Light Cone 2021

Jungmun-dong, Seogwipo-si, December 2nd

Proton 3D tomography at low- and moderate-x via TMD gluon densities

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ECT*/FBK Trento & INFN-TIFPA

In collaboration with **A. Bacchetta** and **M. Radici**

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

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HAS QCD
HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

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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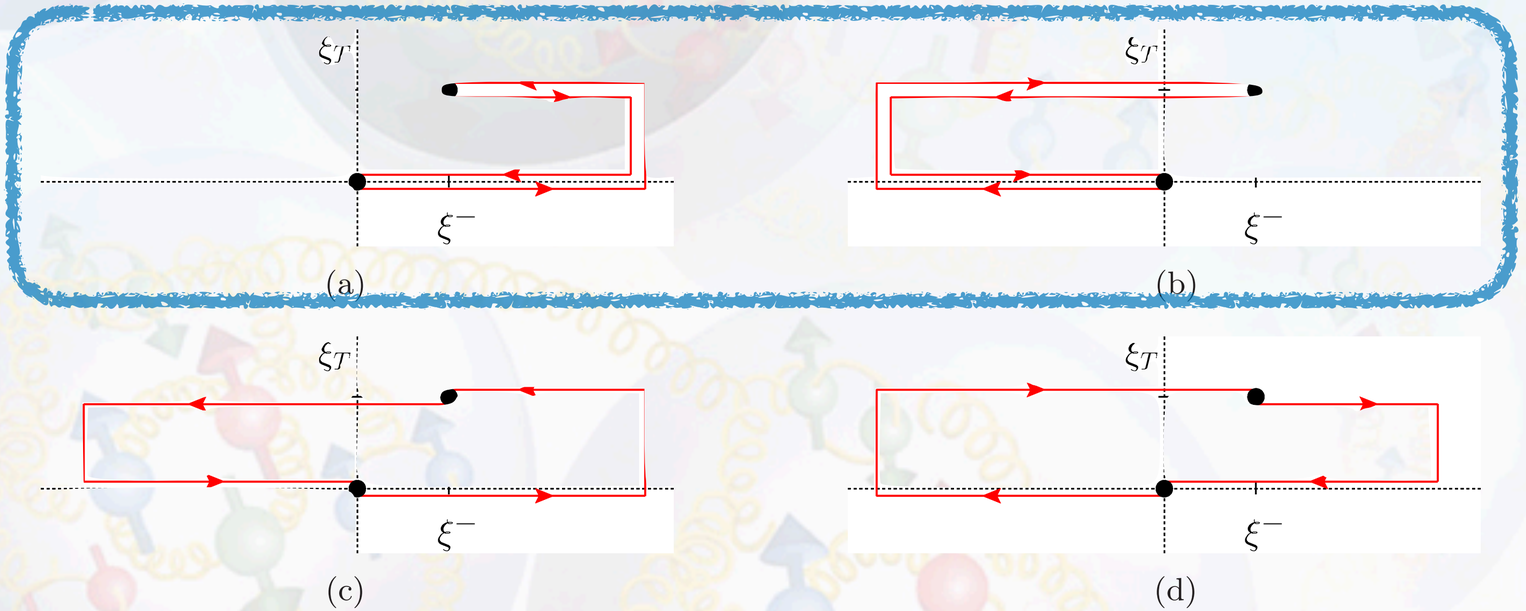
f-type (WW)

(a) [+ , +] or (b) [− , −]



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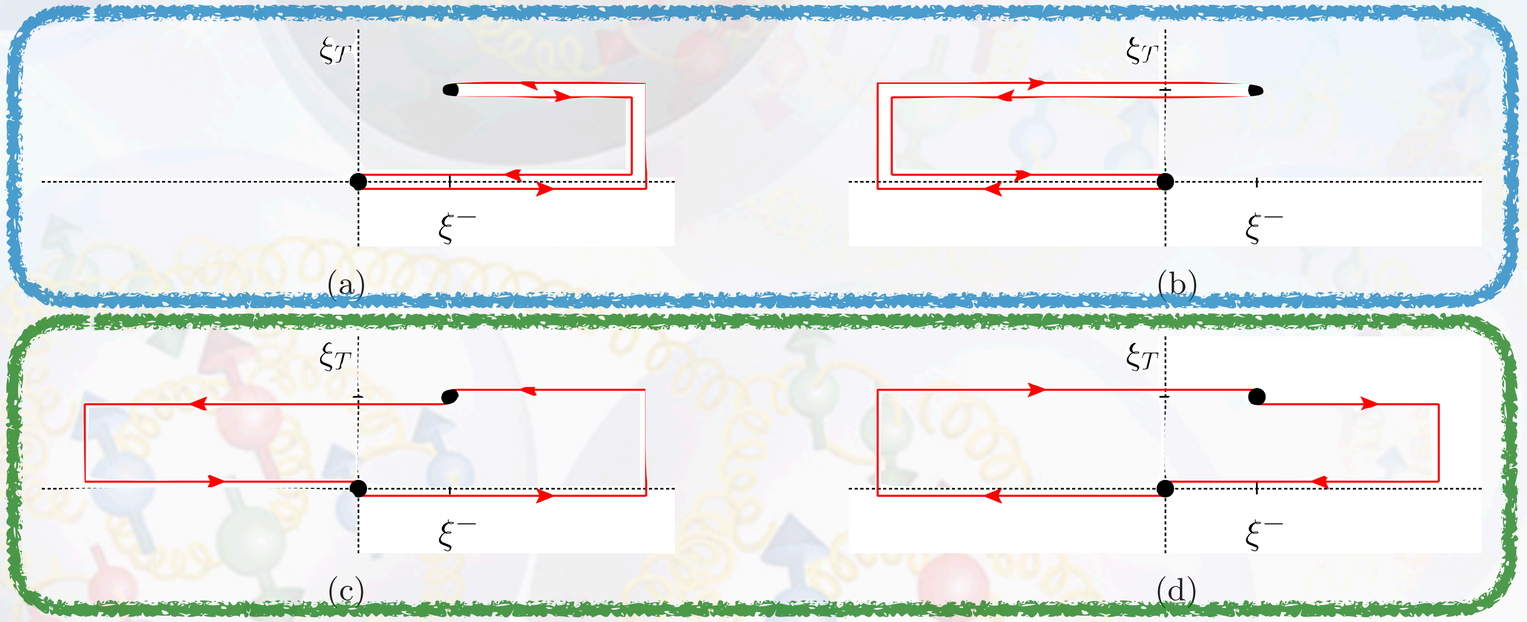
d-type (dipole)

(c) [+ , −] or (d) [− , +]



Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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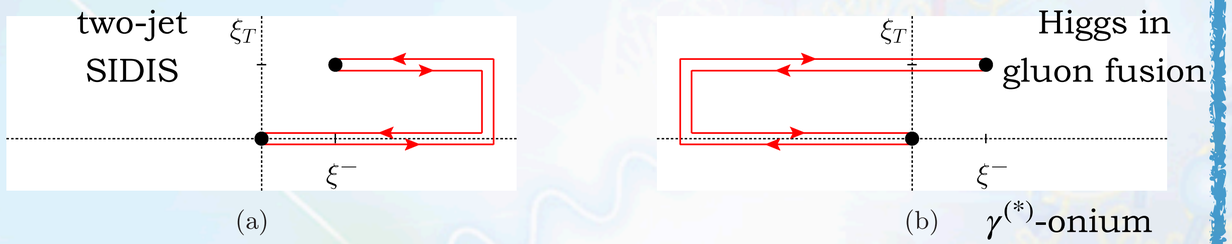

Higgs in gluon fusion

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

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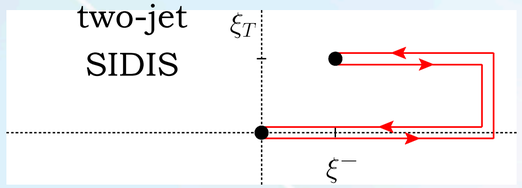
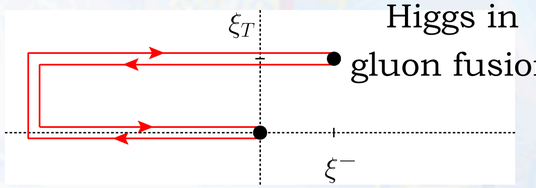


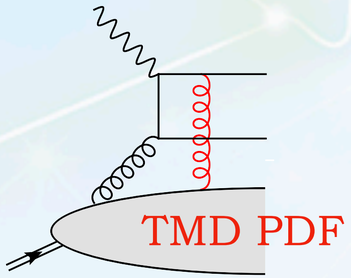
(a)



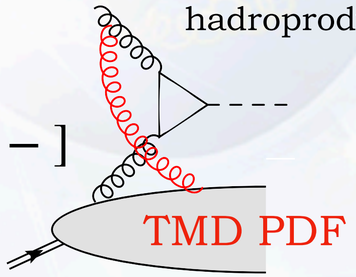
(b) $\gamma^{(*)}$-onium hadroproduction

Higgs in gluon fusion

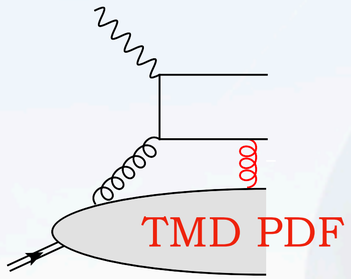
$[+$



$[-,-]$



$+]$



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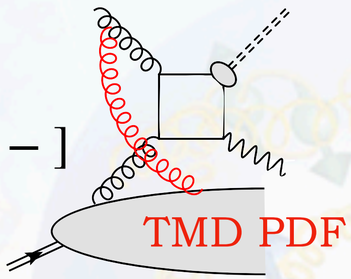
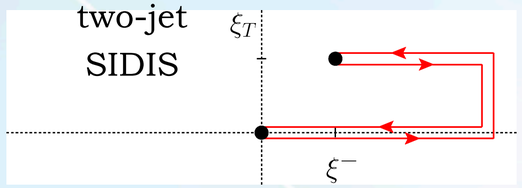


Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

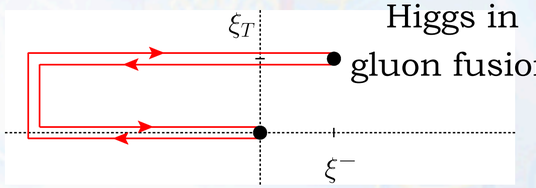
(a) [+,+] or (b) [−,−]

two-jet SIDIS



(a)

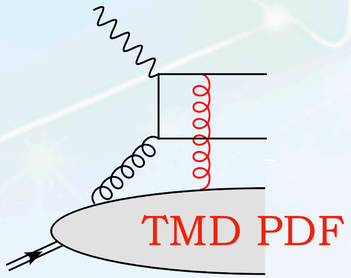
Higgs in gluon fusion



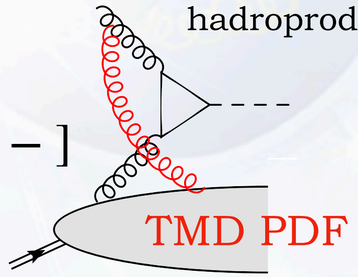
(b)

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

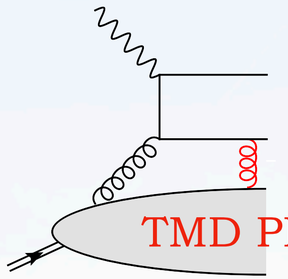
[+



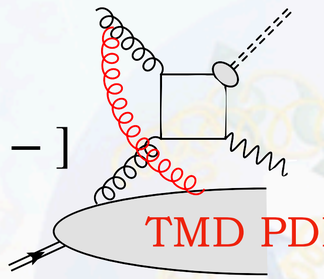
[−,−]



+]

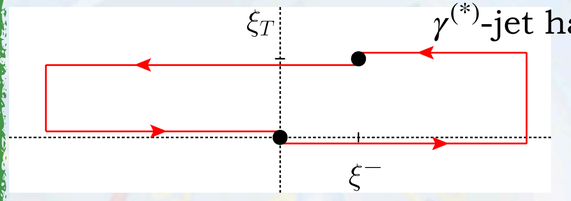


[−,−]



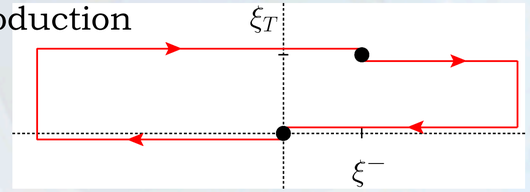
Dipole (DP)

(c) [+,−] or (d) [−,+]



(c)

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



(d)

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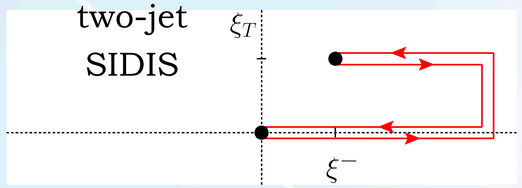

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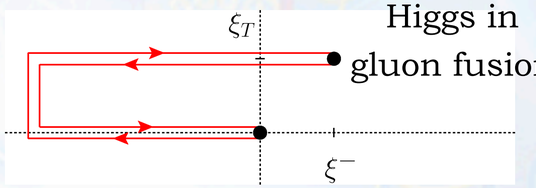

(b) $\gamma^{(*)}$-onium hadroproduction

Higgs in gluon fusion

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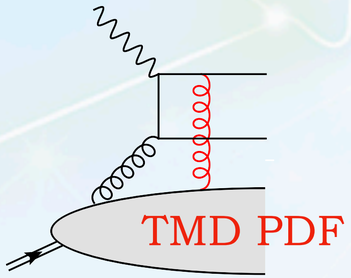
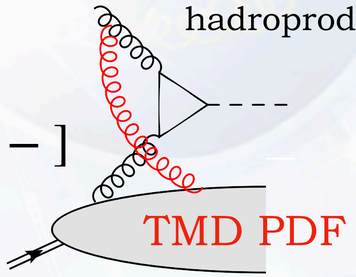
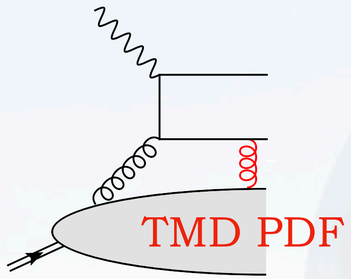


[− , −]



+]



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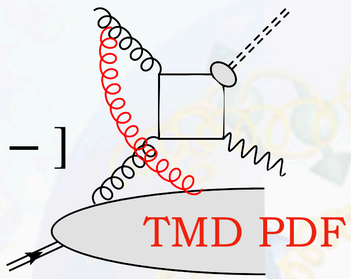

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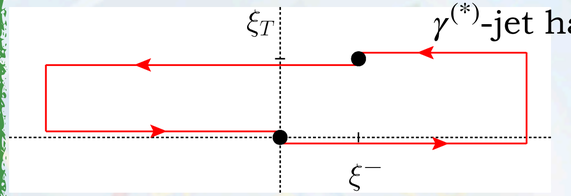

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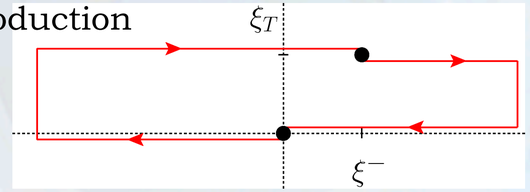
$\gamma^{(*)}$-jet hadroproduction



(d)

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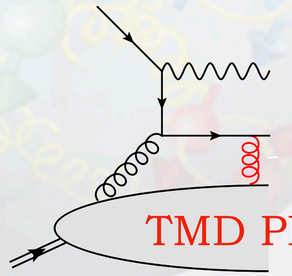
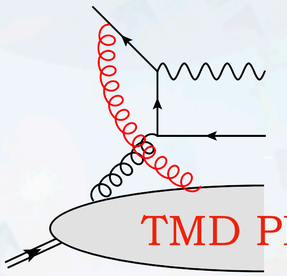


[−



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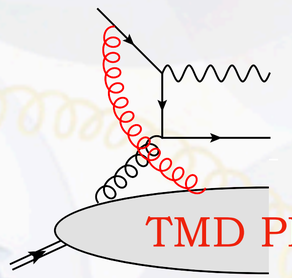

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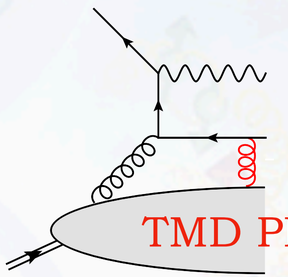

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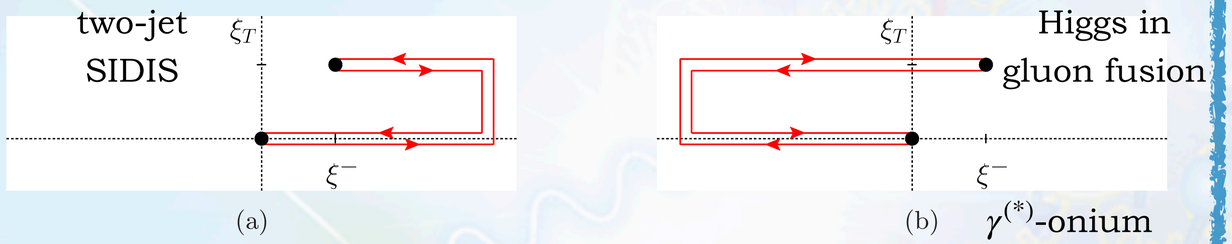

- Color flow annihilated within final/initial state
- f-type gluon TMDs $\rightarrow$ f^{abc} color structure
- Modified universality:

$$f_1^{[+,+]} = f_1^{[-,-]},$$
$$f_{1T}^{\perp[+,+]} = -f_{1T}^{\perp[-,-]}$$

- Phenomenology: Higgs, quarkonia or $\gamma\gamma$ in pp, two-jet SIDIS, heavy-quark pair SIDIS

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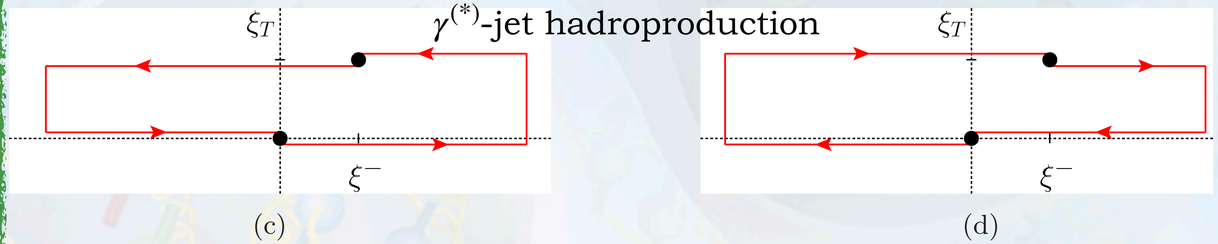


- Color flow involving both initial and final states
- d-type gluon TMDs $\rightarrow$ d^{abc} color structure
- Modified universality:

$$f_1^{[+,-]} = f_1^{[-,+]},$$
$$f_{1T}^{\perp[+,-]} = -f_{1T}^{\perp[-,+]}$$

- Phenomenology: single hadron or $\gamma^{(*)}$-jet hadroproduction, SIDIS or Drell-Yan (subleading)

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

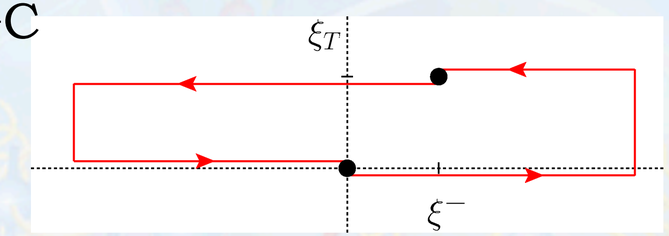
Dihadron hadroproduction and factorization breaking

- 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:

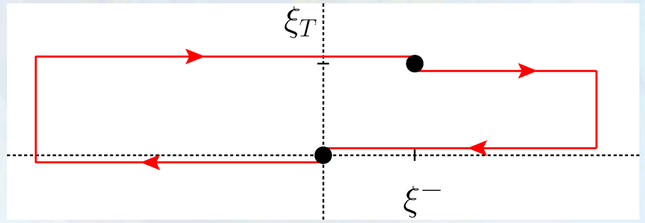
  (c) $[+,-]$ and (d) $[-,+]$
- Appearance of new gauge **loop links**:

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

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



(c)



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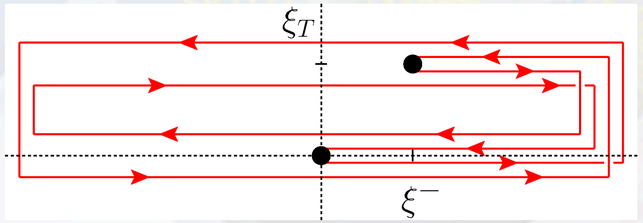

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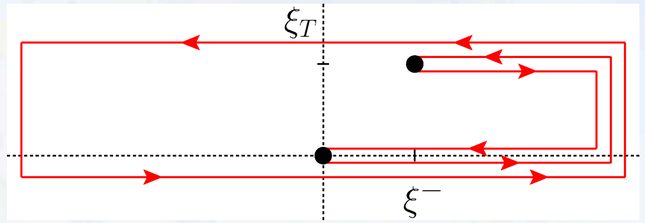
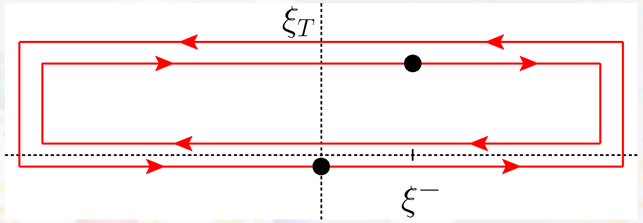
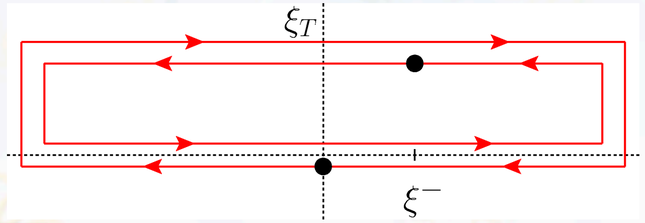


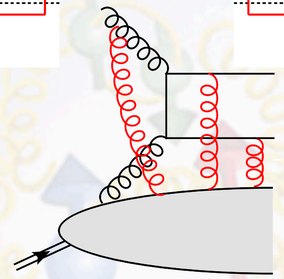
(f)



(g)



(h)



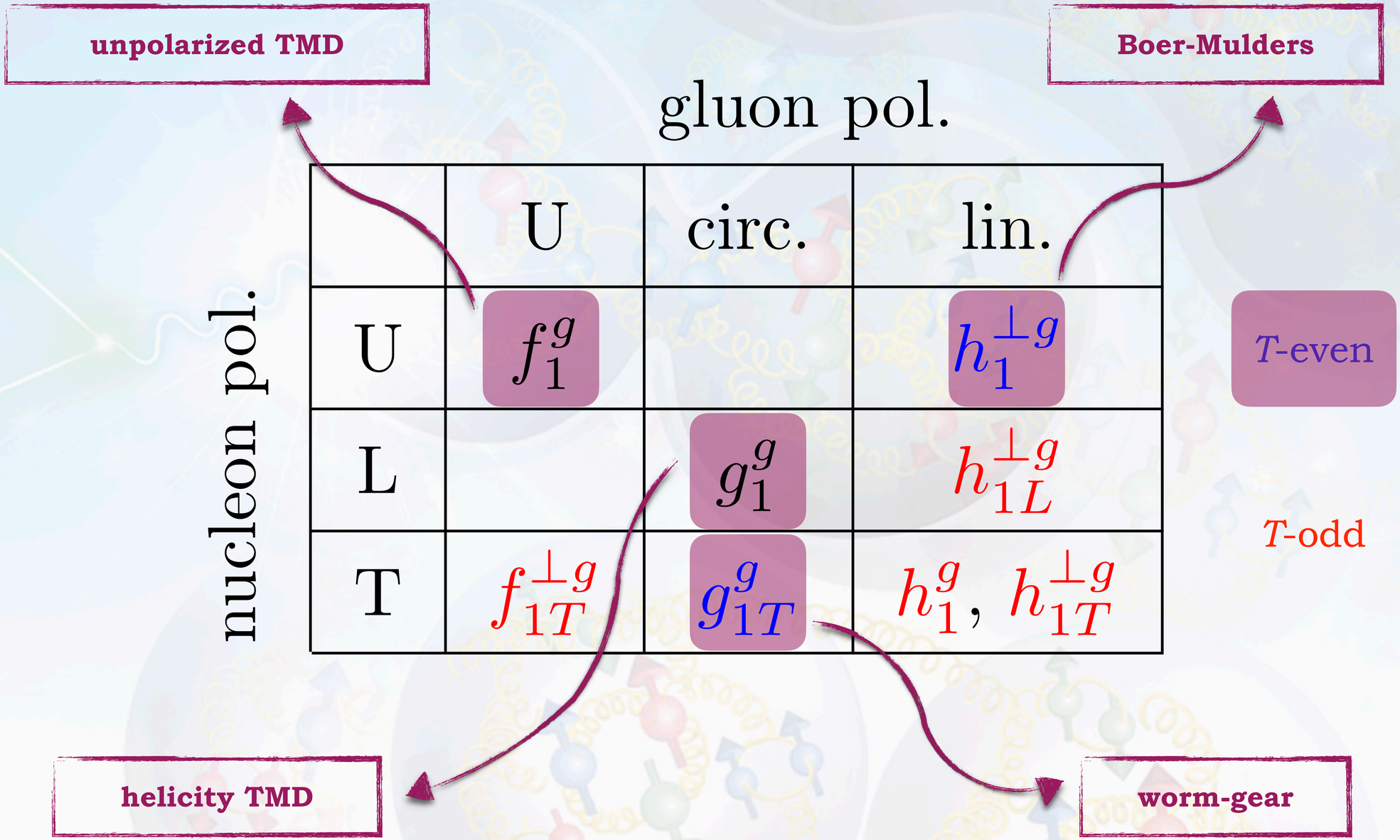
T-even and *T*-odd gluon TMD PDFs at leading-twist

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



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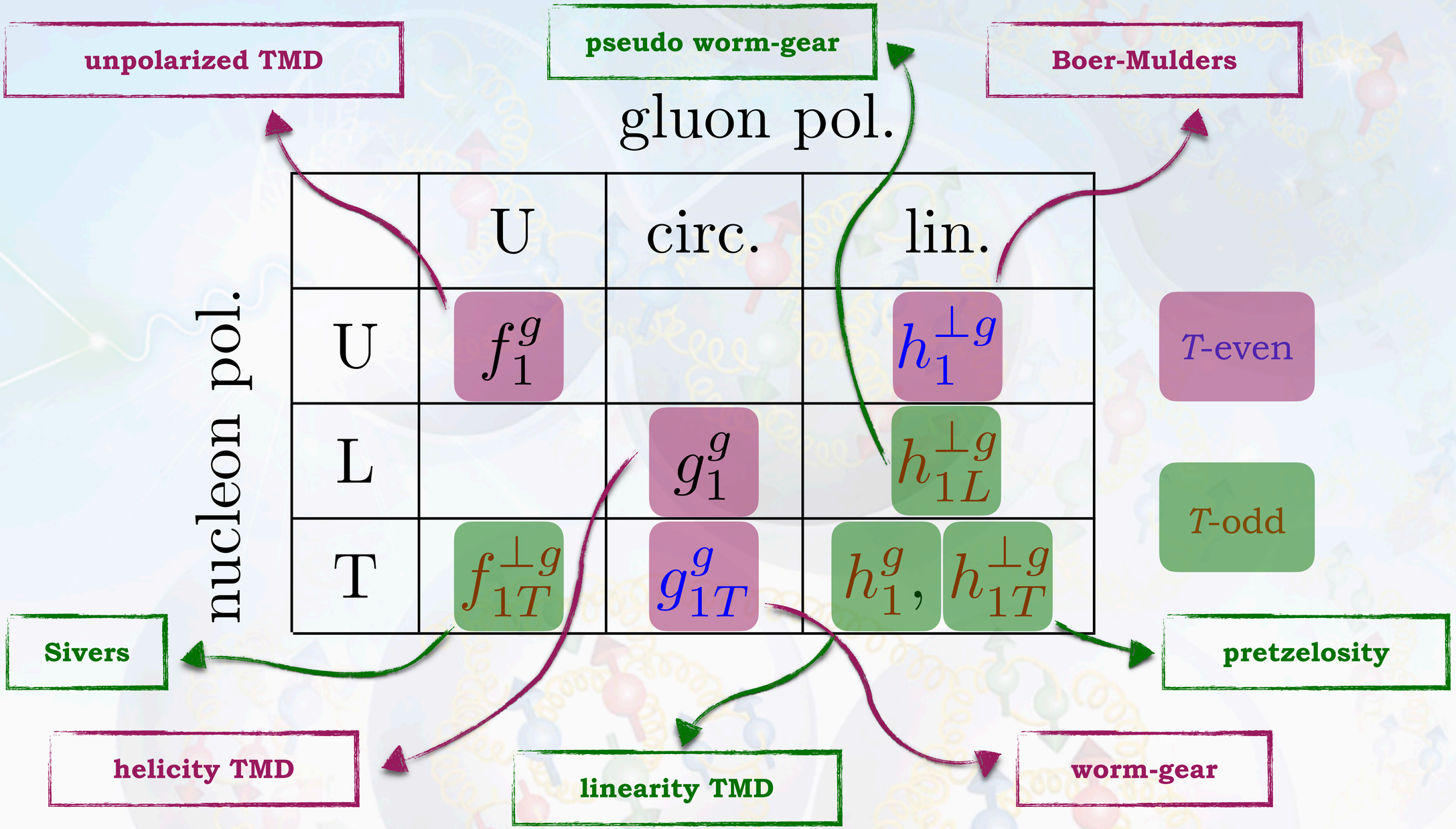
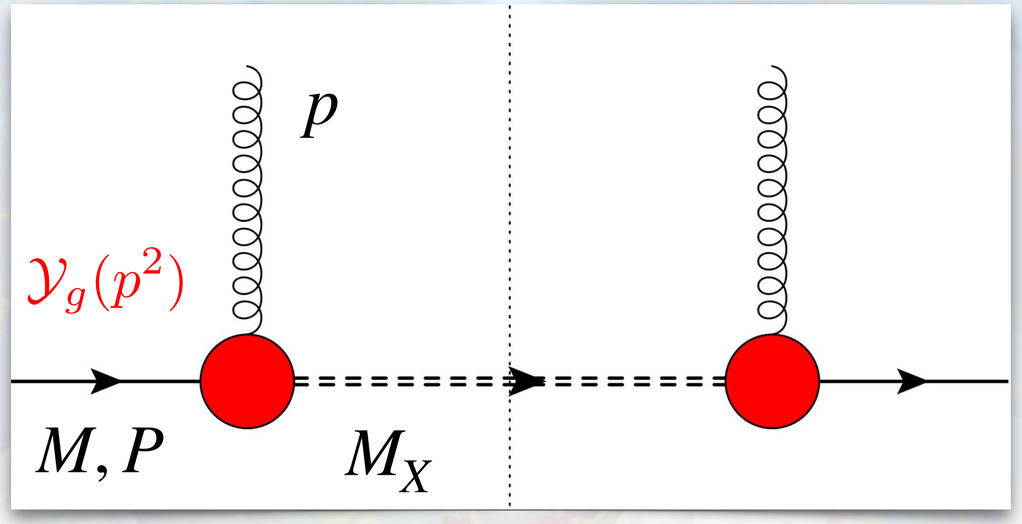


Assumptions of the model

Spin-1/2 spectator

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



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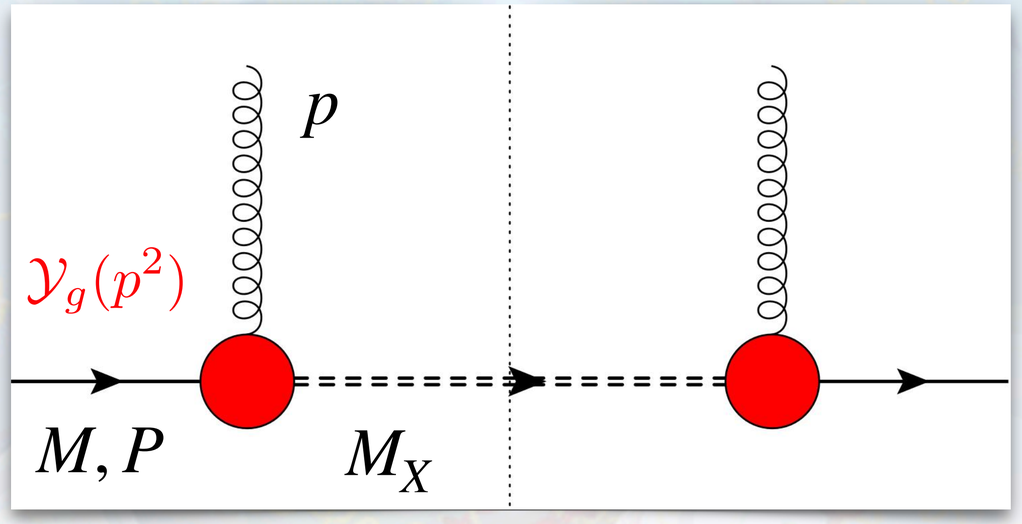

Nucleon-gluon-spectator vertex

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

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

mimics proton form factors
(conserved EM current
of a free nucleon)

Assumptions of the model

Link with collinear factorization

1. p_T-integrated TMDs **have to** reproduce PDFs at the lowest scale (Q_0) *before* evolution
2. TMDs and PDFs *decouple* due to evolution

Assumptions of the model

Link with collinear factorization

1. p_T-integrated TMDs **have to** reproduce PDFs at the lowest scale (Q_0) *before* evolution
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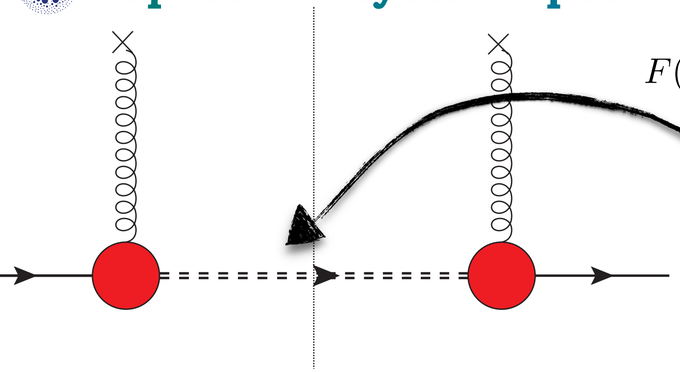
Dipolar form factor(s)

$$g_{1,2}(p^2) = \kappa_{1,2} \frac{p^2}{|p^2 - \Lambda_X^2|^2}$$

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

Our model at a glance

Spectator-system spectral-mass function



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

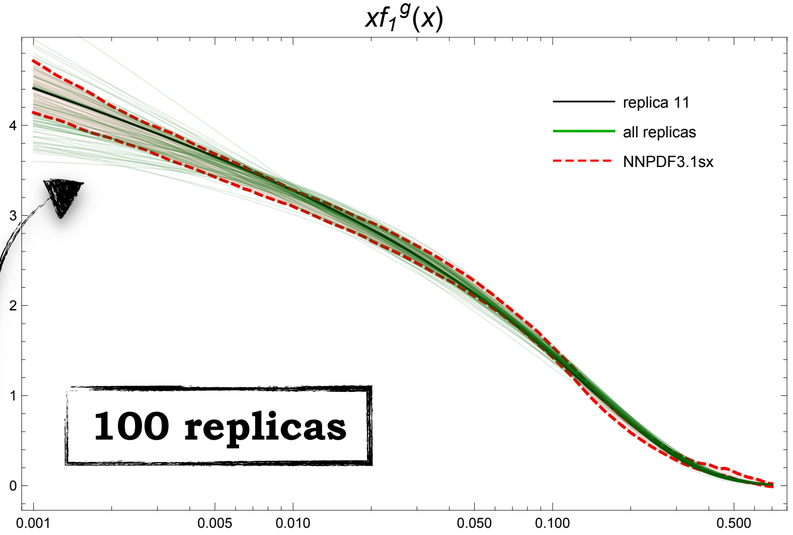
Instead of a single on-shell spectator, a continuum of spectators

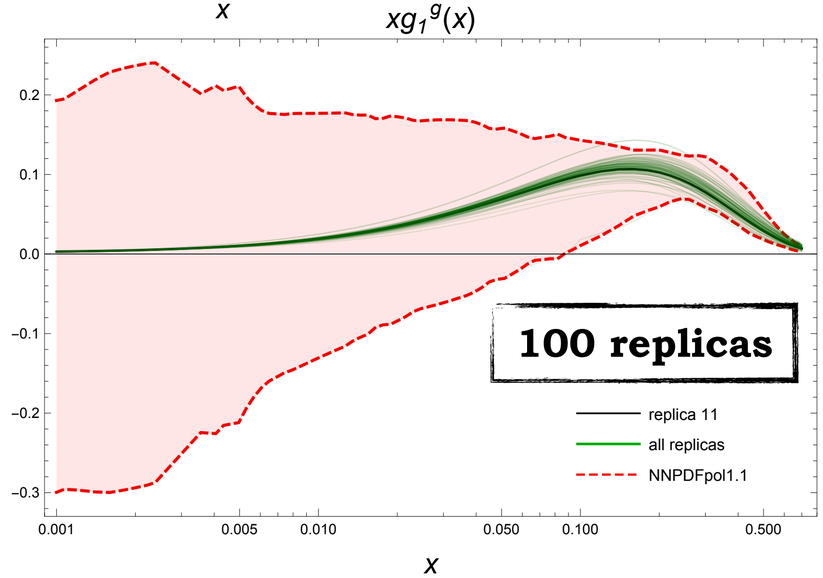
Spectral function **learns** small- and moderate-x info encoded in **NNPDF** collinear parametrizations (`NNPDF3.1sx + NNPDFpol1.1`)

- ☑ **Simultaneous fit** of f_1 and g_1 PDFs
- ☑ Inclusion of small-x resummation effects (**BFKL**)
- ☑ Calculation of all leading-twist T-even gluon TMDs

Link with collinear factorization

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





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

…towards twist-2 *T*-odd gluon TMDs

T-odd gluon TMDs in a spectator model

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

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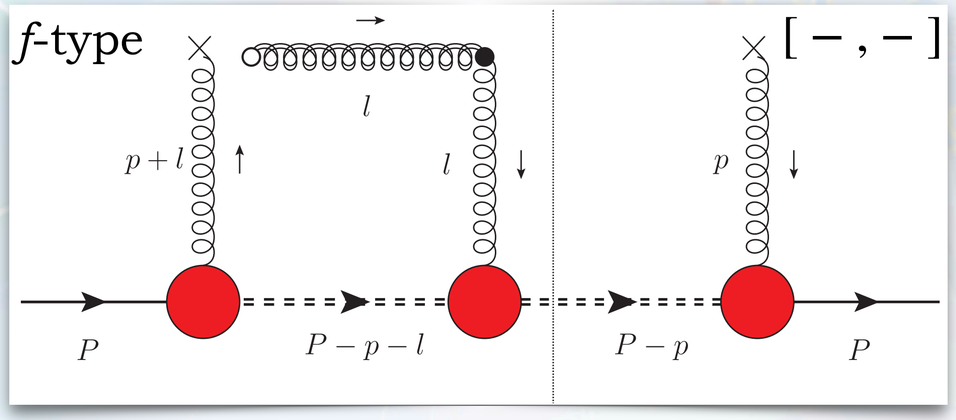
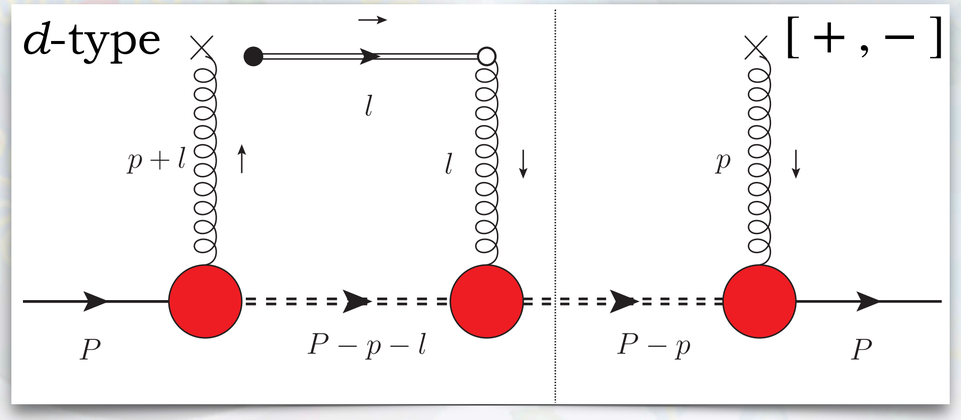
$gg \to H$



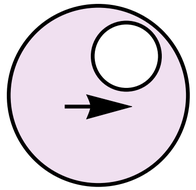
$qg \to \gamma^{(*)}$-jet

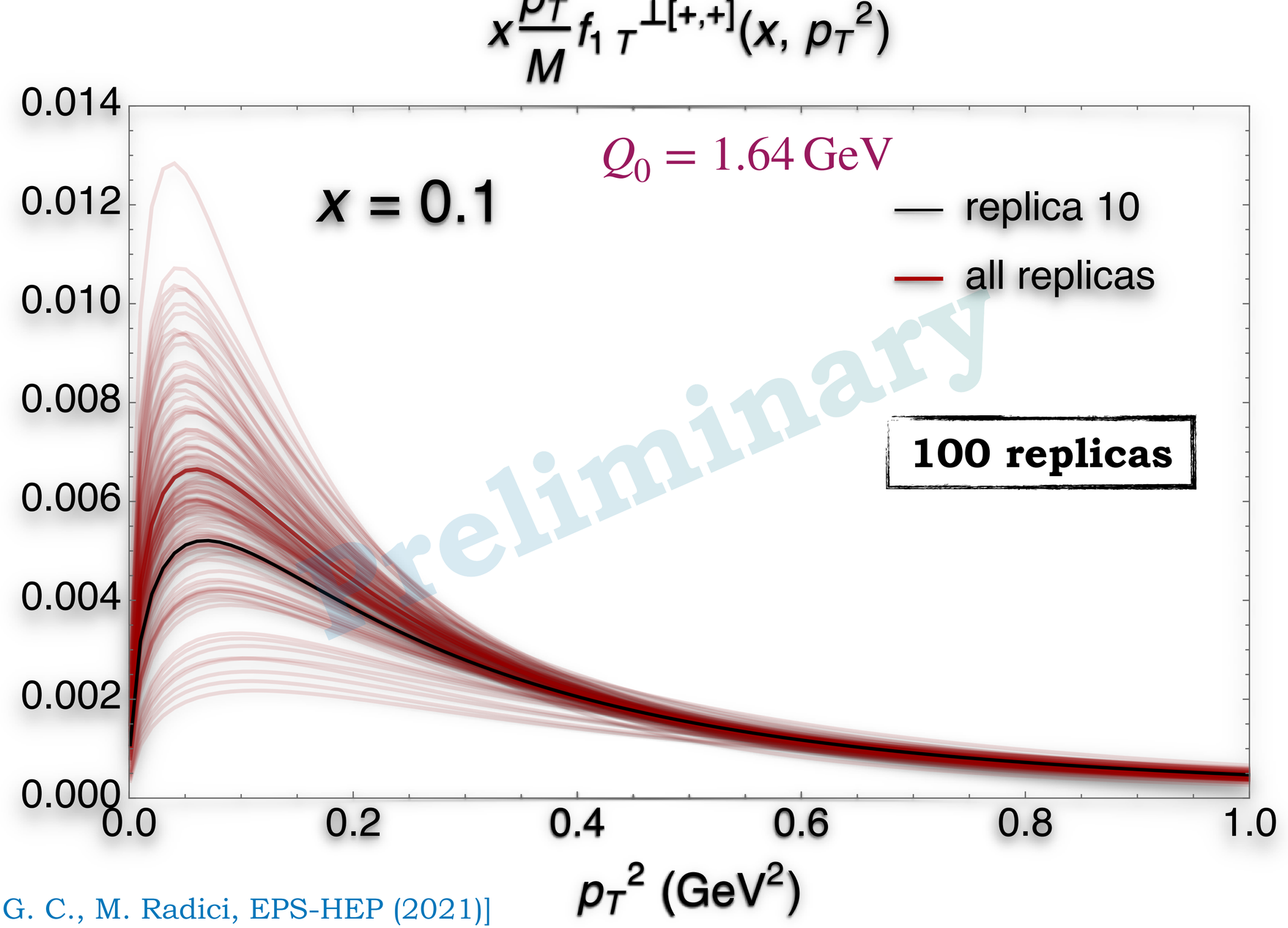


- Leading-twist one-gluon-exchange of the gauge-link operator
- Sensitivity to *f*- and *d*-type structures
- Preliminary results for **Sivers** and **linearity** functions

[A. Bacchetta, F.G. C., M. Radici, EPS-HEP, PANIC (2021)]

f-type Sivers gluon TMD





[A. Bacchetta, F.G. C., M. Radici, EPS-HEP (2021)]

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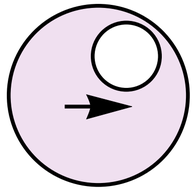
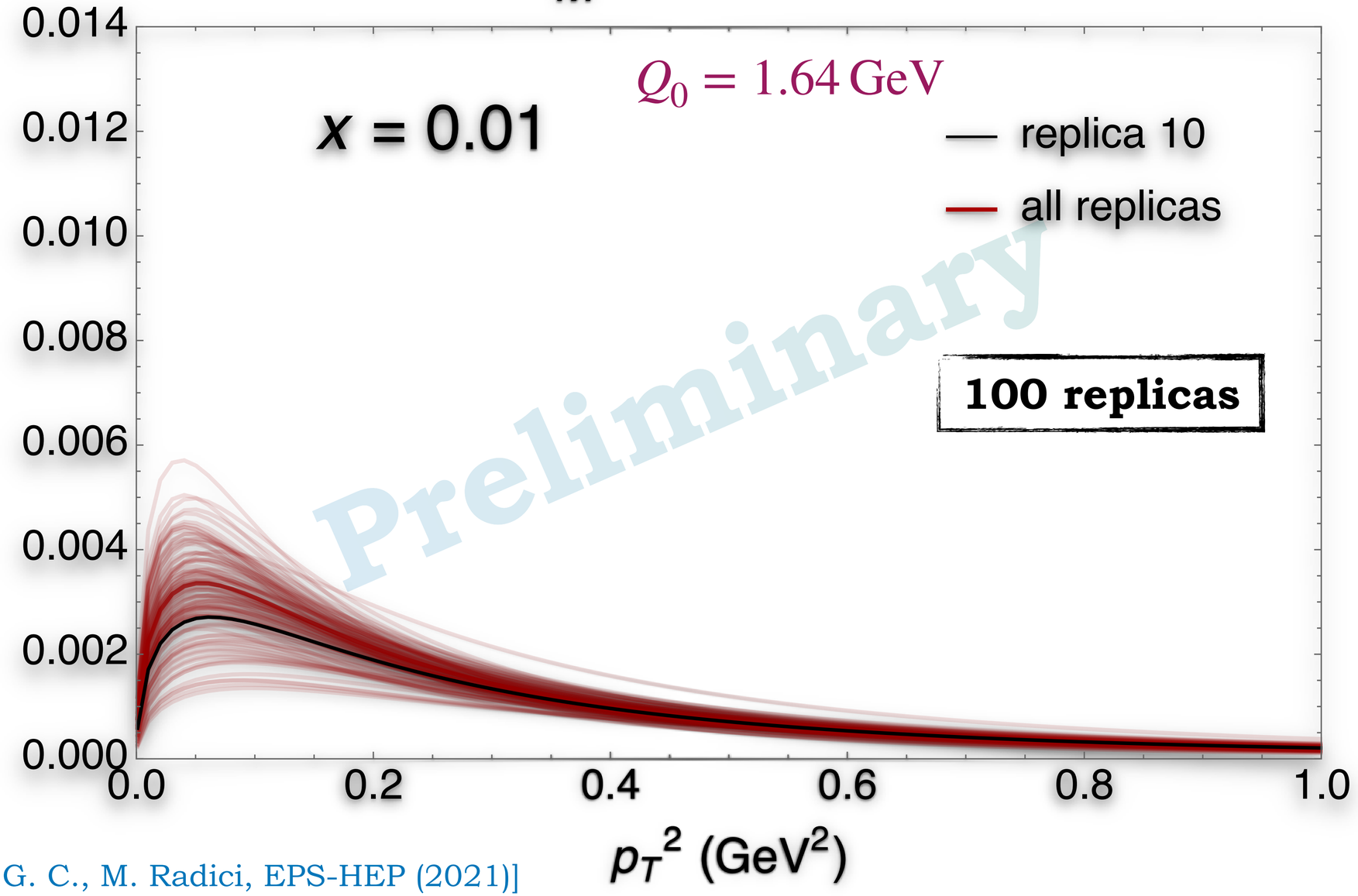


$$x\frac{p_T}{M} f_{1\,T}^{\perp[+,+]}(x, p_T^2)$$



[A. Bacchetta, F.G. C., M. Radici, EPS-HEP (2021)]

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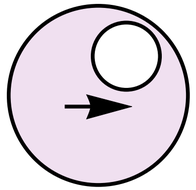

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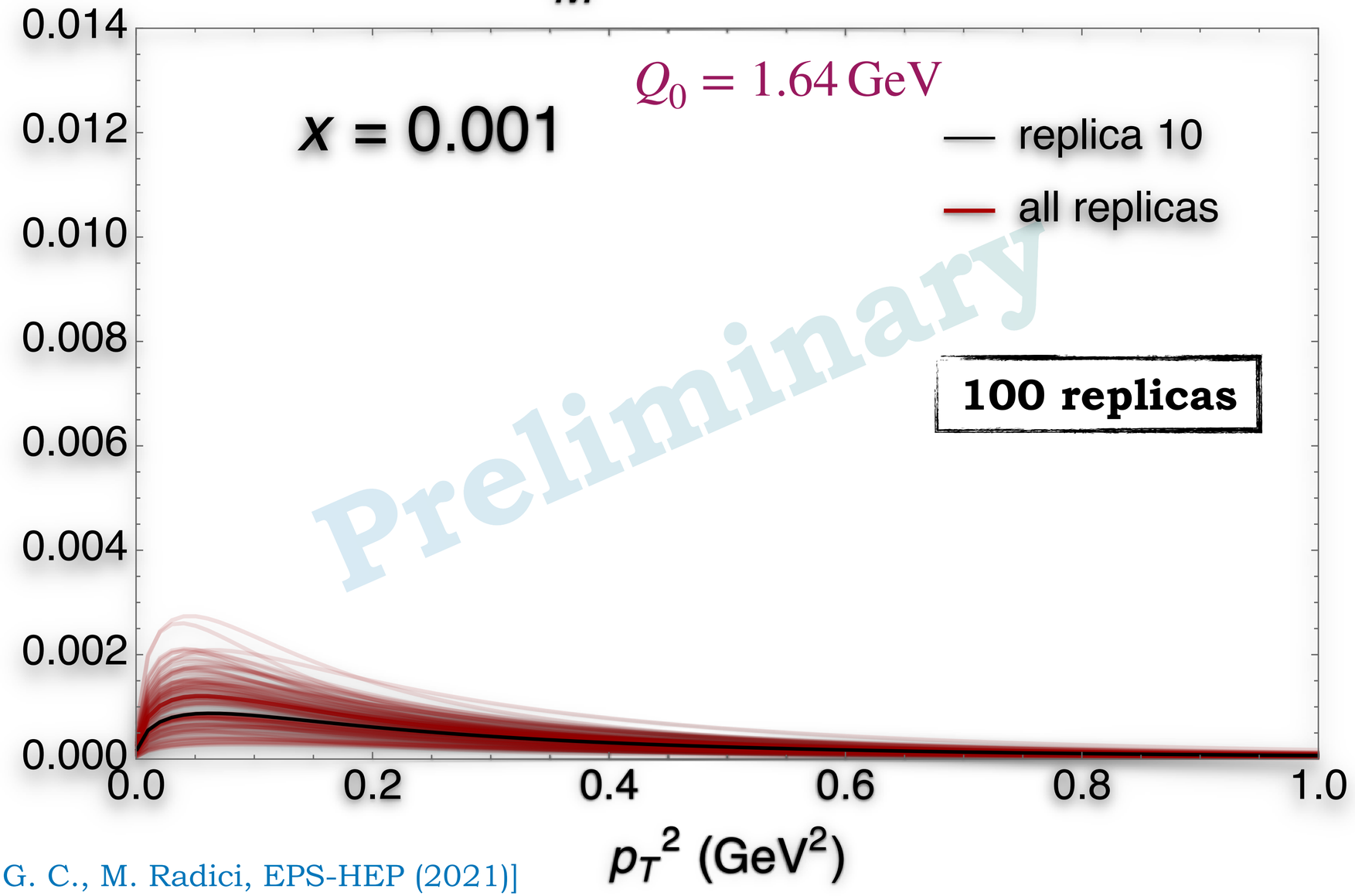
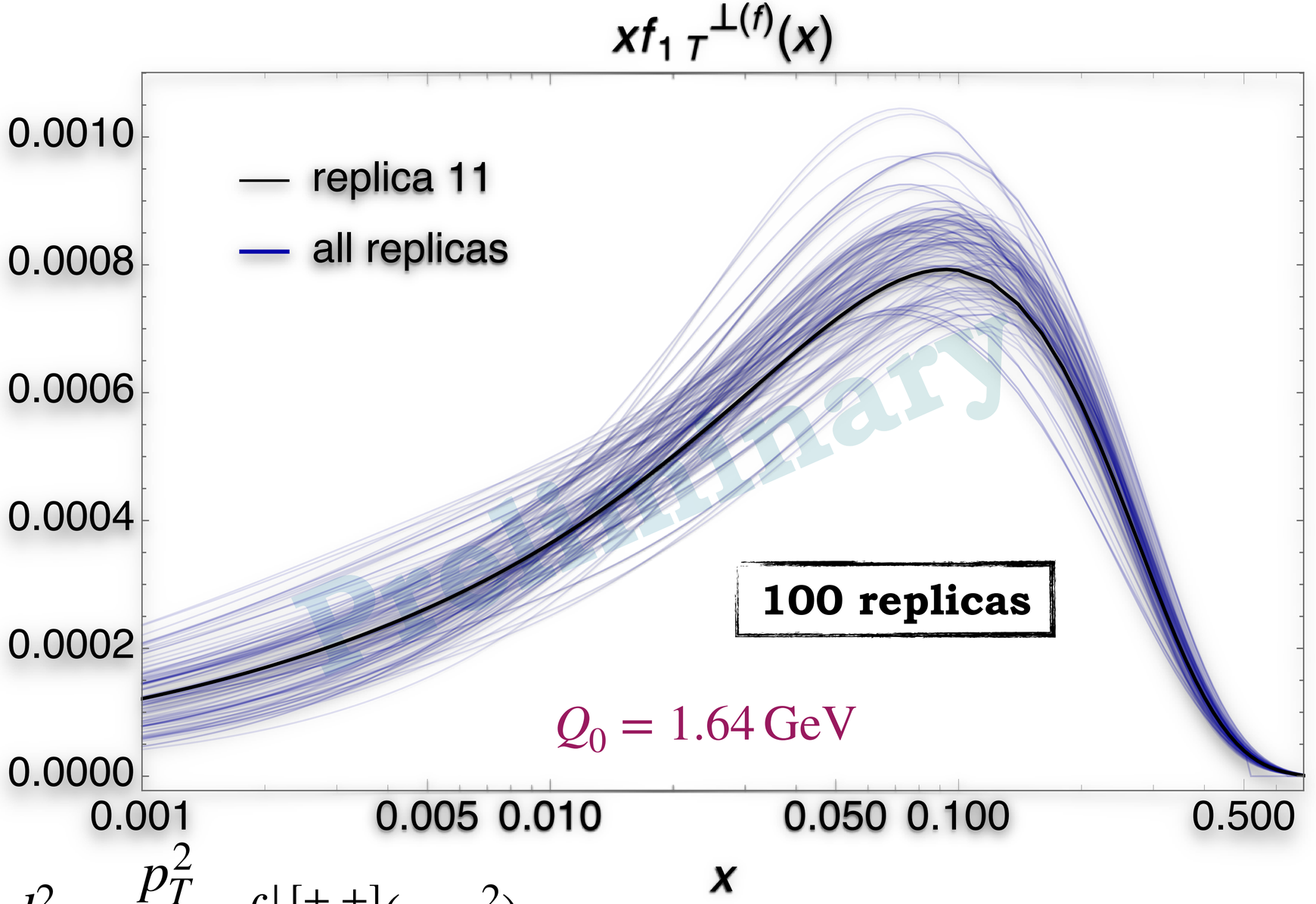


[A. Bacchetta, F.G. C., M. Radici, EPS-HEP (2021)]

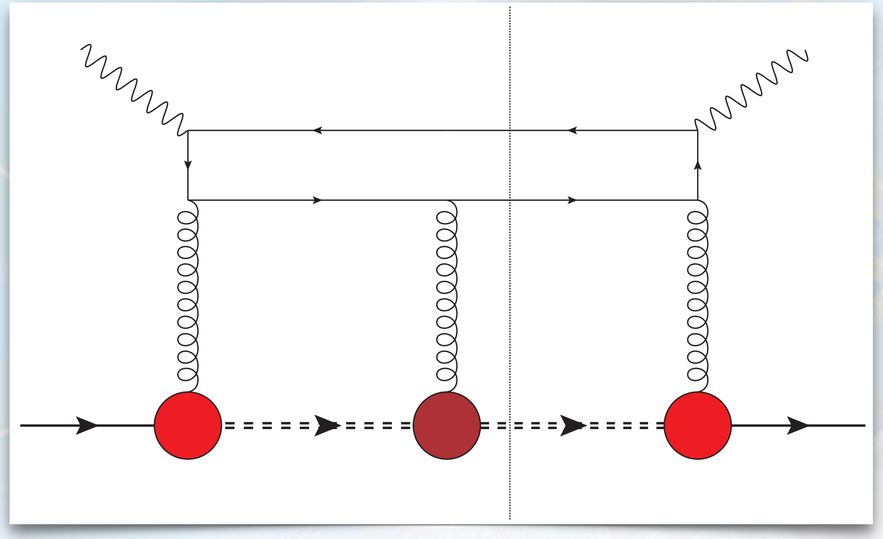
f-type Qiu-Sterman twist-3 gluon PDF

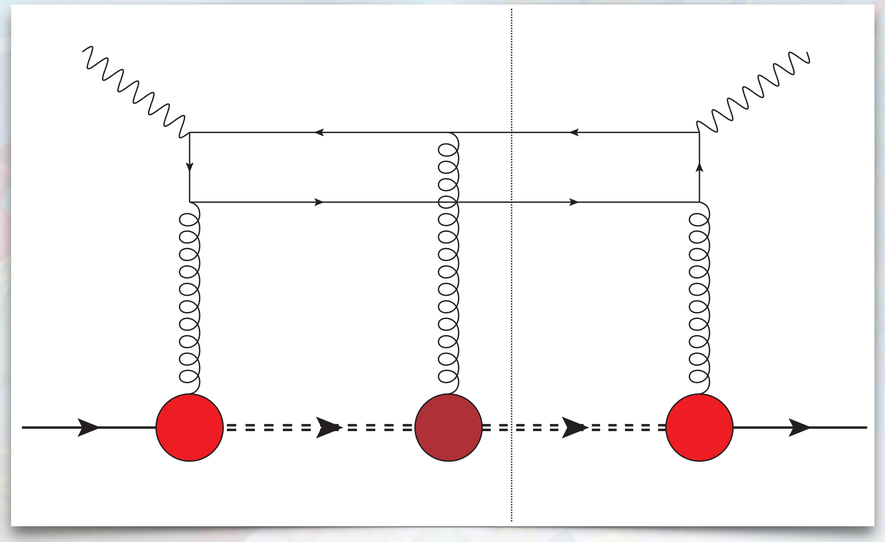


$$f_{1T}^{\perp(f)}(x) = \int d^2p_T \frac{p_T^2}{2M^2} f_{1T}^{\perp[+,+]}(x, p_T^2)$$

Analytic structure of *T*-odd gluon TMDs

Two-jet SIDIS $\Rightarrow$ *f*-type [+ , +]





[A. Bacchetta, F.G. C., M. Radici, *in preparation*]

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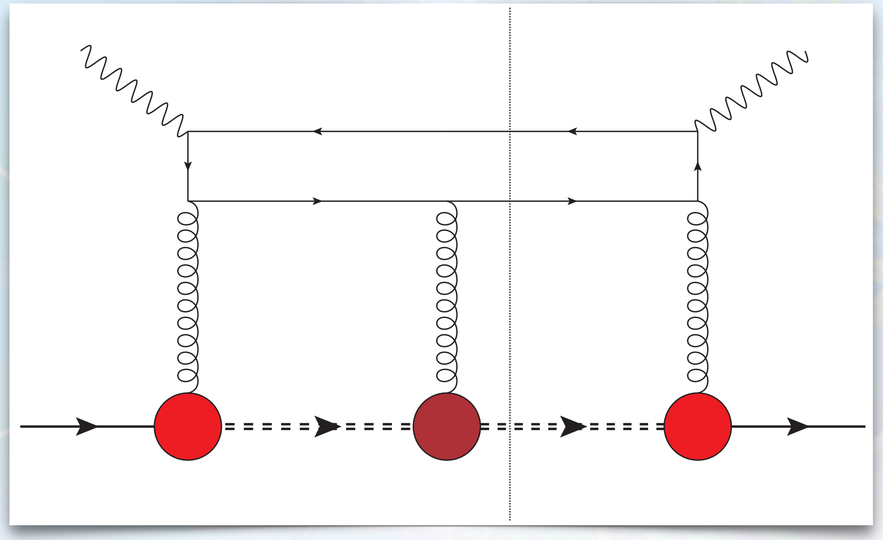

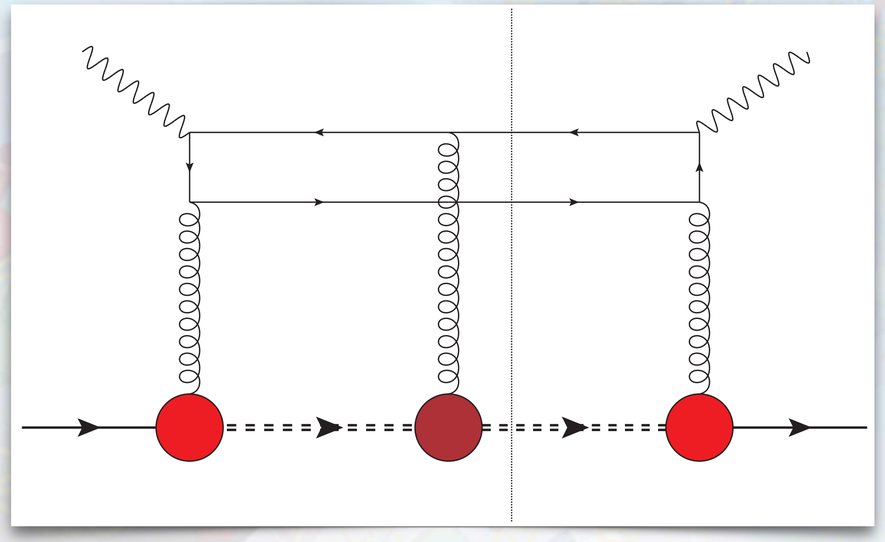

nucleon-gluon-spectator

spectator-gluon-spectator

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

[A. Bacchetta, F.G. C., M. Radici, *in preparation*]

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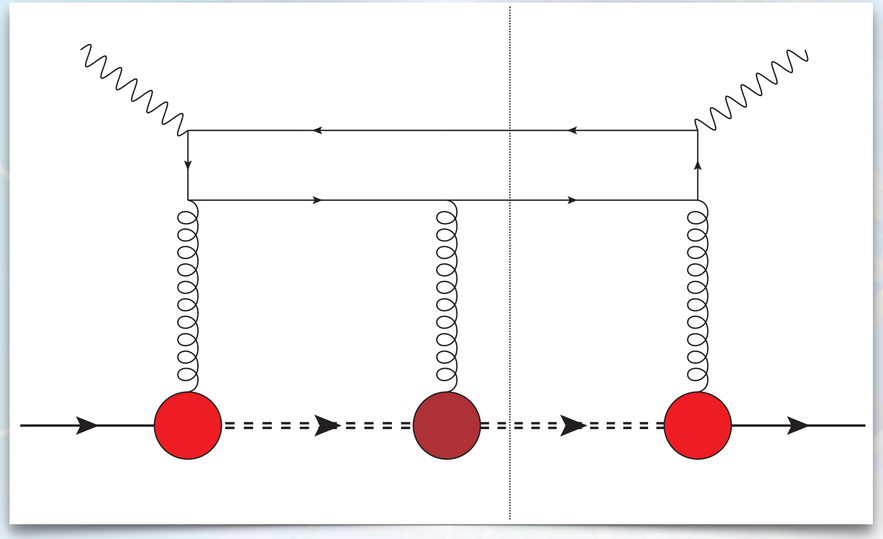

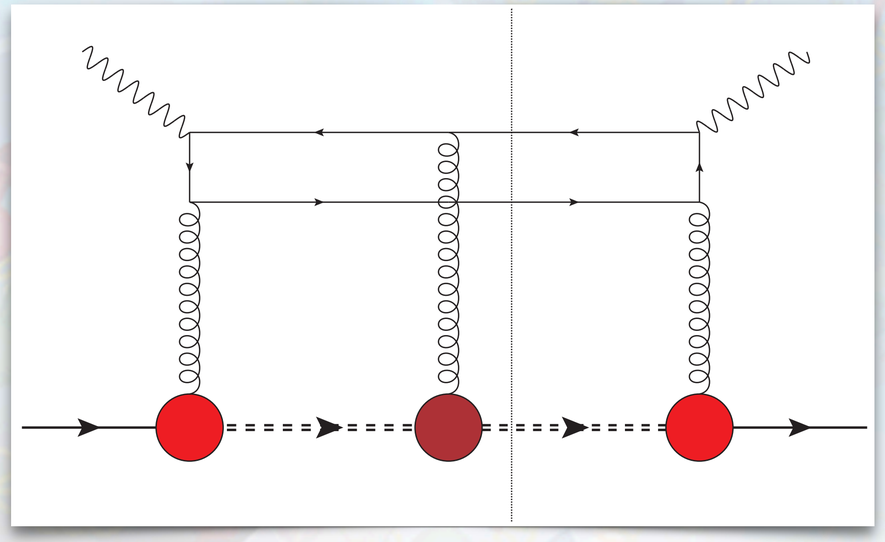

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$8 \times 7 \times 4$

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[A. Bacchetta, F.G. C., M. Radici, *in preparation*]

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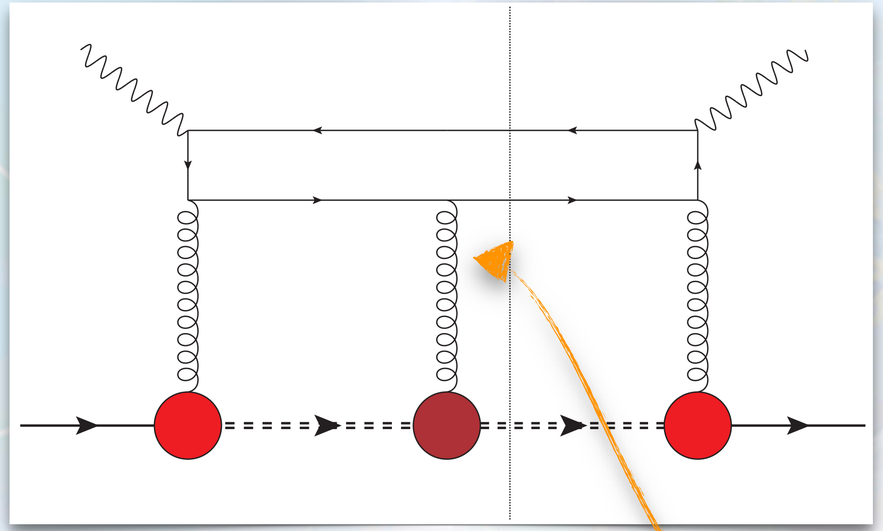

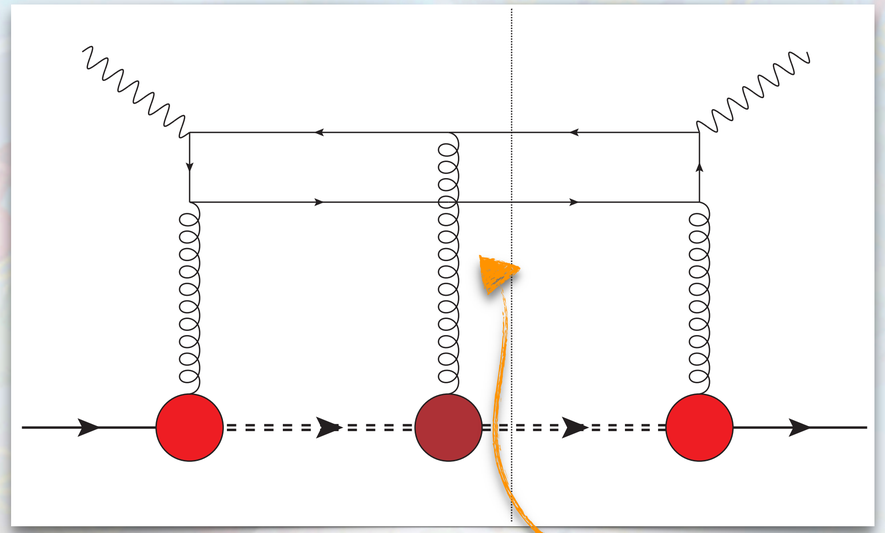

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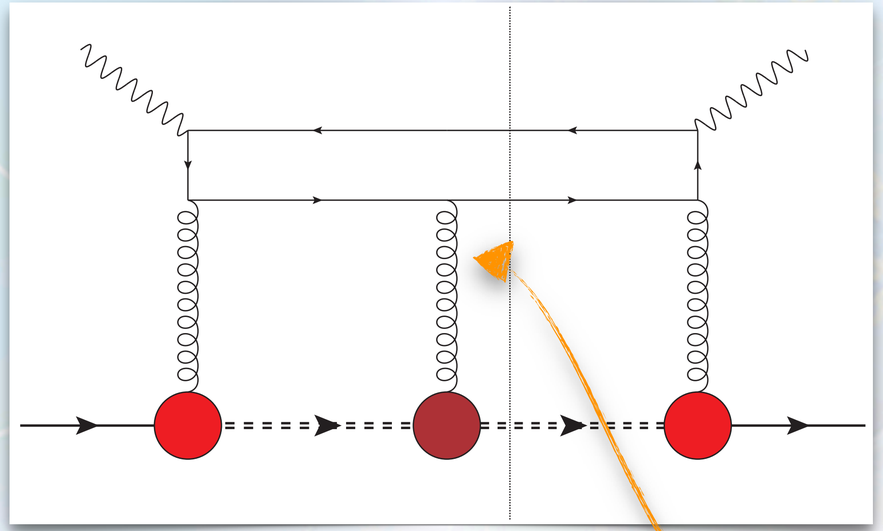

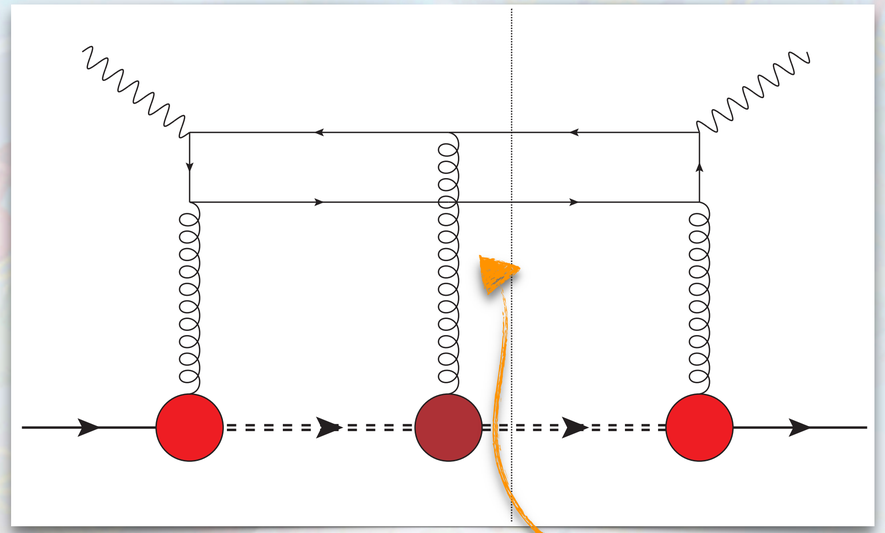

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[A. Bacchetta, F.G. C., M. Radici, *in preparation*]

Checkpoints and further steps

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

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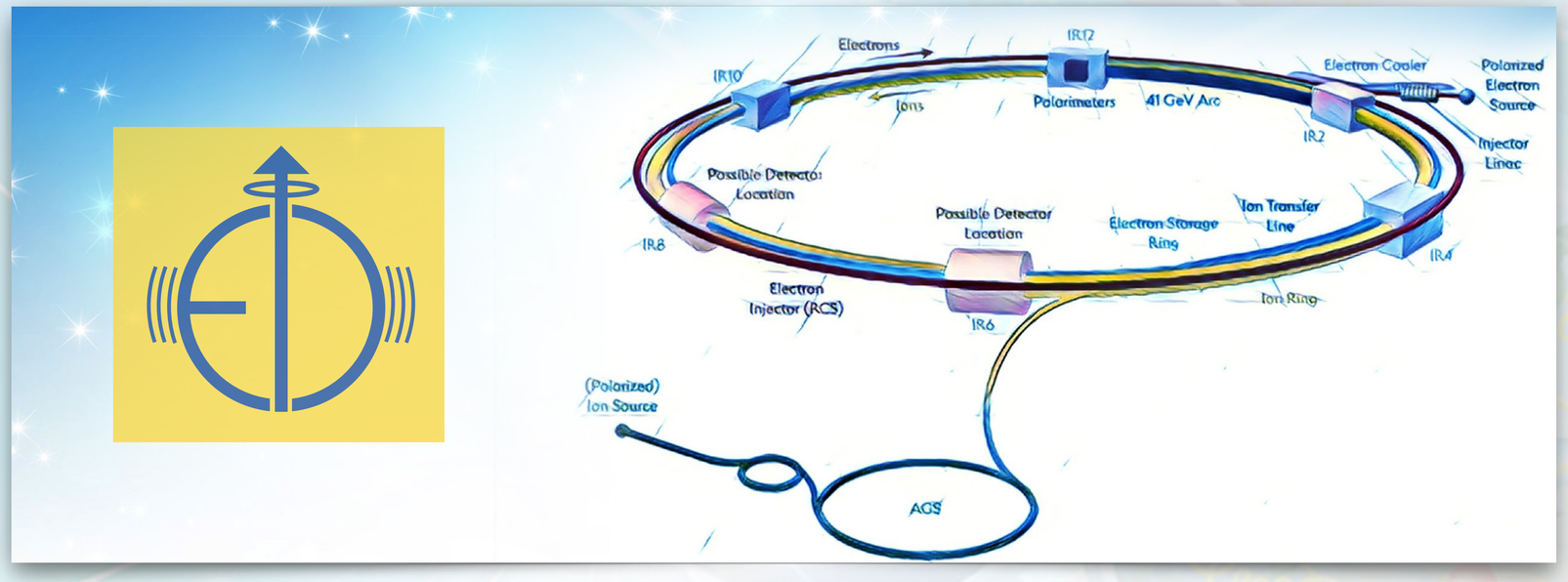
- ☑ **Simultaneous fit** of f_1 and g_1 PDFs via **replica method**
- ☐ Twist-2 T-odd gluon TMDs (**Sivers**, etc.) almost done!
- ☐ Inclusion of standard CSS evolution almost done!
- ☐ Pheno: **spin asymmetries**, **pseudodata** and **impact studies**
- ☐ Extension to quark TMDs, GPDs and the small-x UGD
- ☐ Explorative studies on gauge-link sensitivity and factorization

Backup slides

3D proton tomography at new-generation colliders



Electron-Ion Collider

EIC Yellow Report 🔗 [EICUG [arXiv:2103.05419]]

Accessing the gluon content

Backup

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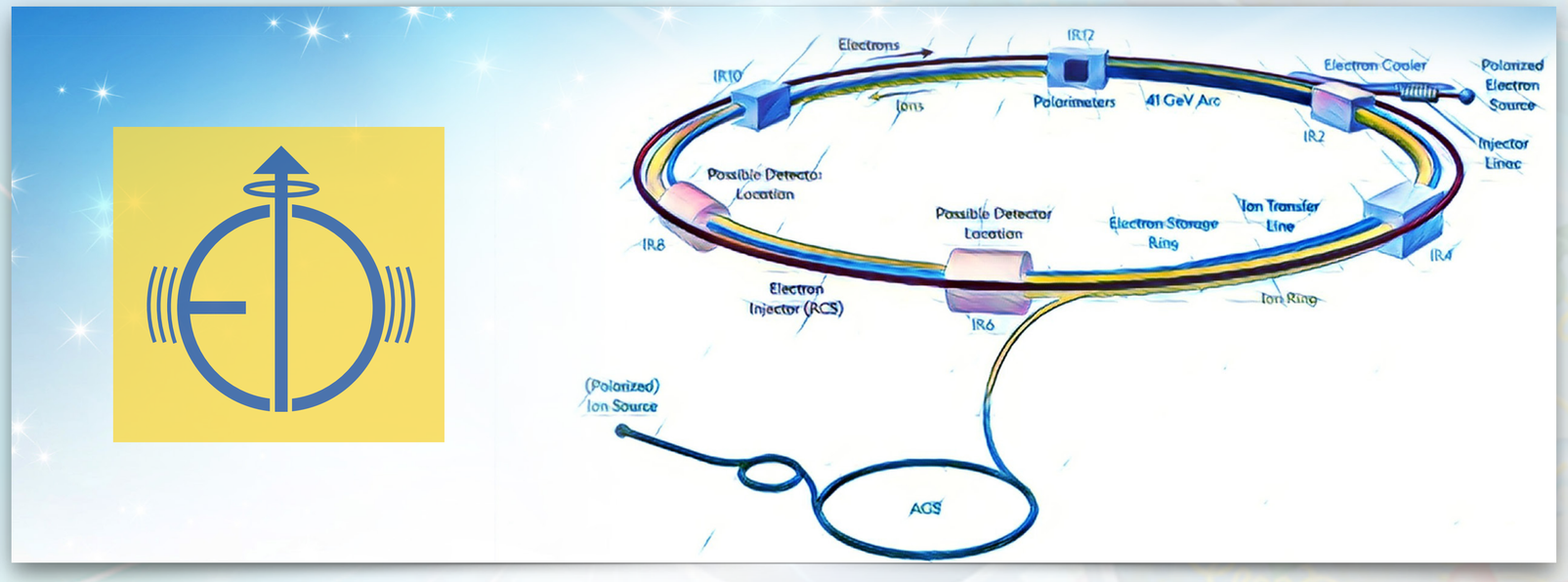

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Accessing the gluon content

Core sector of **EIC** studies

Backup

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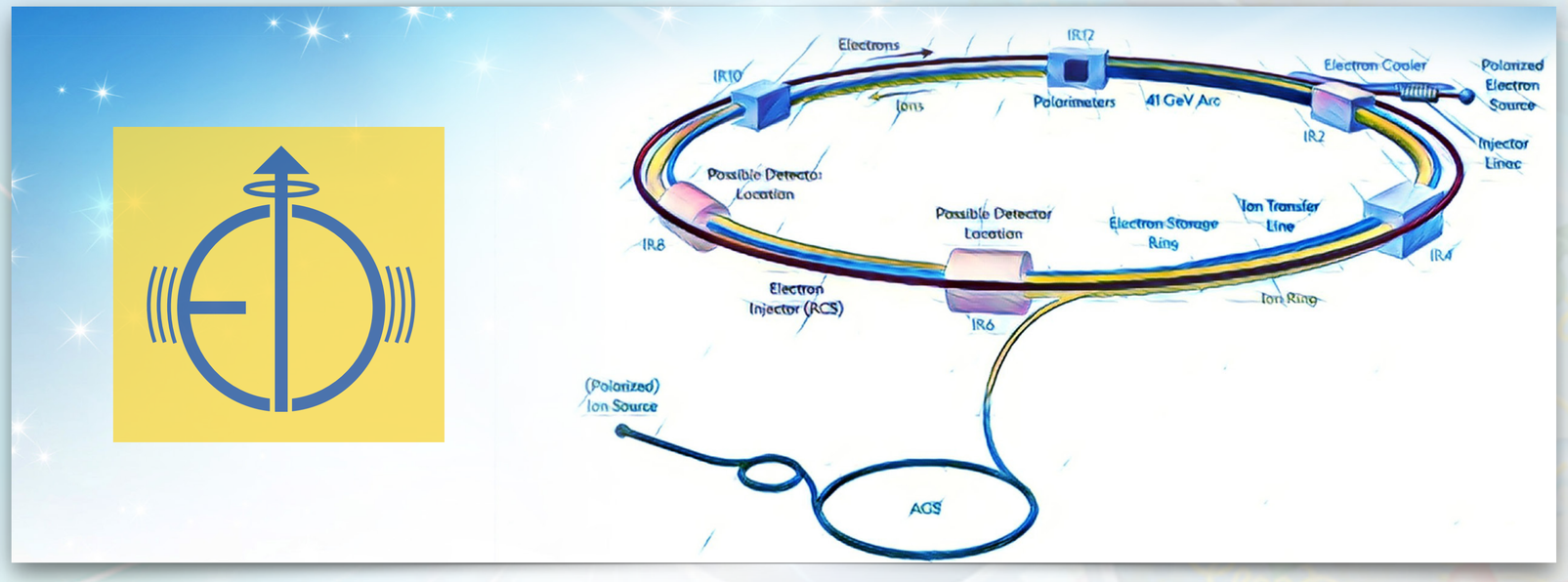


Electron-Ion Collider

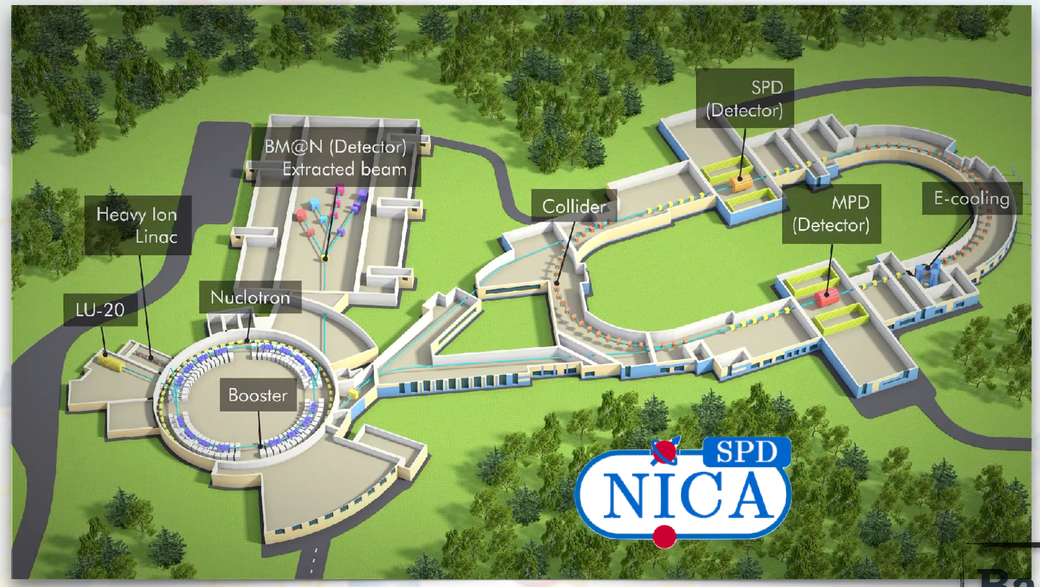
NICA-SPD

EIC Yellow Report 🔗 [EICUG [arXiv:2103.05419]]

Gluon content at **NICA-SPD** 🔗 [NICA [arXiv:2011.15005]]

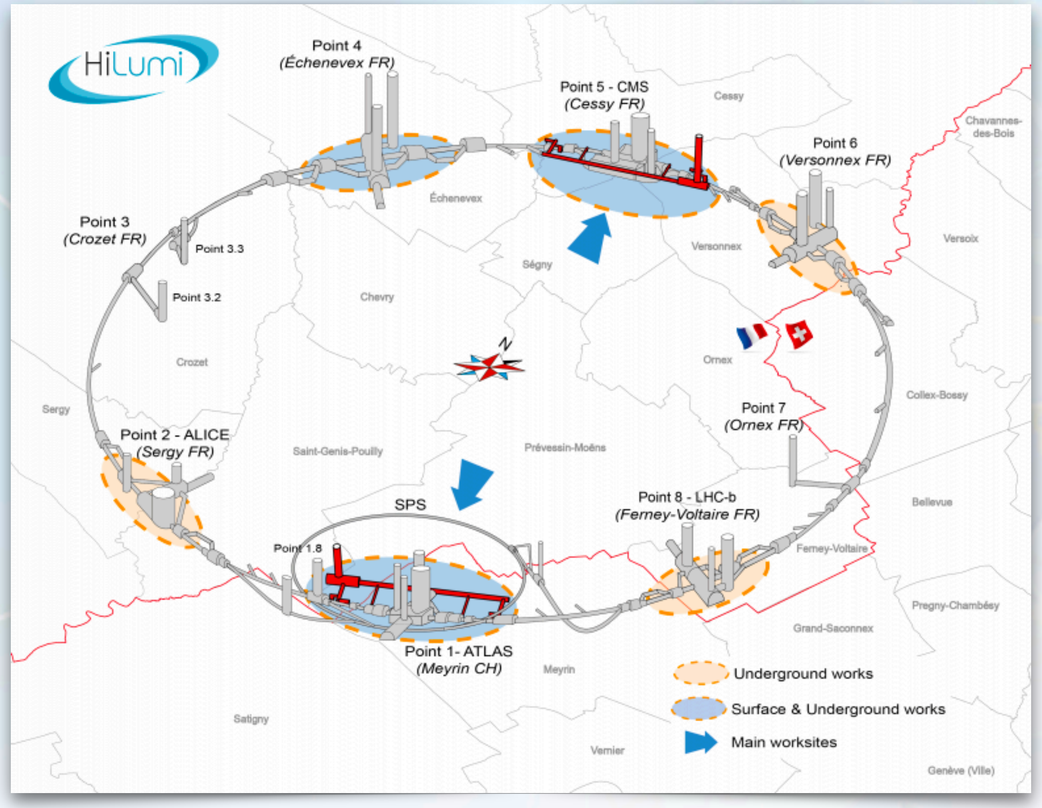
Accessing the gluon content

- *Core* sector of **EIC** studies
- *Significance* of large-x studies at **NICA-SPD**



Backup

3D proton tomography at new-generation colliders



HL-LHC

Quarkonium studies at **HL-LHC** 🔗 [QAT [arXiv:2012.14161]]

Gluon TMDs at high energies

Backup

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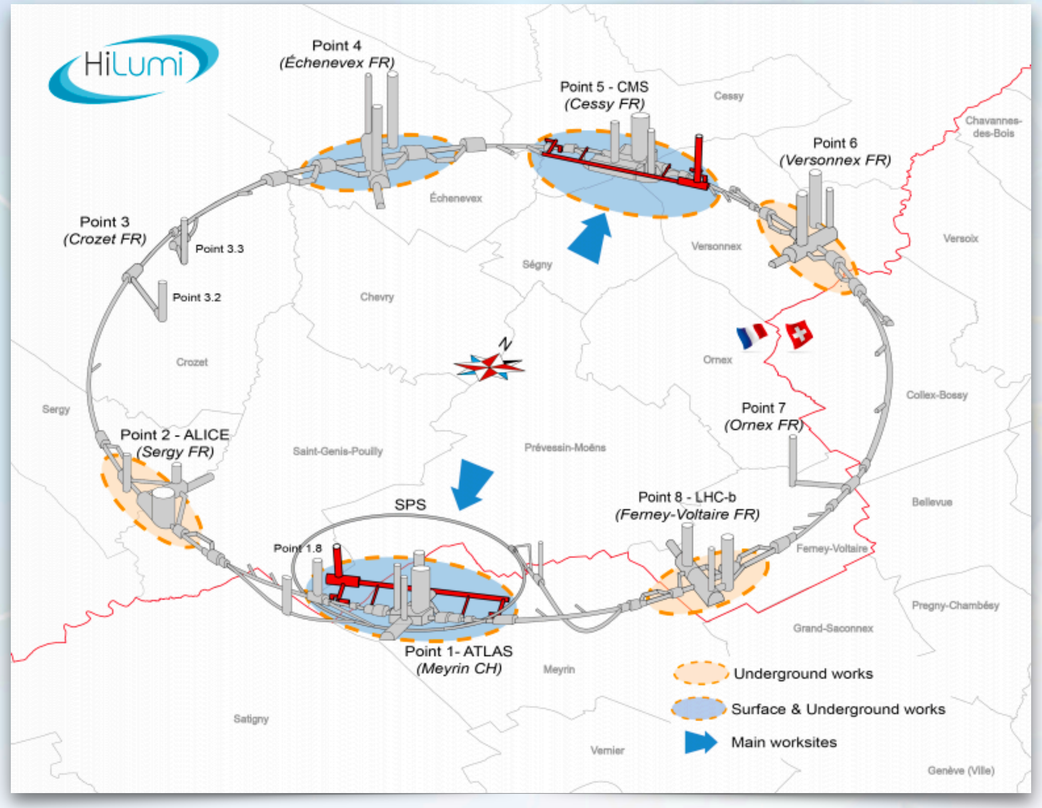

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Intrinsic effect of gluon polarization in **unpolarized** *pp* collisions

Backup

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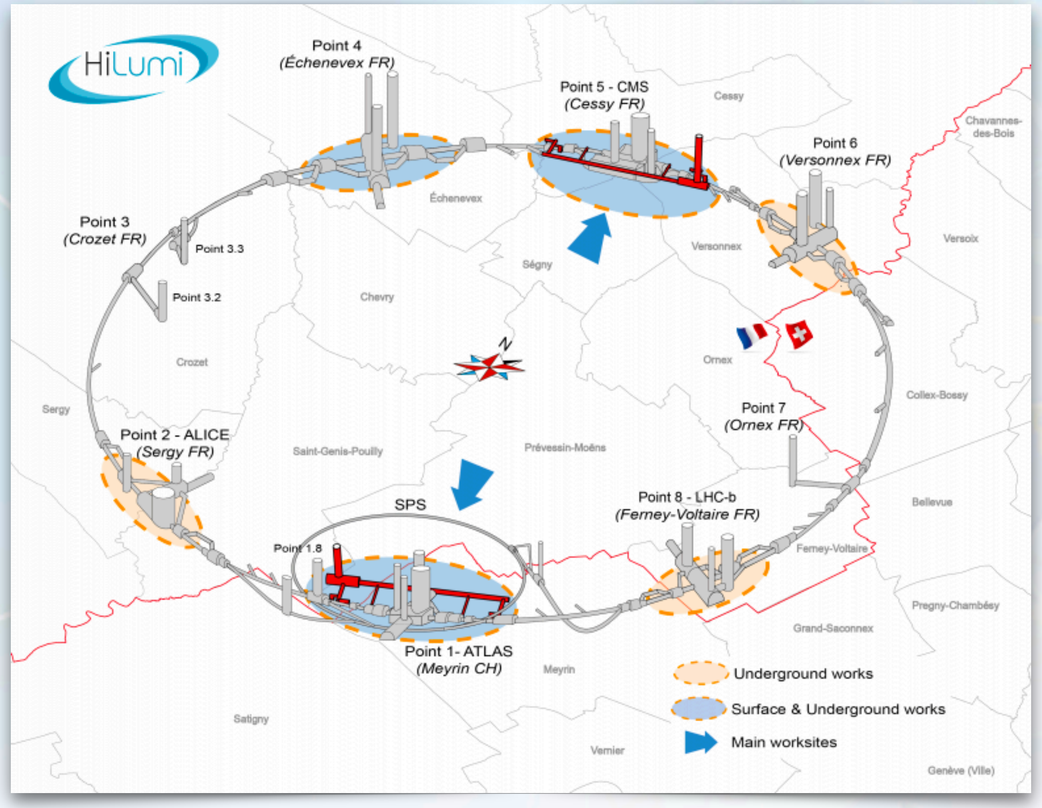

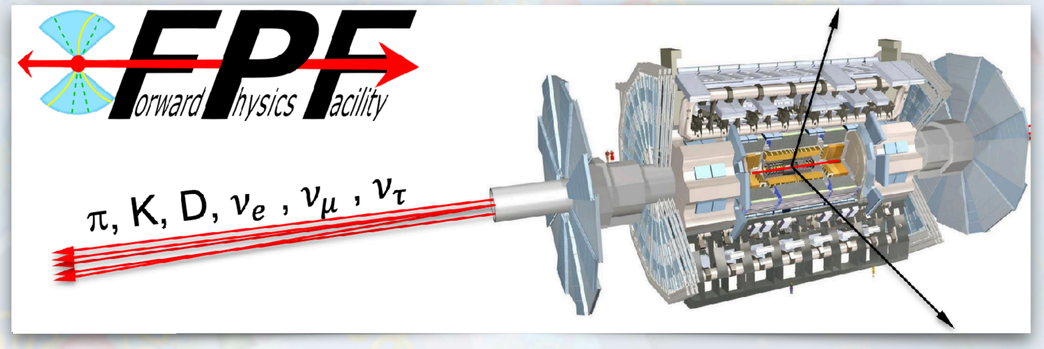

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Forward Physics Facility

Quarkonium studies at **HL-LHC** 🔗 [QAT [arXiv:2012.14161]]

The Forward Physics Facility (**FPF**) 🔗 [FPF [arXiv:2109.10905]]

Gluon TMDs at high energies

- *Intrinsic* effect of gluon polarization in **unpolarized** *pp* collisions
- *Precision* studies of proton structure via **natural stability** of high-energy resummation

Backup

Assumptions of the model

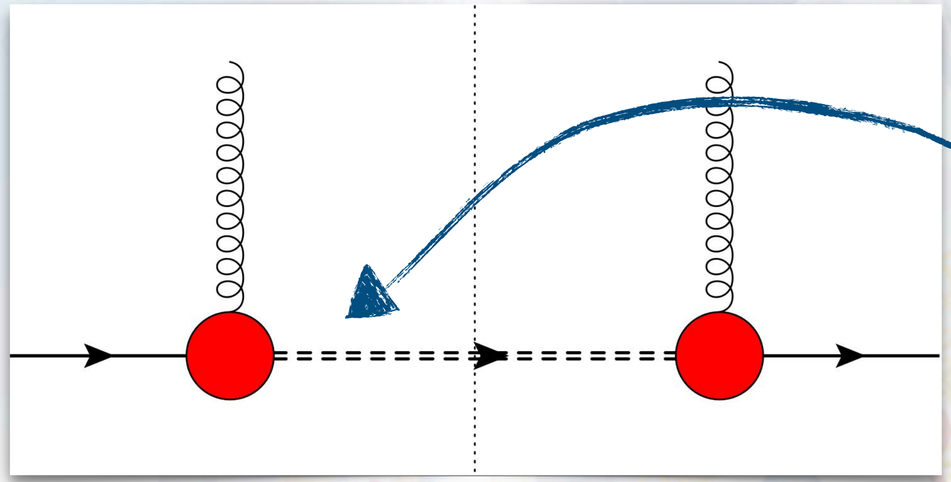
Spectator-system spectral-mass function

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

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

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

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

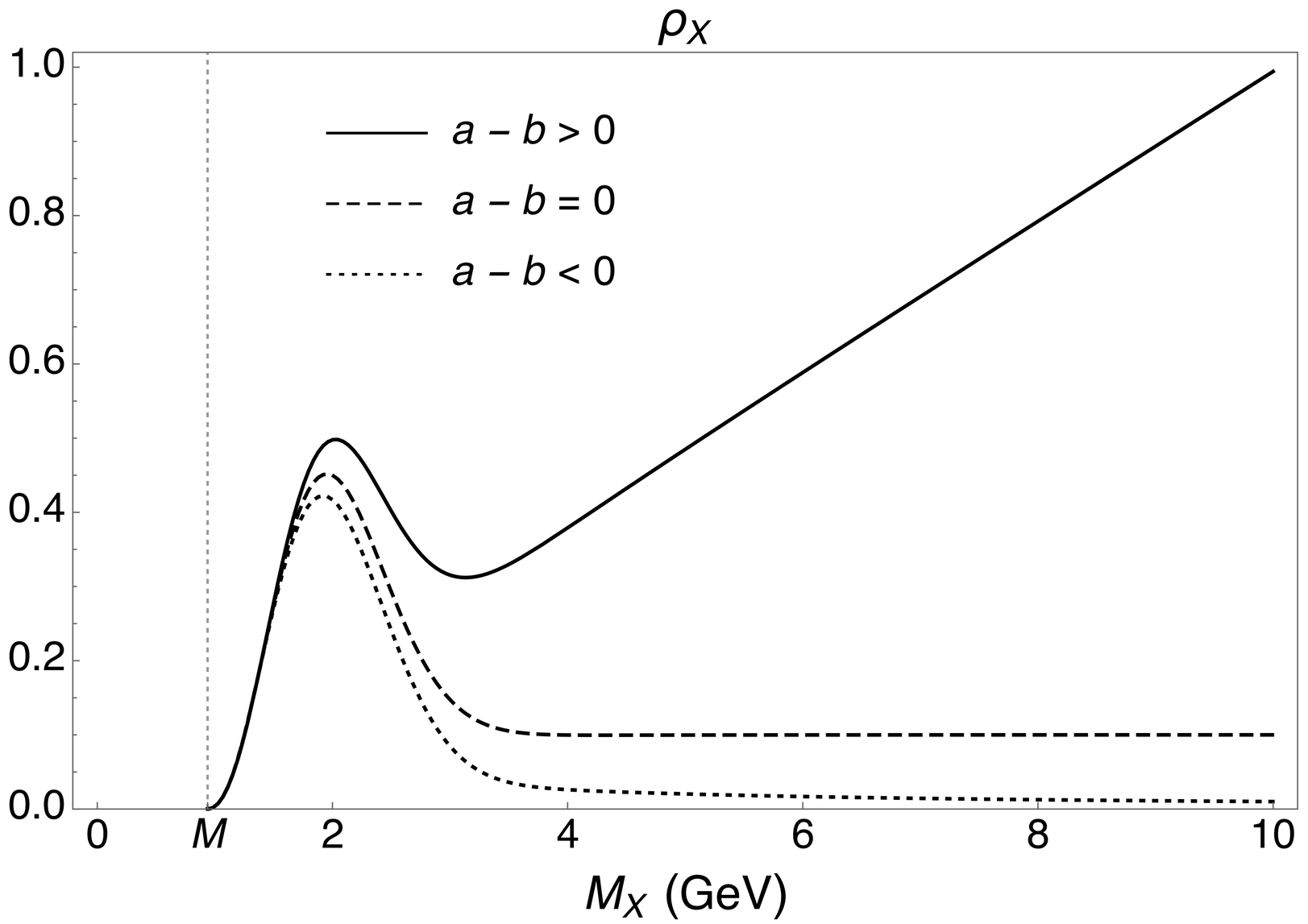
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

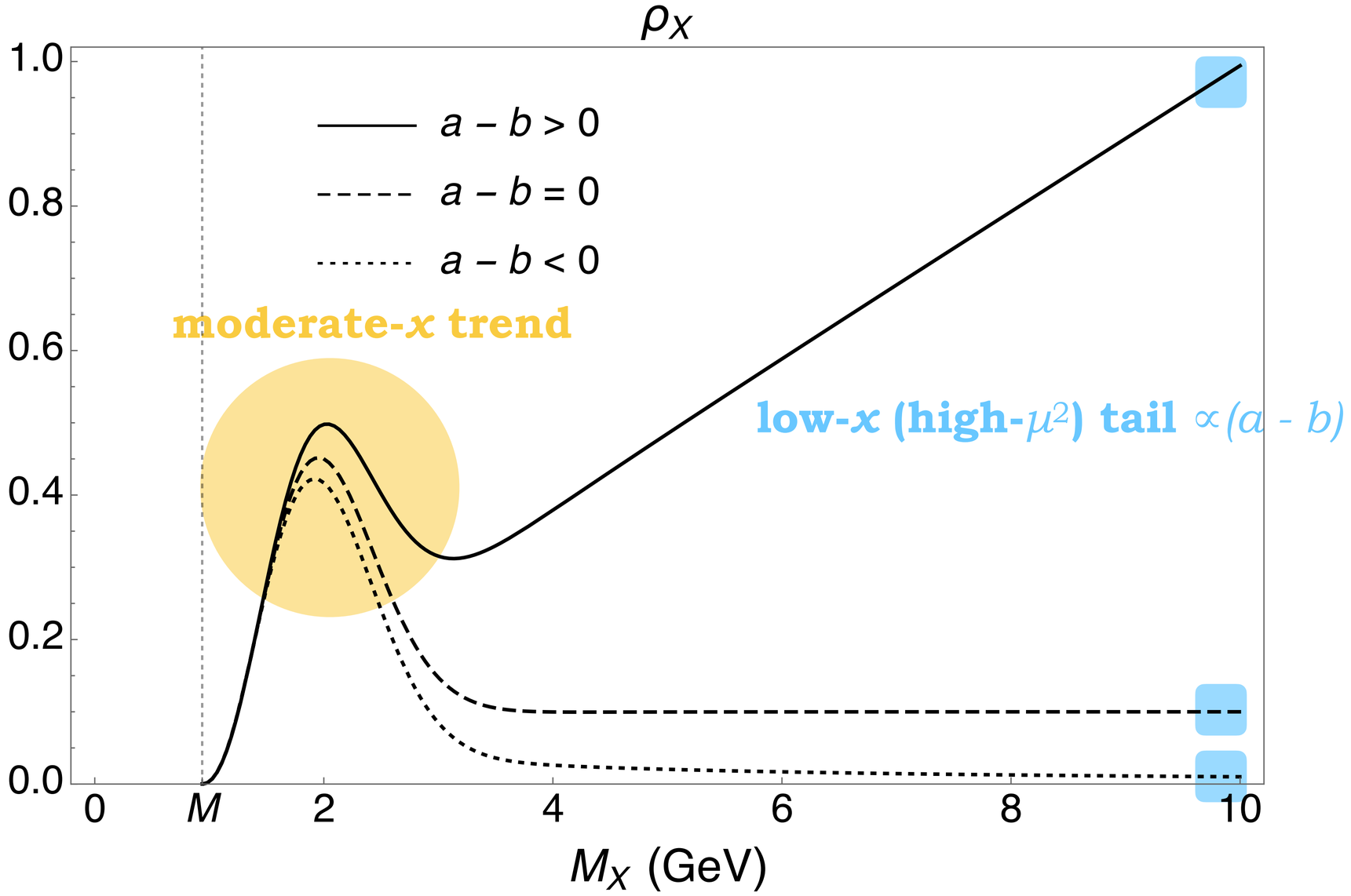
Backup

Spectral function vs *(a - b)*



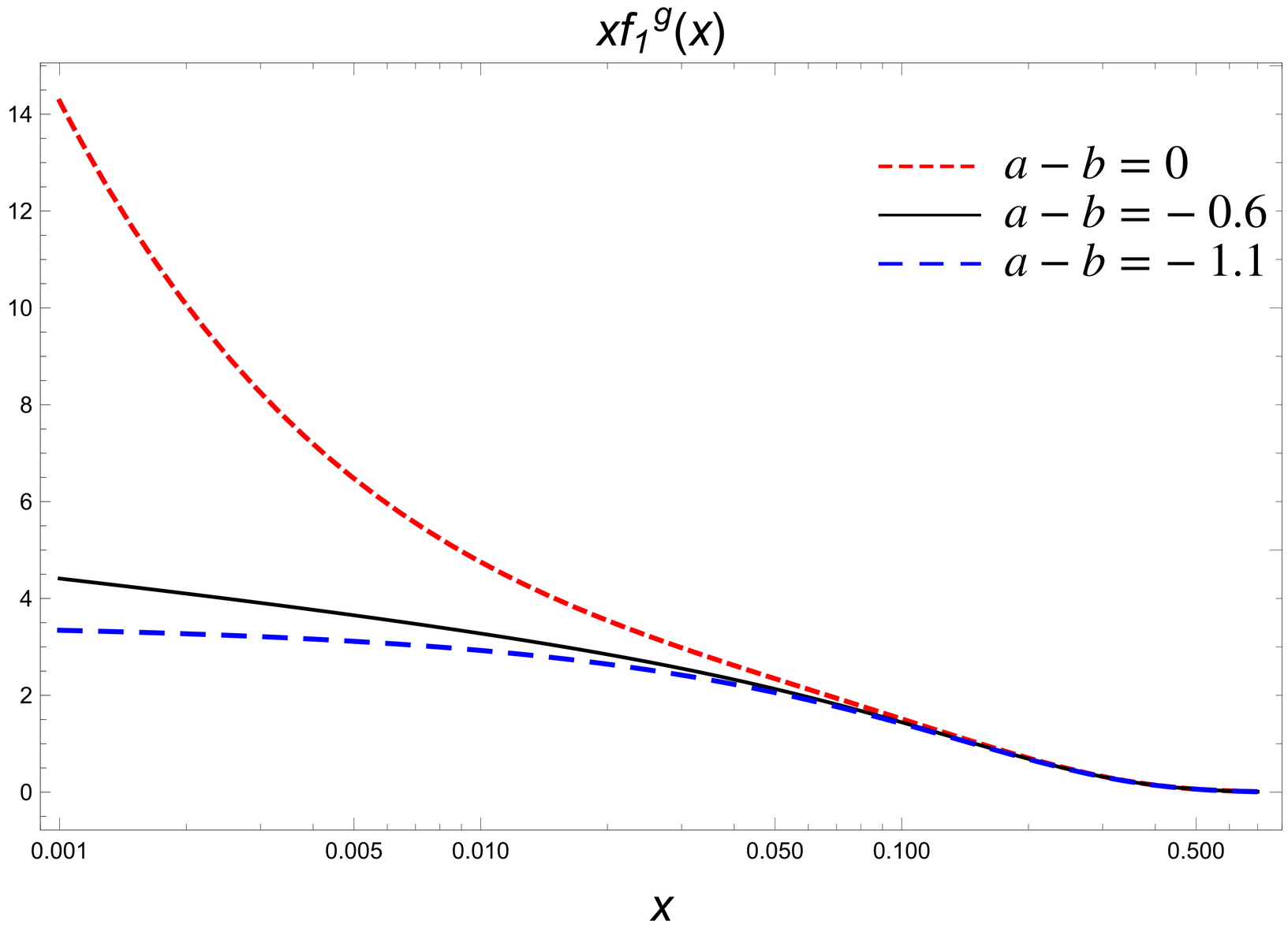
Backup

Spectral function vs $(a - b)$



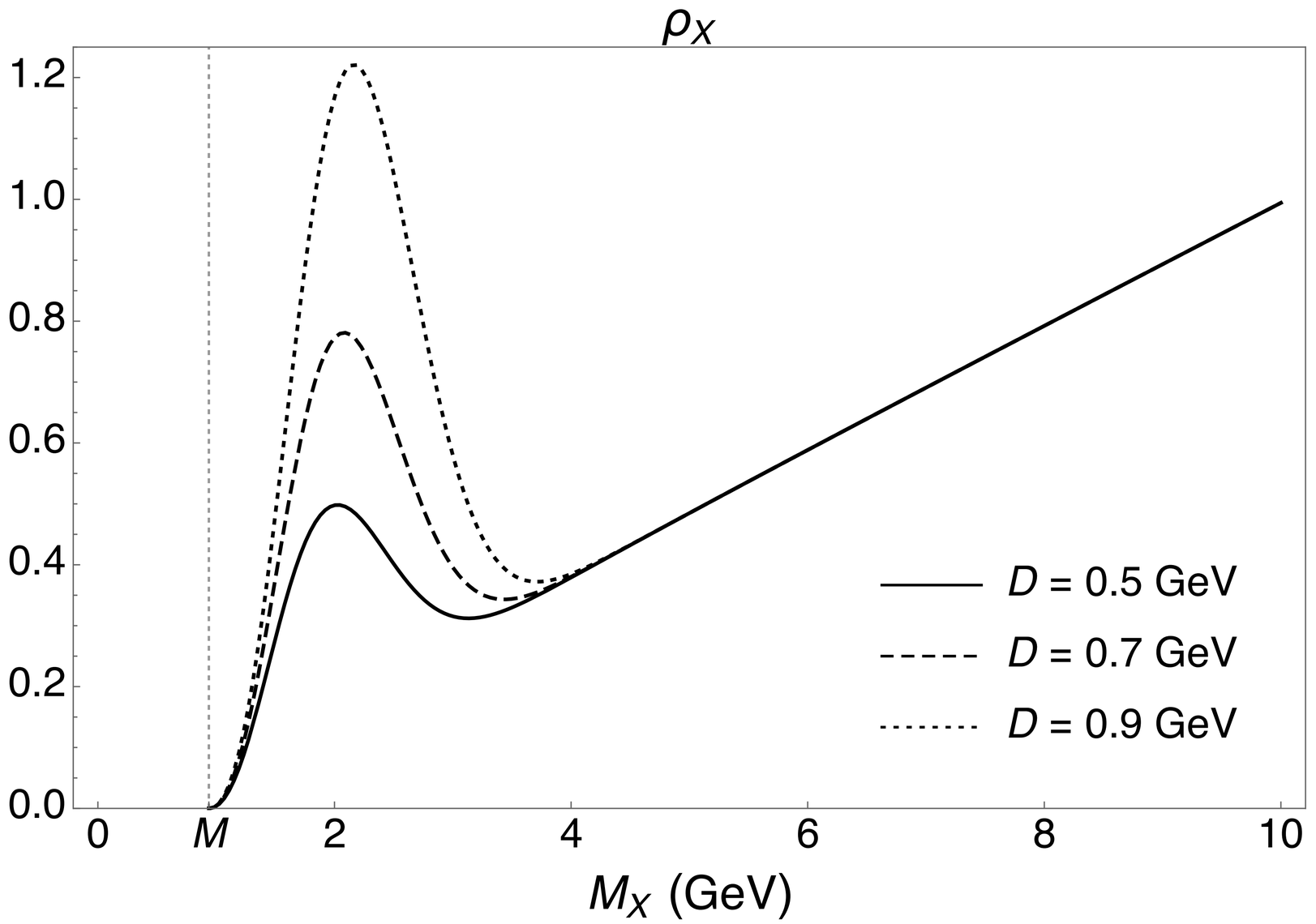
Backup

xf_1 collinear PDF vs $(a - b)$



Backup

Spectral function vs D



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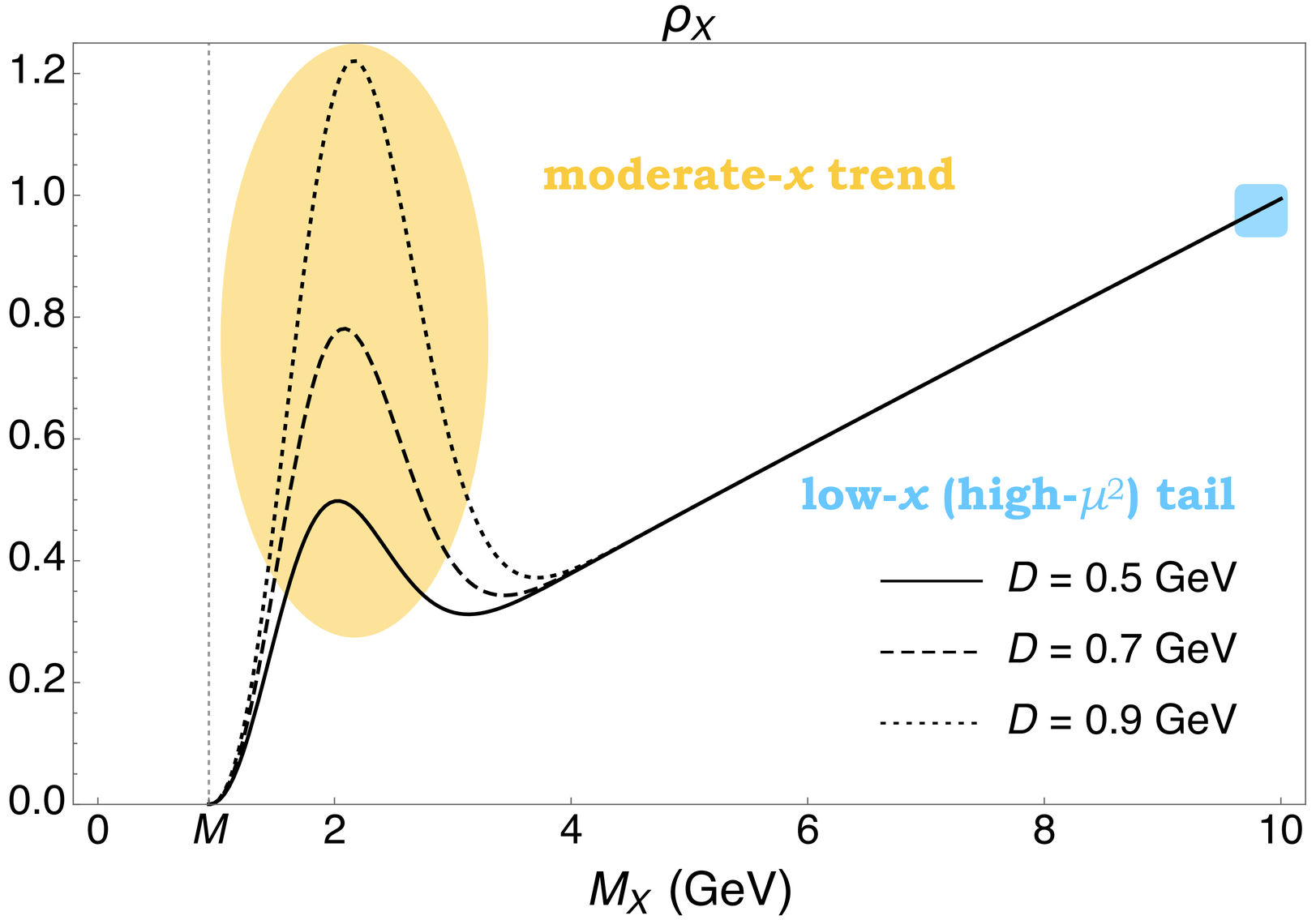
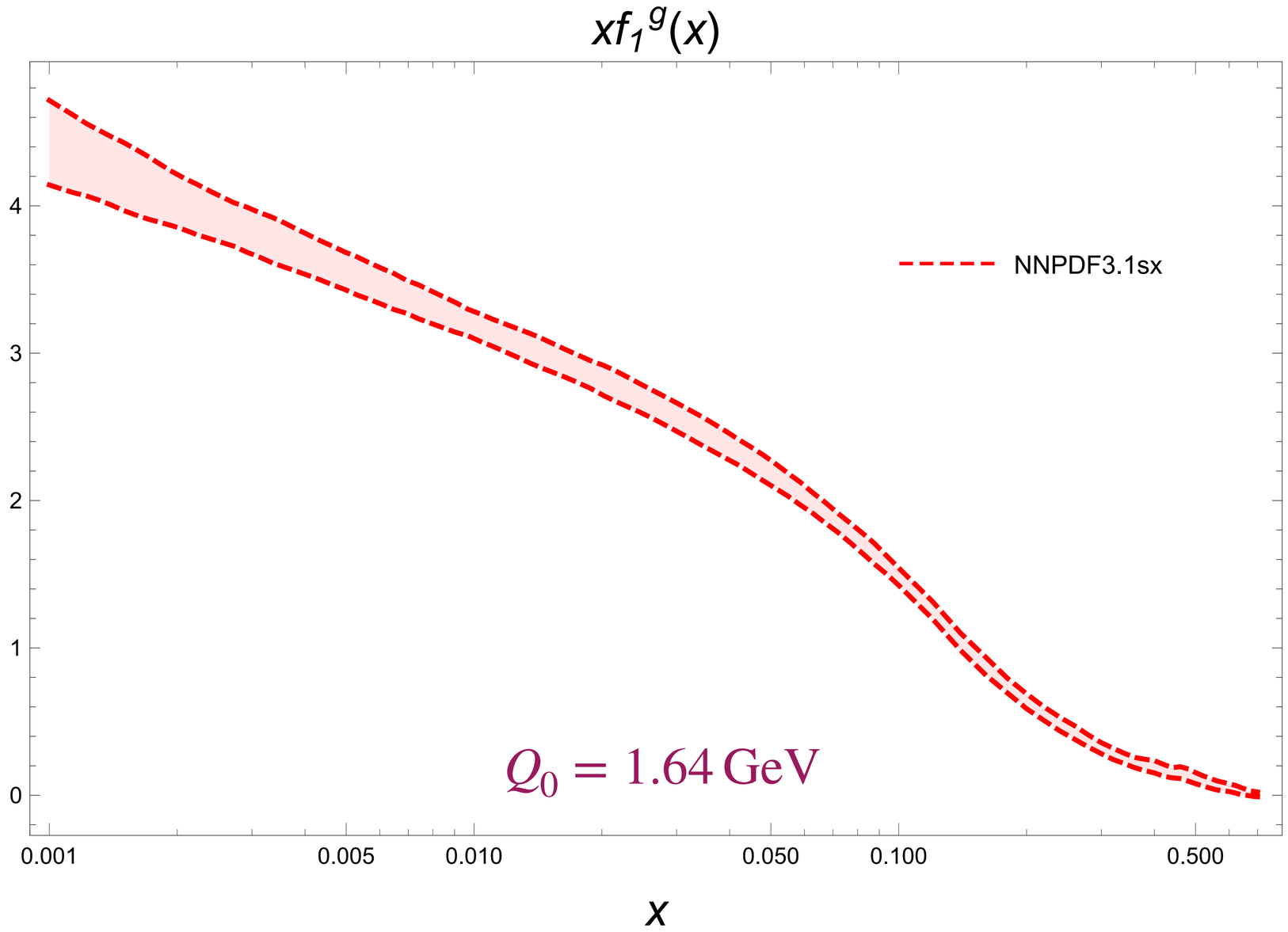


Backup

Unpolarized gluon PDF



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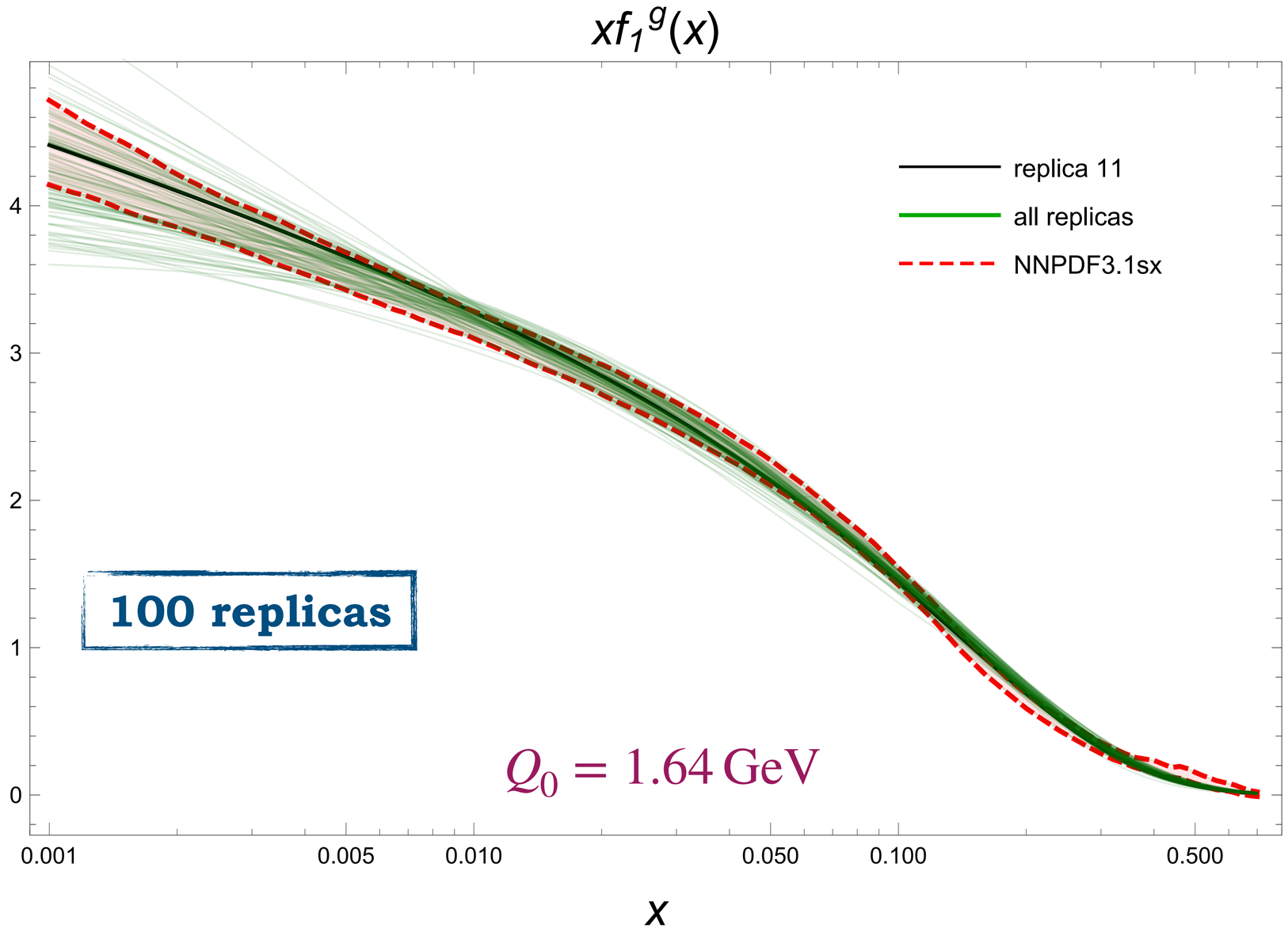

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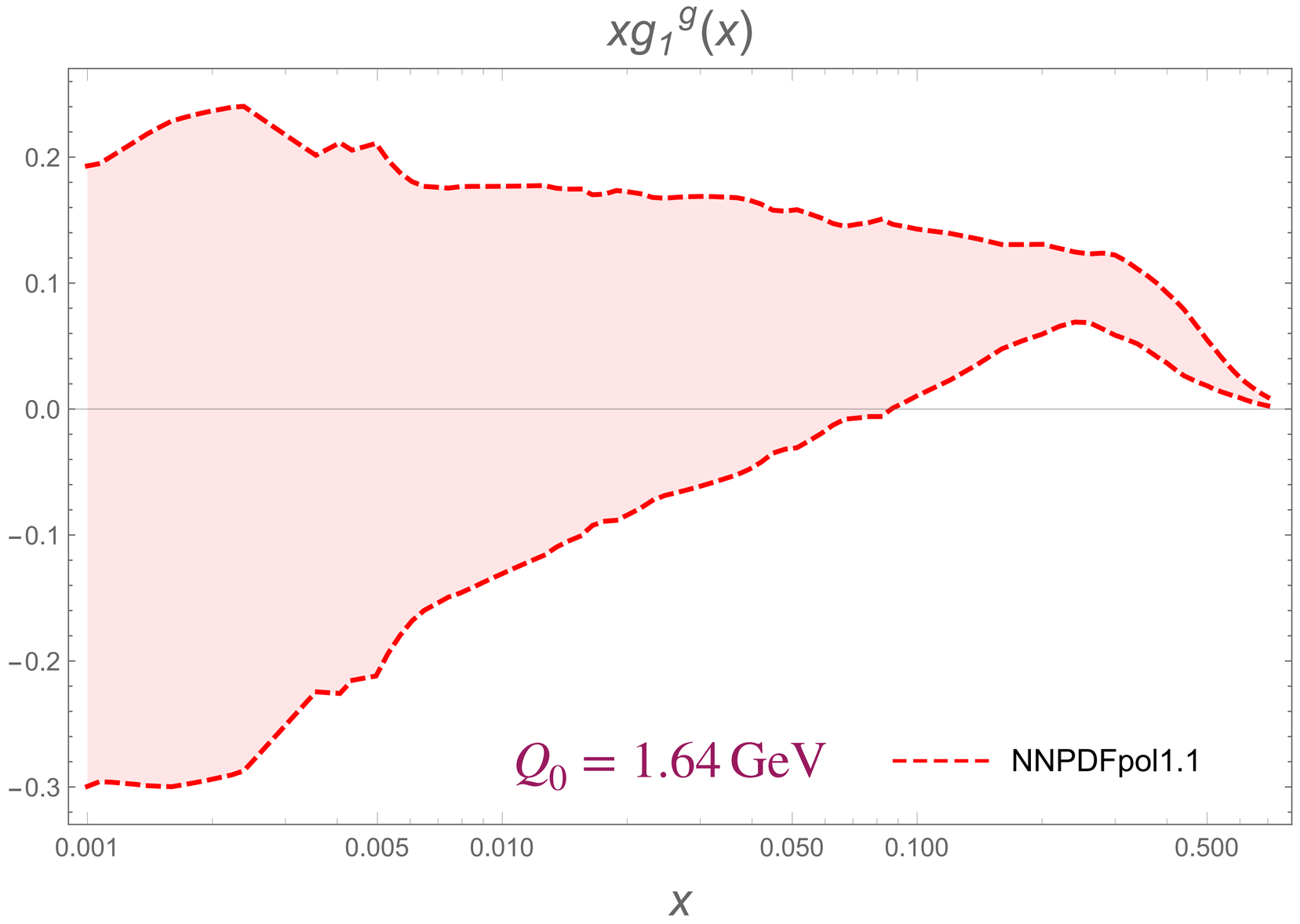
Helicity gluon PDF



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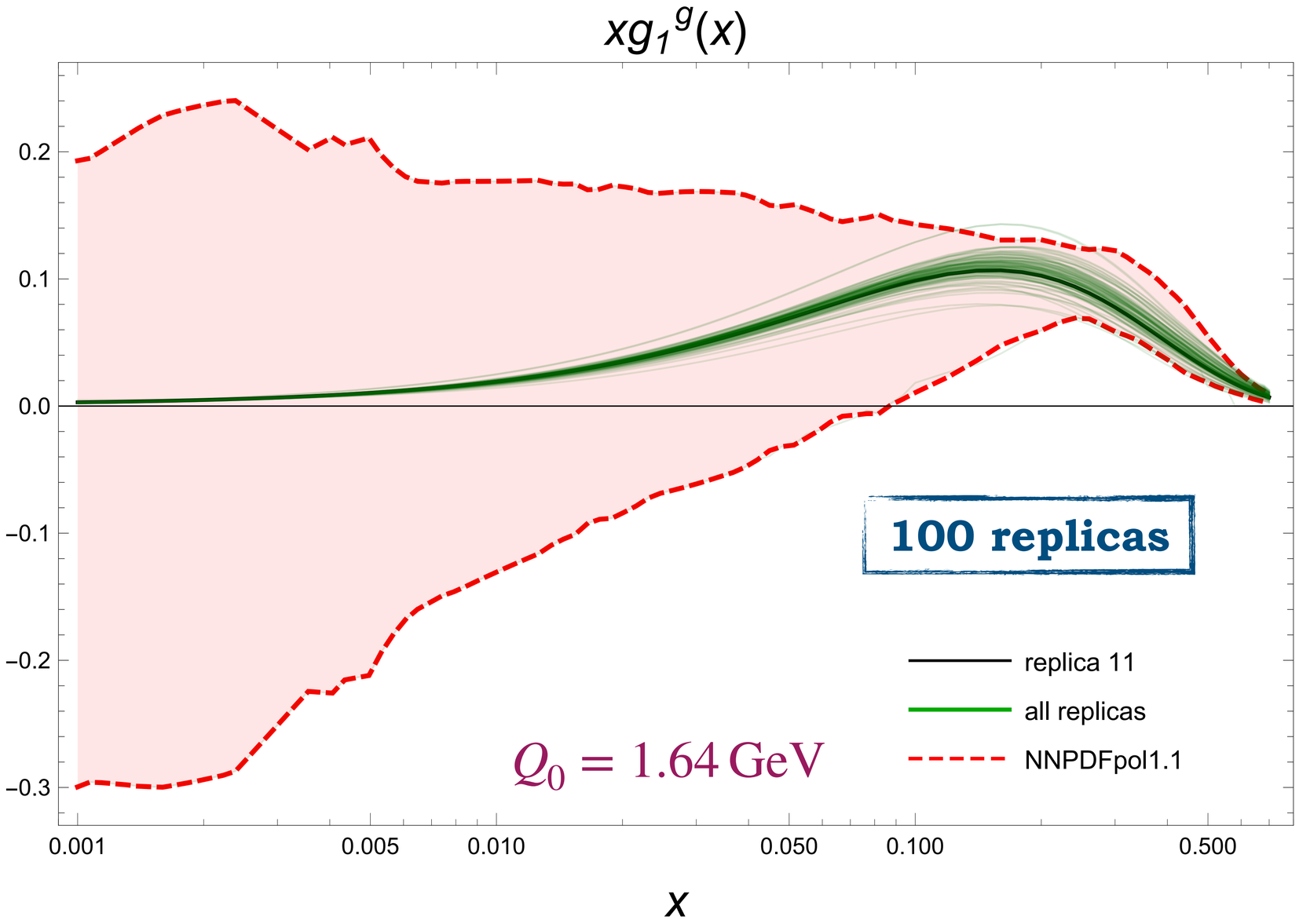

Backup

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

Backup

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

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

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

Our model @ $Q_0 = 1.64$ GeV

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

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

Lattice @ $Q_0 = 2$ GeV

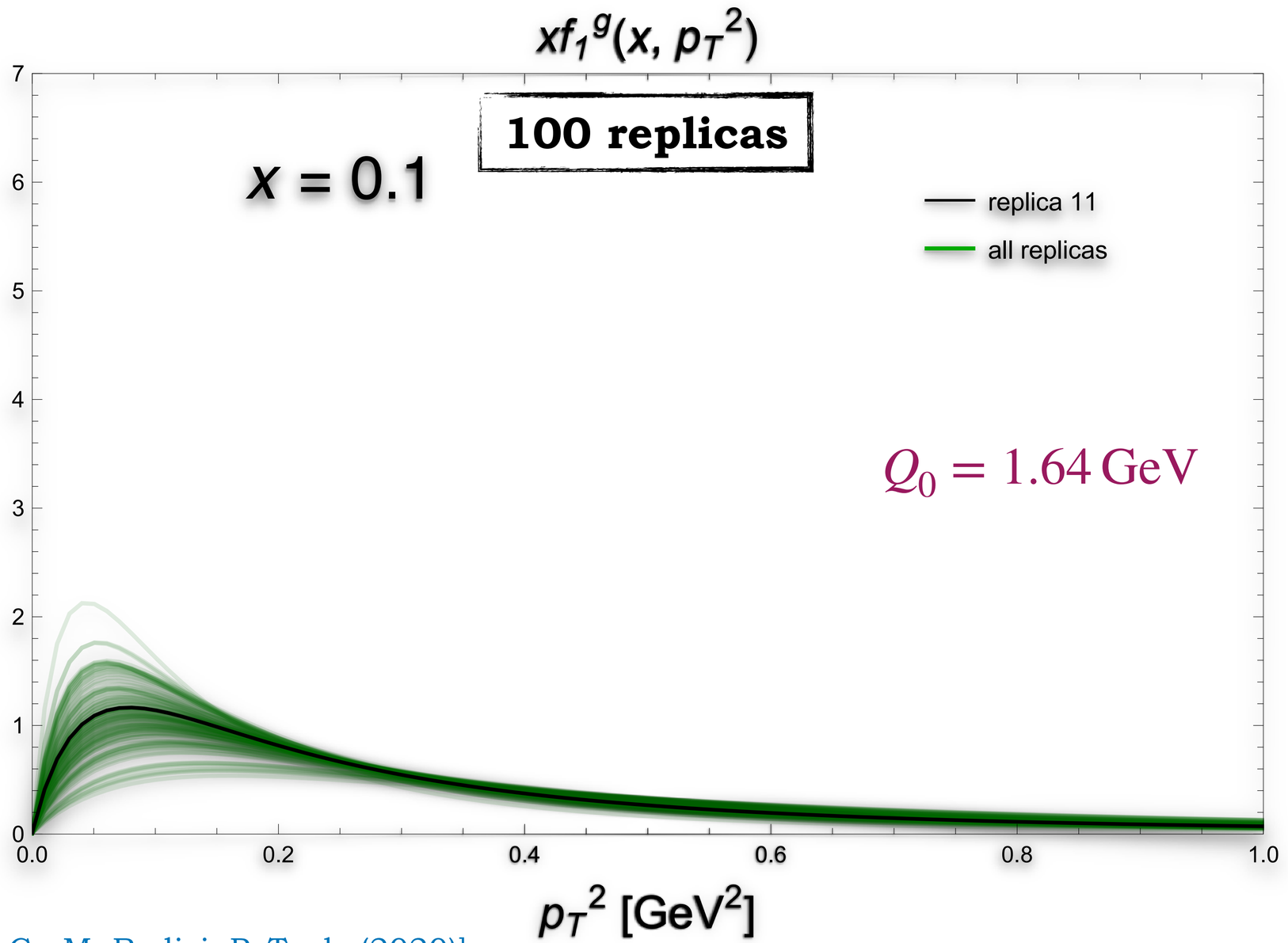
$$\langle x \rangle_g = 0.427(92)$$

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

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

Backup

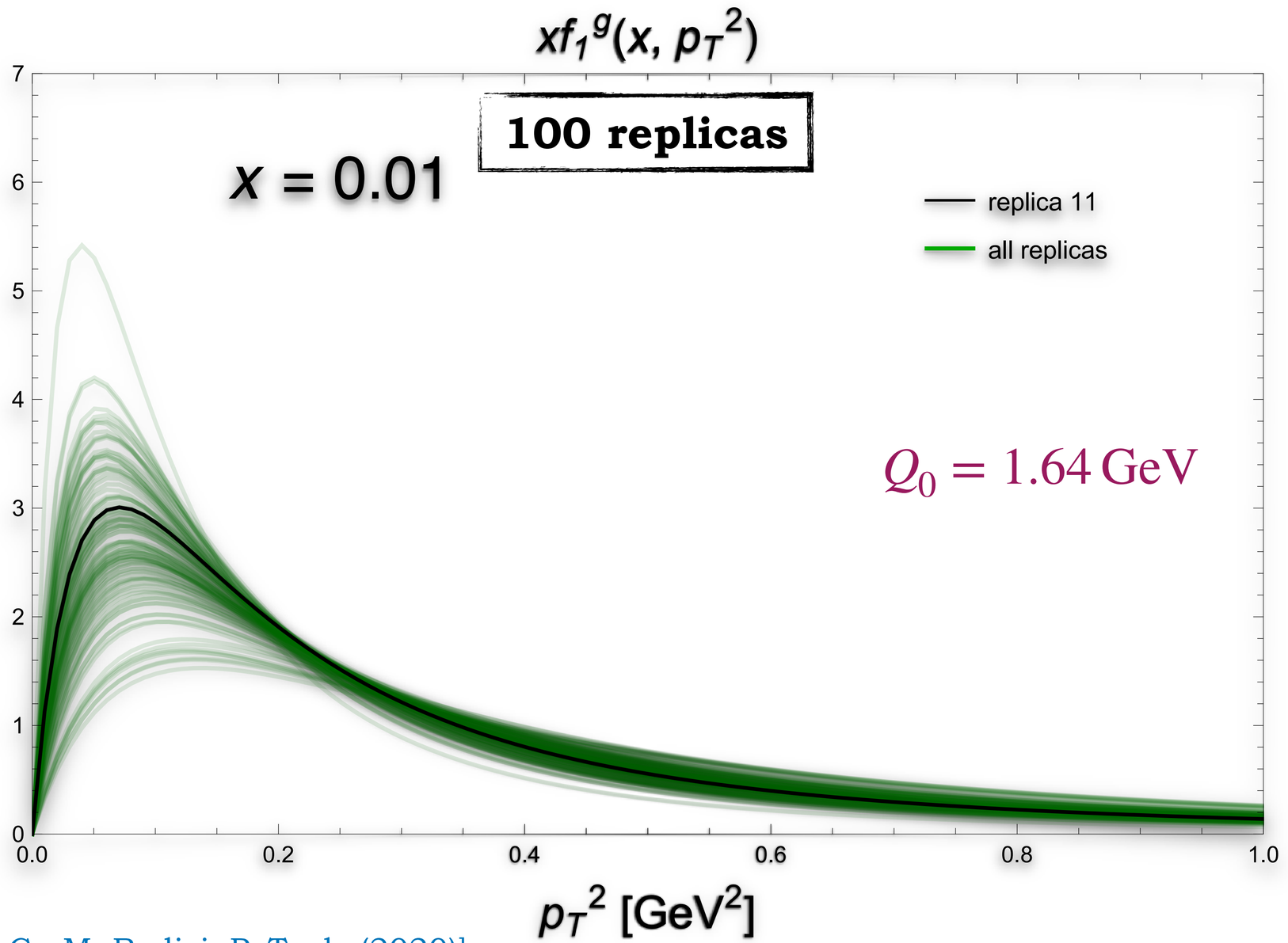
Unpolarized gluon TMD



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

Backup

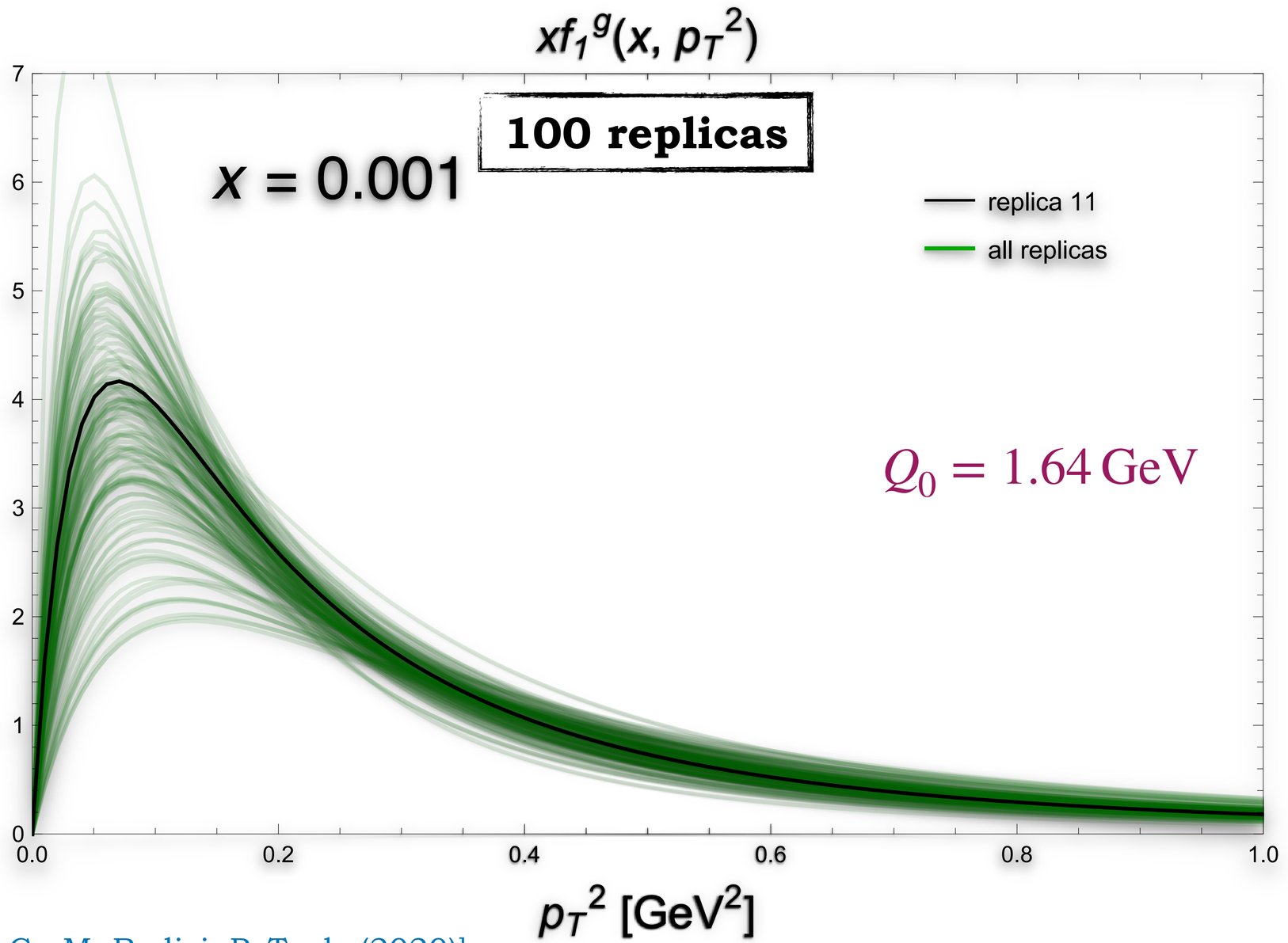
Unpolarized gluon TMD



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

Backup

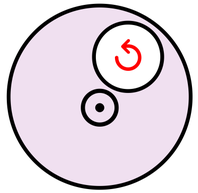
Unpolarized gluon TMD

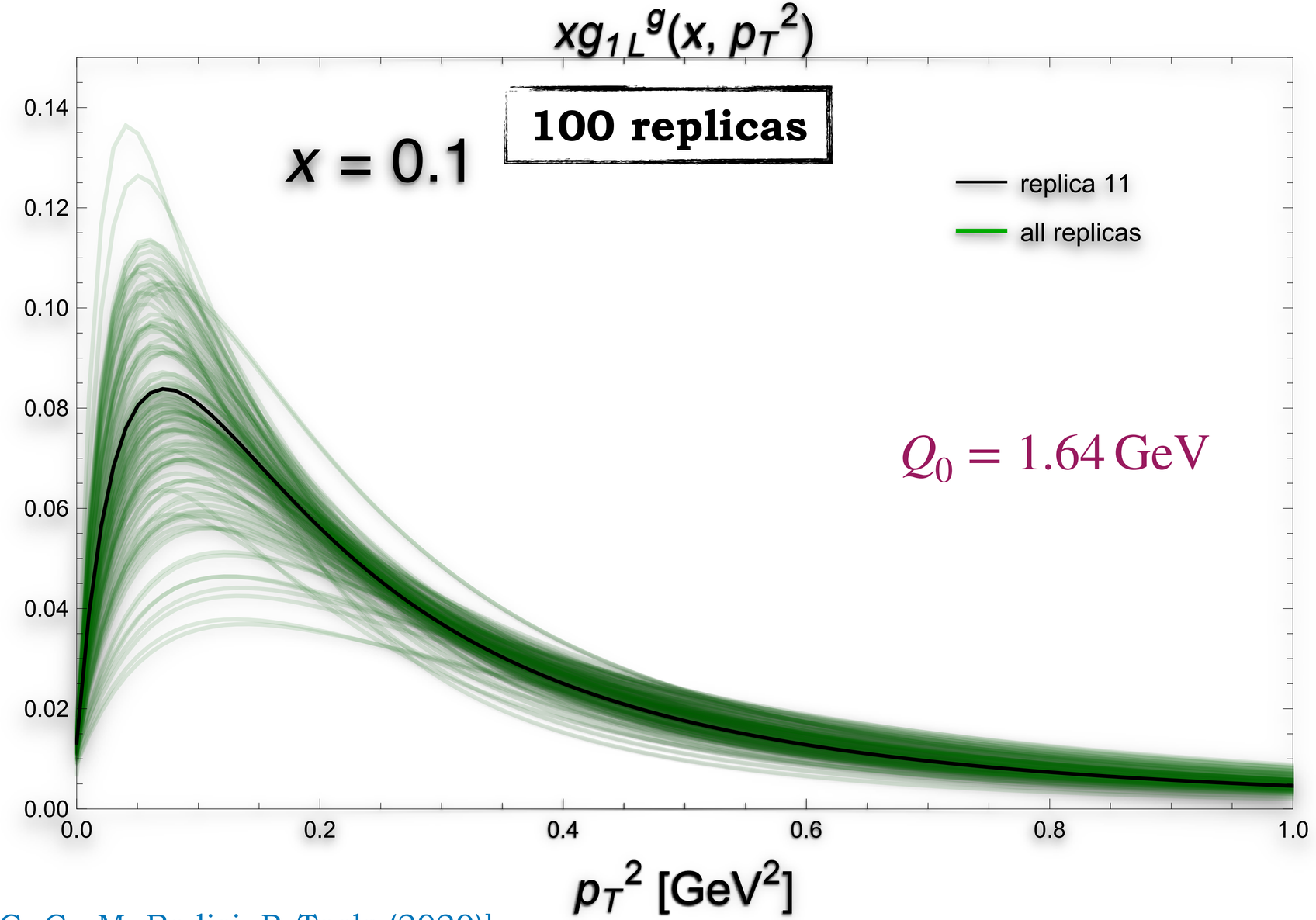


[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Helicity gluon TMD

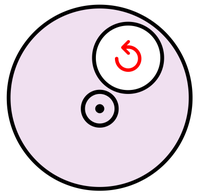


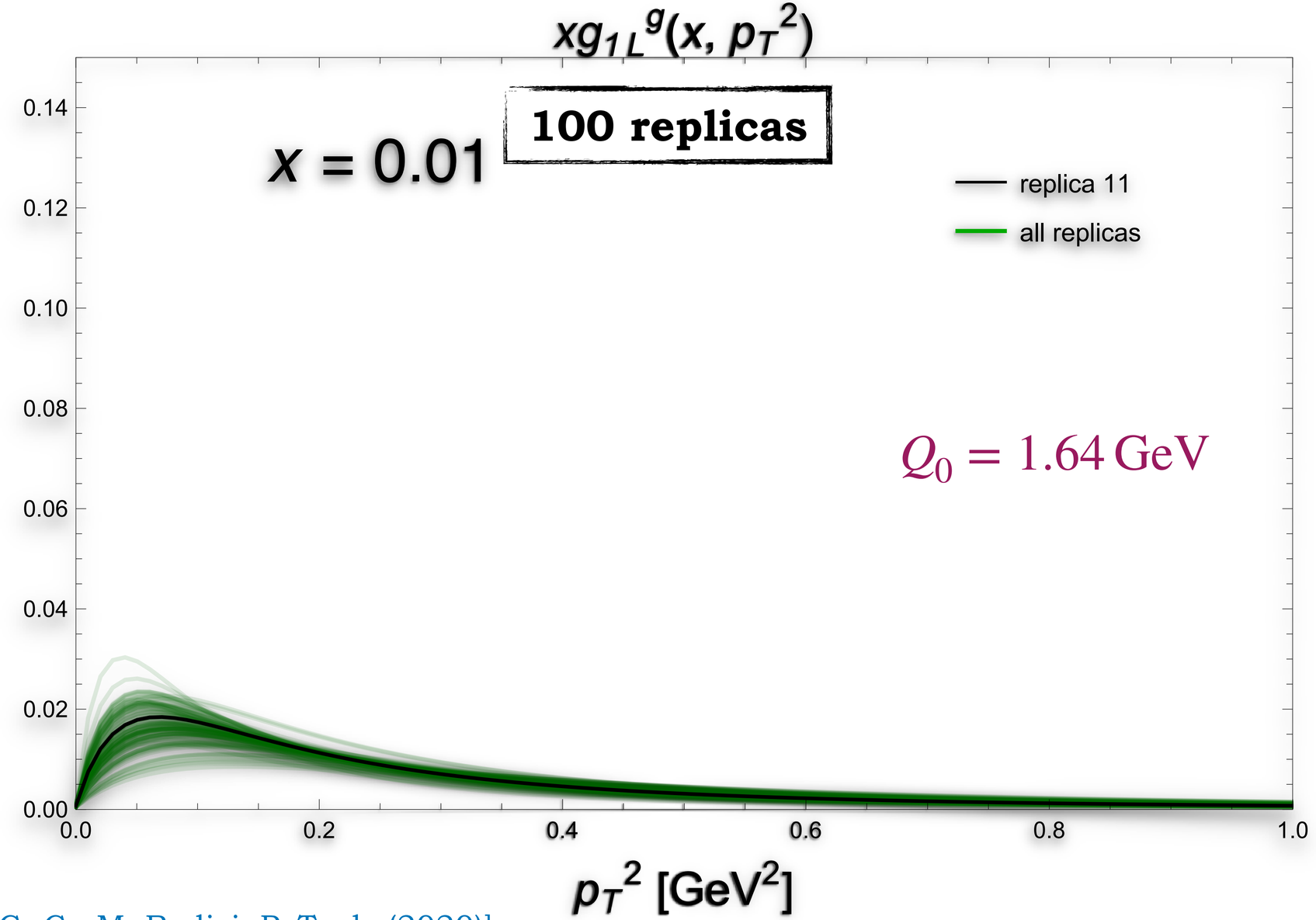


[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Helicity gluon TMD

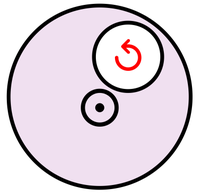


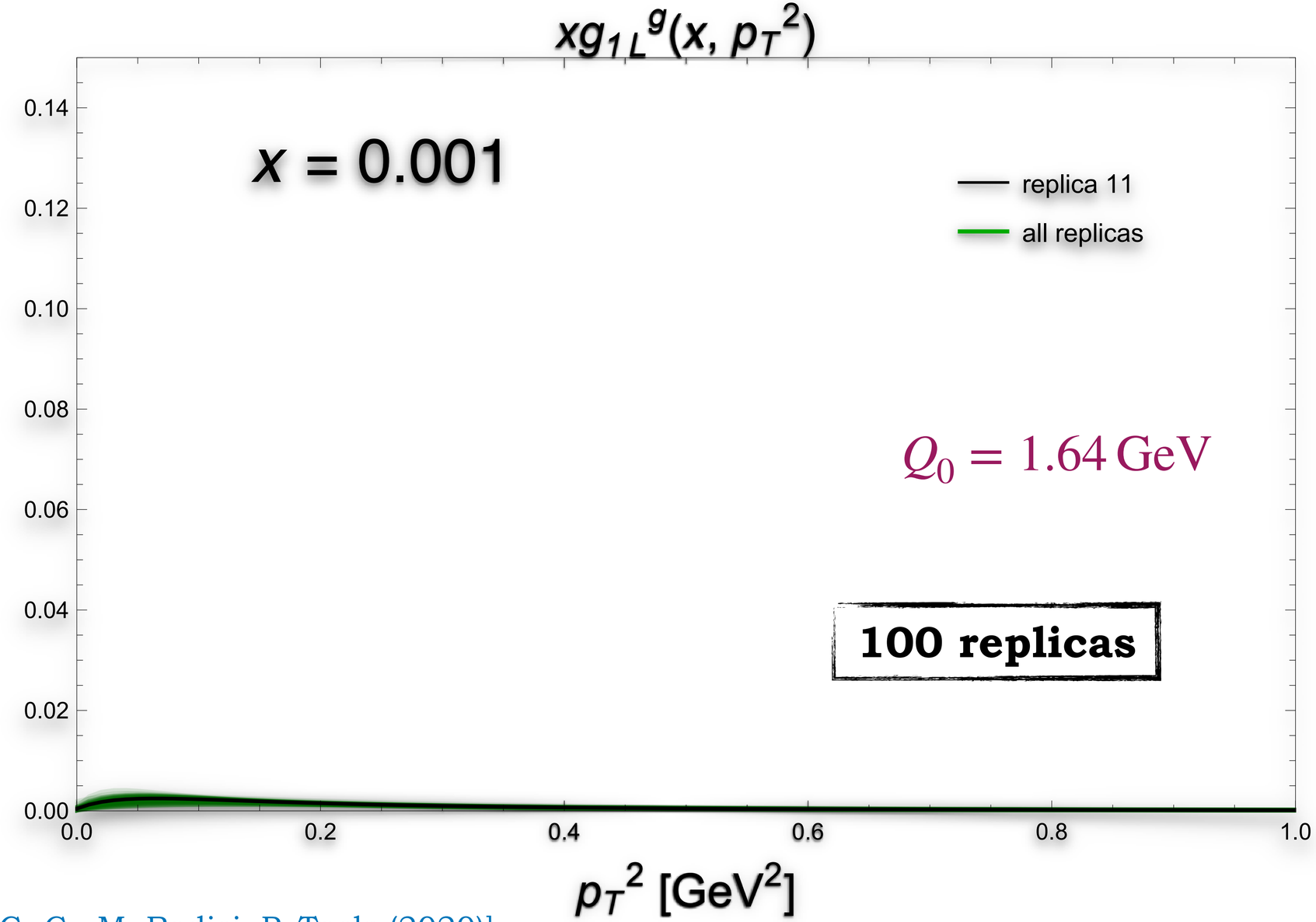


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Helicity gluon TMD

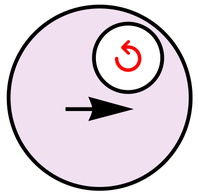


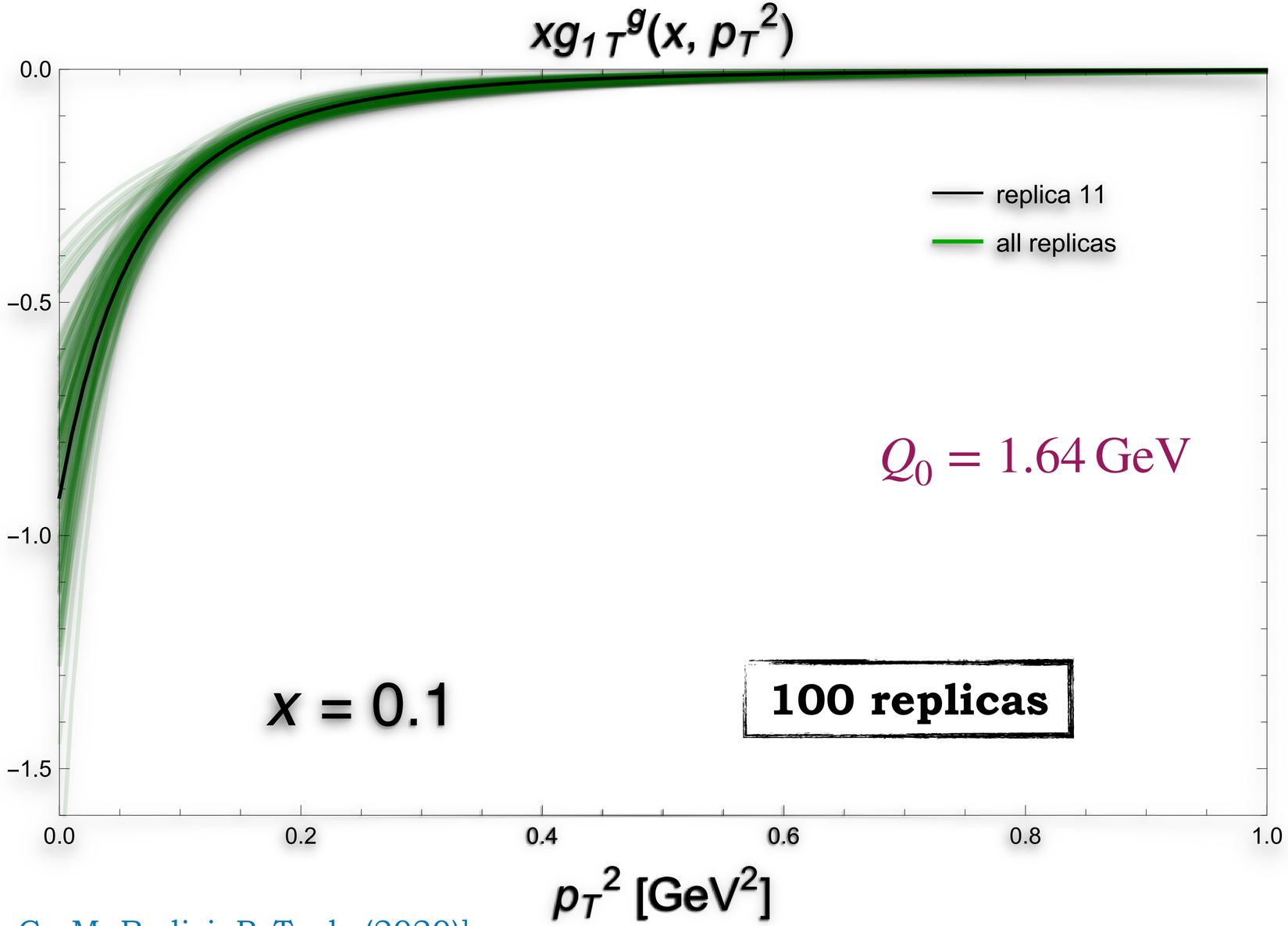


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Worm-gear gluon TMD

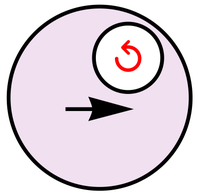


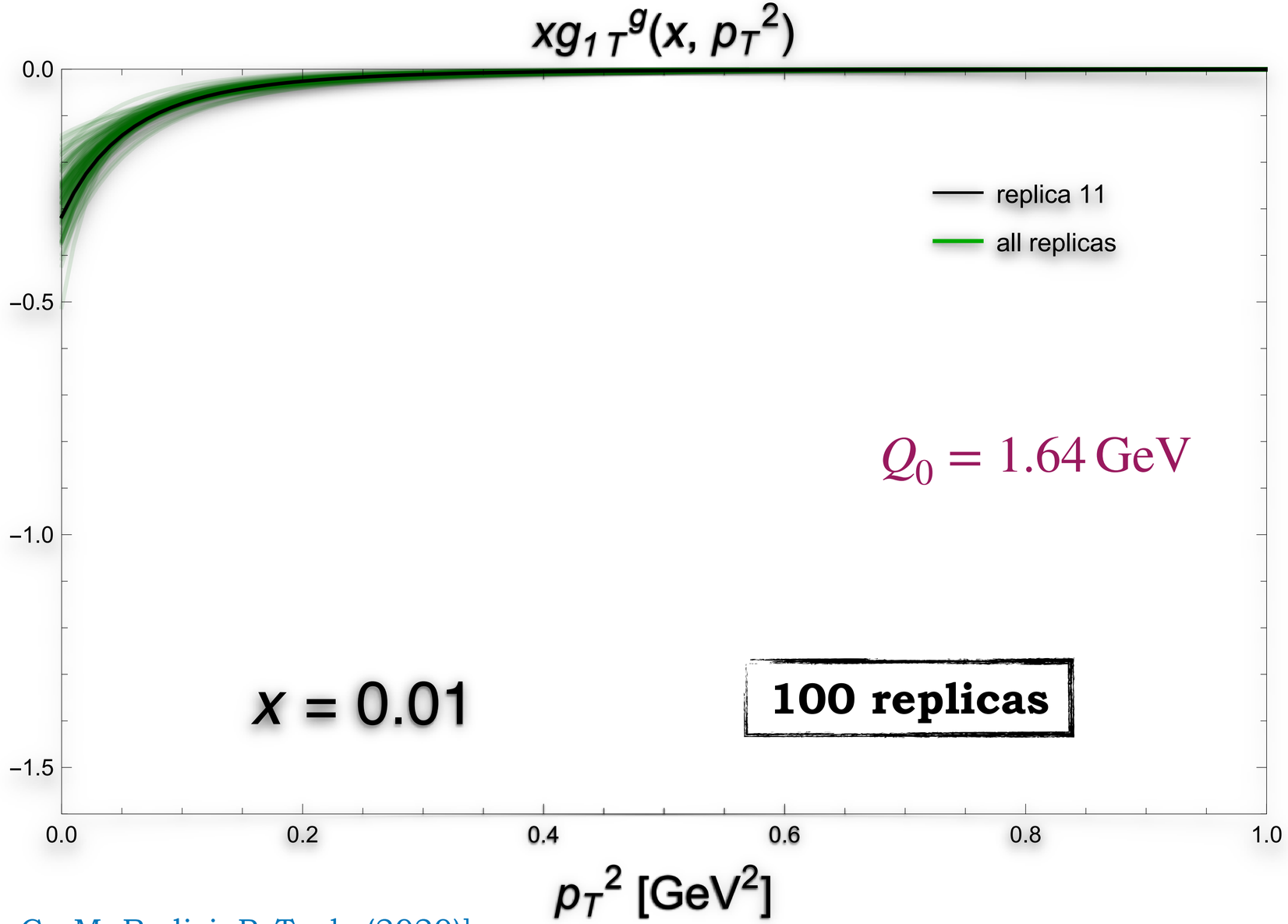


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Worm-gear gluon TMD

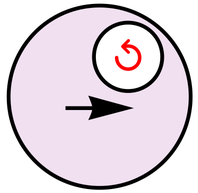


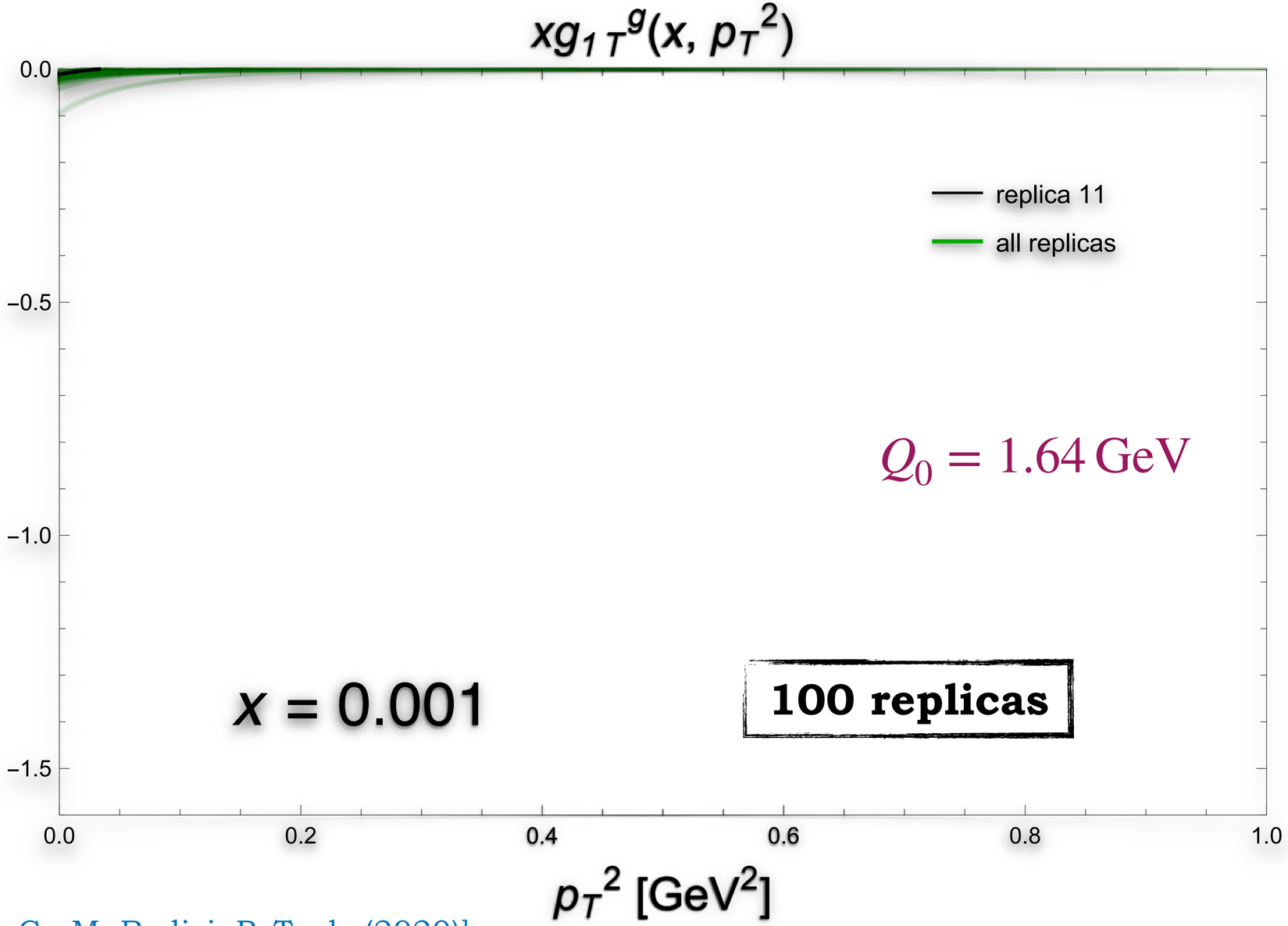


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Worm-gear gluon TMD





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

Backup

Gluon TMD correlator and *T*-odd gluon densities

$$\Gamma_U^{ij}(x,\boldsymbol{k}) = x\left[\delta_T^{ij} f_1(x,\boldsymbol{k}^2) + \frac{k_T^{ij}}{M^2} h_1^{\perp}(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_L^{ij}(x,\boldsymbol{k}) = x\left[i\epsilon_T^{ij} S_L\, g_1(x,\boldsymbol{k}^2) + \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha} S_L}{2M^2} h_{1L}^{\perp}(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_T^{ij}(x,\boldsymbol{k}) = x\left[\frac{\delta_T^{ij}\,\epsilon_T^{S_T k_T}}{M} f_{1T}^{\perp}(x,\boldsymbol{k}^2) + \frac{i\epsilon_T^{ij}\,\boldsymbol{k}\cdot\boldsymbol{S}_T}{M} g_{1T}(x,\boldsymbol{k}^2)\right.$$
$$\left. - \frac{\epsilon_T^{k_T\{i} S_T^{j\}} + \epsilon_T^{S_T\{i} k_T^{j\}}}{4M} h_1(x,\boldsymbol{k}^2) - \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha S_T}}{2M^3} h_{1T}^{\perp}(x,\boldsymbol{k}^2)\right]$$

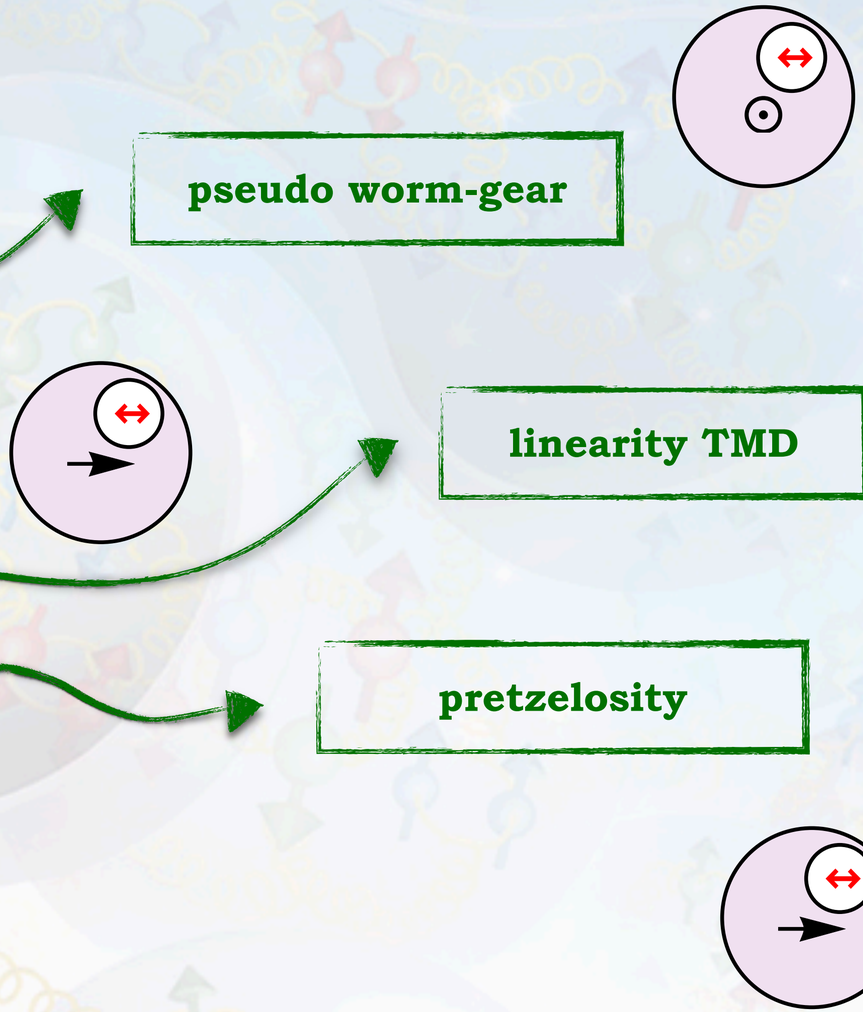
Backup

Gluon TMD correlator and *T*-odd gluon densities

$$\Gamma_U^{ij}(x,\boldsymbol{k}) = x\left[\delta_T^{ij} f_1(x,\boldsymbol{k}^2) + \frac{k_T^{ij}}{M^2} h_1^{\perp}(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_L^{ij}(x,\boldsymbol{k}) = x\left[i\epsilon_T^{ij} S_L\, g_1(x,\boldsymbol{k}^2) + \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha} S_L}{2M^2} h_{1L}^{\perp}(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_T^{ij}(x,\boldsymbol{k}) = x\left[\frac{\delta_T^{ij}\,\epsilon_T^{S_T k_T}}{M} f_{1T}^{\perp}(x,\boldsymbol{k}^2) + \frac{i\epsilon_T^{ij}\,\boldsymbol{k}\cdot\boldsymbol{S}_T}{M} g_{1T}(x,\boldsymbol{k}^2)\right.$$
$$\left. - \frac{\epsilon_T^{k_T\{i} S_T^{j\}} + \epsilon_T^{S_T\{i} k_T^{j\}}}{4M} h_1(x,\boldsymbol{k}^2) - \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha S_T}}{2M^3} h_{1T}^{\perp}(x,\boldsymbol{k}^2)\right]$$



Backup

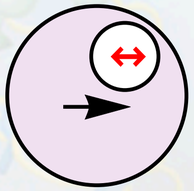
Gluon TMD correlator and *T*-odd gluon densities

$$\Gamma_U^{ij}(x,\boldsymbol{k}) = x\left[\delta_T^{ij} f_1(x,\boldsymbol{k}^2) + \frac{k_T^{ij}}{M^2} h_1^{\perp}(x,\boldsymbol{k}^2)\right]$$

$$\Gamma_L^{ij}(x,\boldsymbol{k}) = x\left[i\epsilon_T^{ij} S_L\, g_1(x,\boldsymbol{k}^2) + \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha} S_L}{2M^2} h_{1L}^{\perp}(x,\boldsymbol{k}^2)\right]$$

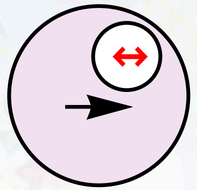
$$\Gamma_T^{ij}(x,\boldsymbol{k}) = x\left[\frac{\delta_T^{ij}\,\epsilon_T^{S_T k_T}}{M} f_{1T}^{\perp}(x,\boldsymbol{k}^2) + \frac{i\epsilon_T^{ij}\,\boldsymbol{k}\cdot\boldsymbol{S}_T}{M} g_{1T}(x,\boldsymbol{k}^2)\right.$$
$$\left. - \frac{\epsilon_T^{k_T\{i} S_T^{j\}} + \epsilon_T^{S_T\{i} k_T^{j\}}}{4M} h_1(x,\boldsymbol{k}^2) - \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha S_T}}{2M^3} h_{1T}^{\perp}(x,\boldsymbol{k}^2)\right]$$

pseudo worm-gear

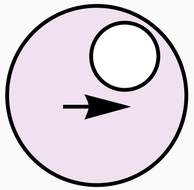


linearity TMD

pretzelosity



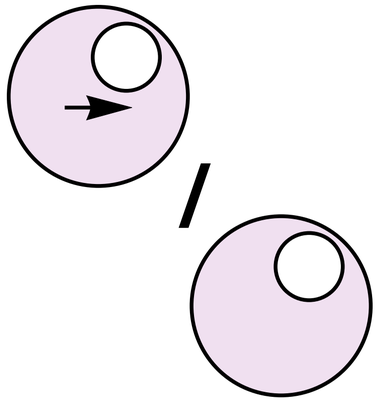
Sivers



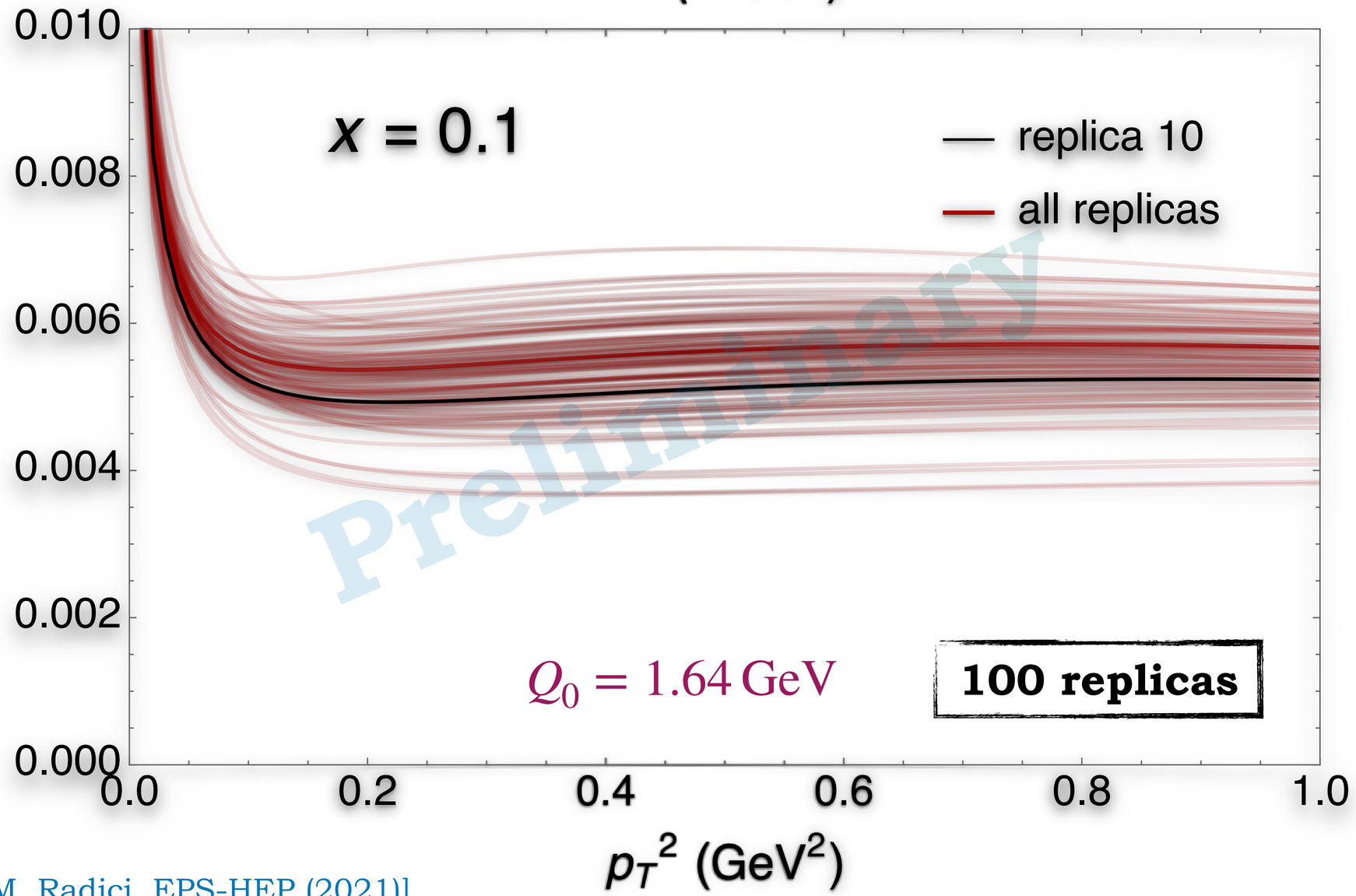
$$\frac{\epsilon_T^{S_T k_T}}{M} f_{1T}^{\perp}(x,\boldsymbol{k}^2) = \frac{1}{2}\,\delta_{Tij}\,\Gamma_T^{ij}(x,\boldsymbol{k})$$

Backup

f-type Sivers / unpol.



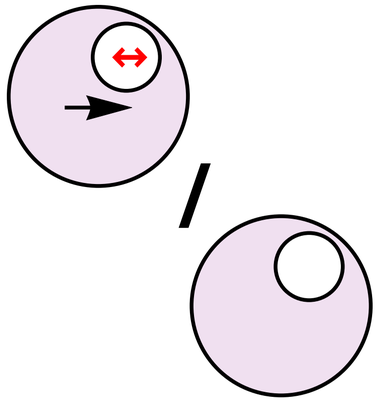
$$\frac{\frac{p_T}{M} f_{1T}^{\perp[+,+]}(x, p_T^2)}{f_1^g(x, p_T^2)}$$



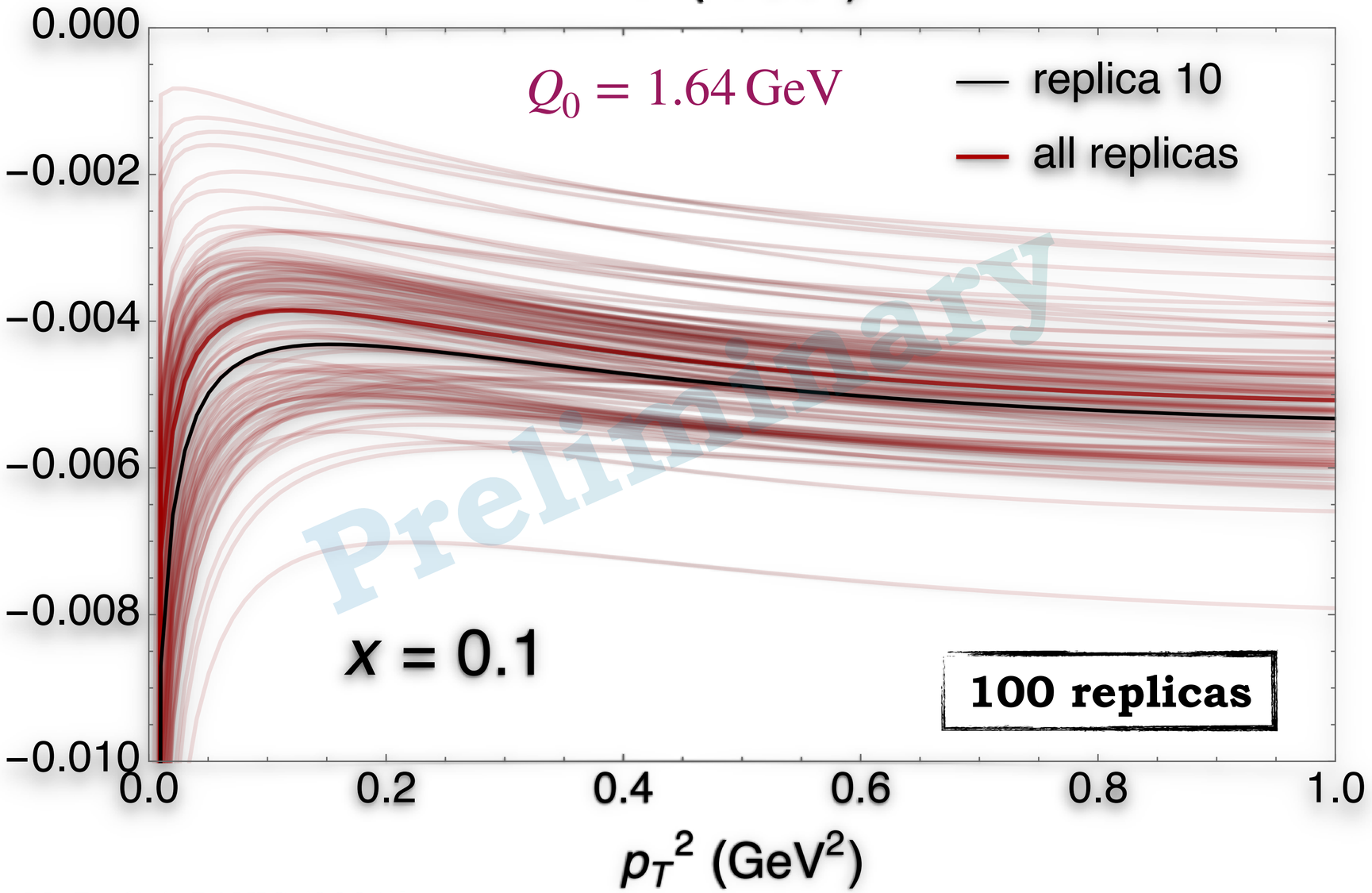
[A. Bacchetta, F.G. C., M. Radici, EPS-HEP (2021)]

Backup

f-type linearity / unpol.



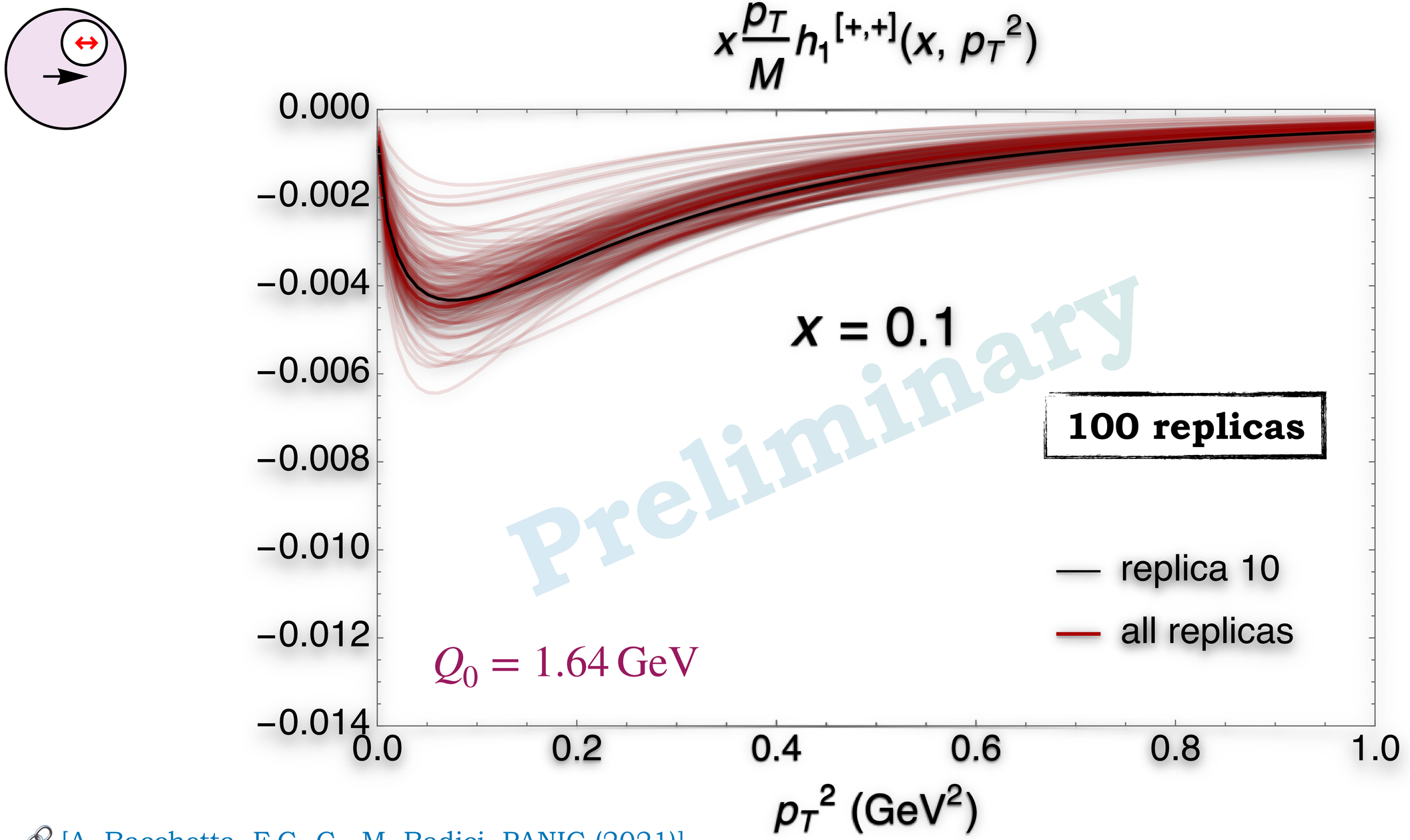
$$\frac{\frac{p_T}{M} h_1^{[+,+]}(x,\ p_T^2)}{f_1^{\,g}(x,\ p_T^2)}$$



🔗 [A. Bacchetta, F.G. C., M. Radici, PANIC (2021)]

Backup

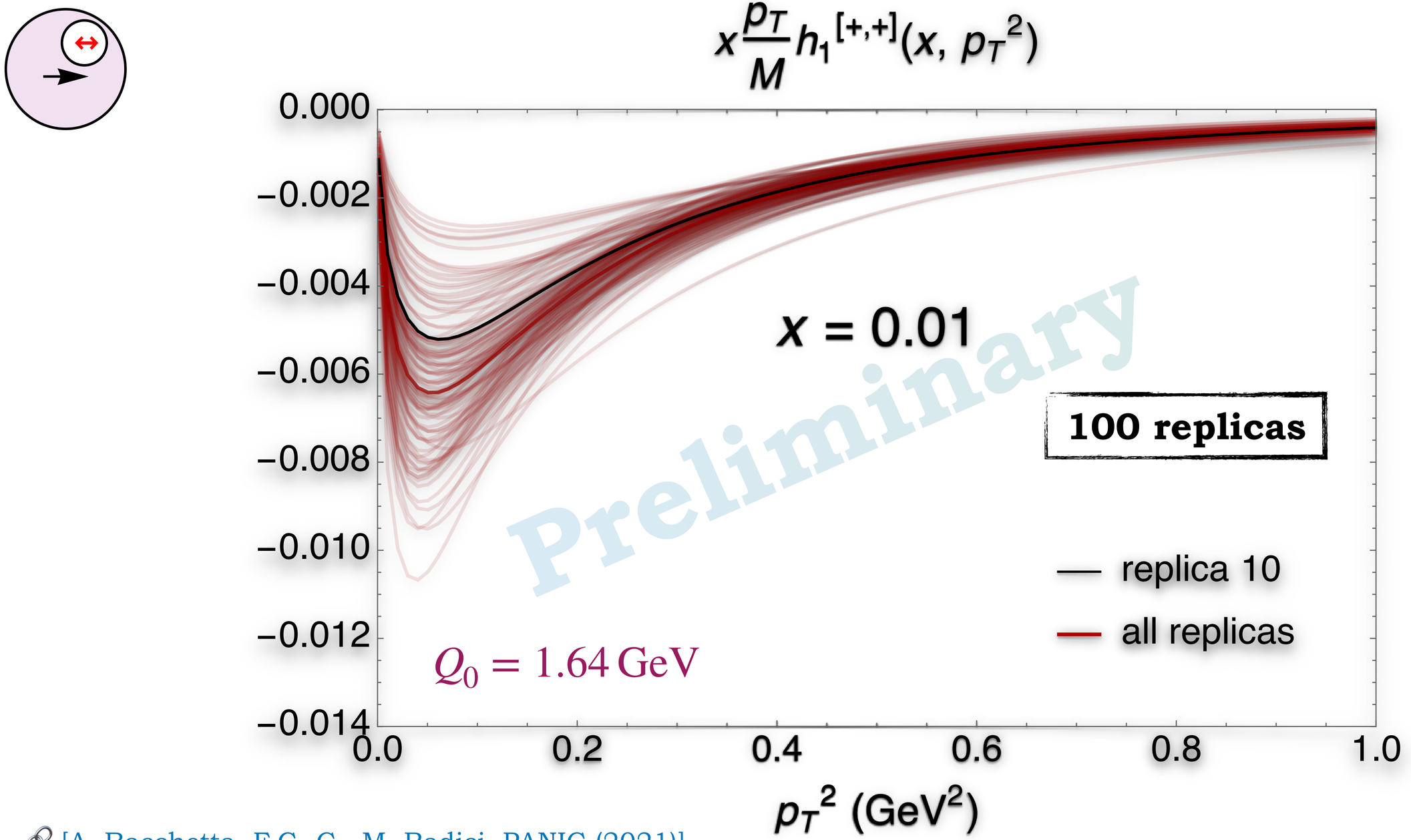
f-type linearity gluon TMD



[A. Bacchetta, F.G. C., M. Radici, PANIC (2021)]

Backup

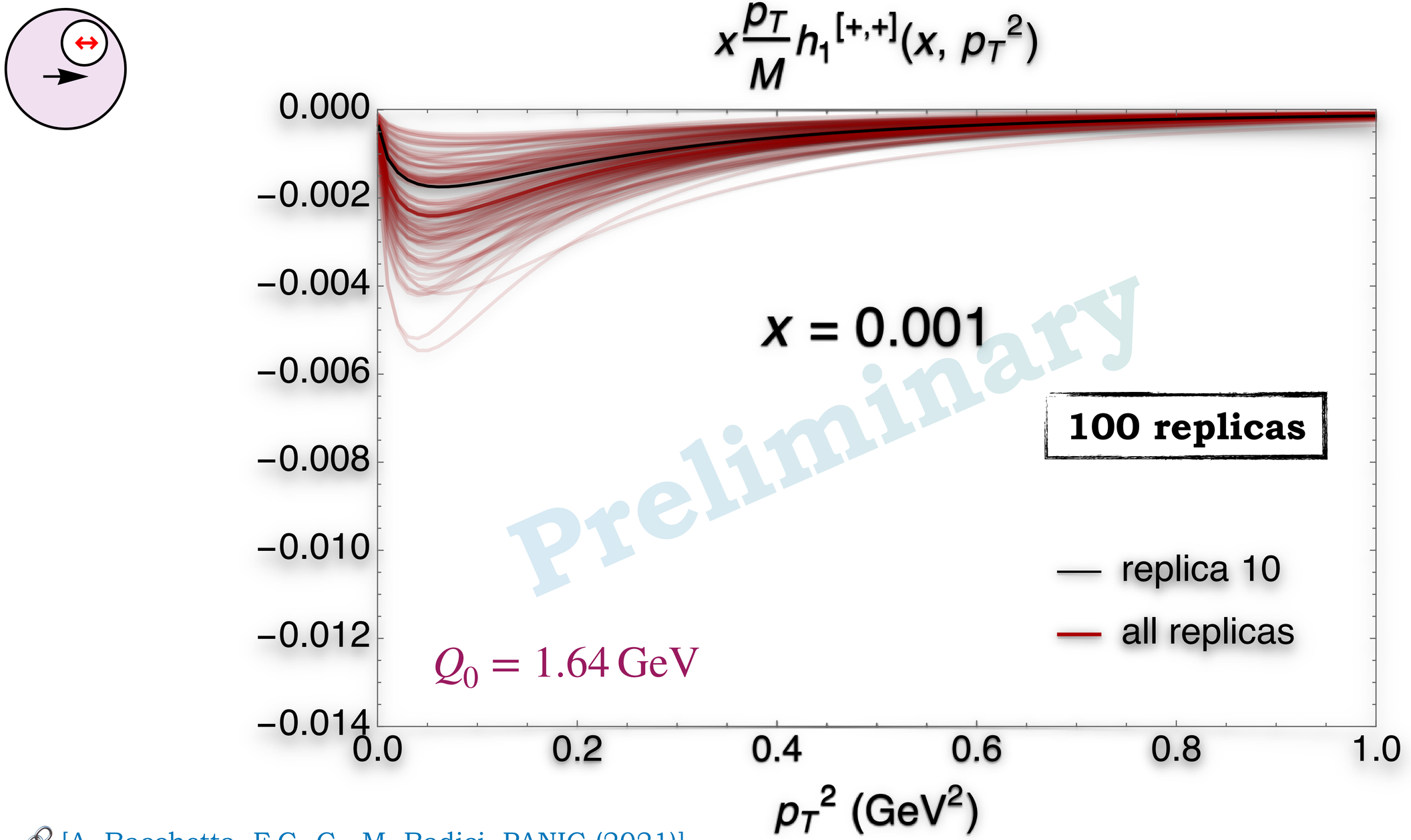
f-type linearity gluon TMD



[A. Bacchetta, F.G. C., M. Radici, PANIC (2021)]

Backup

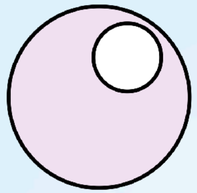
f-type linearity gluon TMD



[A. Bacchetta, F.G. C., M. Radici, PANIC (2021)]

Backup

ρ-densities

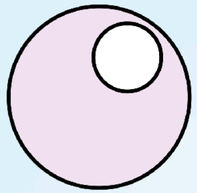


Unpolarized [u/u]

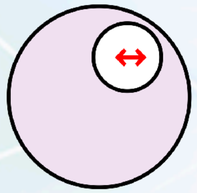
$$f_1(x, p_x, p_y)$$

Backup

ρ-densities



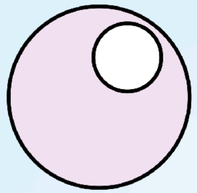
Unpolarized [u/u] $f_1(x, p_x, p_y)$



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

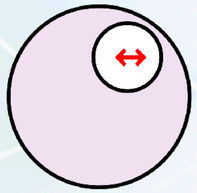
Backup

ρ-densities



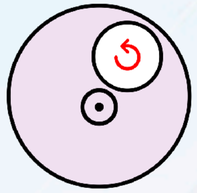
Unpolarized [u/u]

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



Boer-Mulders [↔/u]

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

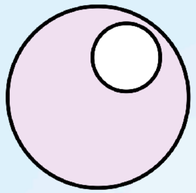


Helicity [↻/+]

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

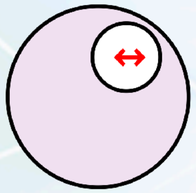
Backup

ρ-densities



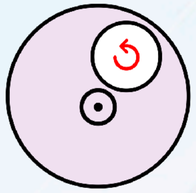
Unpolarized [u/u]

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



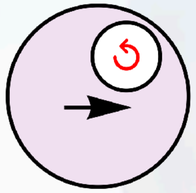
Boer-Mulders [↔/u]

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



Helicity [↺/+]

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

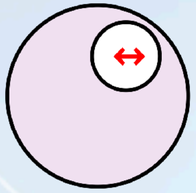


Worm-gear [↺/→]

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

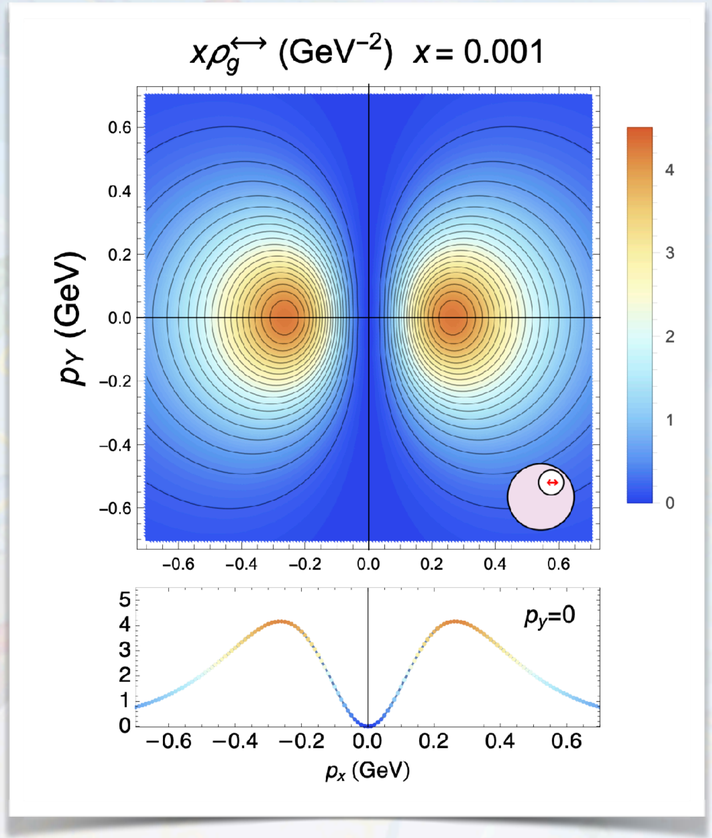
Backup

Boer-Mulders effect in unpolarized *pp* collisions



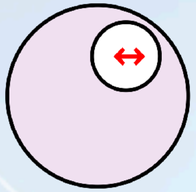
$$[\leftrightarrow/\mathbf{u}] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x,p_x,p_y)$$

unpol. Boer-Mulders



Backup

Boer-Mulders effect in unpolarized *pp* collisions

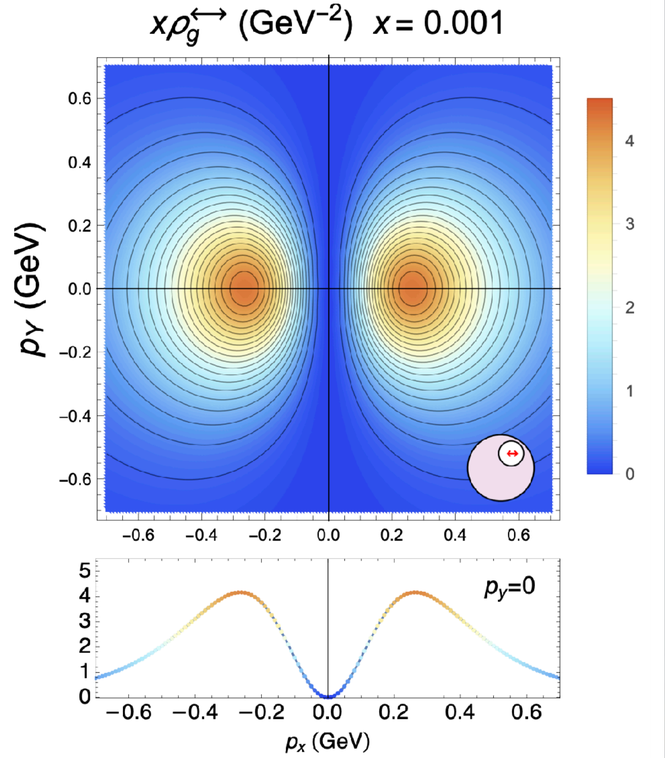


$$[\leftrightarrow/u] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x,p_x,p_y)$$

unpol. — Boer-Mulders

(Pseudo)scalar Higgs p_T-distribution

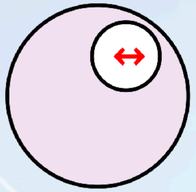
$$\left.\frac{E\,\mathrm{d}\sigma^{H(A)}}{\mathrm{d}^3\vec{q}}\right|_{q_T \ll m_H} = \frac{\pi\sqrt{2}G_F}{128 m_H^2 S}\left(\frac{\alpha_s}{4\pi}\right)^2 \left|\mathcal{A}_{H(A)}(\tau)\right|^2 \times \left(\mathcal{C}\left[f_1^g\, f_1^g\right] \pm \mathcal{C}\left[w_H\, h_1^{\perp g}\, h_1^{\perp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



[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

Backup

Boer-Mulders effect in unpolarized *pp* collisions



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

unpol. Boer-Mulders

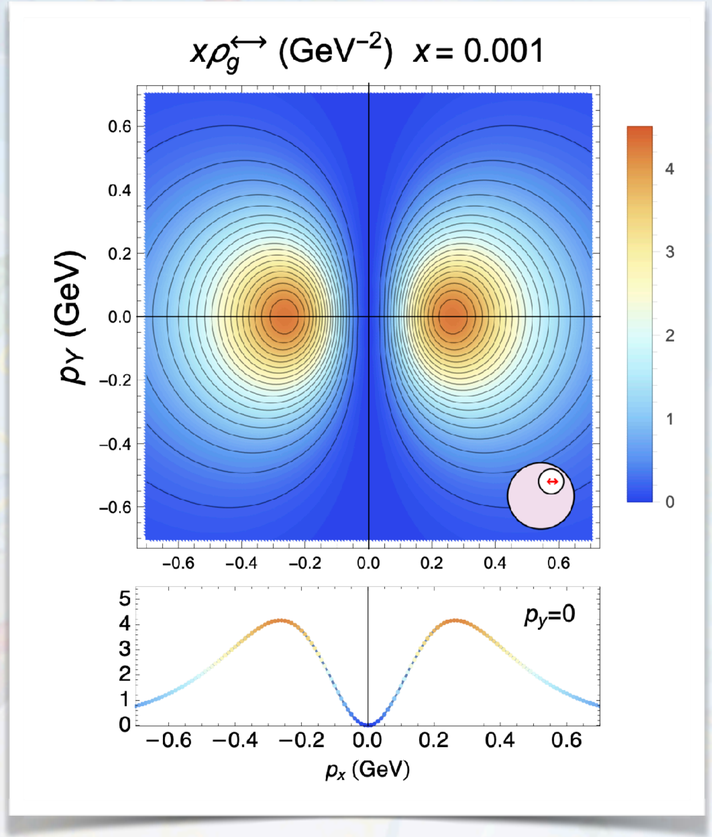
(Pseudo)scalar Higgs p_T-distribution

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

[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

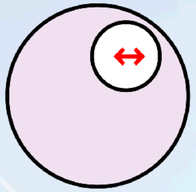
Model prediction at low-x

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



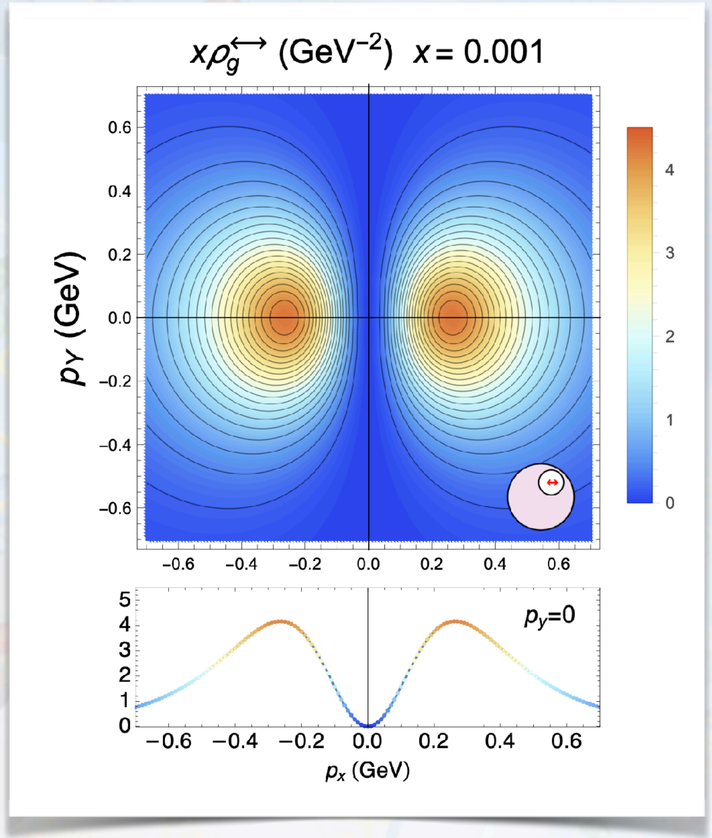
Backup

Boer-Mulders effect in unpolarized *pp* collisions



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

unpol. — Boer-Mulders



(Pseudo)scalar Higgs p_T-distribution

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

[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

Model prediction at low-x

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

HEF regime (linear low-x evolution)

$$f_1^g(x,p_T^2) = h_1^{\perp g}(x,p_T^2) + \text{higher twist}$$

Backup

$\eta_{b,c}$ production in unpolarized pp collisions

TMD phenomenology:

from JLab to the LHC

Andrea Signori

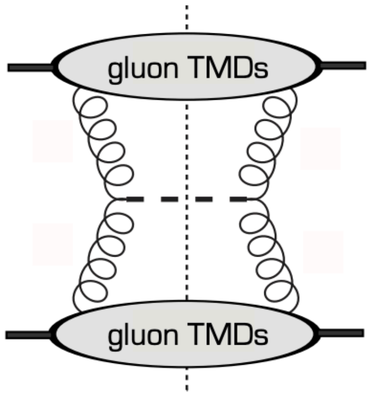
Spatial and momentum
tomography
of hadrons and nuclei

INT 17-3
Sept 25 2017

NRQCD

$$\frac{\text{CS}}{\text{CO}} \sim \frac{1}{v^4}$$

gluon TMD PDFs



pseudoscalar quarkonium production:

$p\ p \to \eta_b\ X$ M = 9.39 GeV

$p\ p \to \eta_c\ X$ M = 2.98 GeV

(see also talk by C. Pisano week 4)

$$\frac{d\sigma}{dq_T} \sim \Phi_A^U\ \Phi_B^U\ |\mathcal{M}|^2$$

unpolarized cross section
at low transverse momentum
for (pseudo)scalar state

$$\sim \mathcal{C}[\ f_1^{g/A}\ f_1^{g/B}\ ] \pm \mathcal{C}[\ h_1^{\perp g/A}\ h_1^{\perp g/B}\ ]$$

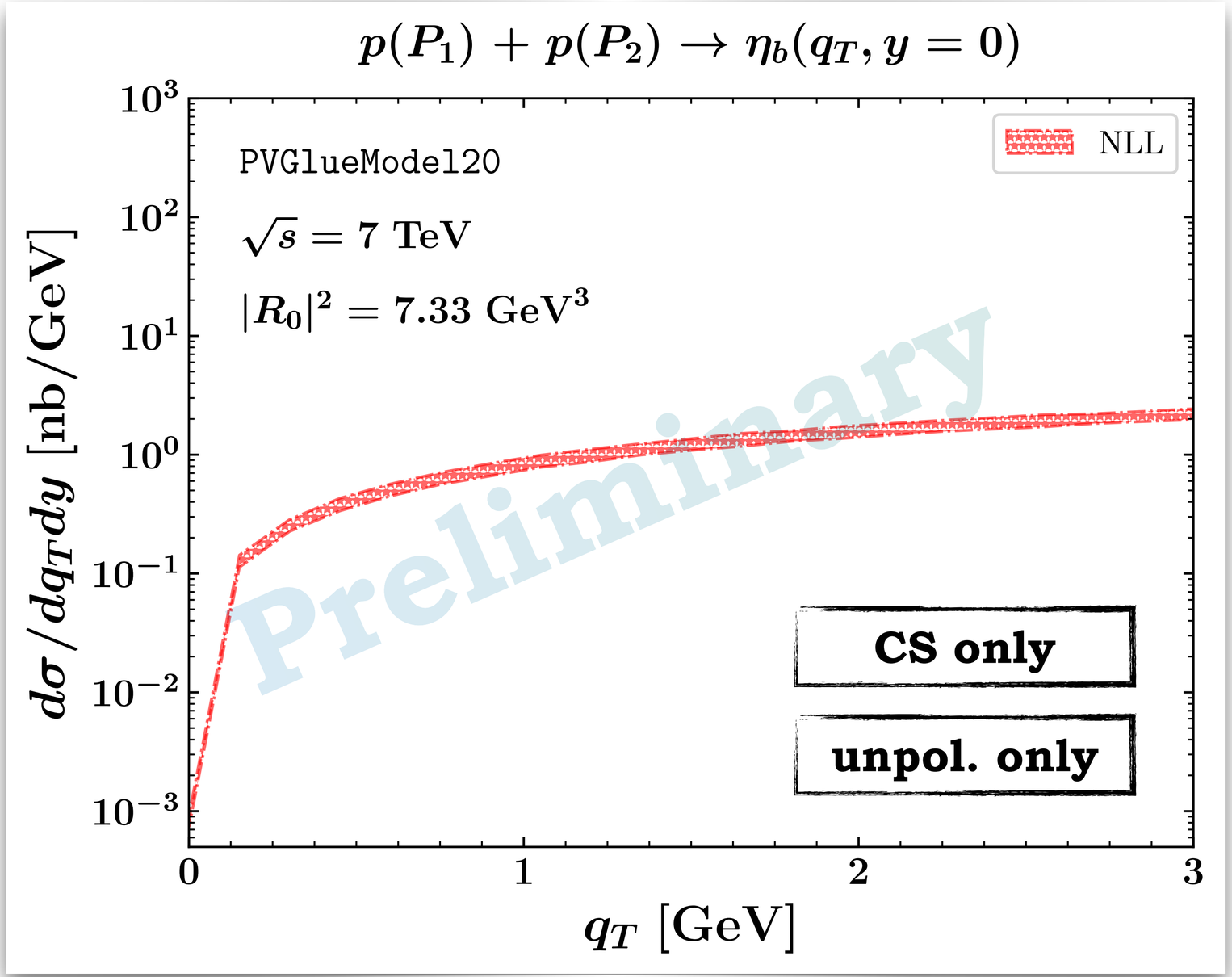
unpolarized gluons

lin. polarized gluons

Jefferson Lab

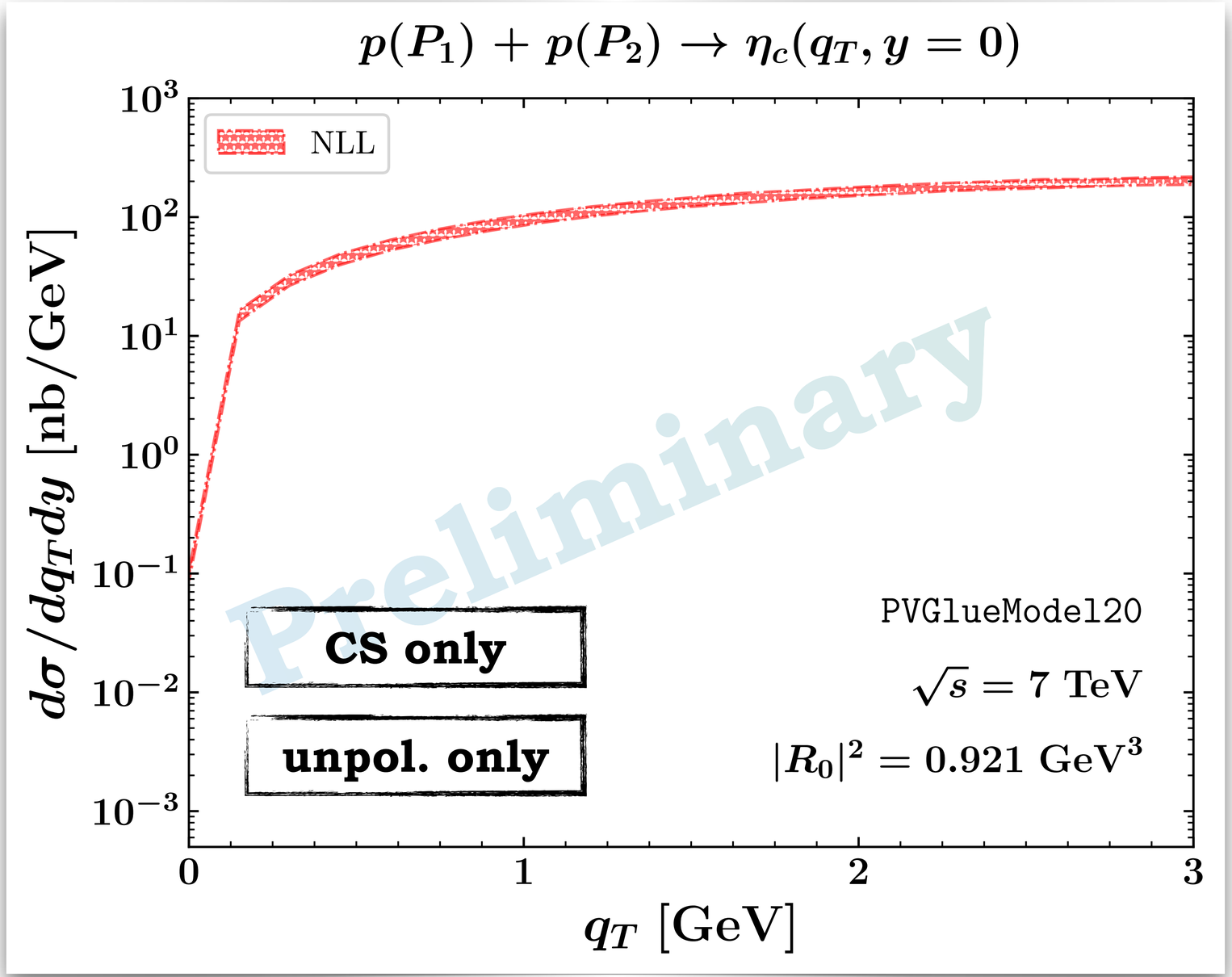
Backup

η_b production @ 7TeV LHC



Backup

η_c production @ 7TeV LHC

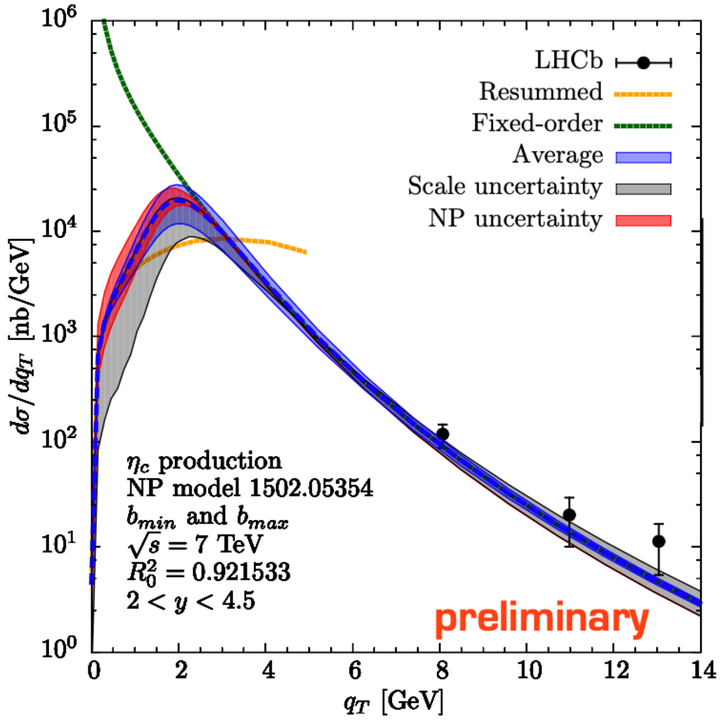


Backup

η_c production @ 7TeV LHC

η_c production at LHC

full transverse momentum spectrum:
low qT matched with high qT region



blue band: uncertainty from matching

grey band: scale uncertainty

red band: nonpert. uncertainty

$$S_{NP}(\bar{b}_T) = -\left[\frac{a_1}{2} + \frac{a_2}{2}\ln Q^2\right]\bar{b}_T^2$$

a_i = 0.5 GeV², var. 50%, envelope

both for unpolarized and
linearly polarized distributions

the formalism is in good shape!
we need the data at low qT

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slide by **Andrea Signori** (INT 2017)

Backup