EIC opportunities at Snowmass

January 26th, 2021

3D proton tomography at the EIC
TMD gluon densities

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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

of quark TMDs are subleading for gluon TMDs

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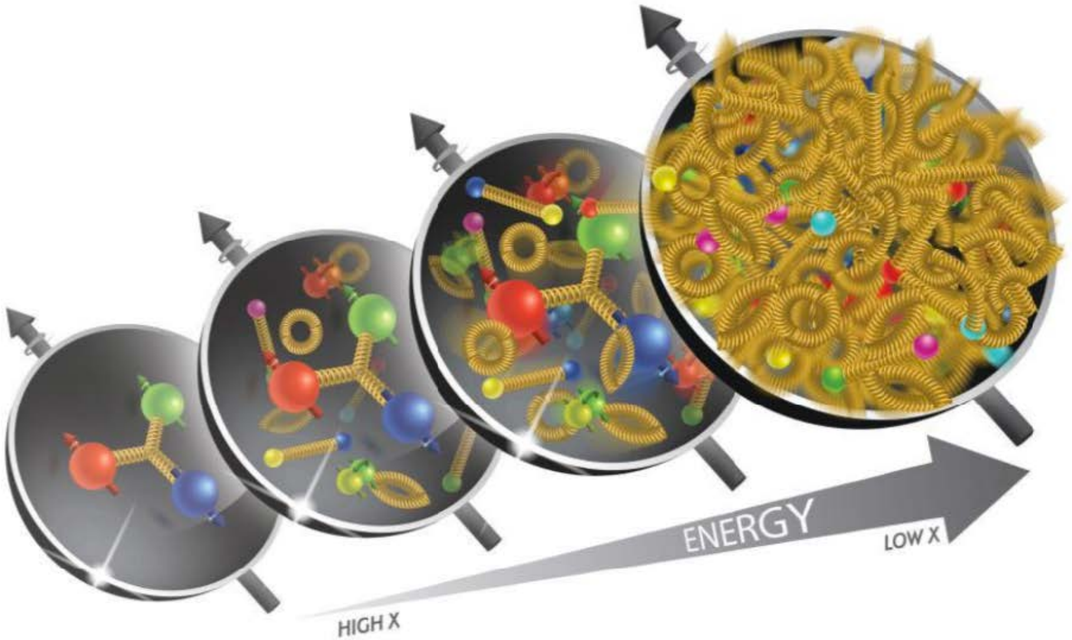
Motivation

- 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

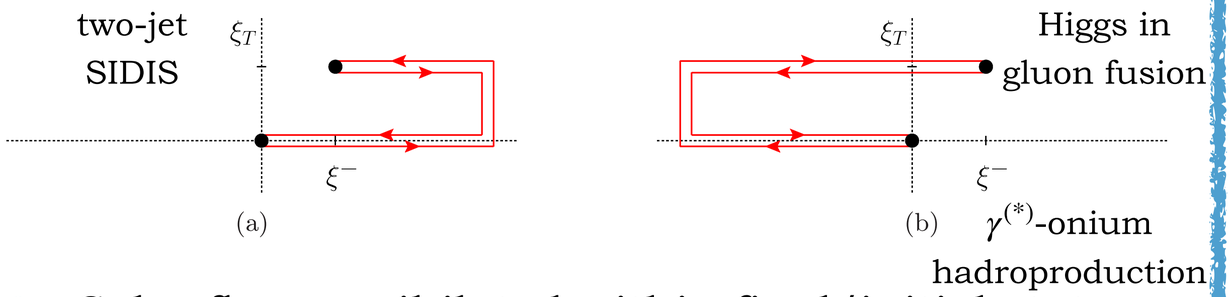


Significance of gluon-TMD studies in a wide range of x

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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



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

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

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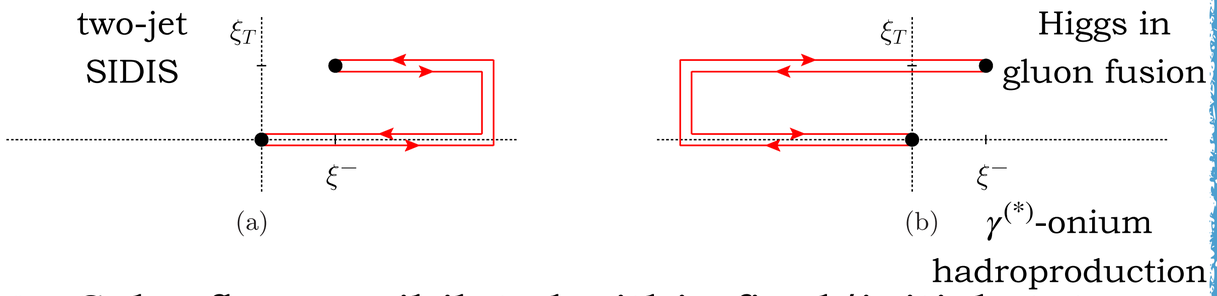

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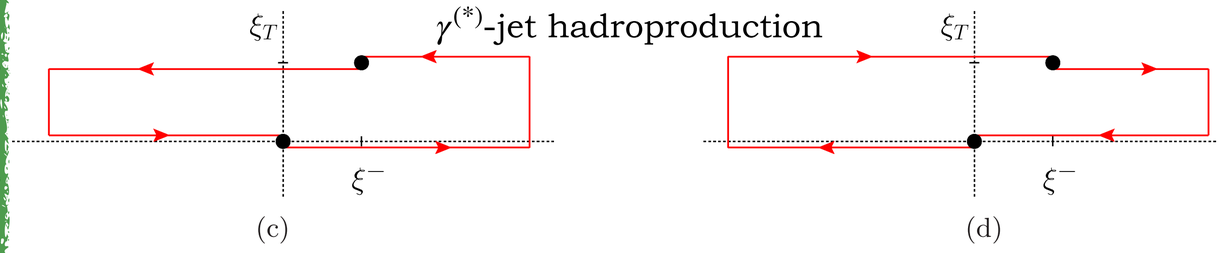
Dipole (DP)

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



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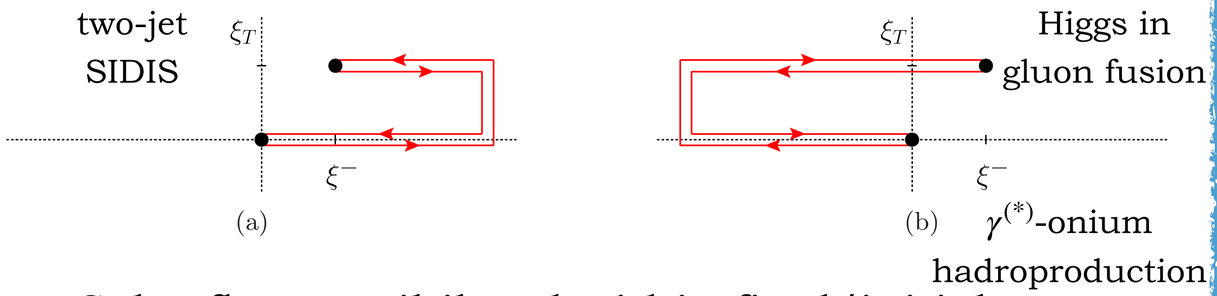

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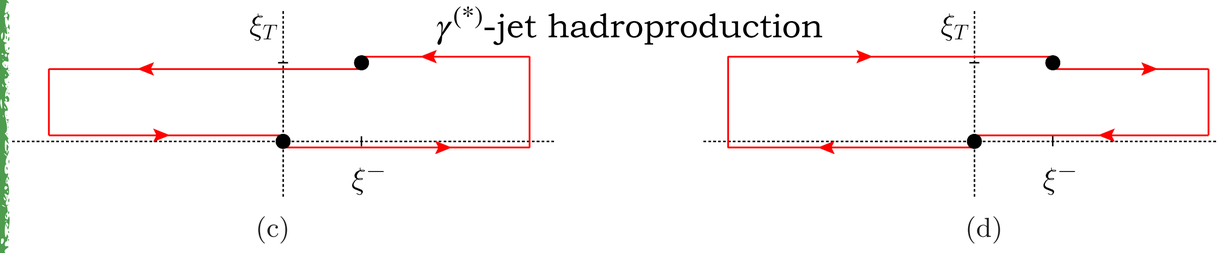

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Gauge link $\rightarrow$ two main independent sets of TMDs, **not related** to each other

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

gluon pol.

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

T-even

T-odd

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

unpolarized TMD

Boer-Mulders

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T-even

T-odd

helicity TMD

worm-gear

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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

Sivers

pretzelosity

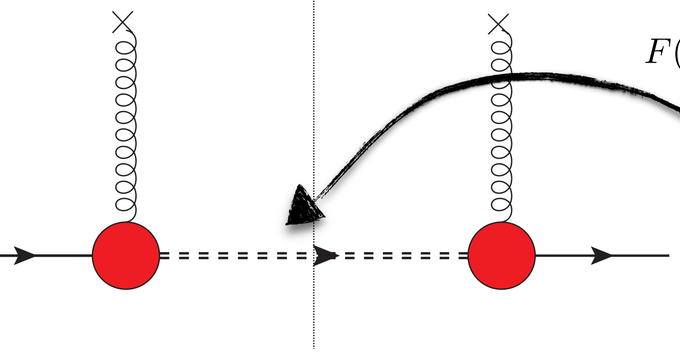
helicity TMD

linearity TMD

worm-gear

Our model at a glance

Spectator-system spectral-mass function

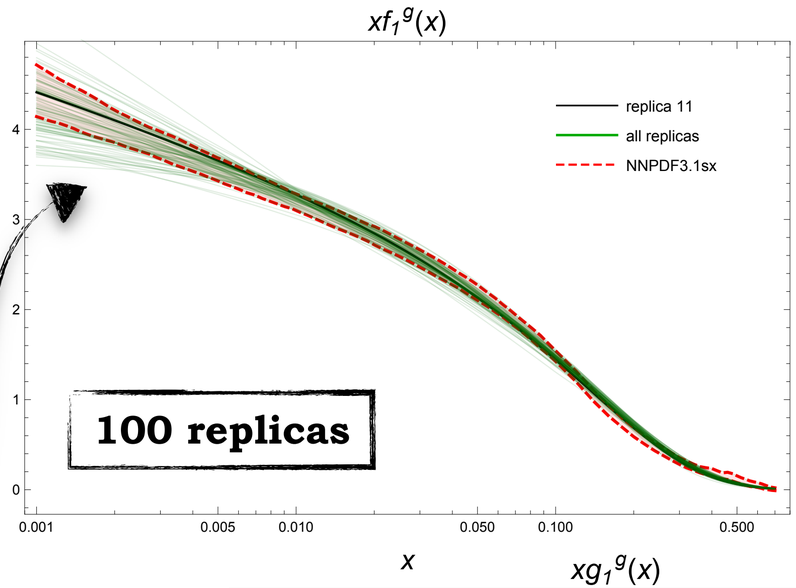


$$F(x, \boldsymbol{p}_T^2) = \int_M^\infty \mathrm{d}M_X \, \rho_X(M_X) \, \hat{F}(x, \boldsymbol{p}_T^2; M_X)$$

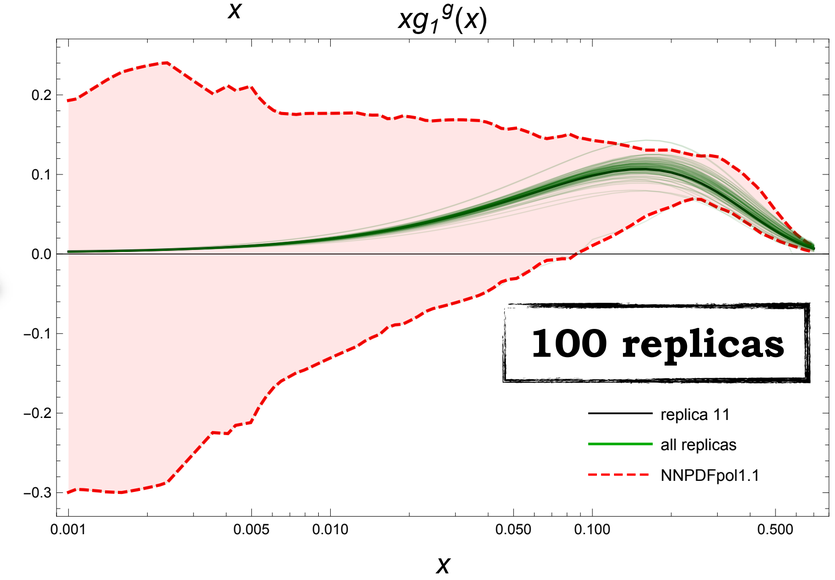
Instead of a single on-shell spectator, a continuum of spectators

Link with collinear factorization

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



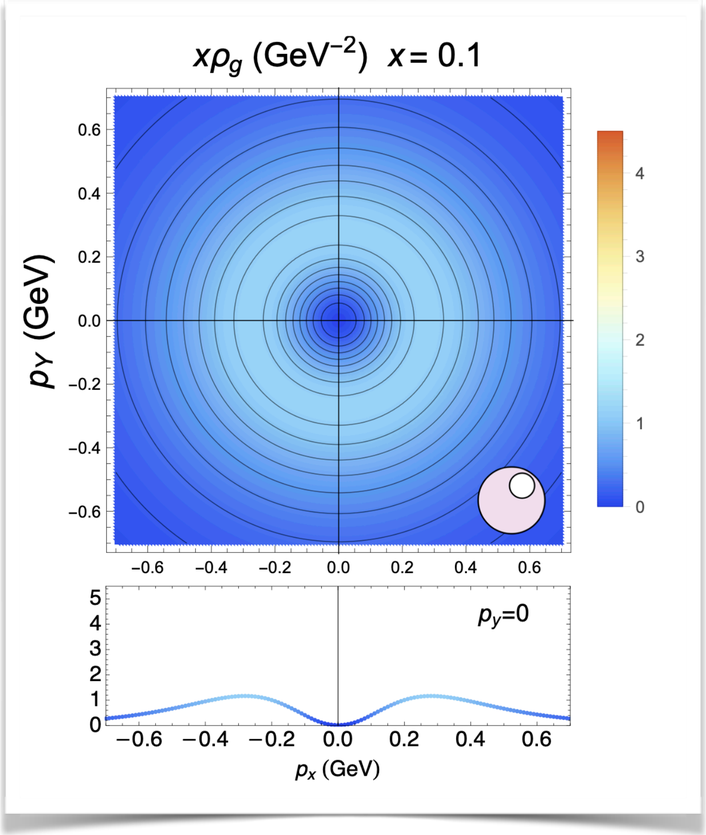
Spectral function **learns** small- and moderate-x info encoded in **NNPDF** collinear parametrizations (`NNPDF3.1sx + NNPDFpol1.1`)



- ☑ **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

3D tomography: the gluon content in the proton

unpolarized TMD



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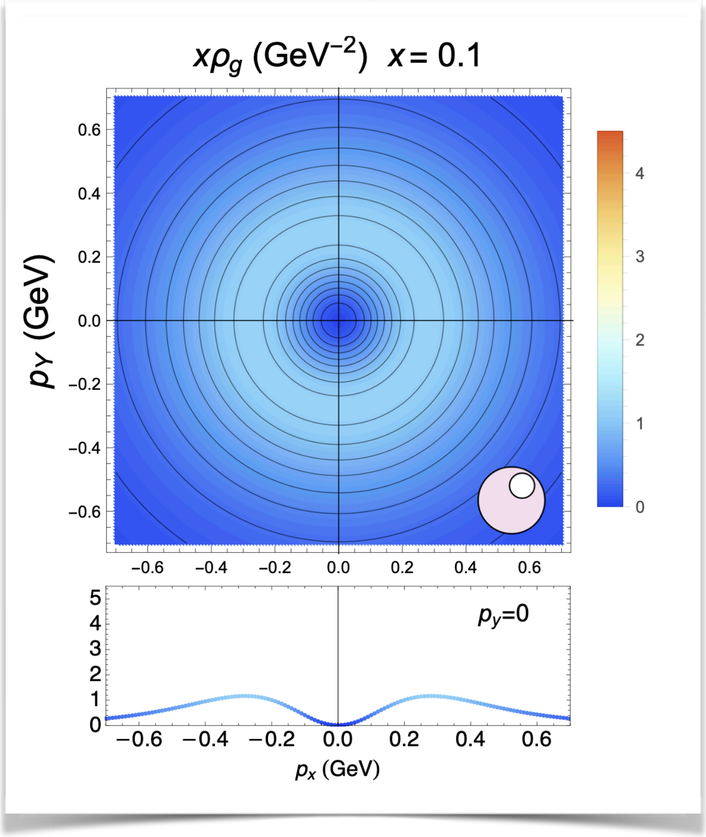
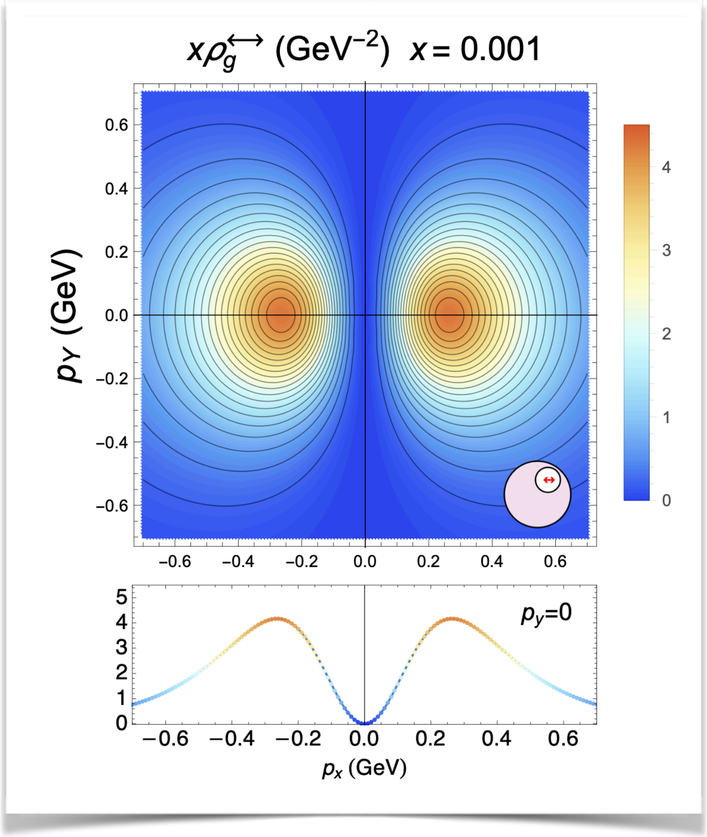


Boer-Mulders



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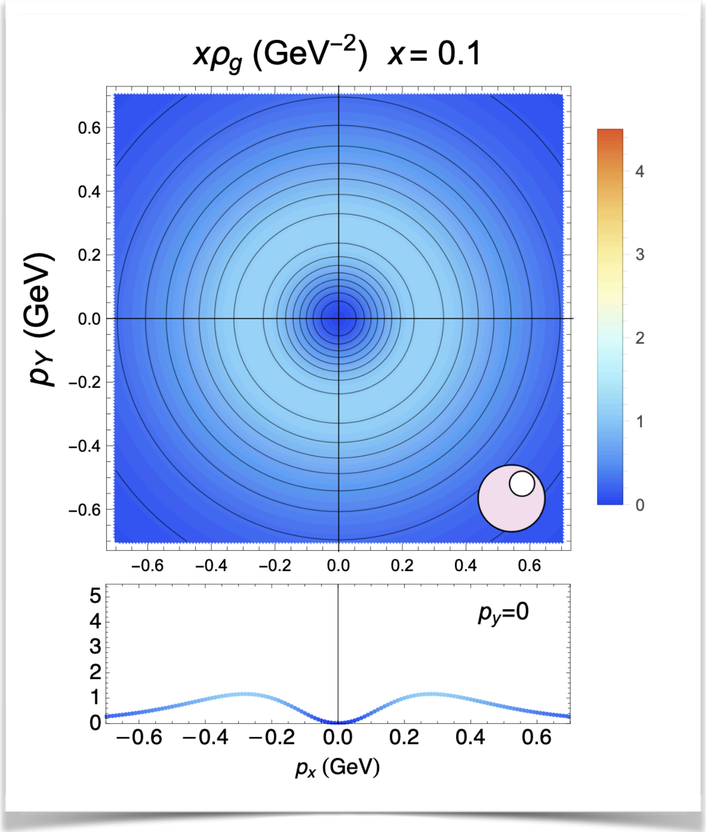

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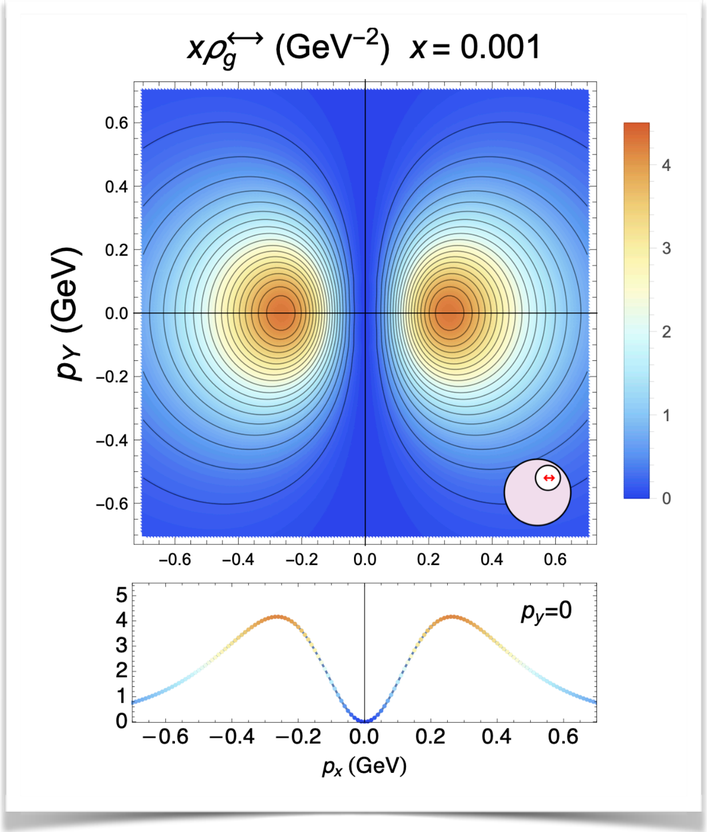
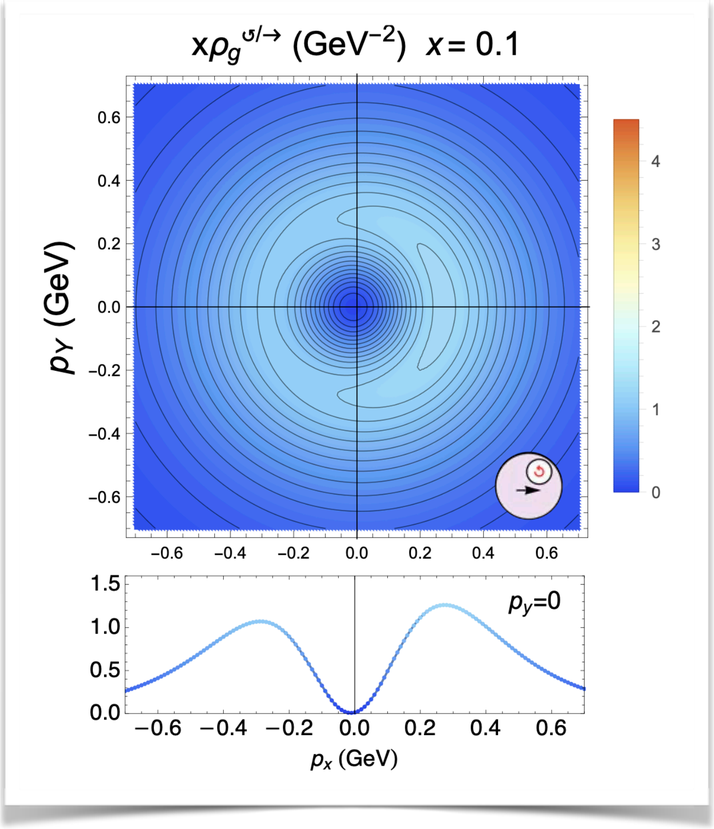


worm-gear



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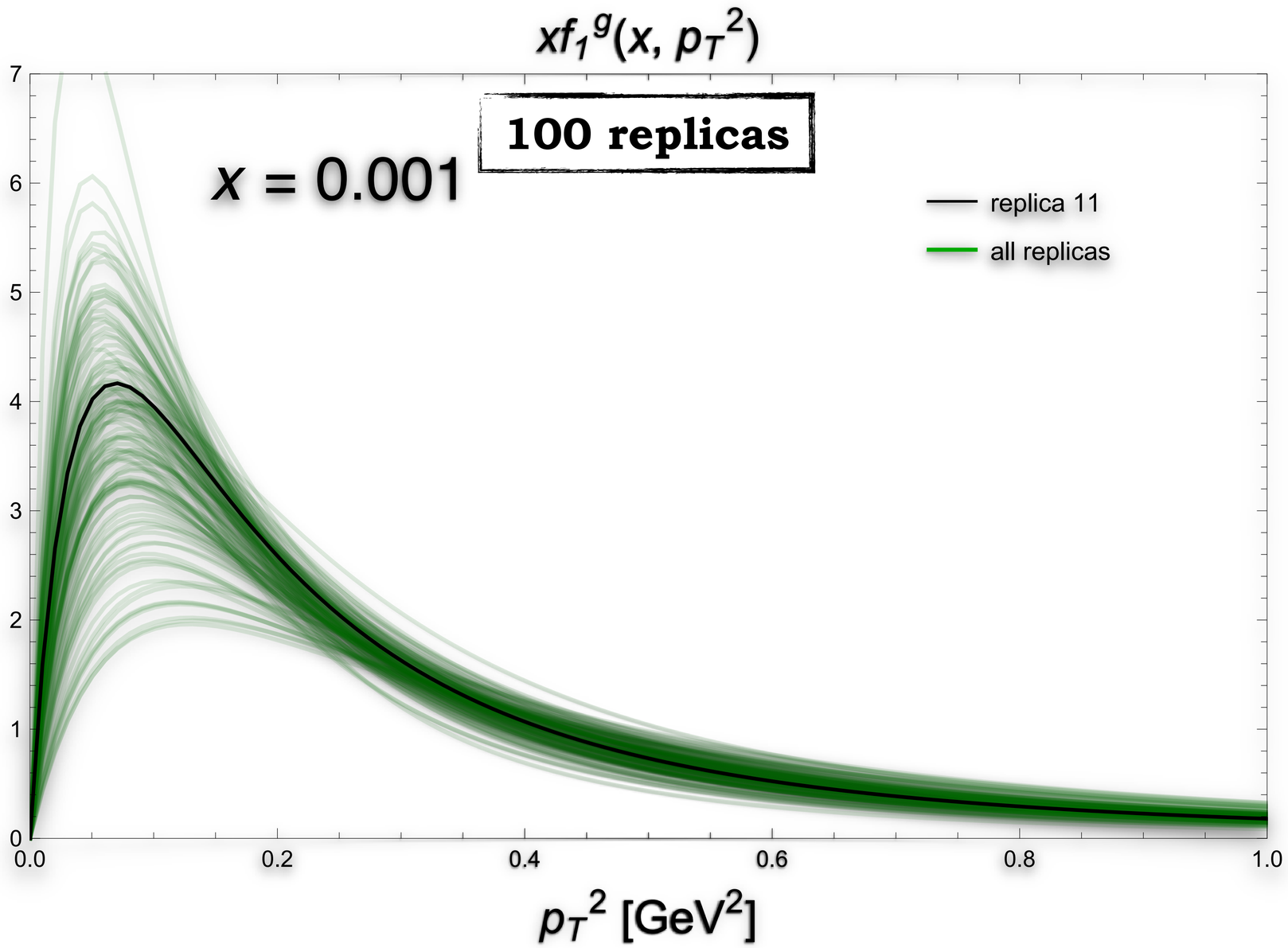

Bottom line

- 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* to be turned on

Hadronic structure at small-x

Incomplete list of small-x formalisms → *linear* (BFKL) or *saturation* (BK/JIMWLK) effects embodied

Unintegrated parton densities

A (hybrid) high-energy factorization established

- **BFKL UGD**: pure small-x evolution, Reggeons
- HEF, CCFM, PRA **uPDFs**: BFKL + collinear matching

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Small-x improved collinear PDFs

DGLAP description improved via BFKL

- **ABF**: PDFs + small-x resummed splitting

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Nonperturbative content via an enhanced spectator model

- **Pavia model**: initial-scale f_1^g and $h_{1\perp}^g$ matched to PDFs

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Need for sub-eikonal corrections, neglected by BFKL

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- **WW** vs **DP** gluon TMDs, **GTMDs**
- **iTMD**: interpolating between TMD and BFKL regimes

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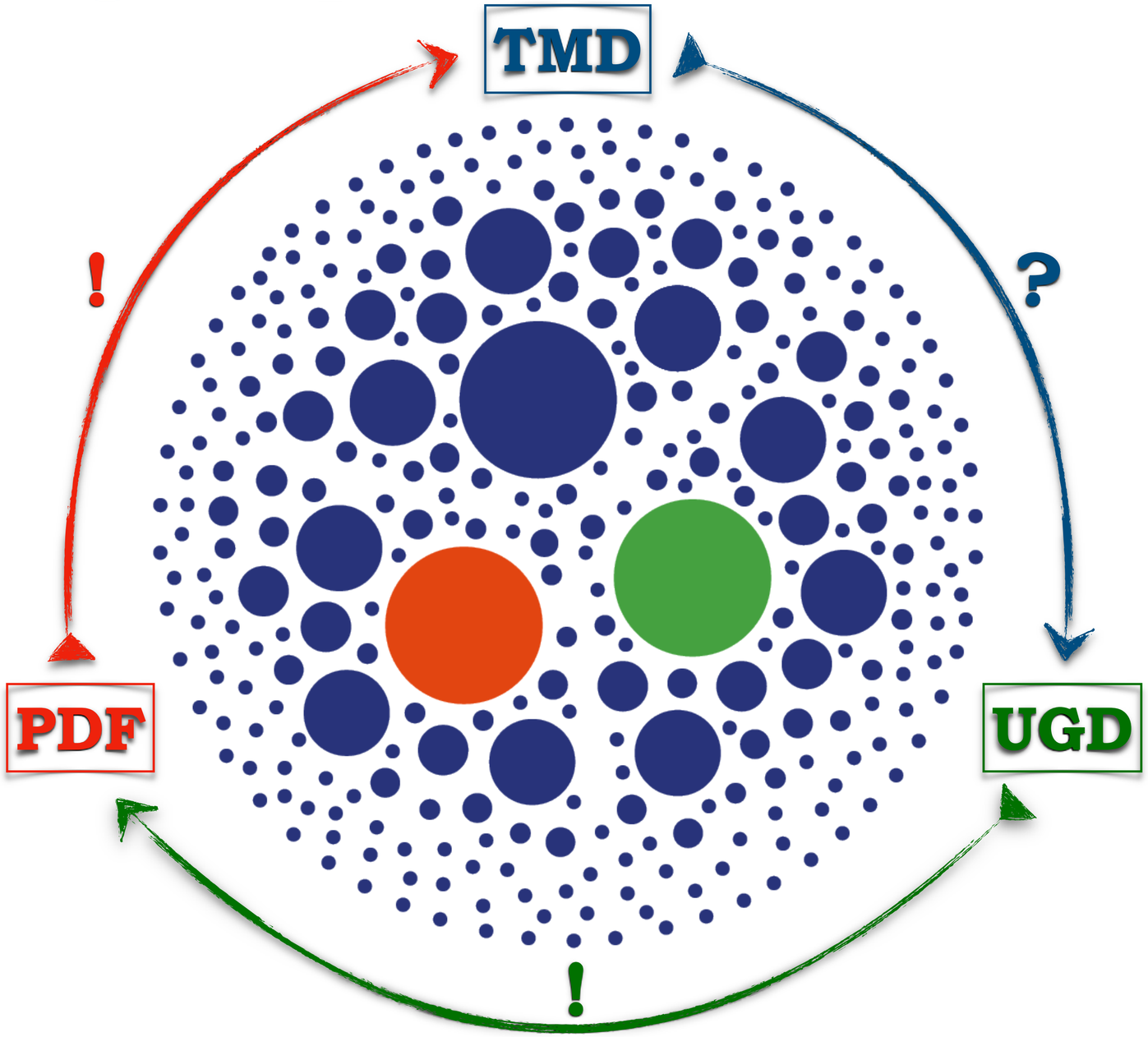
Mapping the proton content at small-x



Backup slides

Parton densities: an incomplete family tree

Wigner distributions **5D**

$$\rho\left(x, \mathbf{k}_T, \mathbf{b}_T\right)$$

$$\int d^2\mathbf{k}_T$$

$$\int d^2\mathbf{b}_T$$

Generalized Parton Distributions

GPDs

Transverse Momentum Distributions

TMDs **3D**

$$\int d^2\mathbf{k}_T$$

Parton Distribution Functions **1D**

PDFs

slide adapted from C. Bissolotti

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...but wait...

where is the

UGD?

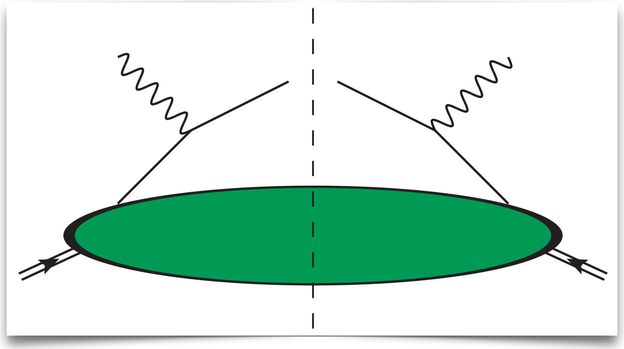
Speaks language of

Reggeized gluons

slide adapted from C. Bissolotti

Backup

Gauge links and process dependence



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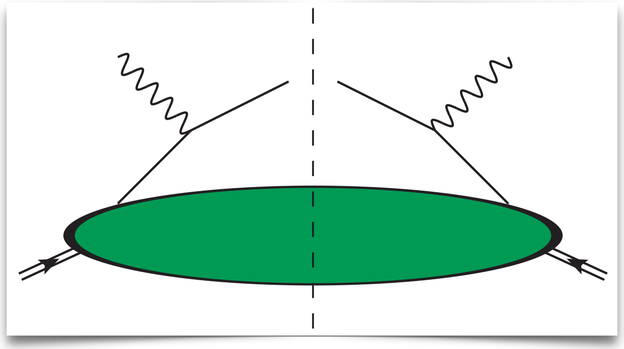
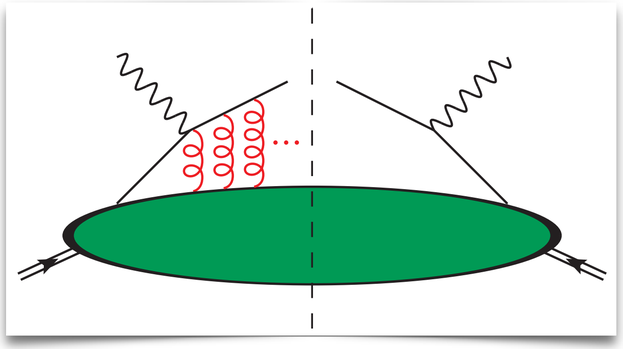


$$\bar{\psi}_j(0)\ U(0,\xi)\ \psi_i(\xi)$$

gauge link



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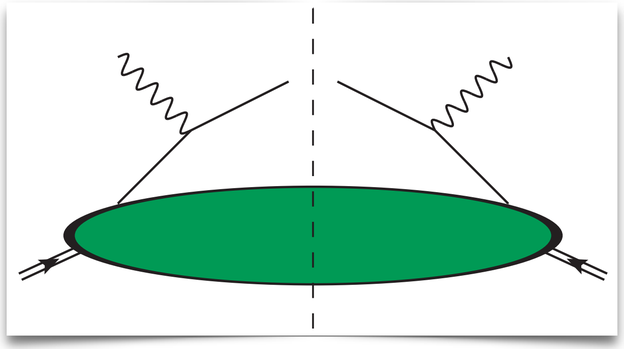

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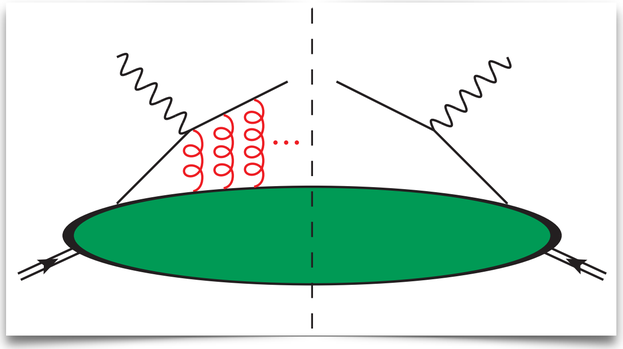
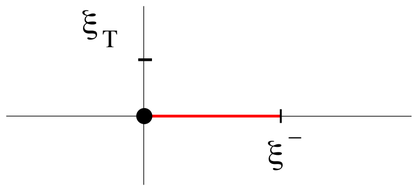


Collinear PDFs

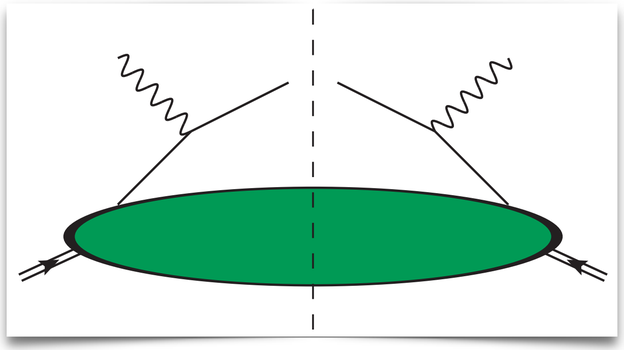
$$\Phi_{ij}(x) \doteq \int d^2\boldsymbol{p}_T \Phi_{ij}(x,\boldsymbol{p}_T) = \int \frac{d\xi^-}{2\pi} e^{ip\cdot\xi} \langle P|\bar{\psi}_j(0)\psi_i(\xi)|P\rangle_{|\xi^+=0,\xi_T=0}$$



- Light-cone: $\xi^+ = 0$, $\boldsymbol{\xi} = 0$
- **Straight** gauge link (unique!)
- $(A^+ = 0)$ light-cone: WL $= \hat{1}$
- ☑ **Universality warranted**

Backup

Gauge links and process dependence



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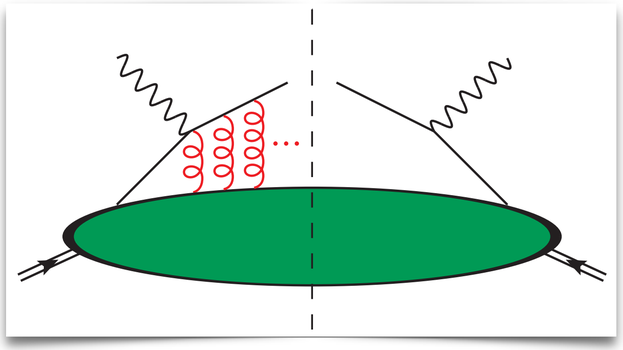

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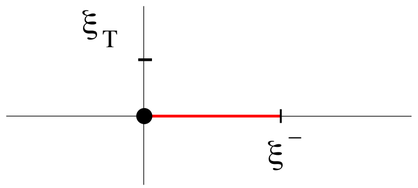

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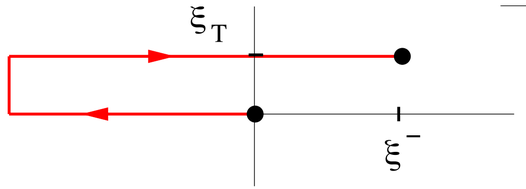
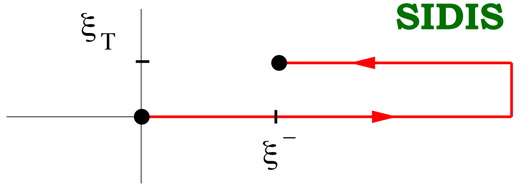
TMD PDFs

- *Transverse* gauge link not eliminated by gauge choice
- **Staple-like** gauge link (not unique!)
- ¡! **Process dependence**



Drell-Yan



SIDIS

Backup

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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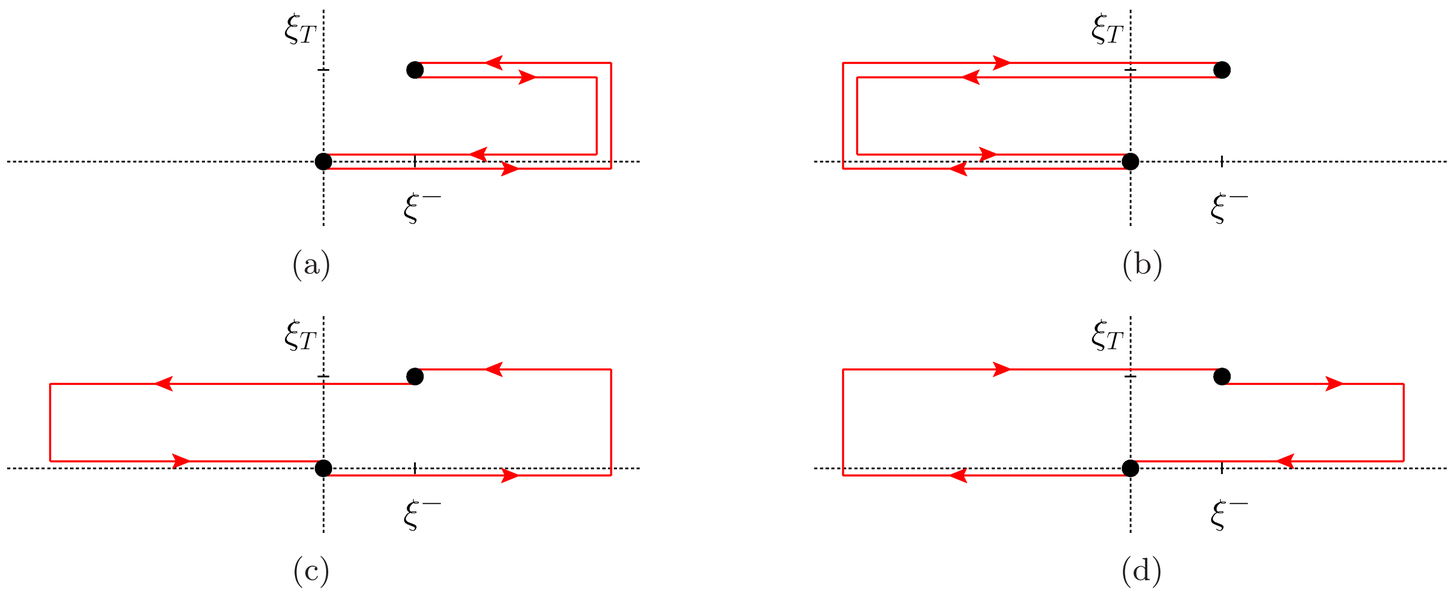

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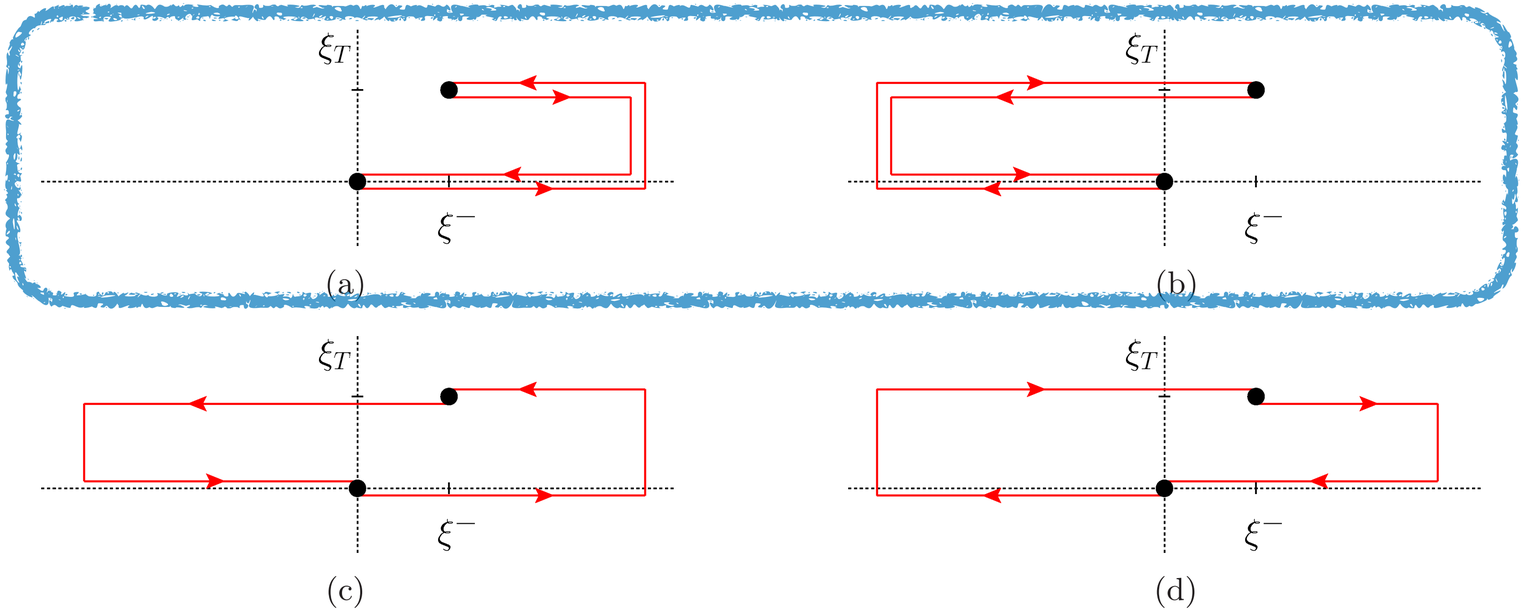
Weiszäcker-Williams (WW)

(a) [+ , +] or (b) [− , −]



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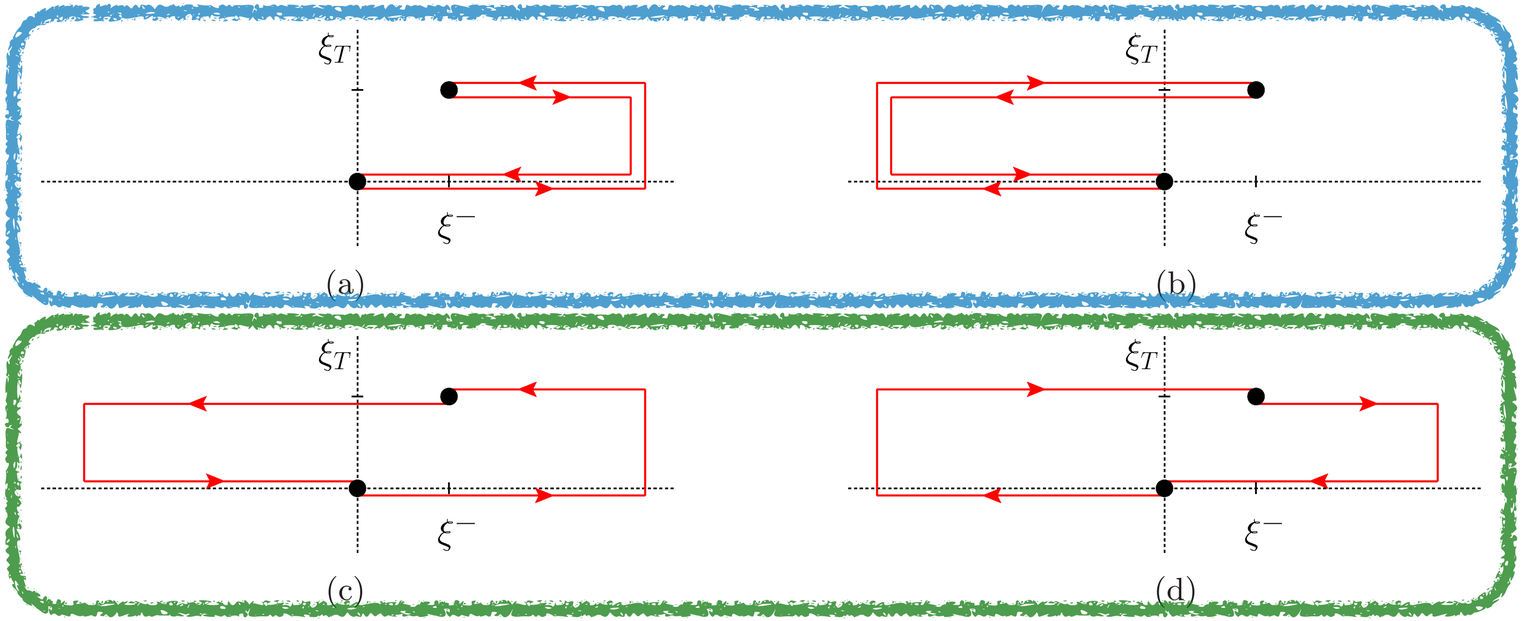
(c) [+ , −] or (d) [− , +]



Backup

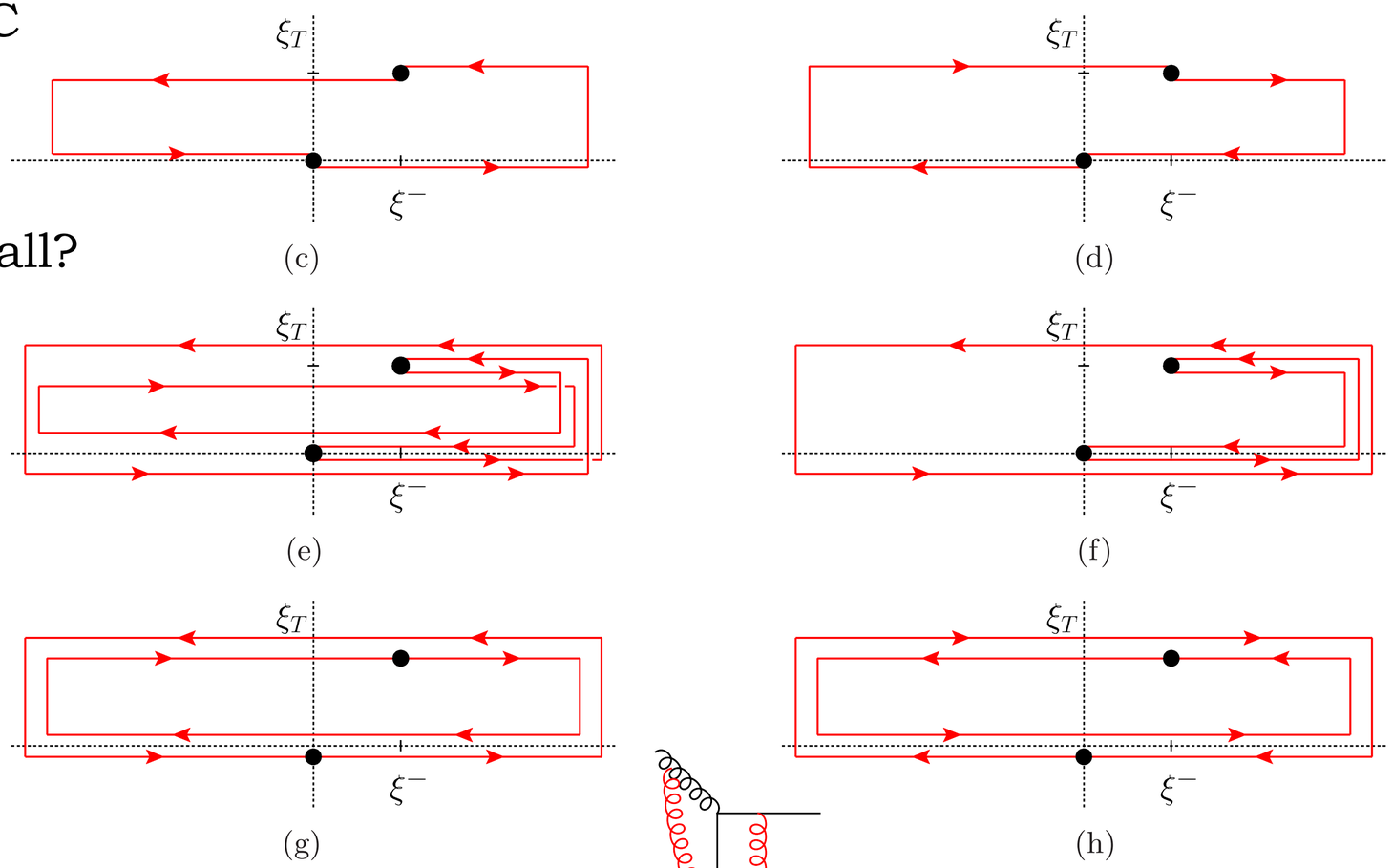
Dihadron hadroproduction and factorization breaking

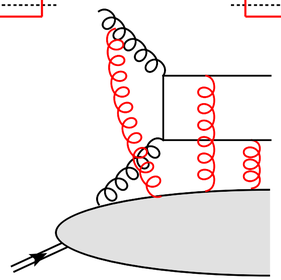
- Proof of factorization violation 🔗 [T.J. Rogers, P.J. Mulders (2010)]
- Assumed factorization in SCET and CGC
- Significance of low-x studies
- Size of factorization-breaking effects small?
- DP TMDs:

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

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

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



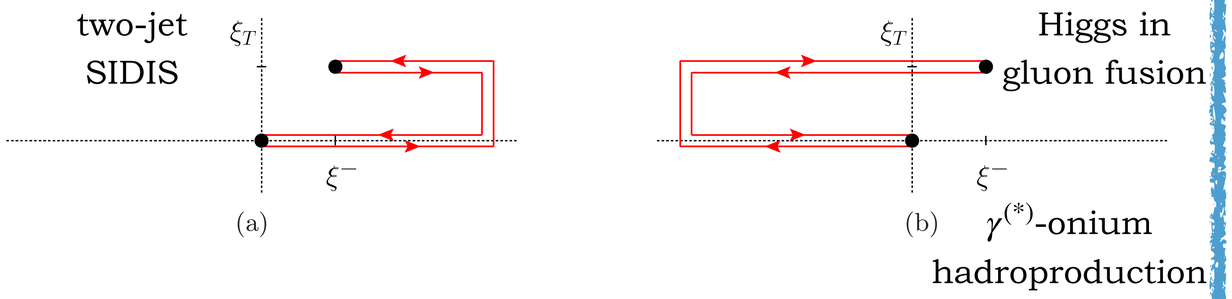


Backup

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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



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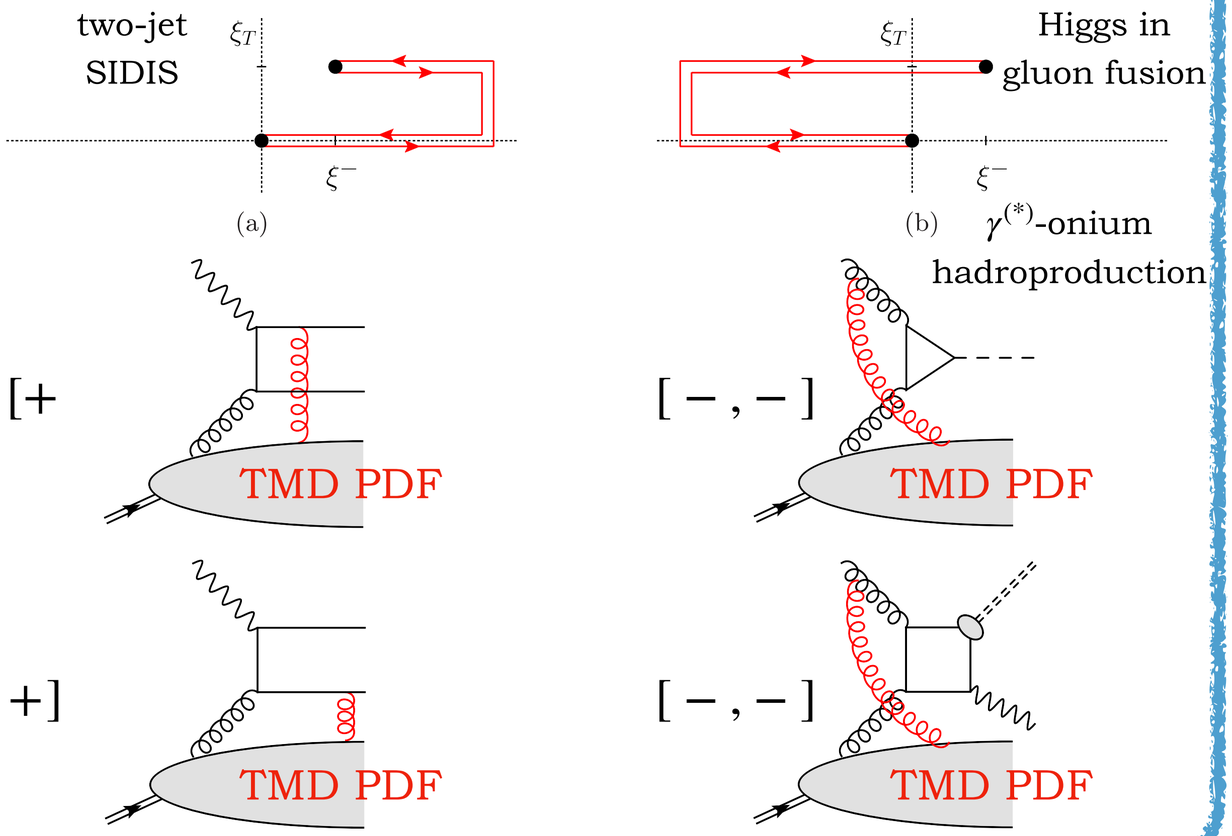

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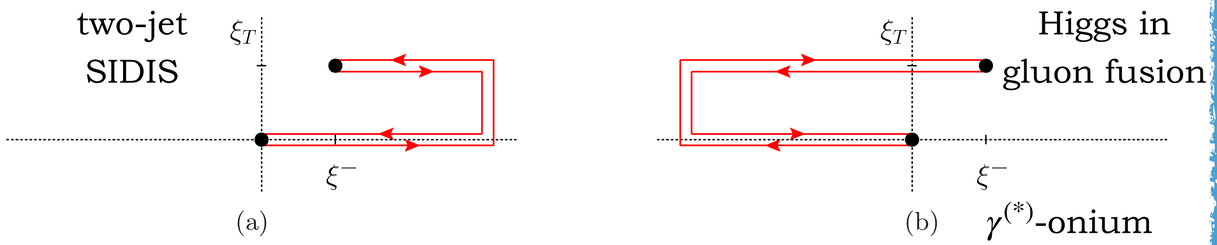
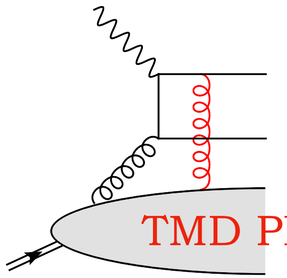
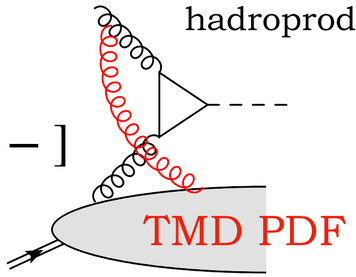


$\gamma^{(*)}$-onium
hadroproduction

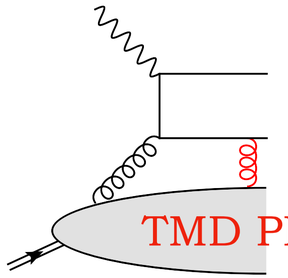
[+



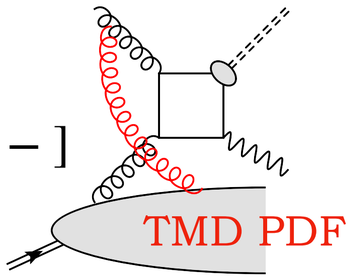
[− , −]



+]

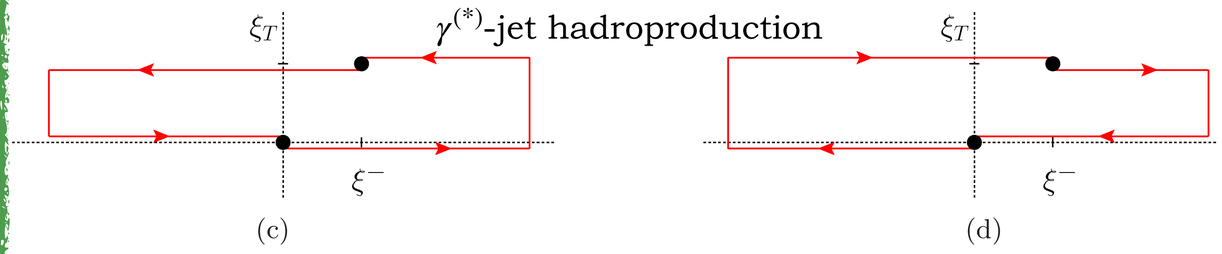


[− , −]



Dipole (DP)

(c) [+ , −] or (d) [− , +]



Backup

Accessing WW and DP gluon TMDs

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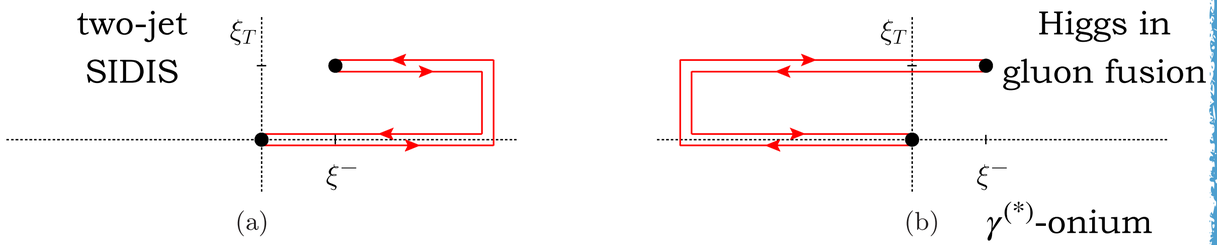

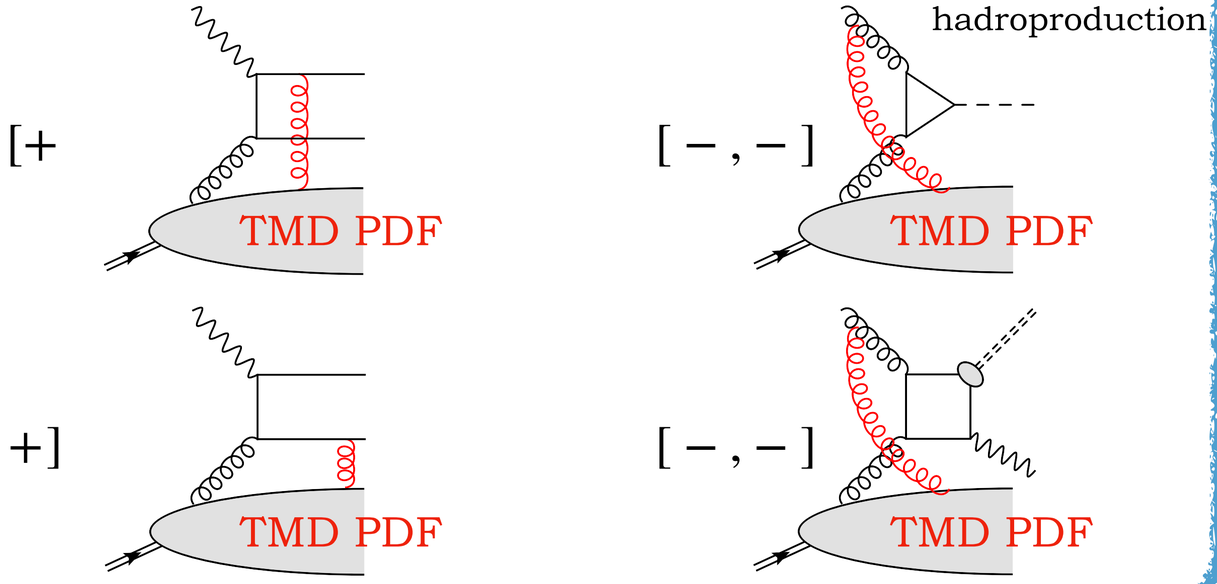

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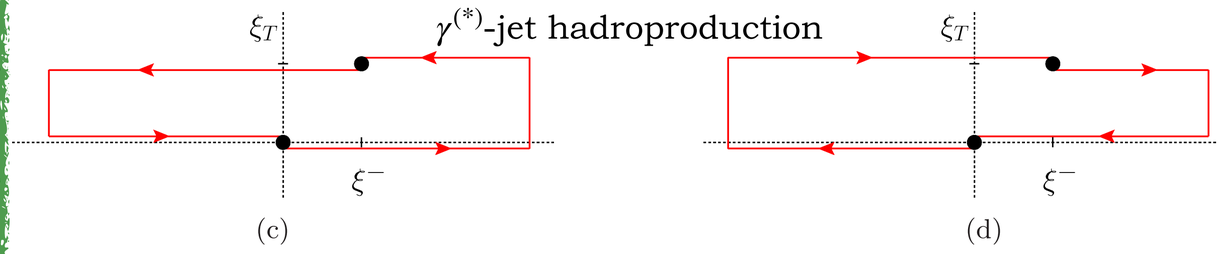
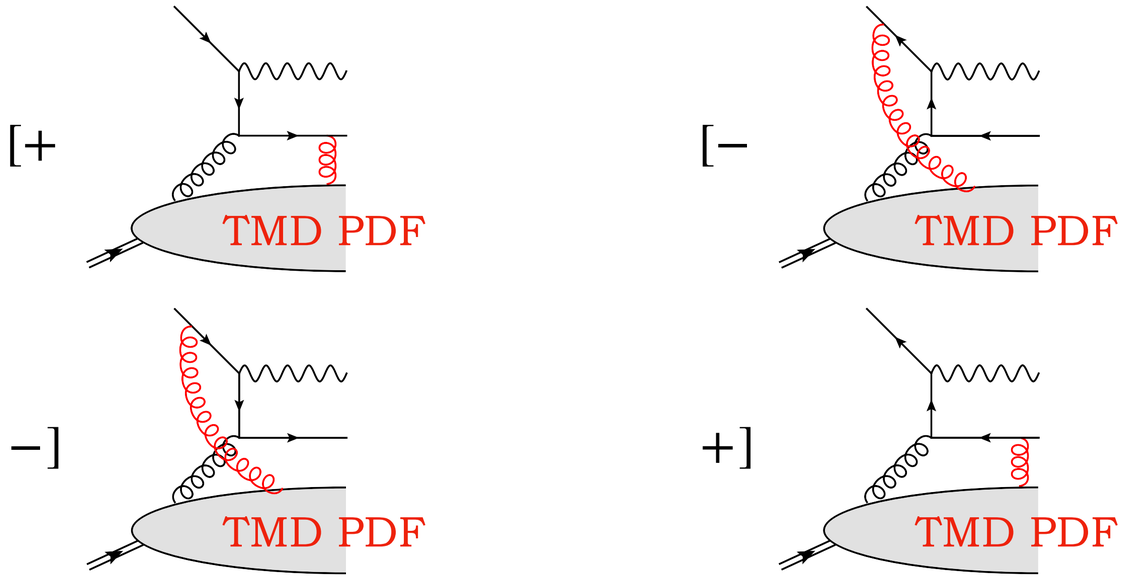


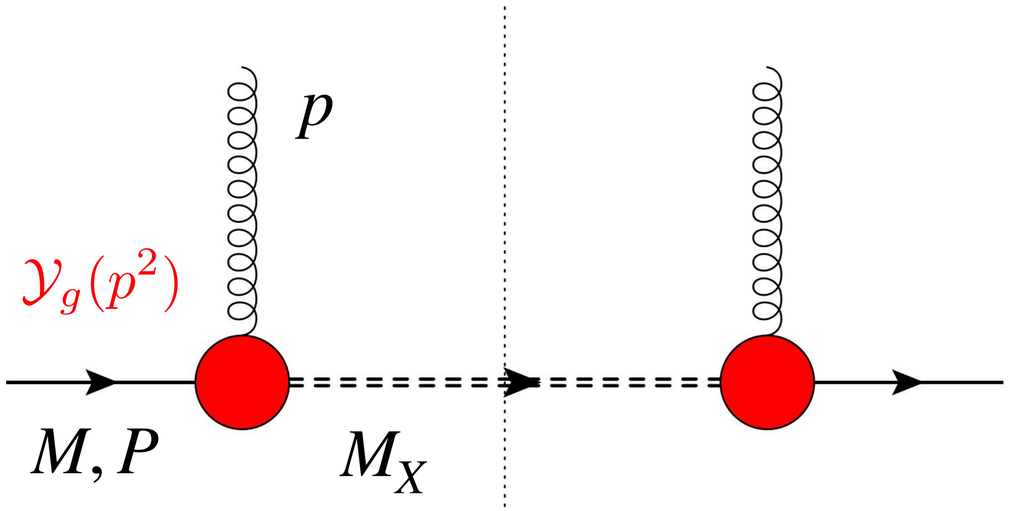


Backup

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

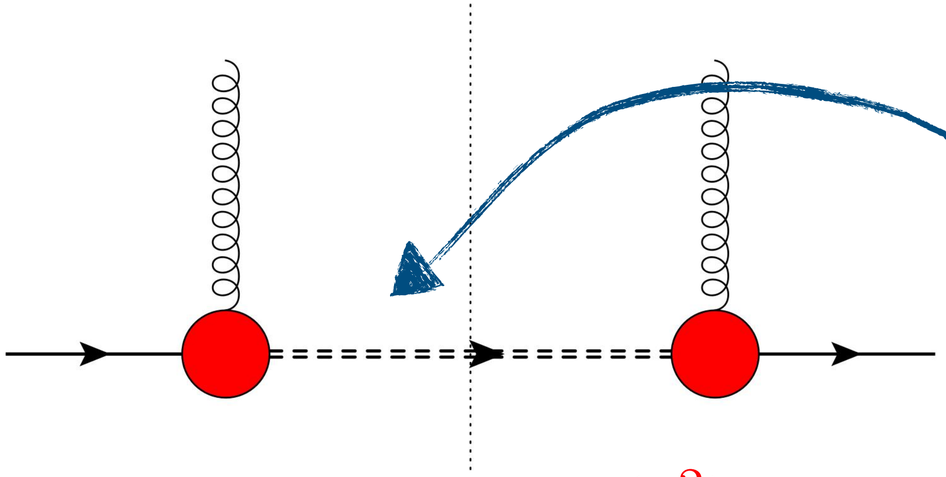
Spectator-system spectral-mass function

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)]



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

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

Backup

Assumptions of the model

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spectral-mass function

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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

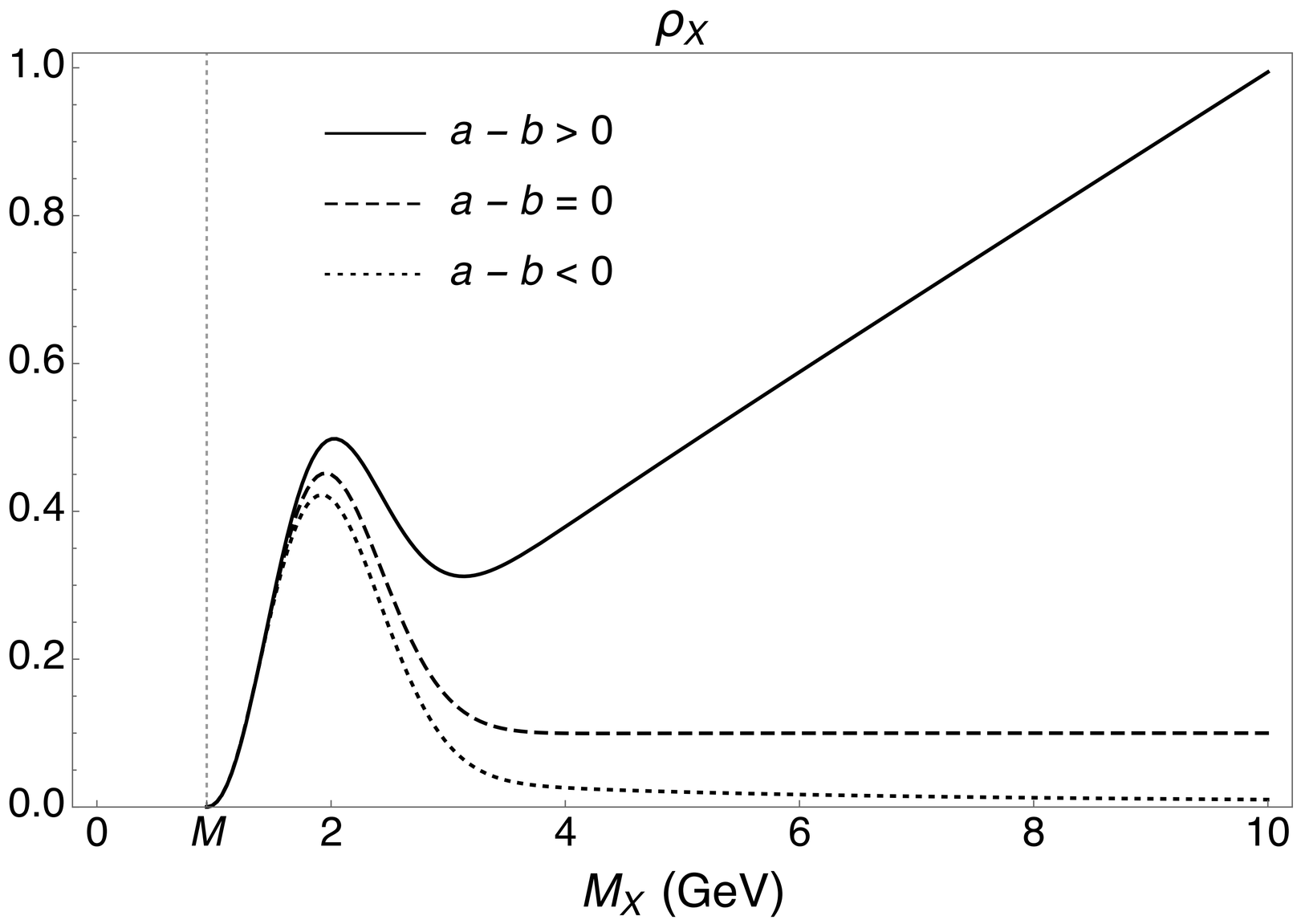
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

Backup

Spectral function vs *(a - b)*



Backup

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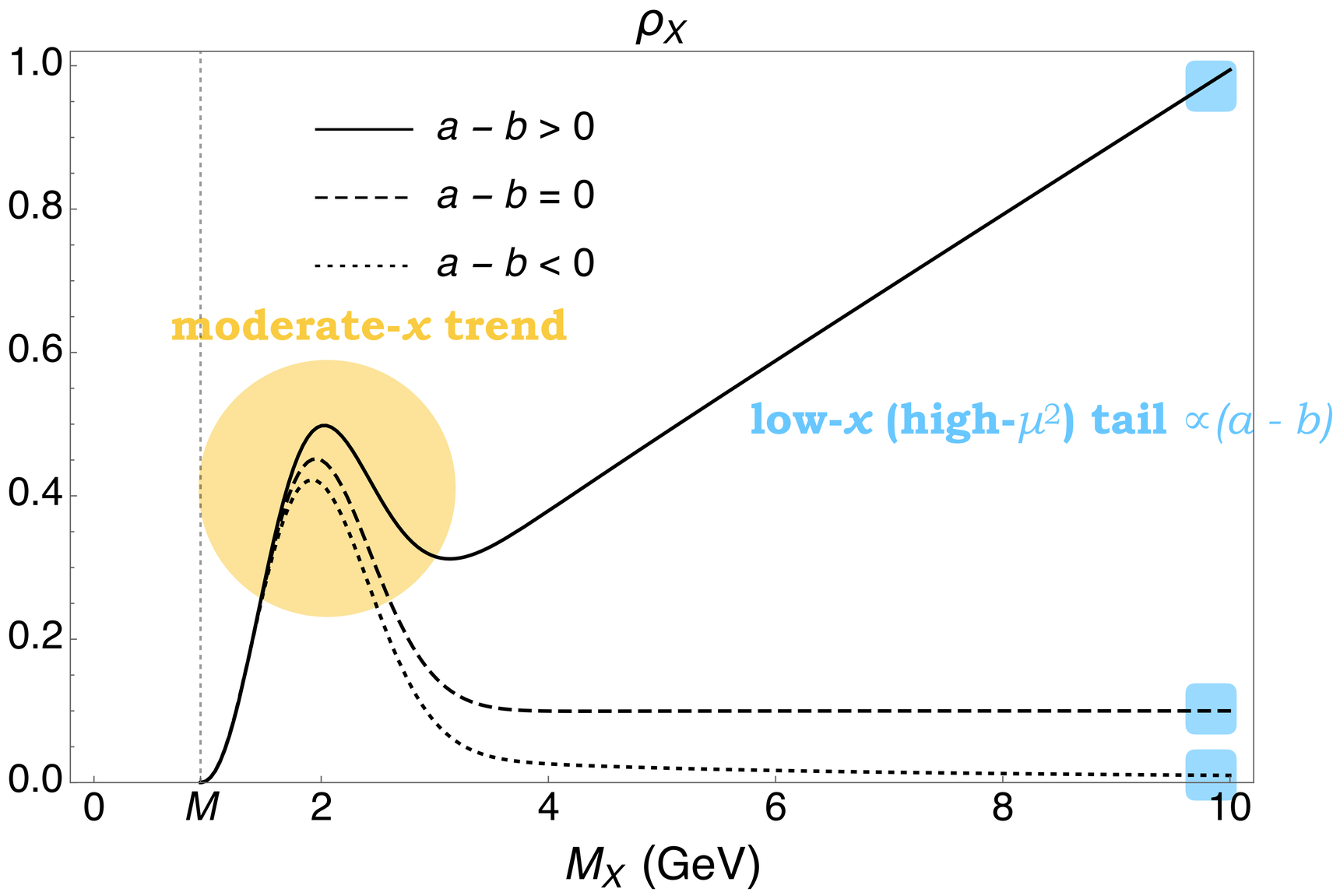
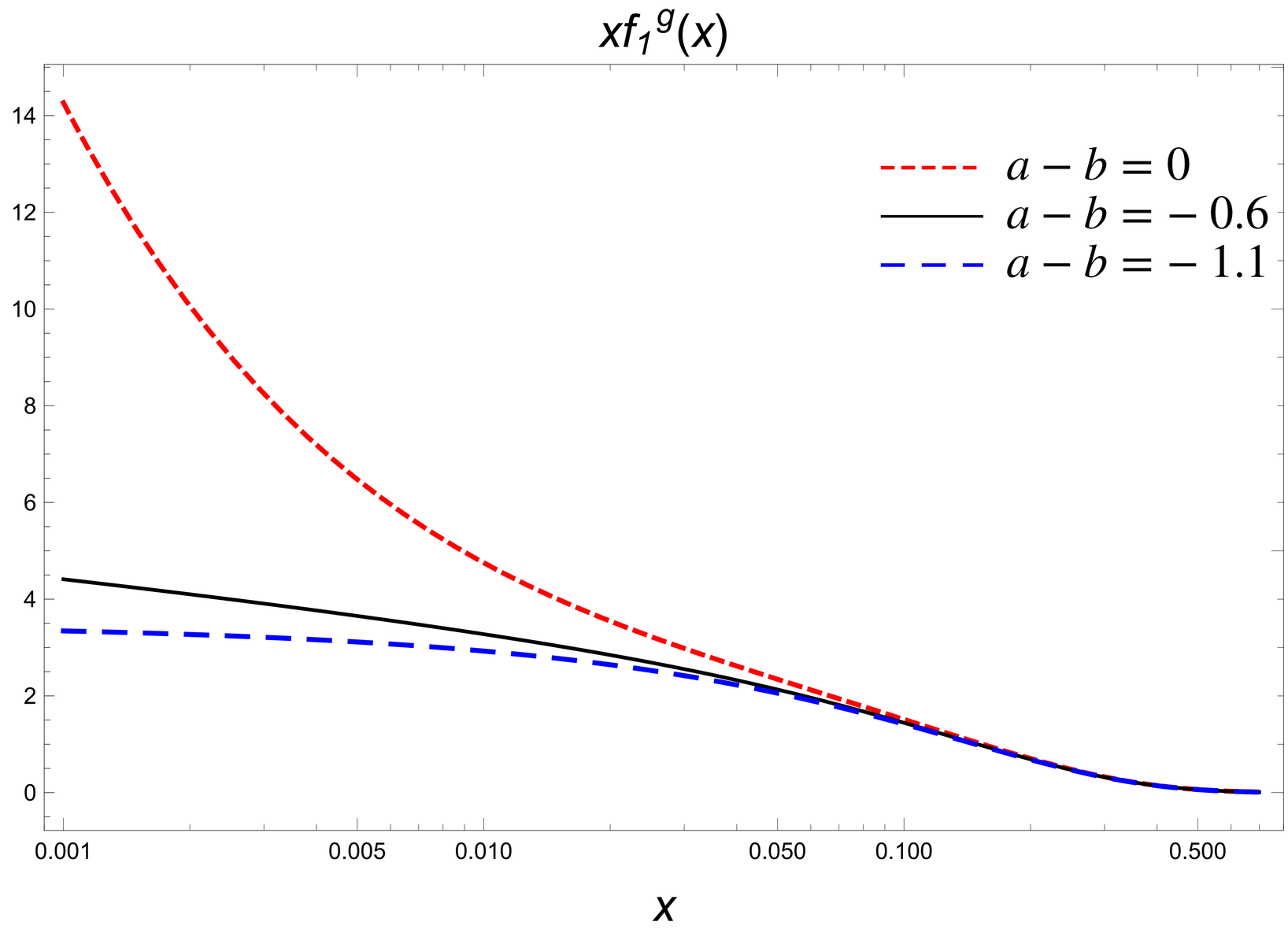


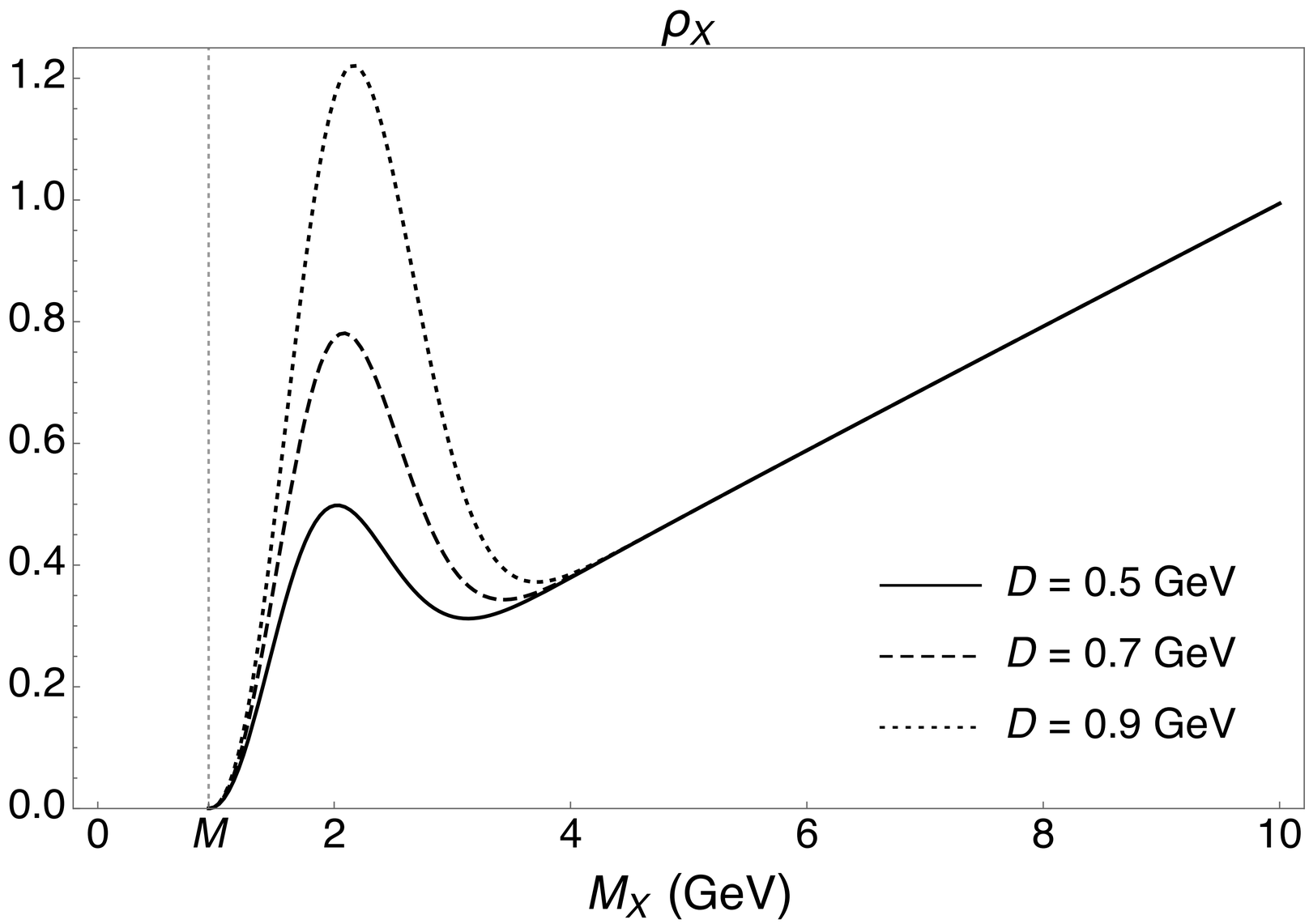
Backup

xf_1 collinear PDF vs $(a - b)$



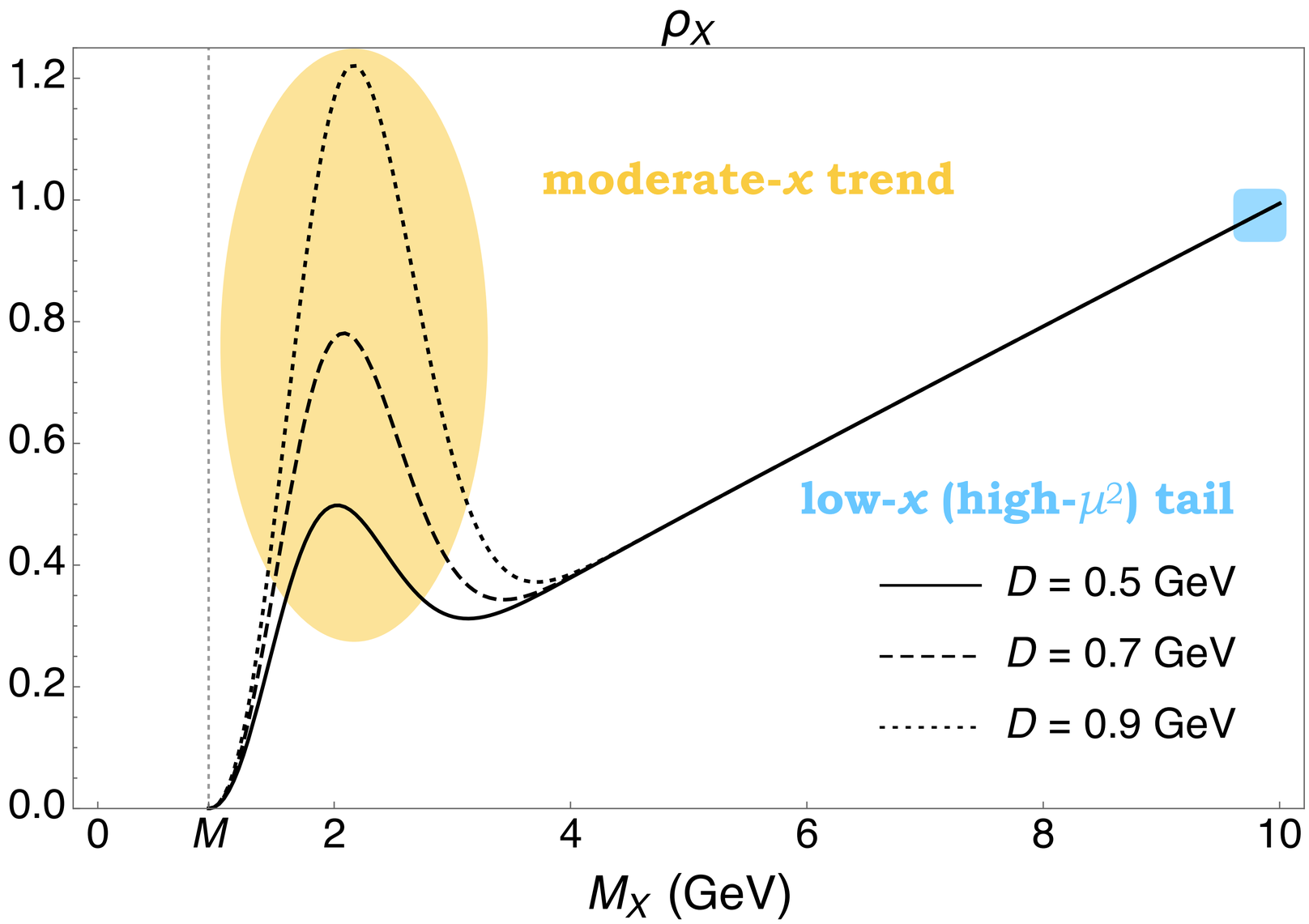
Backup

Spectral function vs D



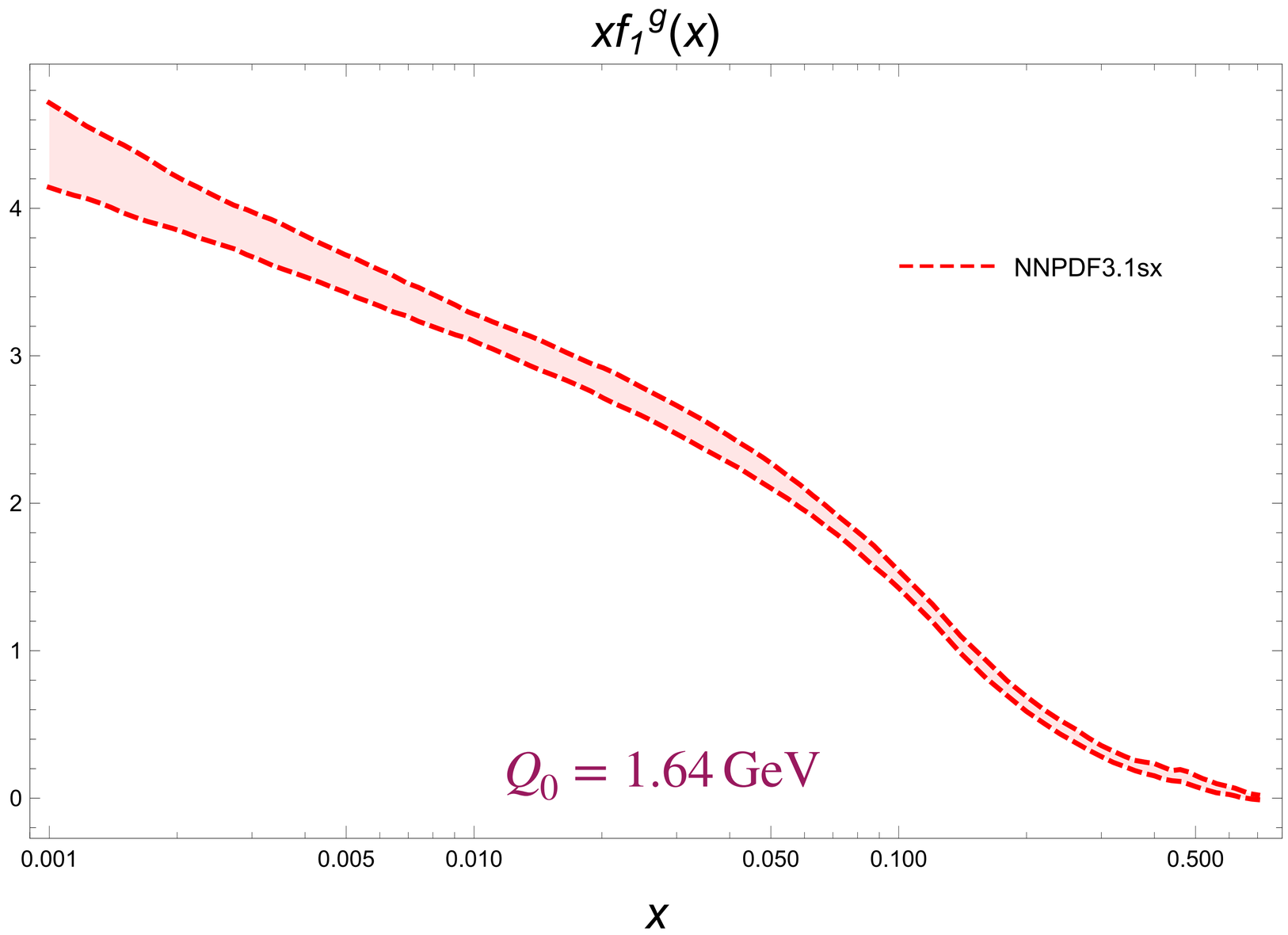
Backup

Spectral function vs D



Backup

Unpolarized gluon PDF



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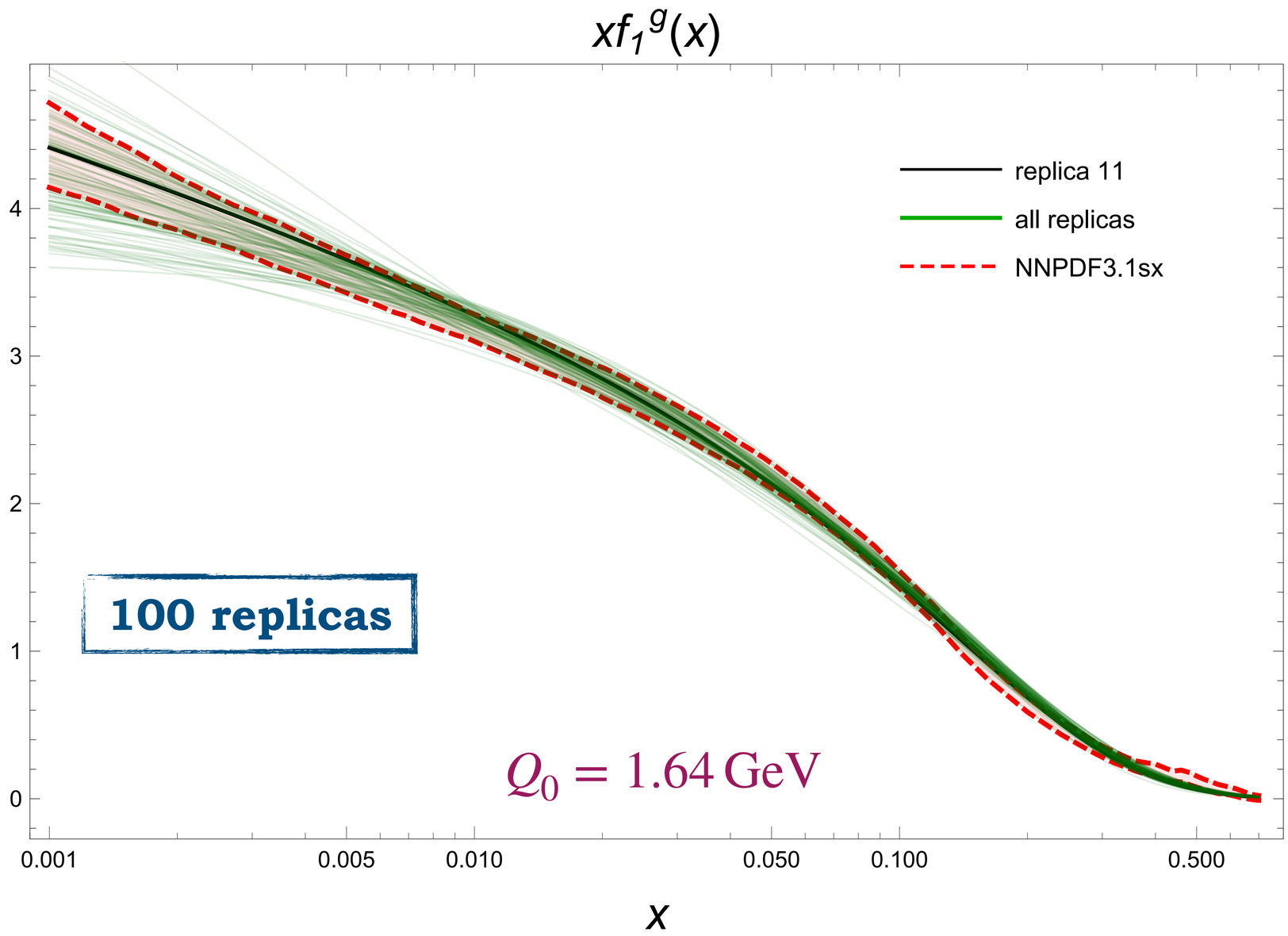

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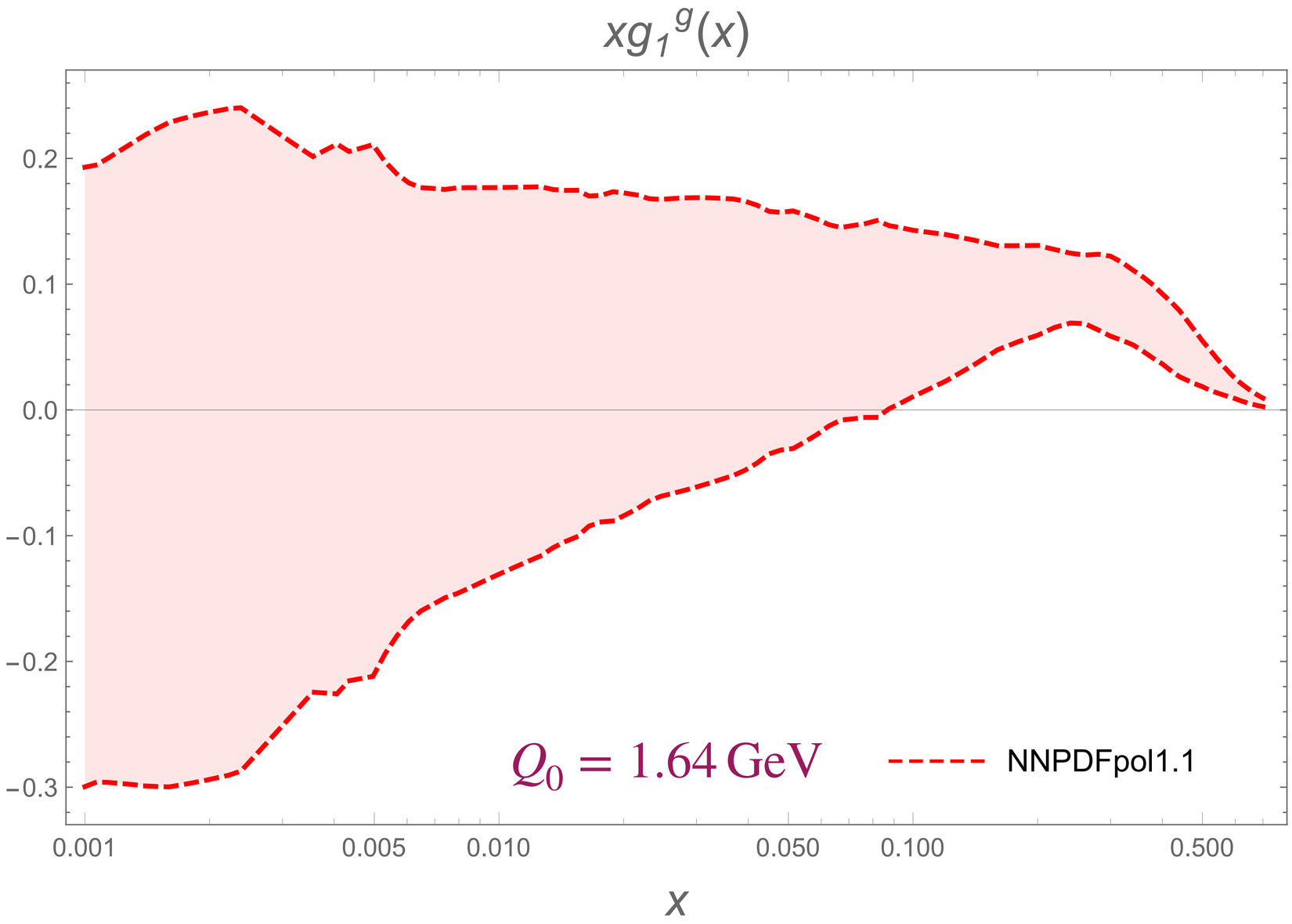
Helicity gluon PDF



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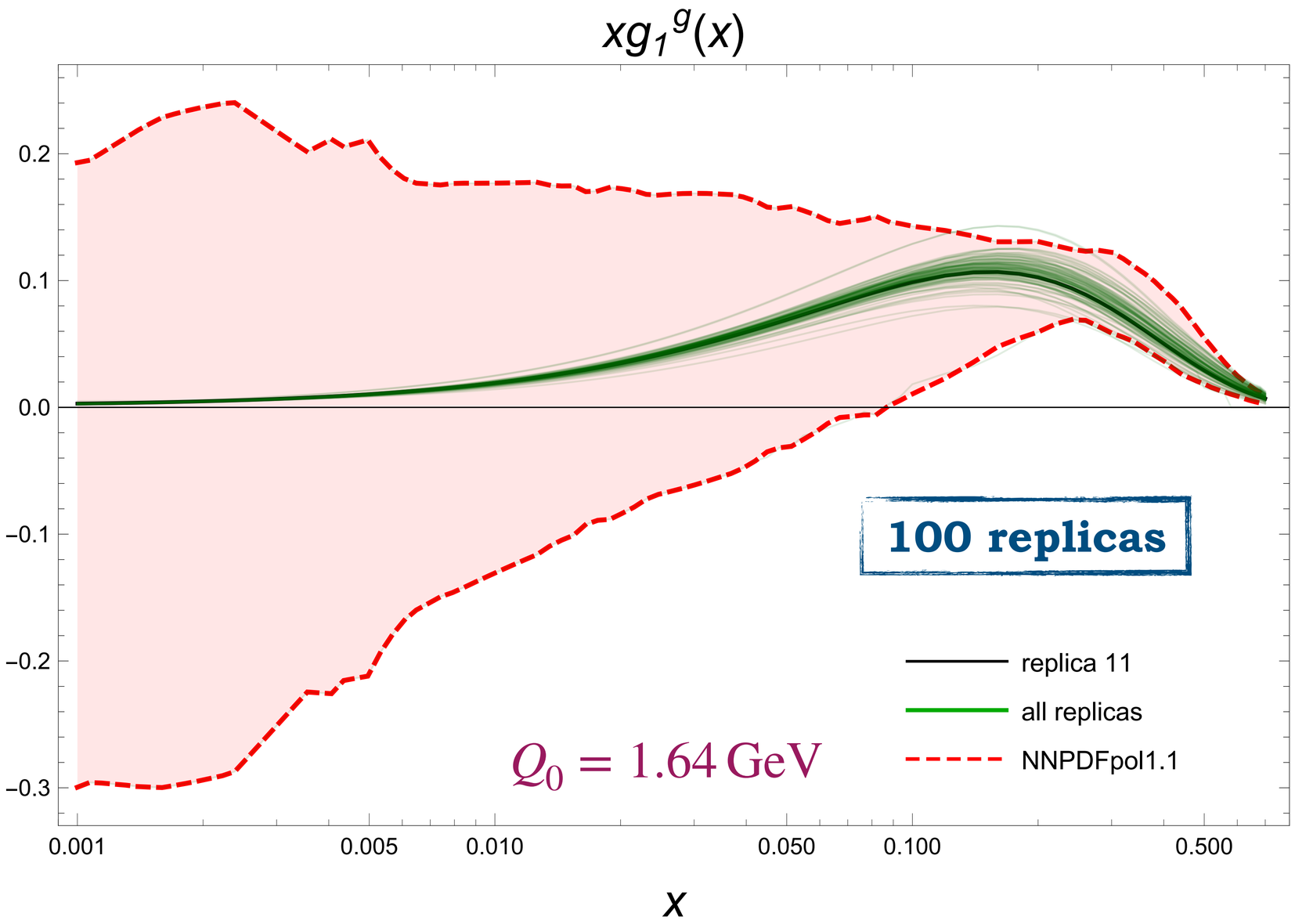
Helicity gluon PDF



Backup

Fit specifics

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

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

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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

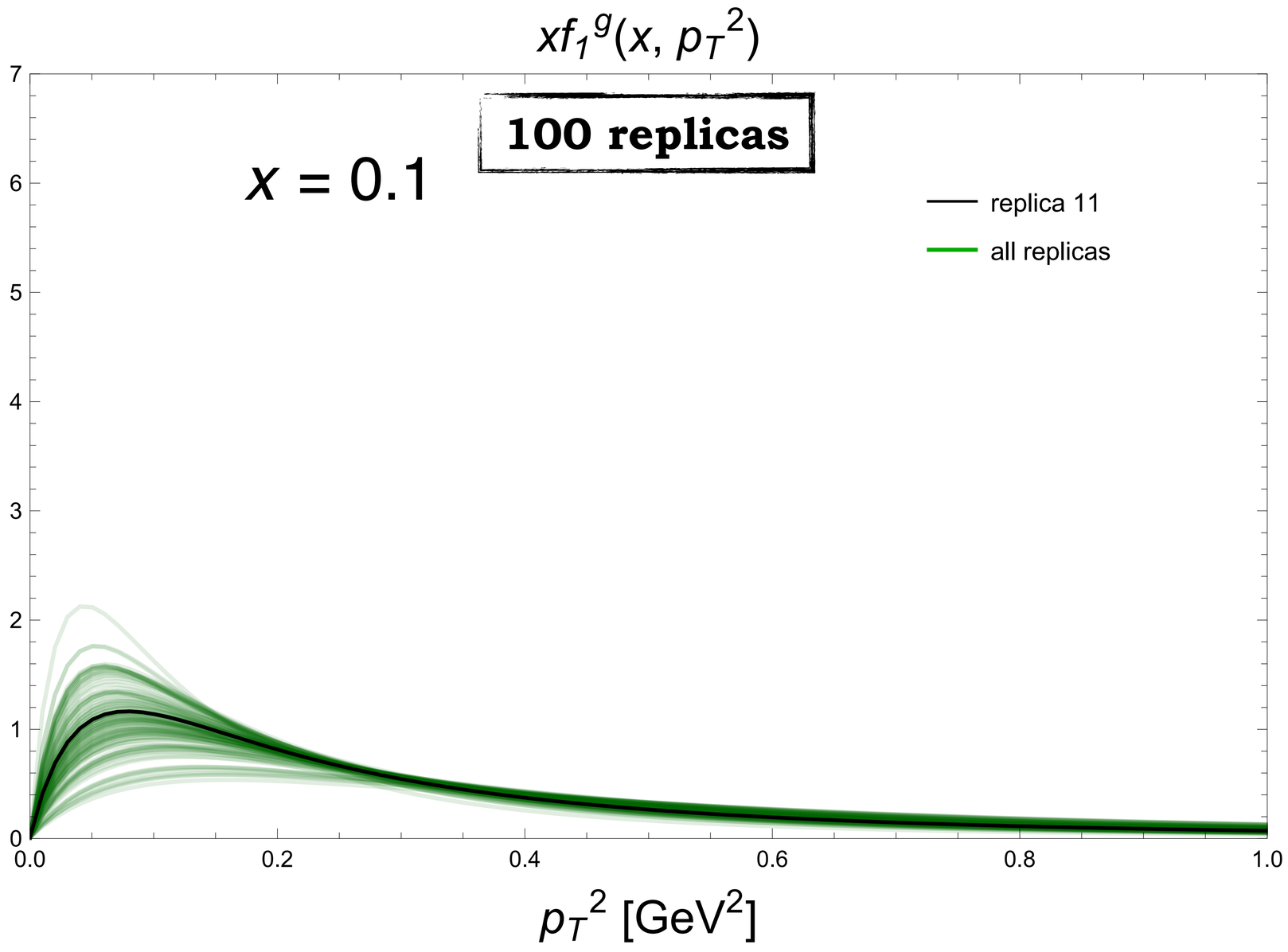
$$\langle x \rangle_g = 0.427(92)$$

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

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

Backup

Unpolarized gluon TMD



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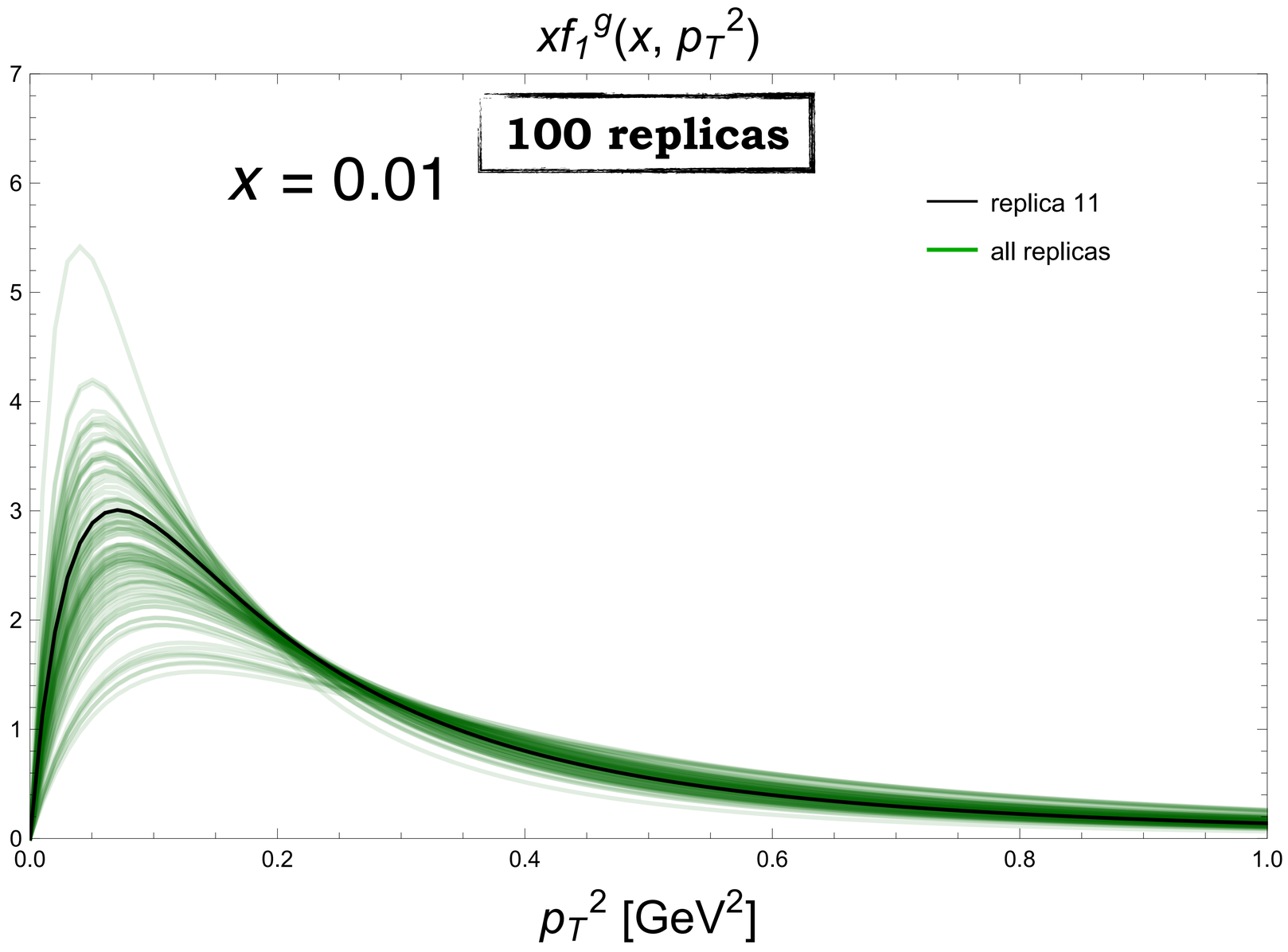
Unpolarized gluon TMD



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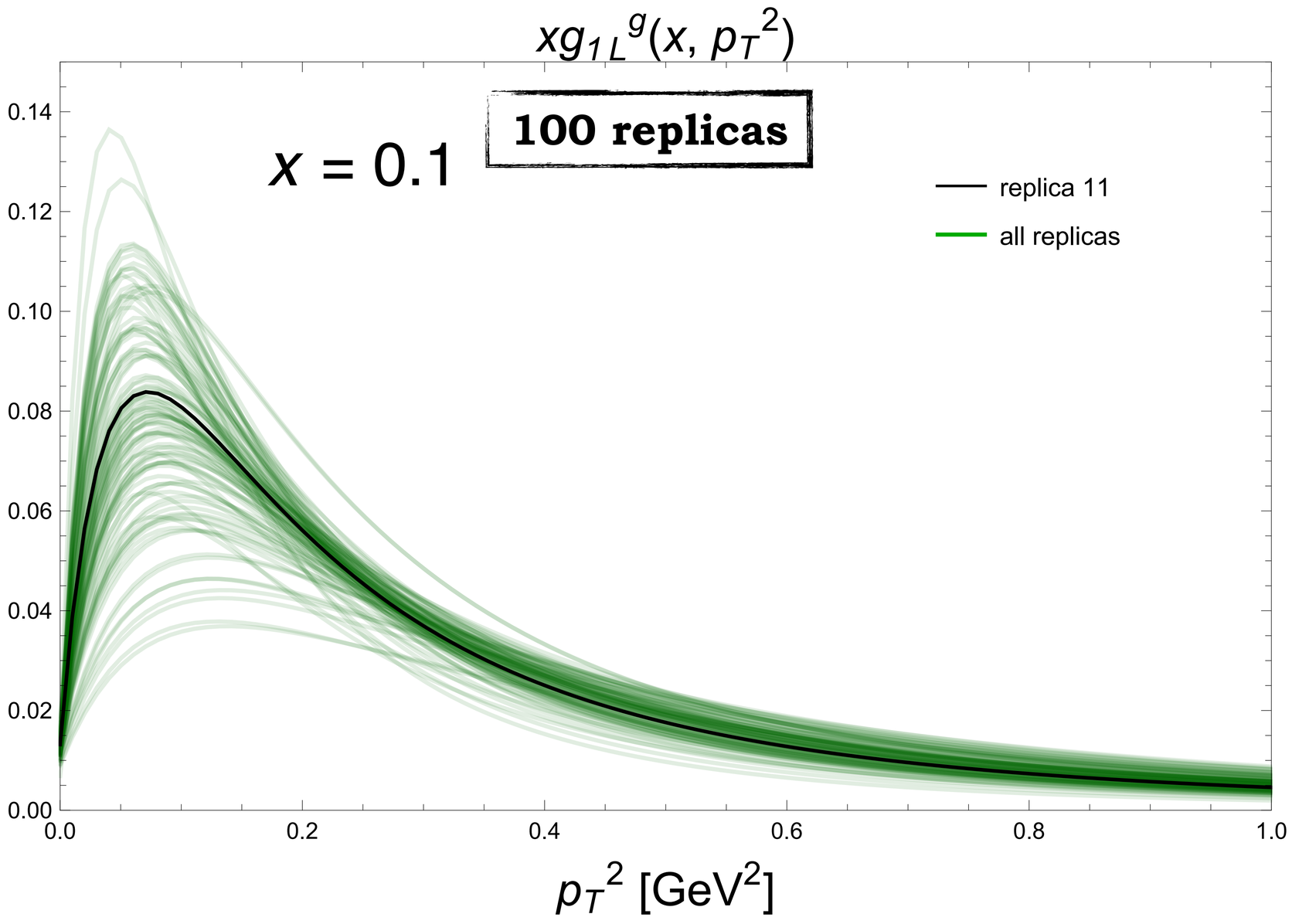

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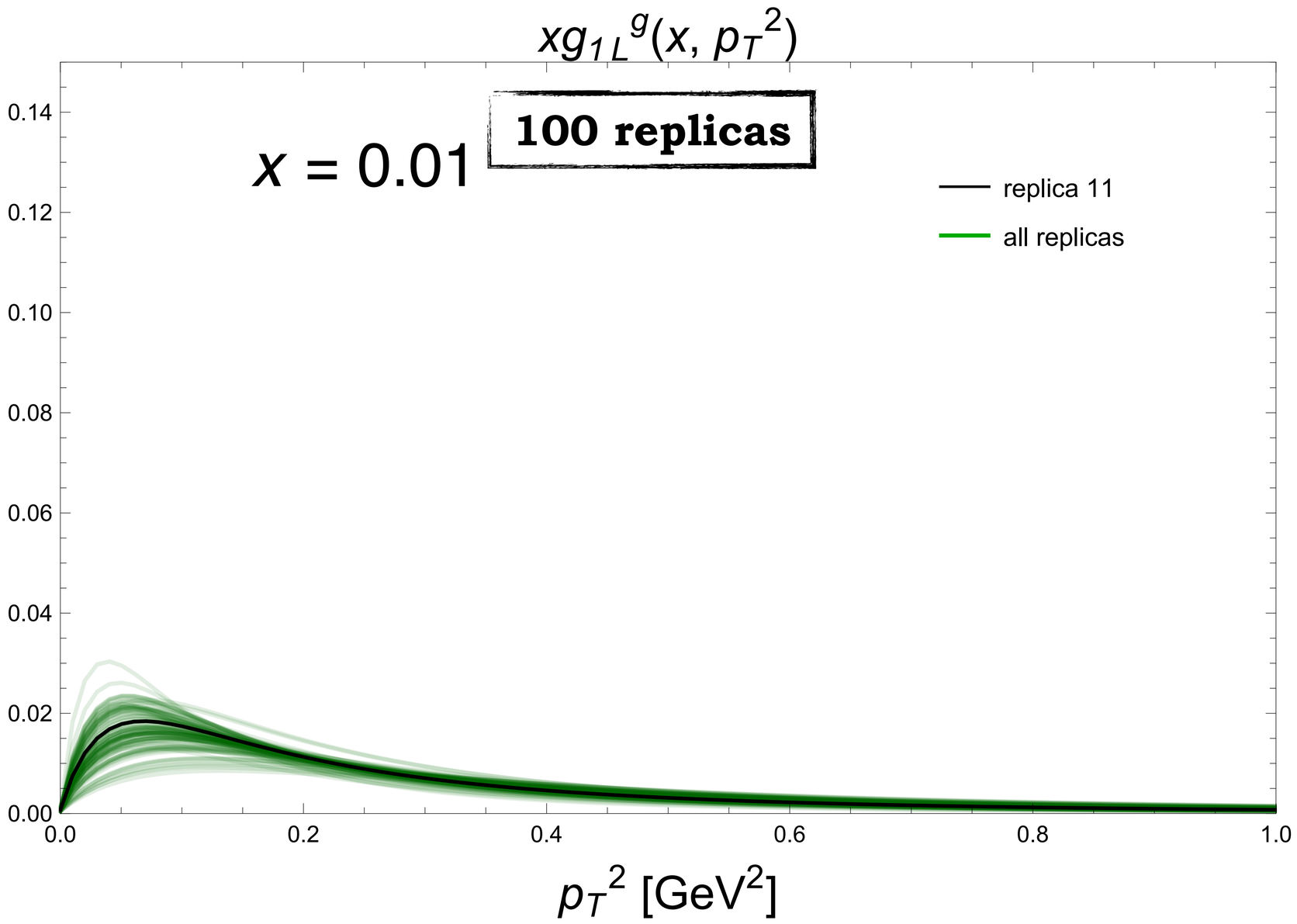

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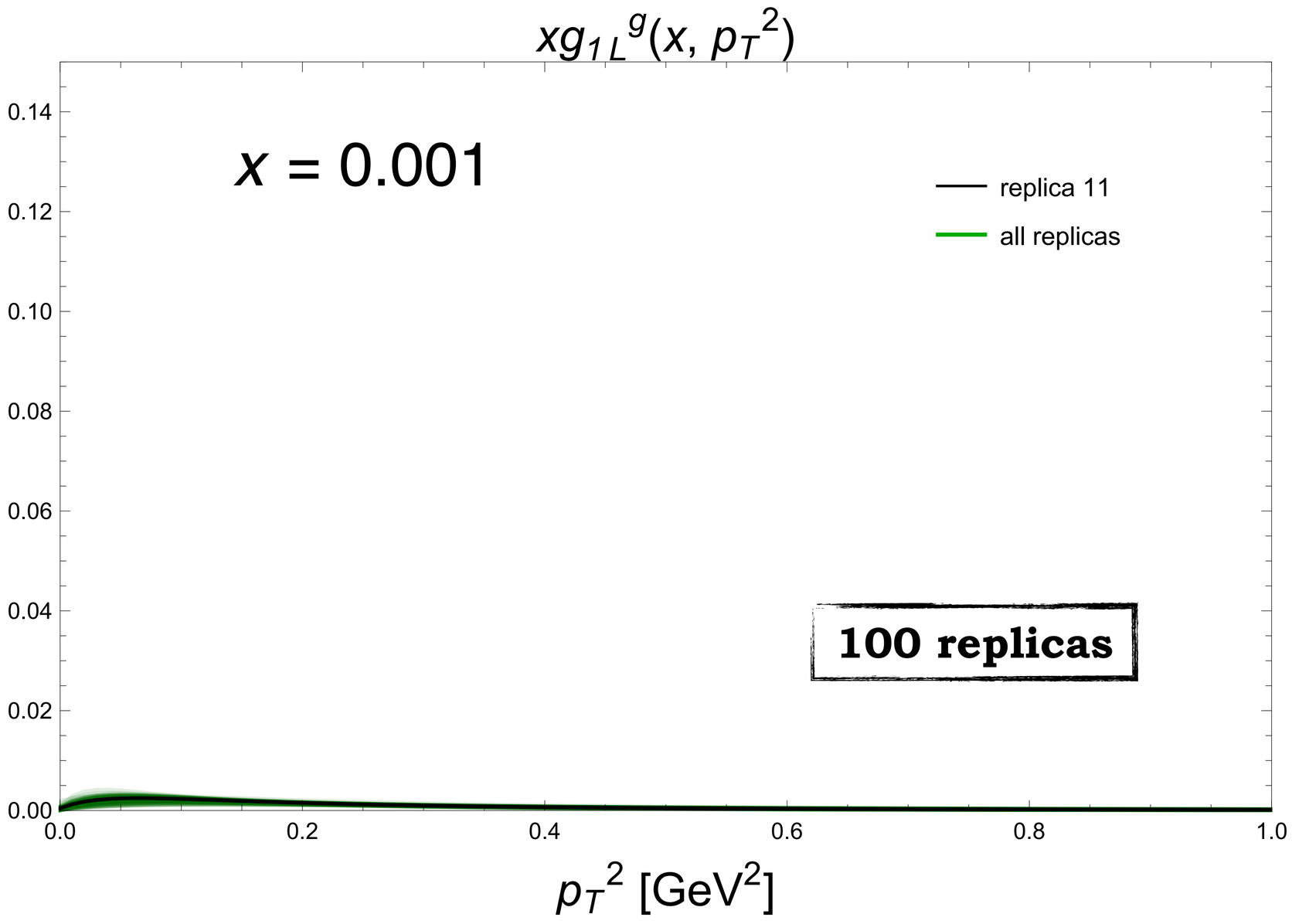
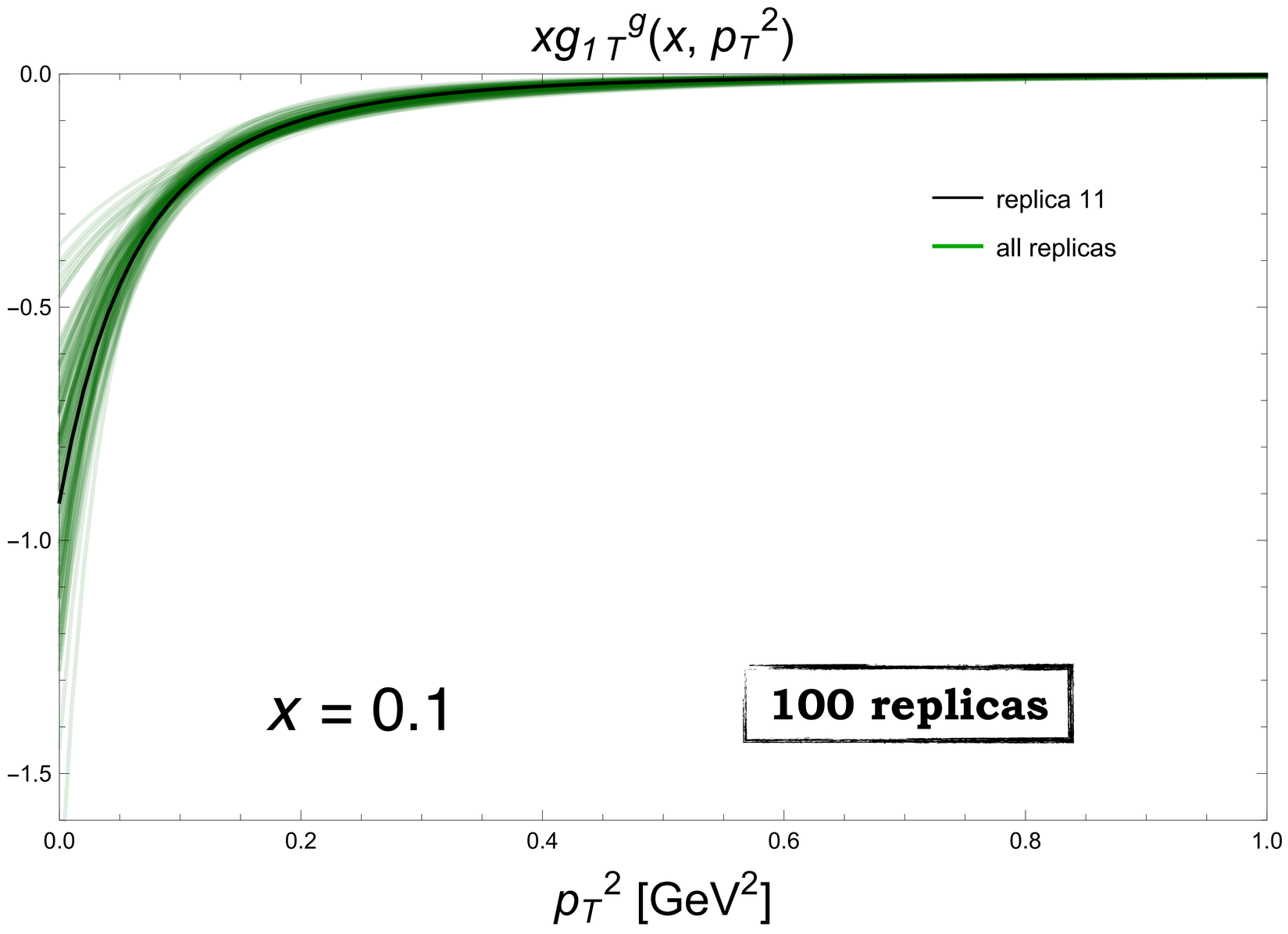


Backup

Worm-gear gluon TMD



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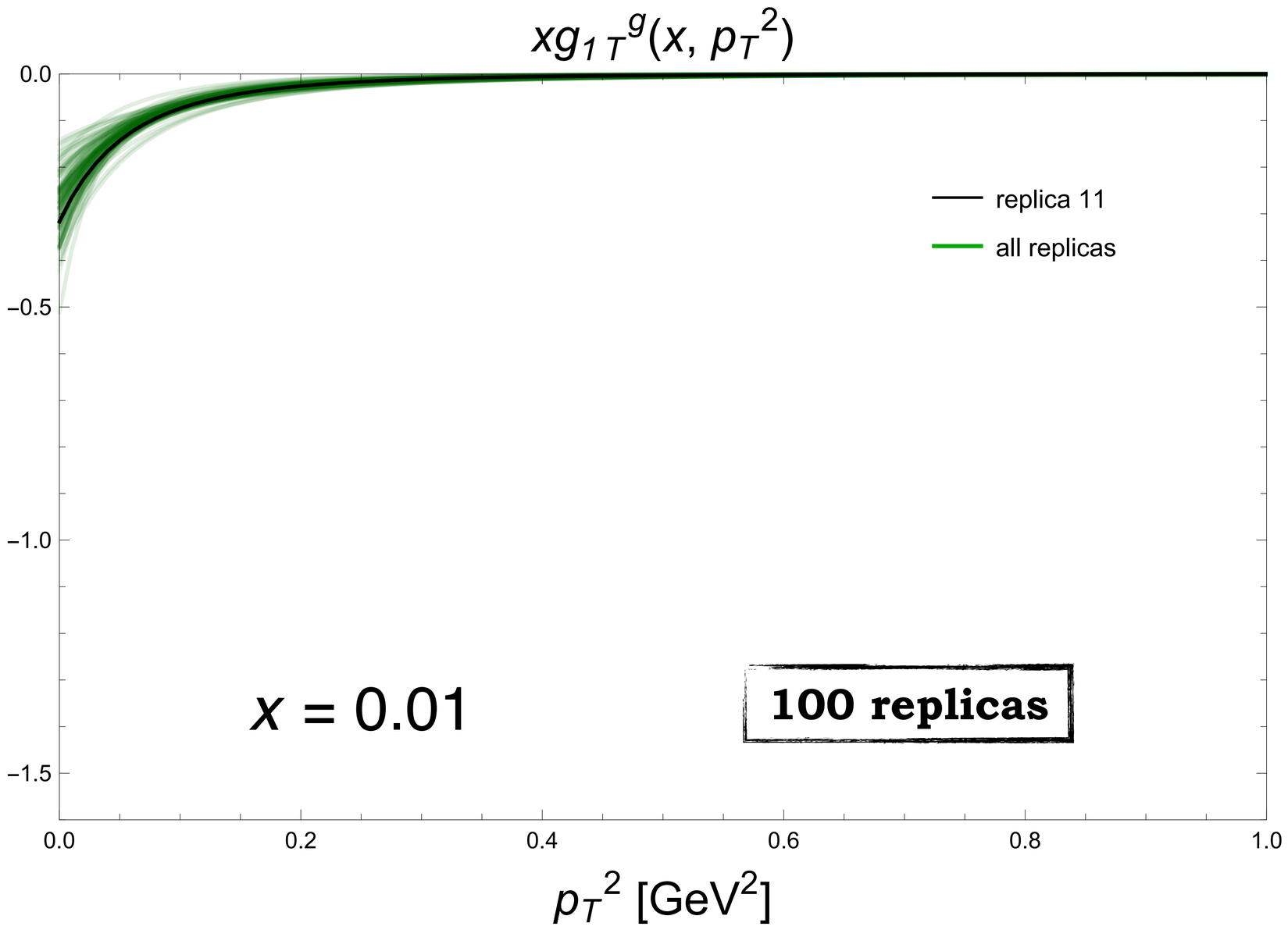
Worm-gear gluon TMD



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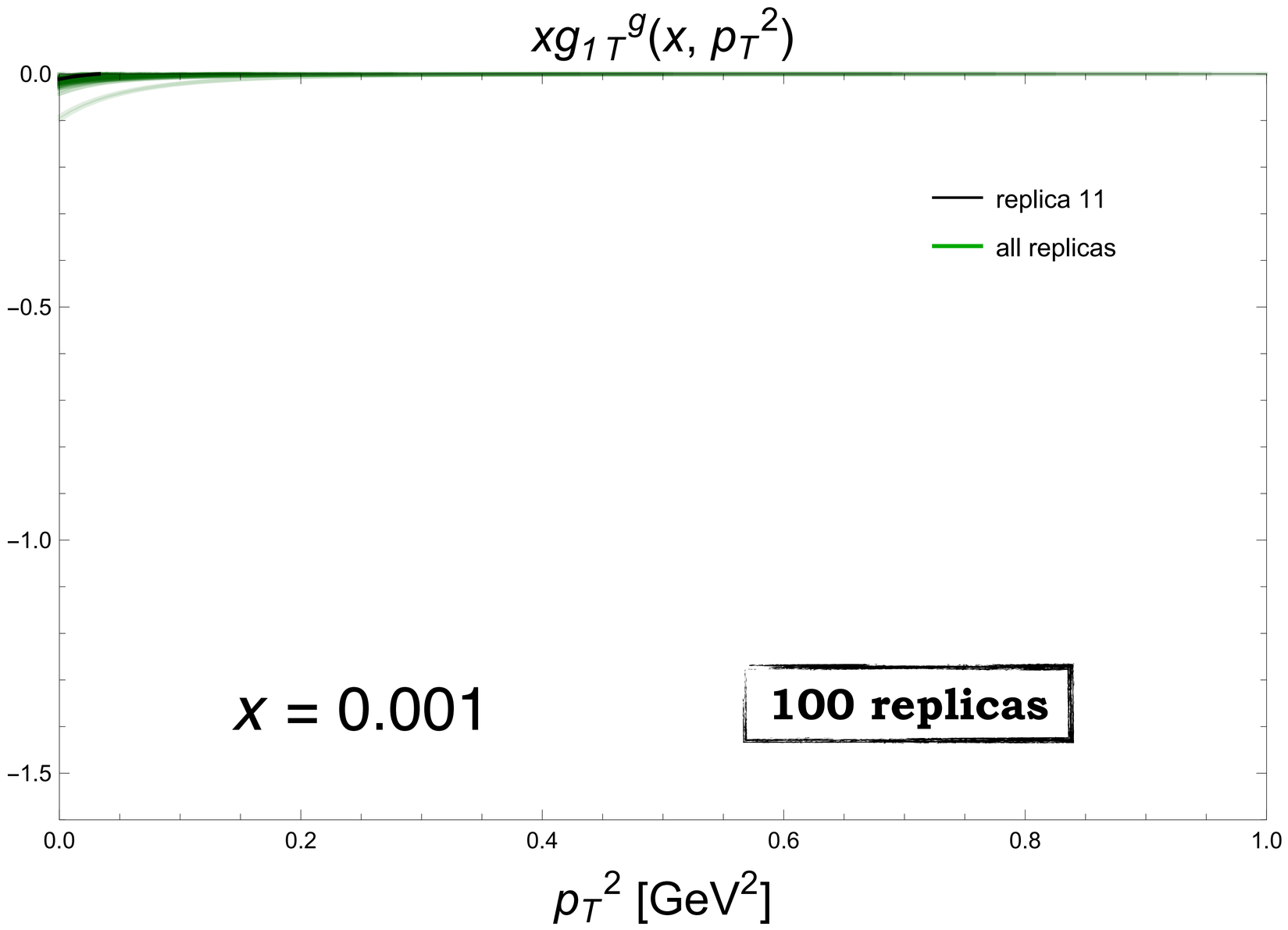
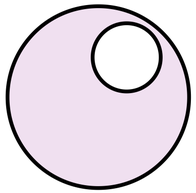
Worm-gear gluon TMD



Backup

ρ-densities

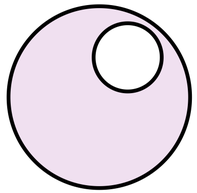


Unpolarized [u/u]

$f_1(x, p_x, p_y)$

Backup

ρ-densities



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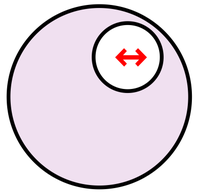
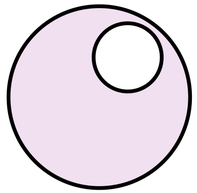


Boer-Mulders [↔/u] $f_1(x, p_x, p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x, p_x, p_y)$

Backup

ρ-densities



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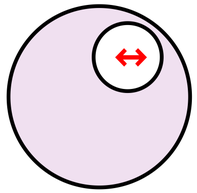
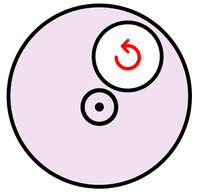


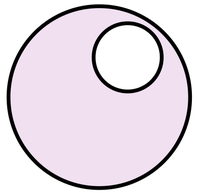
Boer-Mulders [↔/u] $f_1(x, p_x, p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^\perp(x, p_x, p_y)$



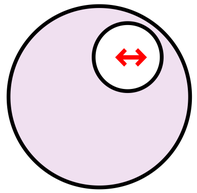
Helicity [↺/+] $\frac{1}{2}\left[f_1(x, p_x, p_y) + g_{1L}(x, p_x, p_y)\right]$

Backup

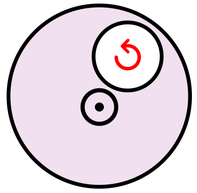
ρ-densities



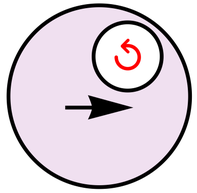
Unpolarized [u/u] $f_1(x, p_x, p_y)$



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

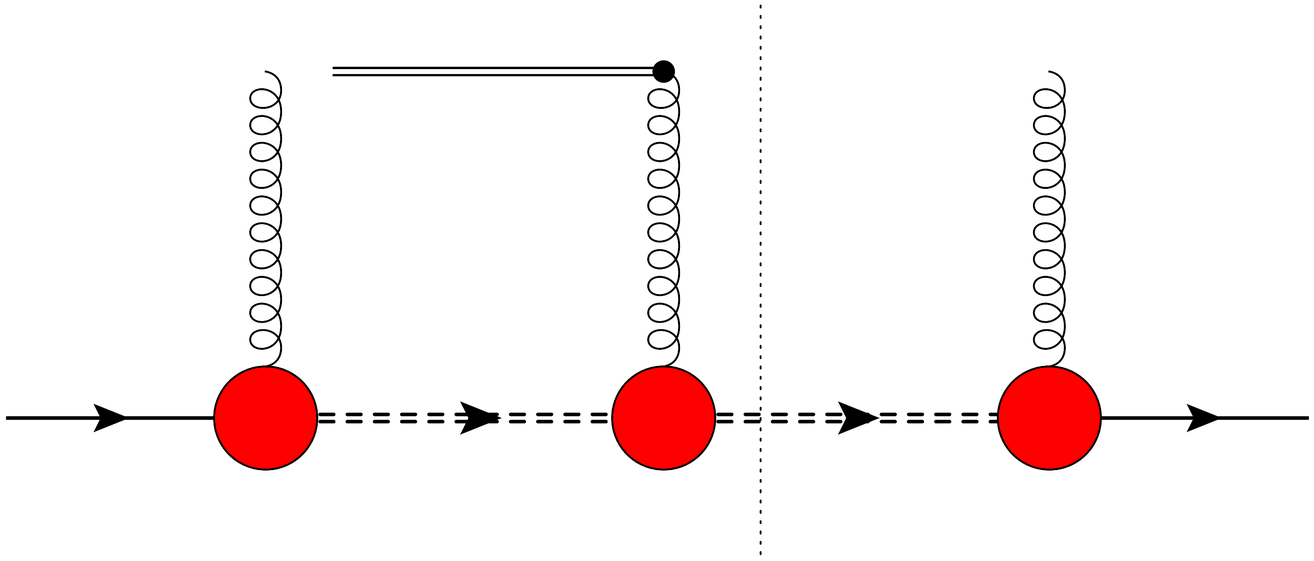


Worm-gear [↻/→] $f_1(x, p_x, p_y) - \frac{p_x}{M} g_{1T}(x, p_x, p_y)$

Backup

T-odd gluon TMDs in a spectator model

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



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

Backup

Sivers

Gluon TMDs: phenomenology

	$e\,p^\uparrow \to e'\,Q\,\overline{Q}\,X$ $e\,p^\uparrow \to e'\,j_1\,j_2\,X$	$p^\uparrow\,A \to h\,X$ $(x_F < 0)$	$p^\uparrow A \to \gamma^{(*)}\,\text{jet}\,X$	$p^\uparrow p \to \gamma\,\gamma\,X$ $p^\uparrow p \to J/\psi\,\gamma\,X$ $p^\uparrow p \to J/\psi\,J/\psi\,X$
$f_{1T}^{\perp\,g\,[+,+]}$	$\surd$	$\times$	$\times$	$\surd$
$f_{1T}^{\perp\,g\,[+,-]}$	$\times$	$\surd$	$\surd$	$\times$

Boer-Mulders

credits: D. Boer

	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$h_1^{\perp\,g\,[+,+]}$ (WW)	$\surd$	$\times$	$\surd$	$\surd$	$\surd$
$h_1^{\perp\,g\,[+,-]}$ (DP)	$\times$	$\surd$	$\times$	$\times$	$\times$

Backup

Sivers

Gluon TMDs: phenomenology

	$e\,p^\uparrow \to e'\,Q\,\overline{Q}\,X$ $e\,p^\uparrow \to e'\,j_1\,j_2\,X$	$p^\uparrow\,A \to h\,X$ $(x_F < 0)$	$p^\uparrow A \to \gamma^{(*)}\,\text{jet}\,X$	$p^\uparrow p \to \gamma\,\gamma\,X$ $p^\uparrow p \to J/\psi\,\gamma\,X$ $p^\uparrow p \to J/\psi\,J/\psi\,X$
$f_{1T}^{\perp\,g\,[+,+]}$	$\surd$	$\times$	$\times$	$\surd$
$f_{1T}^{\perp\,g\,[+,-]}$	$\times$	$\surd$	$\surd$	$\times$

Boer-Mulders

credits: D. Boer

	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$h_1^{\perp\,g\,[+,+]}$ (WW)	$\surd$	$\times$	$\surd$	$\surd$	$\surd$
$h_1^{\perp\,g\,[+,-]}$ (DP)	$\times$	$\surd$	$\times$	$\times$	$\times$

(pheno overview) 🔗 [D. Boer (2017)]

(azimuthal asym. in J/Ψ + jet SIDIS at the EIC) 🔗 [U. D'Alesio, F. Murgia, C. Pisano, P. Taels (2019)]

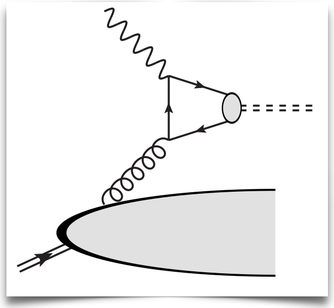
(matching high and low p_T in J/Ψ SIDIS) 🔗 [D. Boer, U. D'Alesio, F. Murgia, C. Pisano, P. Taels (2020)]

(gluon TMDs and NRQCD in J/Ψ at the EIC) 🔗 [A. Bacchetta, D. Boer, C. Pisano, P. Taels (2020)]

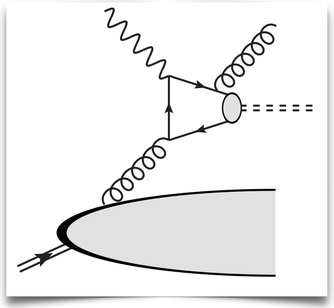
Backup

Gluon TMDs and quarkonia

SIDIS

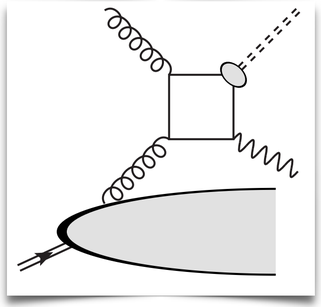


CO



CO + CS

Hadroproduction

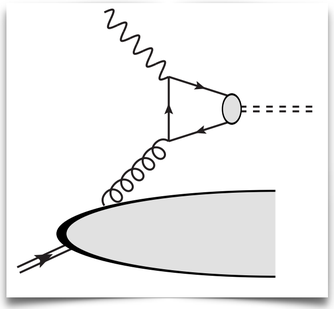


CO + CS

Backup

Gluon TMDs and quarkonia

SIDIS



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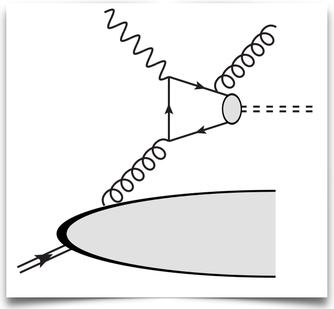
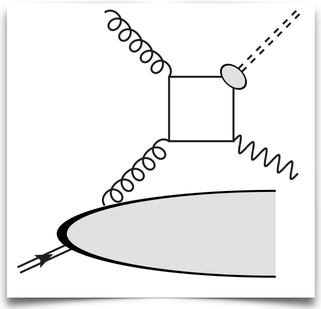


CO + CS

EIC Yellow Report Document
(link to EICUG website)

[EICUG [*in preparation*]]

Hadroproduction

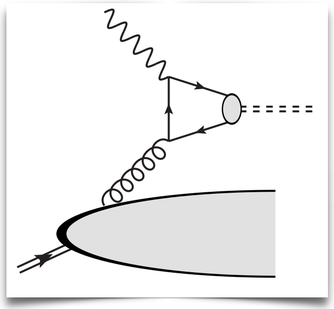


CO + CS

Backup

Gluon TMDs and quarkonia

SIDIS



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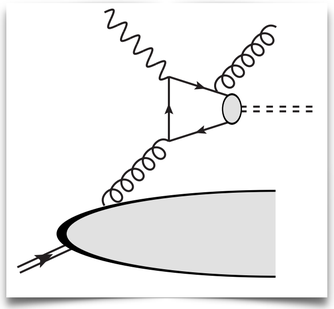


CO + CS

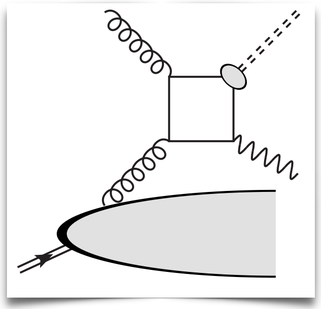
EIC Yellow Report Document
(link to EICUG website)

[EICUG [*in preparation*]]

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

[NICA Collaboration [arXiv:2011.15005]]

Hadroproduction



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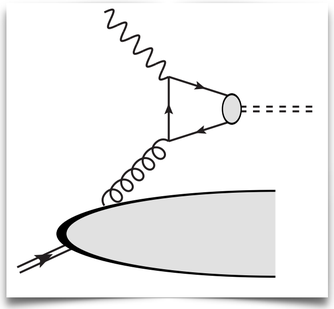
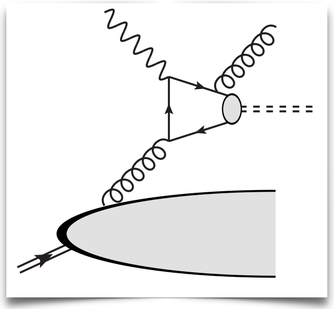
Backup

Gluon TMDs and quarkonia

SIDIS



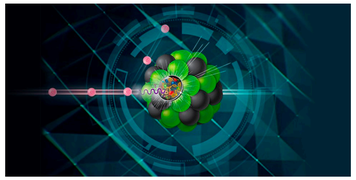
CO

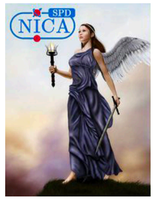


CO + CS

EIC Yellow Report Document
(link to EICUG website)

[EICUG [*in preparation*]]

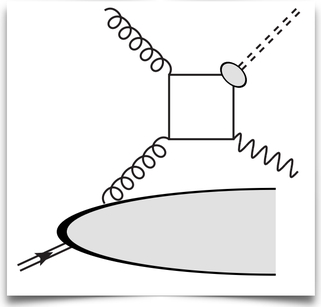




On the physics potential to study the gluon content of proton and deuteron at NICA SPD

[NICA Collaboration [arXiv:2011.15005]]

Hadroproduction



CO + CS

Perspectives for quarkonium studies at the high-luminosity LHC
(link to QAT 2020 Workshop)

[Quarkonia As Tools Collaboration [arXiv:2012.14161]]

Backup