9th Workshop of the APS Topical Group on Hadronic Physics (GHP)

April 15th, 2021

A spectator-model way to TMD gluon distribution functions

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

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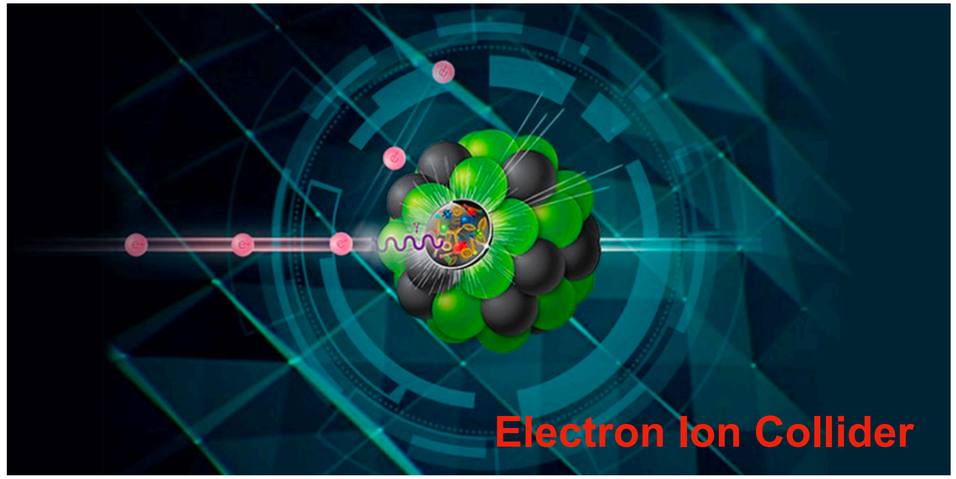

Motivation

- 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

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

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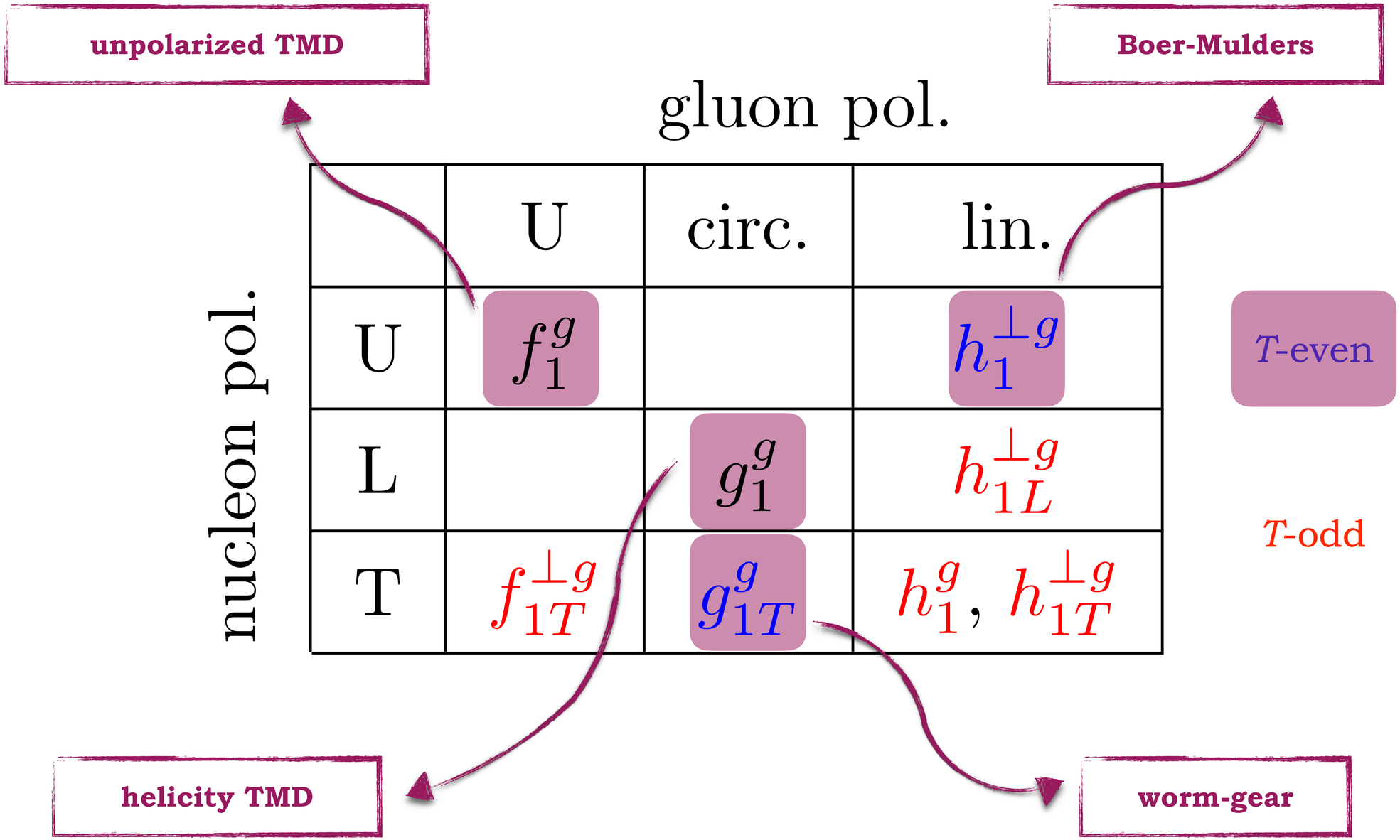

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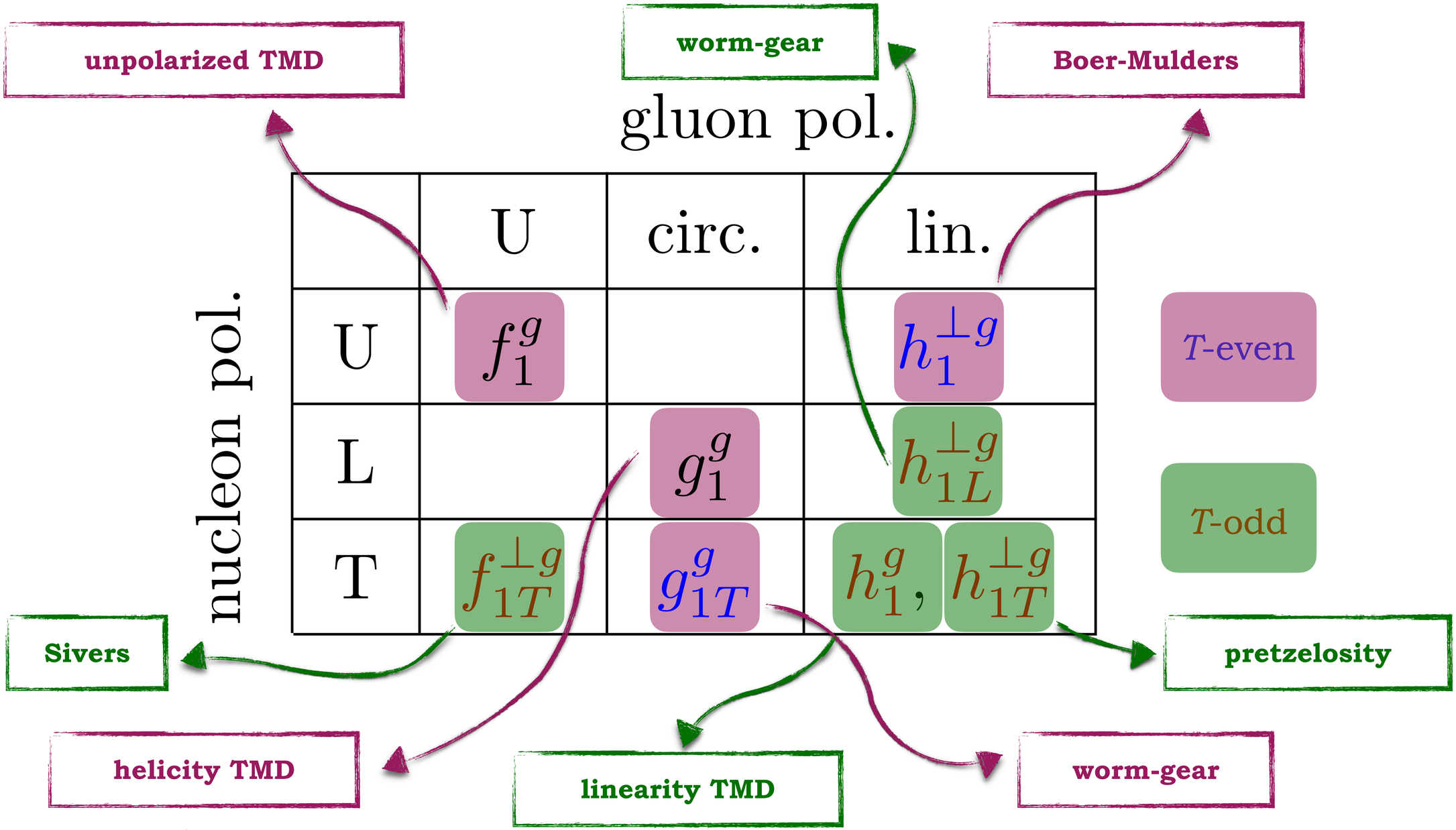

Gluon TMDs: gauge links and modified universality

* **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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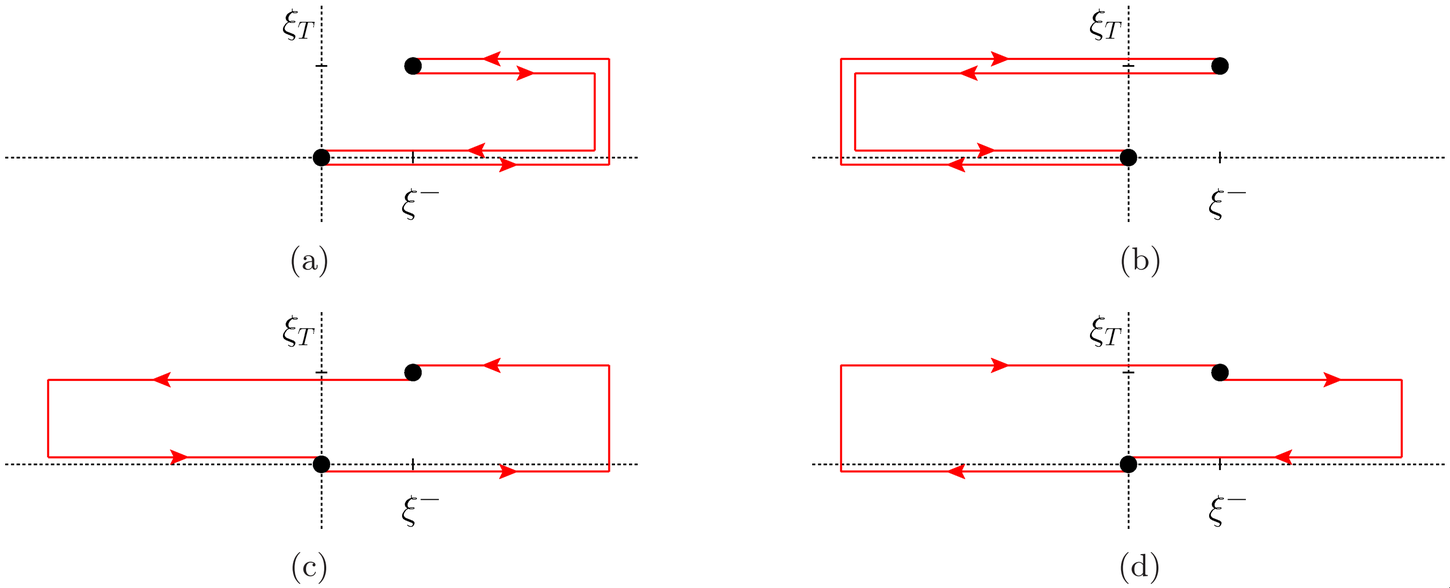

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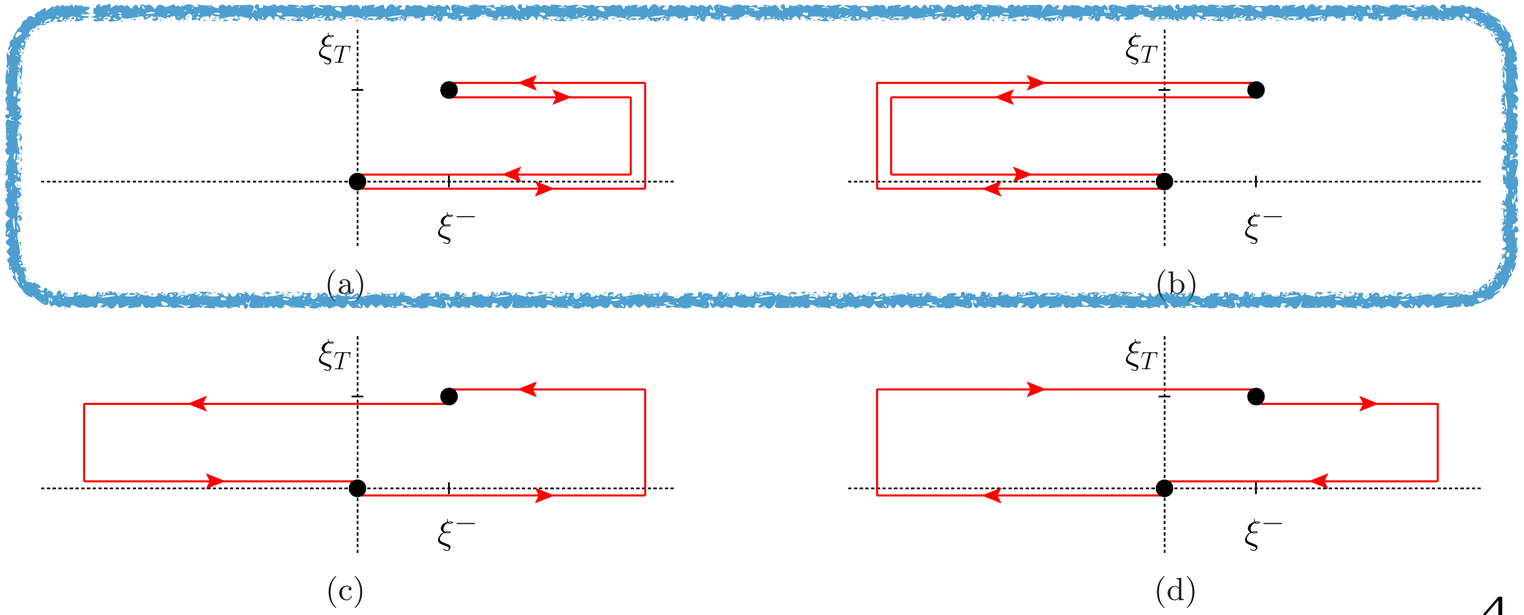
Weiszäcker-Williams (WW)

(a) [+ , +] or (b) [− , −]



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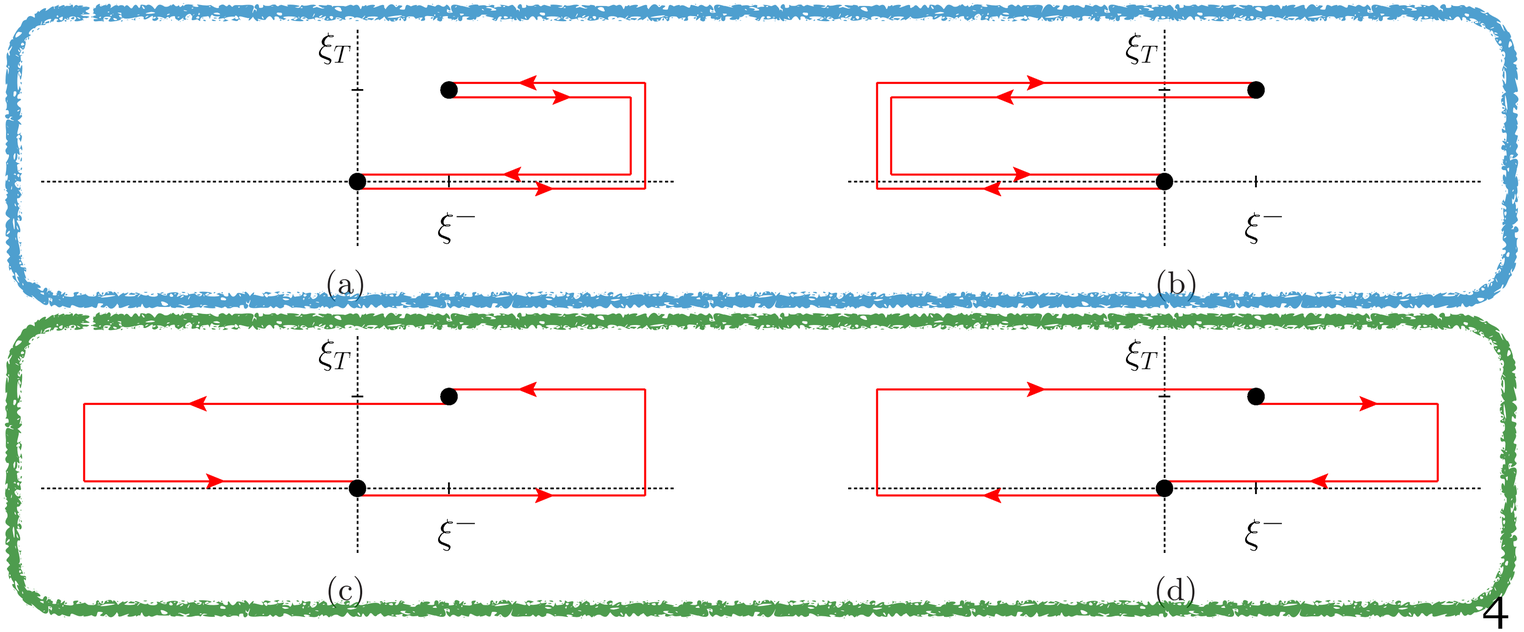
Dipole (DP)

(c) [+ , −] or (d) [− , +]



Accessing WW and DP gluon TMDs

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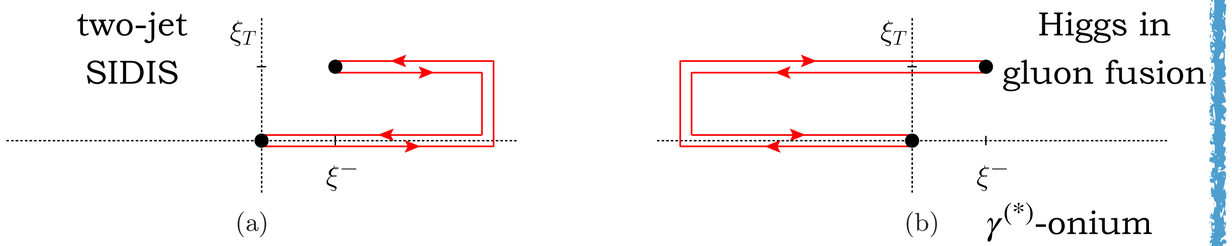

Higgs in gluon fusion

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

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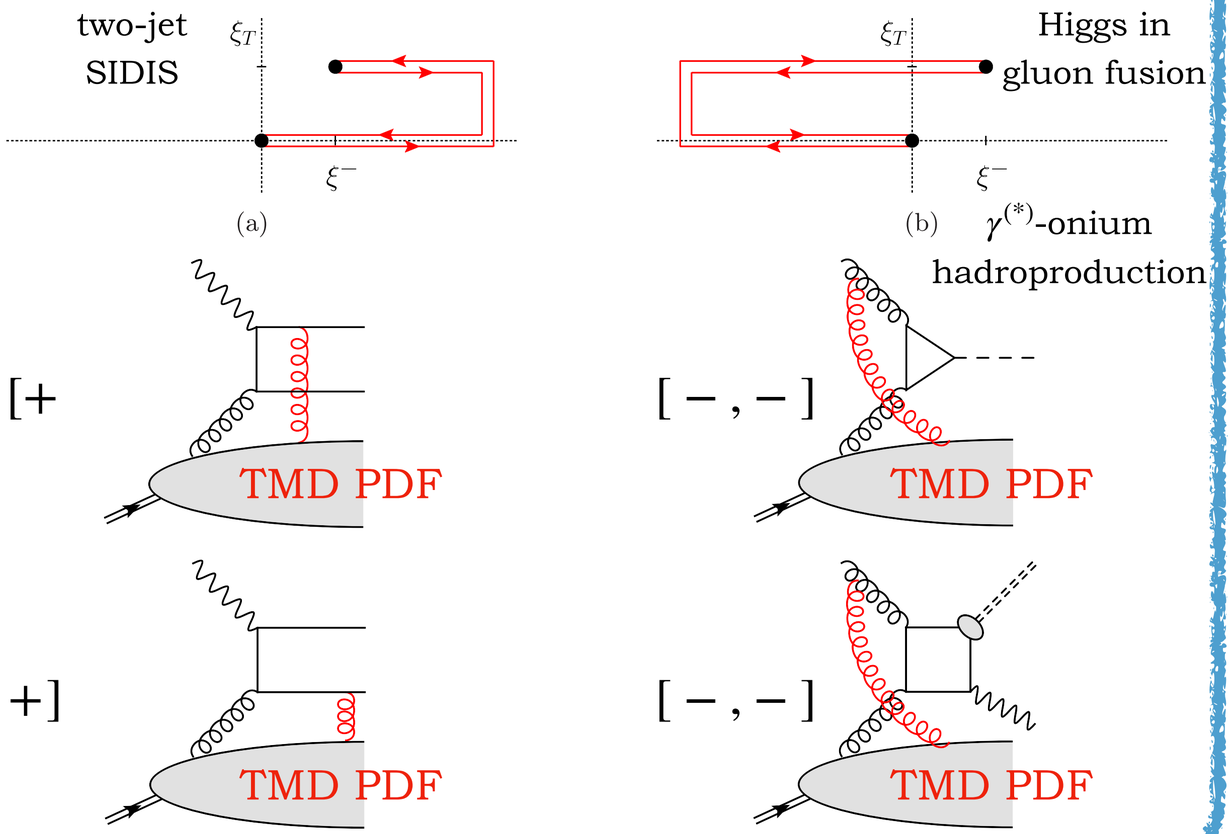

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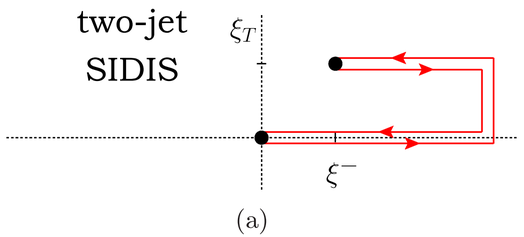
two-jet SIDIS



(a)

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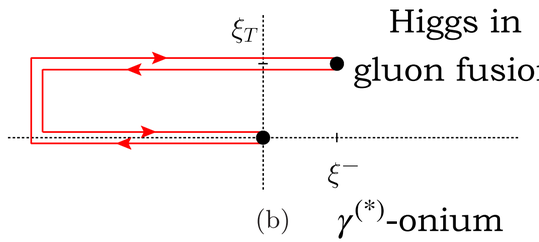
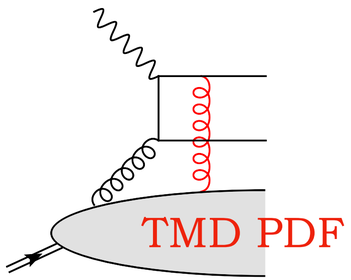


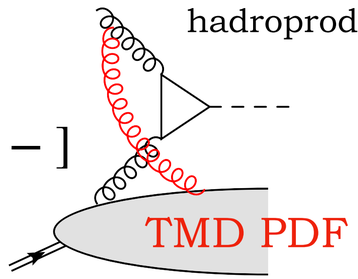
(b)

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

$[+$



$[-,-]$



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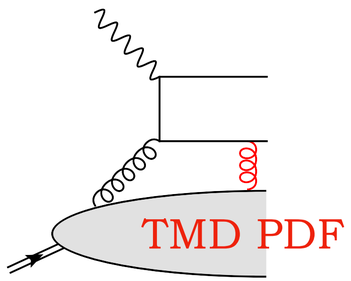

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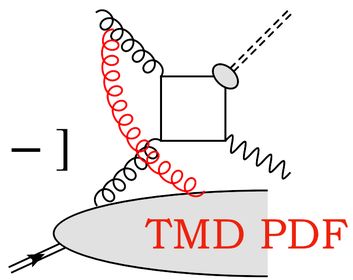

Dipole (DP)

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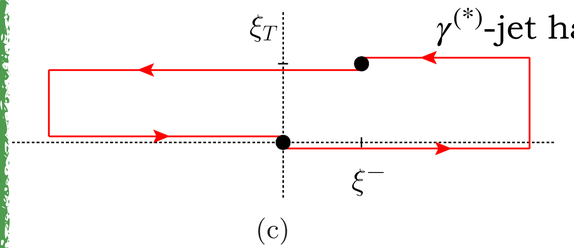
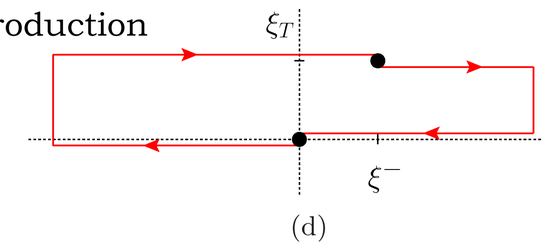


(c)

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



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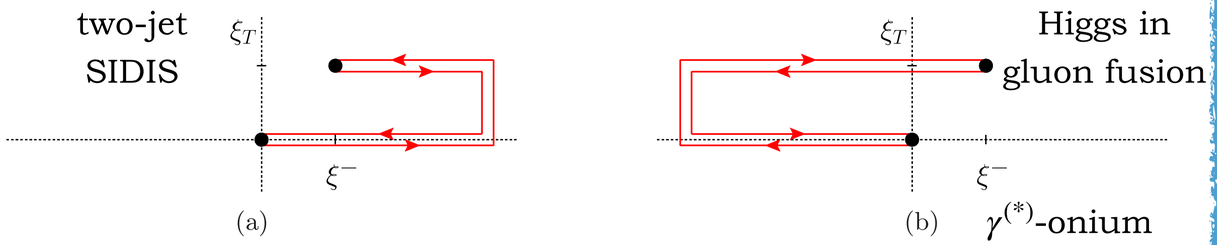

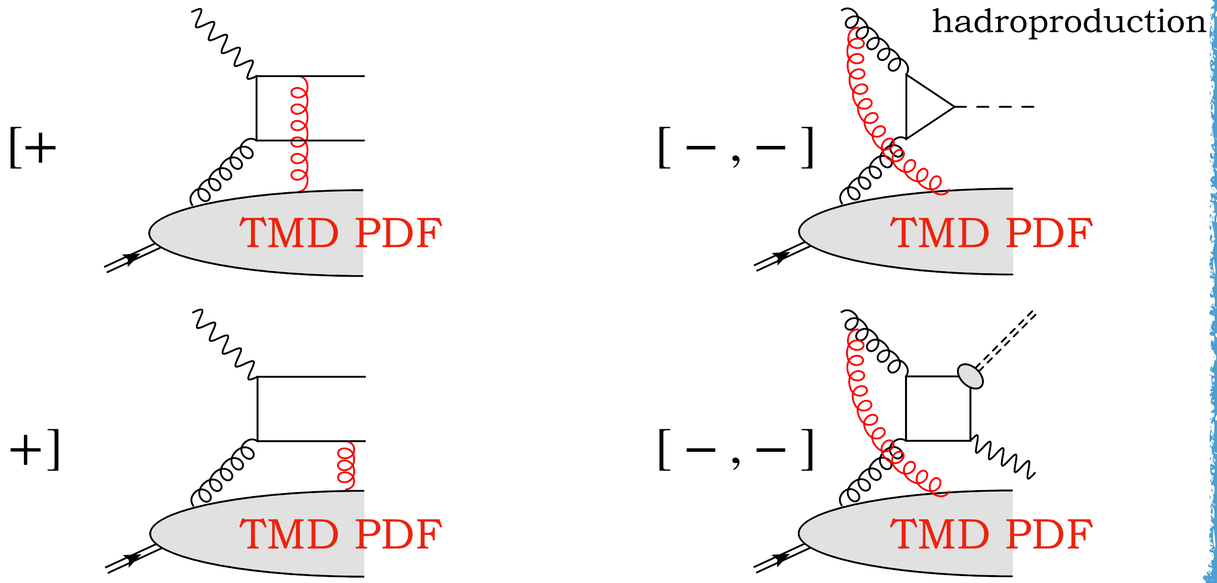

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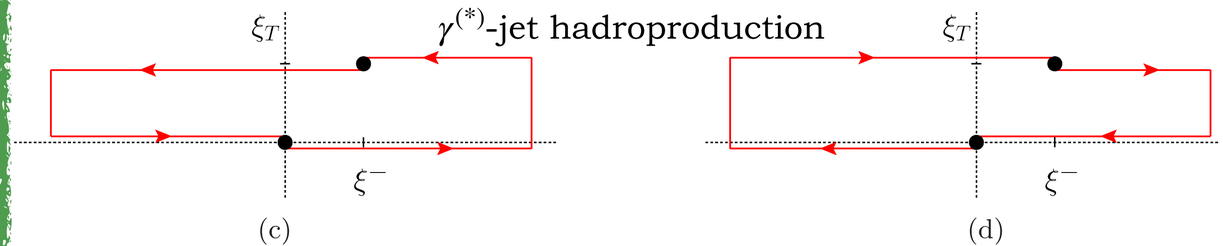

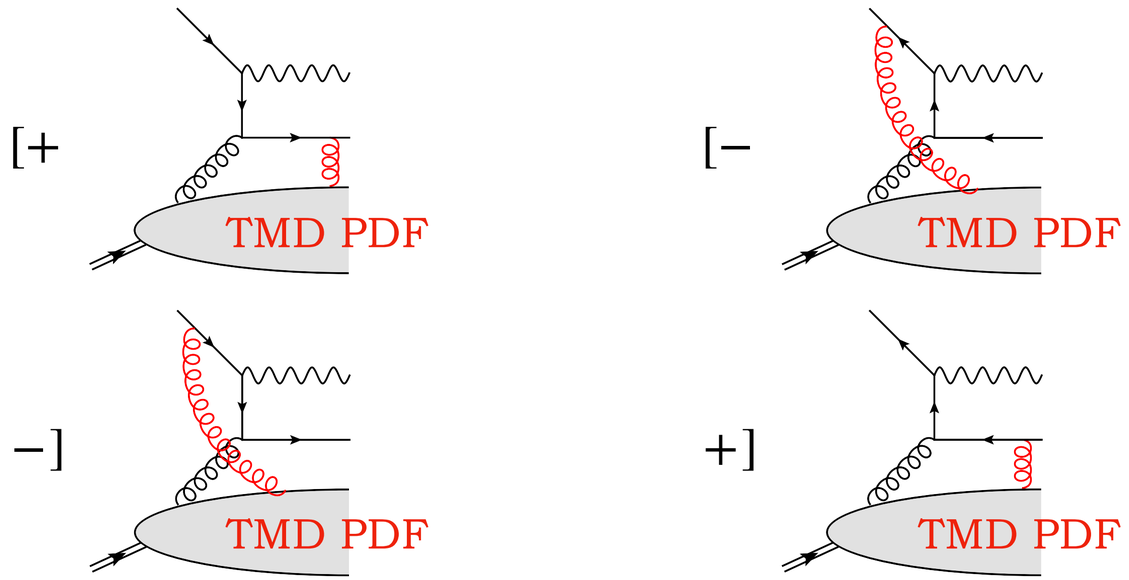

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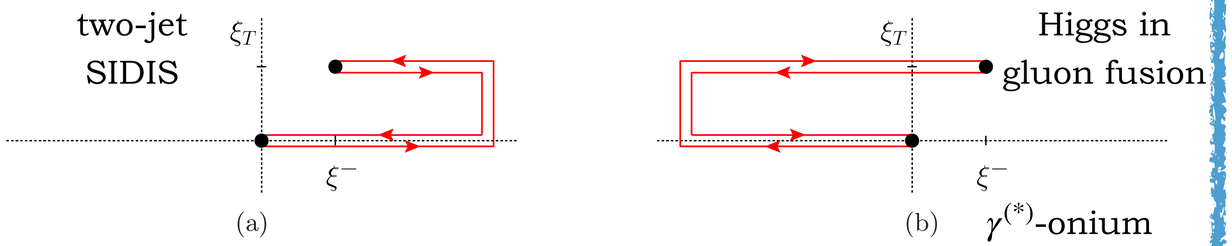

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* f-type gluon TMDs $\rightarrow$ f^{abc} color structure
* Modified universality:

$$f_1^{[+,+]} = f_1^{[-,-]},$$
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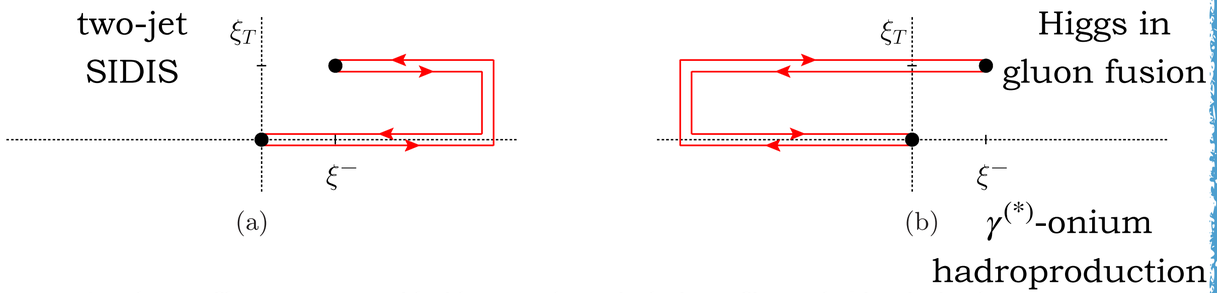

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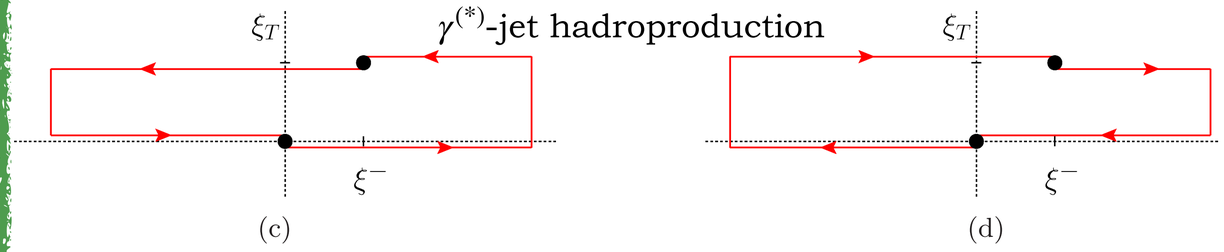

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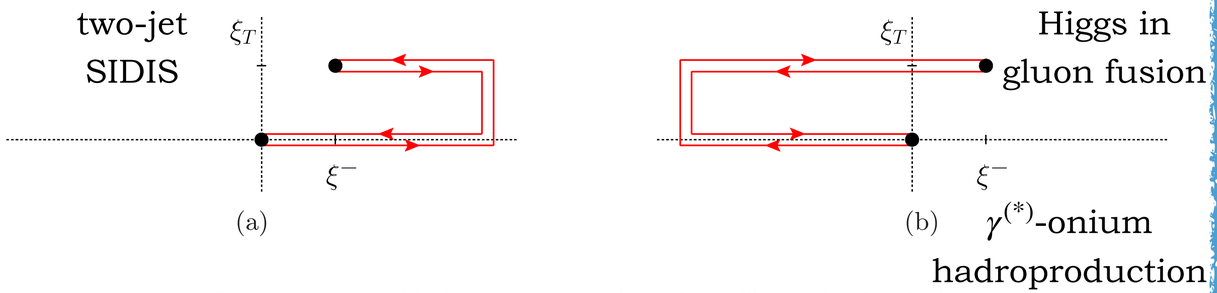

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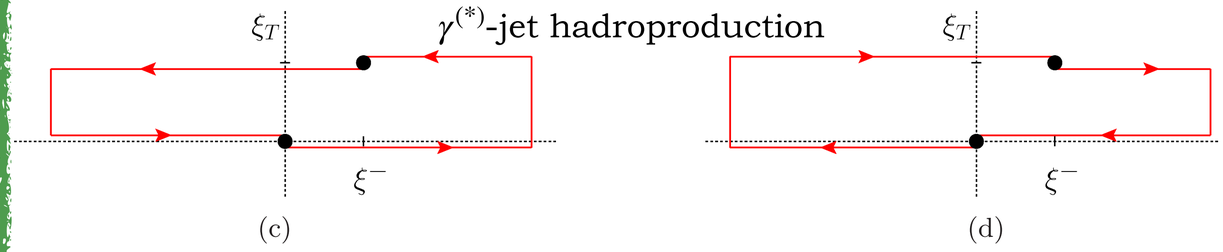

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Gauge link $\rightarrow$ two main independent sets of TMDs, **not related** to each other

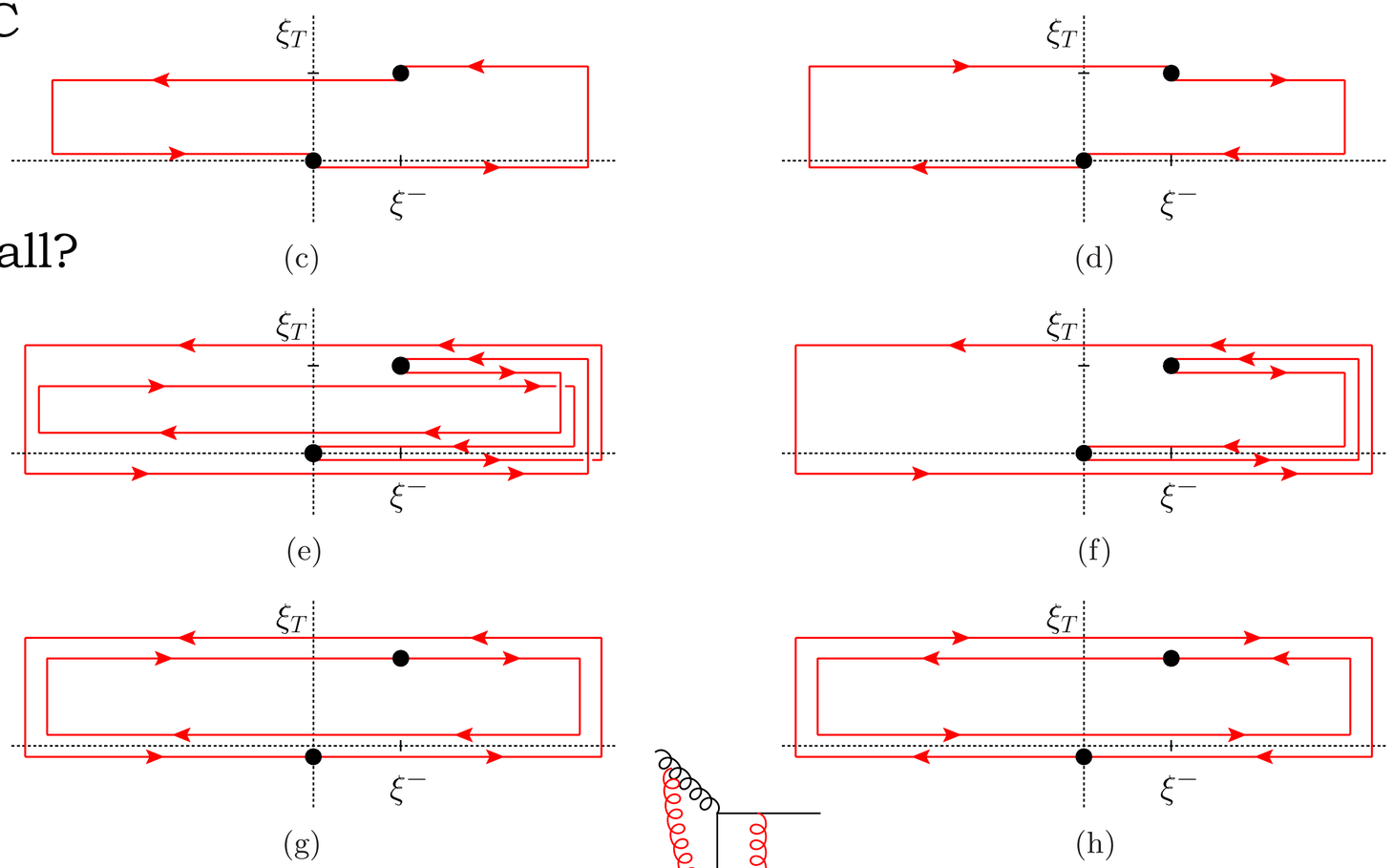
Dihadron hadroproduction and factorization breaking

* 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) $[+,+\square]$,

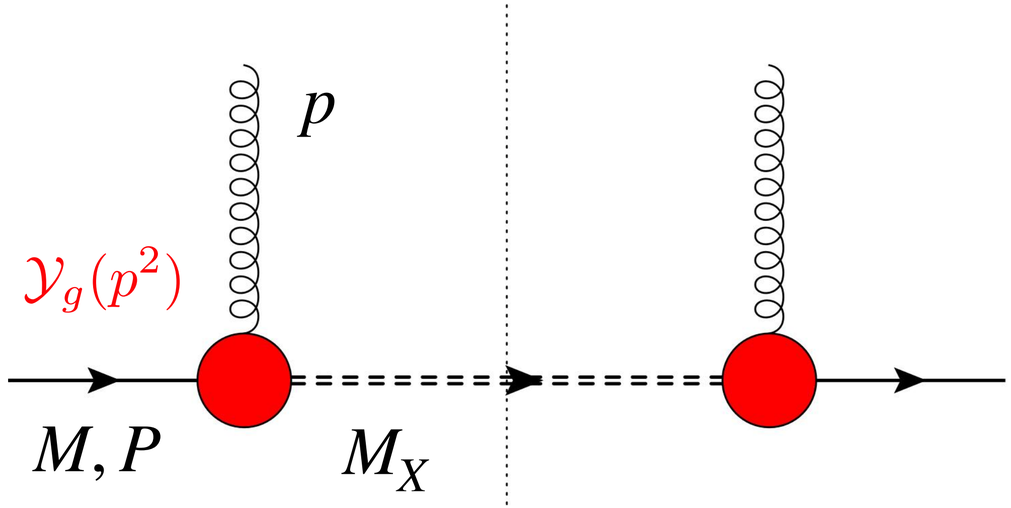
  (g) $[\square,\square]$, and (h) $[\square,\square]$



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)

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

Assumptions of the model

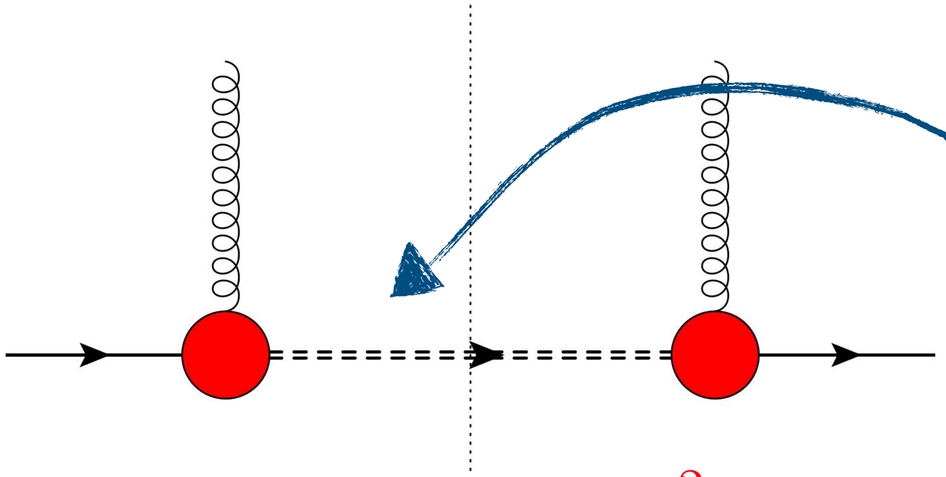
Spectator-system spectral-mass function

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)]

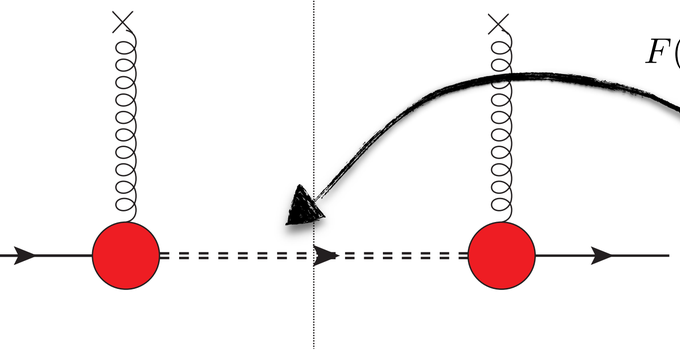


$\mathcal{Y}_g(p^2)$

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

Our model at a glance

Spectator-system spectral-mass function



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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

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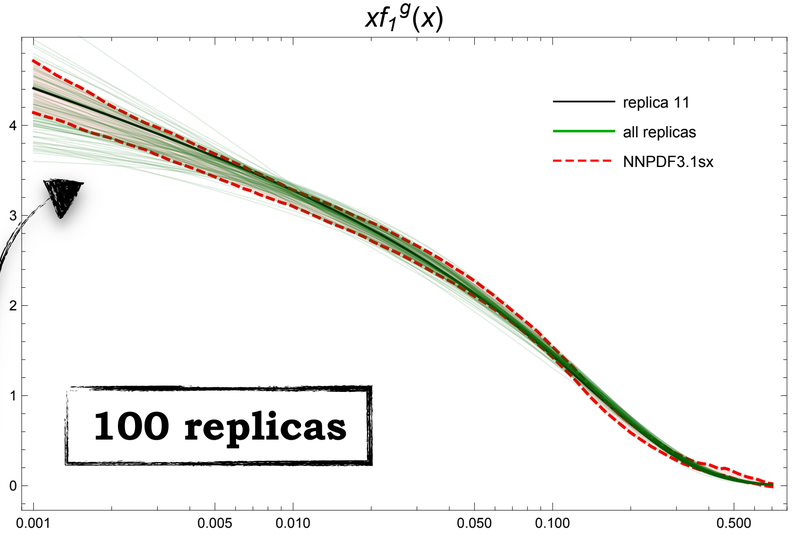

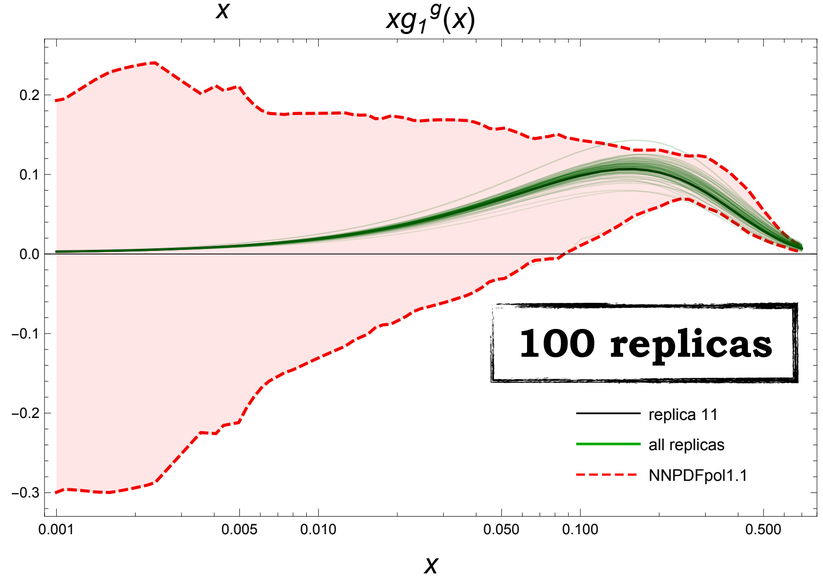

Fit specifics

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

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

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Our model @ $Q_0 = 1.64$ GeV

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

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

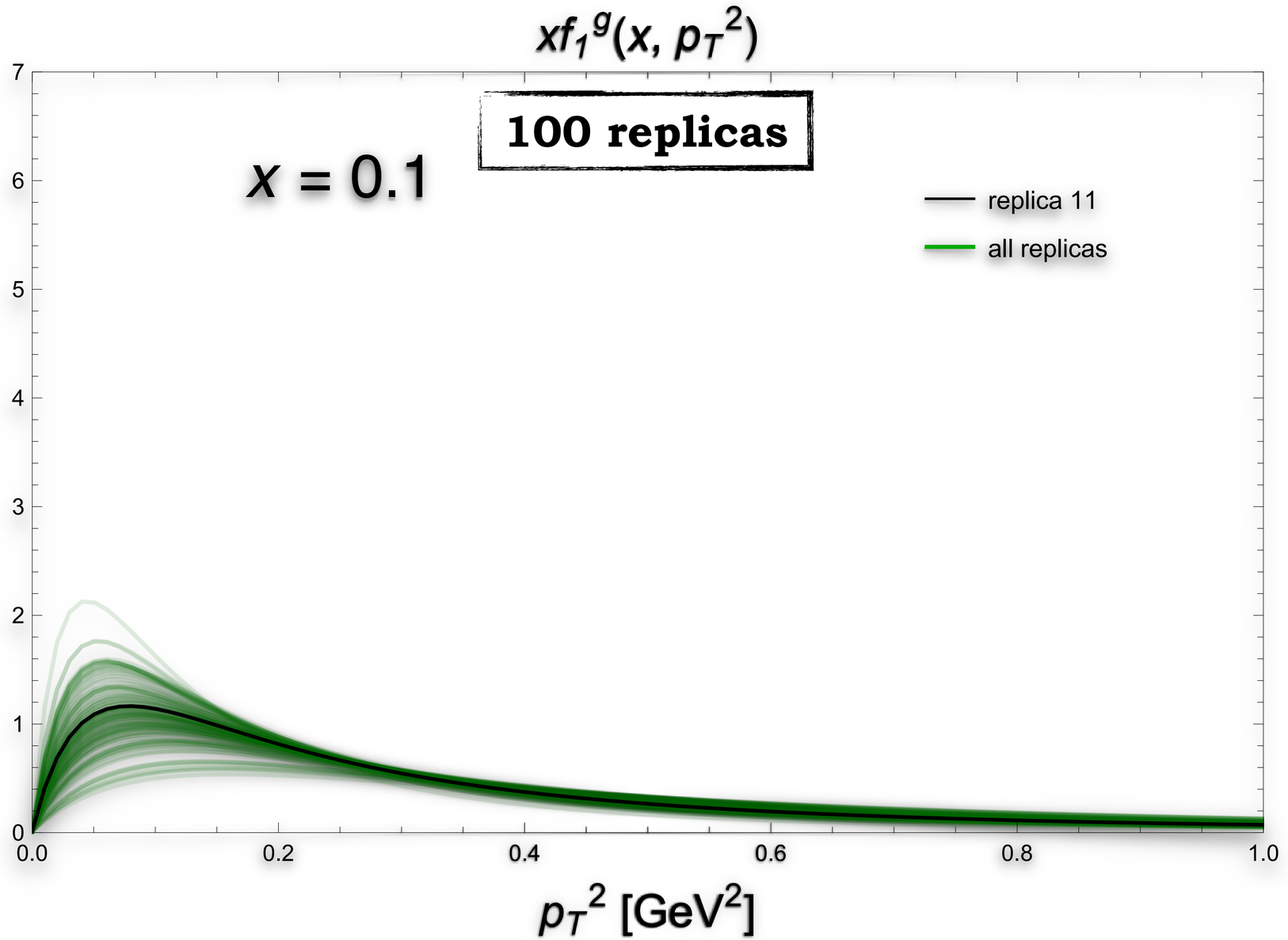
Lattice @ $Q_0 = 2$ GeV

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

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

🔗 [C. Alexandrou *et al.* (2020)]

Unpolarized gluon TMD



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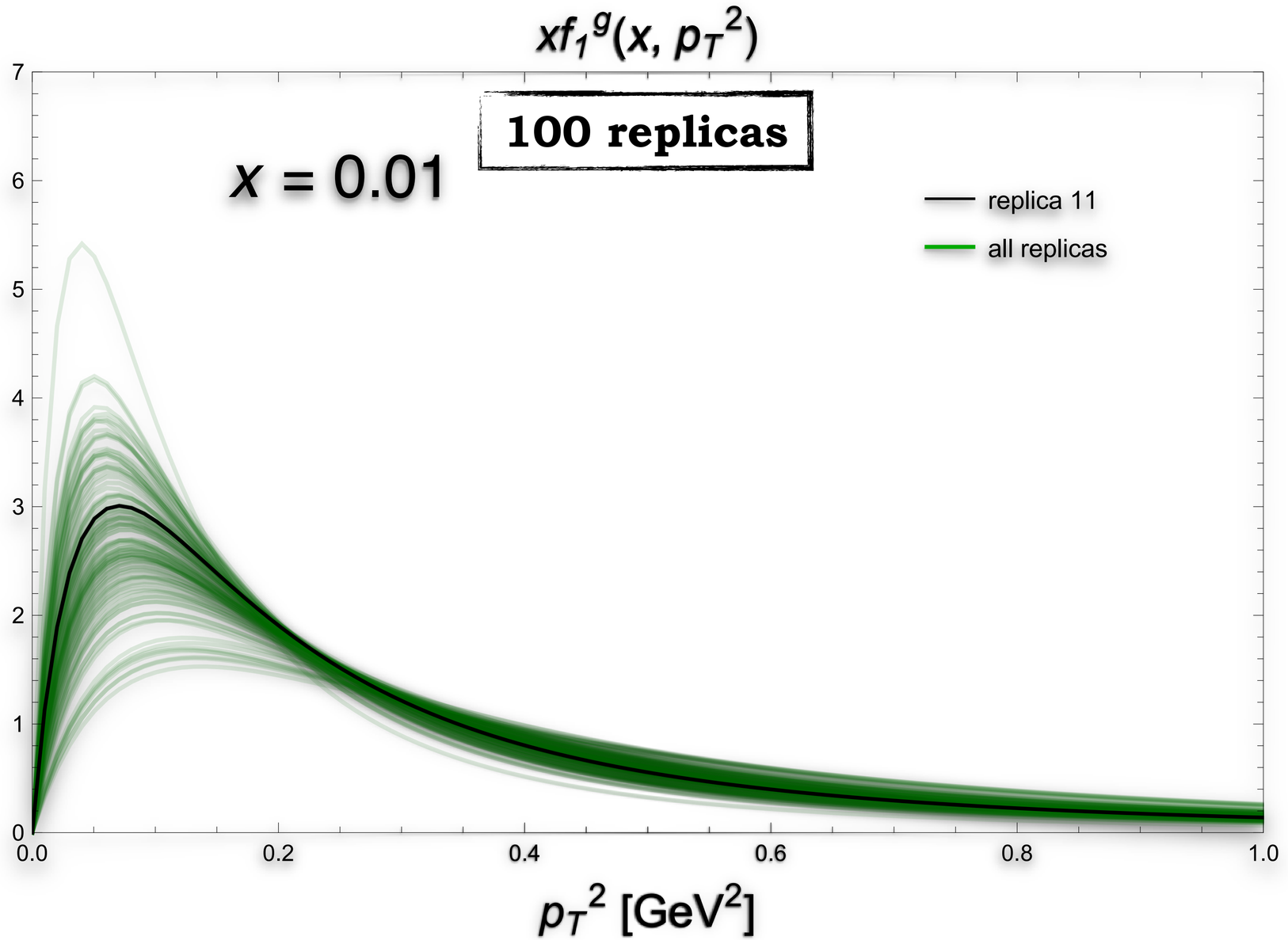

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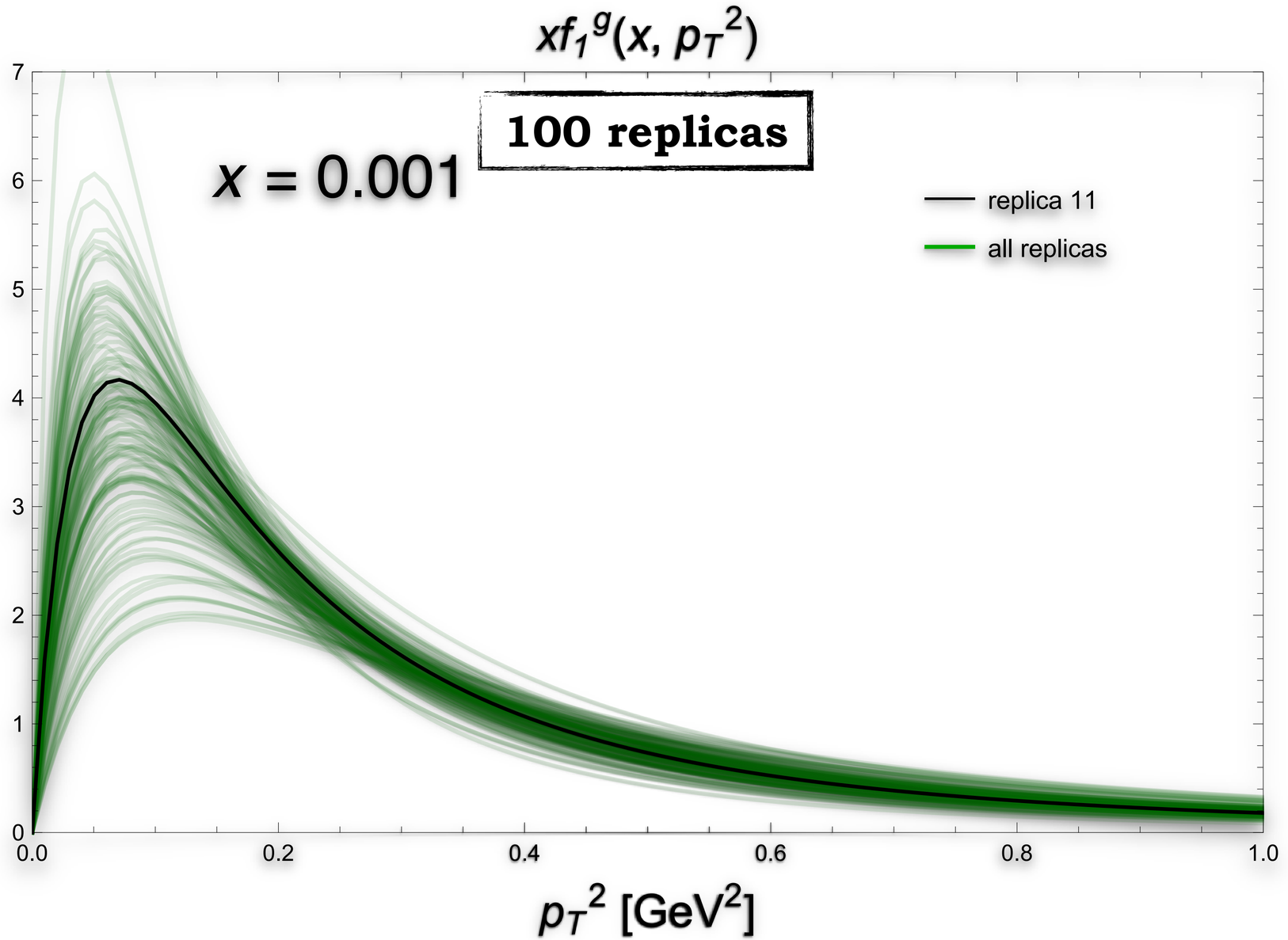
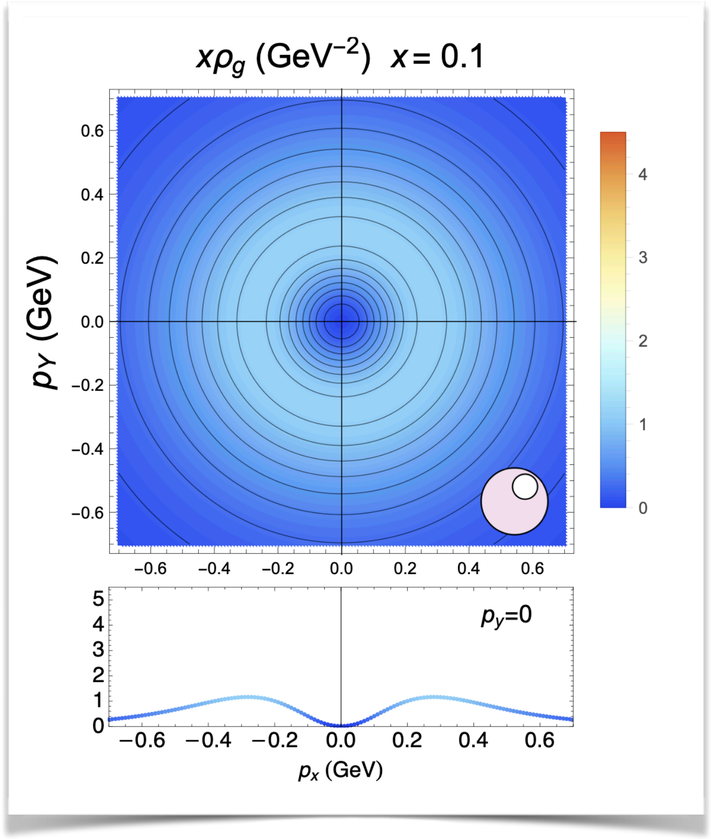


3D tomography: the gluon content in the proton

unpolarized TMD



[A. Bacchetta, F.G.C., M. Radici, P. Taels, *Eur. Phys. J. C* **80** (2020) no.8 [arXiv:2005.02288]]

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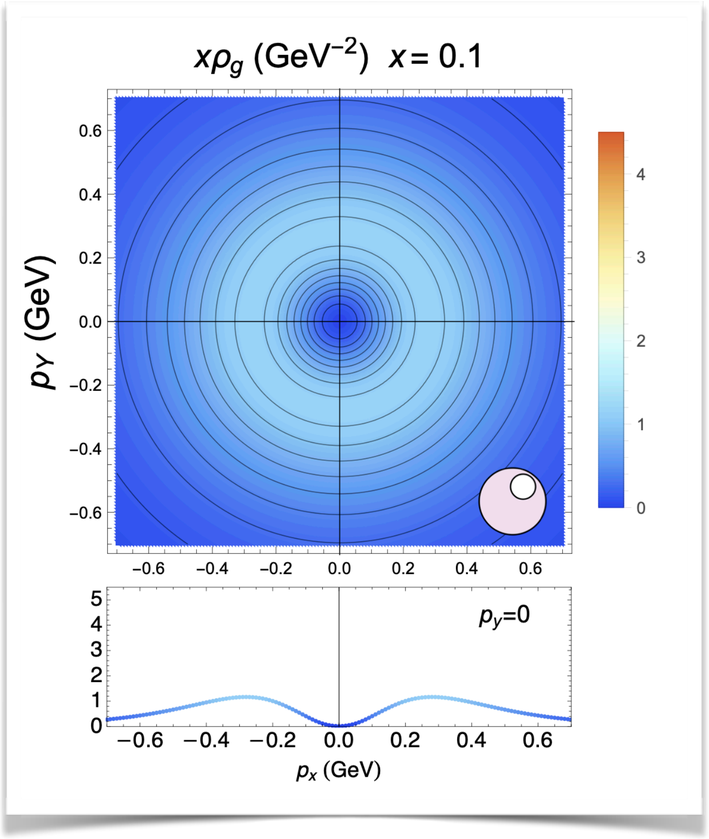
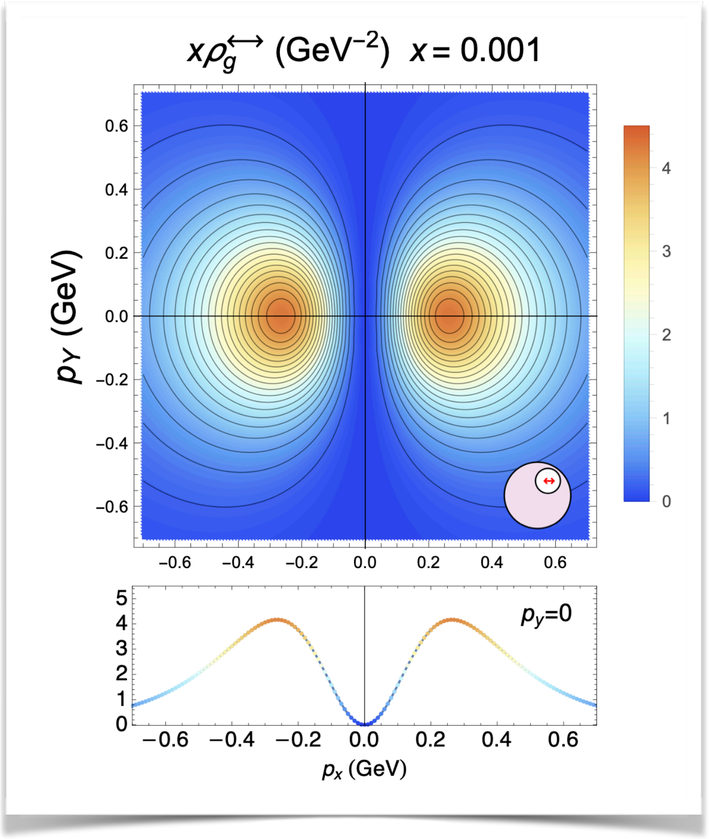


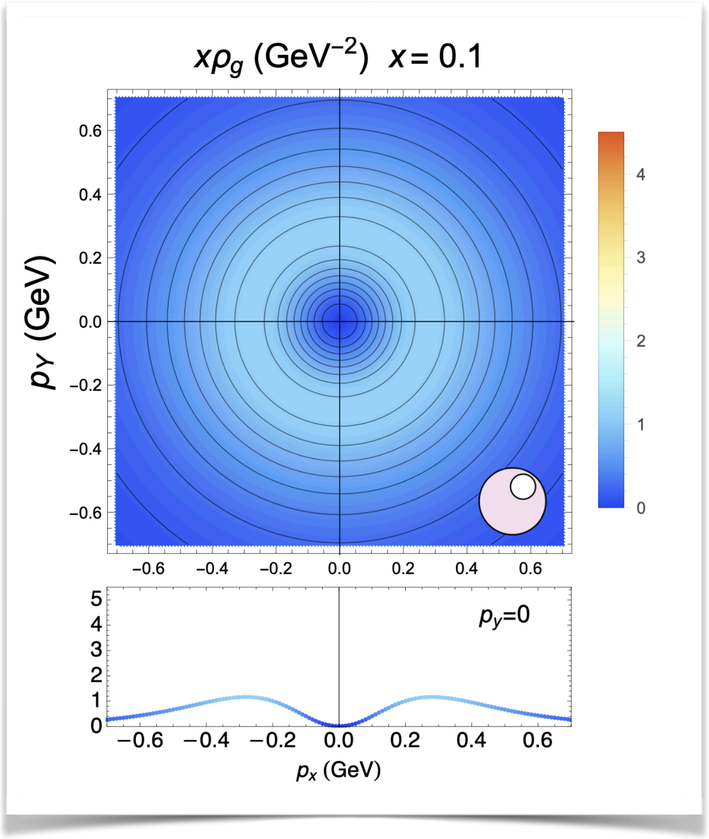
Boer-Mulders



🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels, *Eur. Phys. J. C* **80** (2020) no.8 [arXiv:2005.02288]]

3D tomography: the gluon content in the proton

unpolarized TMD



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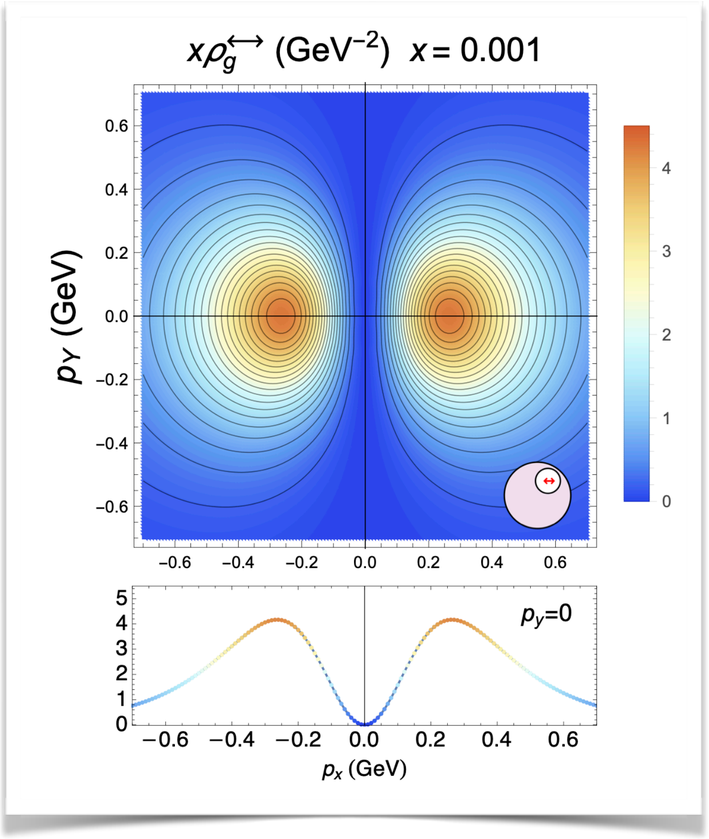
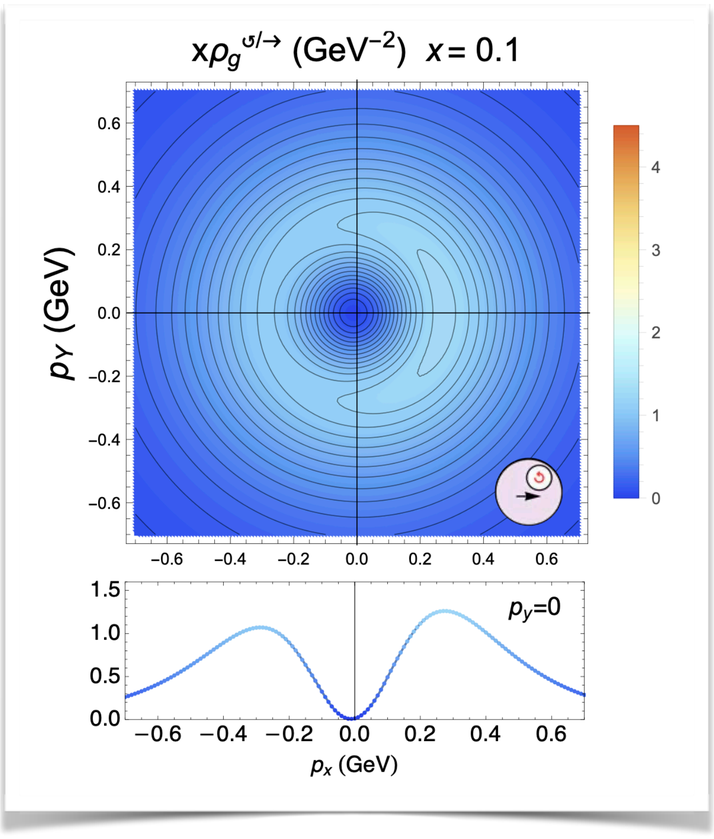


worm-gear



🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels, *Eur. Phys. J. C* **80** (2020) no.8 [arXiv:2005.02288]]

…towards twist-2 *T*-odd gluon TMDs

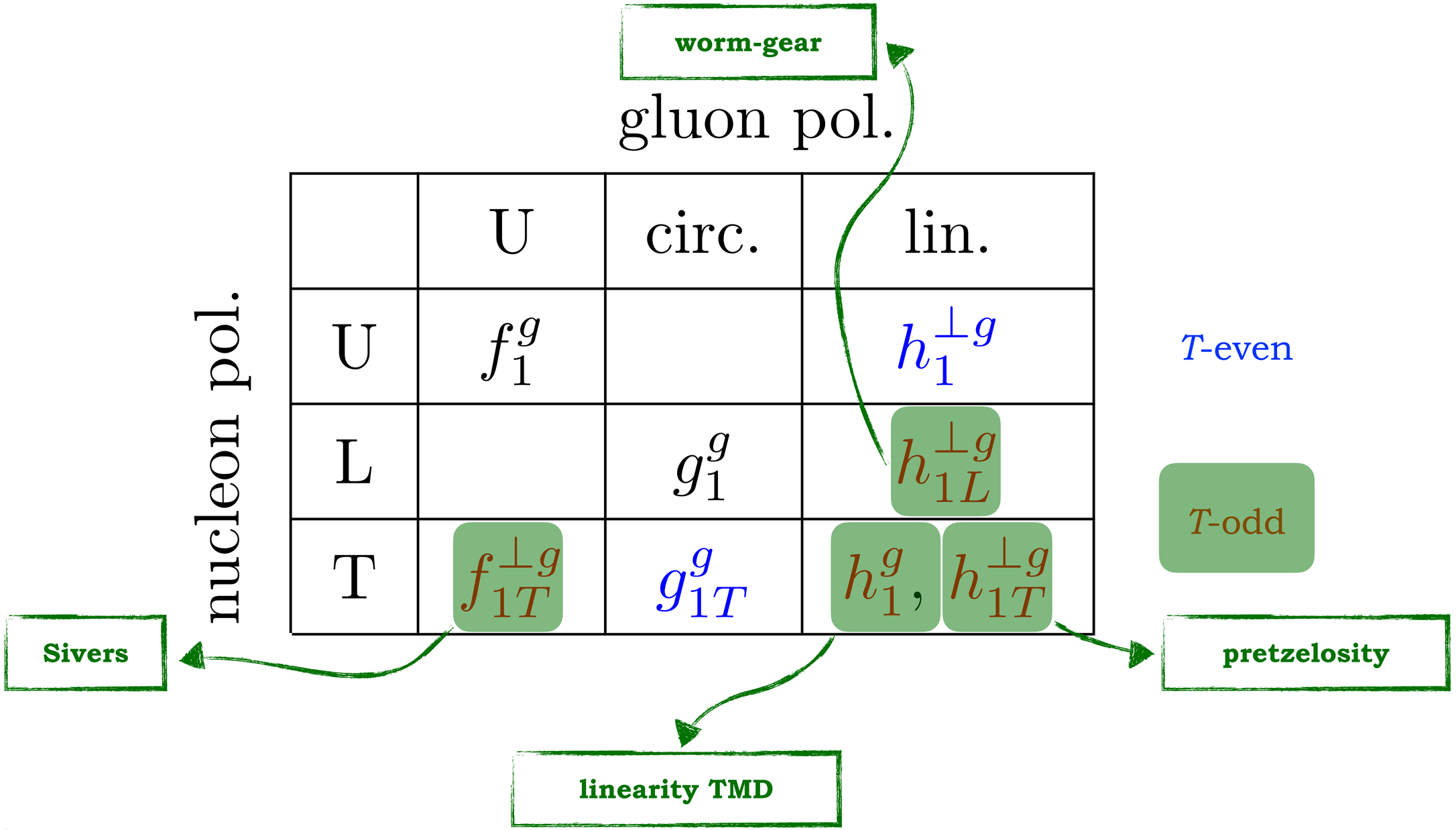
T-odd gluon TMDs at twist-2

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-odd gluon TMDs at twist-2



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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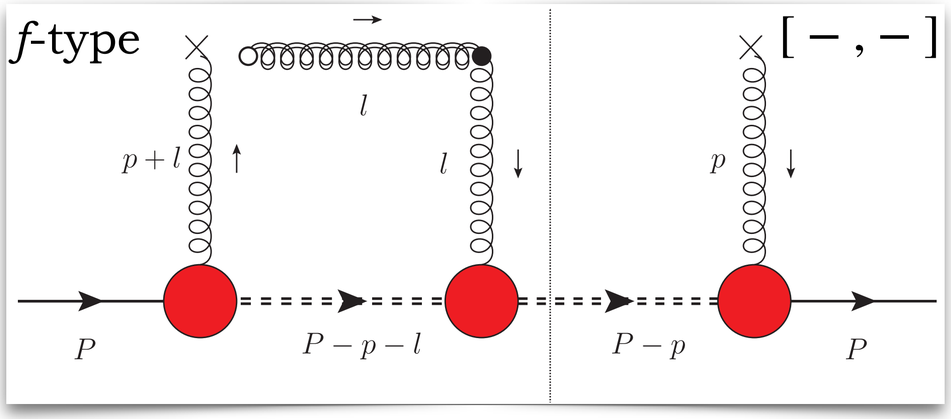
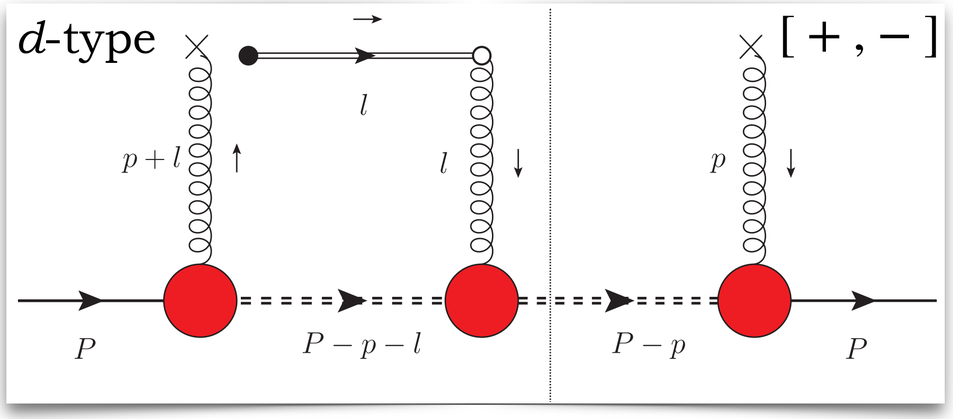
$gg \to H$



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



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

Closing statements

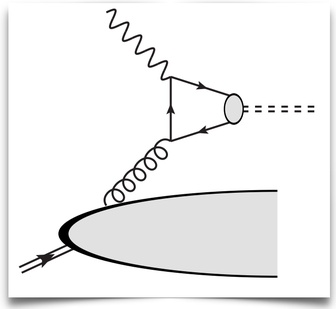
- ☑ Systematic calculation of all twist-2 T-even gluon TMDs
- ☑ Spectral mass to catch small- and large-x effects
- ☑ **Simultaneous fit** of f_1 and g_1 PDFs via **replica method**

Closing statements

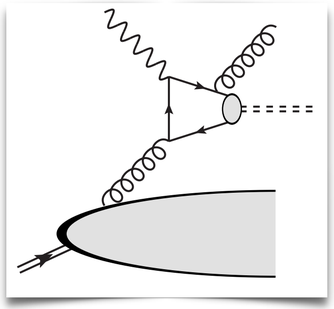
- ☑ Systematic calculation of all twist-2 T-even gluon TMDs
- ☑ Spectral mass to catch small- and large-x effects
- ☑ **Simultaneous fit** of f_1 and g_1 PDFs via **replica method**
- ☐ Twist-2 T-odd gluon TMDs (**Sivers**, etc.) soon available!
- ☐ Pheno: **spin asymmetries**, **pseudodata** and **impact 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

Gluon TMDs and quarkonia

SIDIS



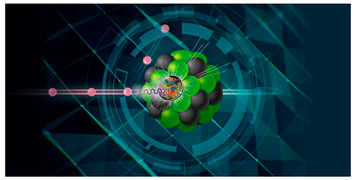
CO

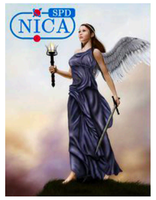


CO + CS

EIC Yellow Report Document
(EICUG website)

[EICUG [arXiv:2103.05419]]



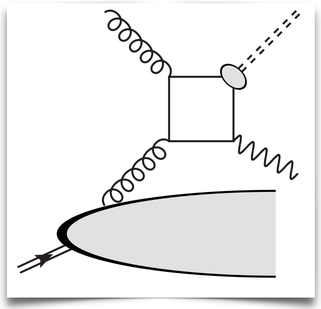


CERN

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 slides

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

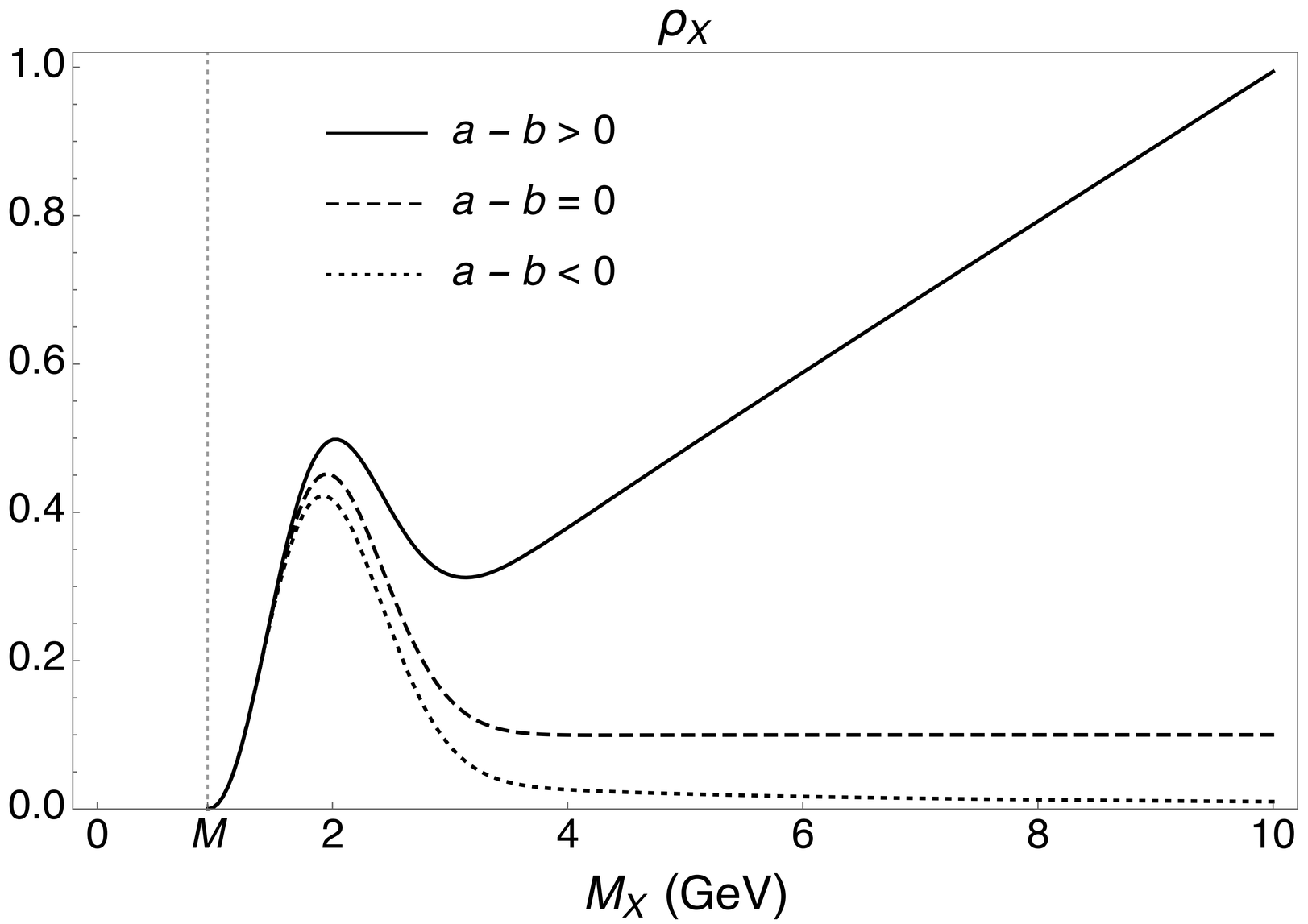
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

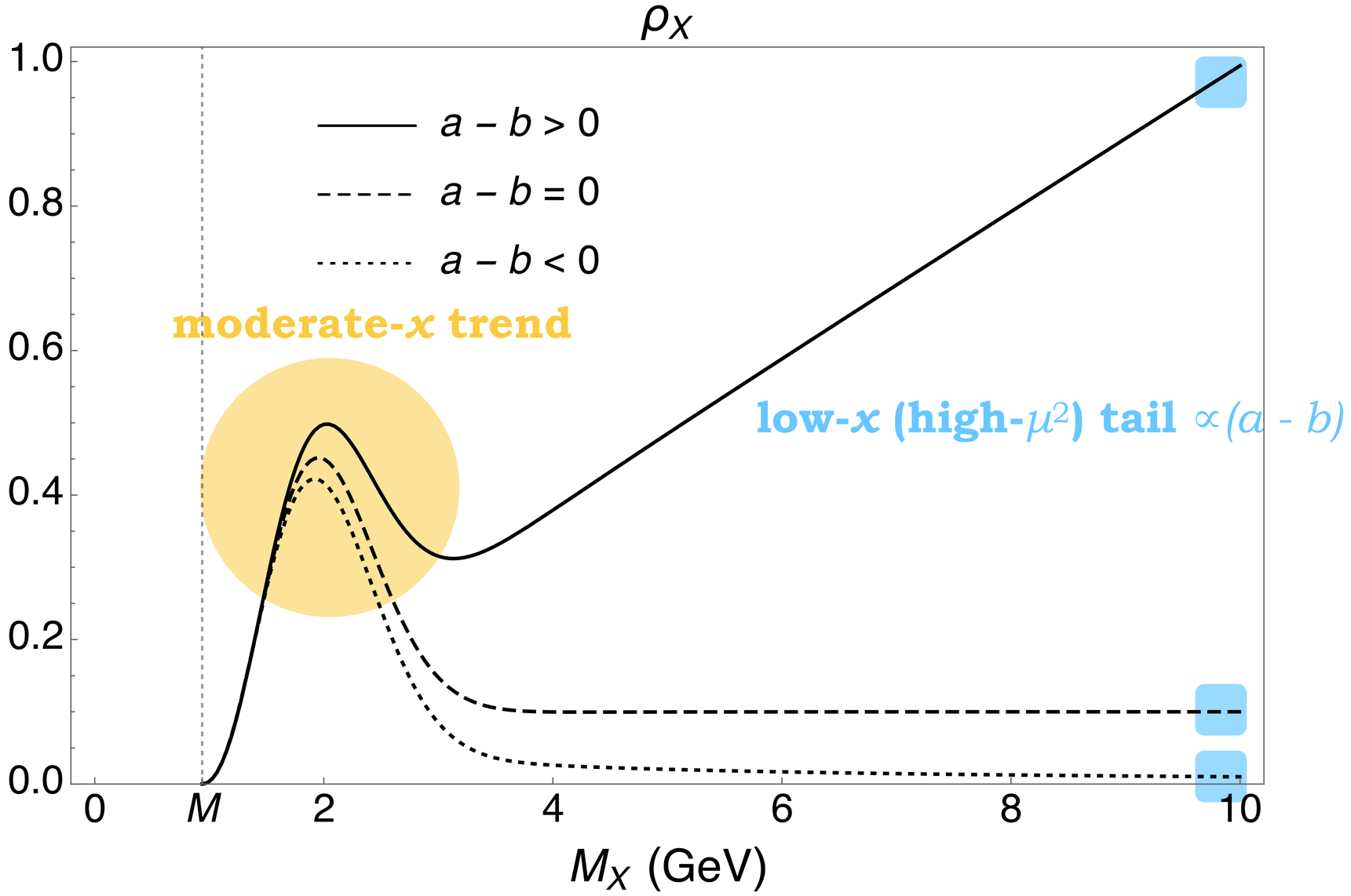
Backup

Spectral function vs *(a - b)*



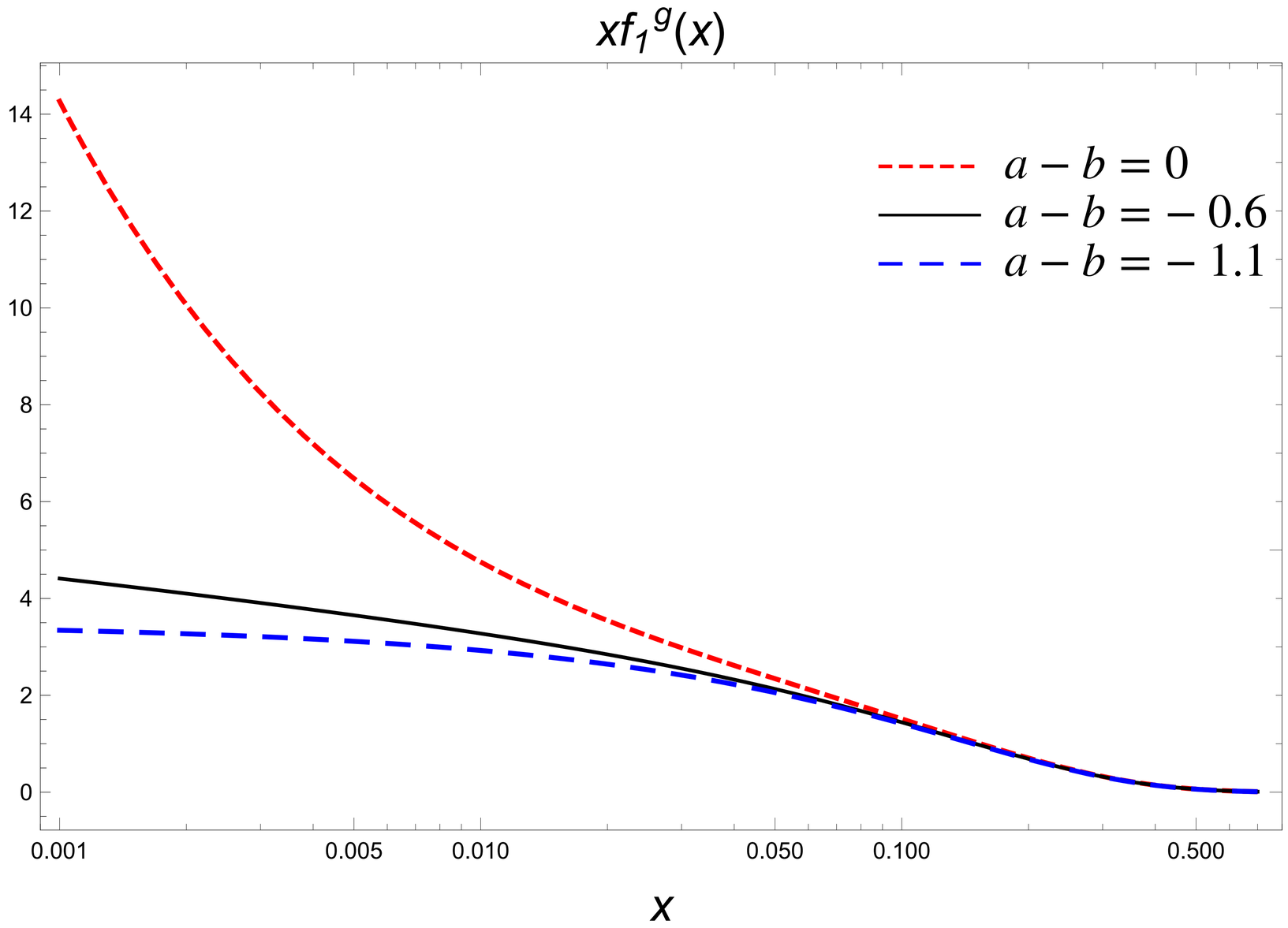
Backup

Spectral function vs $(a - b)$



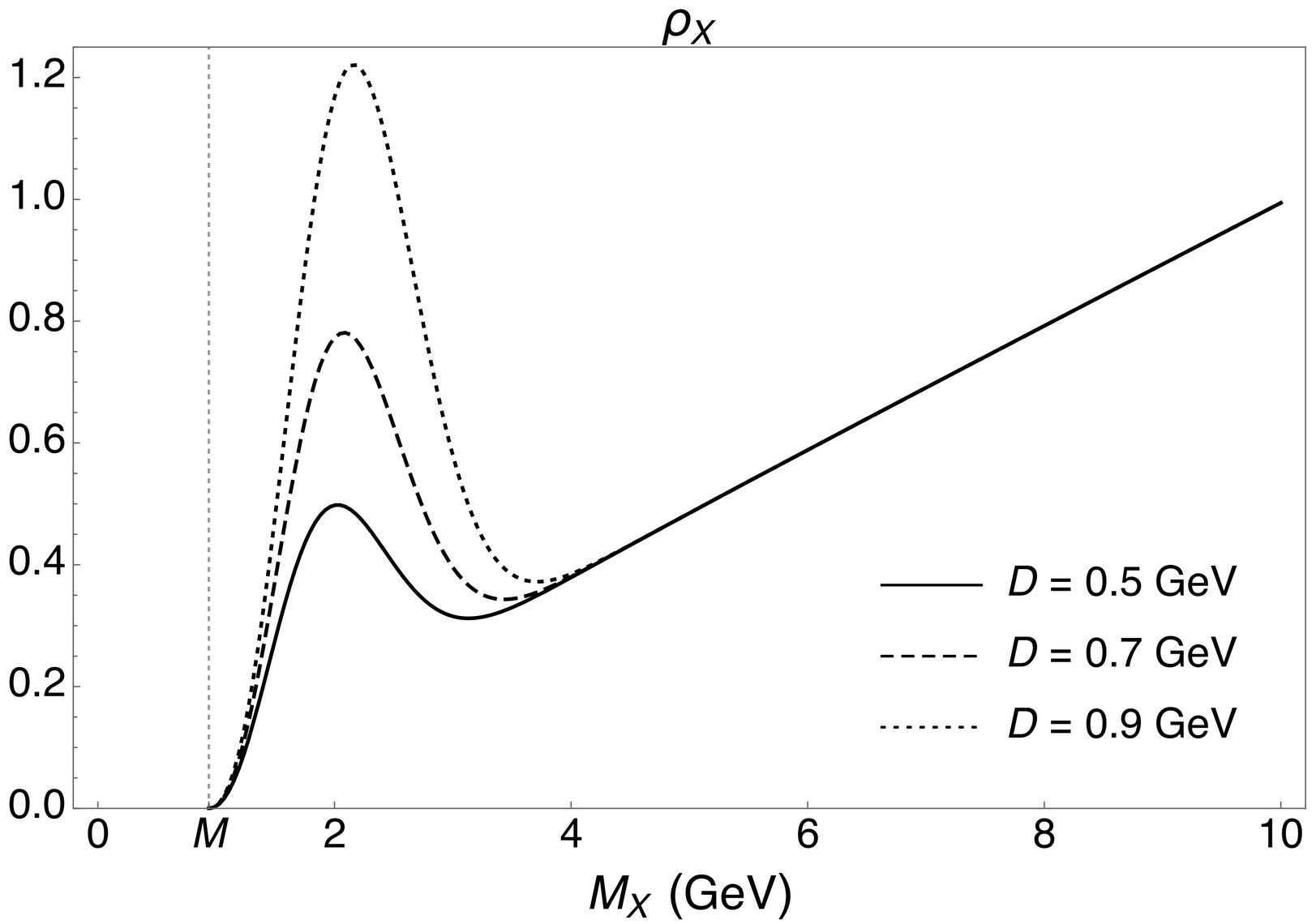
Backup

xf_1 collinear PDF vs $(a - b)$



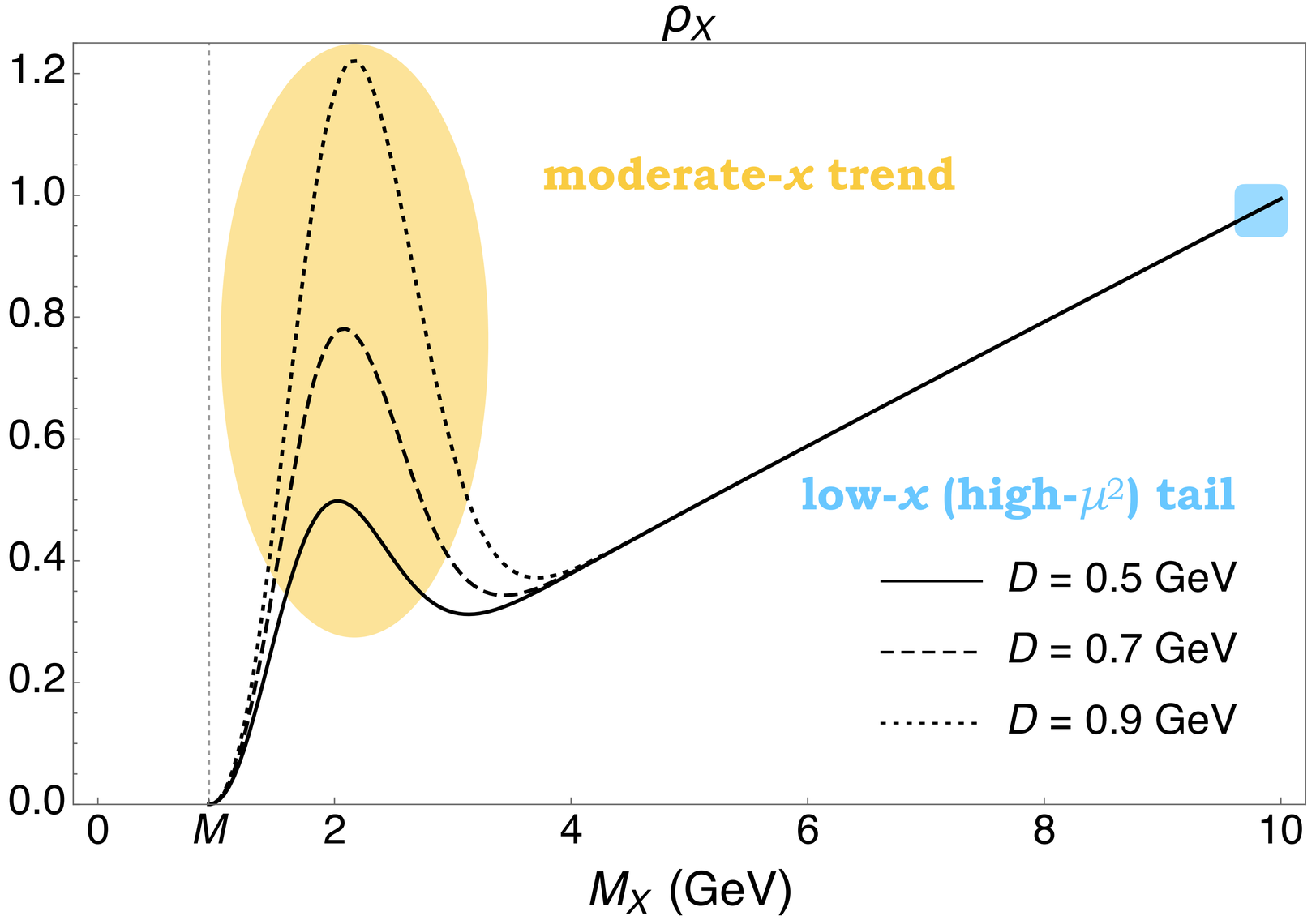
Backup

Spectral function vs D



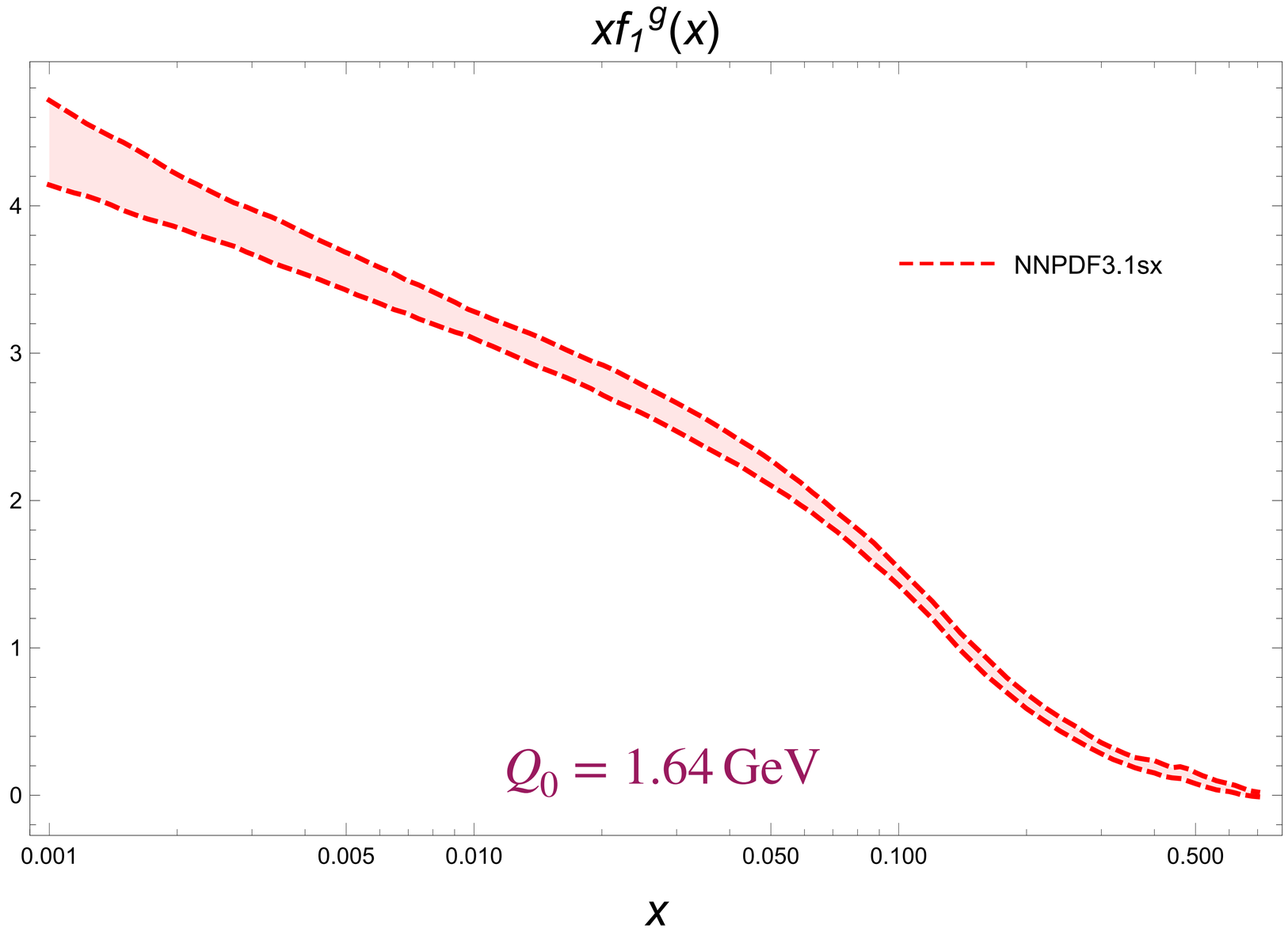
Backup

Spectral function vs D



Backup

Unpolarized gluon PDF



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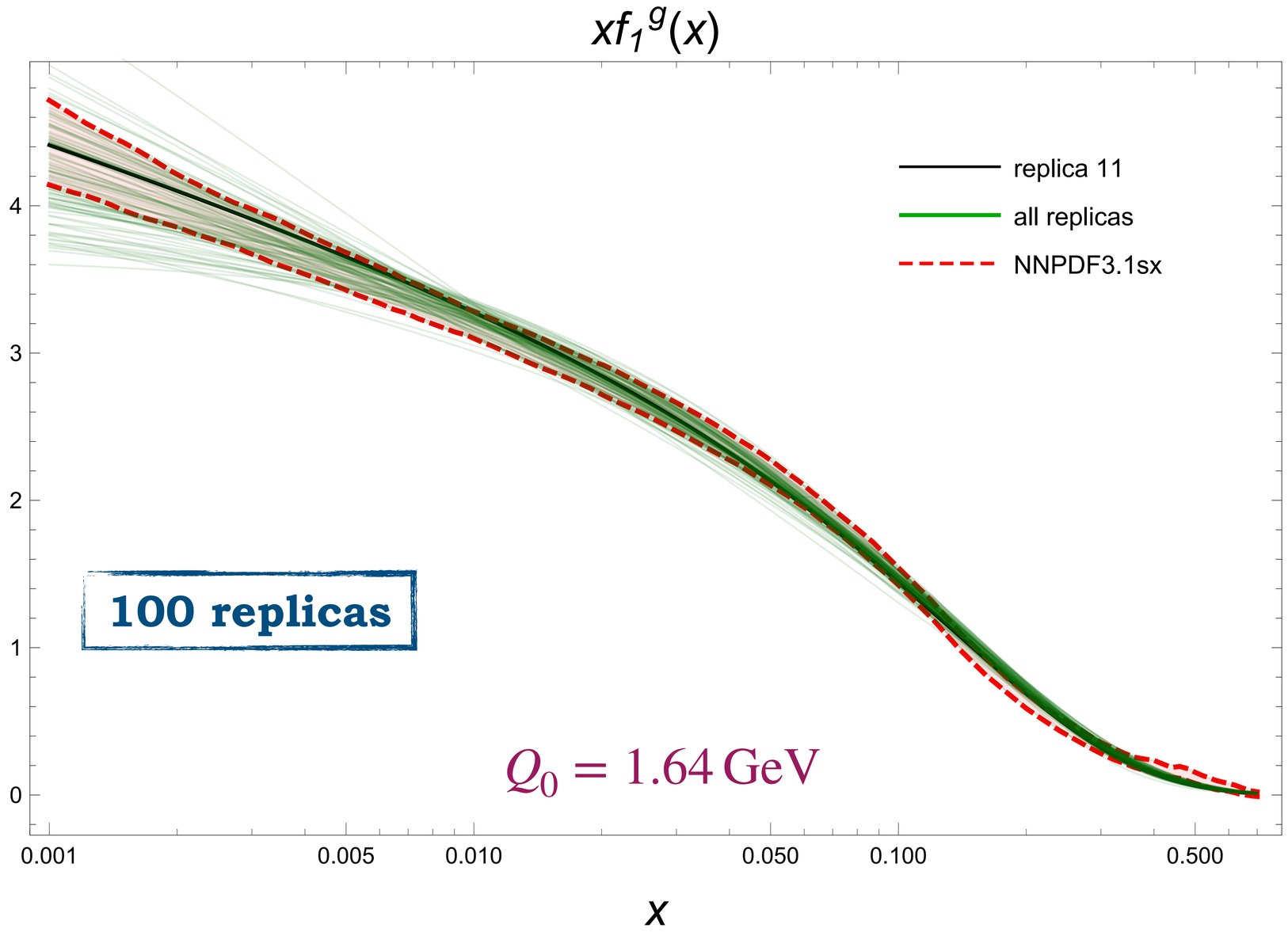
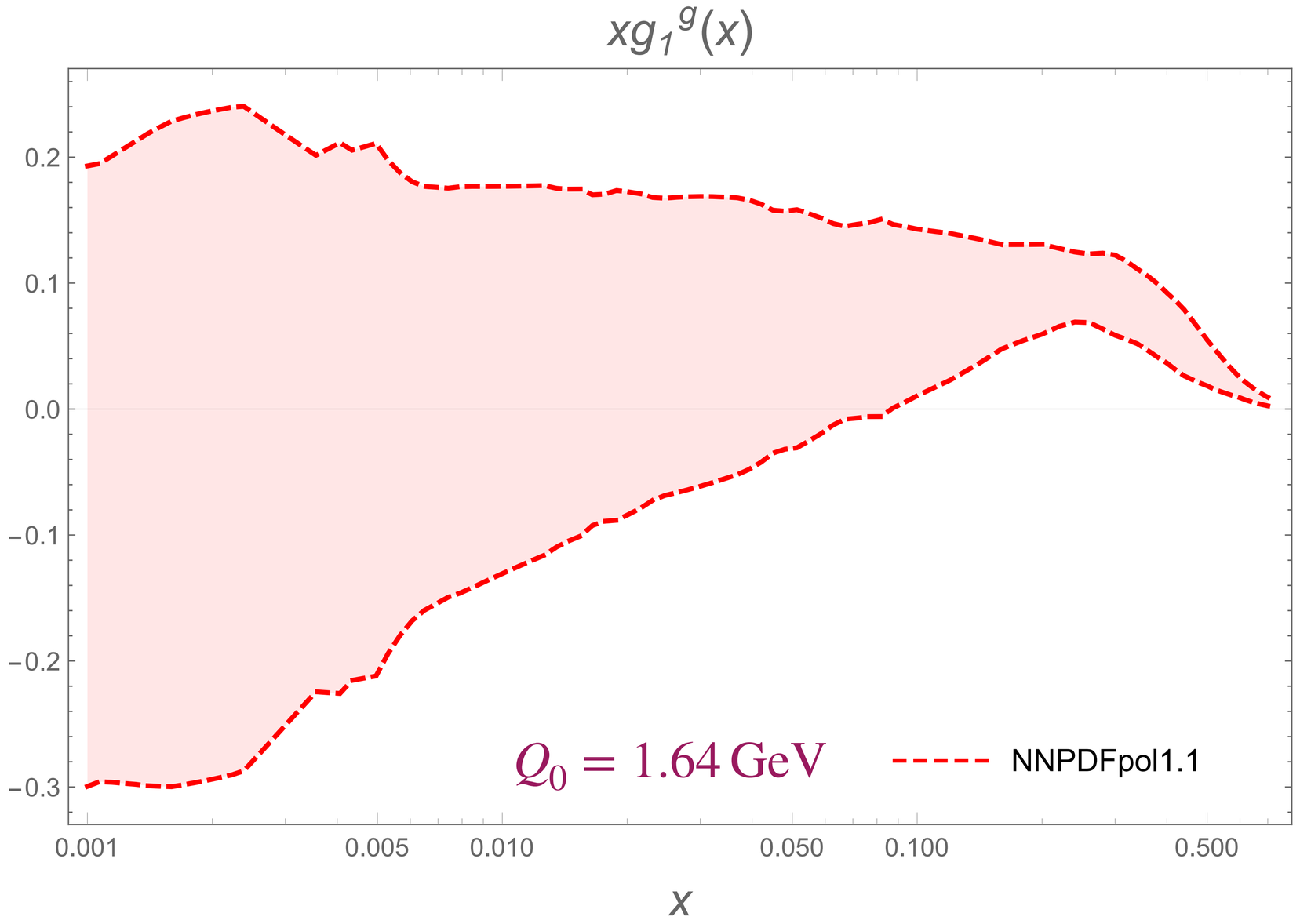
Unpolarized gluon PDF



Backup

Helicity gluon PDF



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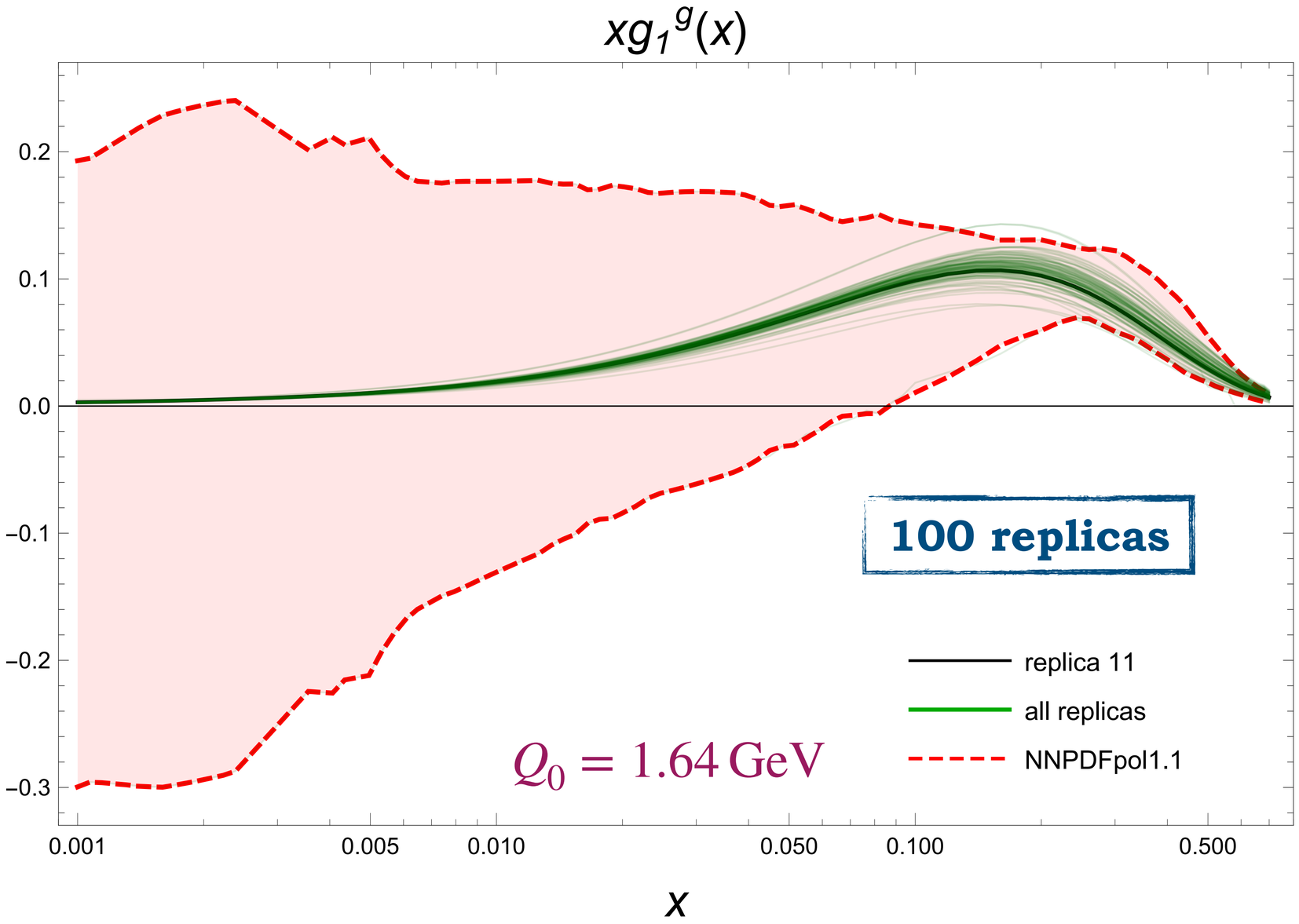
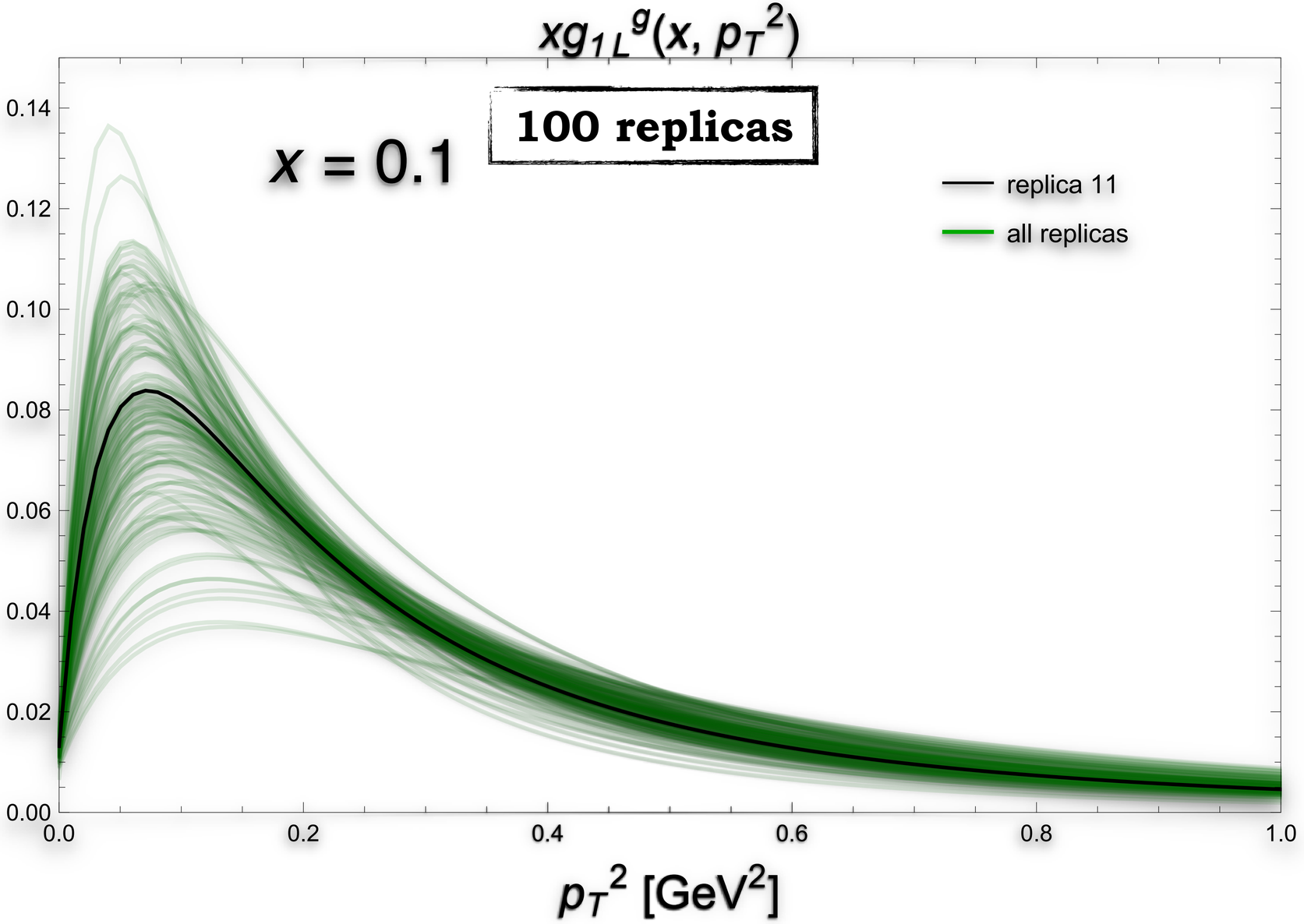
Helicity gluon PDF



Backup

Helicity gluon TMD



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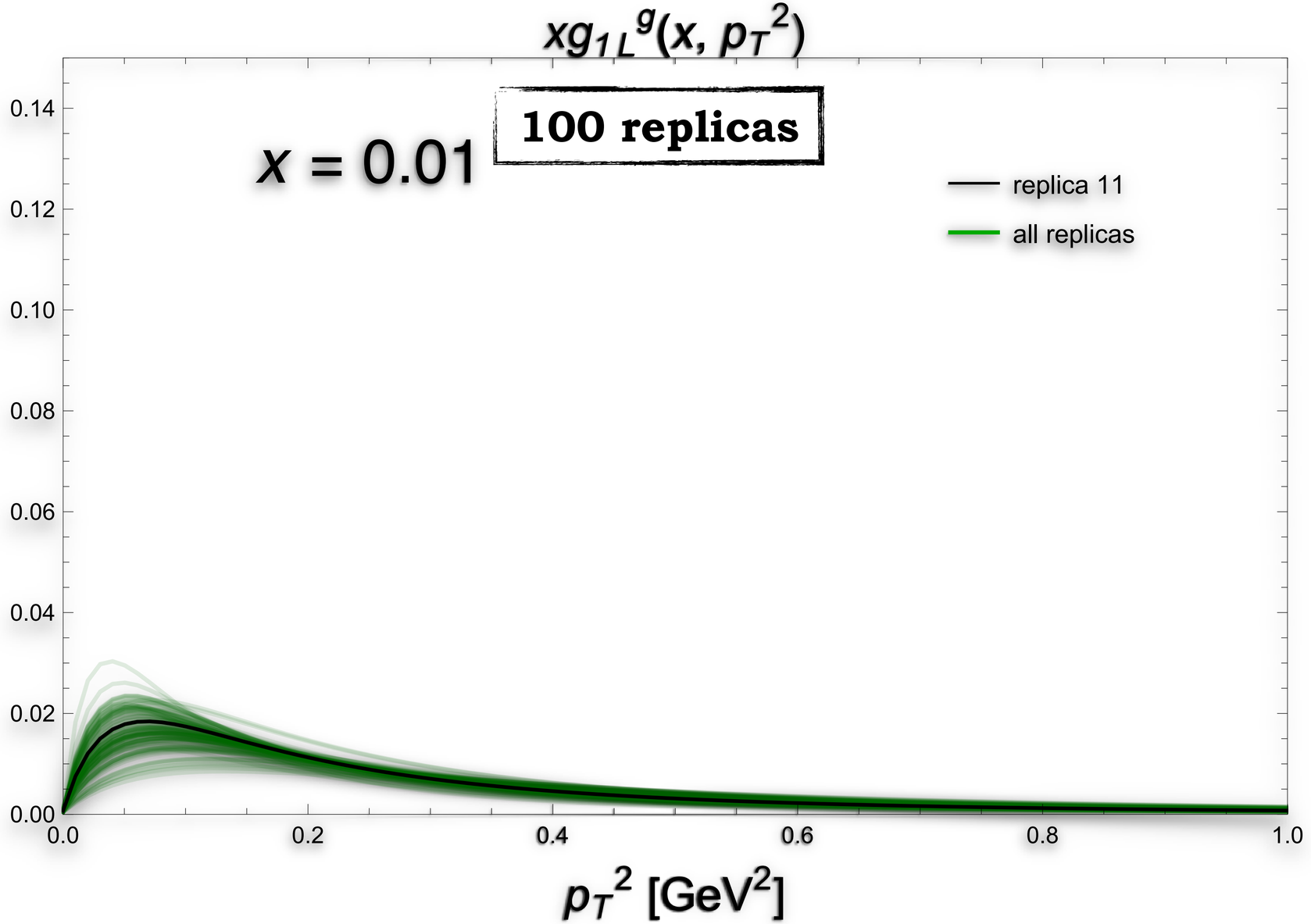
Helicity gluon TMD



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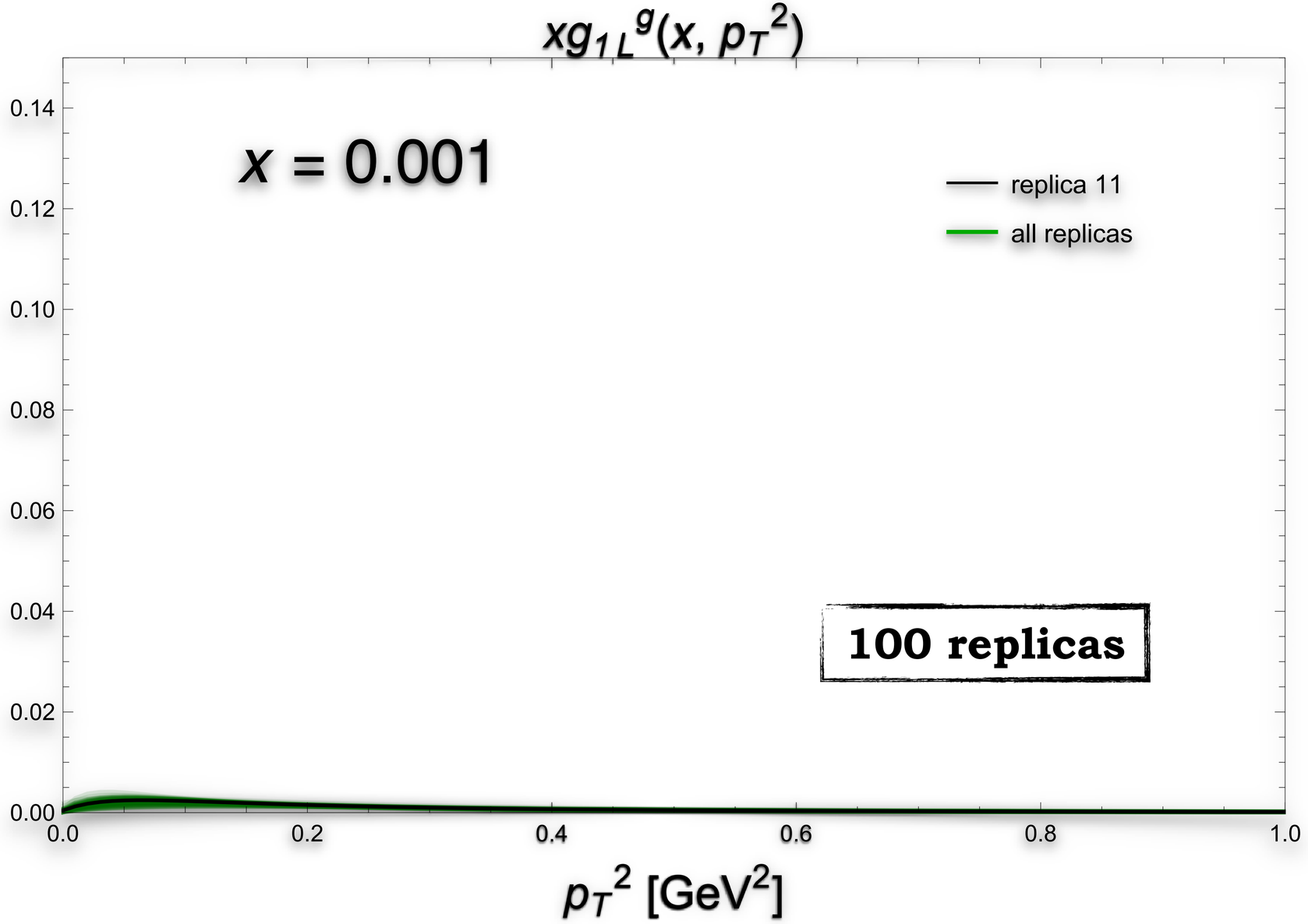
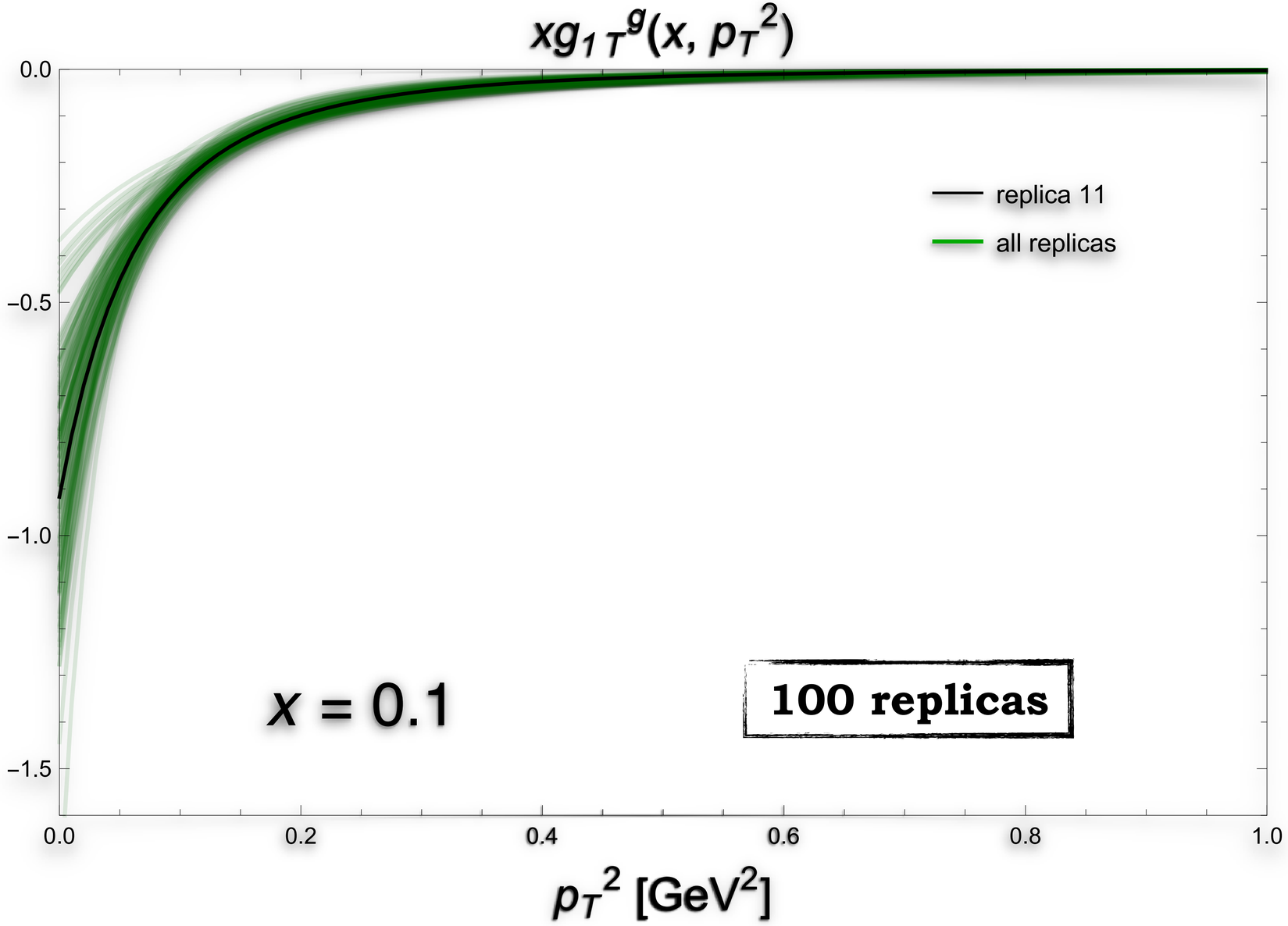


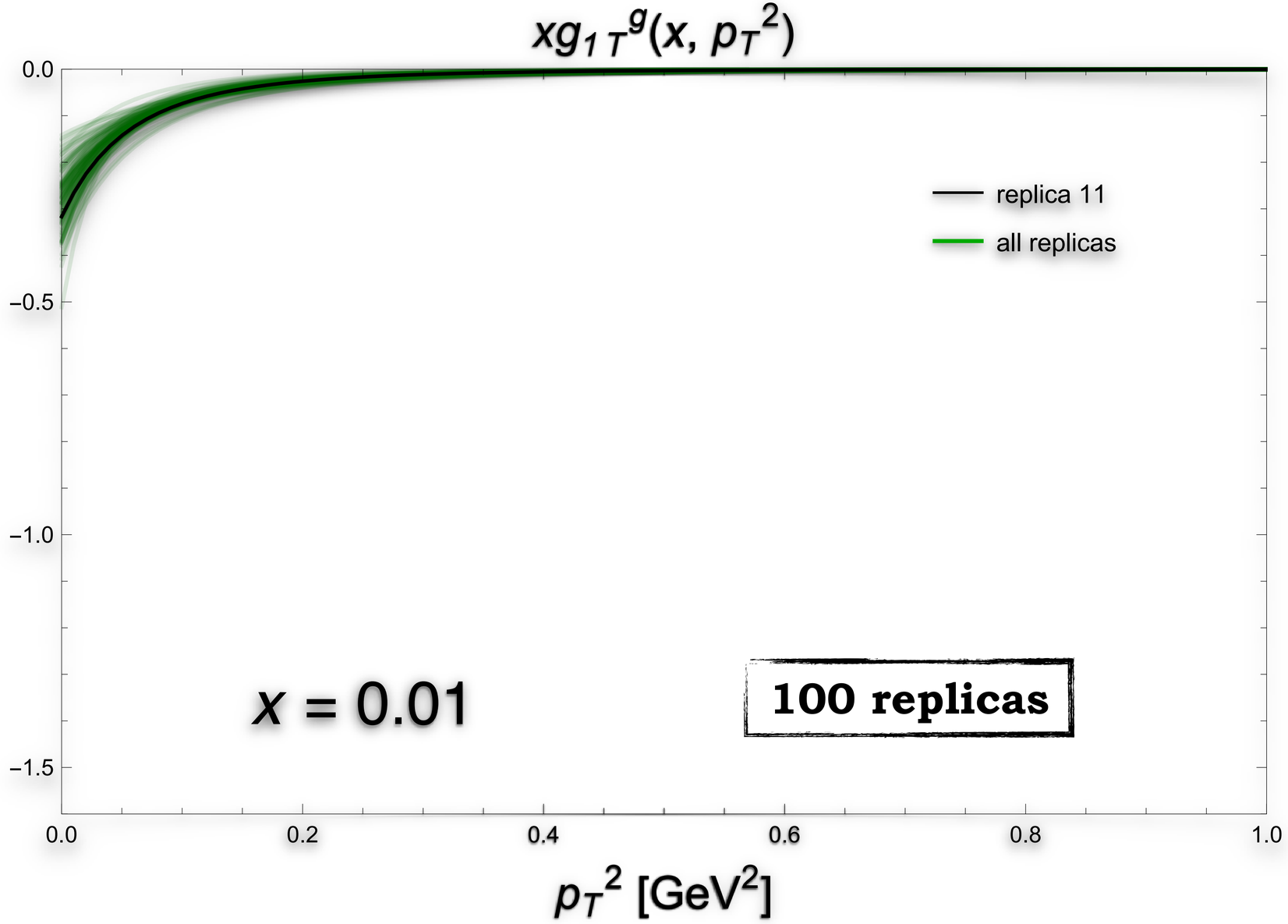
Backup

Worm-gear gluon TMD



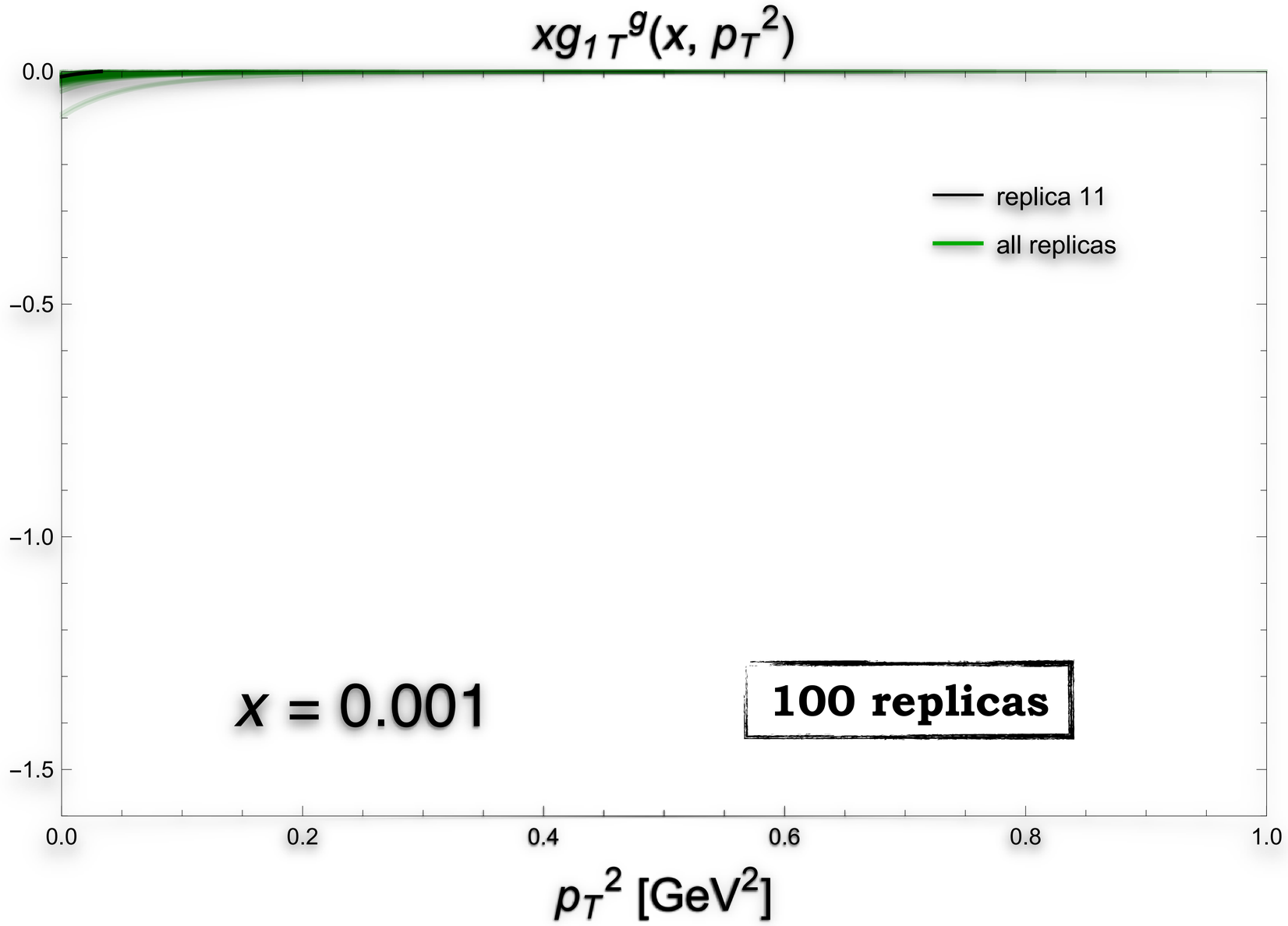
Backup

Worm-gear gluon TMD



Backup

Worm-gear gluon TMD



Backup

Bottom line

- Each TMD shows a distinctive x- and p_T-behavior

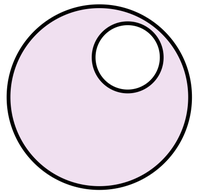
- Data on gluon TMDs will exclude many replicas and constrain parameters not yet so well constrained by collinear PDFs

- Simultaneous fit on two distinct PDFs provides with *corroborating evidence* of reliability of our model

- Standard CSS 🔗 🔗 *evolution* can be turned on

Backup

ρ-densities

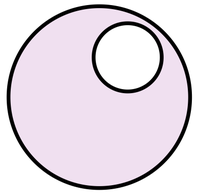


Unpolarized [u/u]

$f_1(x, p_x, p_y)$

Backup

ρ-densities



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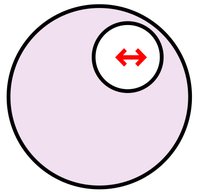
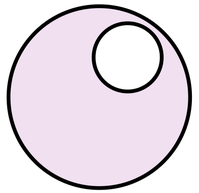


Boer-Mulders [↔/u] $f_1(x, p_x, p_y) + \dfrac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x, p_x, p_y)$

Backup

ρ-densities



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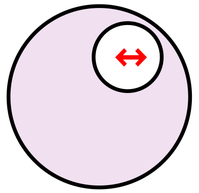

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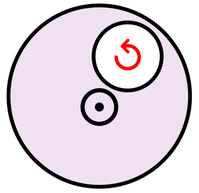
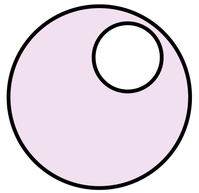


Helicity [↻/+]

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

Backup

ρ-densities



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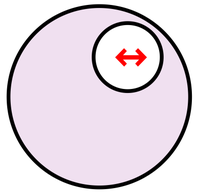

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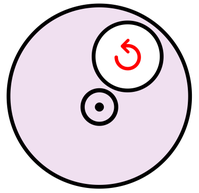

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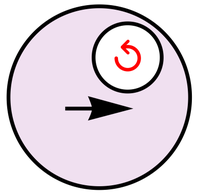


Worm-gear [↺/→]

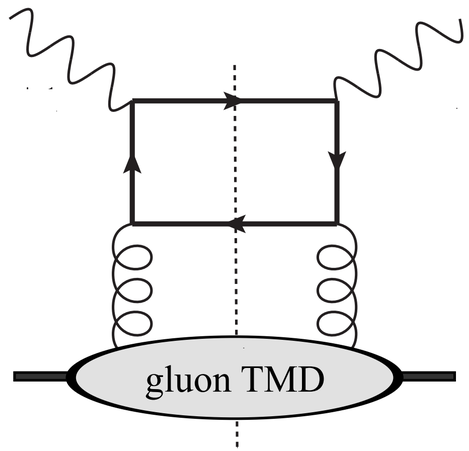
$$f_1(x, p_x, p_y) - \frac{p_x}{M} g_{1T}(x, p_x, p_y)$$

Backup

T-odd gluon TMDs and semi-inclusive reactions

1. Almost back-to-back di-jet production
2. Open-charm (heavy-light meson) states
3. Almost back-to-back J/Ψ-plus-jet production
4. Inclusive J/Ψ production at low p_T

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



Backup

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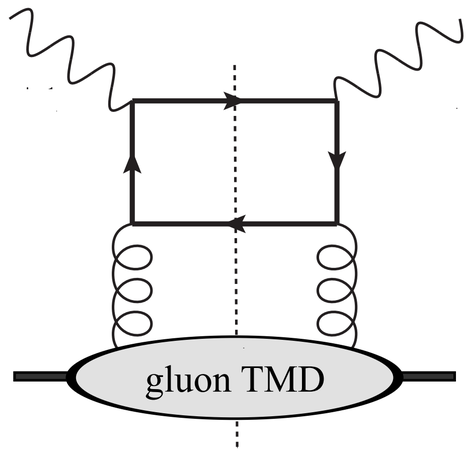

- Gluon-induced processes
- **Spin-asymmetry** studies feasible
- Small- and **large**-x physics supported

Backup