Quarkonia As Tools 2022

January 12th

Gluon TMDs and Quarkonia

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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

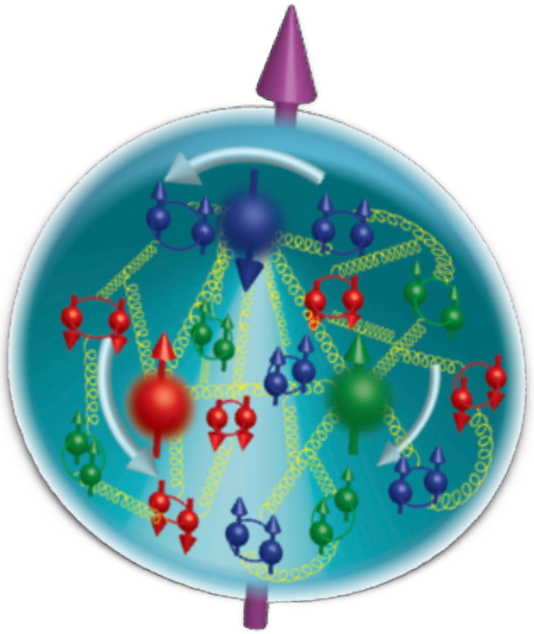
An overview on gluon TMDs

Parton densities: hors d'œuvre

Parton densities → relevant for the search of **New Physics**…

→ …crucial role in the understanding and exploration of **QCD**

- Describe the internal structure of the nucleon in terms of its elementary constituents (quarks and gluons)
- **Nonperturbative** objects that enter the expression of cross sections
- Can be *extracted* from experiments via *global fits*



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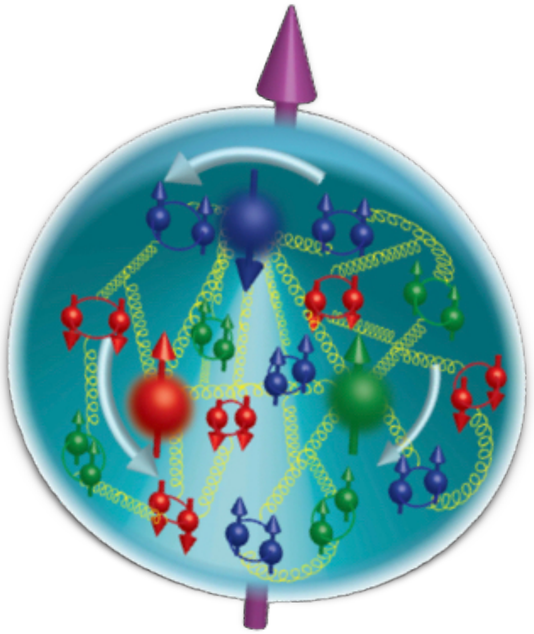
Several types of distributions (1D collinear, **3D TMD**, …)

- Respect different **factorization theorems**
- Exhibit peculiar **universality properties**
- Obey distinct **evolution equations**



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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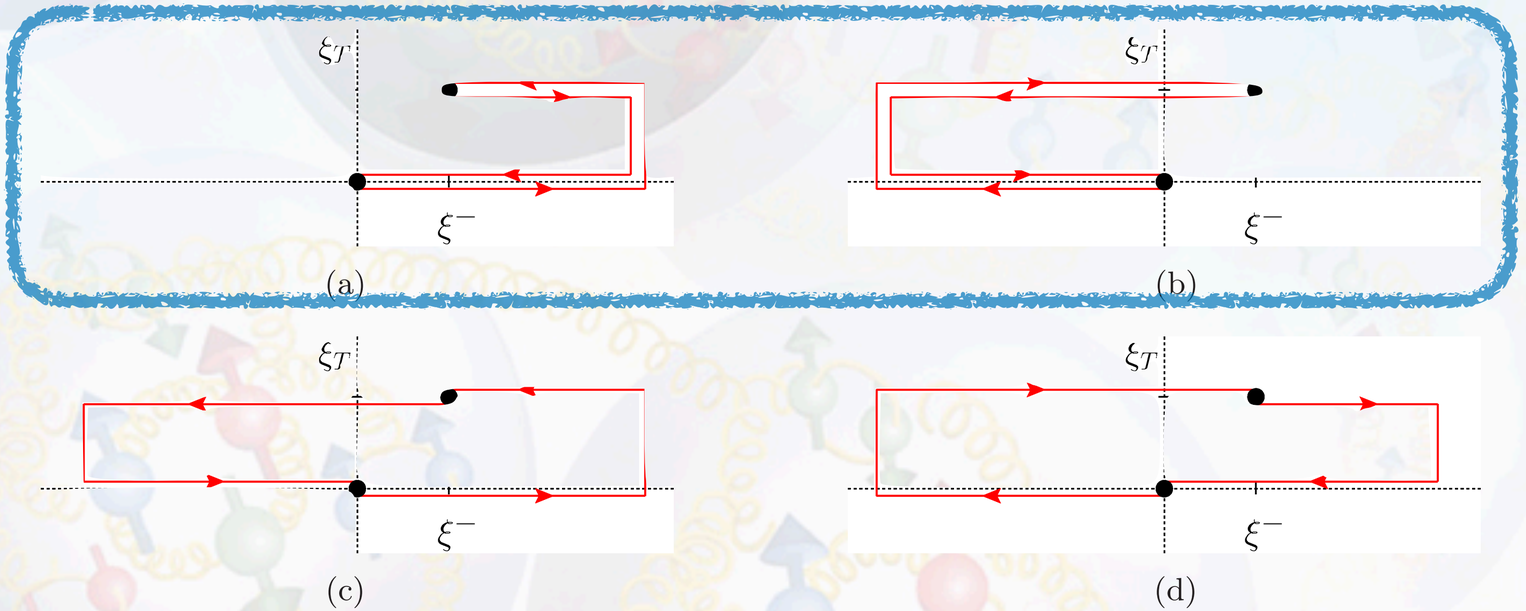
f-type (WW)

(a) [+ , +] or (b) [− , −]



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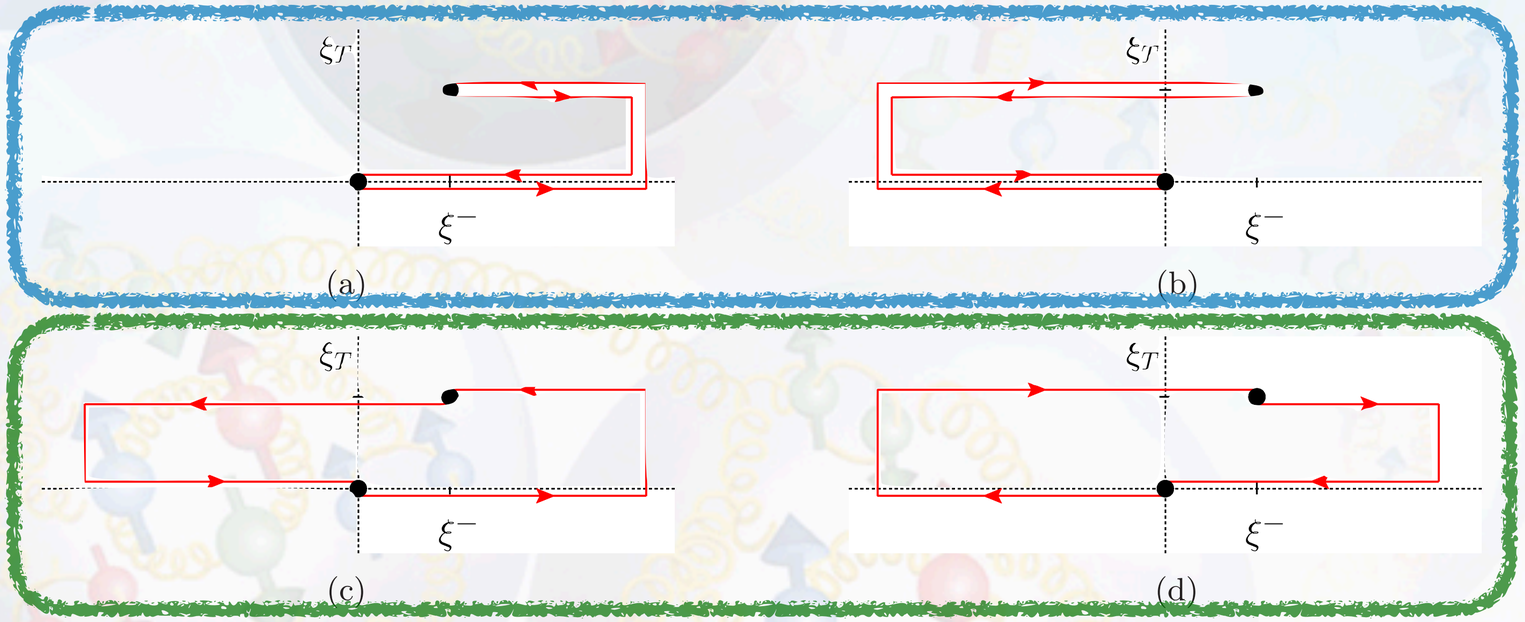
f-type (WW)

(a) [+ , +] or (b) [− , −]

d-type (dipole)

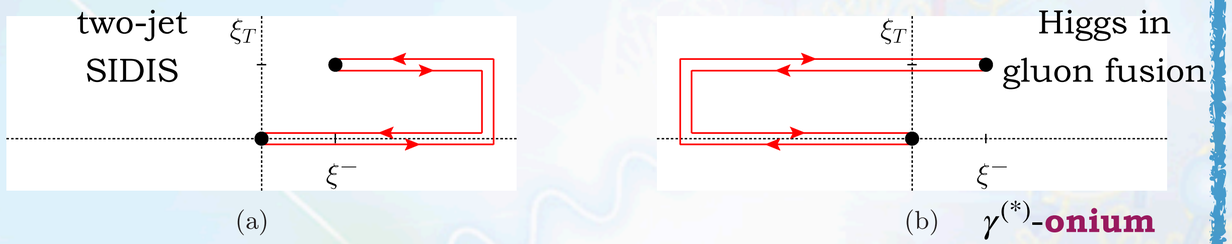
(c) [+ , −] or (d) [− , +]



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:

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

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

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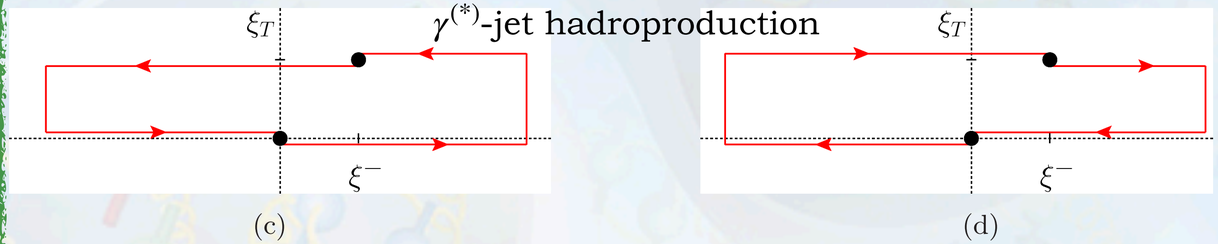
Dipole (DP)

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



- 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

Accessing WW and DP gluon TMDs

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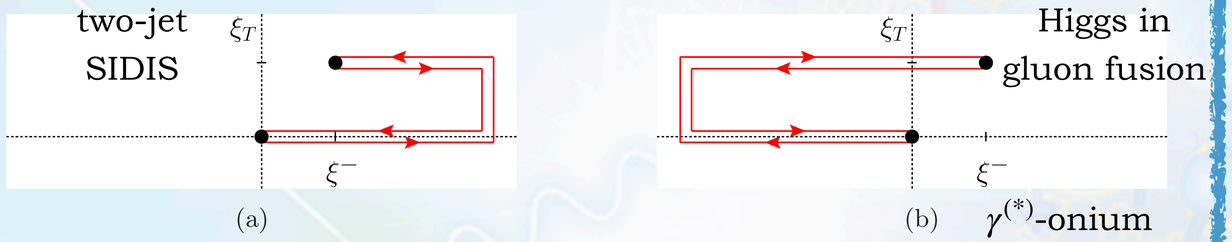

Higgs in gluon fusion

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

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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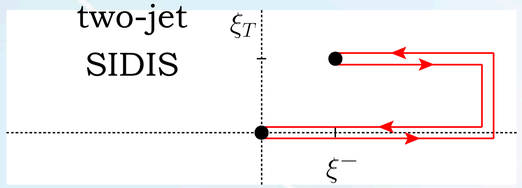
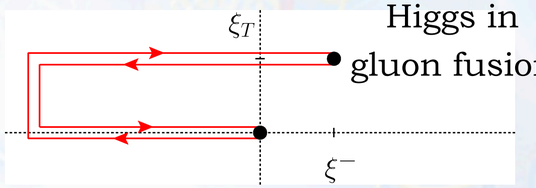
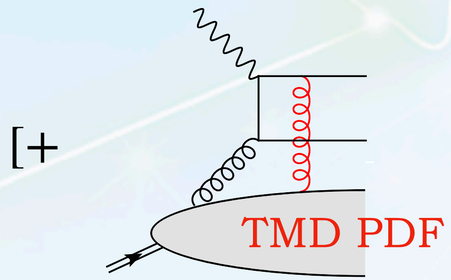


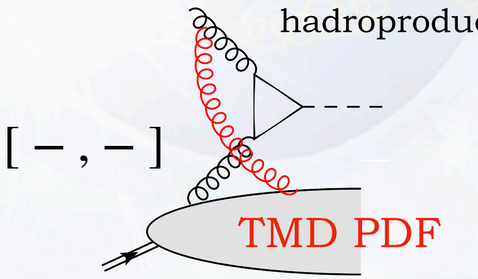
(a)

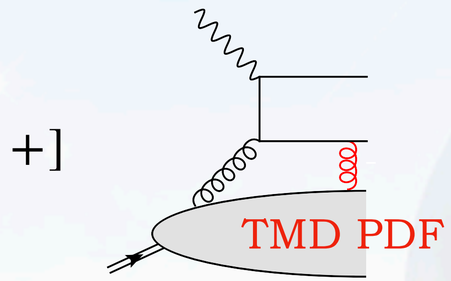


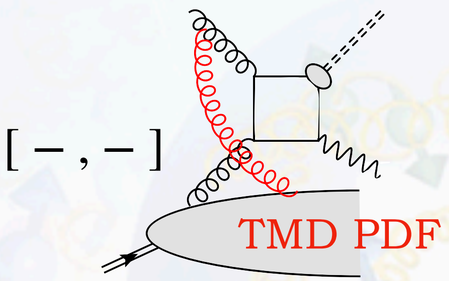
(b) $\gamma^{(*)}$-onium hadroproduction

Higgs in gluon fusion





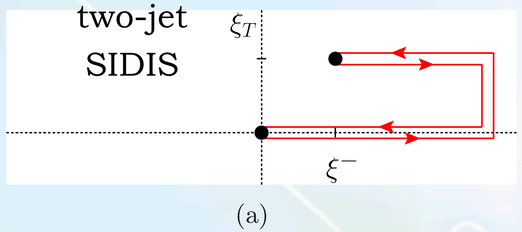


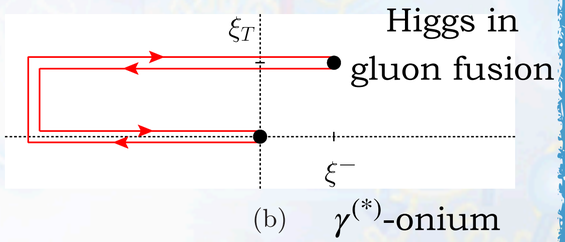


Accessing WW and DP gluon TMDs

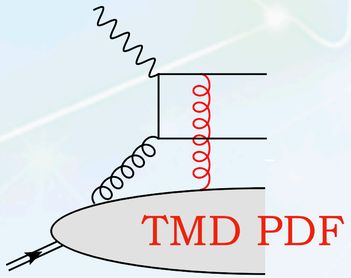
Weiszäcker-Williams (WW)

(a) [+,+] or (b) [−,−]

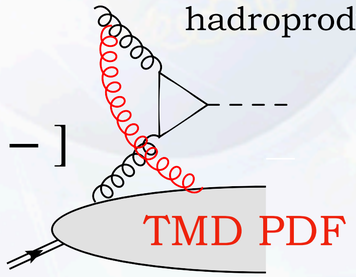




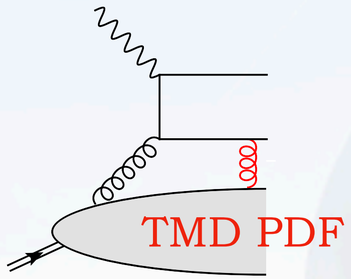
[+



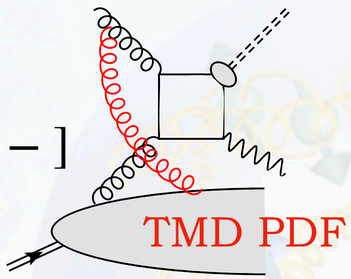
[−,−]



+]

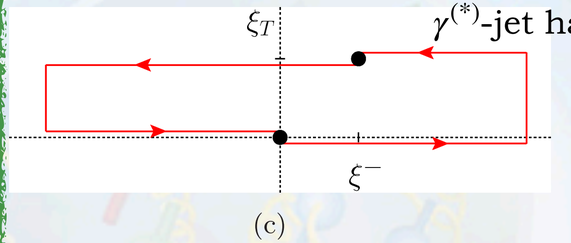


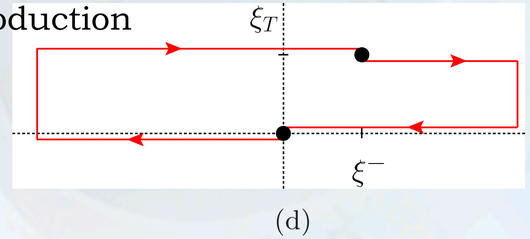
[−,−]



Dipole (DP)

(c) [+,−] or (d) [−,+]





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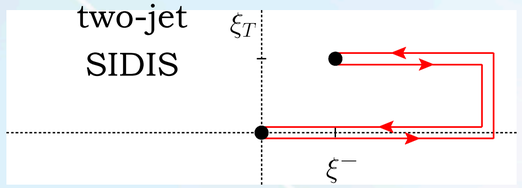

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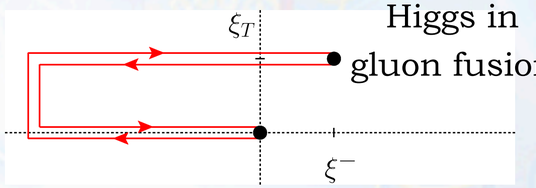
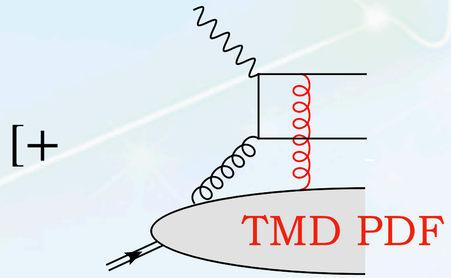
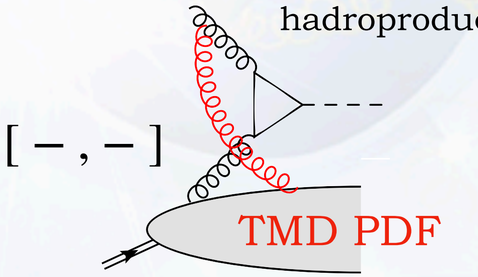
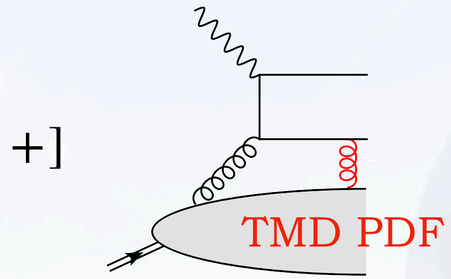
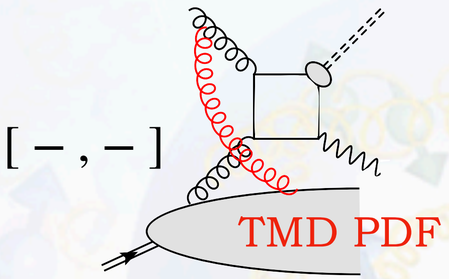


(b) $\gamma^{(*)}$-onium hadroproduction









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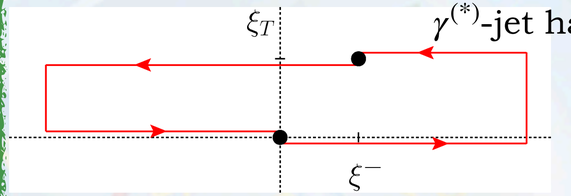
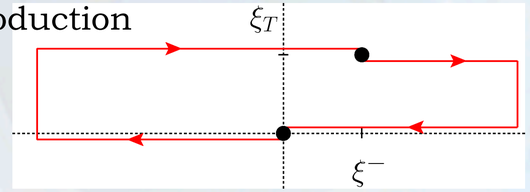
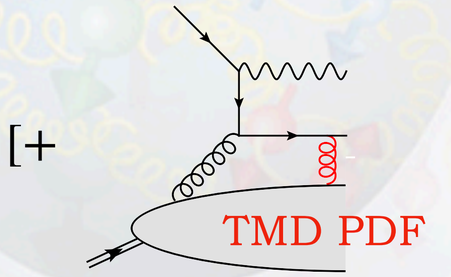
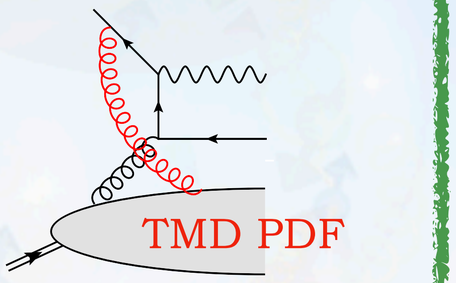


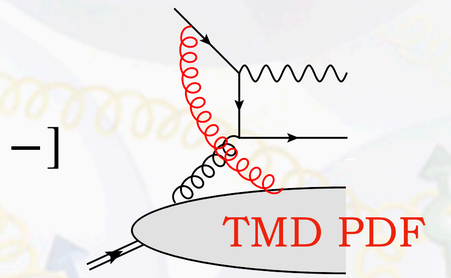
(c)

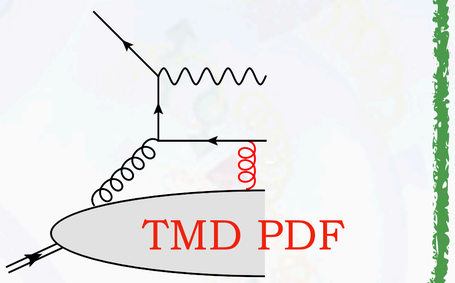


(d)









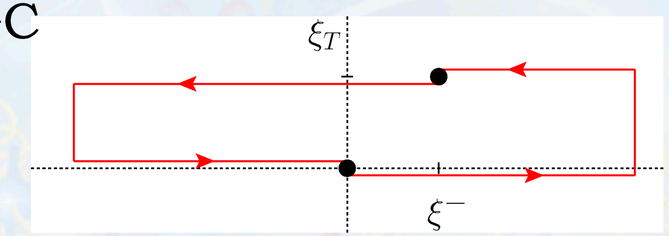
Dihadron hadroproduction and factorization breaking

* 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:

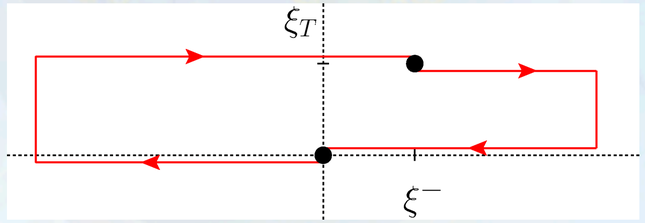
  (c) $[+,-]$ and (d) $[-,+]$
* Appearance of new gauge **loop links**:

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

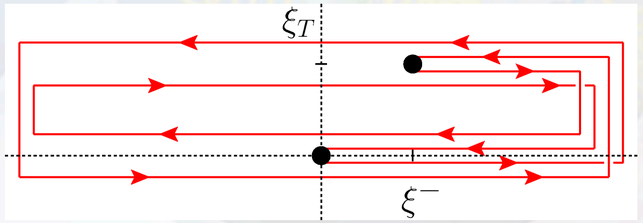
  (g) $[\square,\square]$, and (h) $[\square,\square]$



(c)



(d)



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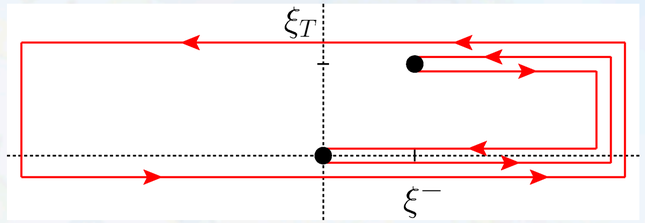
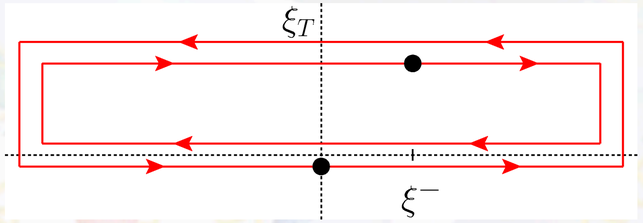
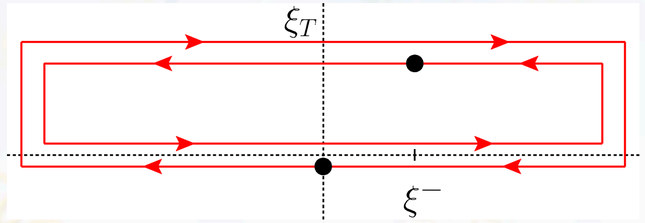


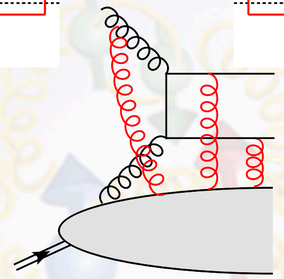
(f)



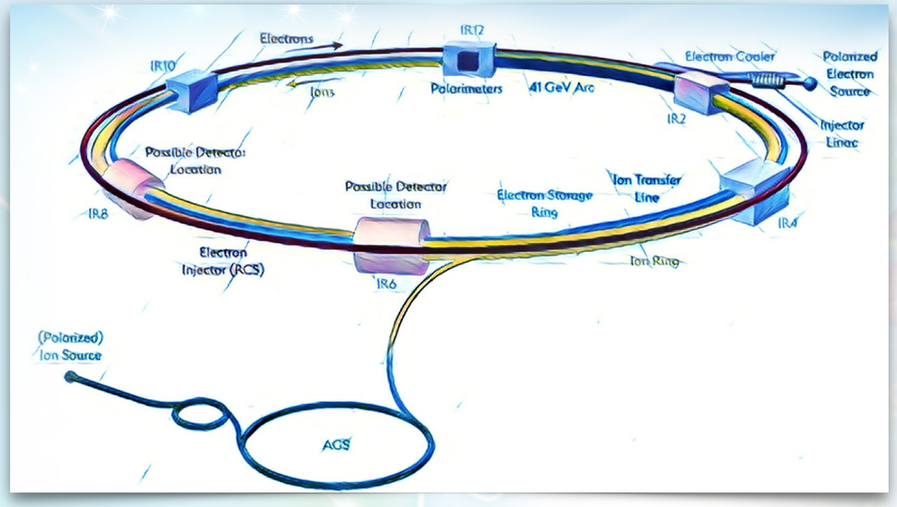
(g)



(h)



3D proton tomography at new-generation colliders

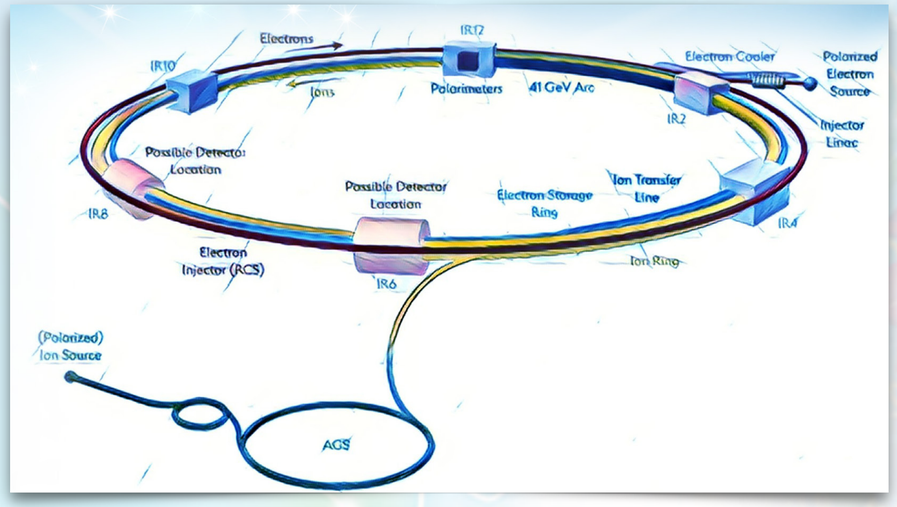


EIC

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

Accessing the proton content

3D proton tomography at new-generation colliders



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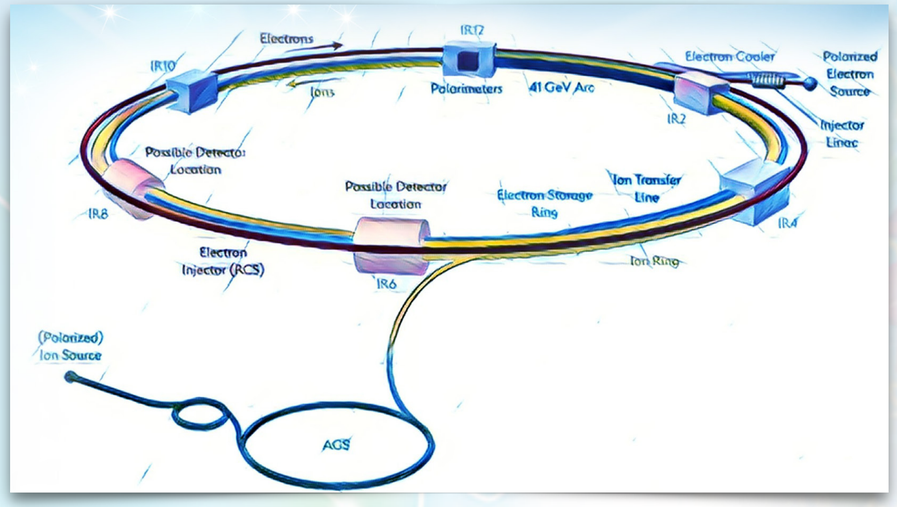
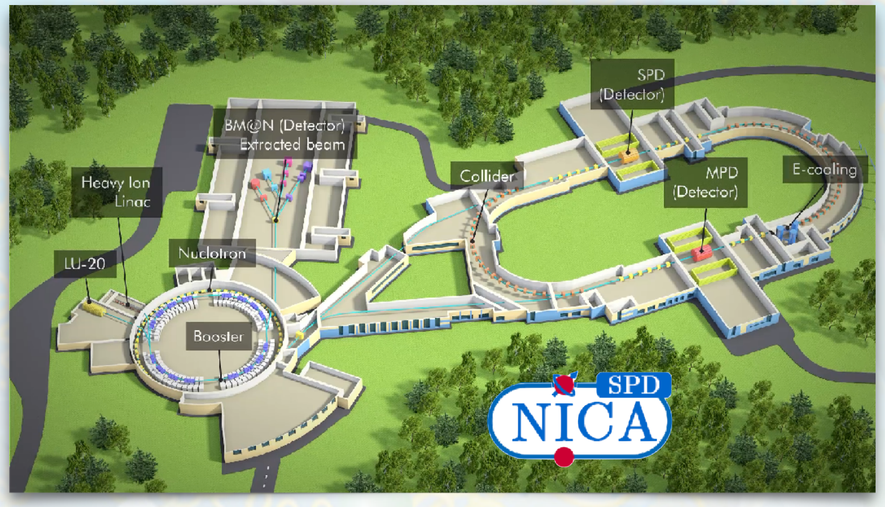
Accessing the proton content

Core sector of **EIC** analyses

3D proton tomography at new-generation colliders





EIC

NICA-SPD

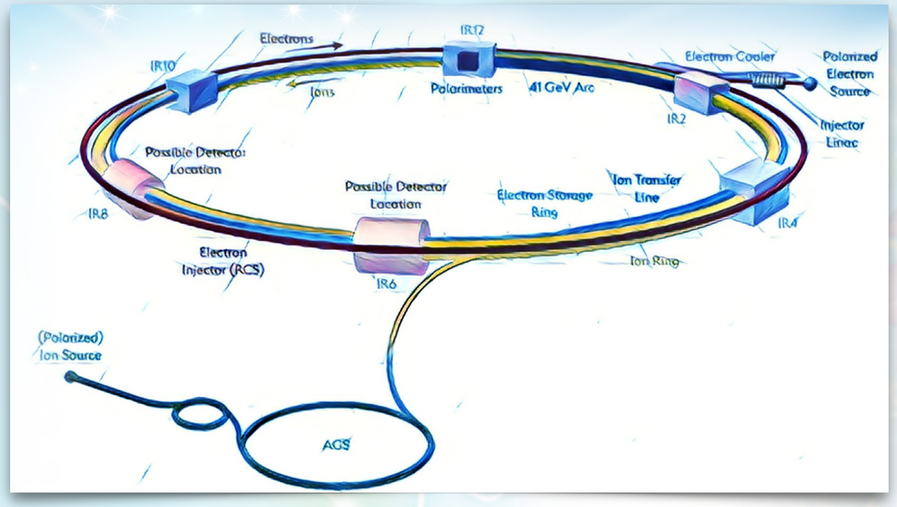
EIC Yellow Report 🔗 [EICUG [arXiv:2103.05419]]

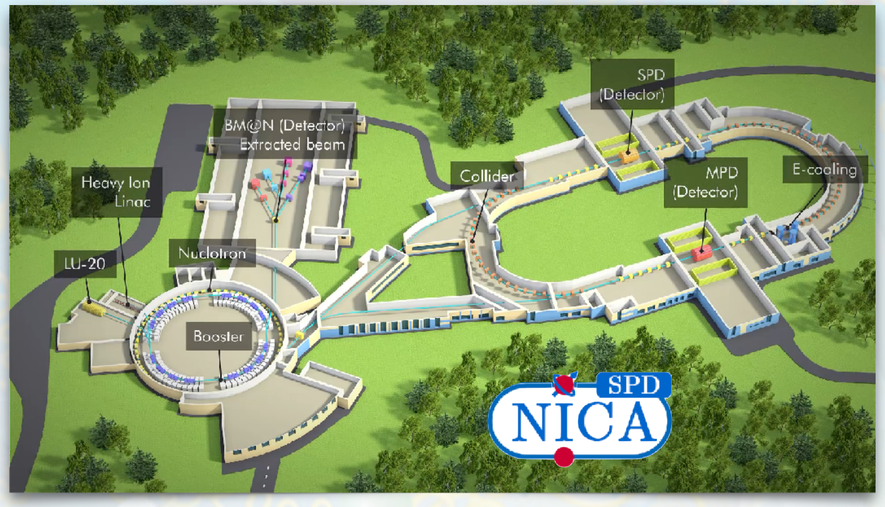
Gluon content at **NICA-SPD** 🔗 [NICA [arXiv:2011.15005]]

Accessing the proton content

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

3D proton tomography at new-generation colliders





EIC

NICA-SPD

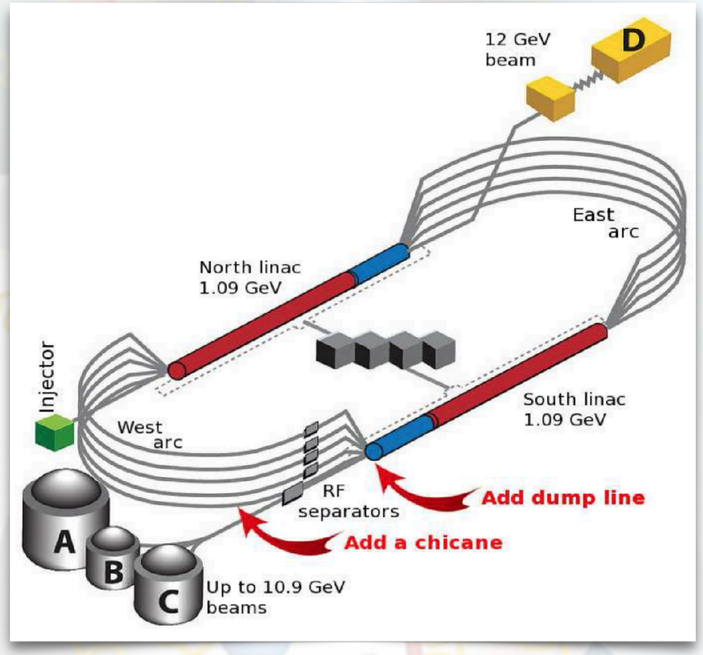
JLab12

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

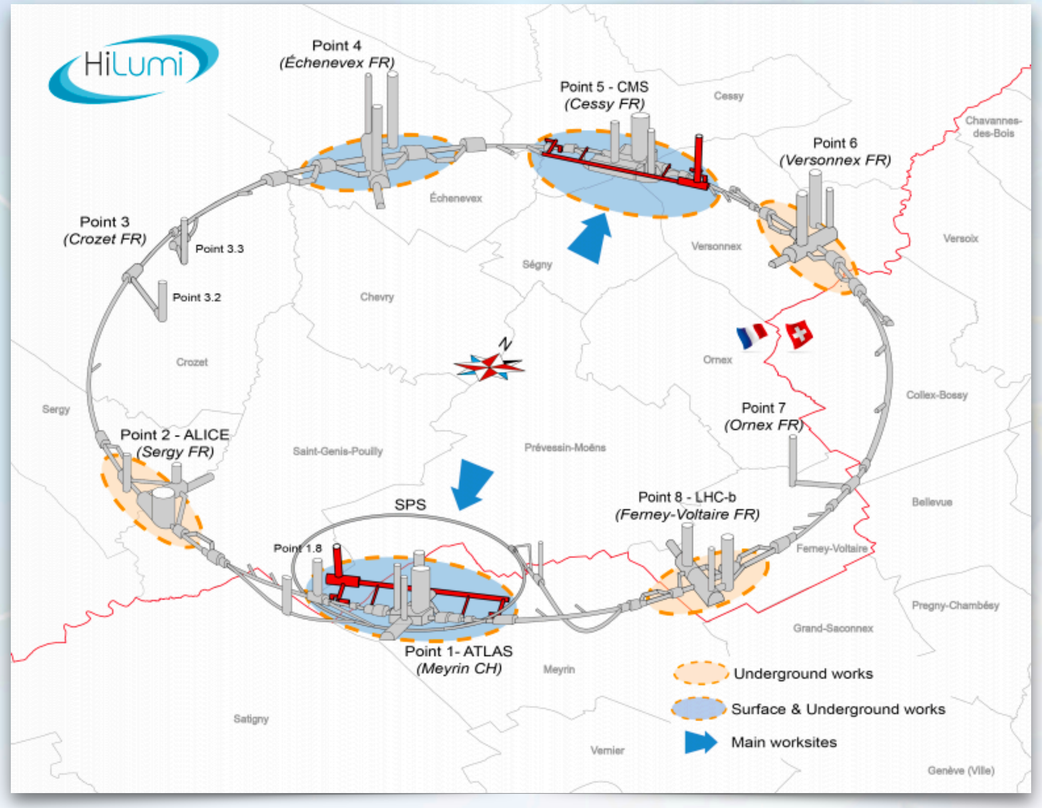
Gluon content at **NICA-SPD** 🔗 [NICA [arXiv:2011.15005]]

Accessing the proton content

- *Core* sector of **EIC** analyses
- *Significance* of large-x studies at **NICA-SPD**
- Gluon-TMD *dynamics* in **JLab12** physics



Connections with high-energy physics

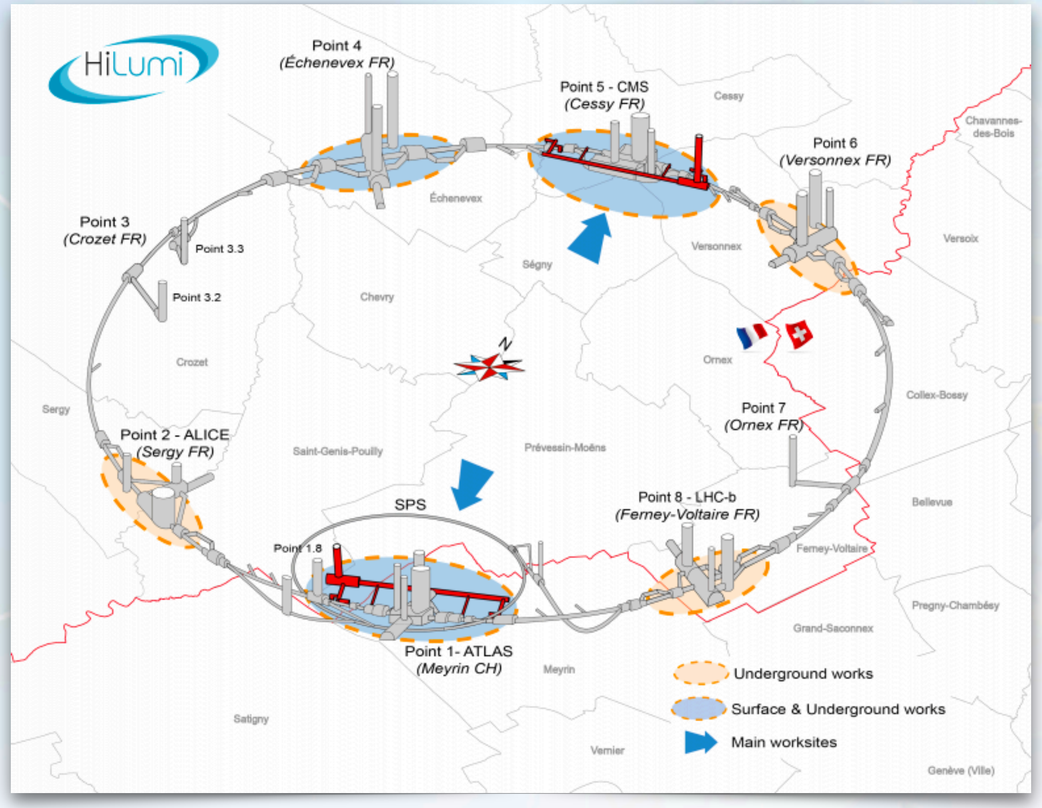


HL-LHC

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

Hadronic structure at high energies

Connections with high-energy physics



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

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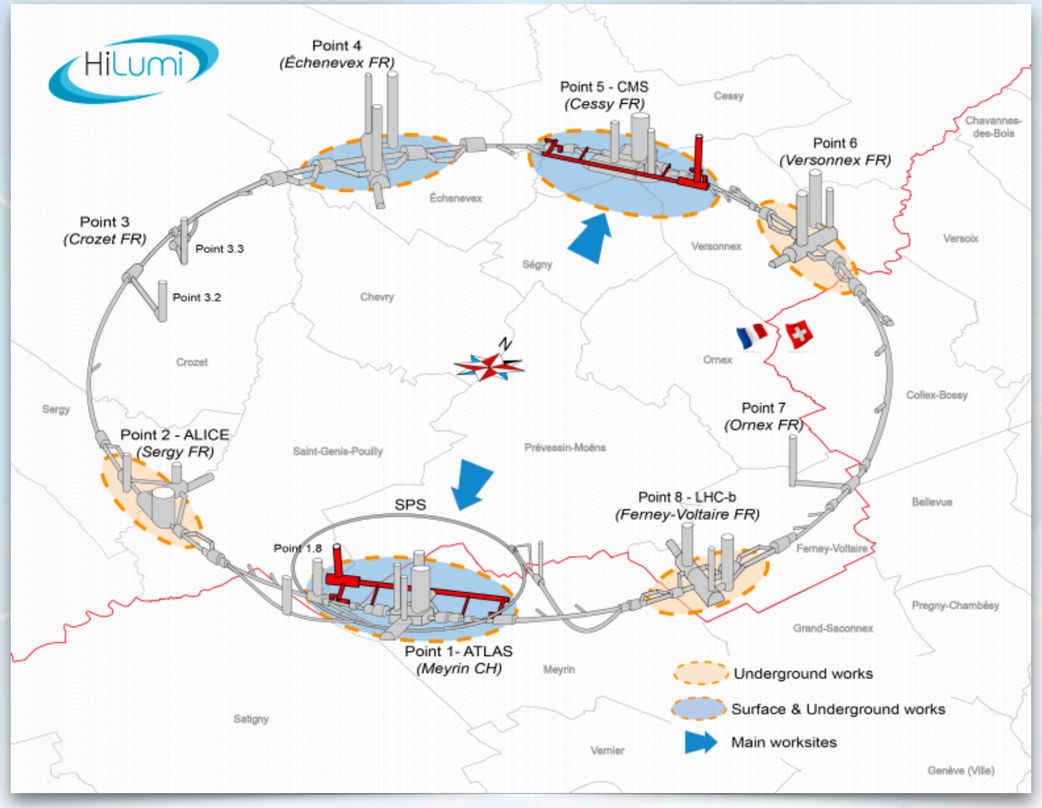
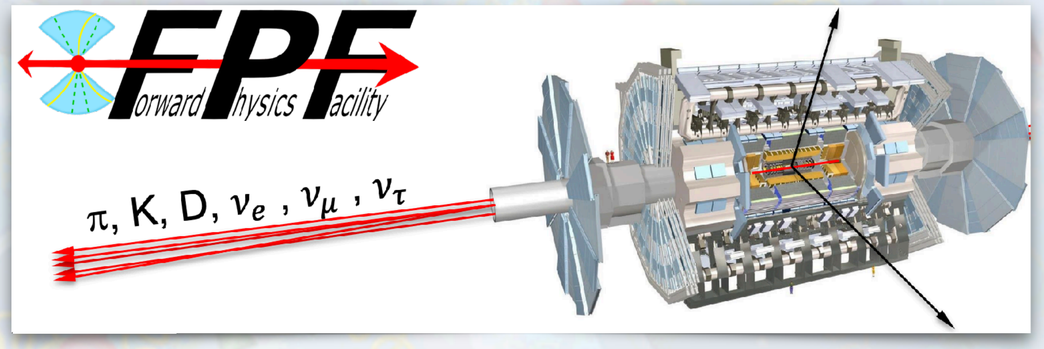




HL-LHC

Forward Physics Facility

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

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

Hadronic structure at high energies

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

Modeling gluon TMDs

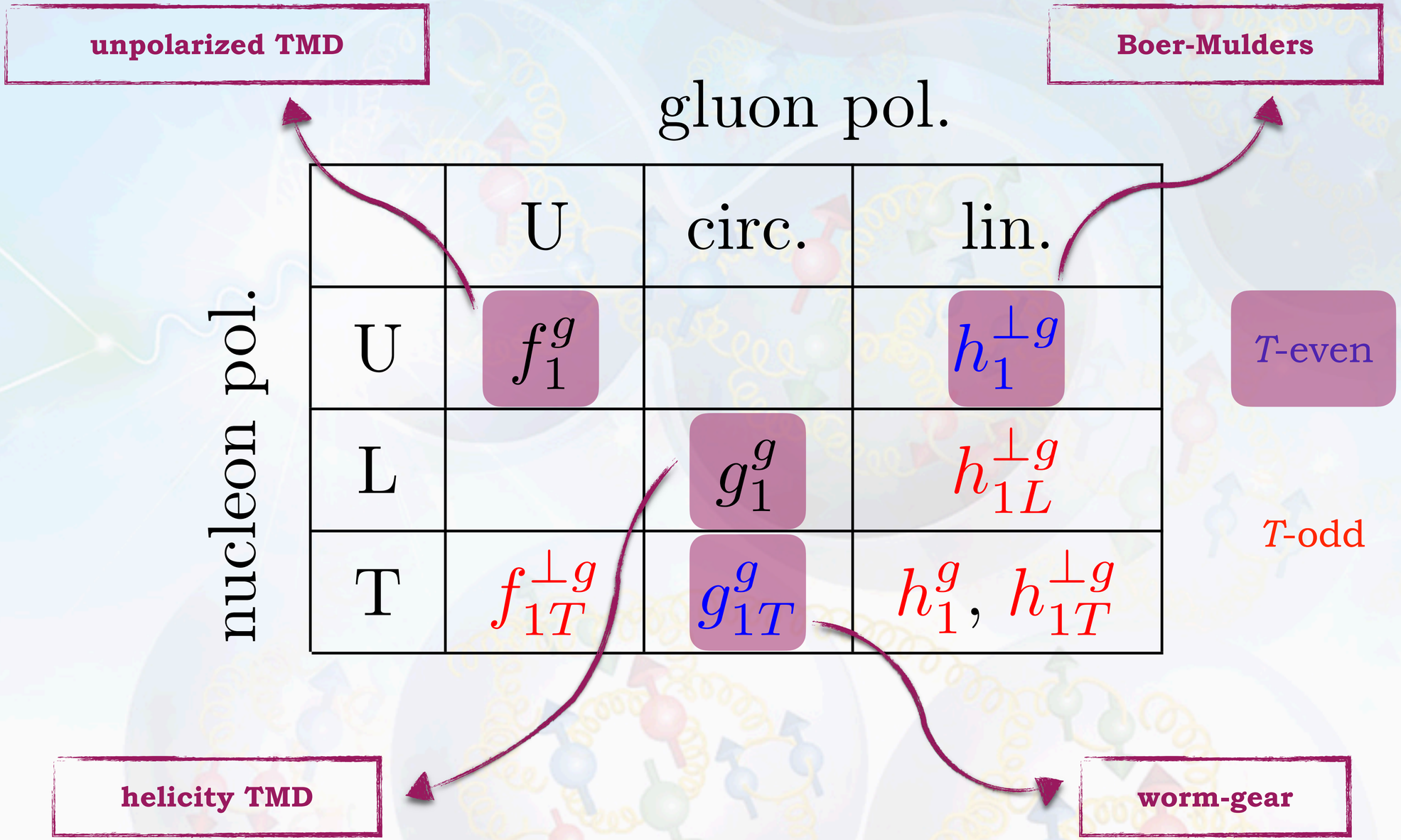
T-even and *T*-odd gluon TMD PDFs at leading-twist

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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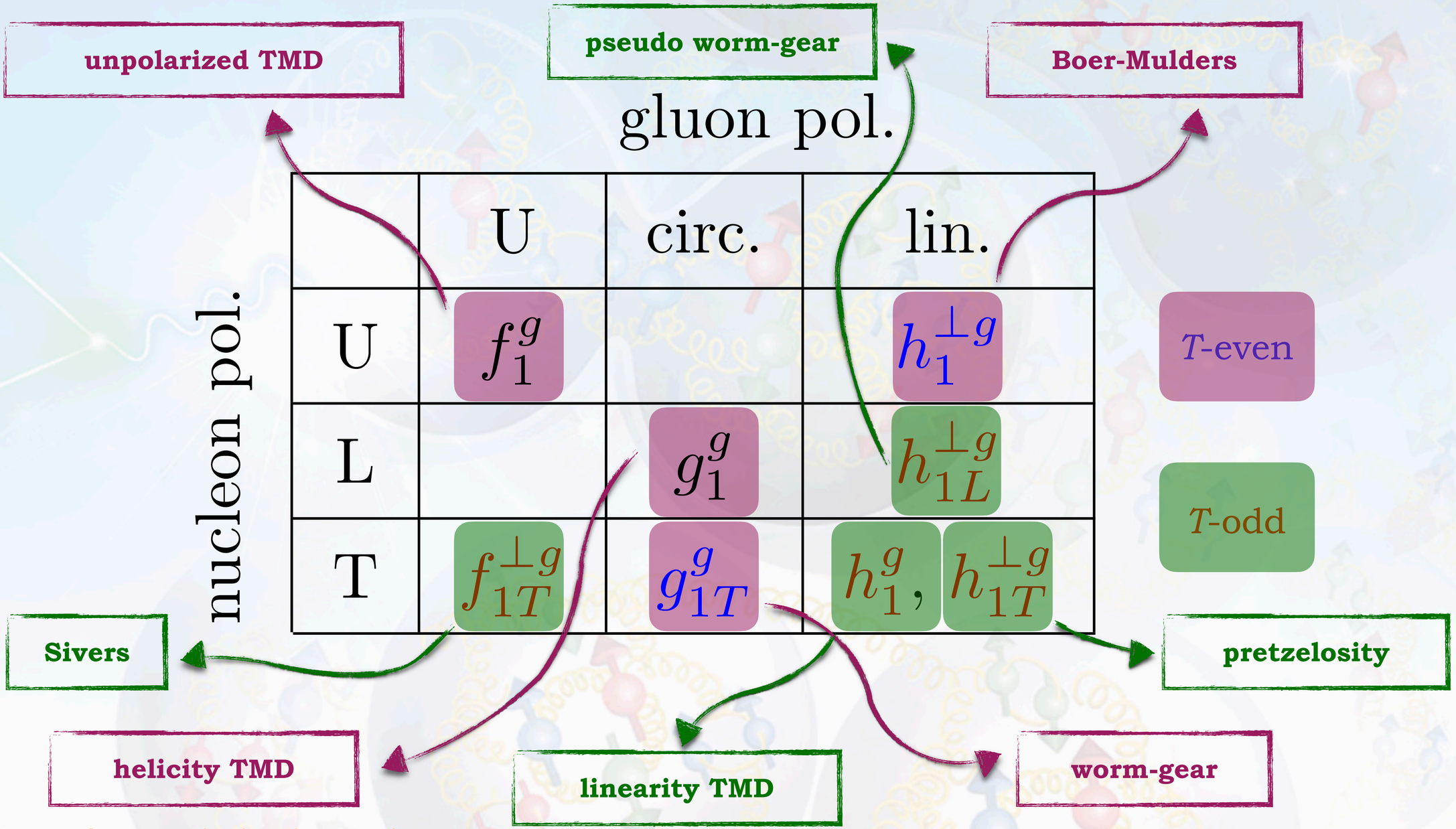
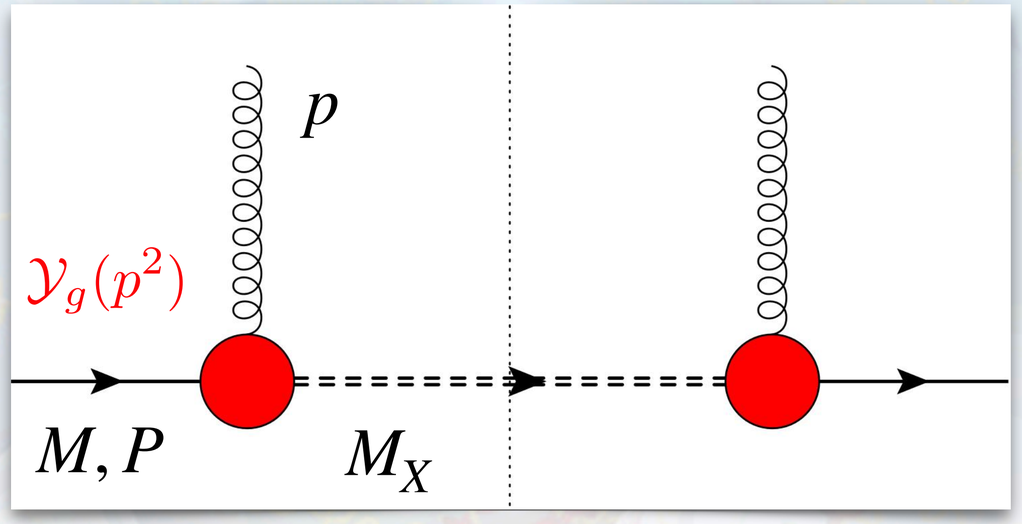


Assumptions of the model

Spin-1/2 spectator

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



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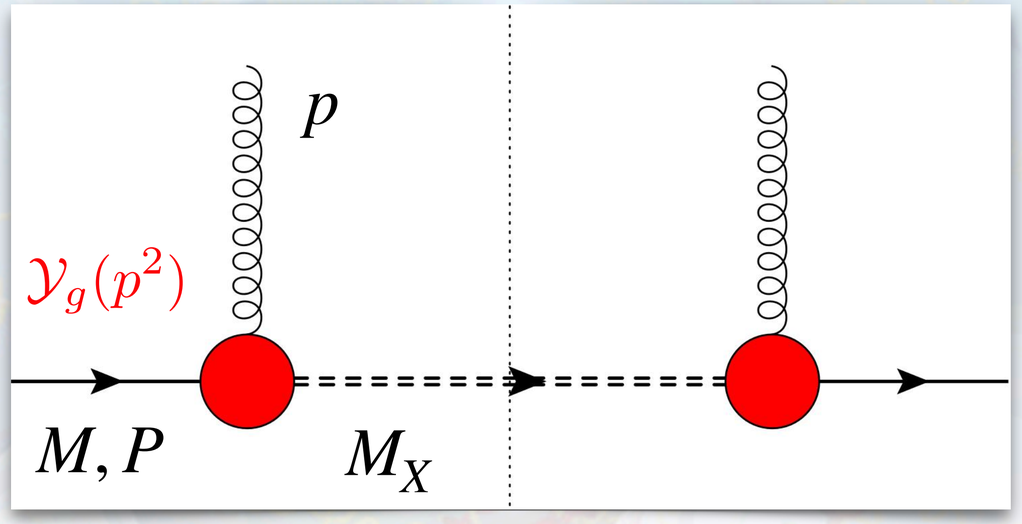


Nucleon-gluon-spectator vertex

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

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

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
2. TMDs and PDFs *decouple* due to evolution

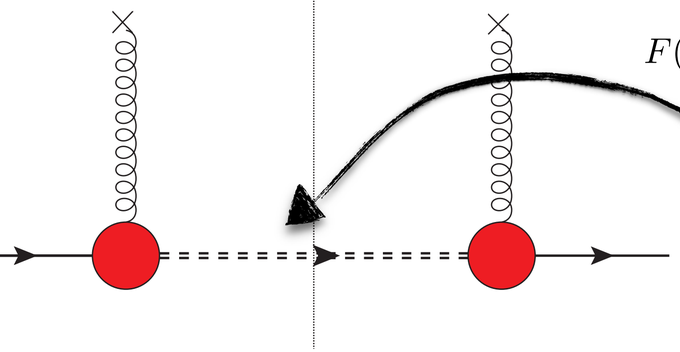
Dipolar form factor(s)

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

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

Our model at a glance

Spectator-system spectral-mass function



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

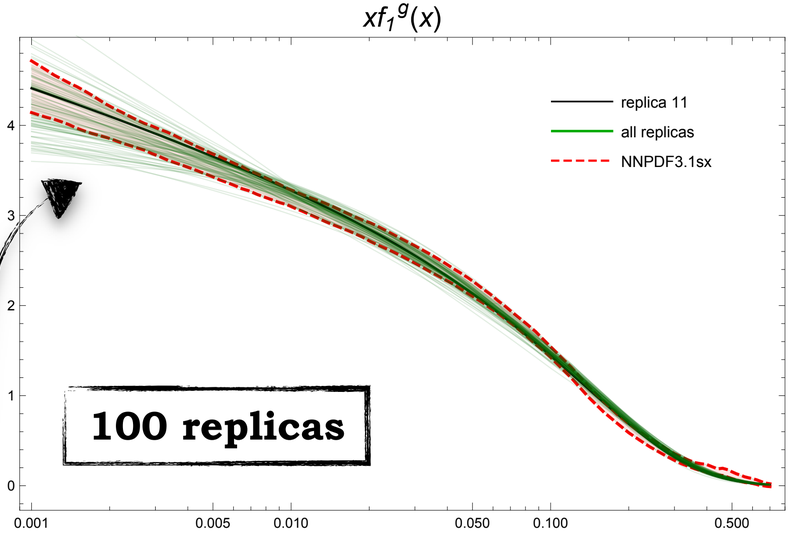
Instead of a single on-shell spectator, a continuum of spectators

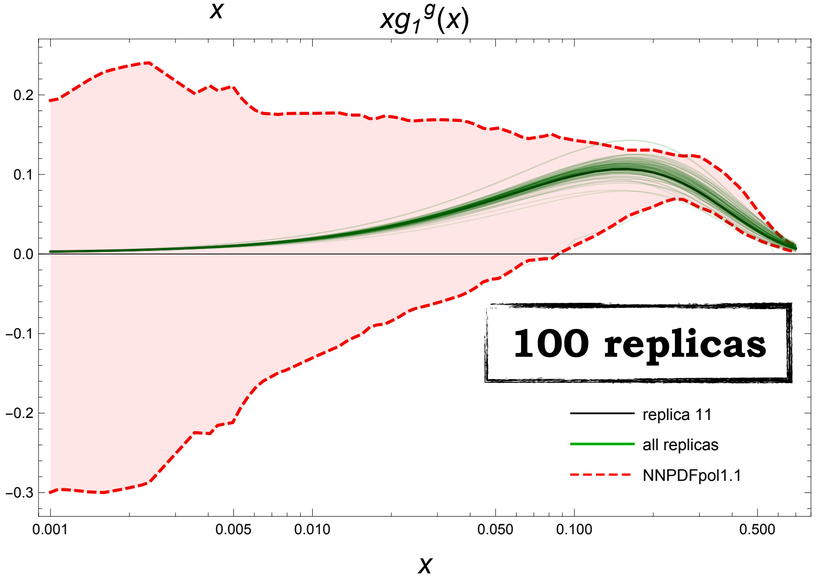
Spectral function **learns** small- and moderate-x info encoded in **NNPDF** collinear parametrizations (`NNPDF3.1sx + NNPDFpol1.1`)

- ☑ **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

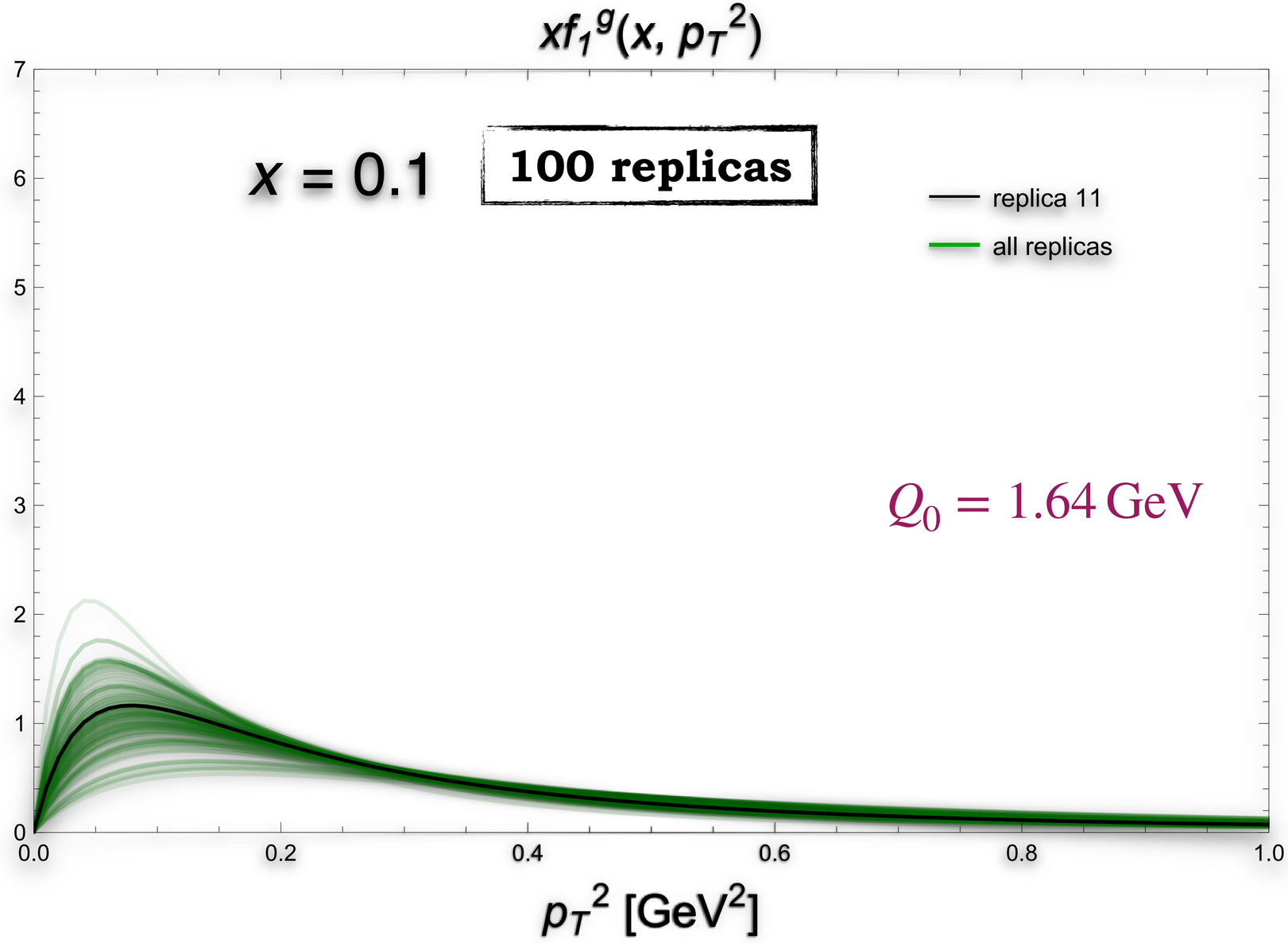
p_T-integrated TMDs **have to** reproduce PDFs at the lowest scale (Q_0) *before* evolution





2.2 *T*-even gluon TMDs 🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Unpolarized gluon TMD



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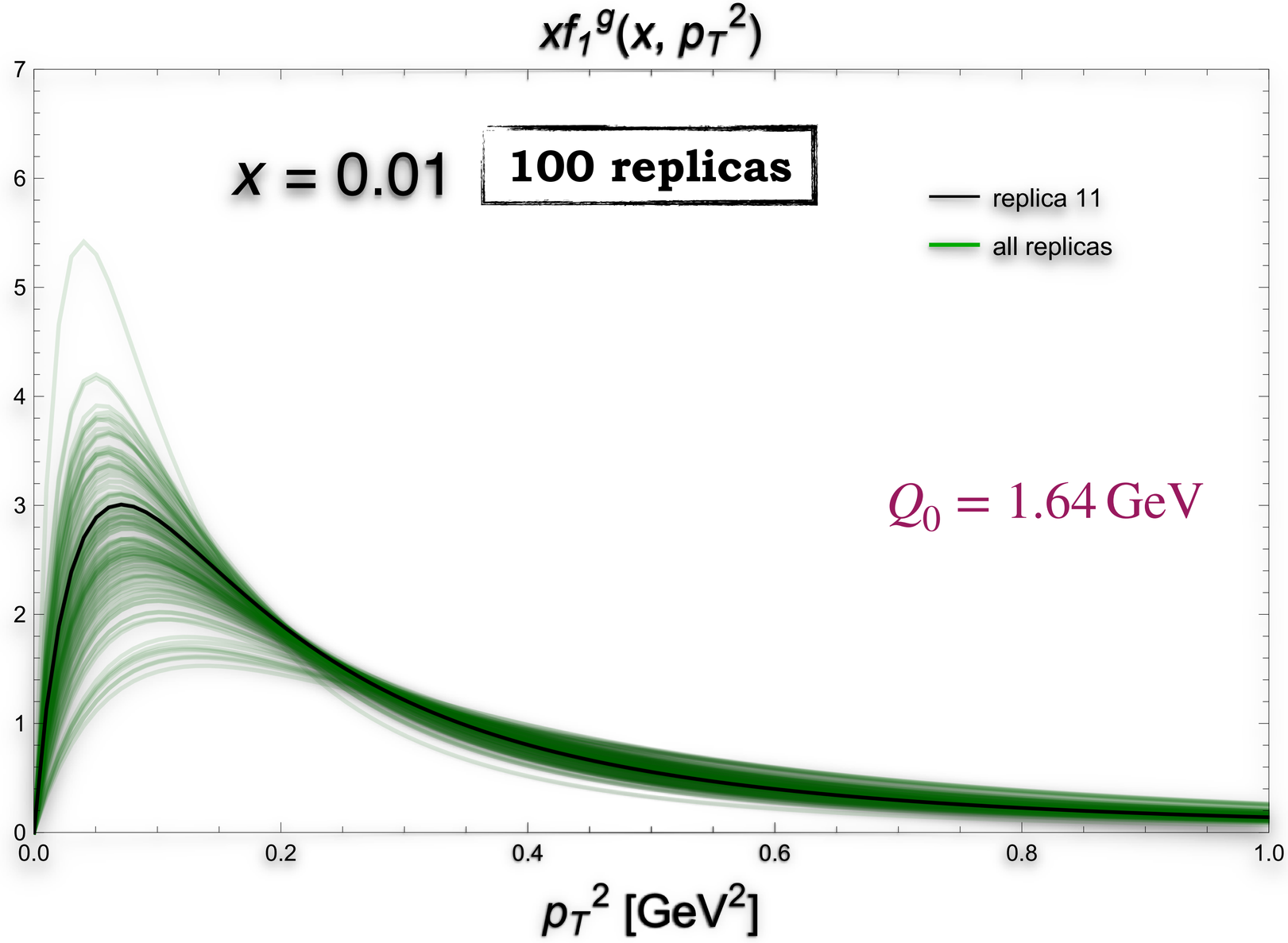

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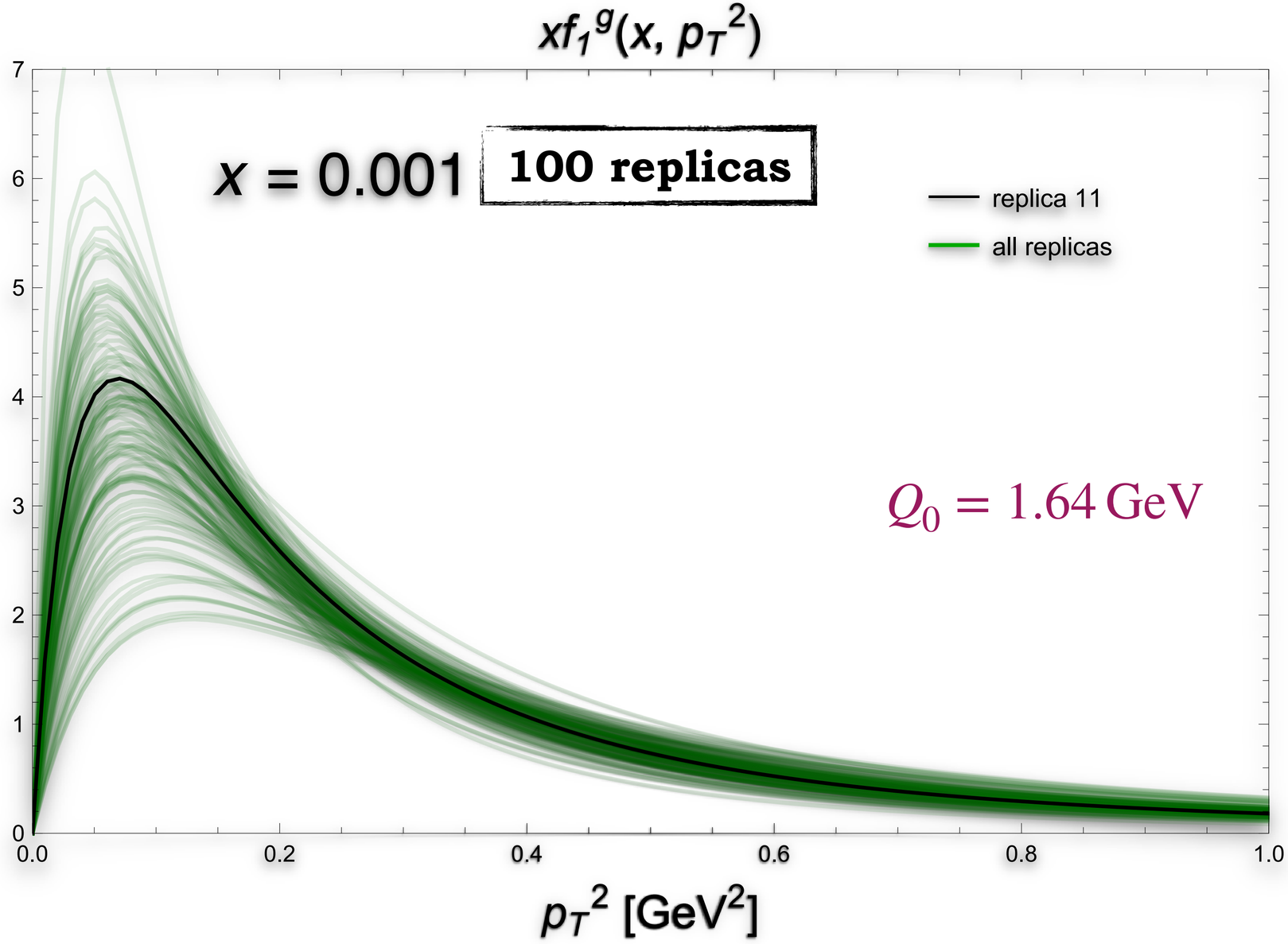
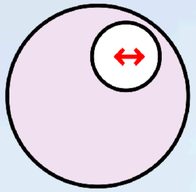


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

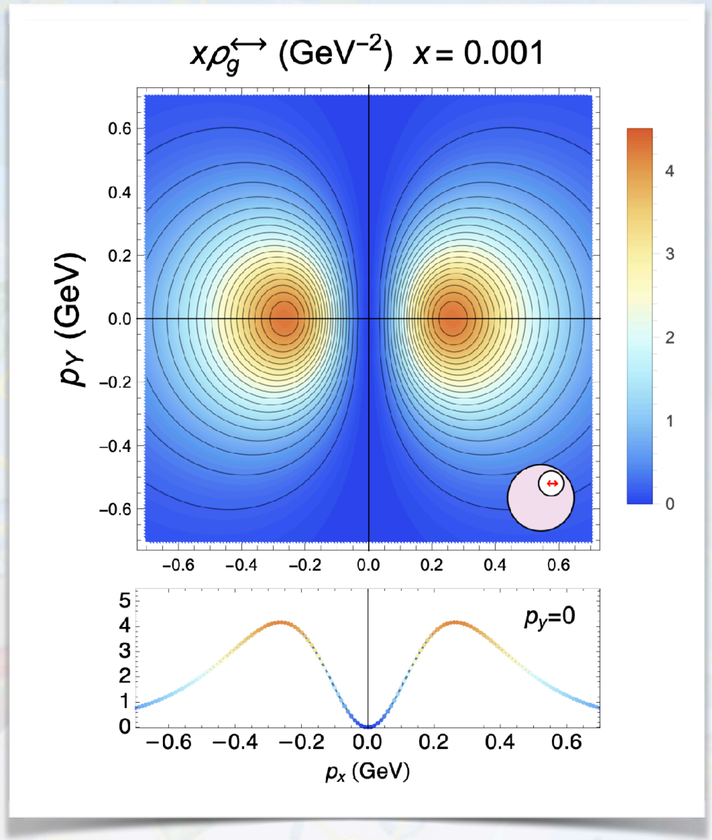
Gluon TMDs and quarkonia in proton collisions

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



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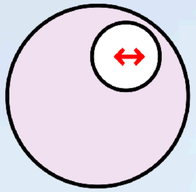

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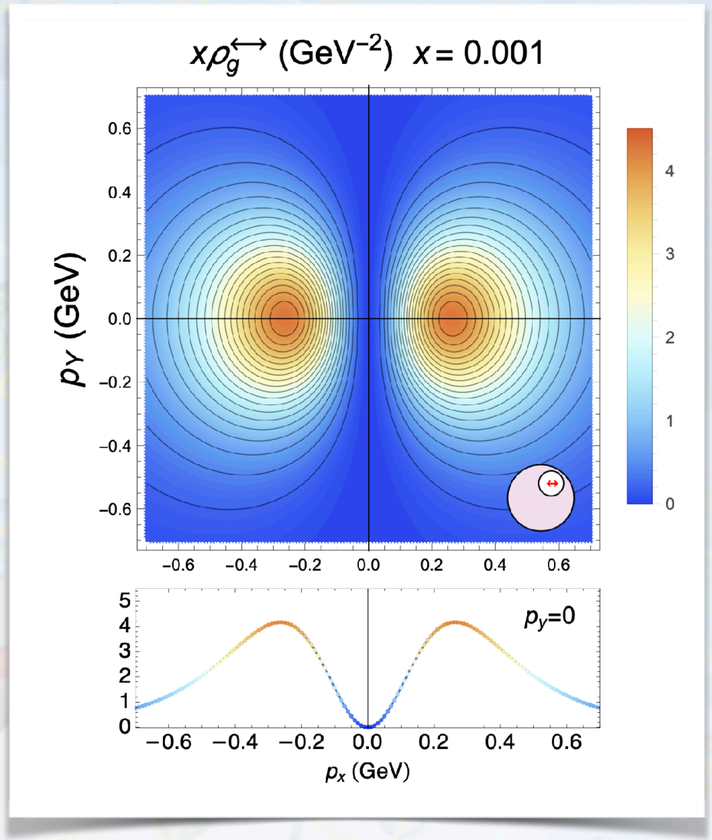
unpol. Boer-Mulders

(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)]



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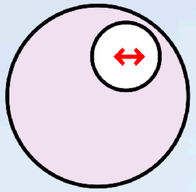

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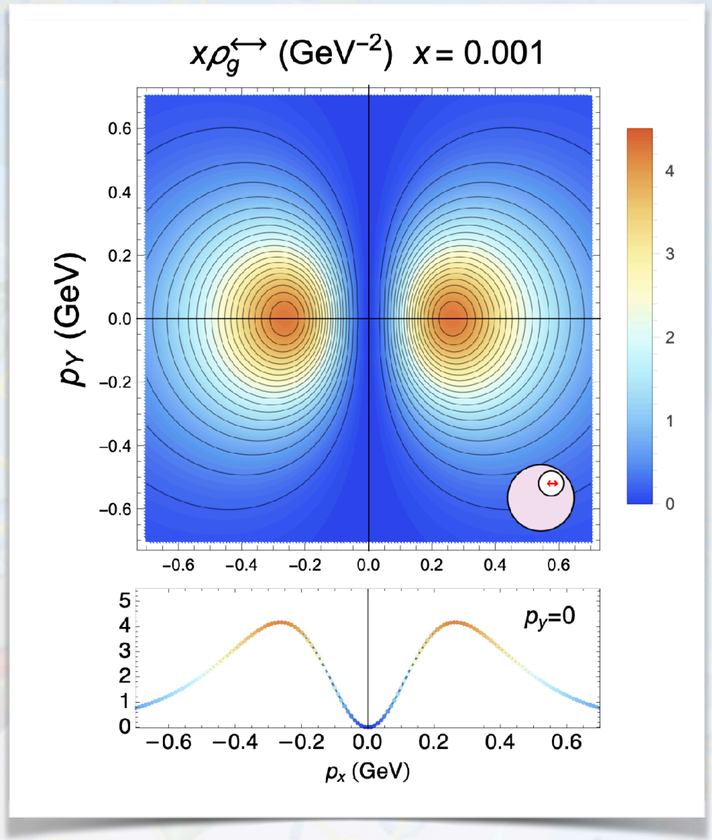

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Model prediction at low-x

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

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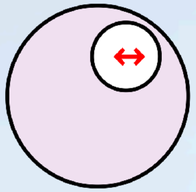

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unpol. Boer-Mulders

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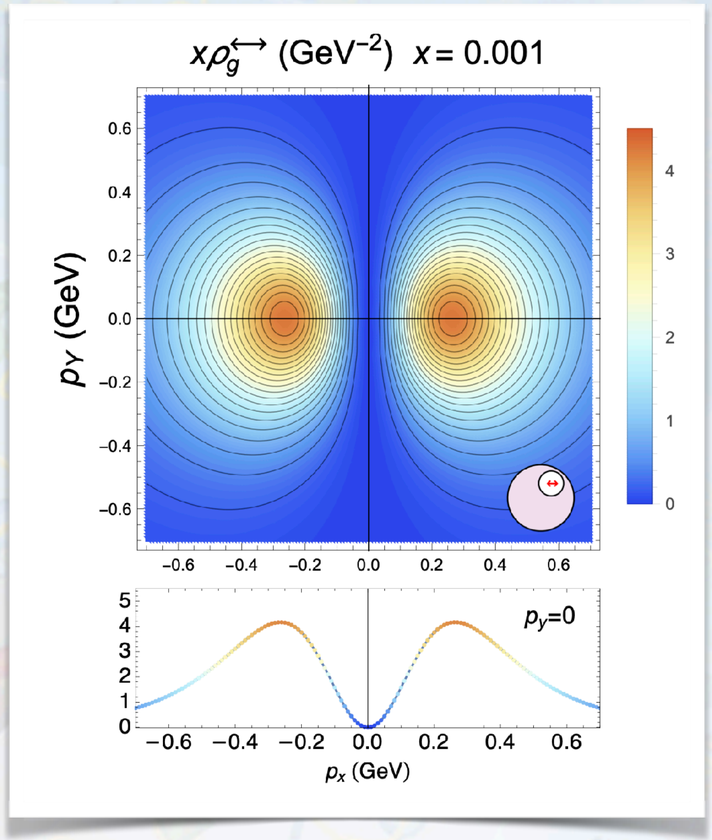

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Model prediction at low-x

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HEF regime (linear low-x evolution)

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

Anatomy of gluon TMDs

matching coefficients

collinear PDF

nonperturbative Sudakov

nonperturbative TMD function

$$F(x,\mathbf{b};\mu,\zeta) = \sum_j \left(C_j^{(F)} \otimes F^j \right)(x,b_*;\mu_b) e^{S(b_*;\mu_b,\mu,\zeta)} e^{S_{\rm NP}(b)} F_{\rm NP}(x,b)$$

perturbative Sudakov

perturbative expansion in $\alpha_s(\mu)$

resummation of

$$L = \ln \frac{Q^2}{\mu_b^2}$$

define logarithmic ordering

Anatomy of gluon TMDs

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perturbative expansion in $\alpha_s(\mu)$

perturbative Sudakov

resummation of $L = \ln \frac{Q^2}{\mu_b^2}$

Model input

define logarithmic ordering

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resummation of $L = \ln \dfrac{Q^2}{\mu_b^2}$

Model input

define logarithmic ordering

$$f_1(x,\mathbf{b},\mu,\zeta) \;\to\; C_j^{(f_1)} \otimes f_1^j = \left[1 + \mathcal{O}(\alpha_s)\right]_j \otimes f_1^j$$

Anatomy of gluon TMDs

matching coefficients

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$$h_1^\perp(x,\mathbf{b},\mu,\zeta) \;\to\; C_j^{(h_1^\perp)} \otimes f_1^j = \left[\mathcal{O}(\alpha_s)\right]_j \otimes f_1^j$$

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matching coefficients

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perturbative expansion in $\alpha_s(\mu)$

perturbative Sudakov

resummation of $L = \ln \dfrac{Q^2}{\mu_b^2}$

define logarithmic ordering

Model input

$$f_1(x,\mathbf{b},\mu,\zeta) \;\to\; C_j^{(f_1)} \otimes f_1^j = \left[1+\mathcal{O}(\alpha_s)\right]_j \otimes f_1^j$$

$$h_1^\perp(x,\mathbf{b},\mu,\zeta) \;\to\; C_j^{(h_1^\perp)} \otimes f_1^j = \left[\mathcal{O}(\alpha_s)\right]_j \otimes f_1^j$$

Suppression of genuine NP effects!

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

TMD phenomenology:

from JLab to the LHC

Andrea Signori

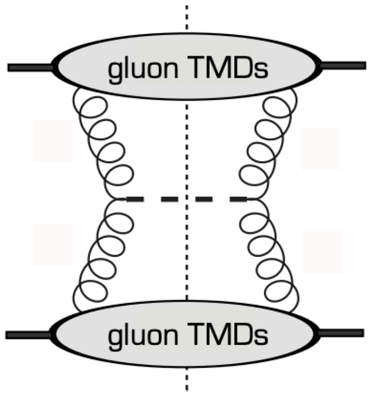
Spatial and momentum tomography of hadrons and nuclei

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

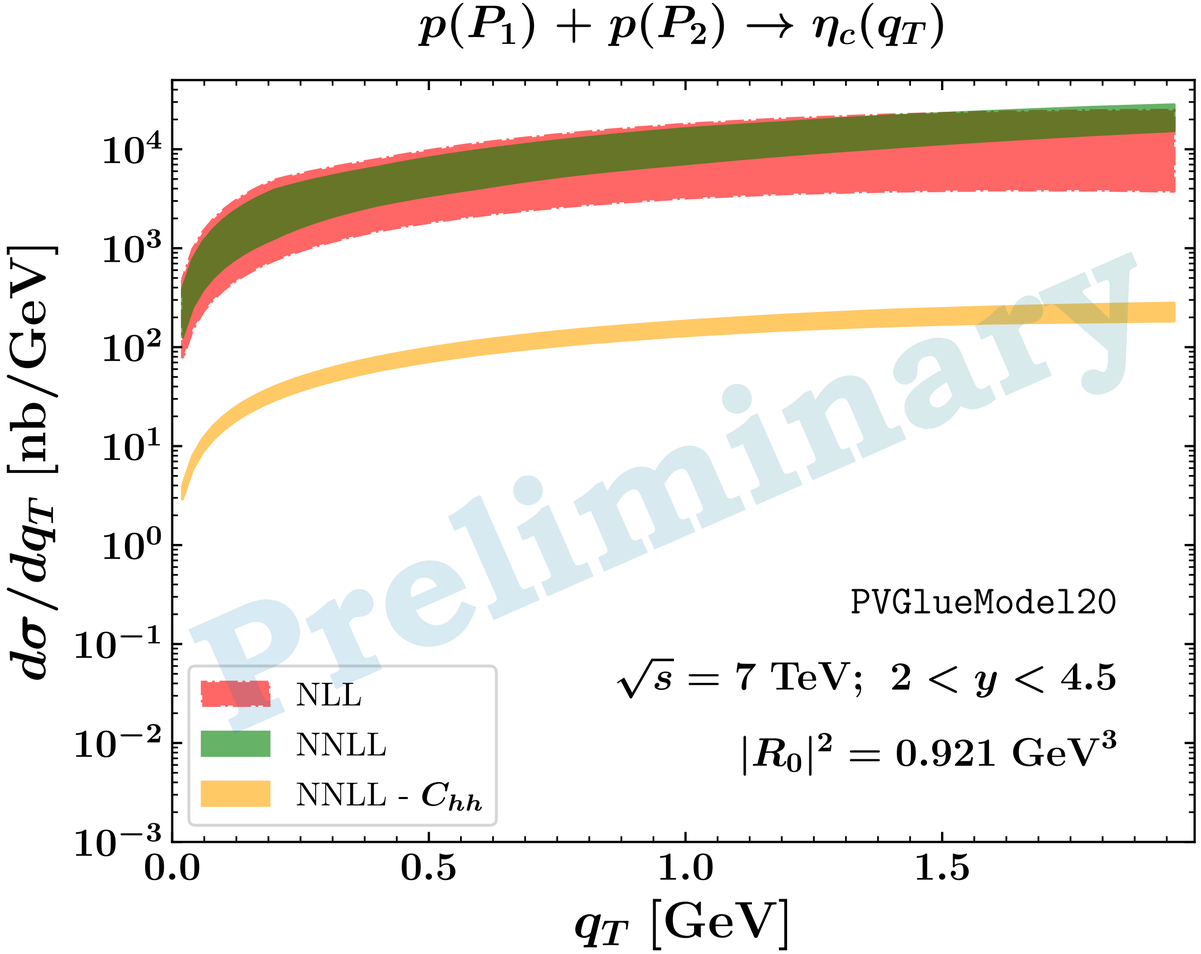
C_{ff} C_{hh}

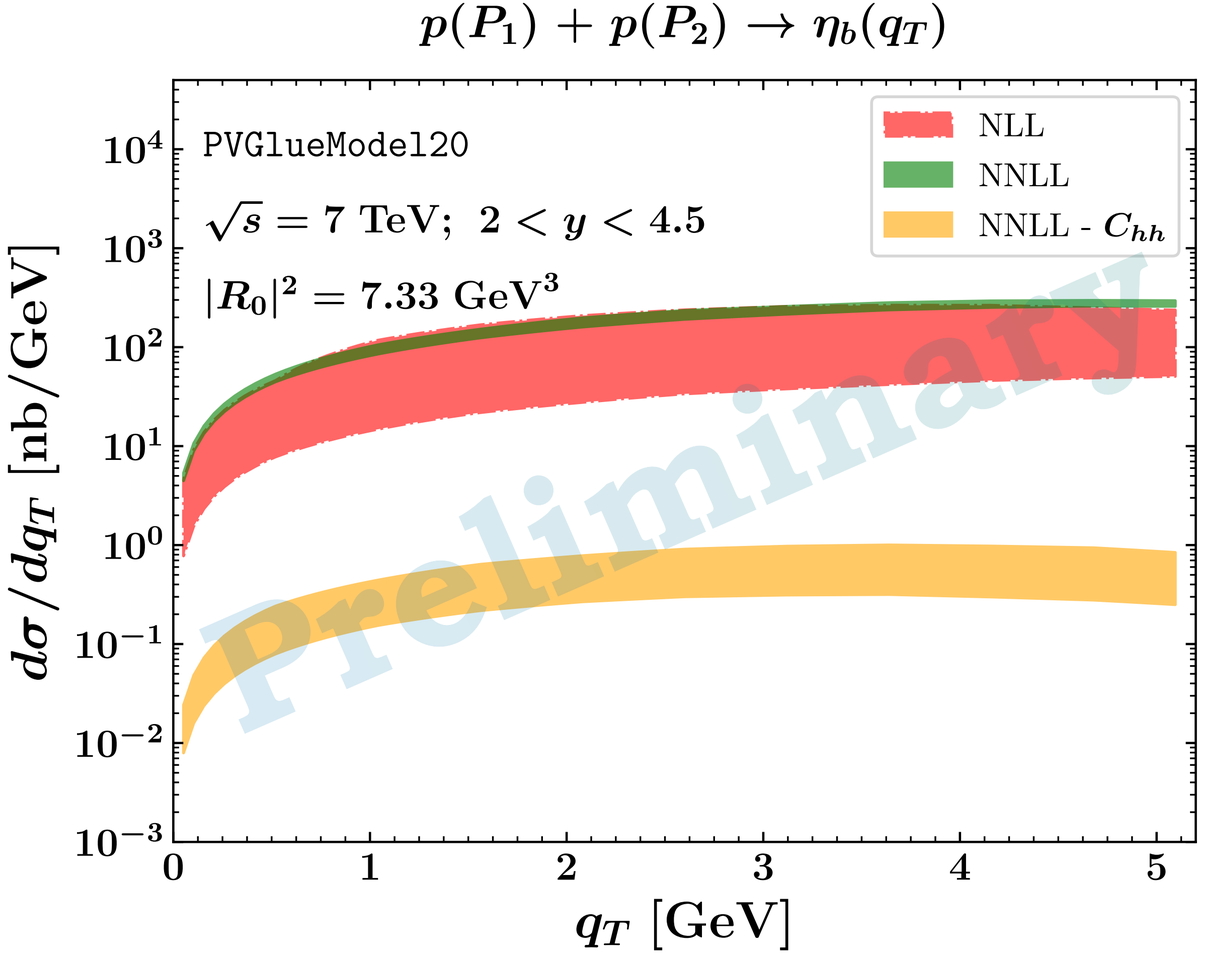
22

Jefferson Lab

$\eta_{b,c}$ production @ 7TeV LHCb

Perturbative-scale variation, NP-evolution parameters fixed, TMD central replica

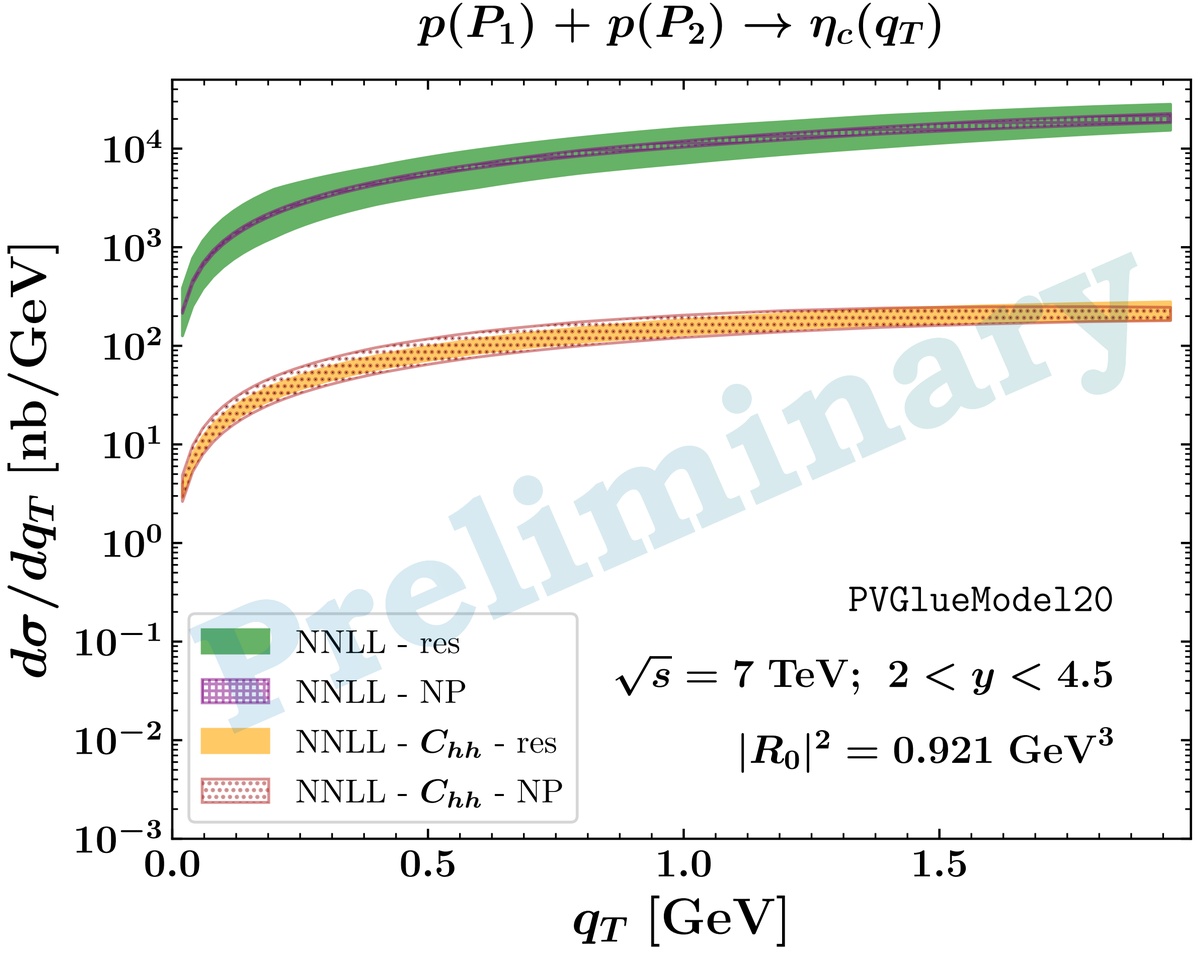


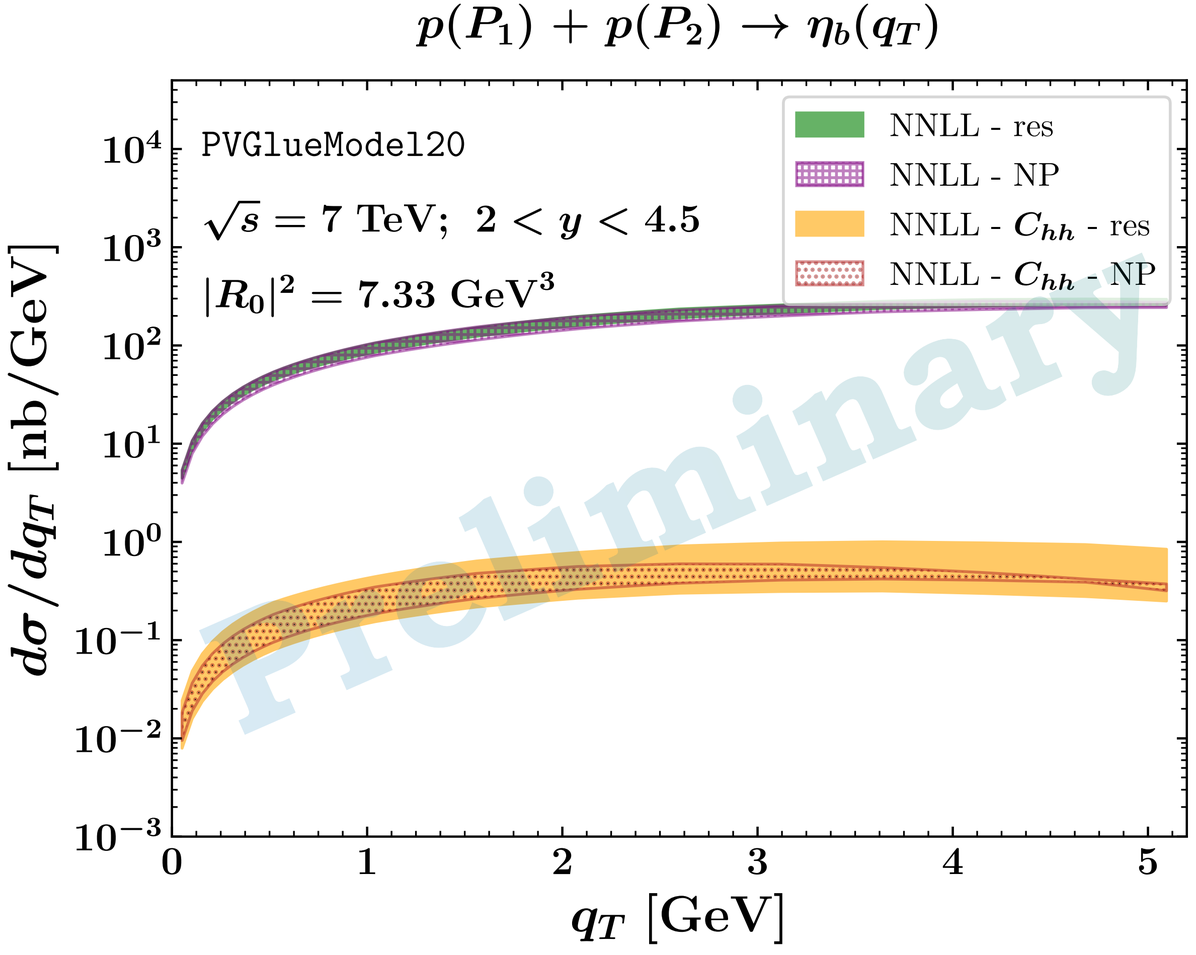


[A. Bacchetta, F.G. C., J.-P. Lansberg, A. Signori (in preparation)]

$\eta_{b,c}$ production @ 7TeV LHCb

Perturbative scales fixed, **NP-evolution parameter** variation, TMD central replica

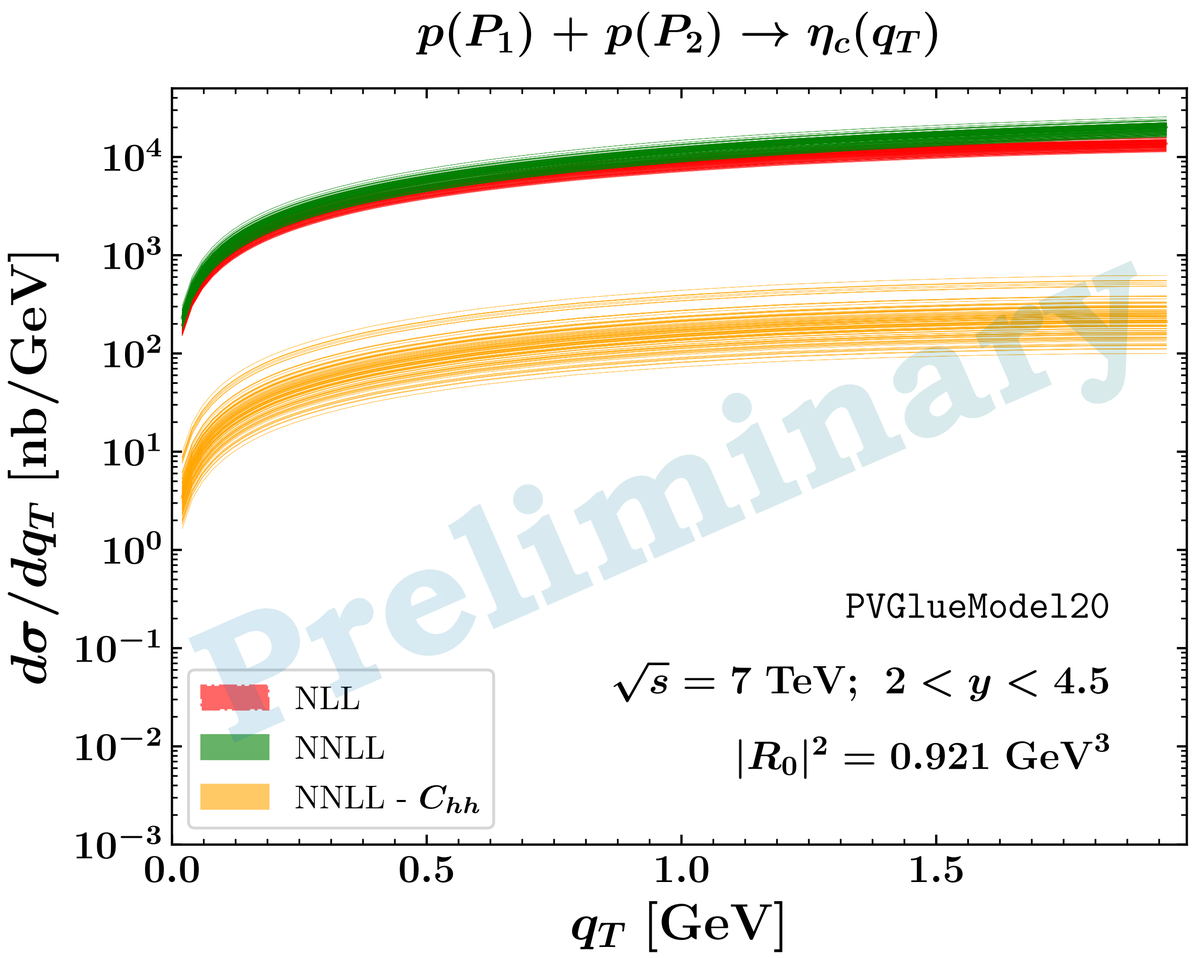


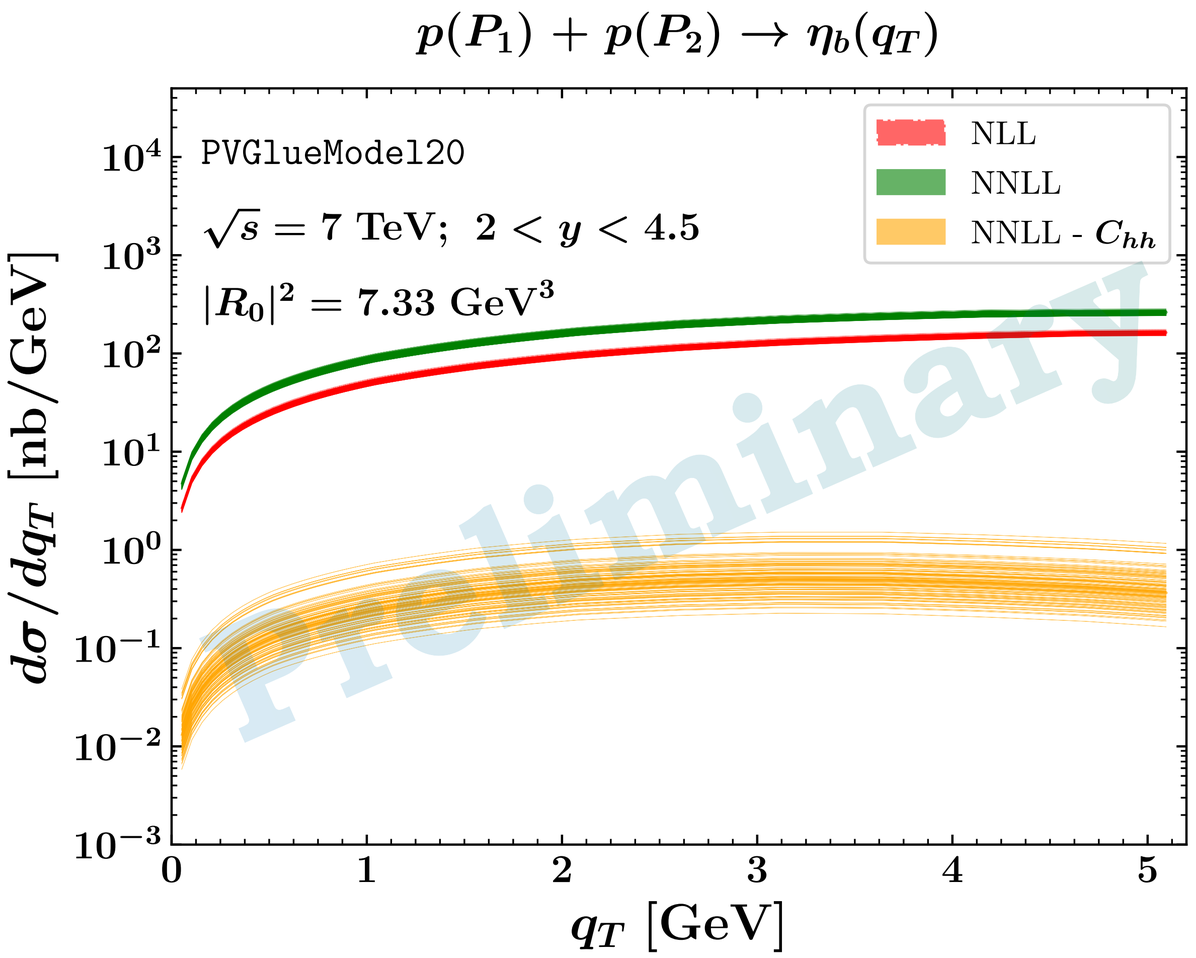


[A. Bacchetta, F.G. C., J.-P. Lansberg, A. Signori (in preparation)]

$\eta_{b,c}$ production @ 7TeV LHCb

Perturbative scales fixed, NP-evolution parameters fixed, **TMD 100-replica analysis**

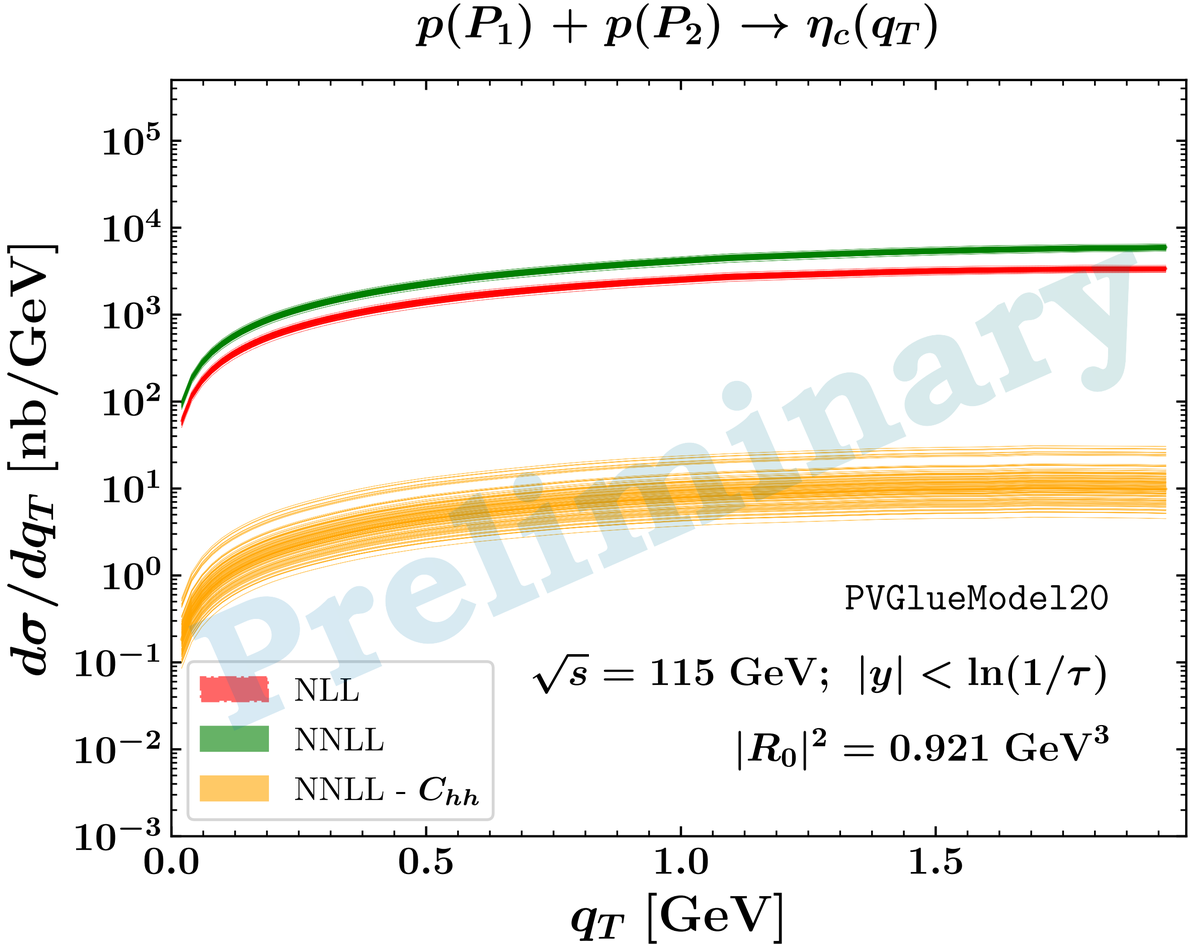


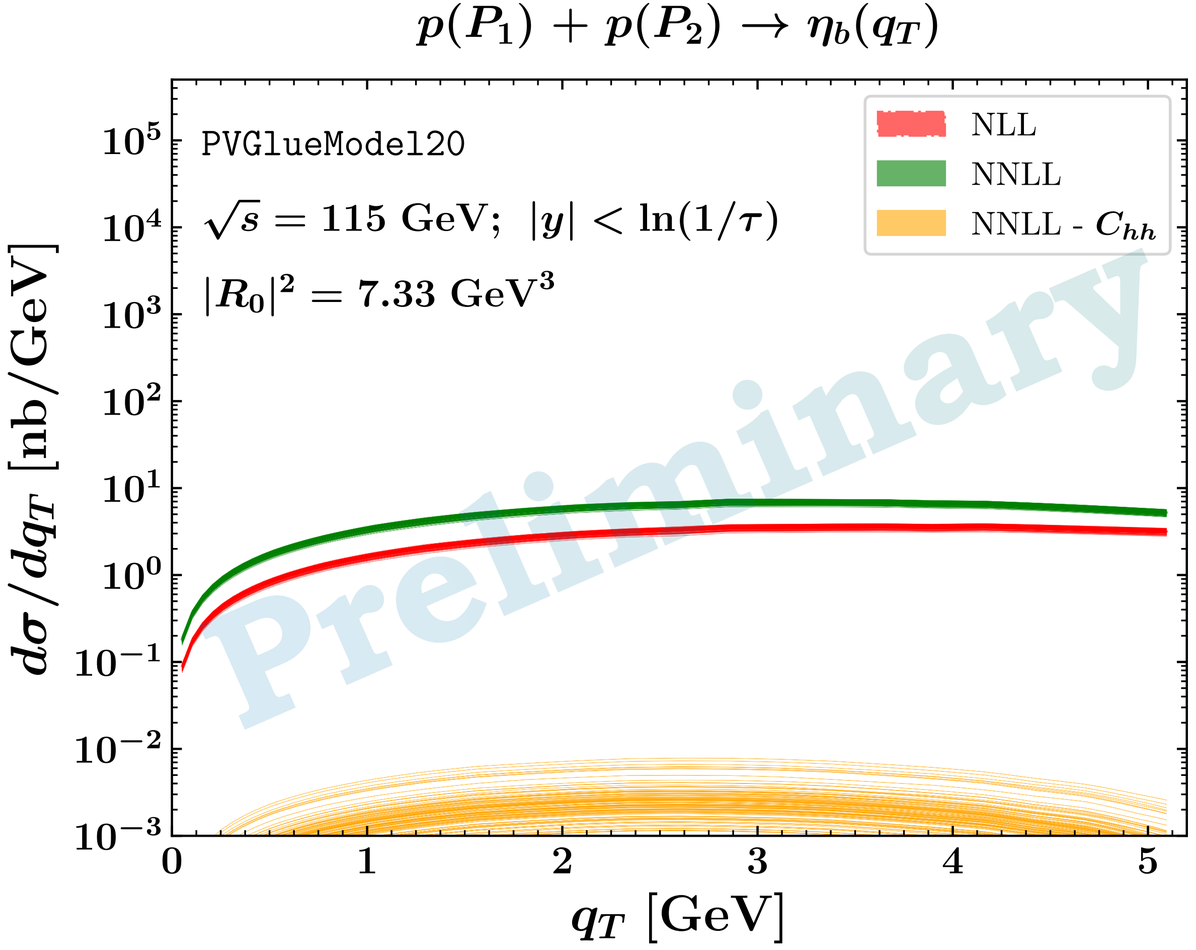


[A. Bacchetta, F.G. C., J.-P. Lansberg, A. Signori (in preparation)]

$\eta_{b,c}$ production @ 115GeV After@LHC

Perturbative scales fixed, nonpertubative parameters fixed, **TMD 100-replica analysis**





[A. Bacchetta, F.G. C., J.-P. Lansberg, A. Signori (in preparation)]

…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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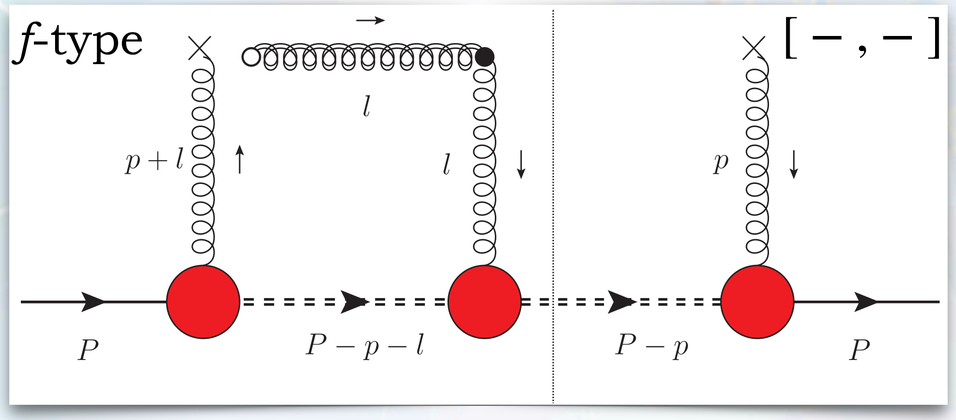
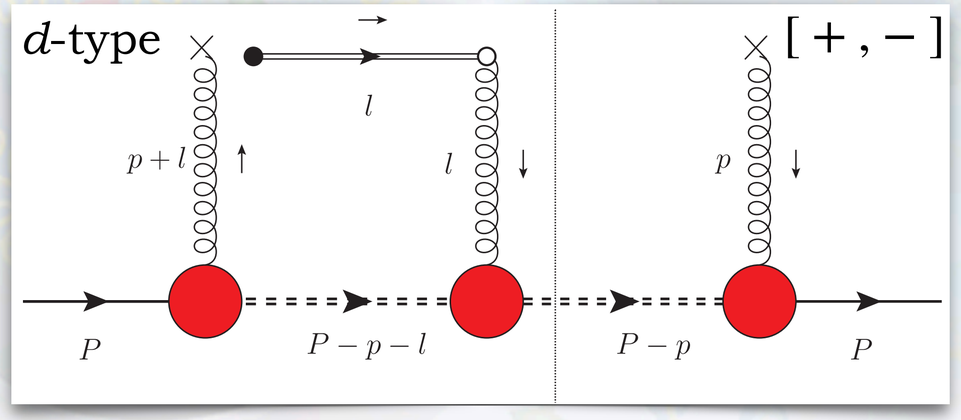
$gg \to H$



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

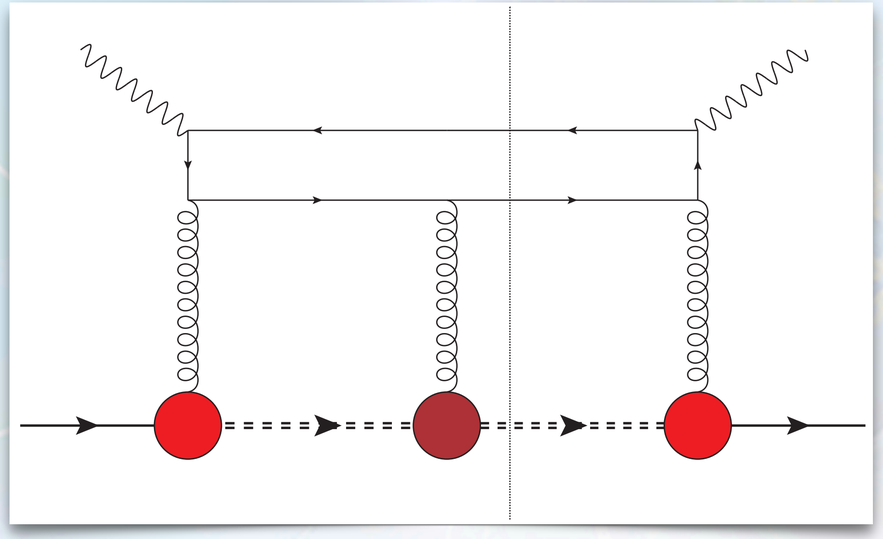


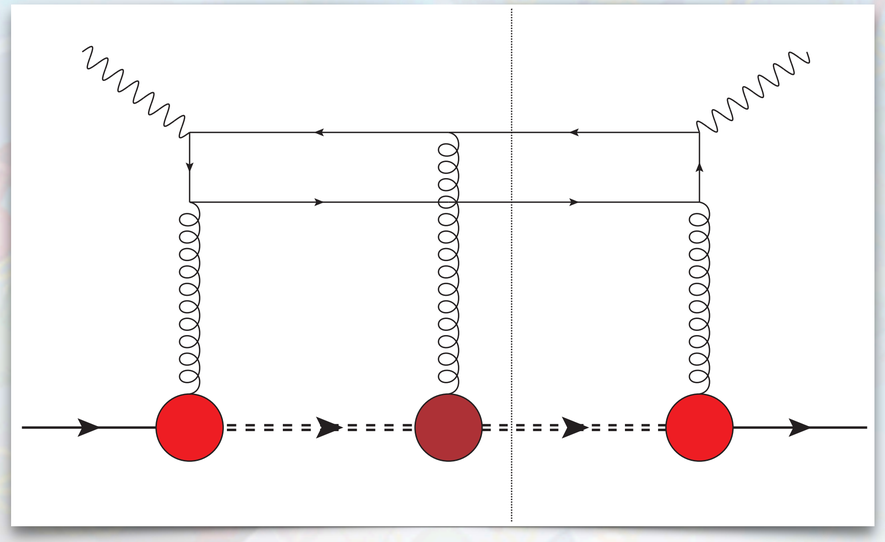
- Leading-twist one-gluon-exchange of the gauge-link operator
- Sensitivity to *f*- and *d*-type structures
- Preliminary results for **Sivers** and **linearity** functions

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

Analytic structure of *T*-odd gluon TMDs

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





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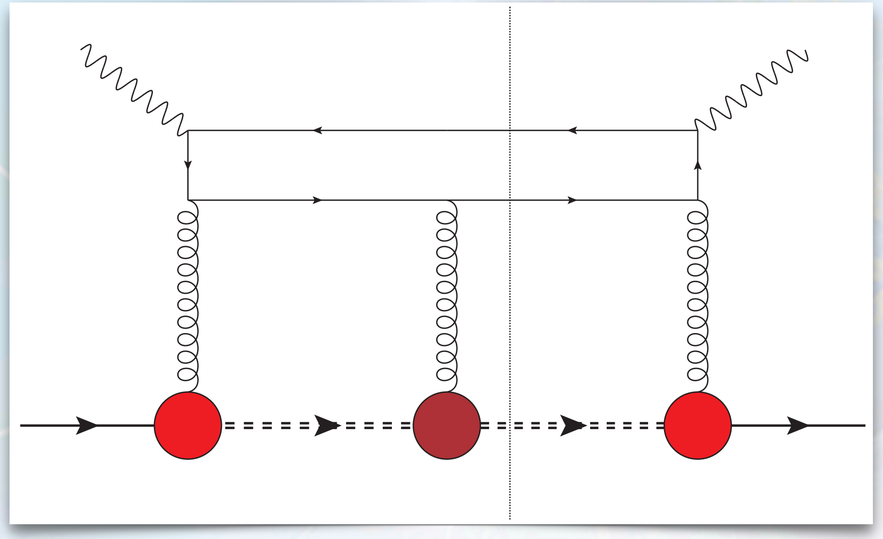

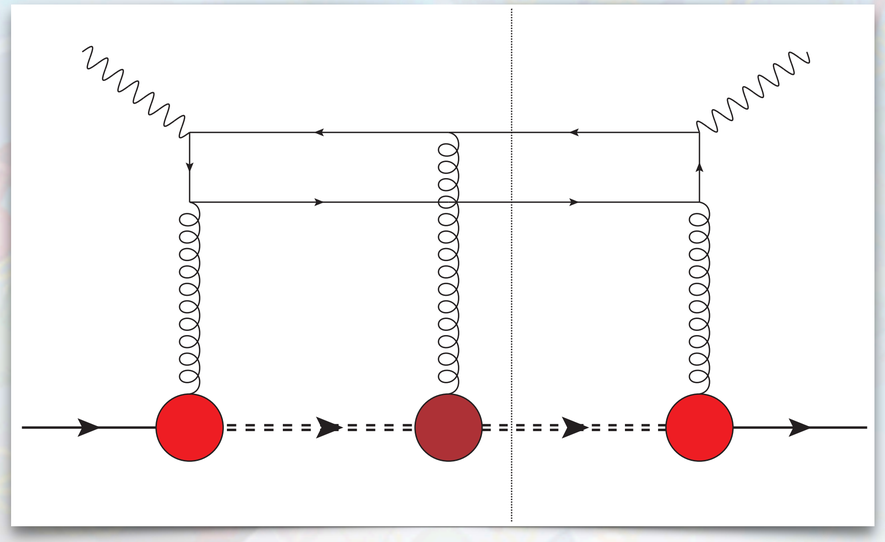

nucleon-gluon-spectator

spectator-gluon-spectator

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

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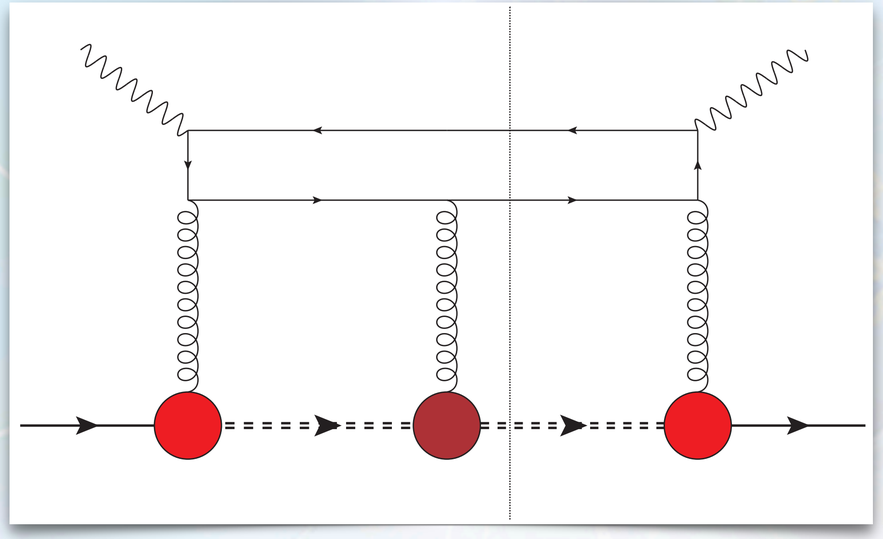

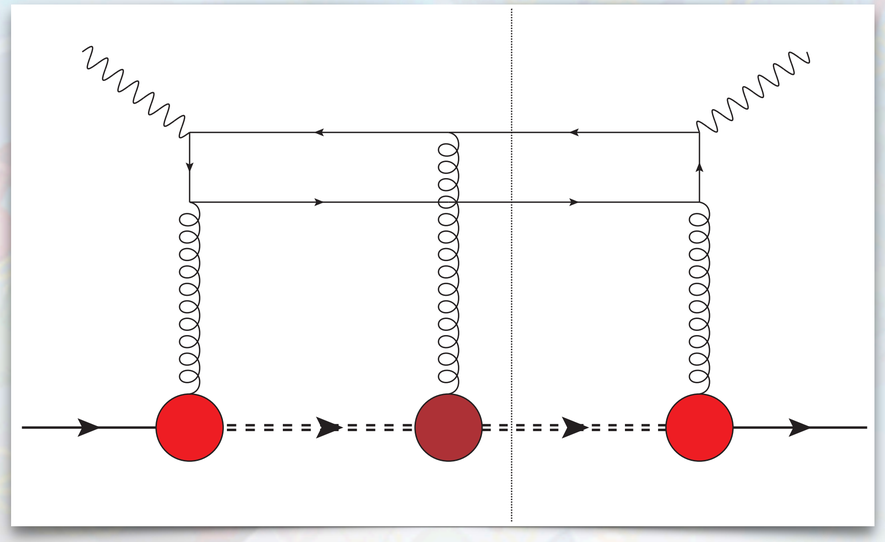

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$8 \times 7 \times 4$

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$$C_{ijk}^{(F)}(x, \boldsymbol{p}_T^2) = \sum_{l=1}^{7} \mathcal{C}_{ijk}^{(F),l}(x, \boldsymbol{p}_T^2)\, \mathcal{D}_l(x, \boldsymbol{p}_T^2)$$

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

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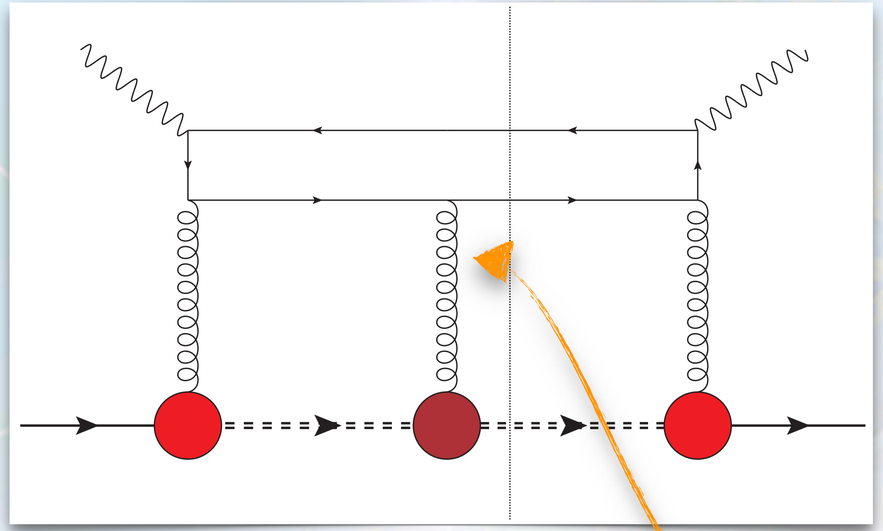

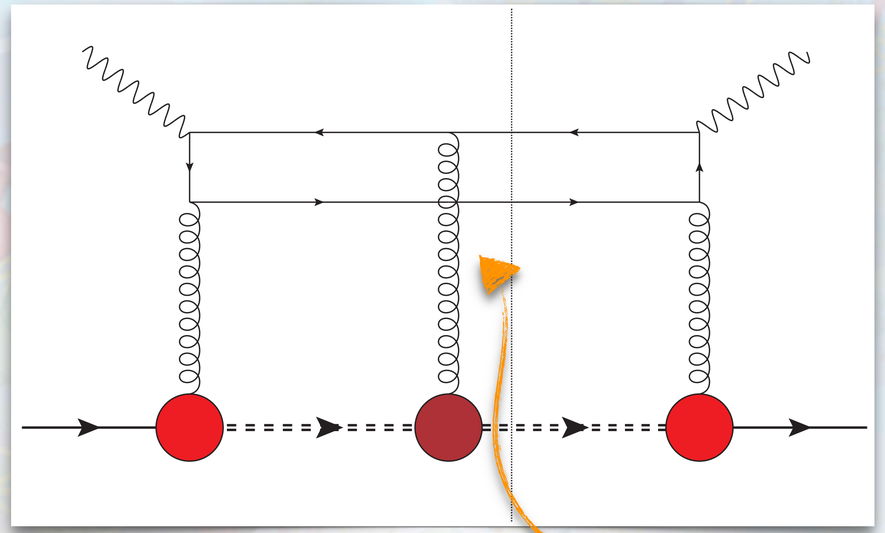

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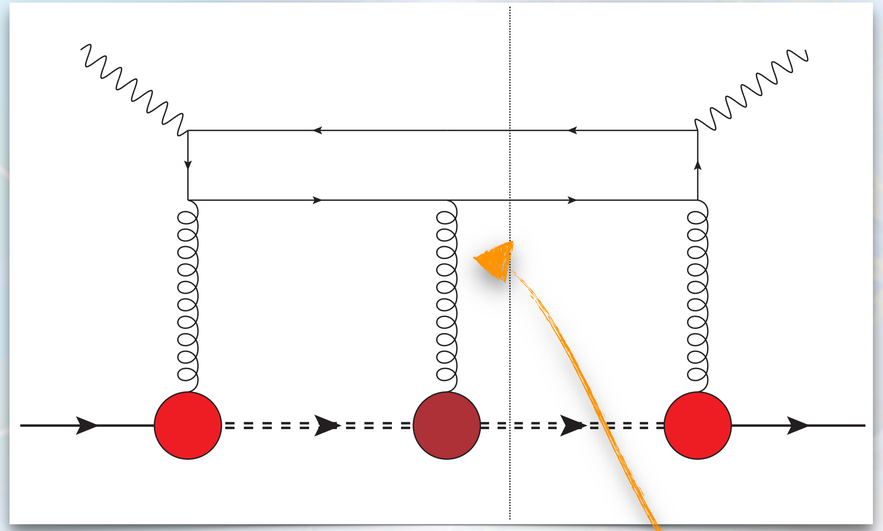

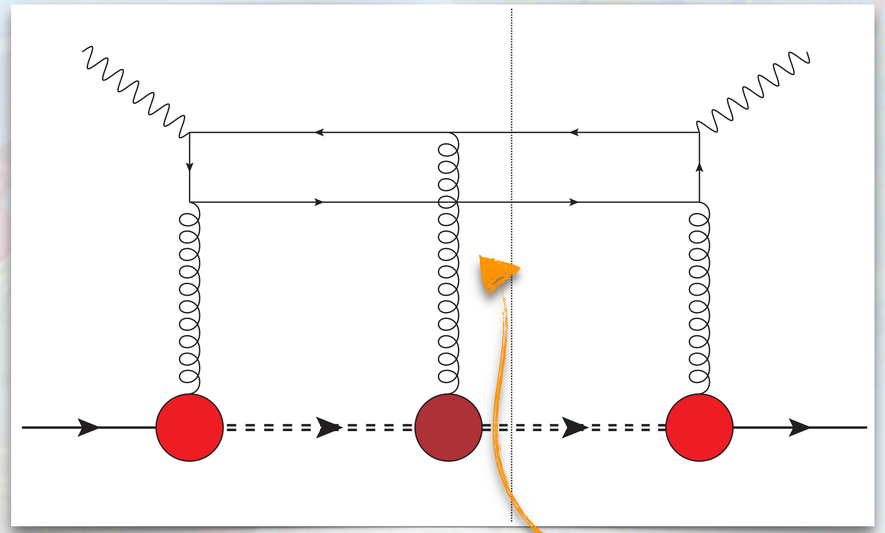

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[A. Bacchetta, F.G. C., M. Radici, *in preparation*]

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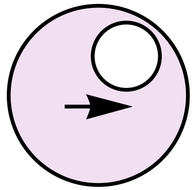
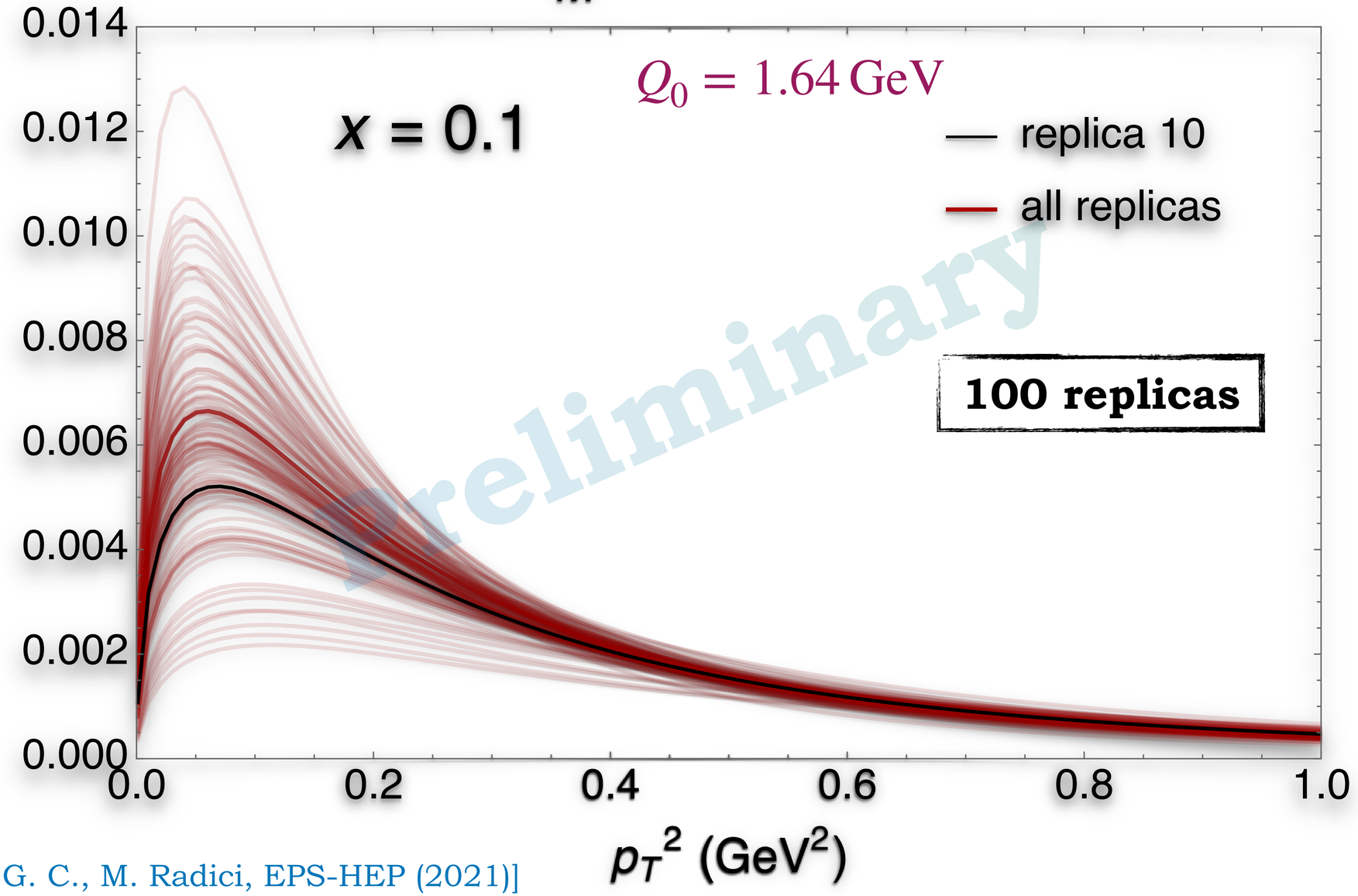


$$x\frac{p_T}{M} f_{1\,T}^{\perp[+,+]}(x, p_T^2)$$



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

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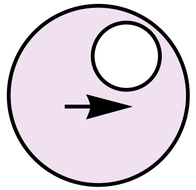

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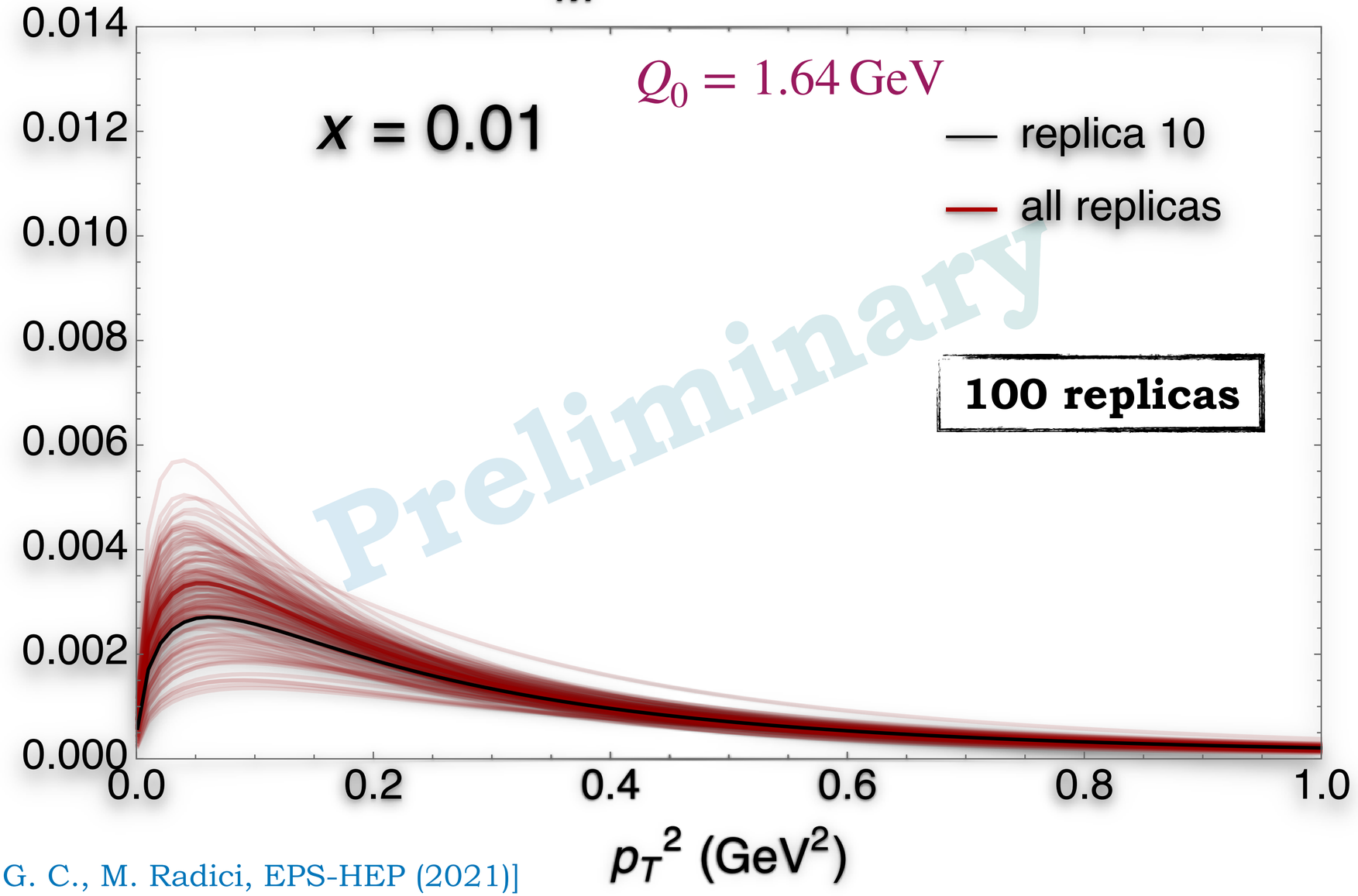

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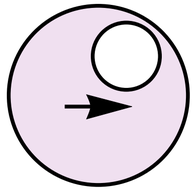

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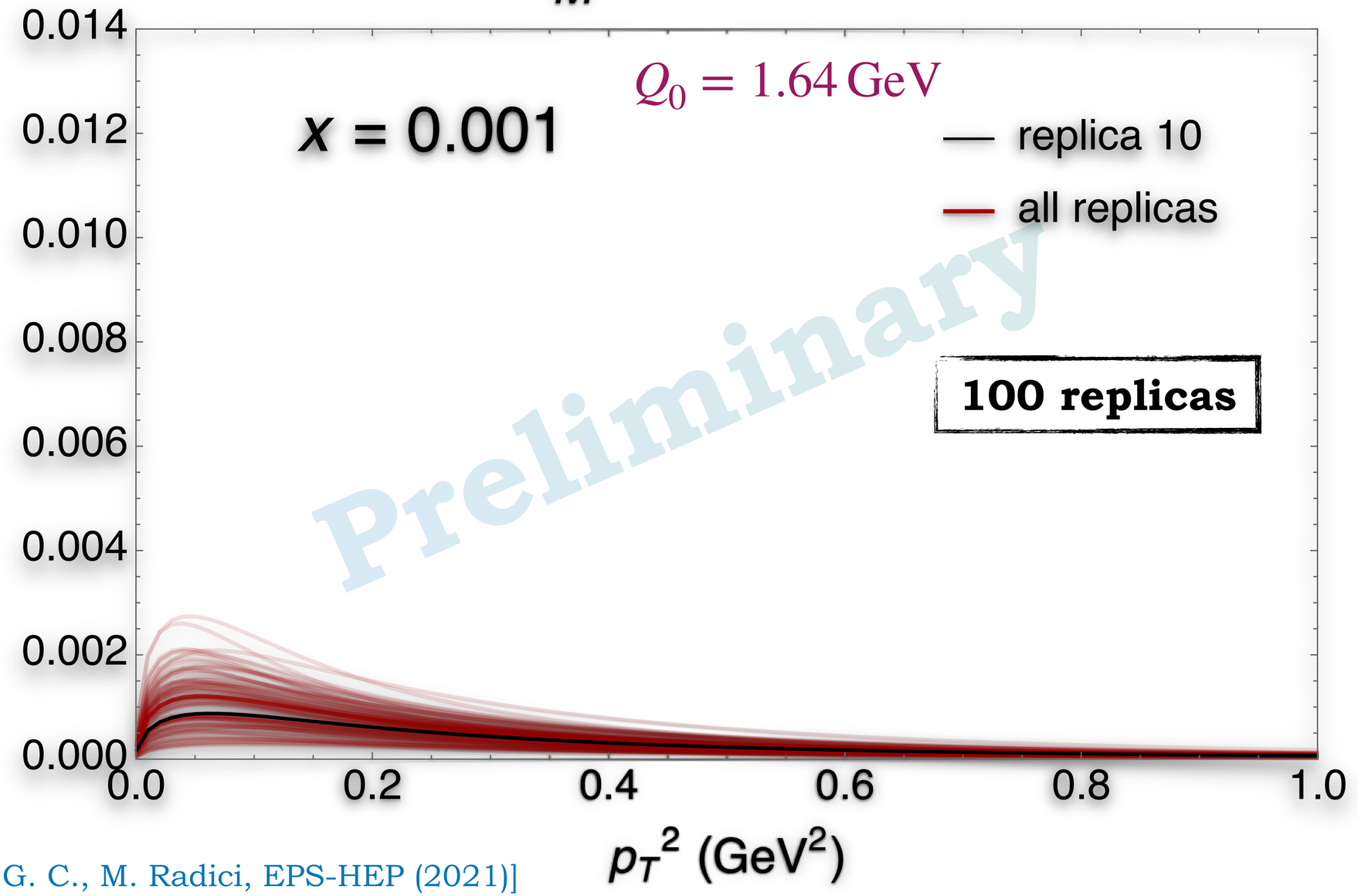
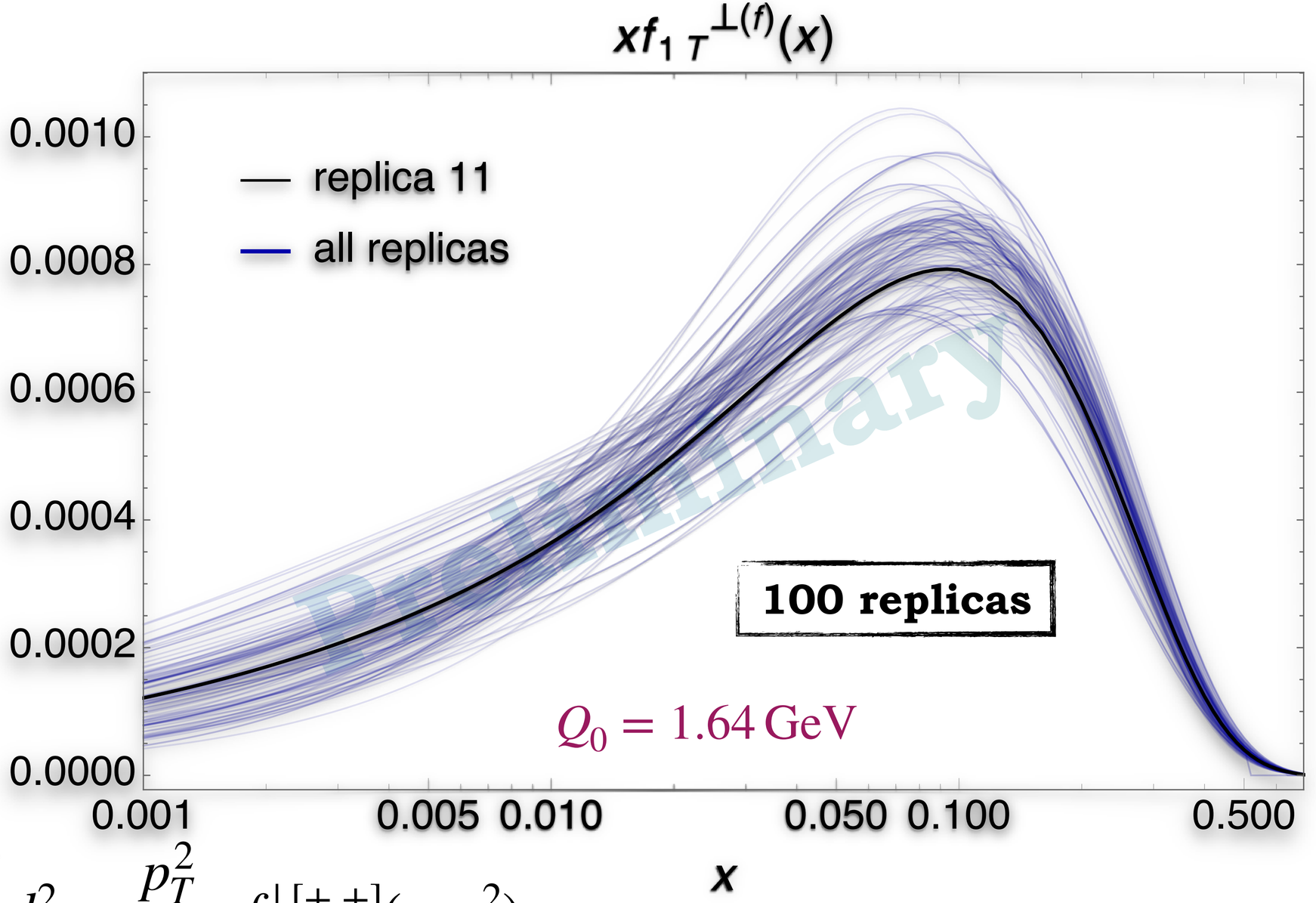


[A. Bacchetta, F.G. C., M. Radici, EPS-HEP (2021)]

f-type Qiu-Sterman twist-3 gluon PDF



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

Checkpoints and further steps

- ☑ Systematic calculation of all twist-2 *T*-even gluon TMDs with CSS evolution
- ☑ Spectral mass to catch small- and large-x effects
- ☑ **Simultaneous fit** of f_1 and g_1 PDFs via **replica method**
- ☑ Inclusion of standard CSS evolution (investigation on *perturbative tail*)

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- ☐ **Quarkonia** As Tools → clean channels for *f*-type gluon TMDs
- ☐ Pheno: **spin asymmetries**, **pseudodata** and **impact studies**
- ☐ Twist-2 *T*-odd gluon TMDs (**Sivers**, etc.) almost done!
- ☐ Explorative studies on gauge-link sensitivity and factorization

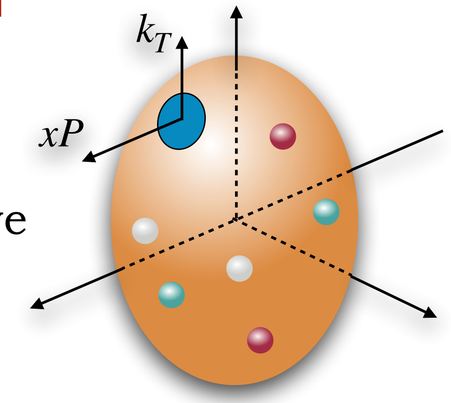
Backup slides

Parton densities: an incomplete family tree

3D

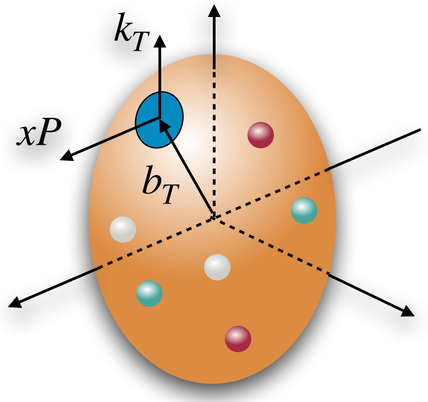
TMDs

(semi-)inclusive



5D

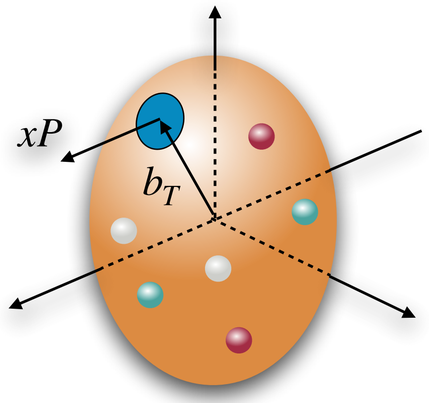
Wigner distributions



3D

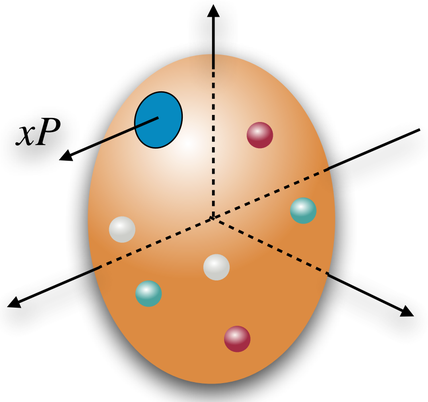
FT of GPDs

exclusive

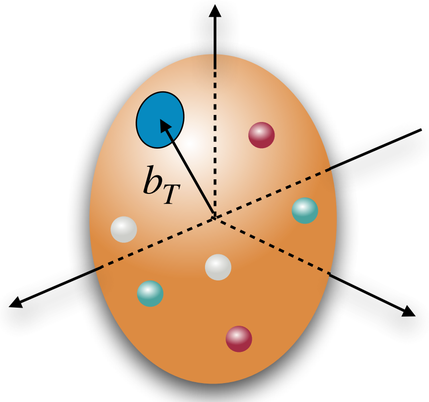


PDFs

(semi-)inclusive



FT of Form Factors



1D

2D

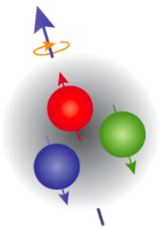
$\vec{b}_\perp$ dependence

$\vec{k}_\perp$ dependence

these two variables are NOT Fourier conjugate

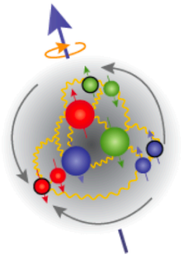
Backup

The proton spin crisis



quarks helicity

~ 30 %



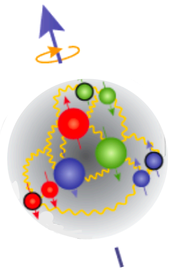
orbital angular momentum

unknown!

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

gluons helicity

~ 20% – 50 % **?**



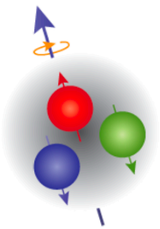
Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description...

🔗 (proton spin crisis) [EMC Collaboration, CERN (1987)]

slide adapted from C. Bissolotti

Backup

The proton spin crisis



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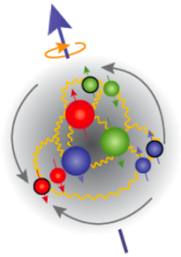

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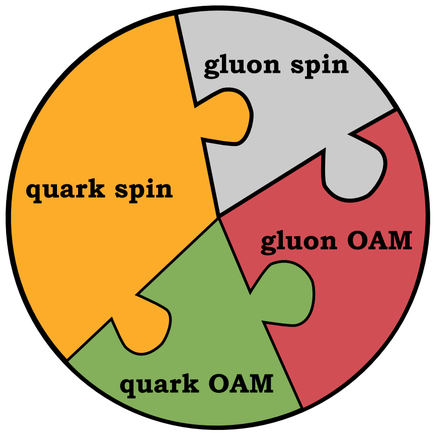

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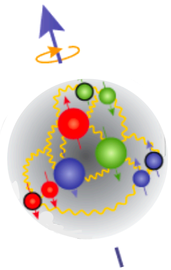

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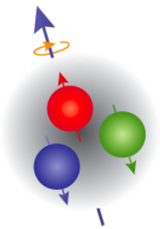

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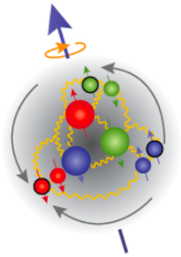

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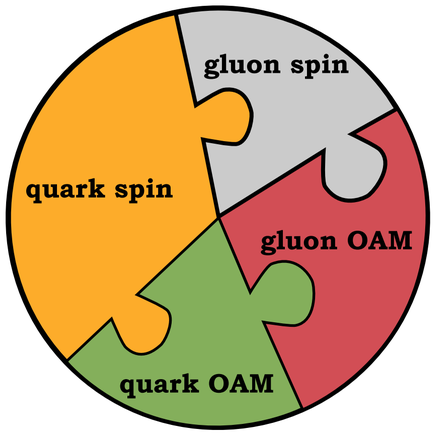

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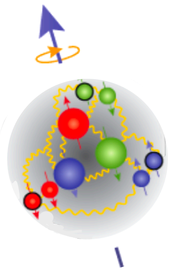

…many other effects in hadronic interactions cannot be understood in the purely collinear approach

Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description…

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slide adapted from C. Bissolotti

Backup

Assumptions of the model

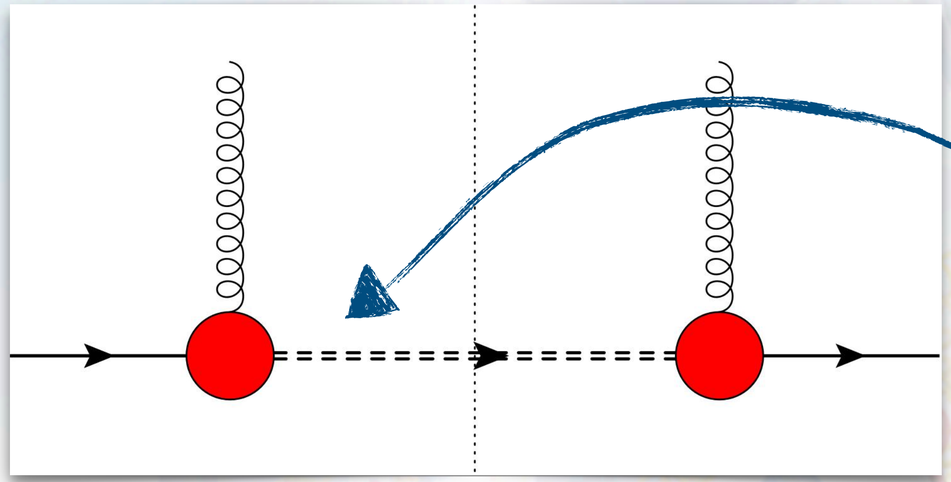
Spectator-system spectral-mass function

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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spectator-model TMD

[Inspired by G.R. Goldstein, J.O.G. Hernandez, S. Liuti (2011)]

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

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

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

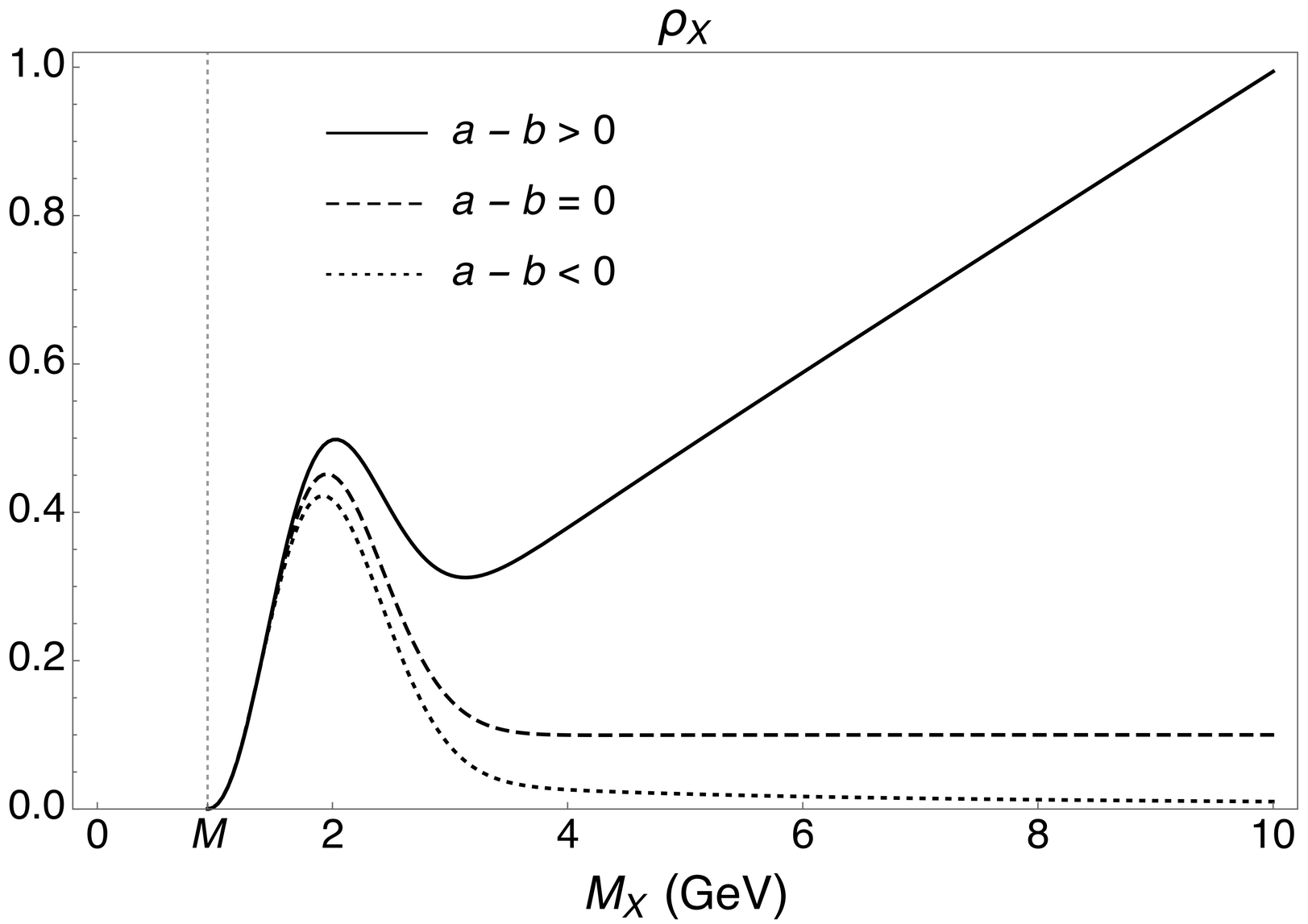
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

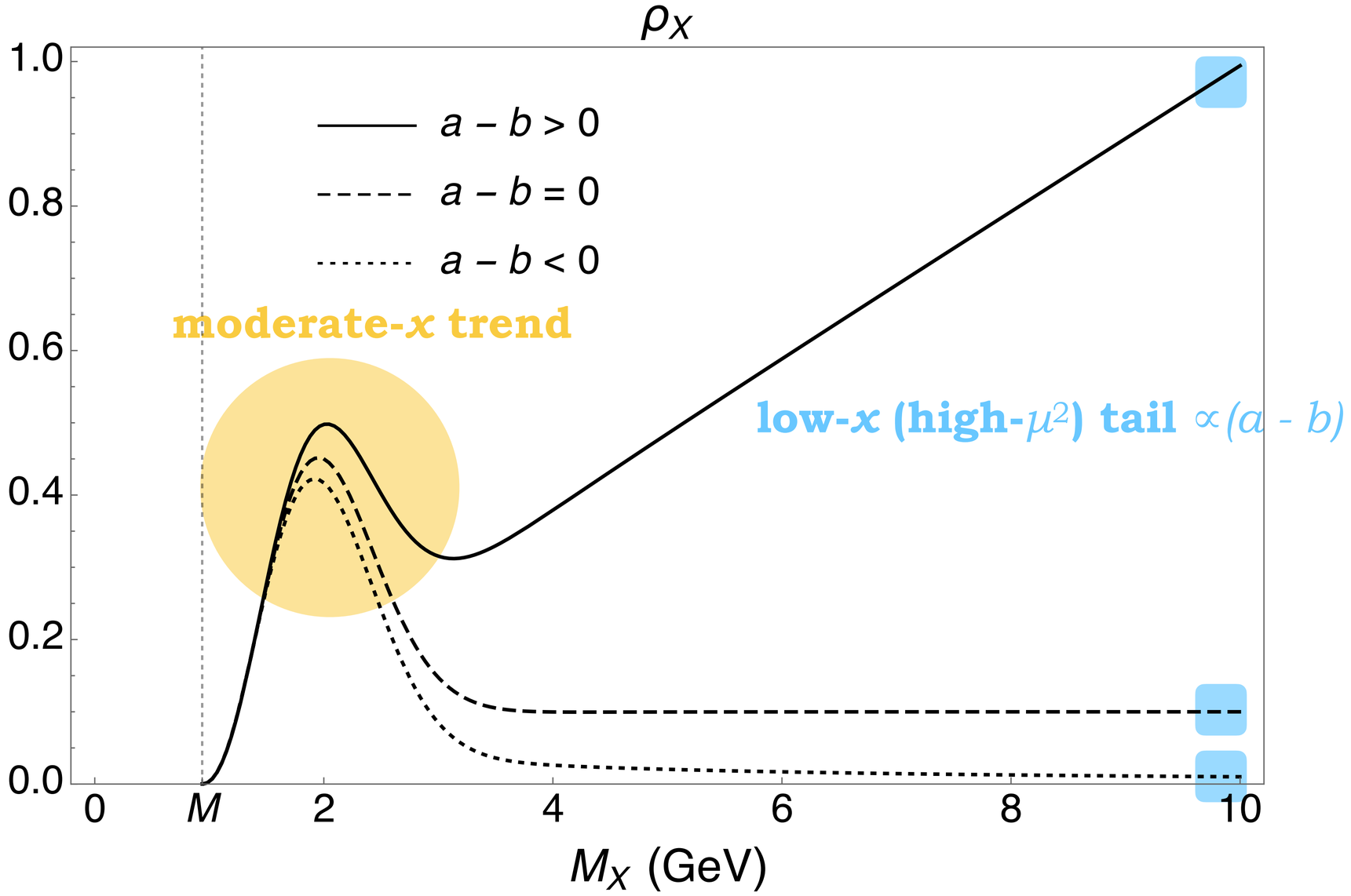
Backup

Spectral function vs *(a - b)*



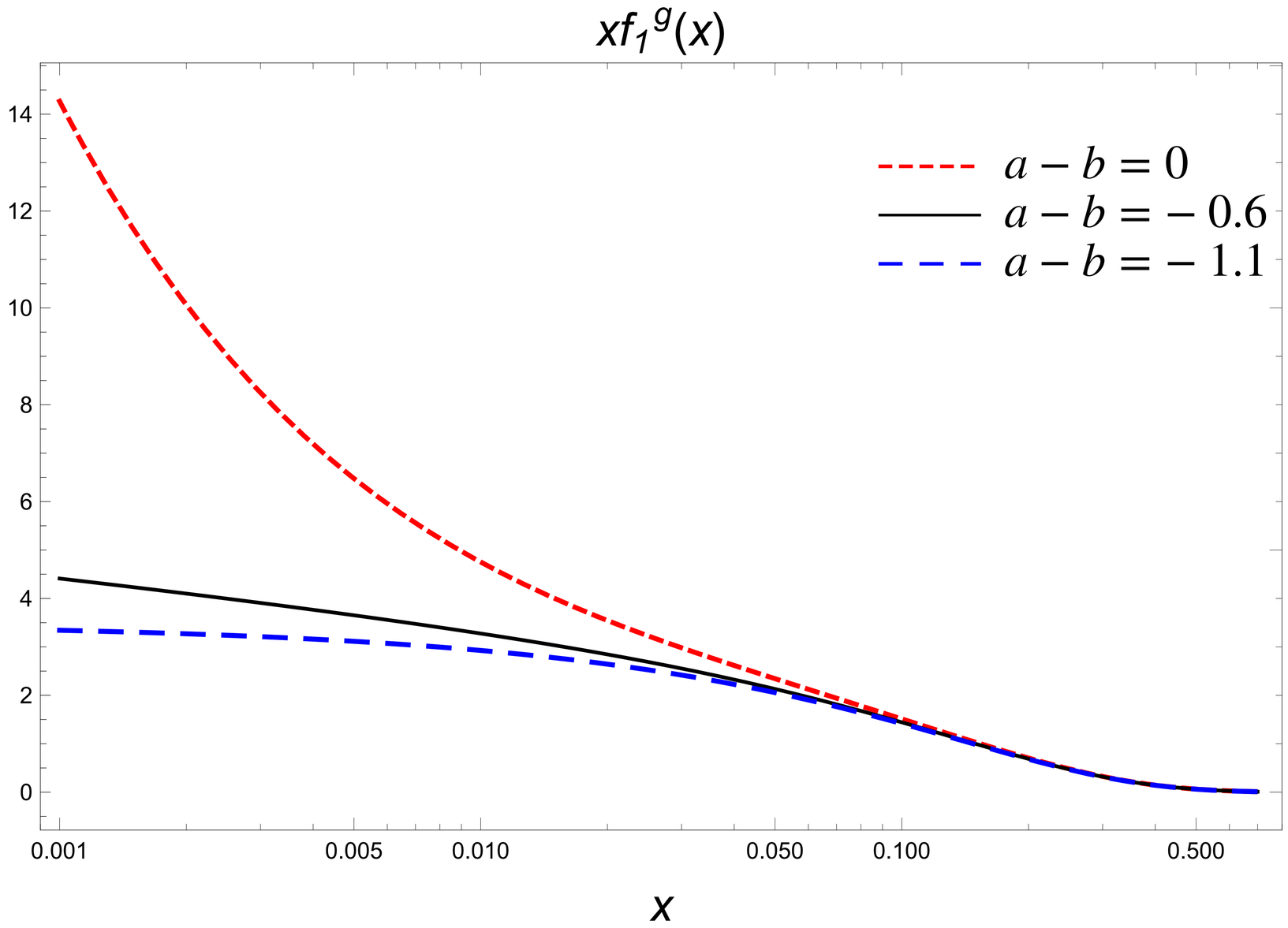
Backup

Spectral function vs $(a - b)$



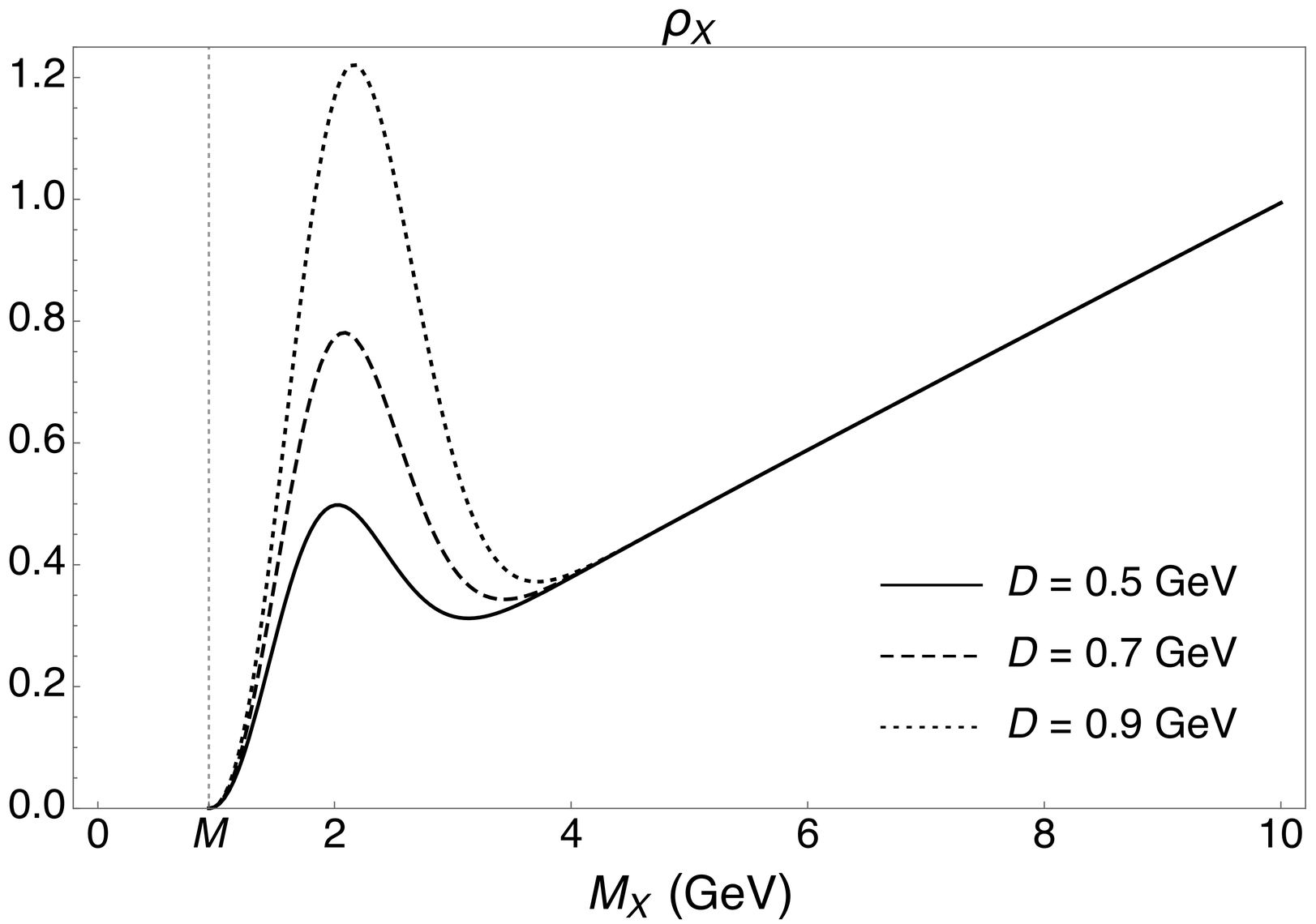
Backup

xf_1 collinear PDF vs $(a - b)$



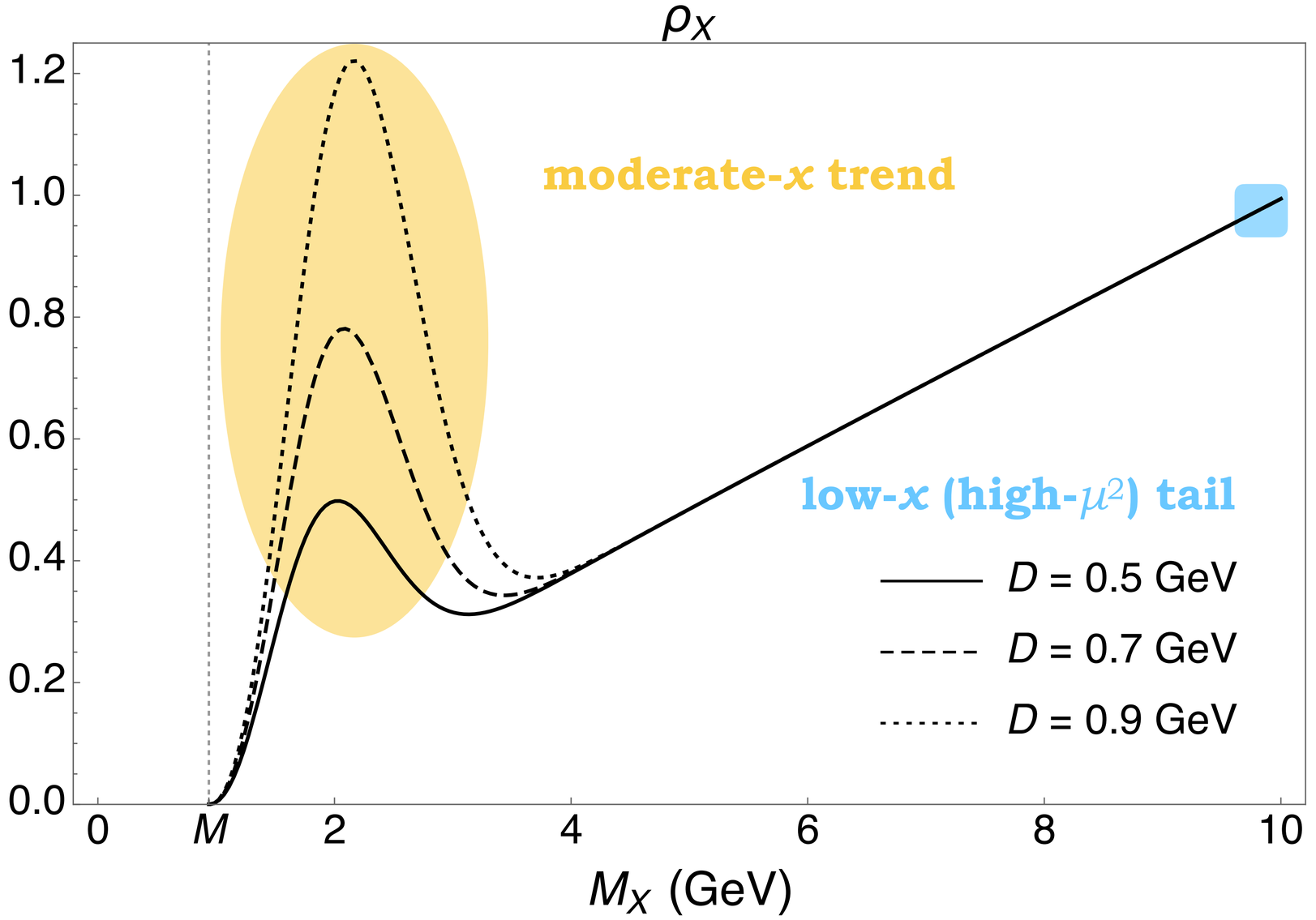
Backup

Spectral function vs D



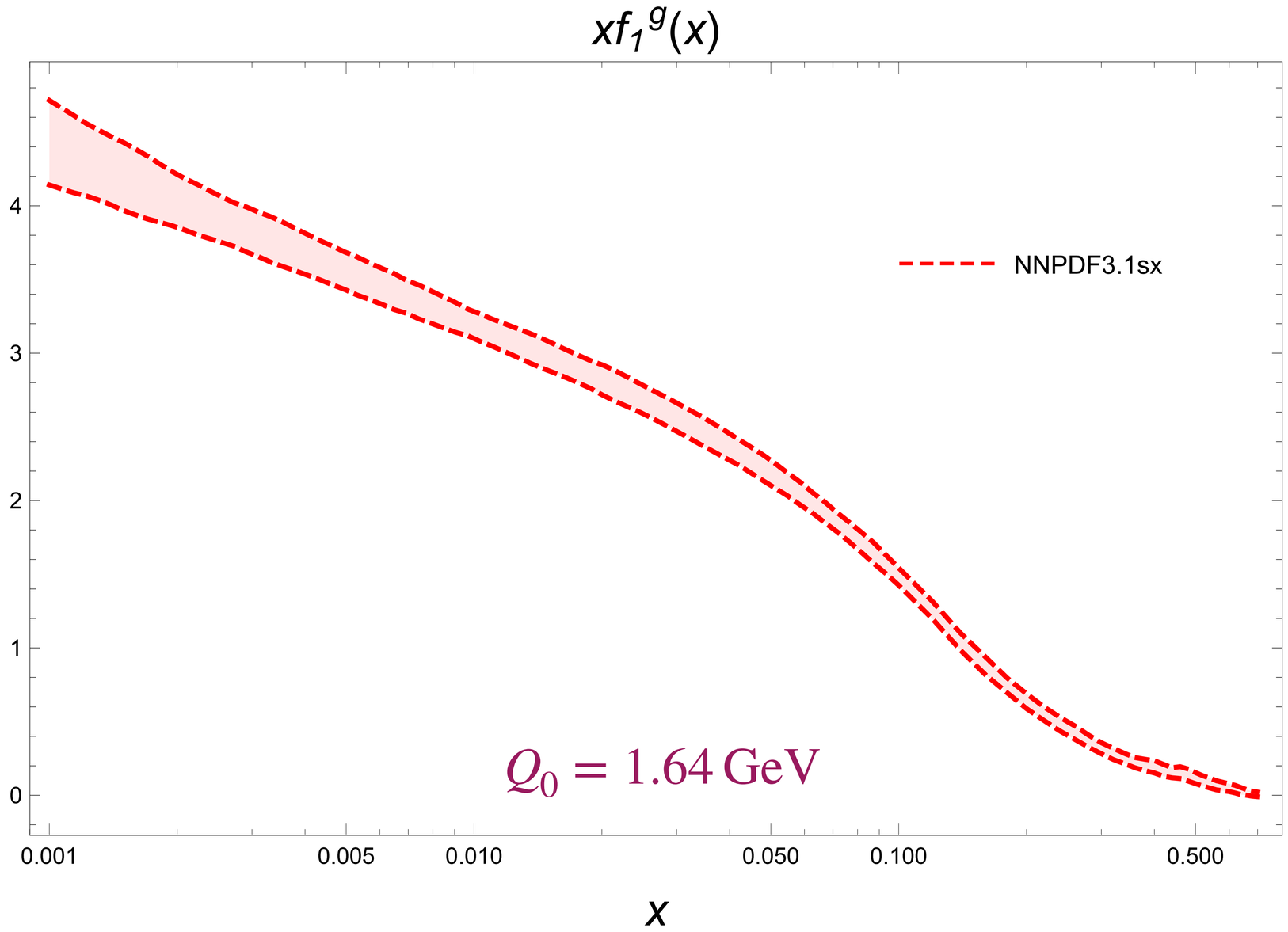
Backup

Spectral function vs D



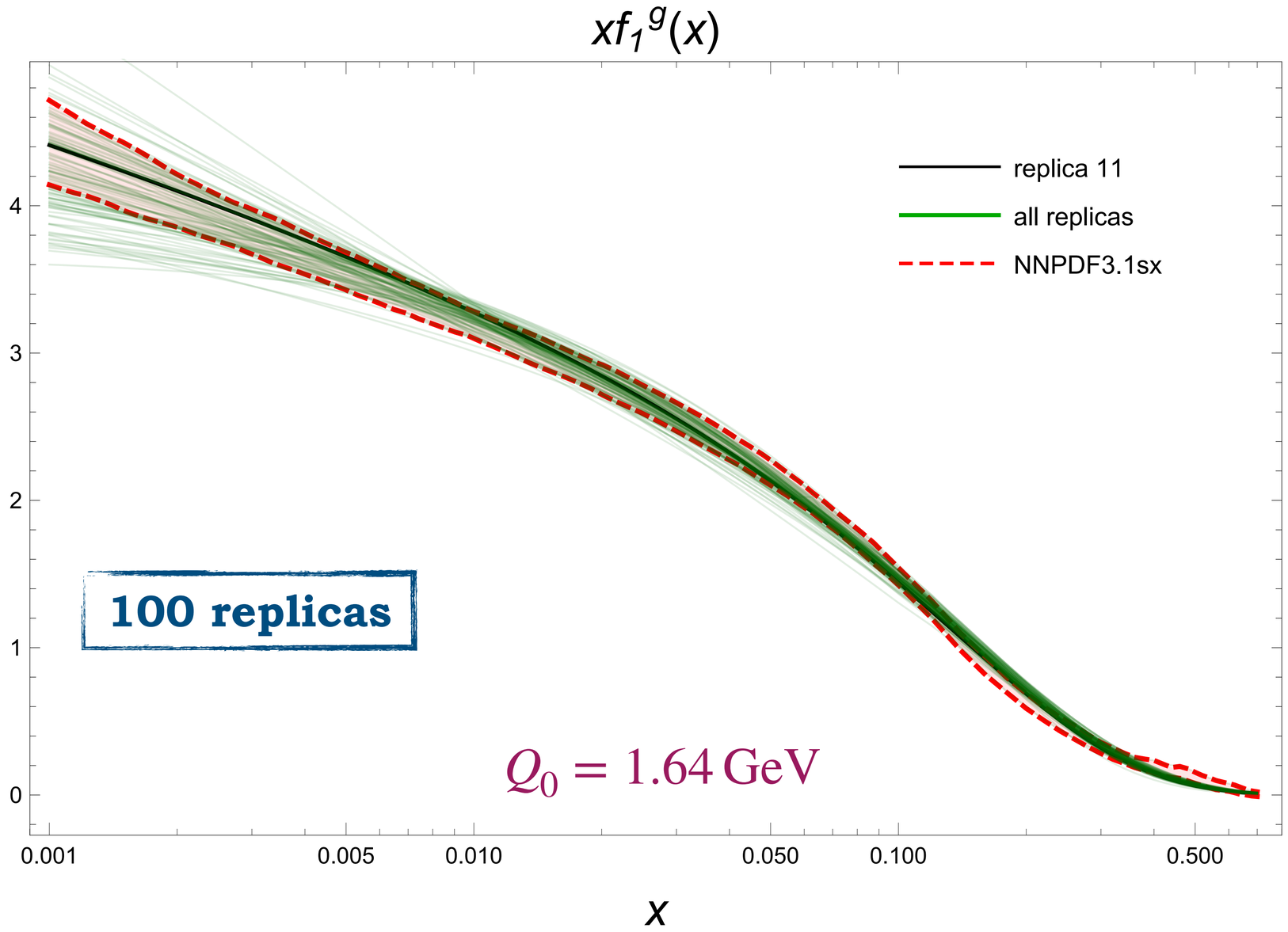
Backup

Unpolarized gluon PDF



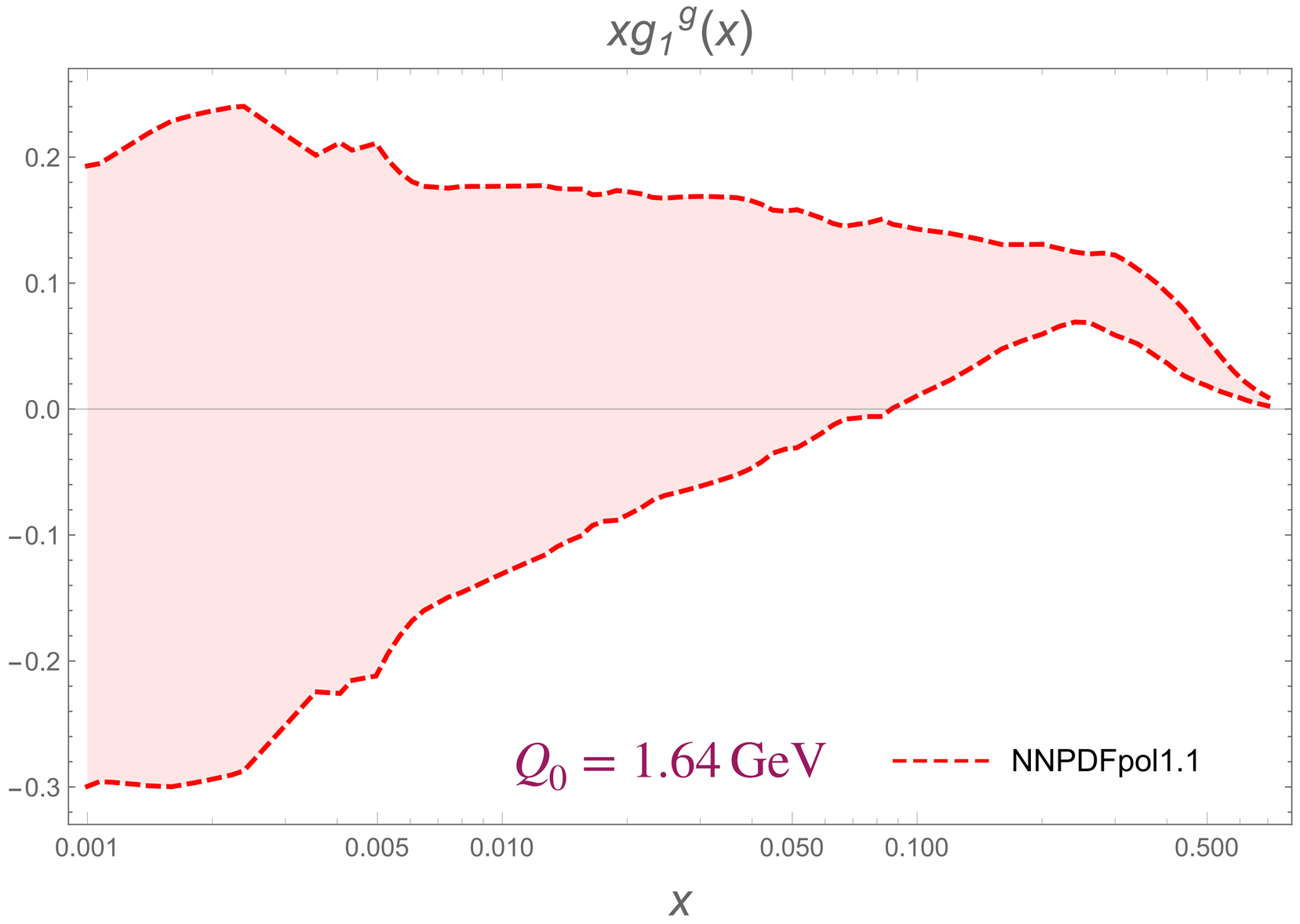
Backup

Unpolarized gluon PDF



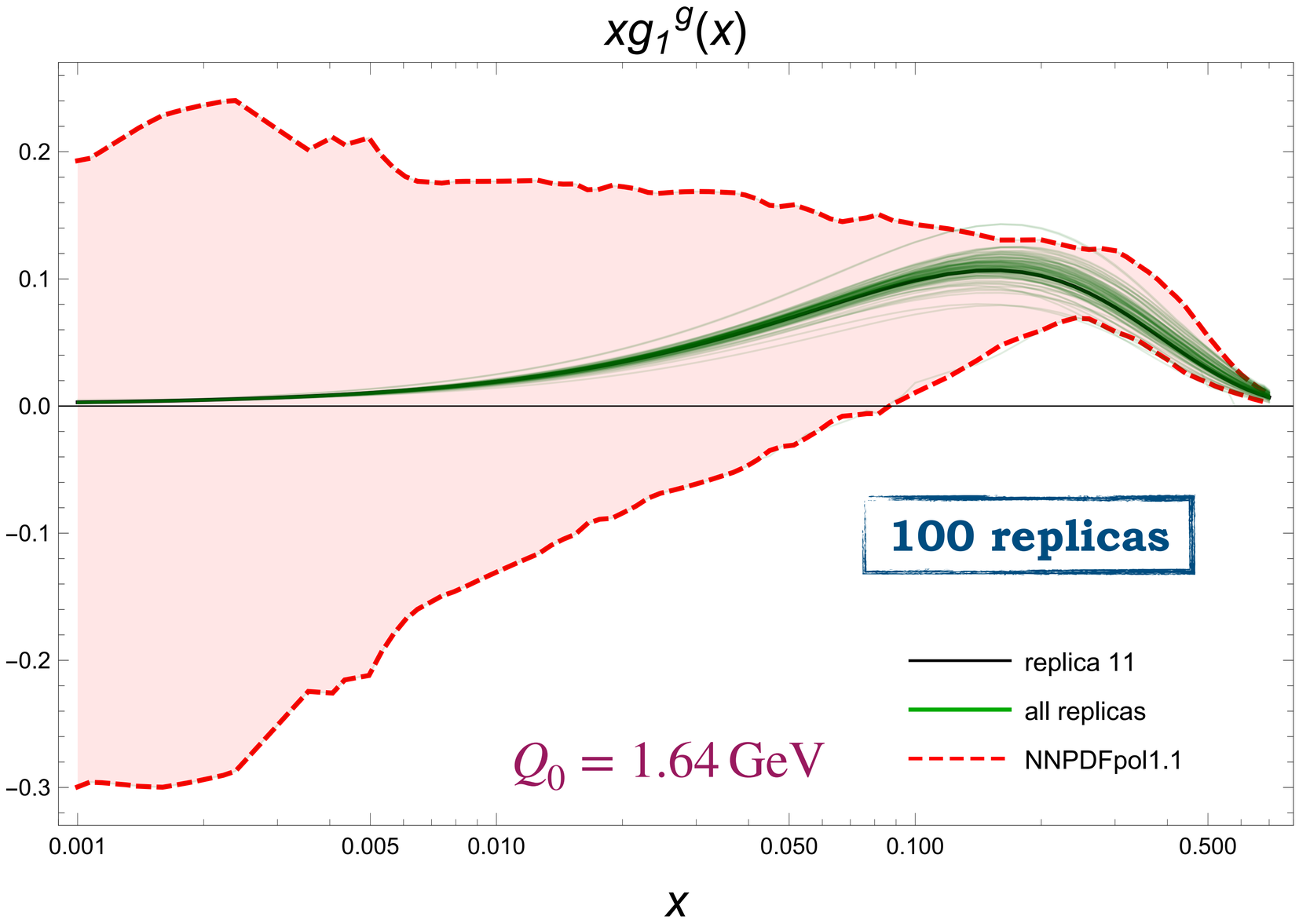
Backup

Helicity gluon PDF



Backup

Helicity gluon PDF



Backup

Fit specifics

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

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

Backup

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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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Our model @ $Q_0 = 1.64$ GeV

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

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

Lattice @ $Q_0 = 2$ GeV

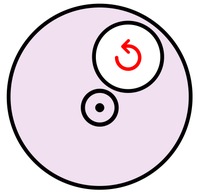
$$\langle x \rangle_g = 0.427(92)$$

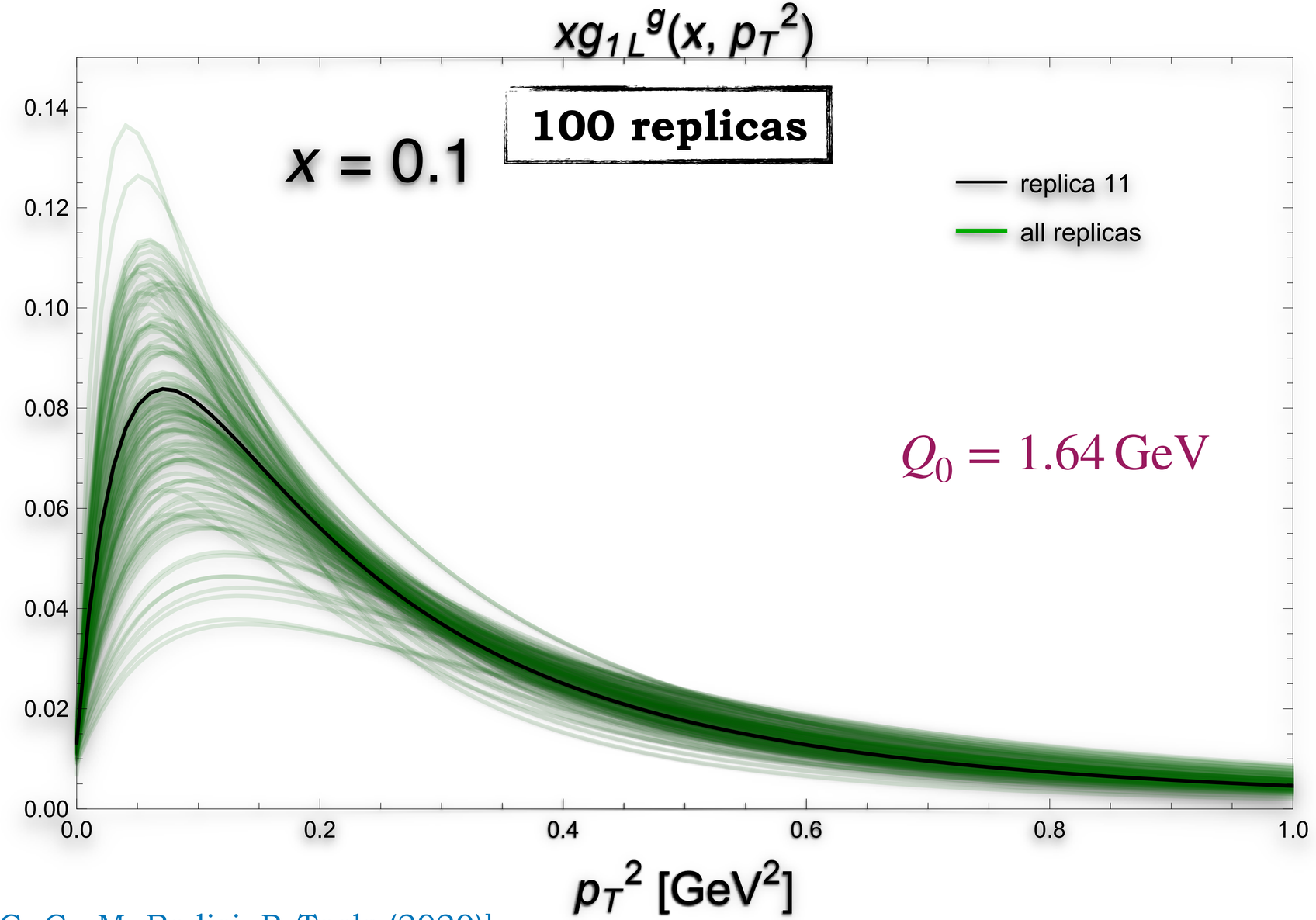
$$\langle J \rangle_g = 0.187(46)$$

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

Backup

Helicity gluon TMD

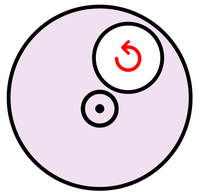


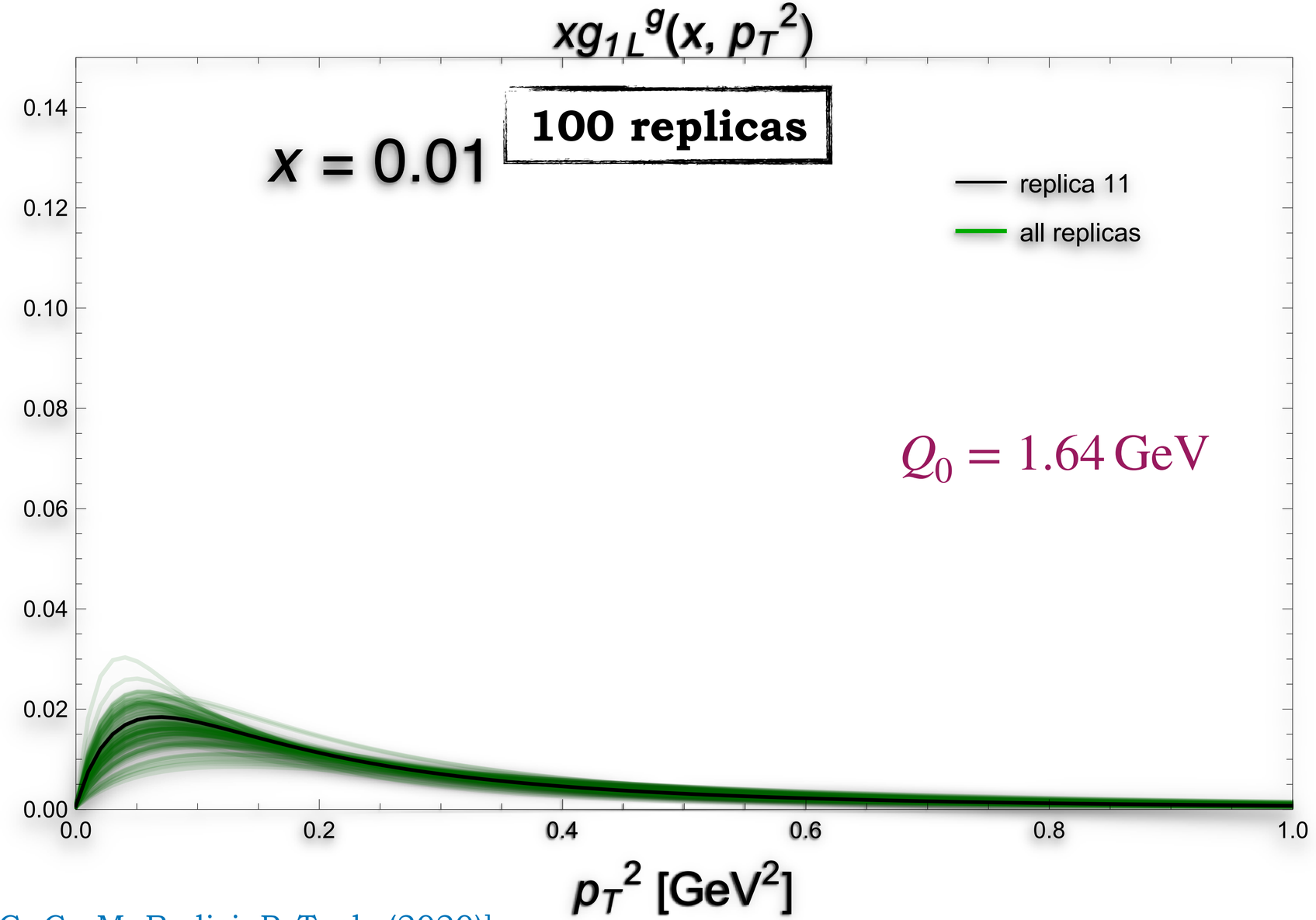


[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Helicity gluon TMD

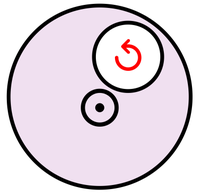


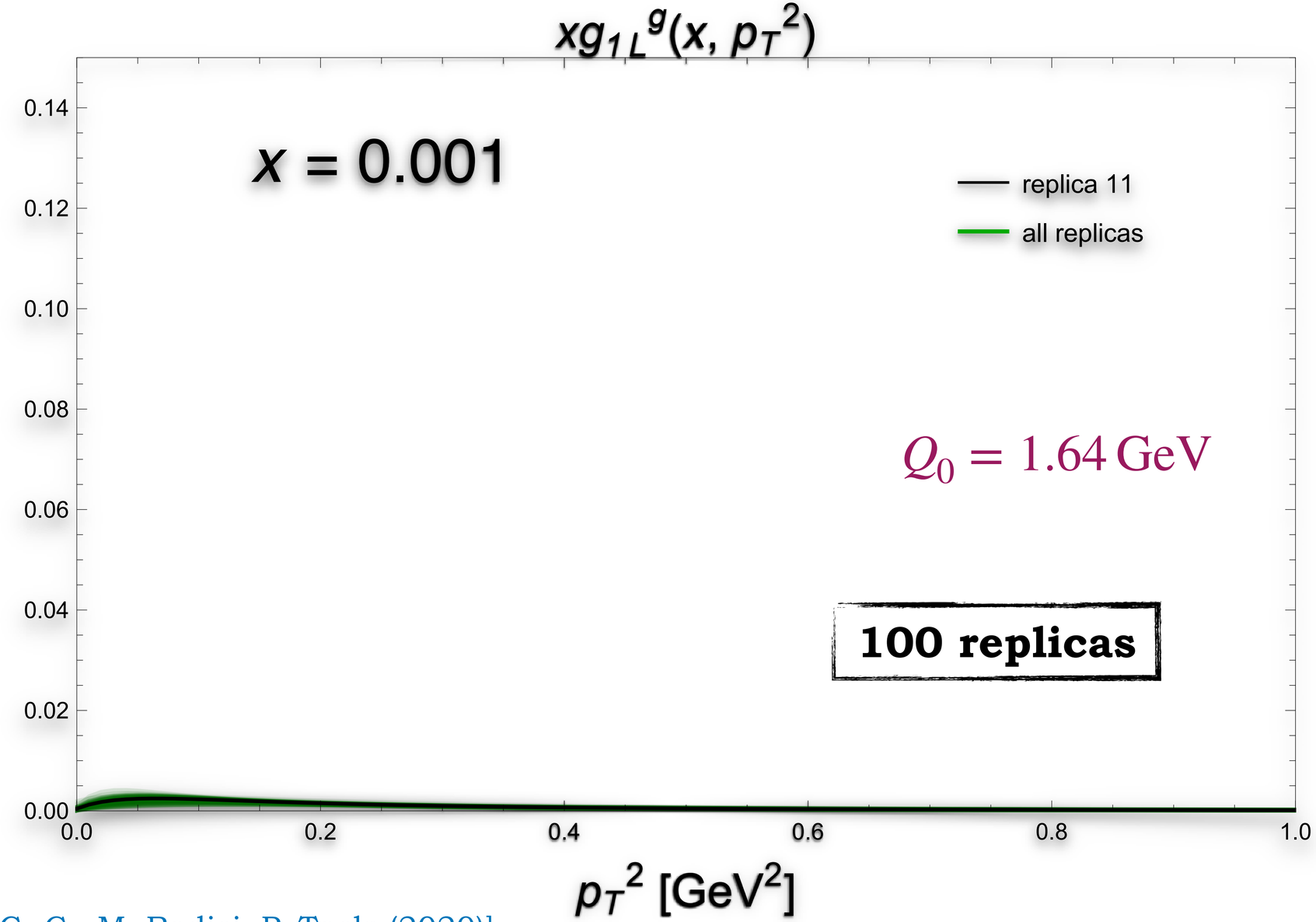


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Helicity gluon TMD

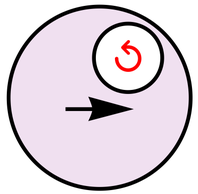


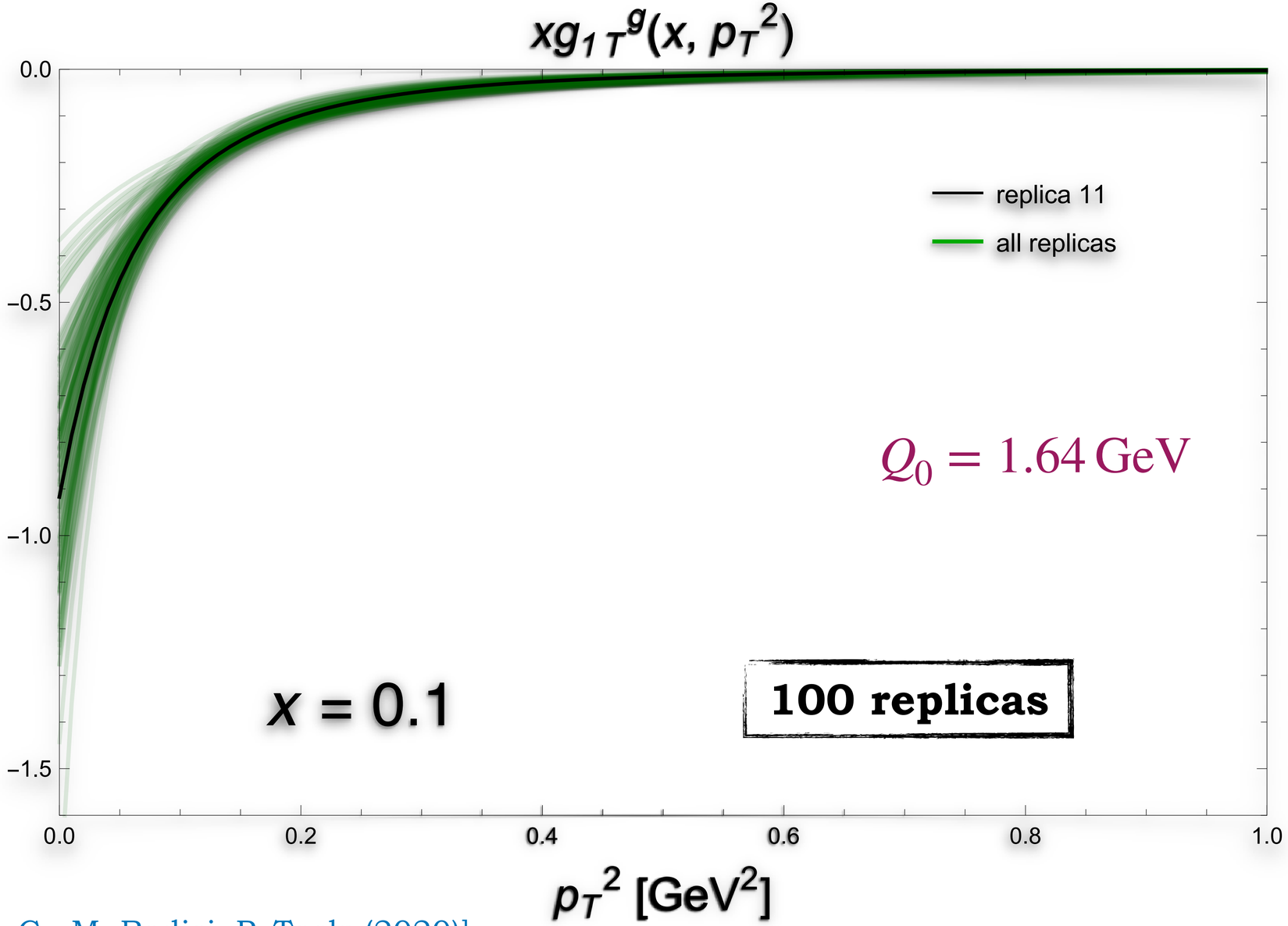


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Worm-gear gluon TMD

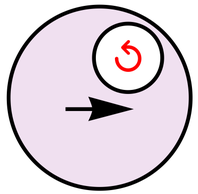


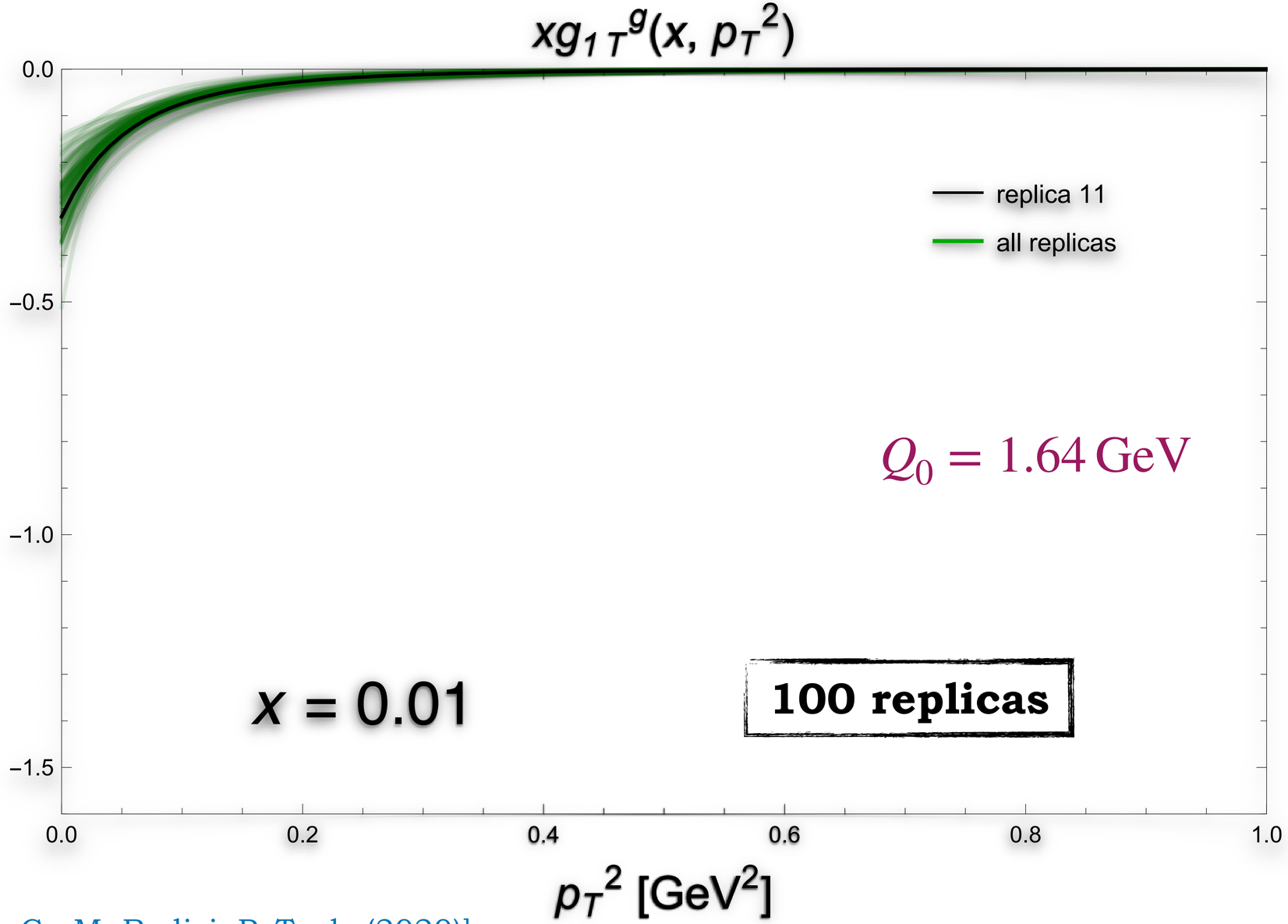


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Worm-gear gluon TMD

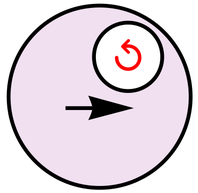


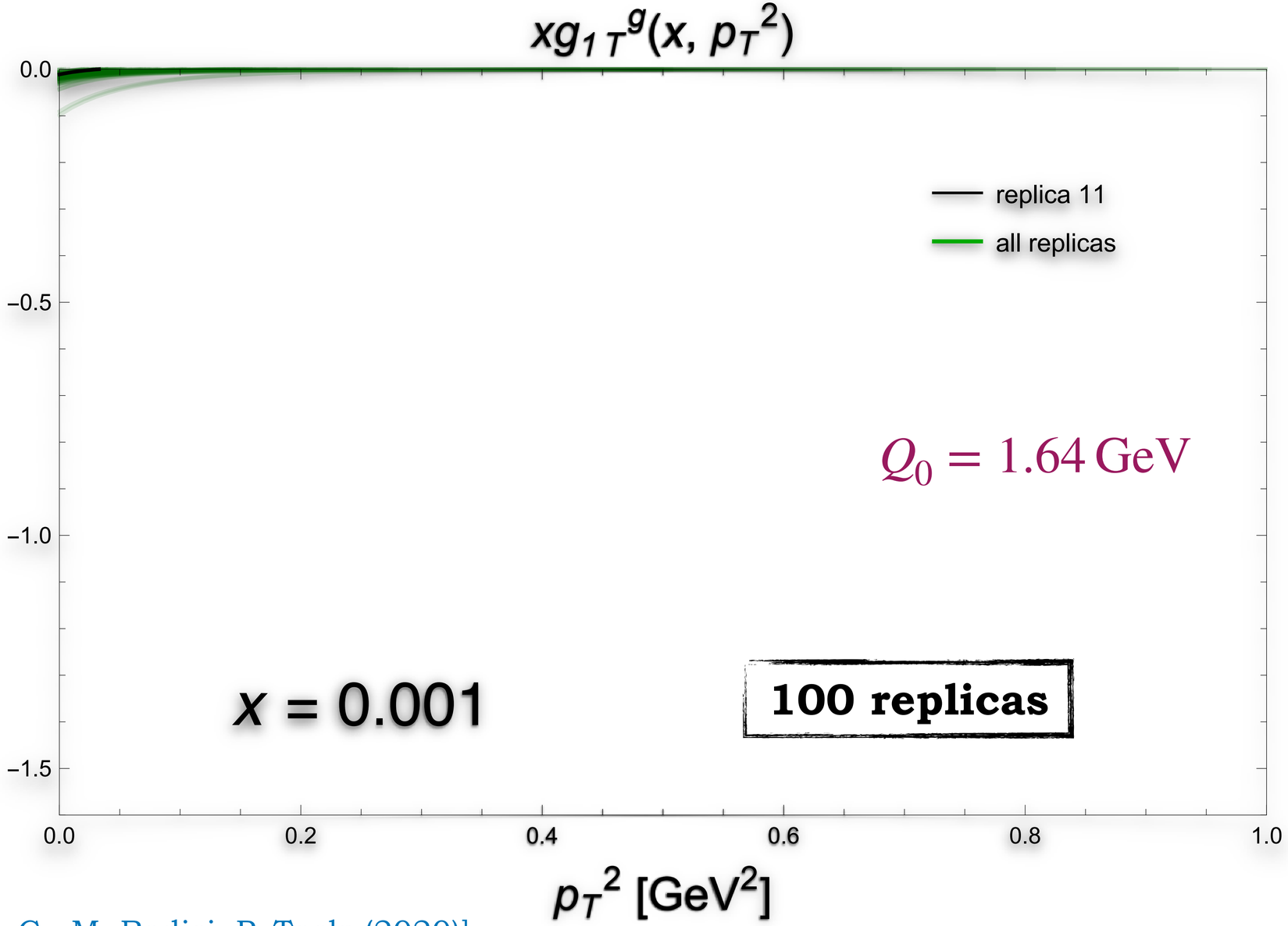


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Worm-gear gluon TMD

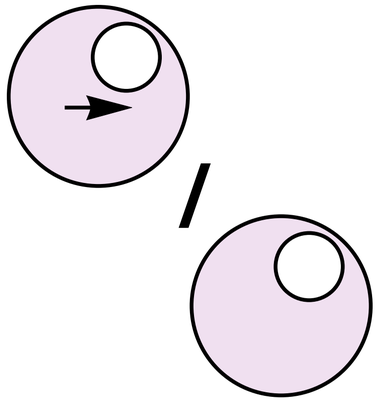




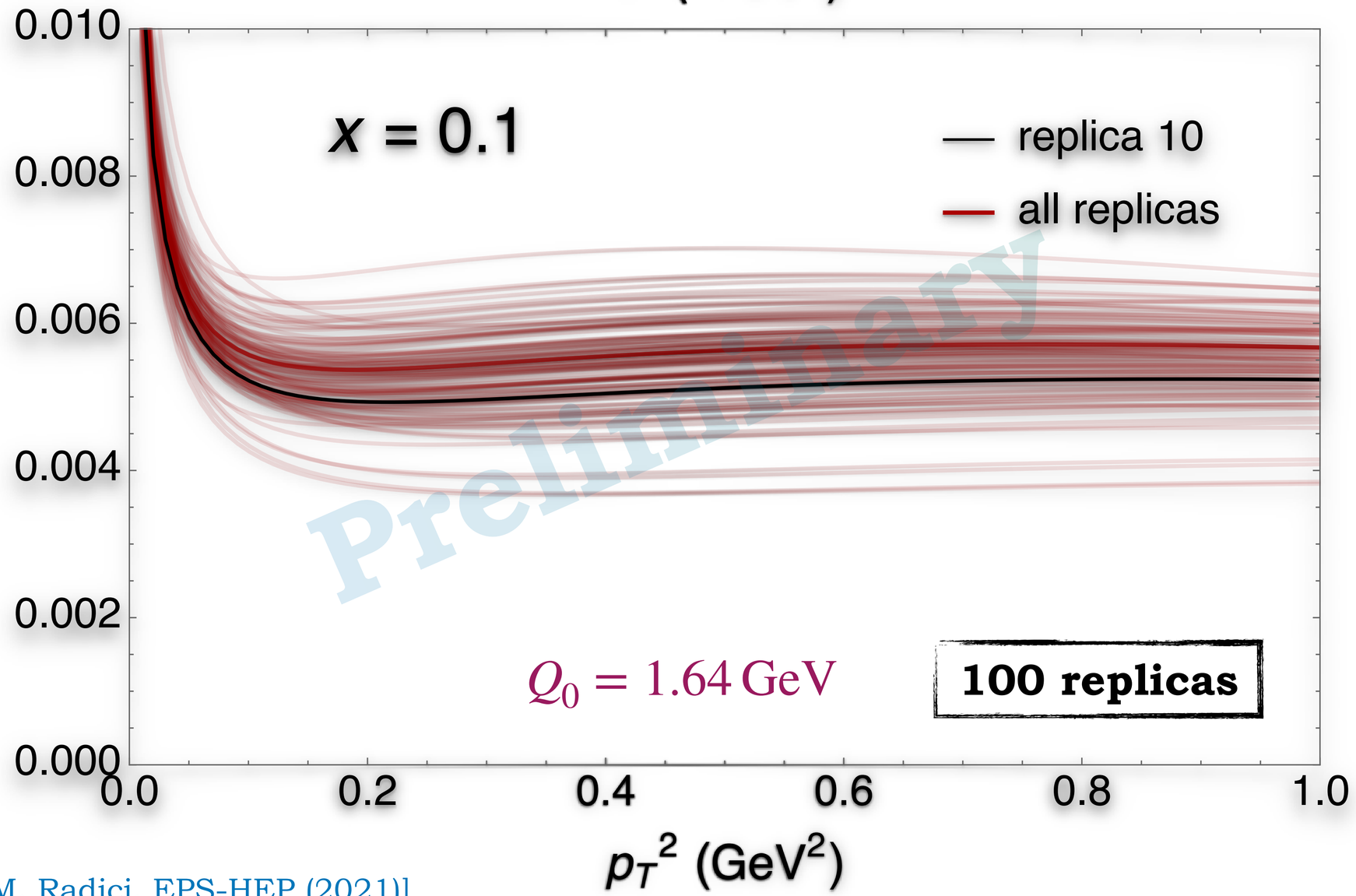
🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

f-type Sivers / unpol.



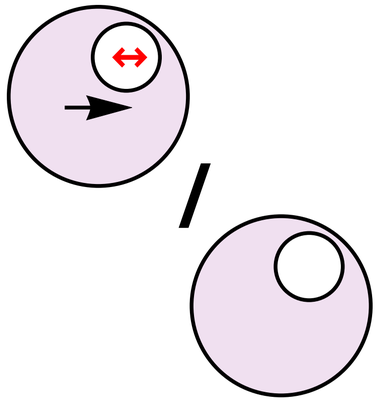
$$\frac{\frac{p_T}{M} f_{1T}^{\perp[+,+]}(x, p_T^2)}{f_1^g(x, p_T^2)}$$



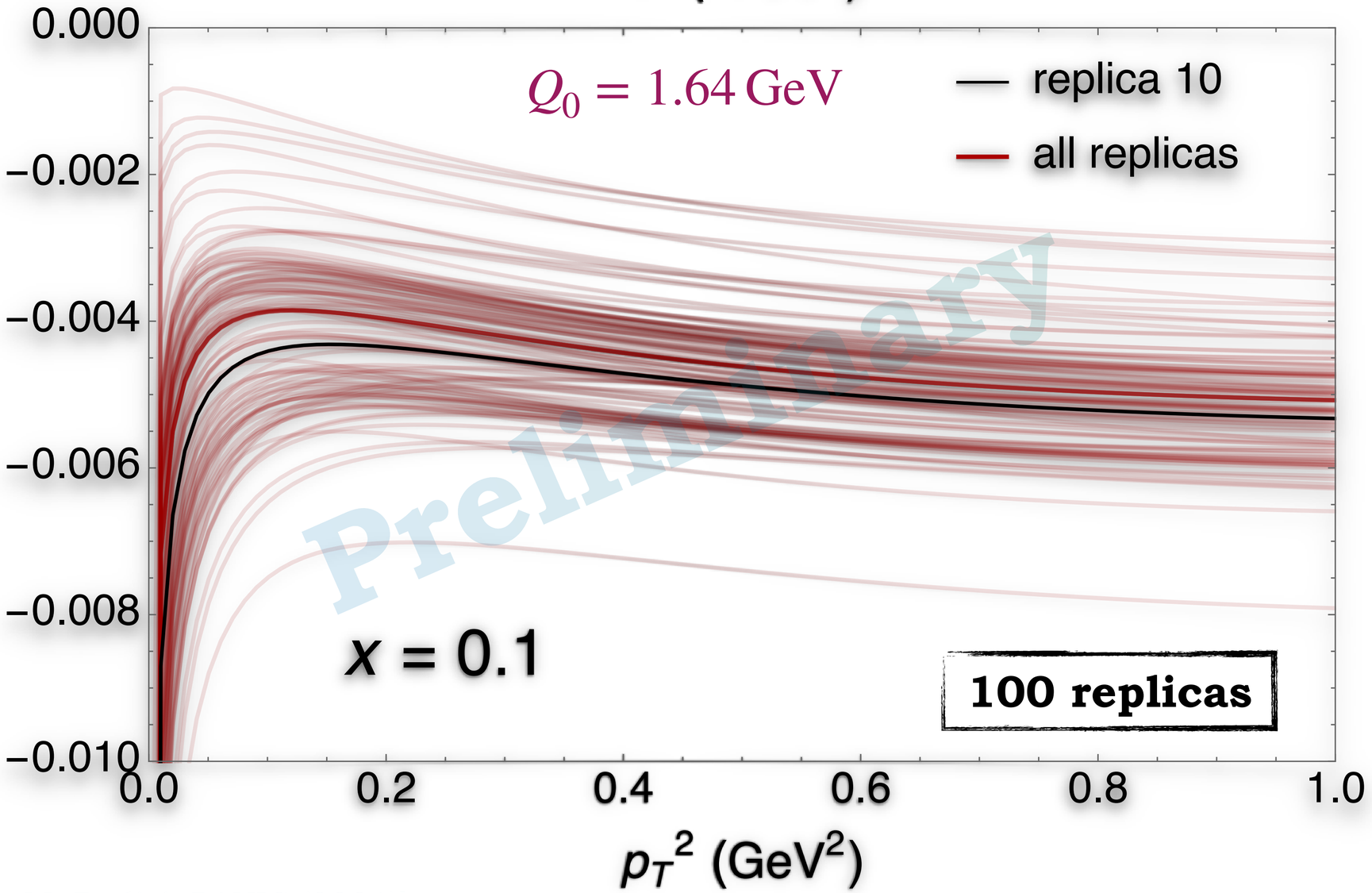
[A. Bacchetta, F.G. C., M. Radici, EPS-HEP (2021)]

Backup

f-type linearity / unpol.



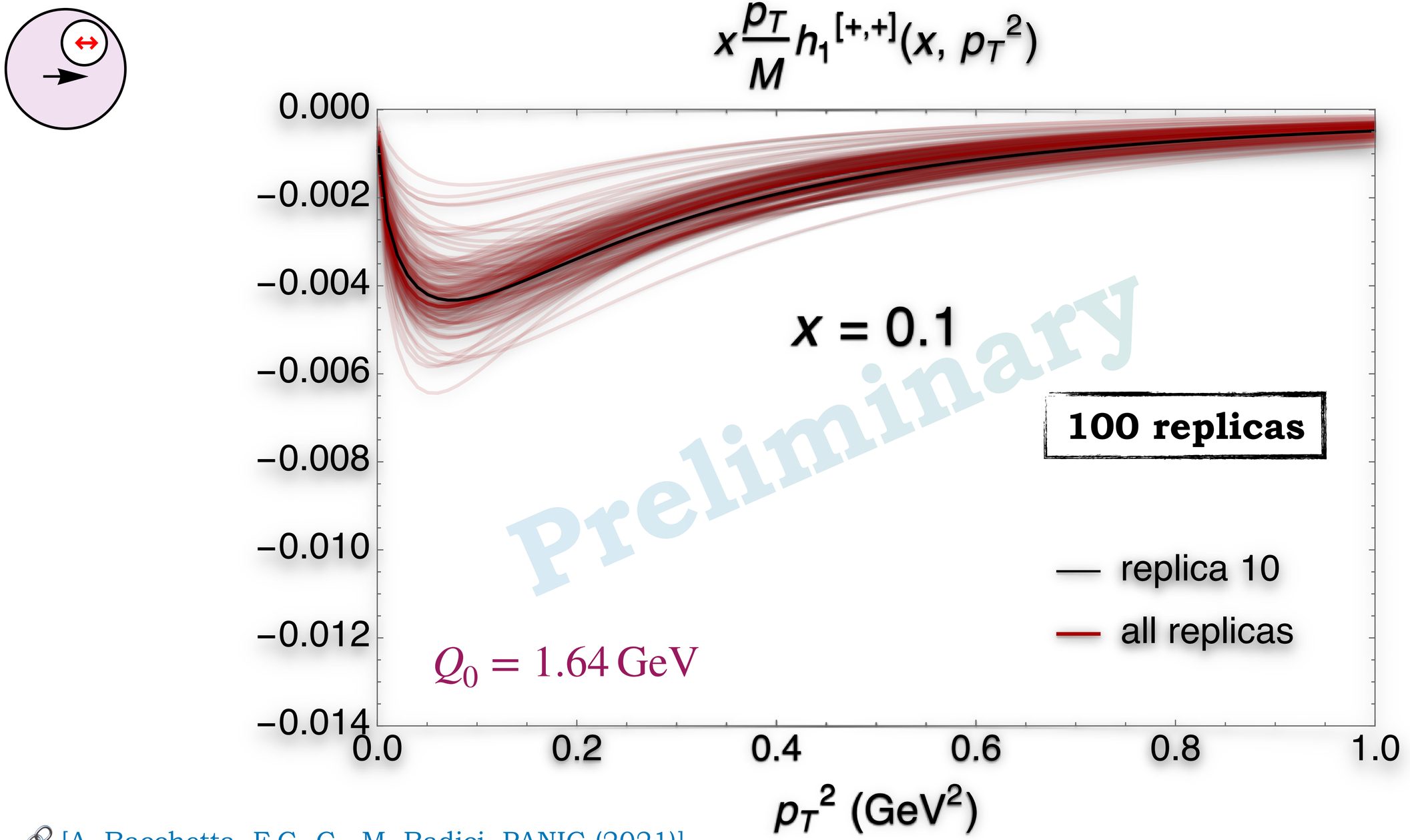
$$\frac{\frac{p_T}{M} h_1^{[+,+]}(x,\ p_T^2)}{f_1^{\,g}(x,\ p_T^2)}$$



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

Backup

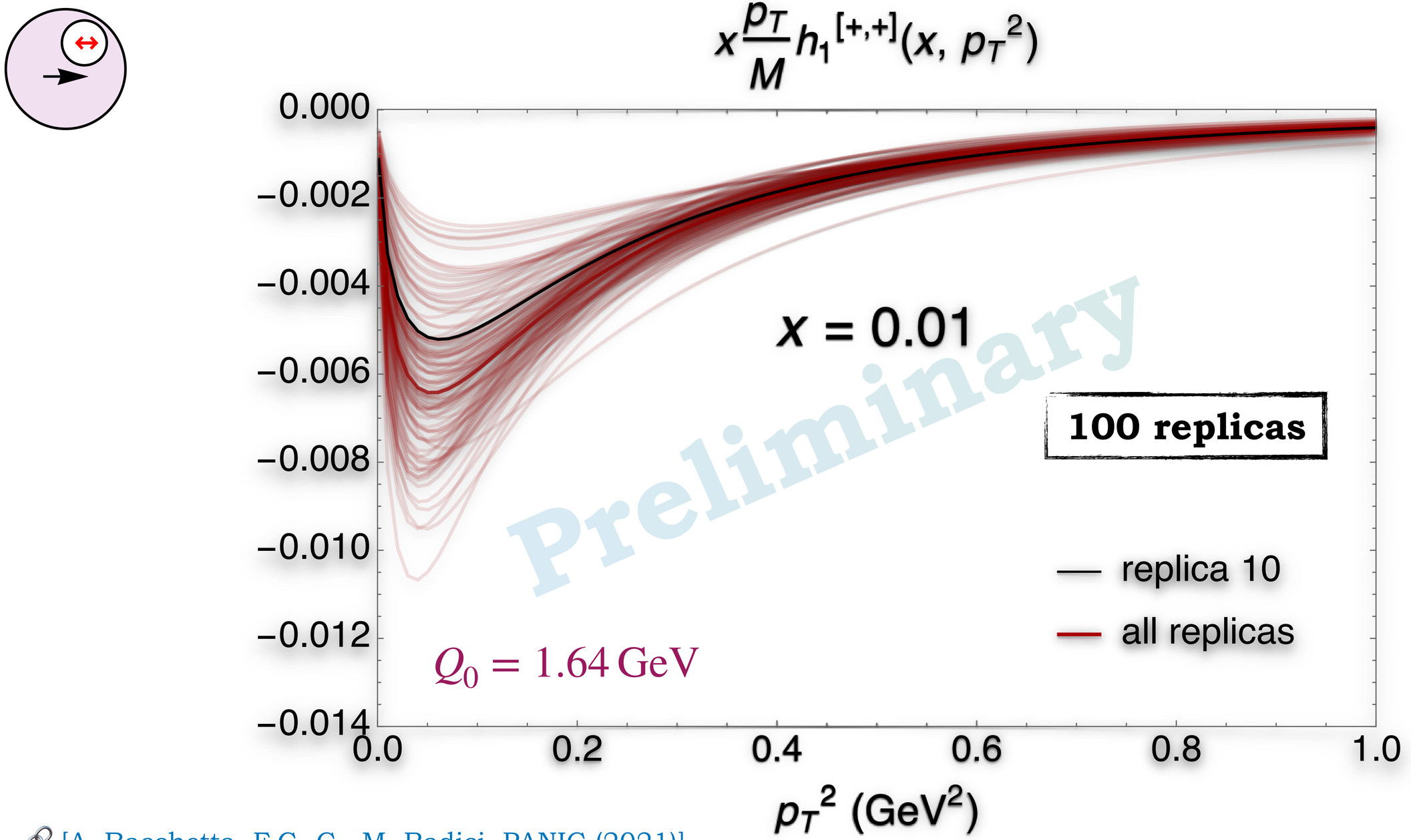
f-type linearity gluon TMD



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

Backup

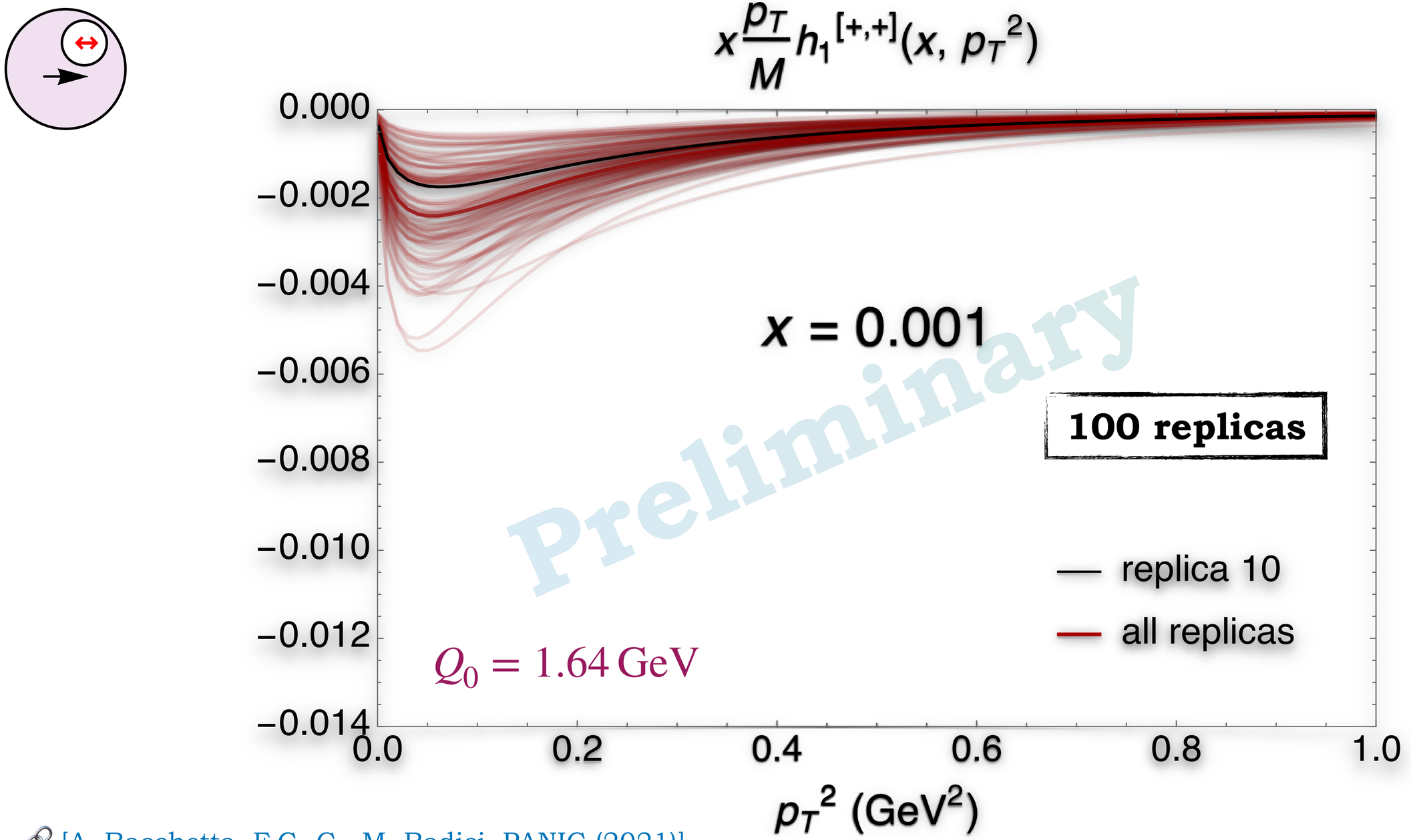
f-type linearity gluon TMD



[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

Gluon TMD correlator and *T*-odd gluon densities

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

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

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

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Gluon TMD correlator and *T*-odd gluon densities

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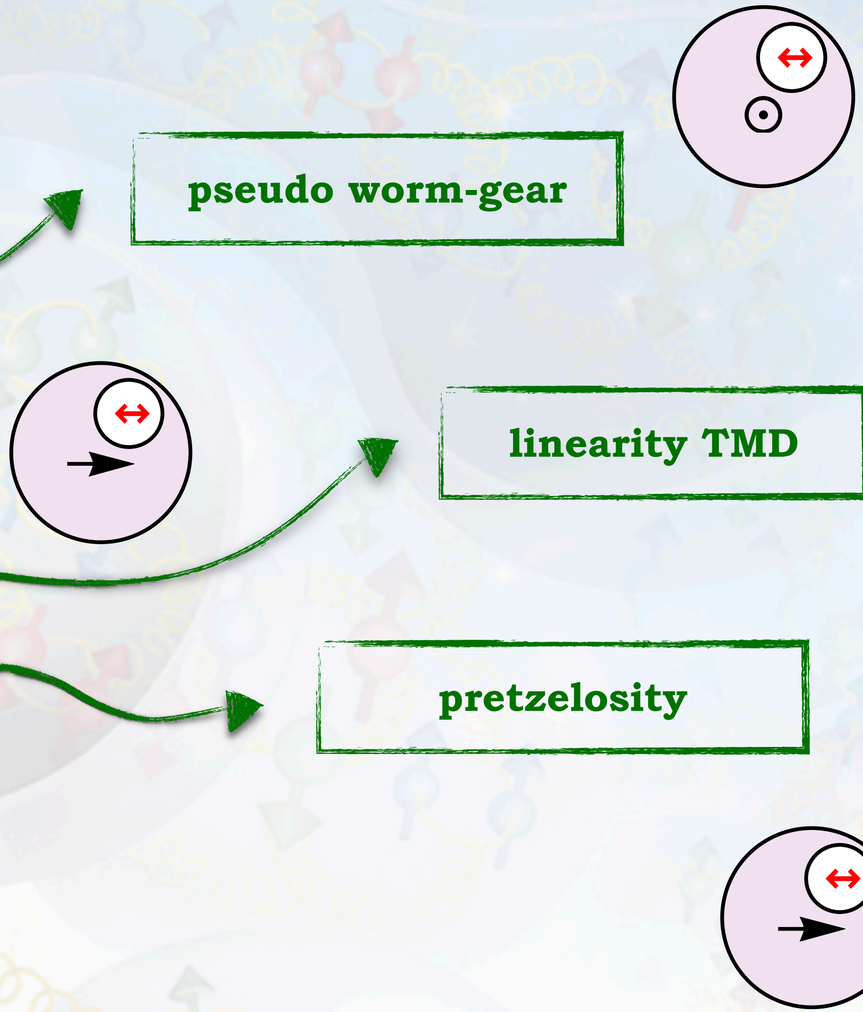
$$\left. - \frac{\epsilon_T^{k_T\{i} S_T^{j\}} + \epsilon_T^{S_T\{i} k_T^{j\}}}{4M} h_1(x,\boldsymbol{k}^2) - \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha S_T}}{2M^3} h_{1T}^{\perp}(x,\boldsymbol{k}^2)\right]$$



Backup

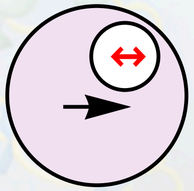
Gluon TMD correlator and *T*-odd gluon densities

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

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

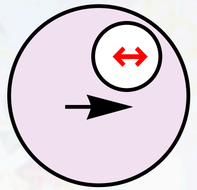
$$\Gamma_T^{ij}(x,\boldsymbol{k}) = x\left[\frac{\delta_T^{ij}\,\epsilon_T^{S_T k_T}}{M} f_{1T}^{\perp}(x,\boldsymbol{k}^2) + \frac{i\epsilon_T^{ij}\,\boldsymbol{k}\cdot\boldsymbol{S}_T}{M} g_{1T}(x,\boldsymbol{k}^2)\right.$$
$$\left. - \frac{\epsilon_T^{k_T\{i} S_T^{j\}} + \epsilon_T^{S_T\{i} k_T^{j\}}}{4M}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

pseudo worm-gear

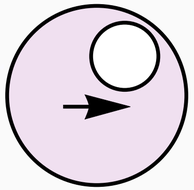


linearity TMD

pretzelosity



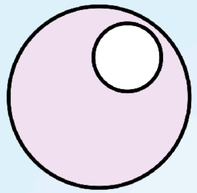
Sivers



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

Backup

ρ-densities

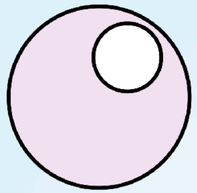


Unpolarized [u/u]

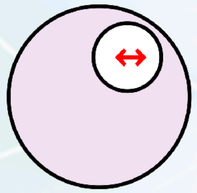
$$f_1(x, p_x, p_y)$$

Backup

ρ-densities



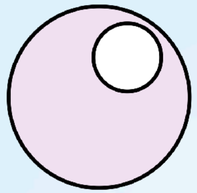
Unpolarized [u/u] $f_1(x, p_x, p_y)$



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

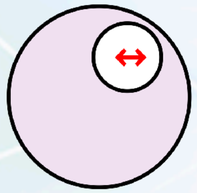
Backup

ρ-densities



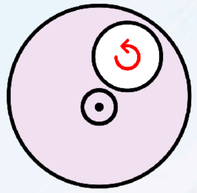
Unpolarized [u/u]

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



Boer-Mulders [↔/u]

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

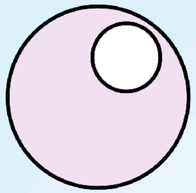


Helicity [↻/+]

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

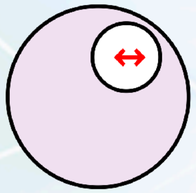
Backup

ρ-densities



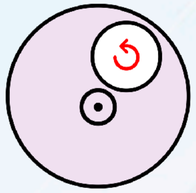
Unpolarized [u/u]

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



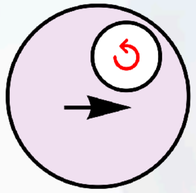
Boer-Mulders [↔/u]

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



Helicity [↺/+]

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



Worm-gear [↺/→]

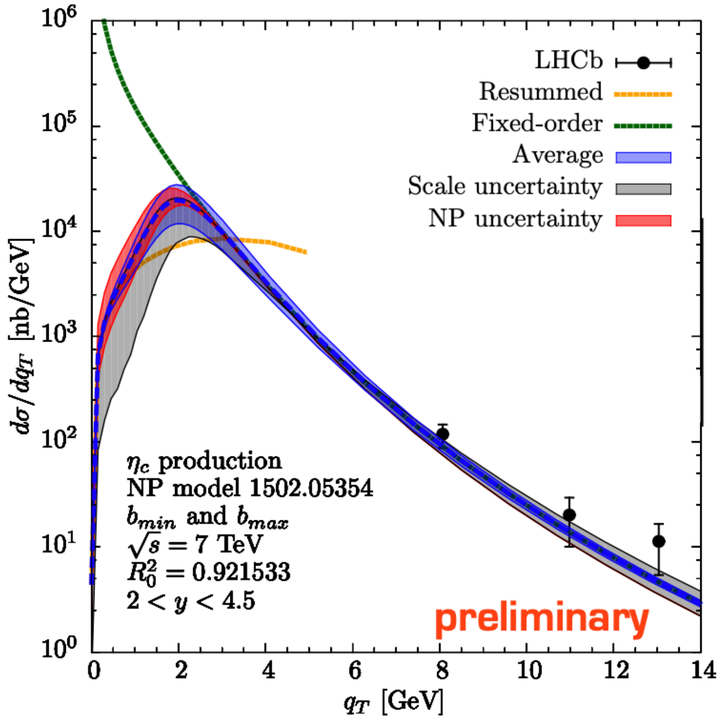
$$f_1(x, p_x, p_y) - \frac{p_x}{M} g_{1T}(x, p_x, p_y)$$

Backup

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

Jefferson Lab

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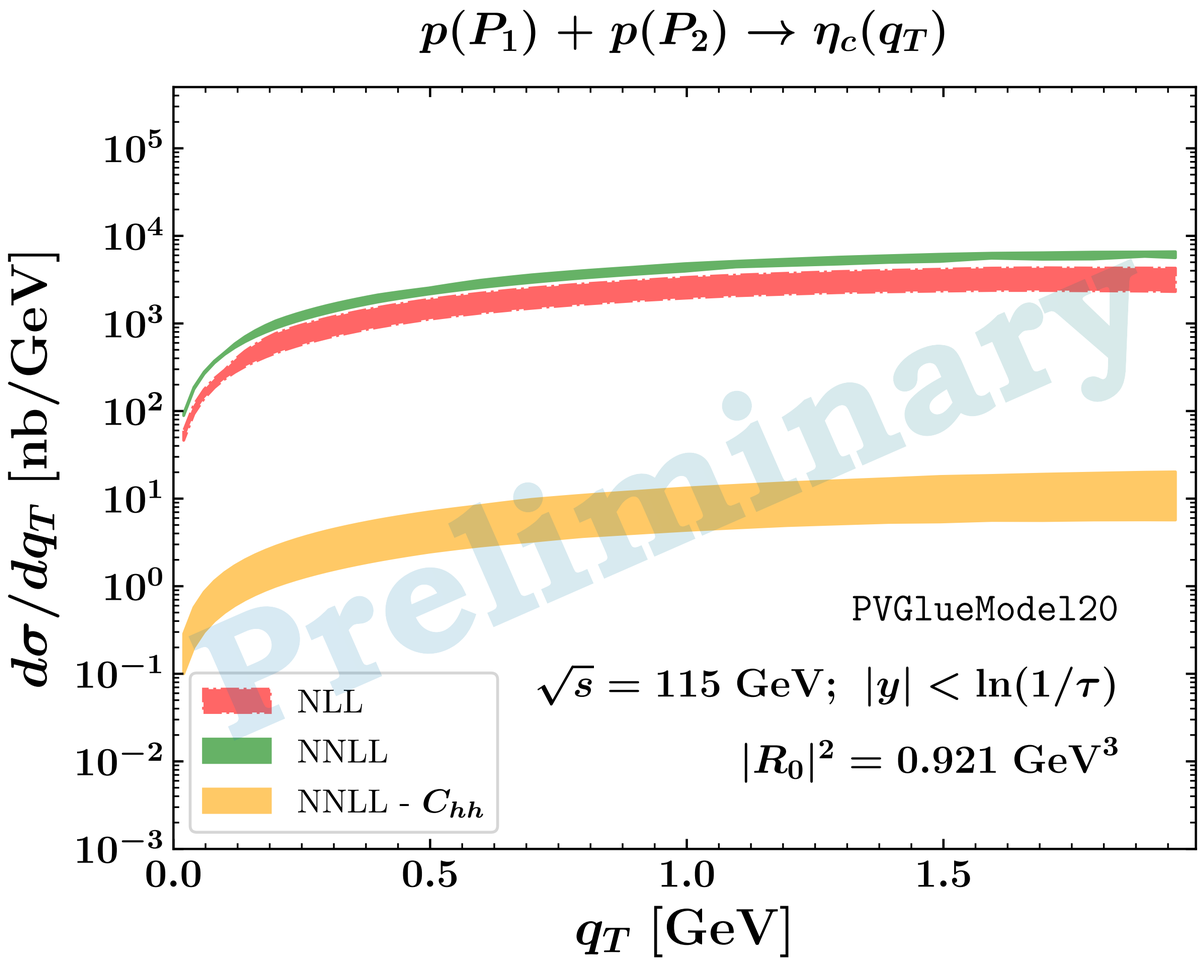
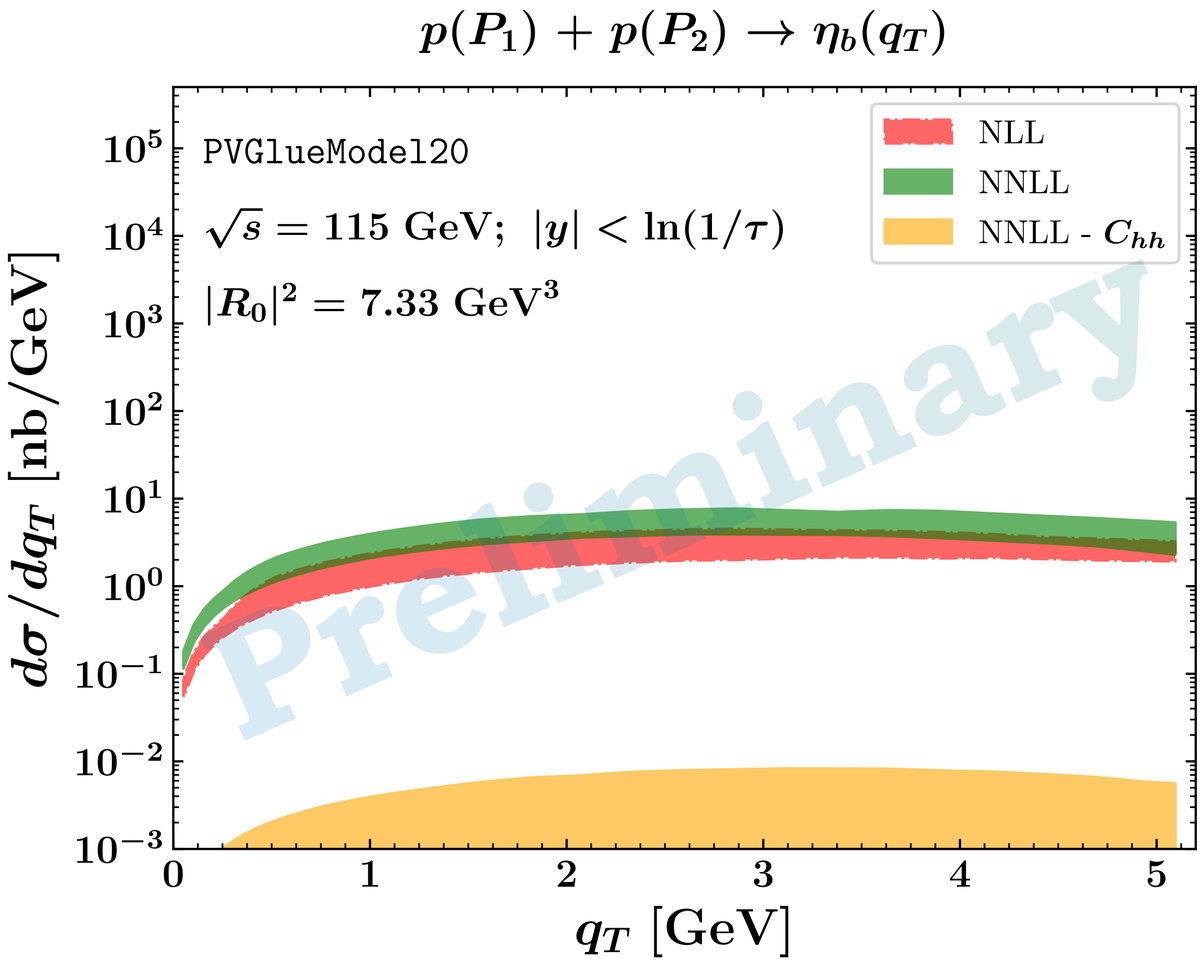
slide by **Andrea Signori** (INT 2017)

Backup

$\eta_{b,c}$ production @ 115GeV After@LHC

Perturbative-scale variation, NP-evolution parameters fixed, TMD central replica



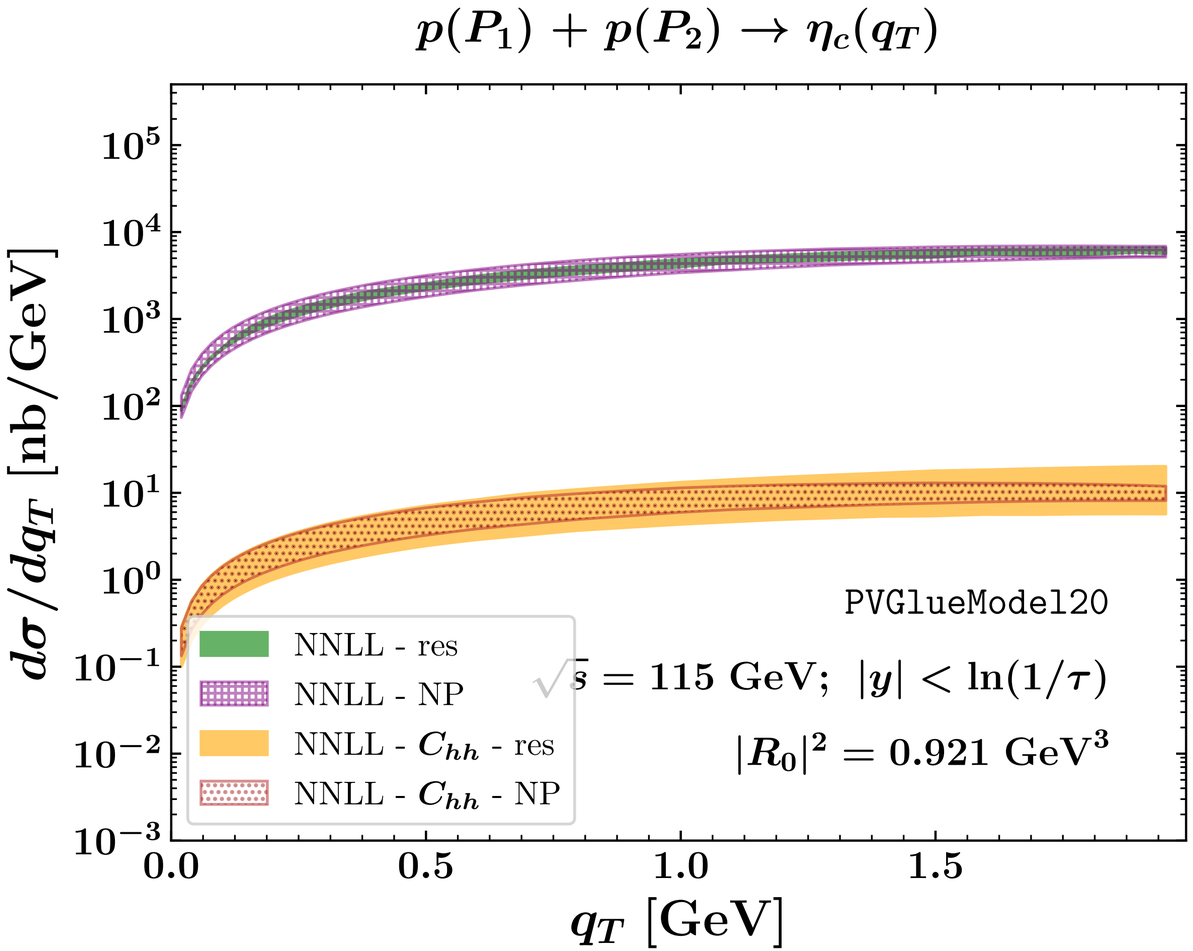


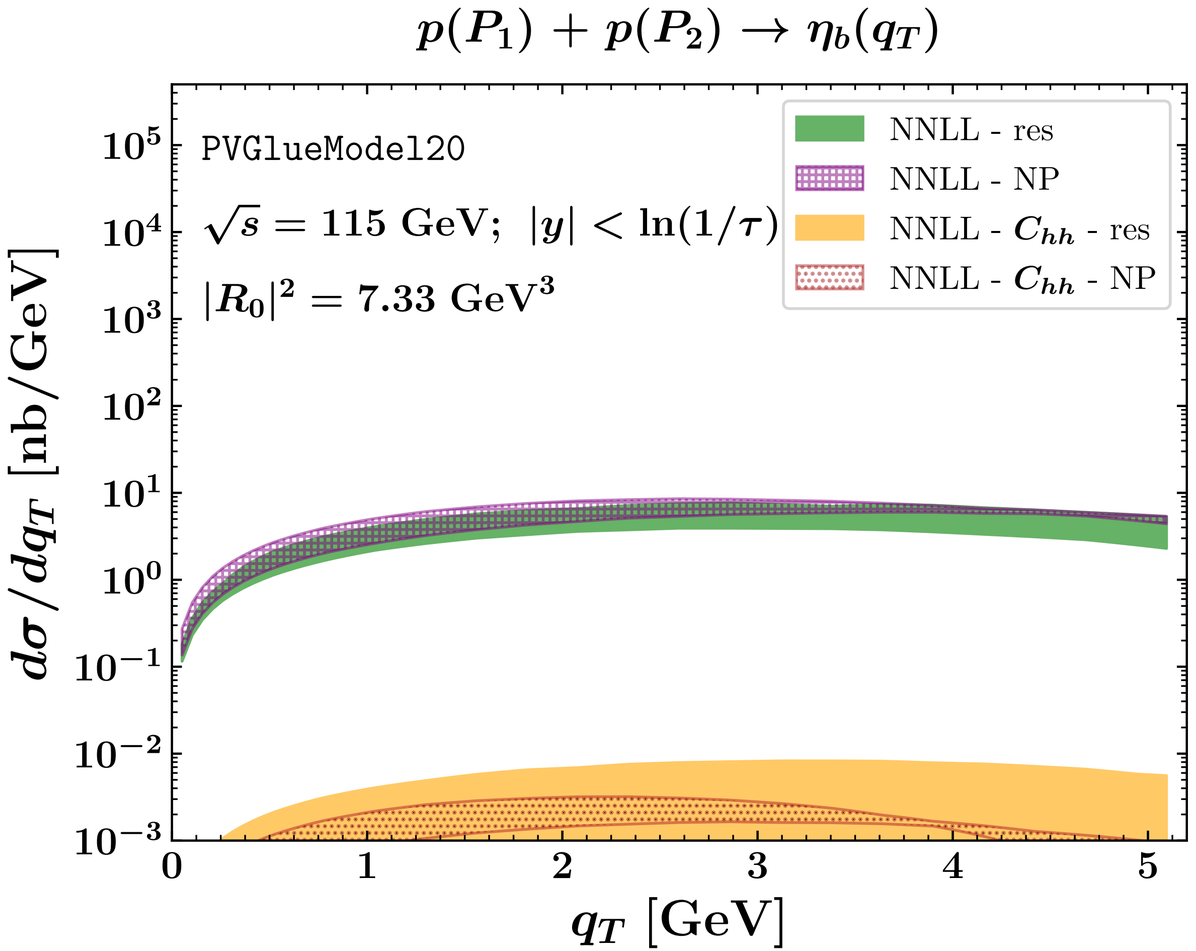
[A. Bacchetta, F.G. C., J.-P. Lansberg, A. Signori (in preparation)]

Backup

$\eta_{b,c}$ production @ 115GeV After@LHC

Perturbative scales fixed, **NP-evolution parameter** variation, TMD central replica





[A. Bacchetta, F.G. C., J.-P. Lansberg, A. Signori (in preparation)]