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Unveiling the proton structure via TMD gluon distributions

Francesco Giovanni Celiberto

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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

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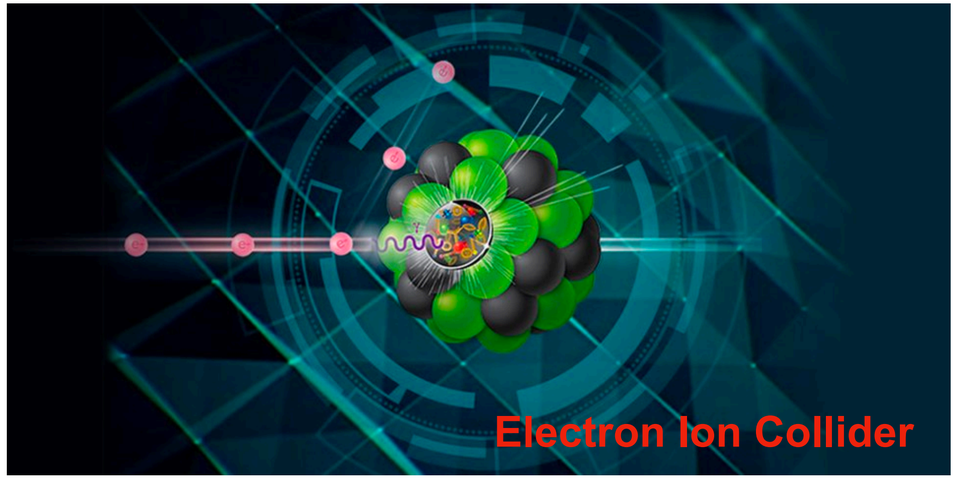

Motivation

- 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

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

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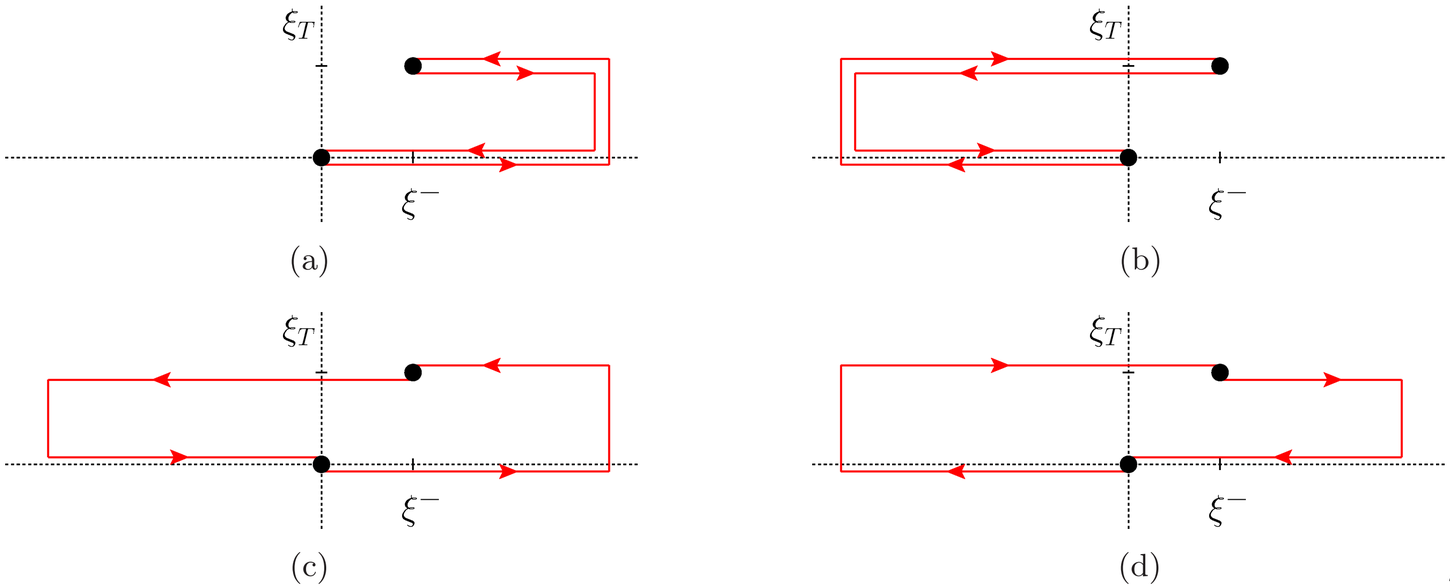

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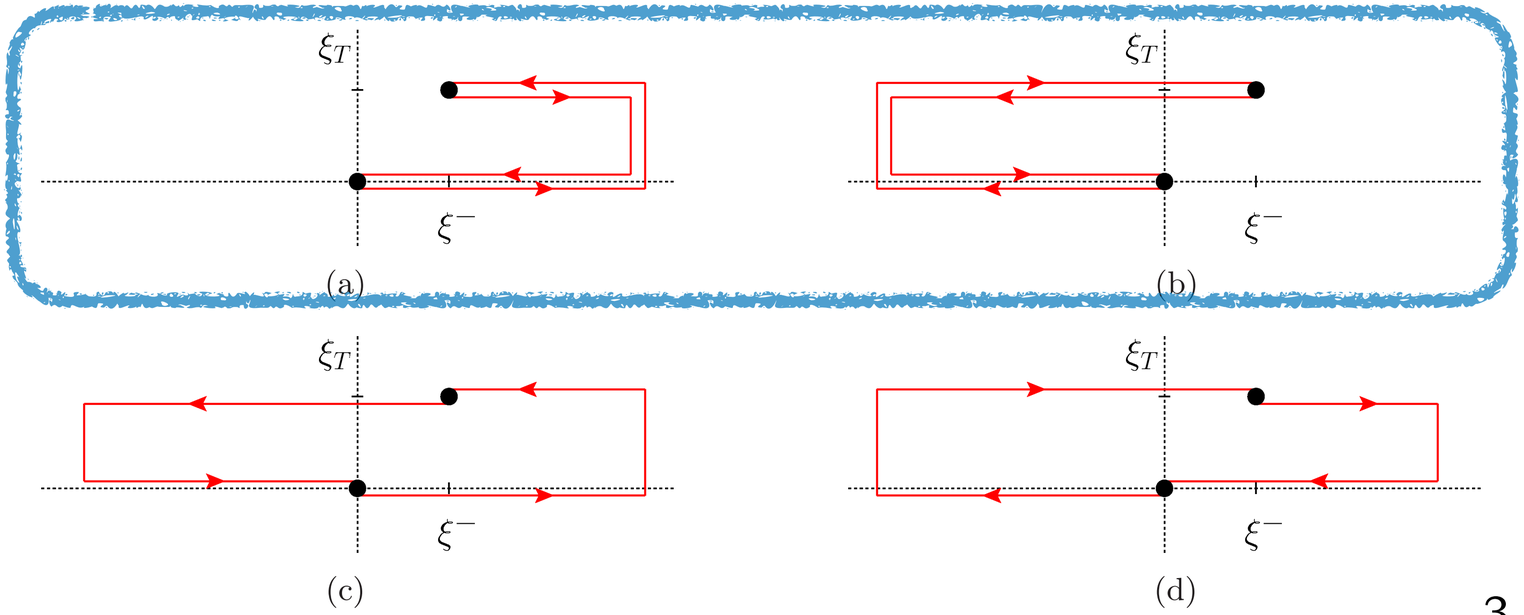
Weiszäcker-Williams (WW)

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



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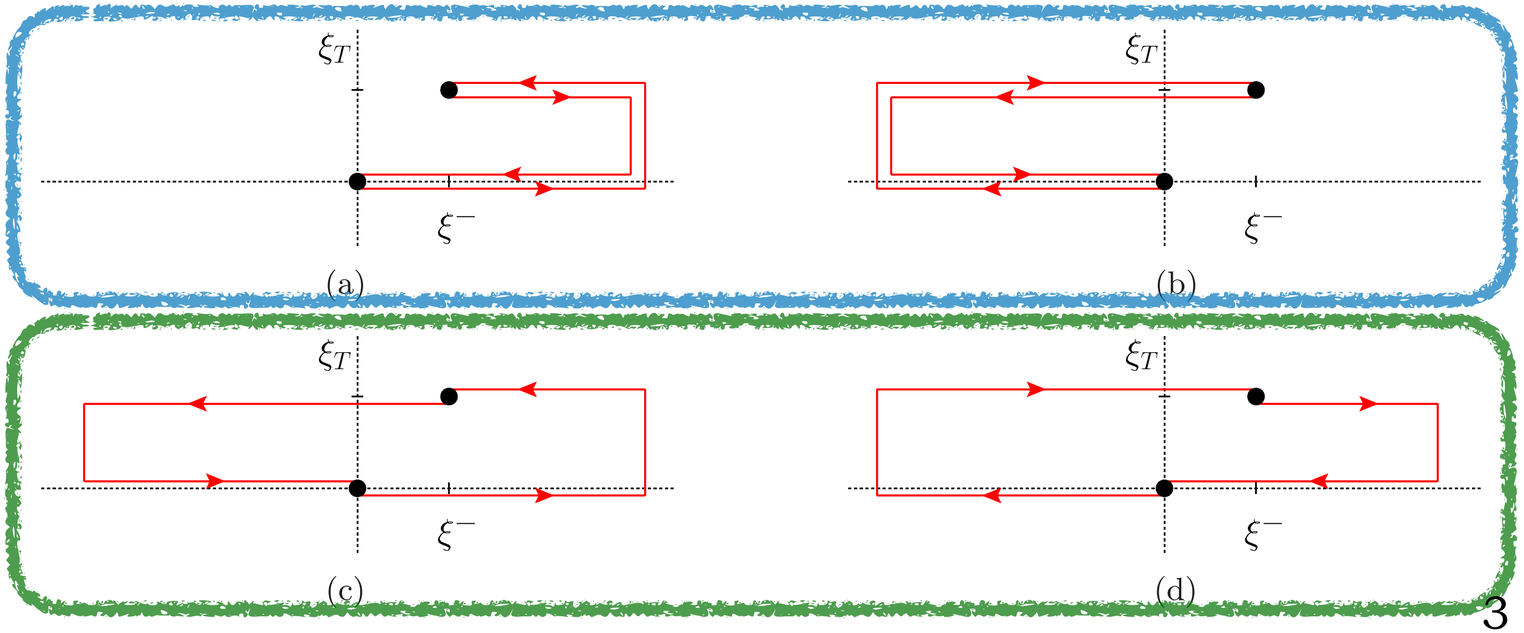
Dipole (DP)

(c) [+ , −] or (d) [− , +]



Accessing WW and DP gluon TMDs

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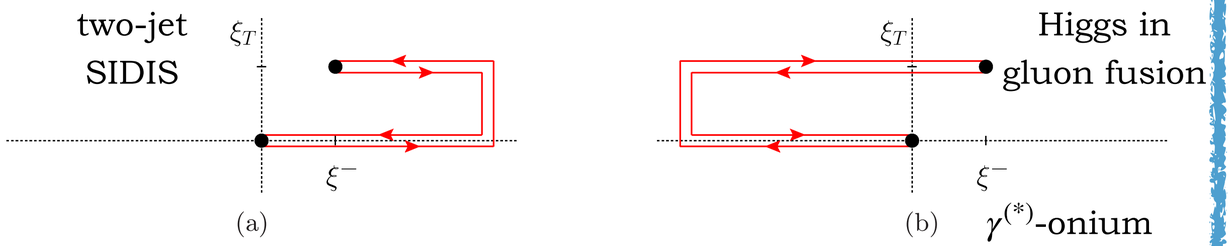

* Color flow annihilated within final/initial state
* f-type gluon TMDs $\rightarrow$ f^{abc} color structure
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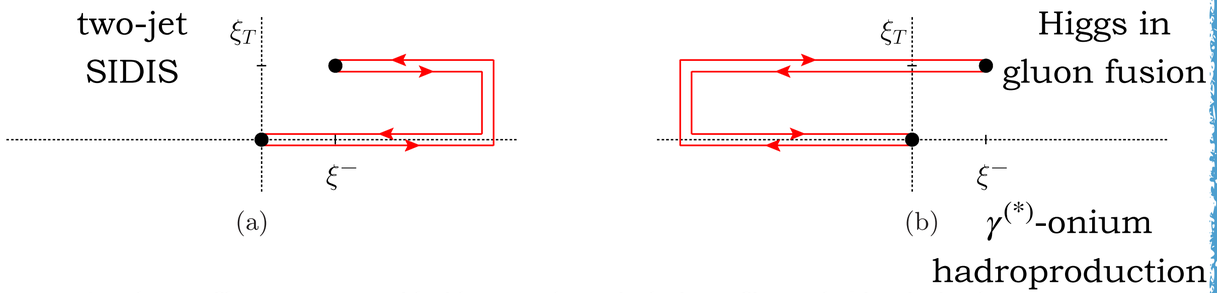

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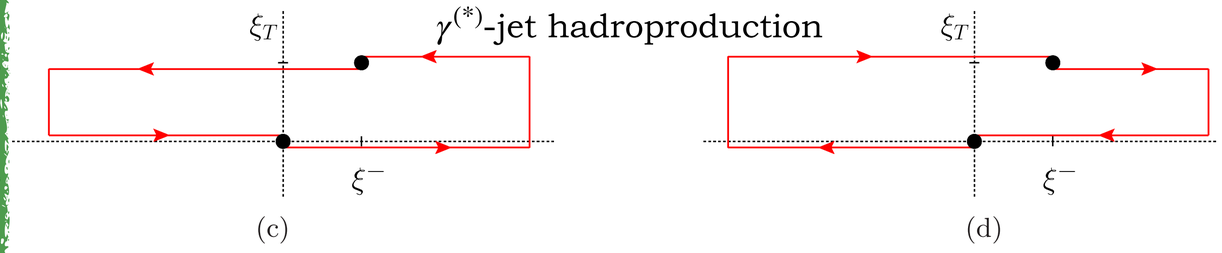

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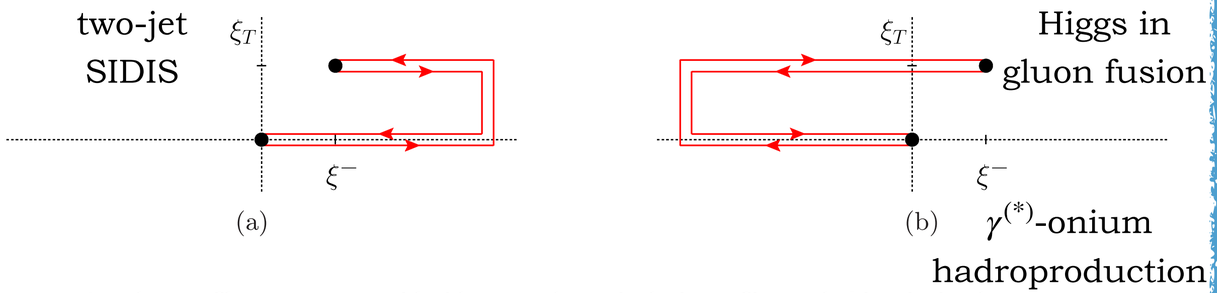

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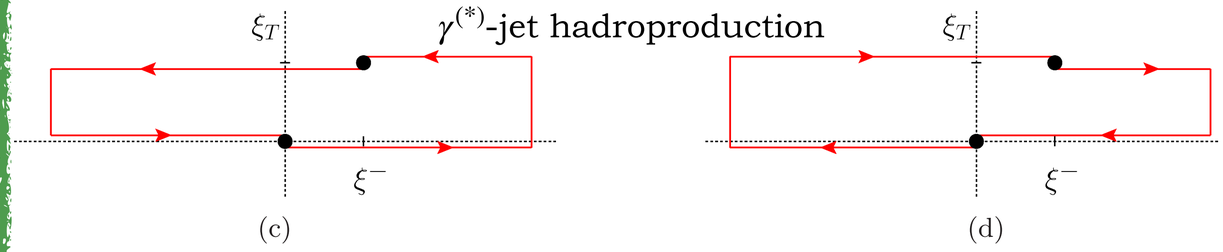

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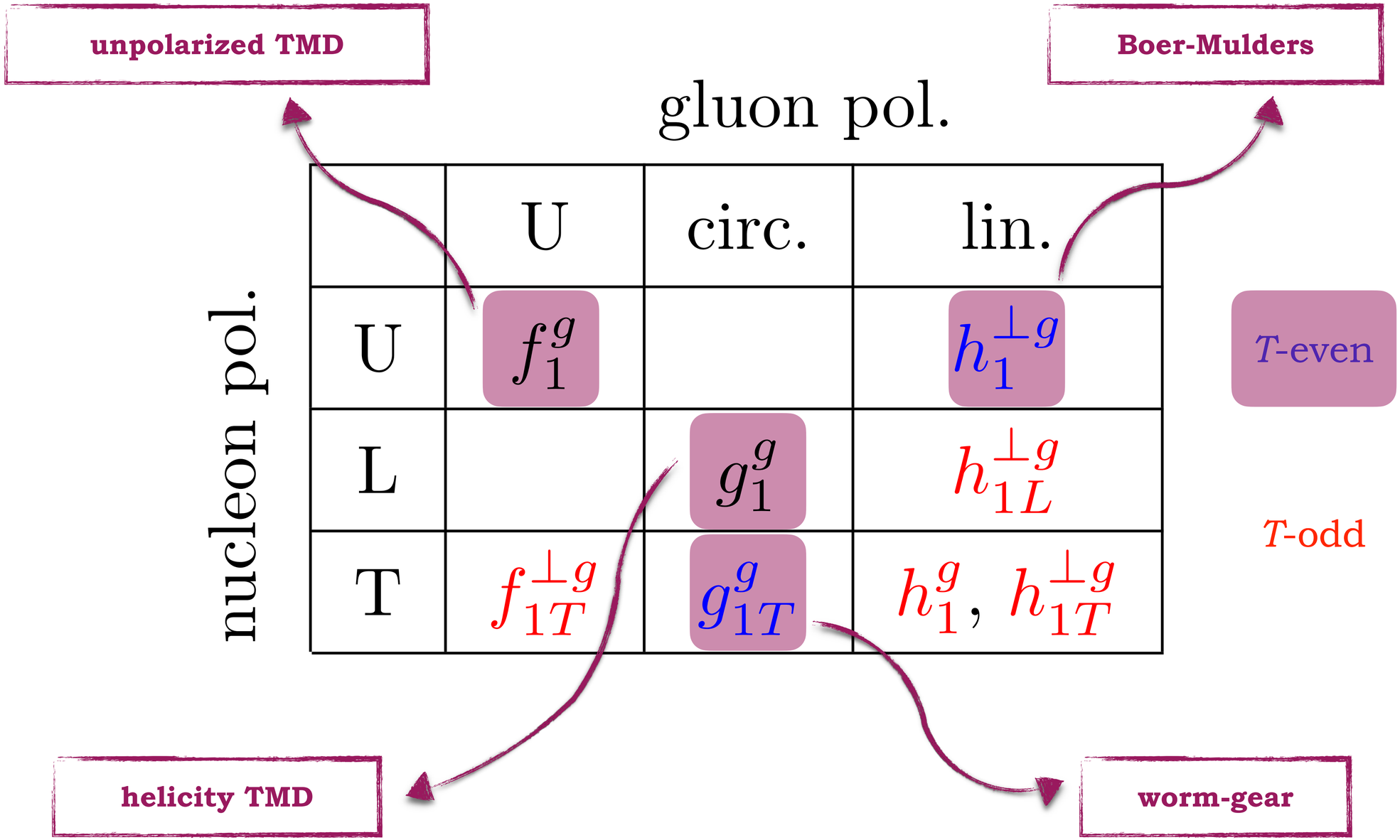
Gauge link → two main independent sets of TMDs, **not related** to each other

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

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

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



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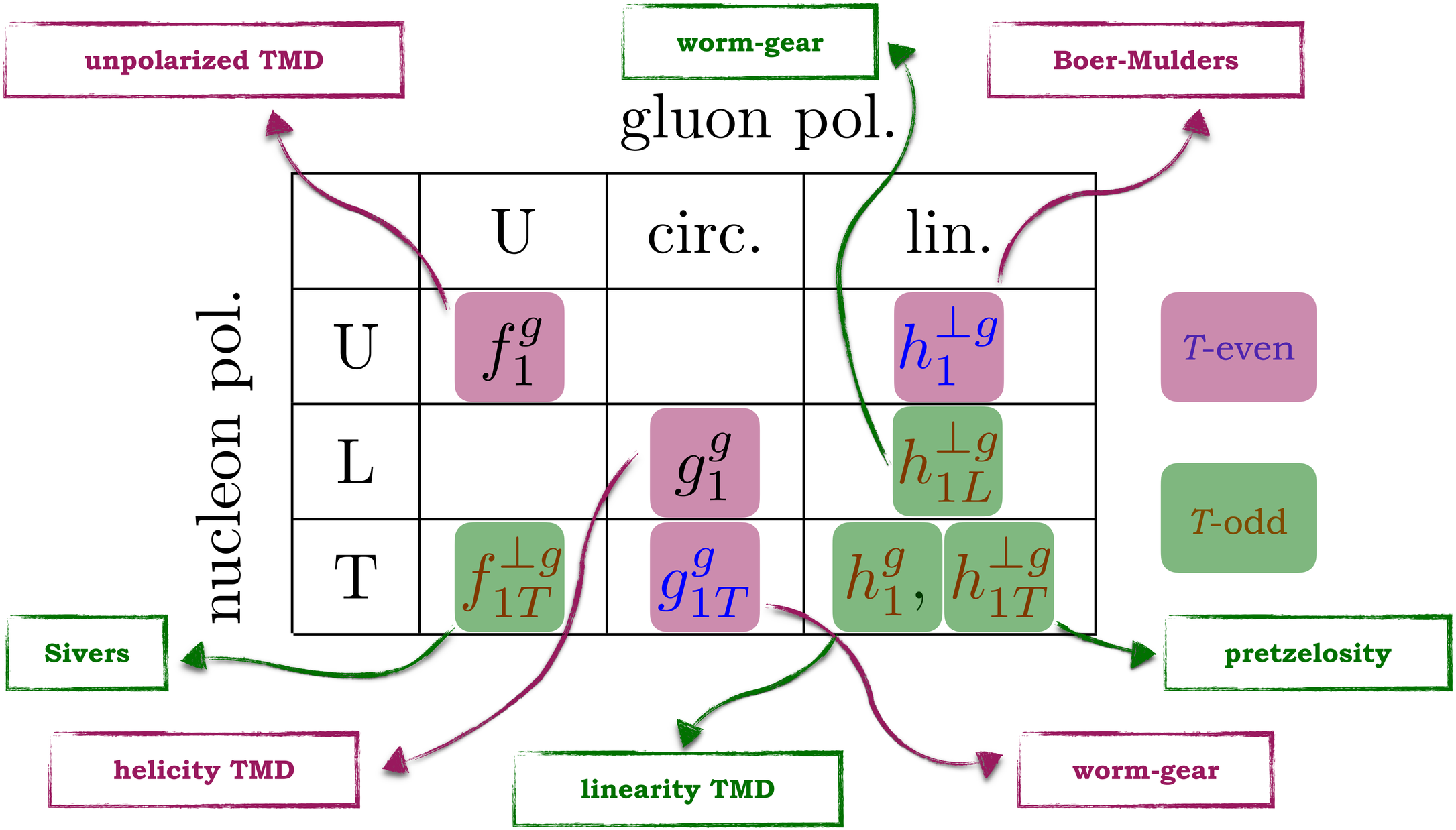
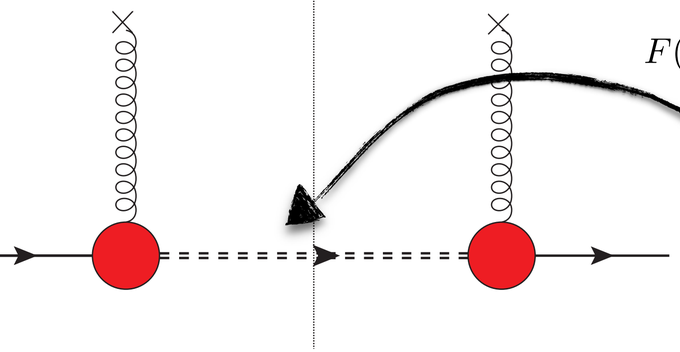


Our model at a glance

Spectator-system spectral-mass function



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

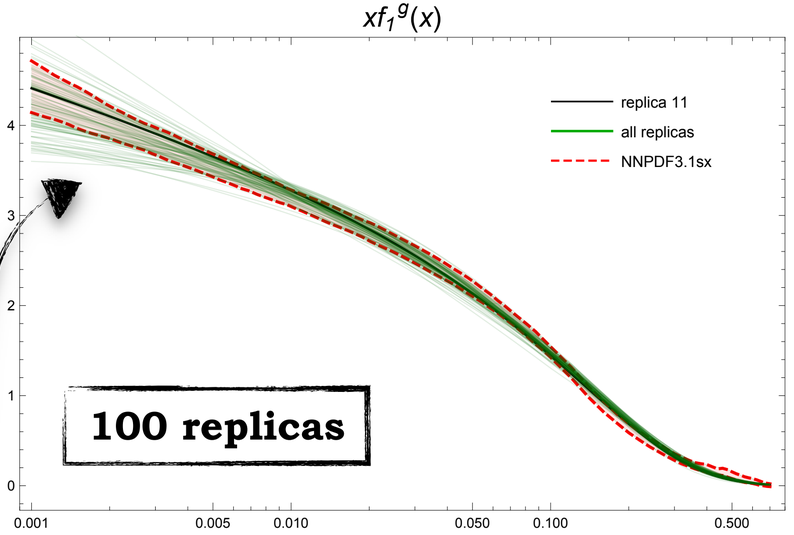
Instead of a single on-shell spectator, a continuum of spectators

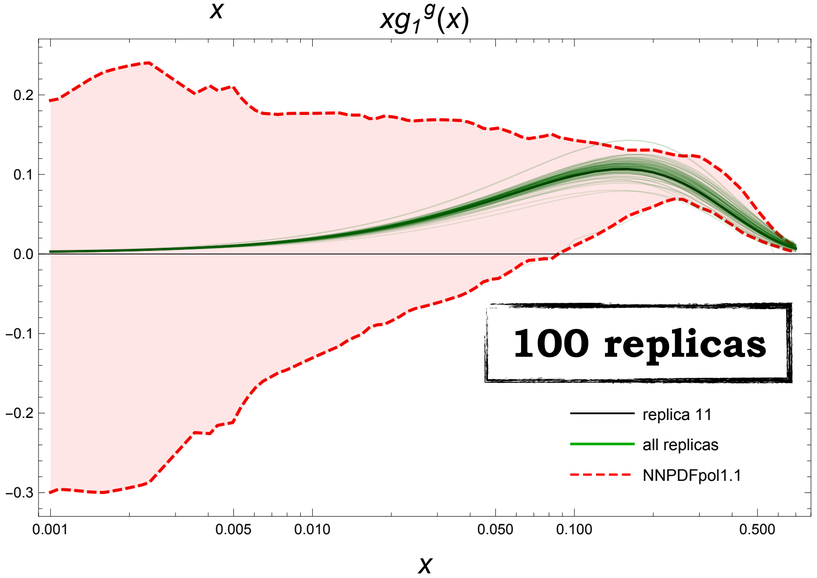
Spectral function **learns** small- and moderate-x info encoded in **NNPDF** collinear parametrizations (`NNPDF3.1sx + NNPDFpol1.1`)

- ☑ **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

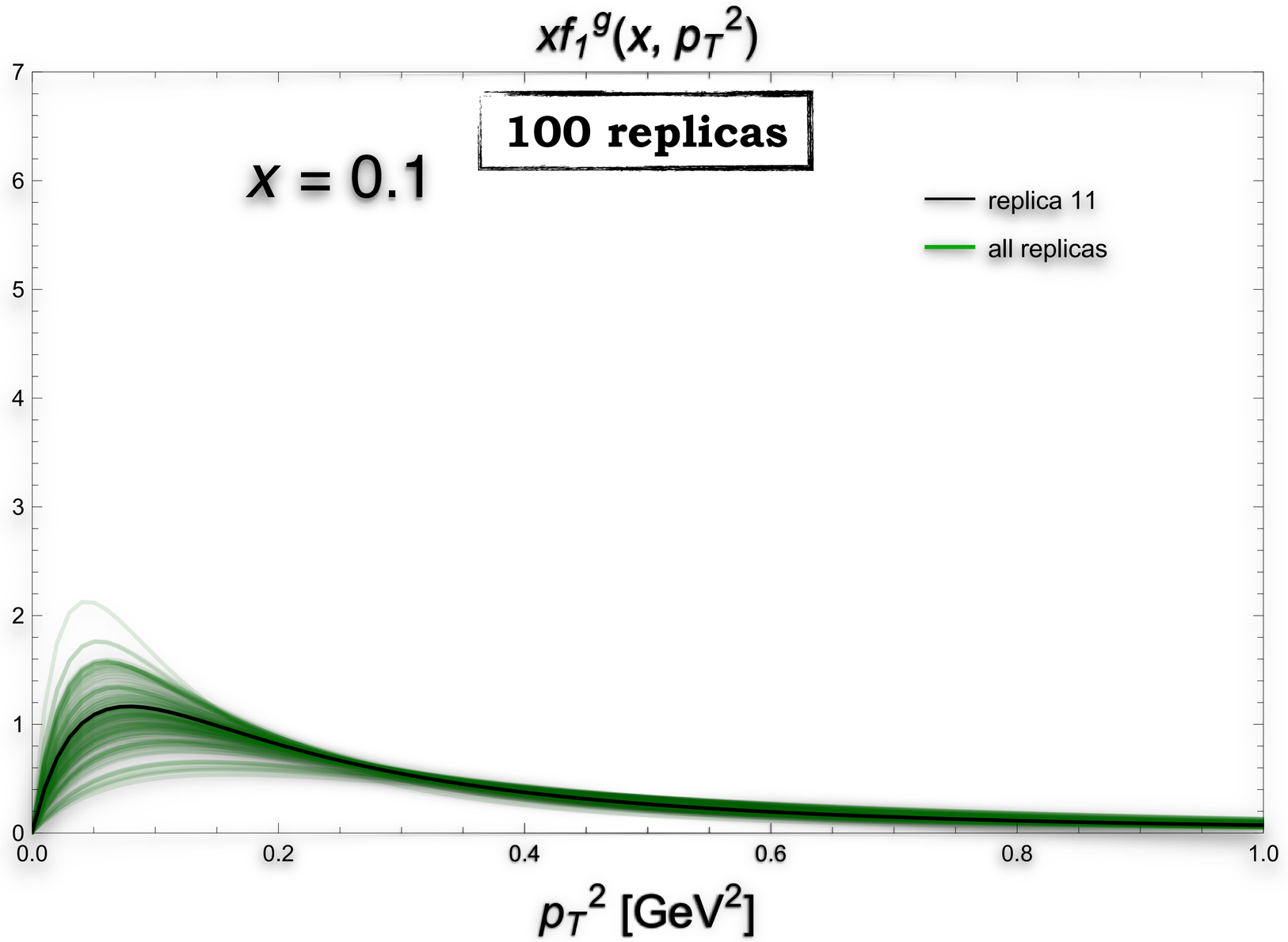
Link with collinear factorization

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





Unpolarized gluon TMD



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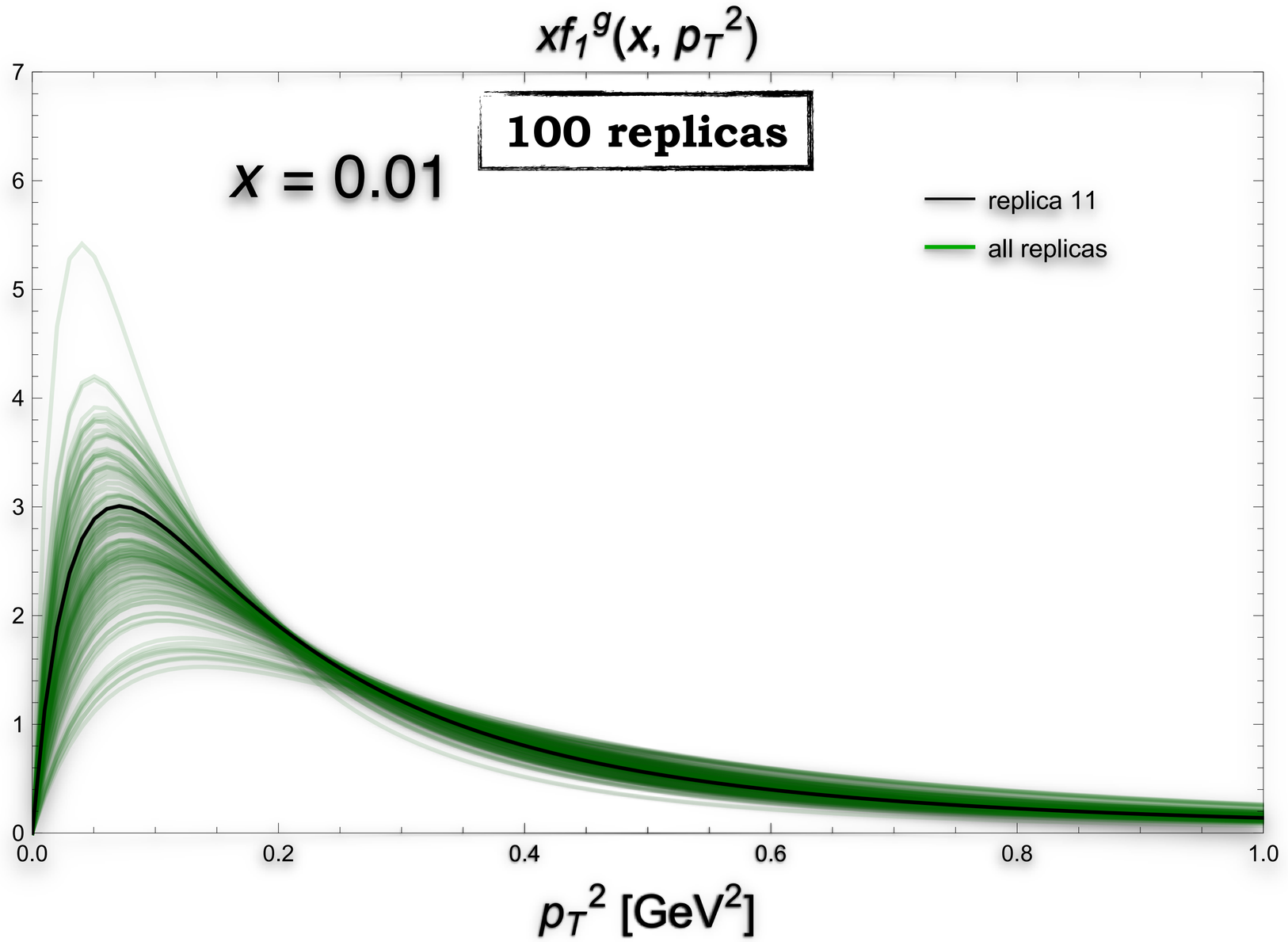

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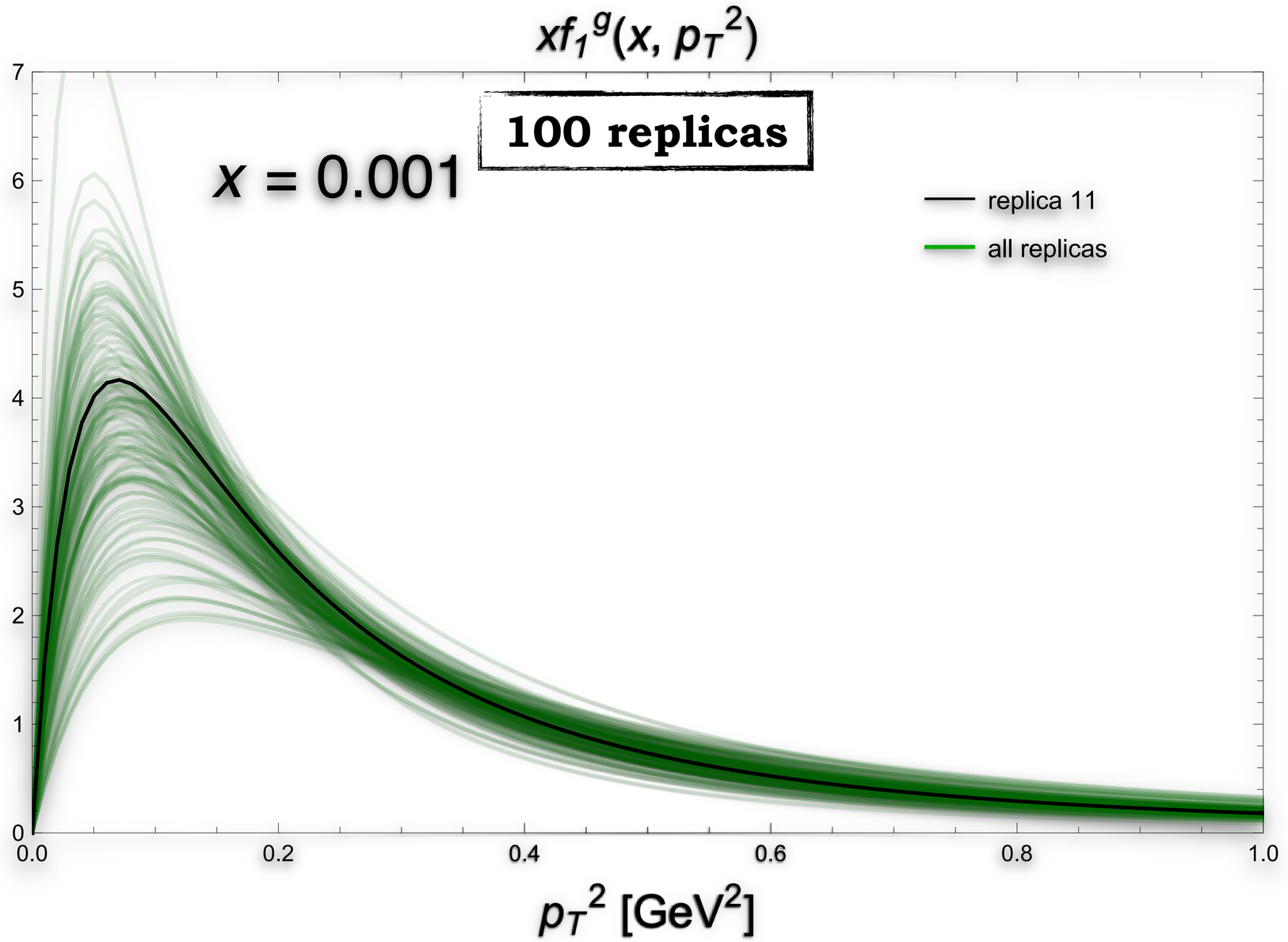
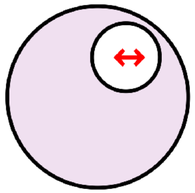
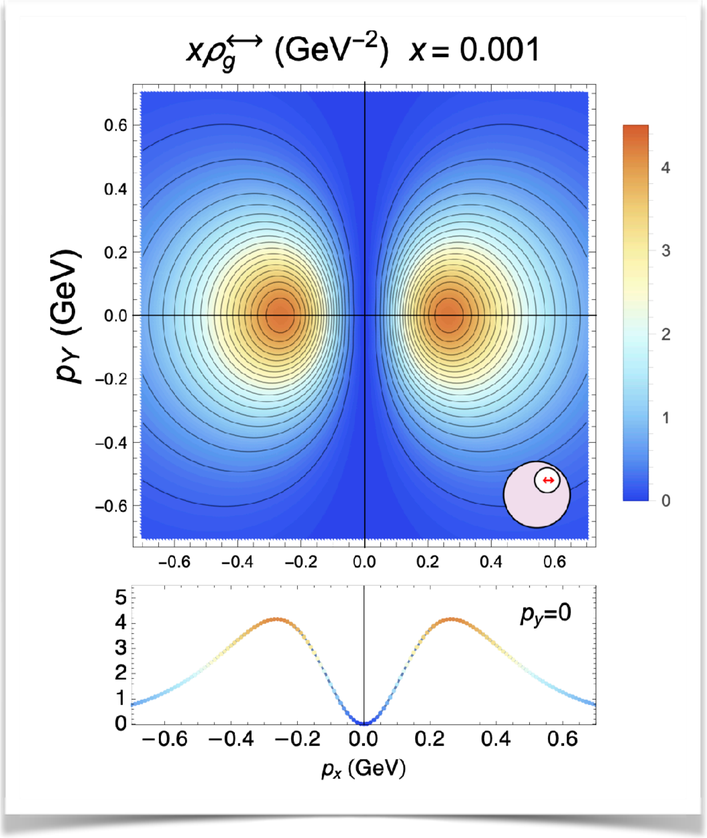


Boer-Mulders effect in unpolarized *pp* collisions



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

unpol. Boer-Mulders



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

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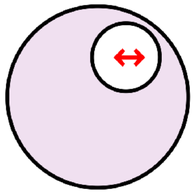

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(Pseudo)scalar Higgs p_T-distribution

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

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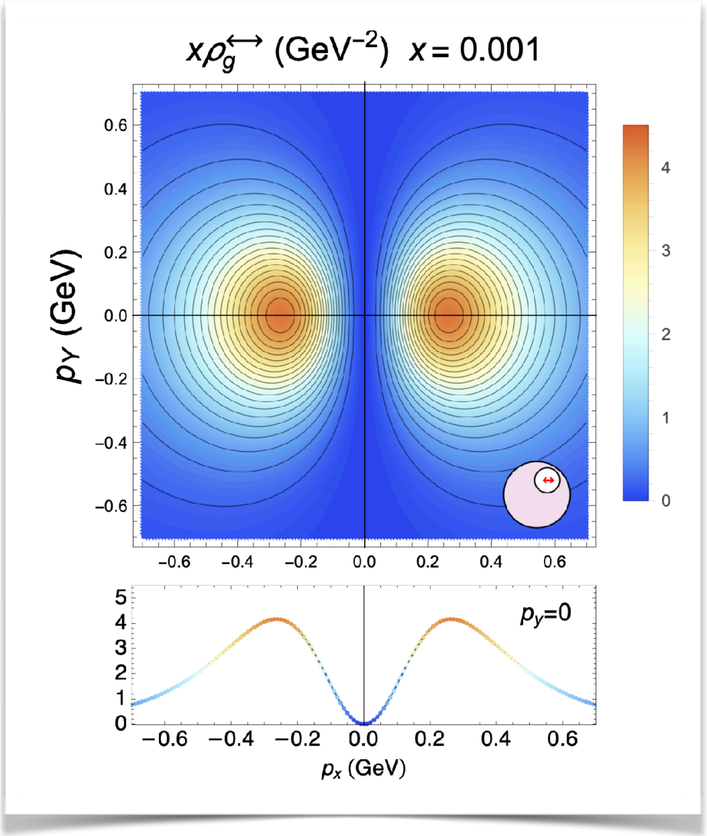
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]



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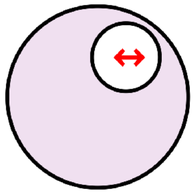

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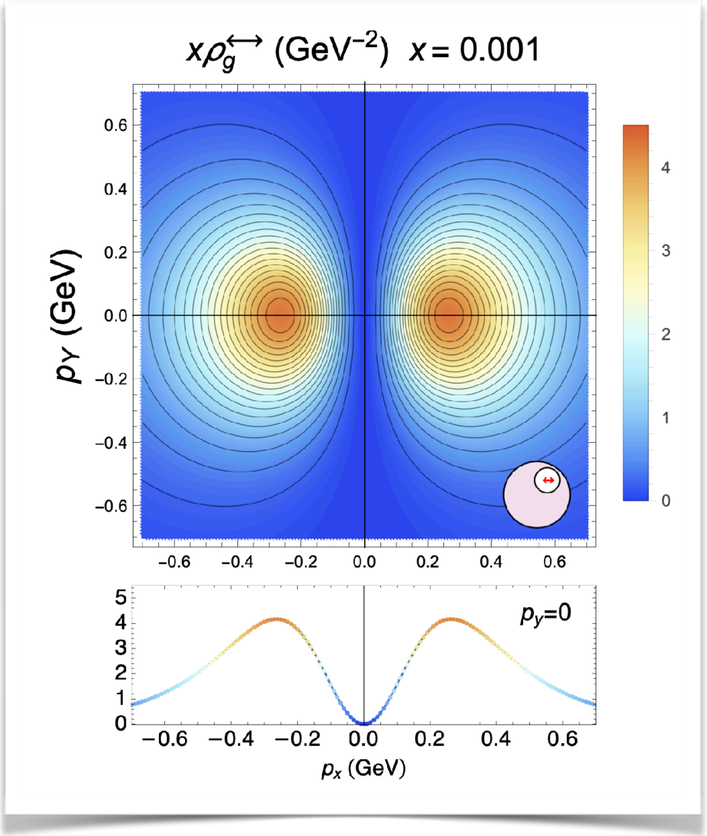
Model prediction at low-x

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



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…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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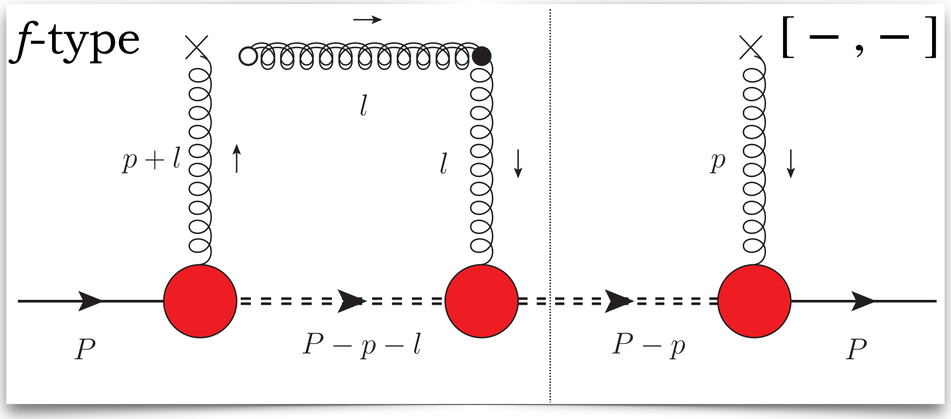
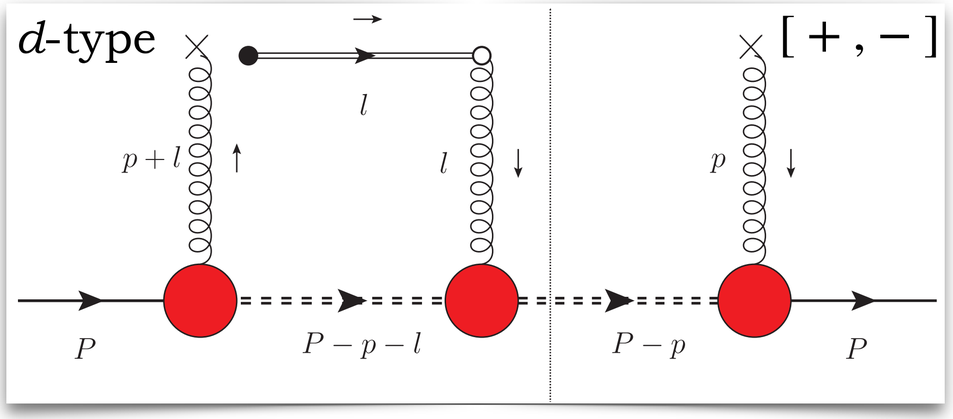
$gg \to H$

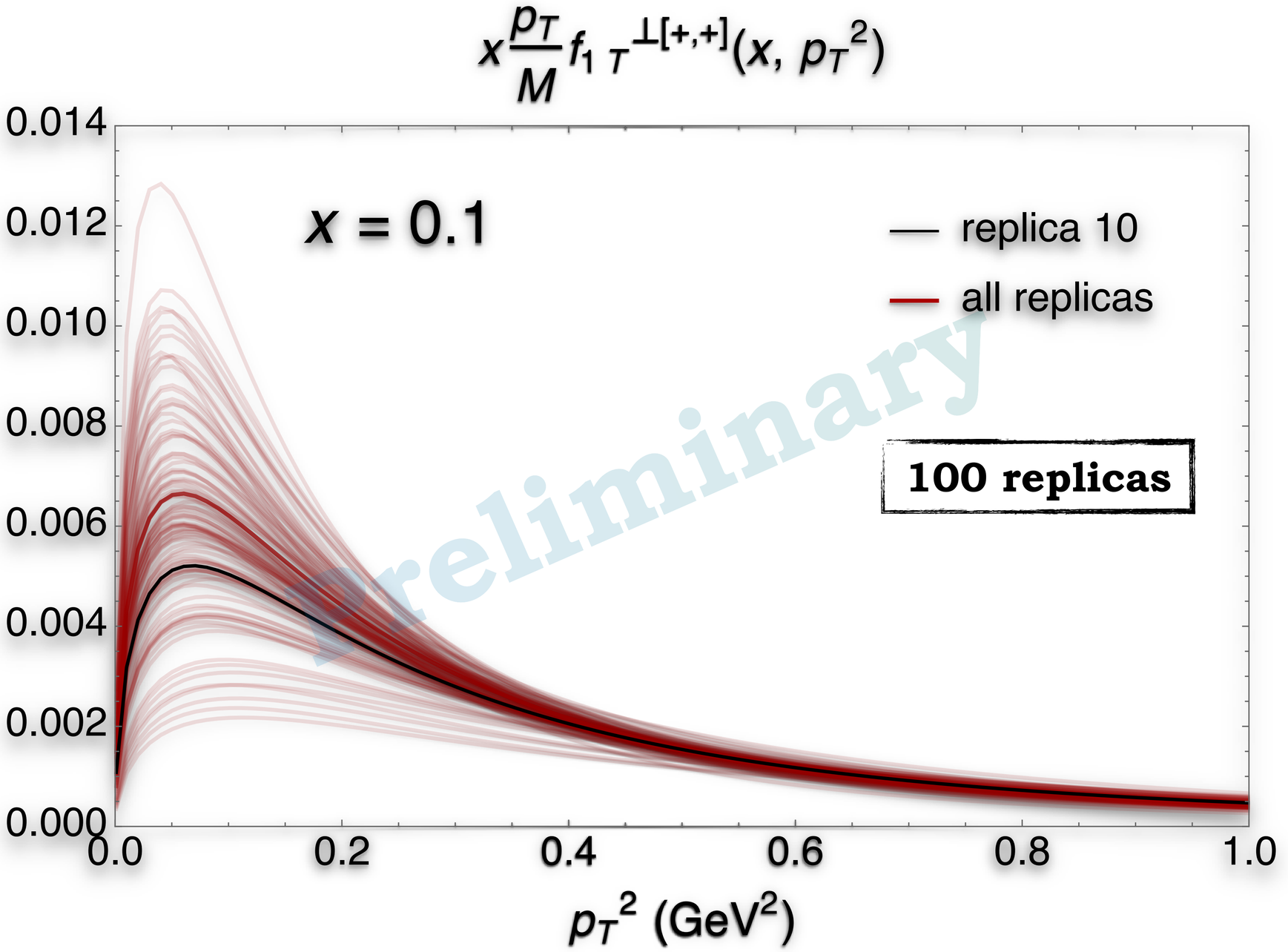


$qg \to \gamma^{(*)}$-jet



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

Sivers gluon TMD



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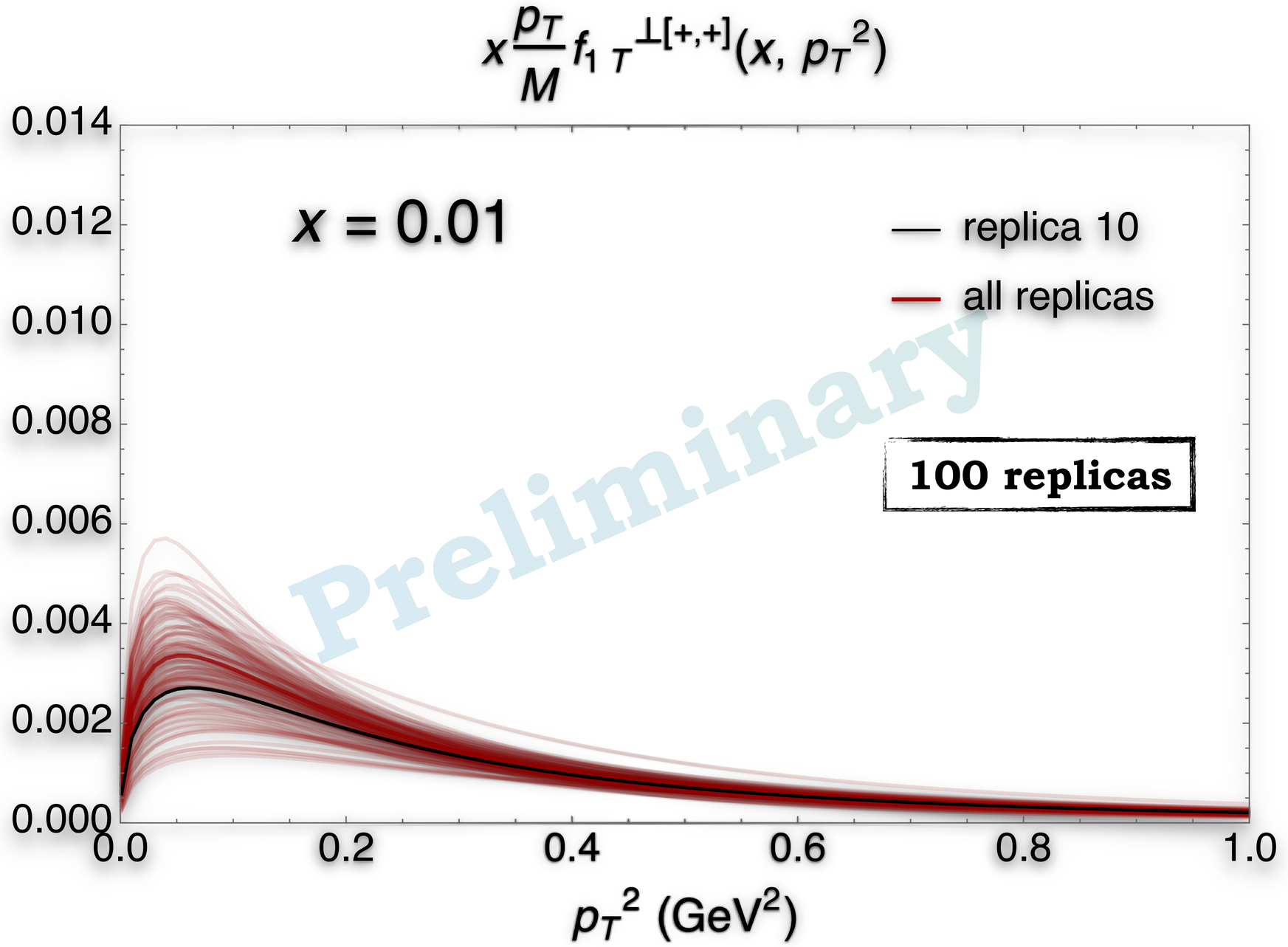

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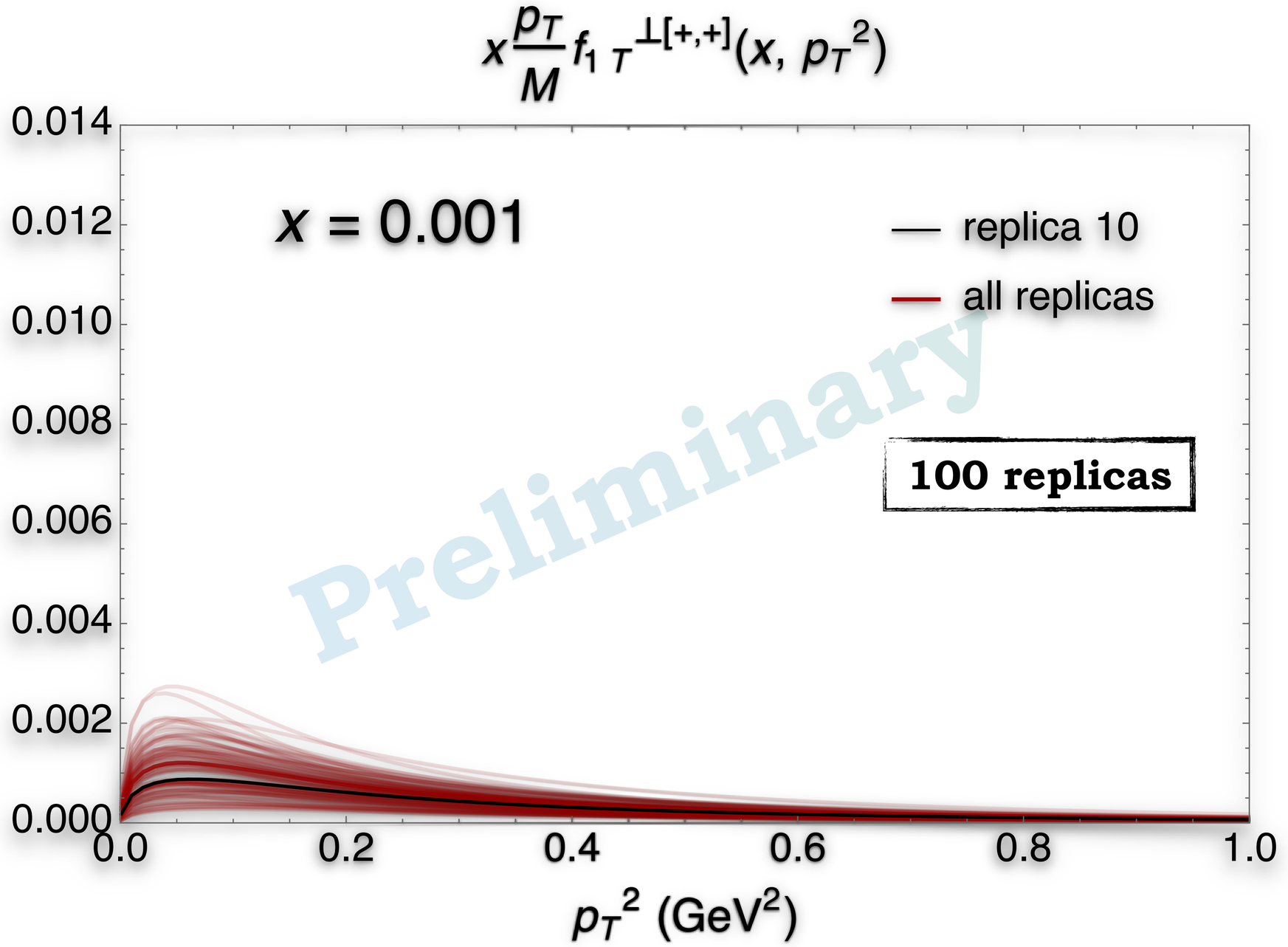
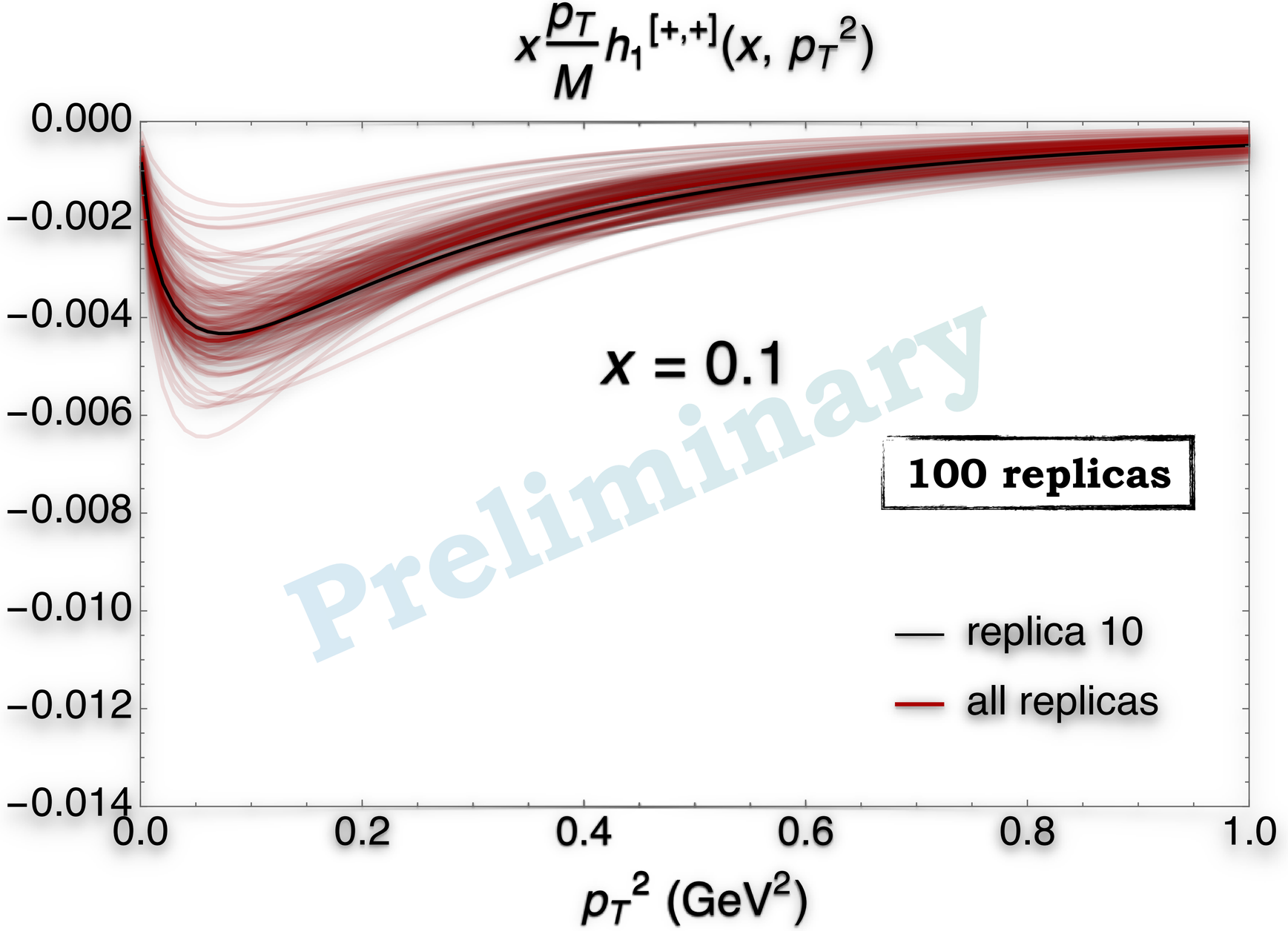


Linearity gluon TMD



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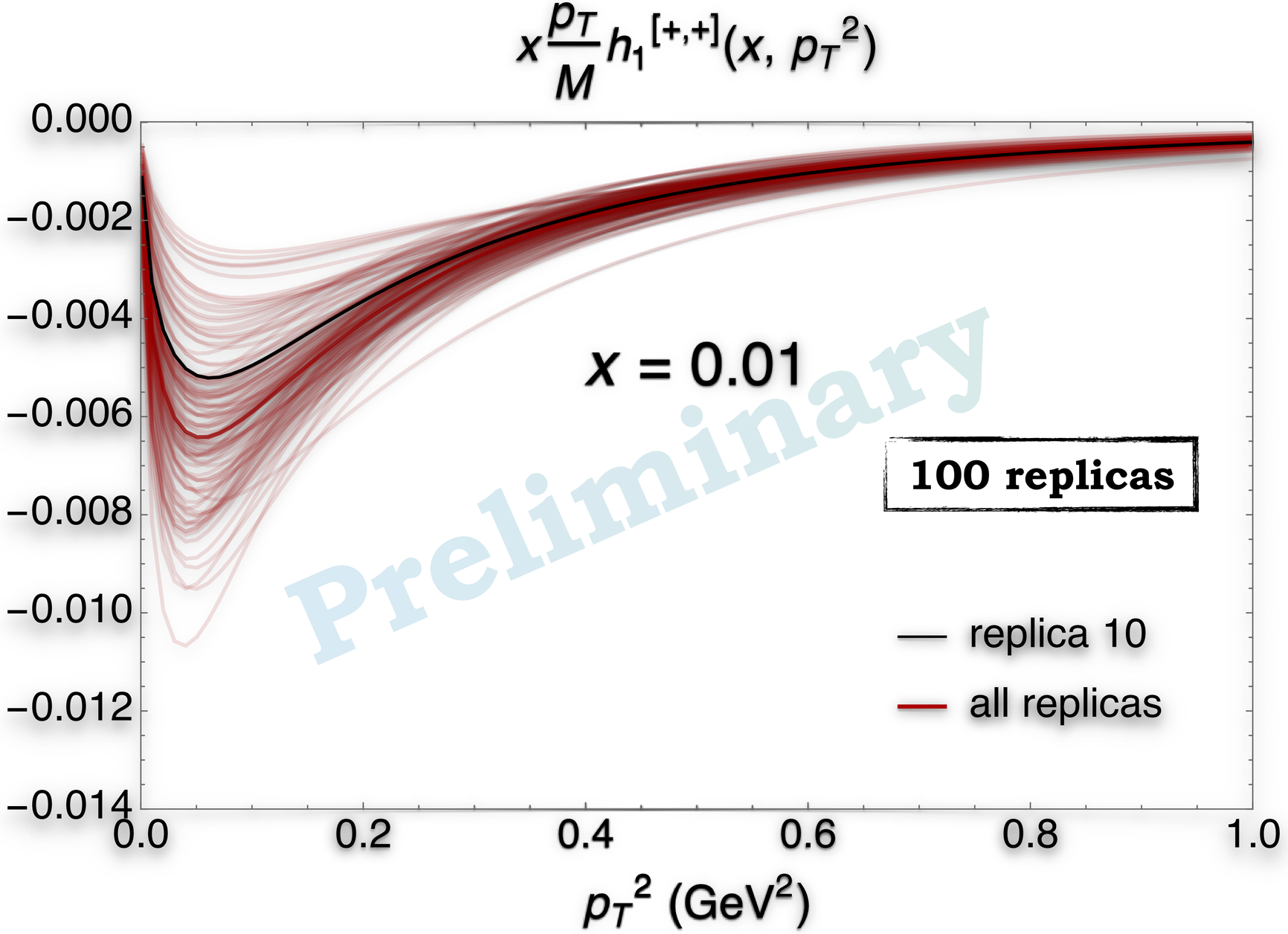

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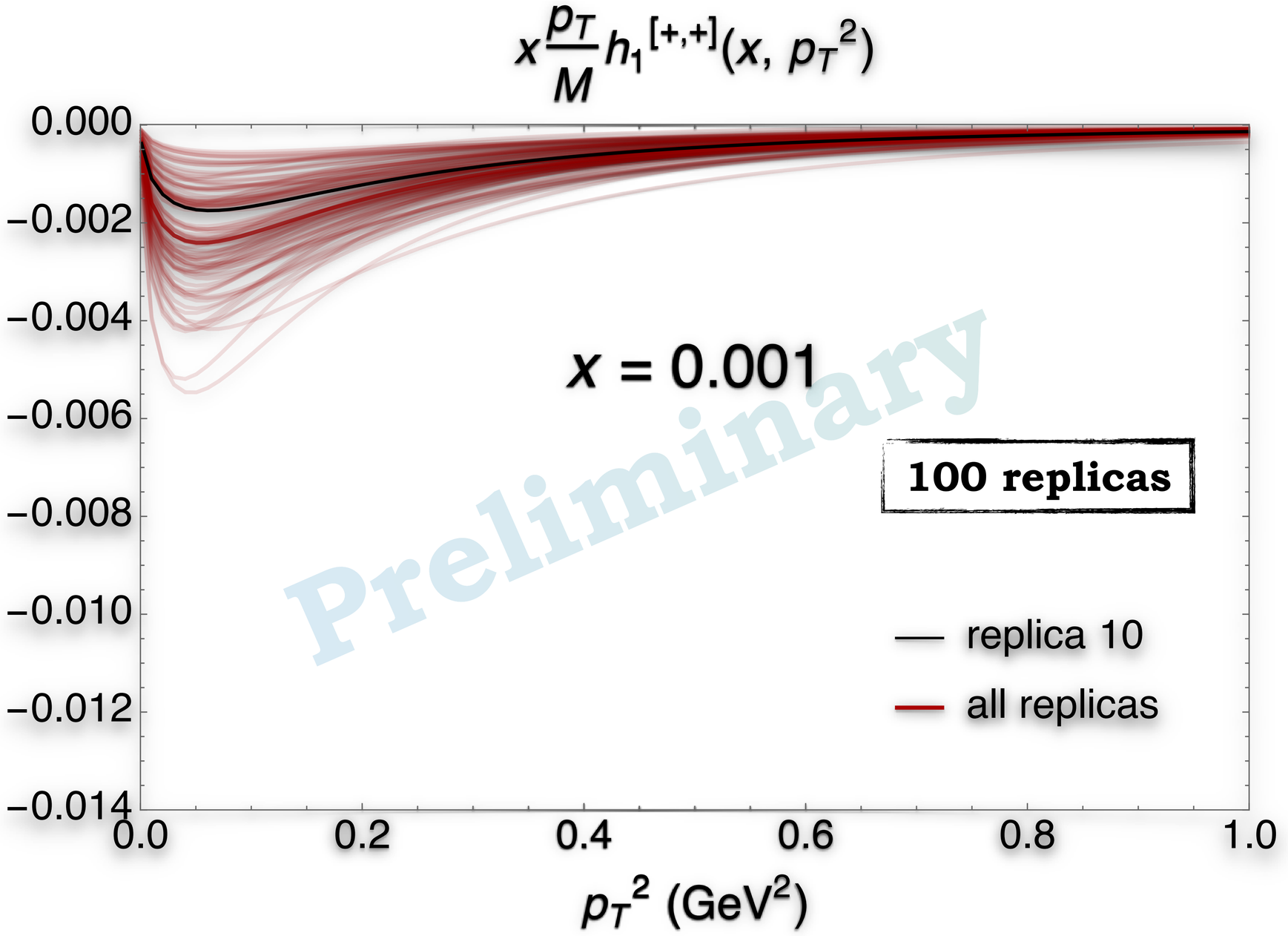

Qiu-Sterman twist-3 gluon PDF

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

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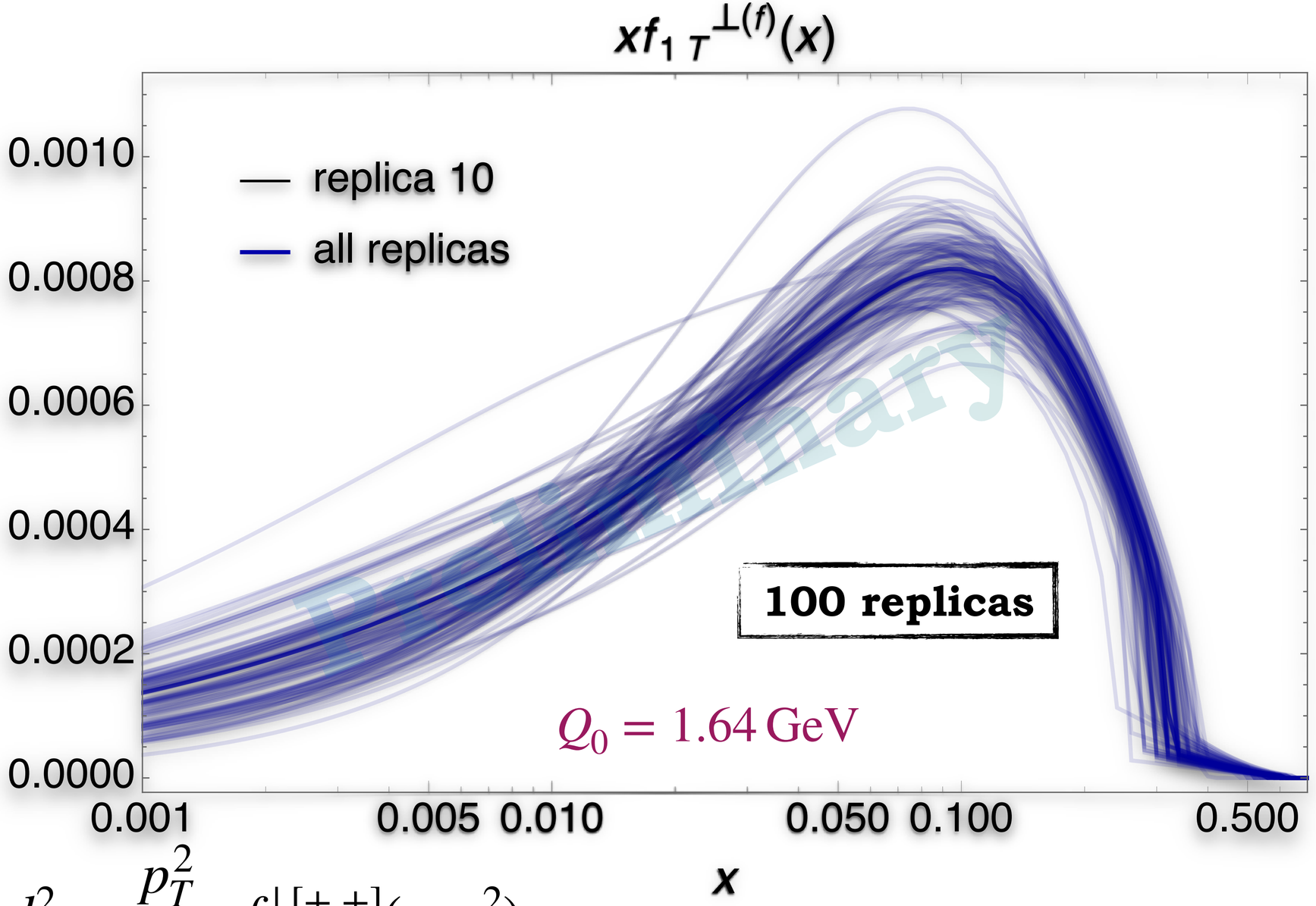

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Checkpoints and further steps

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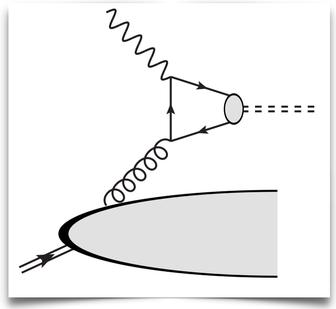
- ☐ Twist-2 T-odd gluon TMDs (**Sivers**, etc.) in progress!
- ☐ Pheno: **spin asymmetries**, **pseudodata** and **impact studies**
- ☐ Evolution: extension to quark TMDs in the same framework
- ☐ Explorative studies on gauge-link sensitivity and factorization
- ☐ Studies on GPD and small-x UGD sectors

Hadronic structure and quarkonia

SIDIS



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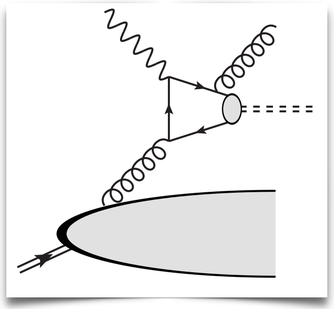
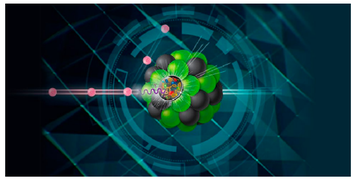
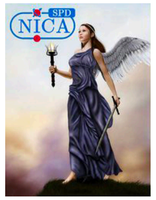


CO + CS

EIC Yellow Report Document
(EICUG website)

[EICUG [arXiv:2103.05419]]

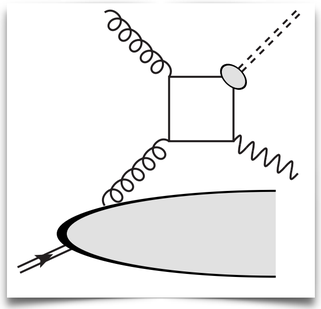




On the physics potential to study the gluon content of proton and deuteron at NICA SPD

[NICA Collaboration [arXiv:2011.15005]]

Hadroproduction



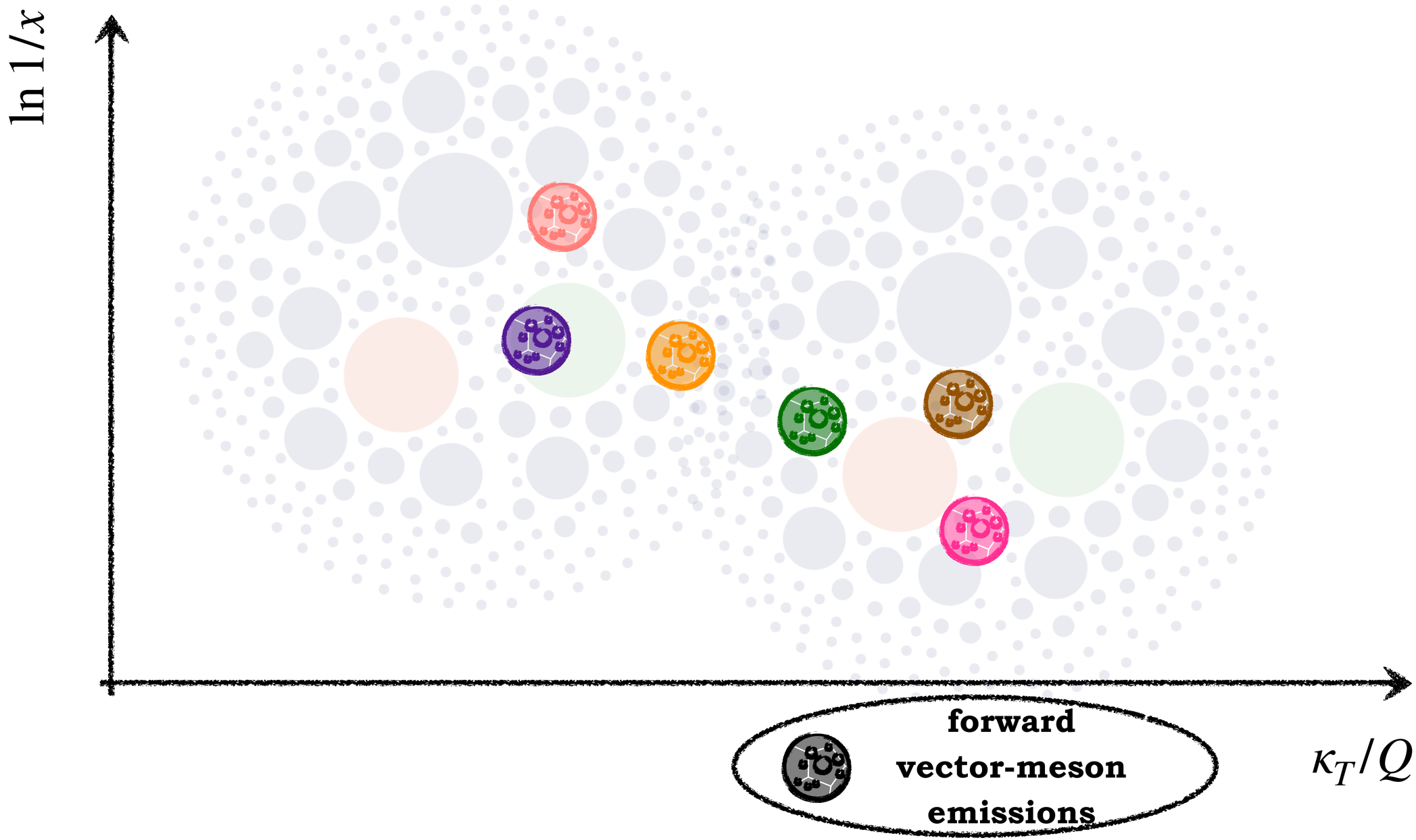
CO + CS

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

[Quarkonia As Tools Collaboration [arXiv:2012.14161]]

Hadronic structure and vector mesons

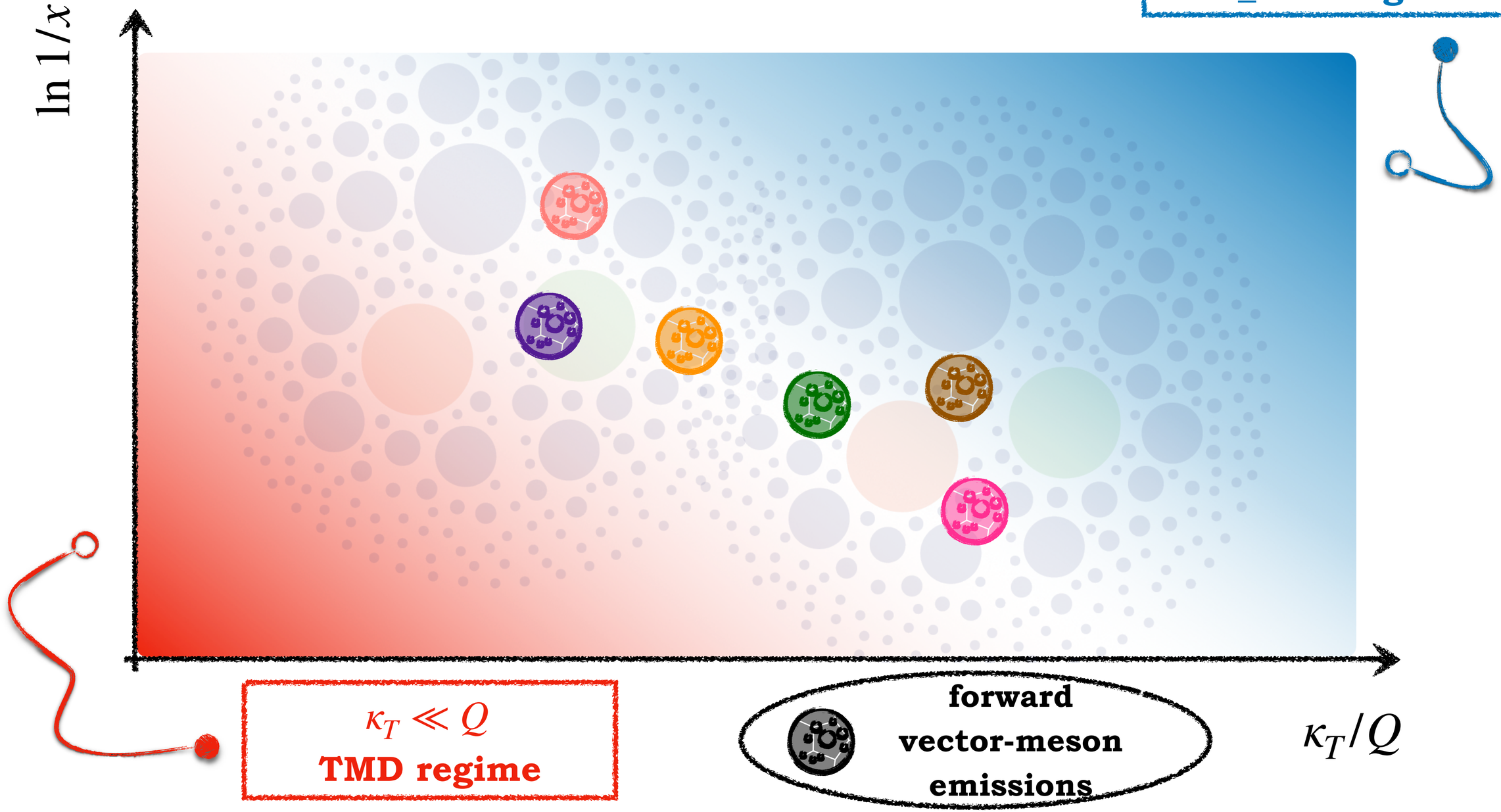
Hadronic structure and vector mesons



Hadronic structure and vector mesons

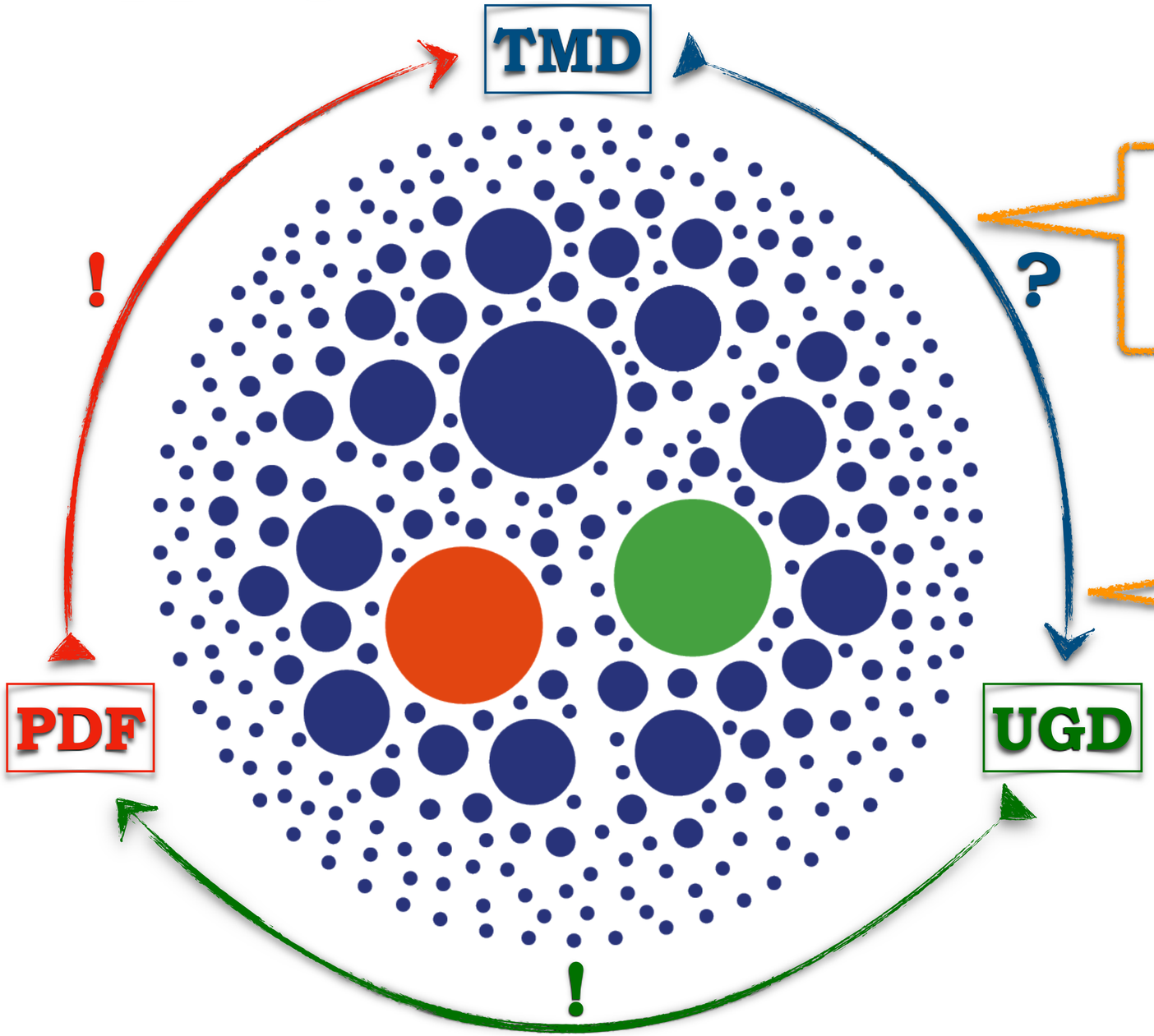
$x \ll 1;\ \kappa_T \approx Q \gg \Lambda_{\mathrm{QCD}}$

AT_HEF regime



...towards a *multi-lateral* formalism

Mapping the proton content

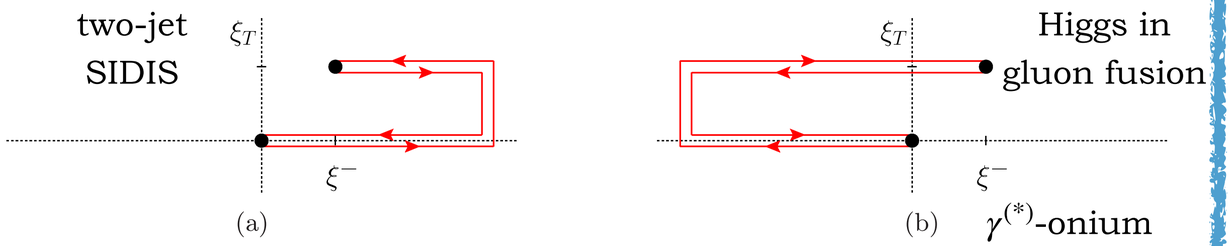


Backup slides

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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



Higgs in gluon fusion

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

Backup

Accessing WW and DP gluon TMDs

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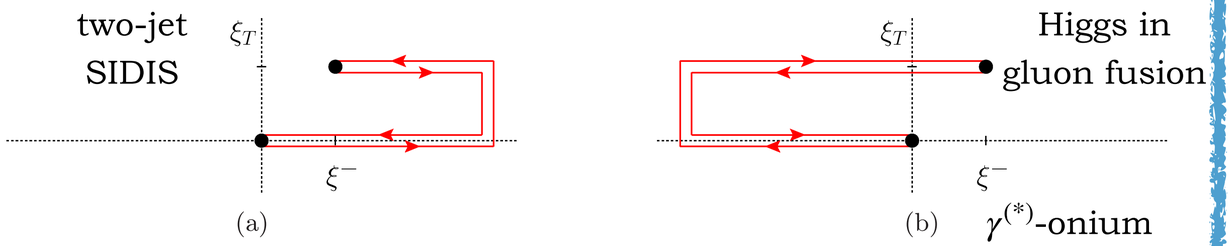
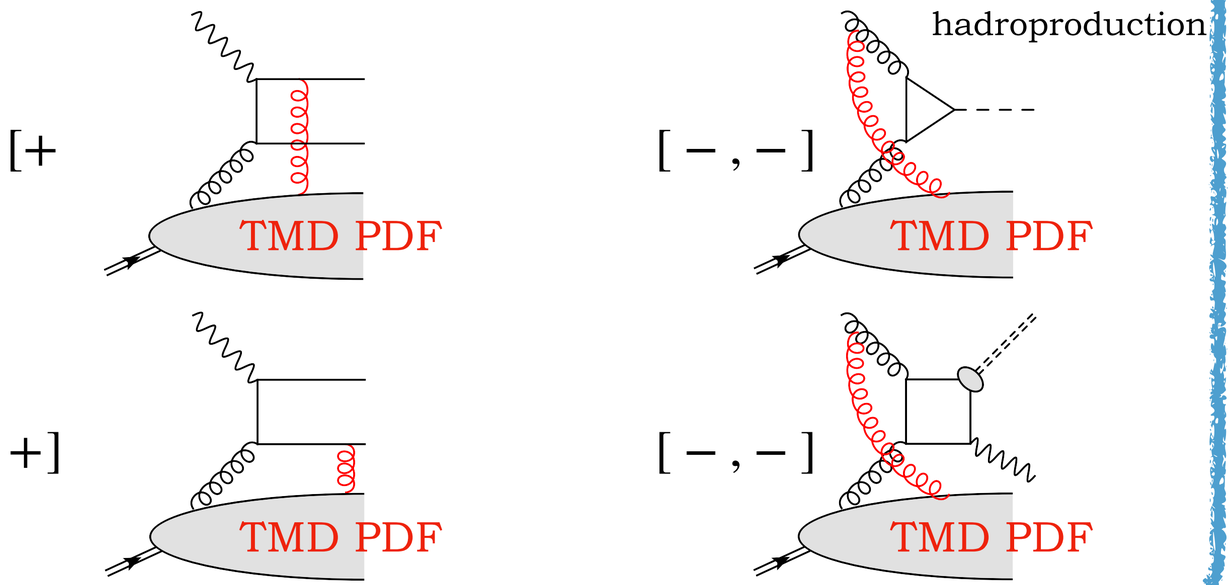




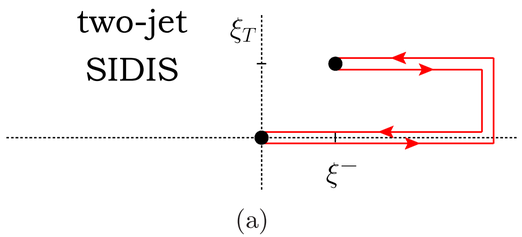
Backup

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

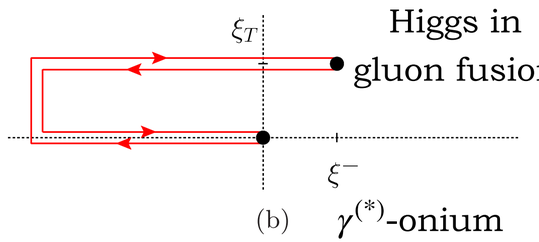
(a) $[+,+]$ or (b) $[-,-]$

two-jet SIDIS



(a)

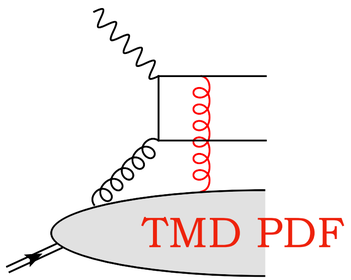
Higgs in gluon fusion



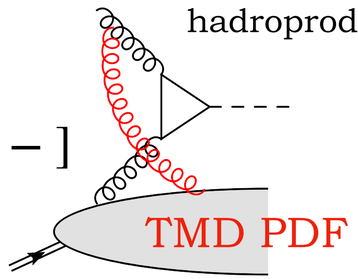
(b)

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

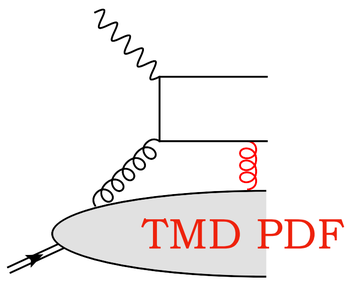
$[+$



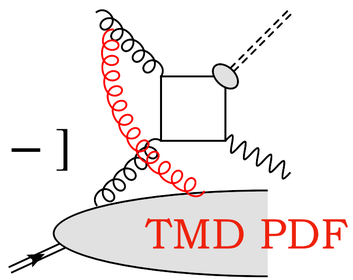
$[-,-]$



$+]$

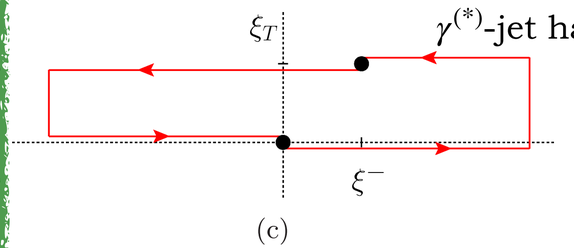


$[-,-]$

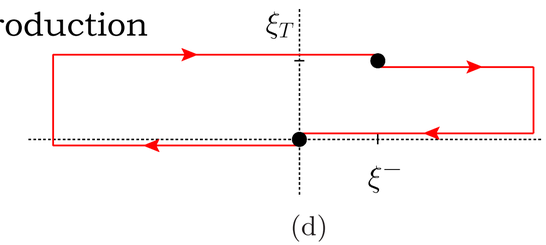


Dipole (DP)

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



(c)



(d)

Backup

Accessing WW and DP gluon TMDs

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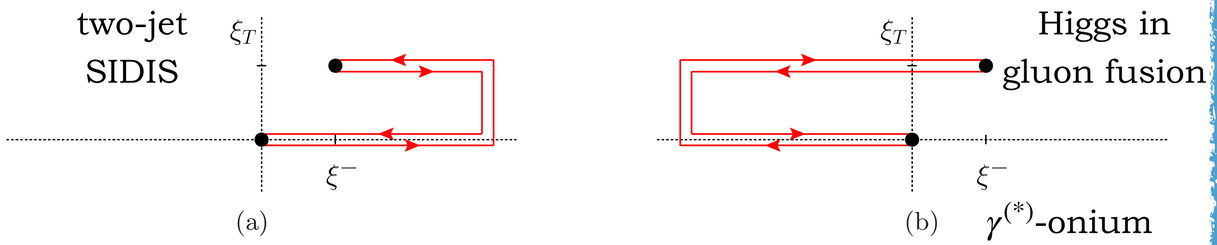
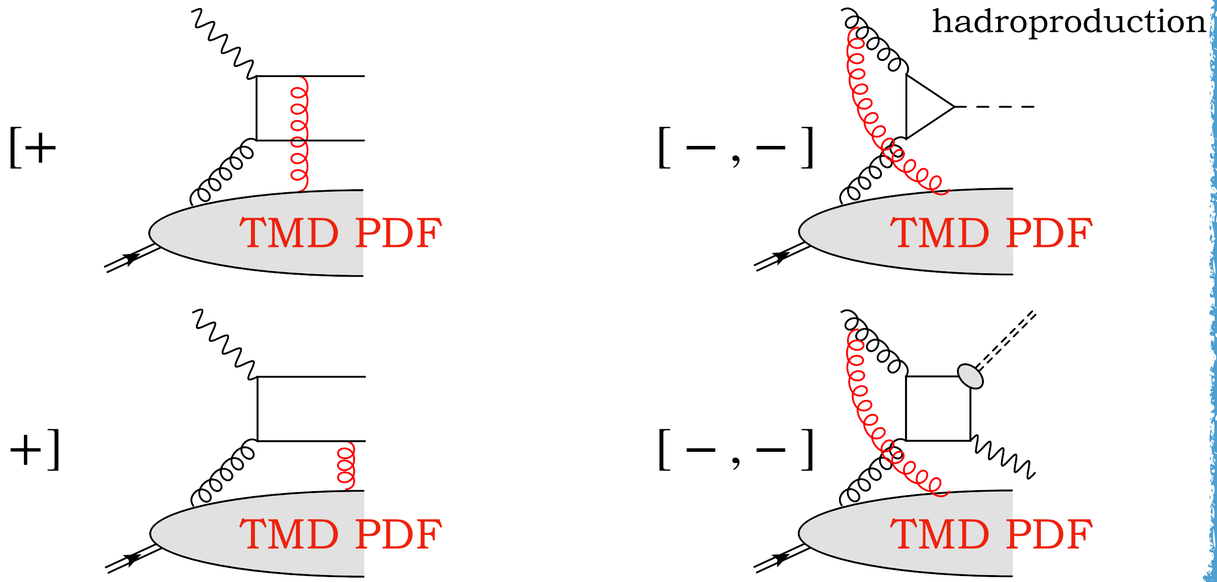
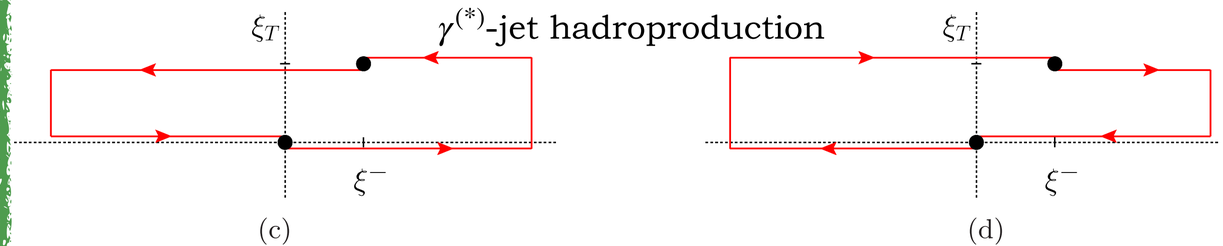


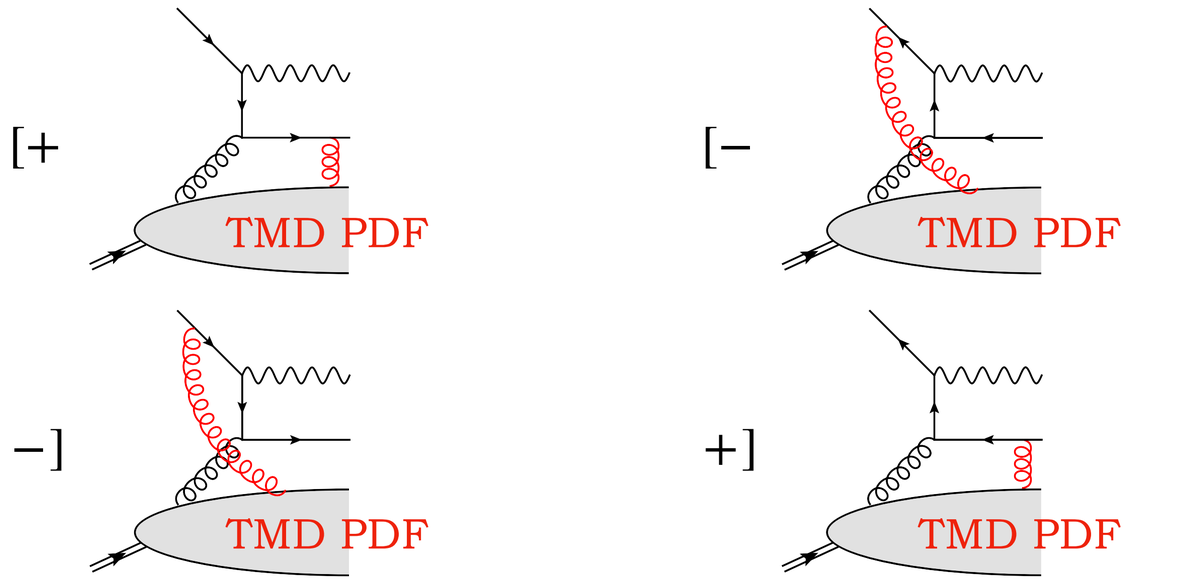
$\gamma^{(*)}$-onium hadroproduction



Dipole (DP)

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





Backup

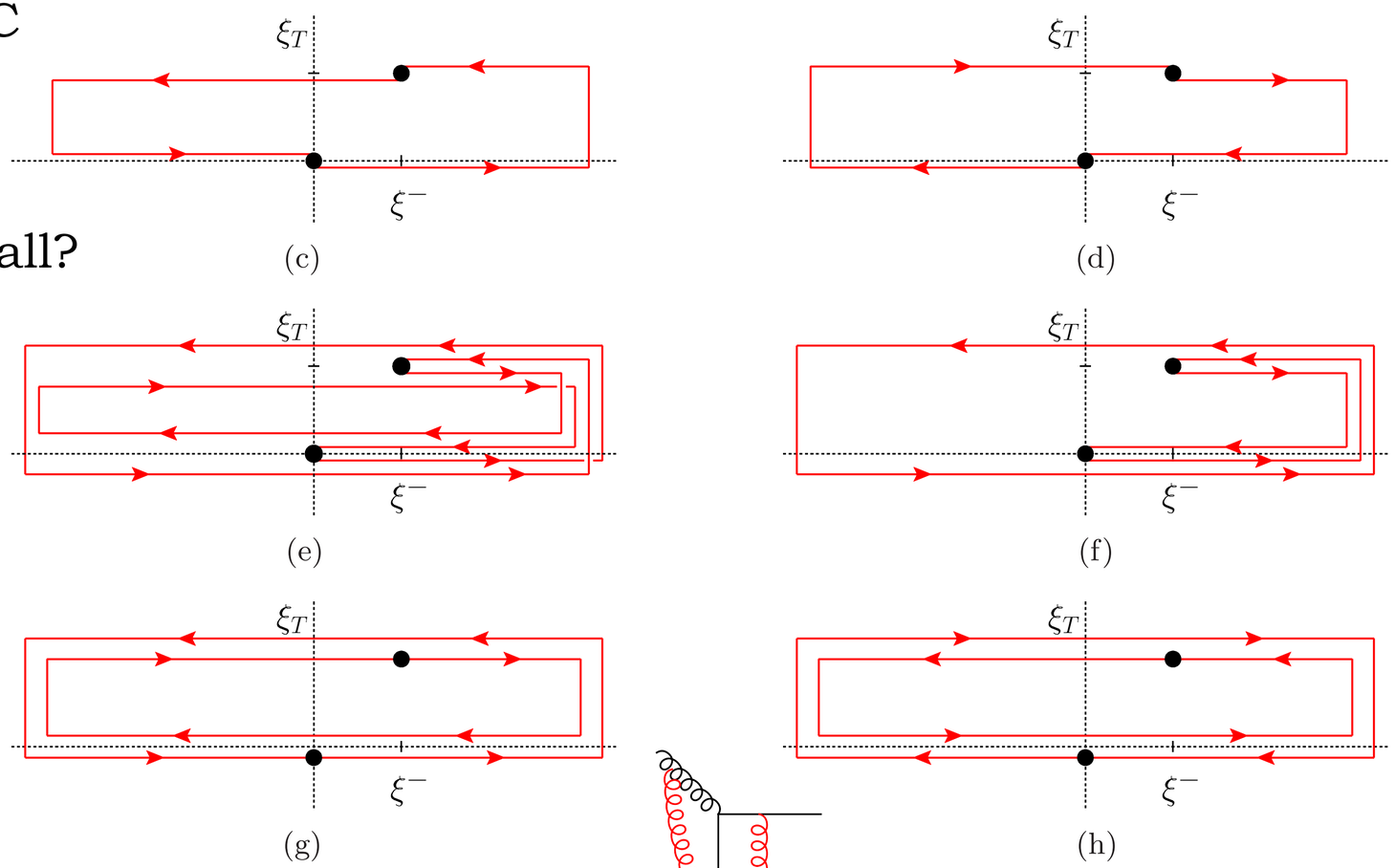
Dihadron hadroproduction and factorization breaking

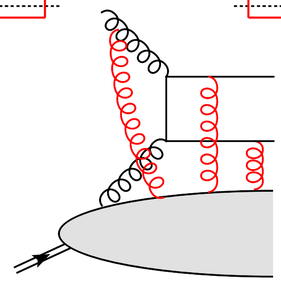
* Proof of factorization violation 🔗 [T. J. Rogers, P. J. Mulders (2010)]
* Assumed factorization in SCET and CGC
* Significance of low-x studies
* Size of factorization-breaking effects small?
* DP TMDs:

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

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

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



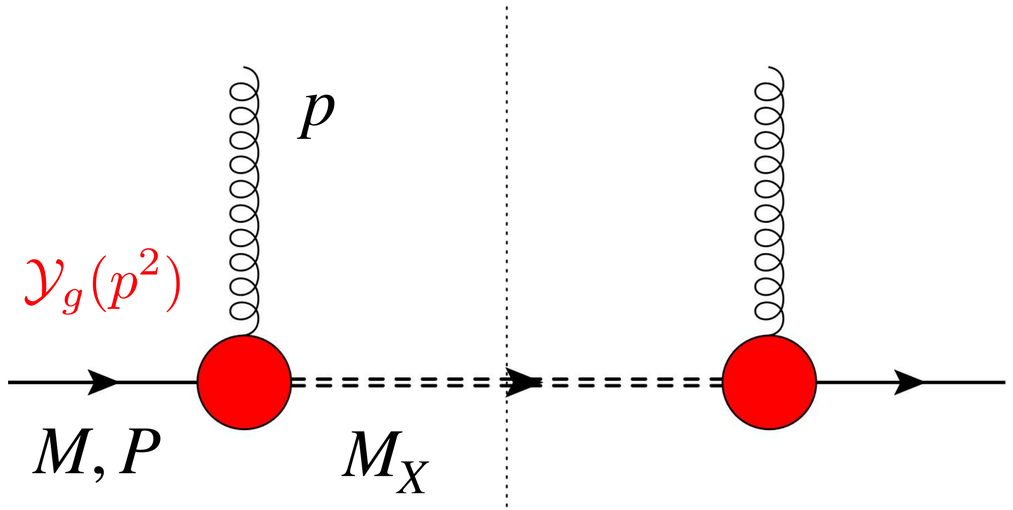


Backup

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

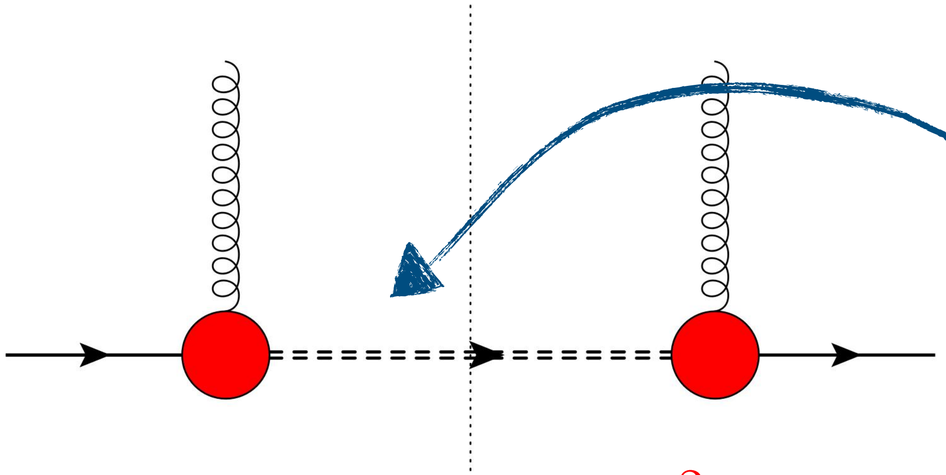
Spectator-system spectral-mass function

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

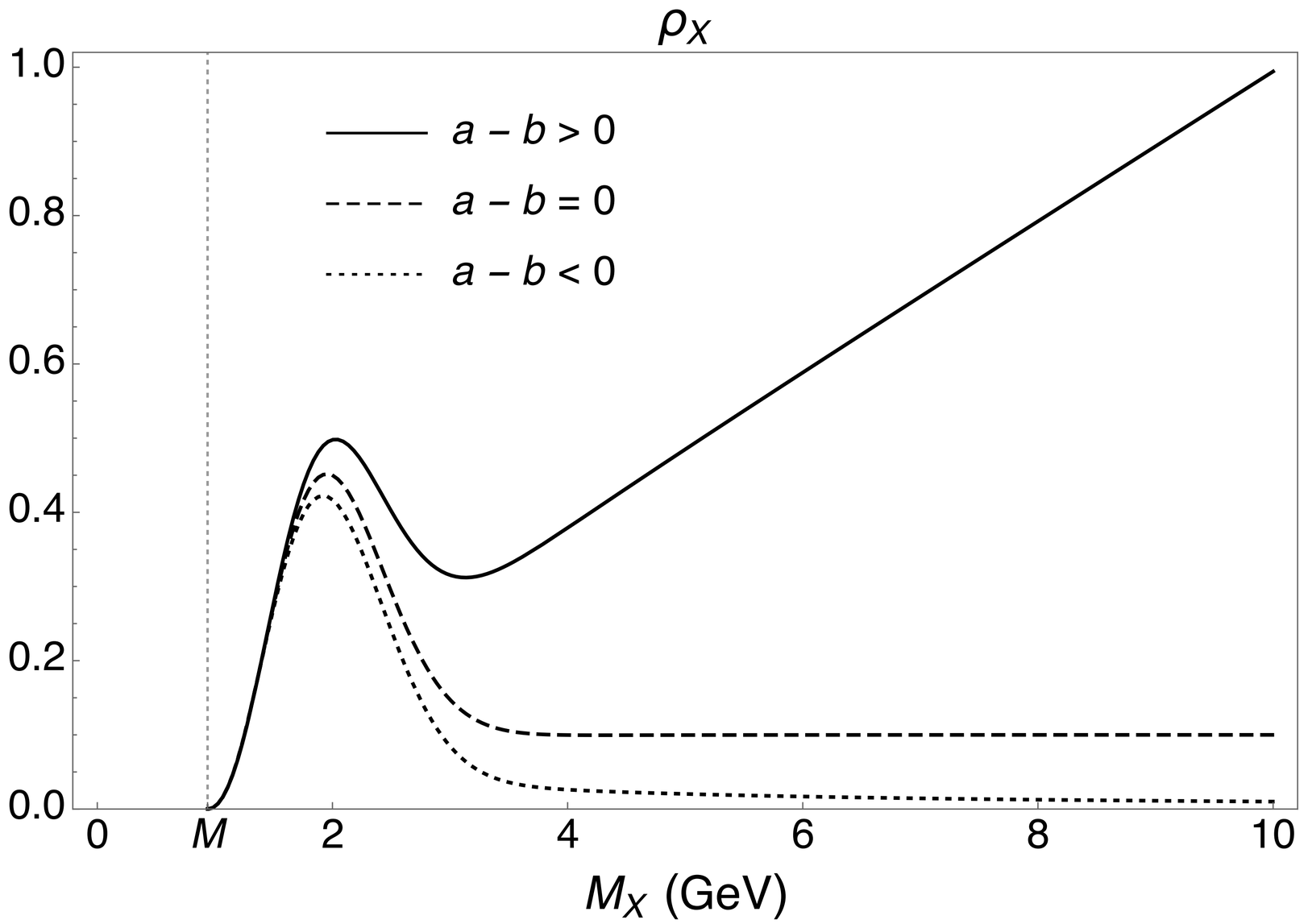
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

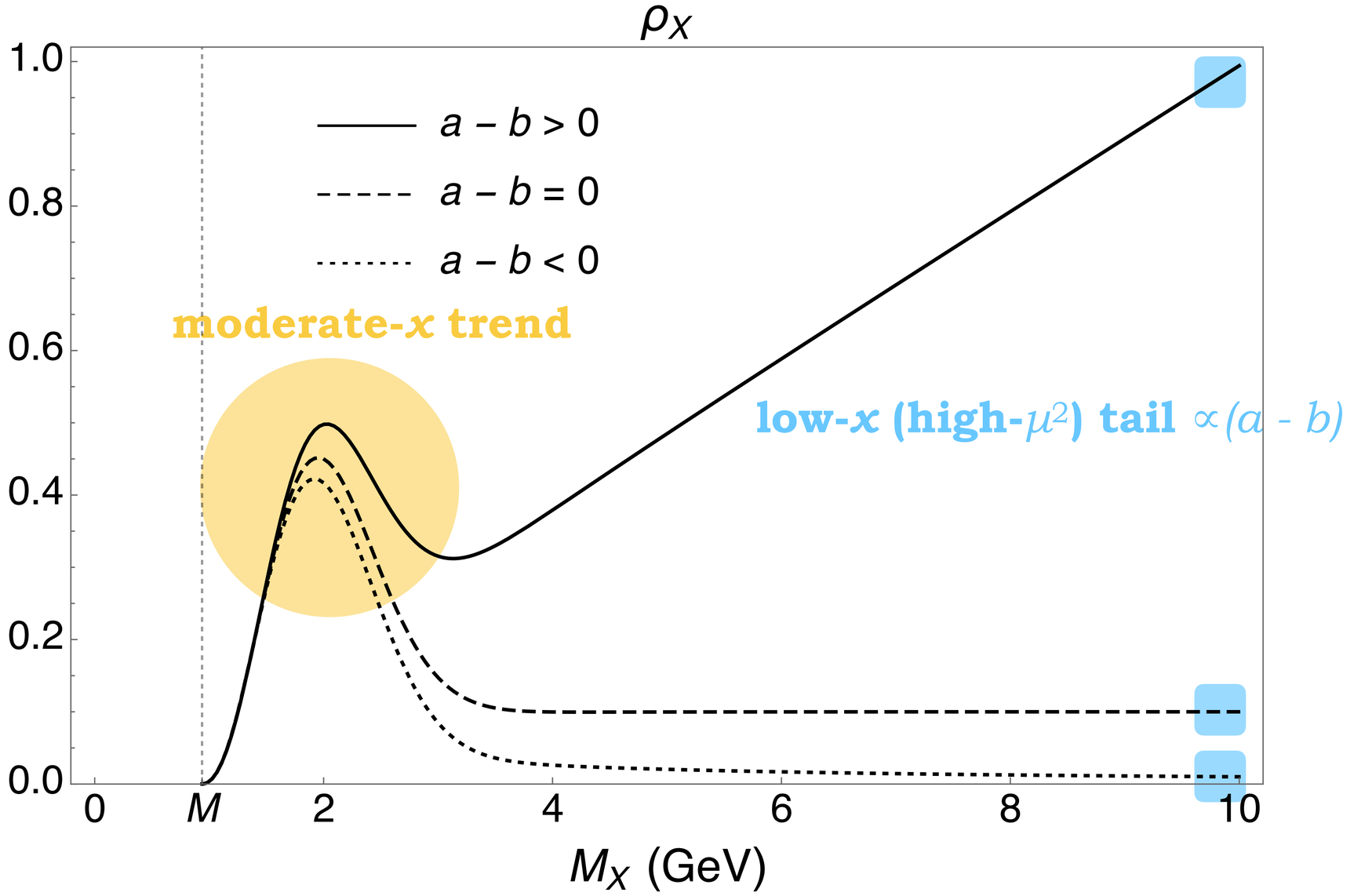
Backup

Spectral function vs *(a - b)*



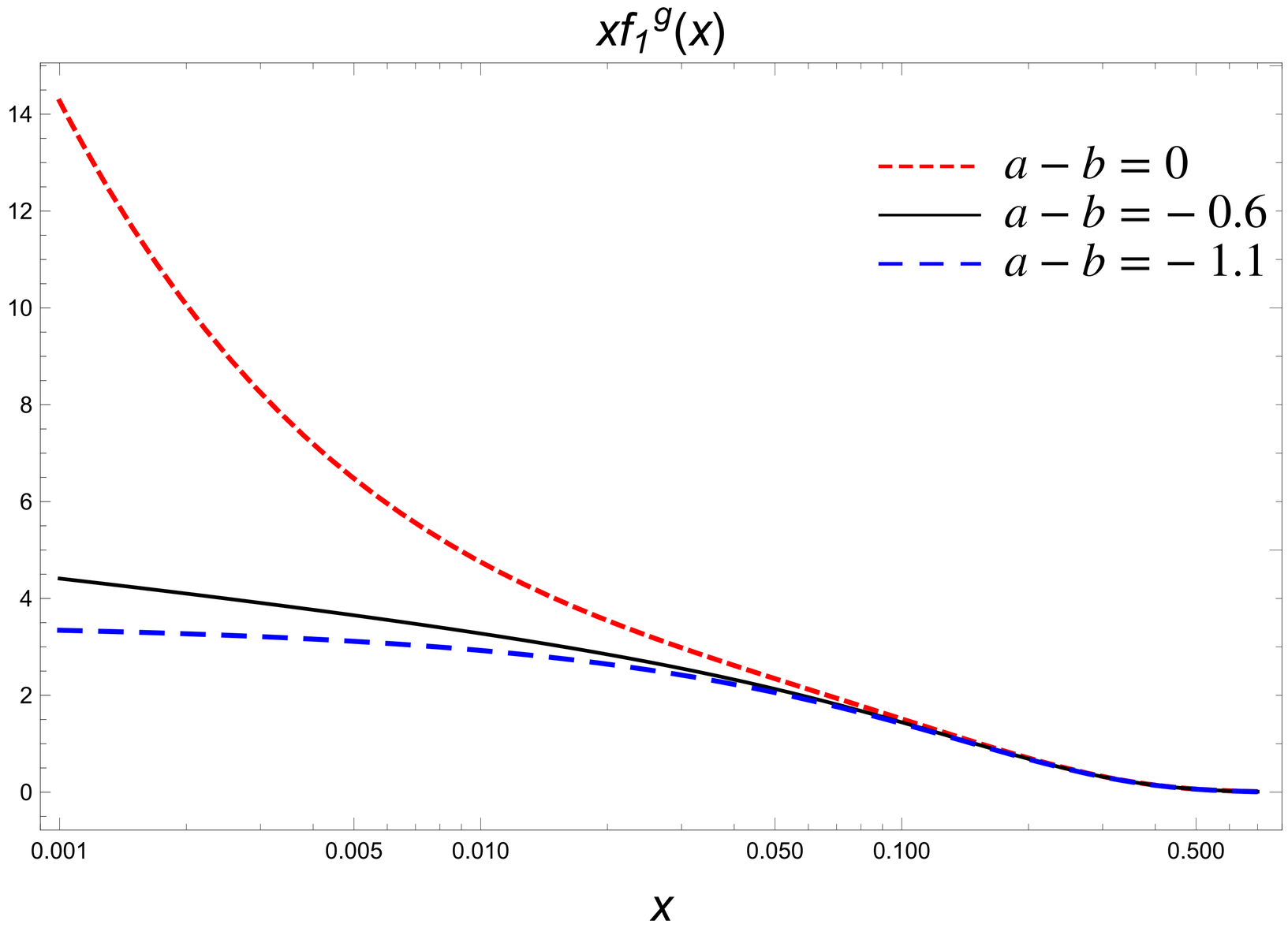
Backup

Spectral function vs $(a - b)$



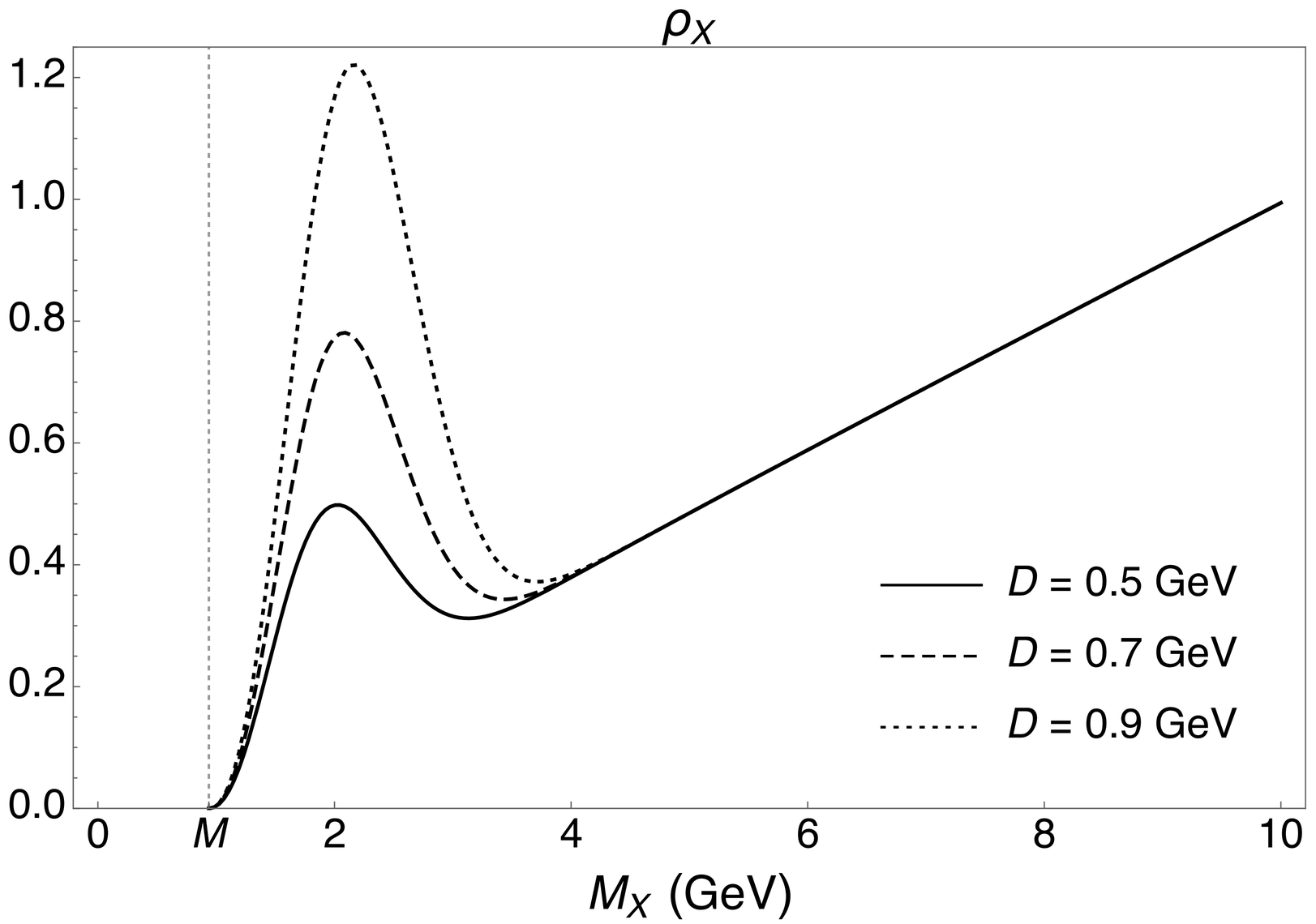
Backup

xf_1 collinear PDF vs $(a - b)$



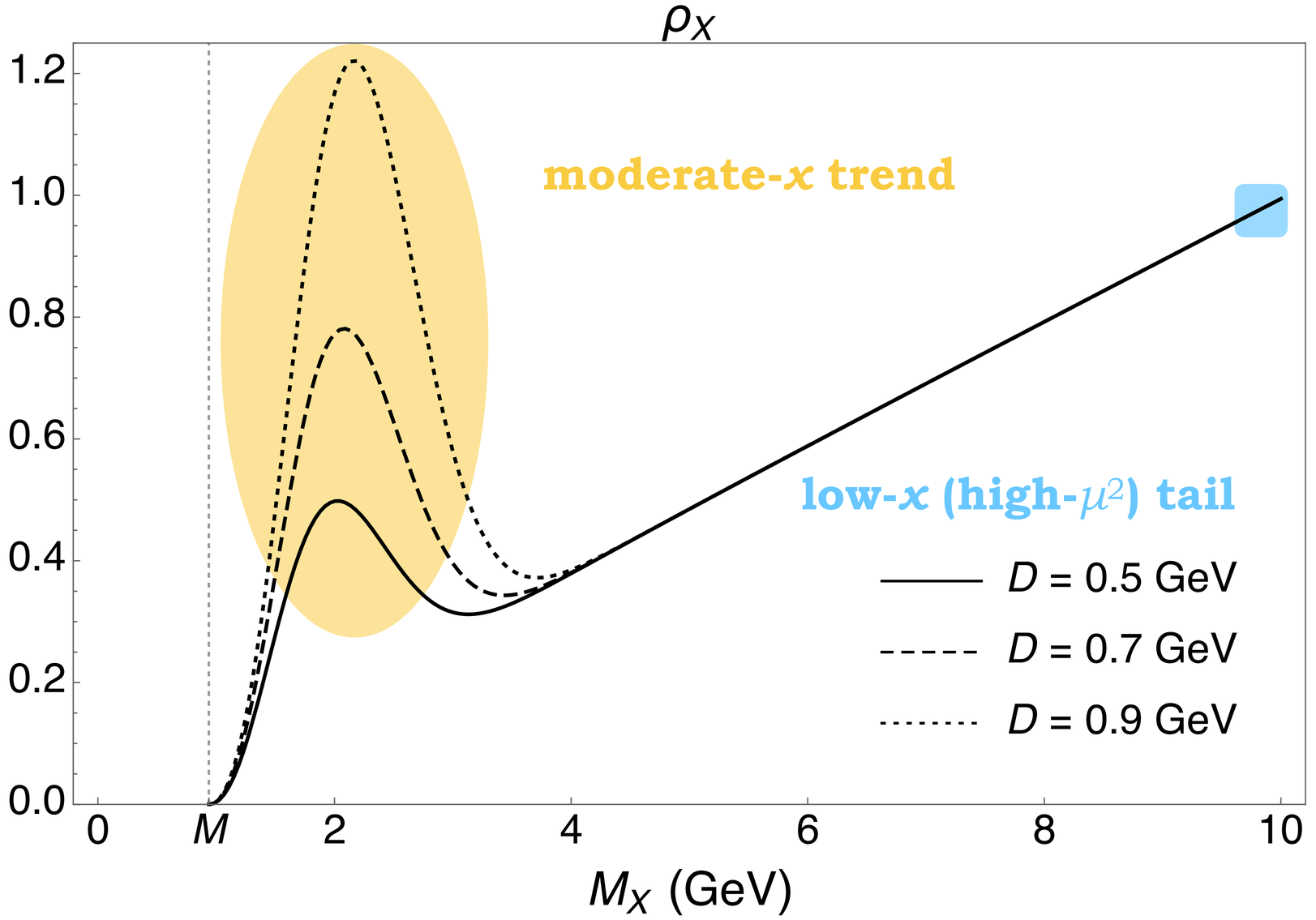
Backup

Spectral function vs D



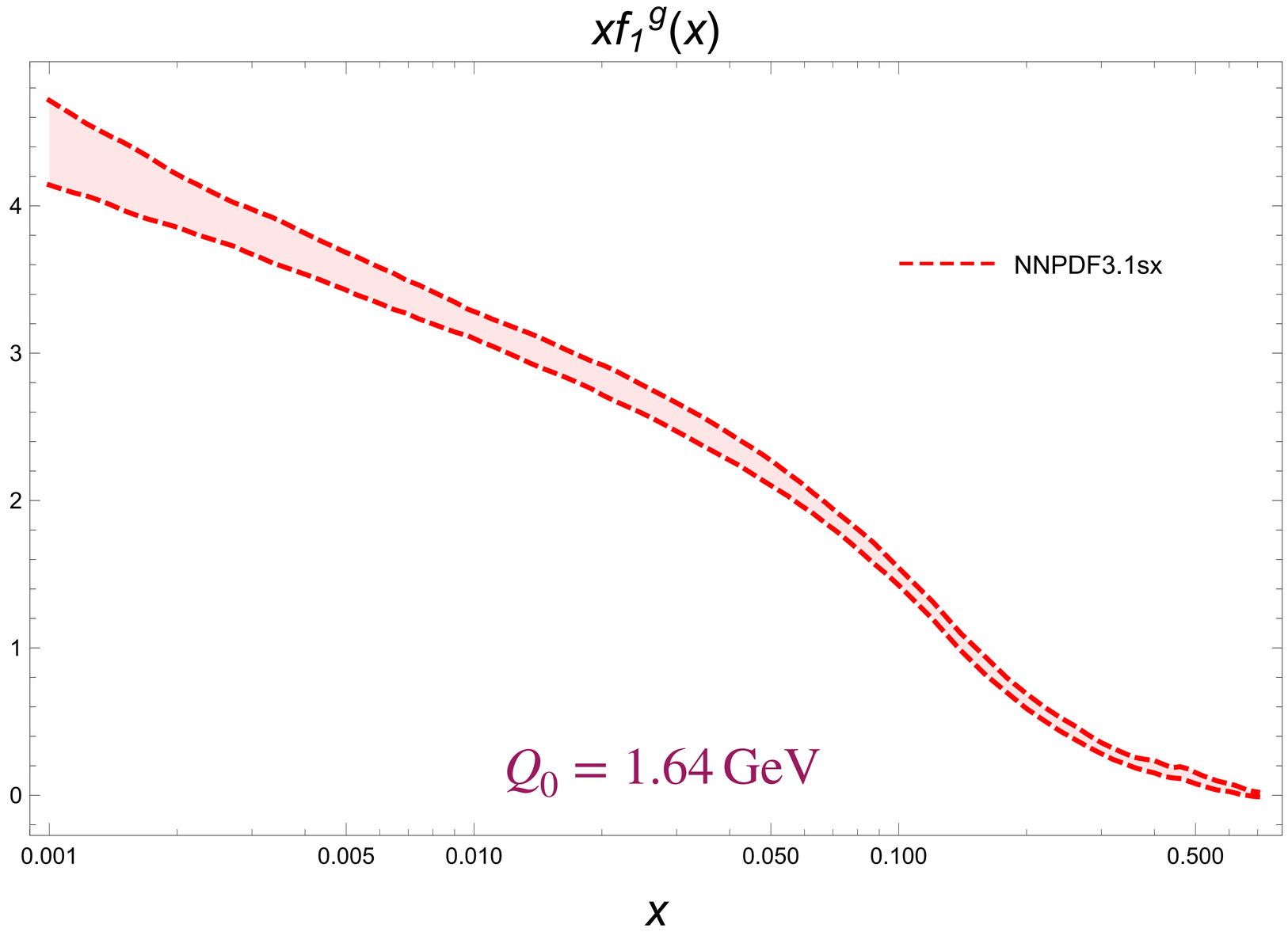
Backup

Spectral function vs D



Backup

Unpolarized gluon PDF



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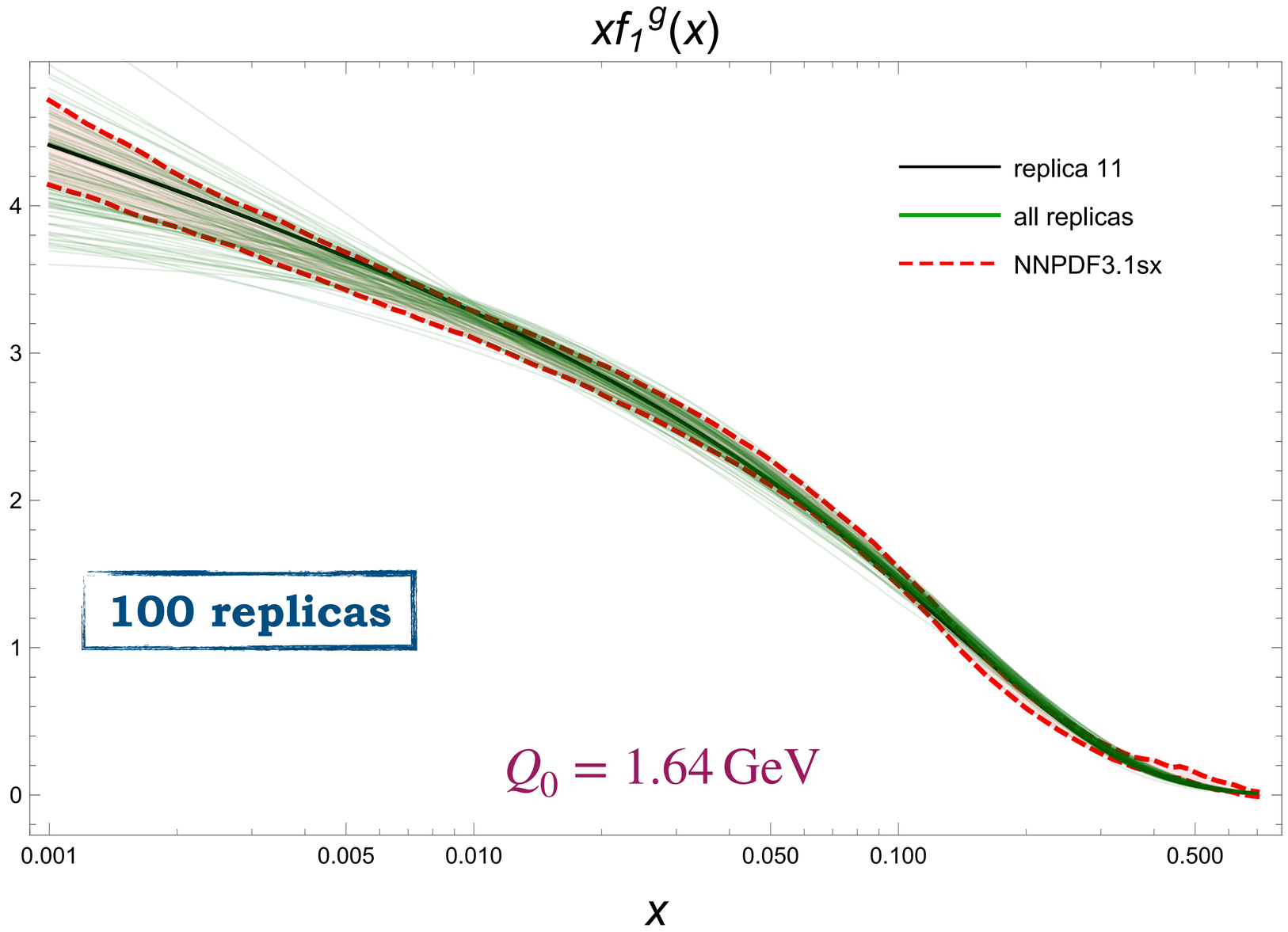
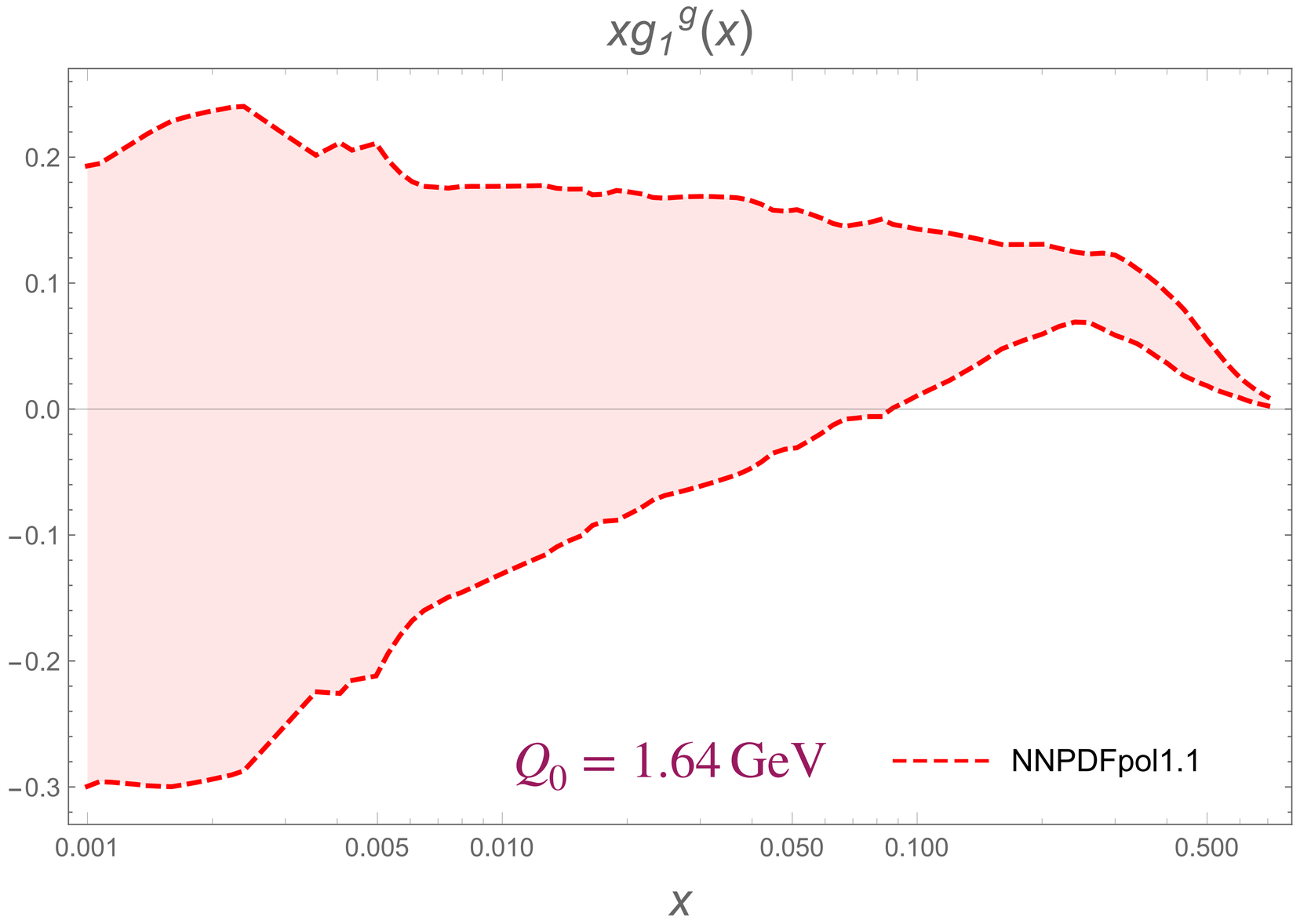
Unpolarized gluon PDF



Backup

Helicity gluon PDF



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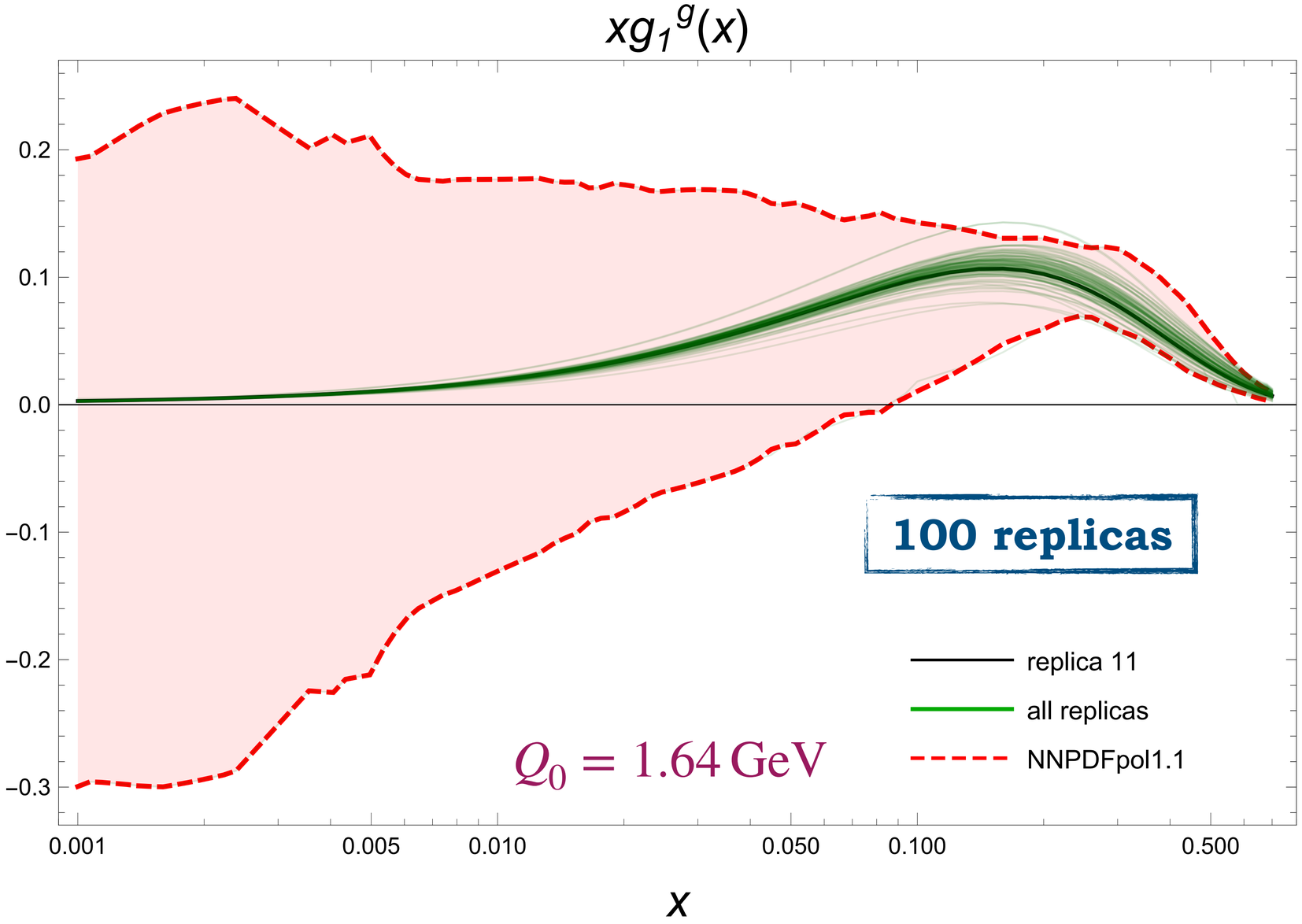
Helicity gluon PDF



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

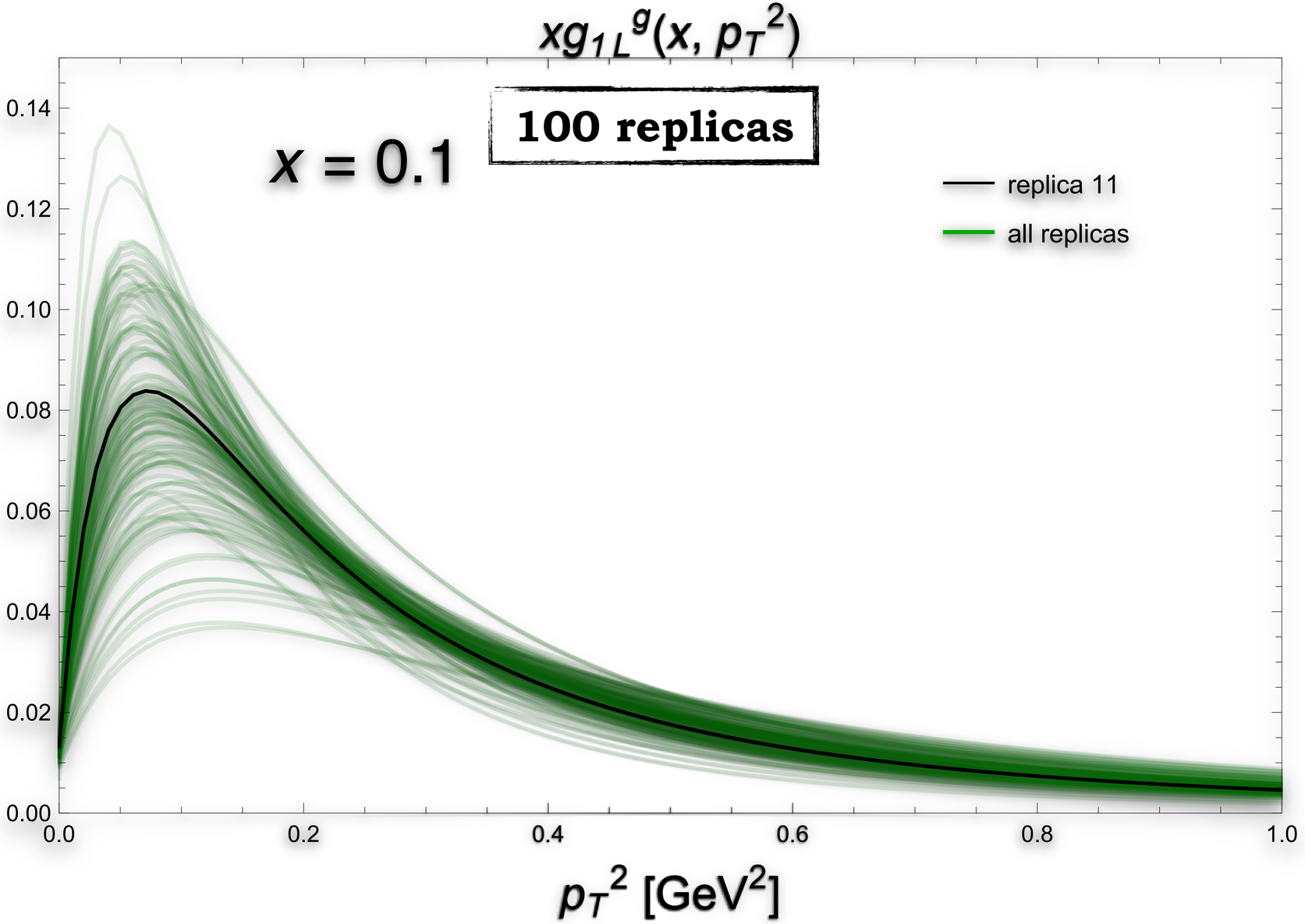
$$\langle x \rangle_g = 0.427(92)$$

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

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

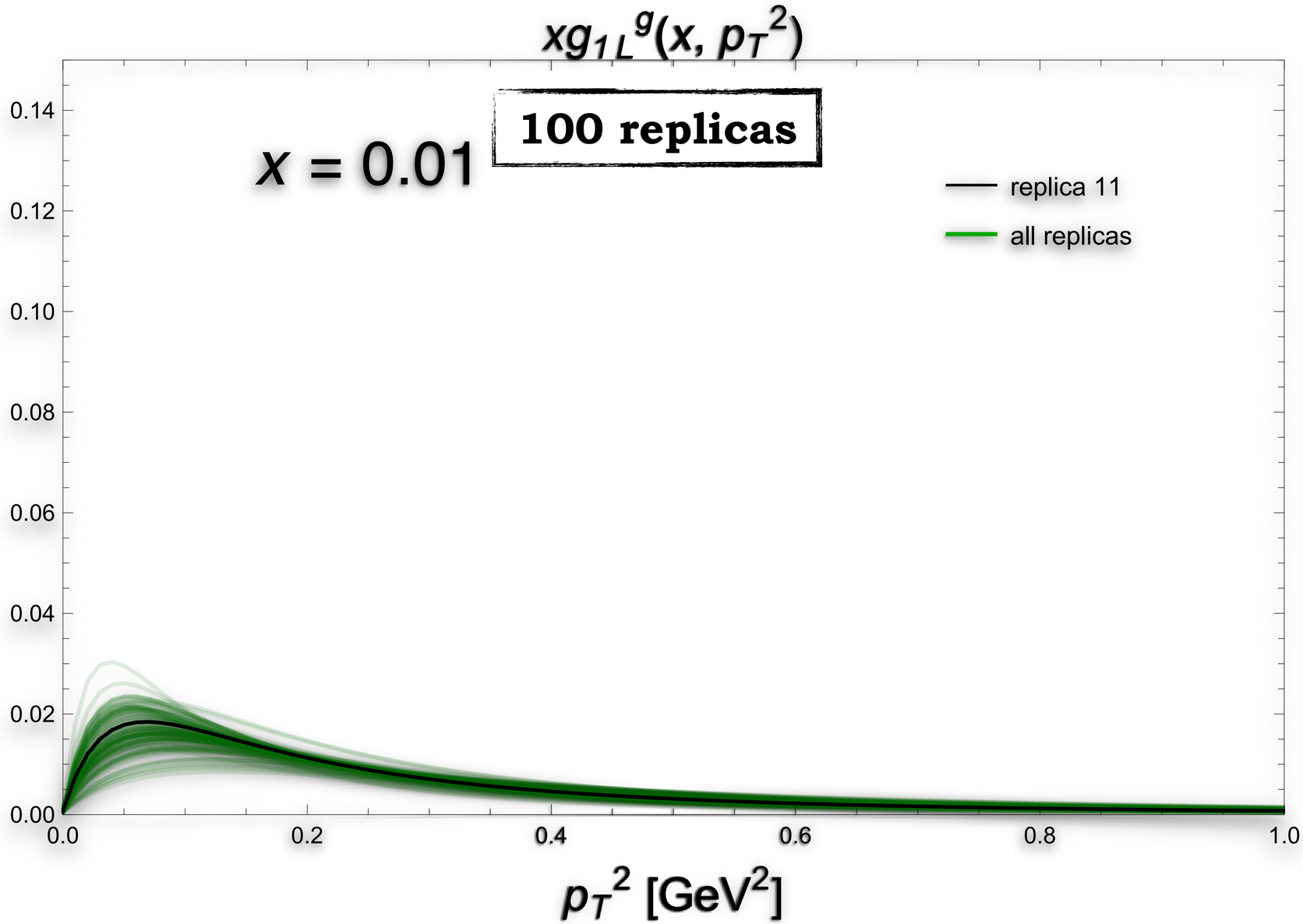
Backup

Helicity gluon TMD



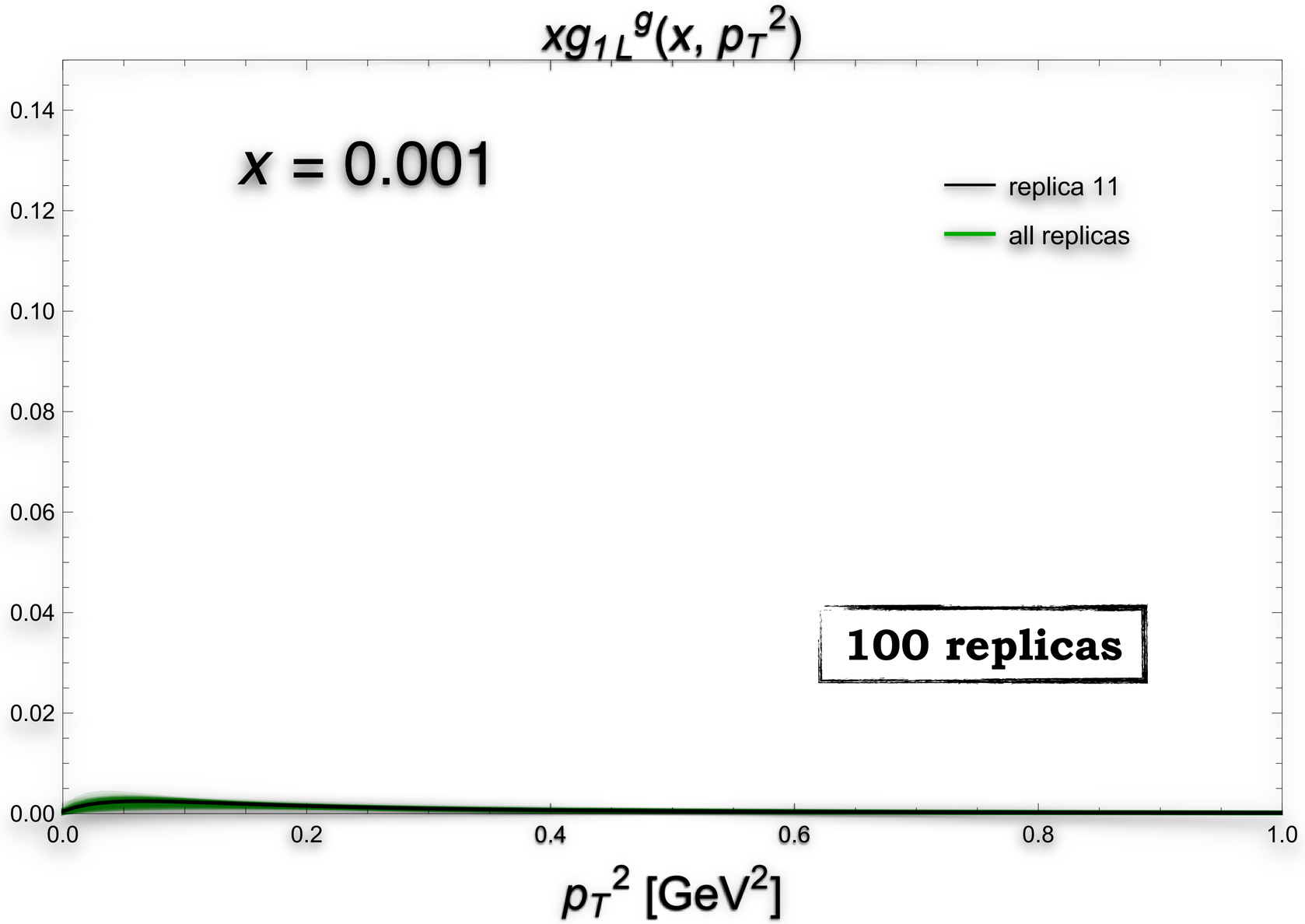
Backup

Helicity gluon TMD



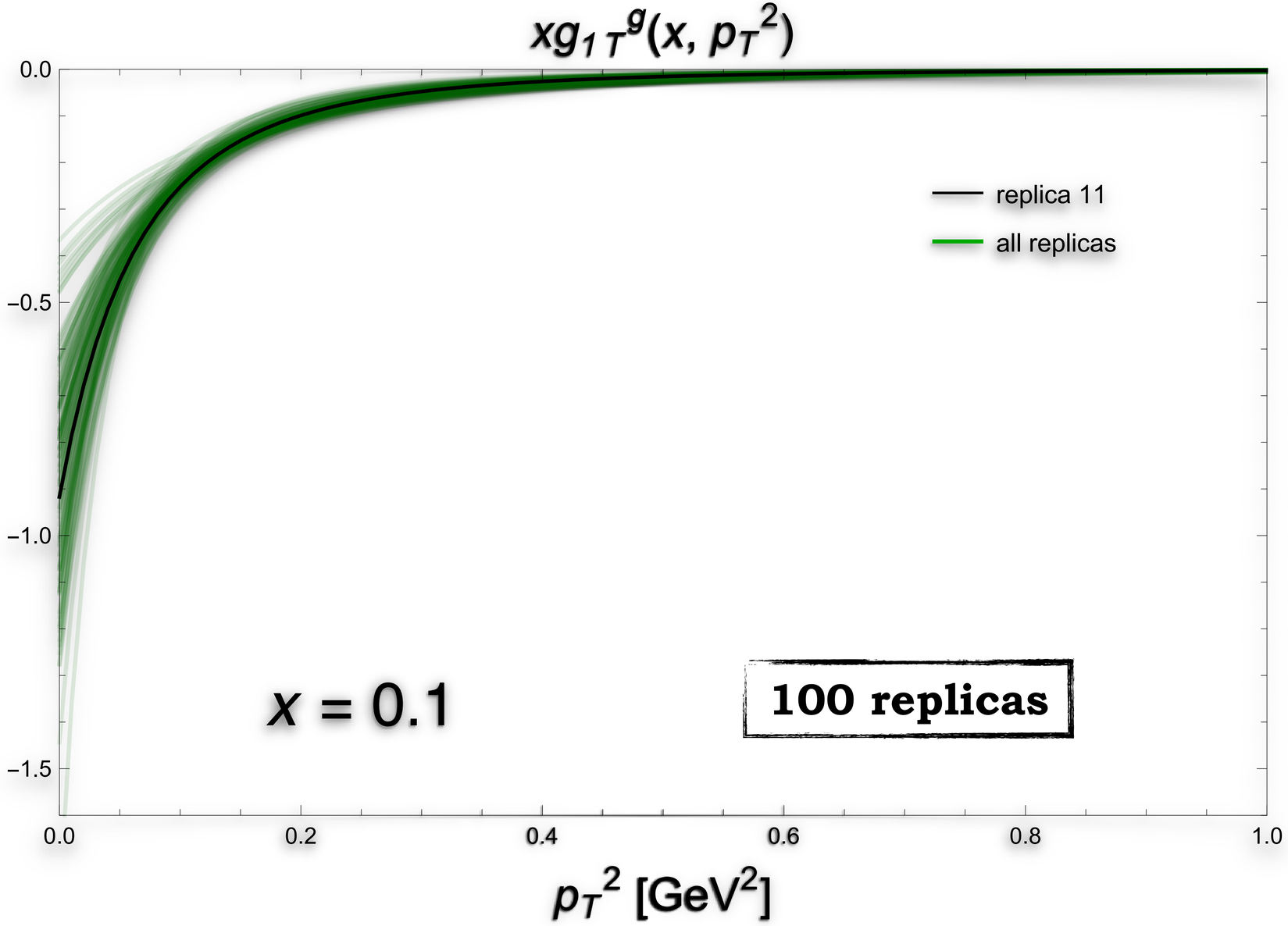
Backup

Helicity gluon TMD



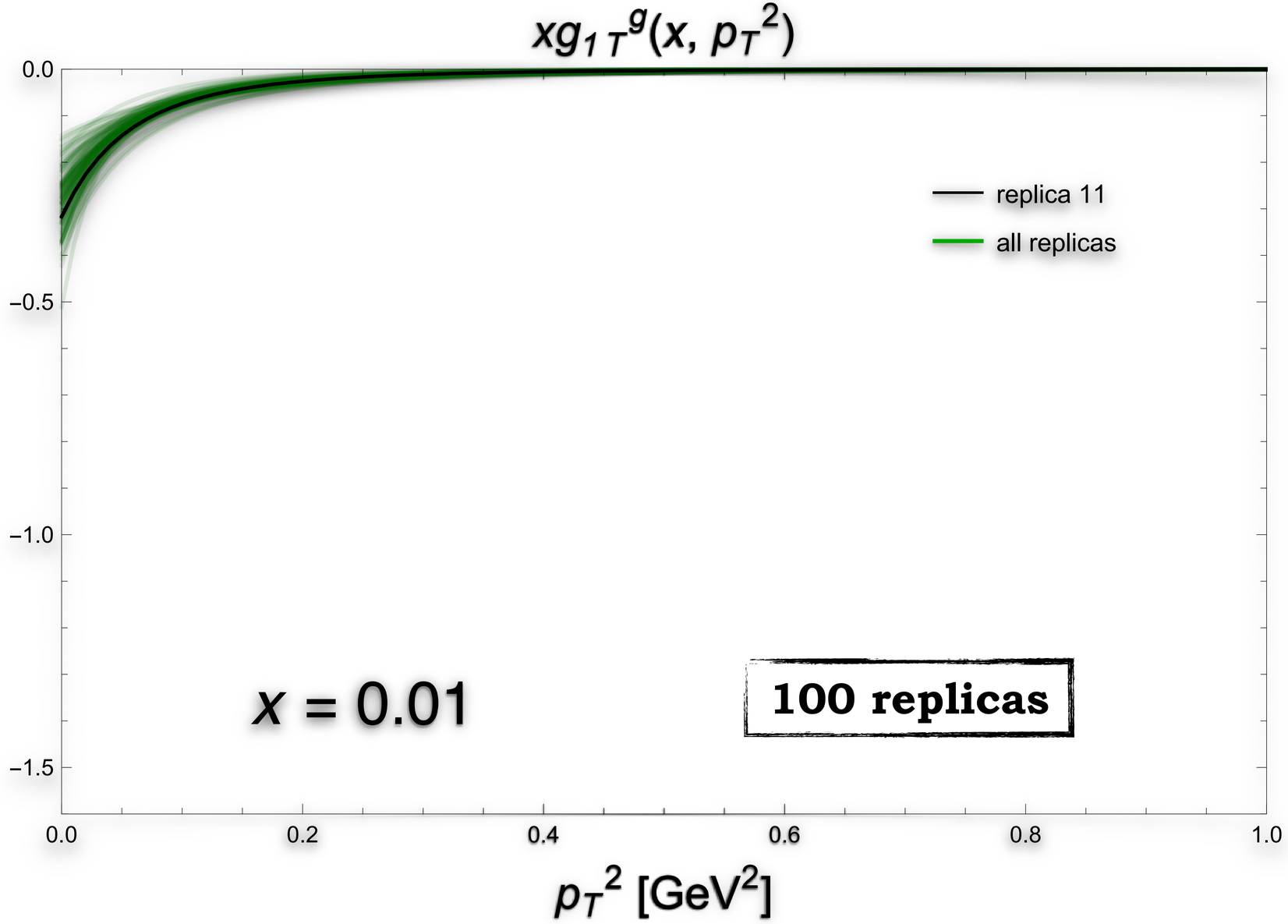
Backup

Worm-gear gluon TMD



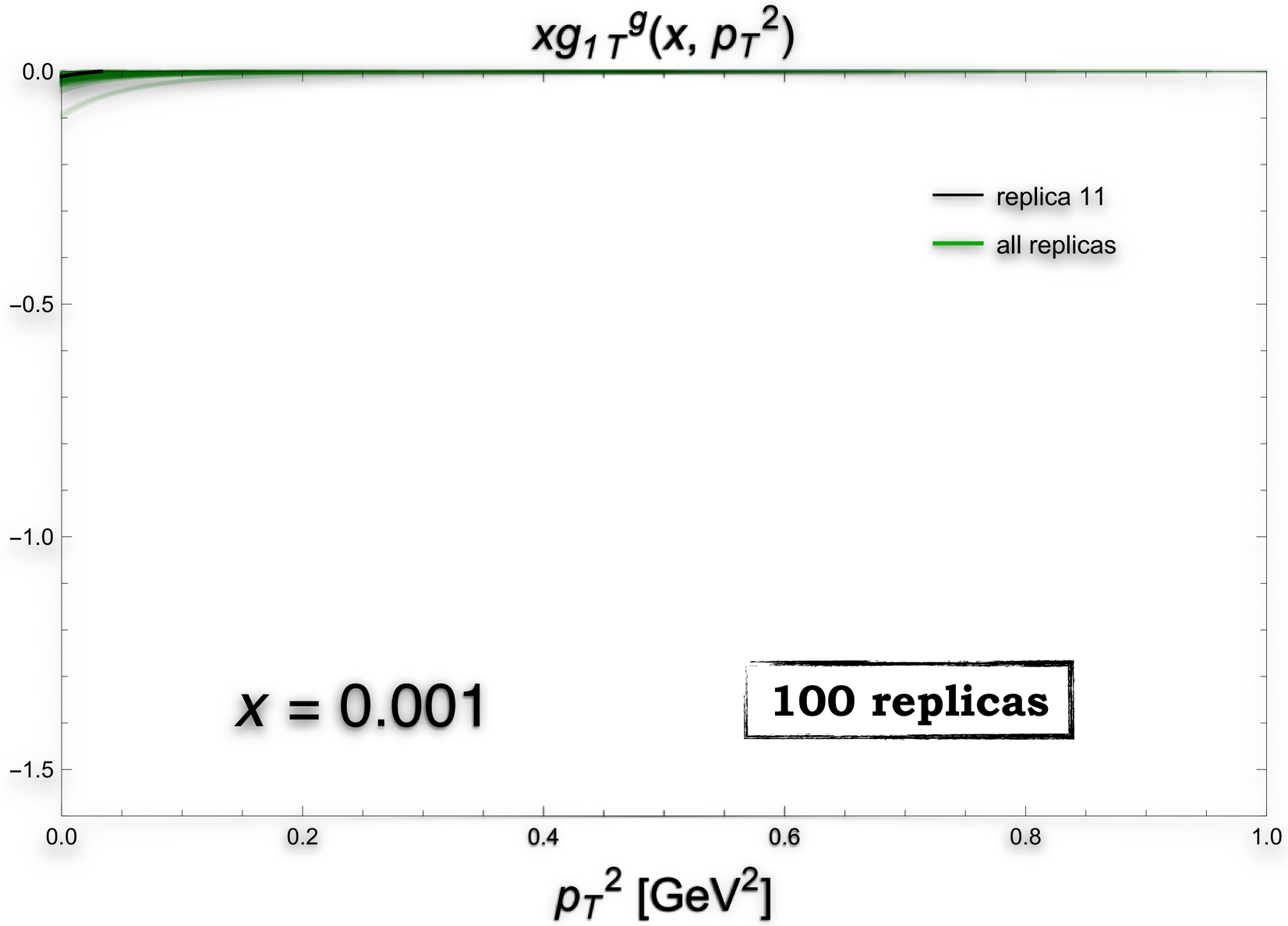
Backup

Worm-gear gluon TMD



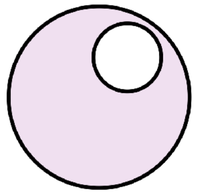
Backup

Worm-gear gluon TMD



Backup

ρ-densities

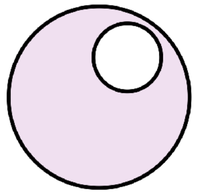


Unpolarized [u/u]

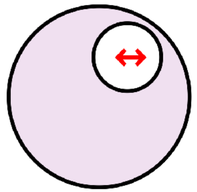
$f_1(x, p_x, p_y)$

Backup

ρ-densities



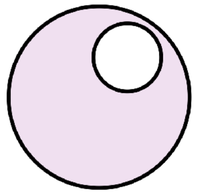
Unpolarized [u/u] $f_1(x, p_x, p_y)$



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

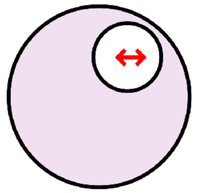
Backup

ρ-densities



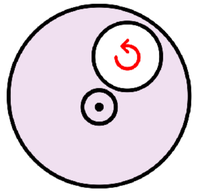
Unpolarized [u/u]

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



Boer-Mulders [↔/u]

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

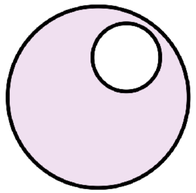


Helicity [↻/+]

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

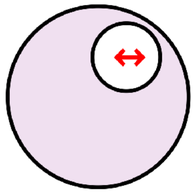
Backup

ρ-densities



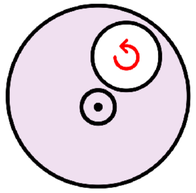
Unpolarized [u/u]

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



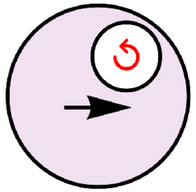
Boer-Mulders [↔/u]

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



Helicity [↻/+]

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



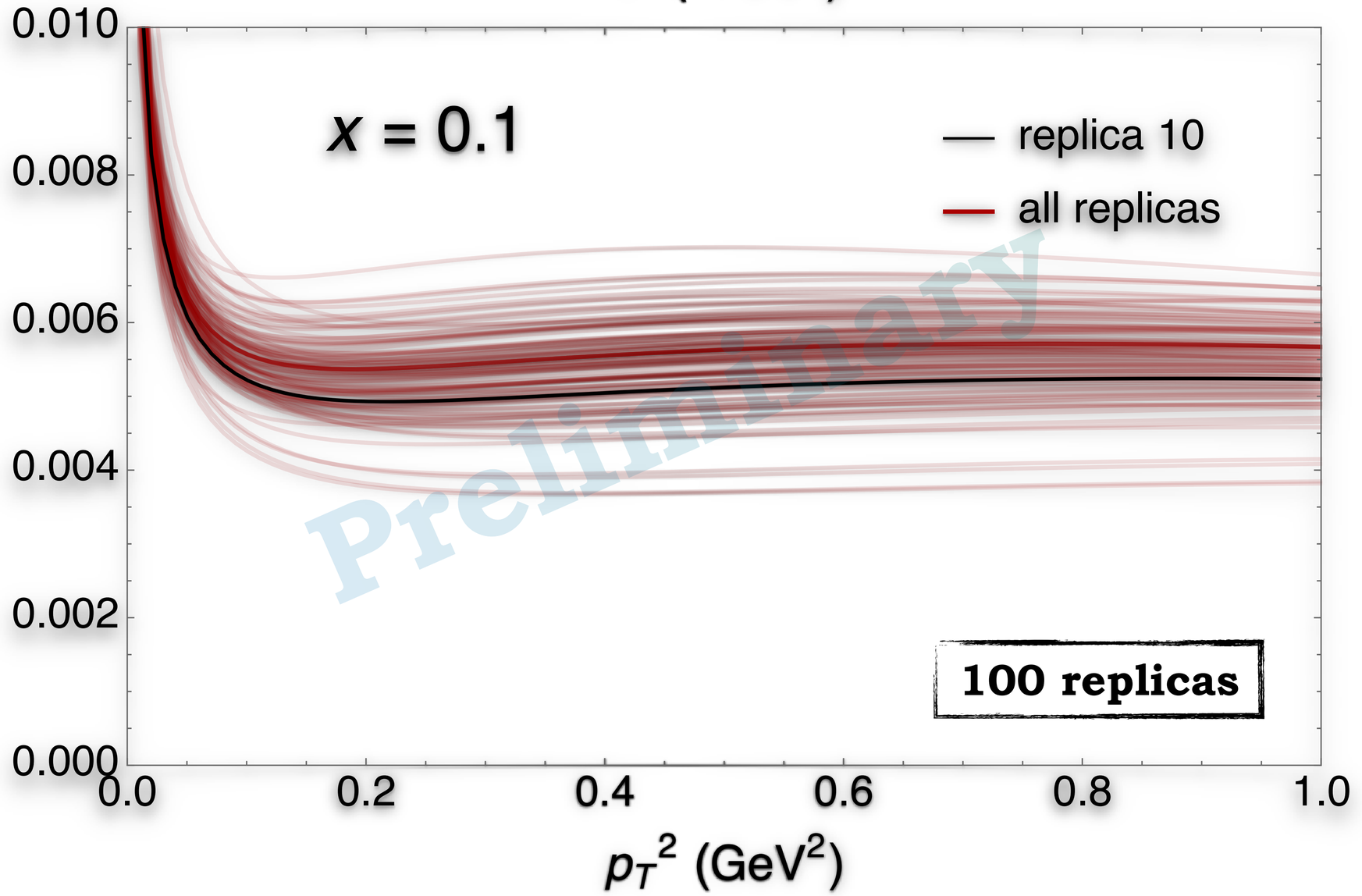
Worm-gear [↻/→]

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

Backup

Sivers / unpol.

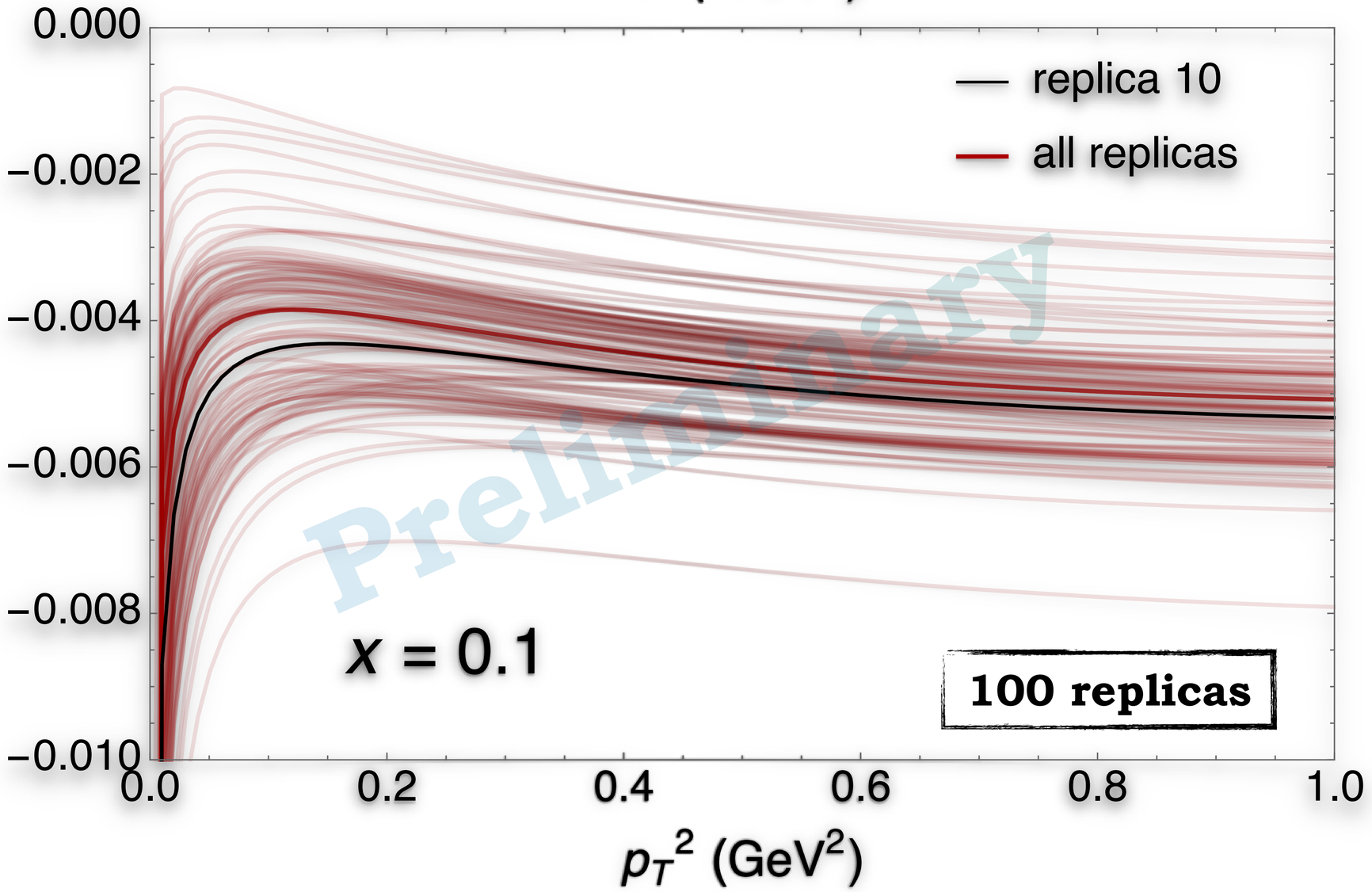
$$\frac{\frac{p_T}{M} f_{1T}^{\perp[+,+]}(x, p_T^2)}{f_1^g(x, p_T^2)}$$



Backup

Linearity / unpol.

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



Backup