EIC UG Early Career Workshop, July 30th, 2021

Toward twist-2 *T*-odd TMD gluon distributions

Francesco Giovanni Celiberto

ECT*/FBK Trento & INFN-TIFPA

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

TIFPA
Trento Institute for Fundamental Physics and Applications

HAS QCD
HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

Gluon TMDs: a largely unexplored territory

Theory: different **gauge-link** structures…

…more diversified kind of **modified universality**!

Pheno: golden channels for extraction

of quark TMDs are subleading for gluon TMDs

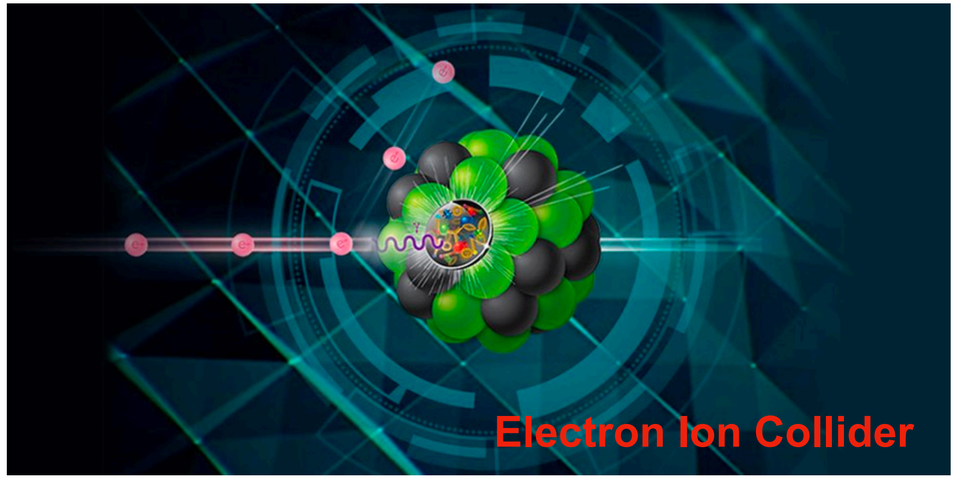
Gluon TMDs: a largely unexplored territory

- ***Theory***: different **gauge-link** structures…

…more diversified kind of **modified universality**!

- ***Pheno***: golden channels for extraction

of quark TMDs are subleading for gluon TMDs



Motivation

- Gluon-TMD PDFs: *core* sector of **EIC** studies
- Need for a *flexible* model, suited to *pheno*
- **Unpolarized** and **polarized gluon TMDs**
- *Consistent* framework for quark TMDs



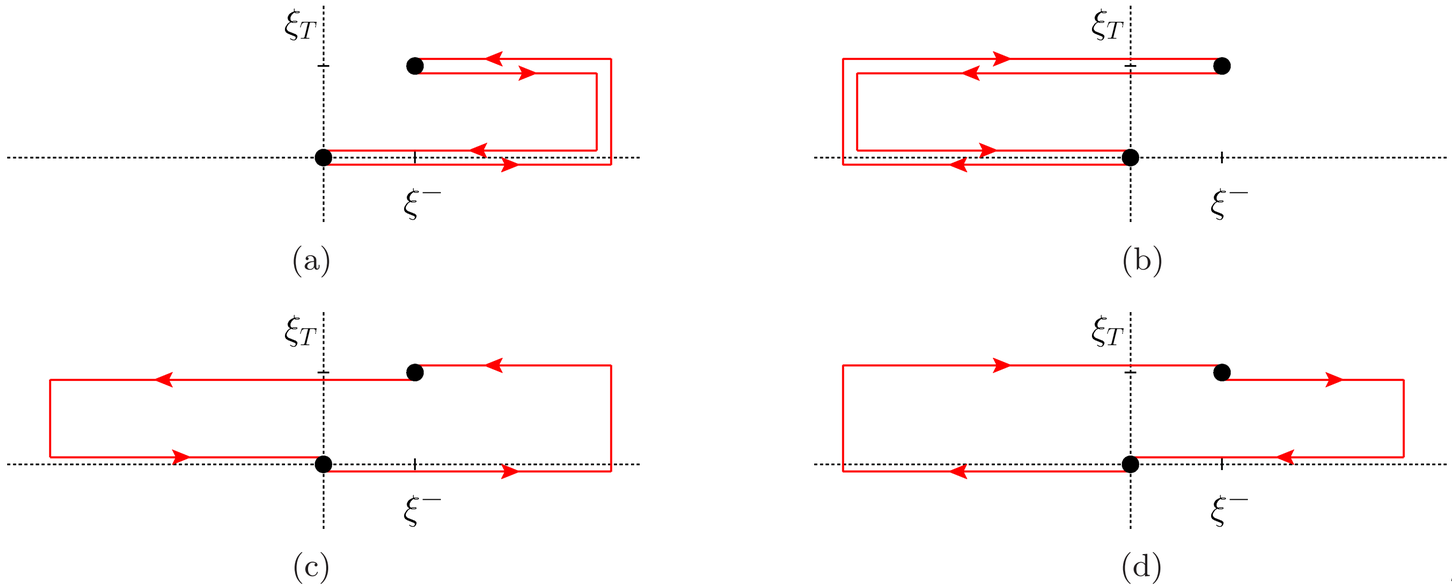
CERN

Gluon TMDs: gauge links and modified universality

* **Single-spin asymmetries** → process dependence of TMDs via **gauge links**
* **Color flow** → integration paths of gauge links calculable
* Gluon TMDs → more complicated structure with respect to quark **staple links**
* **Factorization-preserving** processes → two main kinds of **modified universality**
* Different classes of processes → distinct gluon TMDs, **not related** to each other

Gluon TMDs: gauge links and modified universality

* **Single-spin asymmetries** → process dependence of TMDs via **gauge links**
* **Color flow** → integration paths of gauge links calculable
* Gluon TMDs → more complicated structure with respect to quark **staple links**
* **Factorization-preserving** processes → two main kinds of **modified universality**
* Different classes of processes → distinct gluon TMDs, **not related** to each other

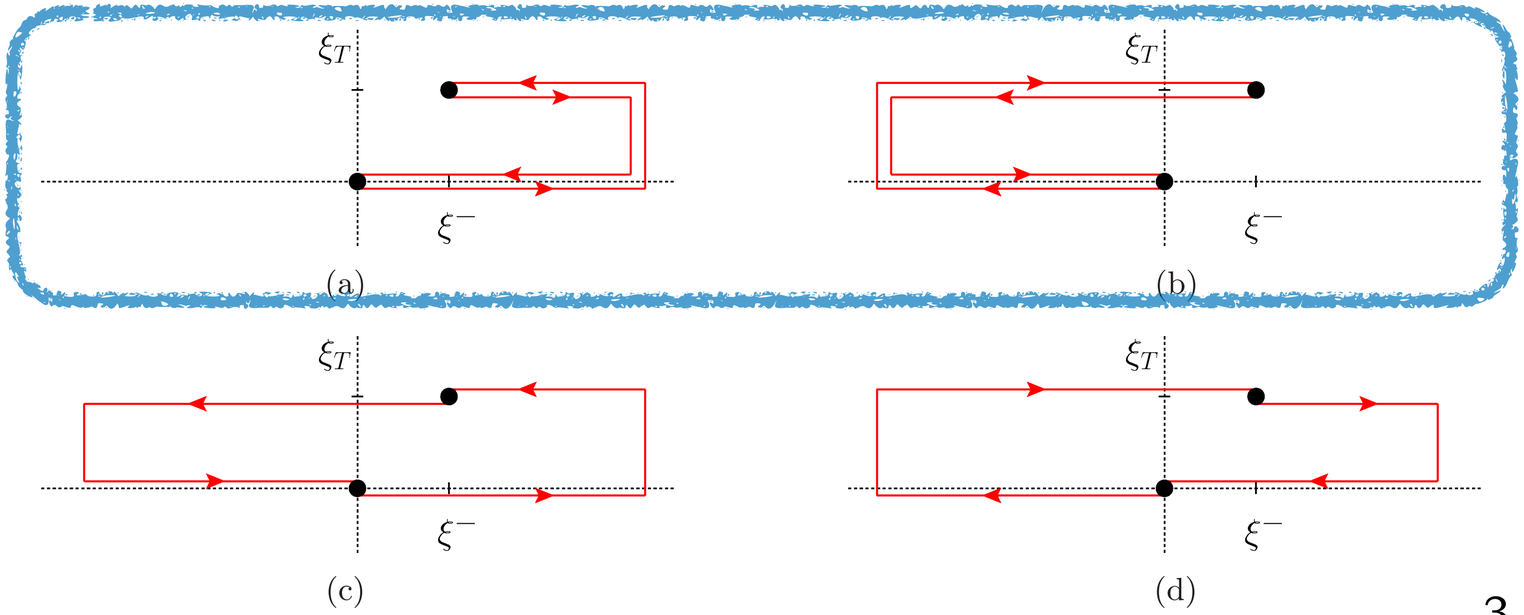


Gluon TMDs: gauge links and modified universality

* **Single-spin asymmetries** → process dependence of TMDs via **gauge links**
* **Color flow** → integration paths of gauge links calculable
* Gluon TMDs → more complicated structure with respect to quark **staple links**
* **Factorization-preserving** processes → two main kinds of **modified universality**
* Different classes of processes → distinct gluon TMDs, **not related** to each other

Weiszäcker-Williams (WW)

(a) [+ , +] or (b) [− , −]



Gluon TMDs: gauge links and modified universality

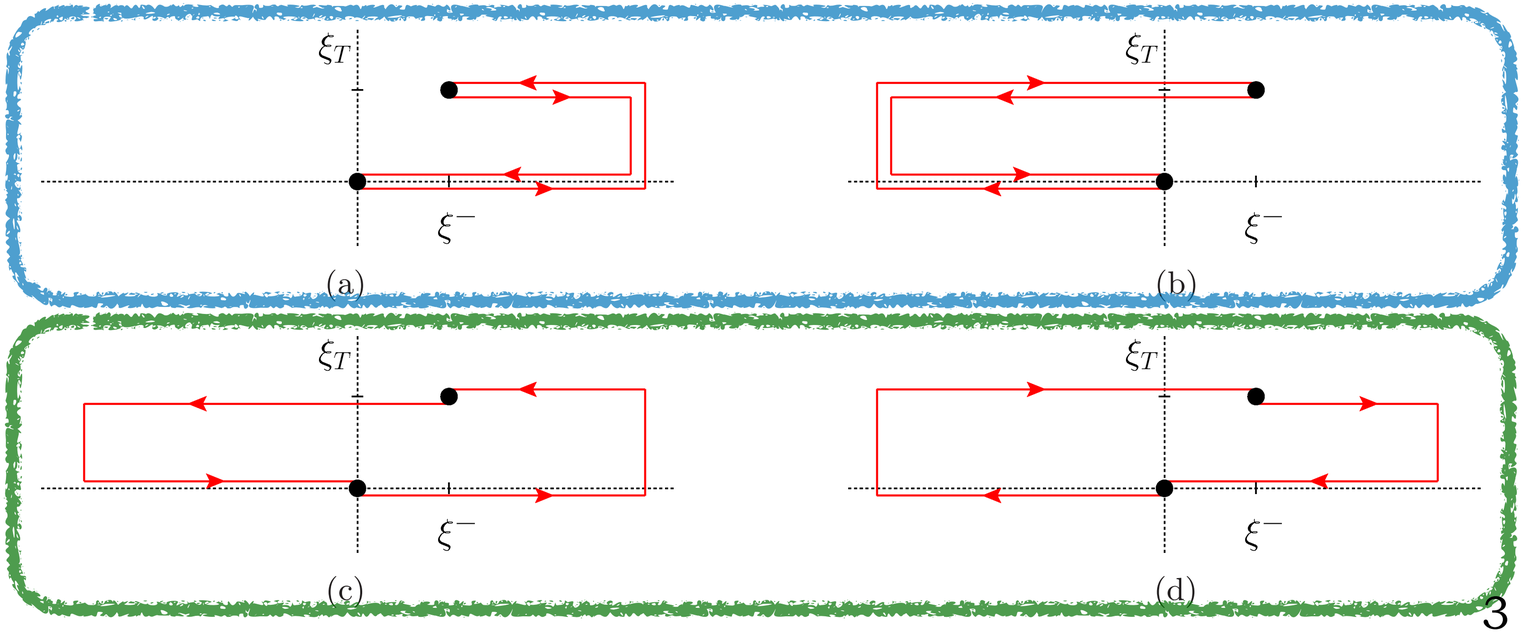
* **Single-spin asymmetries** → process dependence of TMDs via **gauge links**
* **Color flow** → integration paths of gauge links calculable
* Gluon TMDs → more complicated structure with respect to quark **staple links**
* **Factorization-preserving** processes → two main kinds of **modified universality**
* Different classes of processes → distinct gluon TMDs, **not related** to each other

Weiszäcker-Williams (WW)

(a) [+,+] or (b) [−,−]

Dipole (DP)

(c) [+,−] or (d) [−,+]



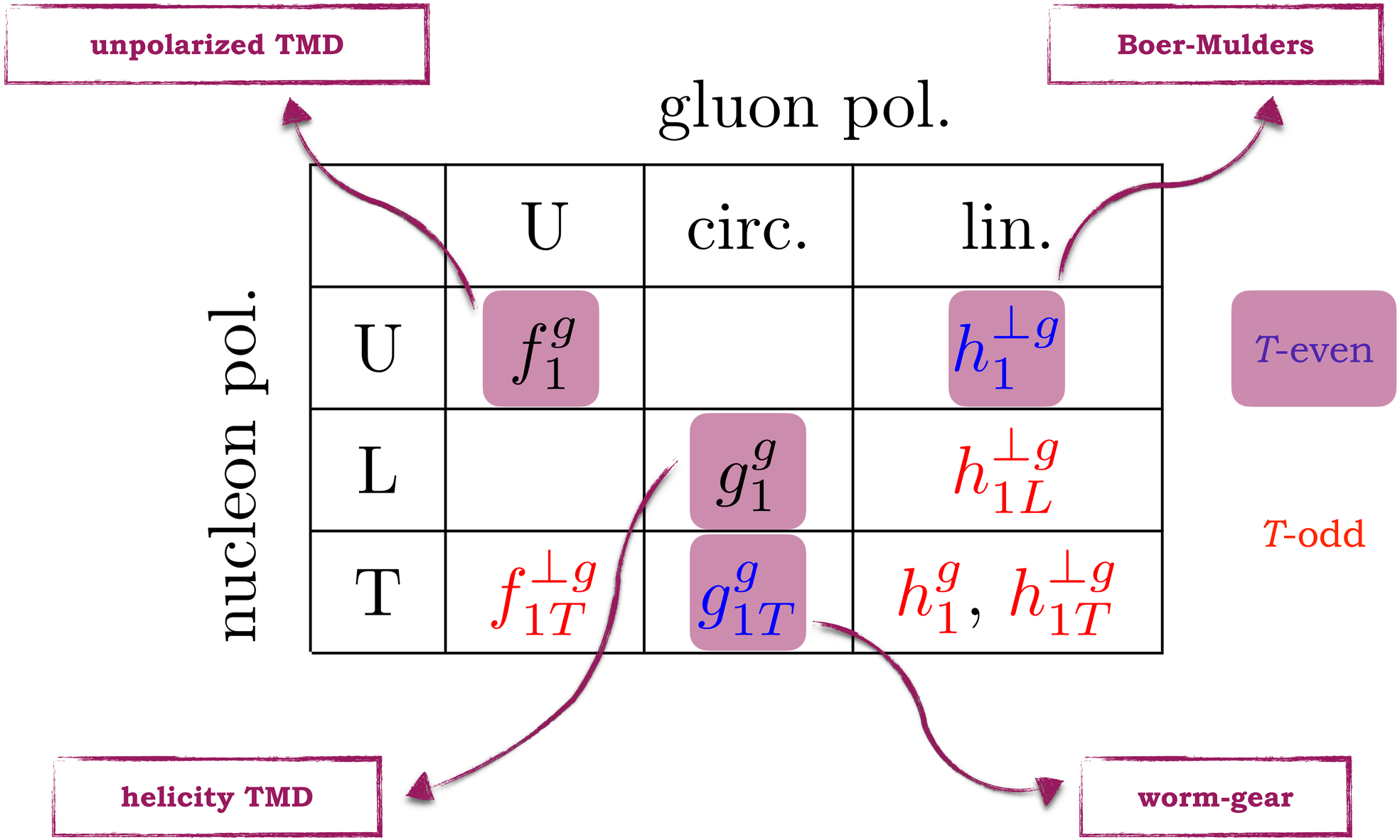
T-even and *T*-odd gluon TMD PDFs at twist-2

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	$h_1^g,\ h_{1T}^{\perp g}$

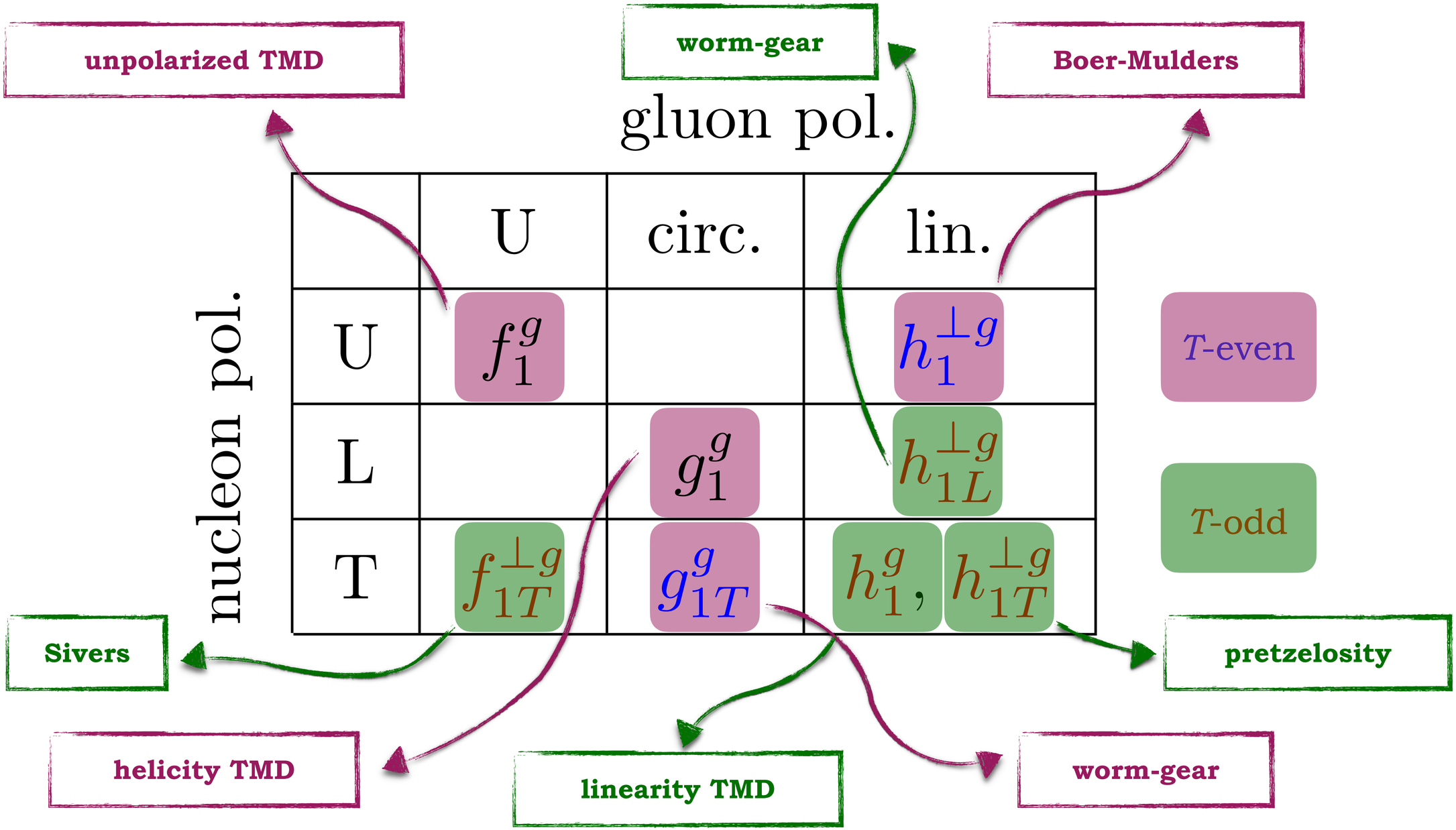
T-even

T-odd

T-even and *T*-odd gluon TMD PDFs at twist-2

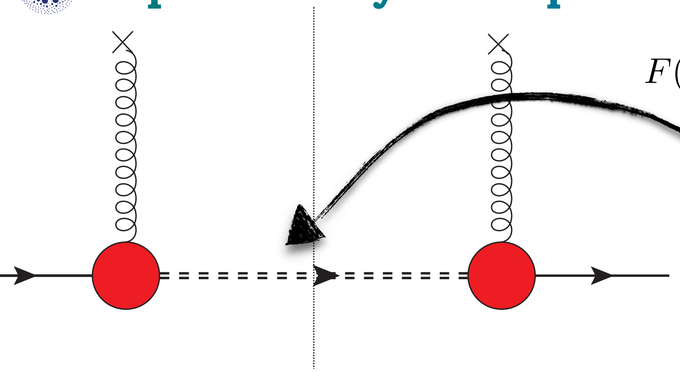


T-even and *T*-odd gluon TMD PDFs at twist-2



Our model at a glance

Spectator-system spectral-mass function



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

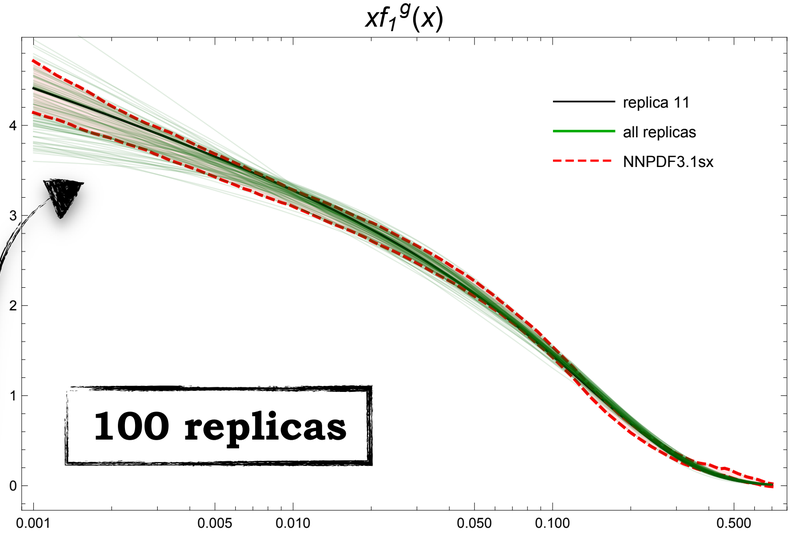
Instead of a single on-shell spectator, a continuum of spectators

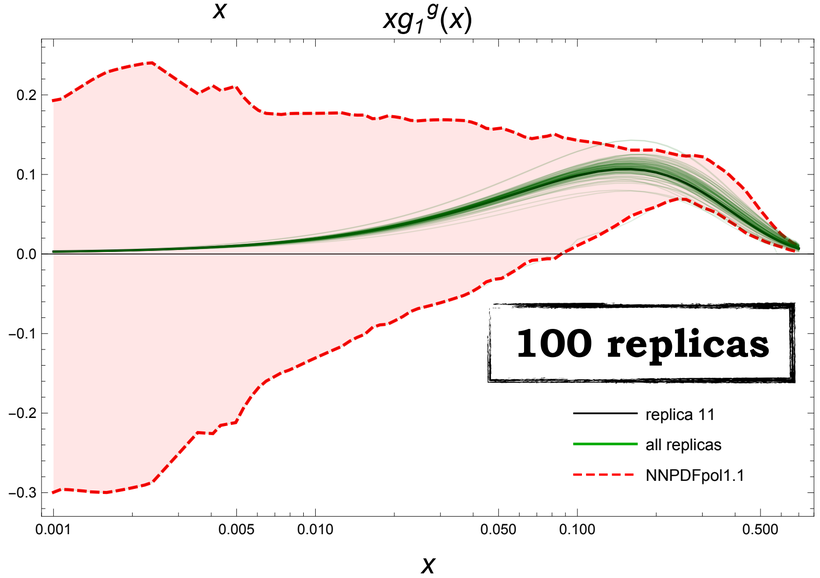
Spectral function **learns** small- and moderate-x info encoded in **NNPDF** collinear parametrizations (`NNPDF3.1sx + NNPDFpol1.1`)

- ☑ **Simultaneous fit** of f_1 and g_1 PDFs
- ☑ Inclusion of small-x resummation effects (**BFKL**)
- ☑ Calculation of all twist-2 T-even gluon TMDs

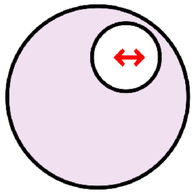
Link with collinear factorization

p_T-integrated TMDs **have to** reproduce PDFs at the lowest scale (Q_0) *before* evolution



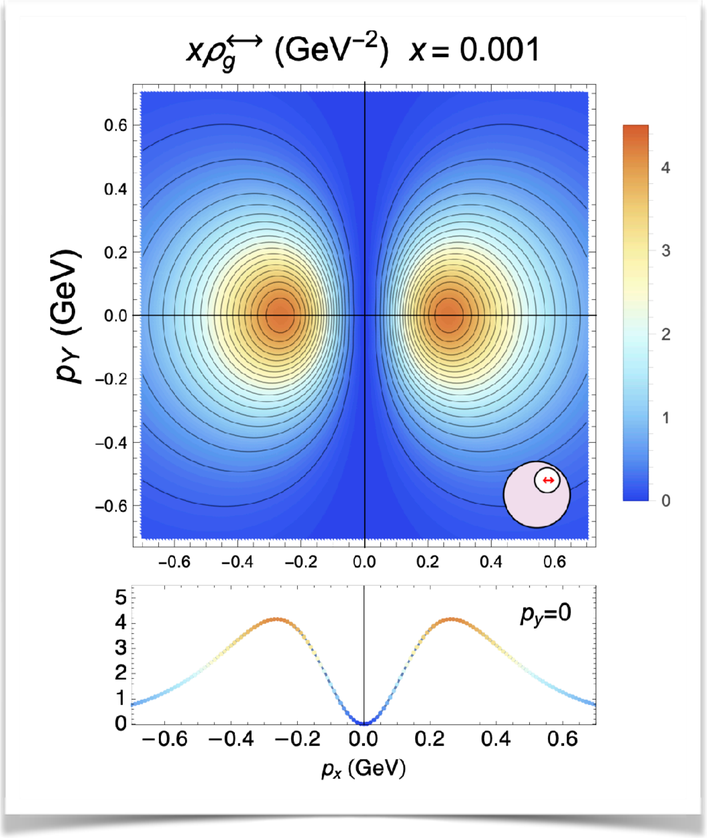


Boer-Mulders effect in unpolarized *pp* collisions



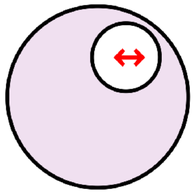
$$[\leftrightarrow/\mathbf{u}] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x,p_x,p_y)$$

unpol. Boer-Mulders



🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

Boer-Mulders effect in unpolarized *pp* collisions



$$[\leftrightarrow/u] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x,p_x,p_y)$$

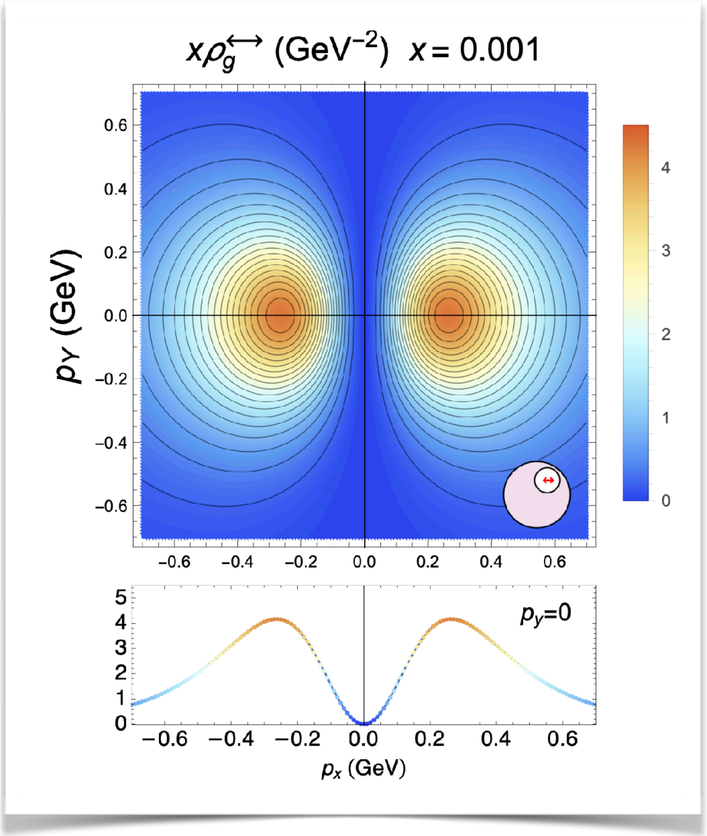
unpol. Boer-Mulders



(Pseudo)scalar Higgs p_T-distribution

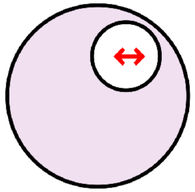
$$\frac{E\,\mathrm{d}\sigma^{H(A)}}{\mathrm{d}^3\vec{q}}\bigg|_{q_T \ll m_H} = \frac{\pi\sqrt{2}G_F}{128 m_H^2 S}\left(\frac{\alpha_s}{4\pi}\right)^2 \left|\mathcal{A}_{H(A)}(\tau)\right|^2 \times \left(\mathcal{C}\left[f_1^g\, f_1^g\right] \pm \mathcal{C}\left[w_H\, h_1^{\perp g}\, h_1^{\perp g}\right]\right) + \mathcal{O}\left(\frac{q_T}{m_H}\right)$$

[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]



[A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

Boer-Mulders effect in unpolarized *pp* collisions



$$[\leftrightarrow/\mathbf{u}] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x,p_x,p_y)$$

unpol. — Boer-Mulders

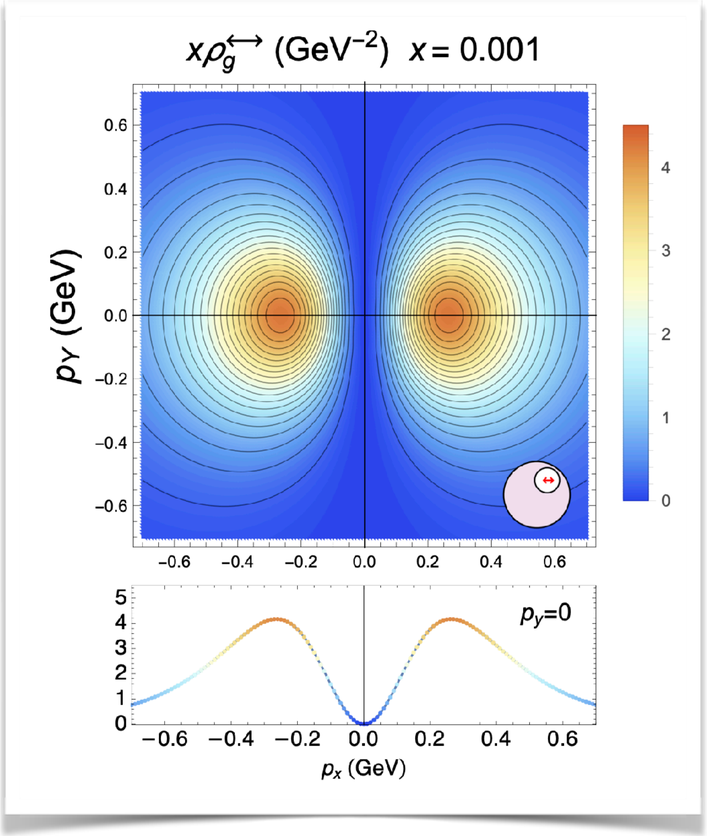
(Pseudo)scalar Higgs p_T-distribution

$$\frac{E\,\mathrm{d}\sigma^{H(A)}}{\mathrm{d}^3\vec{q}}\bigg|_{q_T \ll m_H} = \frac{\pi\sqrt{2}G_F}{128 m_H^2 S}\left(\frac{\alpha_s}{4\pi}\right)^2 \left|\mathcal{A}_{H(A)}(\tau)\right|^2 \times \left(\mathcal{C}\left[f_1^g\, f_1^g\right] \pm \mathcal{C}\left[w_H\, h_1^{\perp g}\, h_1^{\perp g}\right]\right) + \mathcal{O}\left(\frac{q_T}{m_H}\right)$$

[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

Model prediction at low-x

$$\frac{f_1^g(x,p_T^2)}{h_1^{\perp g}(x,p_T^2)} \underset{x\to 0^+}{\sim} \text{constant}$$



[A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

…towards twist-2 *T*-odd gluon TMDs

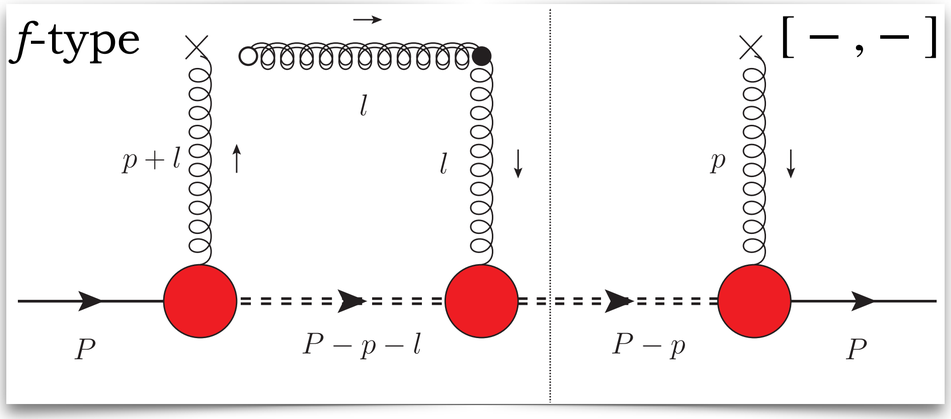
T-odd gluon TMDs in a spectator model

- No residual gluon-spectator interaction at tree level
- *Interference* with one-gluon exchange (*eikonal*)

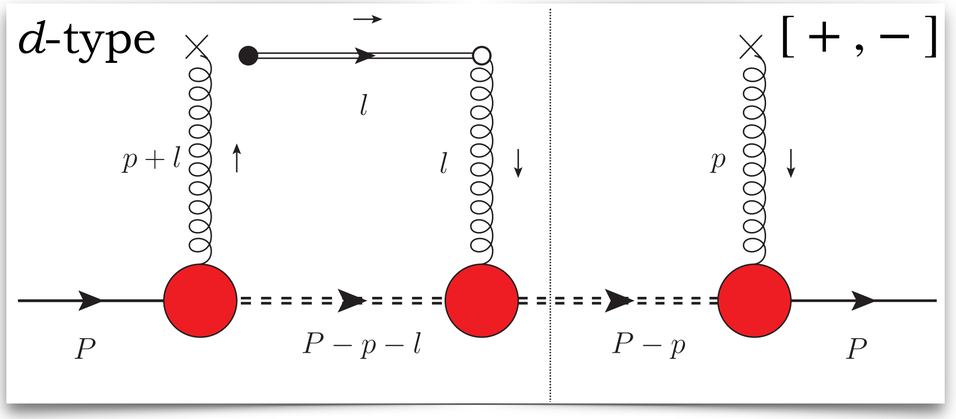
T-odd gluon TMDs in a spectator model

- No residual gluon-spectator interaction at tree level
- *Interference* with one-gluon exchange (*eikonal*)

$gg \to H$

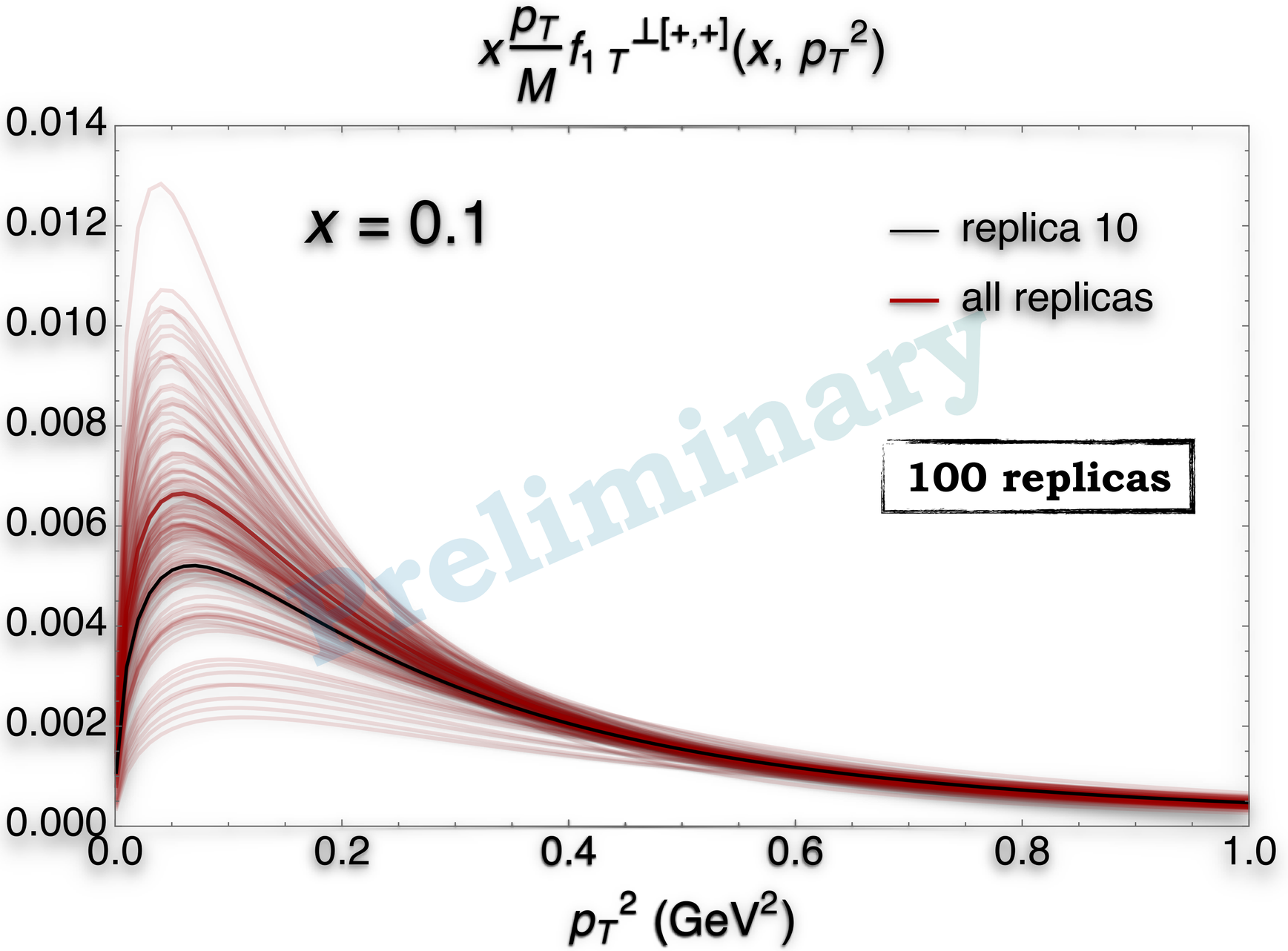


$qg \to \gamma^{(*)}$-jet

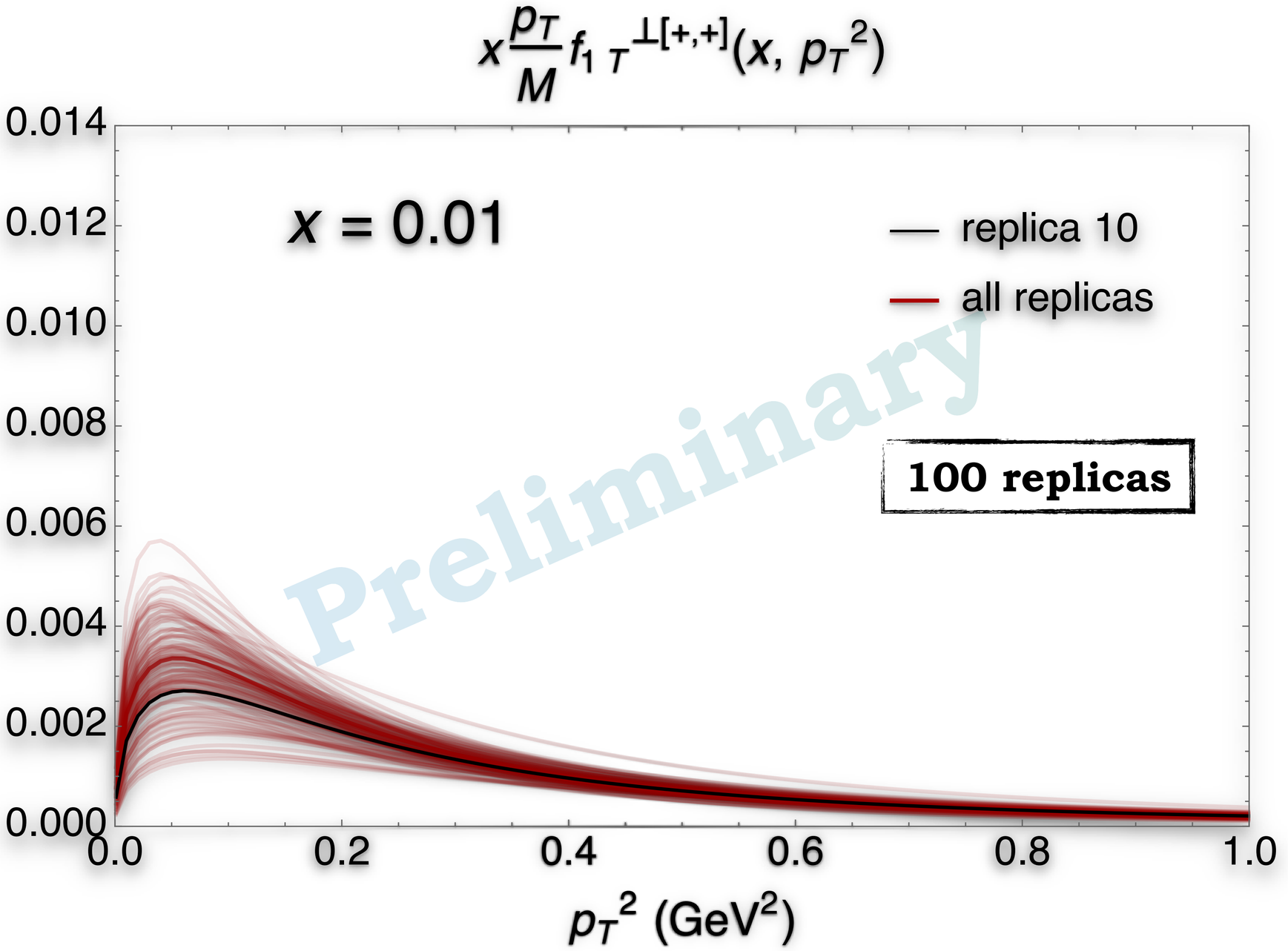


- Leading-twist one-gluon-exchange of the gauge-link operator
- Sensitivity to WW/DP structures
- Calculation of **Sivers** function *underway*!

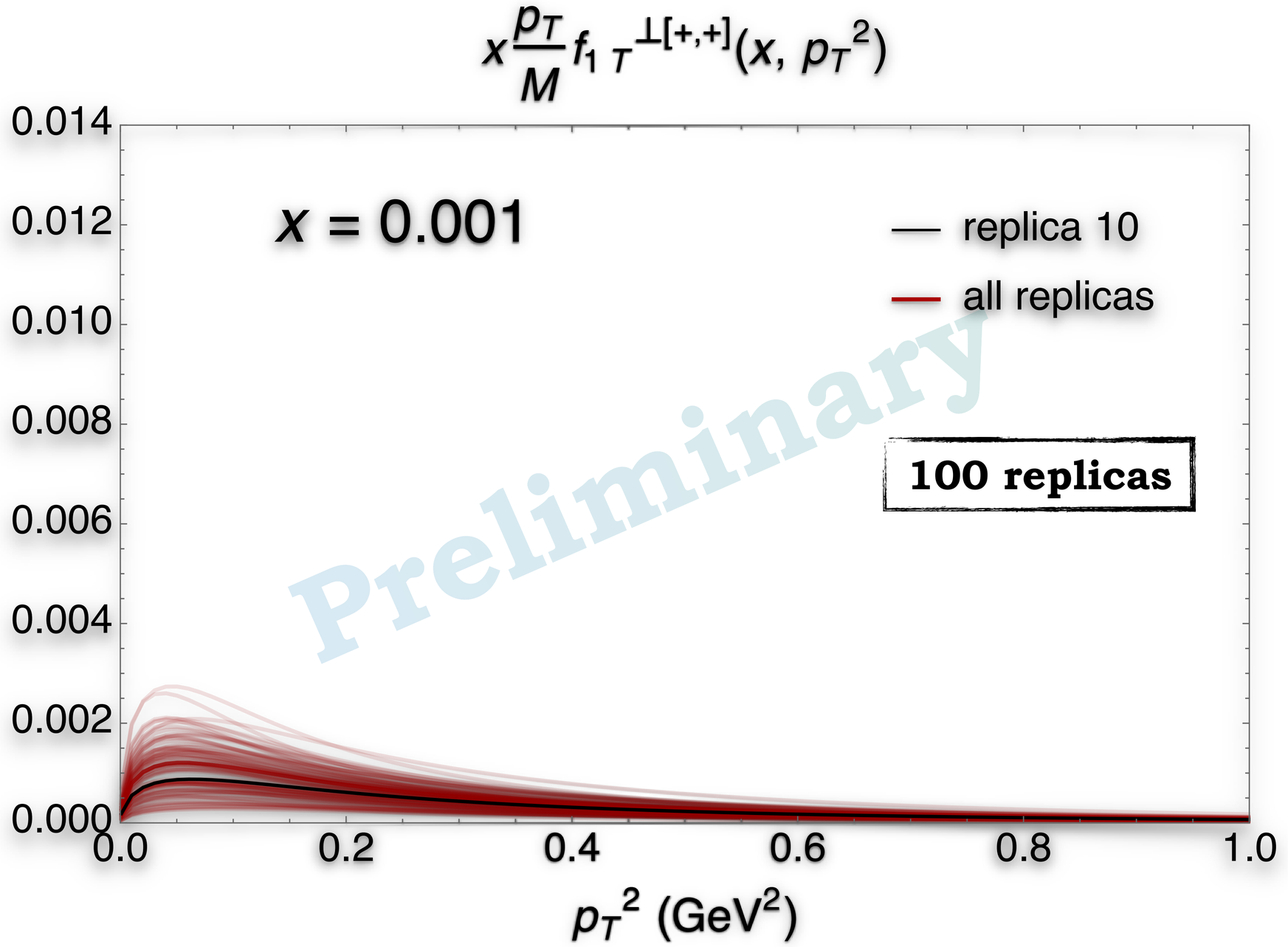
Sivers gluon TMD



Sivers gluon TMD



Sivers gluon TMD



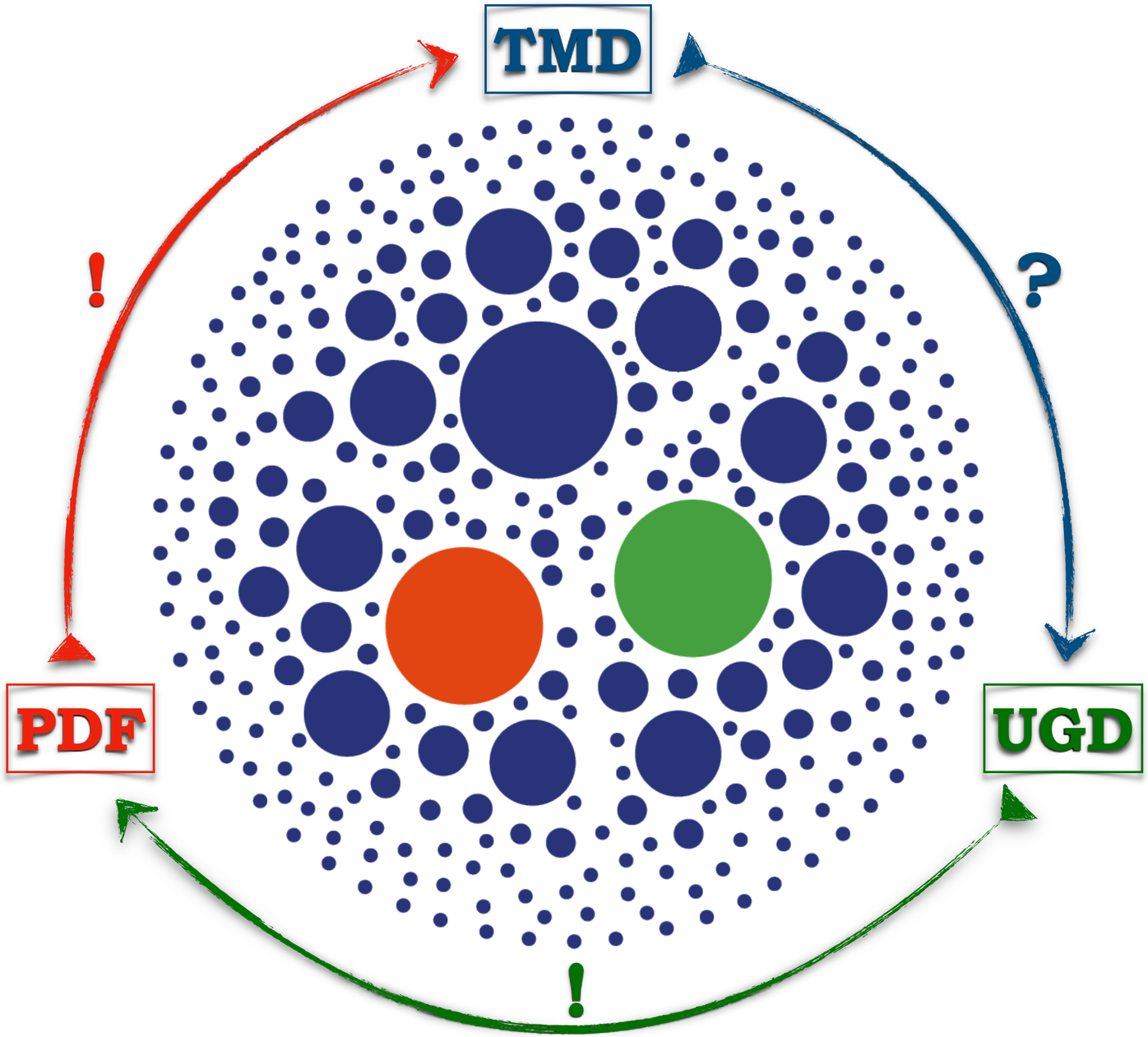
Checkpoints and further steps

- ☑ Systematic calculation of all twist-2 T-even gluon TMDs
- ☑ Spectral mass to catch small- and large-x effects
- ☑ **Simultaneous fit** of f_1 and g_1 PDFs via **replica method**

Checkpoints and further steps

- ☑ Systematic calculation of all twist-2 T-even gluon TMDs
- ☑ Spectral mass to catch small- and large-x effects
- ☑ **Simultaneous fit** of f_1 and g_1 PDFs via **replica method**
- ☐ Twist-2 T-odd gluon TMDs (**Sivers**, etc.) in progress!
- ☐ Pheno: **spin asymmetries**, **pseudodata** and **impact studies**
- ☐ Evolution: extension to quark TMDs in the same framework
- ☐ Explorative studies on gauge-link sensitivity and factorization
- ☐ Studies on GPD and small-x UGD sectors

Mapping the proton content



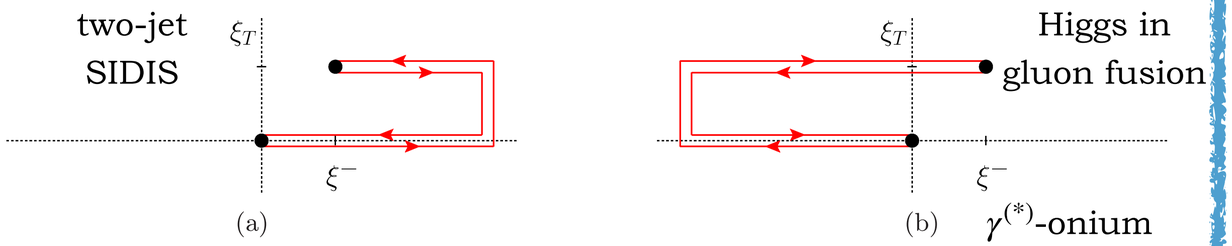


Backup slides

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

(a) $[+,+]$ or (b) $[-,-]$



* Color flow annihilated within final/initial state
* f-type gluon TMDs $\rightarrow$ f^{abc} color structure
* Modified universality:

$$f_1^{[+,+]} = f_1^{[-,-]},$$
$$f_{1T}^{\perp[+,+]} = -f_{1T}^{\perp[-,-]}$$

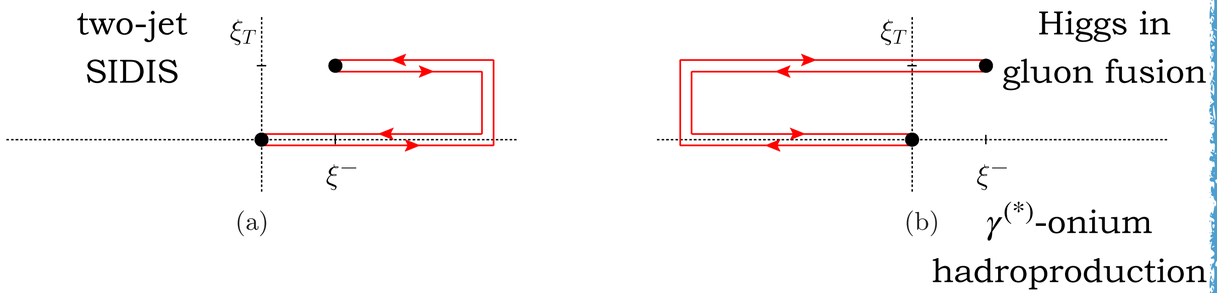
* Phenomenology: Higgs, quarkonia or $\gamma\gamma$ in pp, two-jet SIDIS, heavy-quark pair SIDIS

Backup

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

(a) $[+,+]$ or (b) $[-,-]$



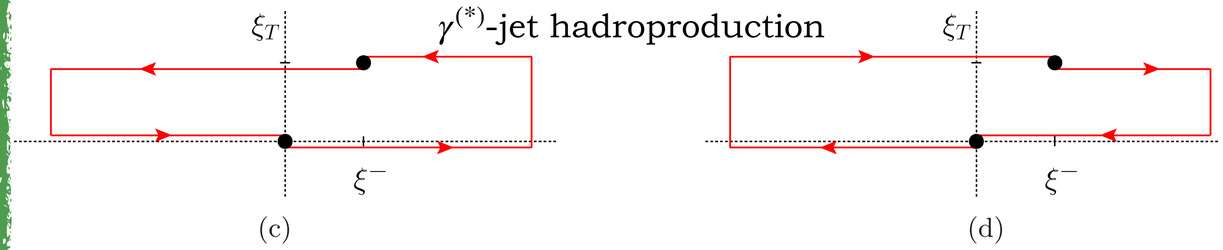
- Color flow annihilated within final/initial state
- f-type gluon TMDs $\rightarrow$ f^{abc} color structure
- Modified universality:

$$f_1^{[+,+]} = f_1^{[-,-]},$$
$$f_{1T}^{\perp[+,+]} = -f_{1T}^{\perp[-,-]}$$

- Phenomenology: Higgs, quarkonia or $\gamma\gamma$ in pp, two-jet SIDIS, heavy-quark pair SIDIS

Dipole (DP)

(c) $[+,-]$ or (d) $[-,+]$



- Color flow involving both initial and final states
- d-type gluon TMDs $\rightarrow$ d^{abc} color structure
- Modified universality:

$$f_1^{[+,-]} = f_1^{[-,+]},$$
$$f_{1T}^{\perp[+,-]} = -f_{1T}^{\perp[-,+]}$$

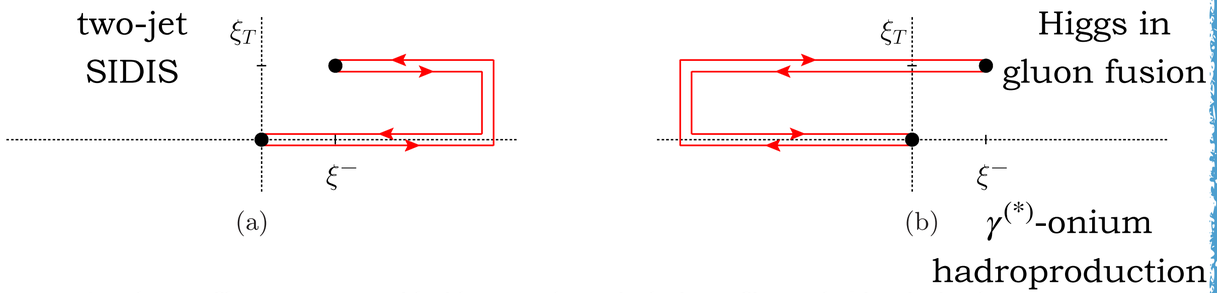
- Phenomenology: single hadron or $\gamma^{(*)}$-jet hadroproduction, SIDIS or Drell-Yan (subleading)

Backup

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

(a) $[+,+]$ or (b) $[-,-]$



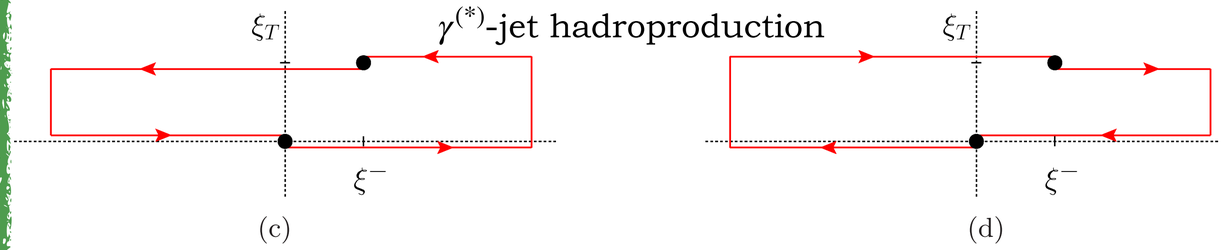
- Color flow annihilated within final/initial state
- f-type gluon TMDs $\rightarrow$ f^{abc} color structure
- Modified universality:

$$f_1^{[+,+]} = f_1^{[-,-]},$$
$$f_{1T}^{\perp[+,+]} = -f_{1T}^{\perp[-,-]}$$

- Phenomenology: Higgs, quarkonia or $\gamma\gamma$ in pp, two-jet SIDIS, heavy-quark pair SIDIS

Dipole (DP)

(c) $[+,-]$ or (d) $[-,+]$



- Color flow involving both initial and final states
- d-type gluon TMDs $\rightarrow$ d^{abc} color structure
- Modified universality:

$$f_1^{[+,-]} = f_1^{[-,+]},$$
$$f_{1T}^{\perp[+,-]} = -f_{1T}^{\perp[-,+]}$$

- Phenomenology: single hadron or $\gamma^{(*)}$-jet hadroproduction, SIDIS or Drell-Yan (subleading)

Gauge link $\rightarrow$ two main independent sets of TMDs, **not related** to each other

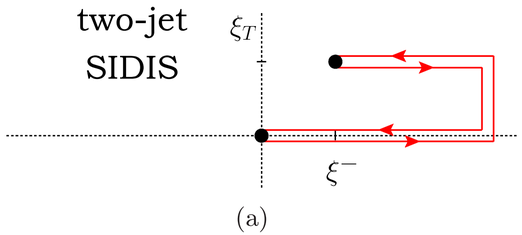
Backup

Accessing WW and DP gluon TMDs

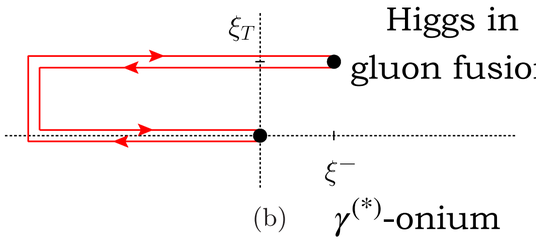
Weiszäcker-Williams (WW)

(a) $[+,+]$ or (b) $[-,-]$

two-jet
SIDIS



(a)



Higgs in
gluon fusion

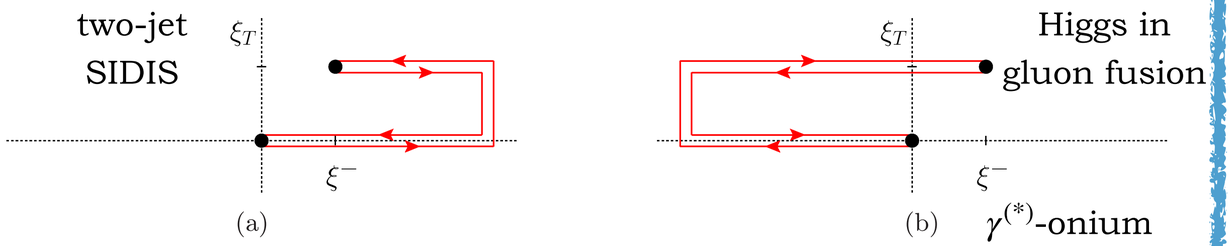
(b) $\gamma^{(*)}$-onium
hadroproduction

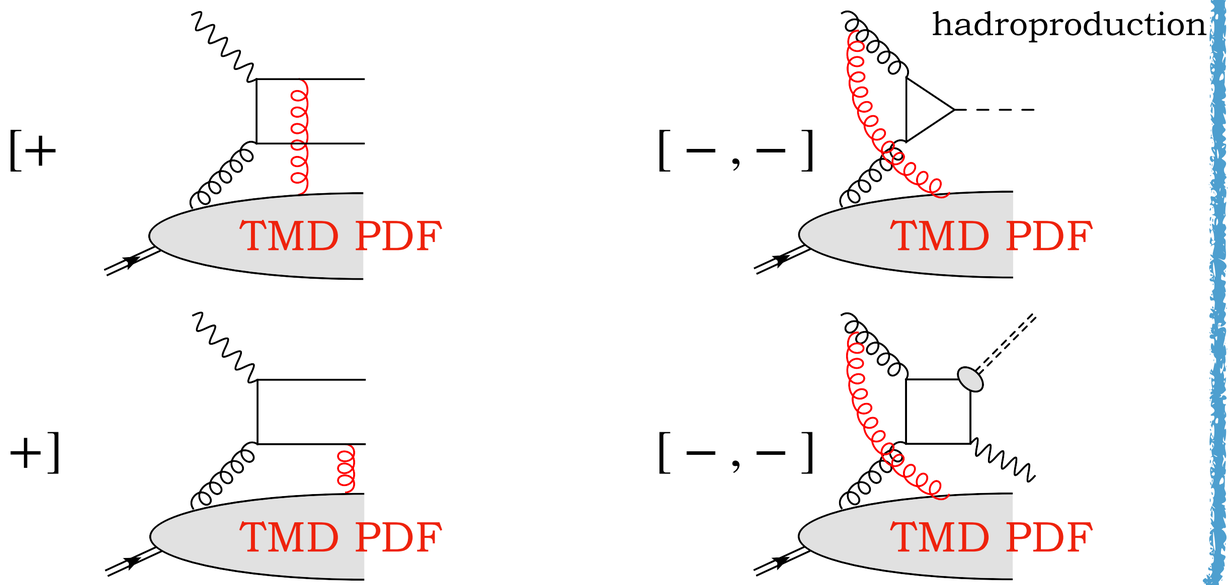
Backup

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

(a) $[+,+]$ or (b) $[-,-]$





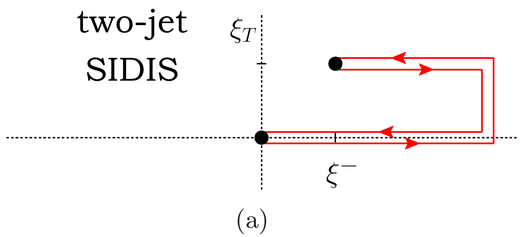
Backup

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

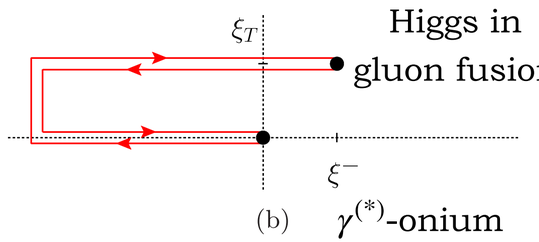
(a) $[+,+]$ or (b) $[-,-]$

two-jet SIDIS



(a)

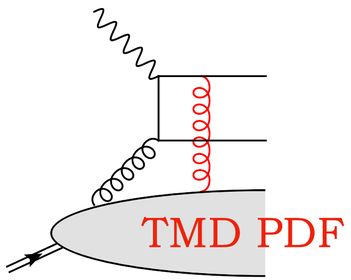
Higgs in gluon fusion



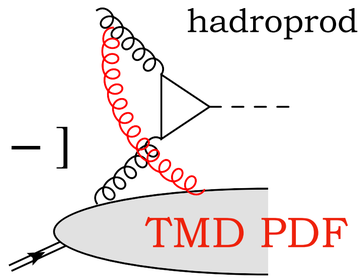
(b)

$\gamma^{(*)}$-onium hadroproduction

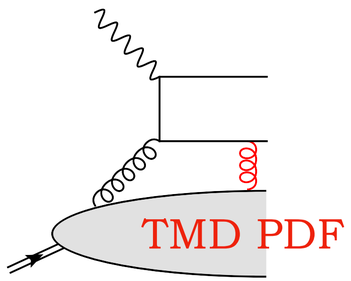
$[+$



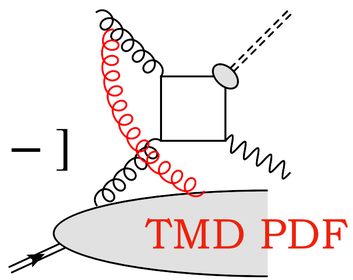
$[-,-]$



$+]$

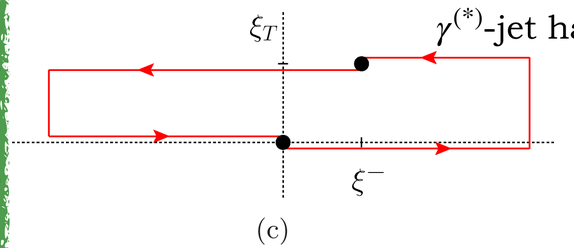


$[-,-]$



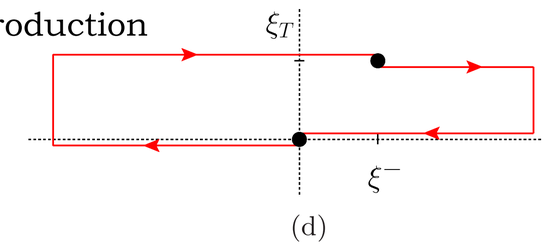
Dipole (DP)

(c) $[+,-]$ or (d) $[-,+]$



(c)

$\gamma^{(*)}$-jet hadroproduction



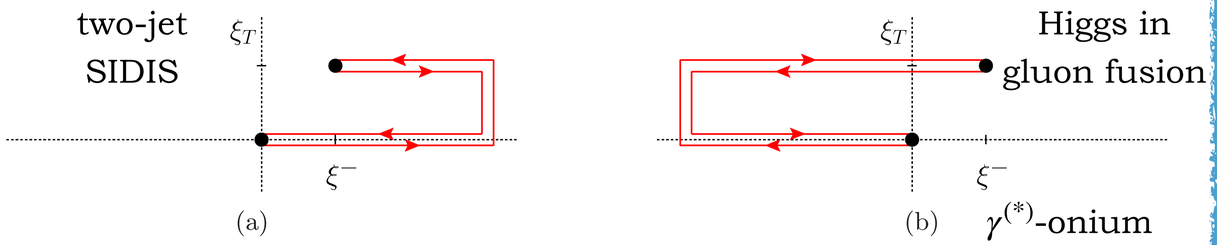
(d)

Backup

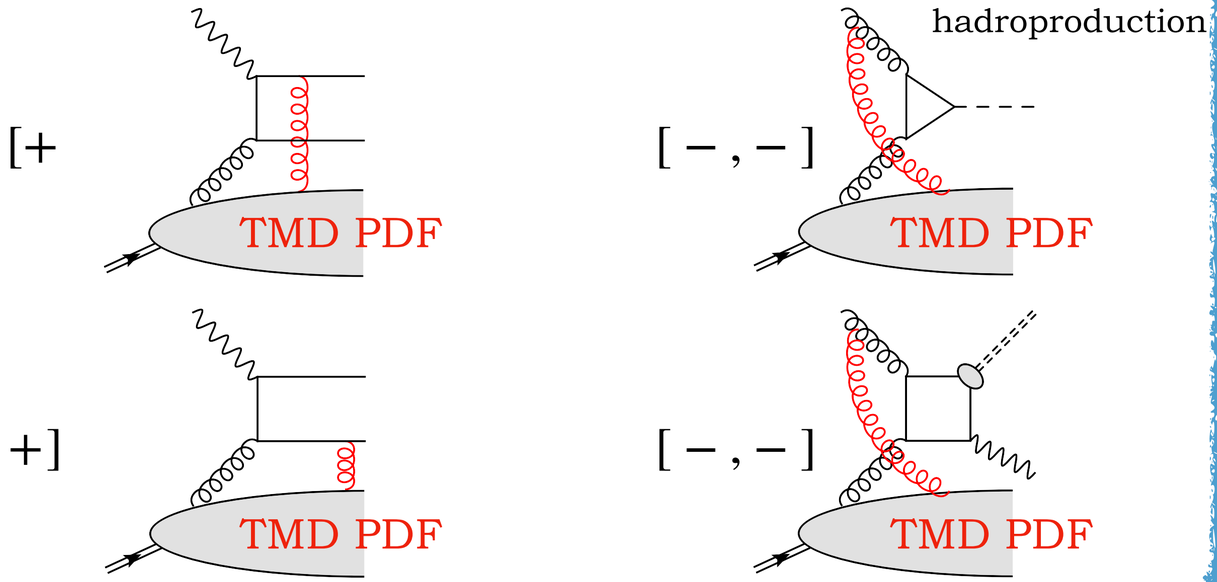
Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

(a) $[+,+]$ or (b) $[-,-]$

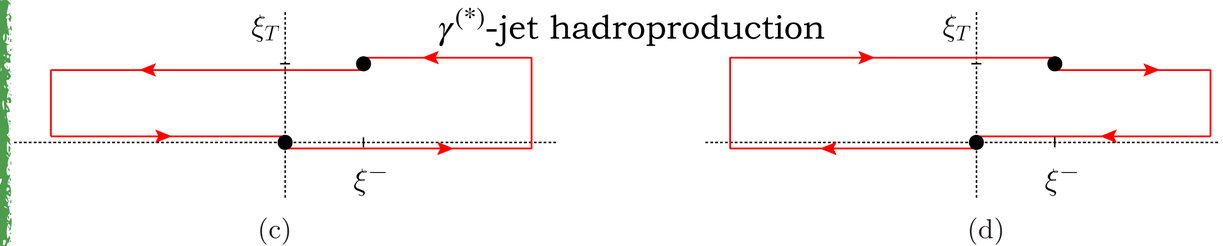


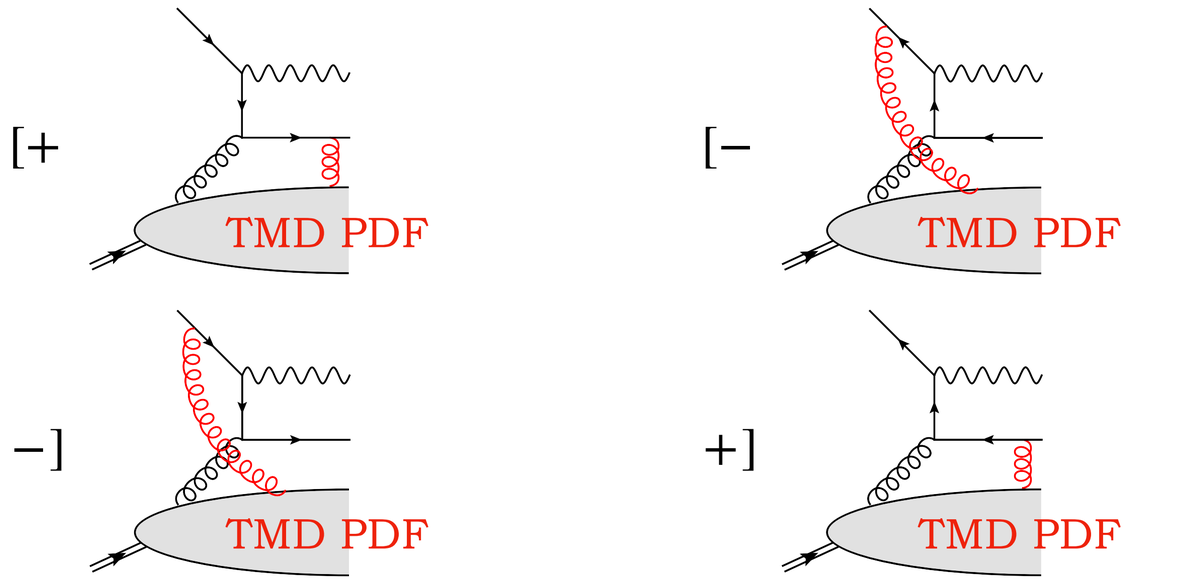
$\gamma^{(*)}$-onium hadroproduction



Dipole (DP)

(c) $[+,-]$ or (d) $[-,+]$





Backup

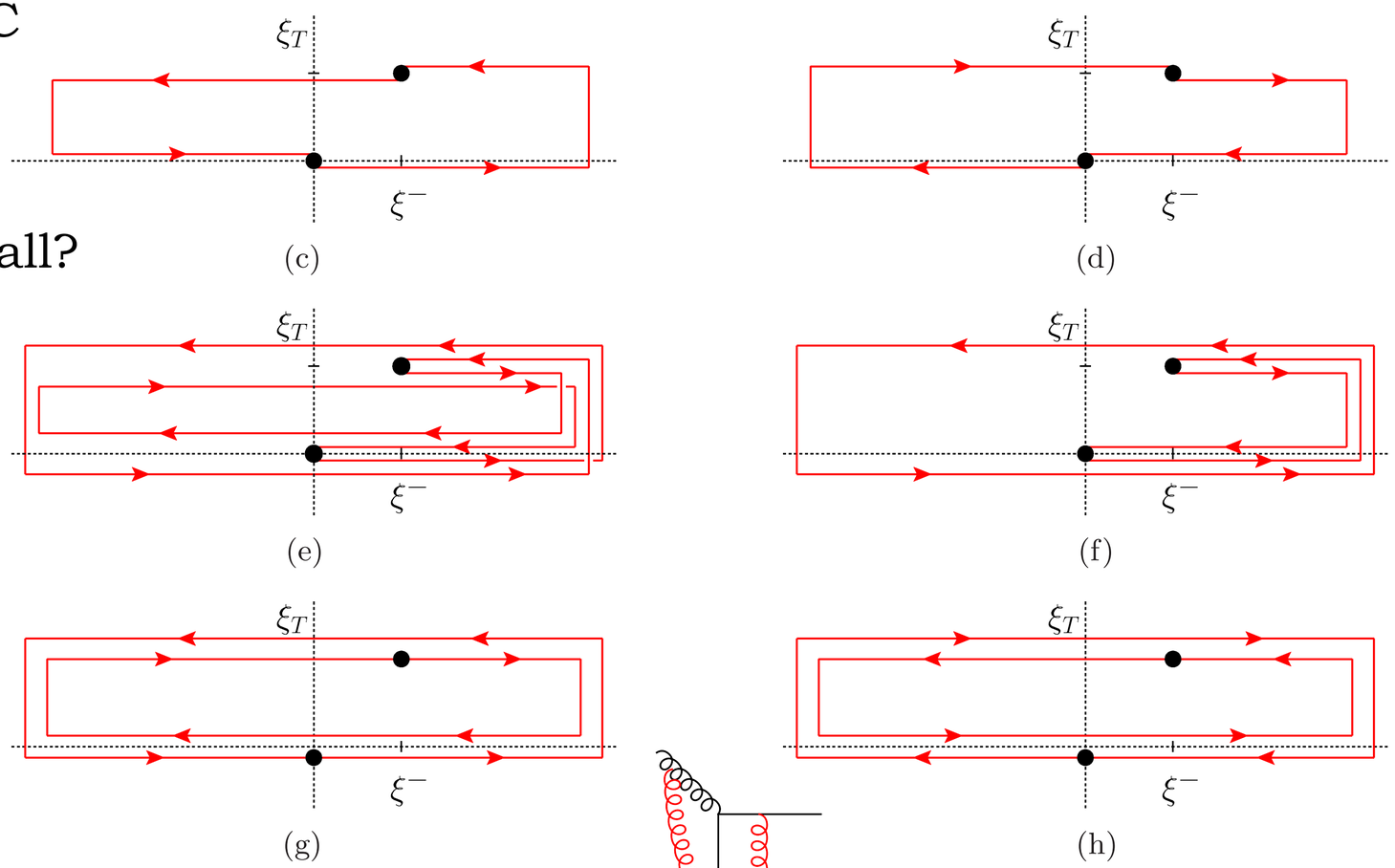
Dihadron hadroproduction and factorization breaking

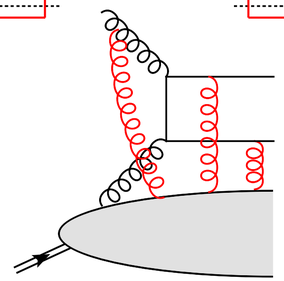
* Proof of factorization violation 🔗 [T. J. Rogers, P. J. Mulders (2010)]
* Assumed factorization in SCET and CGC
* Significance of low-x studies
* Size of factorization-breaking effects small?
* DP TMDs:

  (c) $[+,-]$ and (d) $[-,+]$
* Appearance of new gauge **loop links**:

  (e) $[+\square,+\square]$, (f) $[+,+\square]$,

  (g) $[\square,\square]$, and (h) $[\square,\square]$



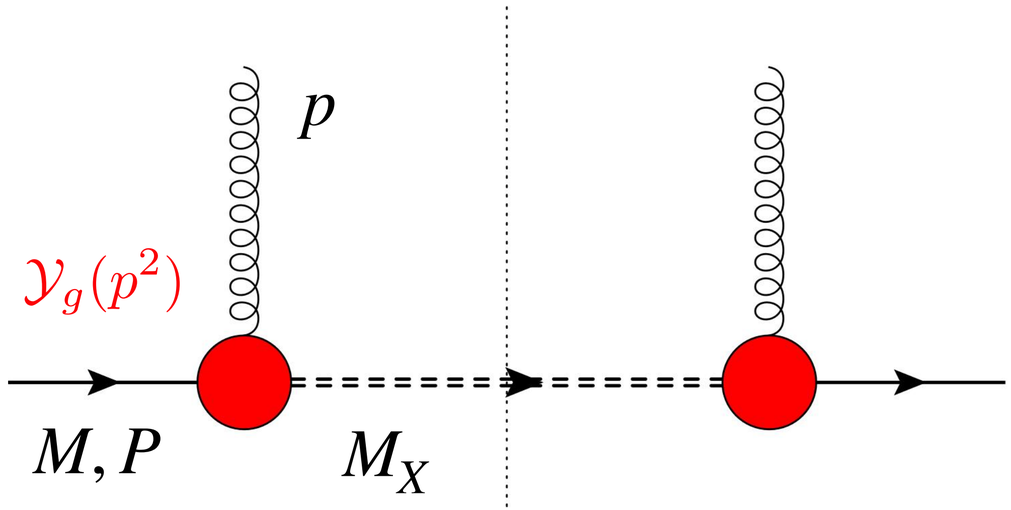


Backup

Assumptions of the model

Effective vertex

Lowest Fock state:
tri-quark spectator
on-shell and
with mass M_X



Spin-1/2 spectator (gluon)

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

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

mimics proton form factors
(conserved EM current
of a free nucleon)

Backup

Assumptions of the model

Link with collinear factorization

p_T-integrated TMDs **have to** reproduce PDFs
at the lowest scale (Q_0) *before* evolution

Dipolar form factor(s)

$$g_{1,2}(p^2) = \kappa_{1,2} \frac{p^2}{|p^2 - \Lambda_X^2|^2}$$

1. Cancels singularity of gluon propagator
2. Suppresses effects of high p_T
3. Compensates log divergences arising from p_T-integration
4. Adds three more parameters: $\kappa_{1,2}$ and Λ_X

Backup

Assumptions of the model

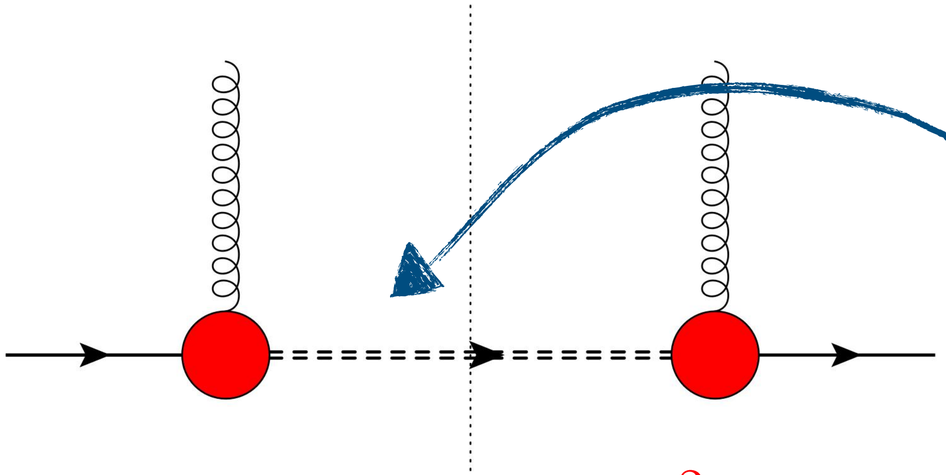
Spectator-system spectral-mass function

spectral-mass function

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

spectator-model TMD

[Inspired by G.R. Goldstein, J.O.G. Hernandez, S. Liuti (2011)]



Instead of a single on-shell spectator, a continuum of spectators

Backup

Assumptions of the model

Spectator-system spectral-mass function

spectral-mass function

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

spectator-model TMD

[Inspired by G.R. Goldstein, J.O.G. Hernandez, S. Liuti (2011)]

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

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

$q\bar{q}$ contributions energetically available at large M_X

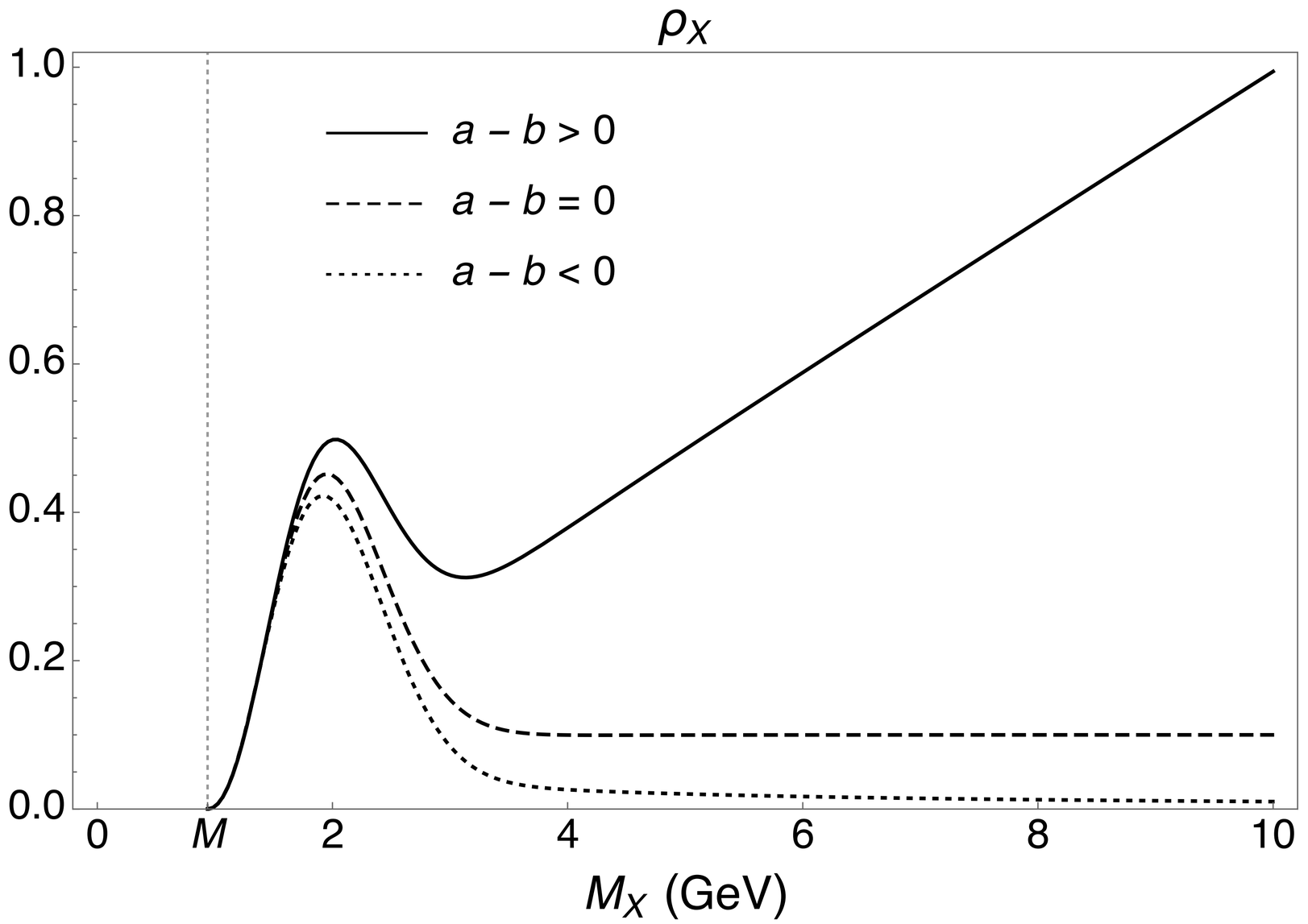
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

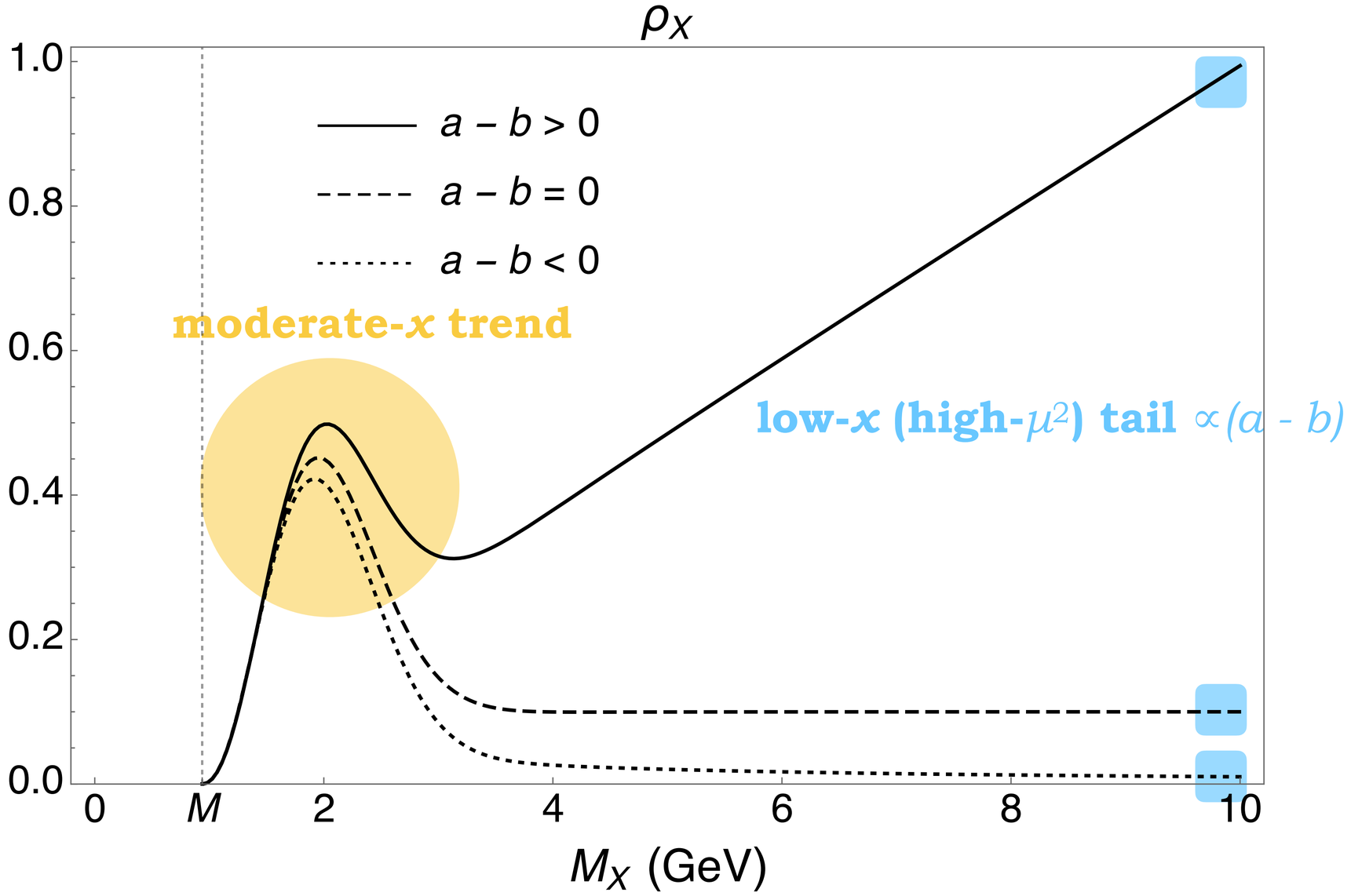
Backup

Spectral function vs *(a - b)*



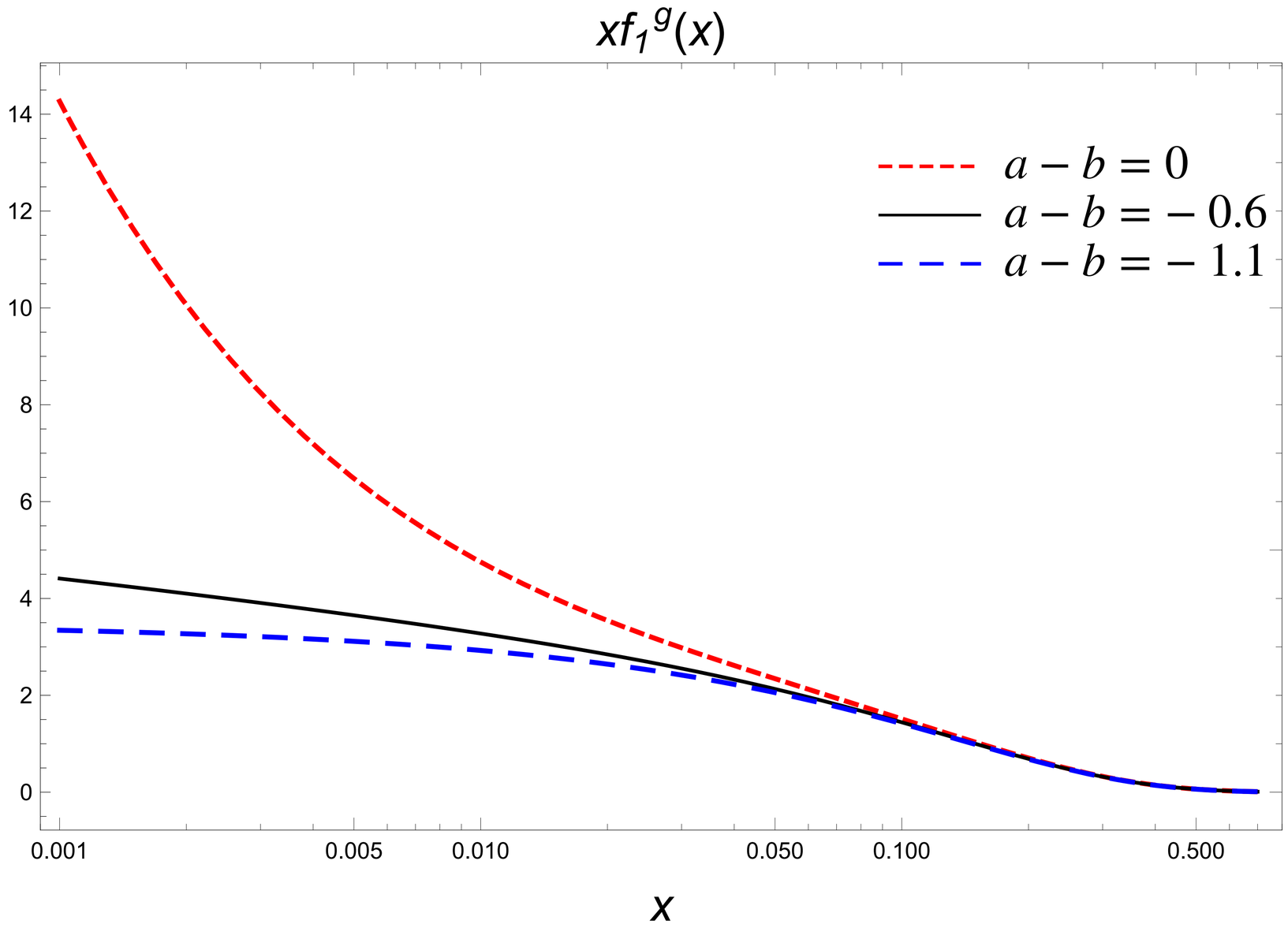
Backup

Spectral function vs $(a - b)$



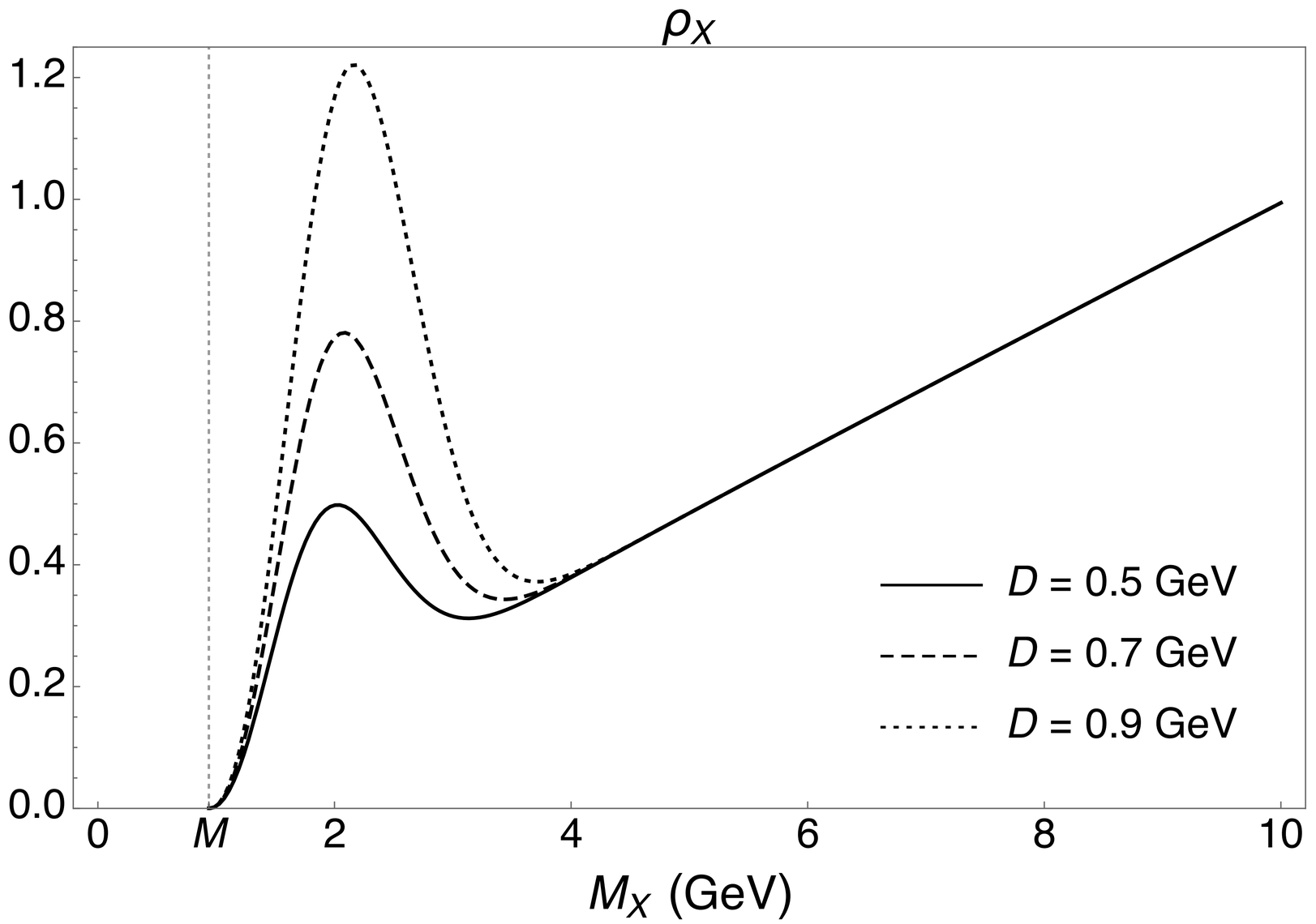
Backup

xf_1 collinear PDF vs $(a - b)$



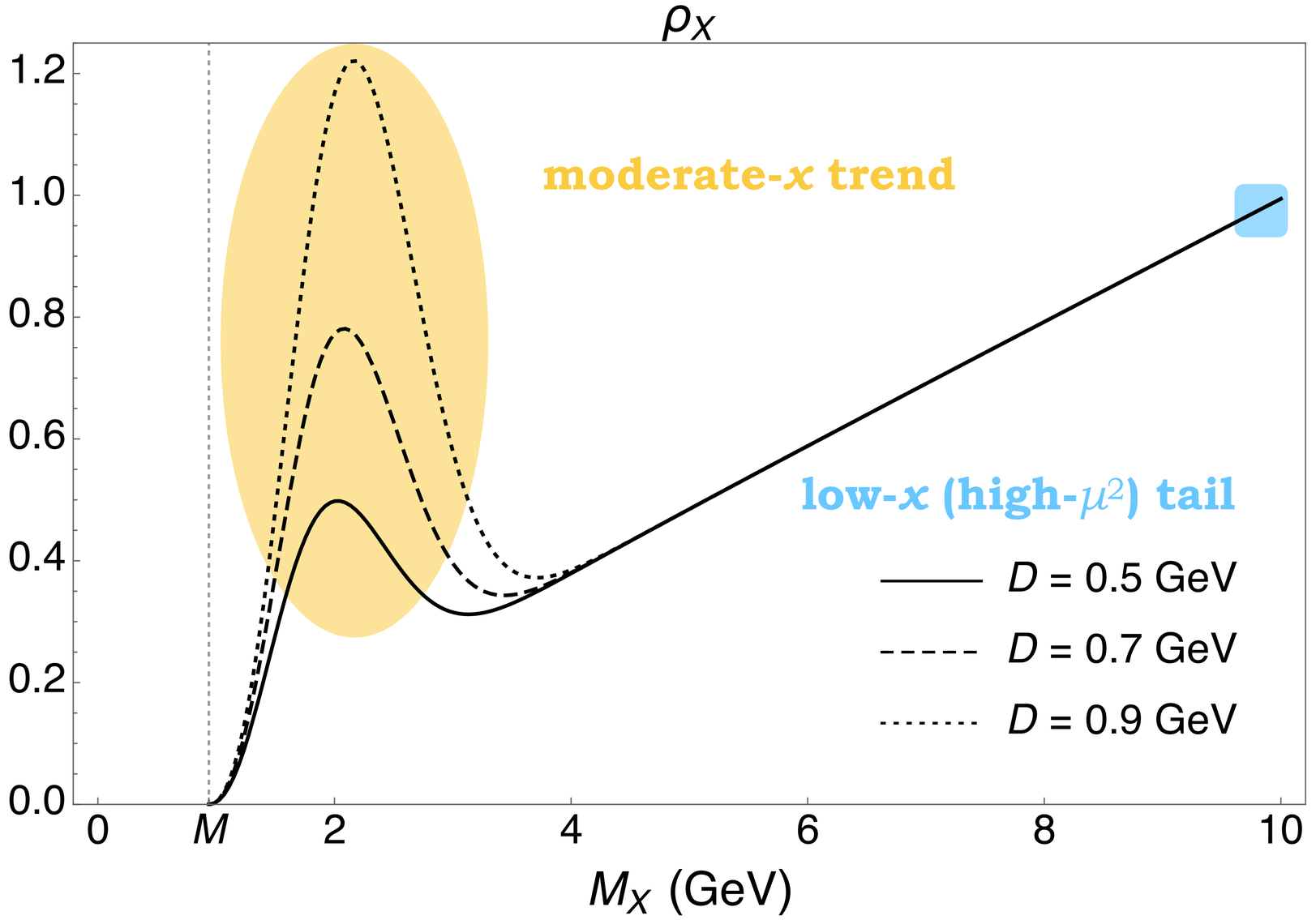
Backup

Spectral function vs D



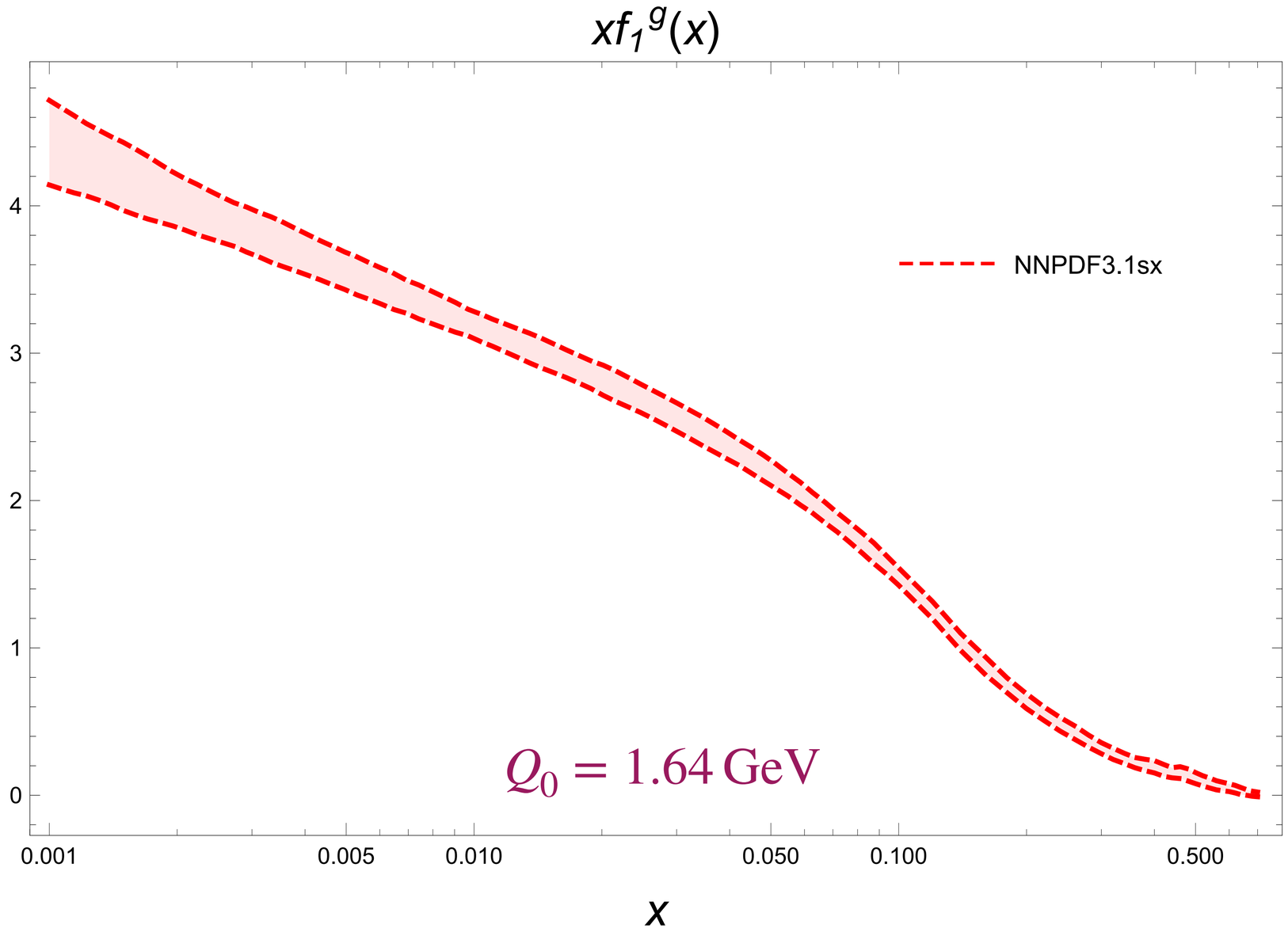
Backup

Spectral function vs D



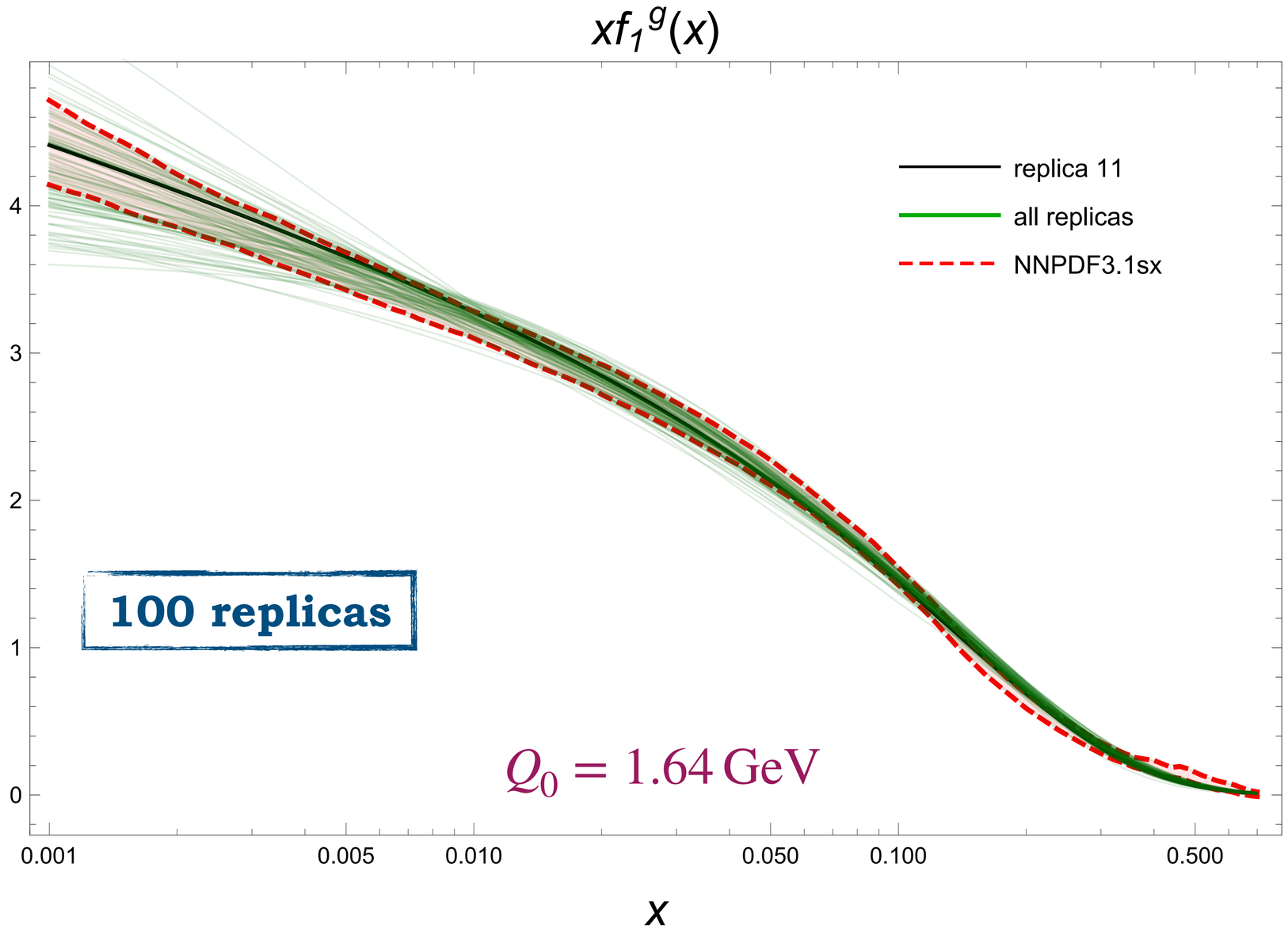
Backup

Unpolarized gluon PDF



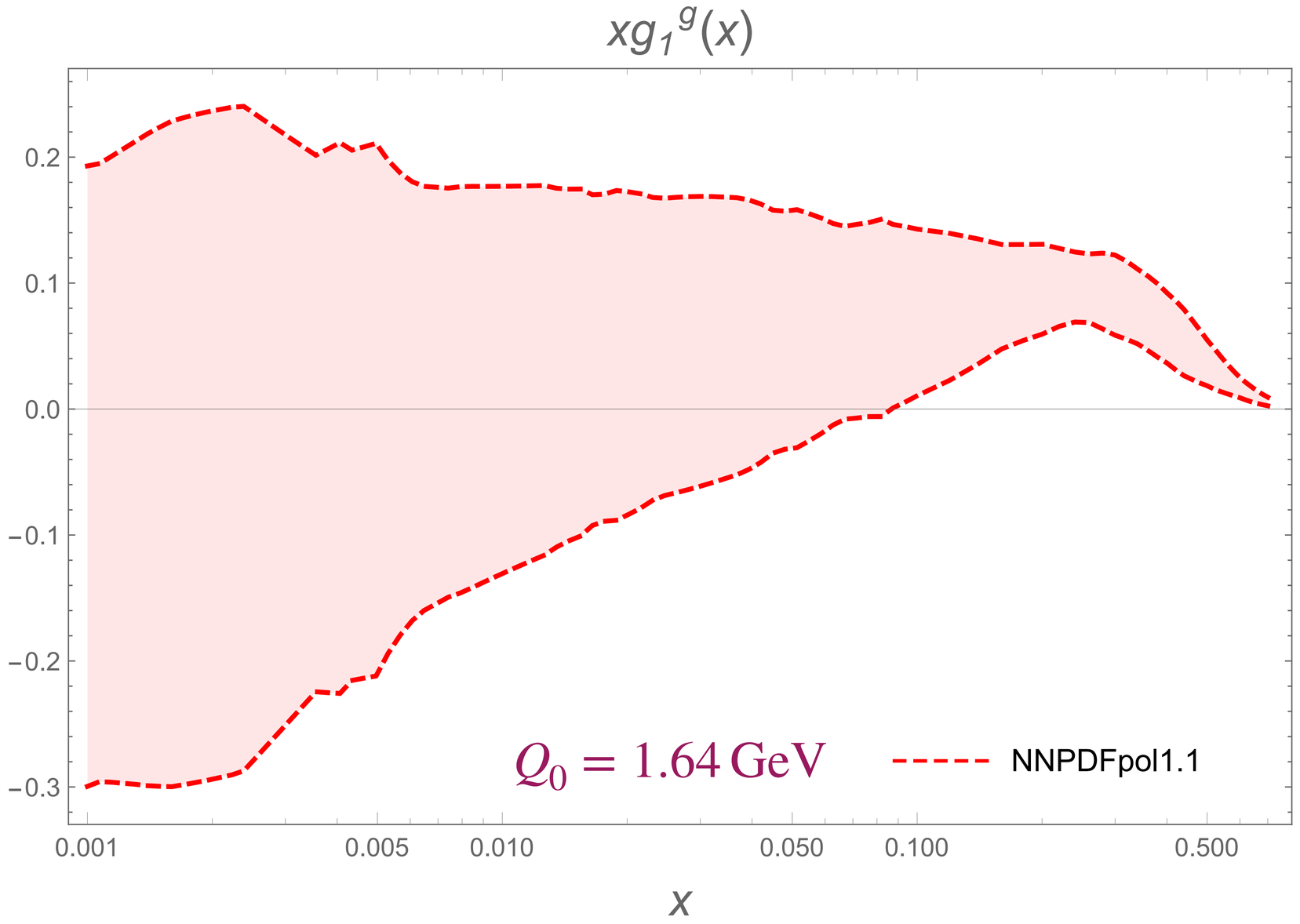
Backup

Unpolarized gluon PDF



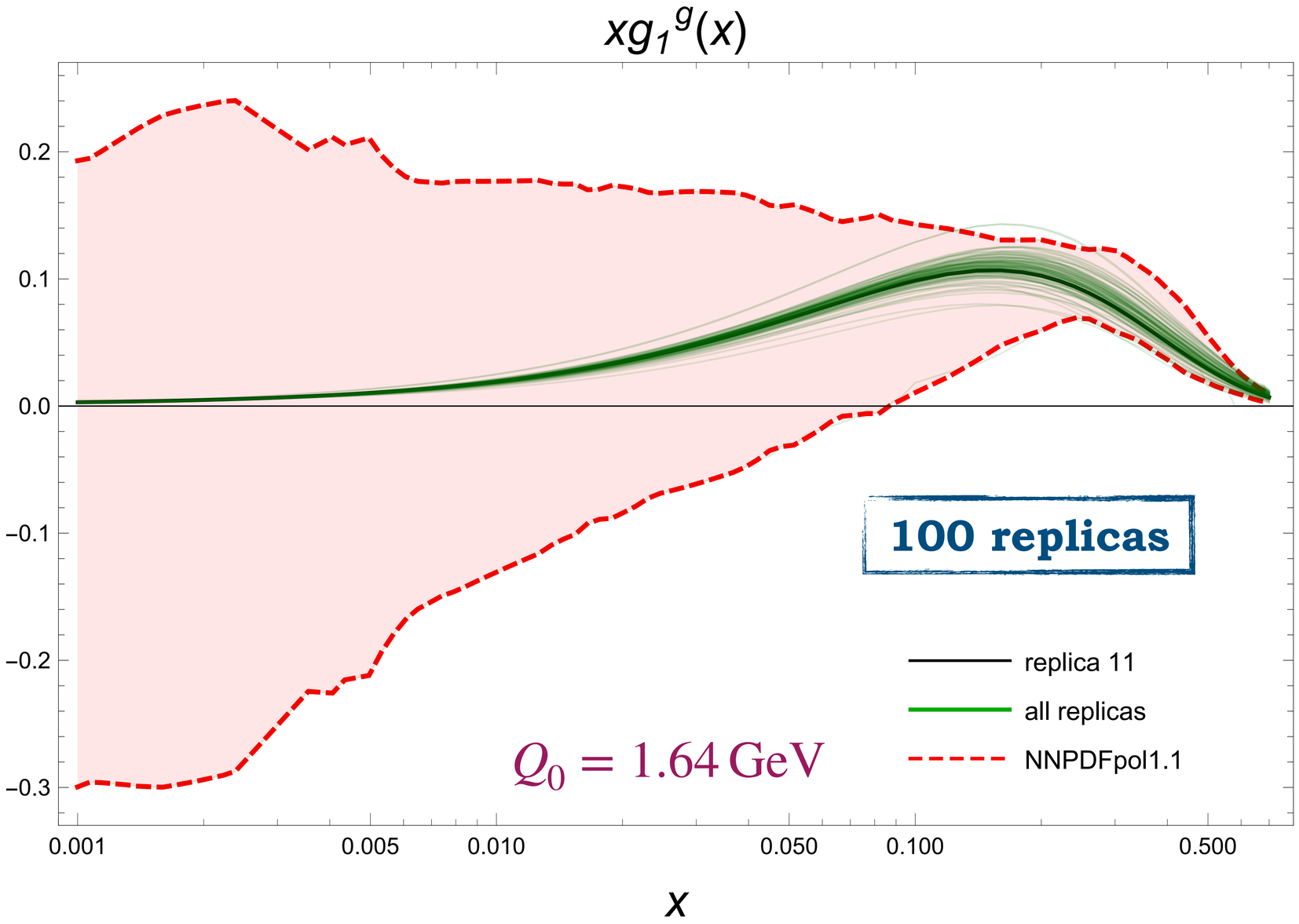
Backup

Helicity gluon PDF



Backup

Helicity gluon PDF



Backup

Fit specifics

$$\chi^2/\text{d.o.f.} = 0.54 \pm 0.38$$

no **overlearning**, just large errors for g_1

Backup

Fit specifics

$$\chi^2/\text{d.o.f.} = 0.54 \pm 0.38$$

no **overlearning**, just large errors for g_1

$$\langle x \rangle_g = \int_0^1 dx\, x f_1^g(x, Q_0) \qquad S_g = \frac{1}{2}\langle 1 \rangle_{\Delta g} = \int_0^1 dx\, g_1^g(x, Q_0)$$

Backup

Fit specifics

$$\chi^2/\text{d.o.f.} = 0.54 \pm 0.38$$

no **overlearning**, just large errors for g_1

$$\langle x \rangle_g = \int_0^1 dx\, x f_1^g(x, Q_0) \qquad S_g = \frac{1}{2}\langle 1 \rangle_{\Delta g} = \int_0^1 dx\, g_1^g(x, Q_0)$$

Our model @ $Q_0 = 1.64$ GeV

$$\langle x \rangle_g = 0.424(9)$$

$$\langle S \rangle_g = 0.159(11)$$

Lattice @ $Q_0 = 2$ GeV

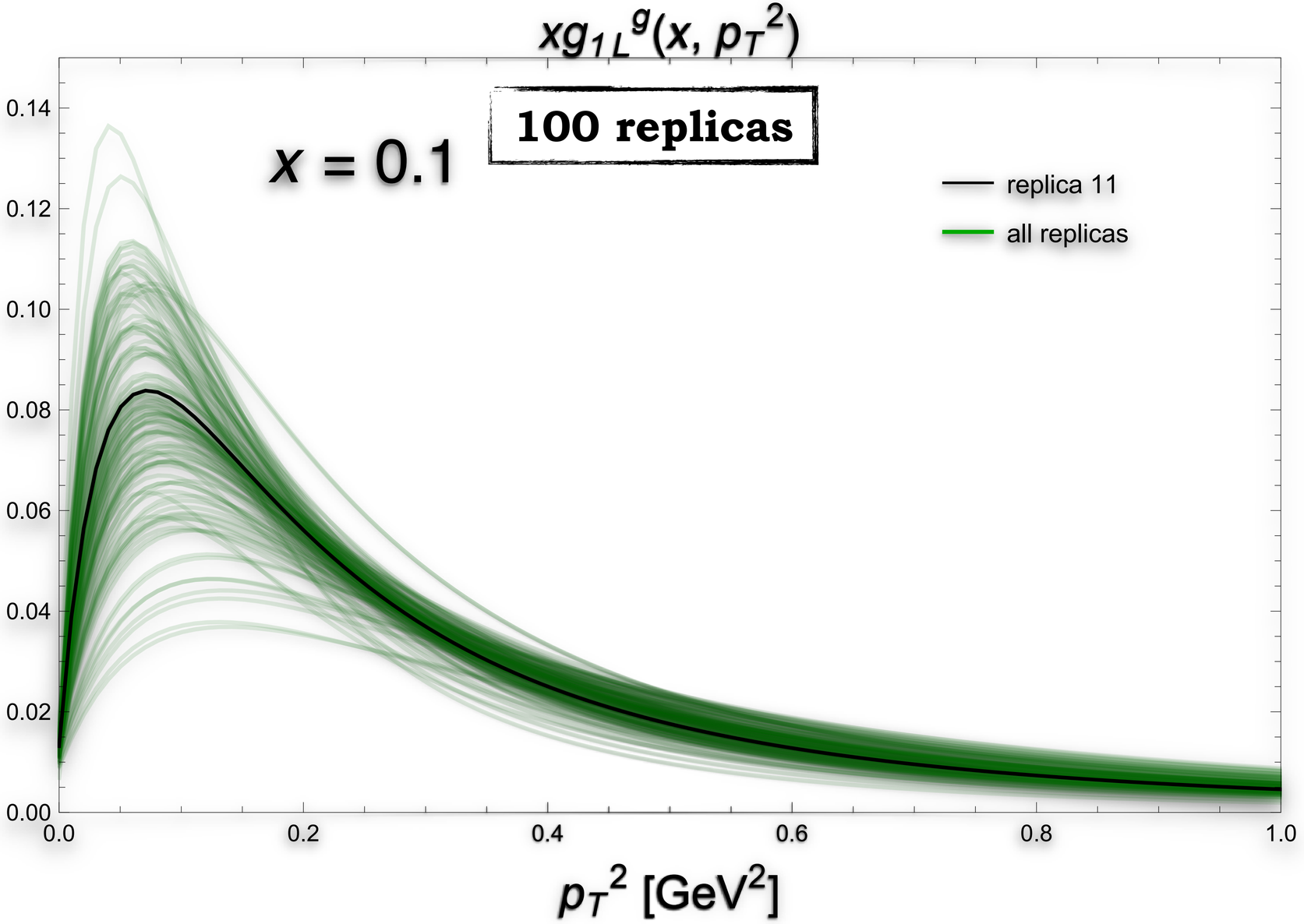
$$\langle x \rangle_g = 0.427(92)$$

$$\langle J \rangle_g = 0.187(46)$$

[C. Alexandrou *et al.* (2020)]

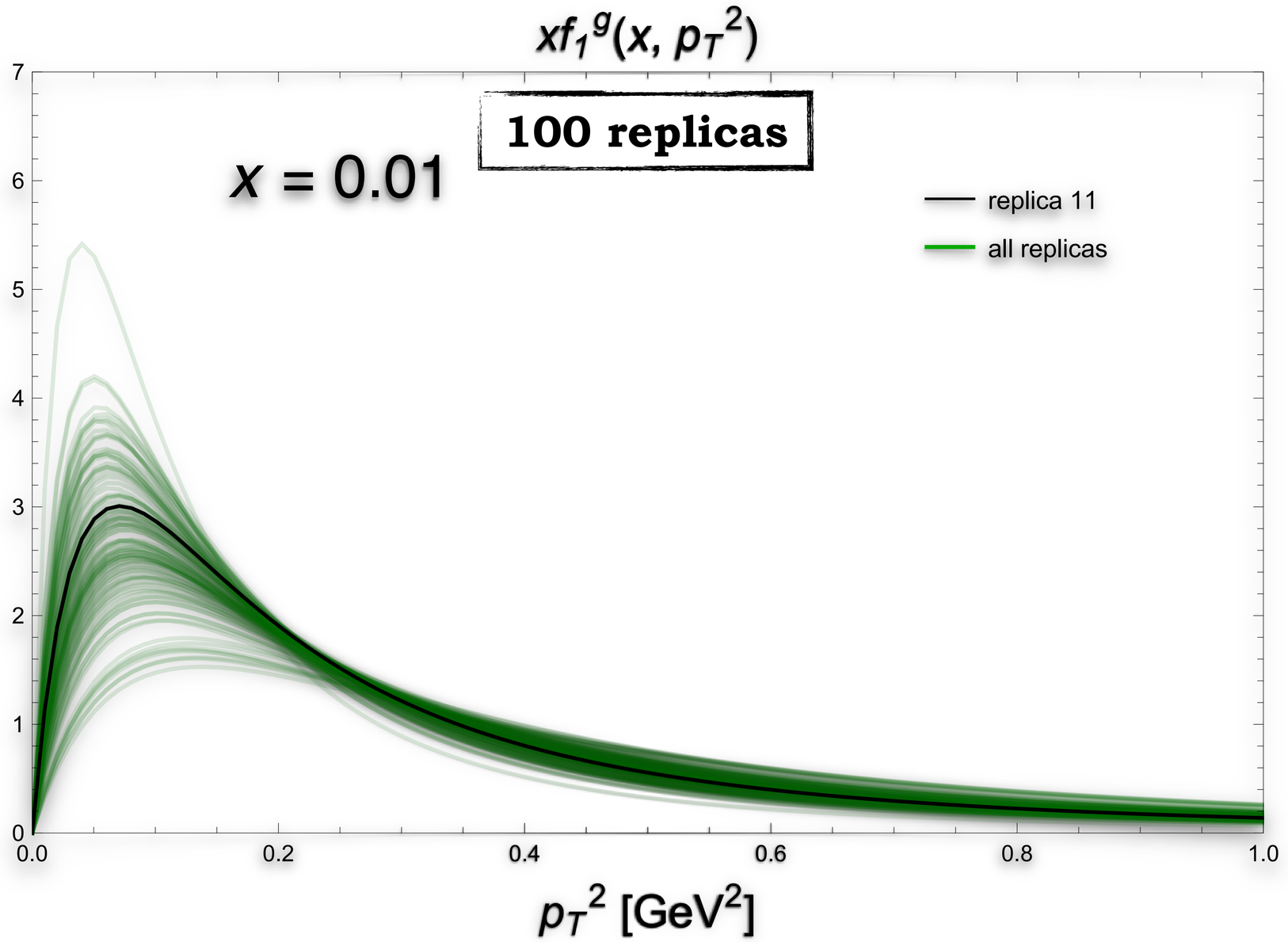
Backup

Helicity gluon TMD



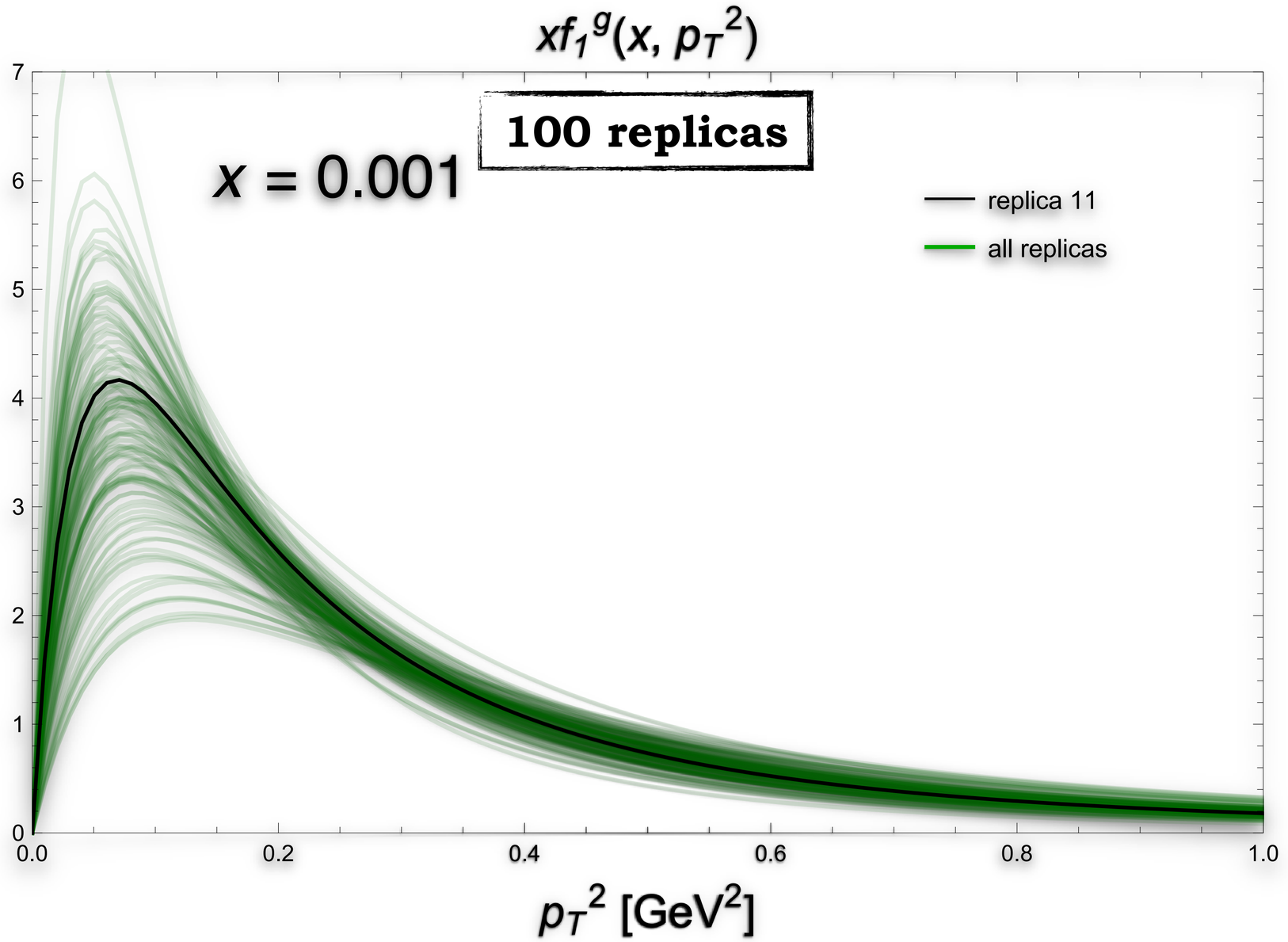
Backup

Unpolarized gluon TMD



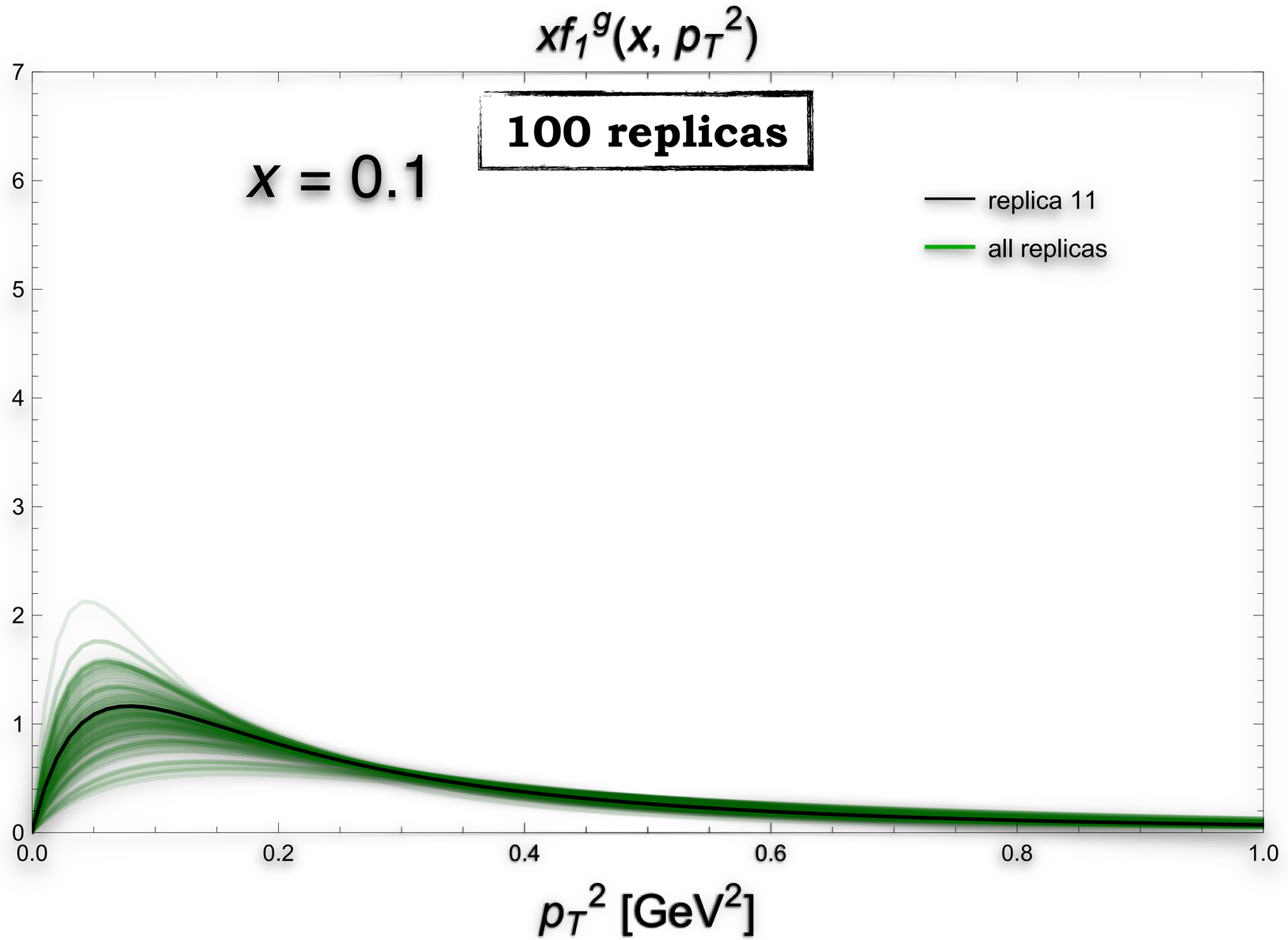
Backup

Unpolarized gluon TMD



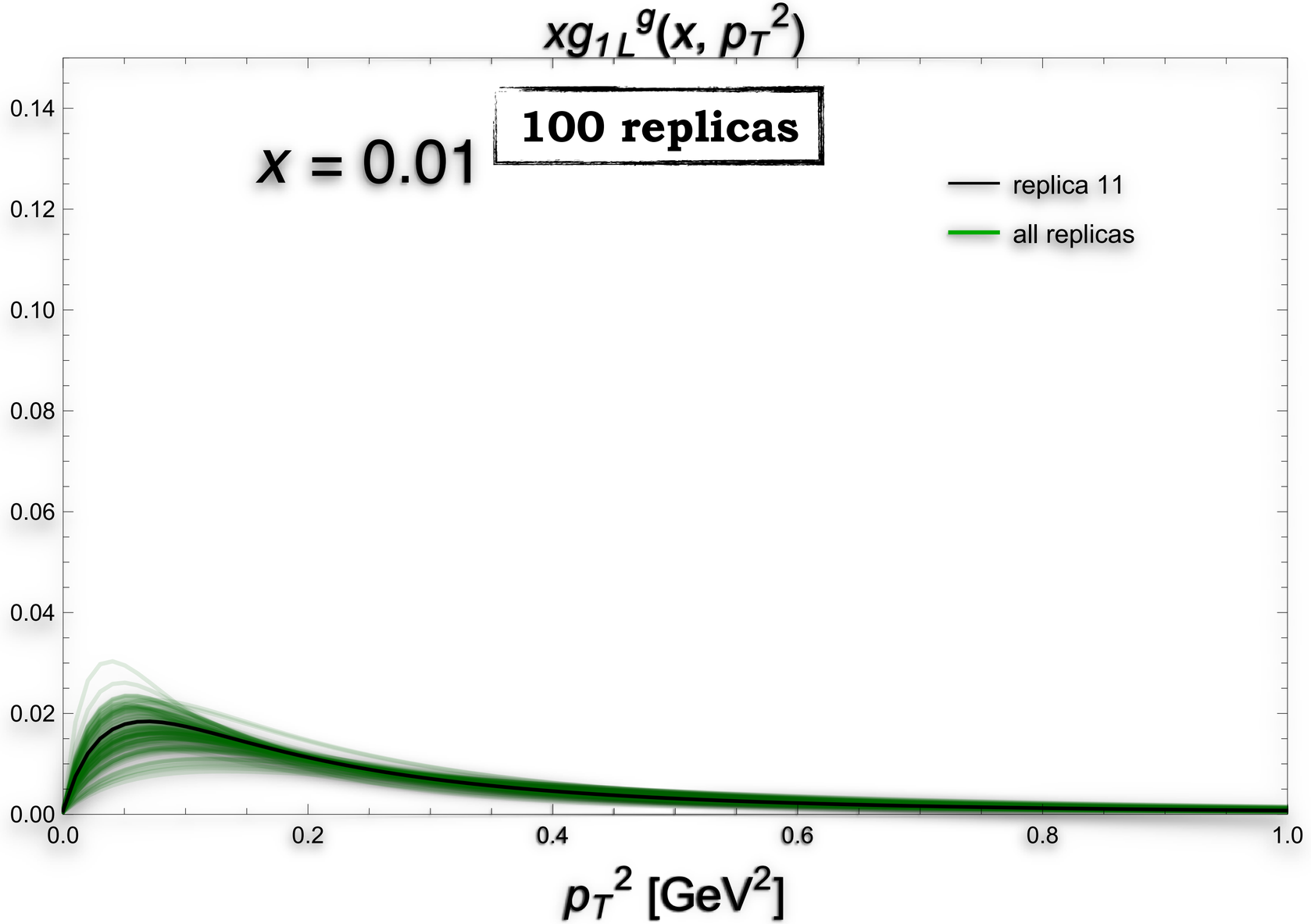
Backup

Unpolarized gluon TMD



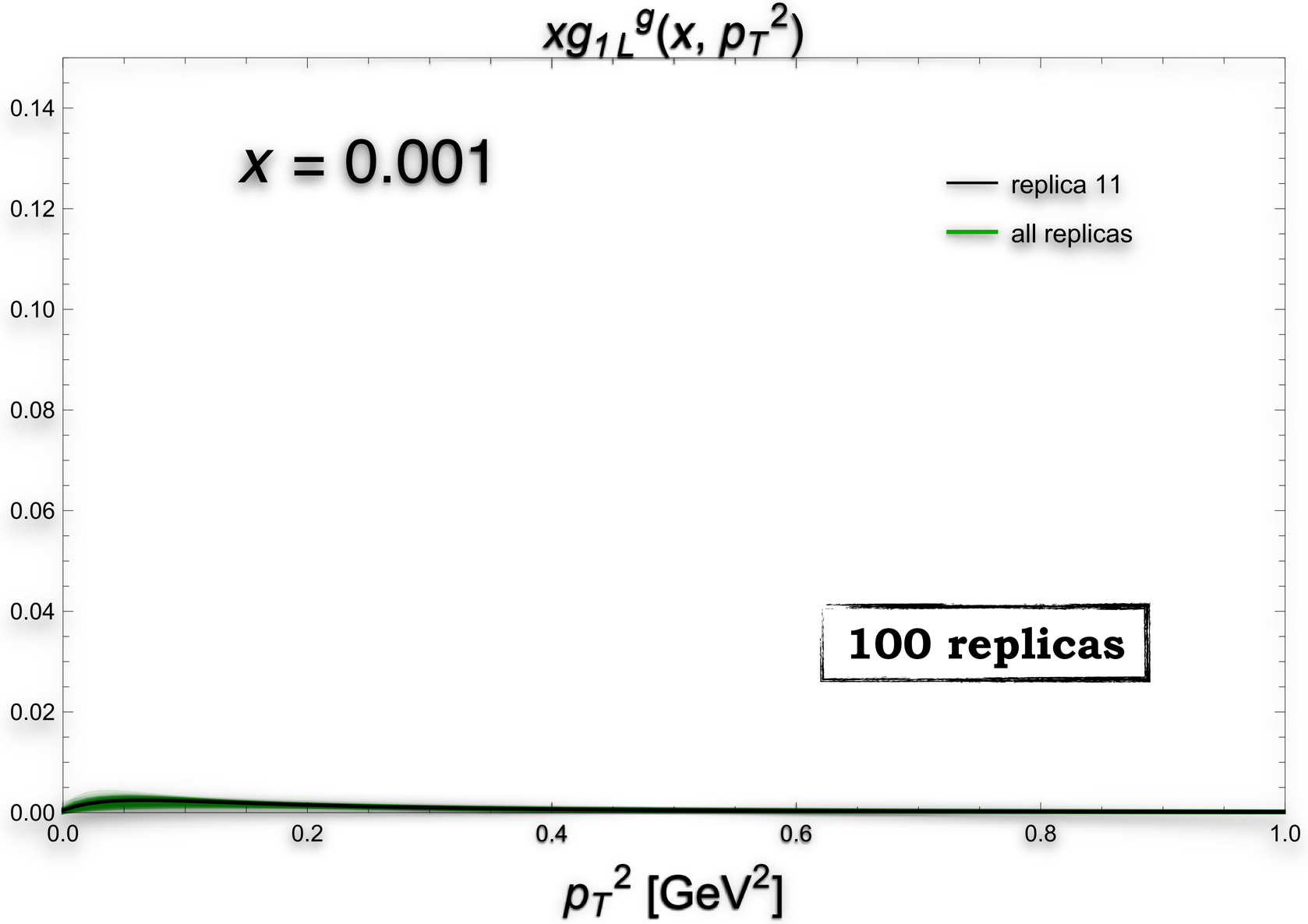
Backup

Helicity gluon TMD



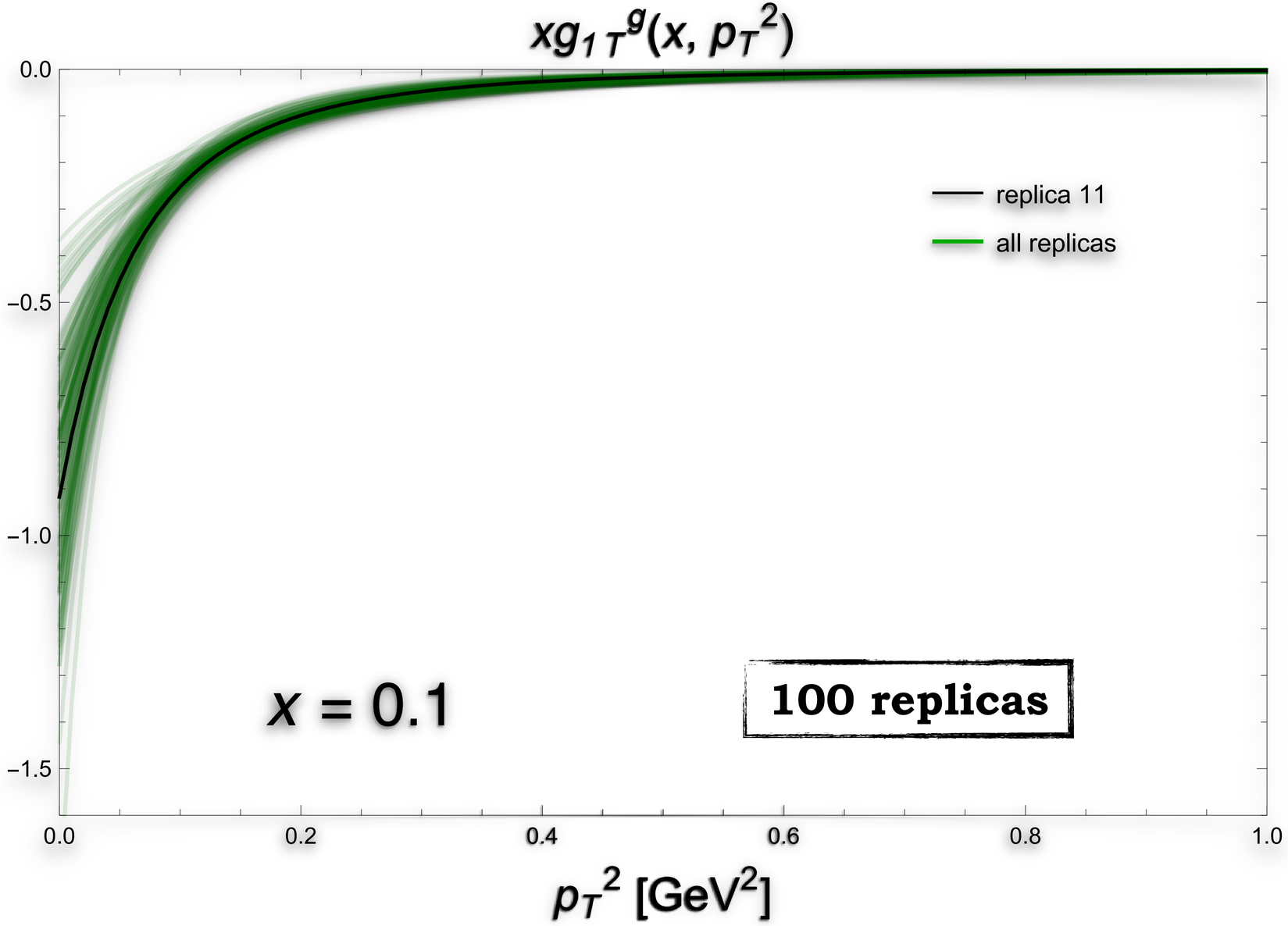
Backup

Helicity gluon TMD



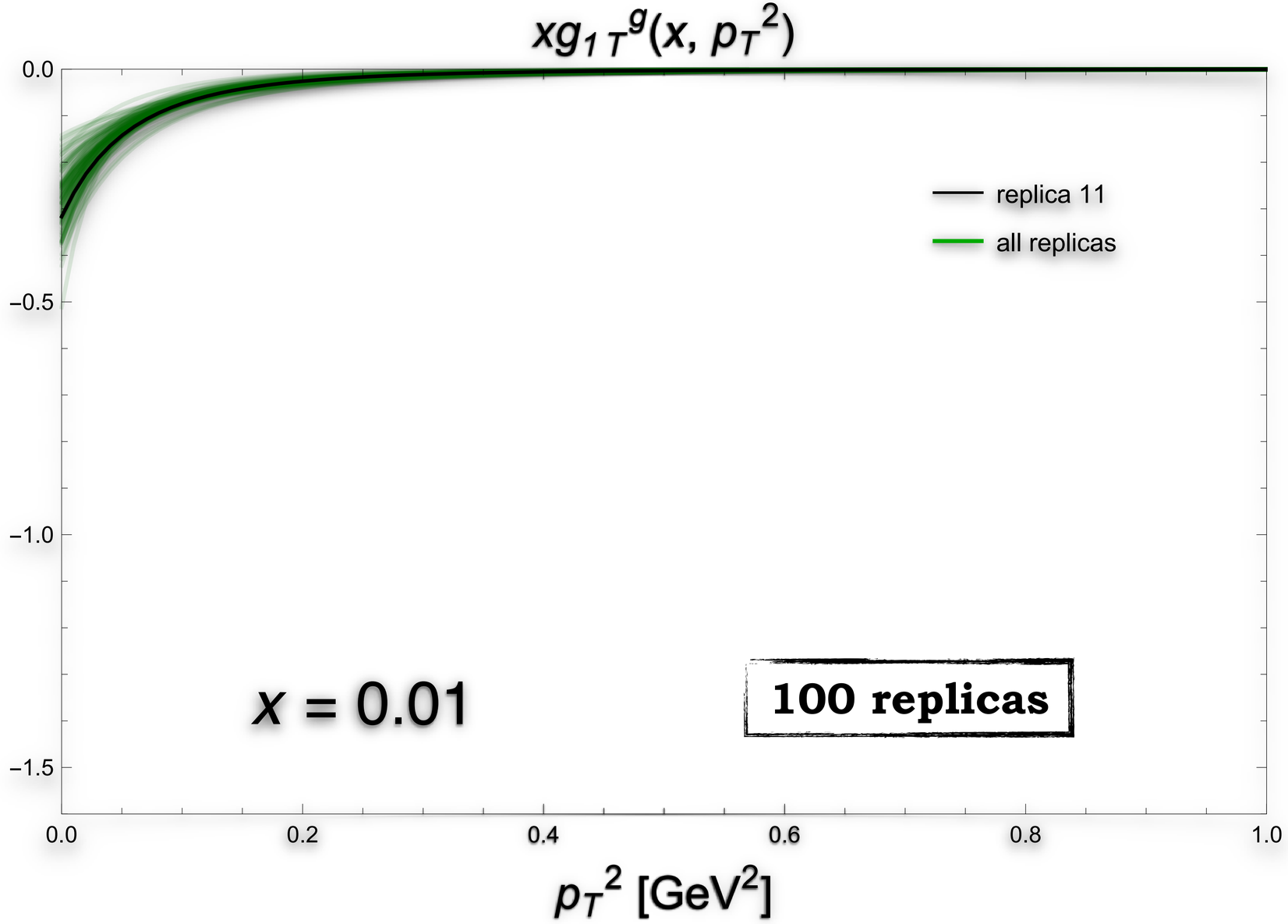
Backup

Worm-gear gluon TMD



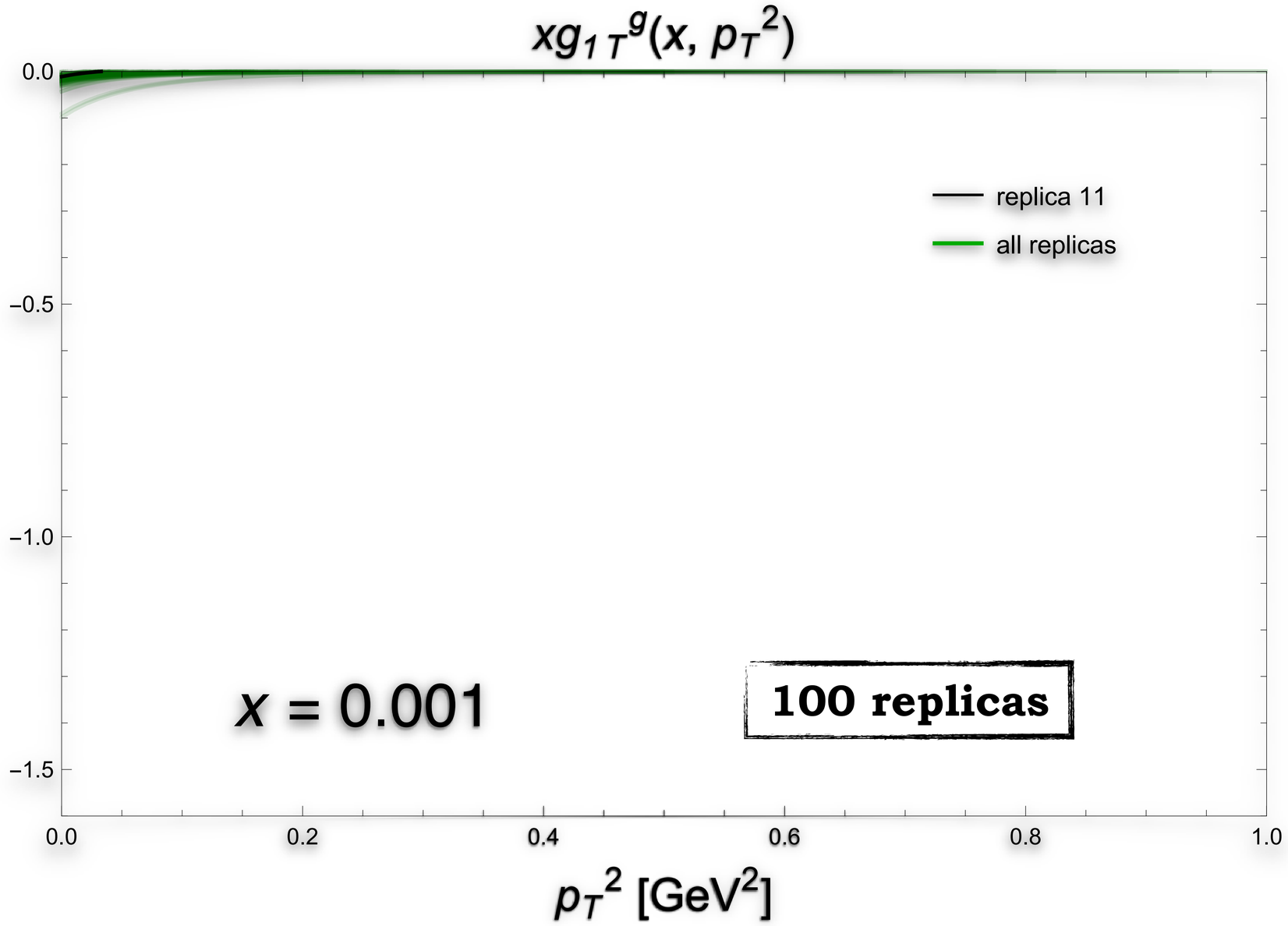
Backup

Worm-gear gluon TMD



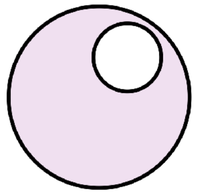
Backup

Worm-gear gluon TMD



Backup

ρ-densities

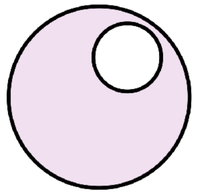


Unpolarized [u/u]

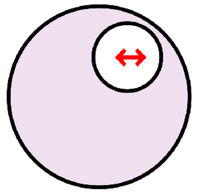
$$f_1(x, p_x, p_y)$$

Backup

ρ-densities



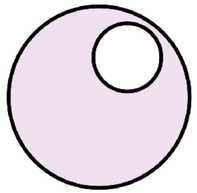
Unpolarized [u/u] $f_1(x, p_x, p_y)$



Boer-Mulders [↔/u] $f_1(x, p_x, p_y) + \dfrac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x, p_x, p_y)$

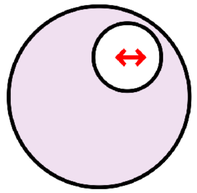
Backup

ρ-densities



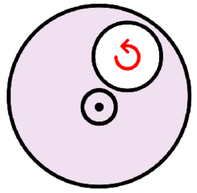
Unpolarized [u/u]

$$f_1(x, p_x, p_y)$$



Boer-Mulders [↔/u]

$$f_1(x, p_x, p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x, p_x, p_y)$$

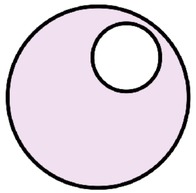


Helicity [↻/+]

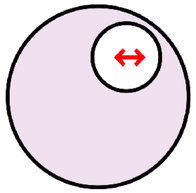
$$\frac{1}{2}\left[f_1(x, p_x, p_y) + g_{1L}(x, p_x, p_y)\right]$$

Backup

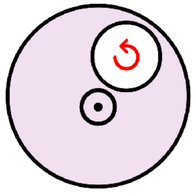
ρ-densities



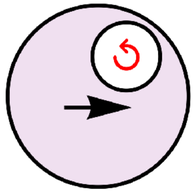
Unpolarized [u/u] $f_1(x, p_x, p_y)$



Boer-Mulders [↔/u] $f_1(x, p_x, p_y) + \dfrac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x, p_x, p_y)$



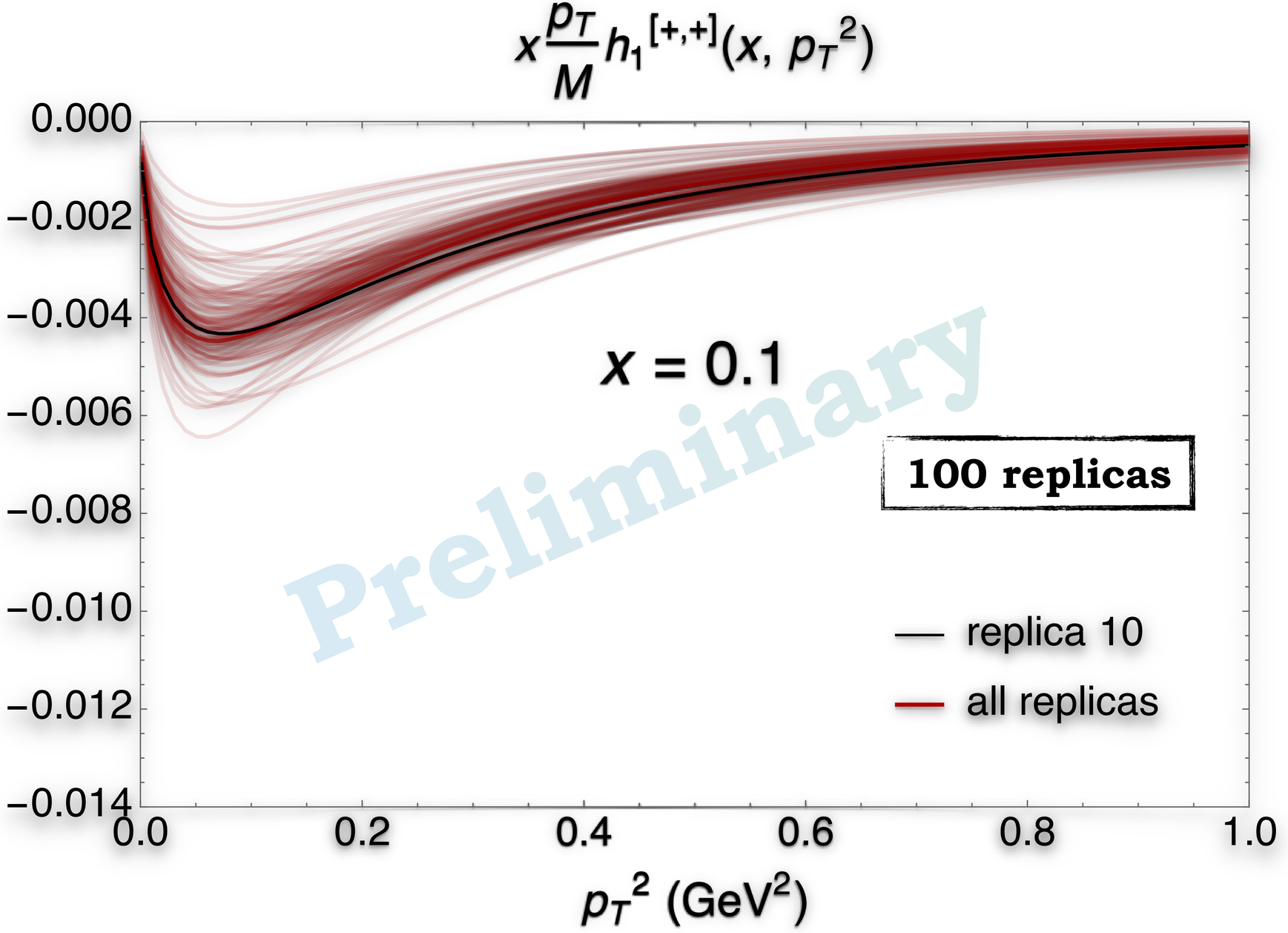
Helicity [↺/+] $\dfrac{1}{2}\left[f_1(x, p_x, p_y) + g_{1L}(x, p_x, p_y)\right]$



Worm-gear [↺/→] $f_1(x, p_x, p_y) - \dfrac{p_x}{M} g_{1T}(x, p_x, p_y)$

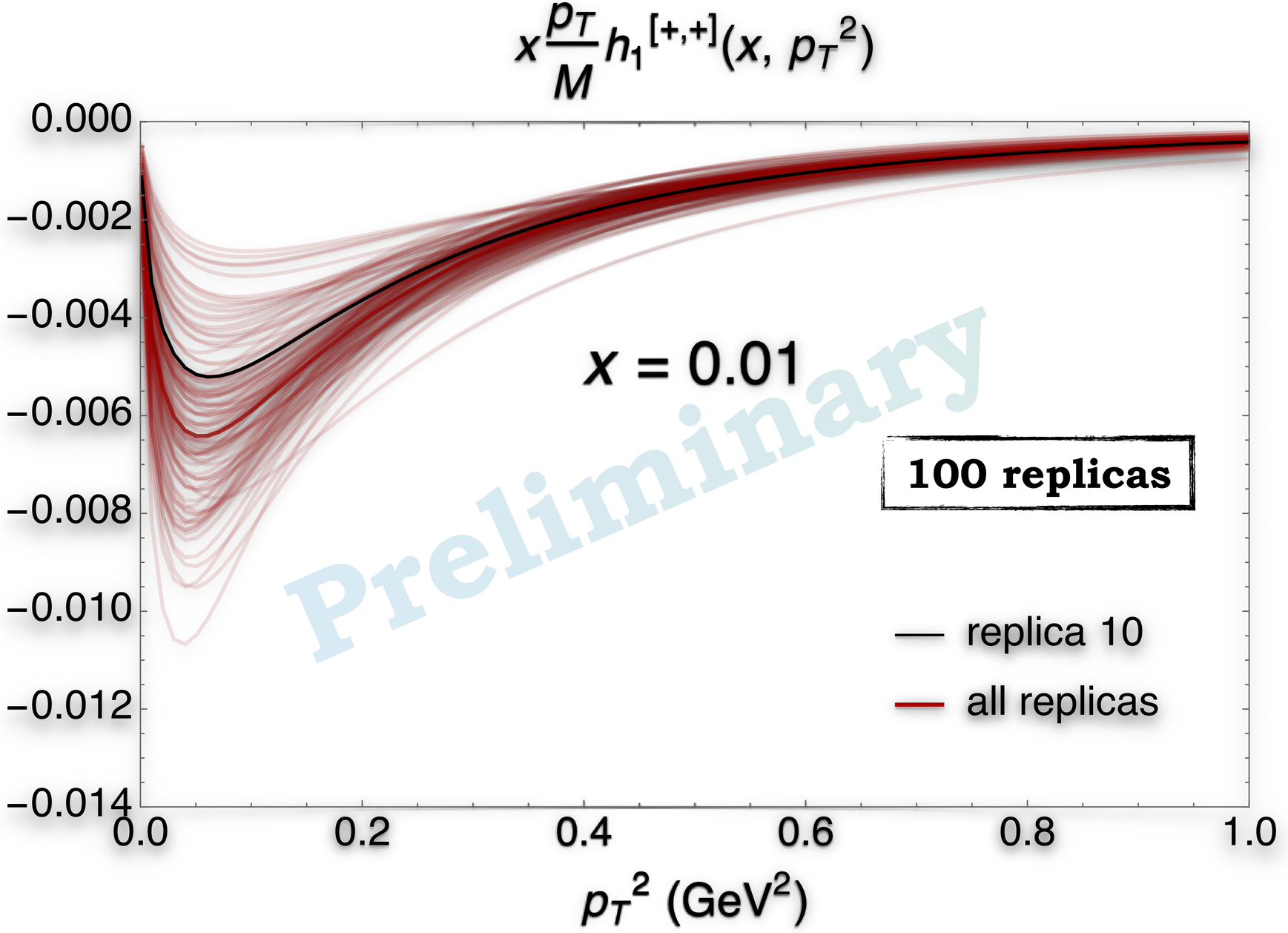
Backup

Linearity gluon TMD



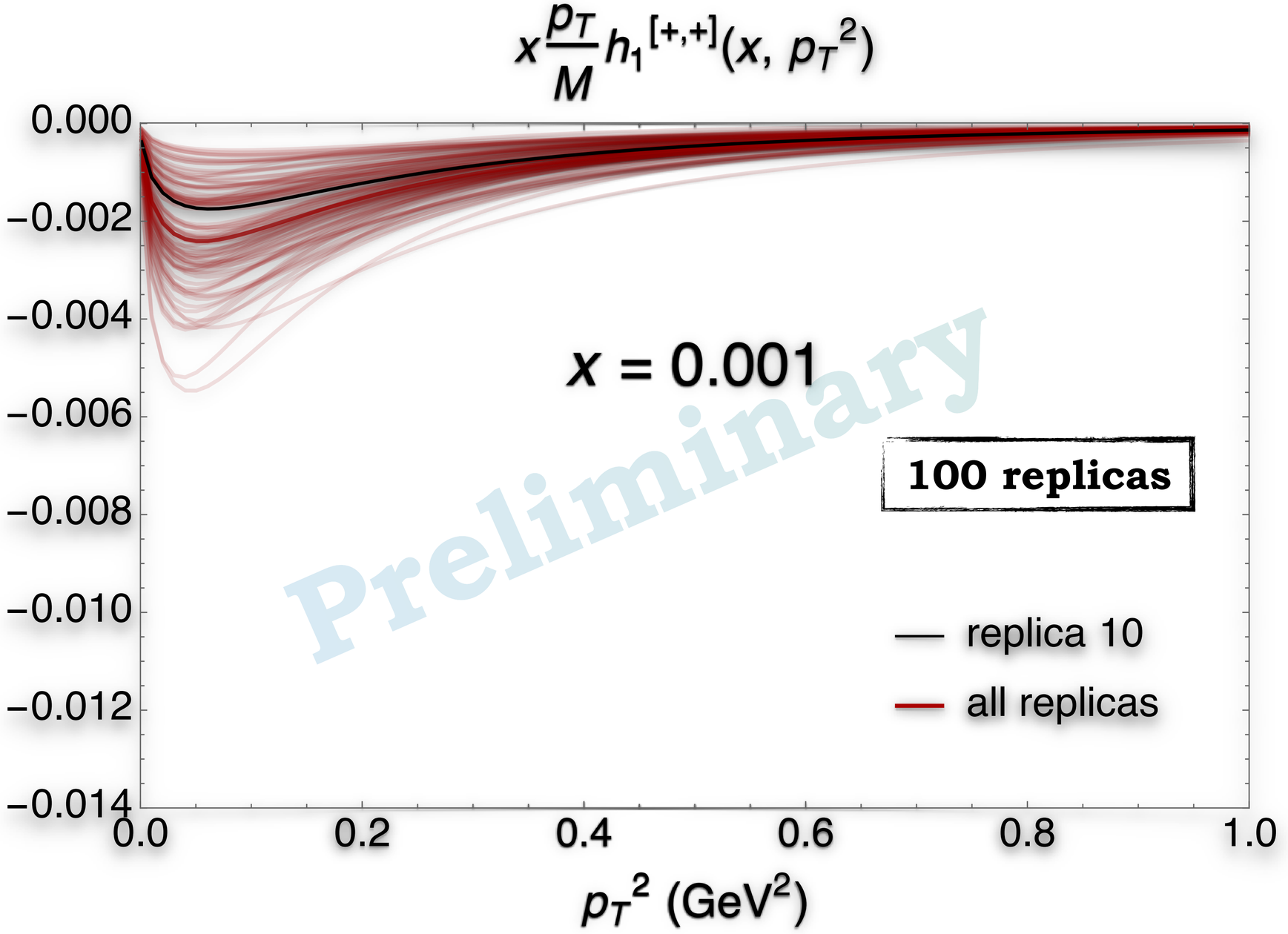
Backup

Linearity gluon TMD



Backup

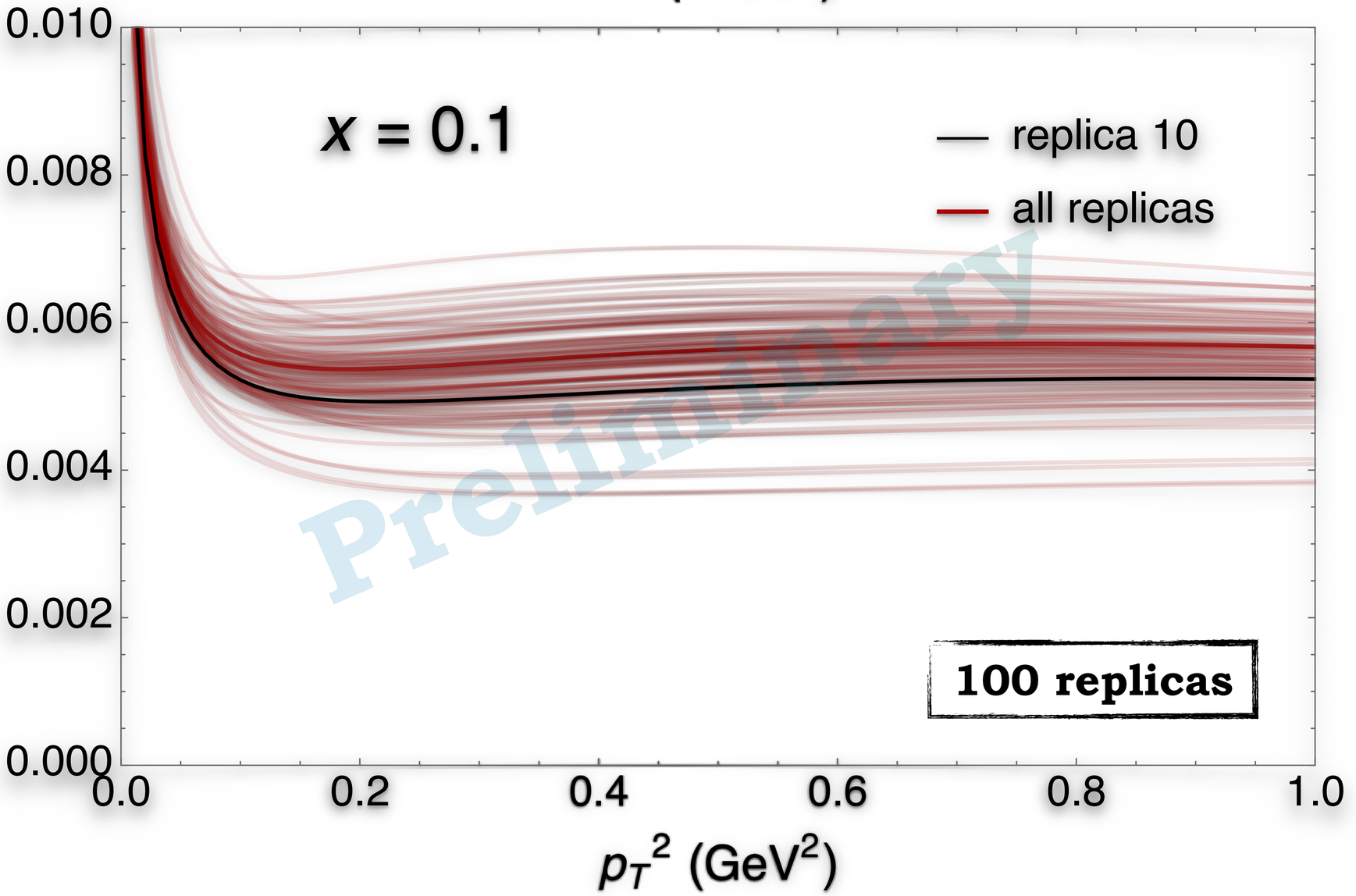
Linearity gluon TMD



Backup

Sivers / unpol.

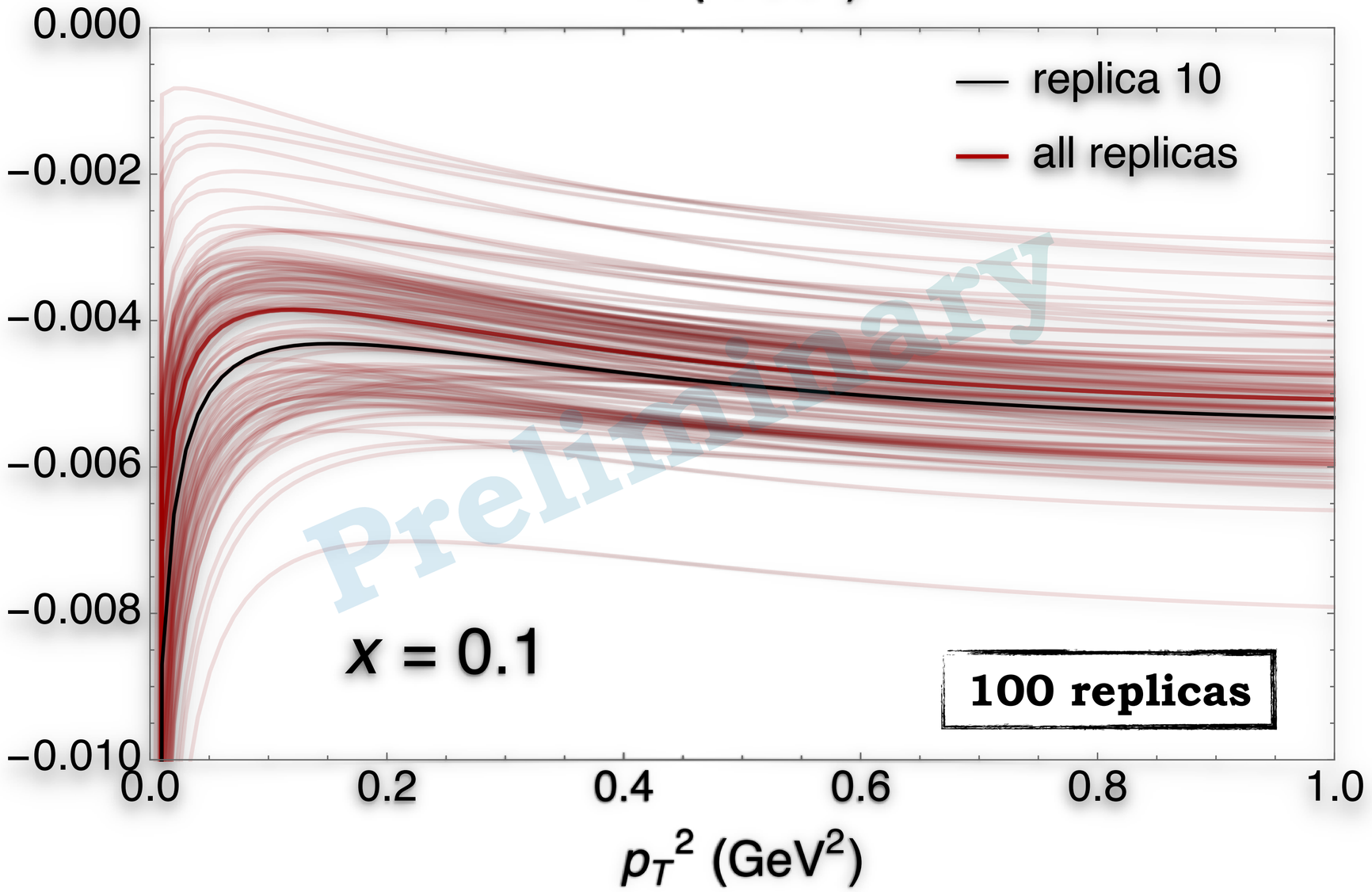
$$\frac{\frac{p_T}{M} f_{1T}^{\perp[+,+]}(x, p_T^2)}{f_1^g(x, p_T^2)}$$



Backup

Linearity / unpol.

$$\frac{\frac{p_T}{M} h_1^{[+,+]}(x,\ p_T^2)}{f_1^g(x,\ p_T^2)}$$



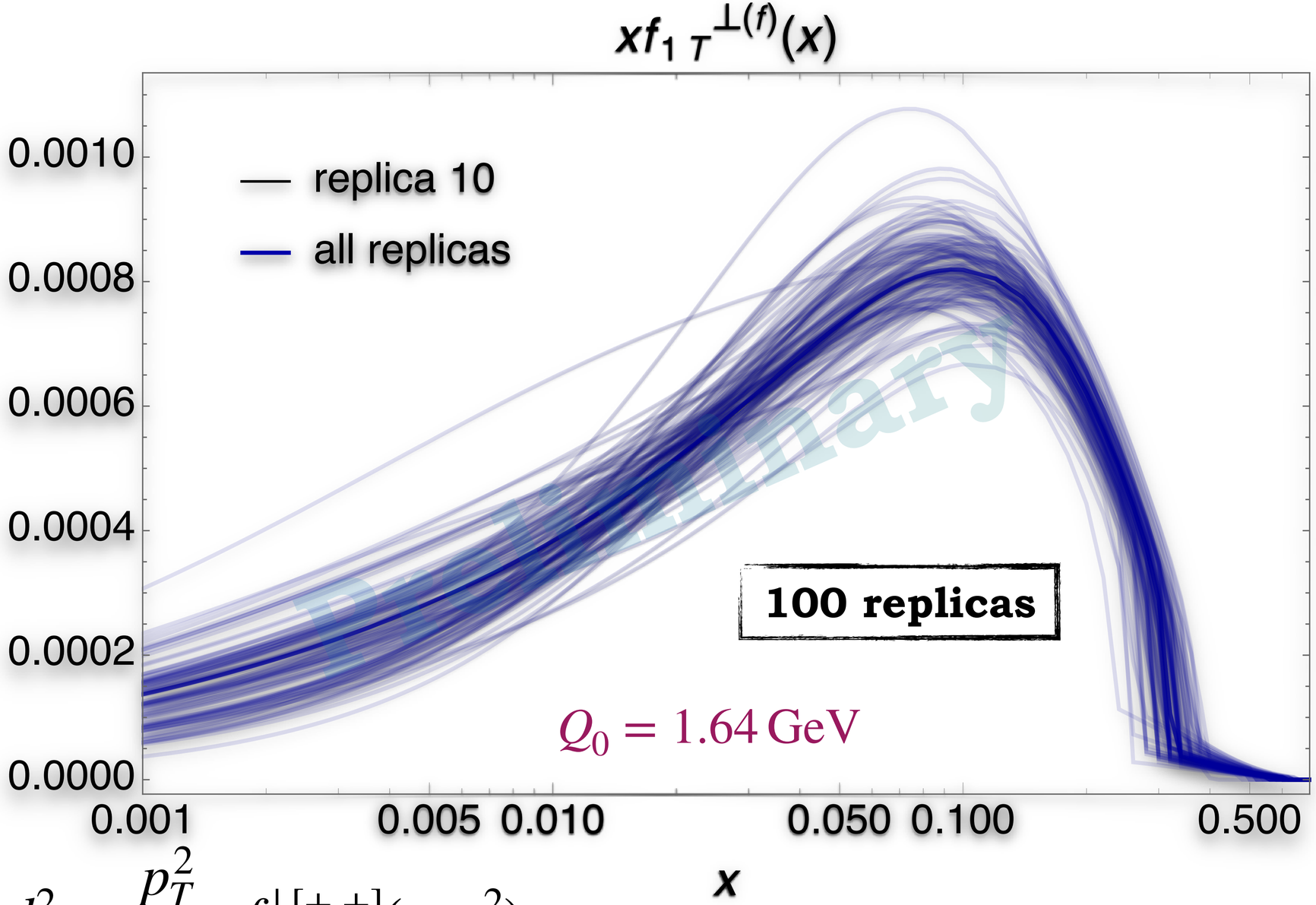
Backup

Qiu-Sterman twist-3 gluon PDF

$$f_{1T}^{\perp(f)}(x) = \int d^2p_T \frac{p_T^2}{2M^2} f_{1T}^{\perp[+,+]}(x, p_T^2)$$

Backup

Qiu-Sterman twist-3 gluon PDF

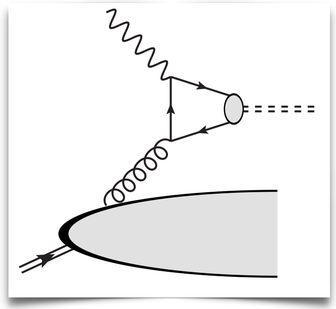


$$f_{1T}^{\perp(f)}(x) = \int d^2p_T \frac{p_T^2}{2M^2} f_{1T}^{\perp[+,+]}(x, p_T^2)$$

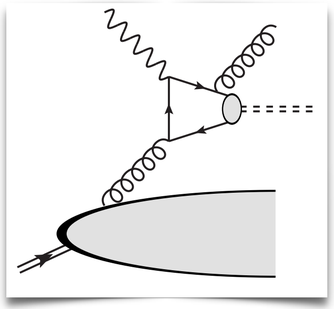
Backup

Hadronic structure and quarkonia

SIDIS



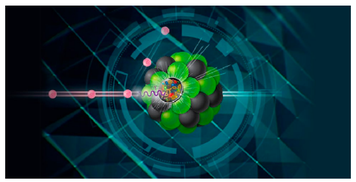
CO

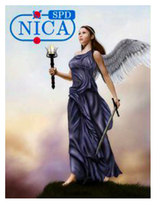


CO + CS

EIC Yellow Report Document
(EICUG website)

[EICUG [arXiv:2103.05419]]



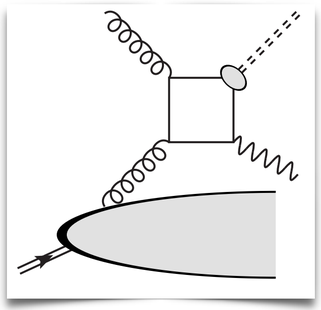




On the physics potential to study the gluon content of proton and deuteron at NICA SPD

[NICA Collaboration [arXiv:2011.15005]]

Hadroproduction



CO + CS

Perspectives for quarkonium studies at the high-luminosity LHC
(QAT 2021 Workshop)

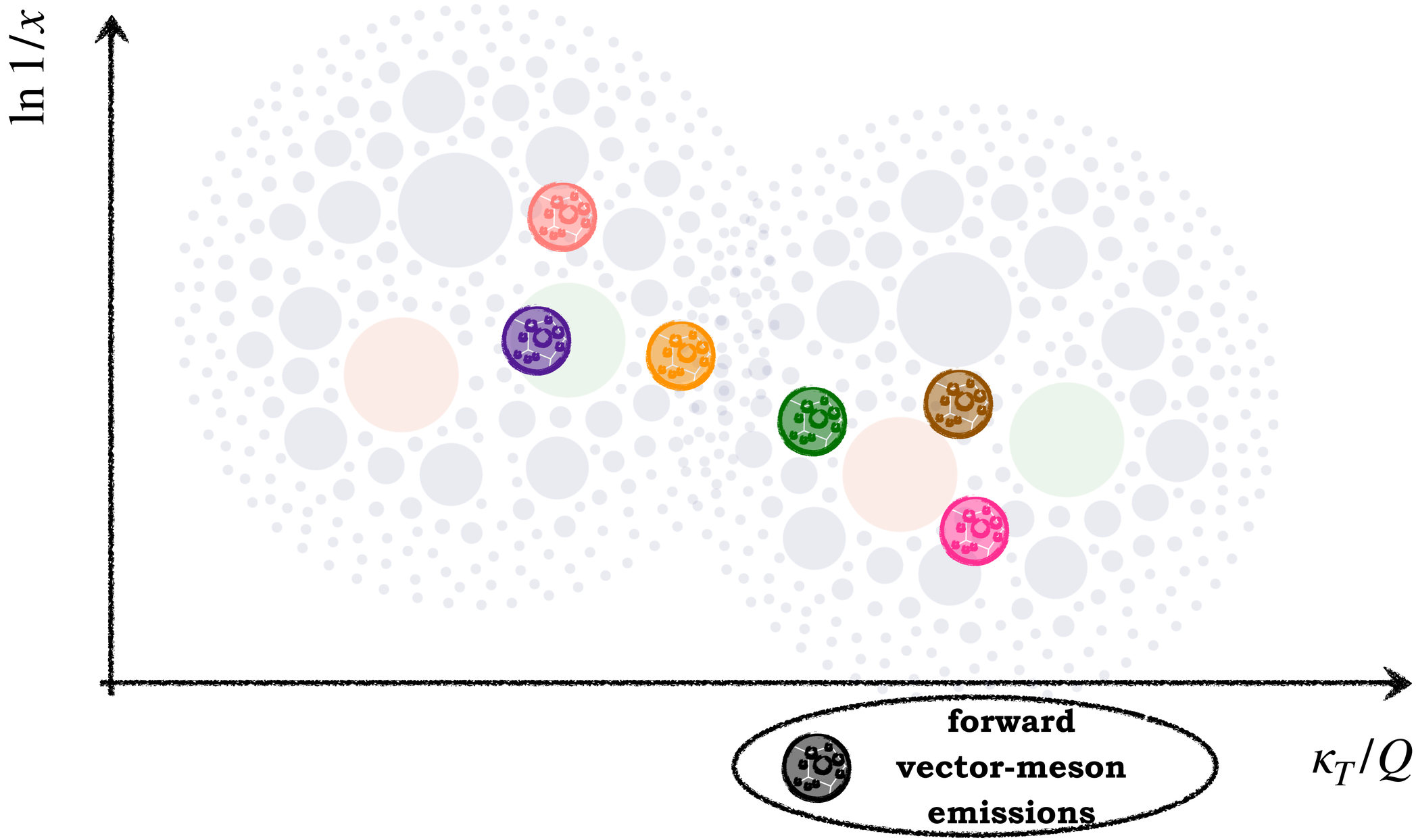
[Quarkonia As Tools Collaboration [arXiv:2012.14161]]

Backup

Hadronic structure and vector mesons

Backup

Hadronic structure and vector mesons

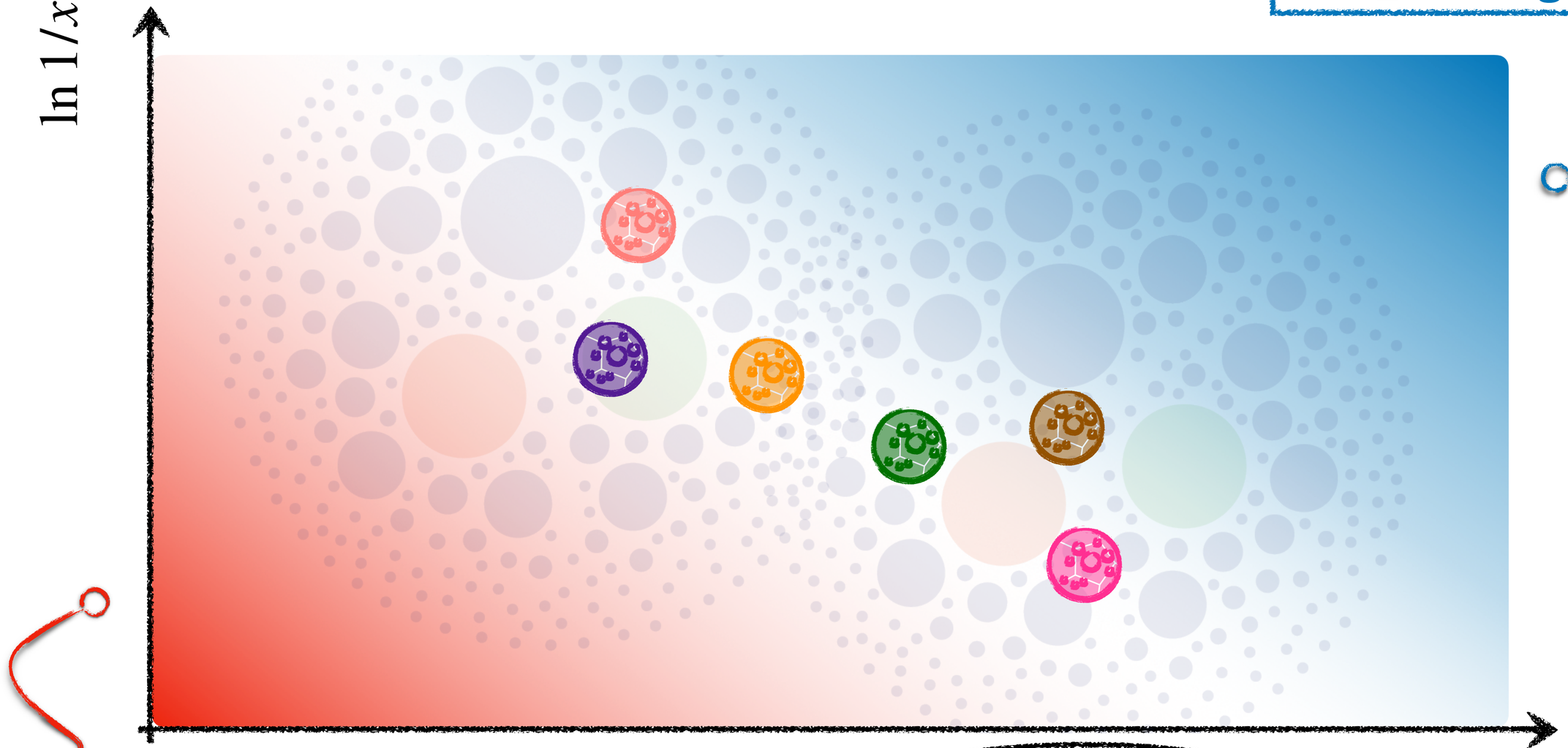


Backup

Hadronic structure and vector mesons

$x \ll 1;\ \kappa_T \approx Q \gg \Lambda_{\mathrm{QCD}}$

AT_HEF regime



$\kappa_T \ll Q$

TMD regime

forward vector-meson emissions

Backup