Correlations in Partonic and Hadronic Interactions - CPHI-2022

March 10th

Accessing the proton content via TMD gluon distributions

Francesco Giovanni Celiberto

ECT*/FBK Trento & INFN-TIFPA

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

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

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TIFPA
Trento Institute for Fundamental Physics and Applications

HAS QCD
HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

An overview on gluon TMDs

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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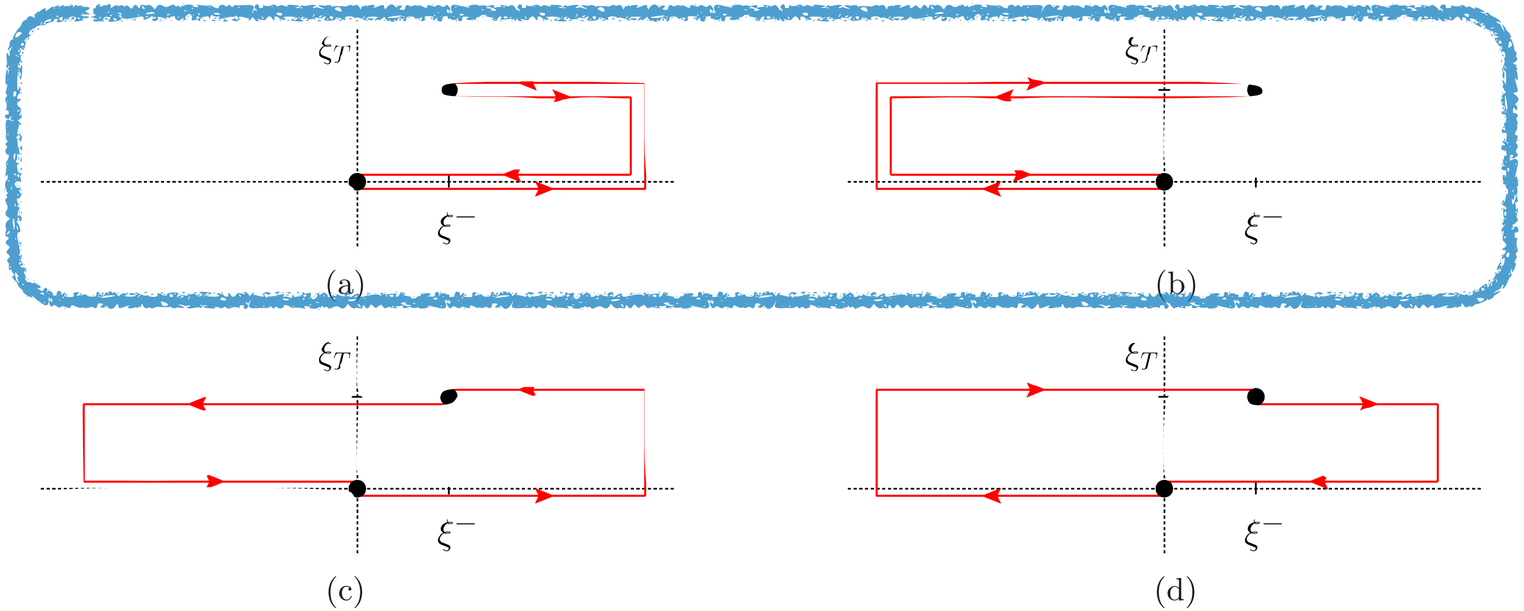
f-type (WW)

(a) [+ , +] or (b) [− , −]



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d-type (dipole)

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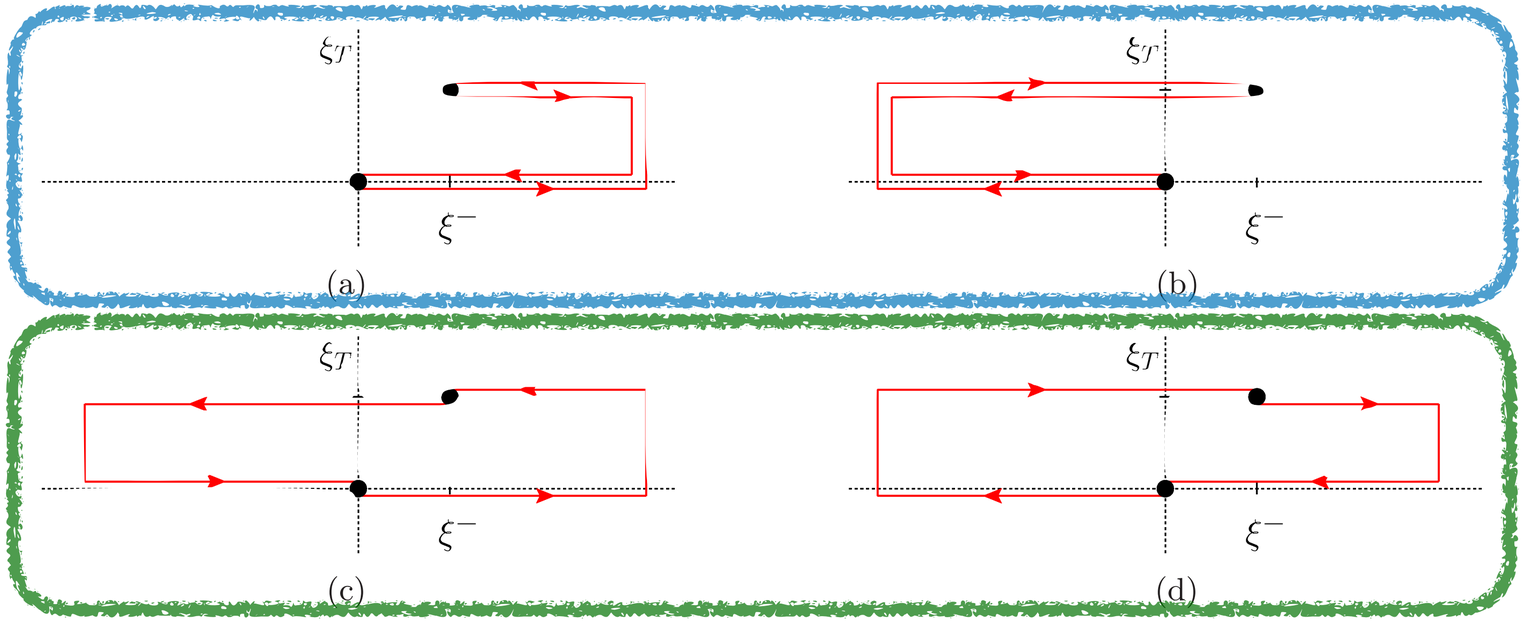

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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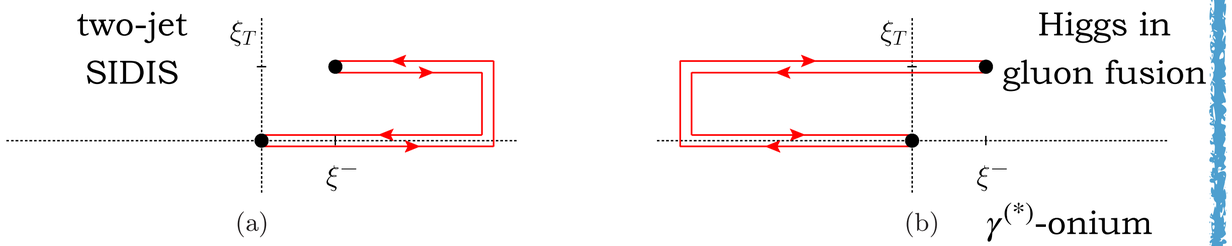

Higgs in gluon fusion

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

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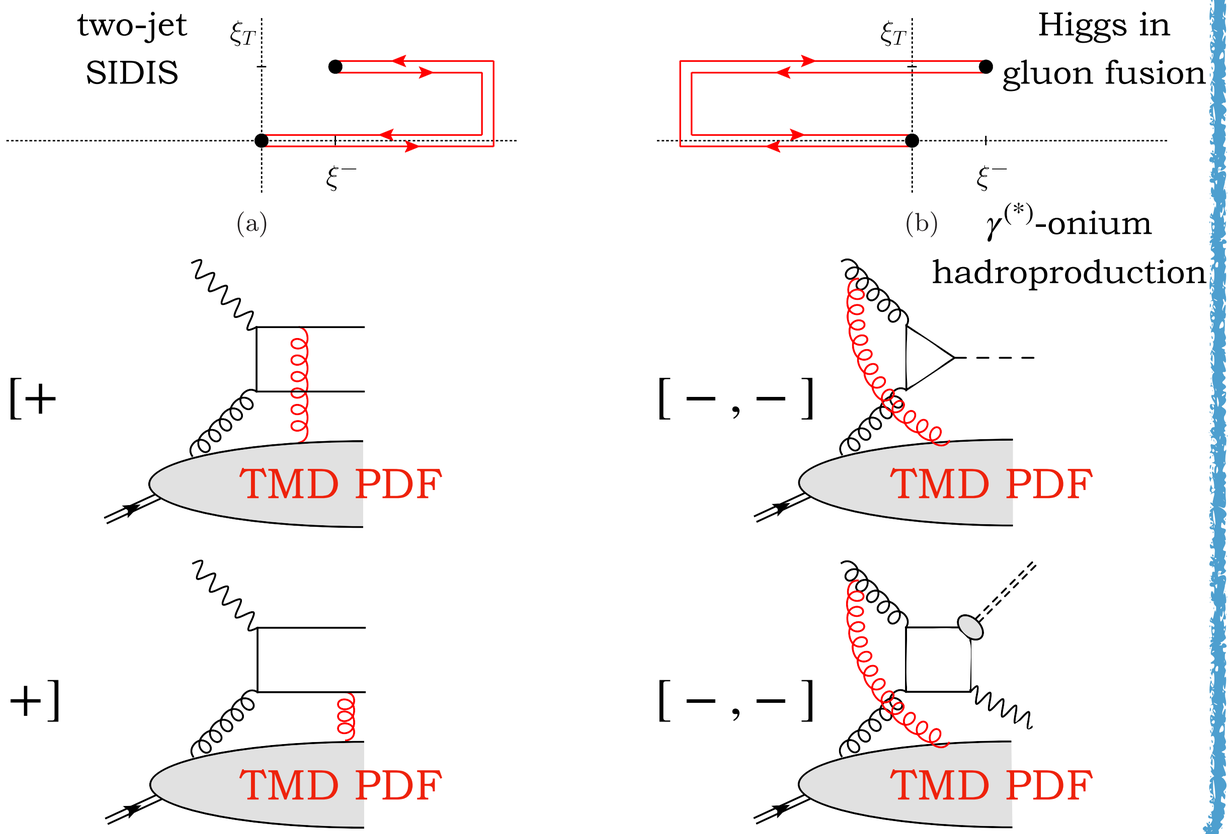

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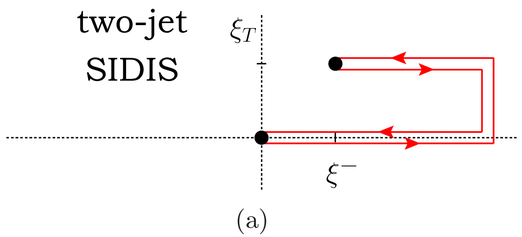
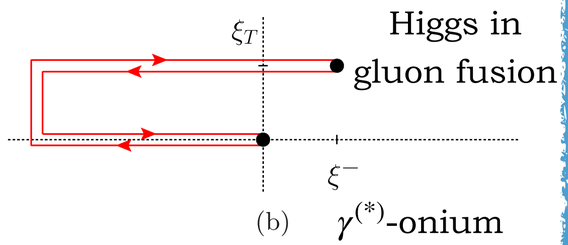
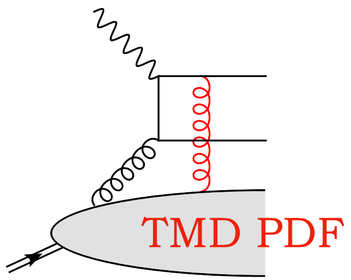




$\gamma^{(*)}$-onium hadroproduction

$[+$



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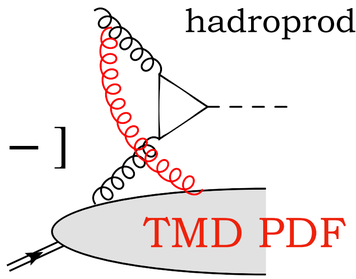
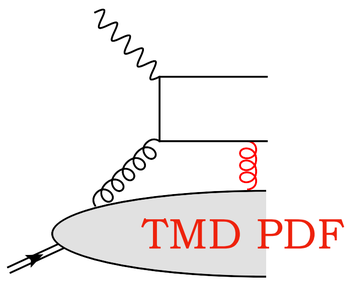


$+]$



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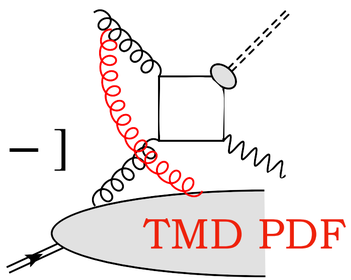
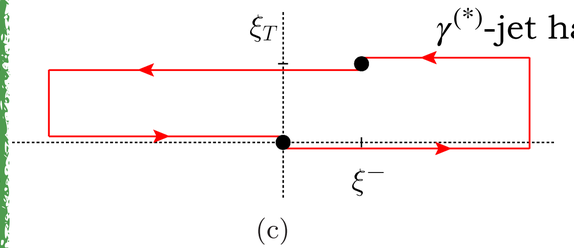
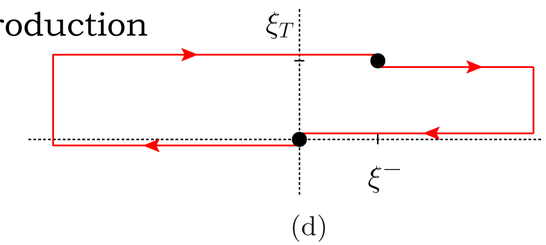


Dipole (DP)

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





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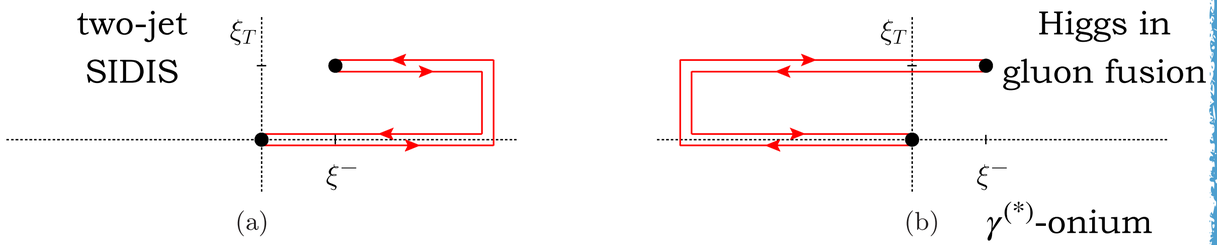

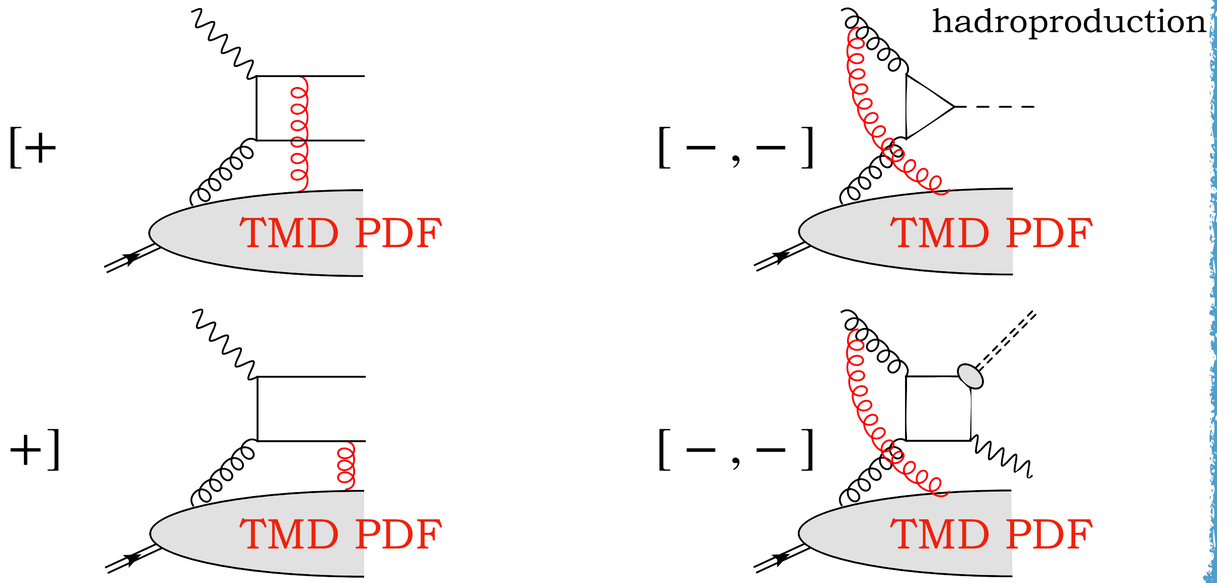

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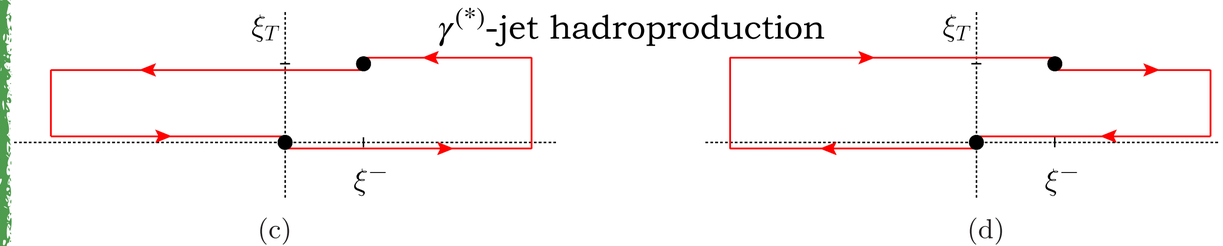

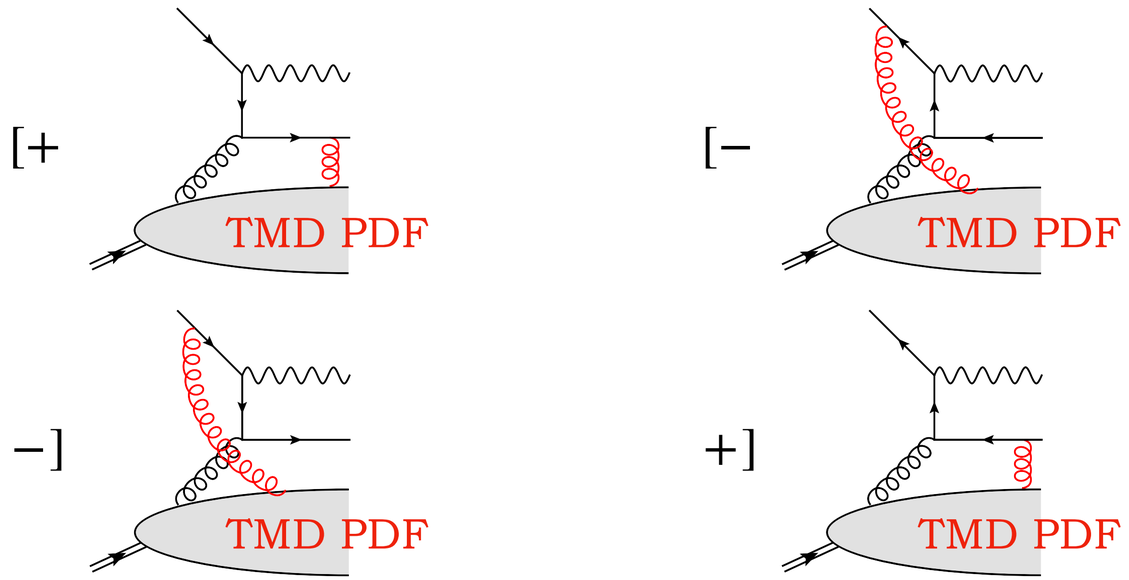

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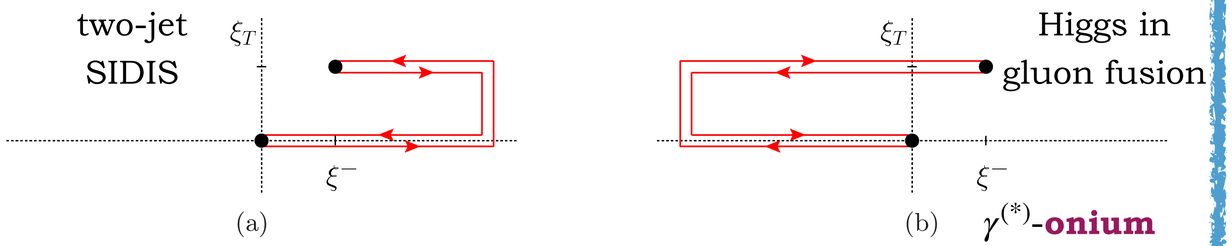

Higgs in gluon fusion

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

* 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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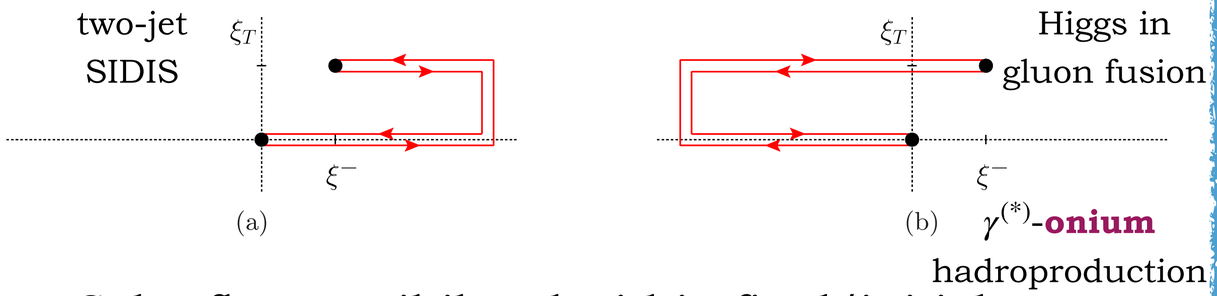

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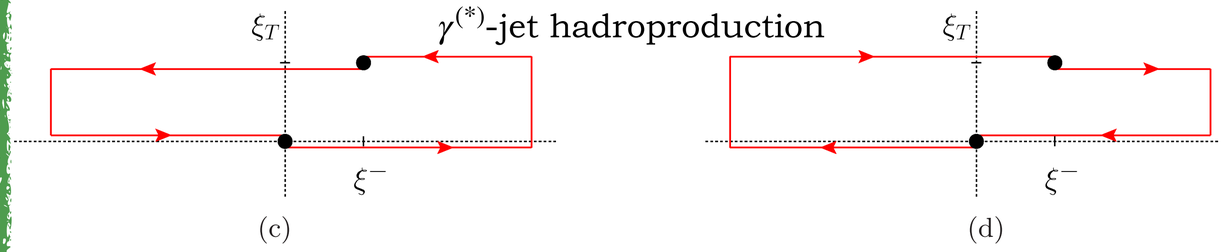

- Color flow involving both initial and final states
- d-type gluon TMDs $\rightarrow$ d^{abc} color structure
- Modified universality:

$$f_1^{[+,-]} = f_1^{[-,+]},$$
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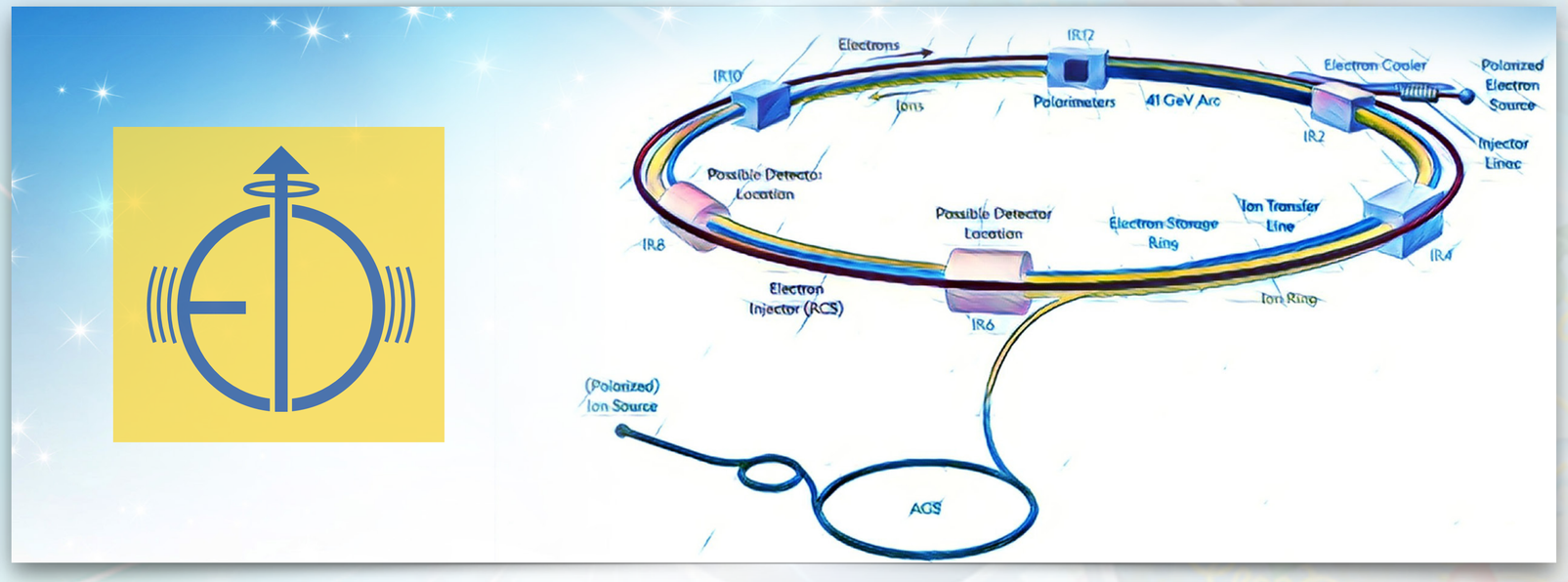
- Phenomenology: single hadron or $\gamma^{(*)}$-jet hadroproduction, SIDIS or Drell-Yan (subleading)

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

3D proton tomography at new-generation colliders



Electron-Ion Collider

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

Accessing the gluon content

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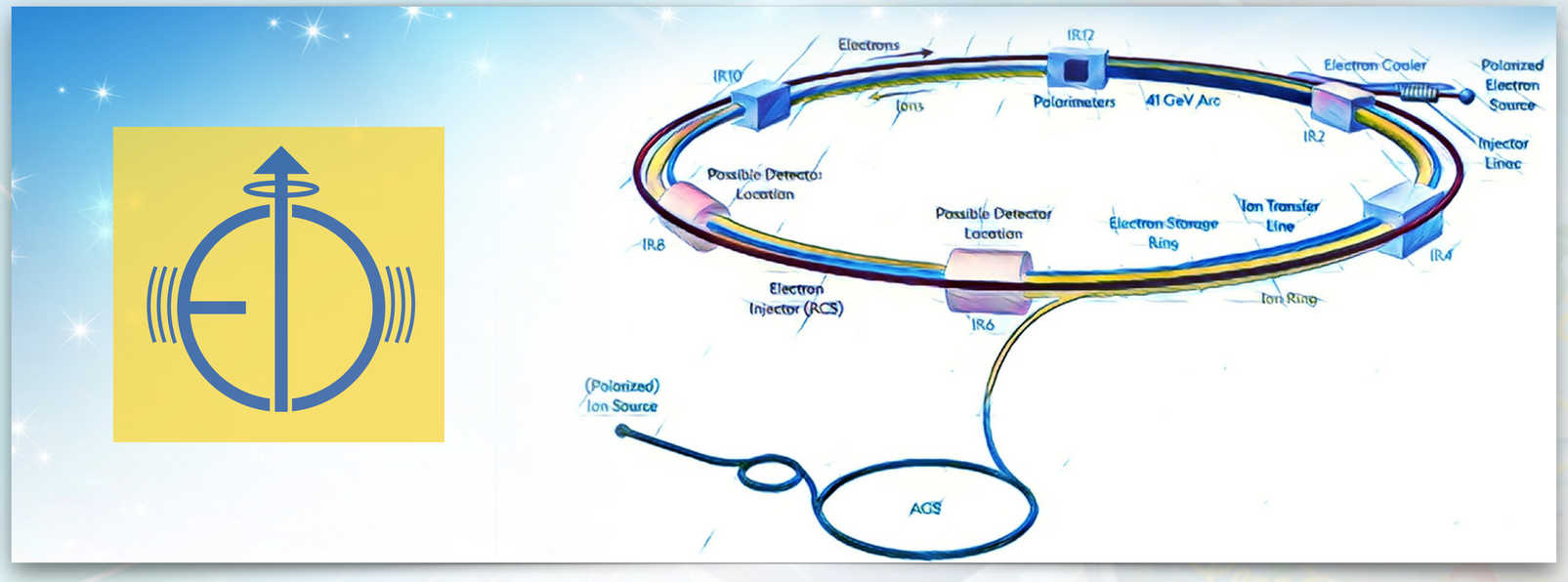

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Core sector of **EIC** studies

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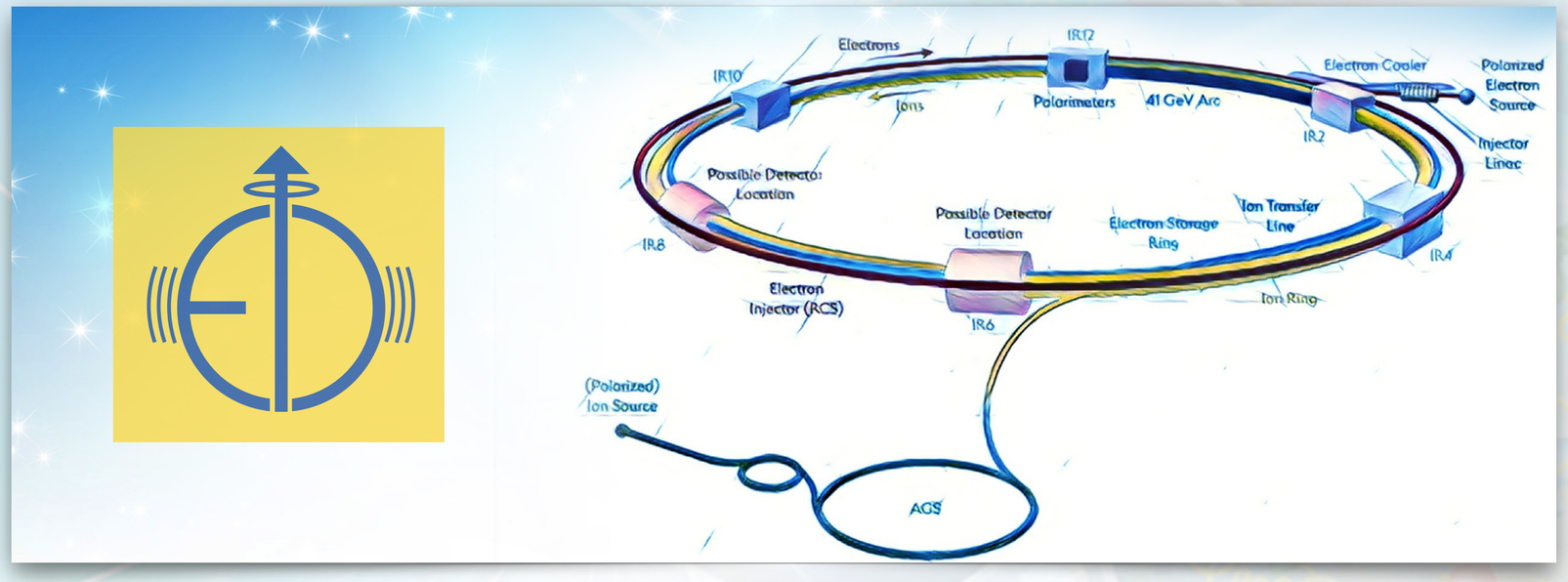

Electron-Ion Collider

NICA-SPD

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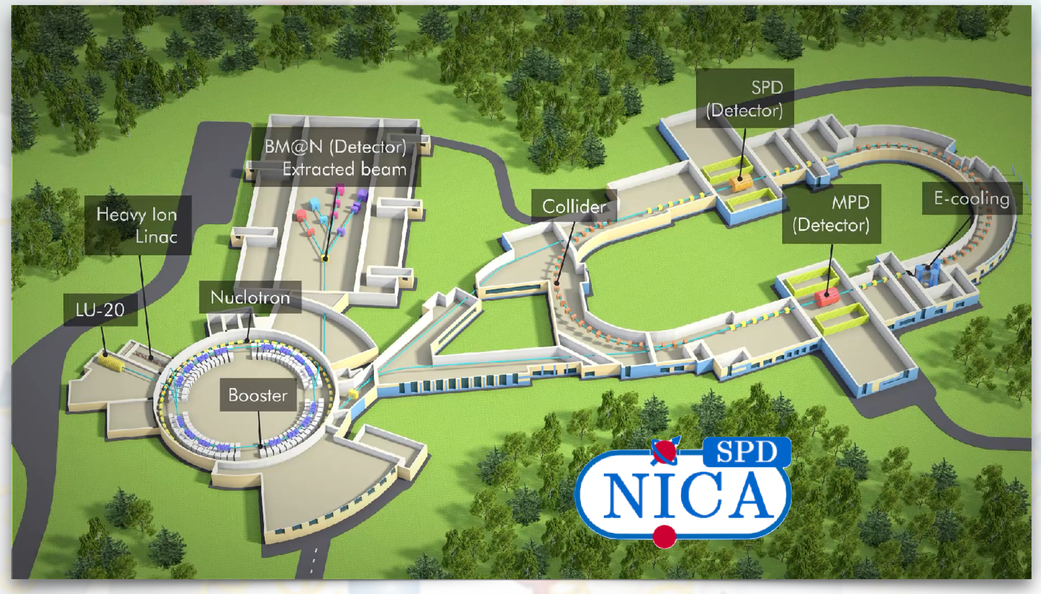
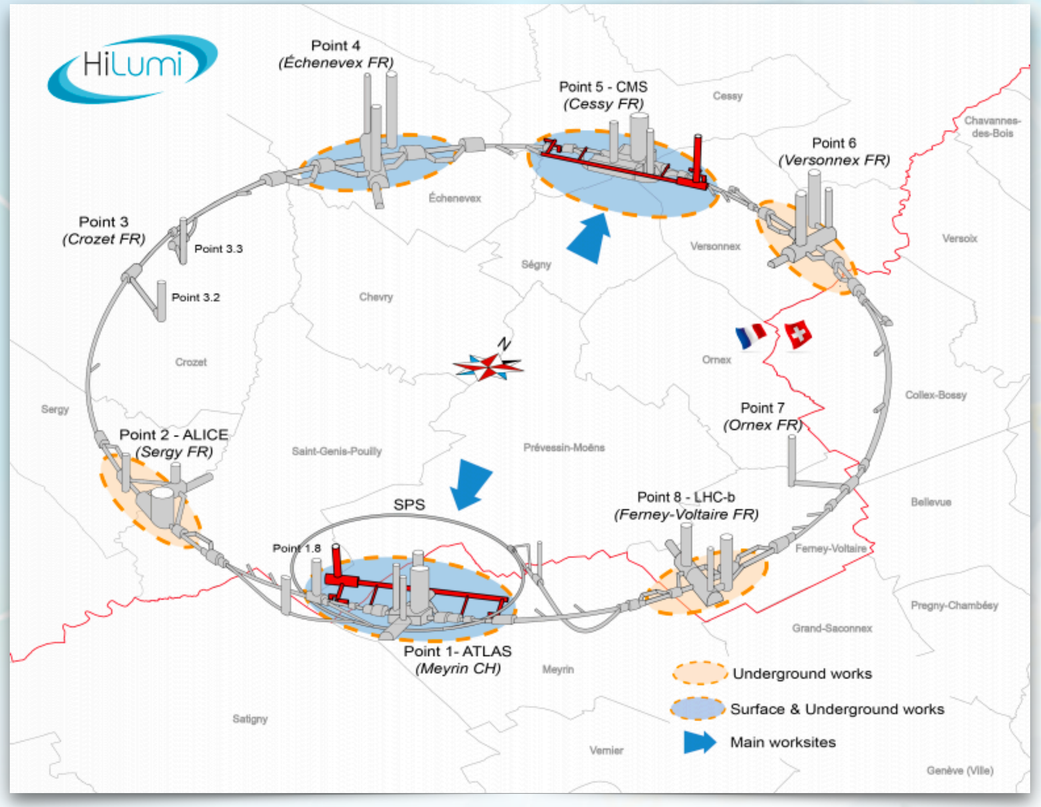
Gluon content at **NICA-SPD** [NICA [arXiv:2011.15005]]



Accessing the gluon content

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

Connections with high-energy physics



HL-LHC

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

Hadronic structure at high energies

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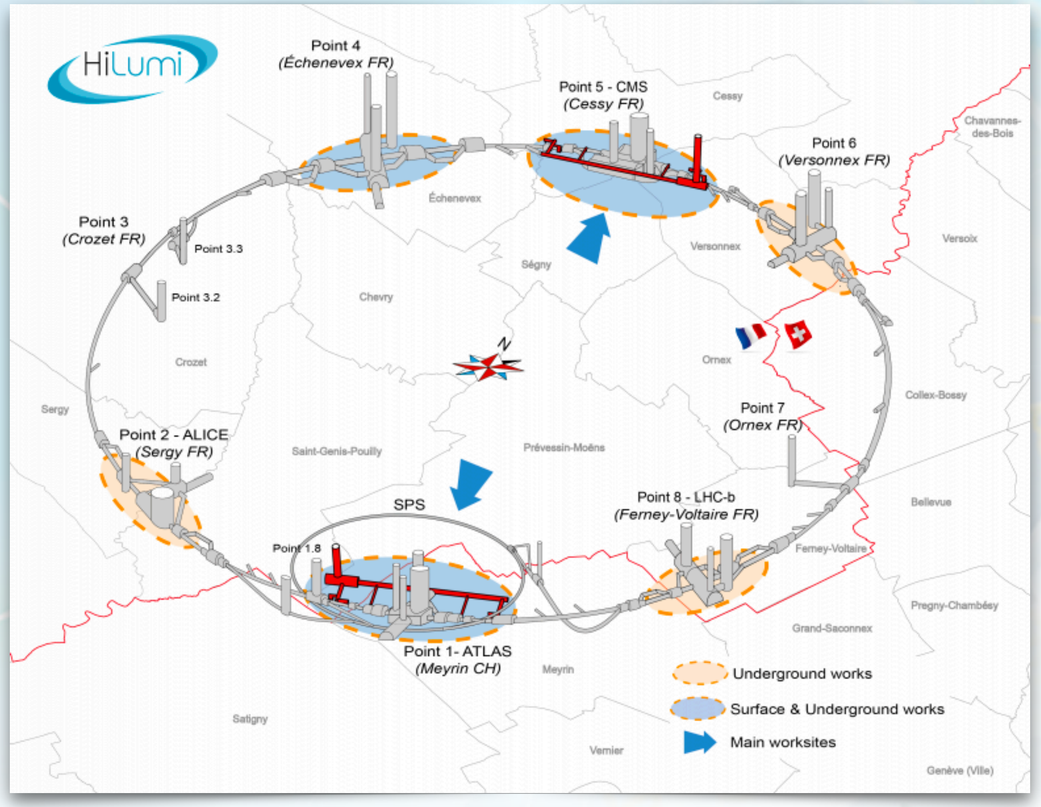

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Intrinsic effect of gluon polarization in **unpolarized** *pp* collisions

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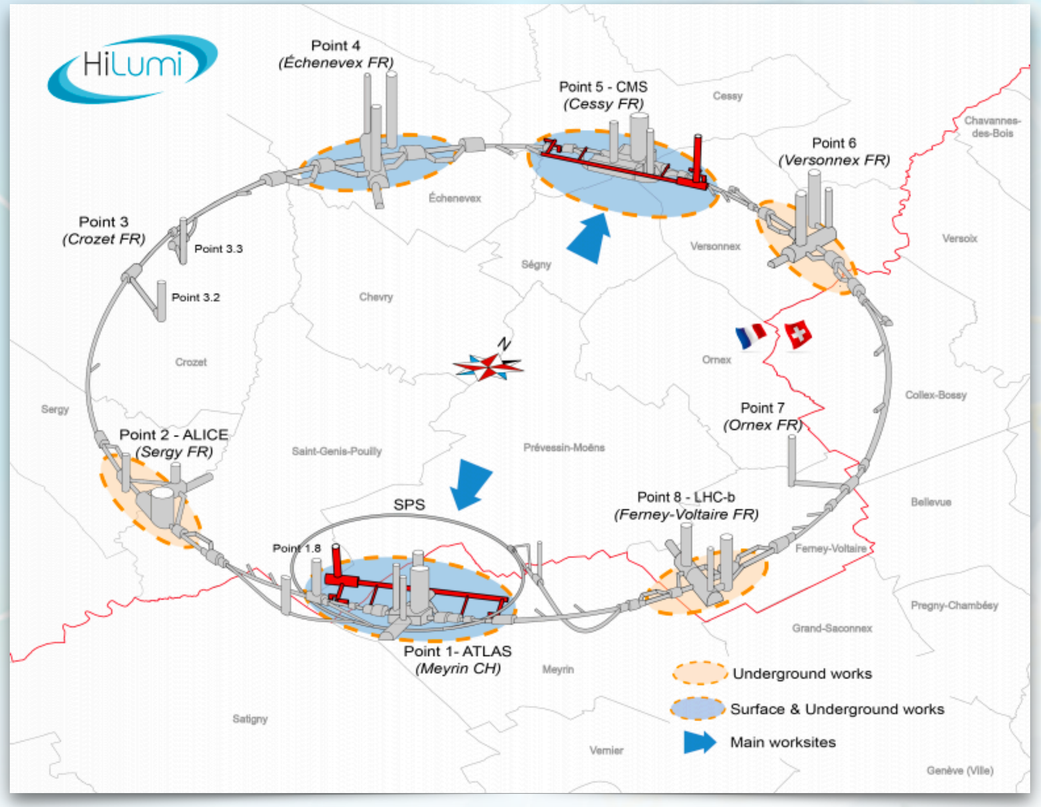
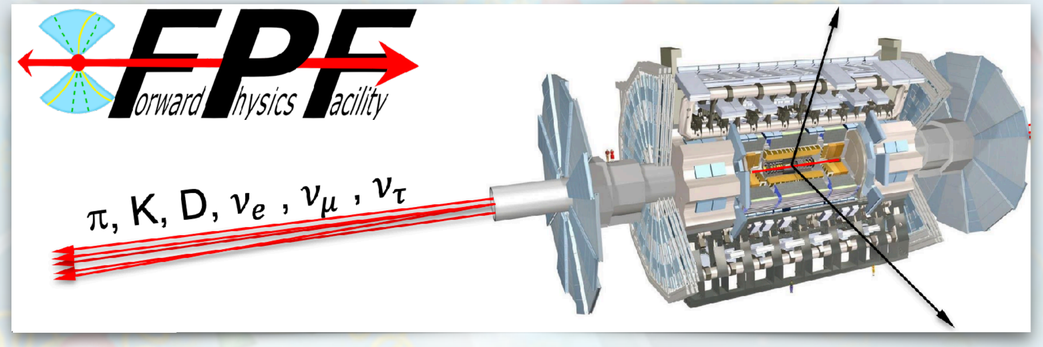




HL-LHC

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

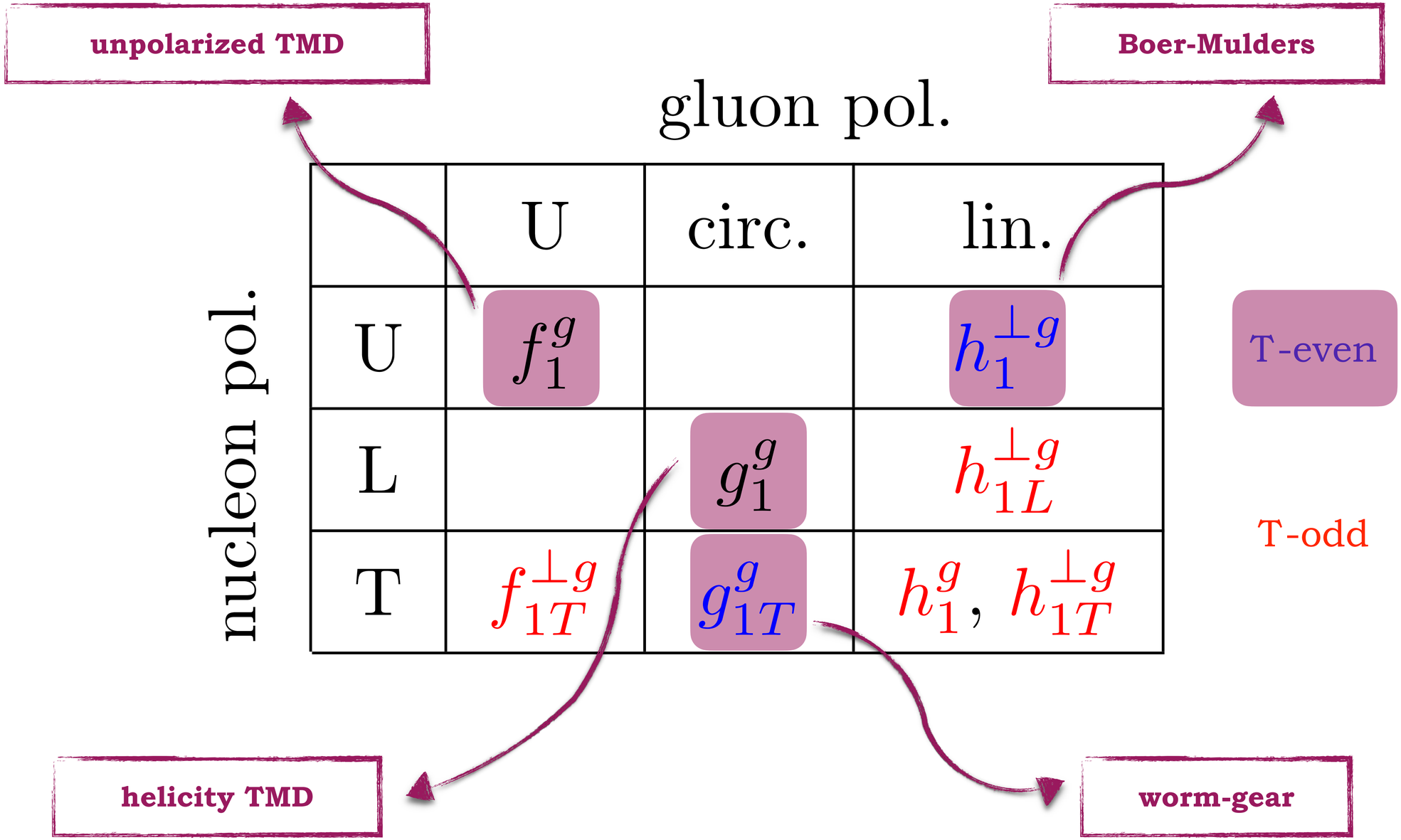
T-even and T-odd gluon TMD PDFs at leading-twist

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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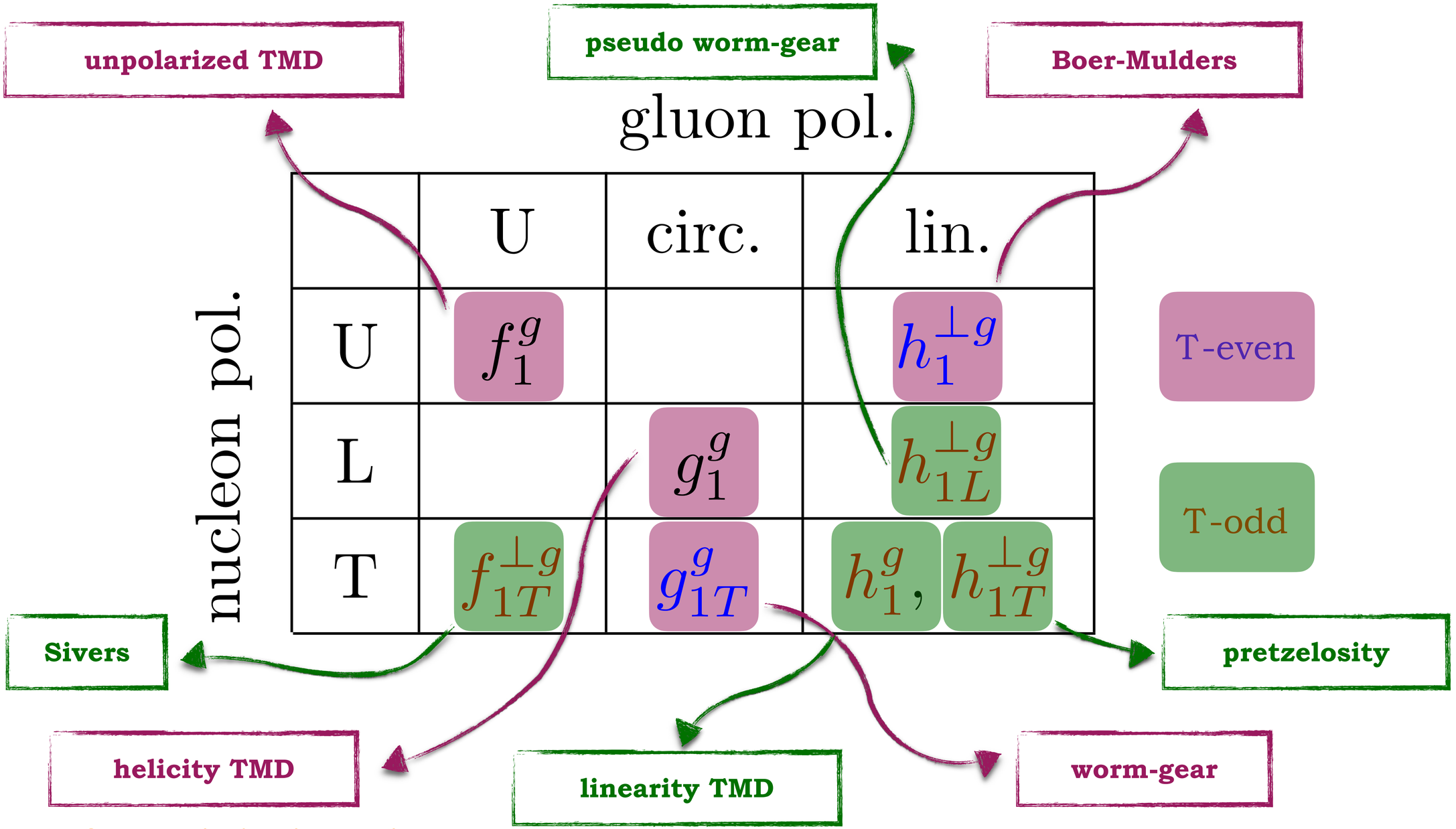
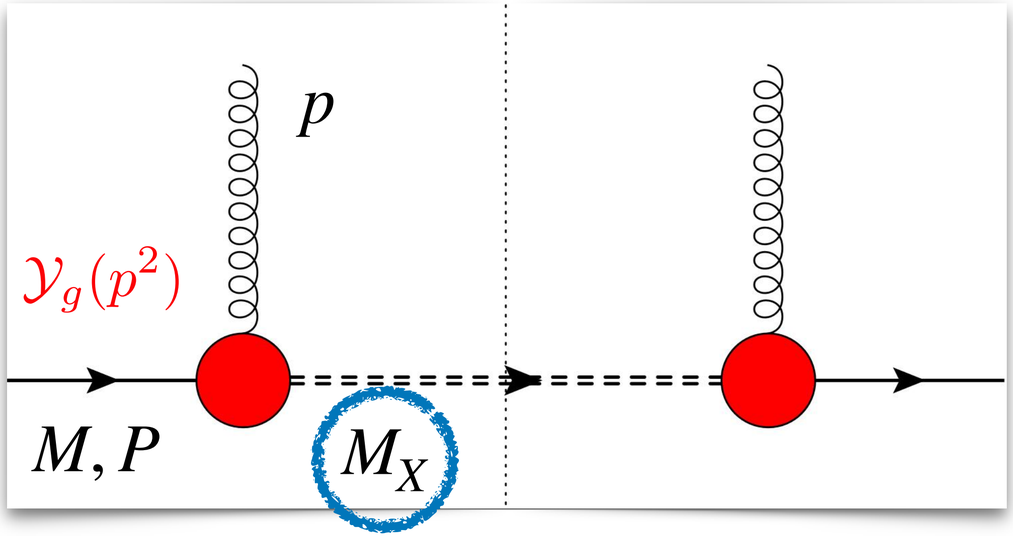


Assumptions of the model

Spin-1/2 spectator

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



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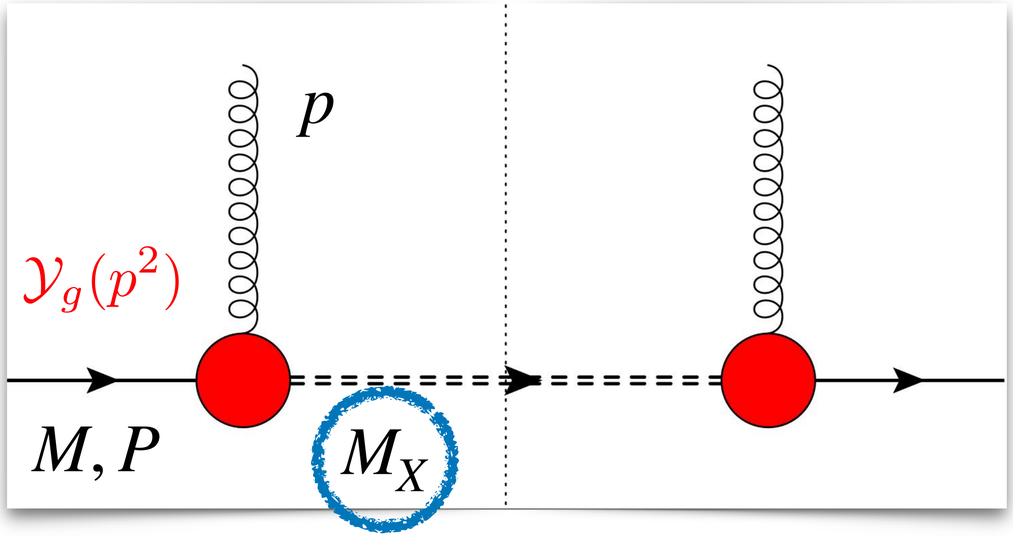

Nucleon-gluon-spectator vertex

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

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

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

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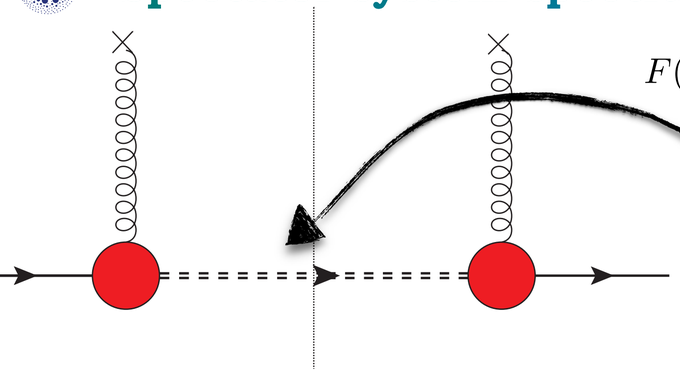
Dipolar form factor(s)

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

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

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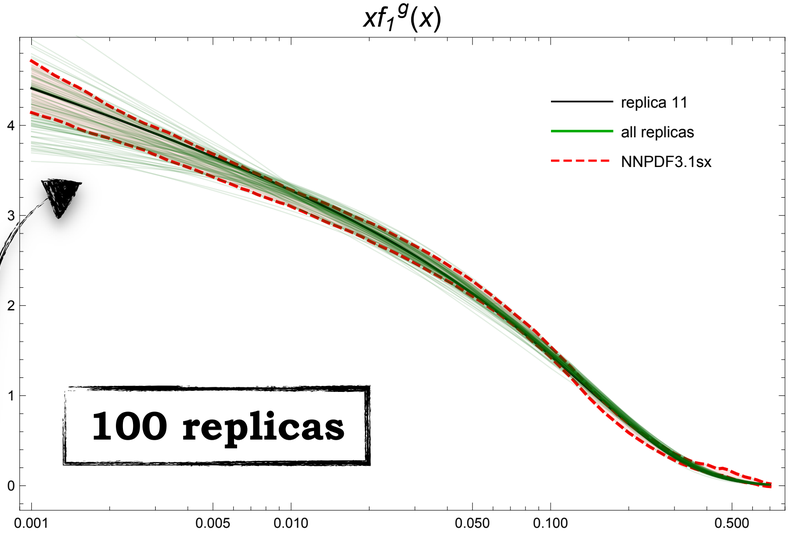

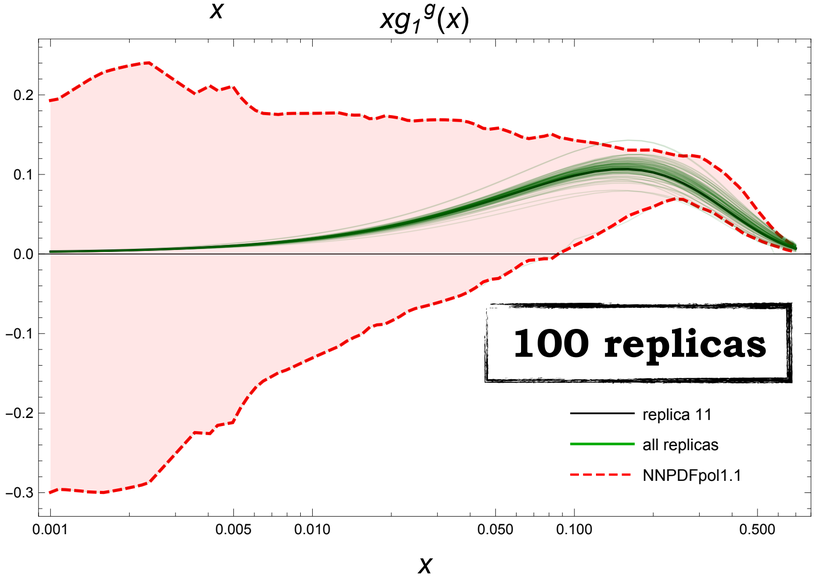

🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Unpolarized gluon TMD

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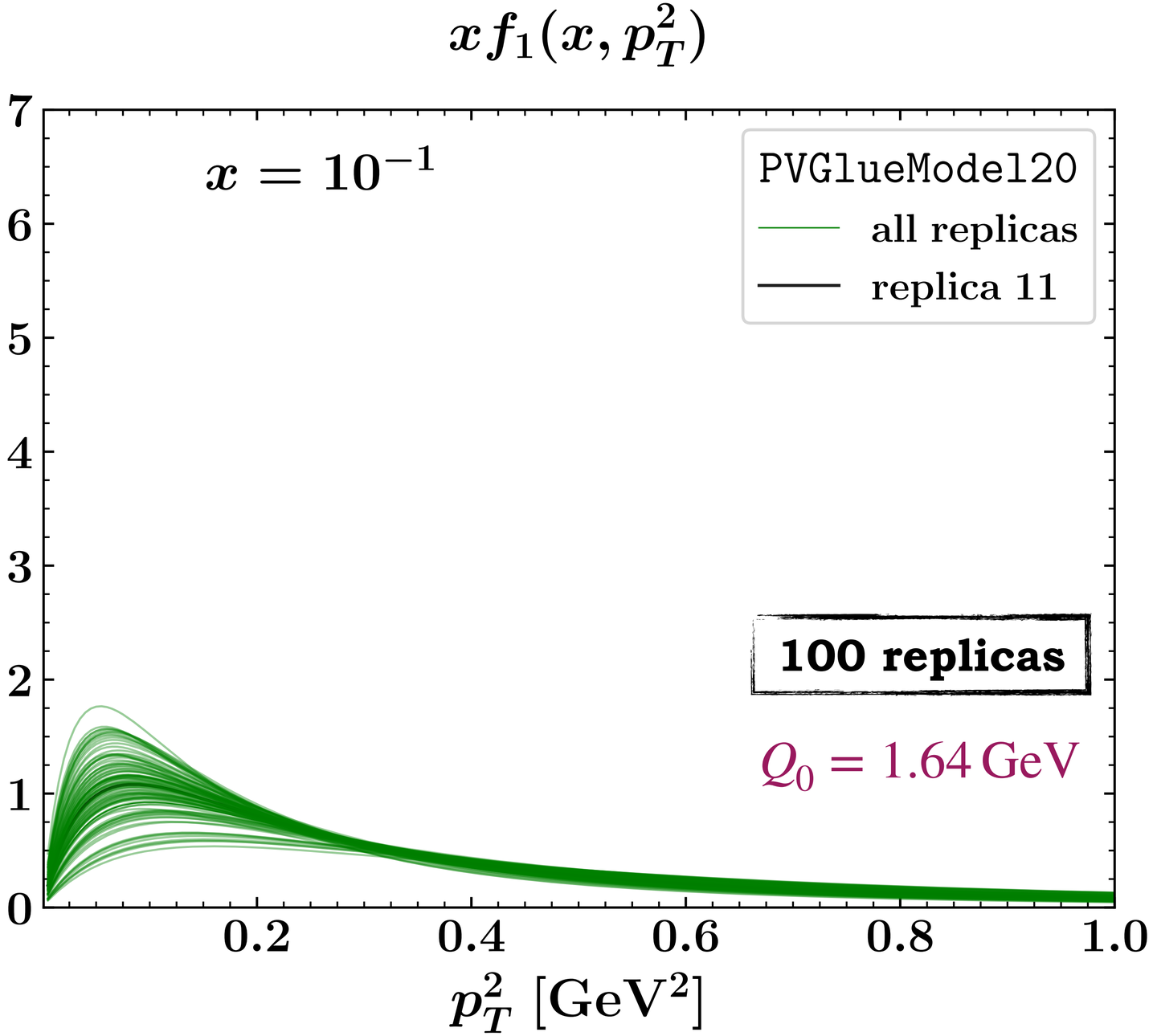

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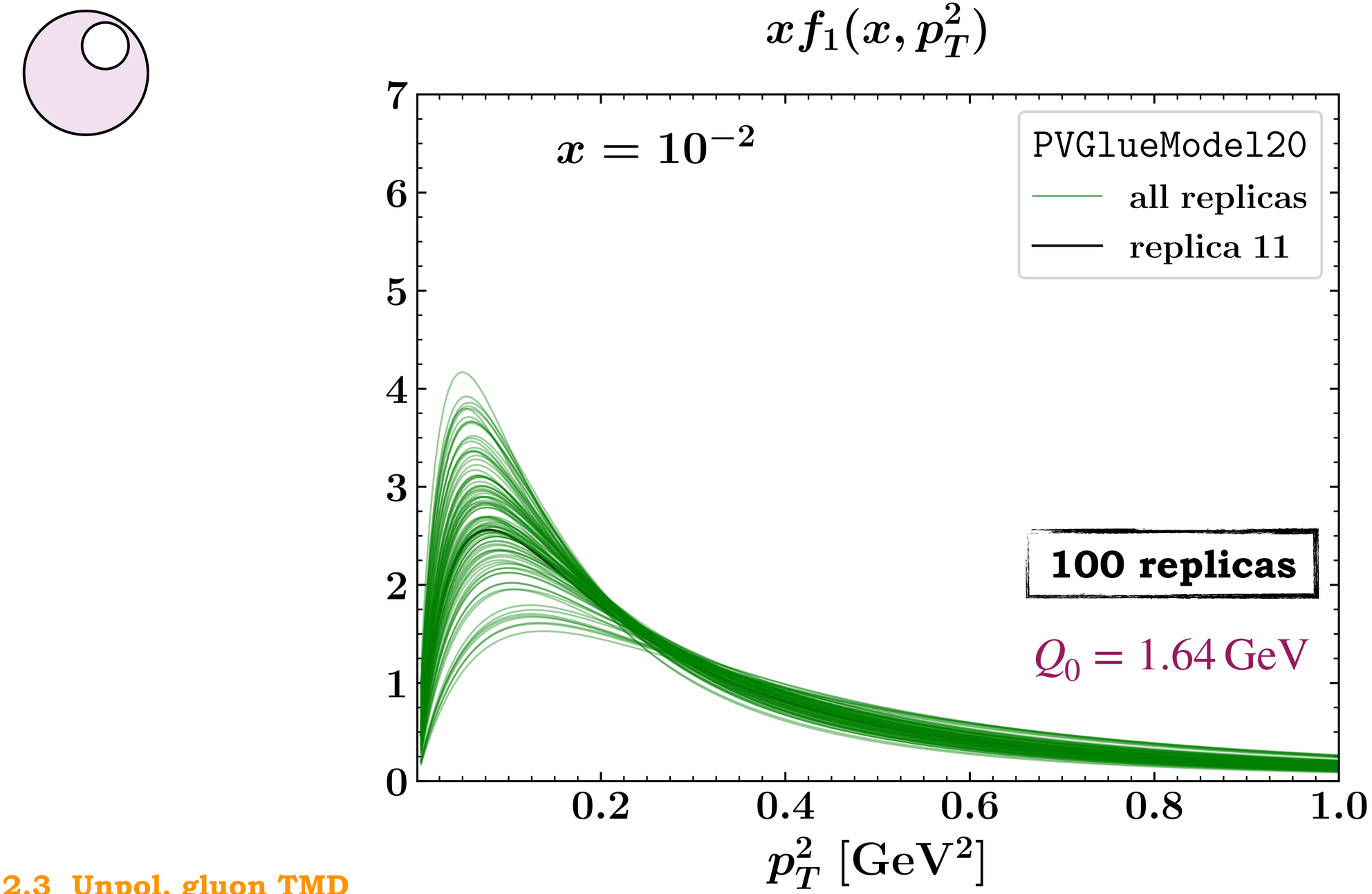

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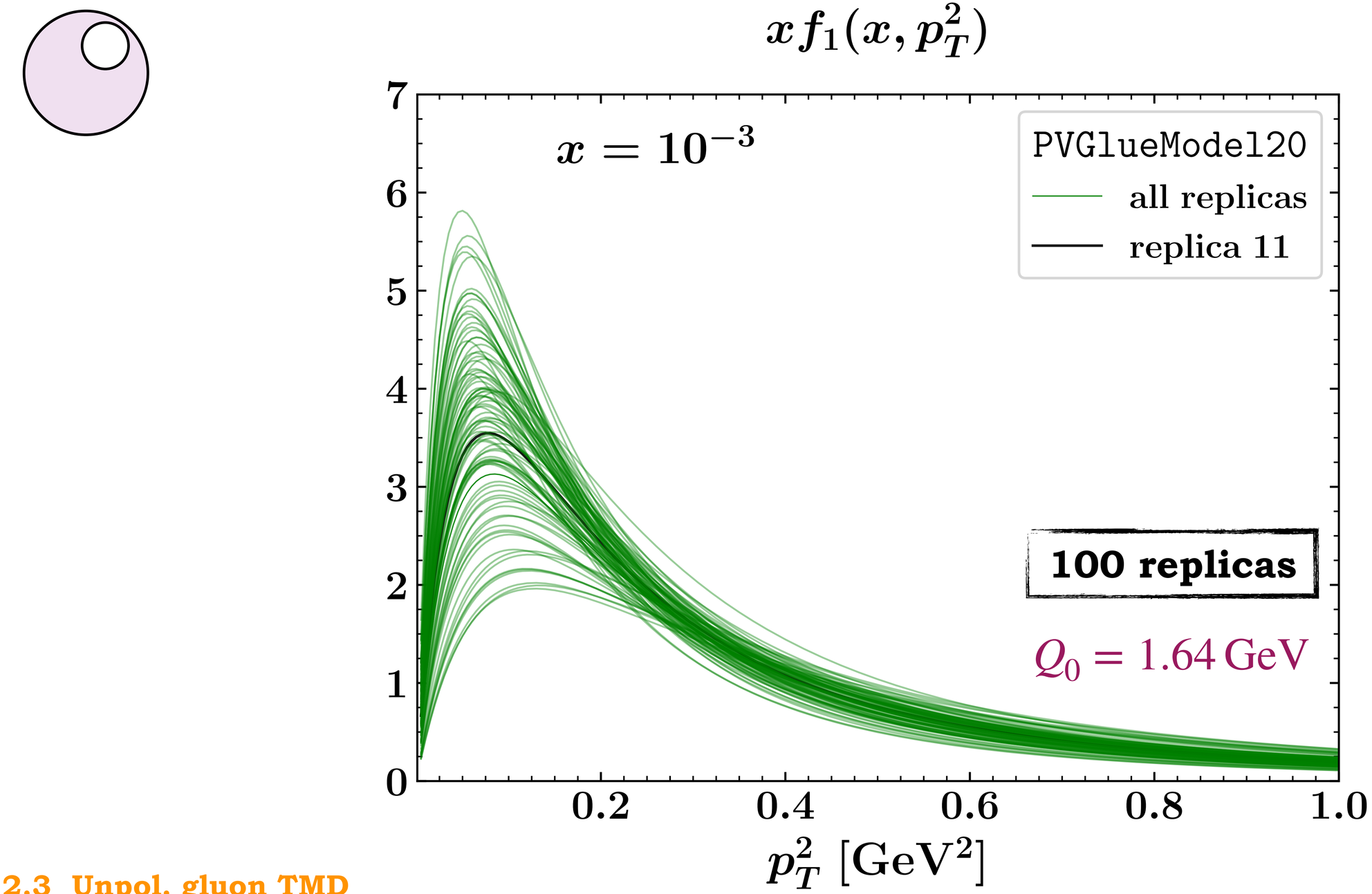
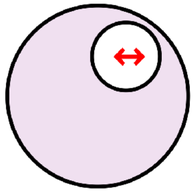


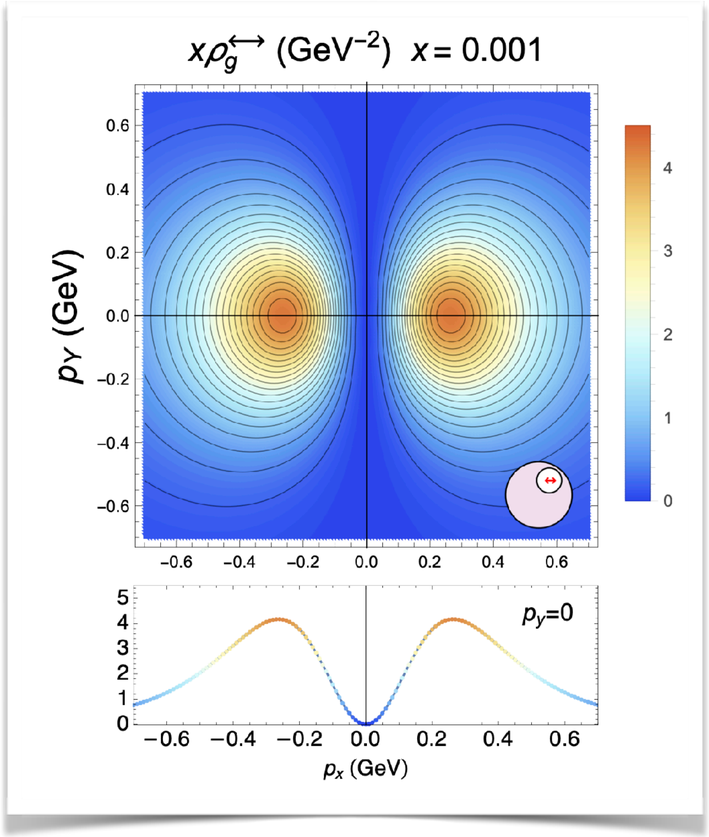
Gluon TMDs in proton collisions

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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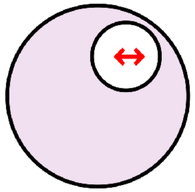

$$[\leftrightarrow/u] \qquad f_1(x,p_x,p_y) + \frac{p_x^2 - p_y^2}{2M^2} h_1^{\perp}(x,p_x,p_y)$$

unpol. Boer-Mulders

(Pseudo)scalar p_T-distribution: Higgs, $\eta_{b,c}$

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

at low transverse momentum for (pseudo)scalar state

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unpolarized gluons — **lin. polarized** gluons

[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
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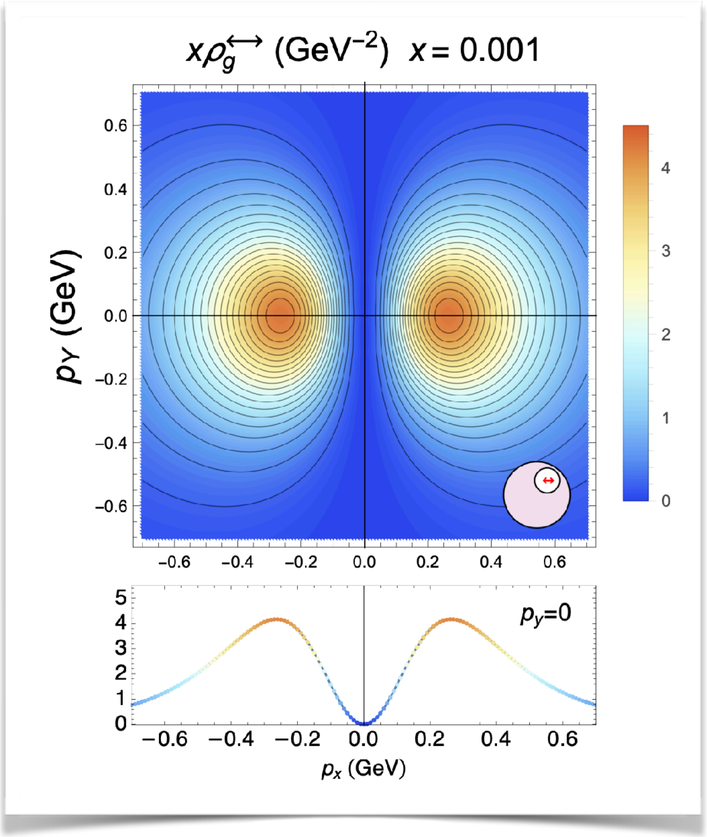

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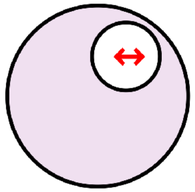

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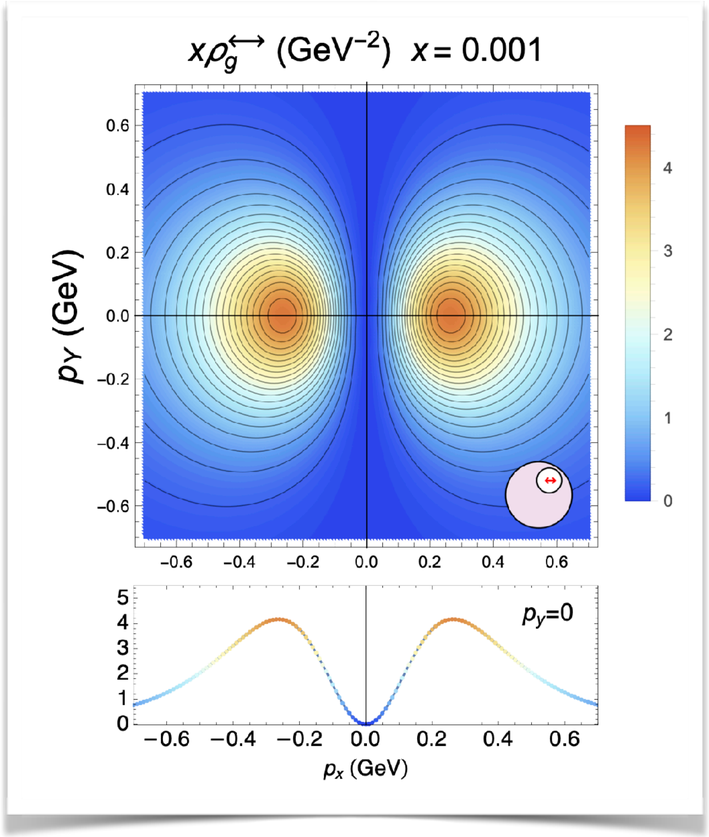

[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Model prediction at low-x

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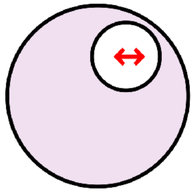

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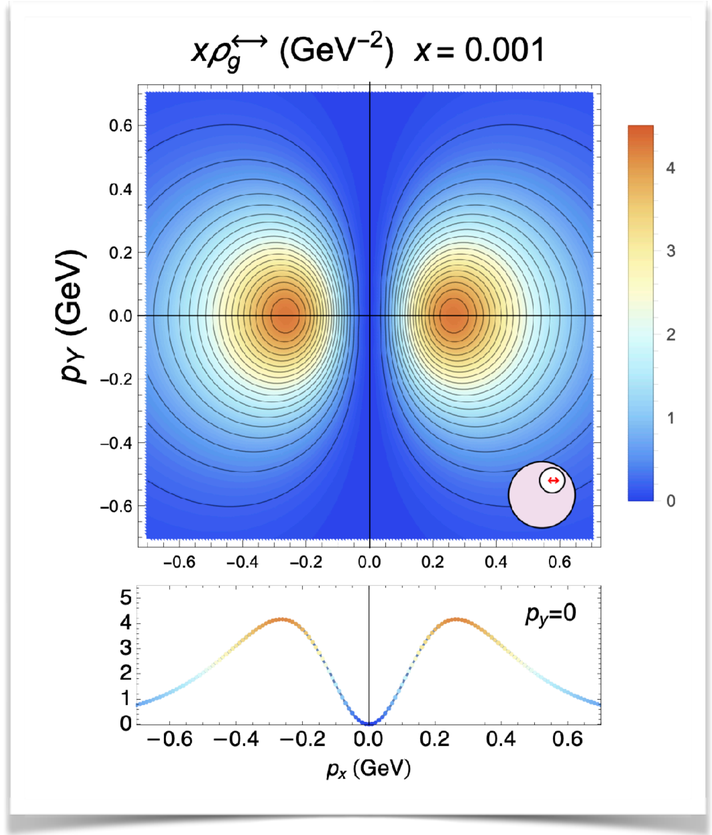

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$$f_1^g(x,p_T^2) = h_1^{\perp g}(x,p_T^2) + \text{higher twist}$$

HEF regime (linear low-x evolution)

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

slide adapted from C. Bissolotti

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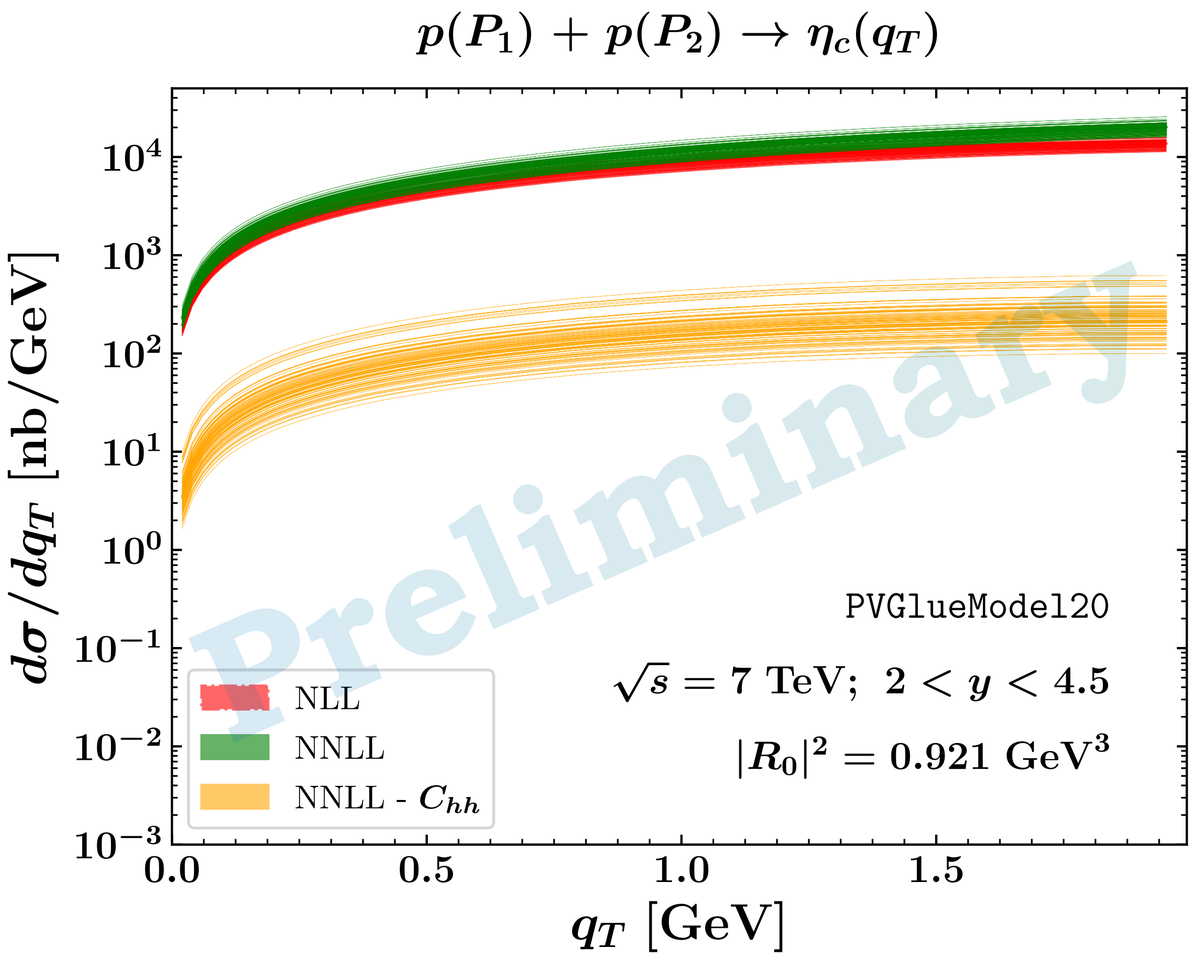
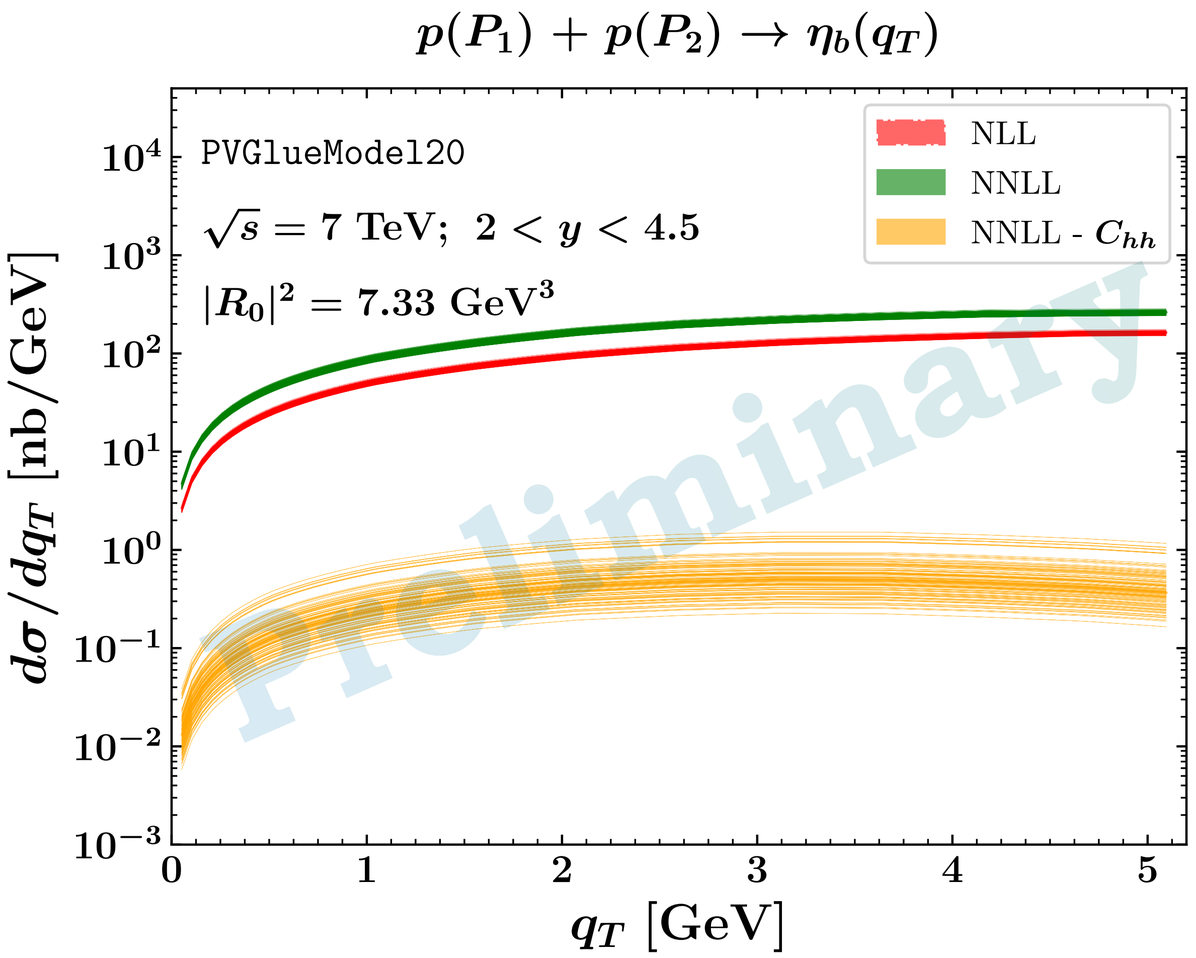
Suppression of genuine NP effects!

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

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





[A. Bacchetta, F.G. C., J.-P. Lansberg, M. Radici, 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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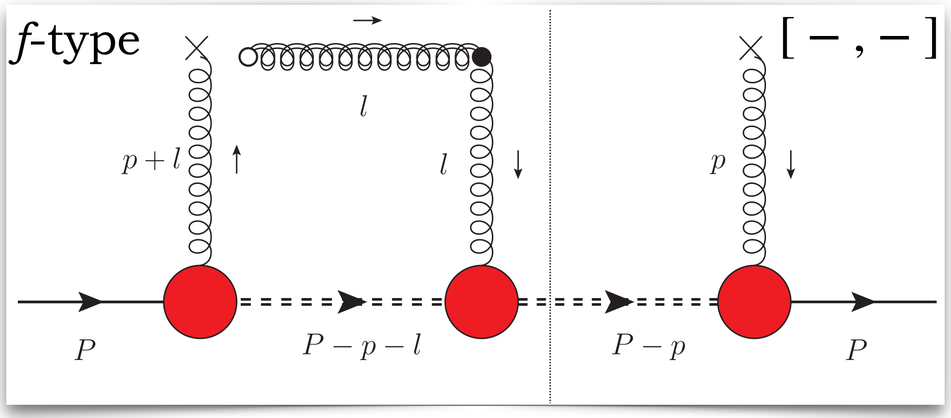
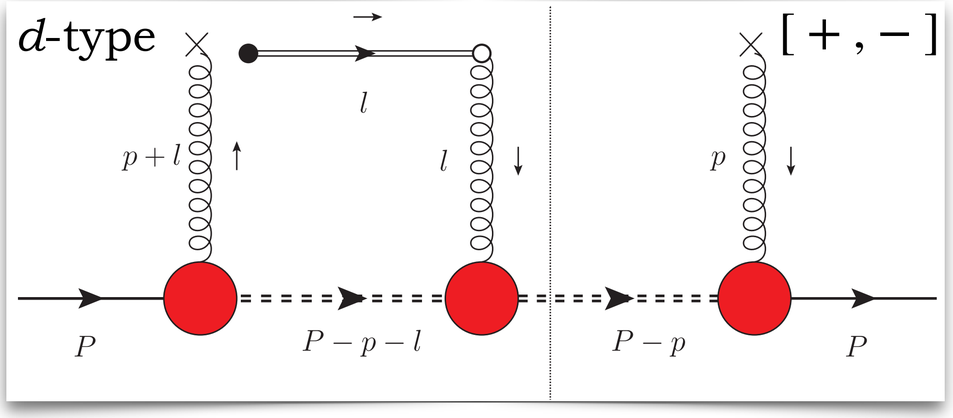
$gg \to H$



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

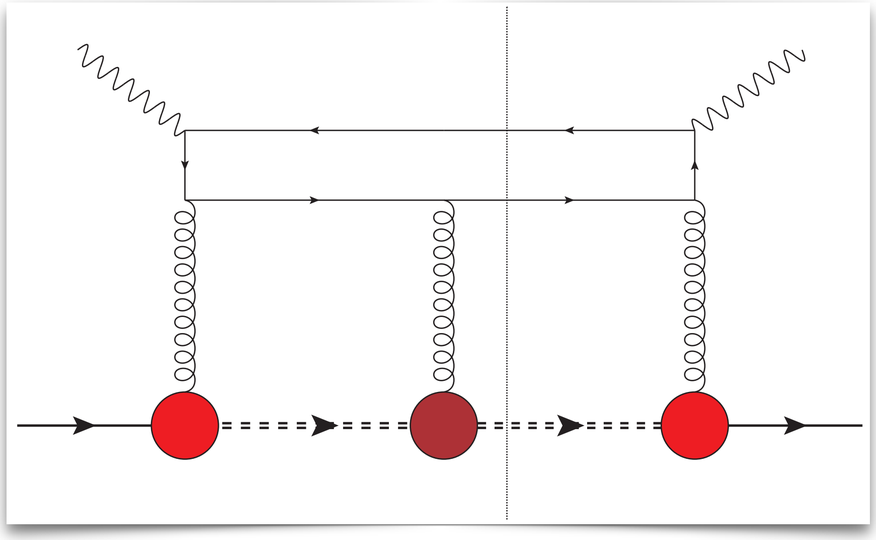


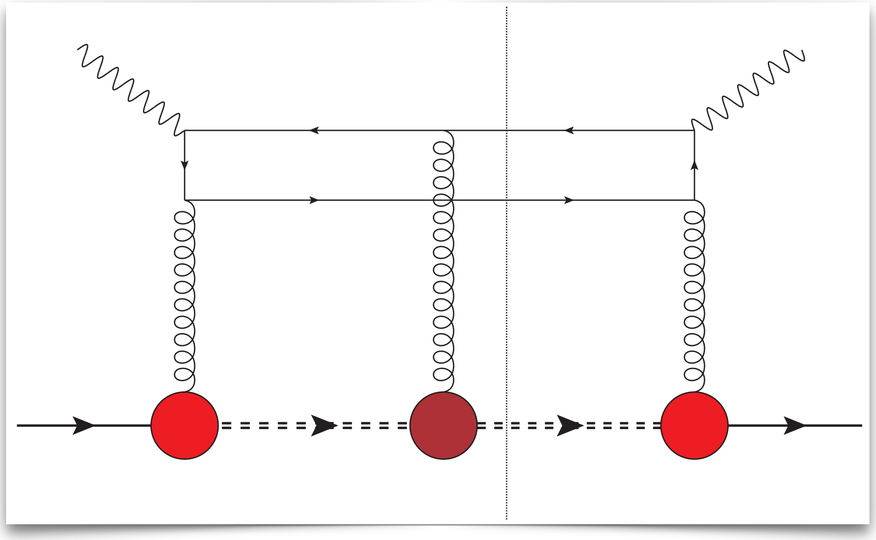
- Leading-twist one-gluon-exchange of the gauge-link operator
- Sensitivity to *f*- and *d*-type structures
- Preliminary results for **Sivers** and **linearity** functions (g_1-vertex)

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

Analytic structure of T-odd gluon TMDs

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





$$\mathcal{Y}^{\mu}_{bc}(p^2) = \delta_{bc}\left[g_1(p^2)\,\gamma_\mu + g_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$$

3.1 T-odd gluon correlator

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

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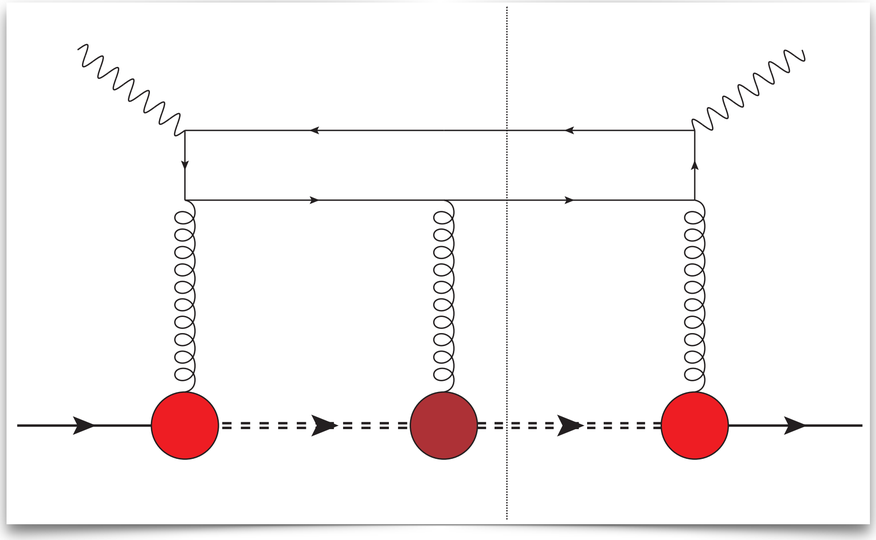

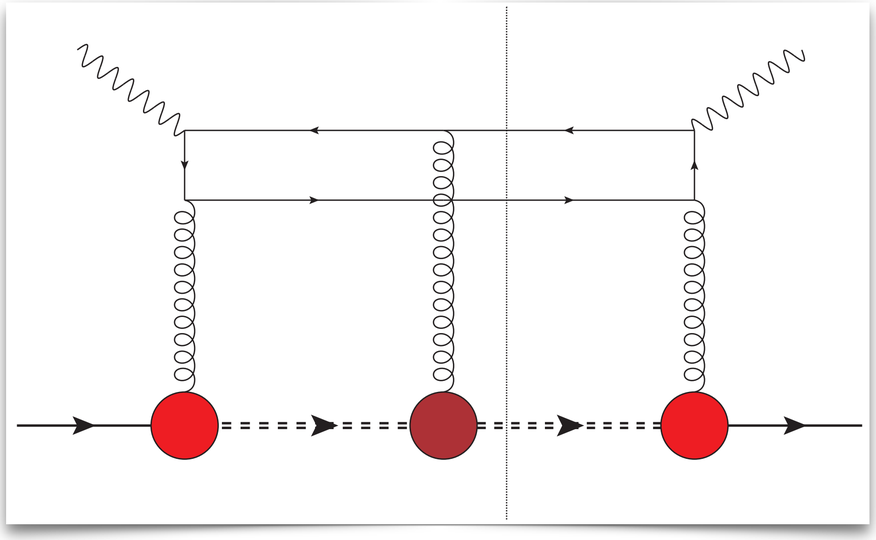

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spectator-gluon-spectator

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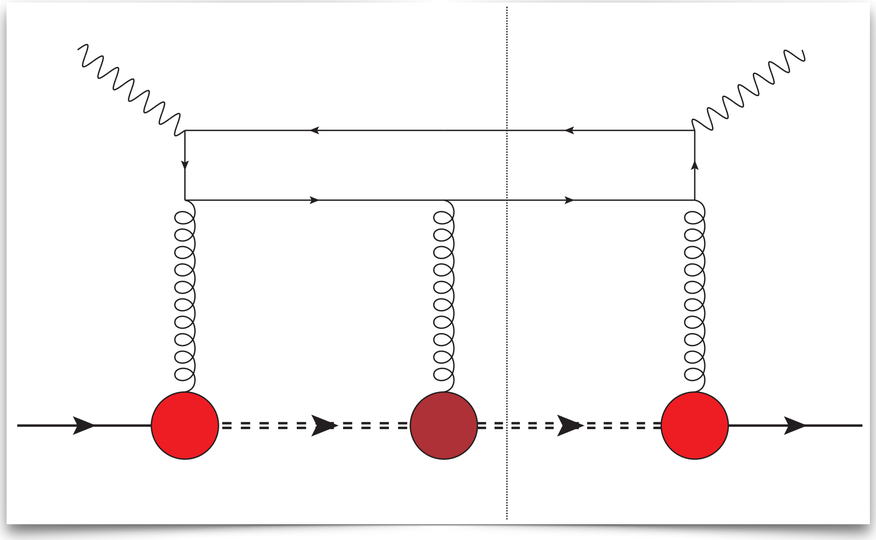

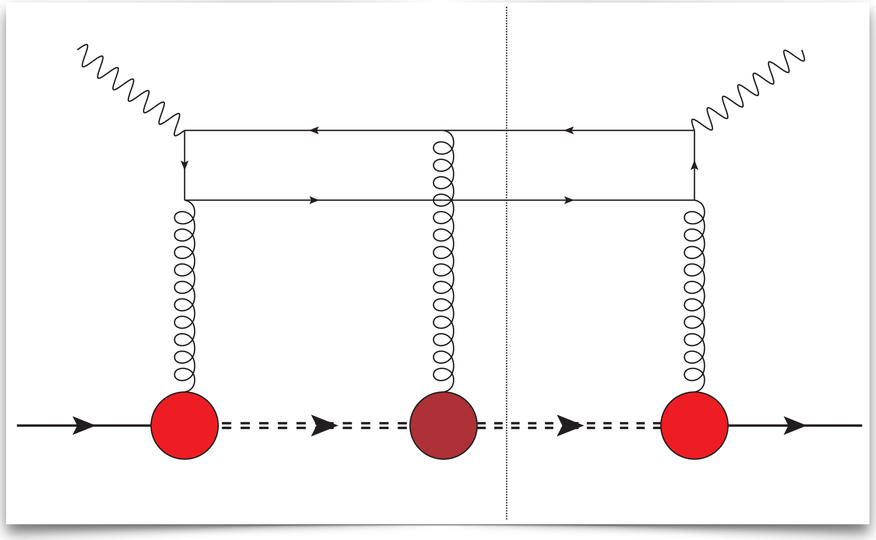

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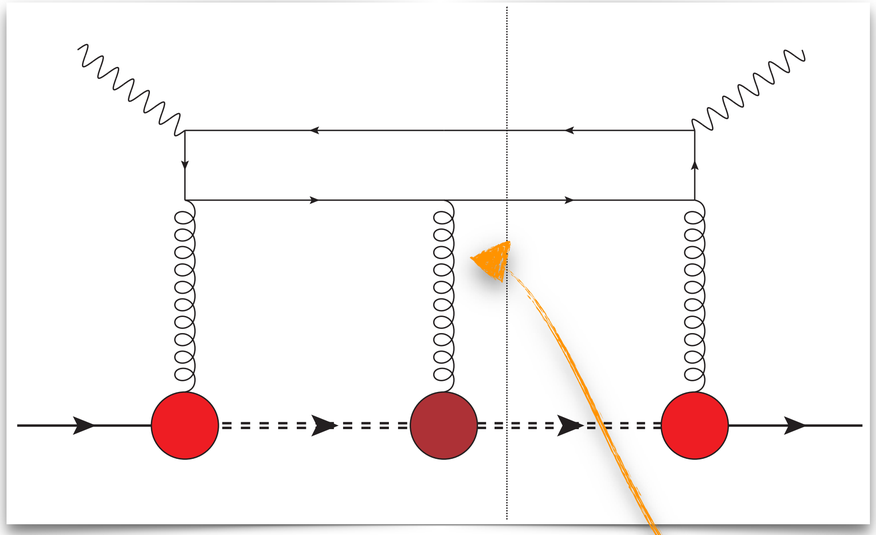

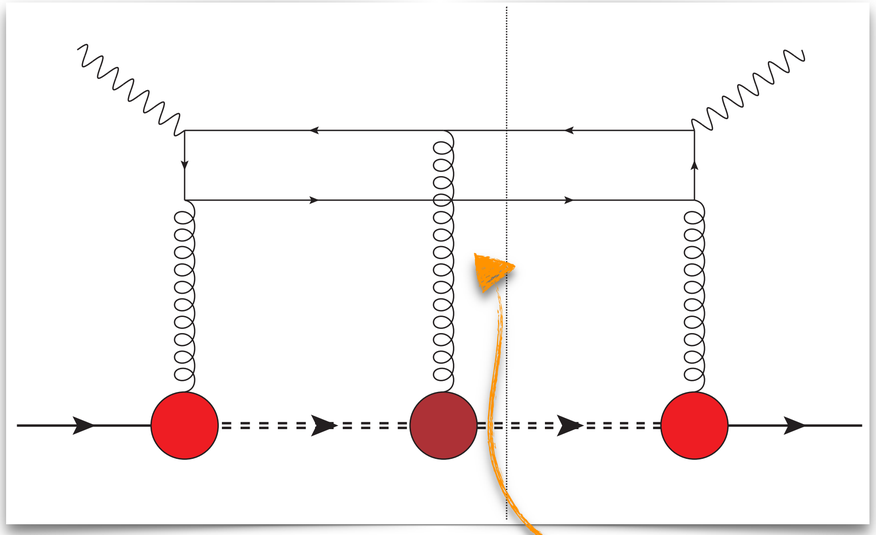

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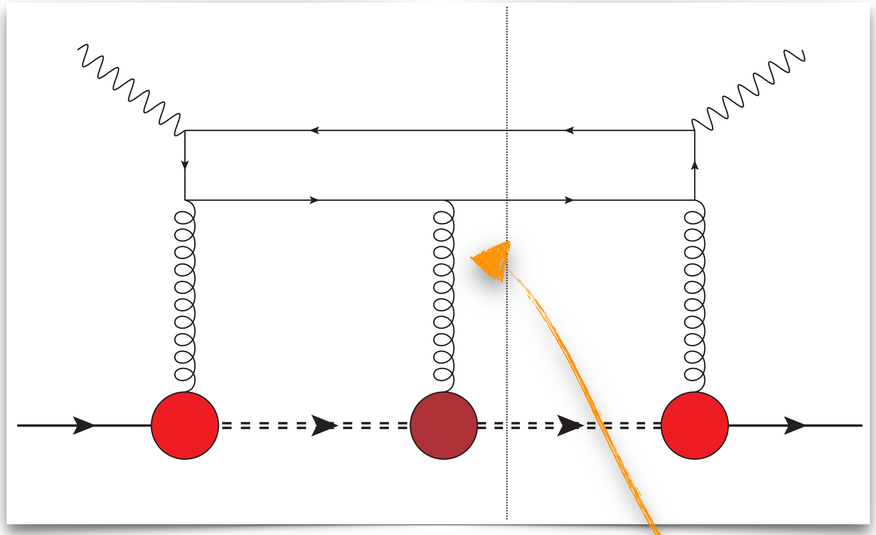

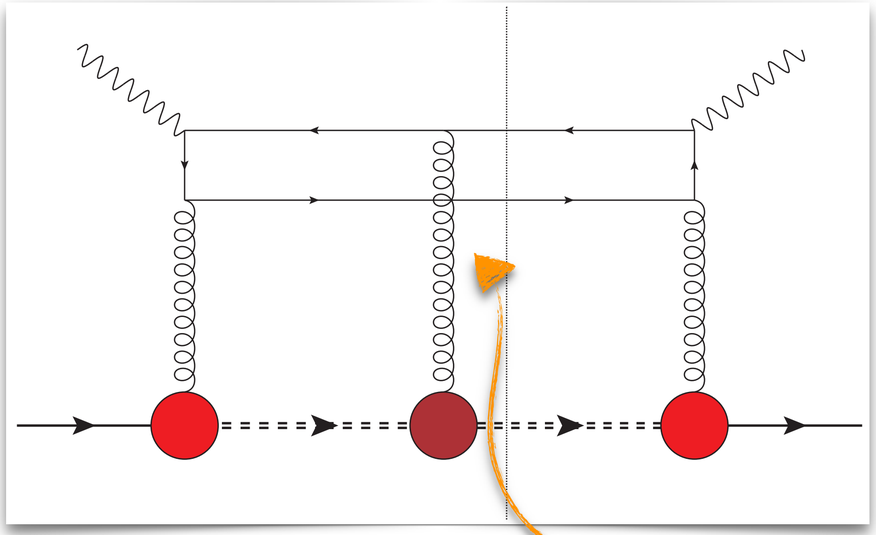

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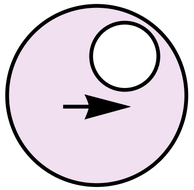

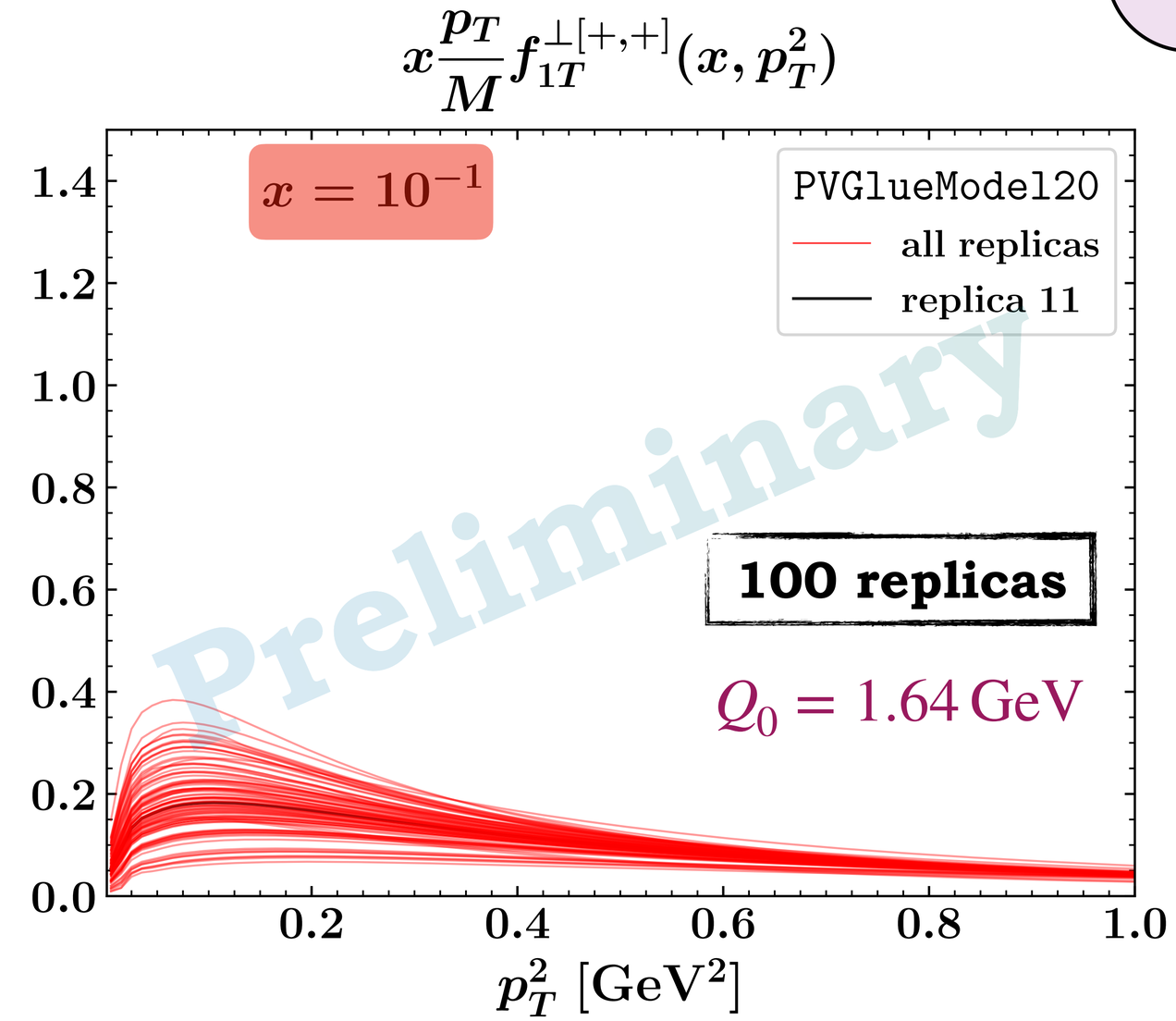

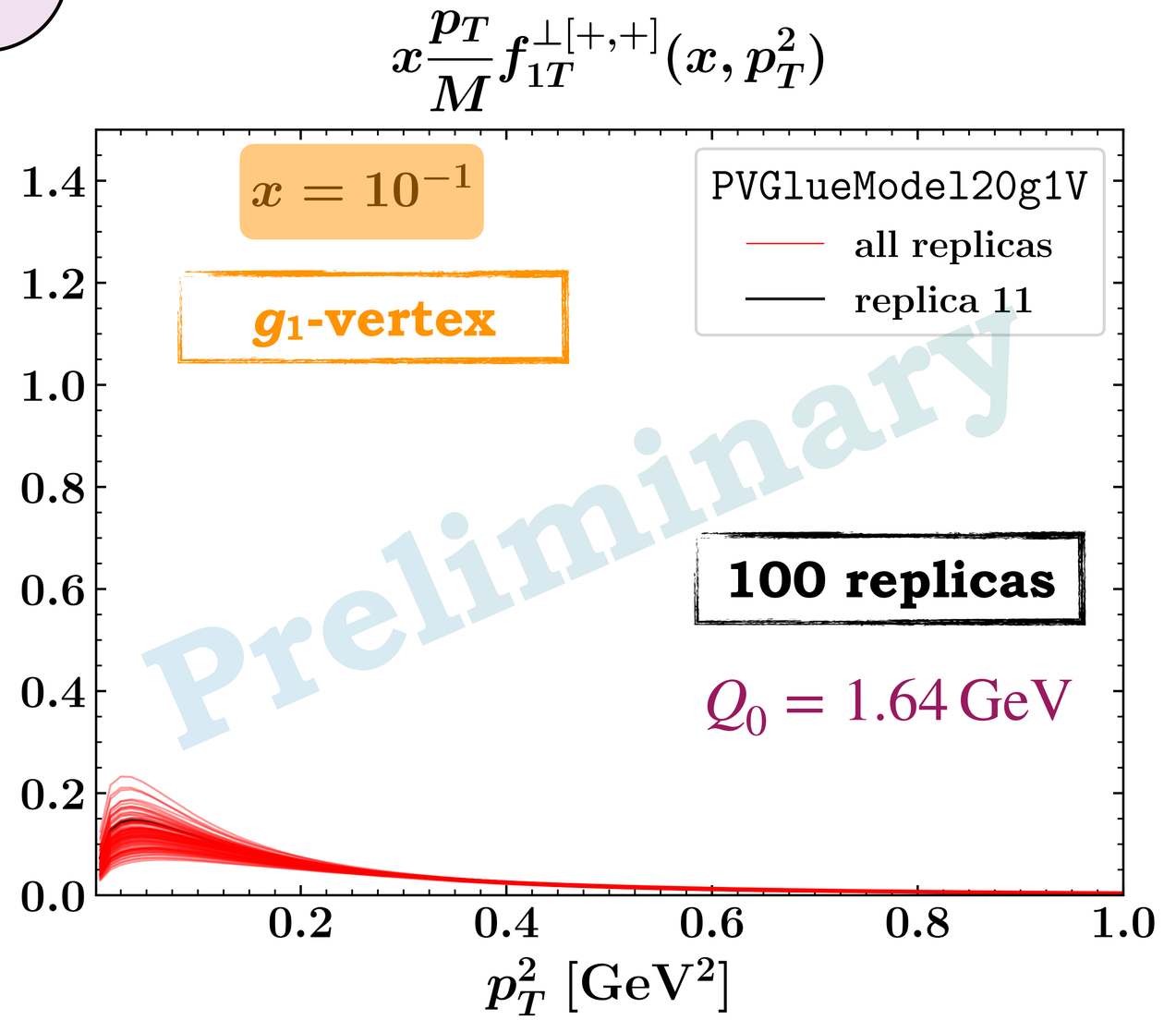

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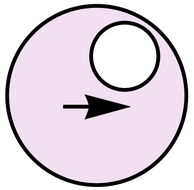
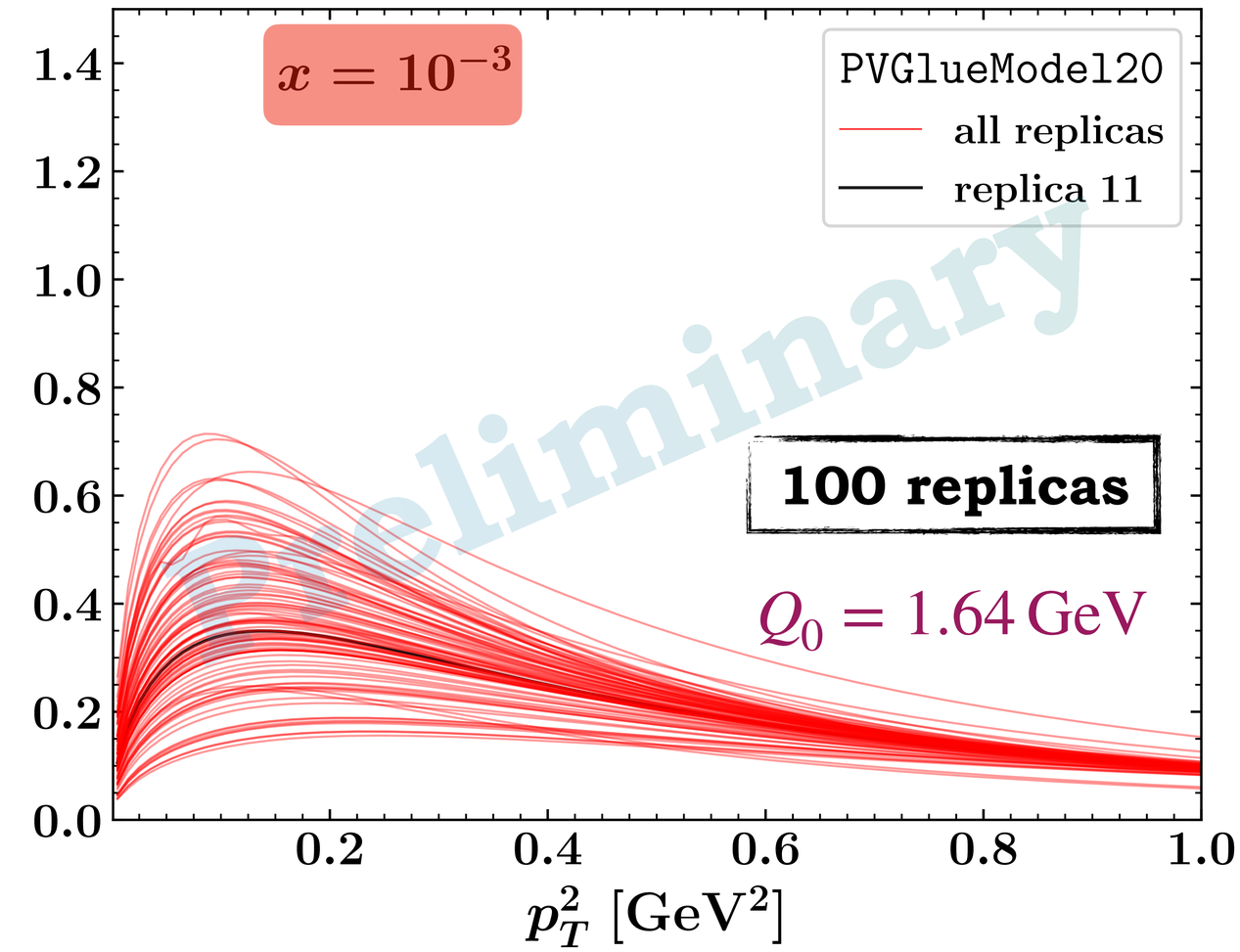
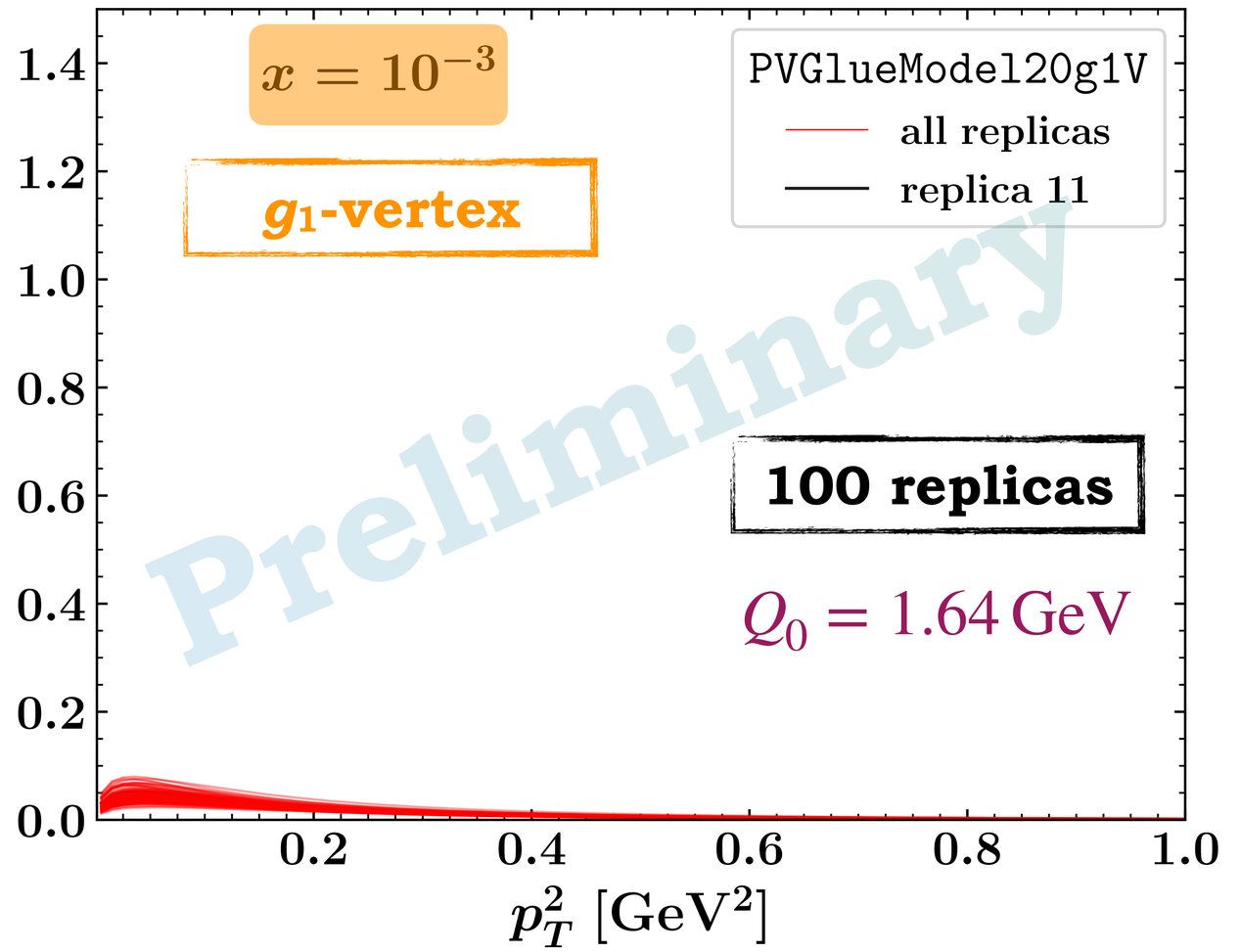
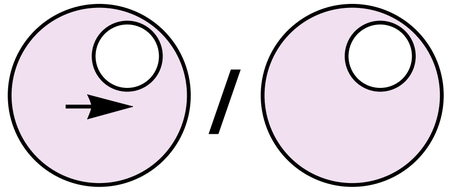


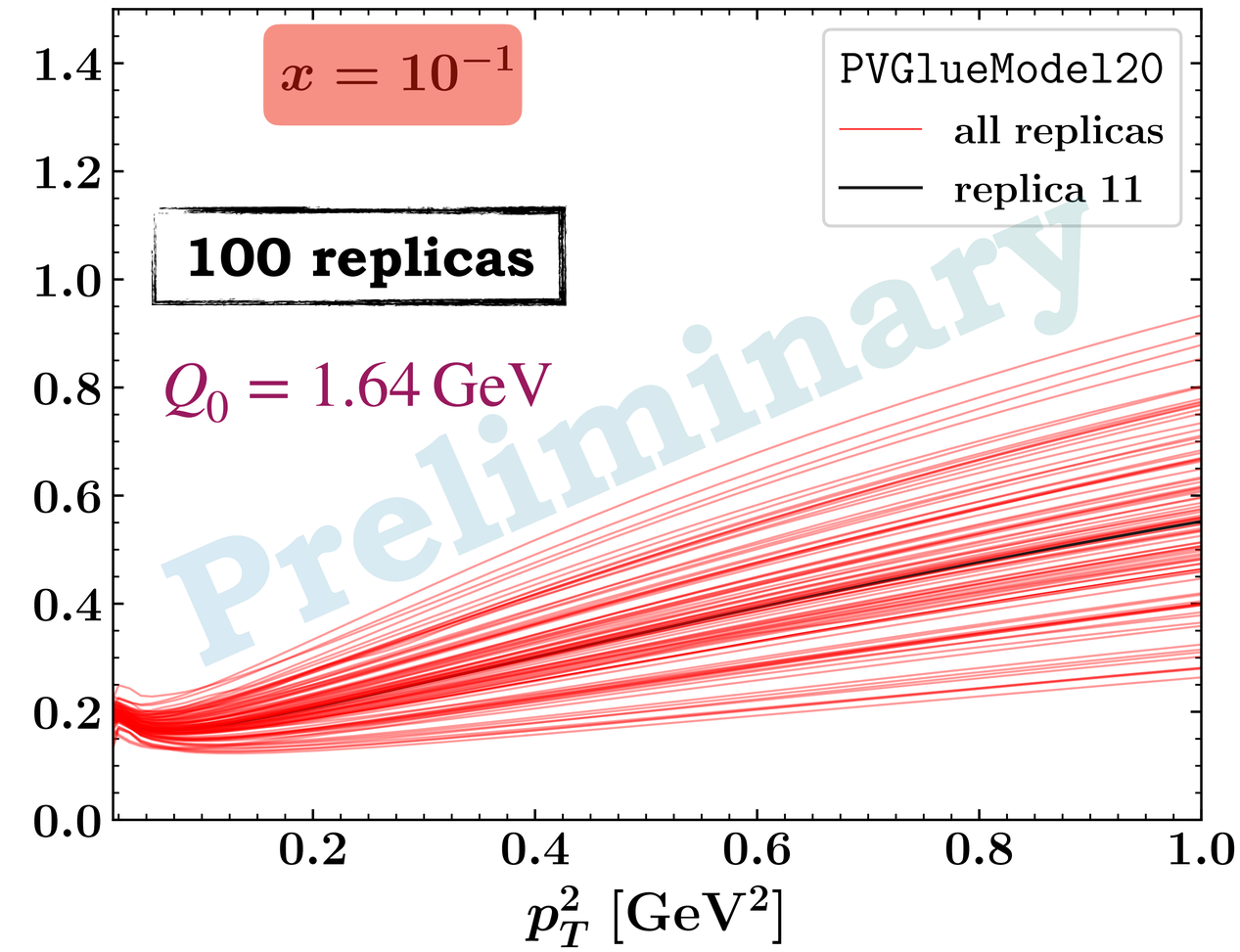


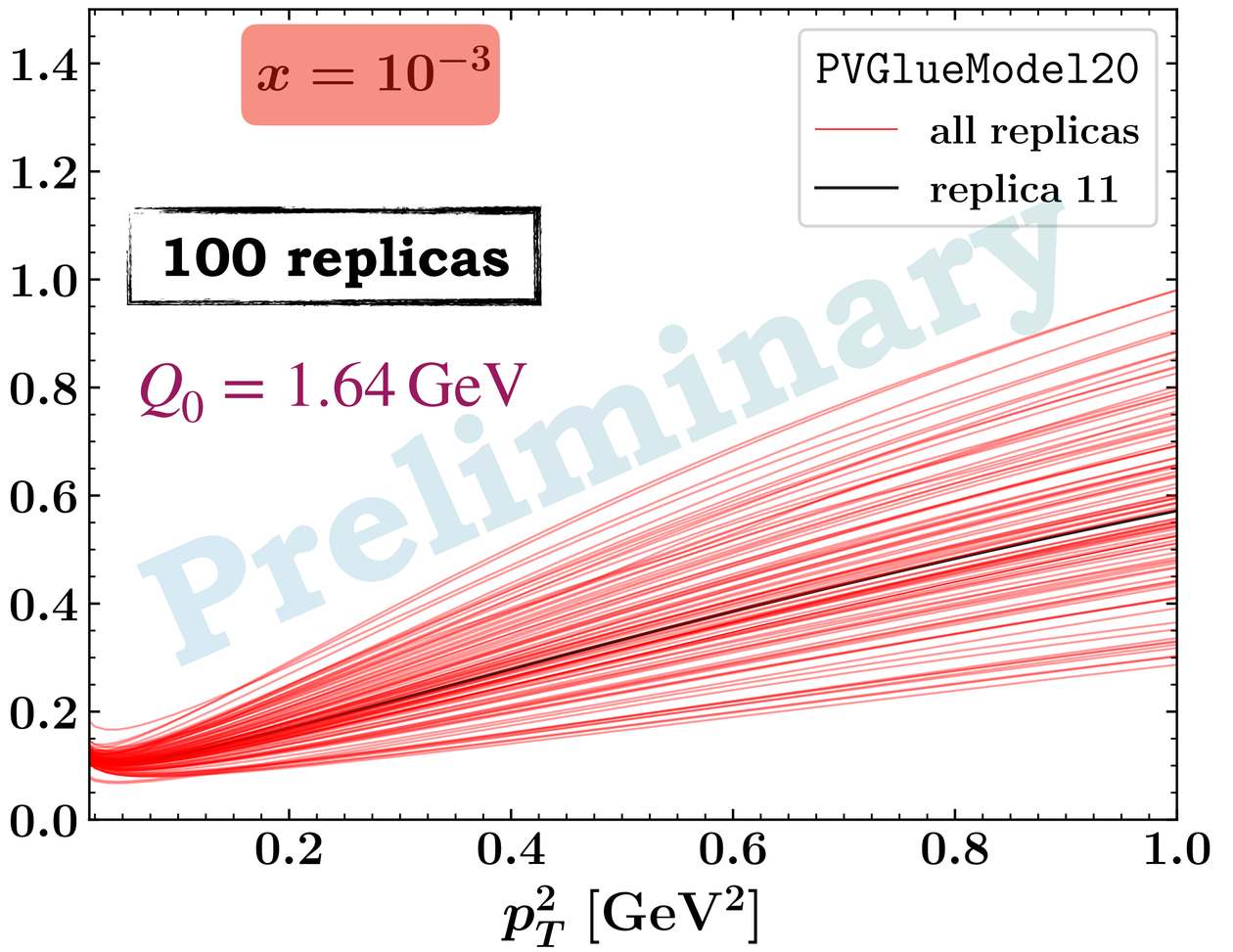


f-type Sivers/unpol.

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







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 *collinear matching*)

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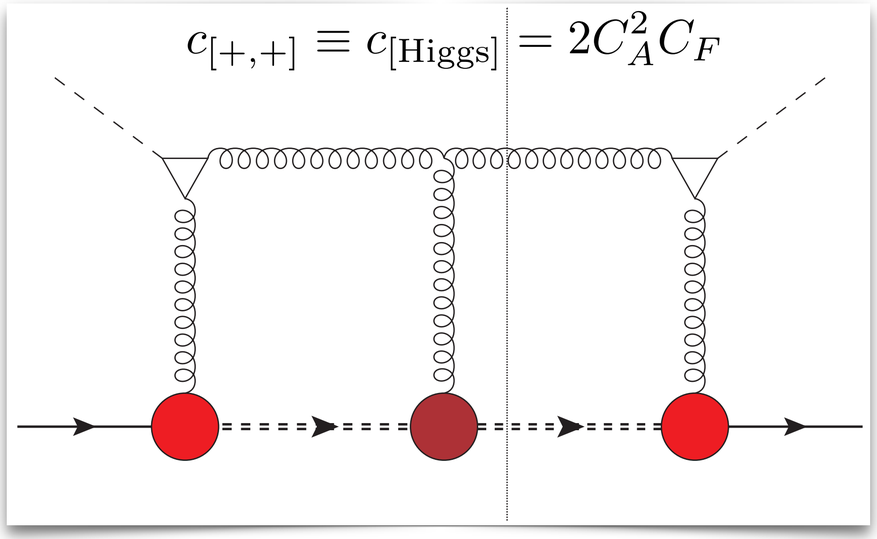
- ☐ Pheno: **spin asymmetries**, **pseudodata** and **impact studies**
- ☐ Twist-2 T-odd gluon TMDs (**Sivers**, etc.) almost done!
- ☐ Explorative studies on gauge-link sensitivity and factorization

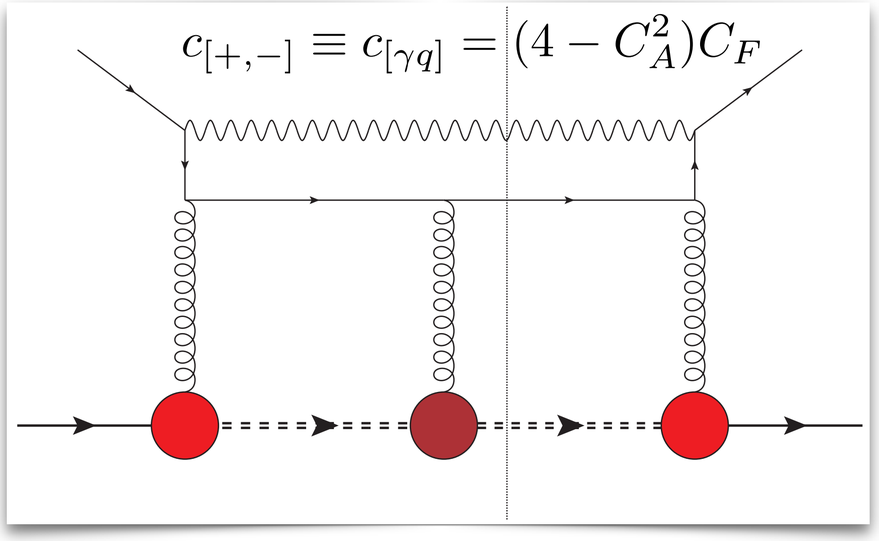
Backup slides

Gauge-link dependence of T-odd gluon TMDs

Higgs-gluon fusion $\Rightarrow$ f-type [+ , +]



Photon-jet emission $\Rightarrow$ d-type [+ , −]



Backup

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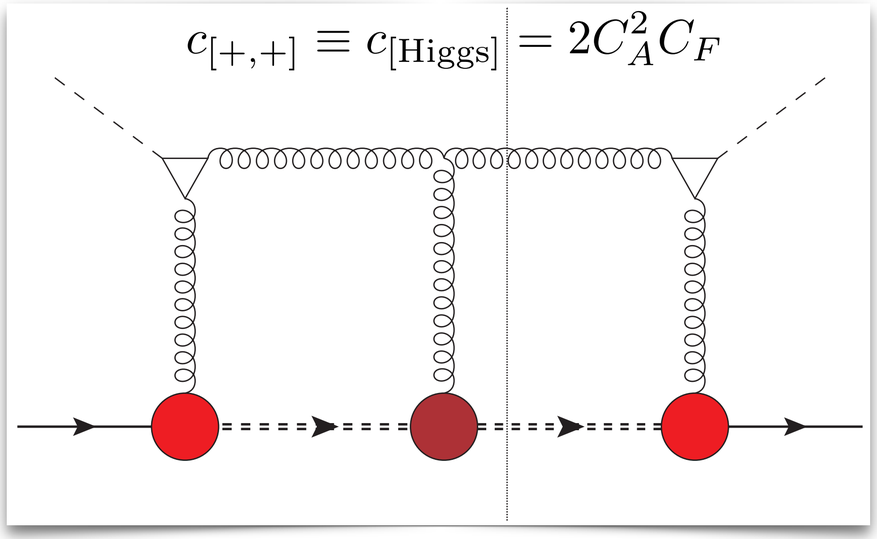
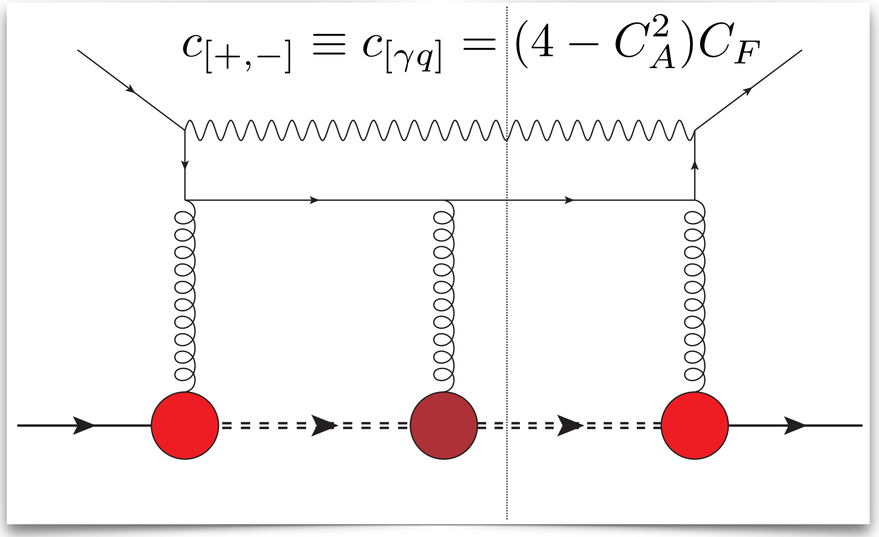


Photon-jet emission $\Rightarrow$ d-type $[+,-]$



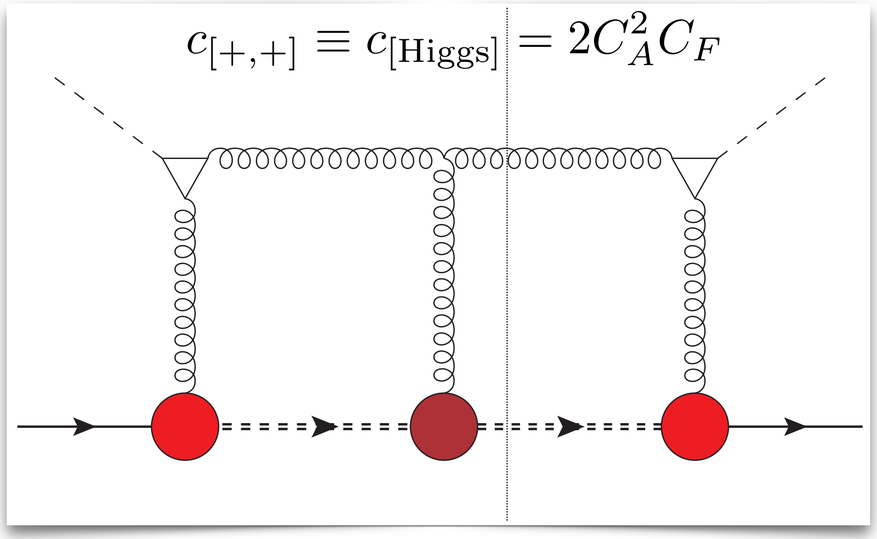
nucleon-gluon-spectator $\quad \mathcal{Y}^{\mu}_{bc}(p^2) = \delta_{bc}\left[g_1(p^2)\,\gamma_\mu + g_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$

spectator-gluon-spectator $\quad \mathcal{X}^{\mu}_{abc}(p^2) = f^{abc}\left[g_1^f(p^2)\,\gamma^\mu + g_2^f(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right] - i\,d^{abc}\left[g_1^d(p^2)\,\gamma^\mu + g_2^d(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$

Backup

Gauge-link dependence of T-odd gluon TMDs

Higgs-gluon fusion $\Rightarrow$ f-type $[+,+]$



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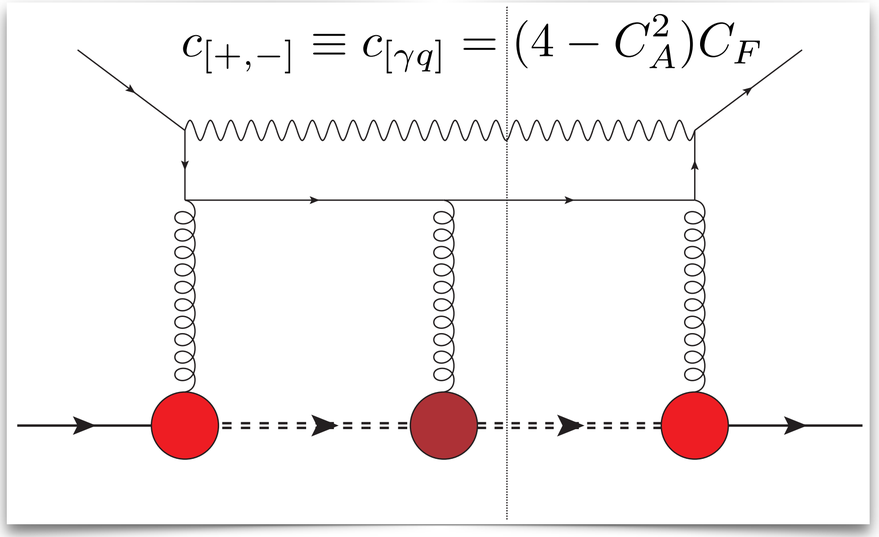

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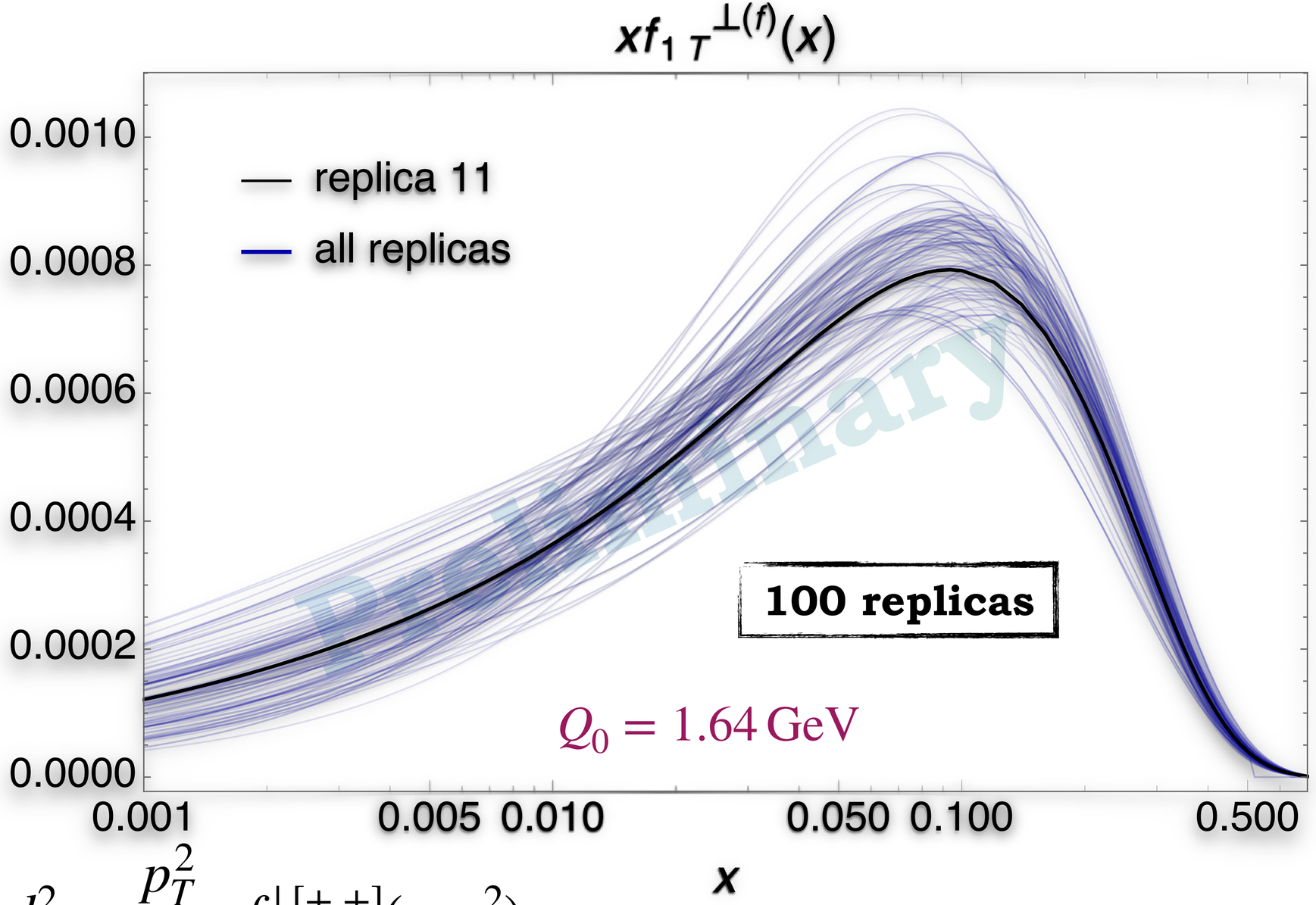
Assumption: $\quad g^d_{1,2}(p^2) = g^f_{1,2}(p^2) \equiv g_{1,2}(p^2) \quad \Leftrightarrow \quad f_{1T}^{\perp[+,-]} = \frac{c_{[+,-]}}{c_{[+,+]}} f_{1T}^{\perp[+,+]} \equiv -\frac{5}{18} f_{1T}^{\perp[+,+]}$

Backup

f-type Qiu-Sterman twist-3 gluon PDF



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

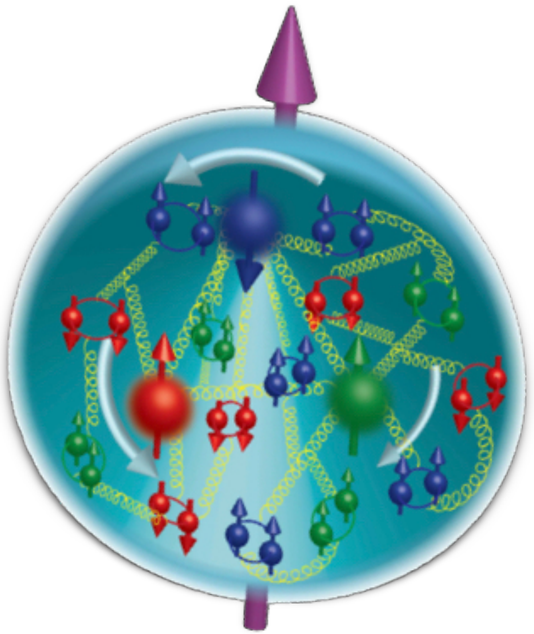
Backup

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*



Backup

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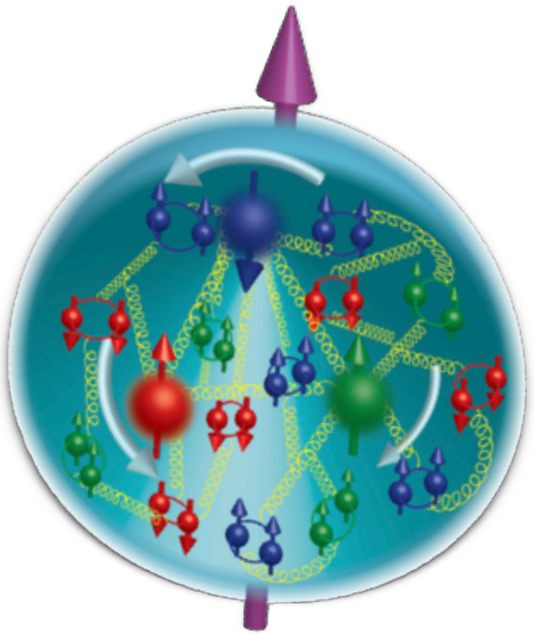
Several types of distributions (1D collinear, **3D TMD**, …)

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



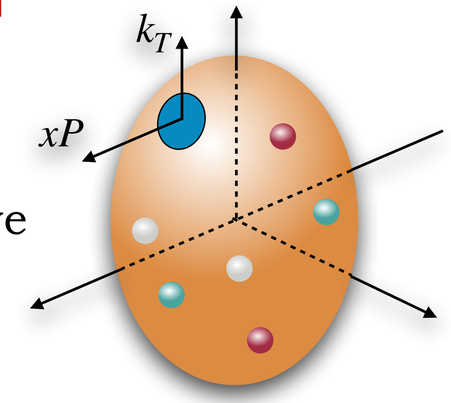
Backup

Parton densities: an incomplete family tree

3D

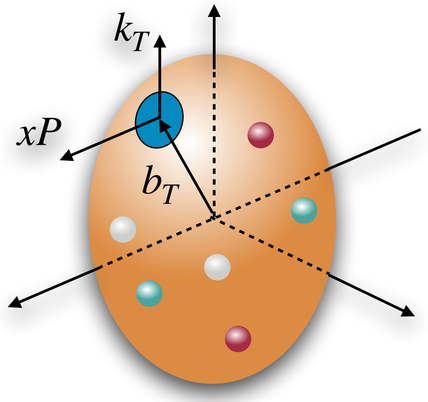
TMDs

(semi-)inclusive



5D

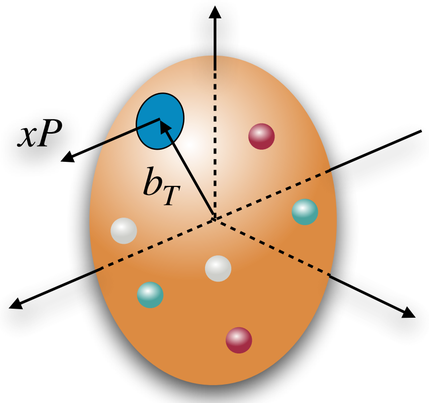
Wigner distributions



3D

FT of GPDs

exclusive



PDFs

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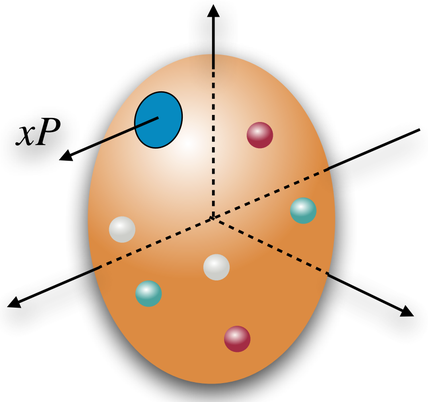
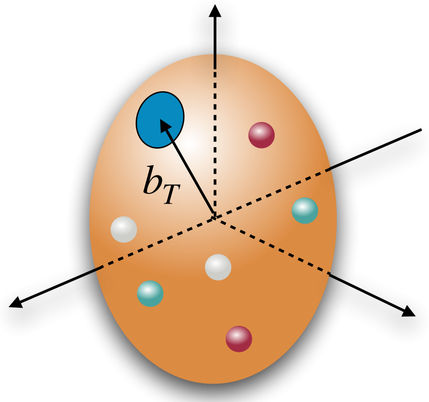


FT of Form Factors



1D

2D

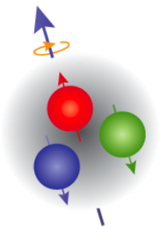
$\vec{b}_\perp$ dependence

$\vec{k}_\perp$ dependence

these two variables are NOT Fourier conjugate

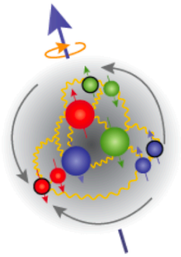
Backup

The proton spin crisis



quarks helicity

~ 30 %



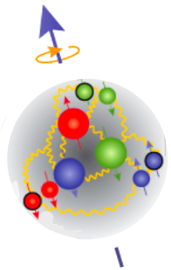
orbital angular momentum

unknown!

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

gluons helicity

~ 20% – 50 % **?**



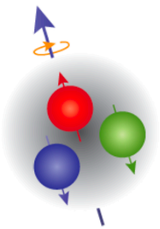
Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description...

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

slide adapted from C. Bissolotti

Backup

The proton spin crisis



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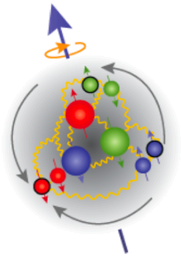

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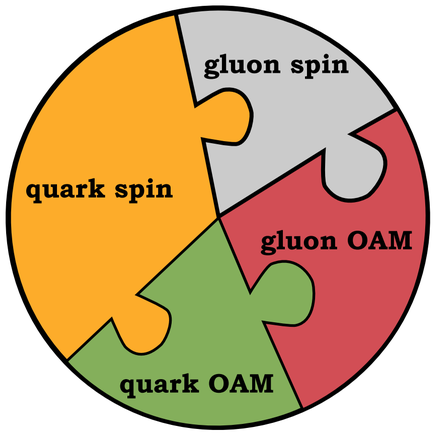

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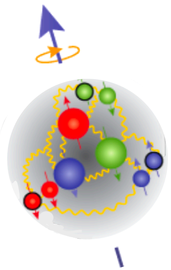

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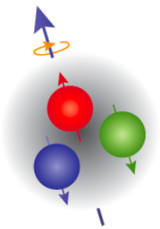

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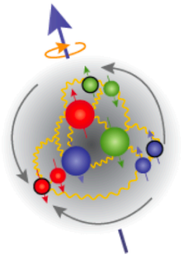

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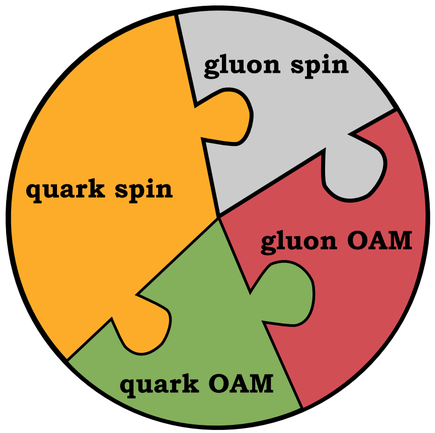

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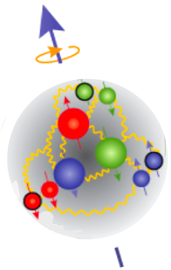

…many other effects in hadronic interactions cannot be understood in the purely collinear approach

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

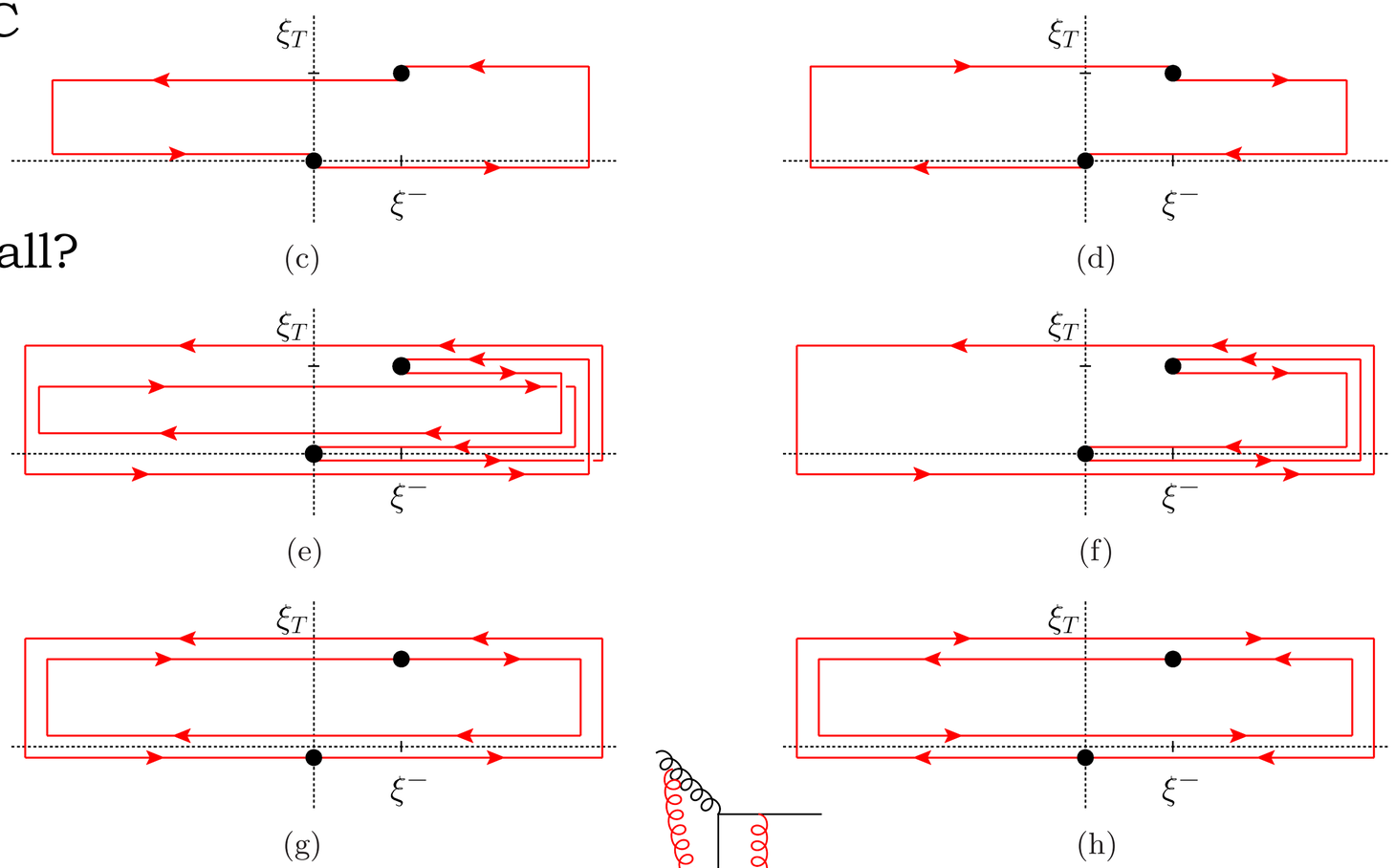
Dihadron hadroproduction and factorization breaking

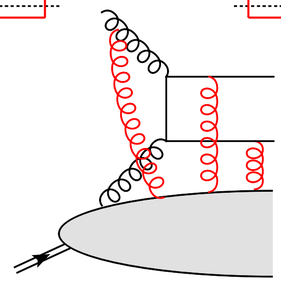
* Proof of factorization violation 🔗 [T. J. Rogers, P. J. Mulders (2010)]
* Assumed factorization in SCET and CGC
* Significance of low-x studies
* Size of factorization-breaking effects small?
* DP TMDs:

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

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

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





Backup

Assumptions of the model

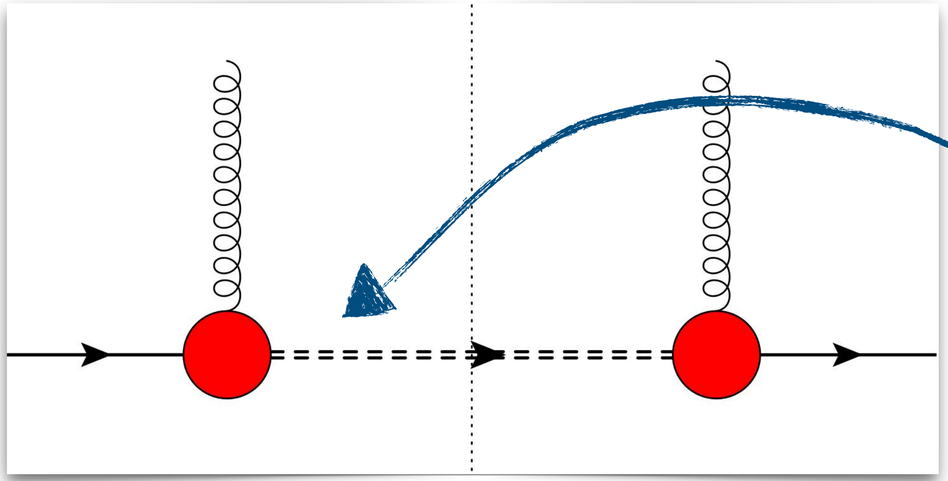
Spectator-system spectral-mass function

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

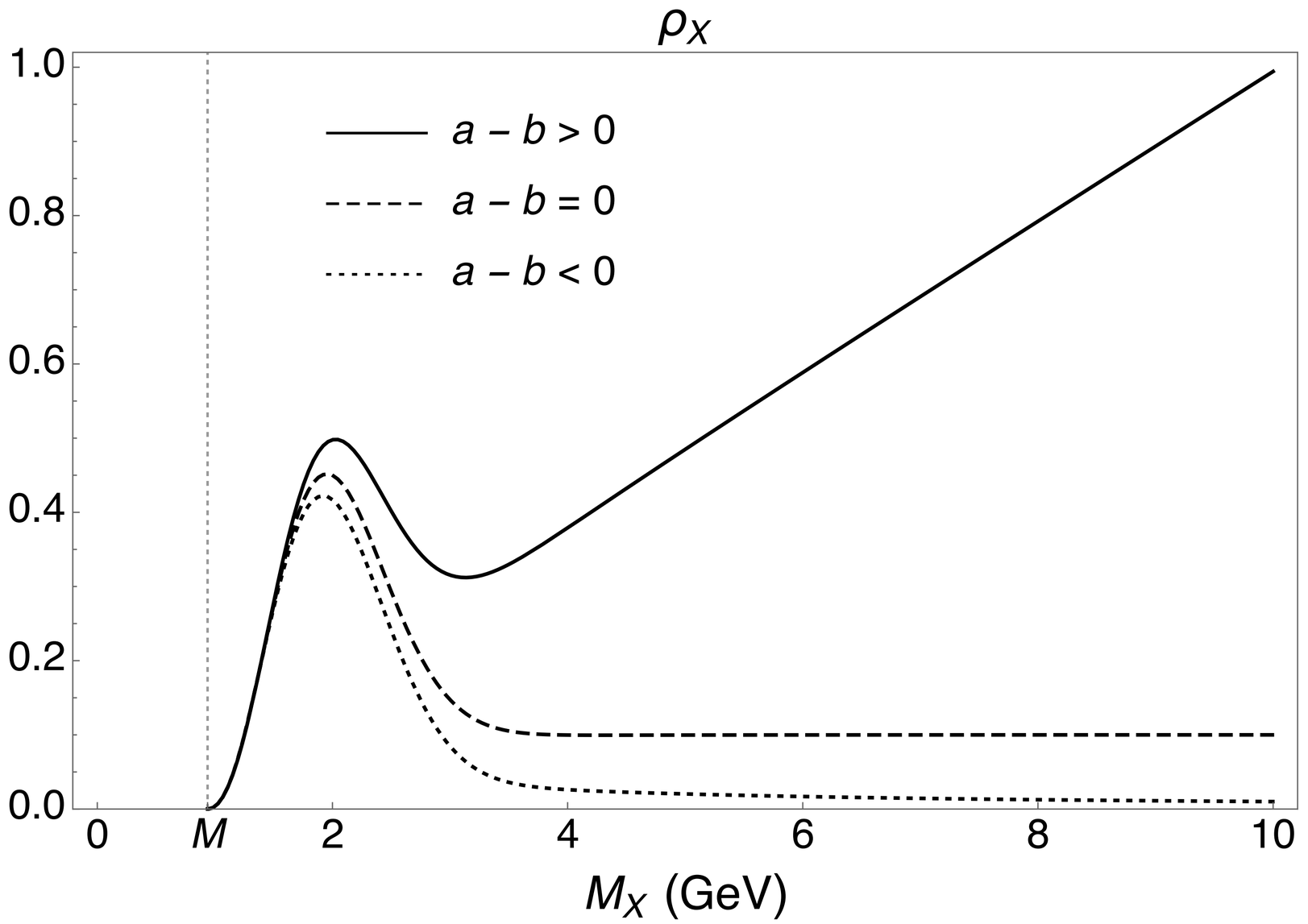
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

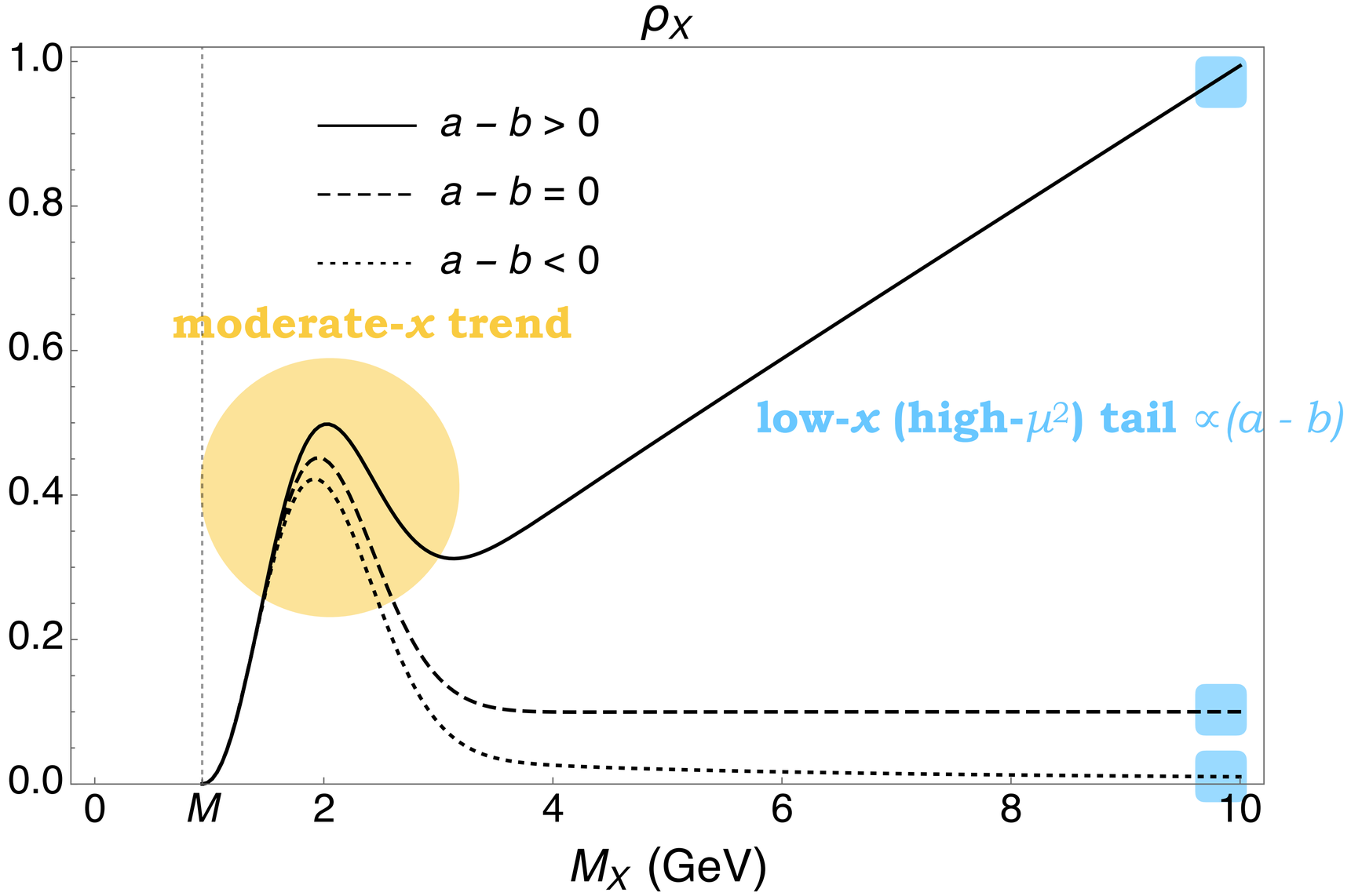
Backup

Spectral function vs *(a - b)*



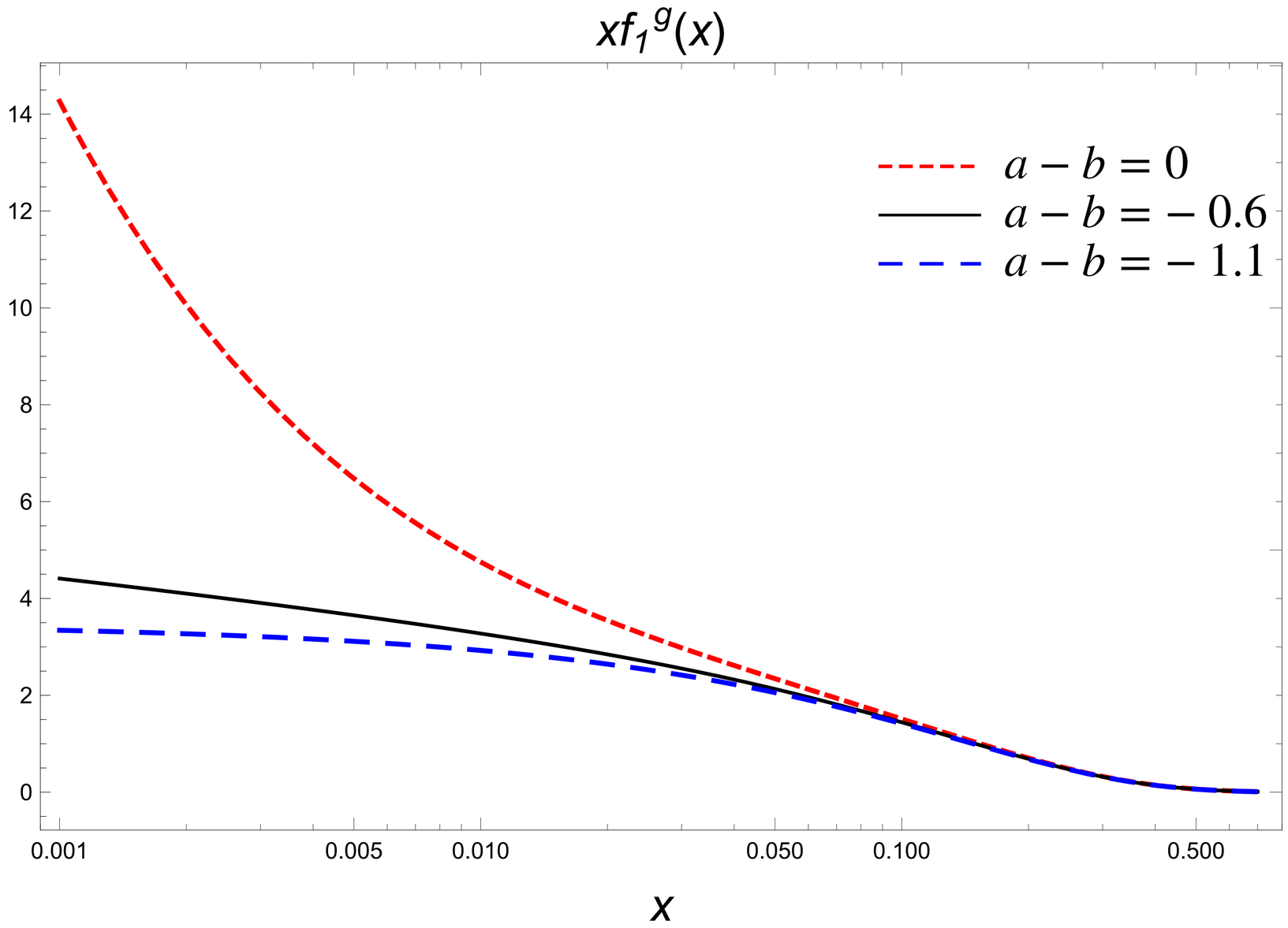
Backup

Spectral function vs $(a - b)$



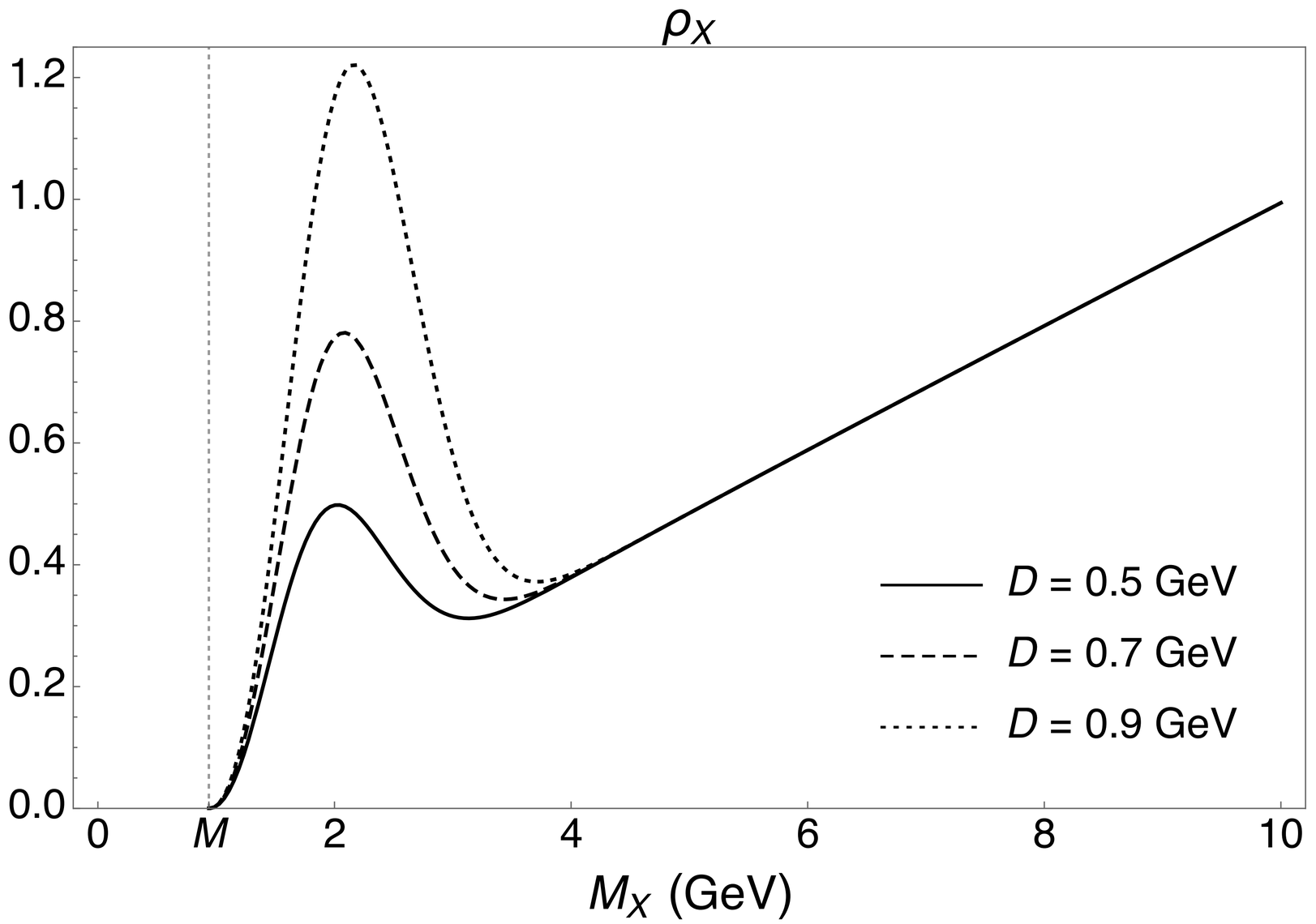
Backup

xf_1 collinear PDF vs $(a - b)$



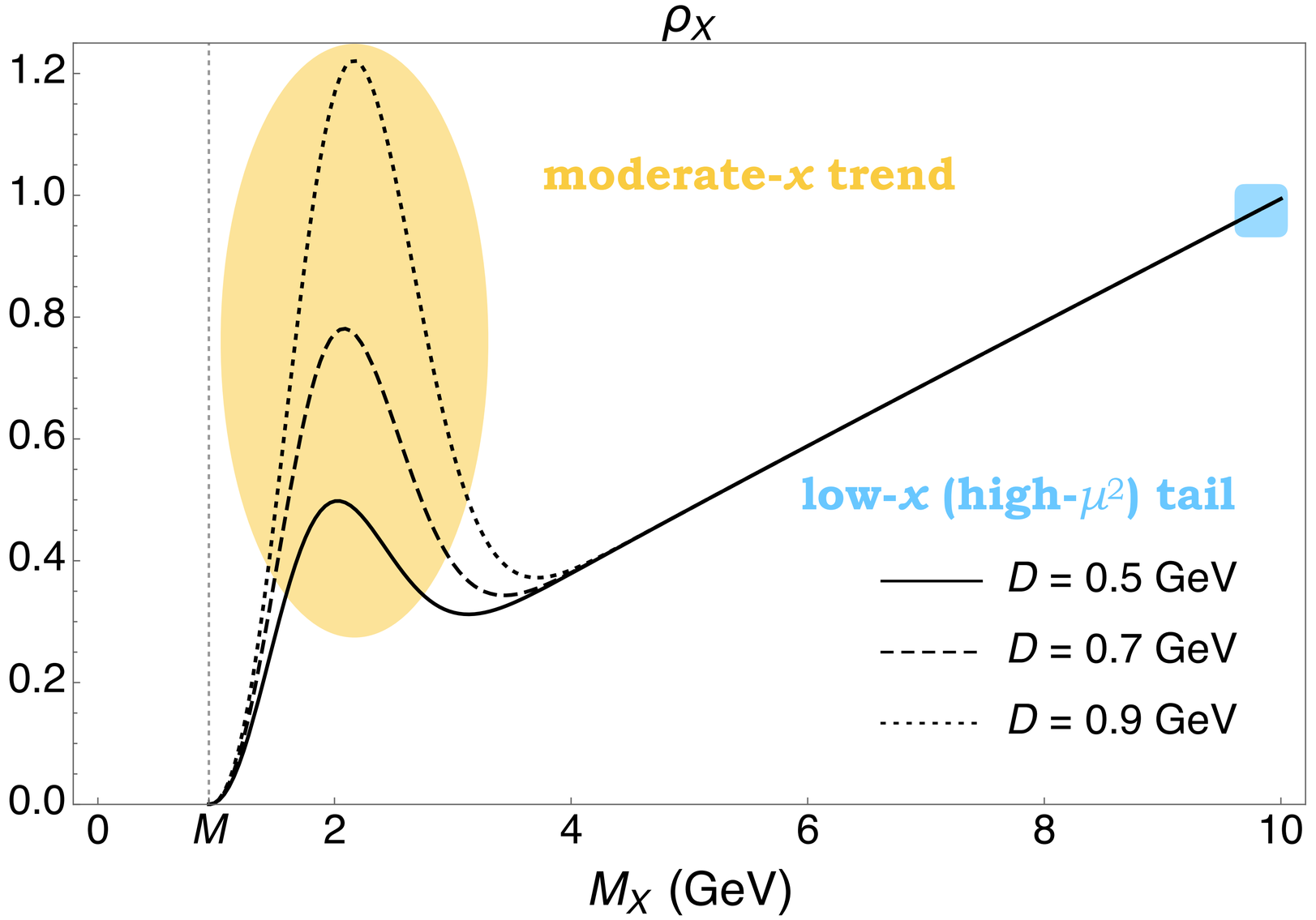
Backup

Spectral function vs D



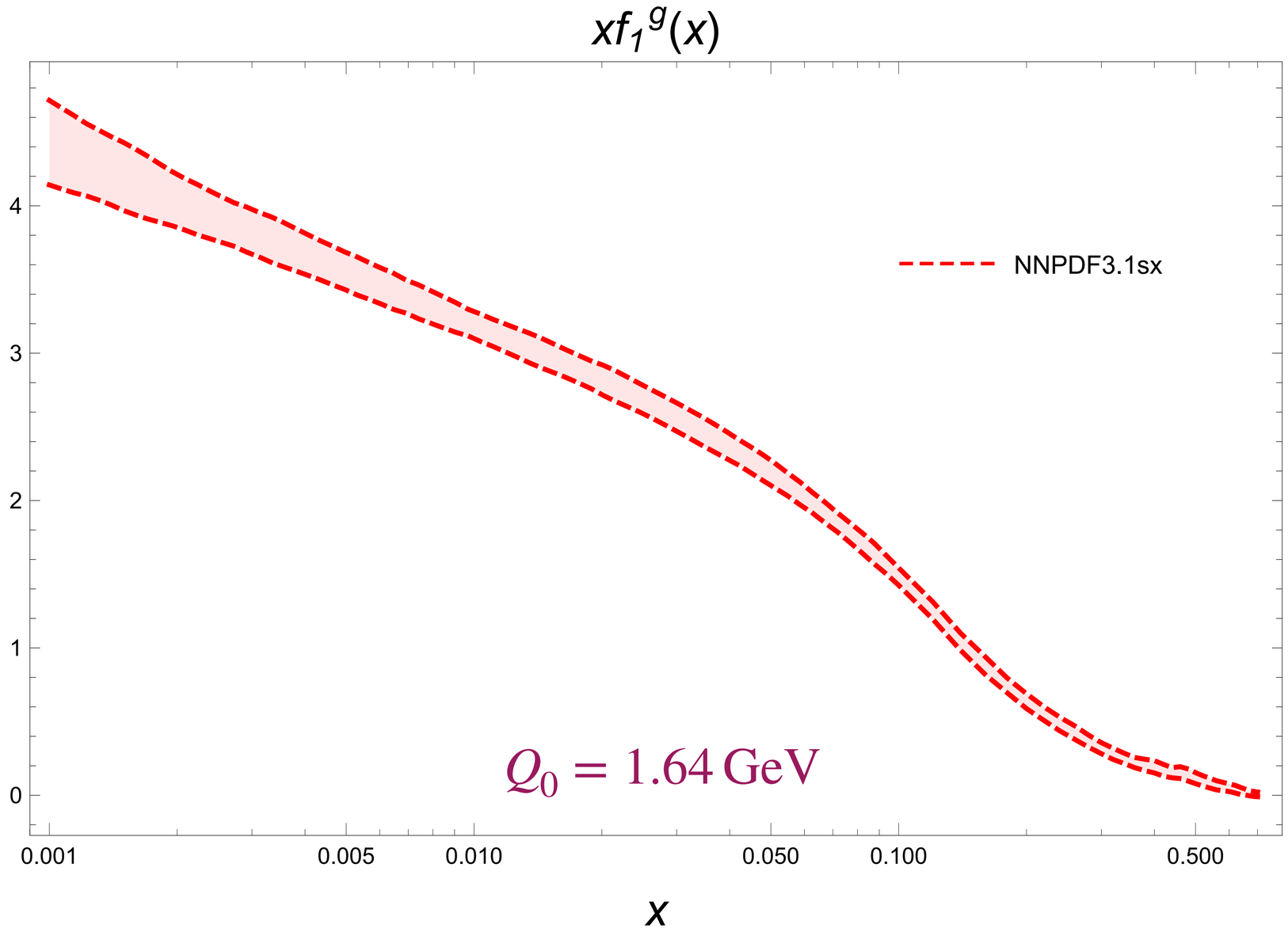
Backup

Spectral function vs D



Backup

Unpolarized gluon PDF



Backup

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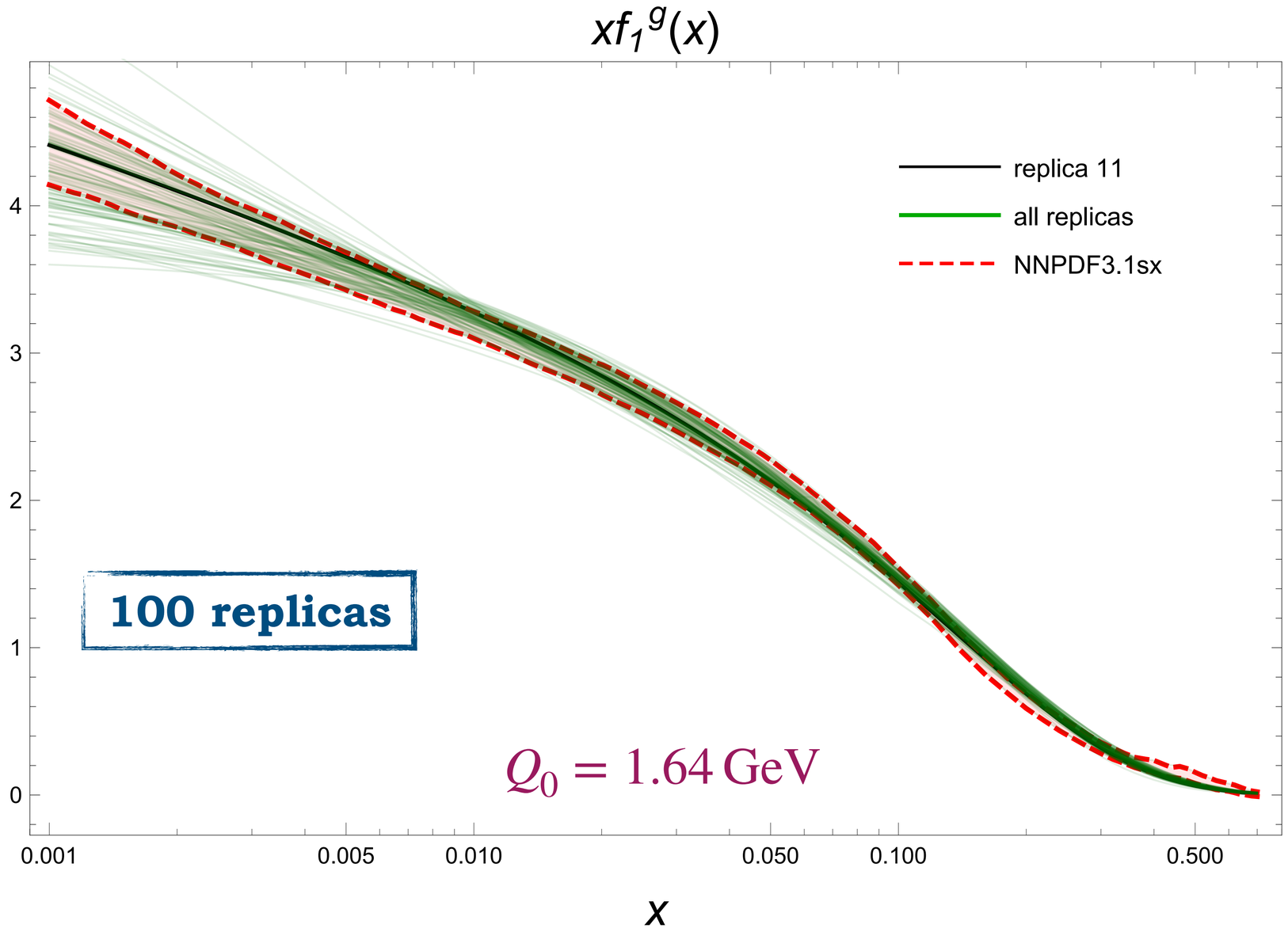
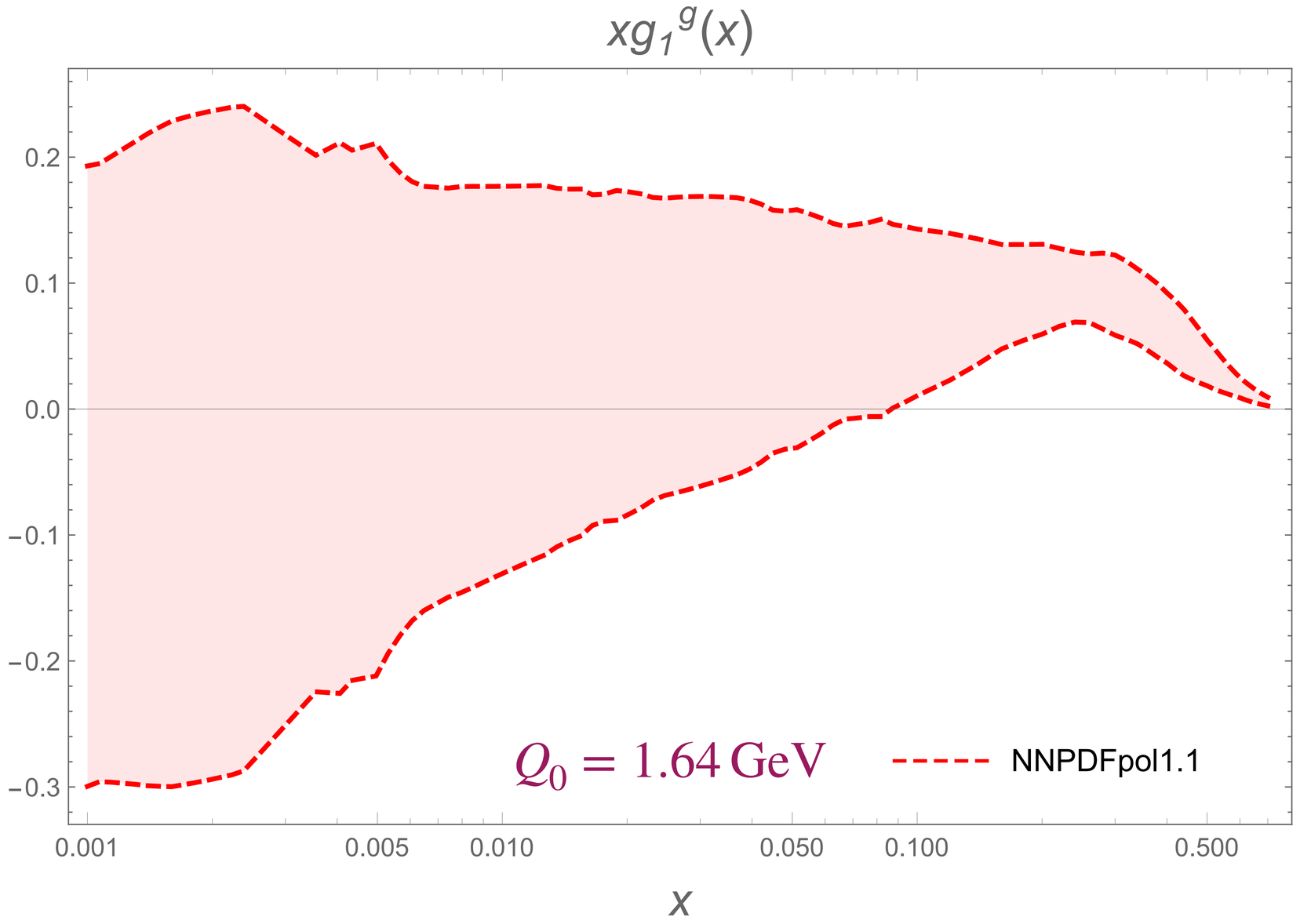


Backup

Helicity gluon PDF



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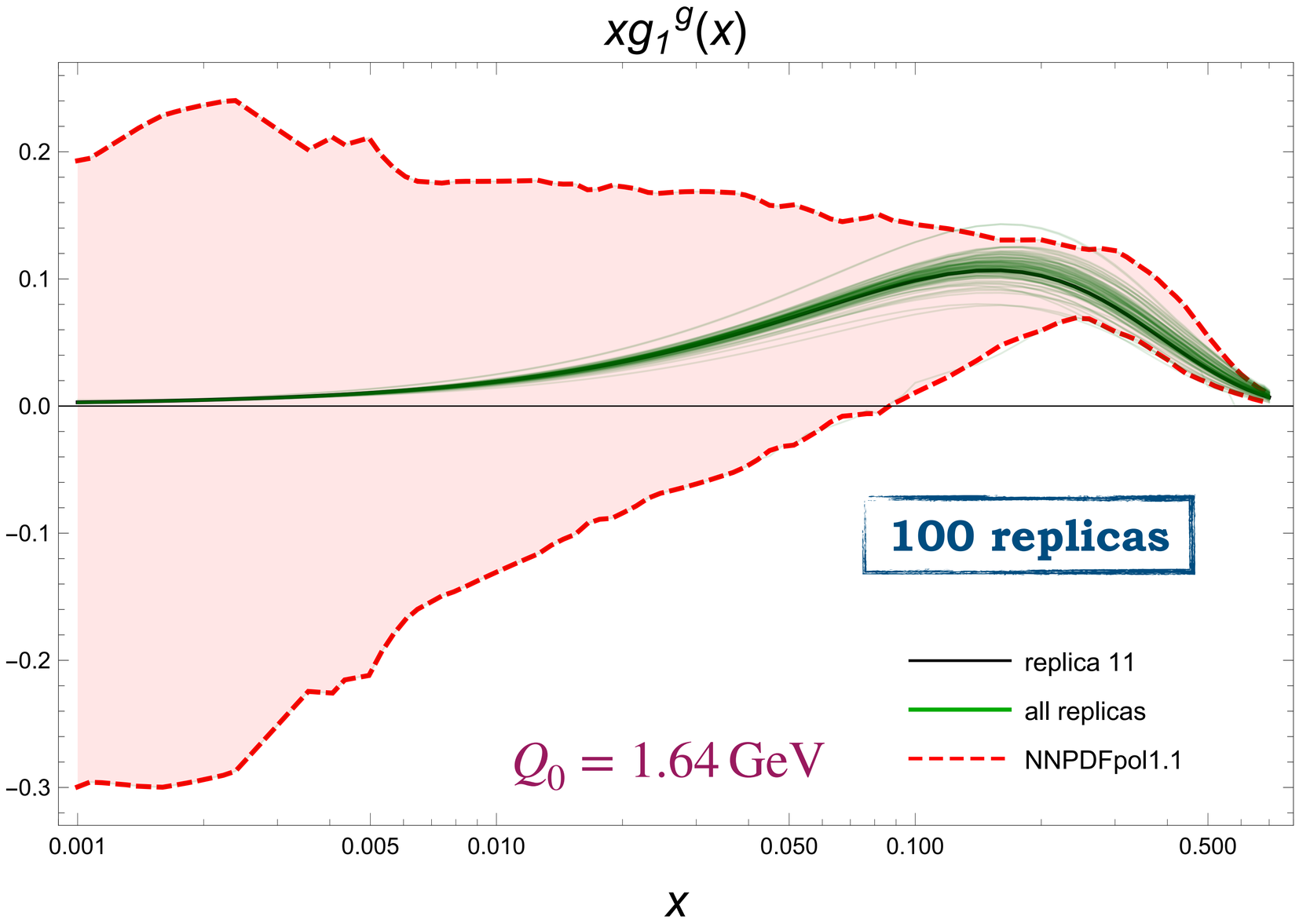

Backup

Fit specifics

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

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

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

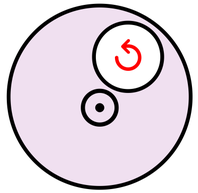
$$\langle x \rangle_g = 0.427(92)$$

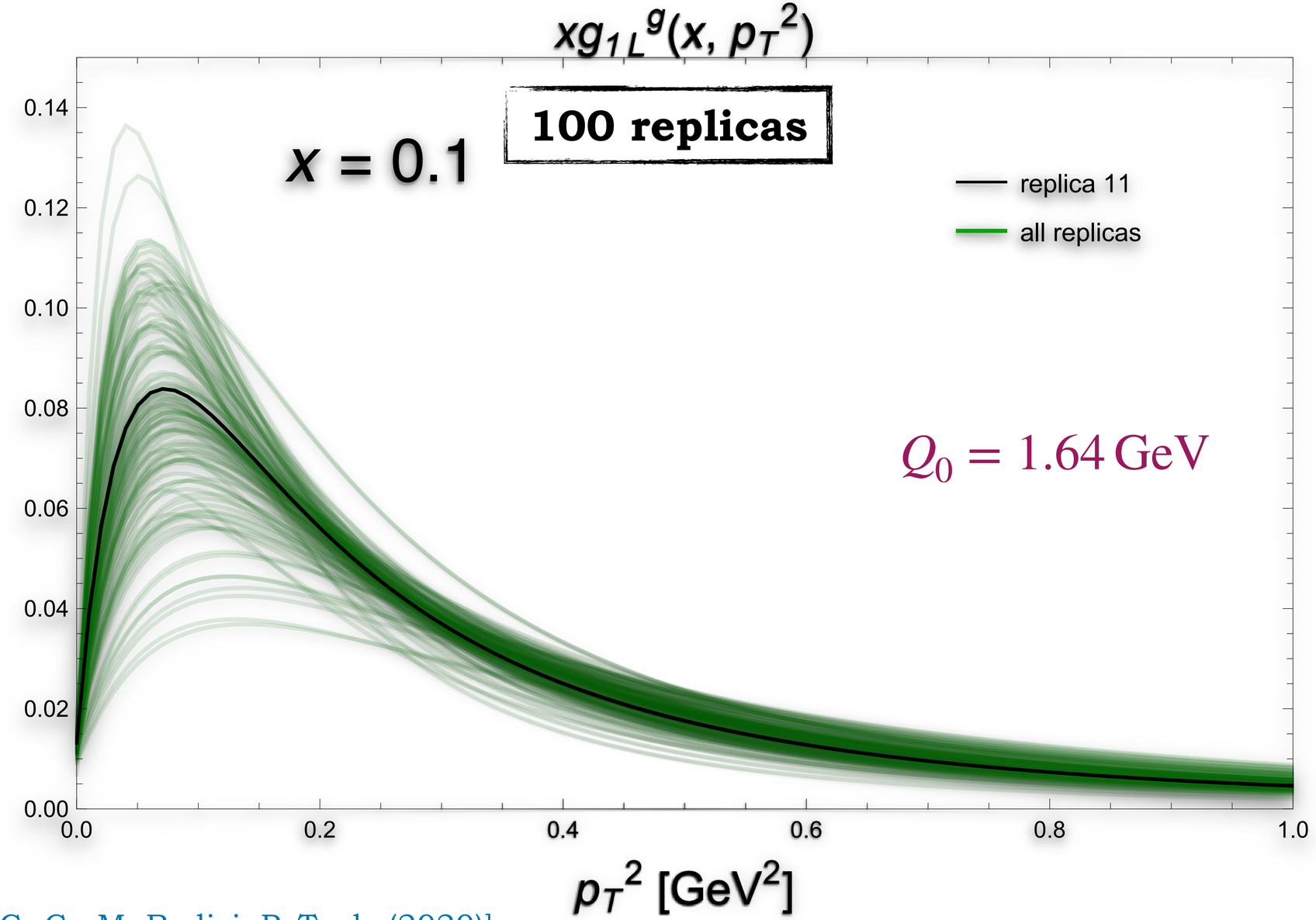
$$\langle J \rangle_g = 0.187(46)$$

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

Backup

Helicity gluon TMD

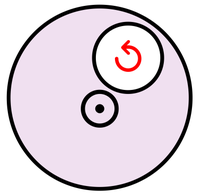


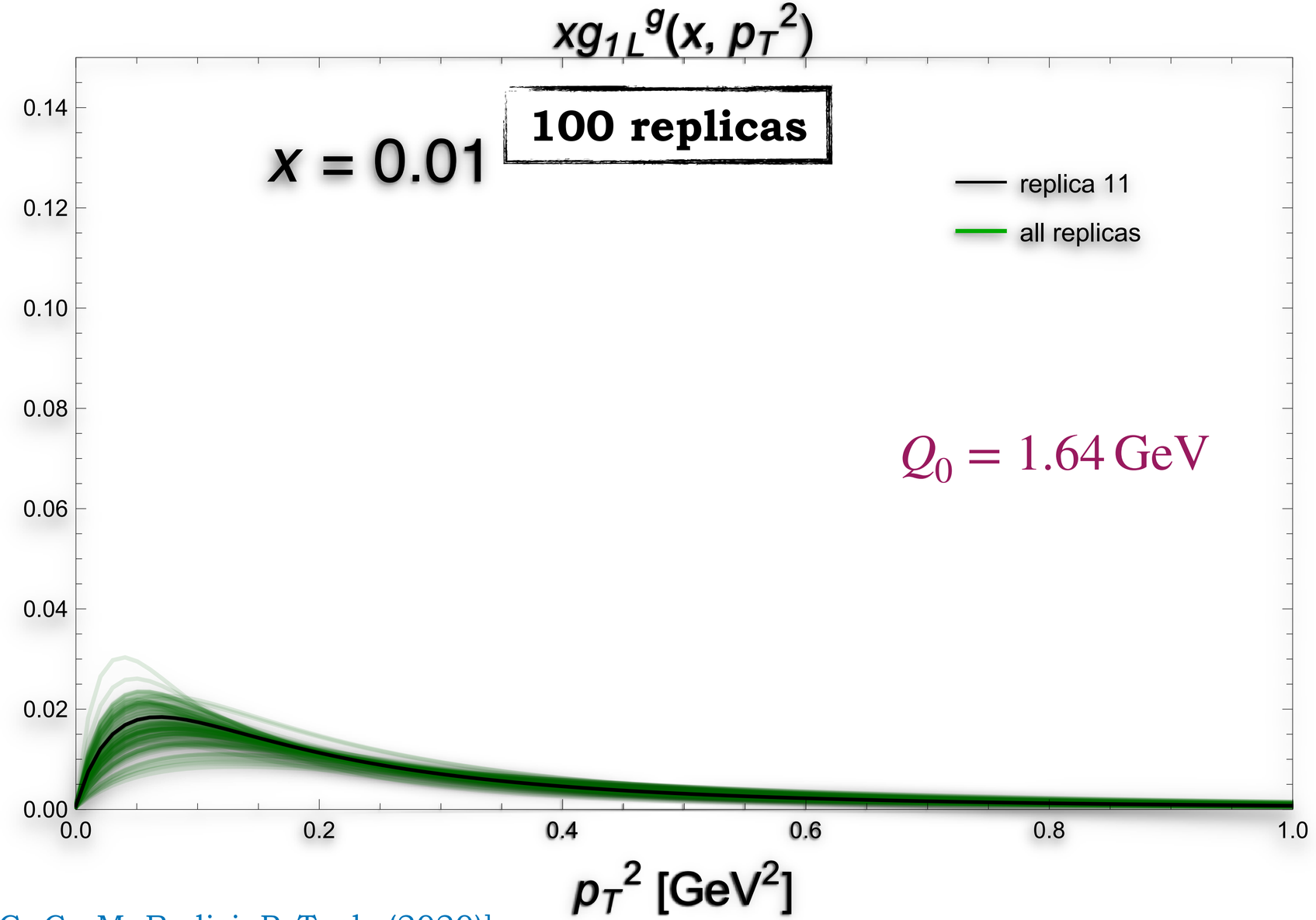


[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Helicity gluon TMD





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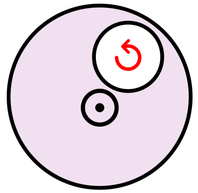
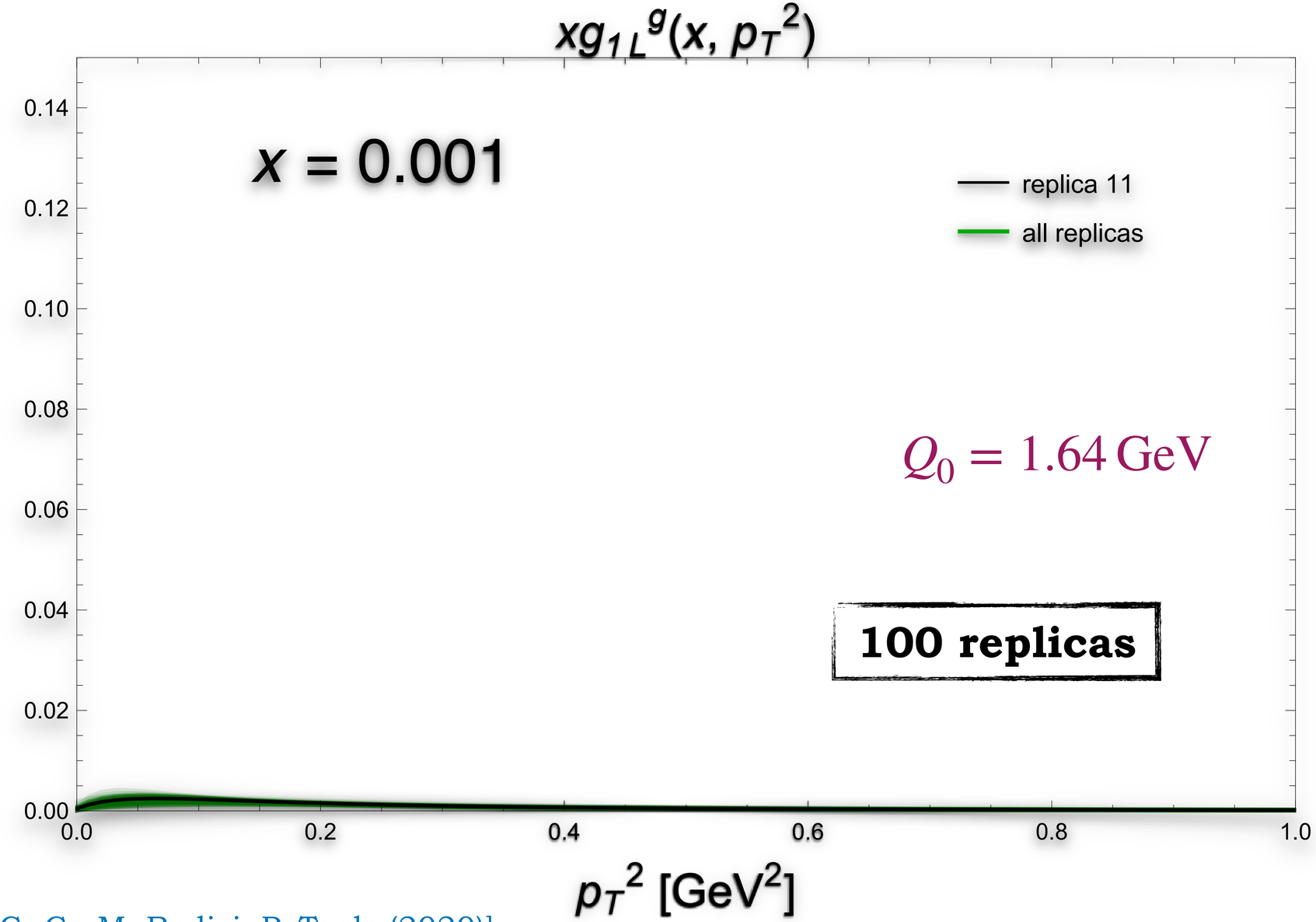
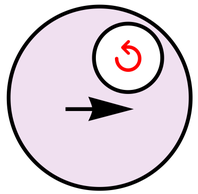


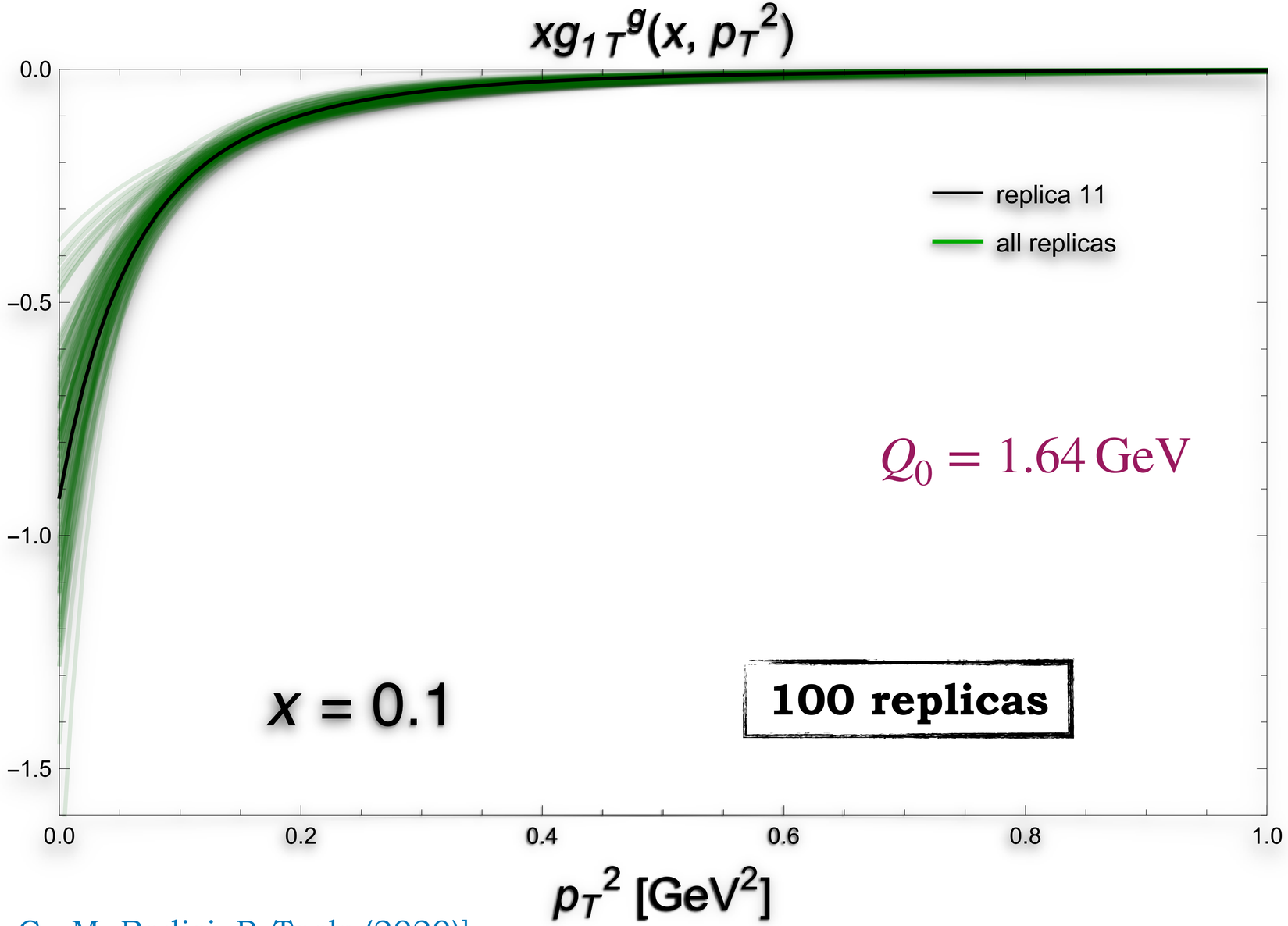


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Worm-gear gluon TMD

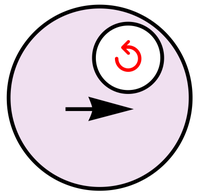


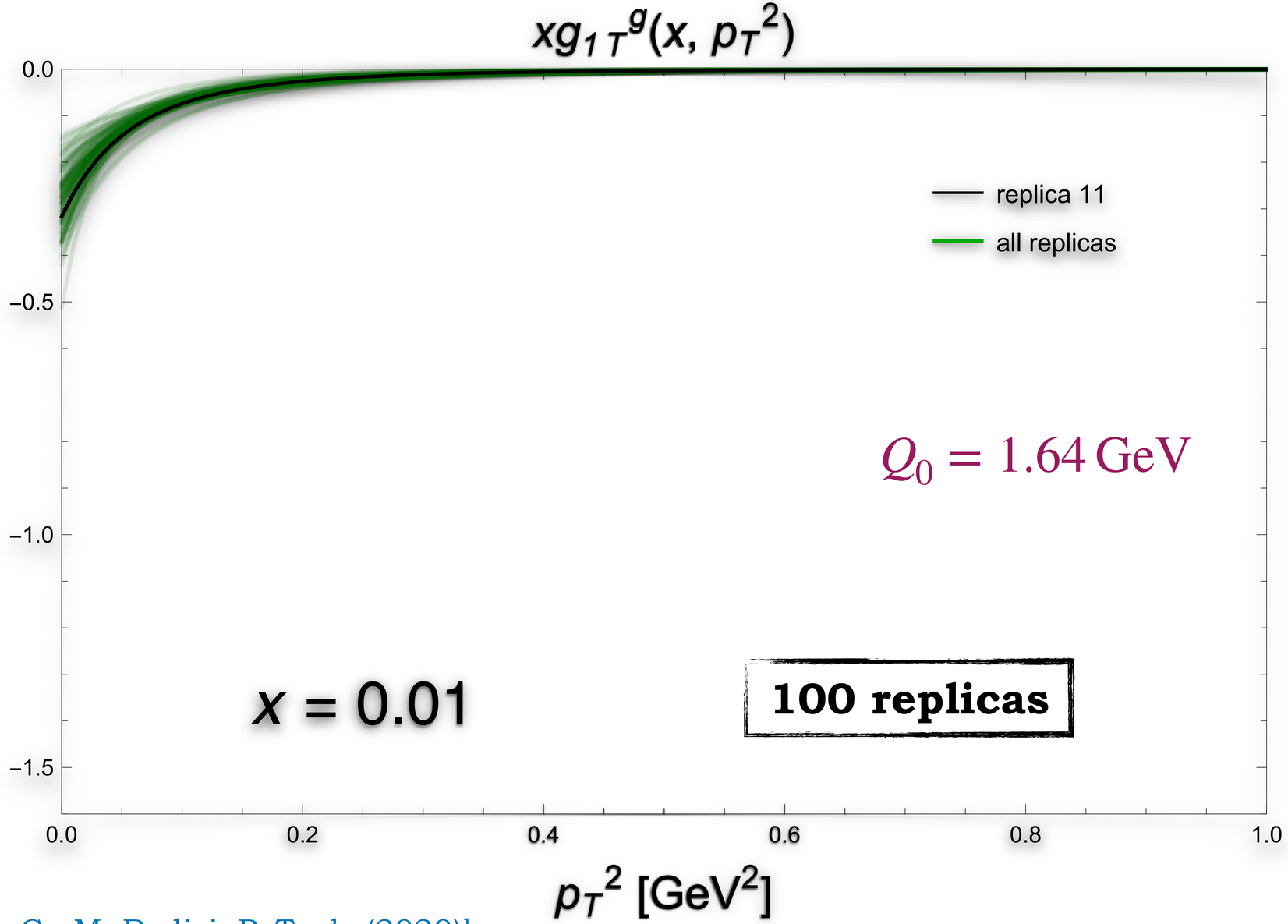


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Worm-gear gluon TMD

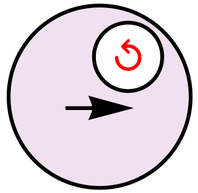


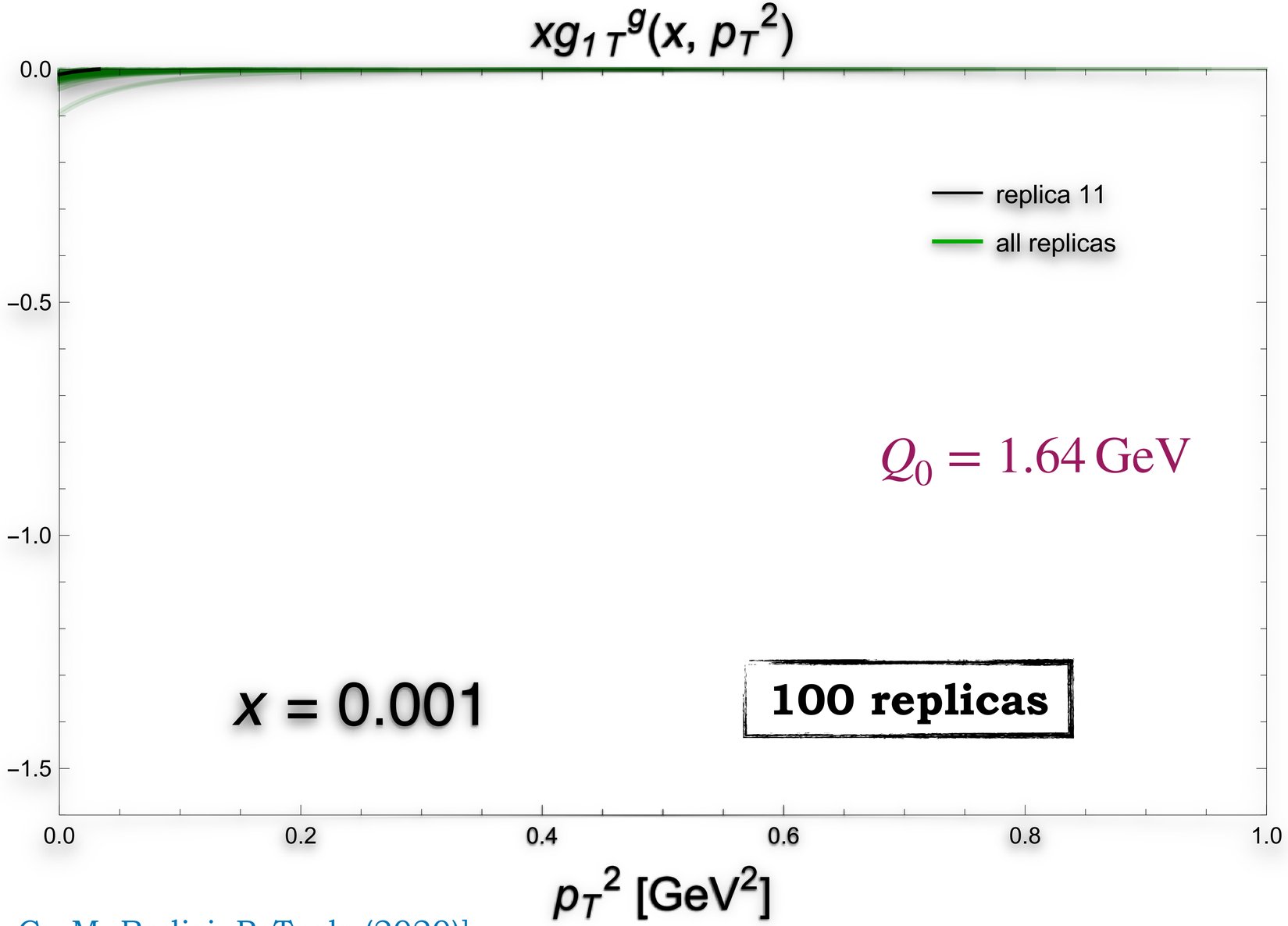


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

Backup

Worm-gear gluon TMD



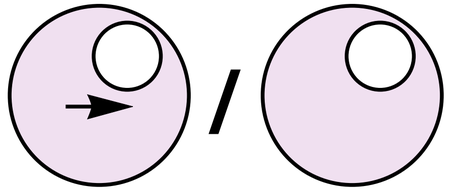


🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

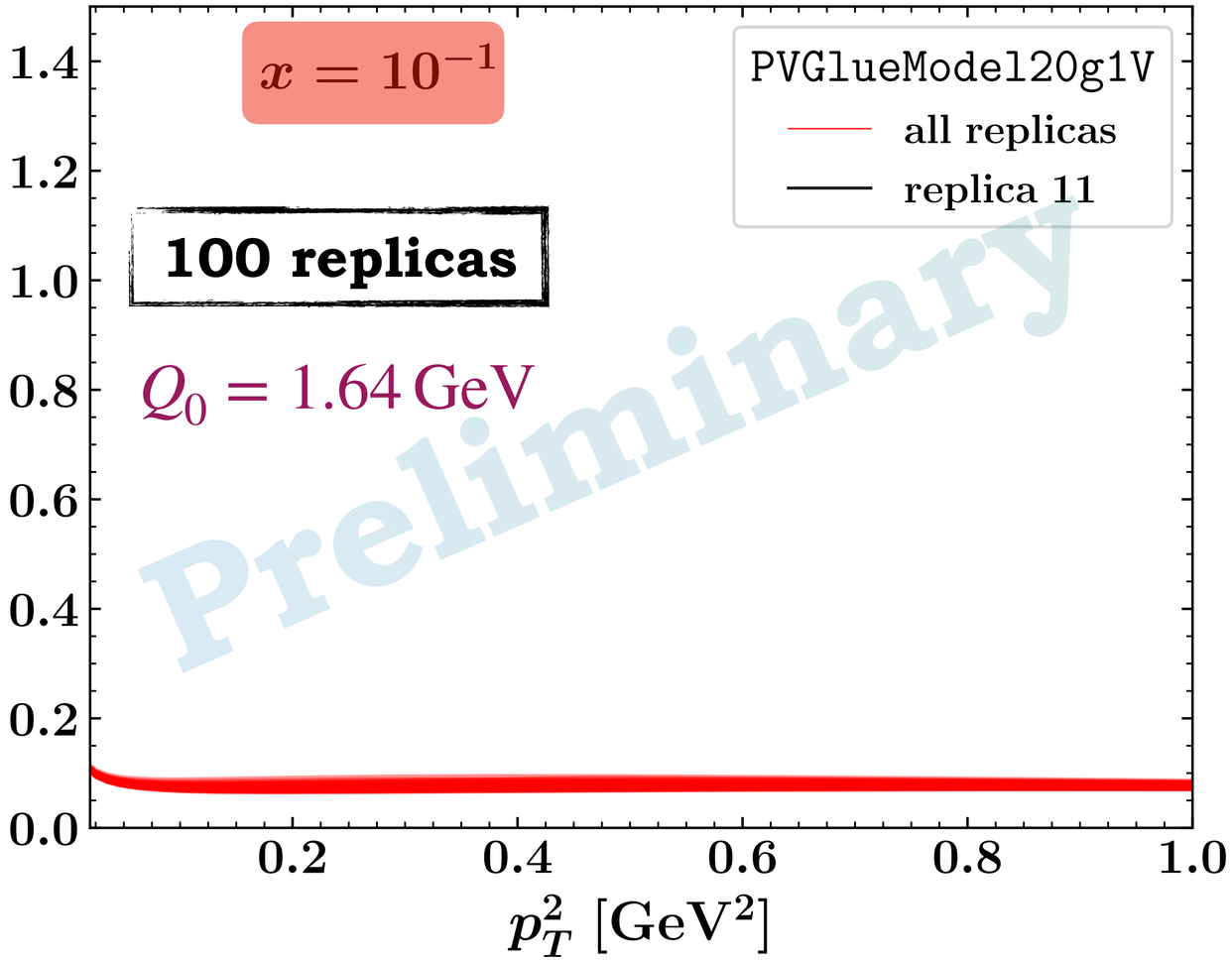
Backup

f-type Sivers/unpol.

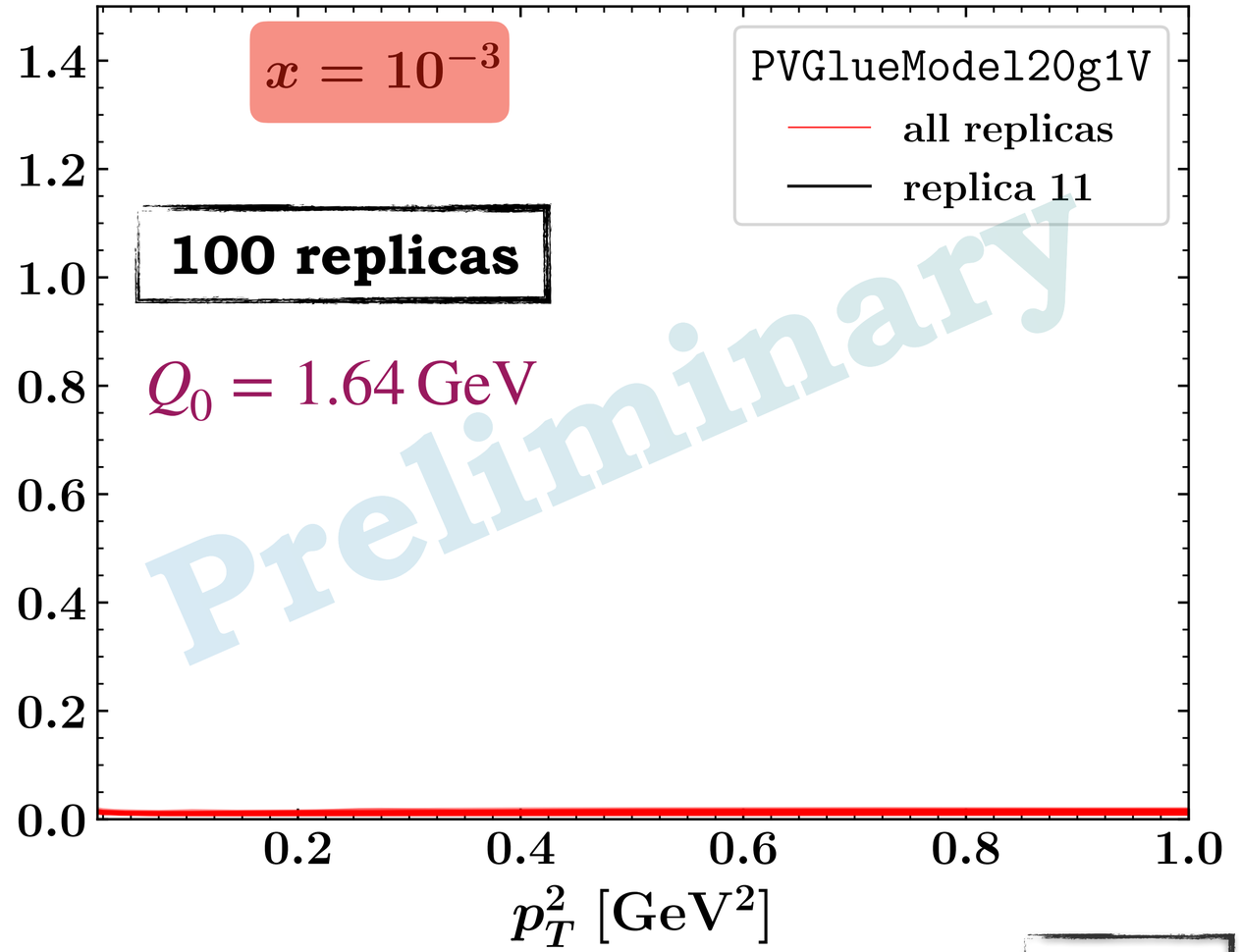
[A. Bacchetta, F.G. C., M. Radici (in preparation)]



$\frac{p_T}{M} f_{1T}^{\perp[+,+]} / f_1$



$\frac{p_T}{M} f_{1T}^{\perp[+,+]} / f_1$



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

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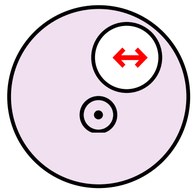
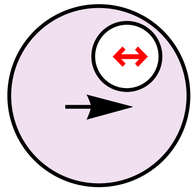
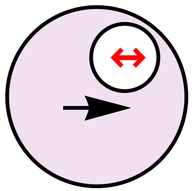


pseudo worm-gear



linearity TMD

pretzelosity



Backup

Gluon TMD correlator and T-odd gluon densities

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

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

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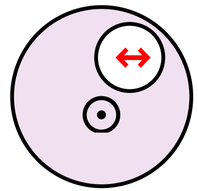
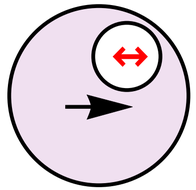
$$\left. - \frac{\epsilon_T^{k_T\{i} S_T^{j\}} + \epsilon_T^{S_T\{i} k_T^{j\}}}{4M} h_1(x,\boldsymbol{k}^2) - \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha S_T}}{2M^3} h_{1T}^{\perp}(x,\boldsymbol{k}^2)\right]$$

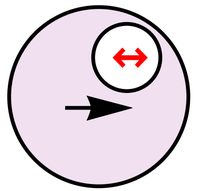
pseudo worm-gear



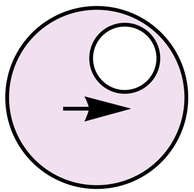
linearity TMD



pretzelosity



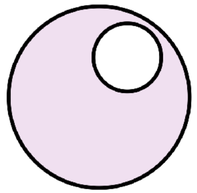
Sivers



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

Backup

ρ-densities

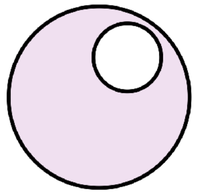


Unpolarized [u/u]

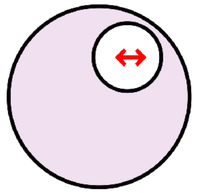
$$f_1(x, p_x, p_y)$$

Backup

ρ-densities



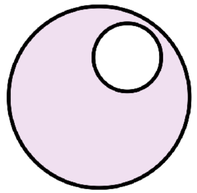
Unpolarized [u/u] $f_1(x, p_x, p_y)$



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

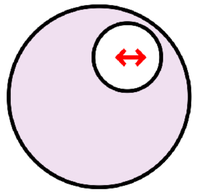
Backup

ρ-densities



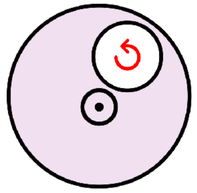
Unpolarized [u/u]

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



Boer-Mulders [↔/u]

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

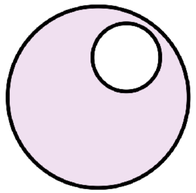


Helicity [↻/+]

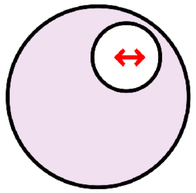
$$\frac{1}{2}\left[f_1(x, p_x, p_y) + g_{1L}(x, p_x, p_y)\right]$$

Backup

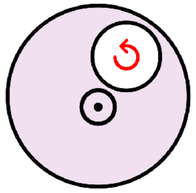
ρ-densities



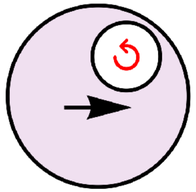
Unpolarized [u/u] $f_1(x, p_x, p_y)$



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



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



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

Backup

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

TMD phenomenology:

from JLab to the LHC

Andrea Signori

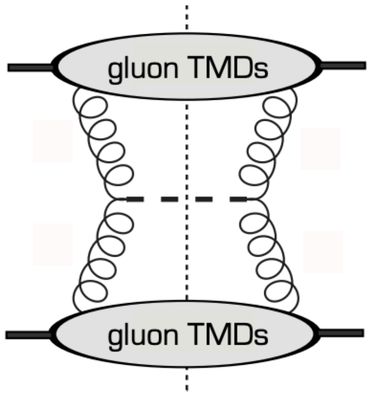
Spatial and momentum tomography of hadrons and nuclei

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

C_{ff} C_{hh}

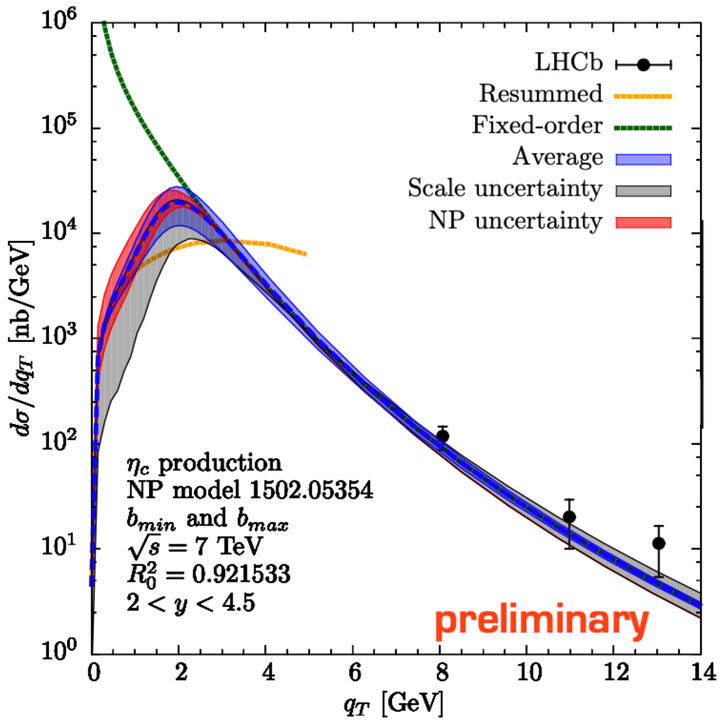
Jefferson Lab

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 GeV^2, 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

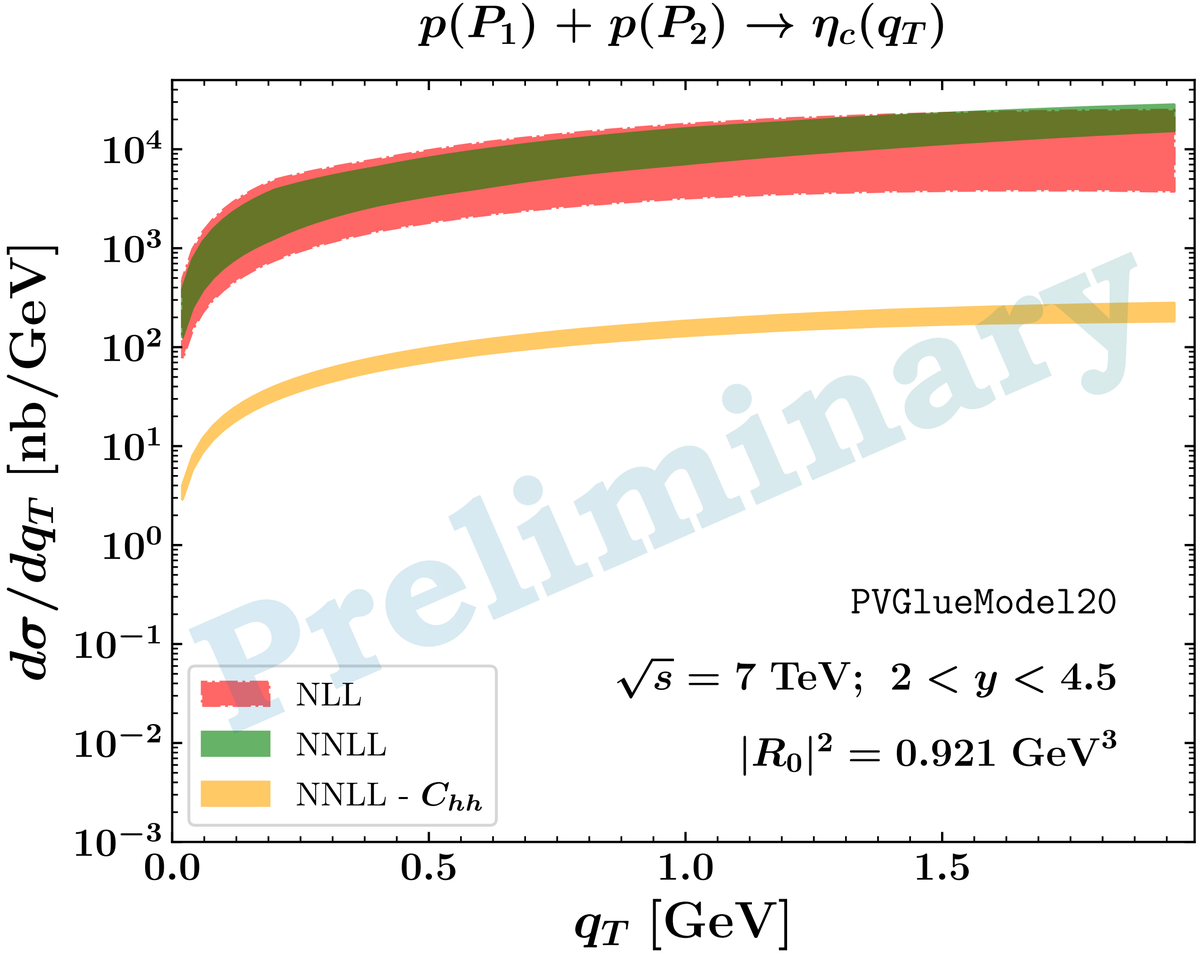
25

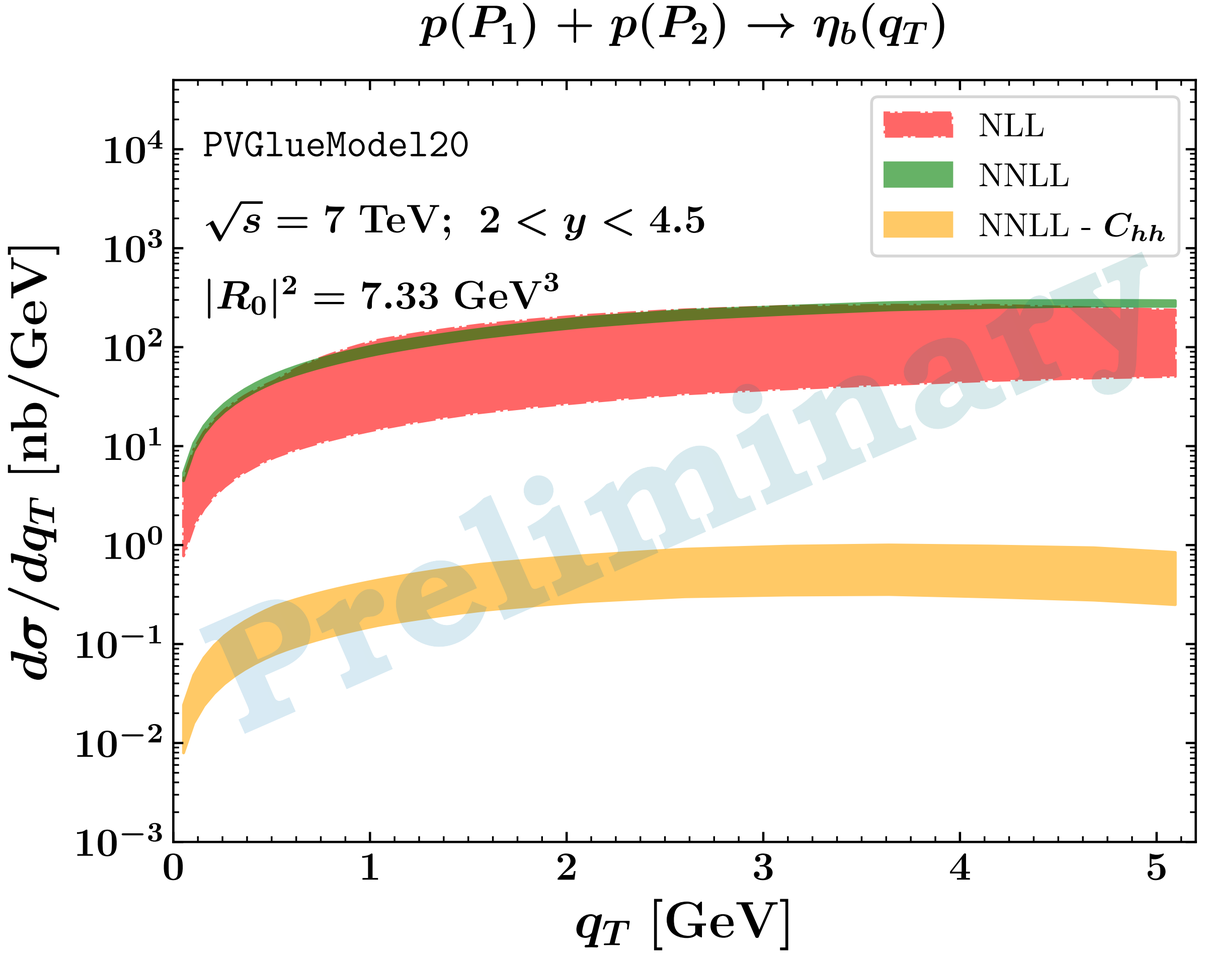
slide by **Andrea Signori** (INT 2017)

Backup

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

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



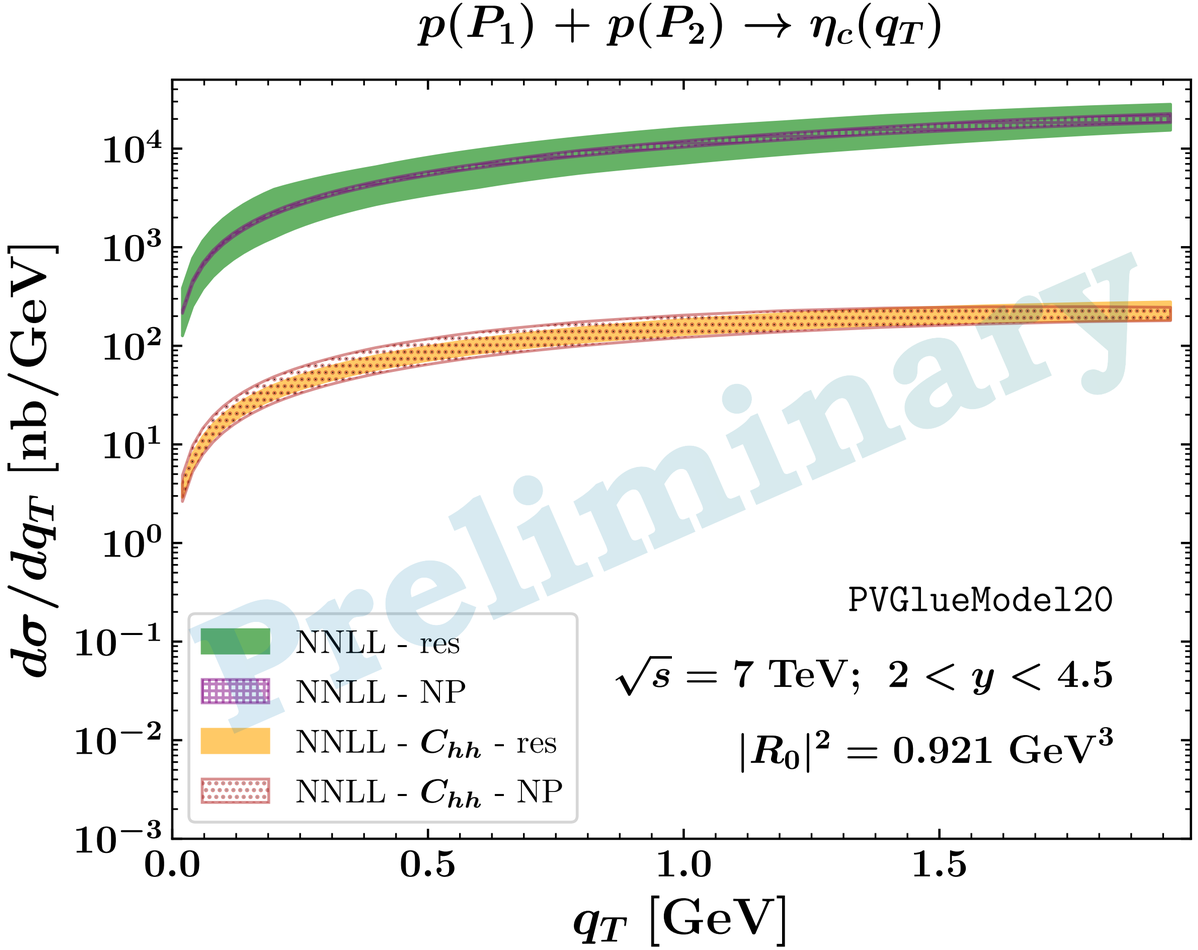


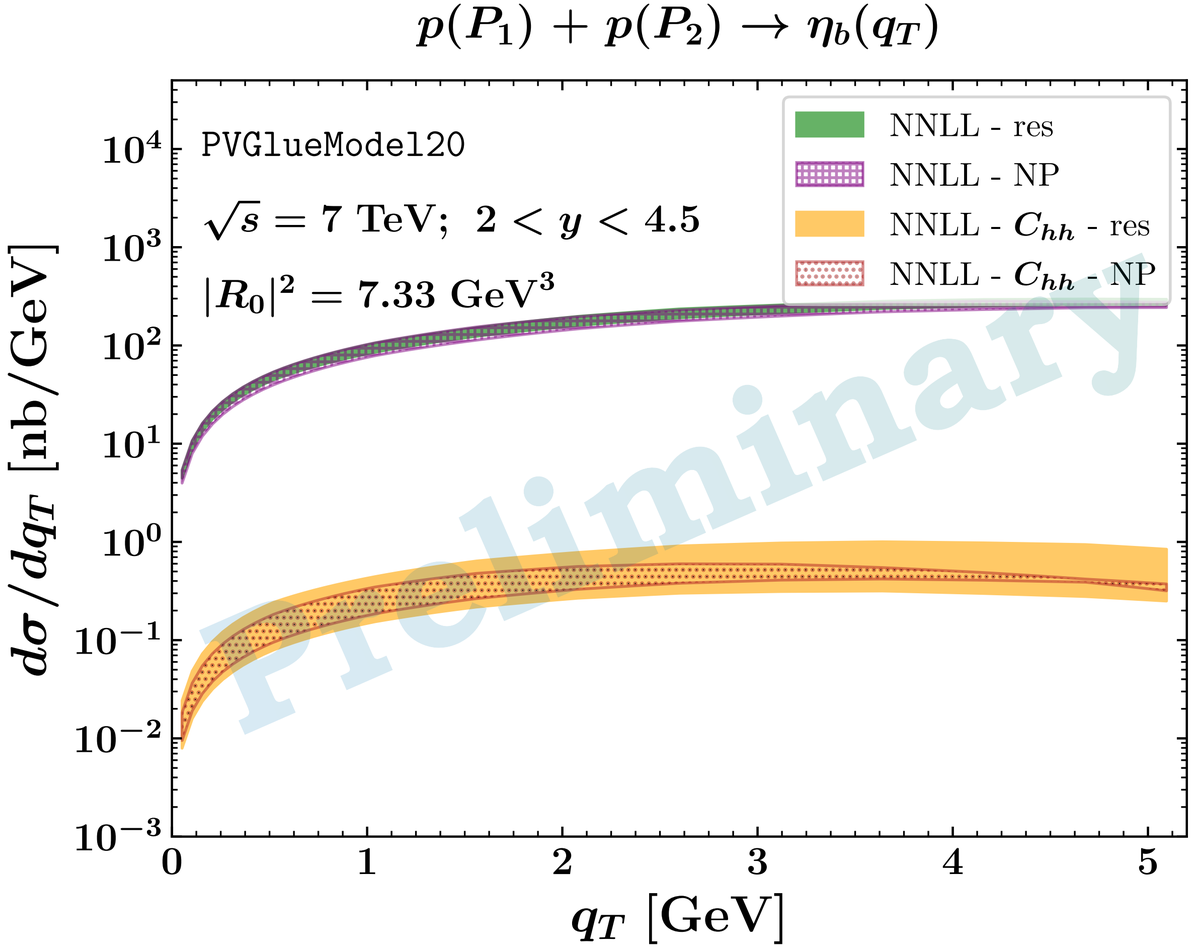
[A. Bacchetta, F.G. C., J.-P. Lansberg, M. Radici, A. Signori (in preparation)]

Backup

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

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



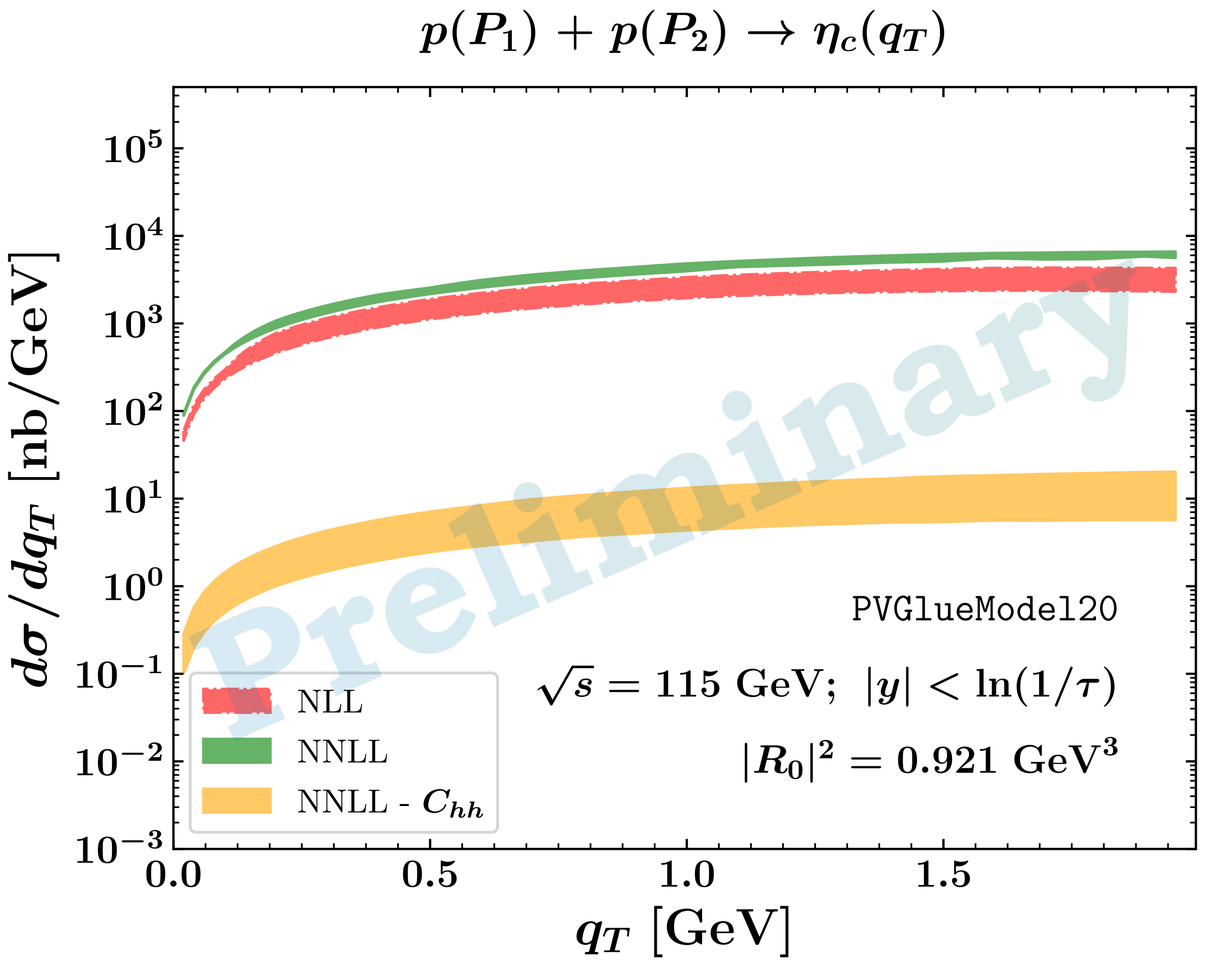


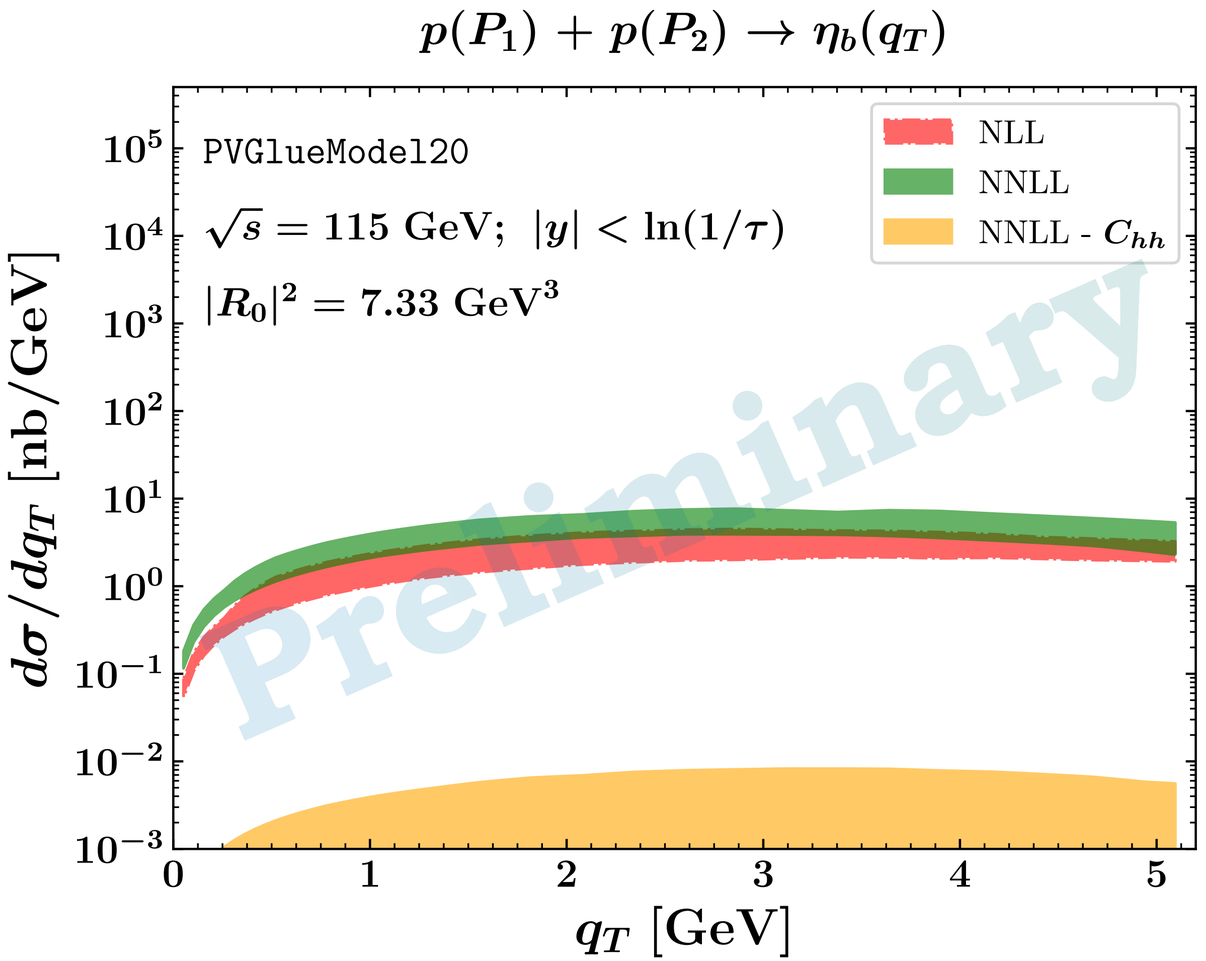
[A. Bacchetta, F.G. C., J.-P. Lansberg, M. Radici, A. Signori (in preparation)]

Backup

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

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



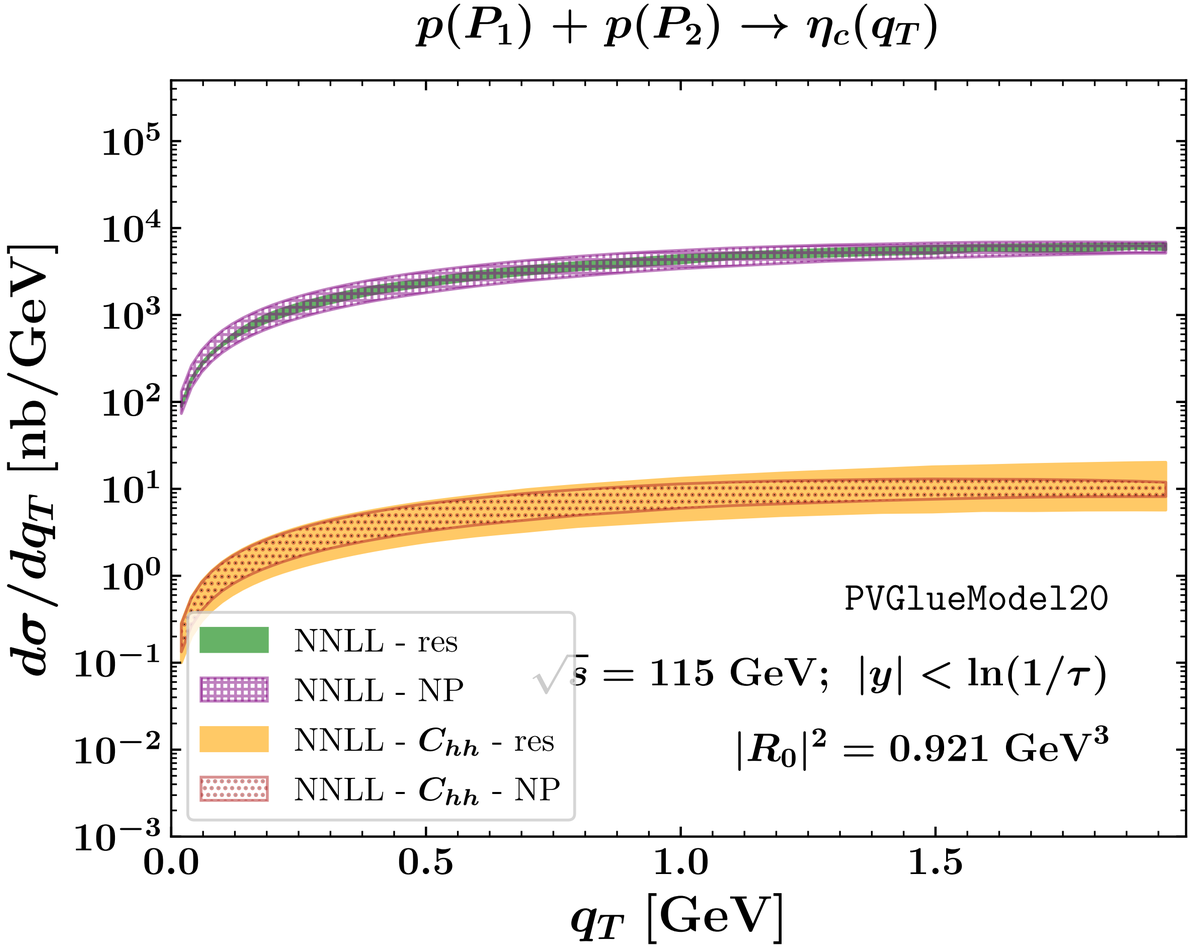


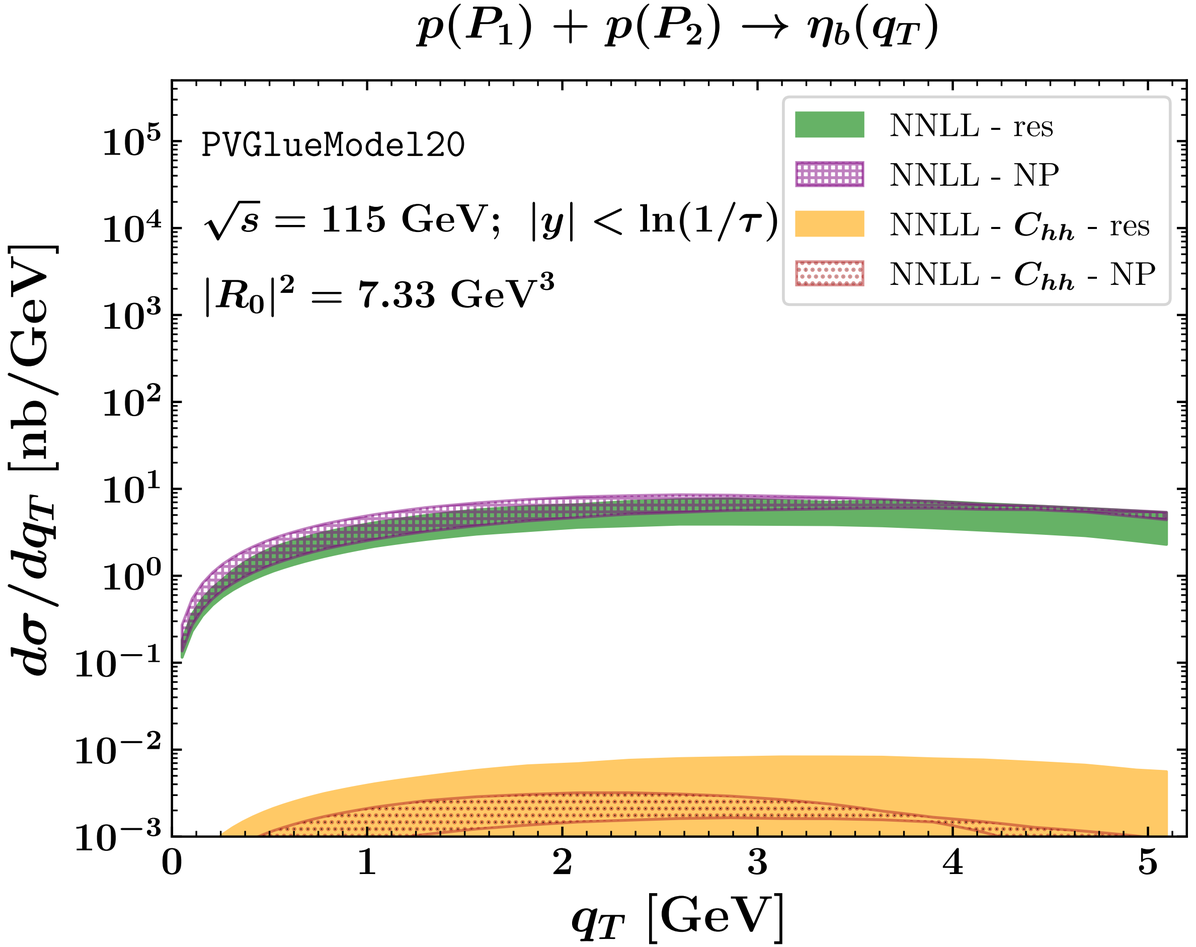
[A. Bacchetta, F.G. C., J.-P. Lansberg, M. Radici, A. Signori (in preparation)]

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, M. Radici, A. Signori (in preparation)]

Backup