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Proton 3D imaging via TMD gluon densities

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

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ON KNOWLEDGE

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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

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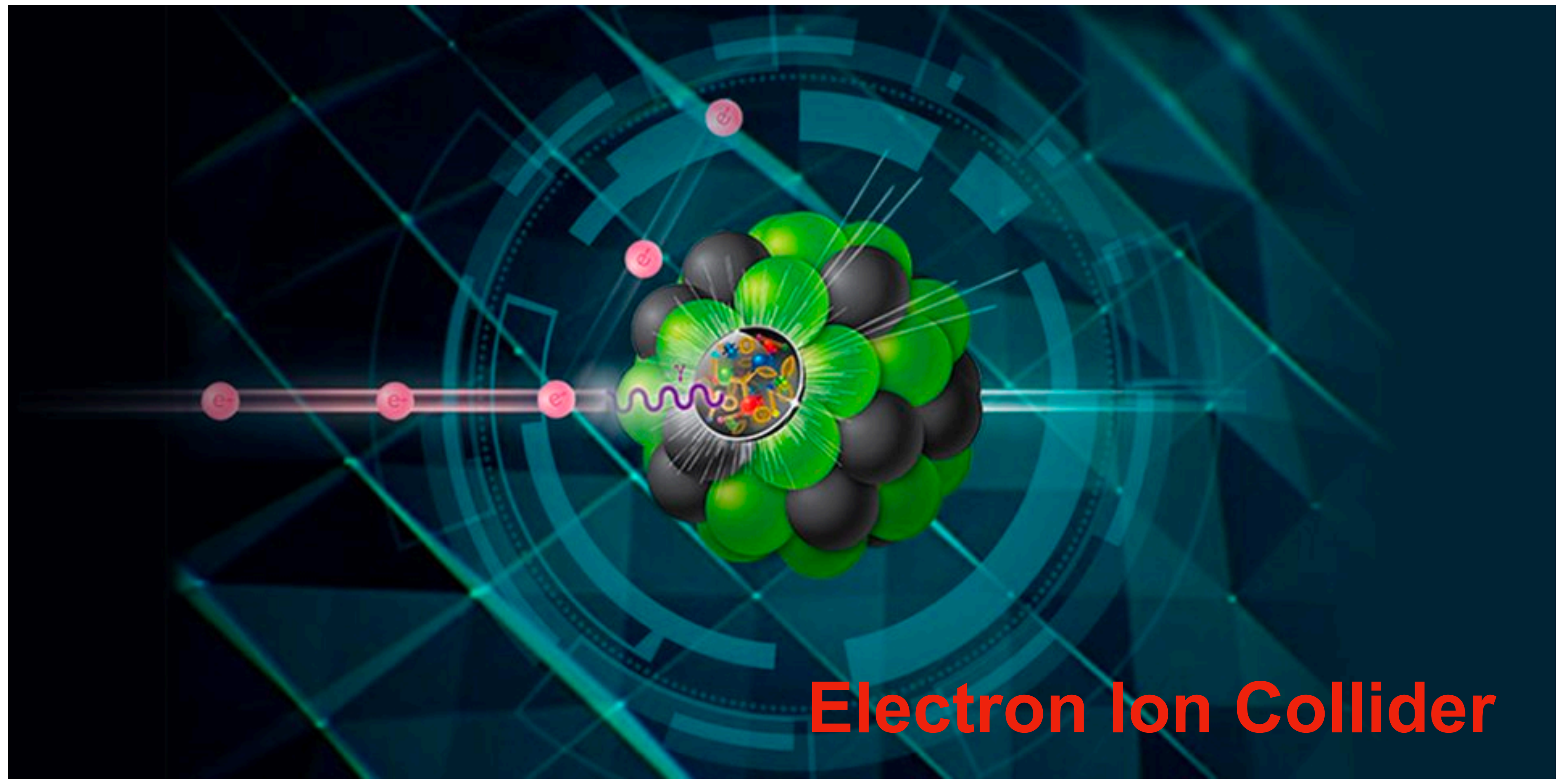

Motivation

- 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

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

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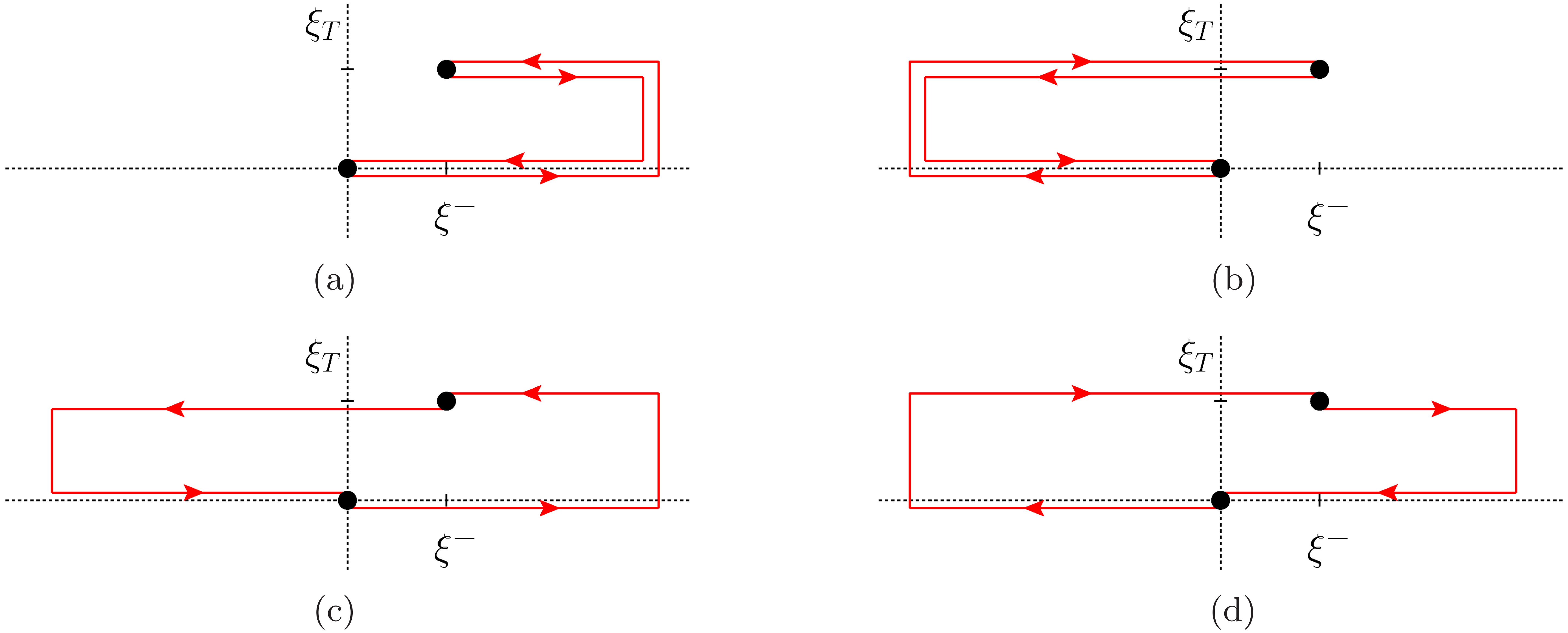

(a) (b) (c) (d)

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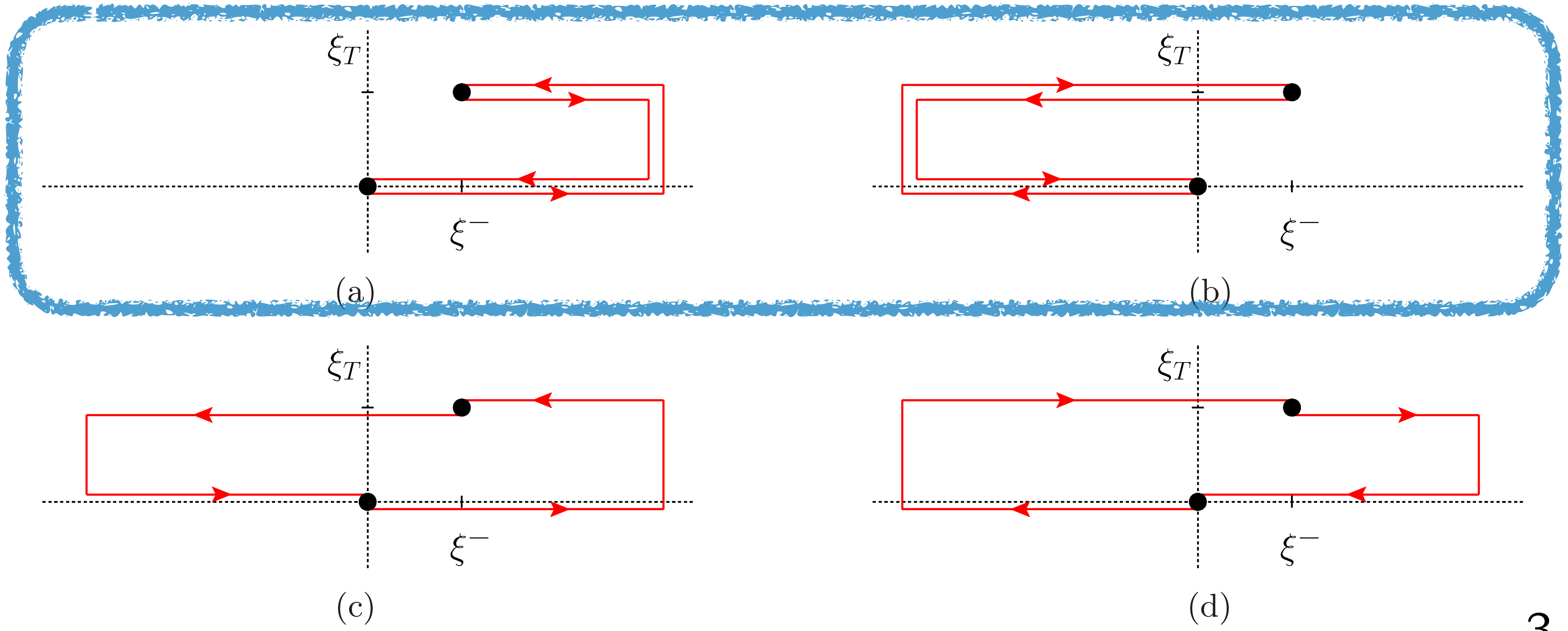

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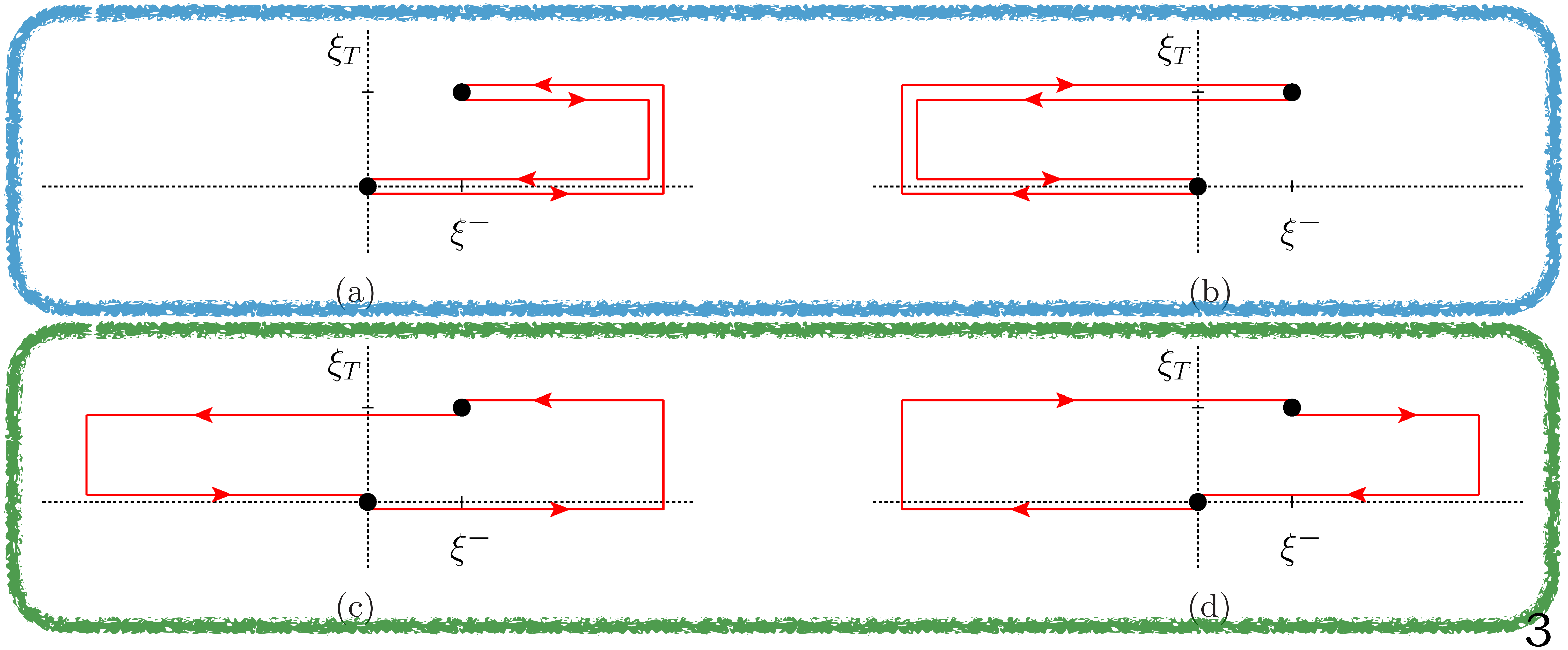

T-even and T-odd gluon TMD PDFs at twist-2

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

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unpolarized TMD

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helicity TMD

worm-gear

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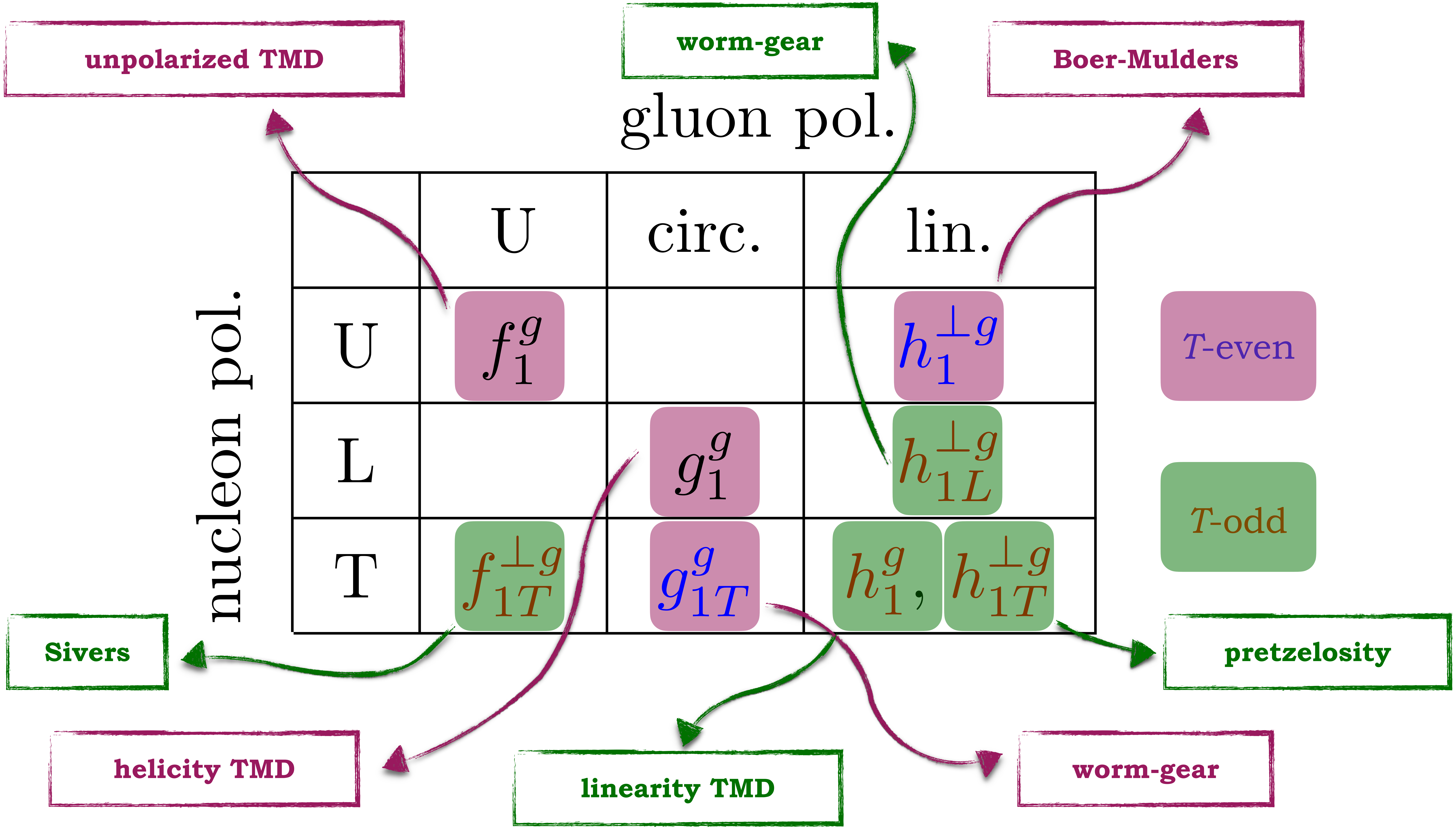

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Sivers

pretzelosity

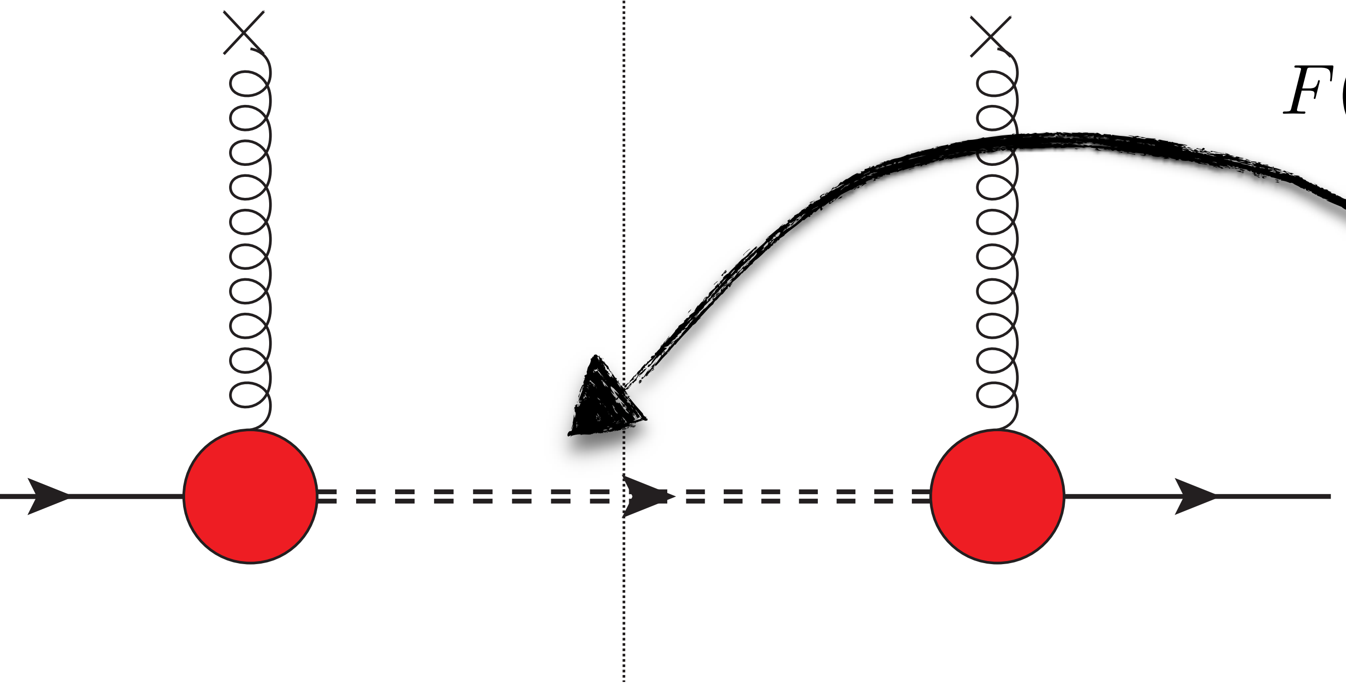
helicity TMD

linearity TMD

worm-gear

Our model at a glance

Spectator-system spectral-mass function



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

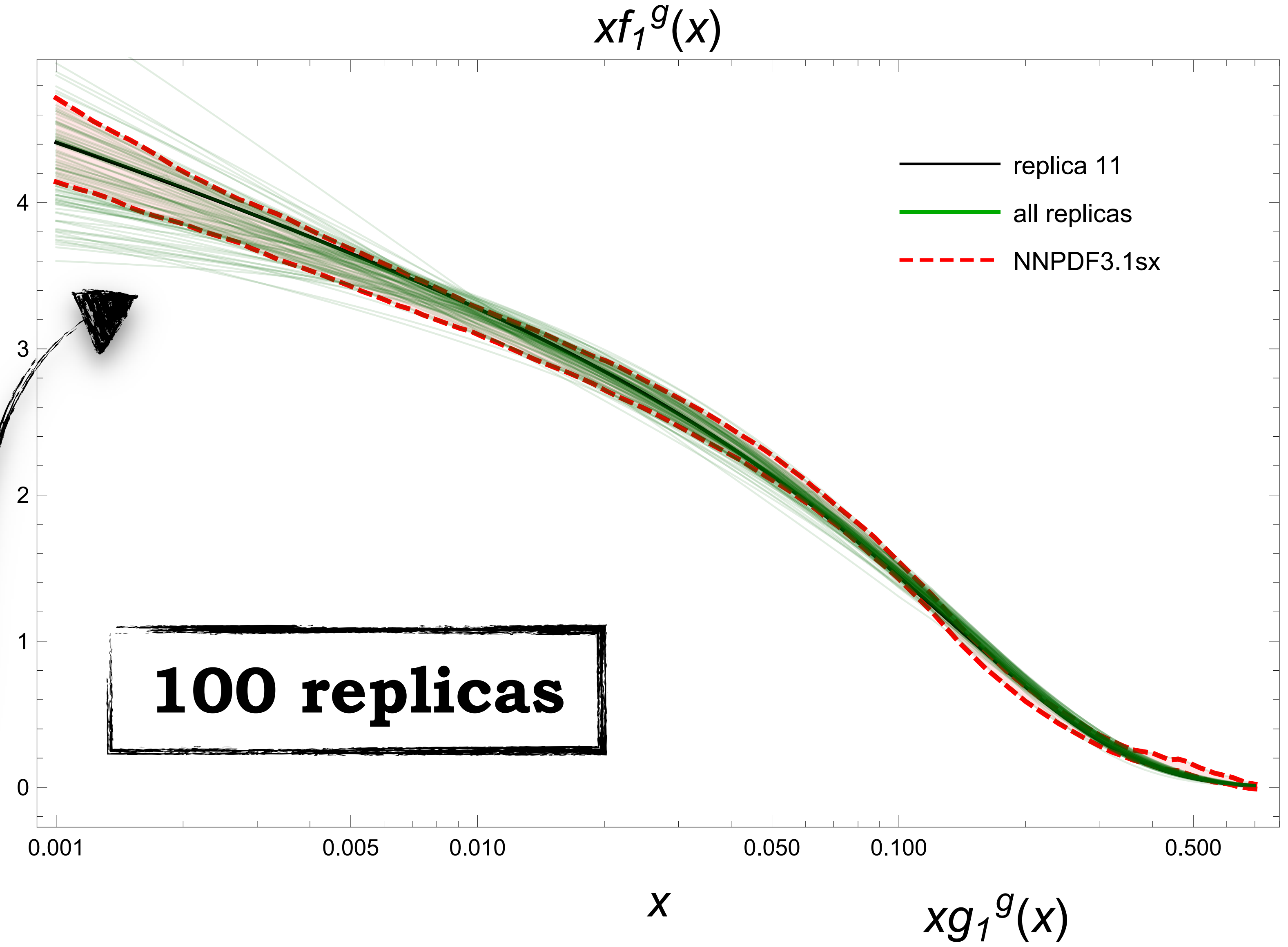
Instead of a single on-shell spectator, a continuum of spectators

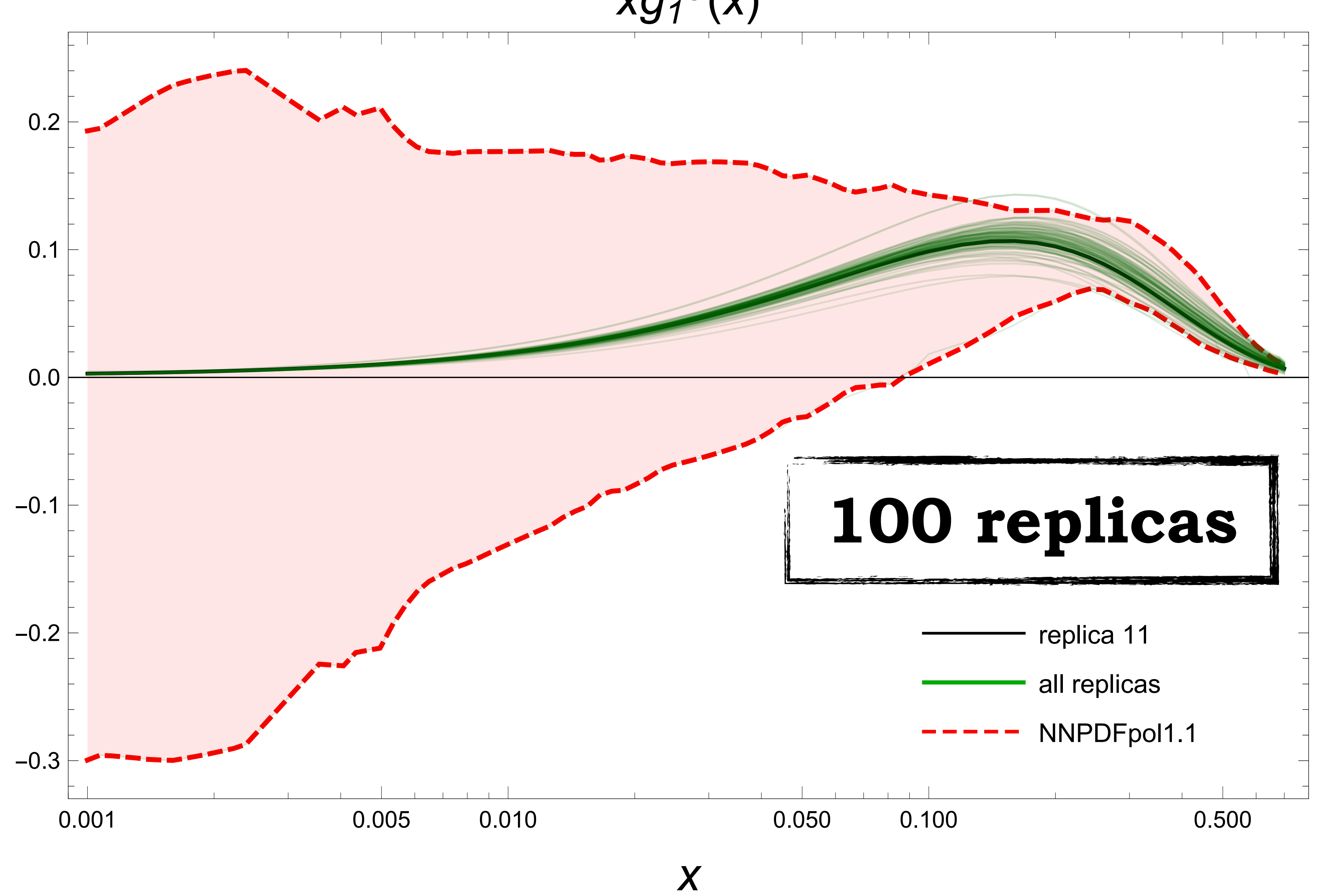
Spectral function **learns** small- and moderate-*x* info encoded in **NNPDF** collinear parametrizations (`NNPDF3.1sx + NNPDFpol1.1`)

- ☑ **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

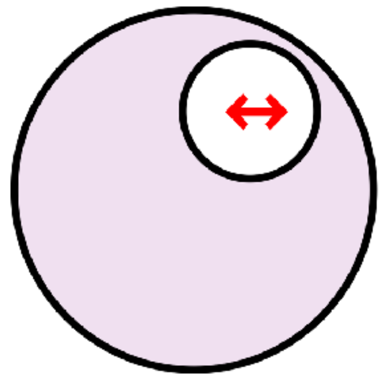
Link with collinear factorization

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





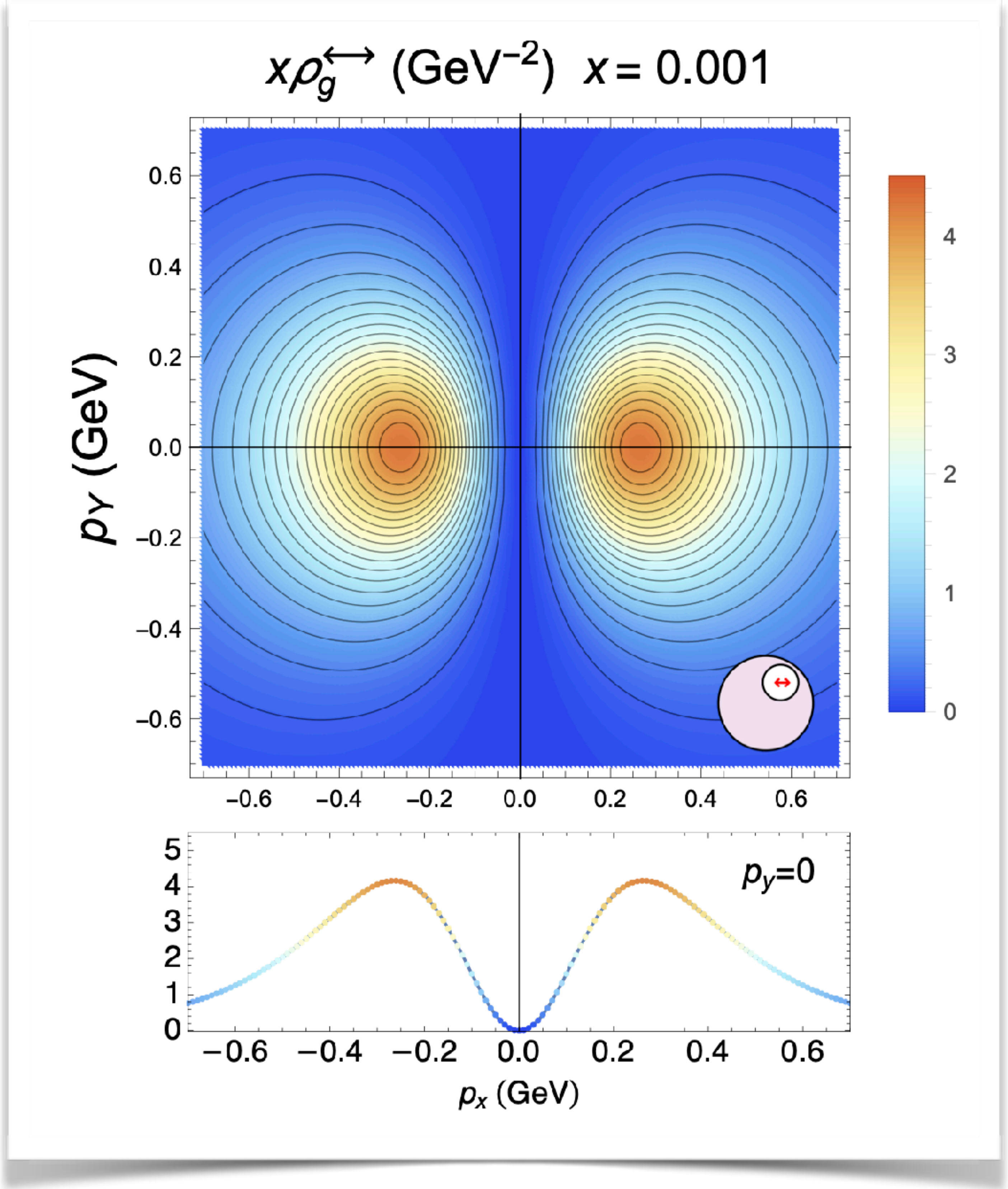
Boer-Mulders effect in unpolarized *pp* collisions



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

unpol.

Boer-Mulders



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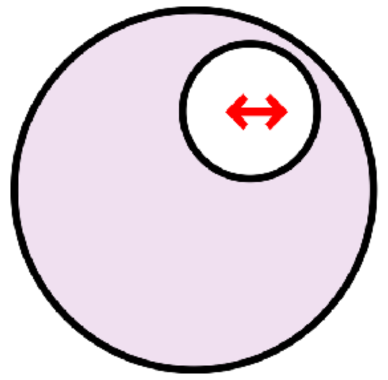

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Boer-Mulders

(Pseudo)scalar Higgs p_T-distribution

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

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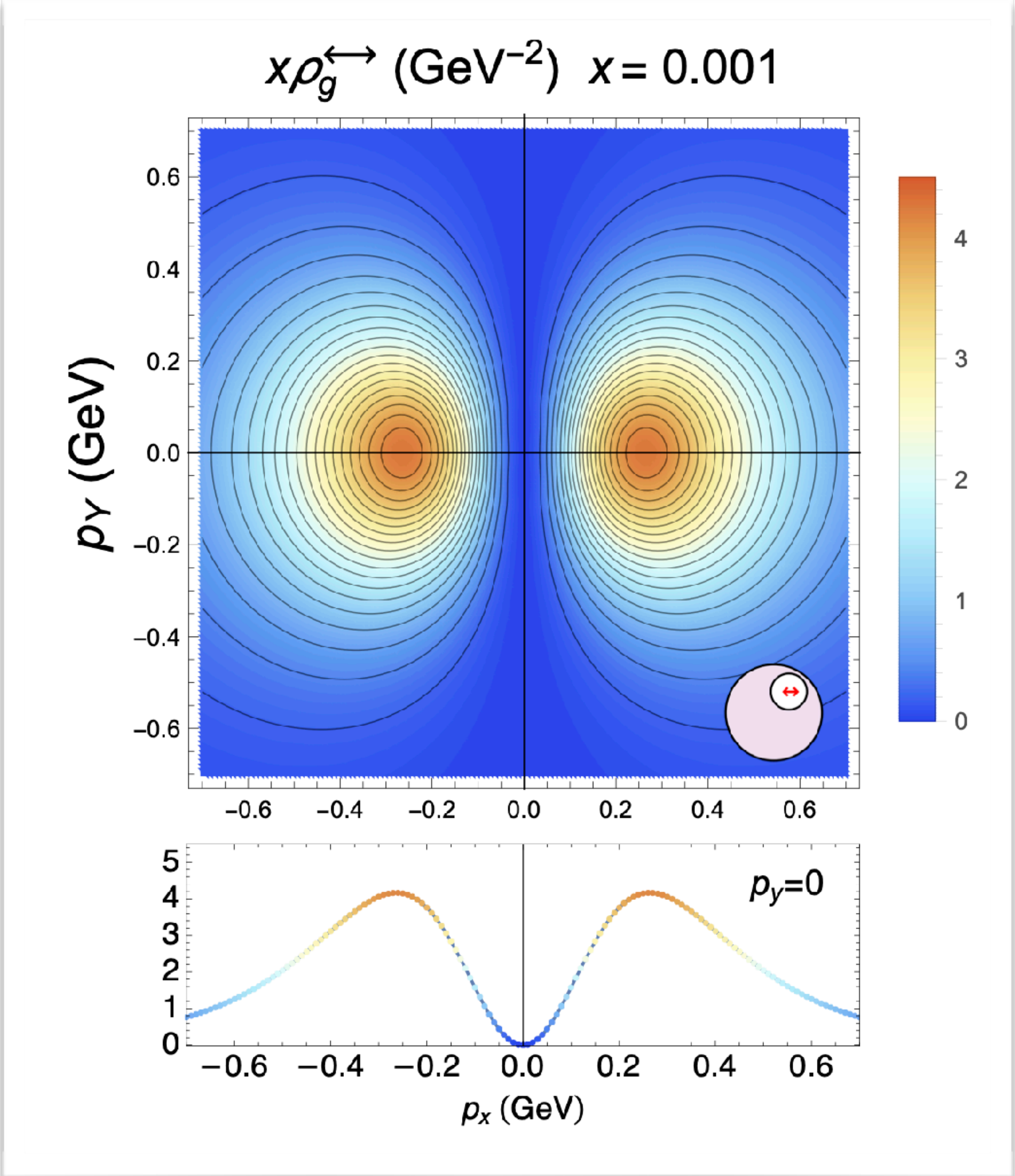
(Higgs+jet angular distributions) 🔗 [D. Boer, C. Pisano (2015)]



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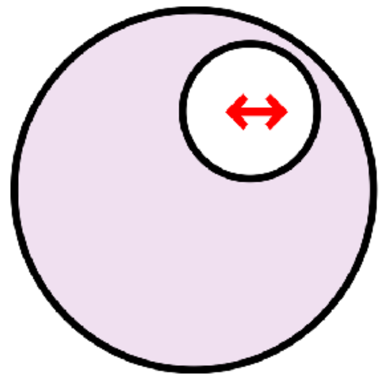

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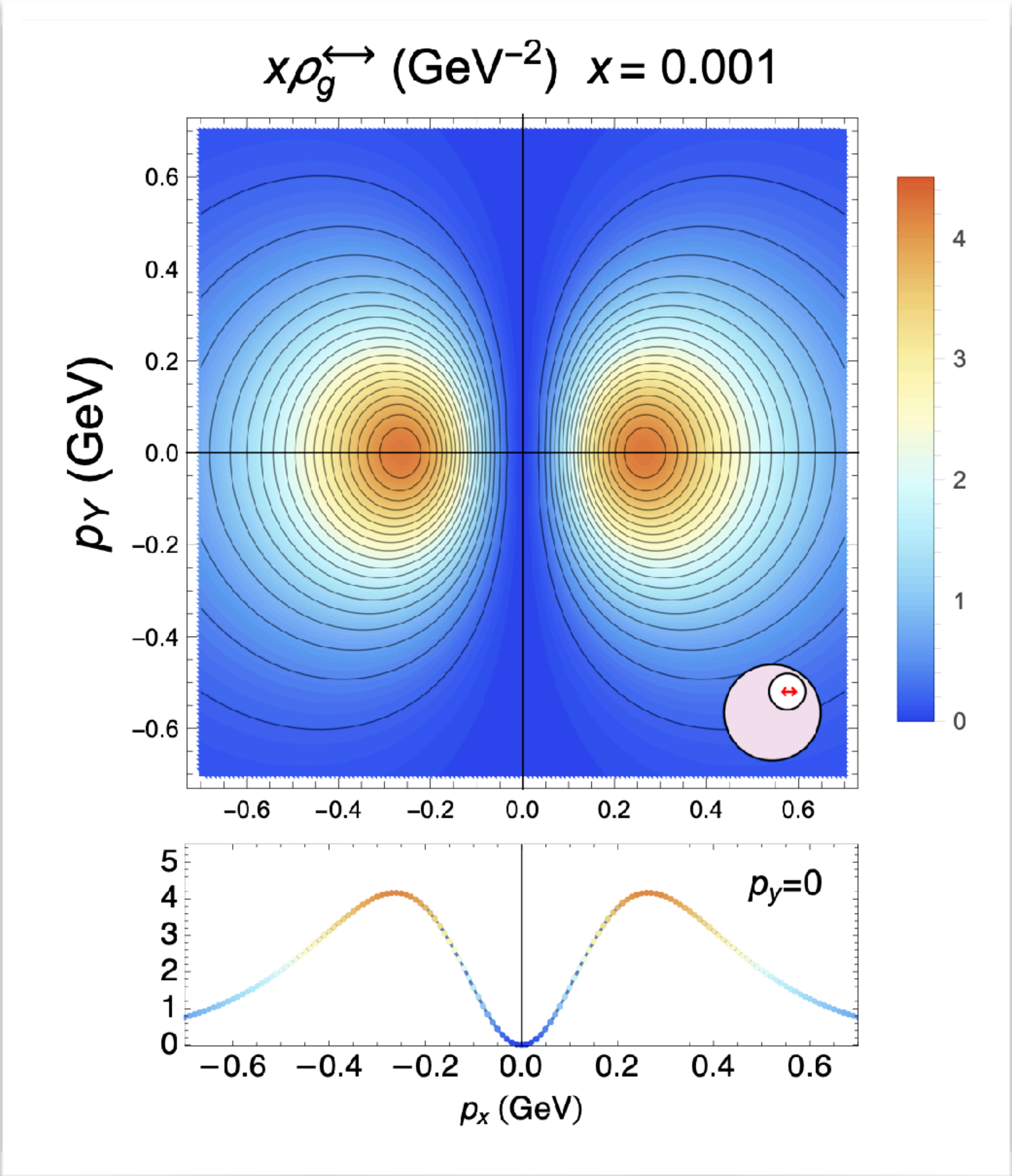

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Model prediction at low-*x*

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

…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*)

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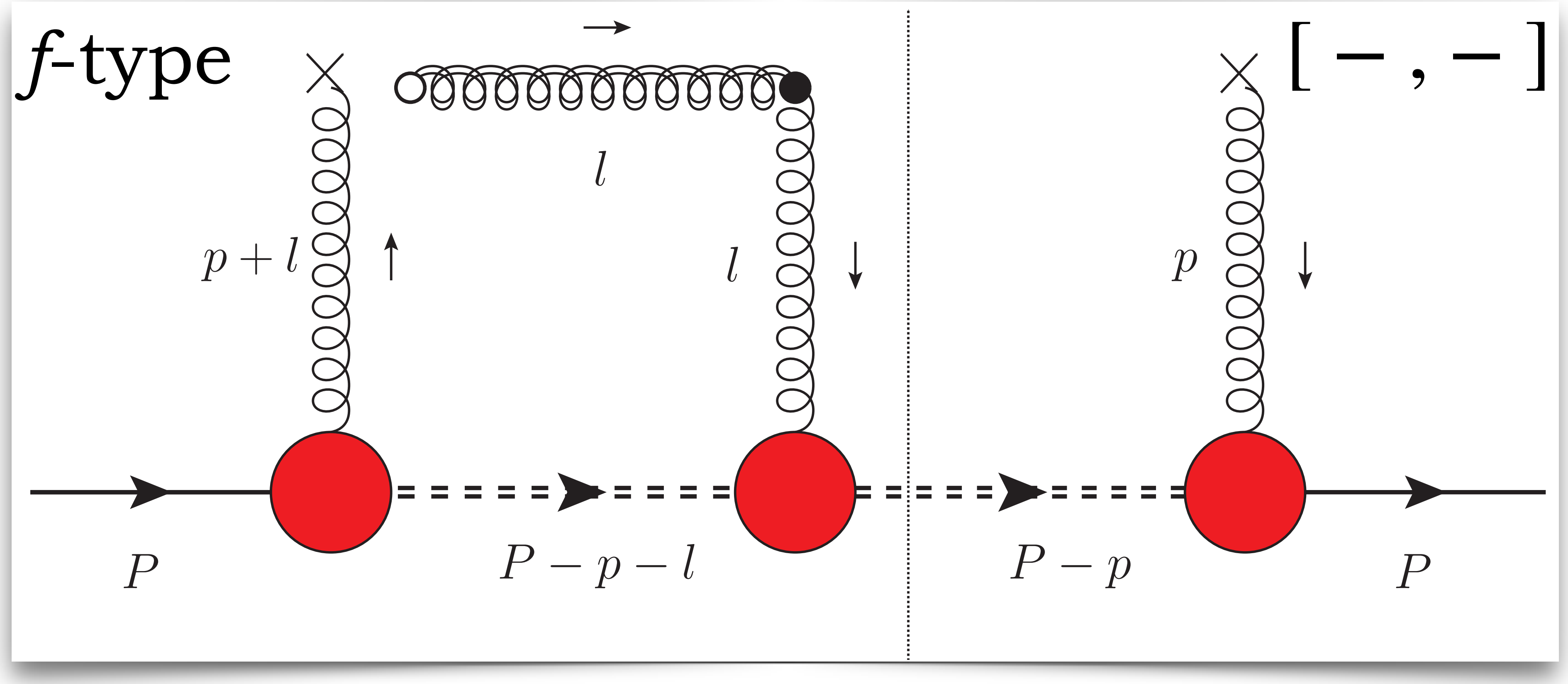
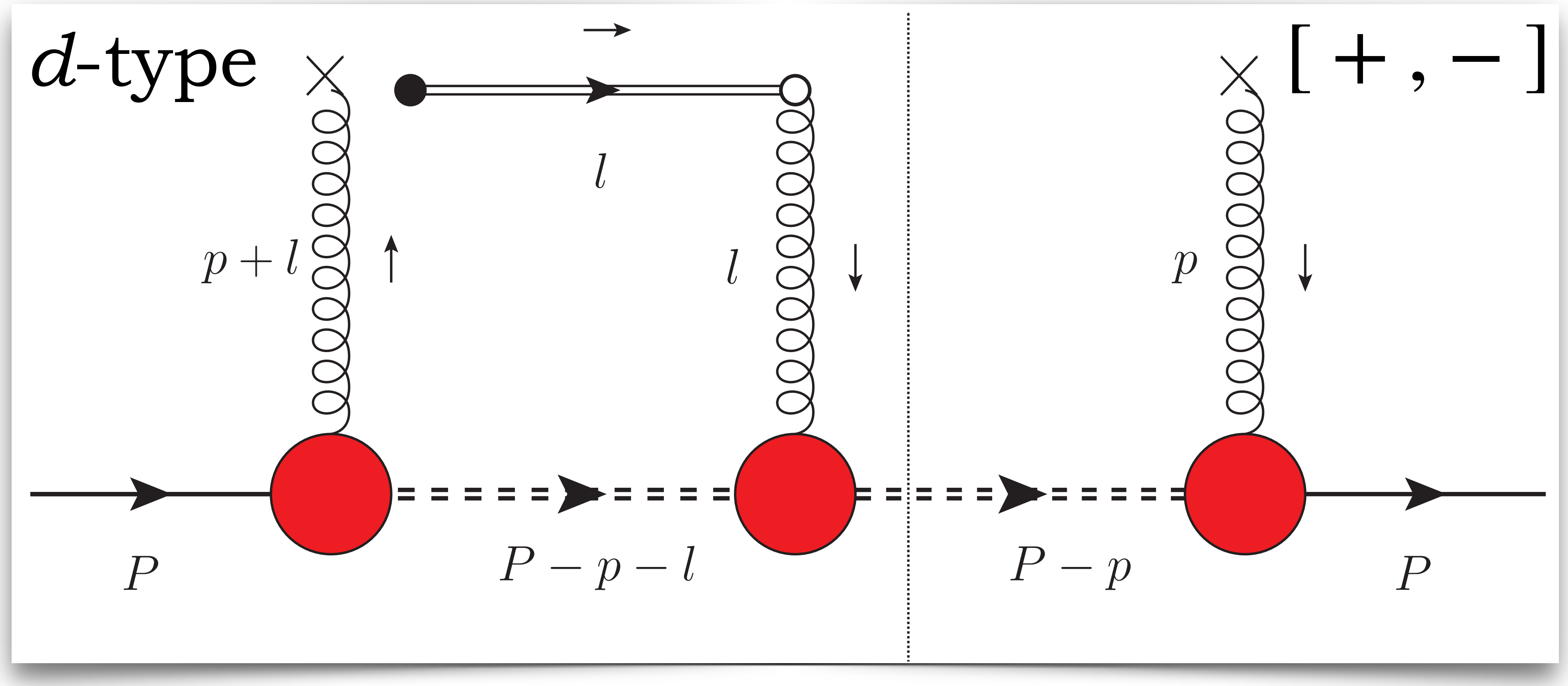
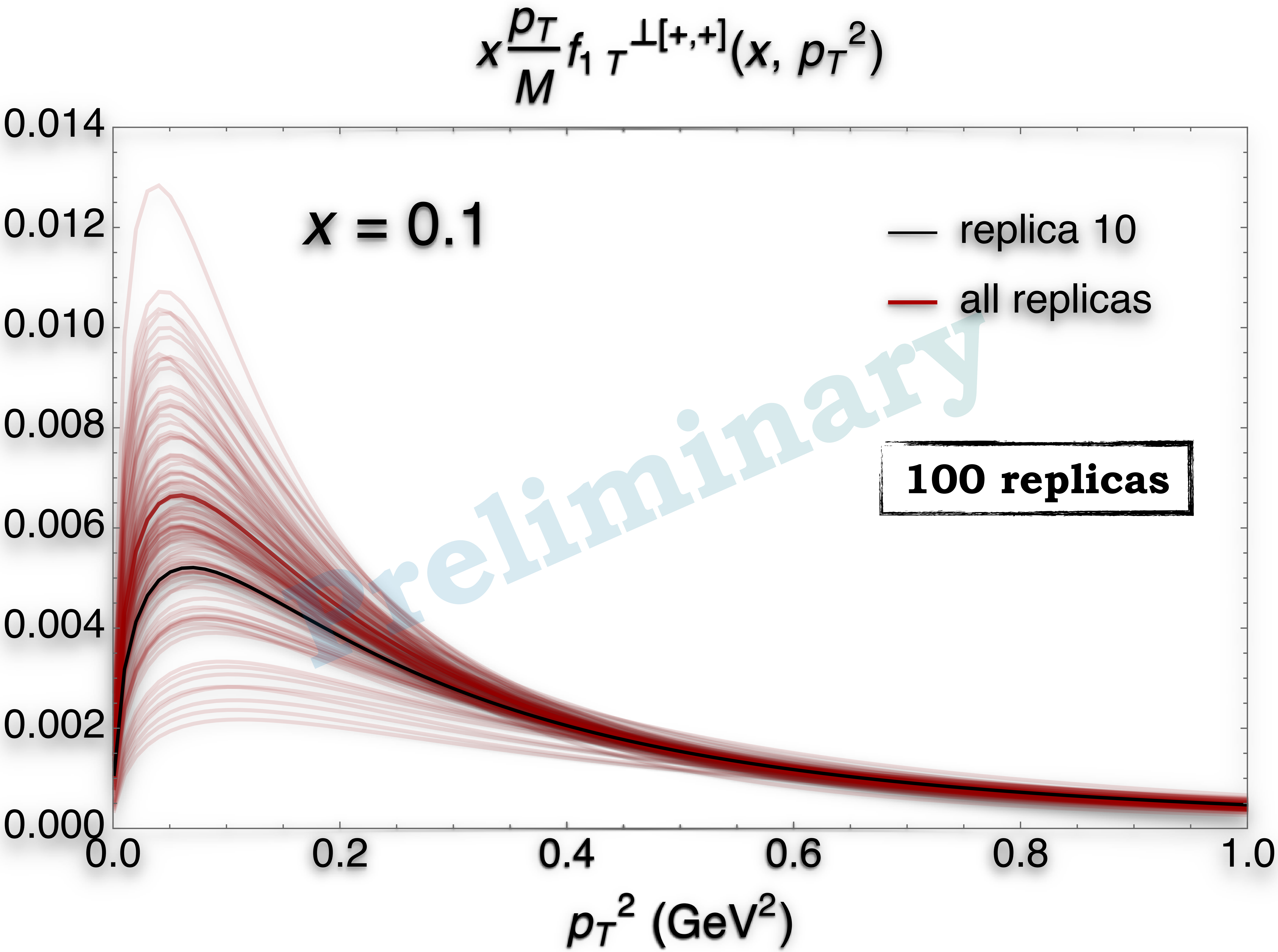


$qg \to \gamma^{(*)}$-jet



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

Sivers gluon TMD



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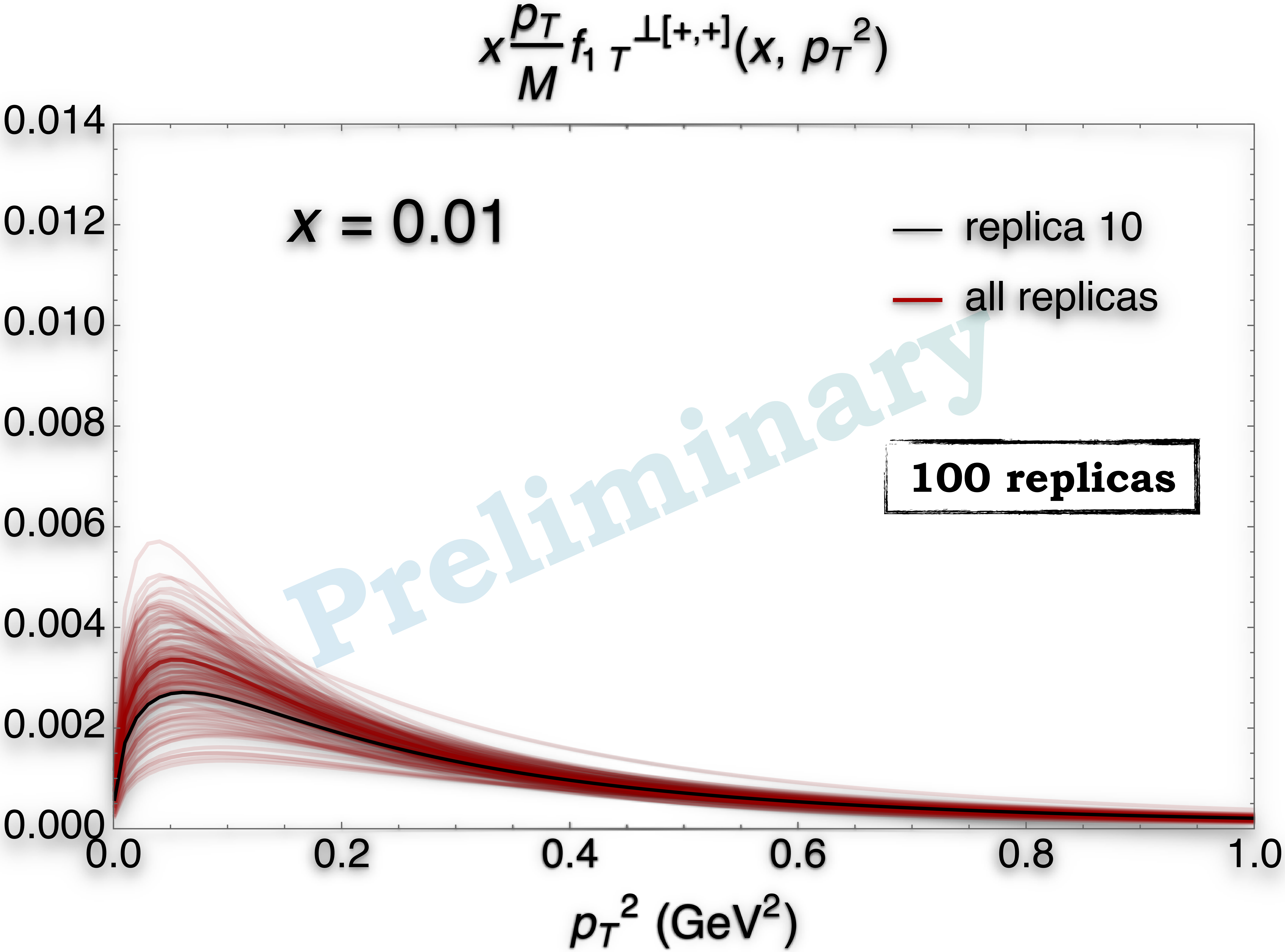

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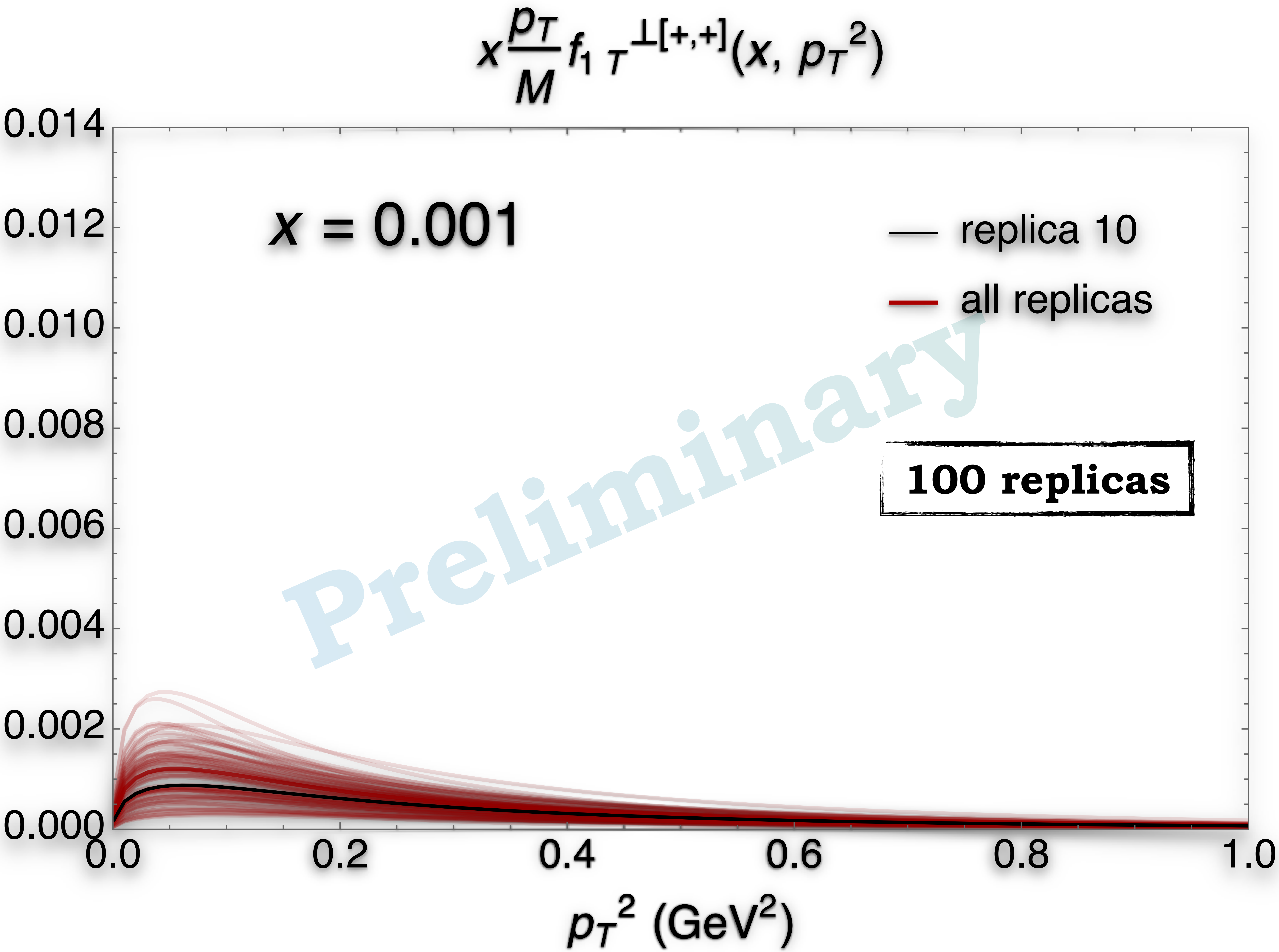

Qiu-Sterman twist-3 gluon PDF

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

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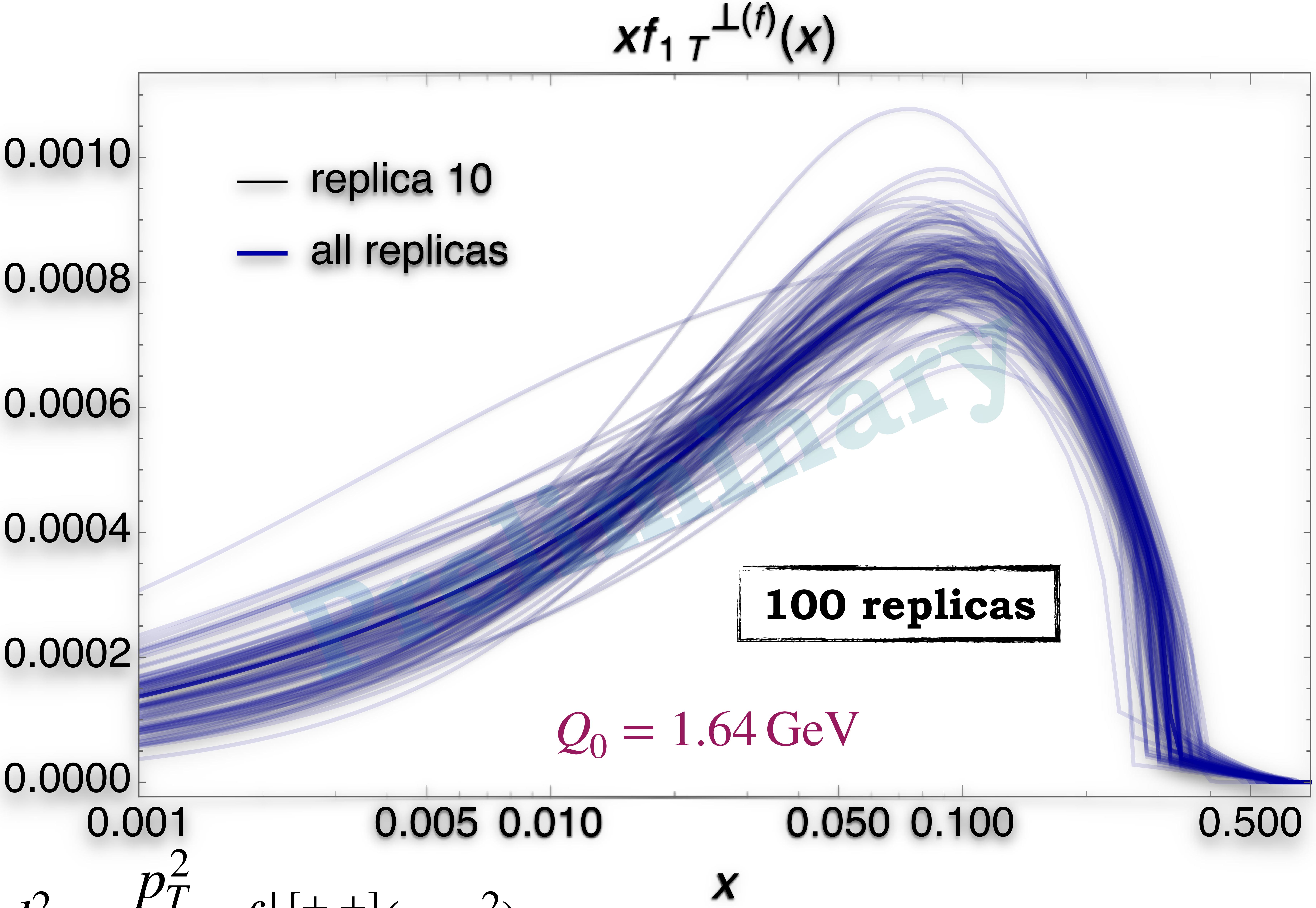

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Checkpoints and further steps

- ☑ 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**

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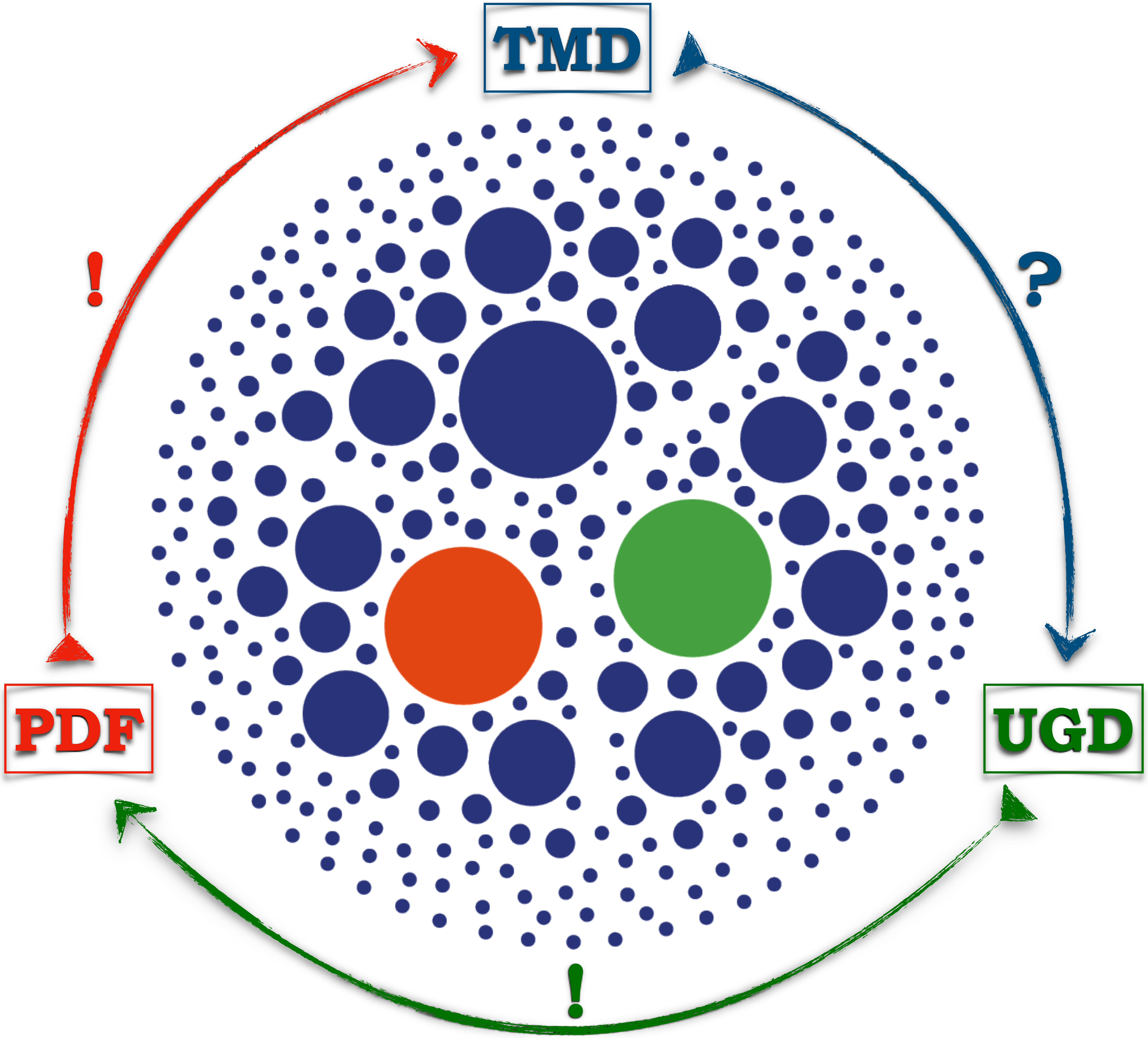
- ☐ Twist-2 T-odd gluon TMDs (**Sivers**, etc.) in progress!
- ☐ Pheno: **spin asymmetries**, **pseudodata** and **impact studies**
- ☐ Evolution: extension to quark TMDs in the same framework
- ☐ Explorative studies on gauge-link sensitivity and factorization
- ☐ Studies on GPD and small-x UGD sectors

Mapping the proton content



TMD

!

?

PDF

UGD

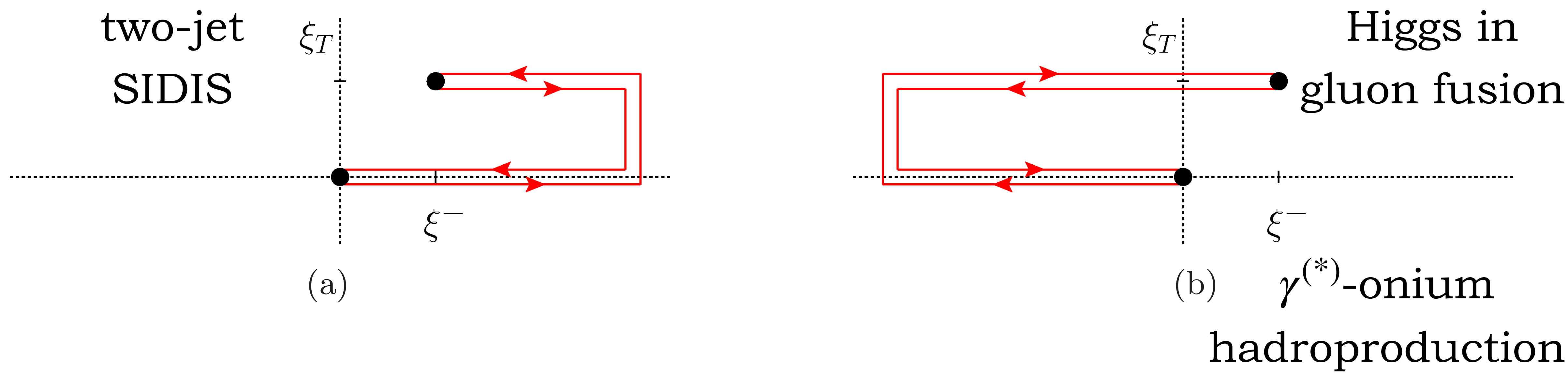
!

Backup slides

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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



- Color flow annihilated within final/initial state
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- Modified universality:

$$f_1^{[+,+]} = f_1^{[-,-]},$$
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- Phenomenology: Higgs, quarkonia or $\gamma\gamma$ in pp, two-jet SIDIS, heavy-quark pair SIDIS

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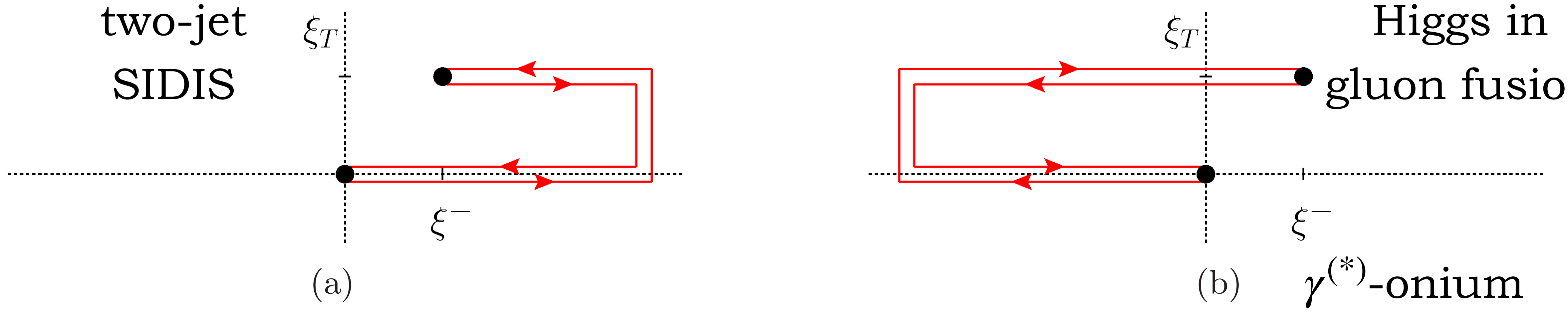

two-jet SIDIS

Higgs in gluon fusion

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

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Dipole (DP)

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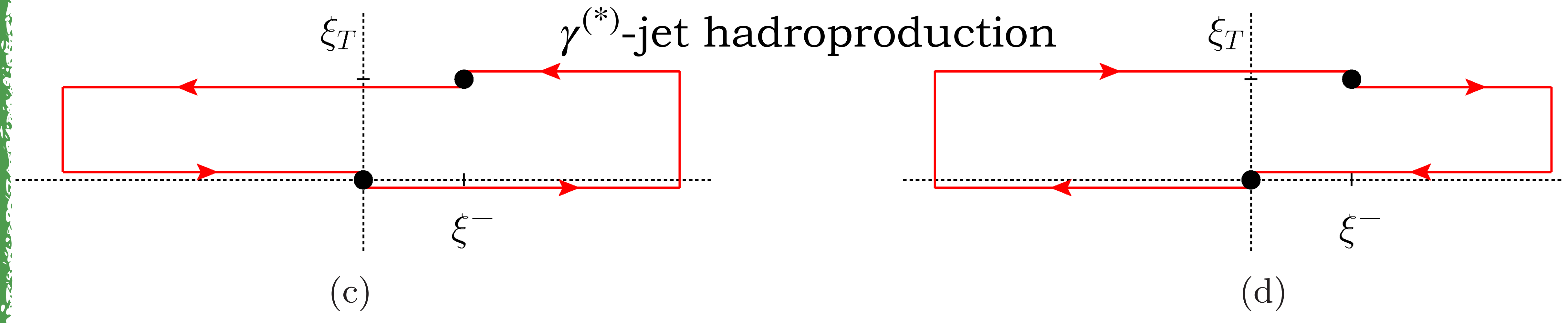

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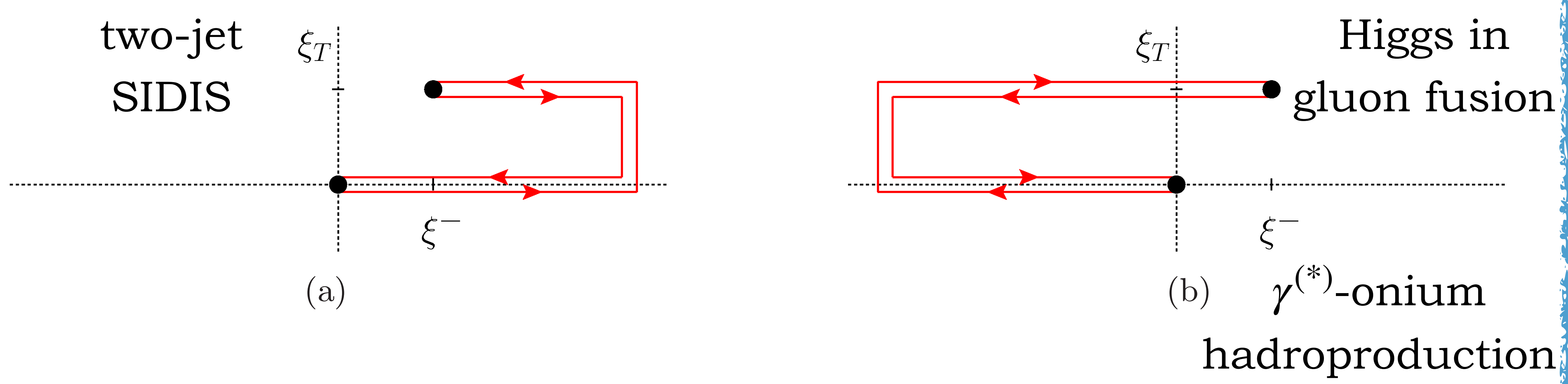

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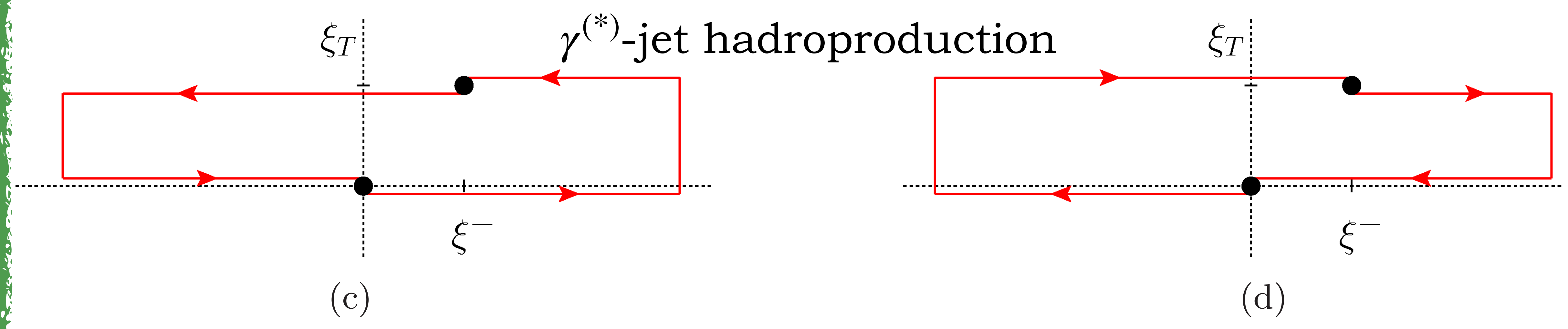

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Gauge link → two main independent sets of TMDs, **not related** to each other

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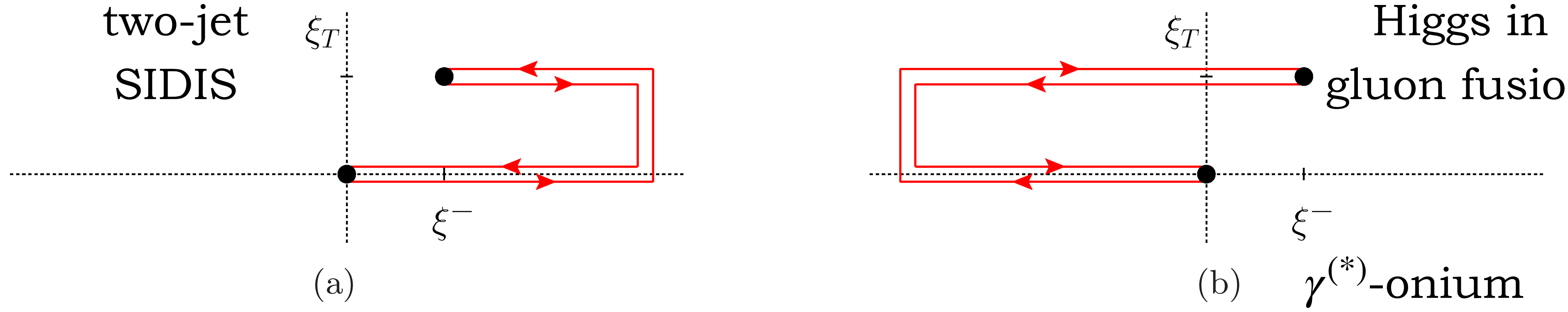

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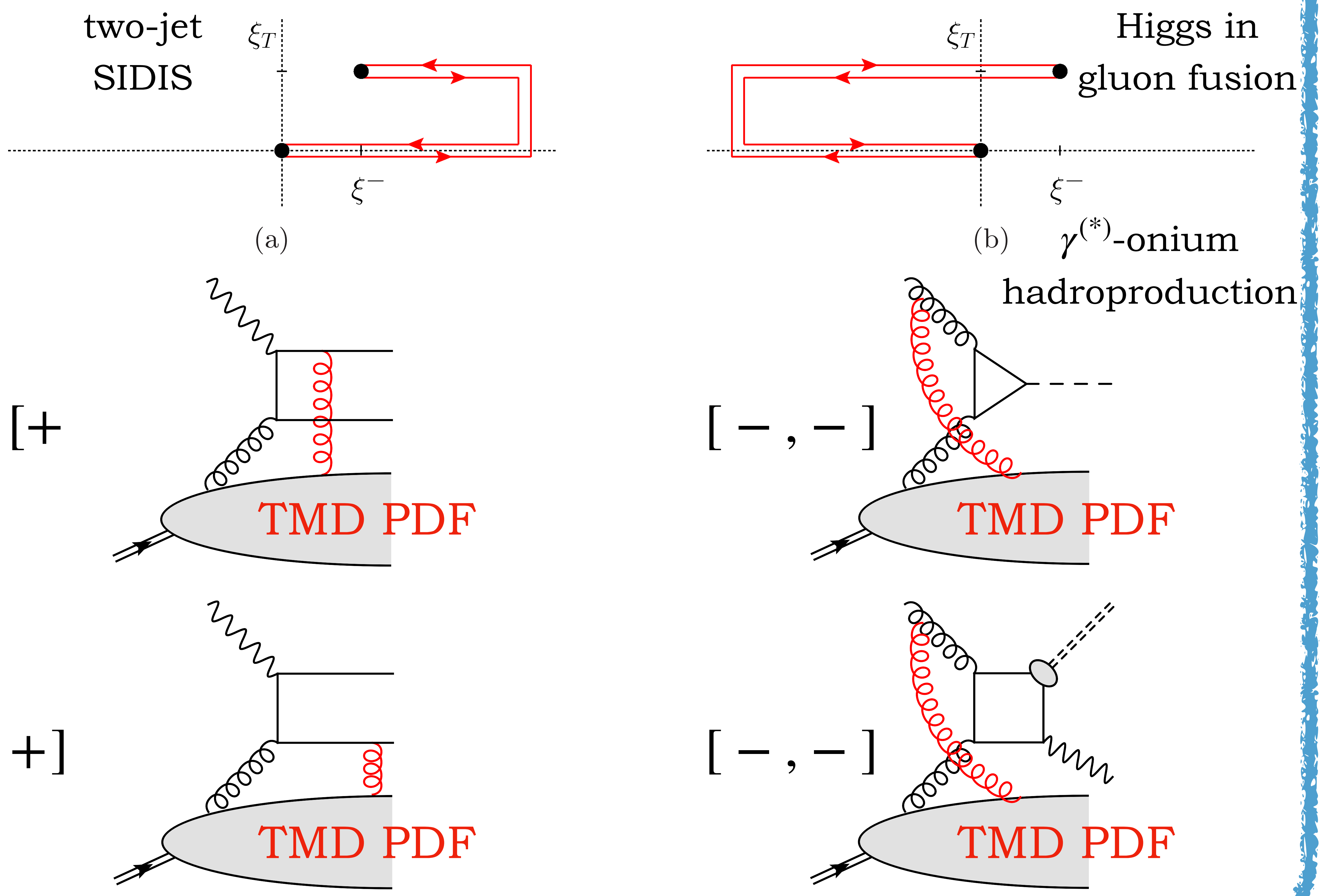

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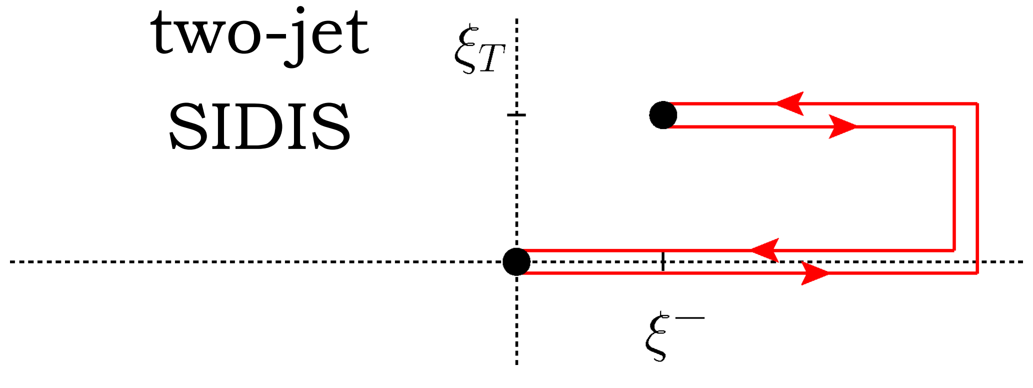
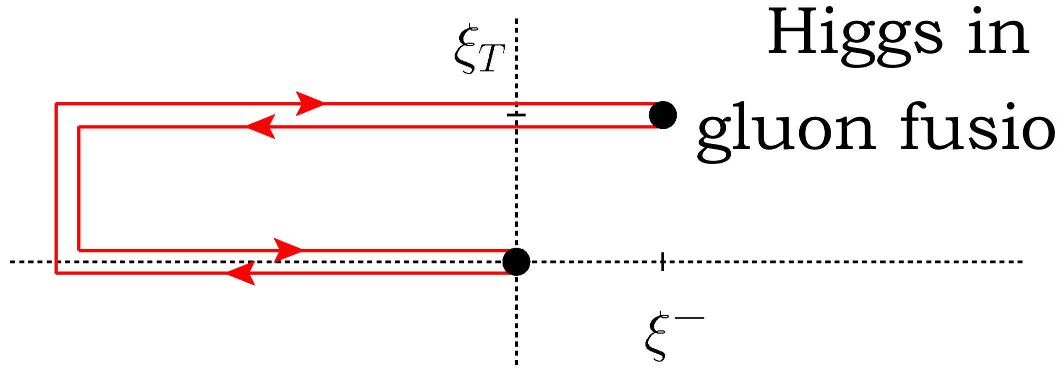


(a)

Higgs in gluon fusion

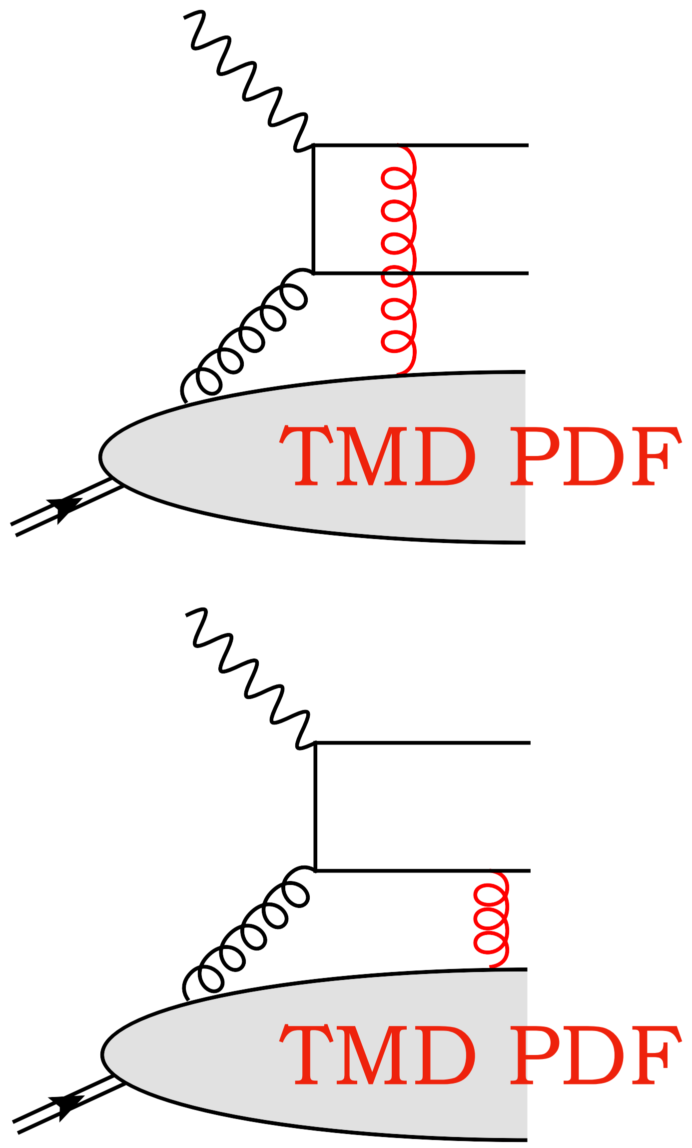


(b)

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

$[+$

$+]$



$[-,-]$

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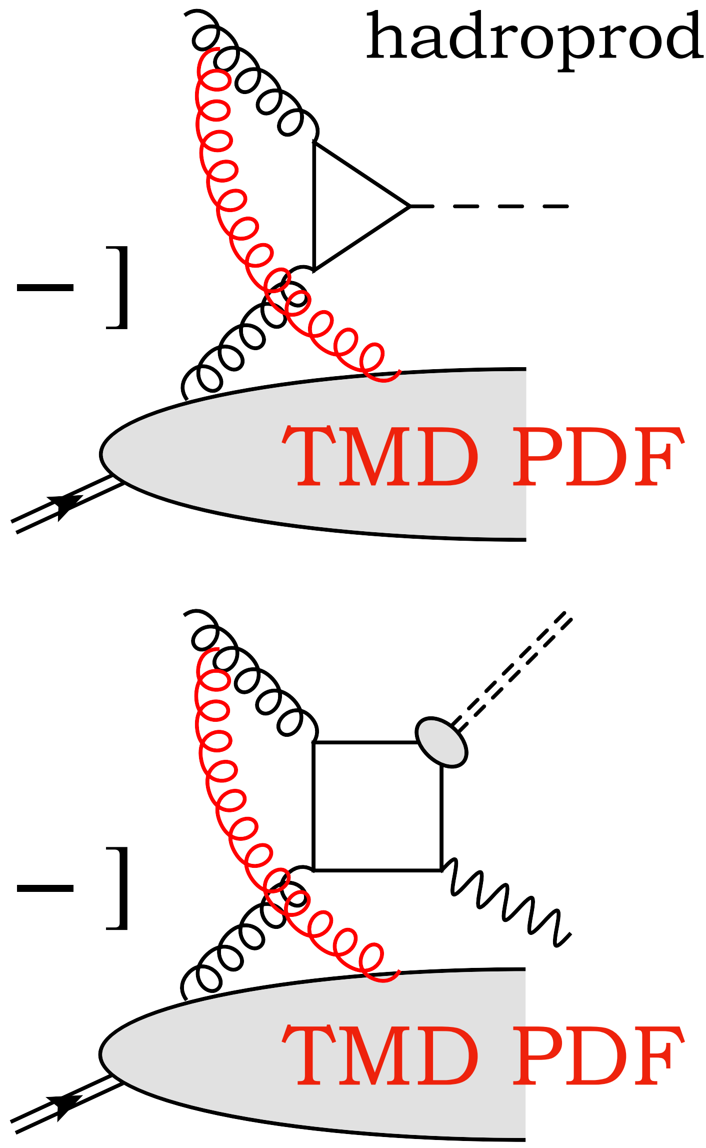

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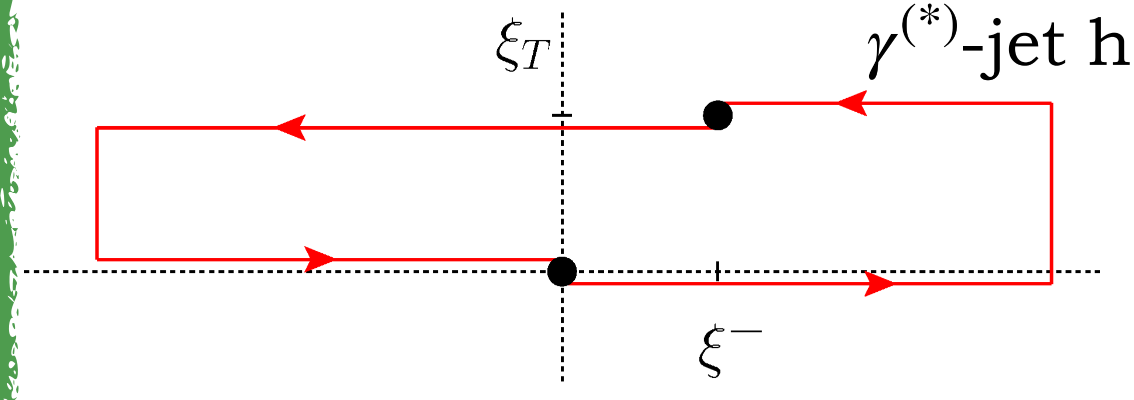
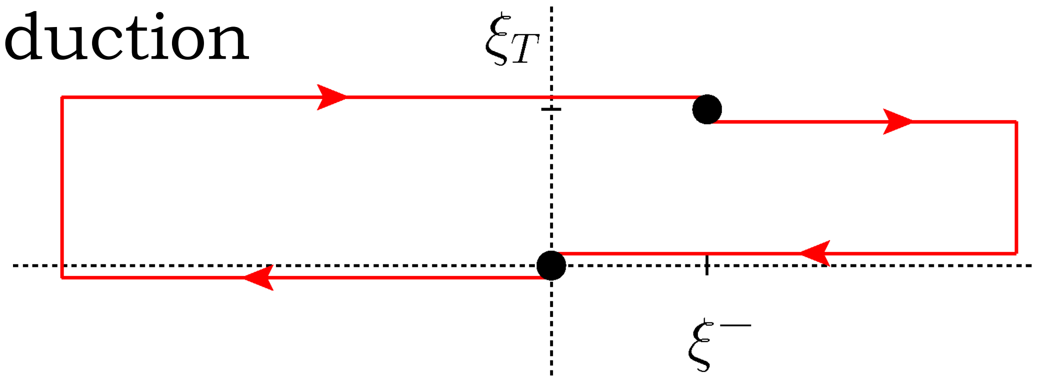


(c)



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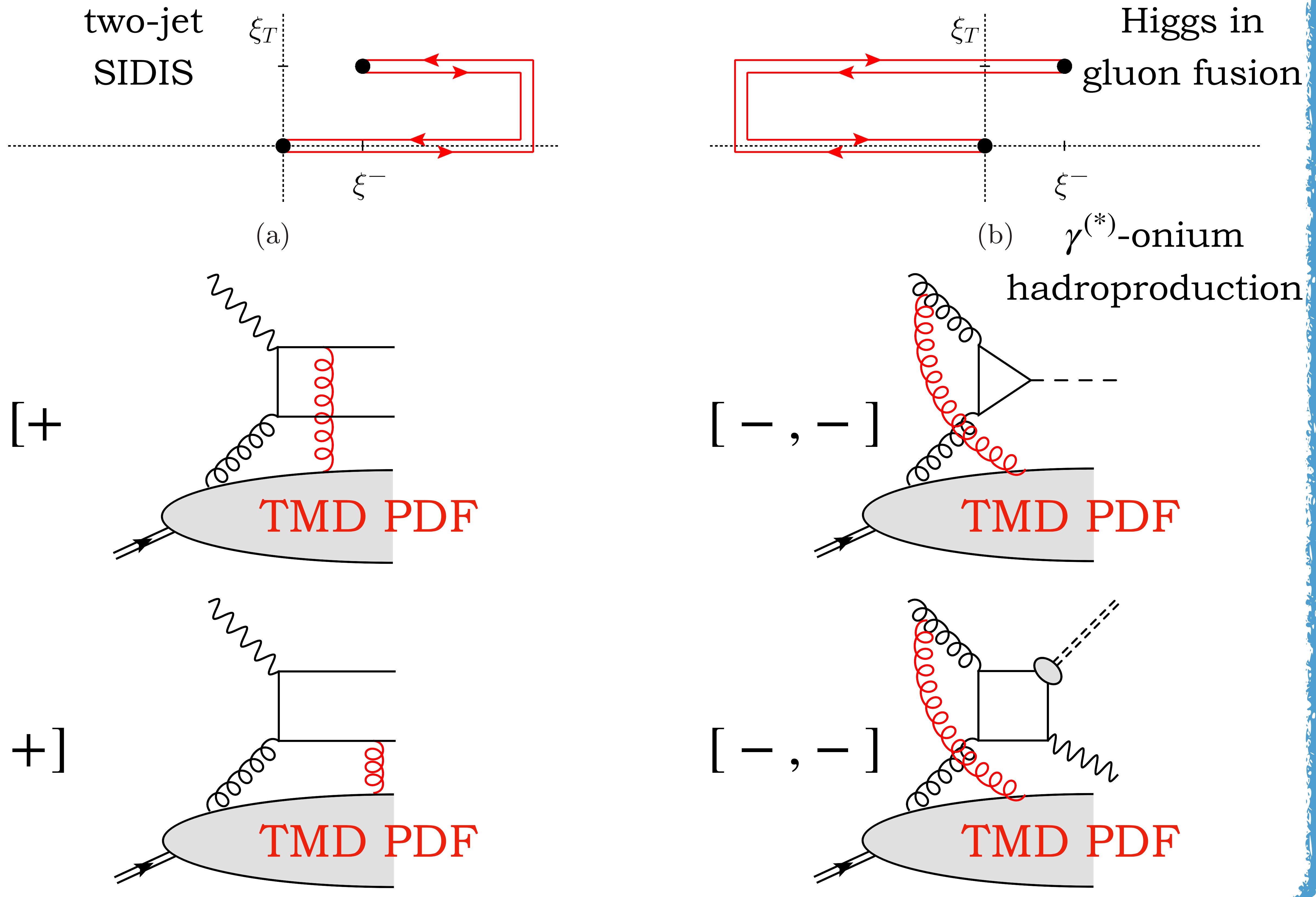
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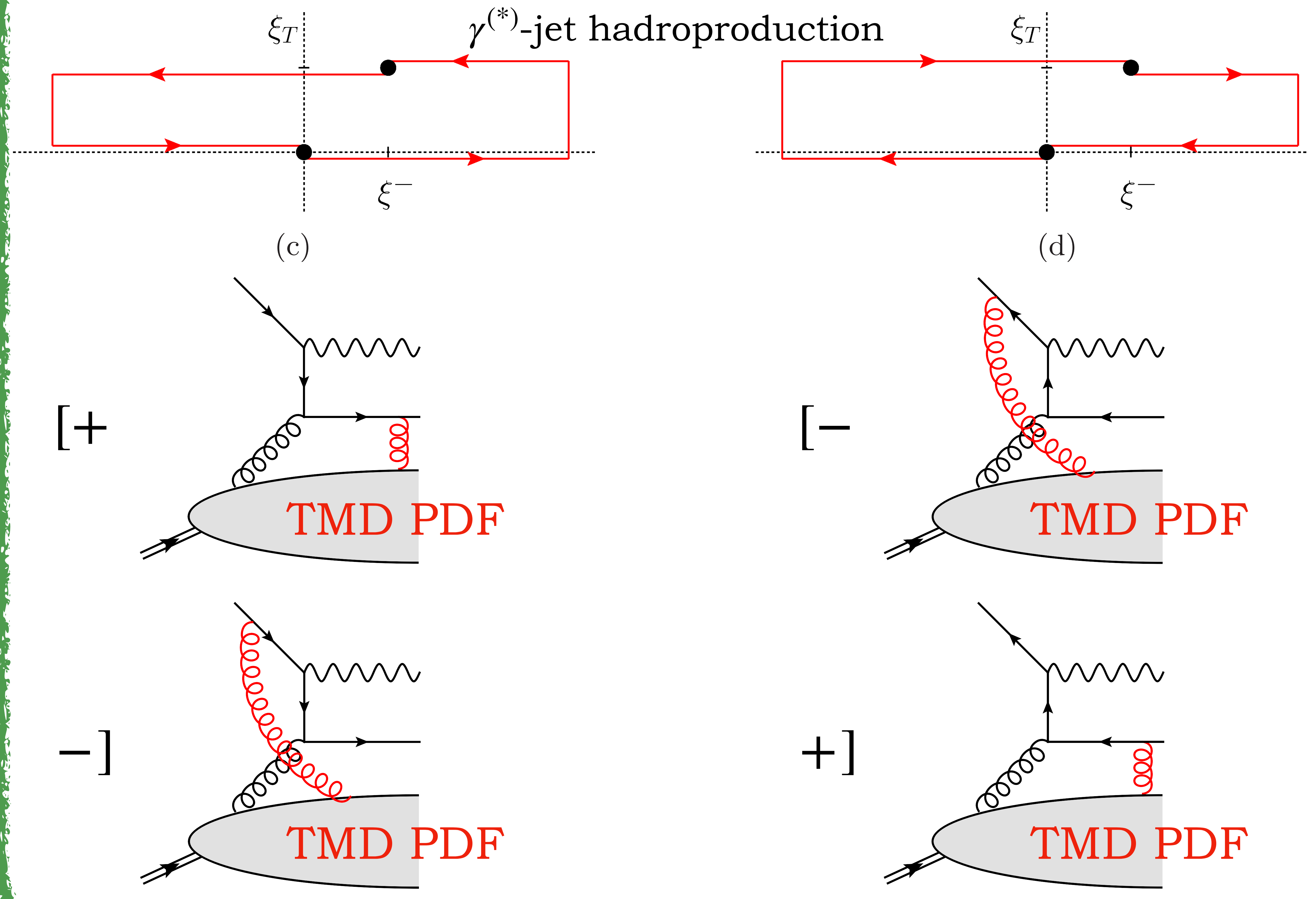
Dipole (DP)

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


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

Backup

Dihadron hadroproduction and factorization breaking

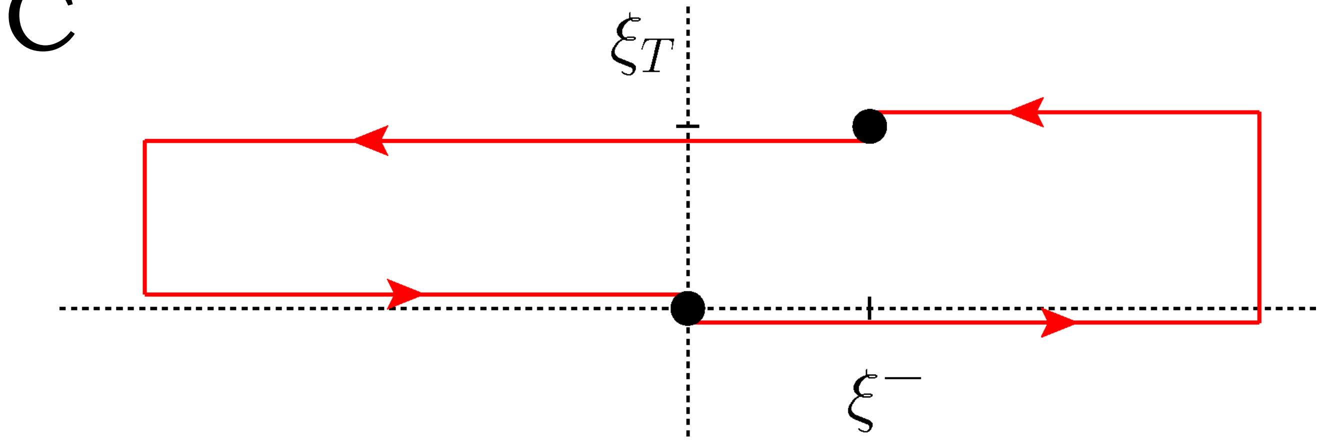
- Proof of factorization violation [T. J. Rogers, P. J. Mulders (2010)]
- Assumed factorization in SCET and CGC
- Significance of low-x studies
- Size of factorization-breaking effects small?
- DP TMDs:

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

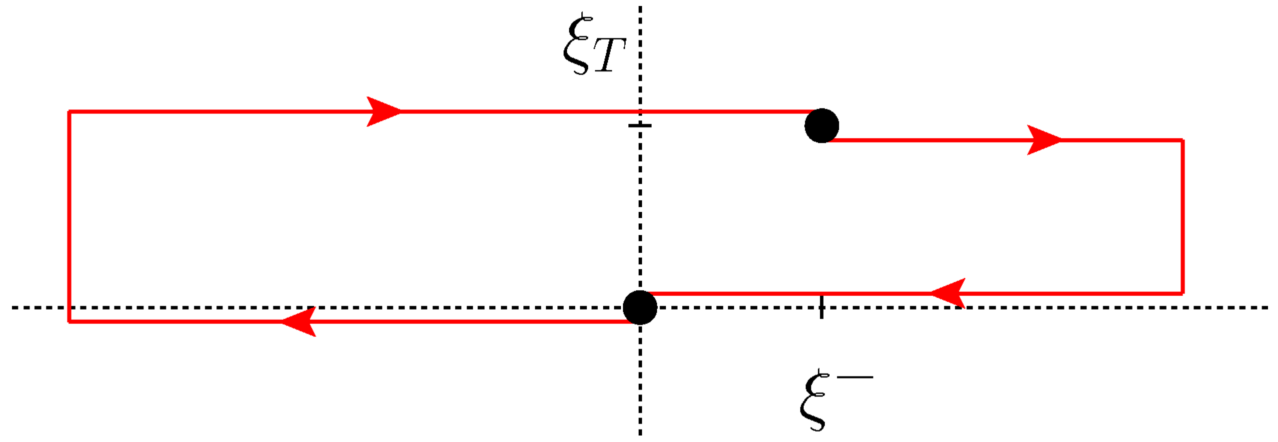
- Appearance of new gauge **loop links**:

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

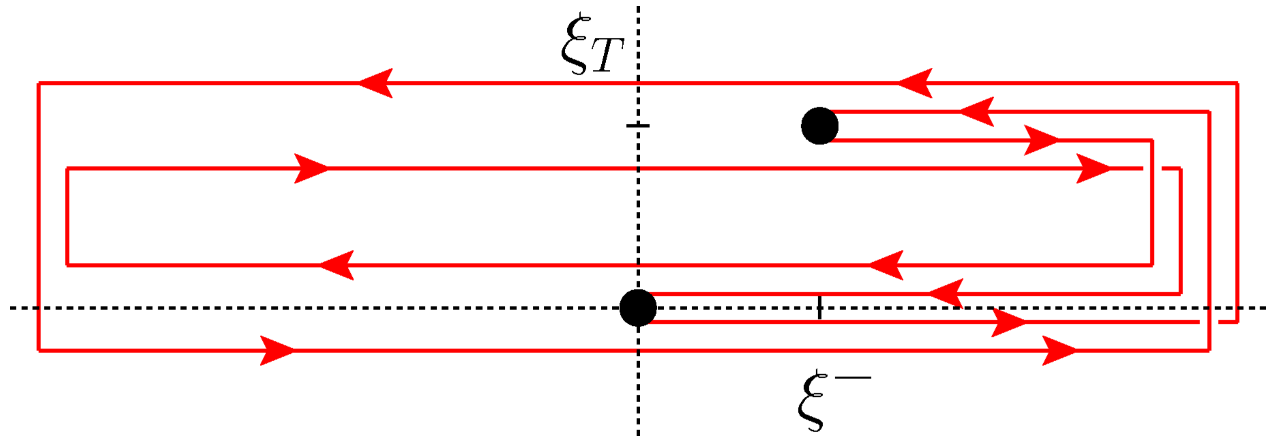
  (g) $[\Box,\Box]$, and (h) $[\Box,\Box]$



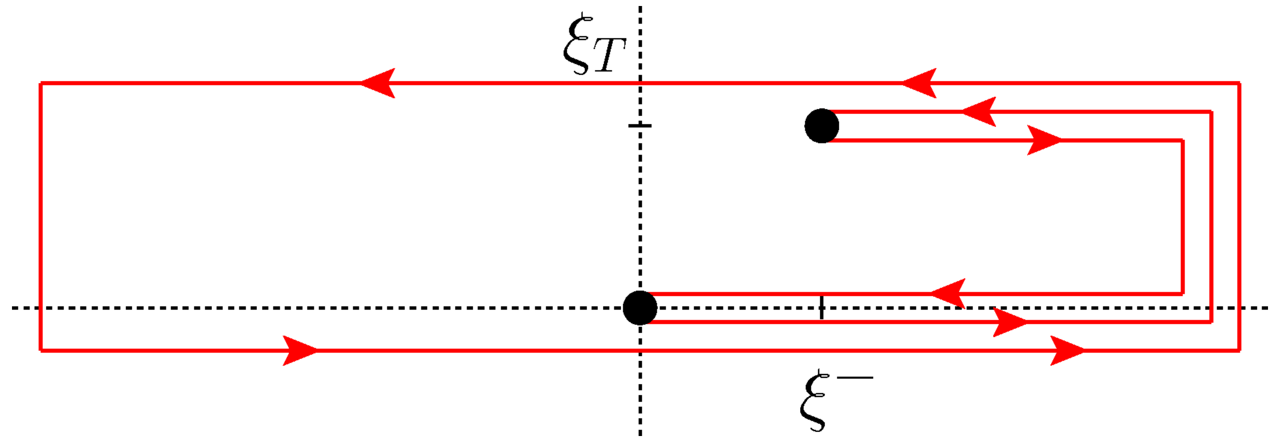
(c)



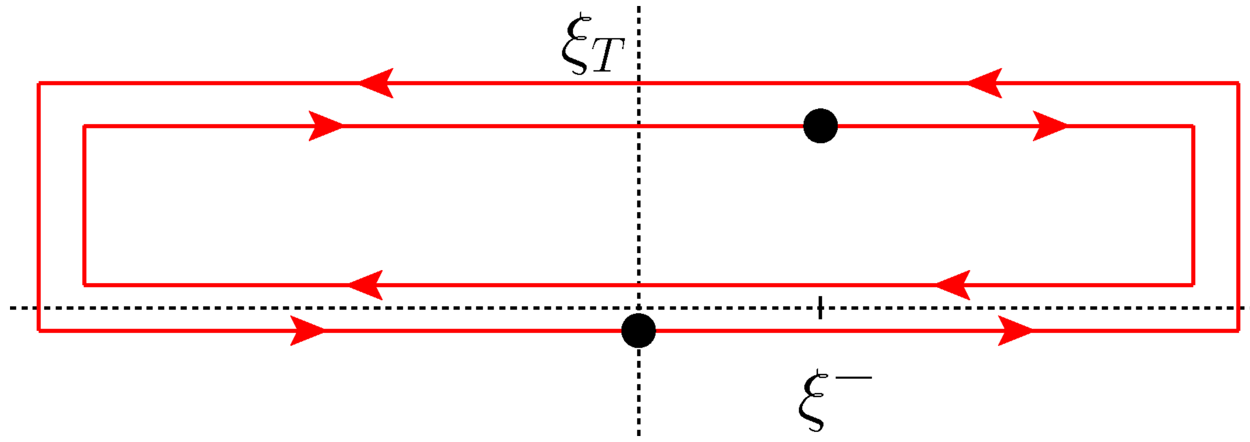
(d)



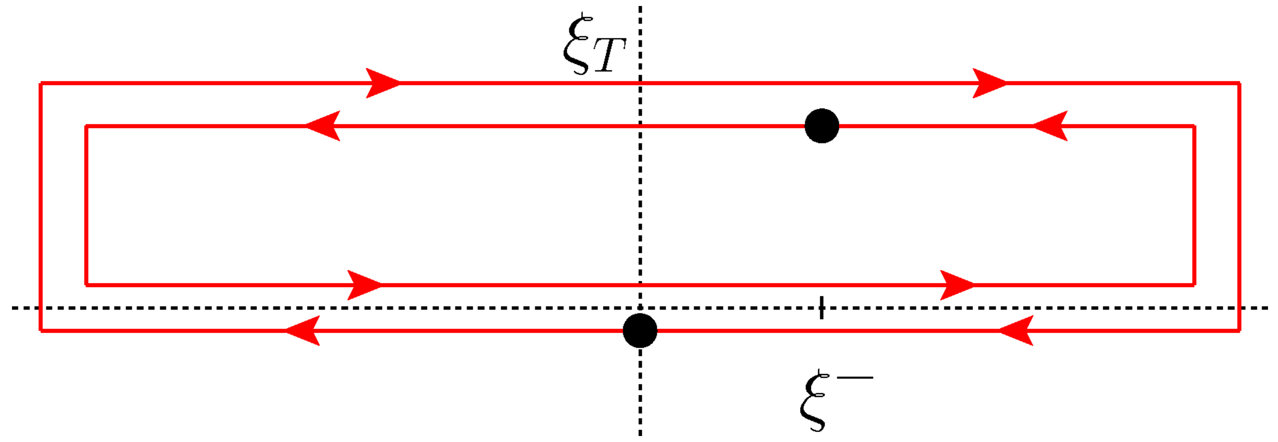
(e)



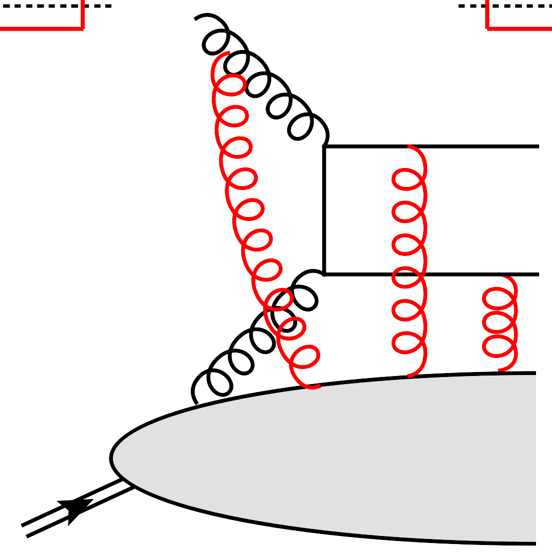
(f)



(g)



(h)

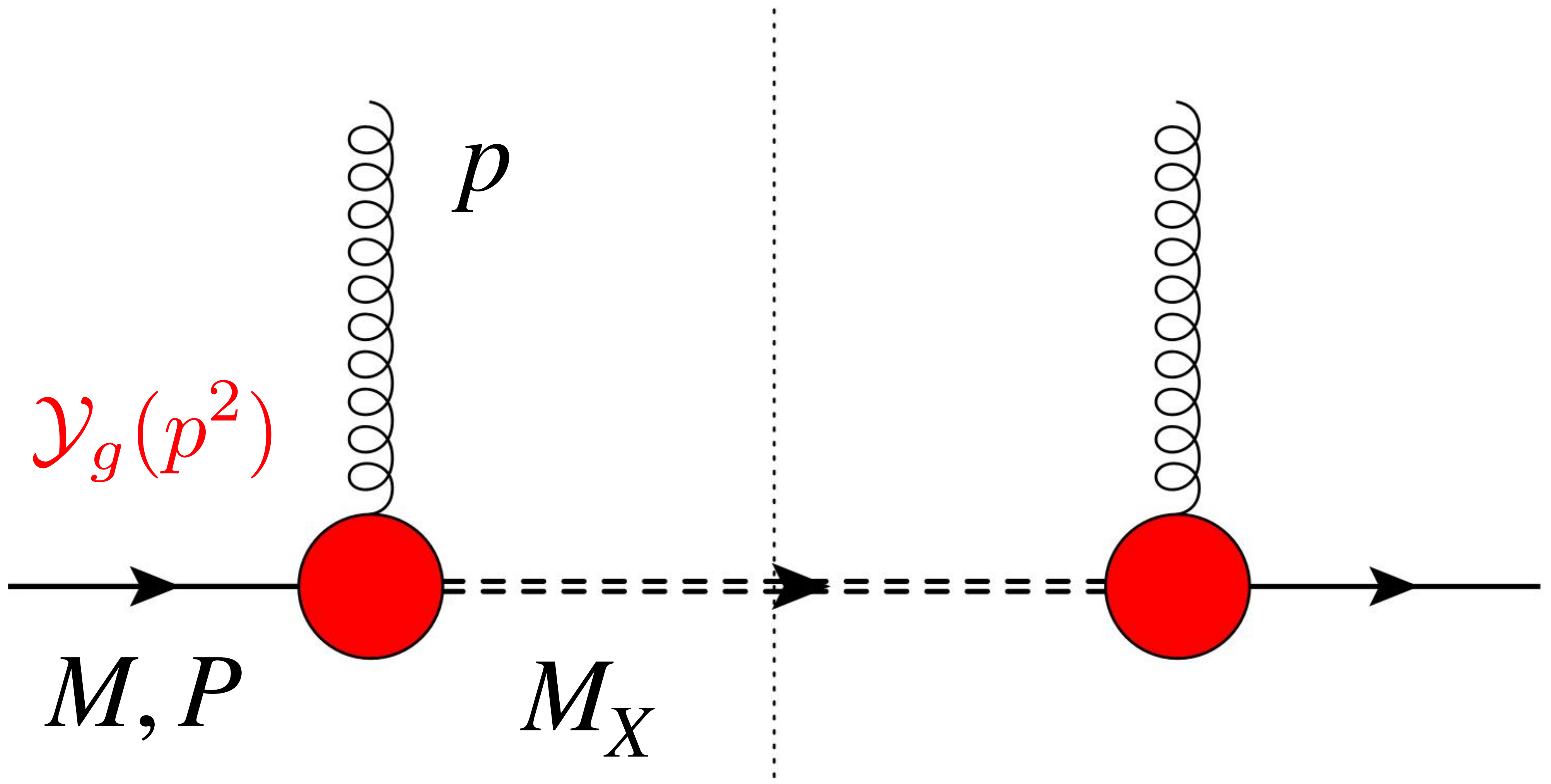


Backup

Assumptions of the model

Effective vertex

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



Spin-1/2 spectator (gluon)

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

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

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

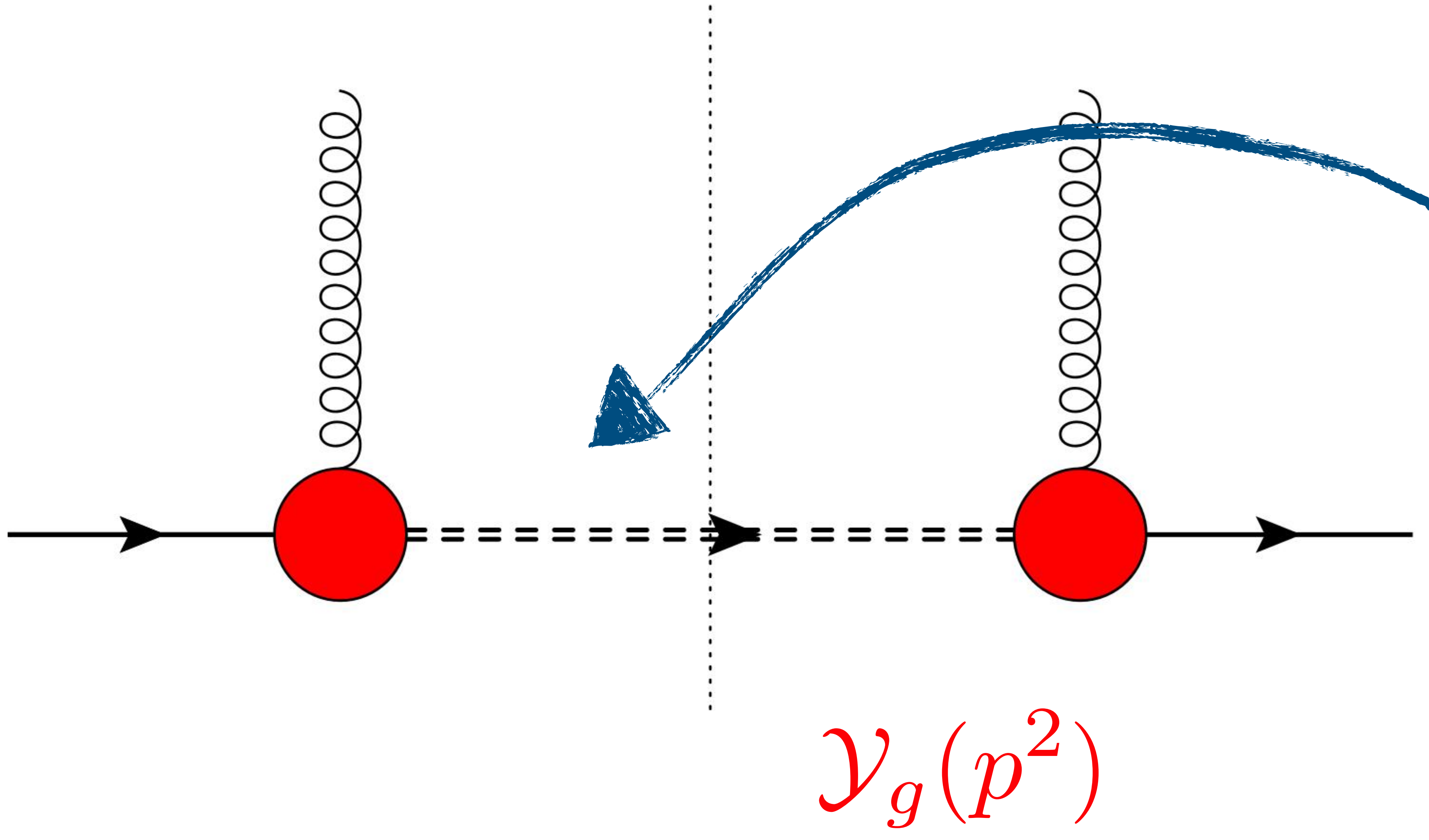
Spectator-system spectral-mass function

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

spectral-mass function

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)]

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

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

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

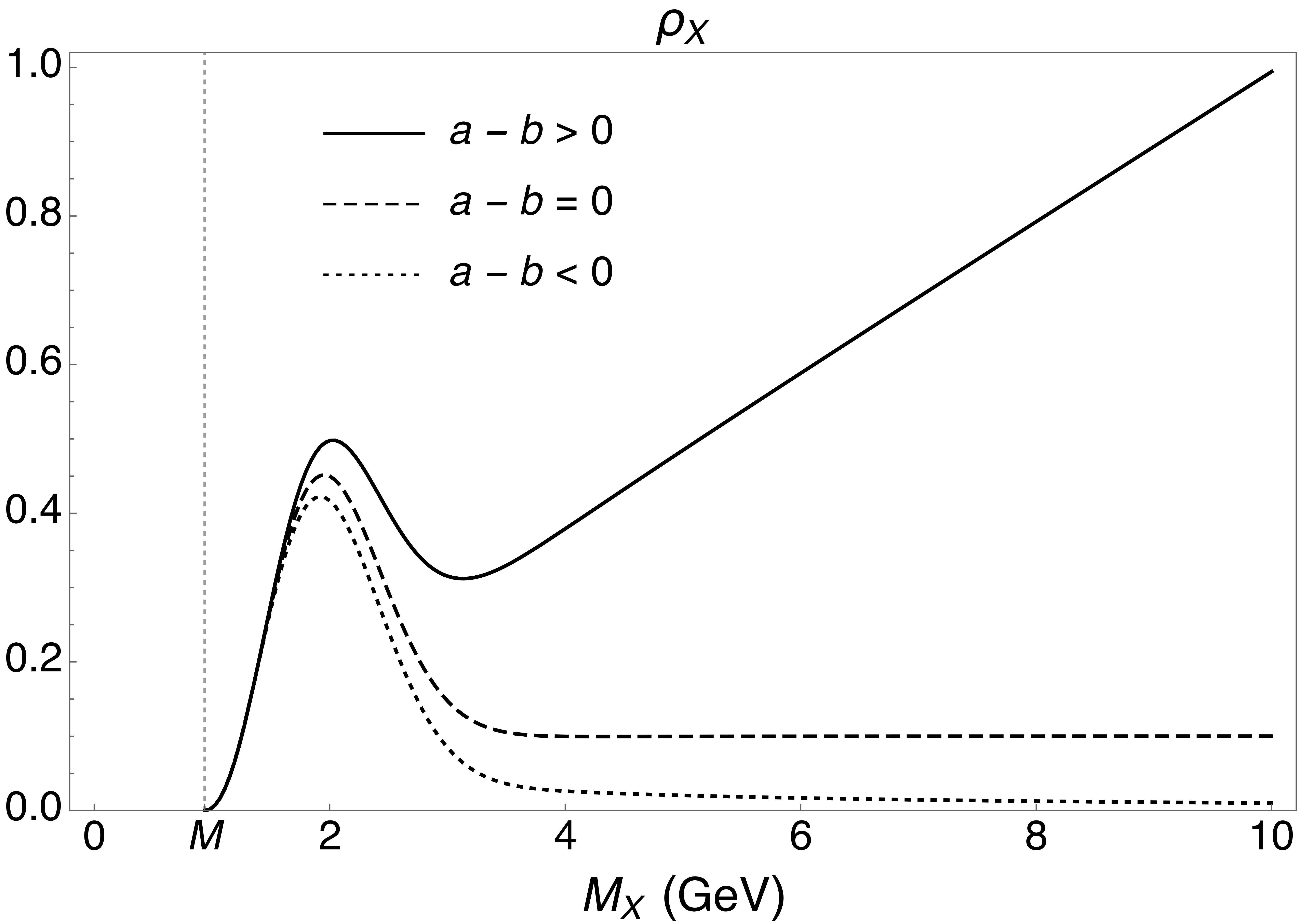
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

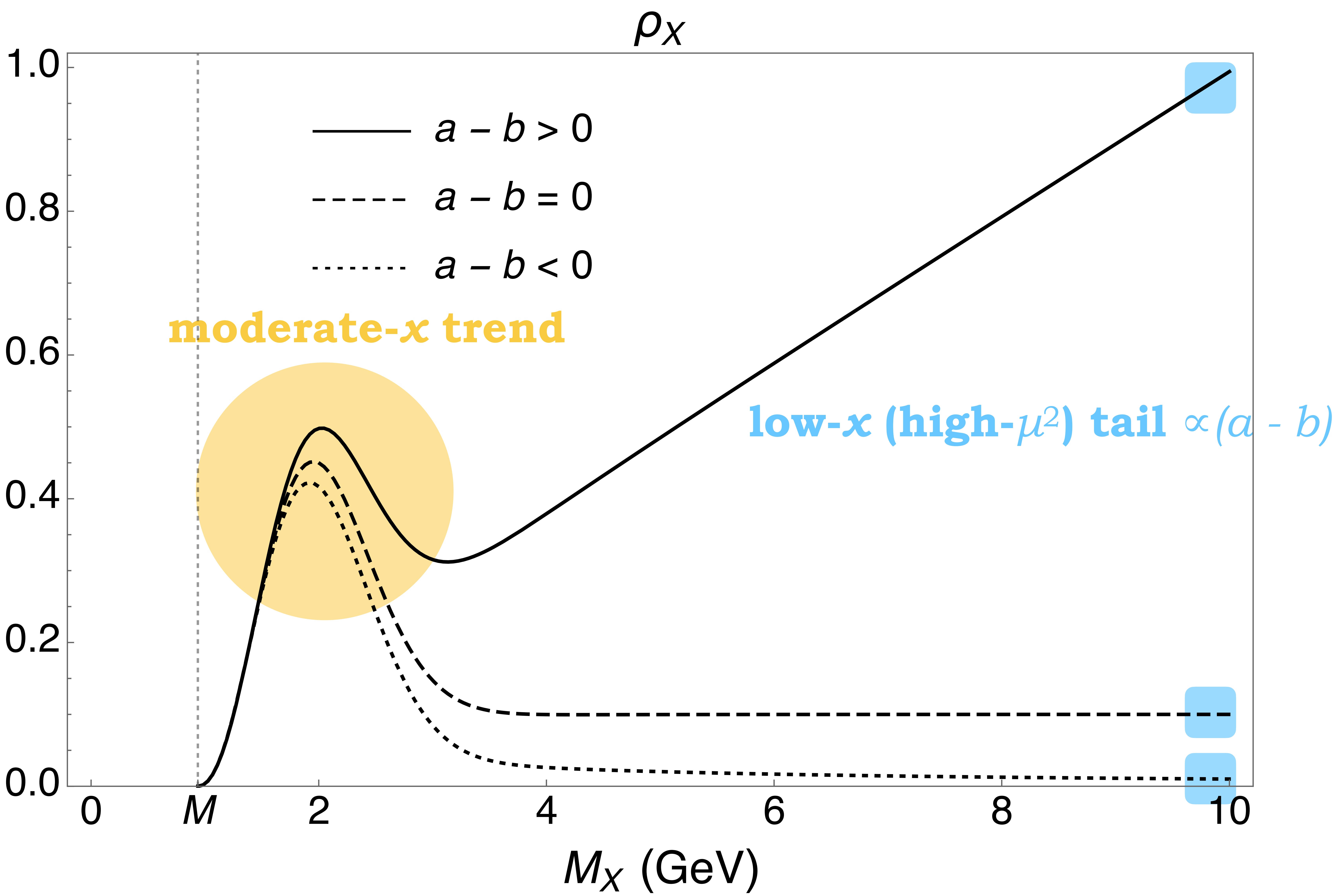
Backup

Spectral function vs *(a - b)*



Backup

Spectral function vs *(a - b)*

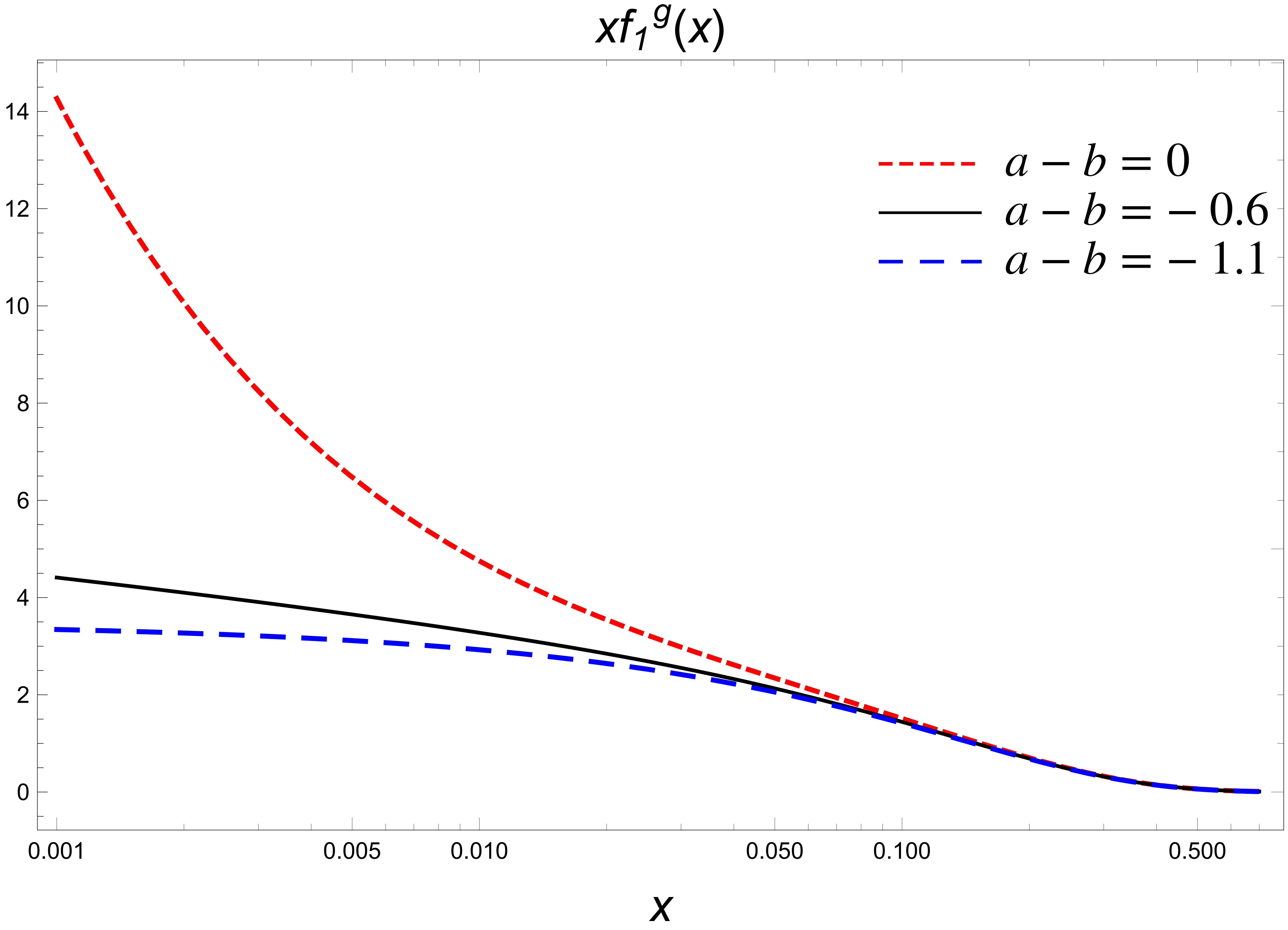


moderate-x trend

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

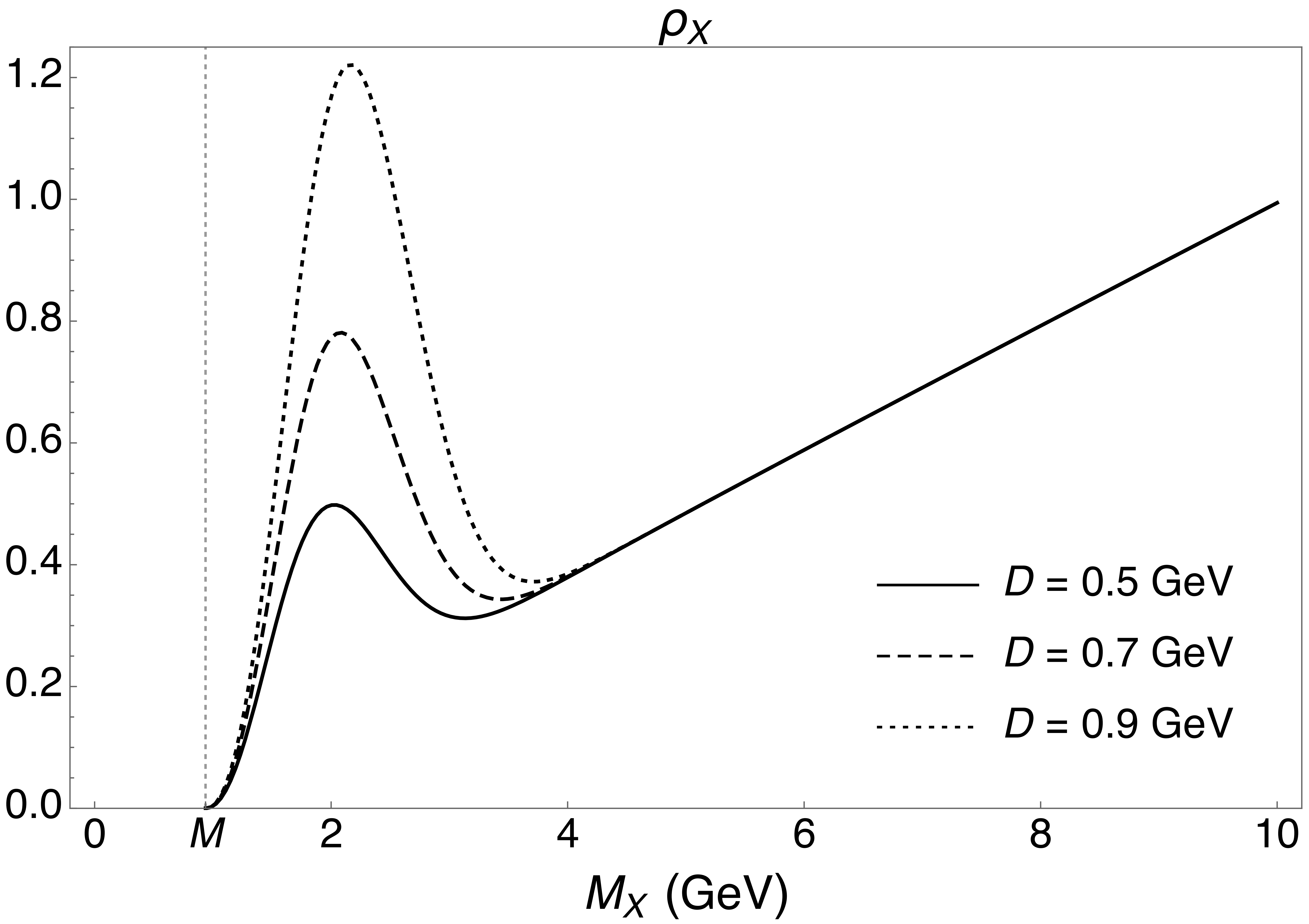
Backup

xf_1 collinear PDF vs *(a - b)*



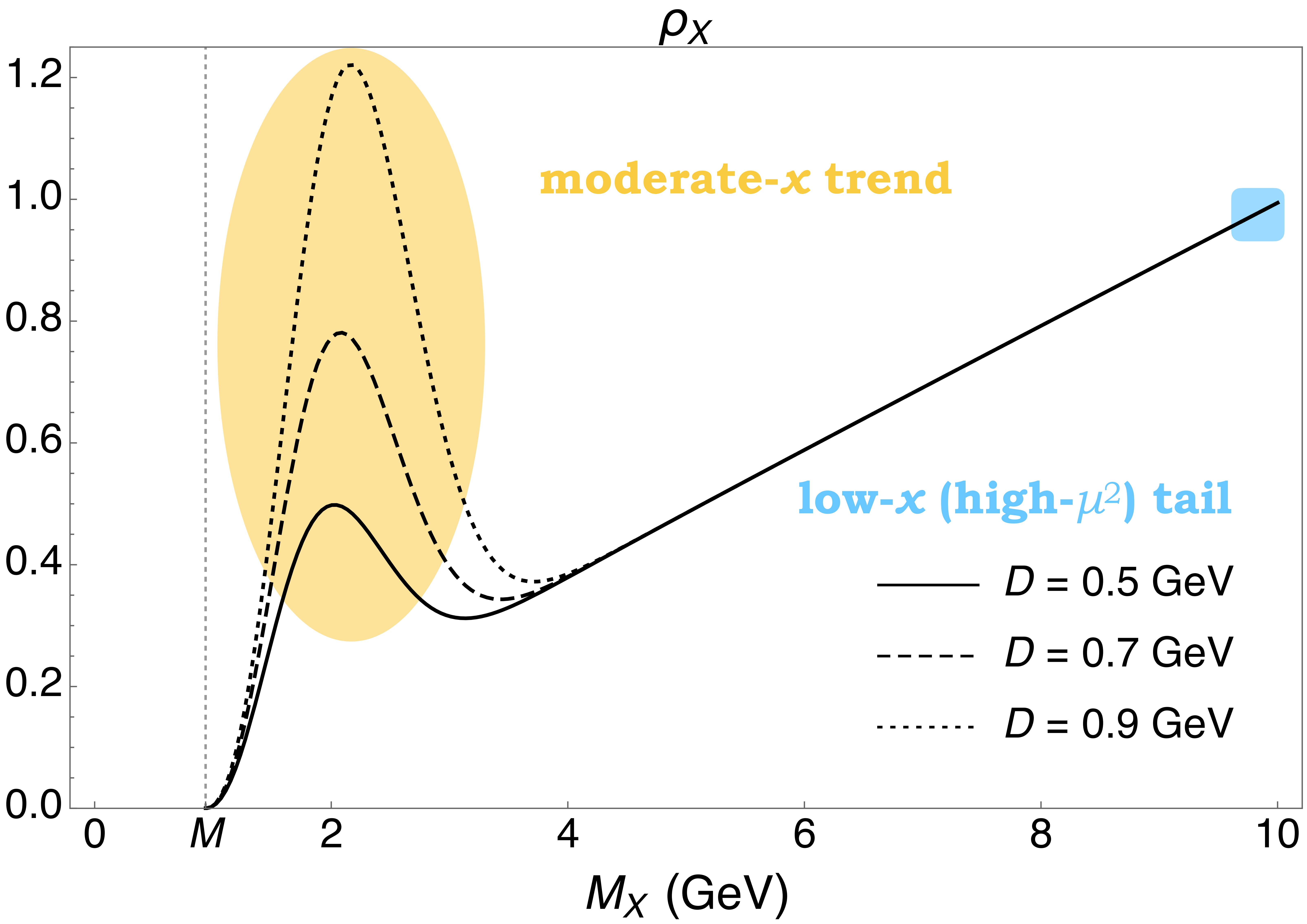
Backup

Spectral function vs D



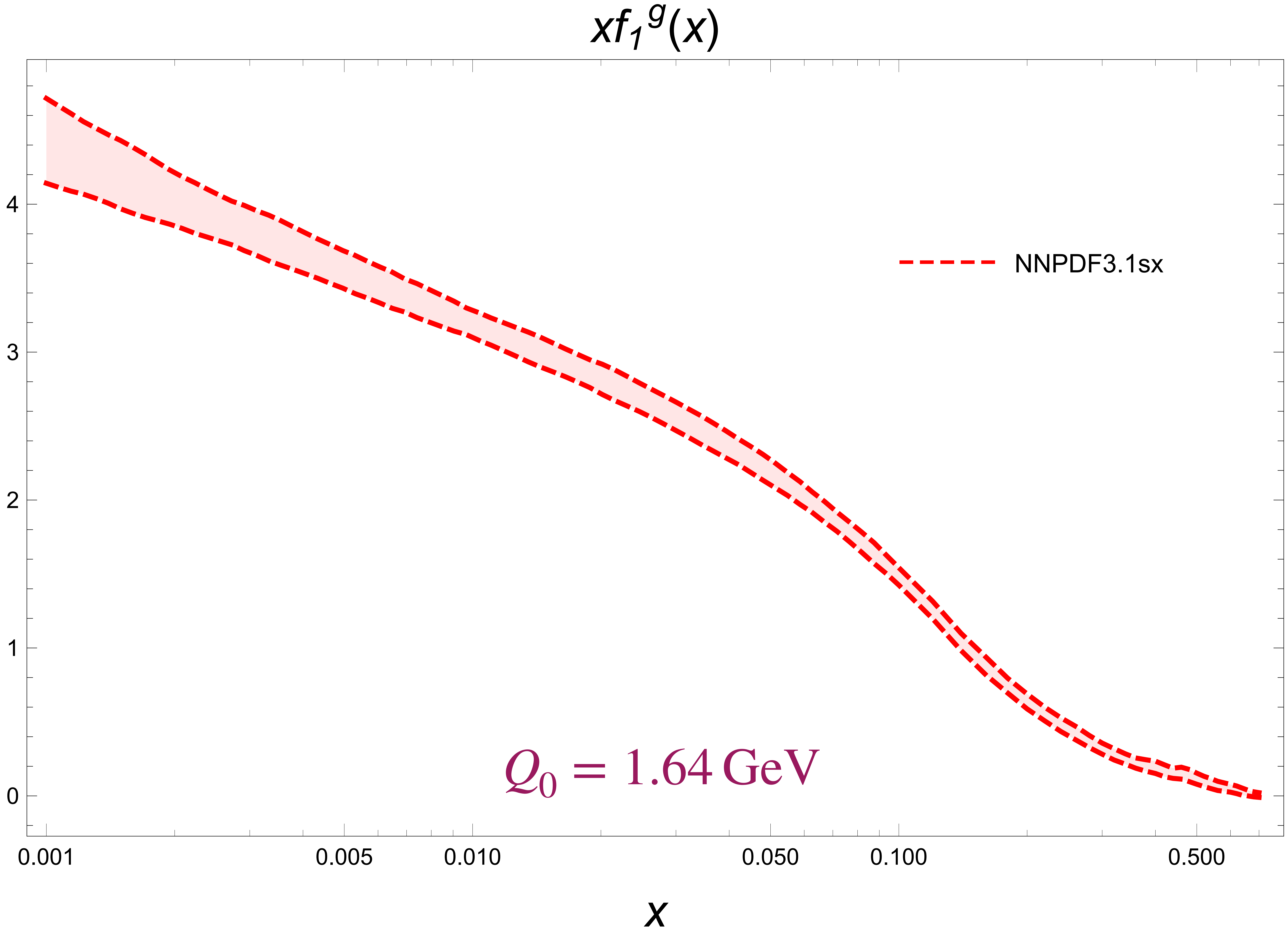
Backup

Spectral function vs D



Backup

Unpolarized gluon PDF



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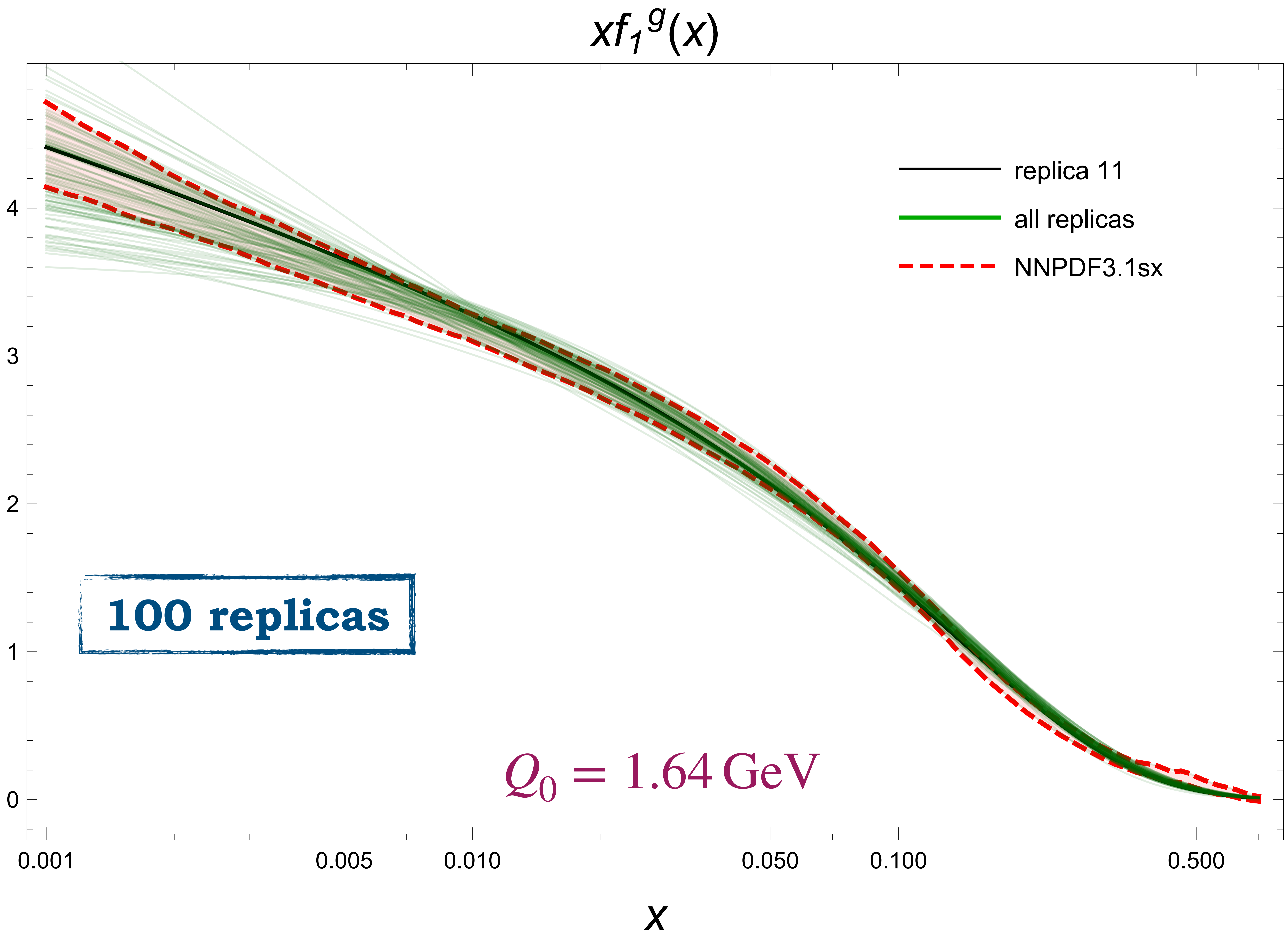
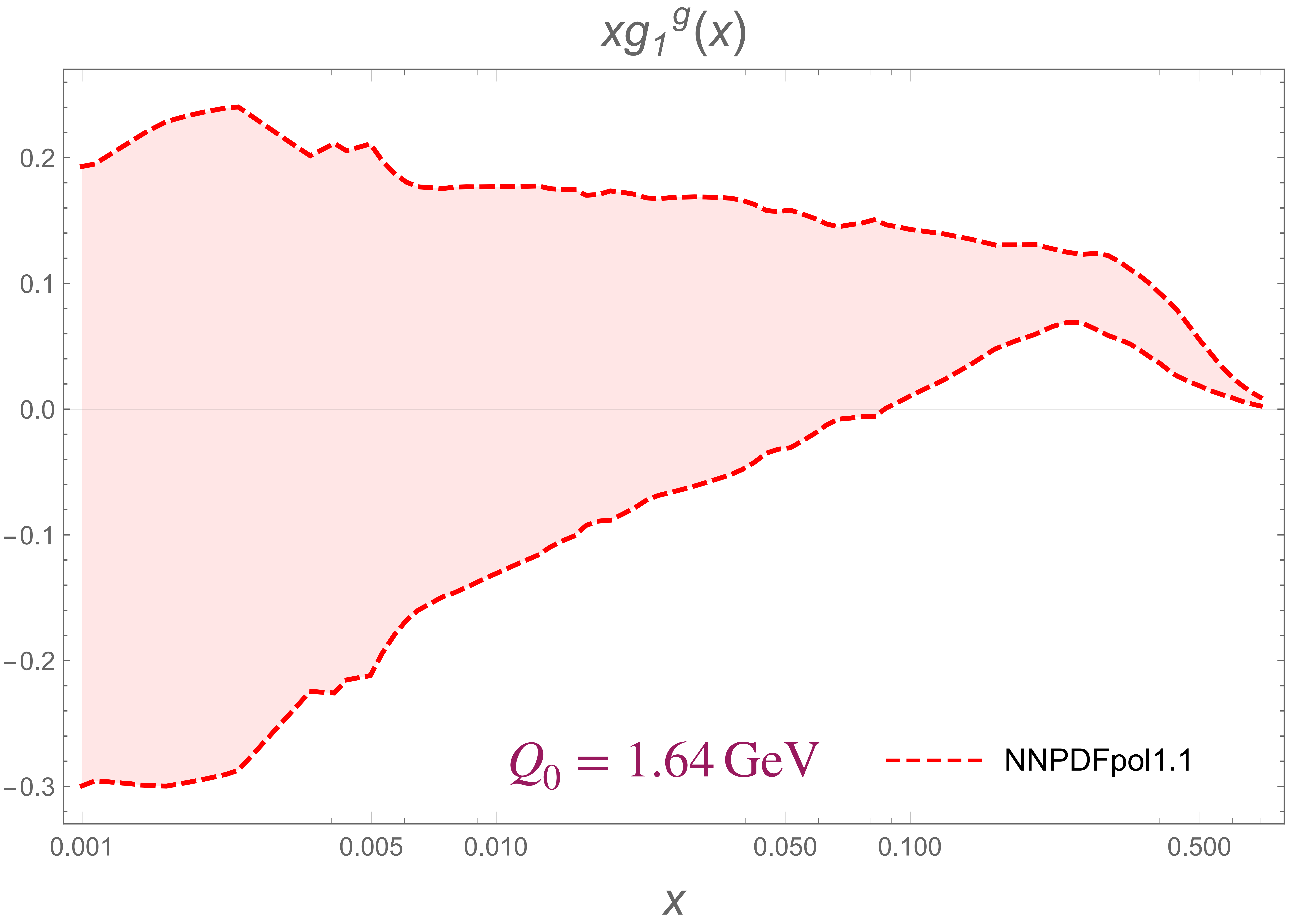
Unpolarized gluon PDF



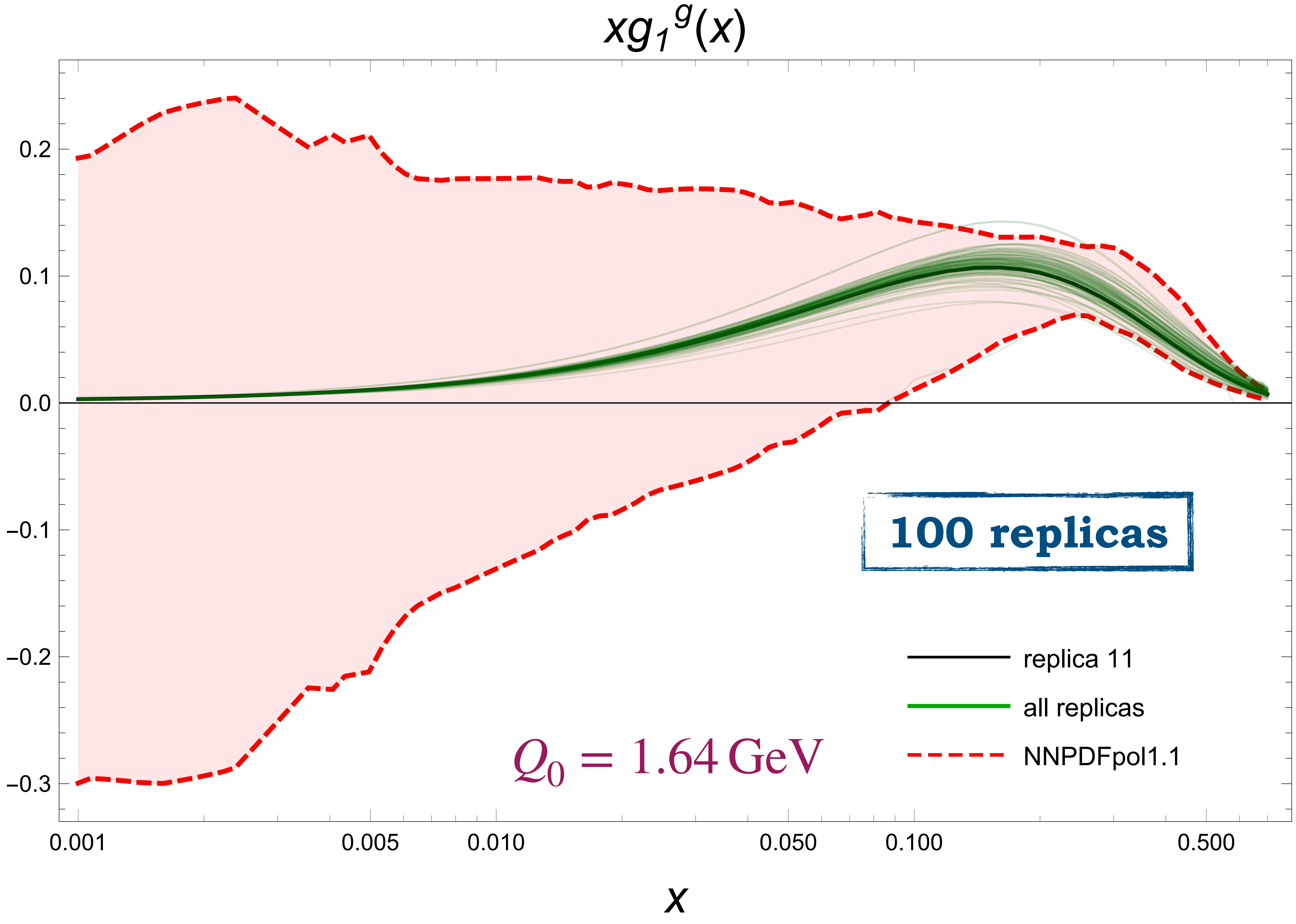
Backup

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

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

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

Backup

Fit specifics

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

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

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

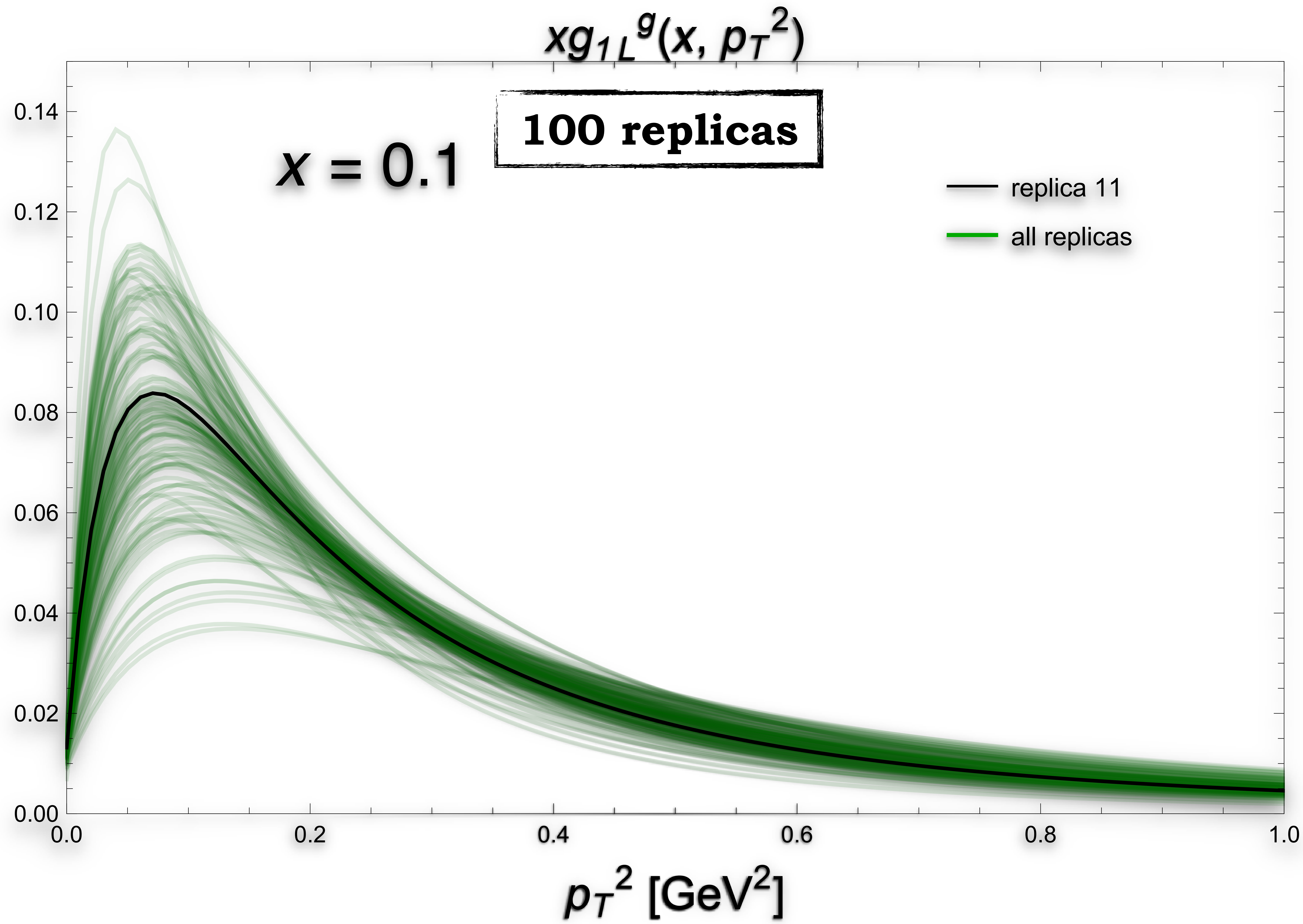
$$\langle x \rangle_g = 0.427(92)$$

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

🔗 [C. Alexandrou *et al.* (2020)]

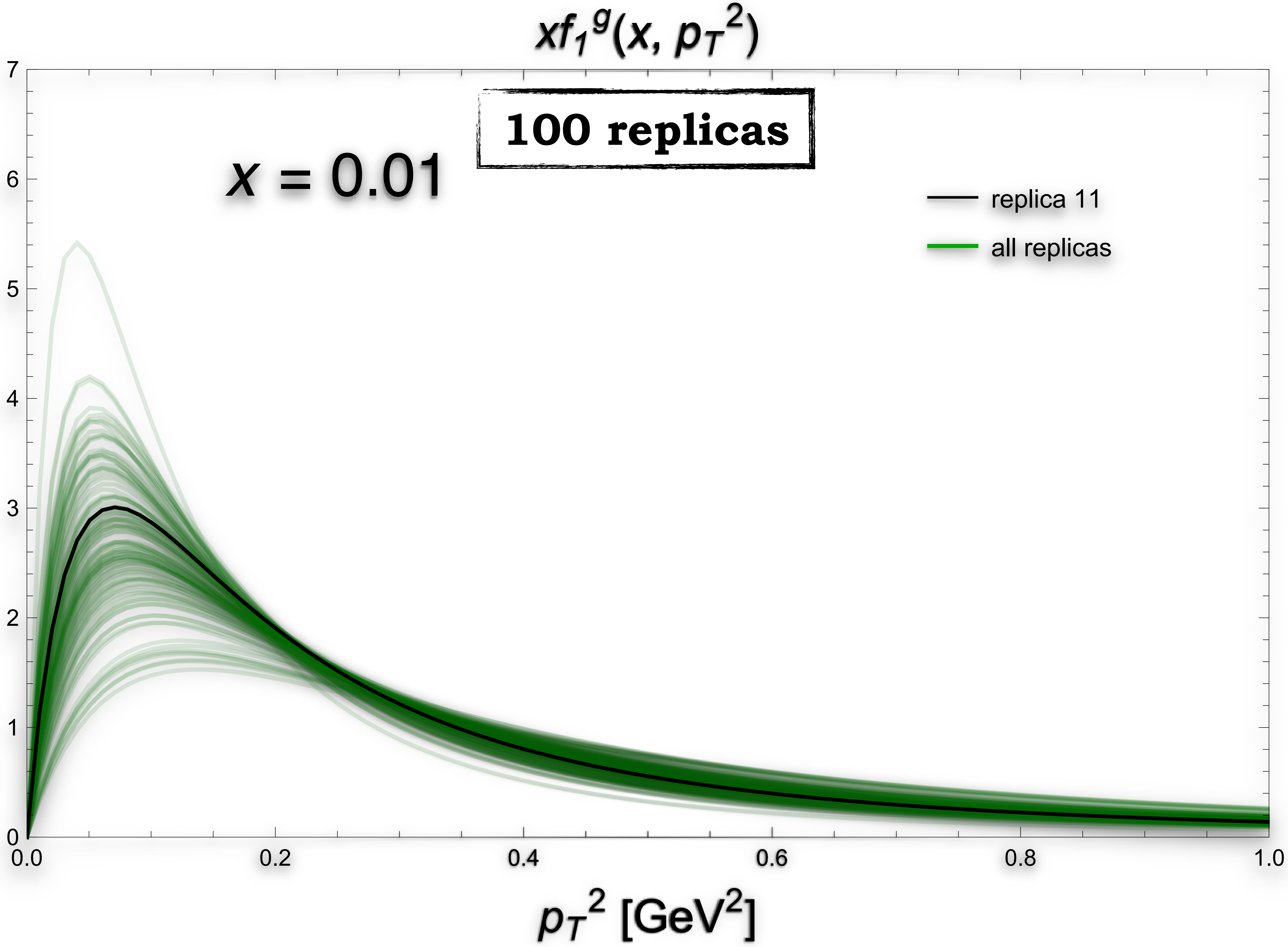
Backup

Helicity gluon TMD



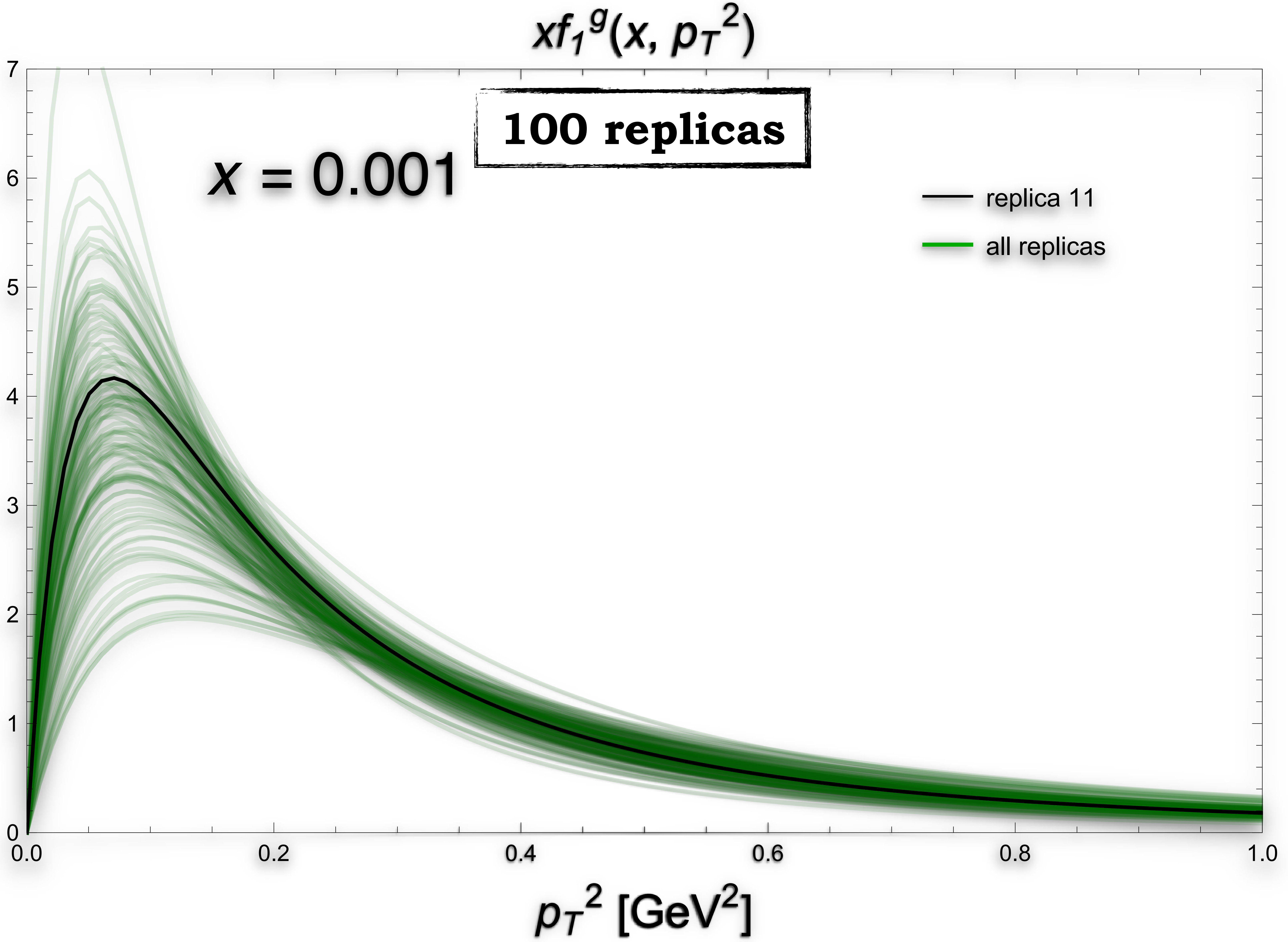
Backup

Unpolarized gluon TMD



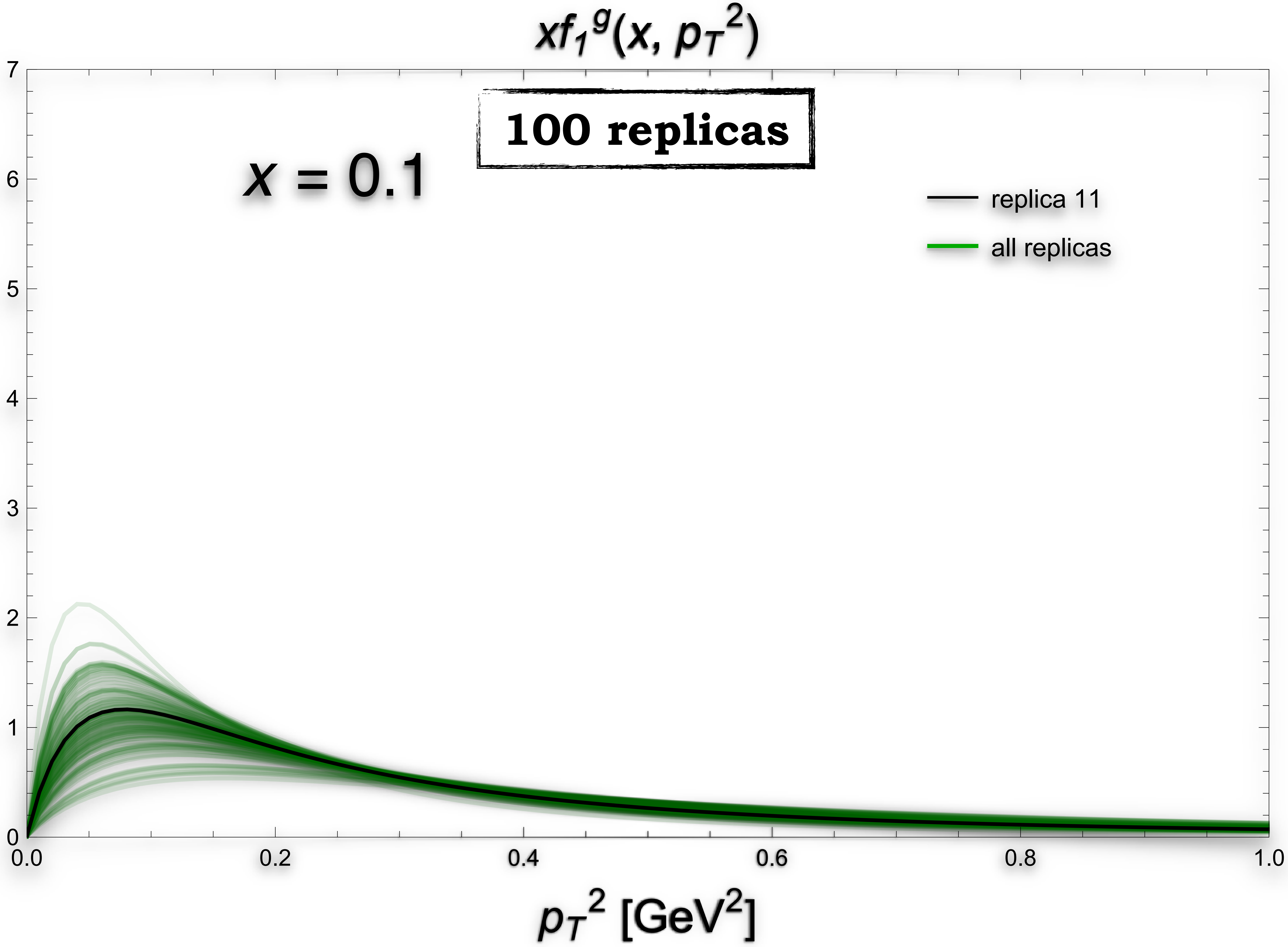
Backup

Unpolarized gluon TMD



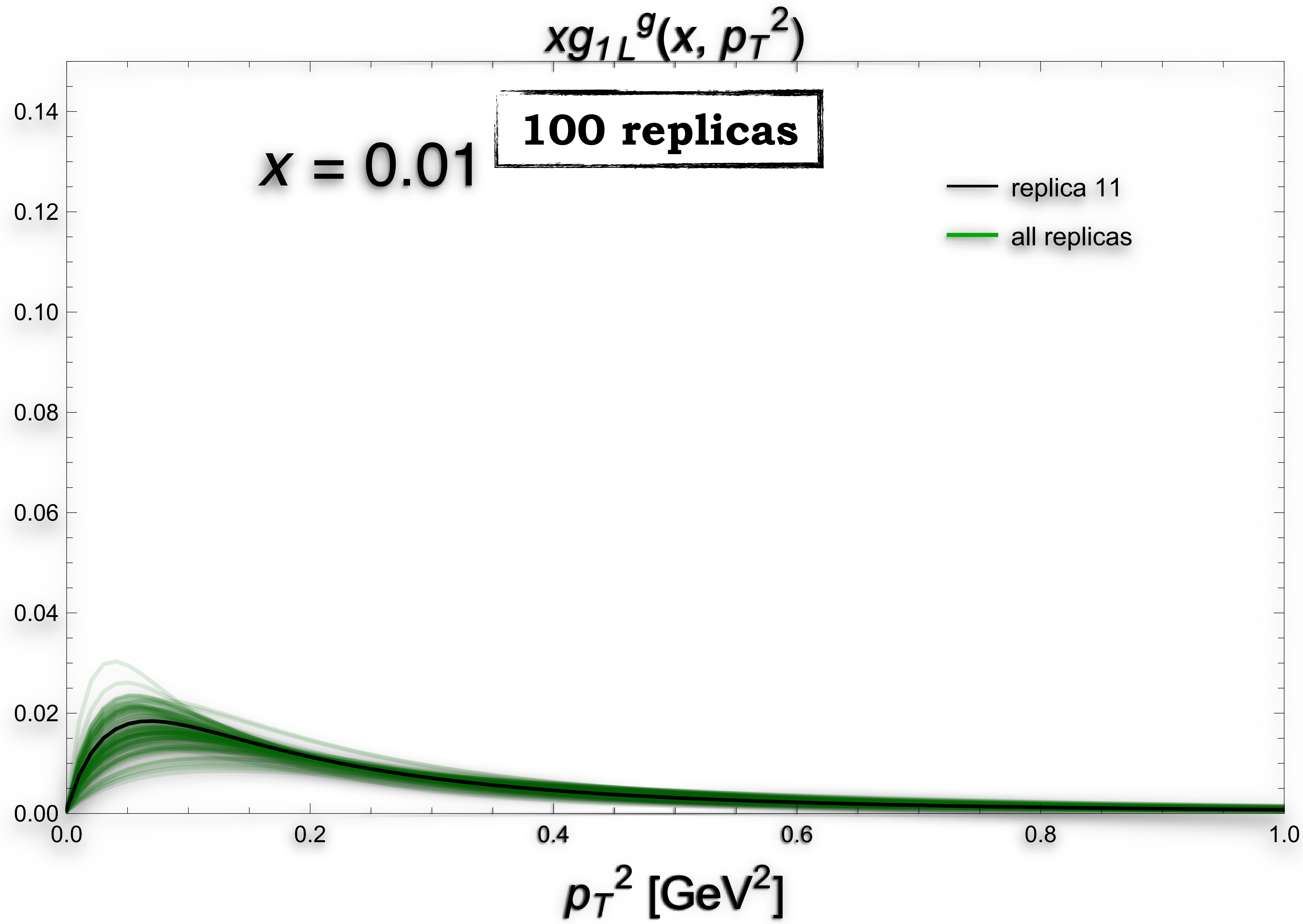
Backup

Unpolarized gluon TMD



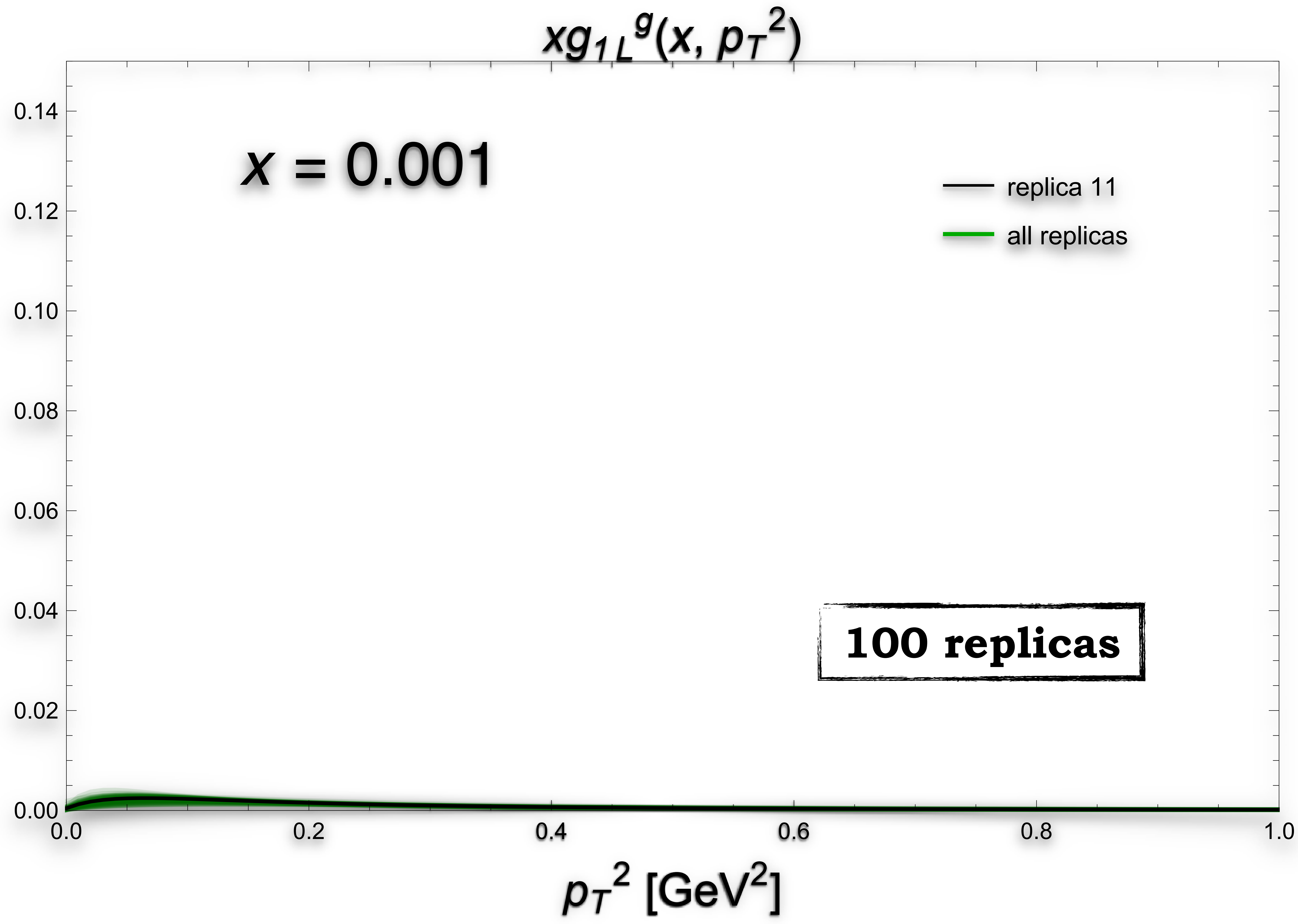
Backup

Helicity gluon TMD



Backup

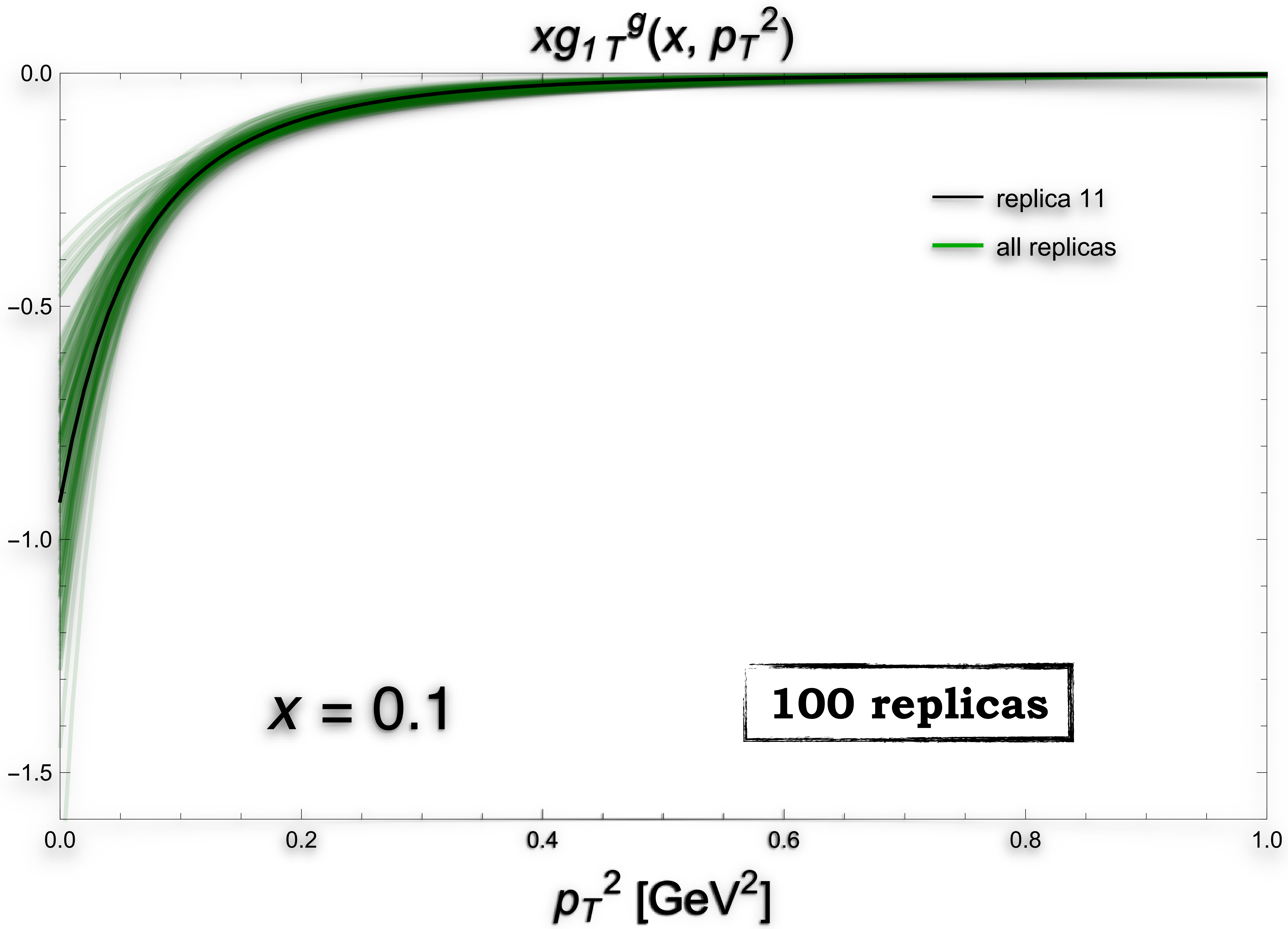
Helicity gluon TMD



100 replicas

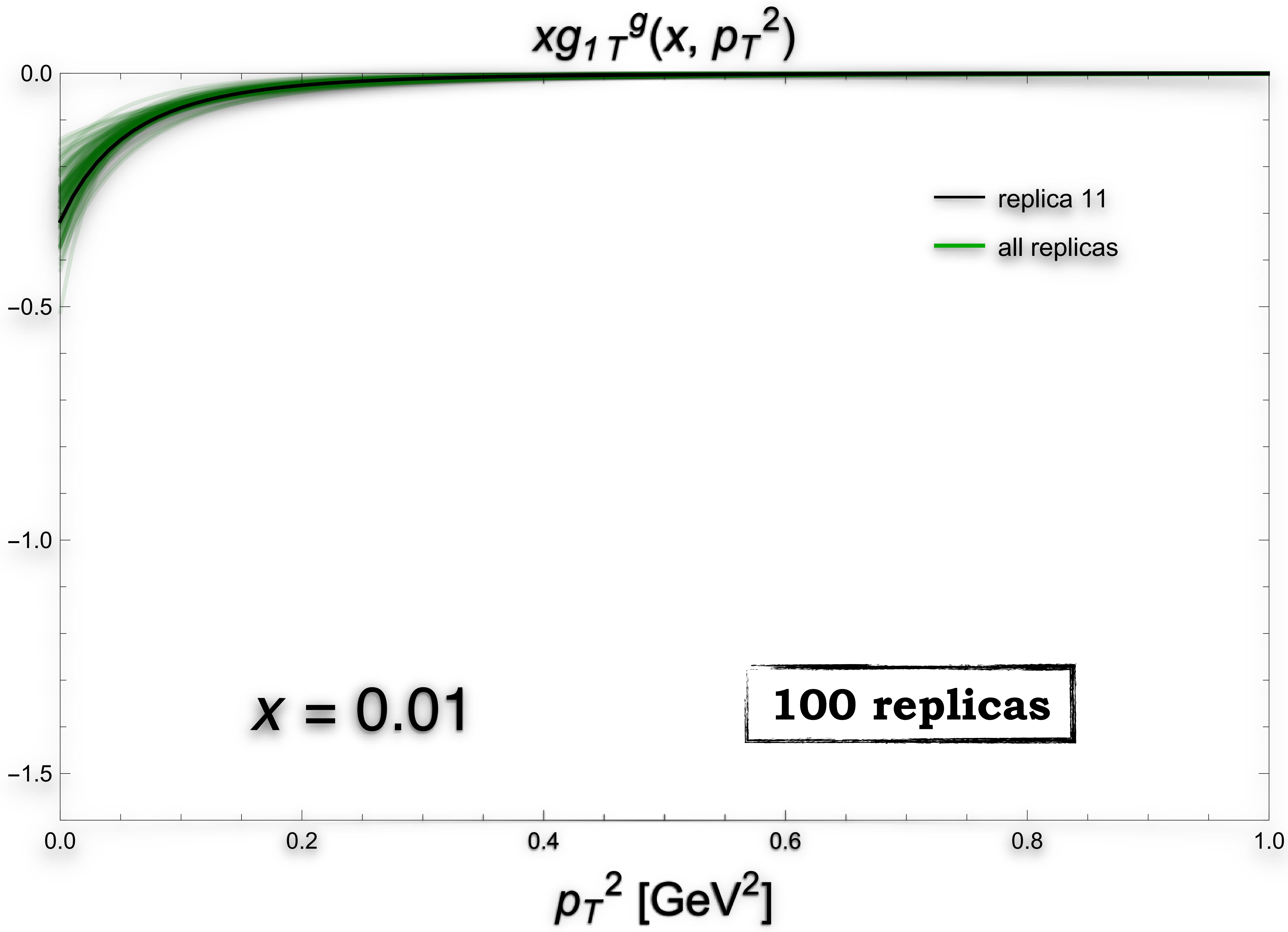
Backup

Worm-gear gluon TMD



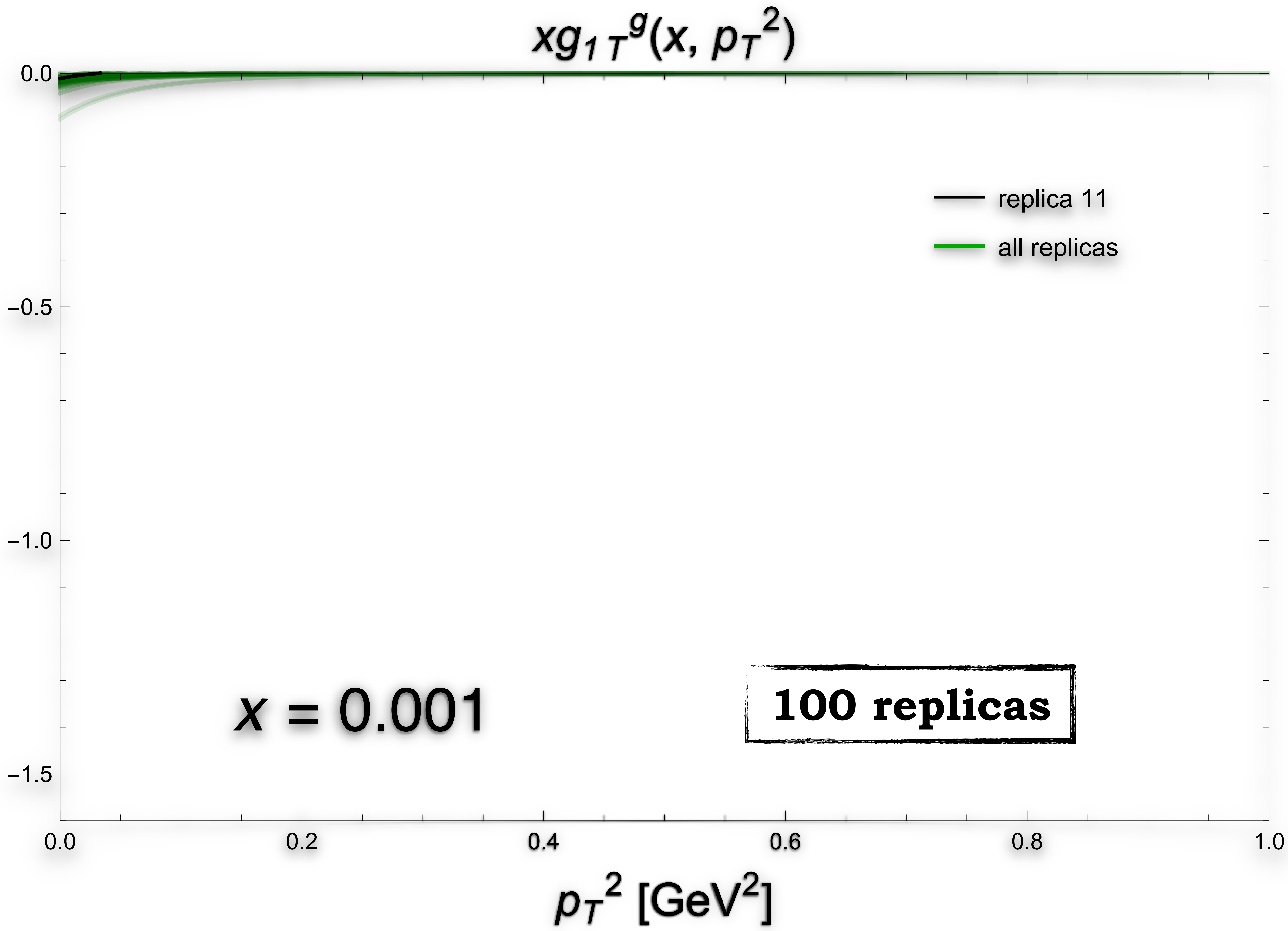
Backup

Worm-gear gluon TMD



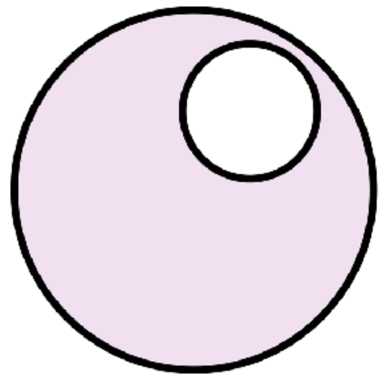
Backup

Worm-gear gluon TMD



Backup

ρ-densities

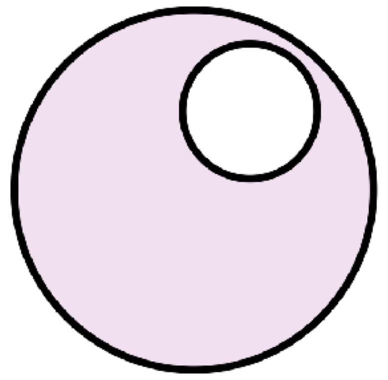


Unpolarized [u/u]

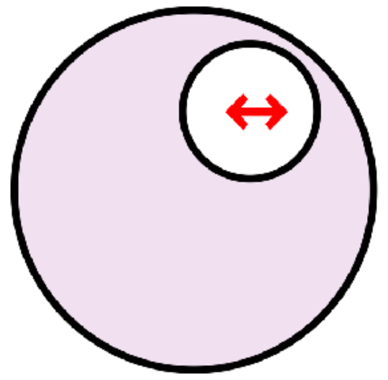
$f_1(x, p_x, p_y)$

Backup

ρ-densities



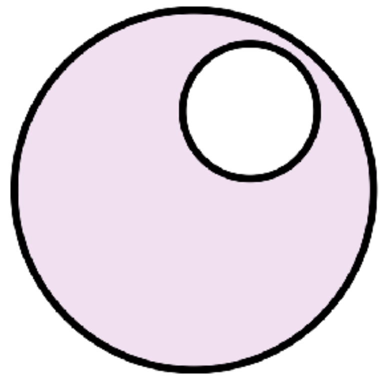
Unpolarized [u/u] $f_1(x, p_x, p_y)$



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



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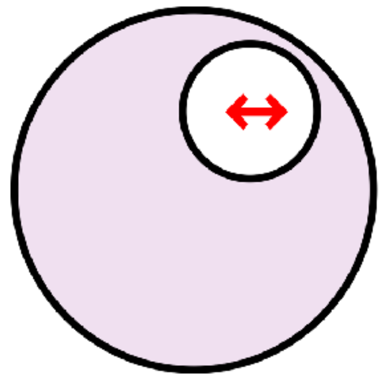

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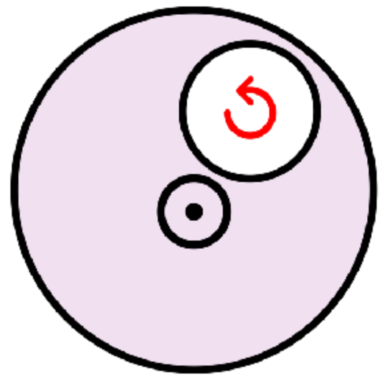
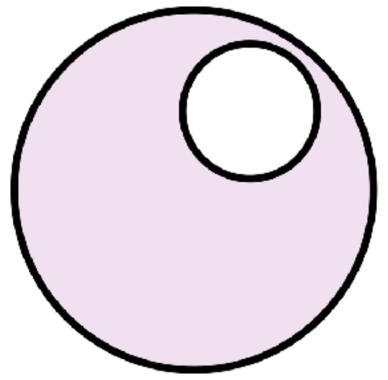


Helicity [↺/+] $\dfrac{1}{2}\left[f_1(x, p_x, p_y) + g_{1L}(x, p_x, p_y)\right]$

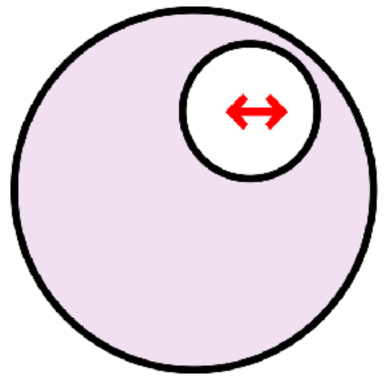
Backup

ρ-densities



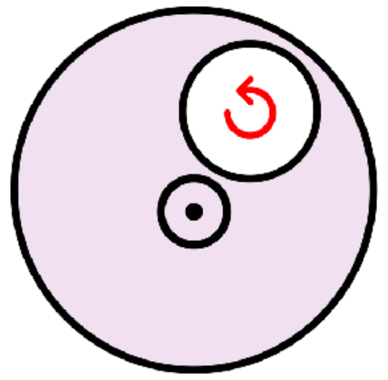
Unpolarized [u/u]

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



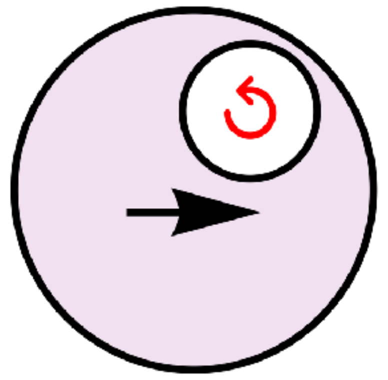
Boer-Mulders [↔/u]

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



Helicity [↺/+]

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

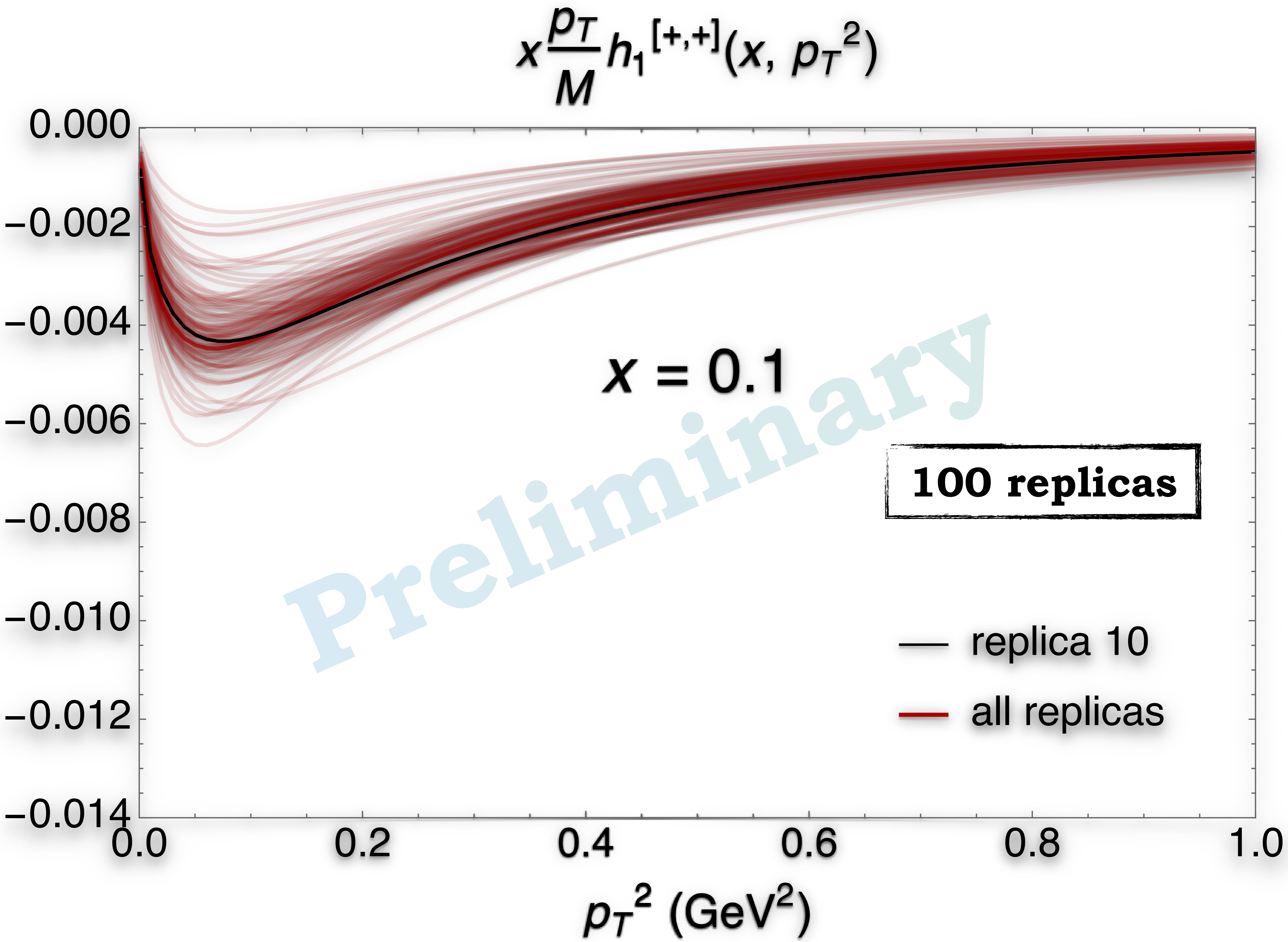


Worm-gear [↺/→]

$$f_1(x, p_x, p_y) - \frac{p_x}{M} g_{1T}(x, p_x, p_y)$$

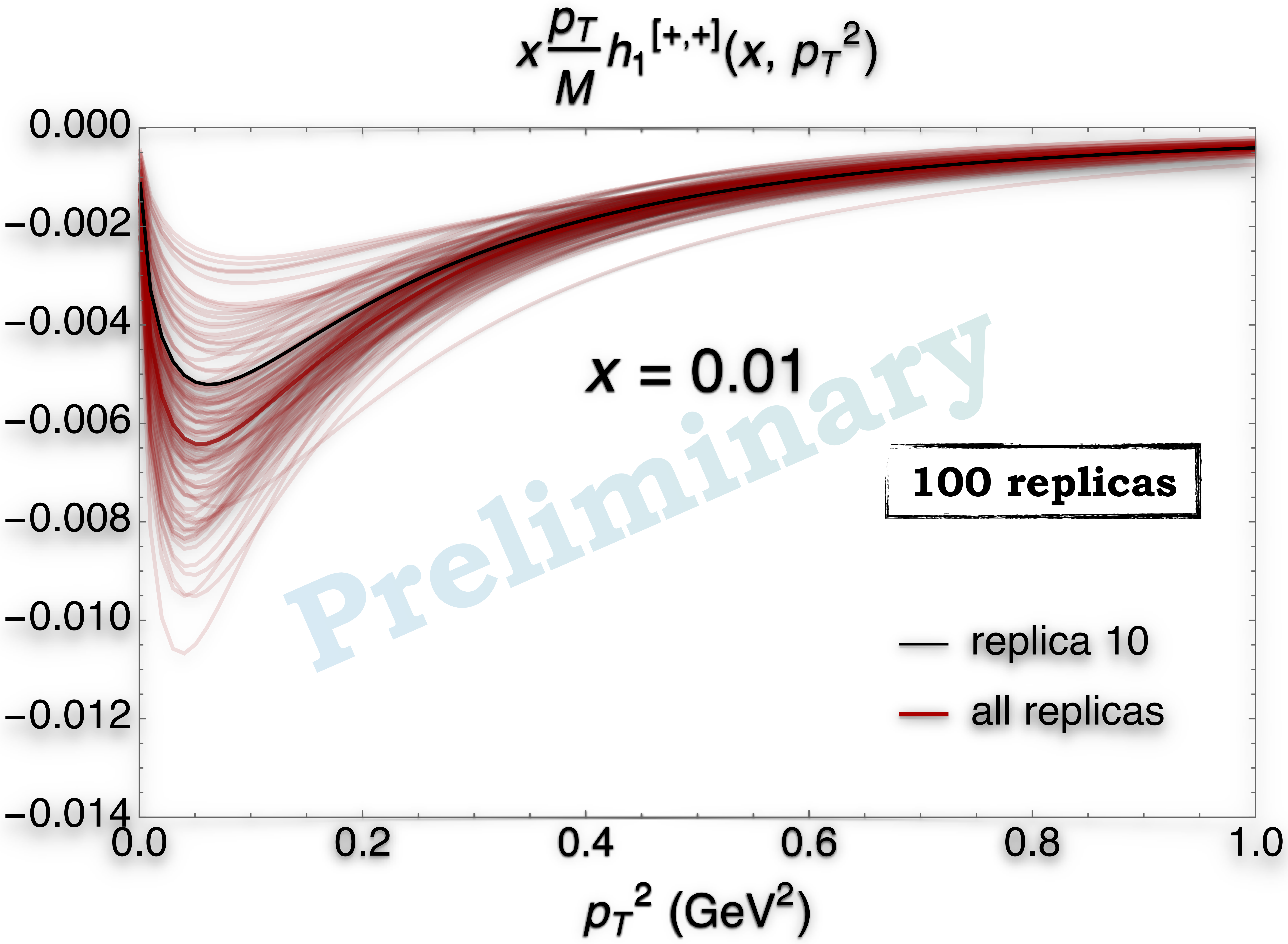
Backup

Linearity gluon TMD



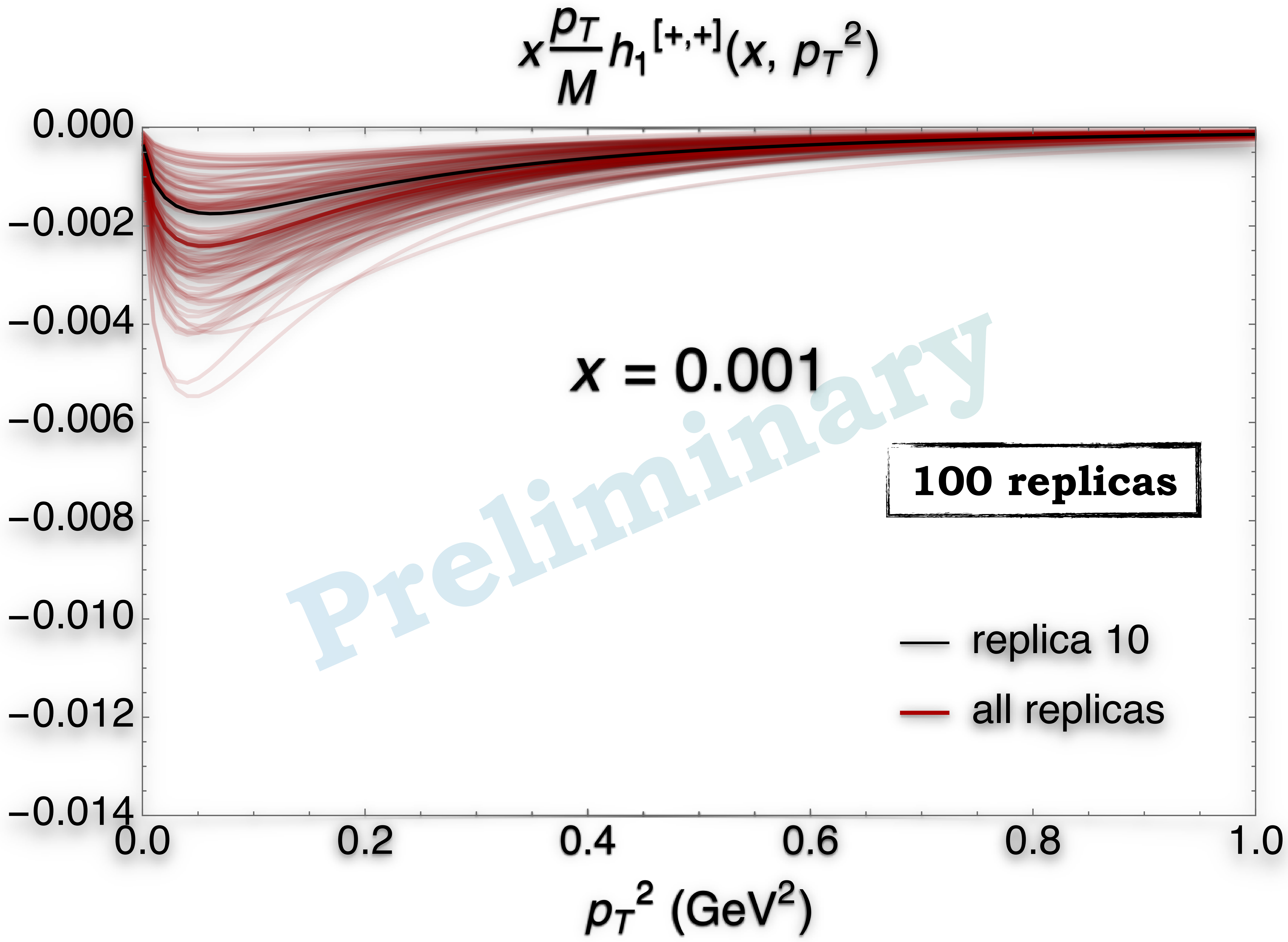
Backup

Linearity gluon TMD



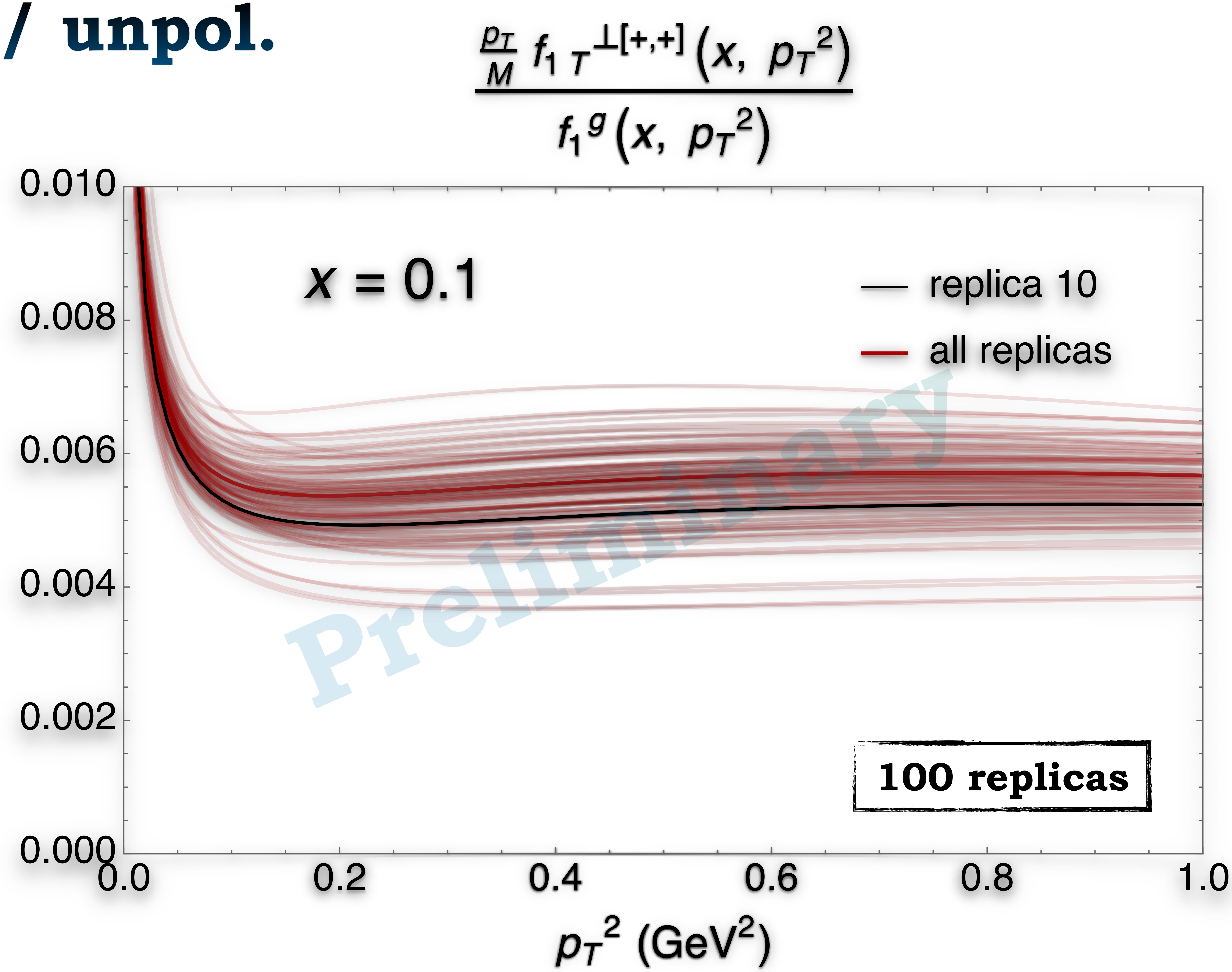
Backup

Linearity gluon TMD



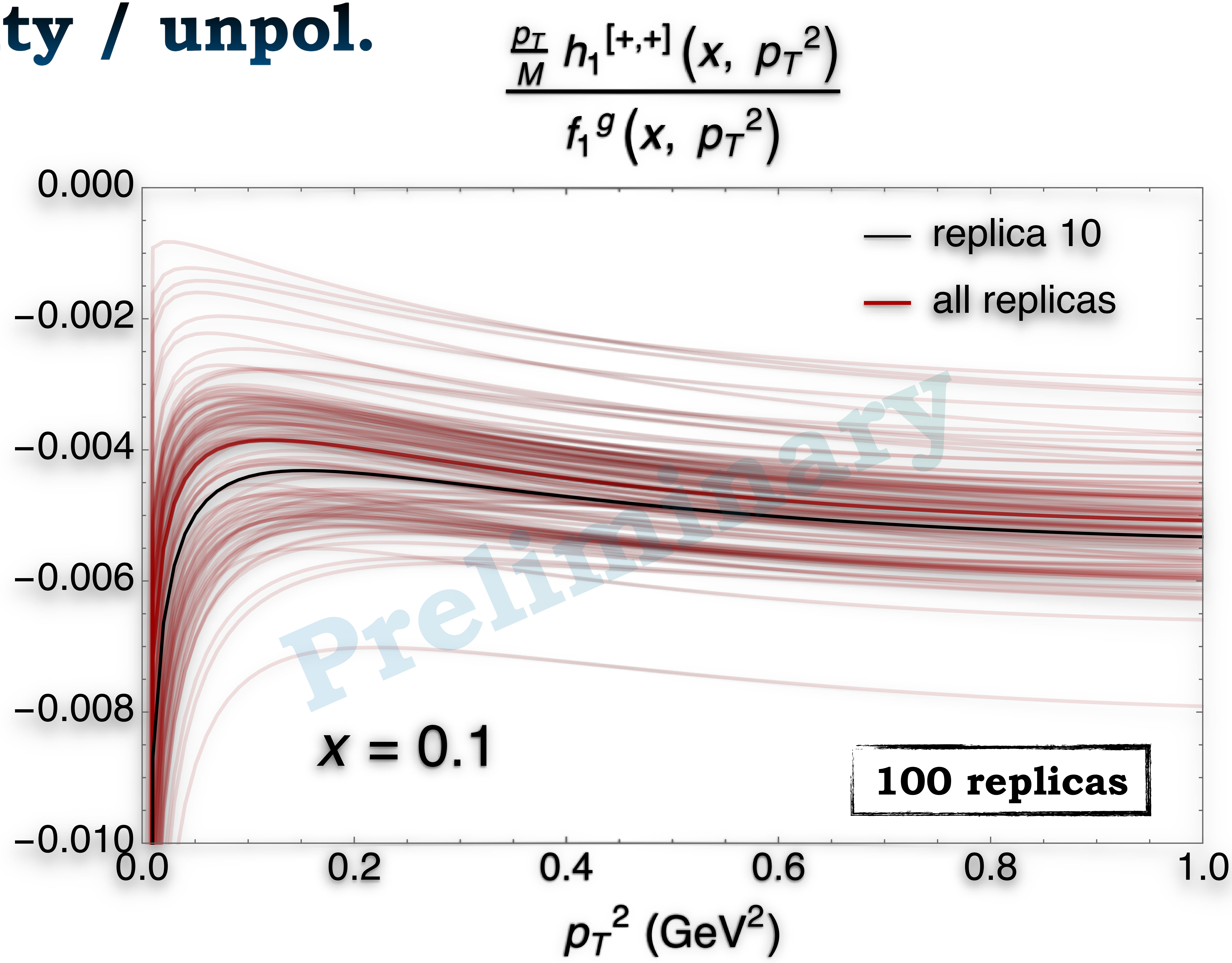
Backup

Sivers / unpol.



Backup

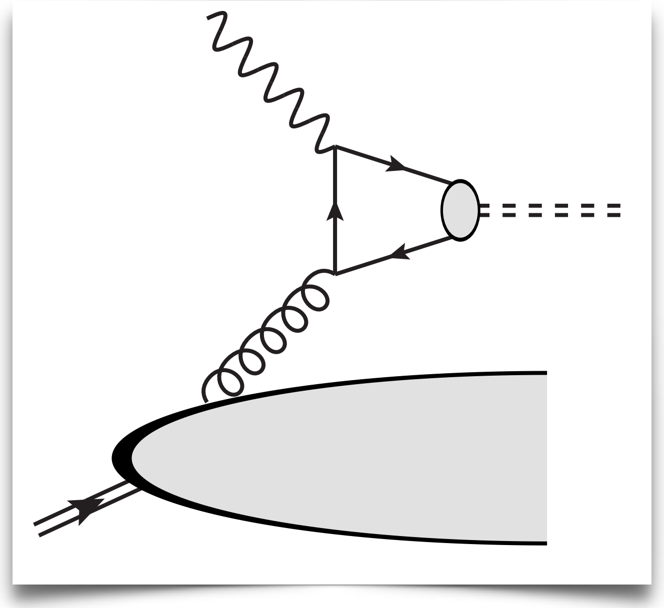
Linearity / unpol.



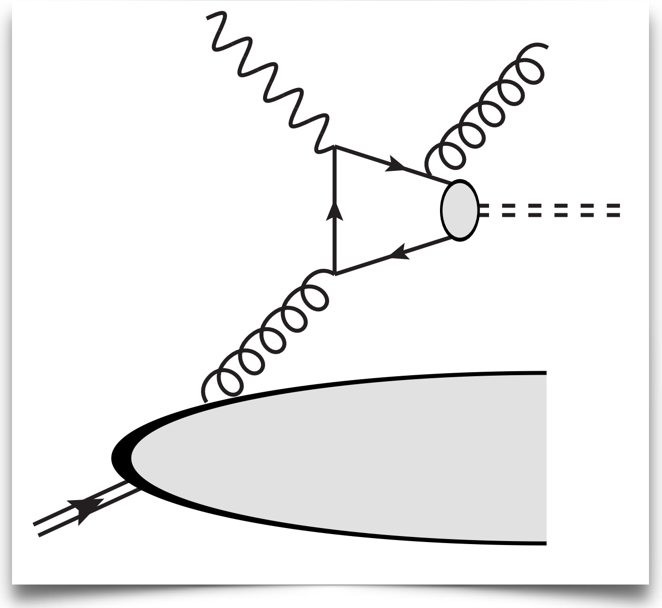
Backup

Hadronic structure and quarkonia

SIDIS



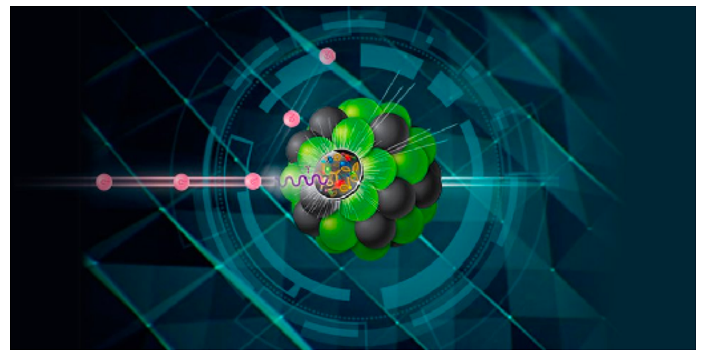
CO

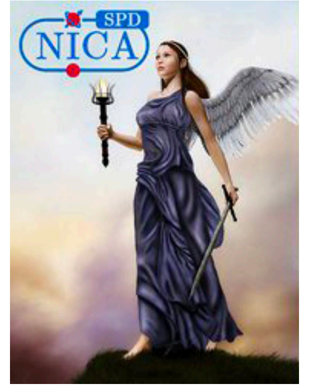


CO + CS

EIC Yellow Report Document
🔗 (EICUG website)

🔗 [EICUG [arXiv:2103.05419]]

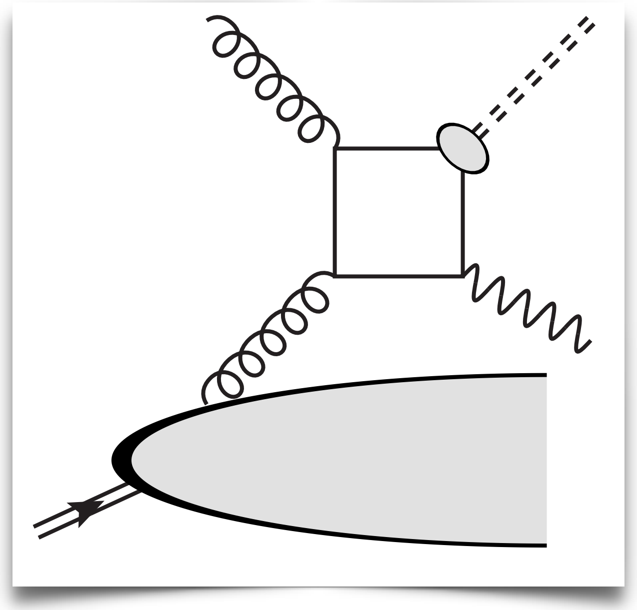




On the physics potential to study the gluon content of proton and deuteron at NICA SPD

🔗 [NICA Collaboration [arXiv:2011.15005]]

Hadroproduction



CO + CS

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

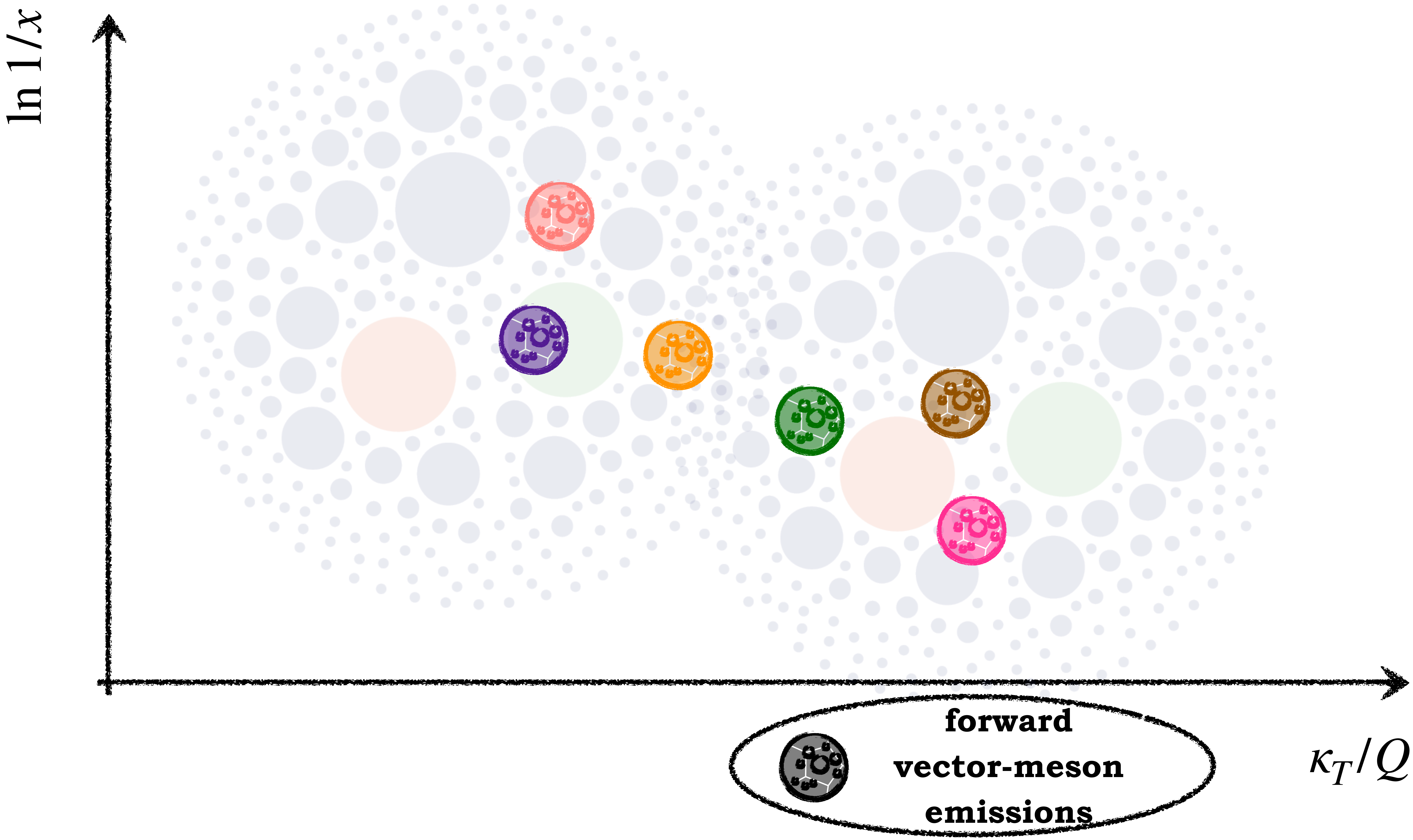
🔗 [Quarkonia As Tools Collaboration [arXiv:2012.14161]]

Backup

Hadronic structure and vector mesons

Backup

Hadronic structure and vector mesons

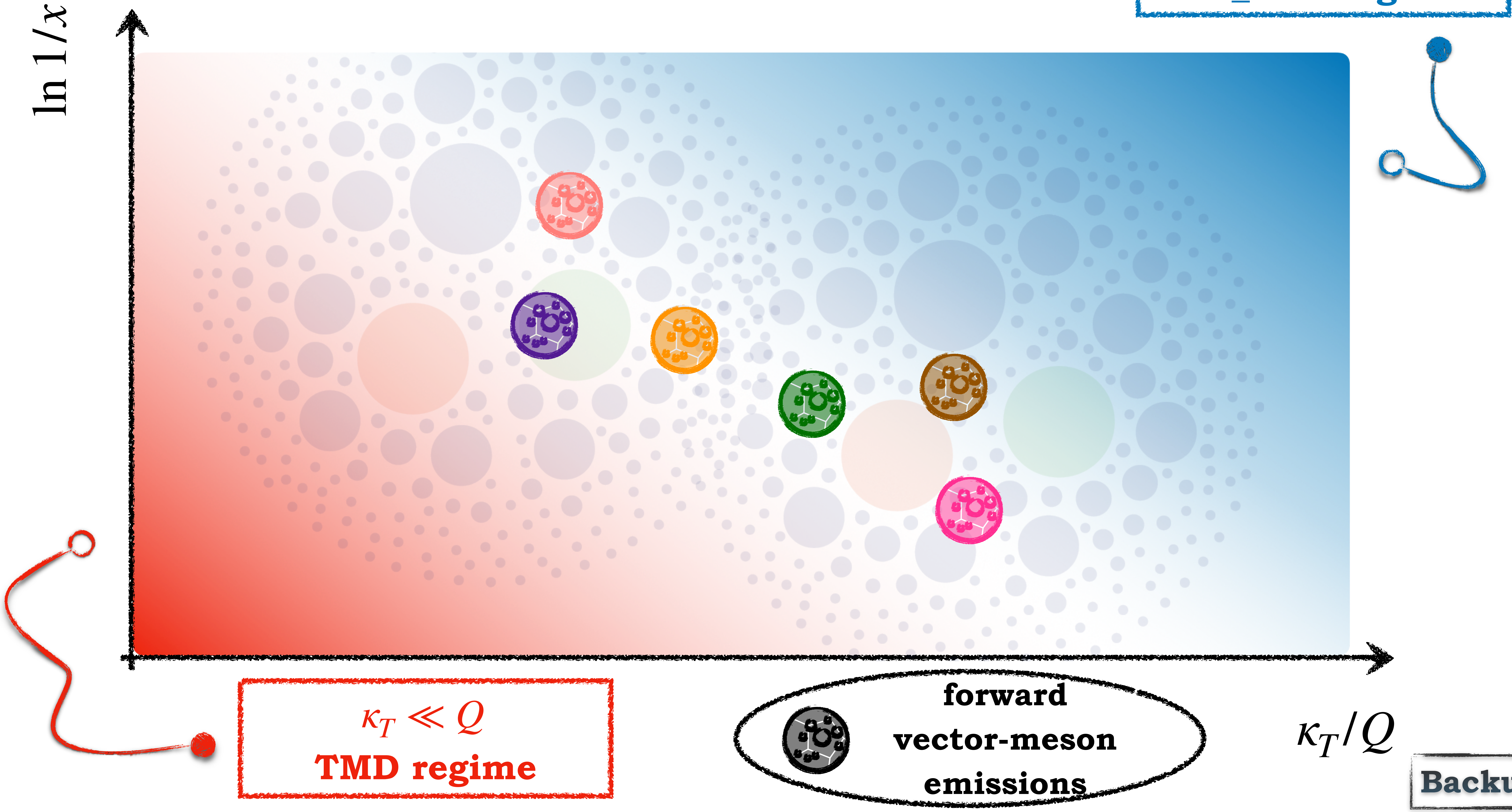


Backup

Hadronic structure and vector mesons

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

AT_HEF regime



$\kappa_T \ll Q$

TMD regime

forward vector-meson emissions

Backup