DIS 2021

April 13th, 2021

A spectator-model way to TMD gluon distribution functions

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EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

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FUTURE BUILT ON KNOWLEDGE

TIFPA
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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

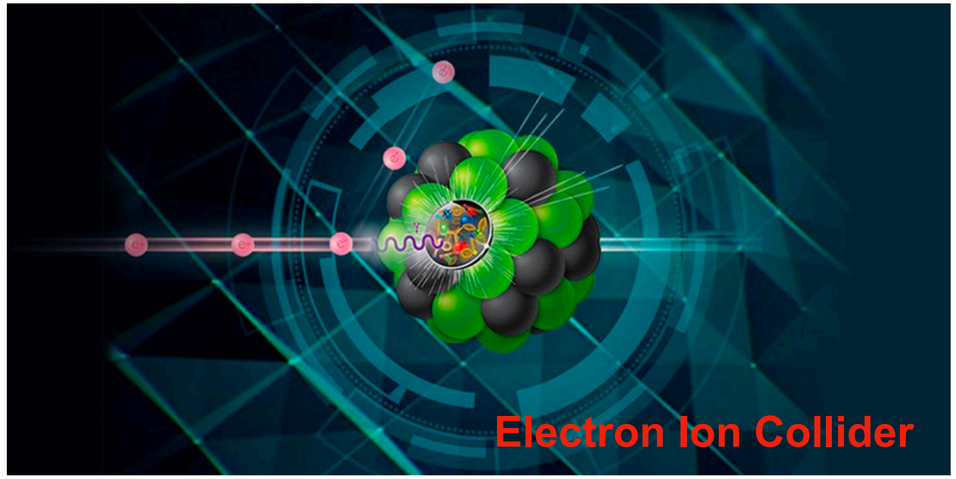
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- ***Pheno***: golden channels for extraction

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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

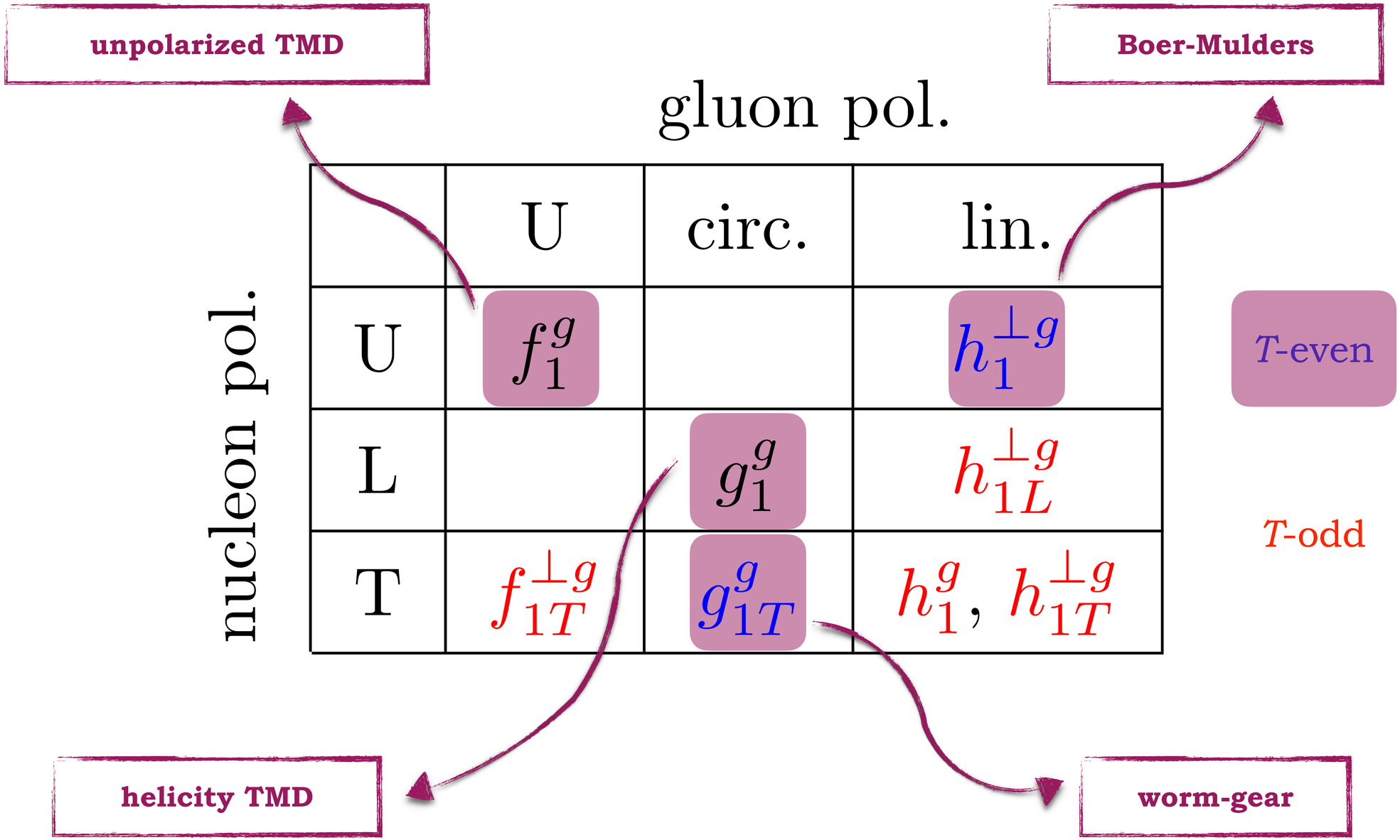


CERN

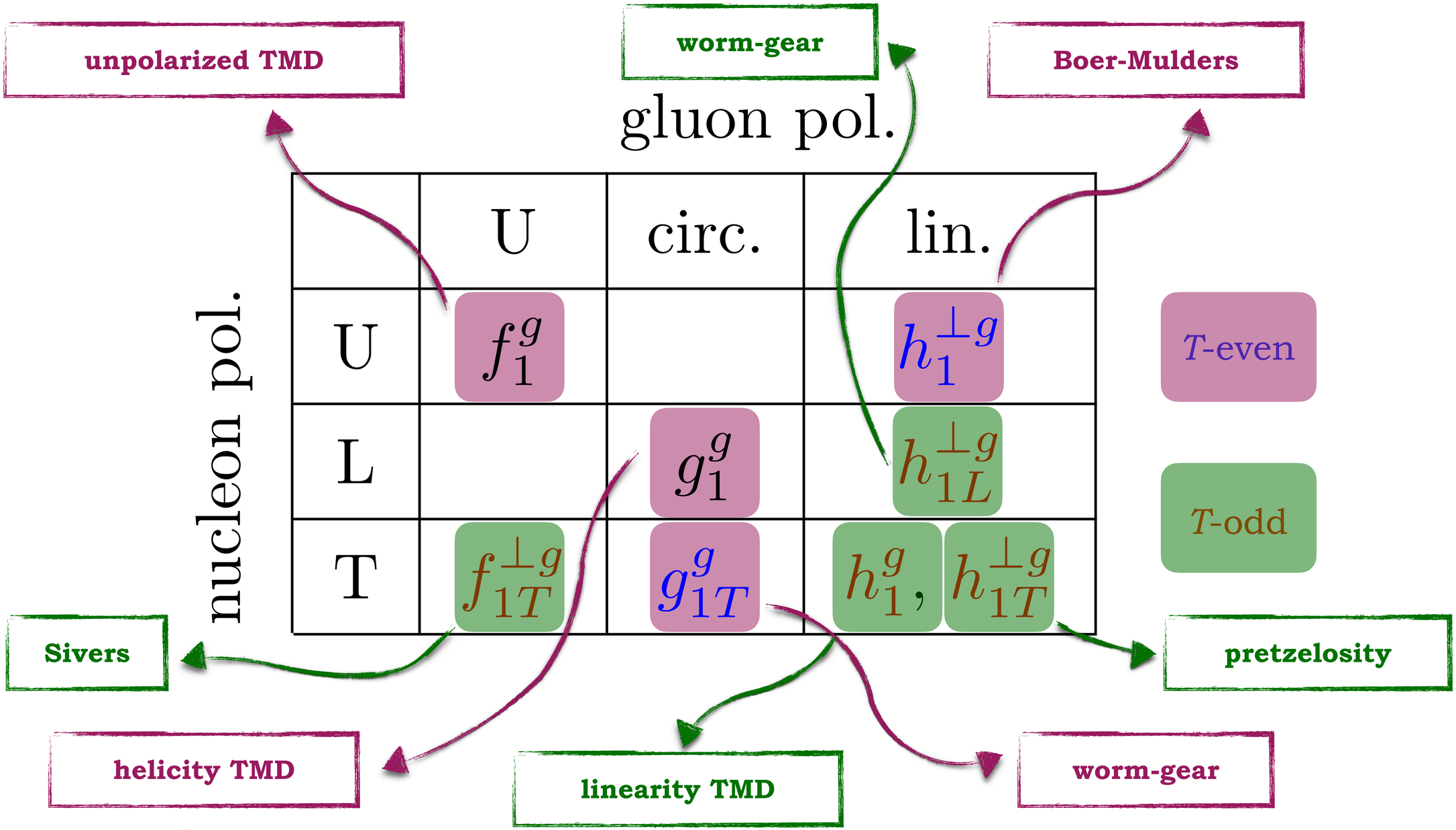
T-even and *T*-odd gluon TMD PDFs at twist-2

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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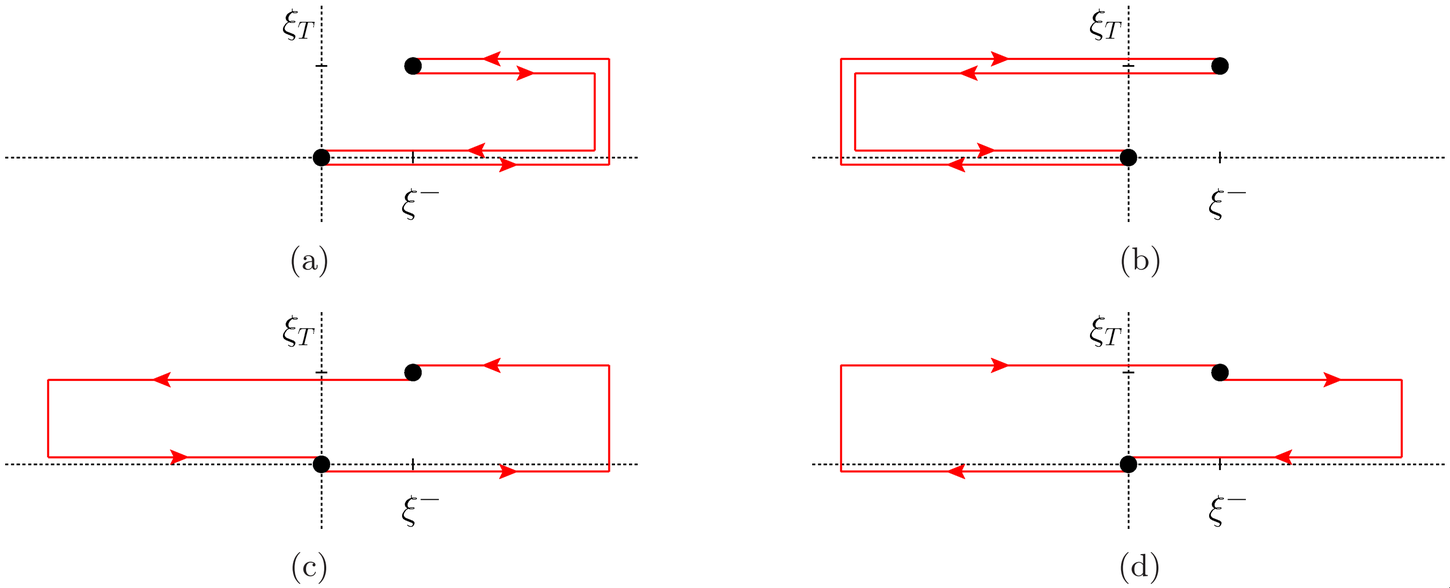


Gluon TMDs: gauge links and modified universality

* **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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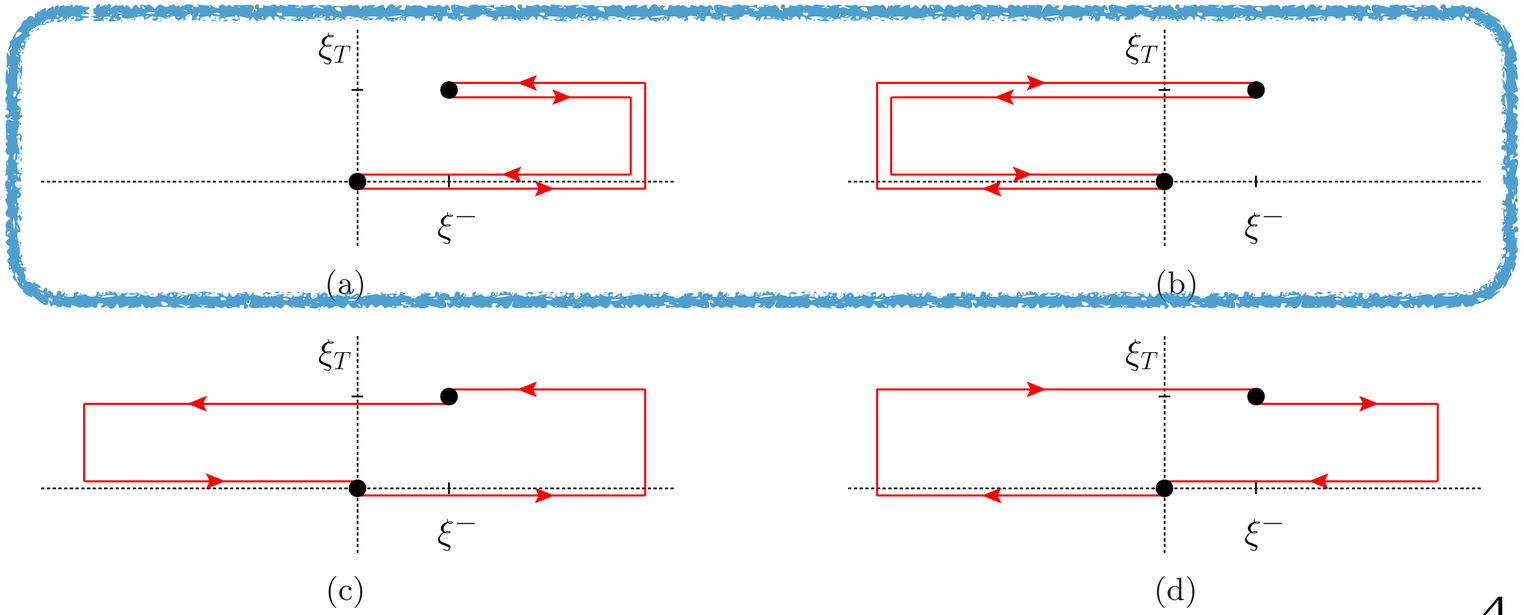


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Weiszäcker-Williams (WW)

(a) [+ , +] or (b) [− , −]



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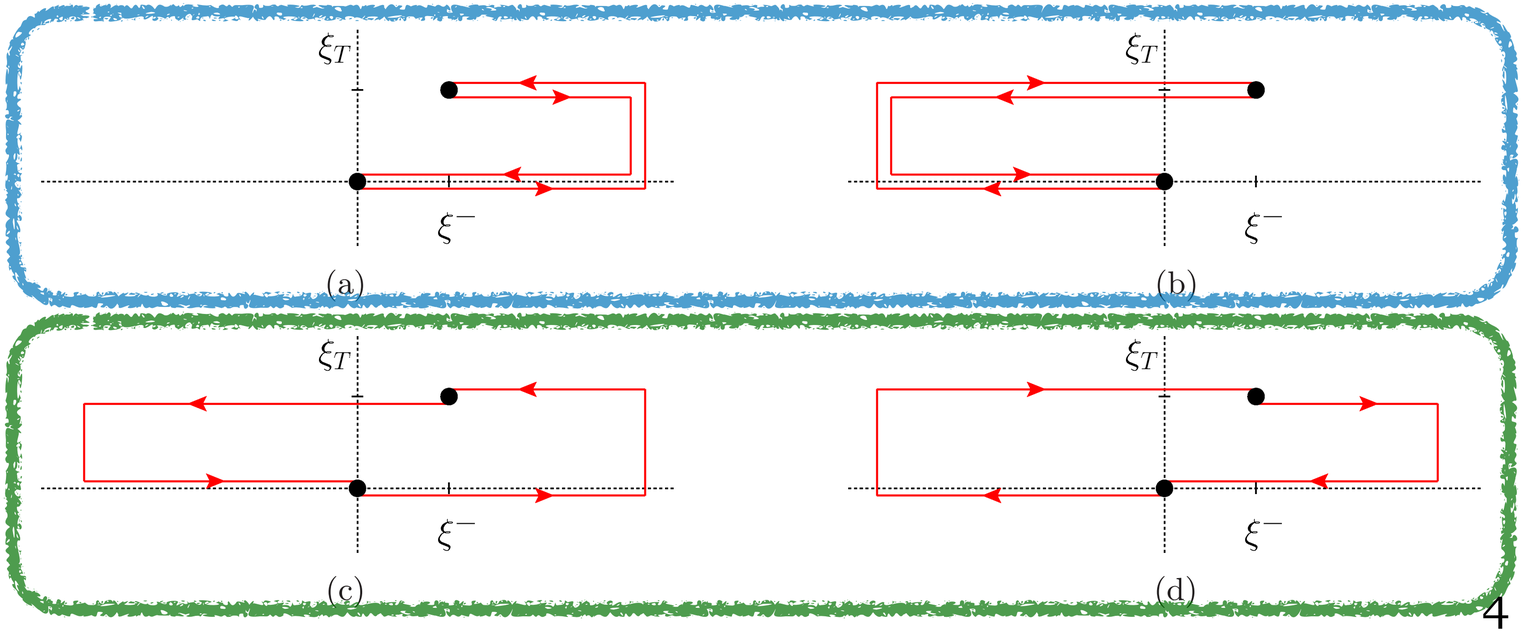
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(a) [+ , +] or (b) [− , −]

Dipole (DP)

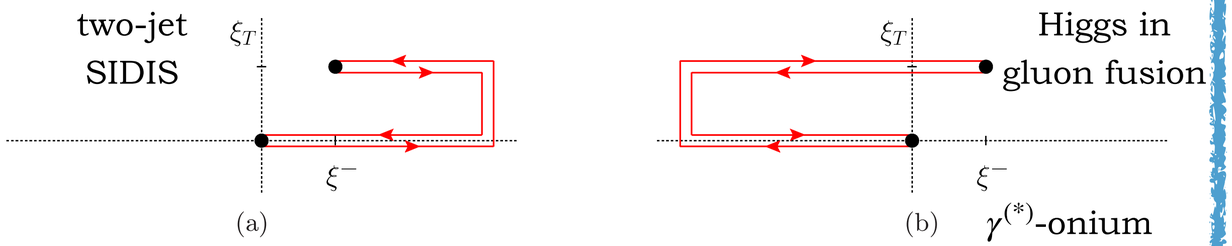
(c) [+ , −] or (d) [− , +]



Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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



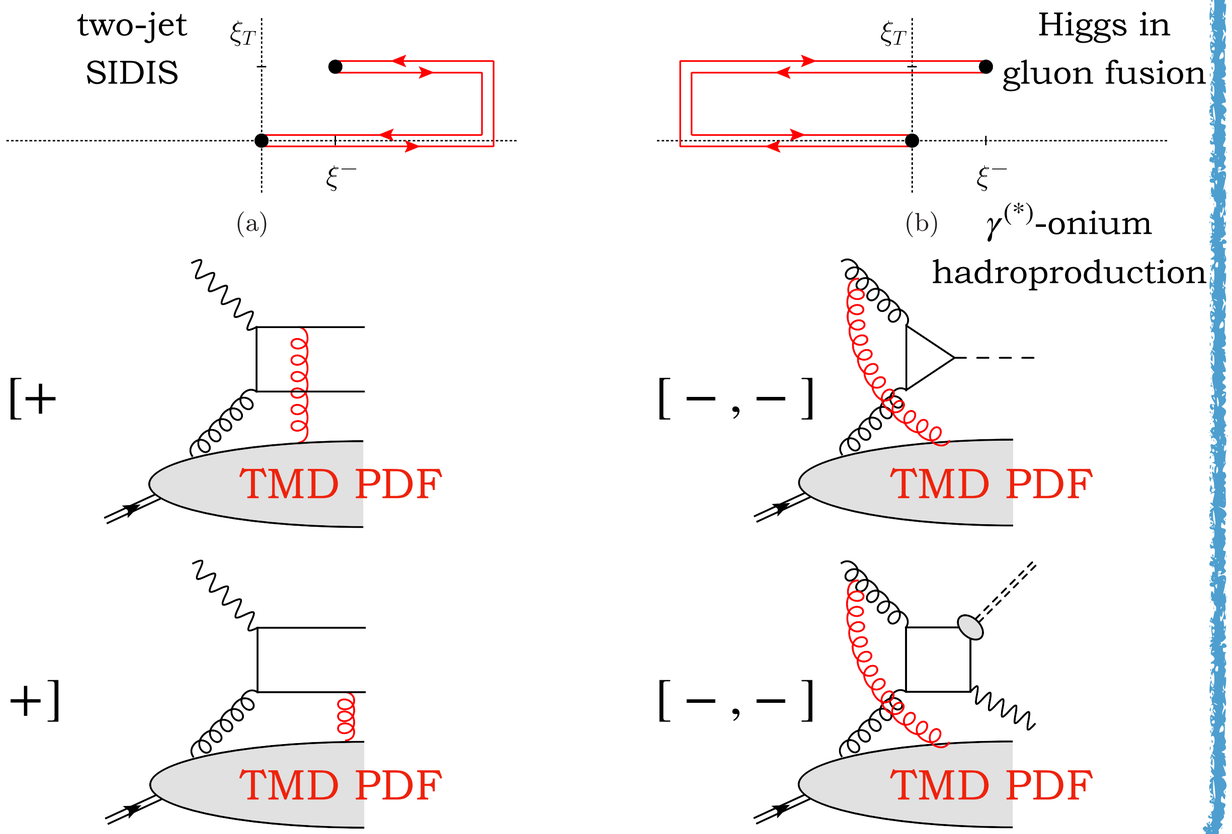
Higgs in gluon fusion

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

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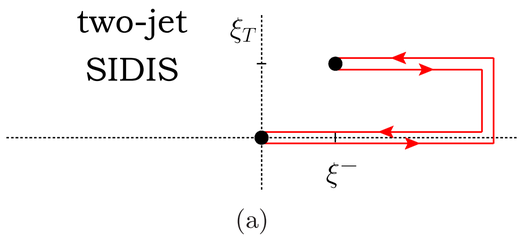


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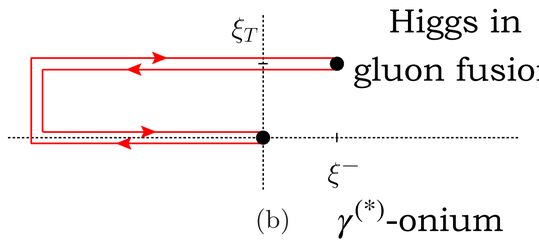
(a) $[+,+]$ or (b) $[-,-]$

two-jet SIDIS



(a)

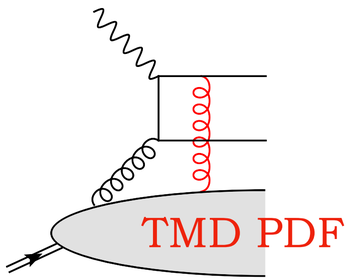
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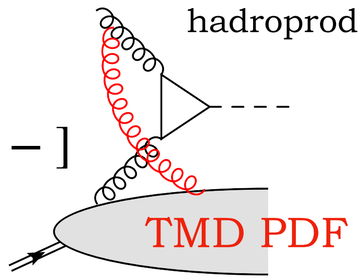
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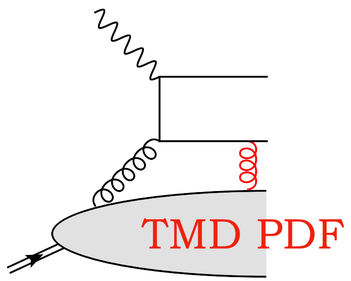
$[+$



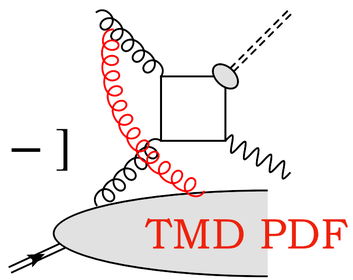
$[-,-]$



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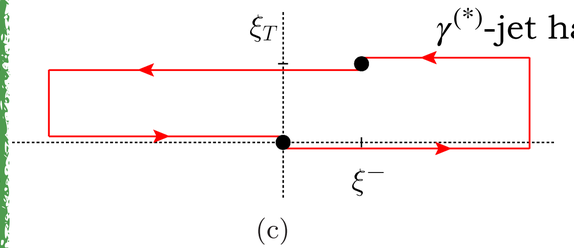


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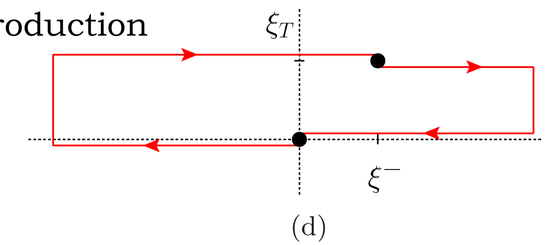
Dipole (DP)

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



(c)

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

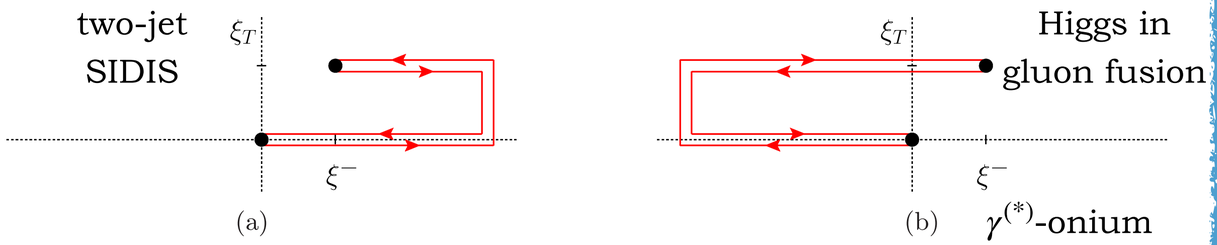


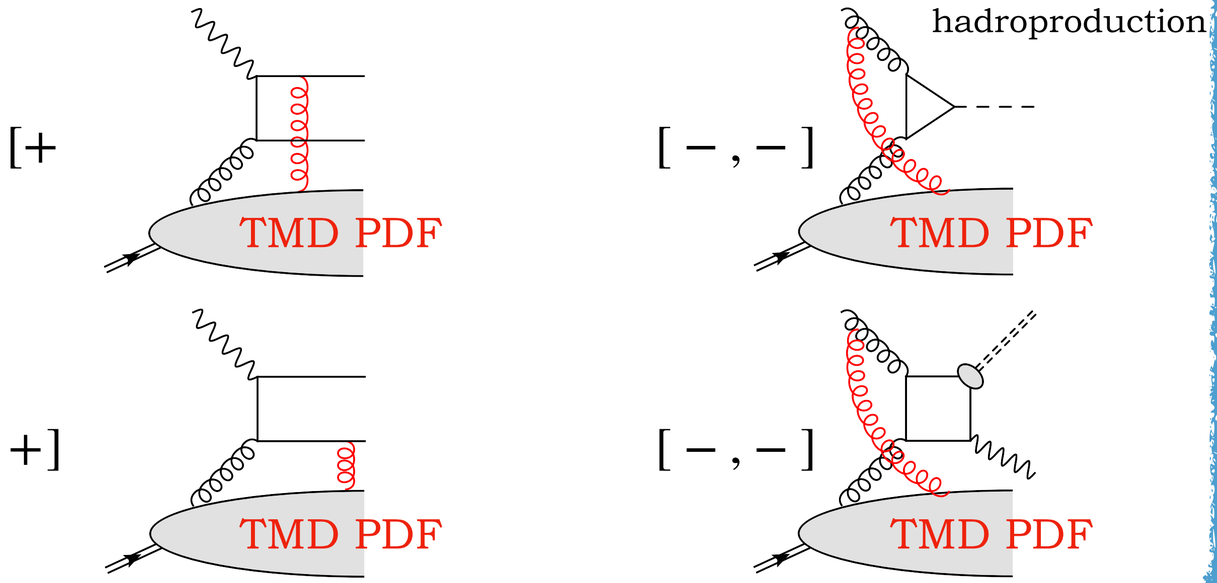
(d)

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

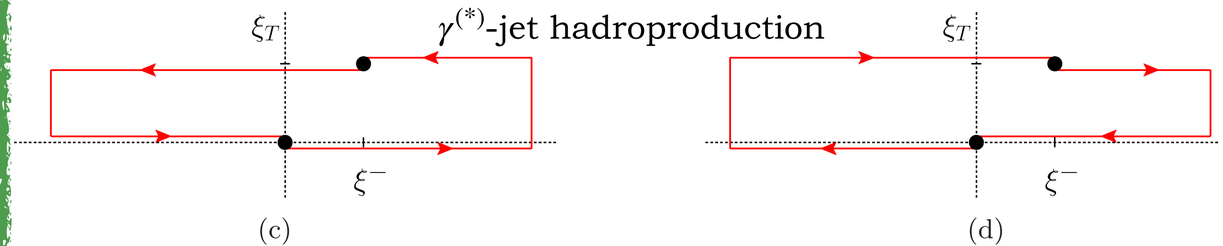
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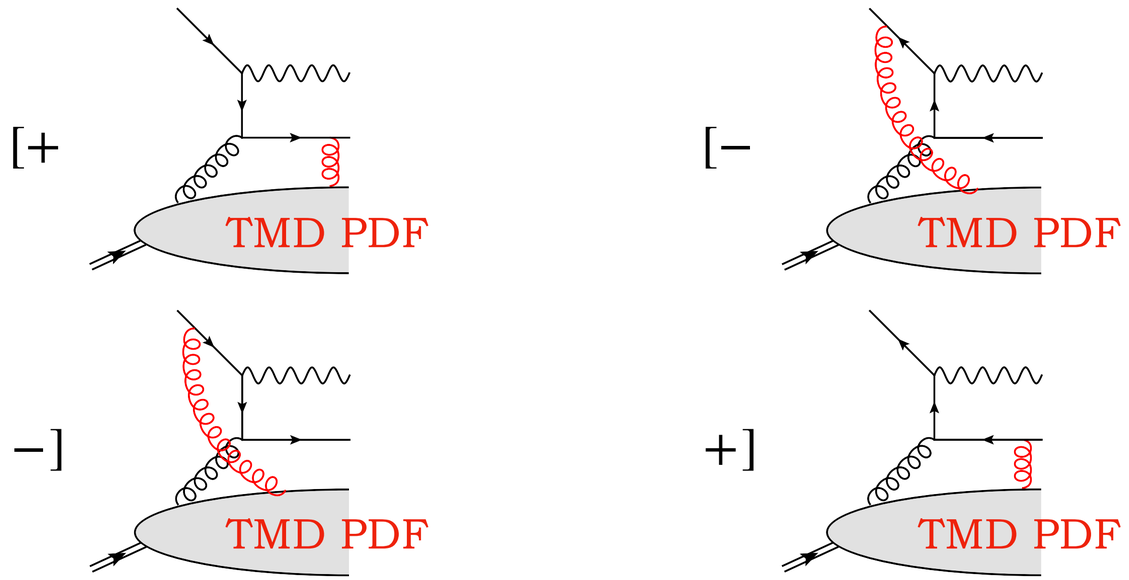




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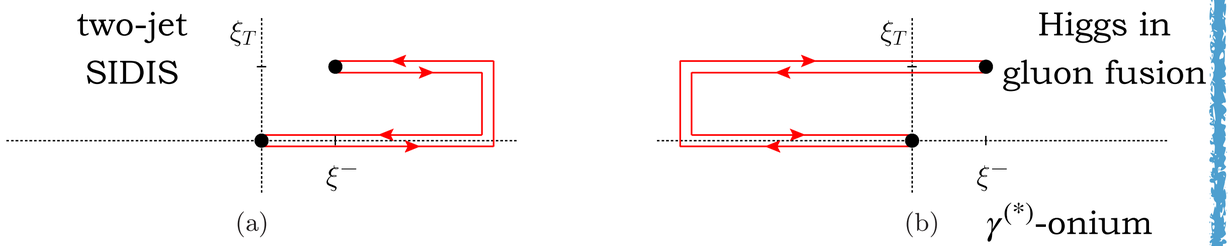




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* Color flow annihilated within final/initial state
* f-type gluon TMDs $\rightarrow$ f^{abc} color structure
* Modified universality:

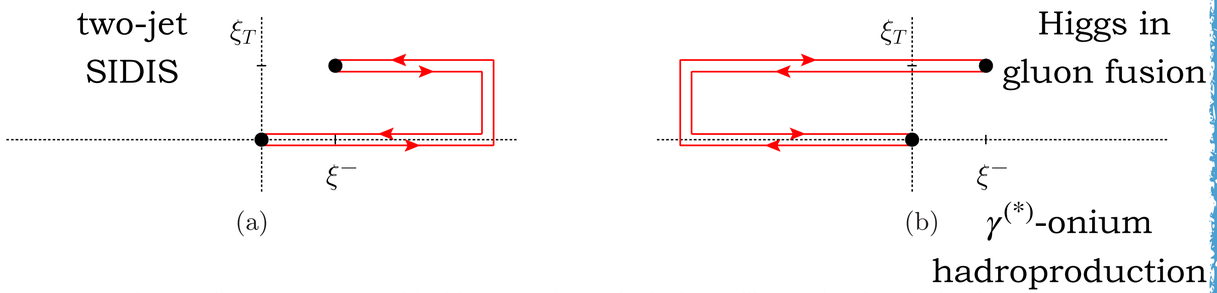
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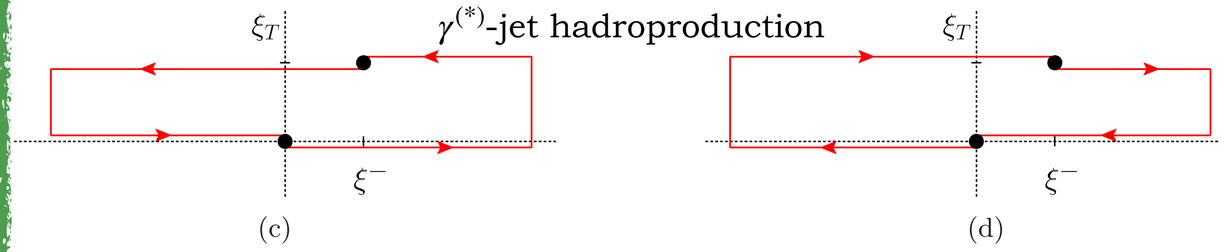
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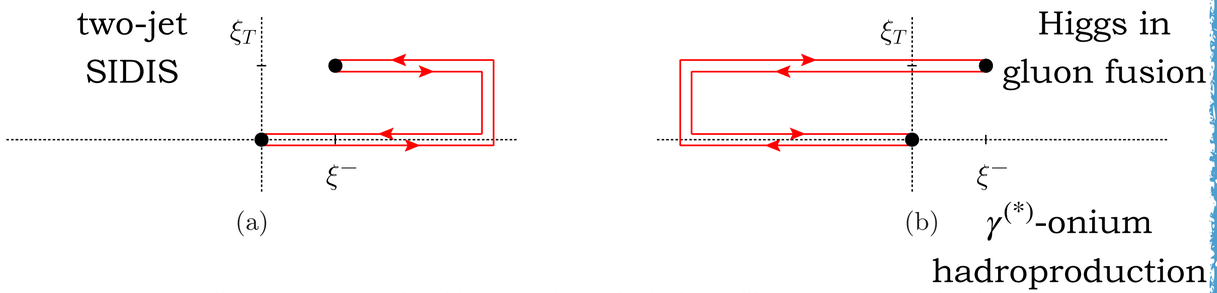
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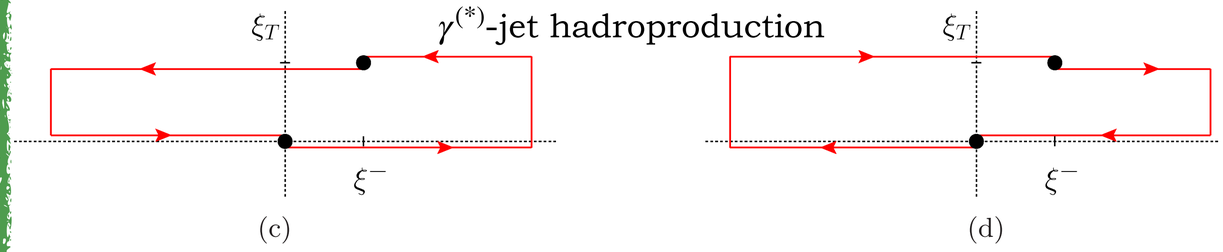
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Gauge link $\rightarrow$ two main independent sets of TMDs, **not related** to each other

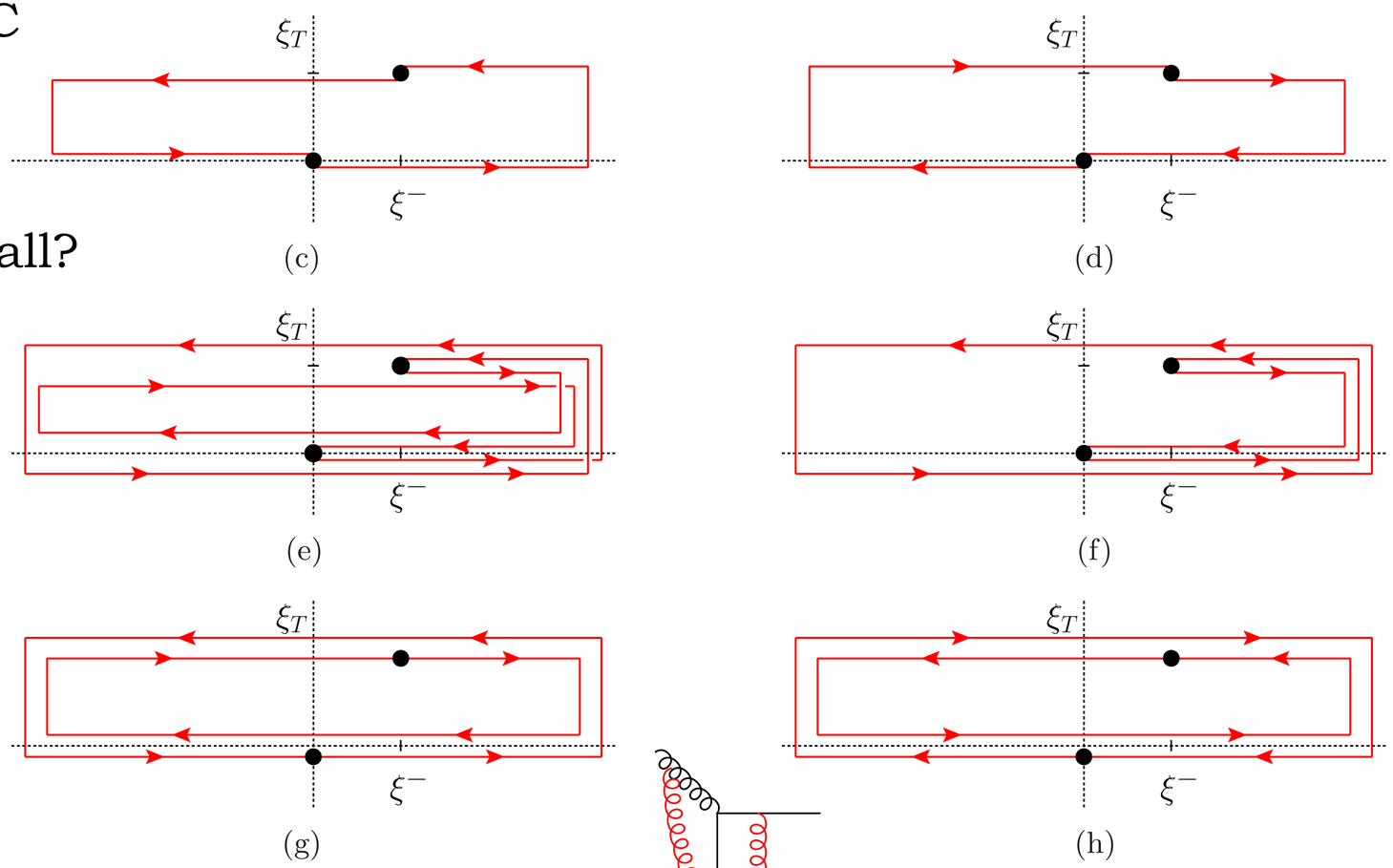
Dihadron hadroproduction and factorization breaking

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

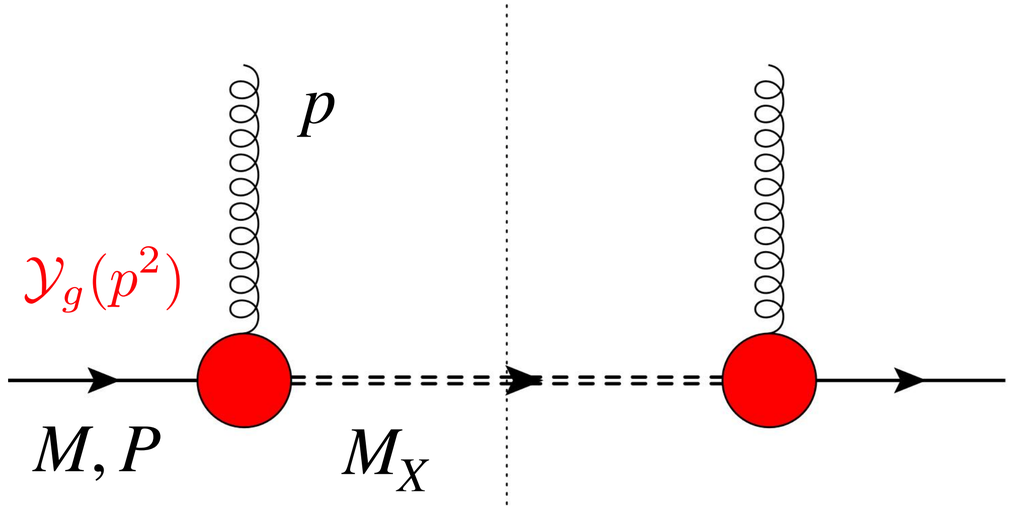
  (g) $[\square,\square]$, and (h) $[\square,\square]$



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

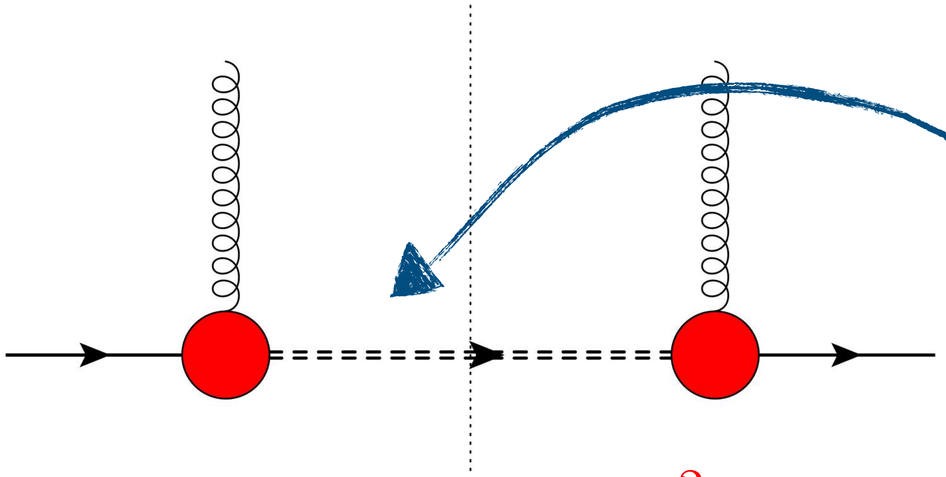
Spectator-system spectral-mass function

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)]

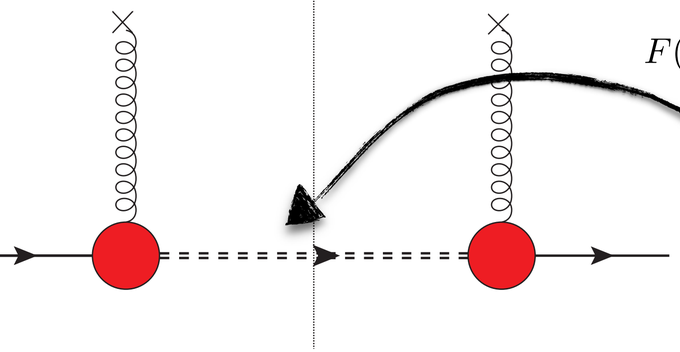


$\mathcal{Y}_g(p^2)$

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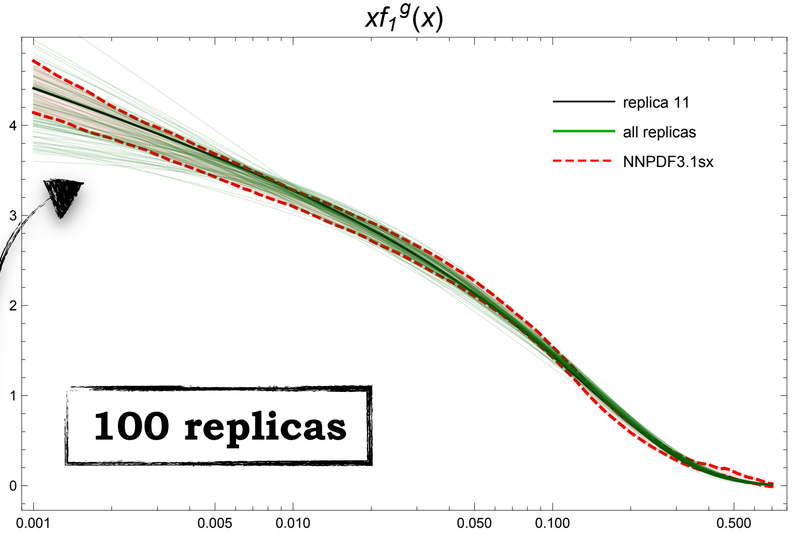
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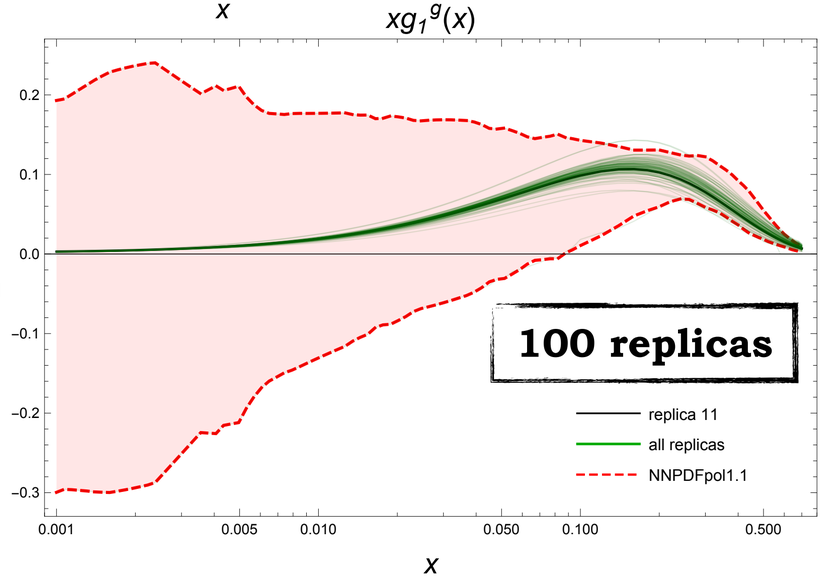
Spectral function **learns** small- and moderate-x info encoded in **NNPDF** collinear parametrizations (`NNPDF3.1sx + NNPDFpol1.1`)

- ☑ **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

Link with collinear factorization

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





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

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Our model @ $Q_0 = 1.64$ GeV

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

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

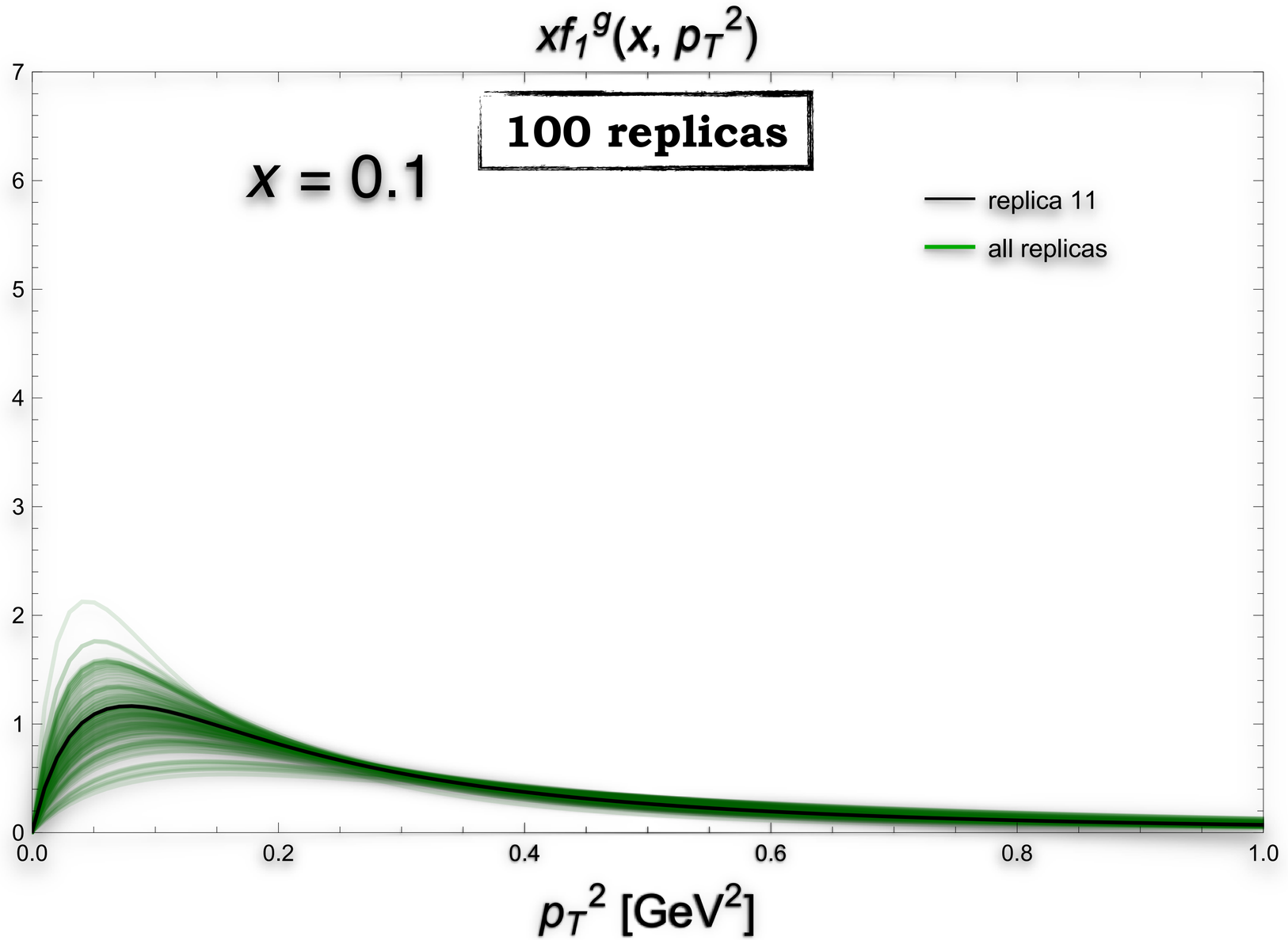
Lattice @ $Q_0 = 2$ GeV

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

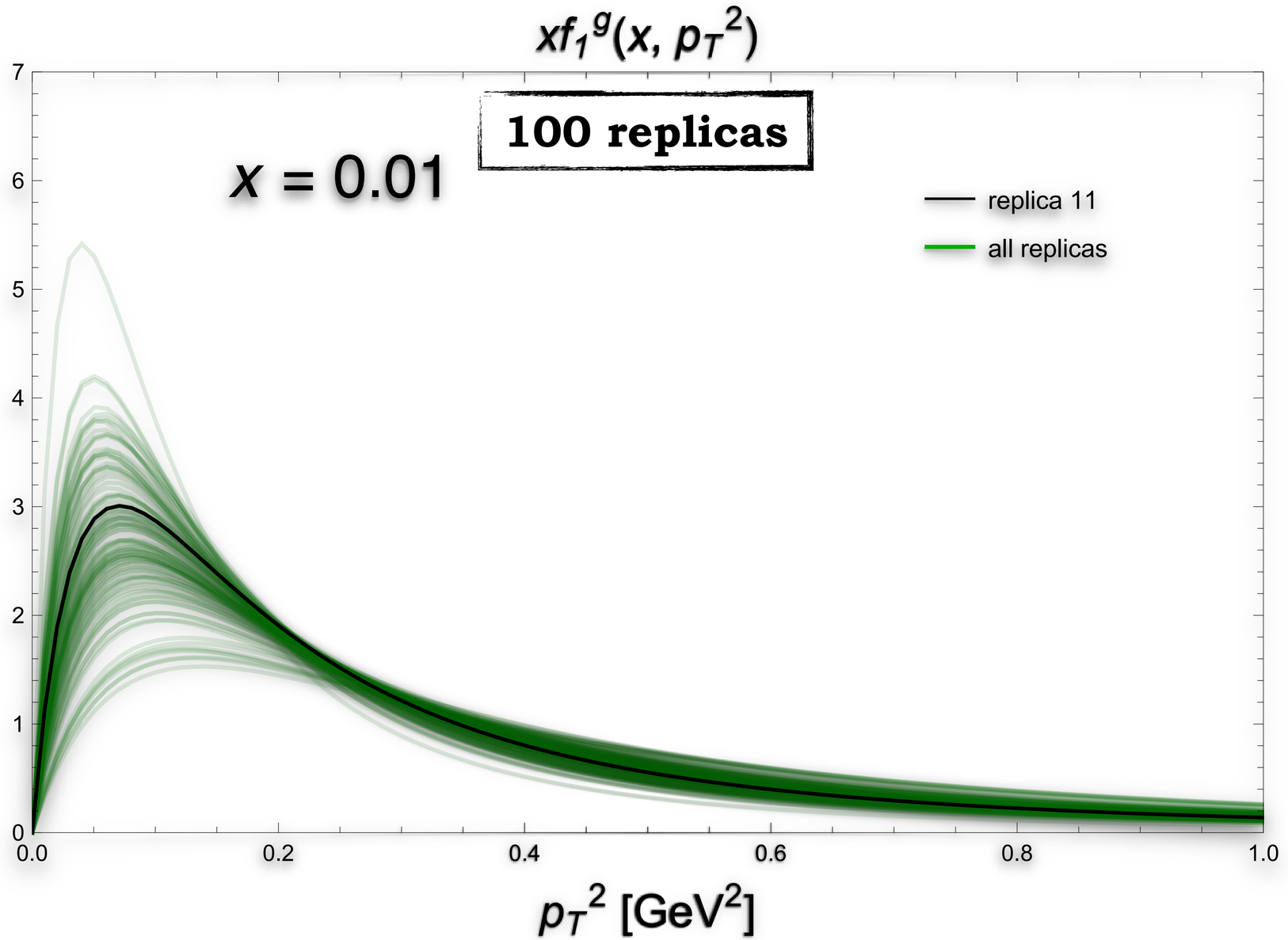
$$\langle J \rangle_g = 0.187(46)$$

🔗 [C. Alexandrou *et al.* (2020)]

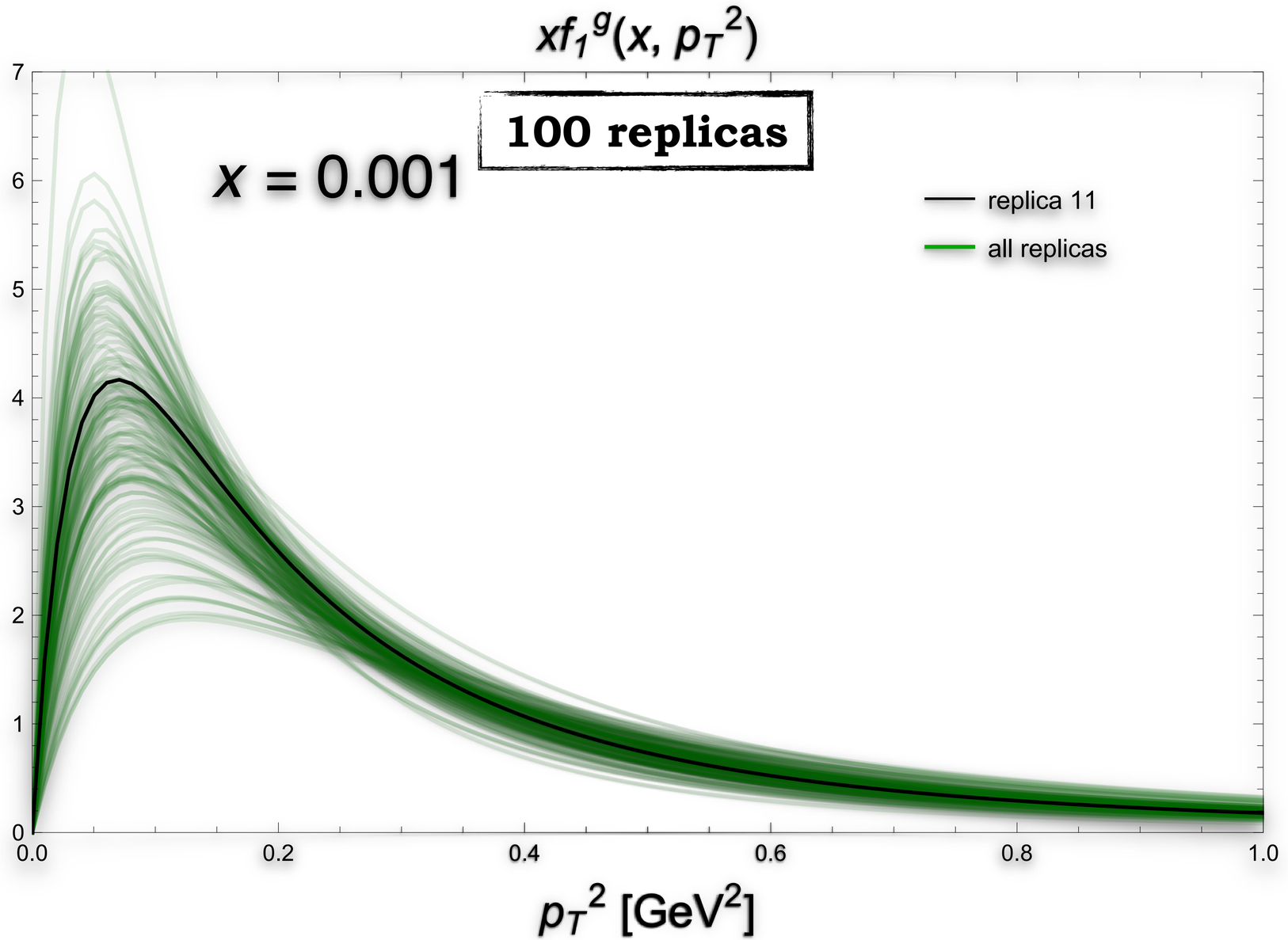
Unpolarized gluon TMD



Unpolarized gluon TMD

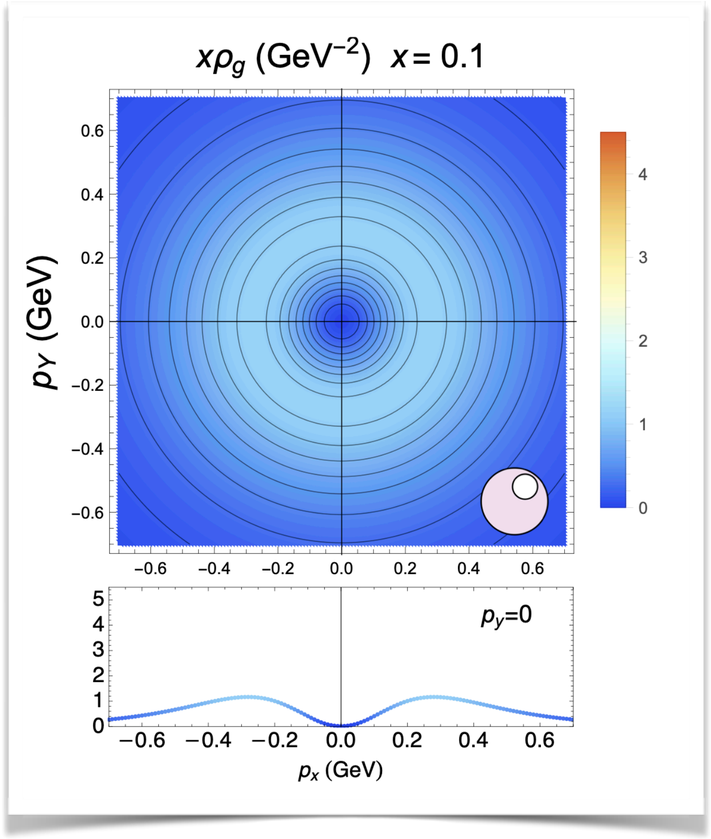


Unpolarized gluon TMD



3D tomography: the gluon content in the proton

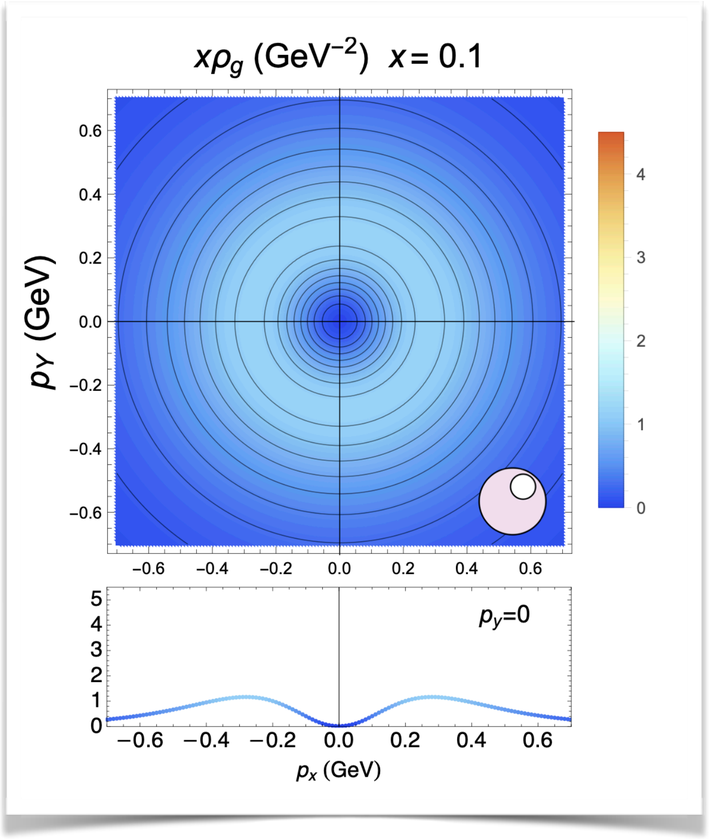
unpolarized TMD



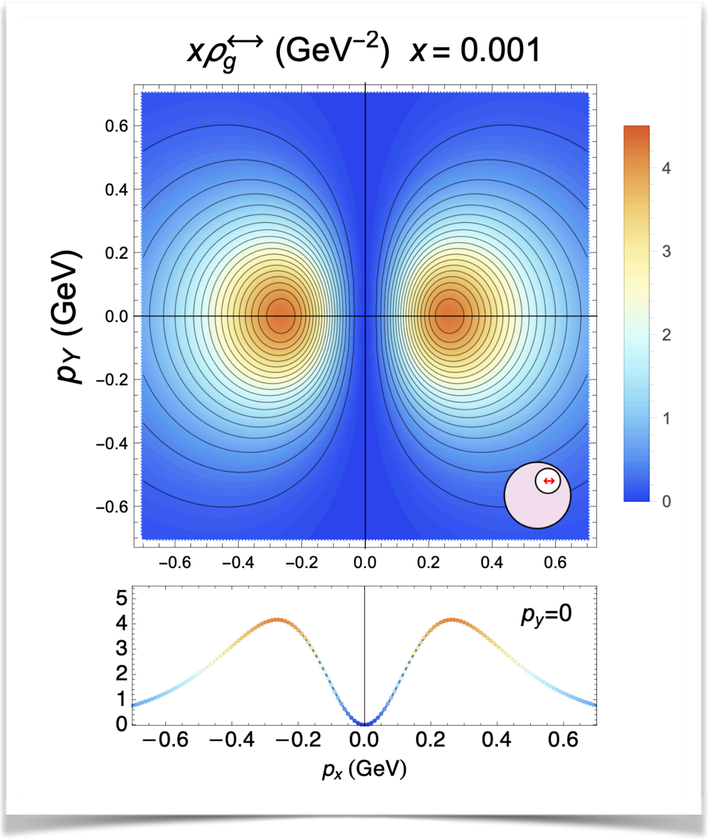
[A. Bacchetta, F.G.C., M. Radici, P. Taels, *Eur. Phys. J. C* **80** (2020) no.8 [arXiv:2005.02288]]

3D tomography: the gluon content in the proton

unpolarized TMD



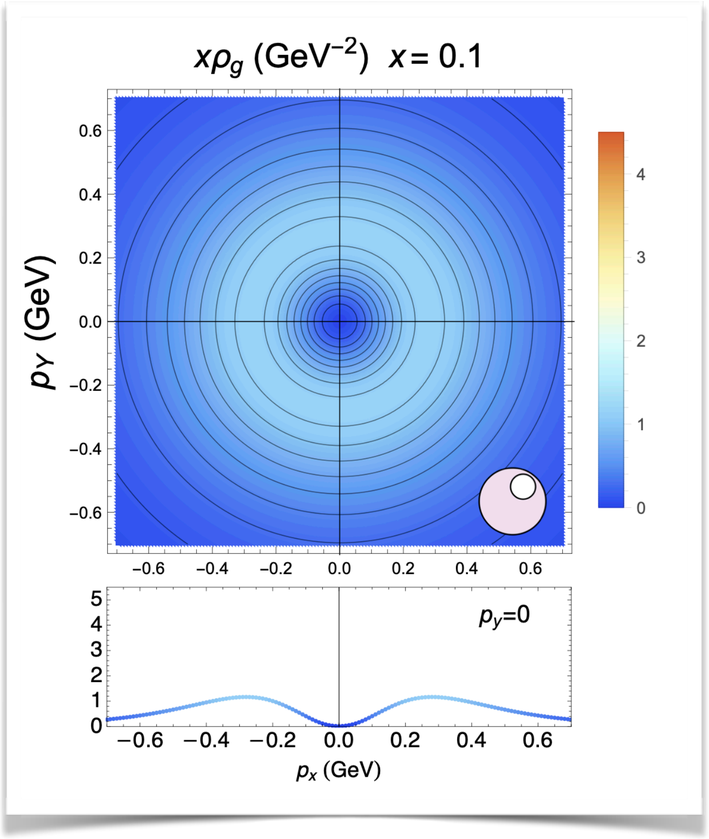
Boer-Mulders



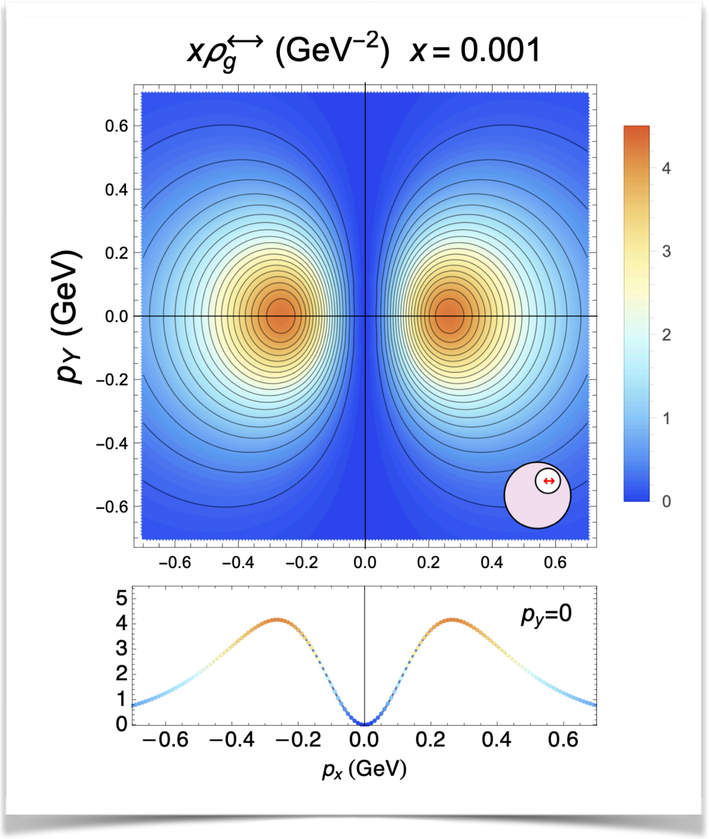
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3D tomography: the gluon content in the proton

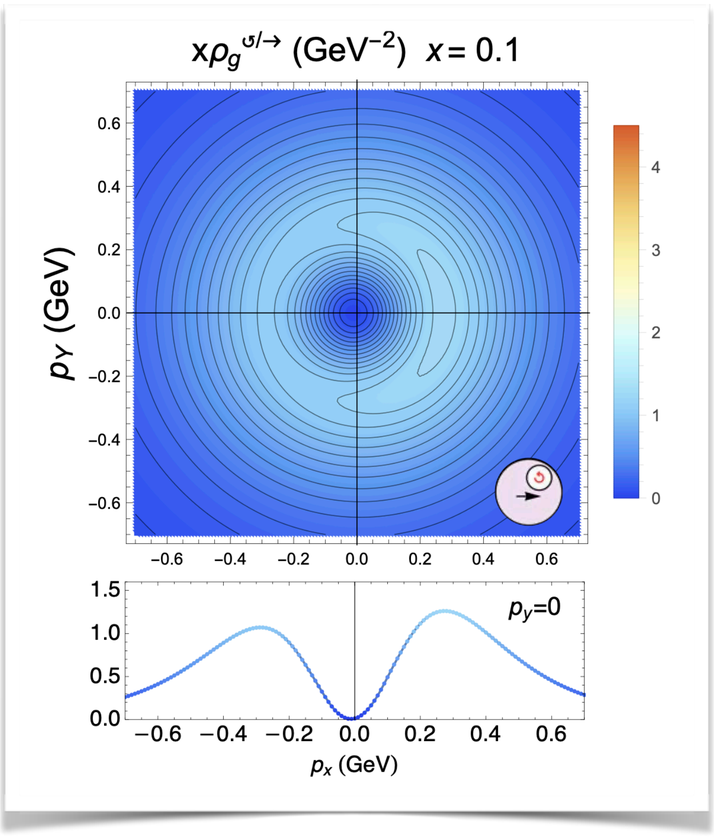
unpolarized TMD



Boer-Mulders



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

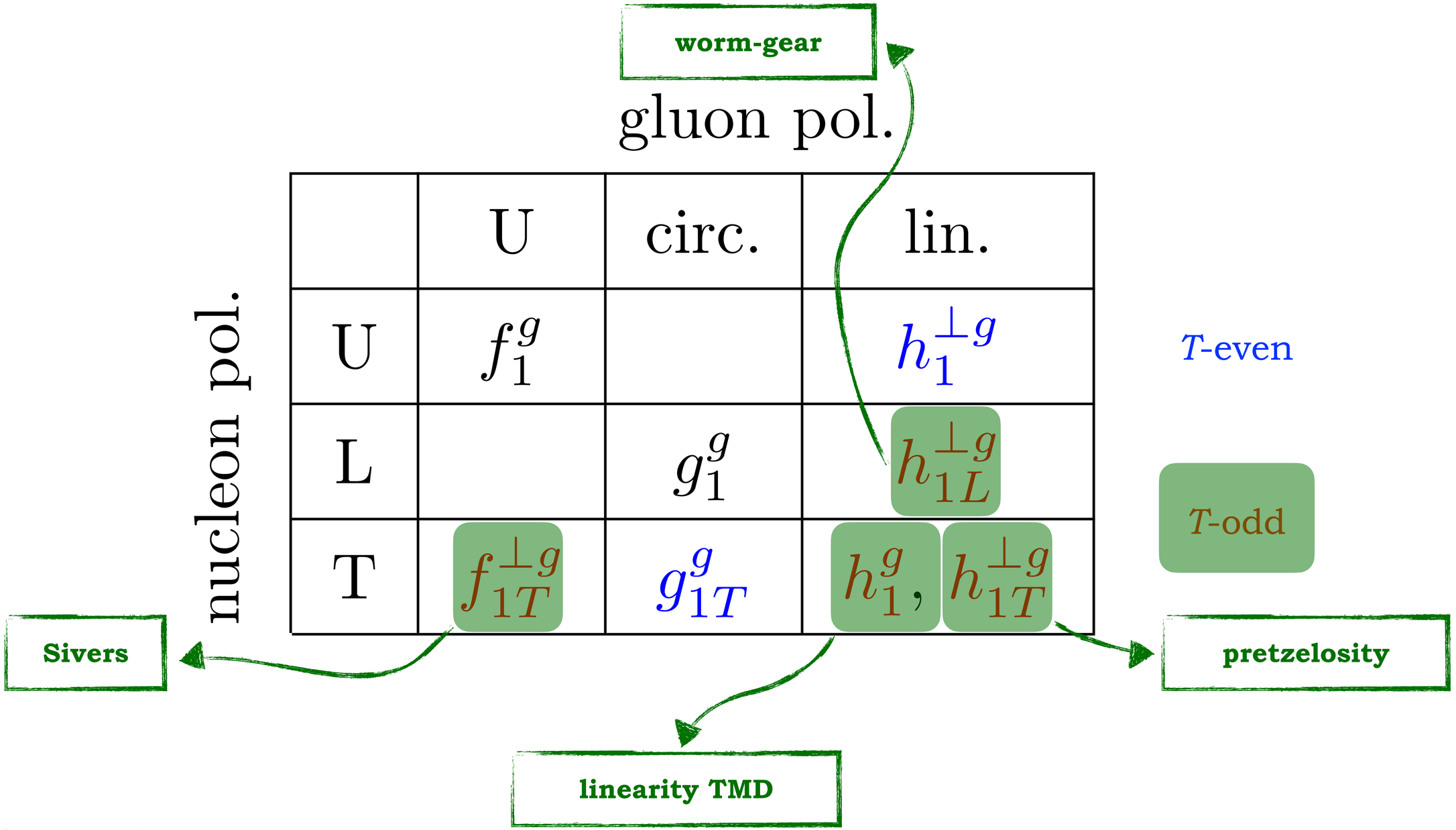
T-odd gluon TMDs at twist-2

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



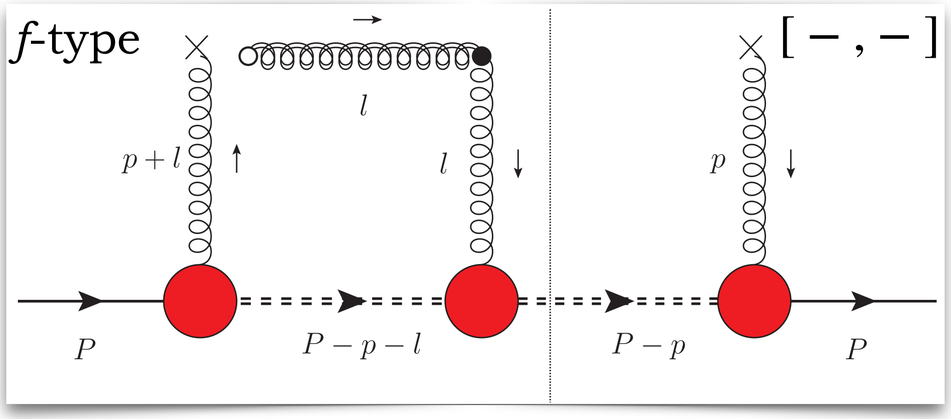
T-odd gluon TMDs in a spectator model

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

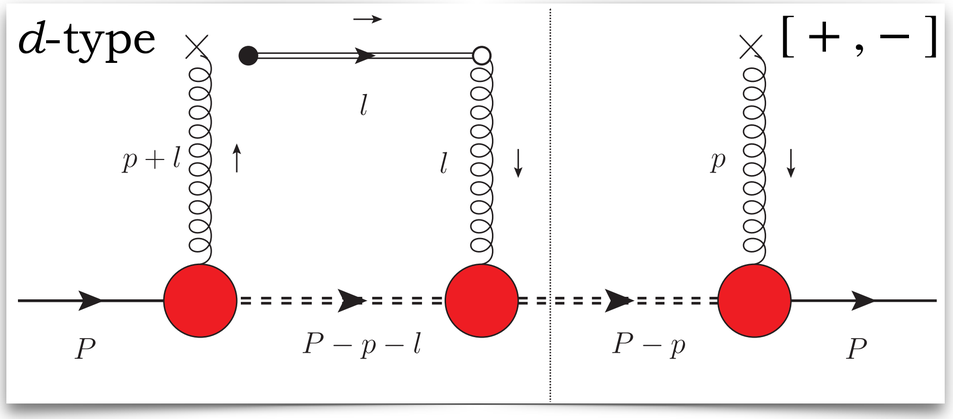
T-odd gluon TMDs in a spectator model

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

$gg \to H$



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



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

Closing statements

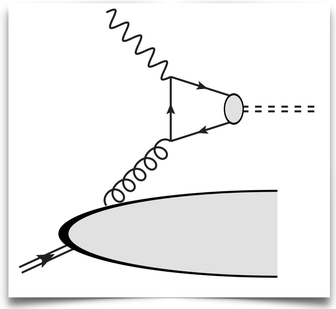
- ☑ Systematic calculation of all twist-2 T-even gluon TMDs
- ☑ Spectral mass to catch small- and large-x effects
- ☑ **Simultaneous fit** of f_1 and g_1 PDFs via **replica method**

Closing statements

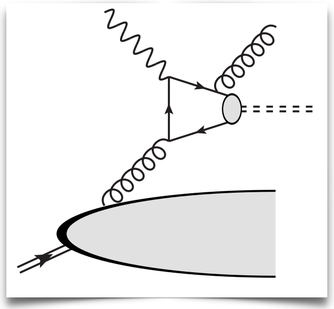
- ☑ Systematic calculation of all twist-2 T-even gluon TMDs
- ☑ Spectral mass to catch small- and large-x effects
- ☑ **Simultaneous fit** of f_1 and g_1 PDFs via **replica method**
- ☐ Twist-2 T-odd gluon TMDs (**Sivers**, etc.) soon available!
- ☐ Pheno: **spin asymmetries**, **pseudodata** and **impact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



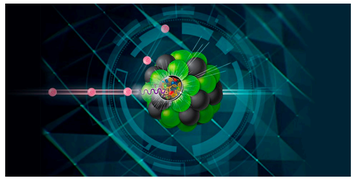
CO

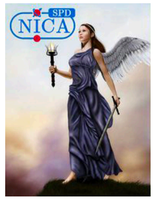


CO + CS

EIC Yellow Report Document
(EICUG website)

[EICUG [arXiv:2103.05419]]



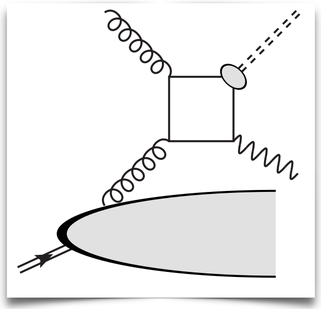


CERN

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

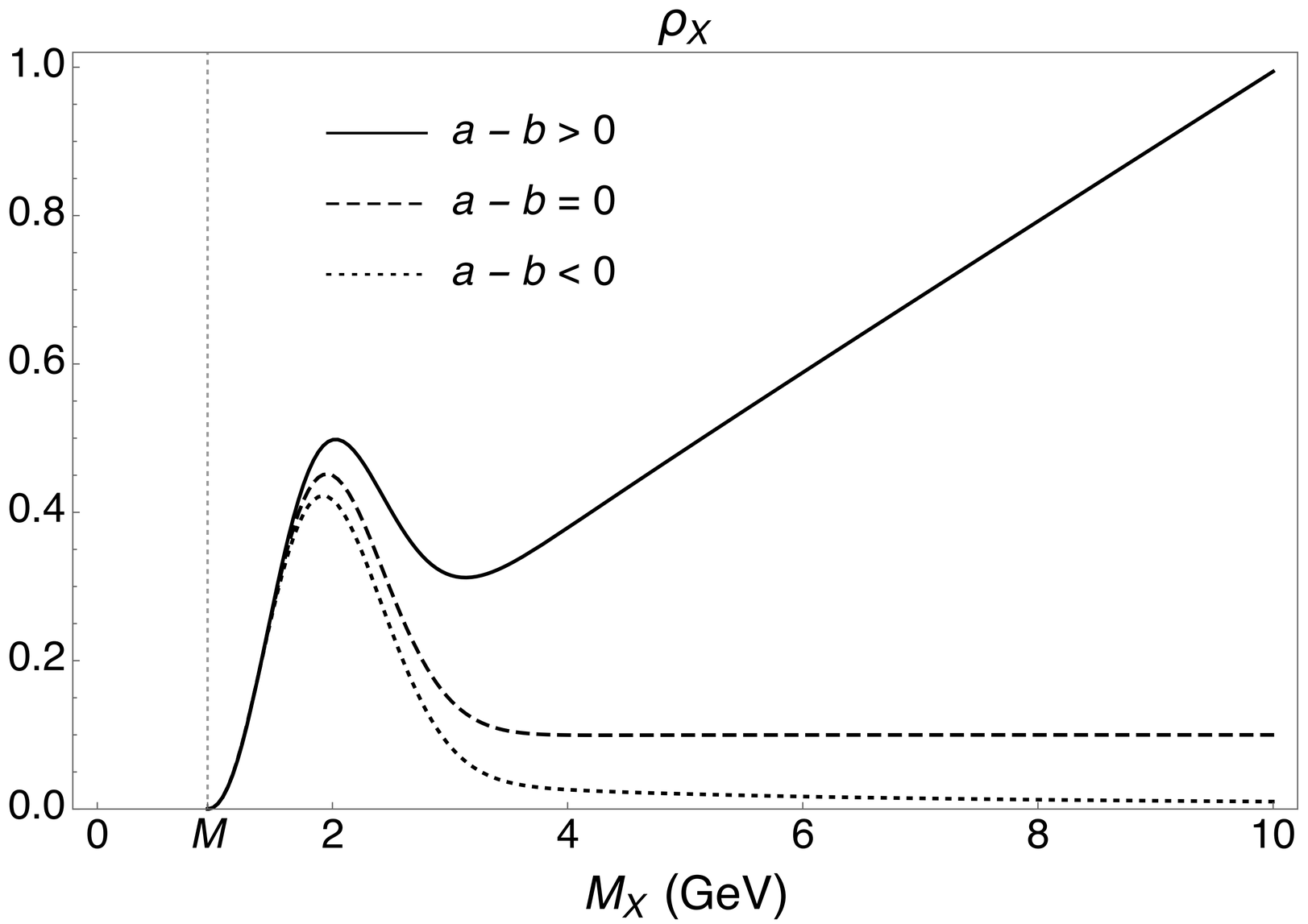
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

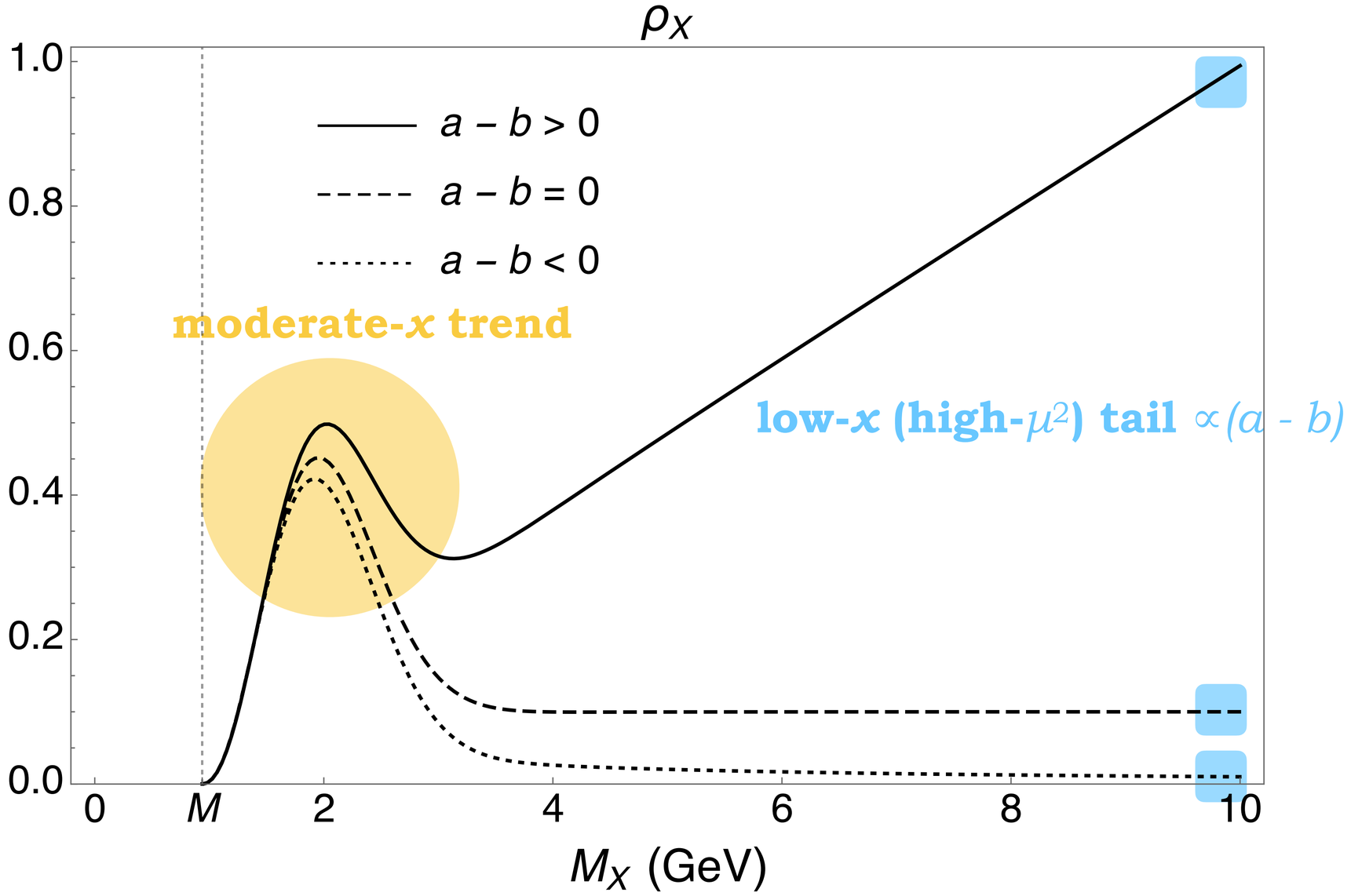
Backup

Spectral function vs *(a - b)*



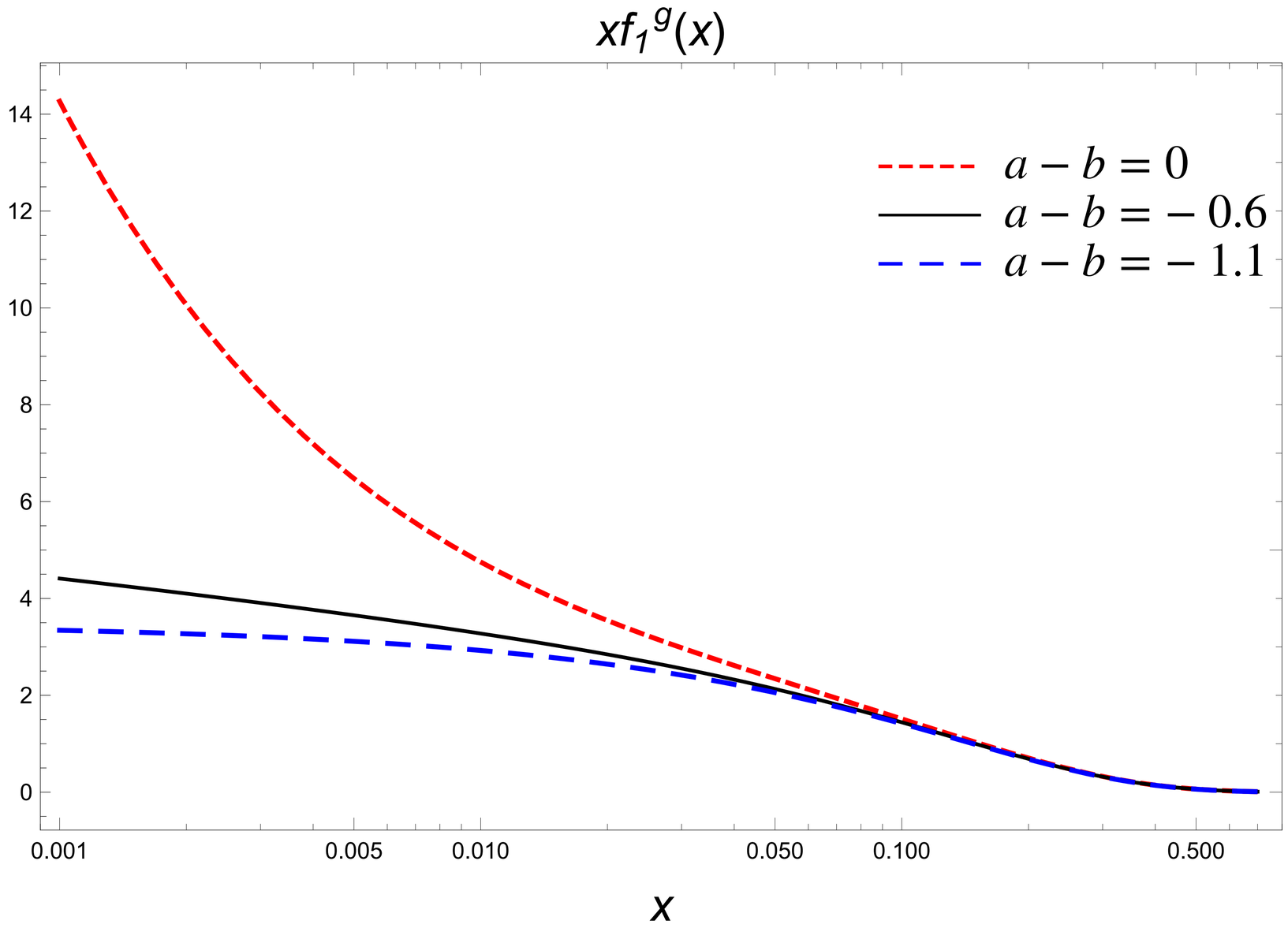
Backup

Spectral function vs $(a - b)$



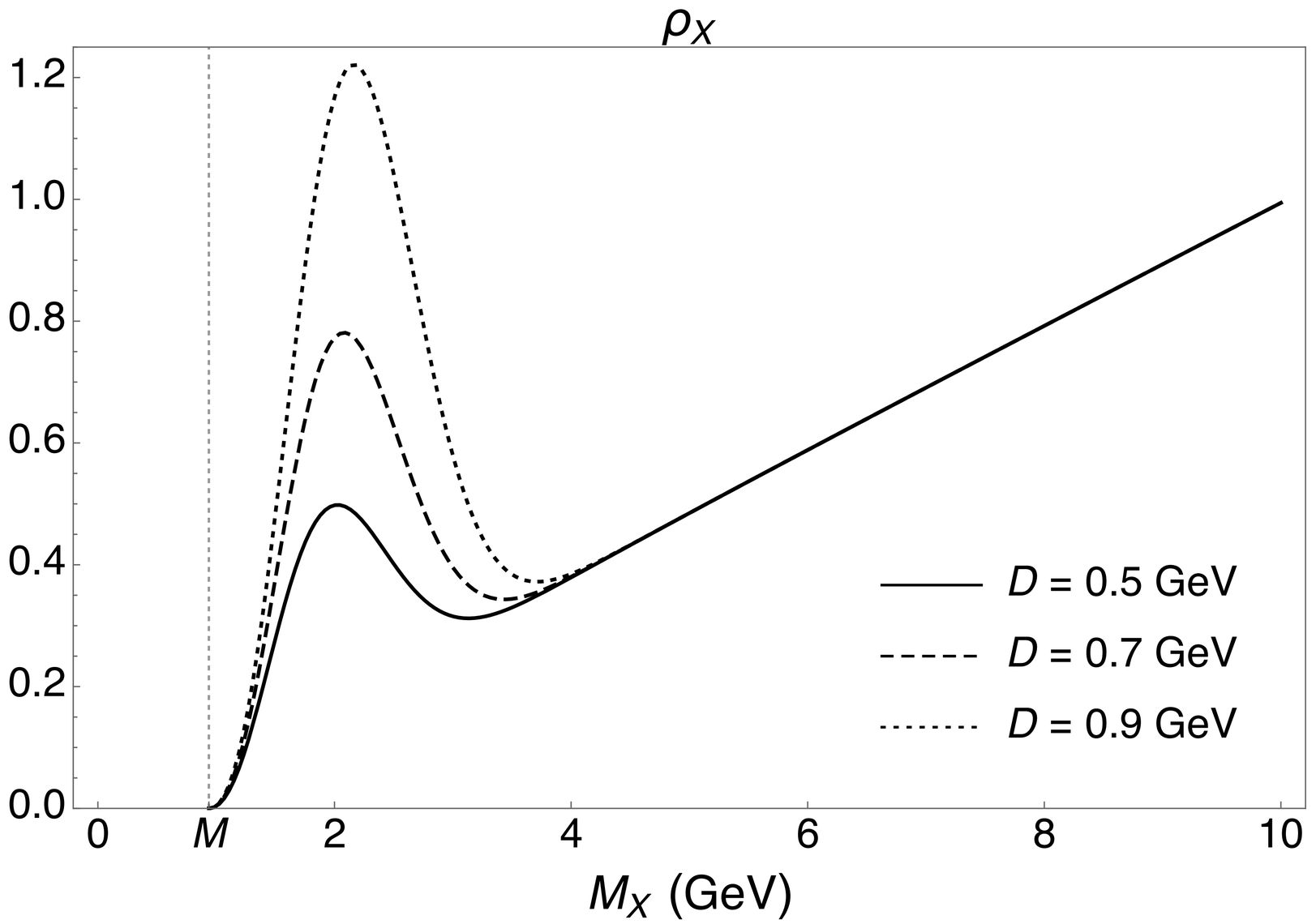
Backup

xf_1 collinear PDF vs $(a - b)$



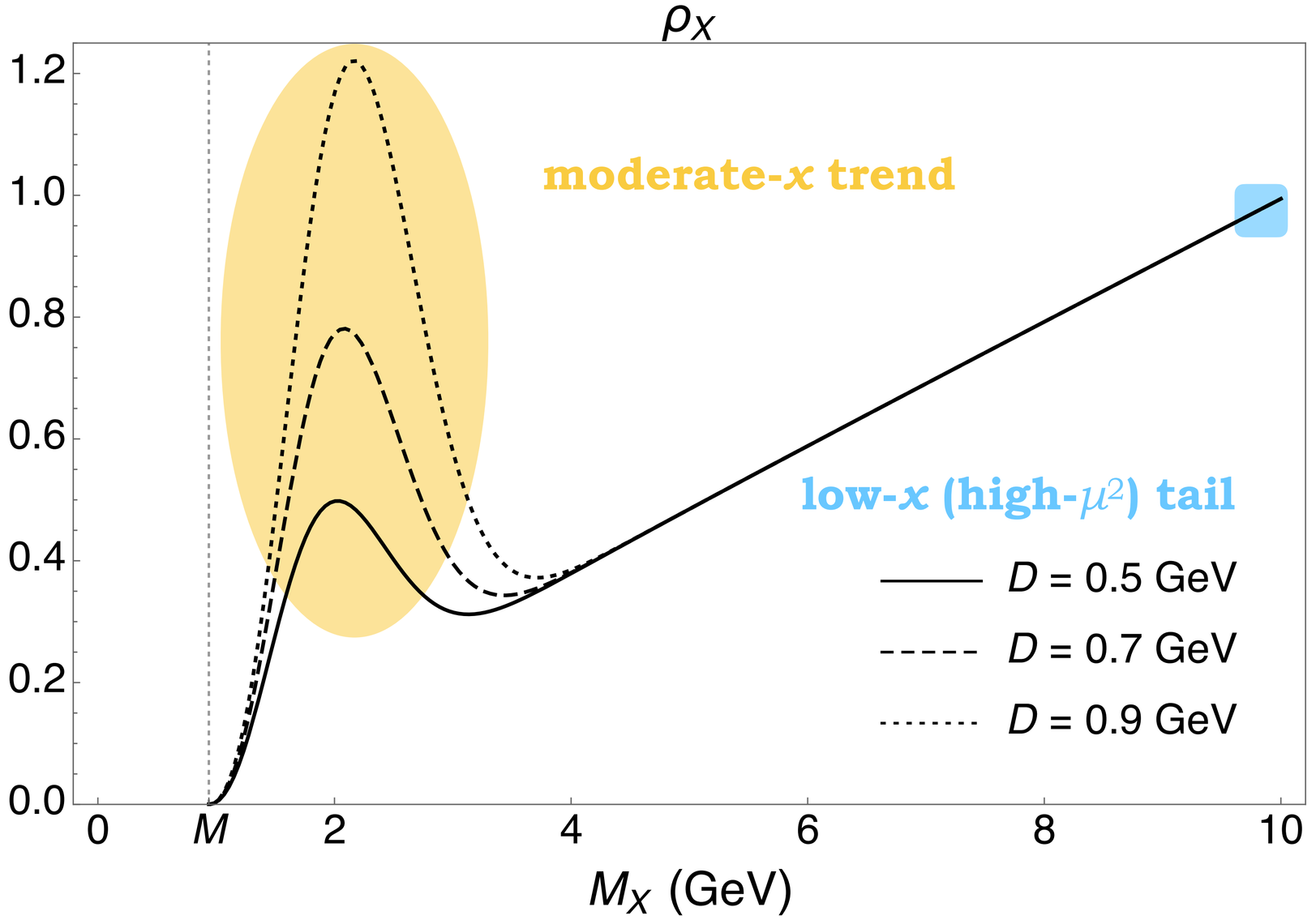
Backup

Spectral function vs D



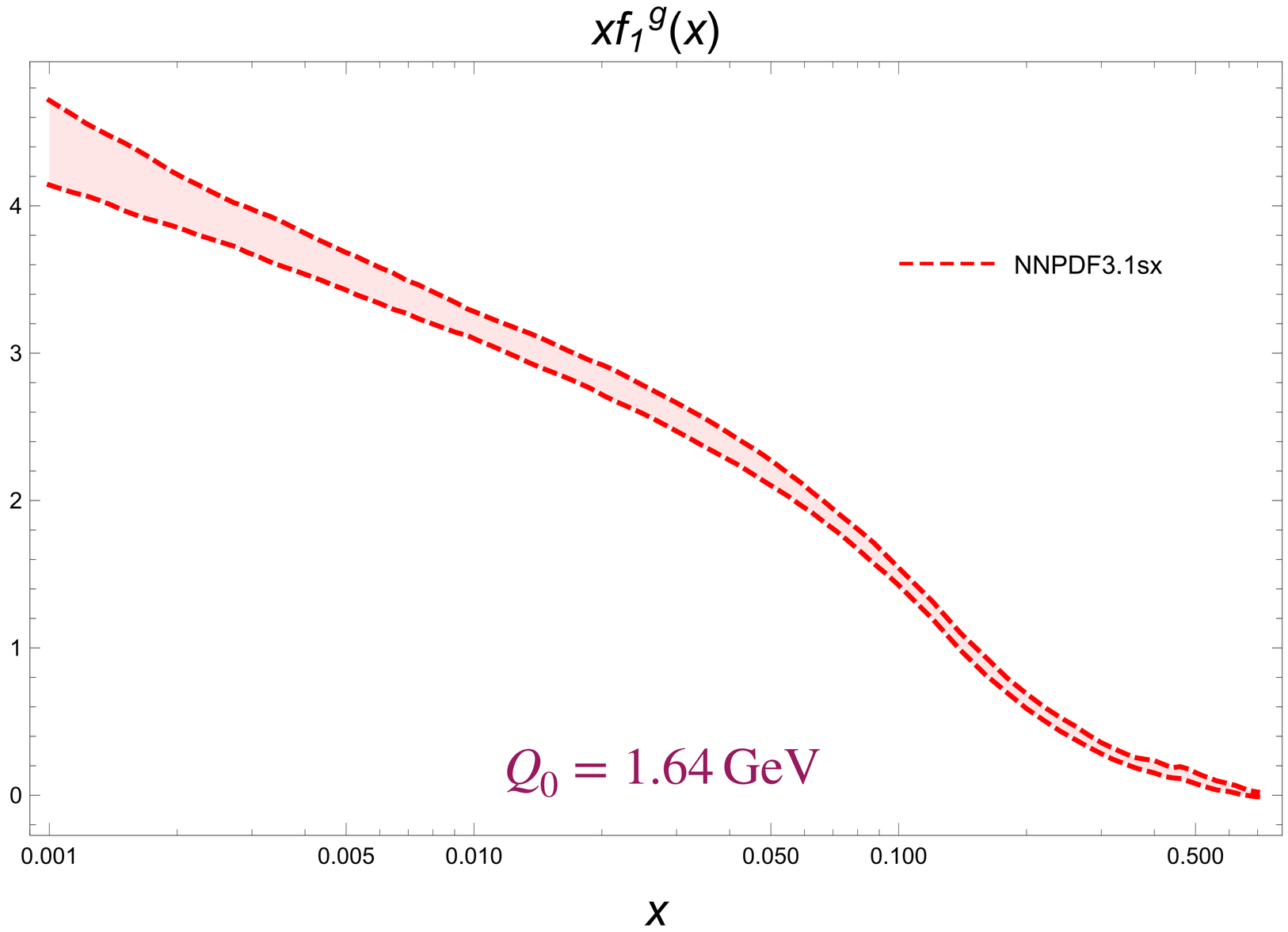
Backup

Spectral function vs D



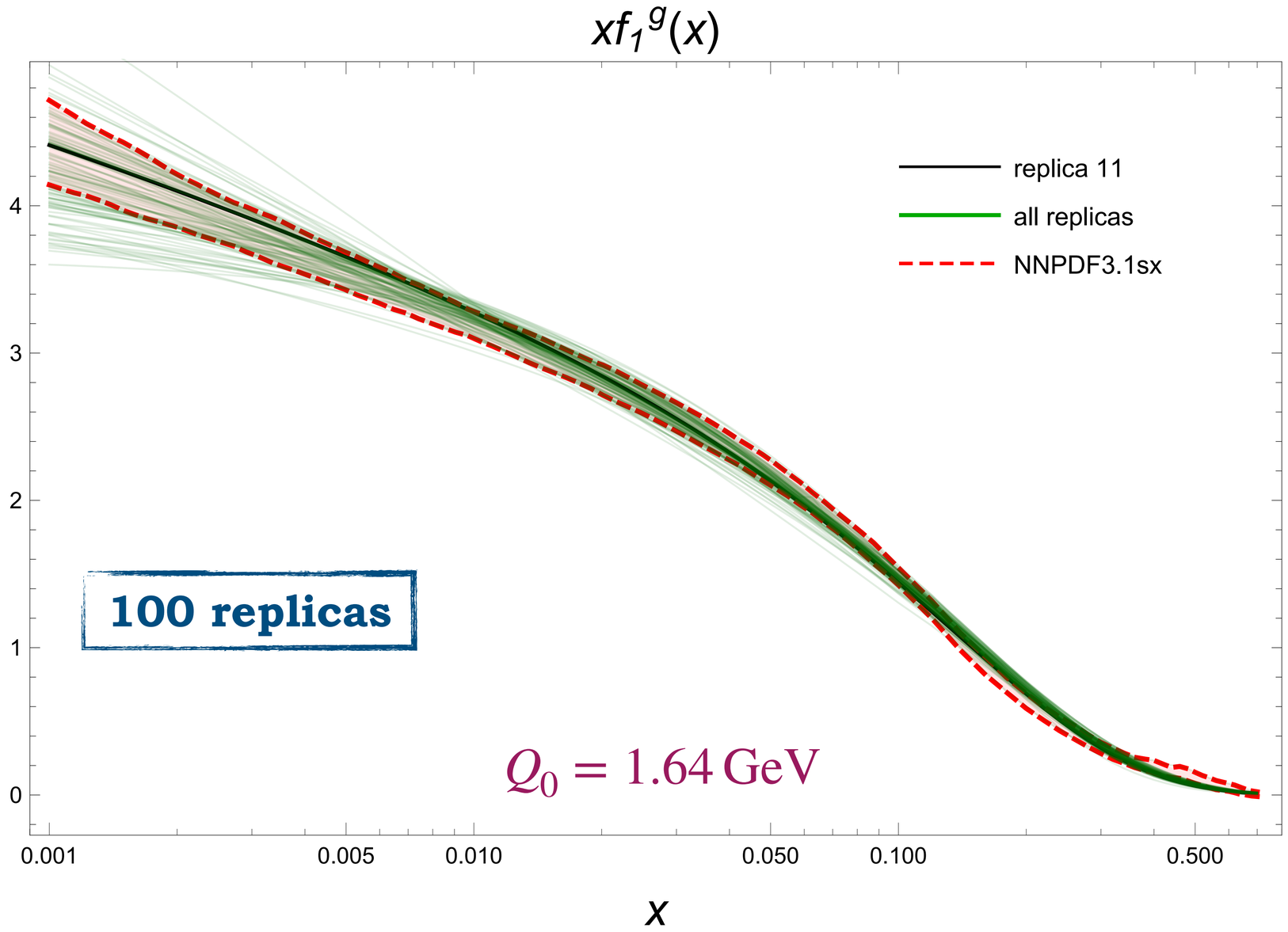
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Unpolarized gluon PDF



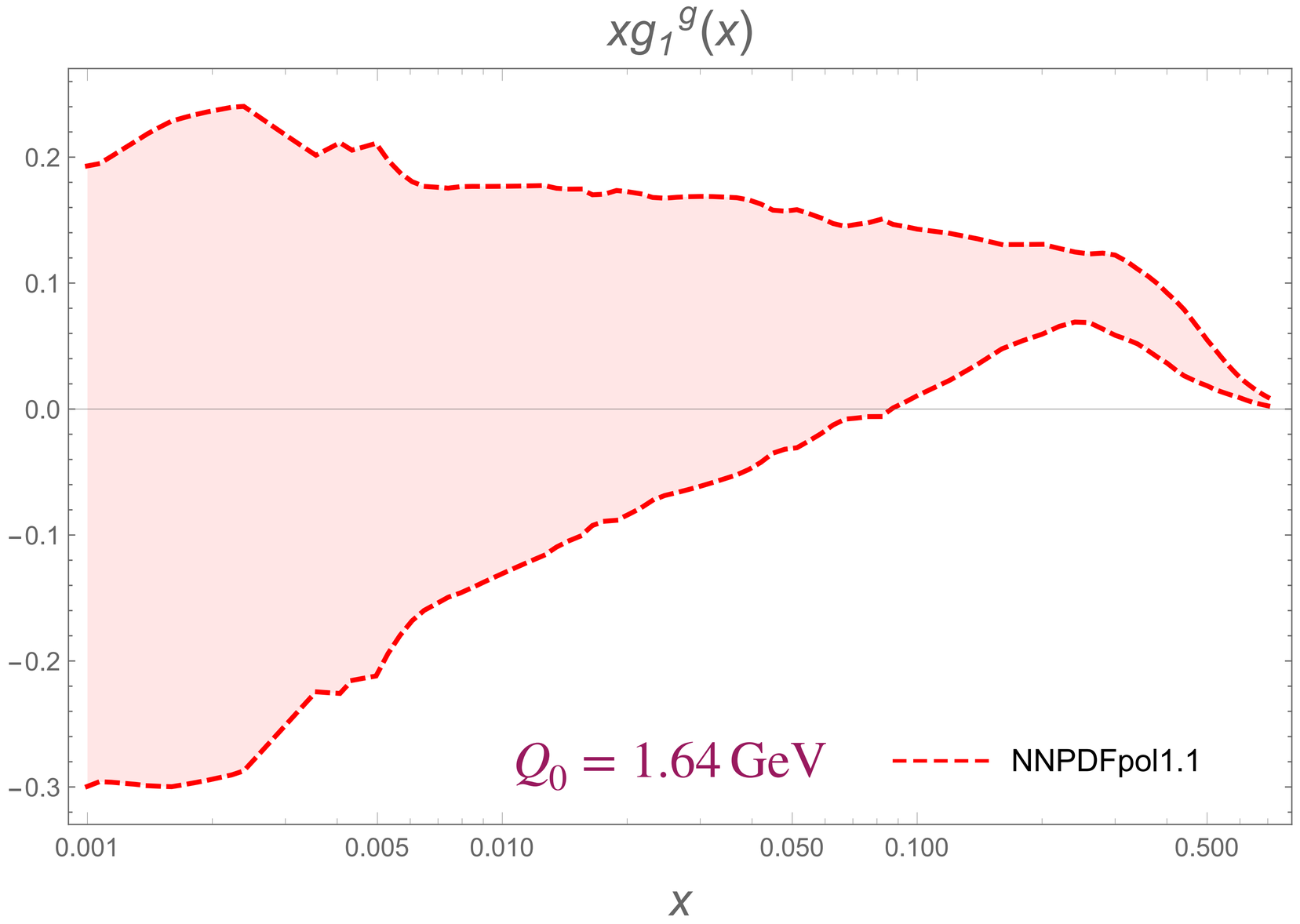
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Unpolarized gluon PDF



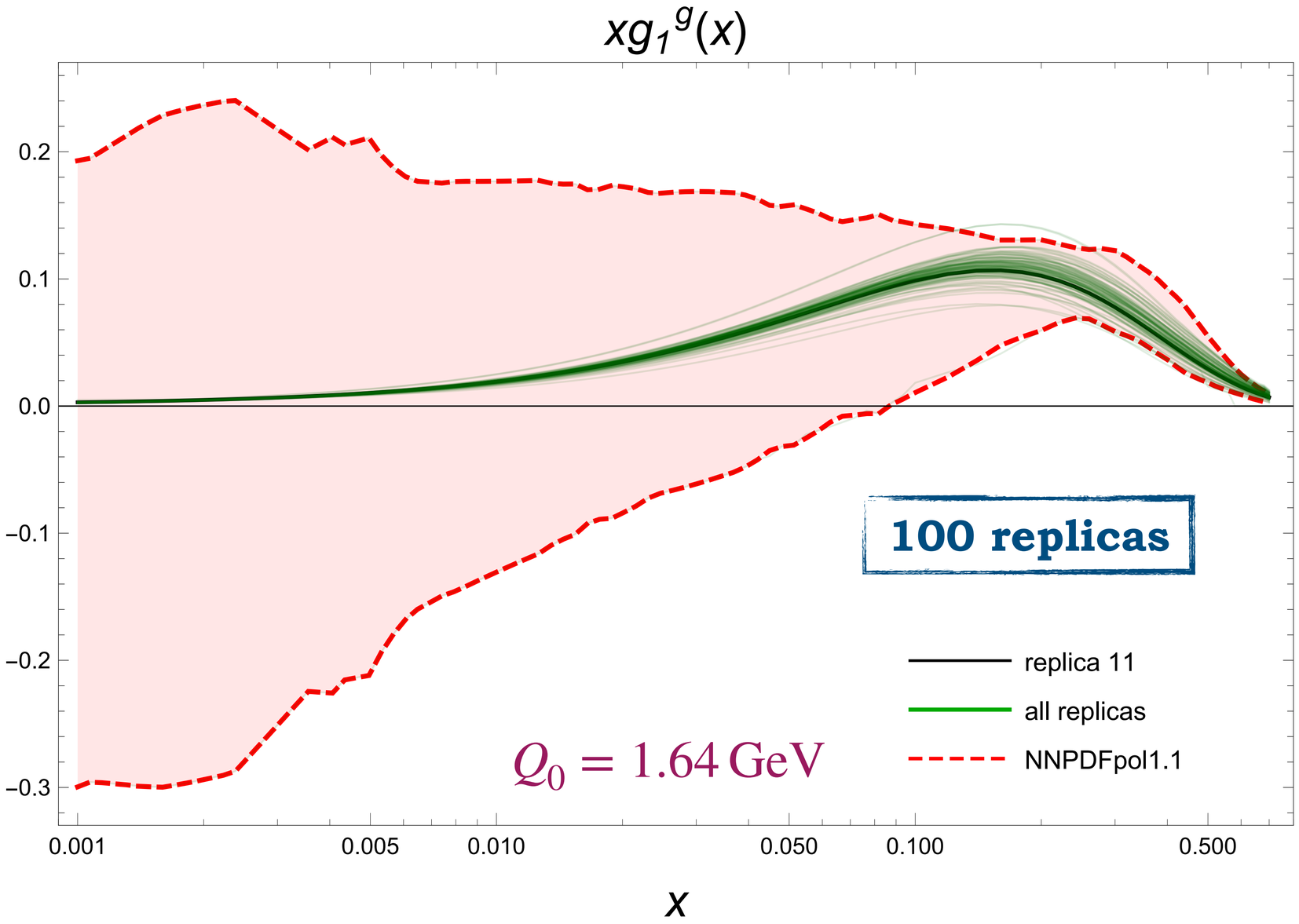
Backup

Helicity gluon PDF



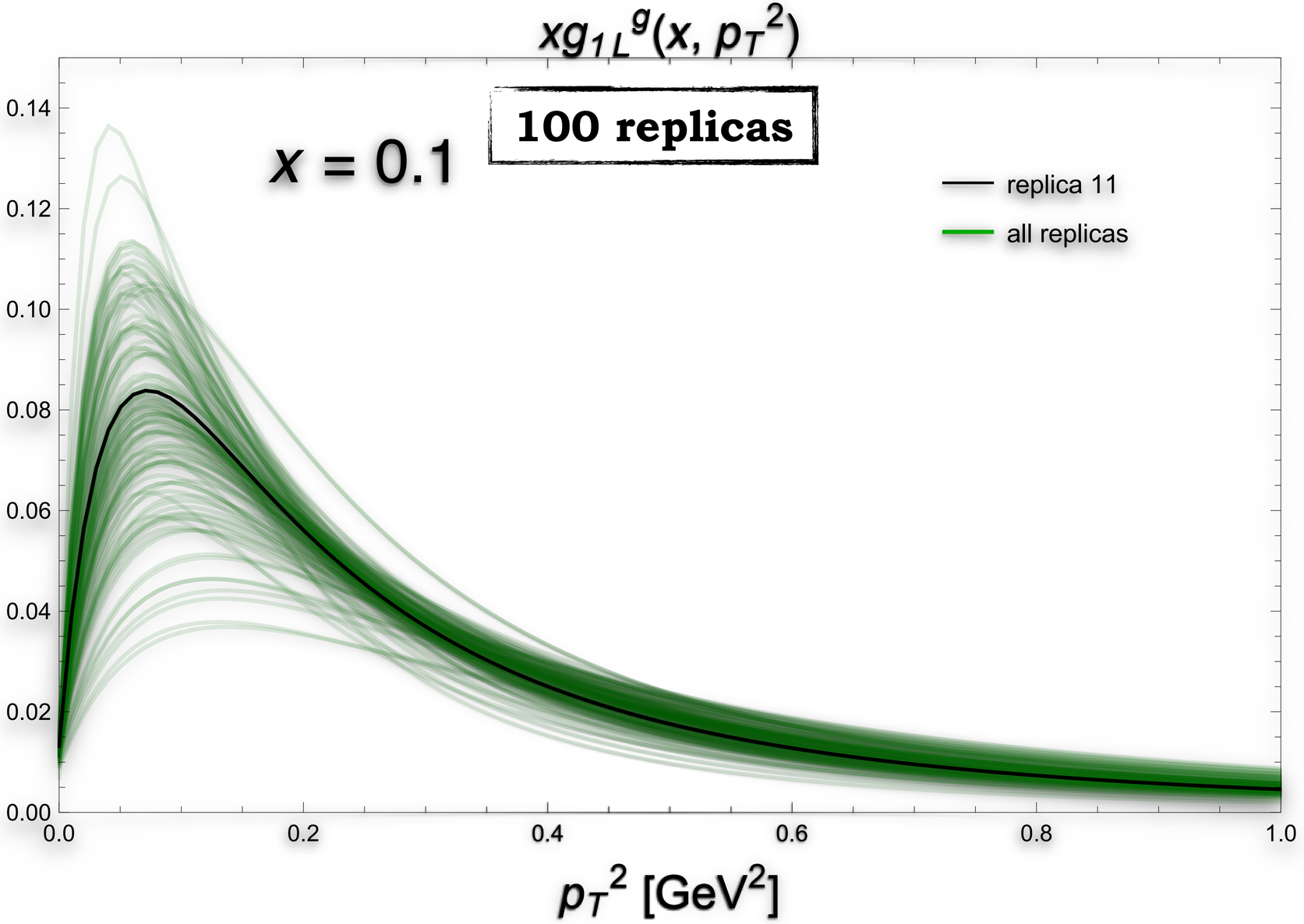
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Helicity gluon PDF



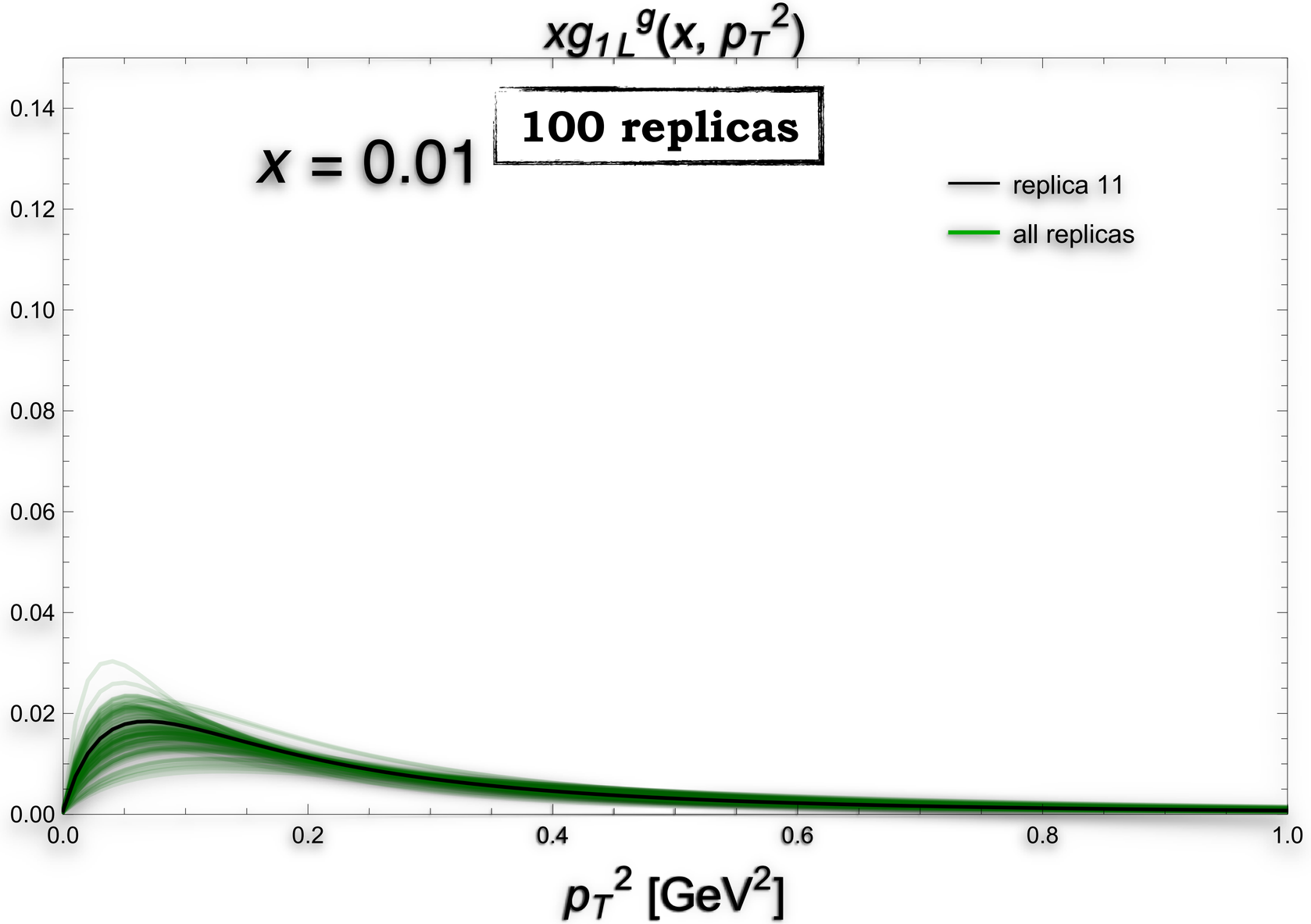
Backup

Helicity gluon TMD



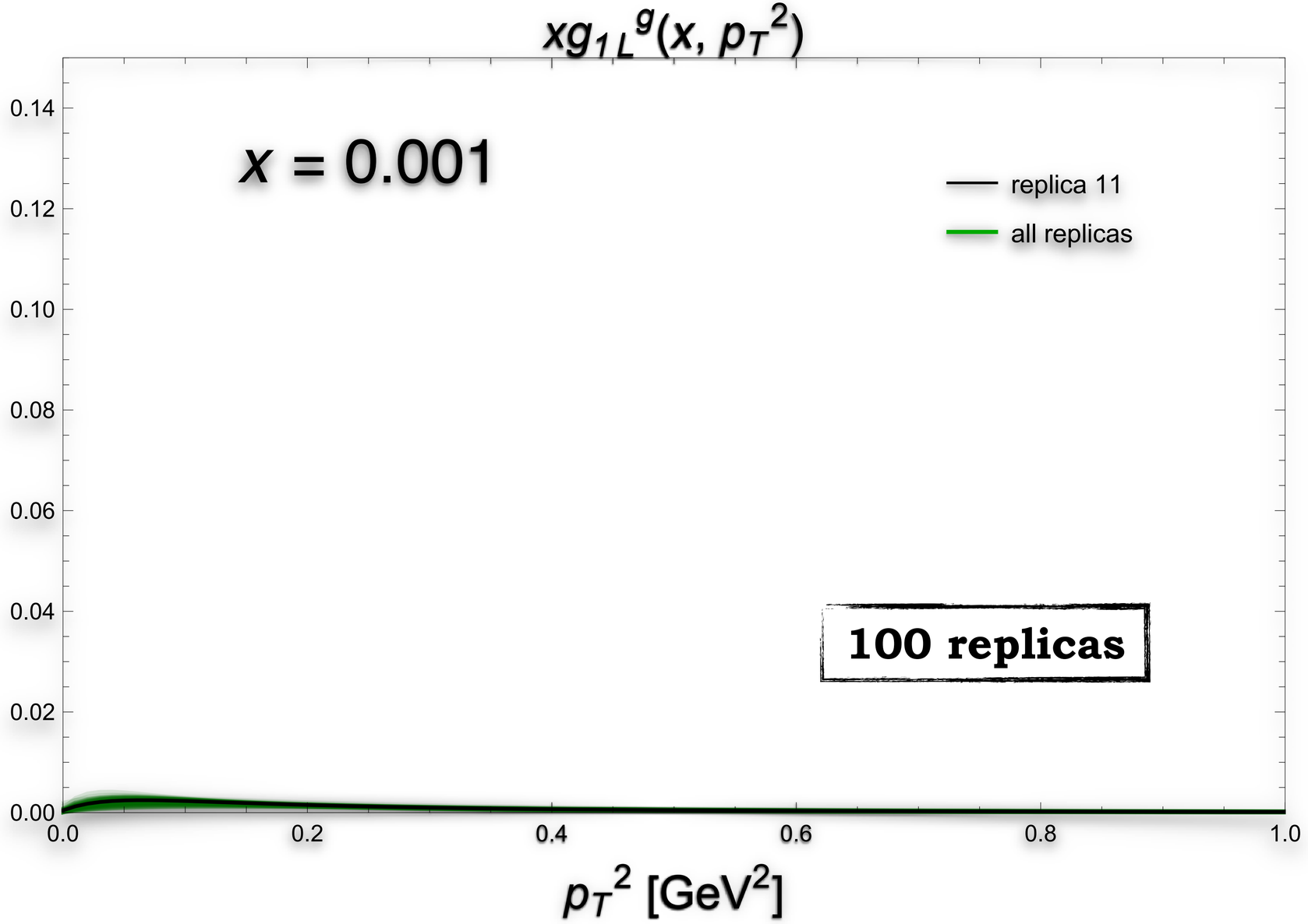
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Helicity gluon TMD



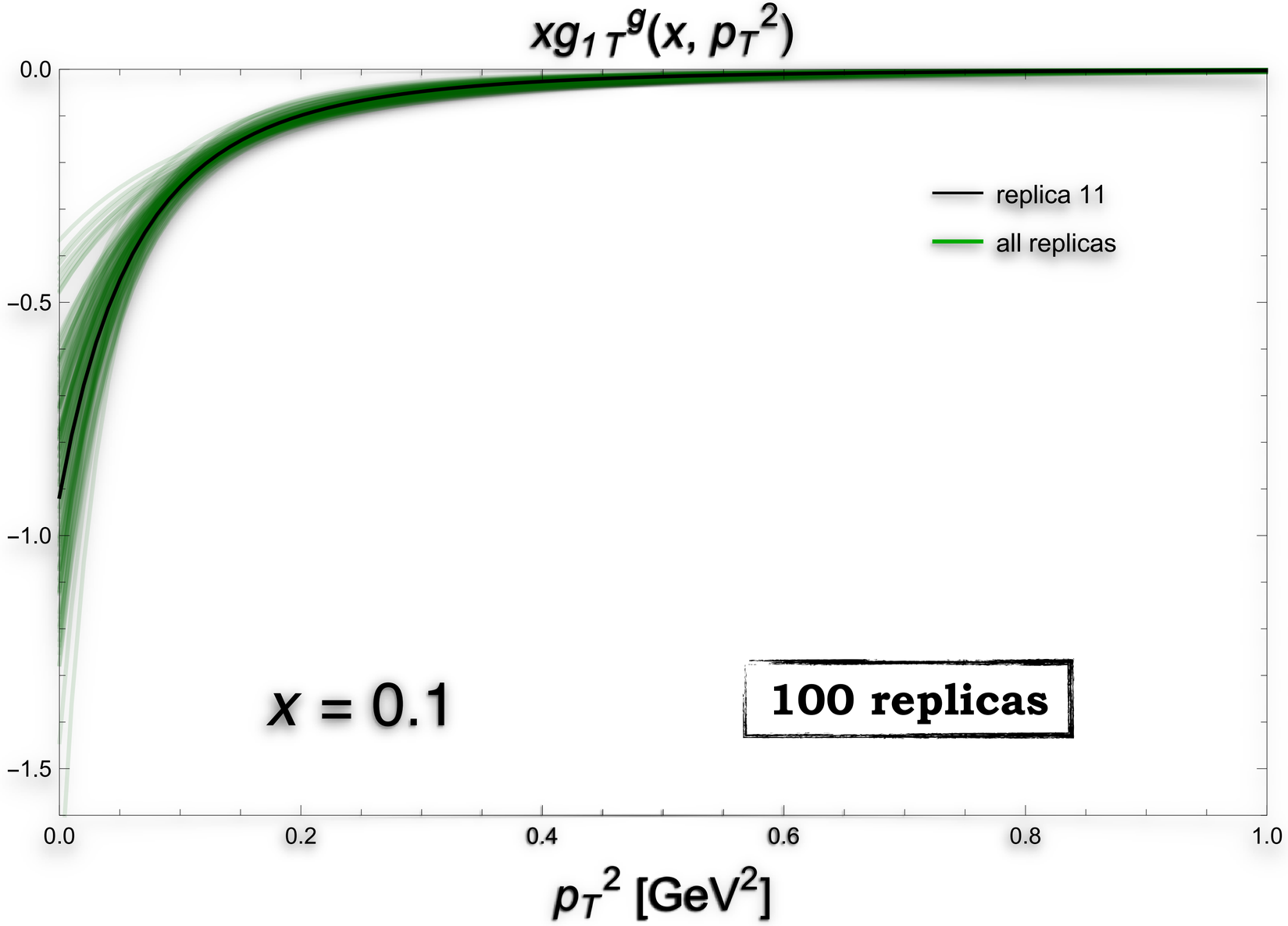
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Helicity gluon TMD



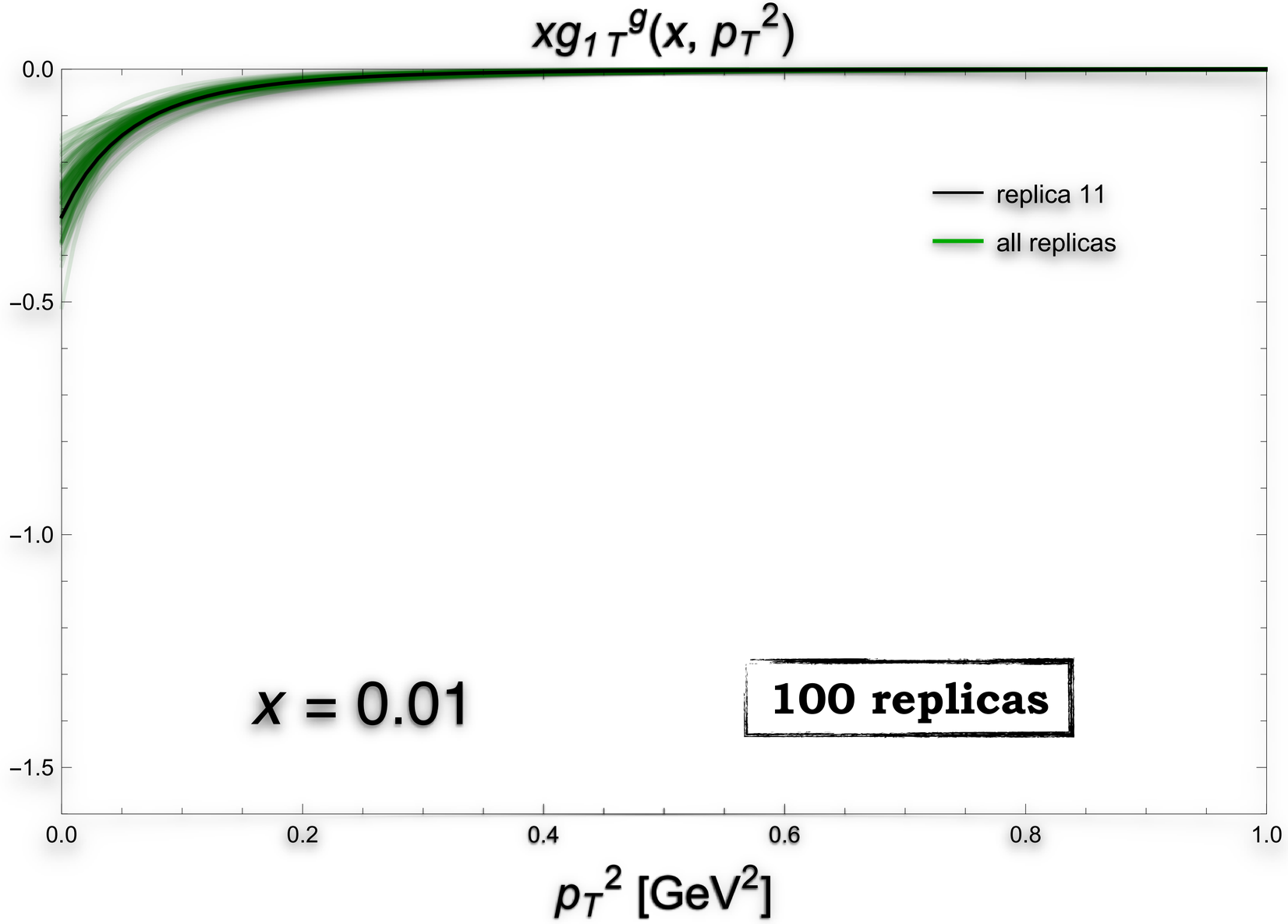
Backup

Worm-gear gluon TMD



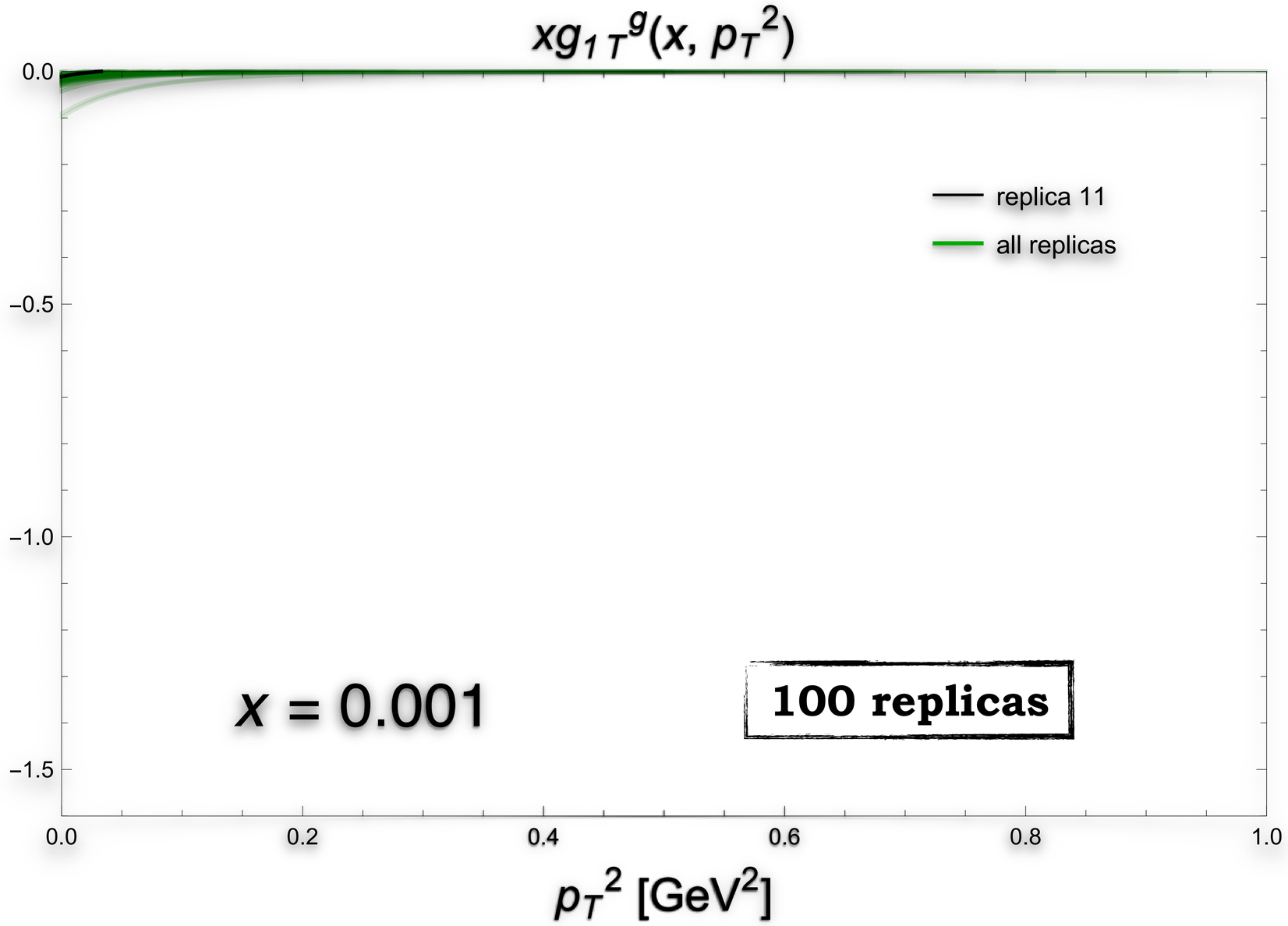
Backup

Worm-gear gluon TMD



Backup

Worm-gear gluon TMD



Backup

Bottom line

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

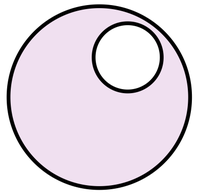
- Data on gluon TMDs will exclude many replicas and constrain parameters not yet so well constrained by collinear PDFs

- 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

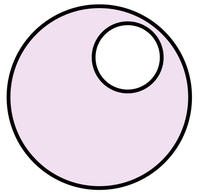


Unpolarized [u/u]

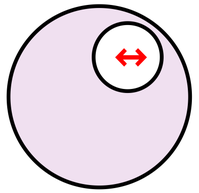
$f_1(x, p_x, p_y)$

Backup

ρ-densities



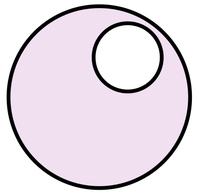
Unpolarized [u/u] $f_1(x, p_x, p_y)$



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

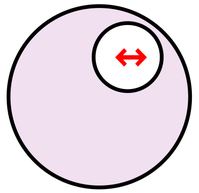
Backup

ρ-densities



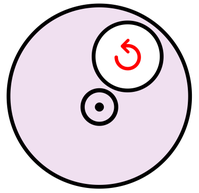
Unpolarized [u/u]

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



Boer-Mulders [↔/u]

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

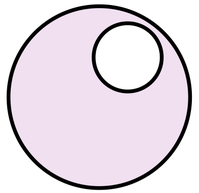


Helicity [↻/+]

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

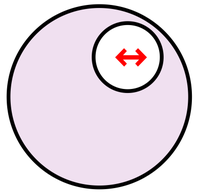
Backup

ρ-densities



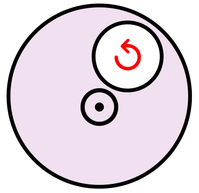
Unpolarized [u/u]

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



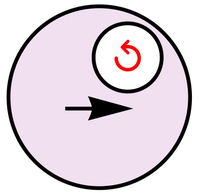
Boer-Mulders [↔/u]

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



Helicity [↺/+]

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



Worm-gear [↺/→]

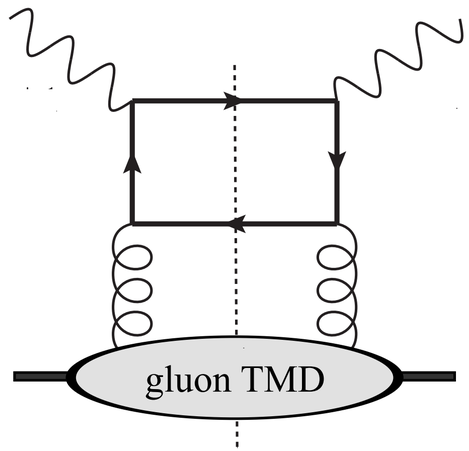
$$f_1(x, p_x, p_y) - \frac{p_x}{M} g_{1T}(x, p_x, p_y)$$

Backup

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

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

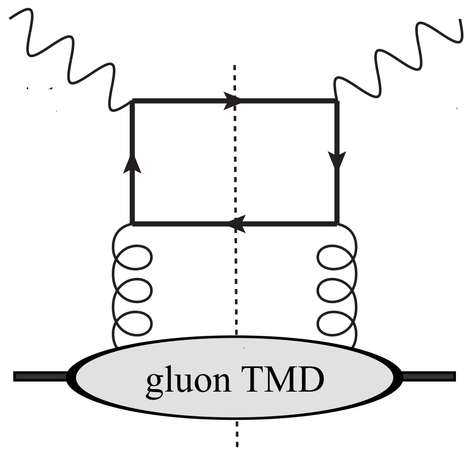


Backup

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4. Inclusive J/Ψ production at low p_T

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



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

Backup