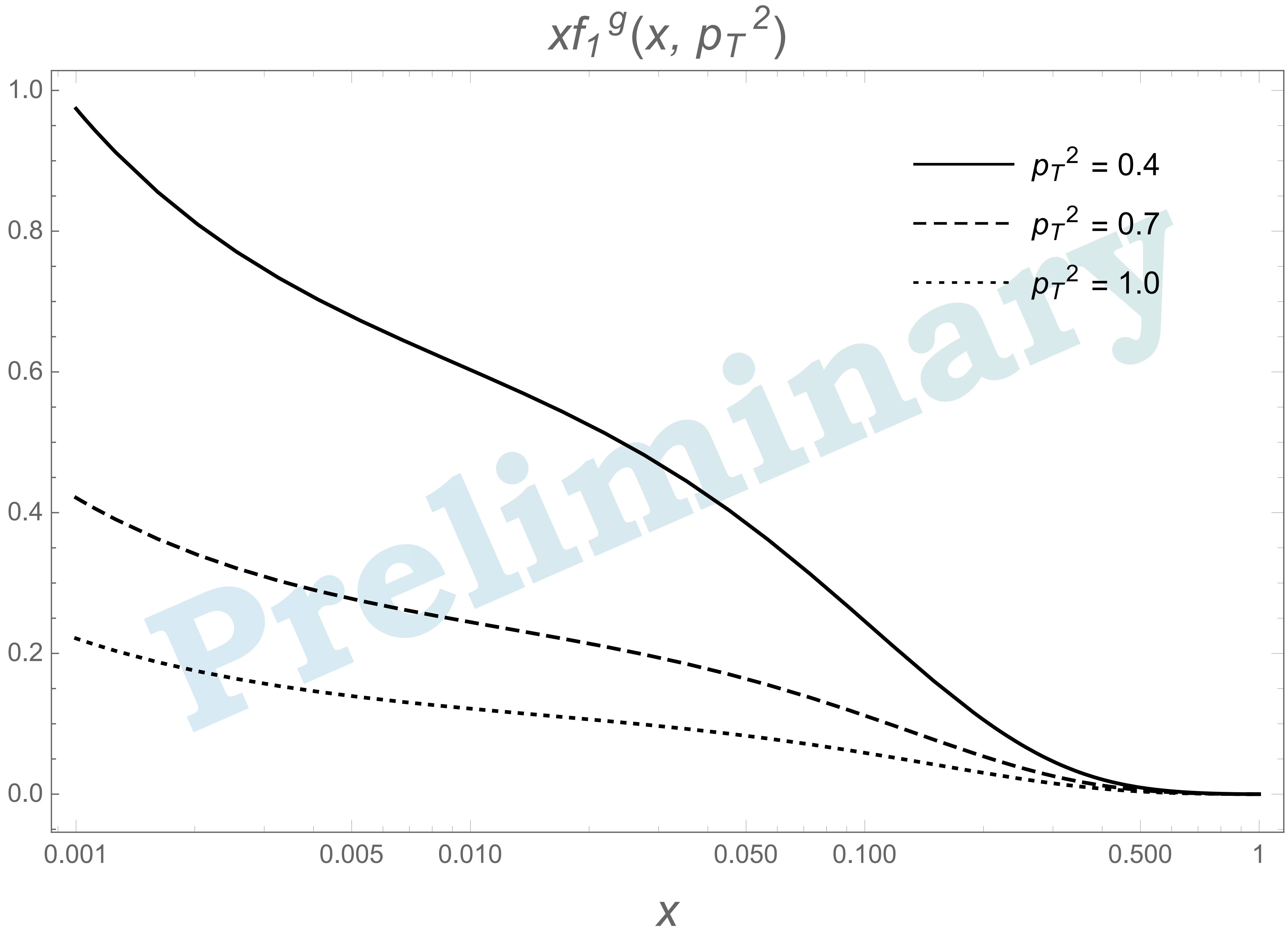
$$h_1^{q(a)}(x, \boldsymbol{p}_T^2) = h_{1T}^{q(a)}(x, \boldsymbol{p}_T^2)$$

$$L_X^2(m^2) = x M_X^2 + (1-x)m^2 - x(1-x)M_H^2$$

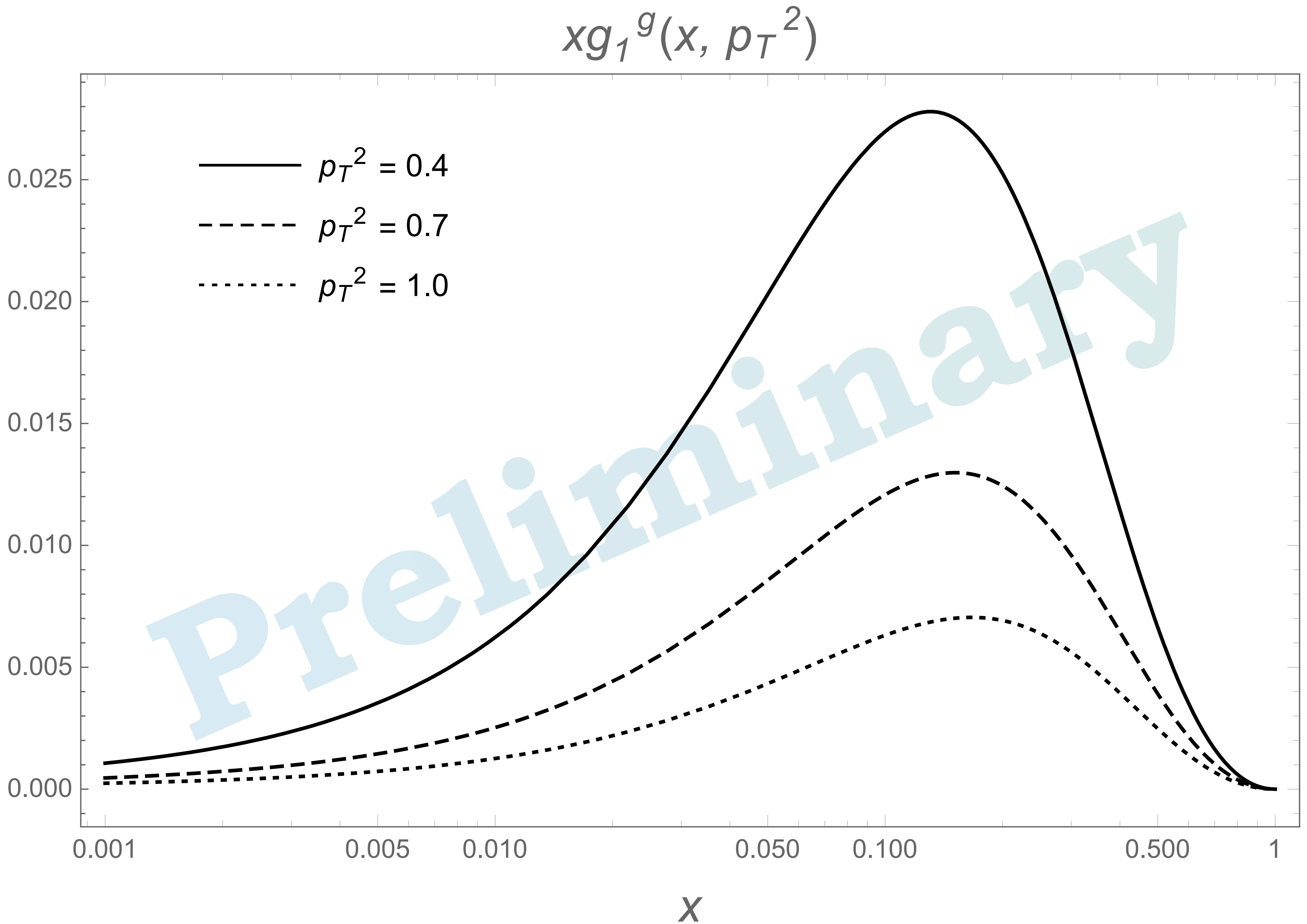
Nucleon-parton-spectator effective vertex

$$g_X(p^2) = \begin{cases} g_X^{p.l.} & \text{pointlike} \\ g_X^{dip} \dfrac{p^2 - m^2}{|p^2 - \Lambda_X^2|^2} & \text{dipolar} \\ g_X^{exp} \, e^{(p^2 - m^2)/\Lambda_X^2} & \text{exponential} \end{cases}$$

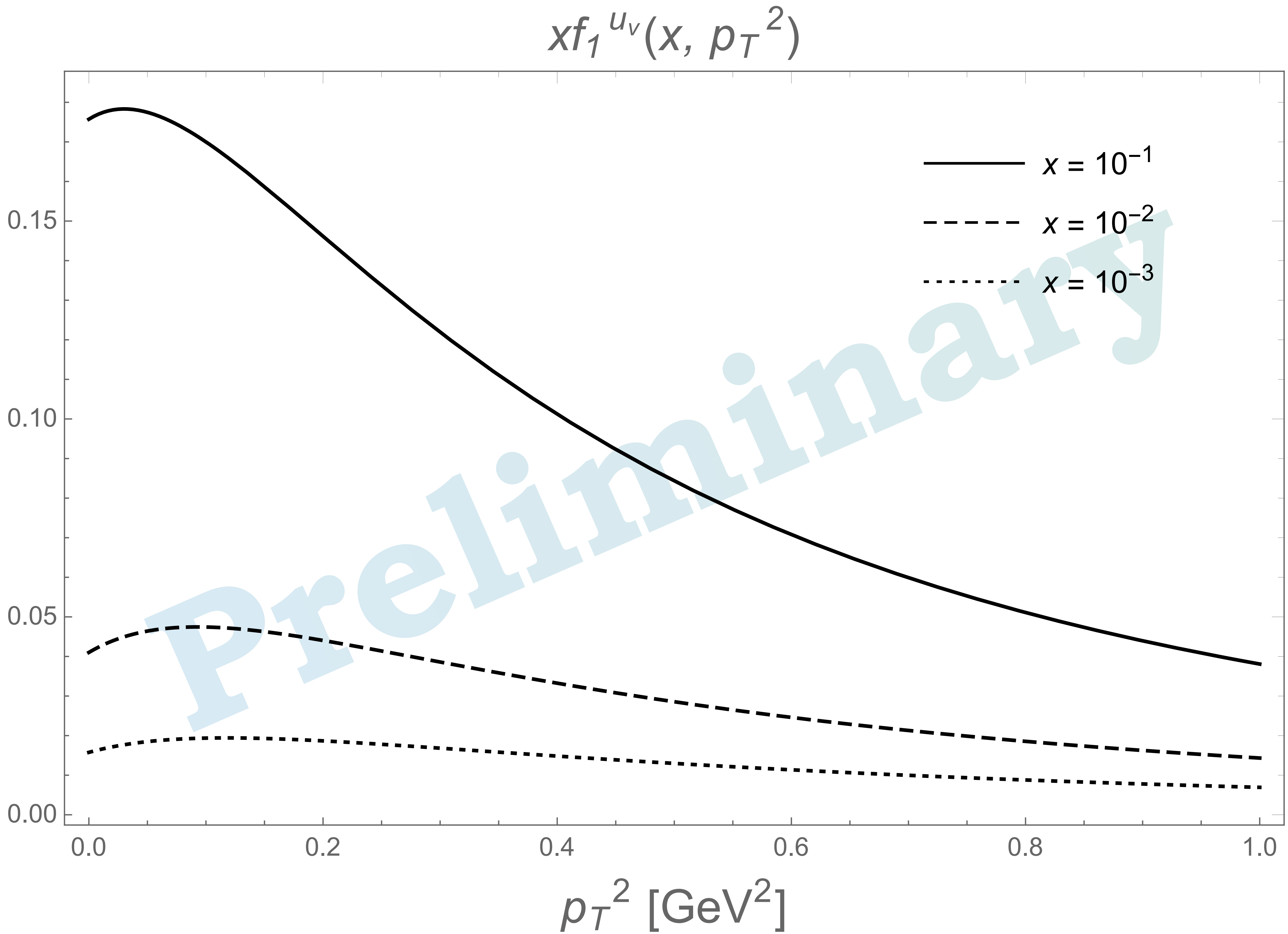
Unpolarized gluon TMD



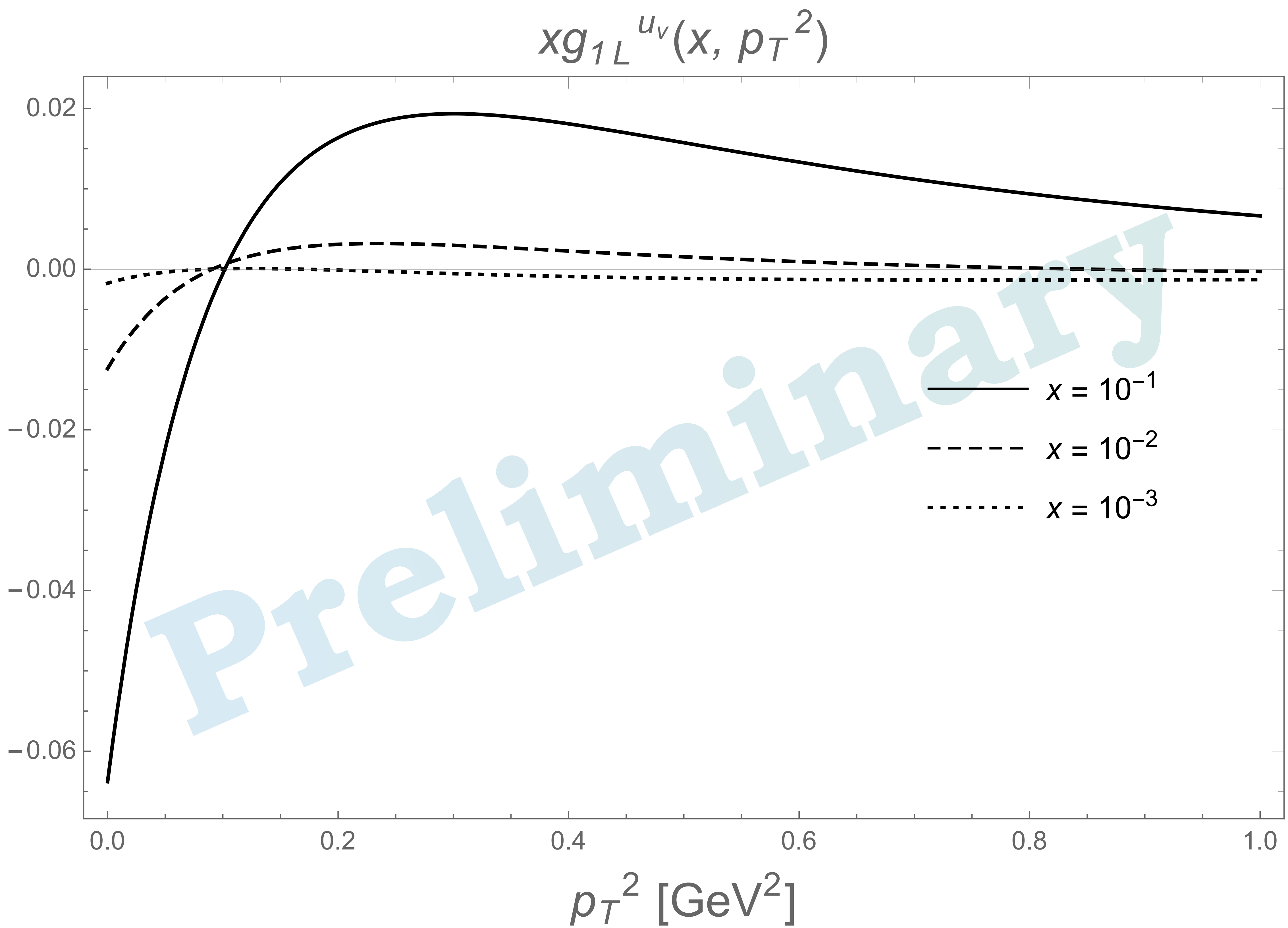
Helicity gluon TMD



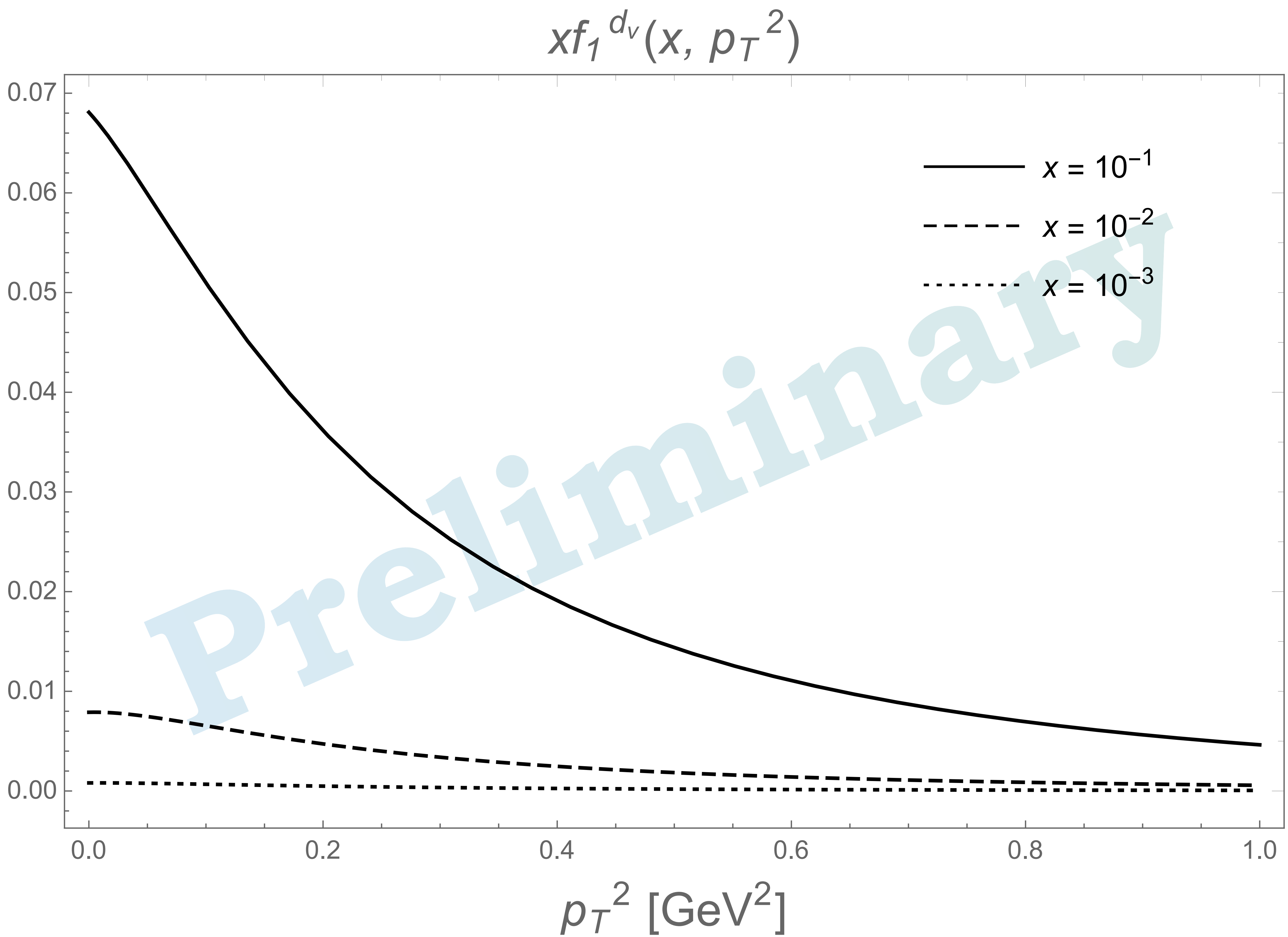
Unpolarized valence-up TMD



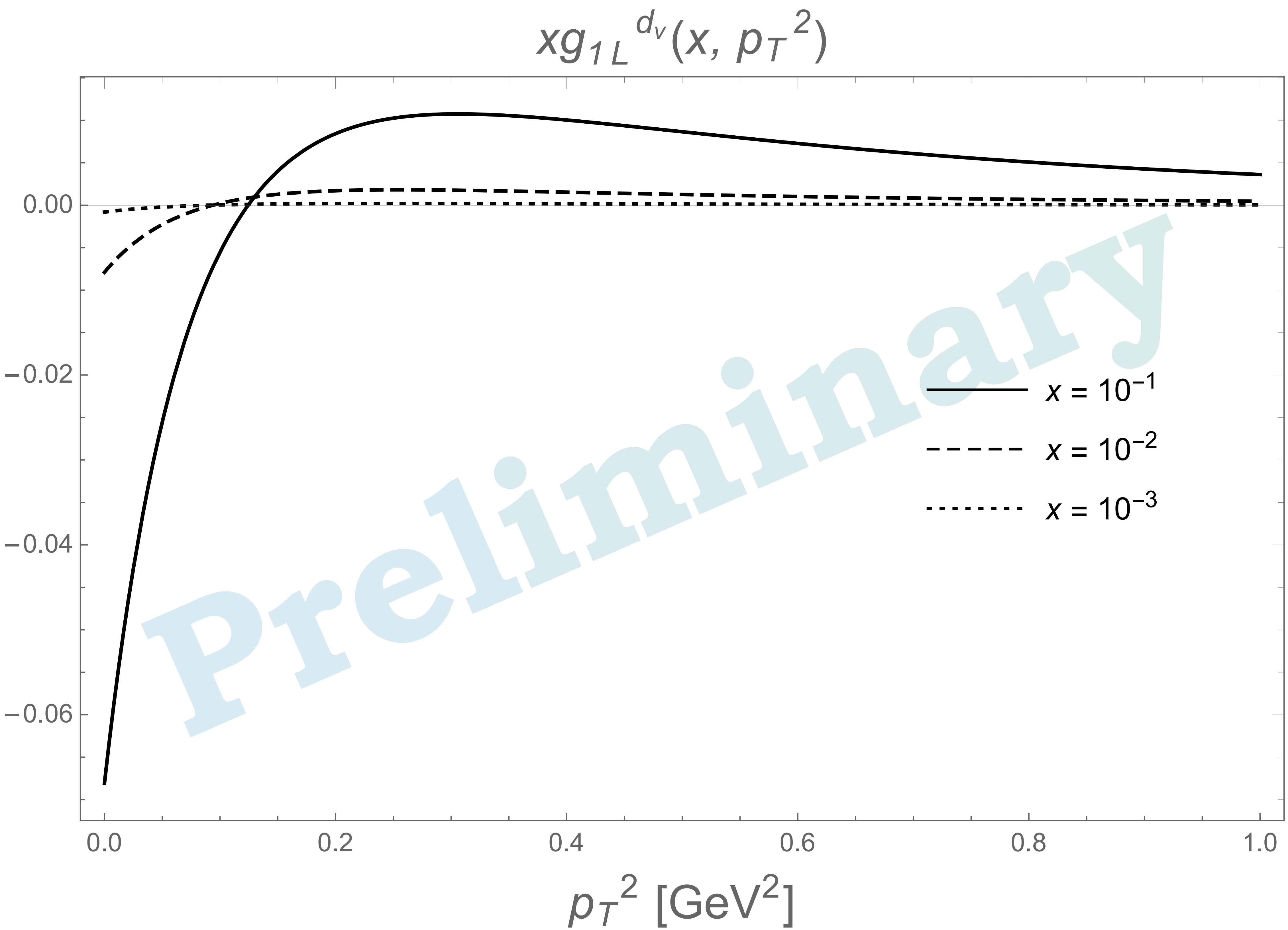
Helicity valence-up TMD



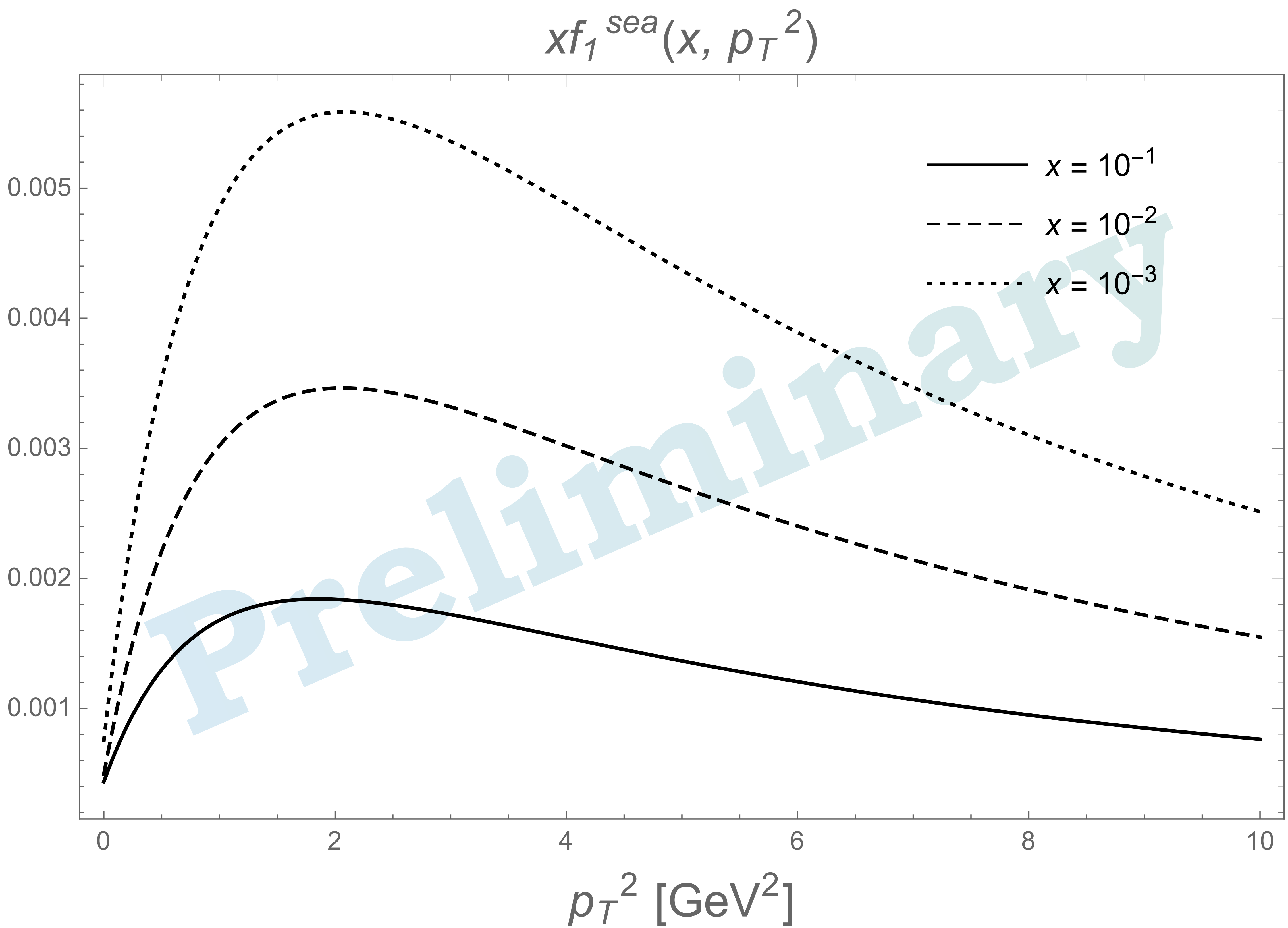
Unpolarized valence-down TMD



Helicity valence-down TMD



Unpolarized sea TMD



Helicity sea TMD