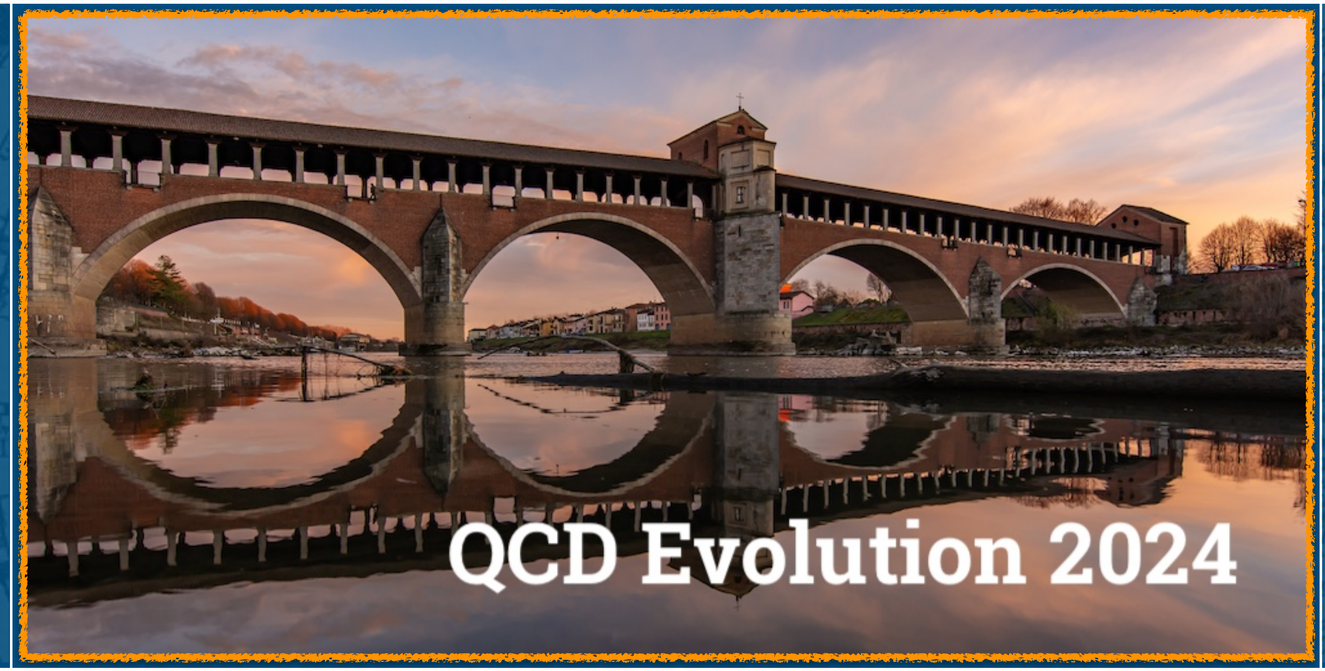
GLUON TMD MODELING & PROTON 3D IMAGING

Francesco Giovanni Celiberto, UAH Madrid

🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels, *Eur. Phys. J.* C 80 (2020) 8, 733]

🔗 [A. Bacchetta, F.G.C., M. Radici, *Eur. Phys. J.* C, *in press*]



Madrid UAH

talento cm Programa de atracción de talento investigador Comunidad de Madrid

ANIVERSARIO PATRIMONIO MUNDIAL

1. PROCESS DEPENDENCE

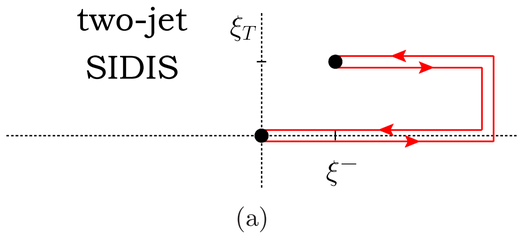


Accessing f-type and d-type gluon TMD PDFs

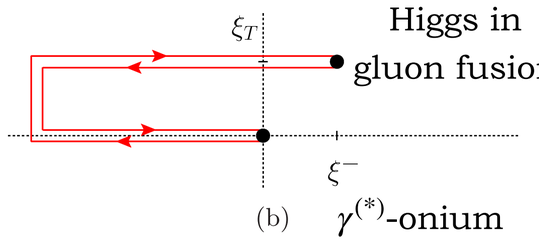
f-type (WW)

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

two-jet SIDIS



(a)



(b)

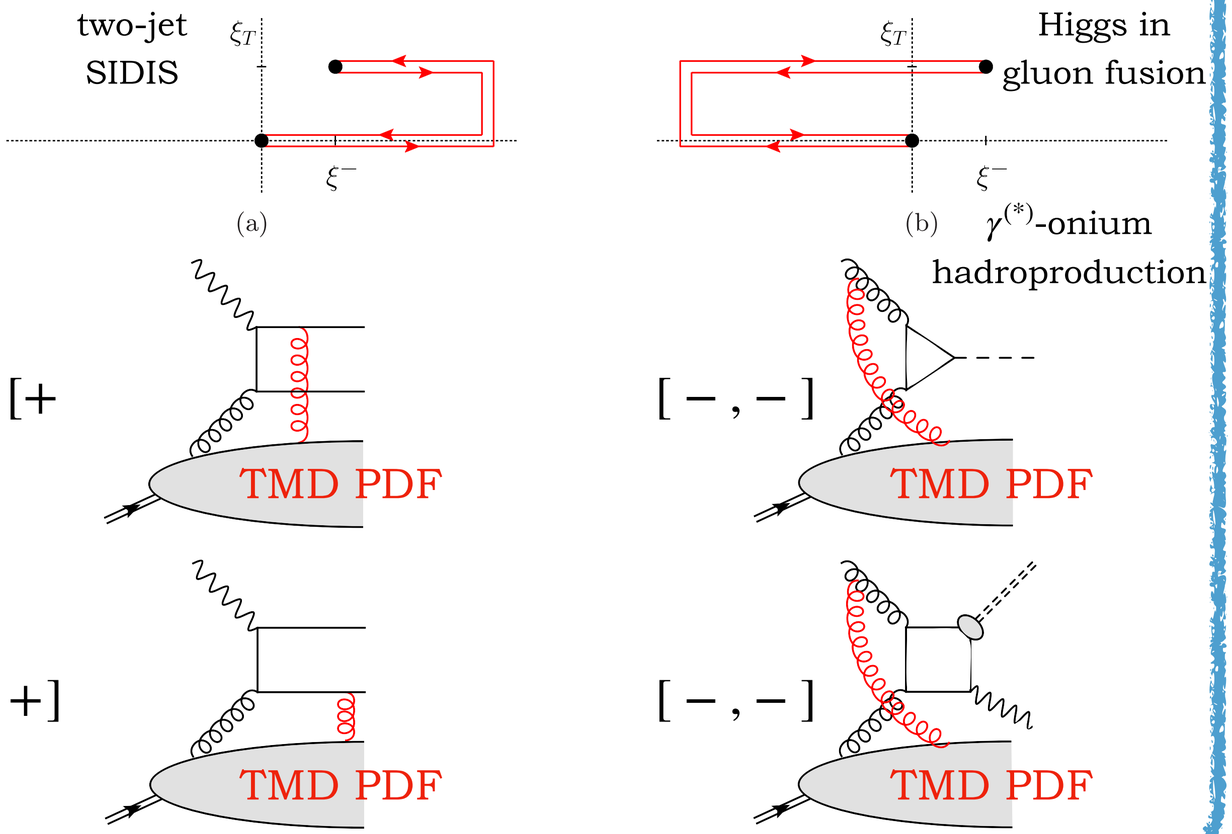
Higgs in gluon fusion

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

Accessing f-type and d-type gluon TMD PDFs

f-type (WW)

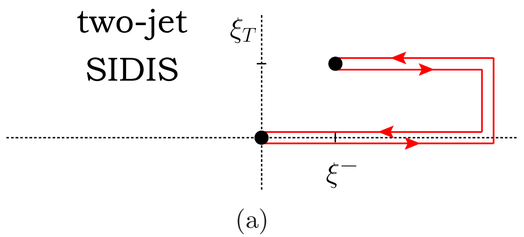
(a) $[+,+]$ or (b) $[-,-]$

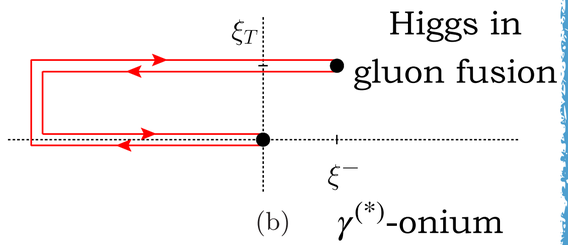


Accessing f-type and d-type gluon TMD PDFs

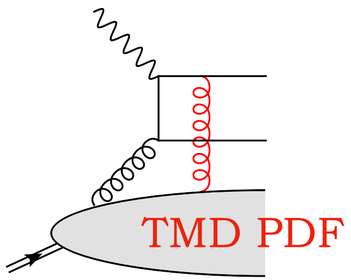
f-type (WW)

(a) [+,+] or (b) [−,−]

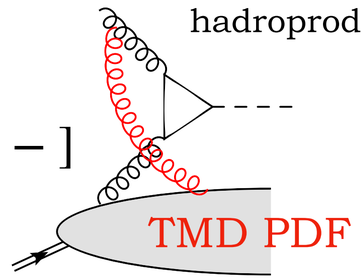




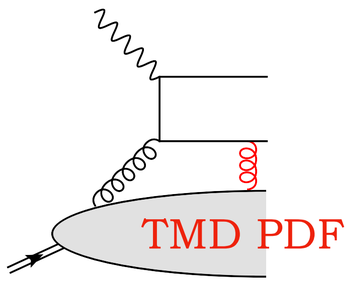
[+



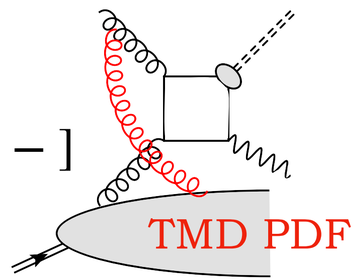
[−,−]



+]

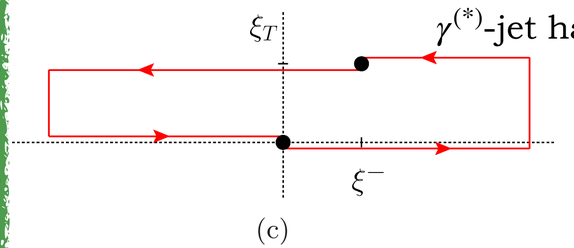


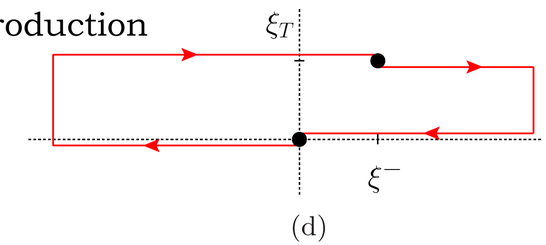
[−,−]



d-type (DP)

(c) [+,−] or (d) [−,+]

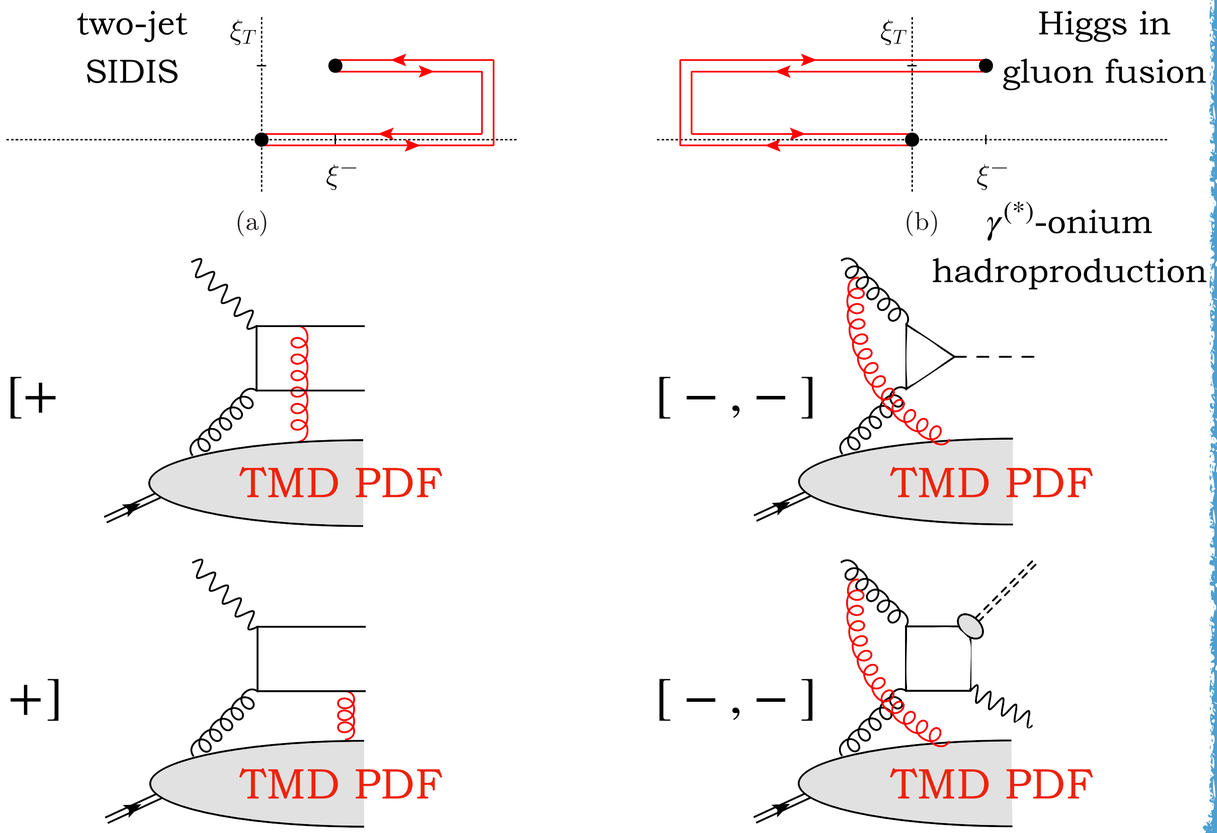




Accessing f-type and d-type gluon TMD PDFs

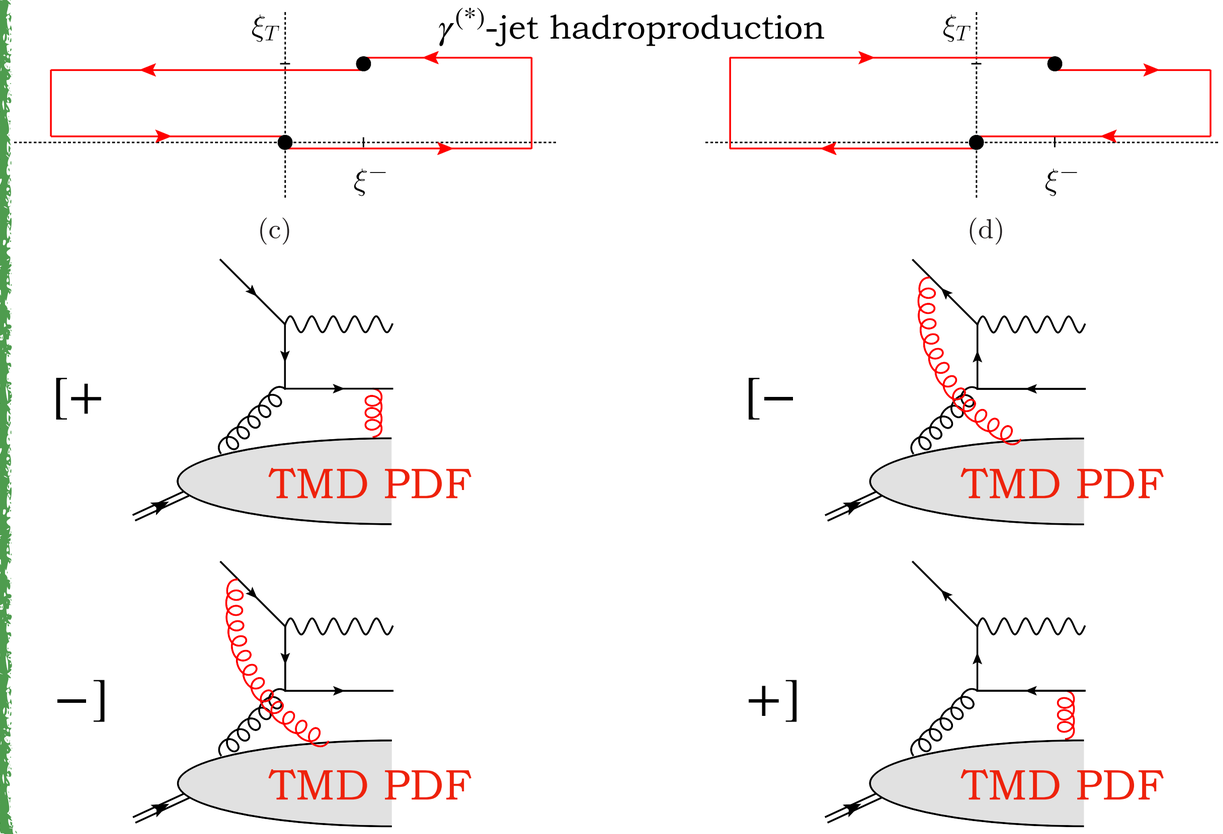
f-type (WW)

(a) [+ , +] or (b) [− , −]



d-type (DP)

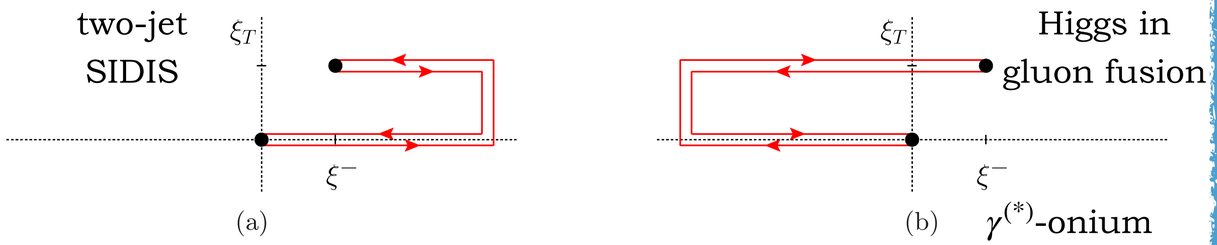
(c) [+ , −] or (d) [− , +]

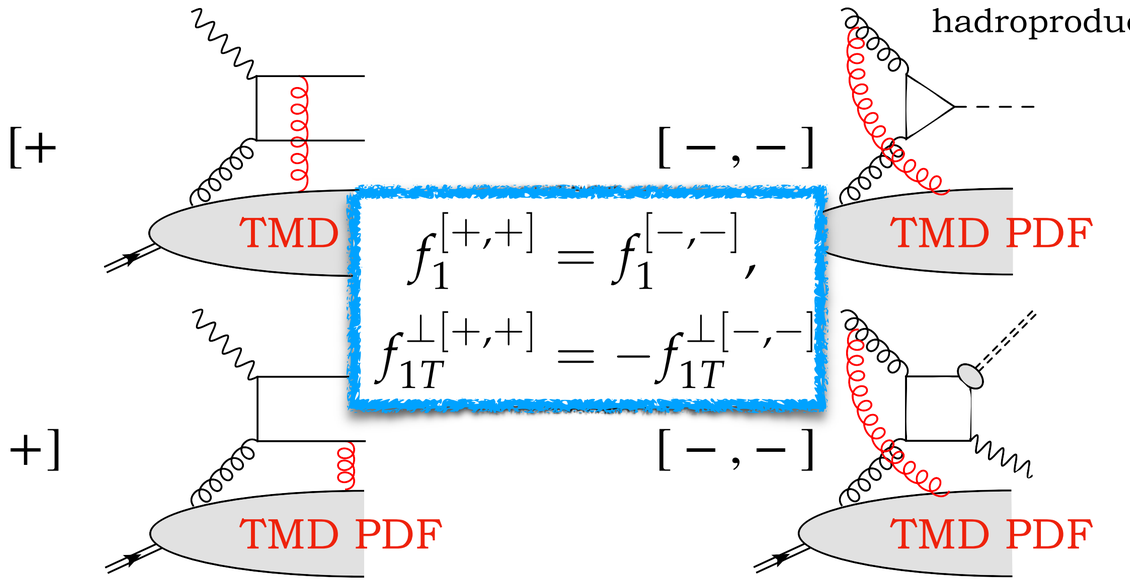


Accessing f-type and d-type gluon TMD PDFs

f-type (WW)

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

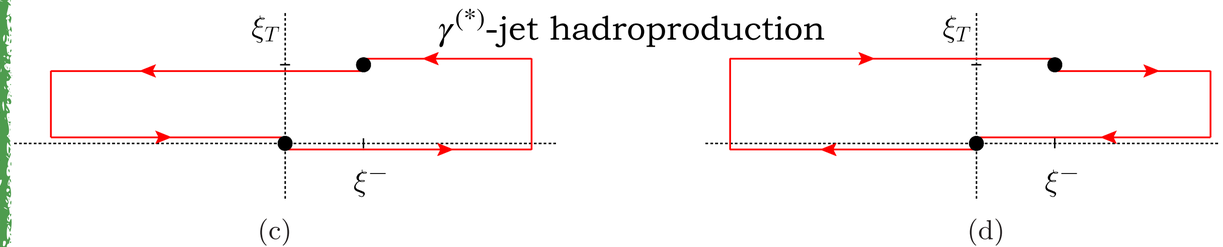


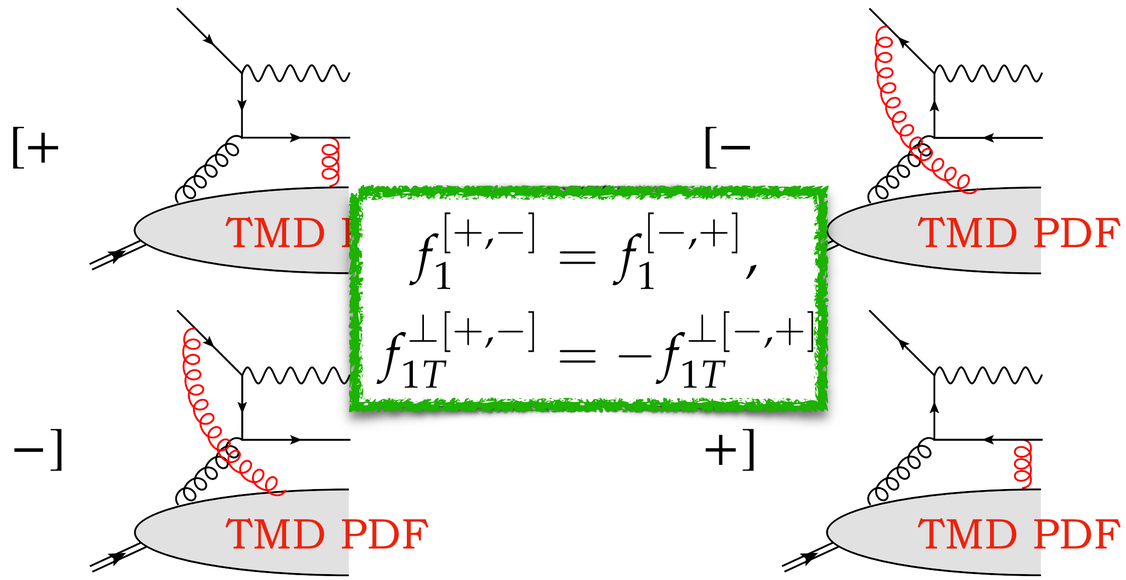


$$f_1^{[+,+]} = f_1^{[-,-]},$$
$$f_{1T}^{\perp[+,+]} = -f_{1T}^{\perp[-,-]}$$

d-type (DP)

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





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

¡ Gauge link → two main **independent** sets of TMD PDFs, **not related** to each other !

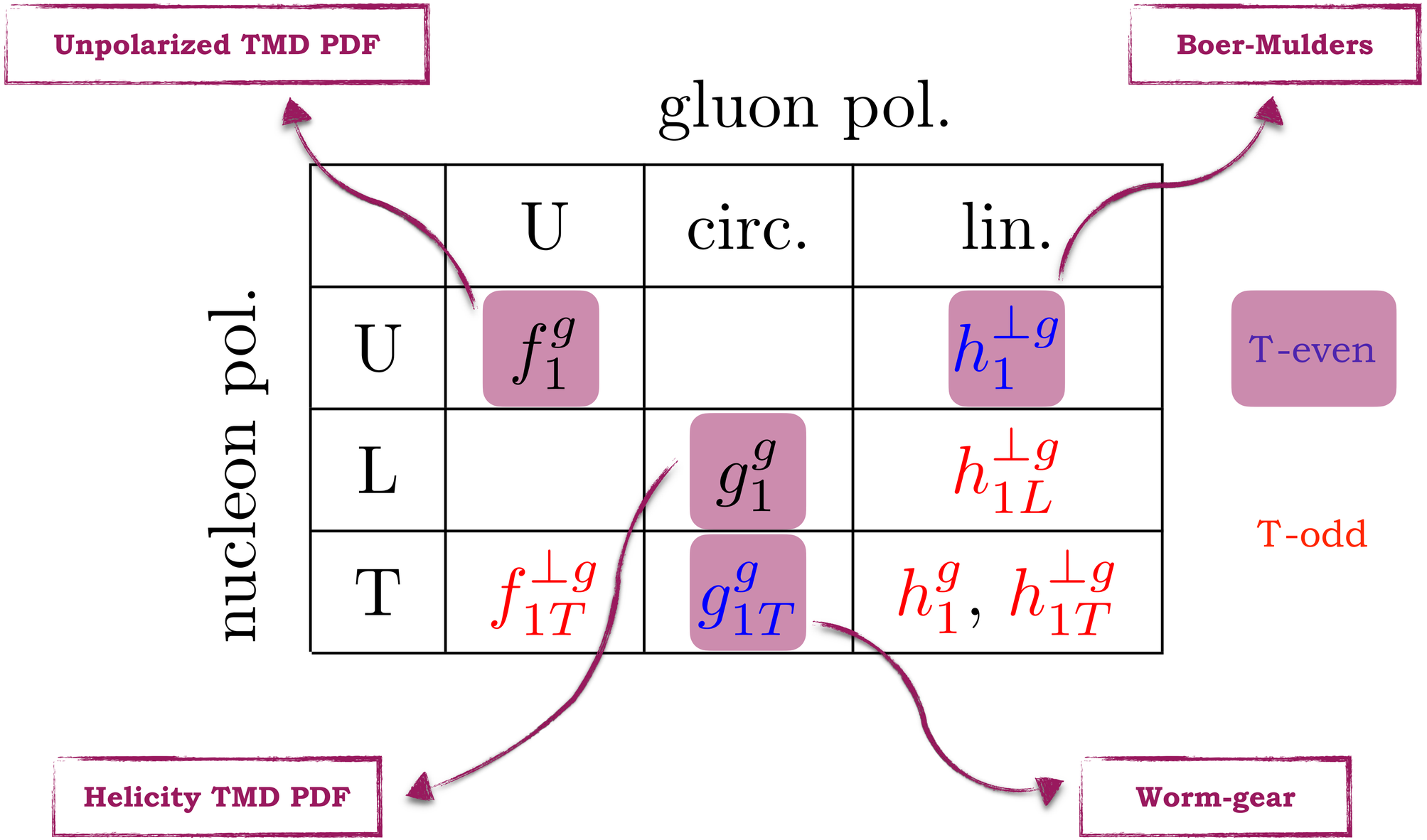
Gluon TMD PDFs at leading twist

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	$h_1^g,\ h_{1T}^{\perp g}$

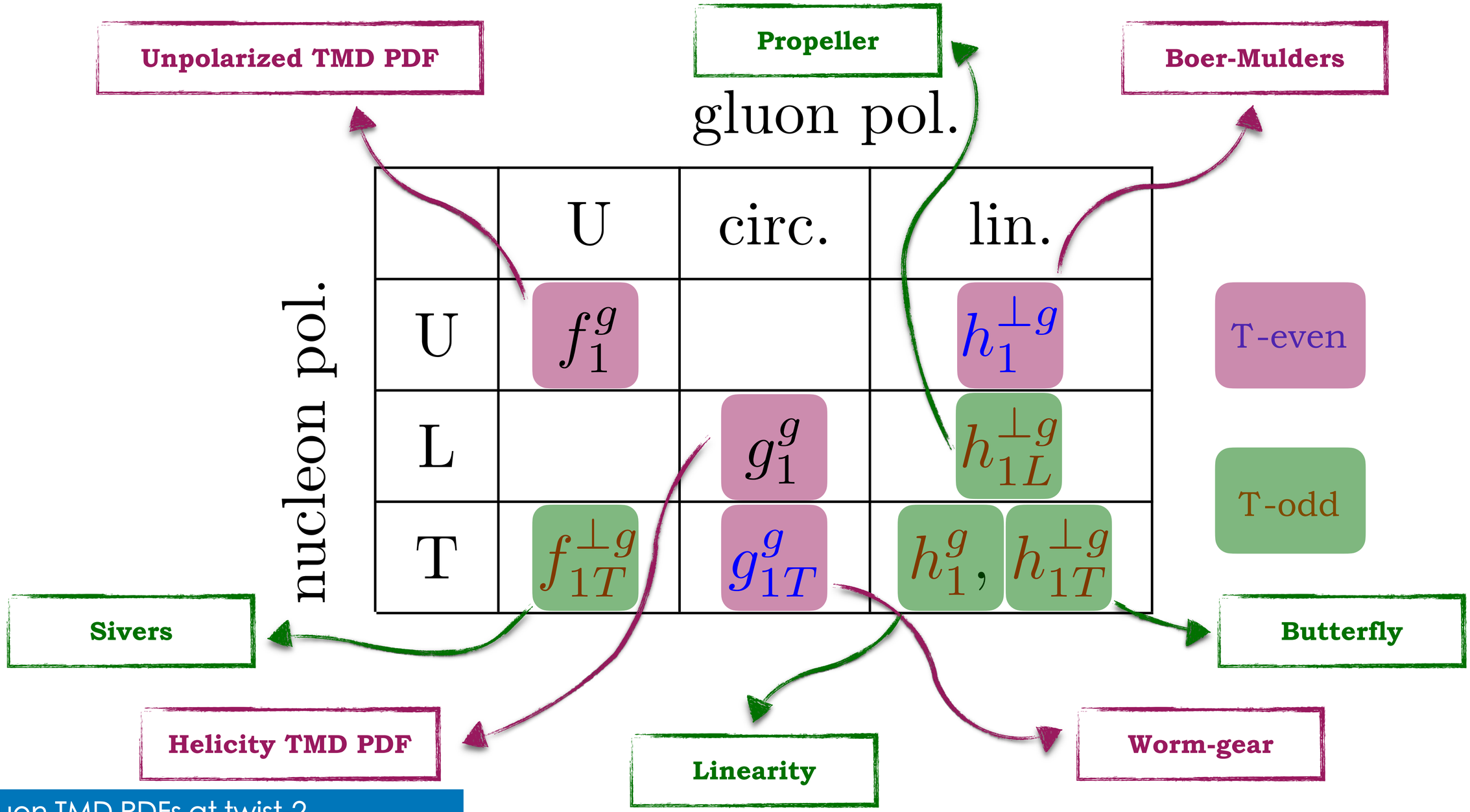
T-even

T-odd

Gluon TMD PDFs at leading twist



Gluon TMD PDFs at leading twist



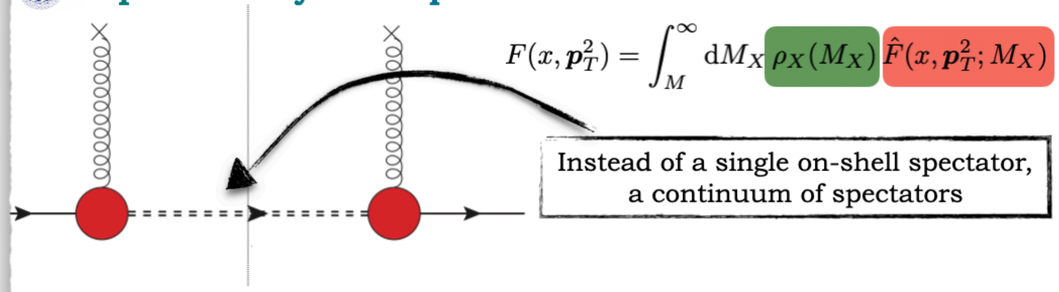
2. MODELING GLUON TMD DENSITIES



Spectator-model gluon TMD PDFs

Our model at a glance

Spectator-system spectral-mass function



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

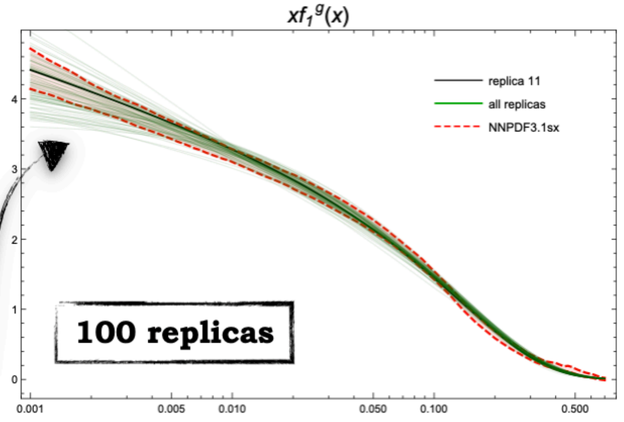
Instead of a single on-shell spectator, a continuum of spectators

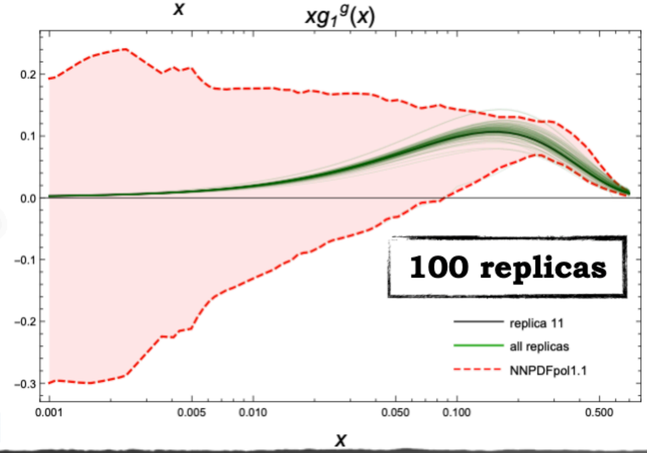
Spectral function **learns** small- and moderate-x info encoded in **NNPDF** collinear parametrizations (`NNPDF3.1sx + NNPDFpol1.1`)

- ☑ **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



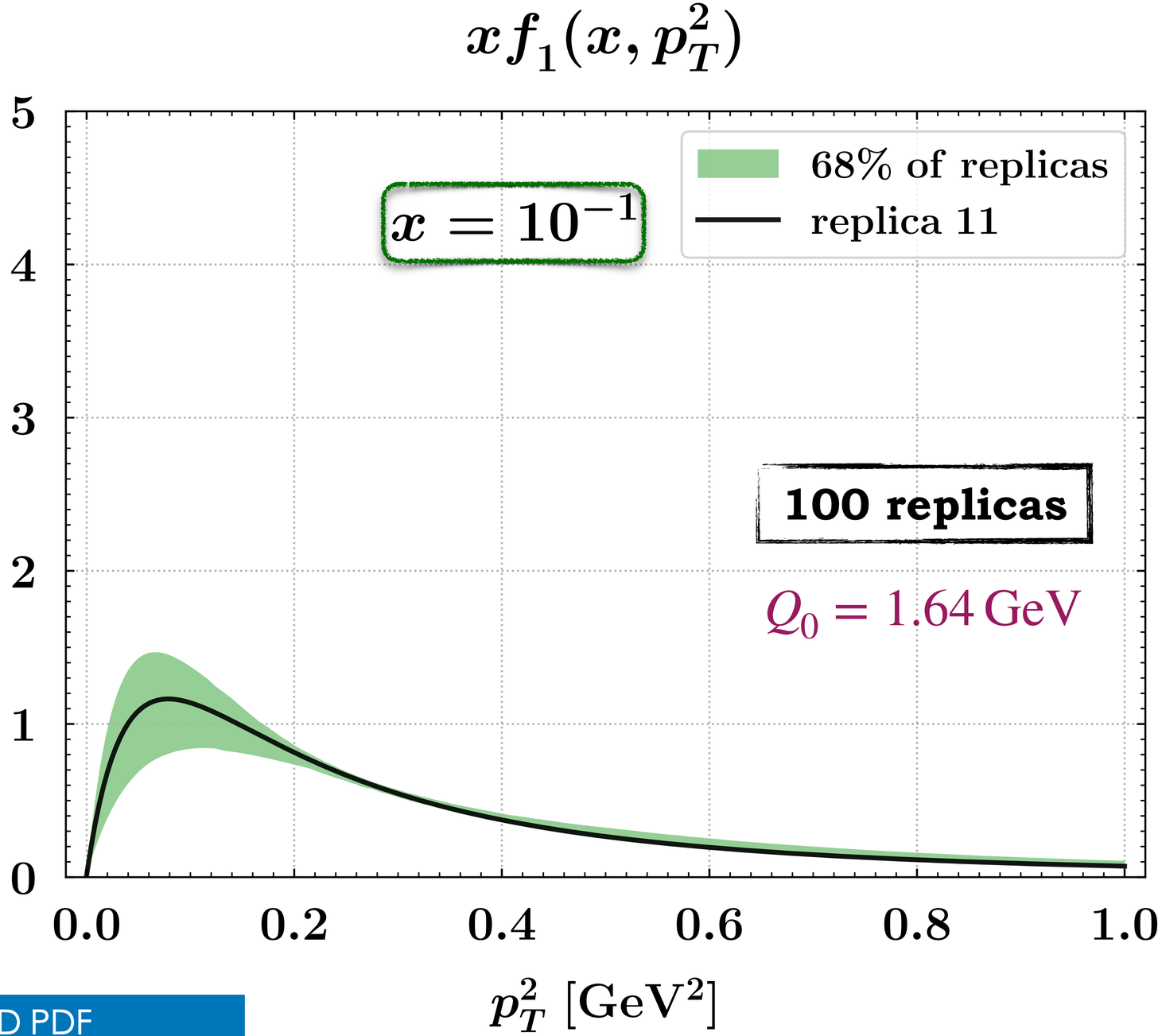


2.3 Modeling gluon TMDs [A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

14

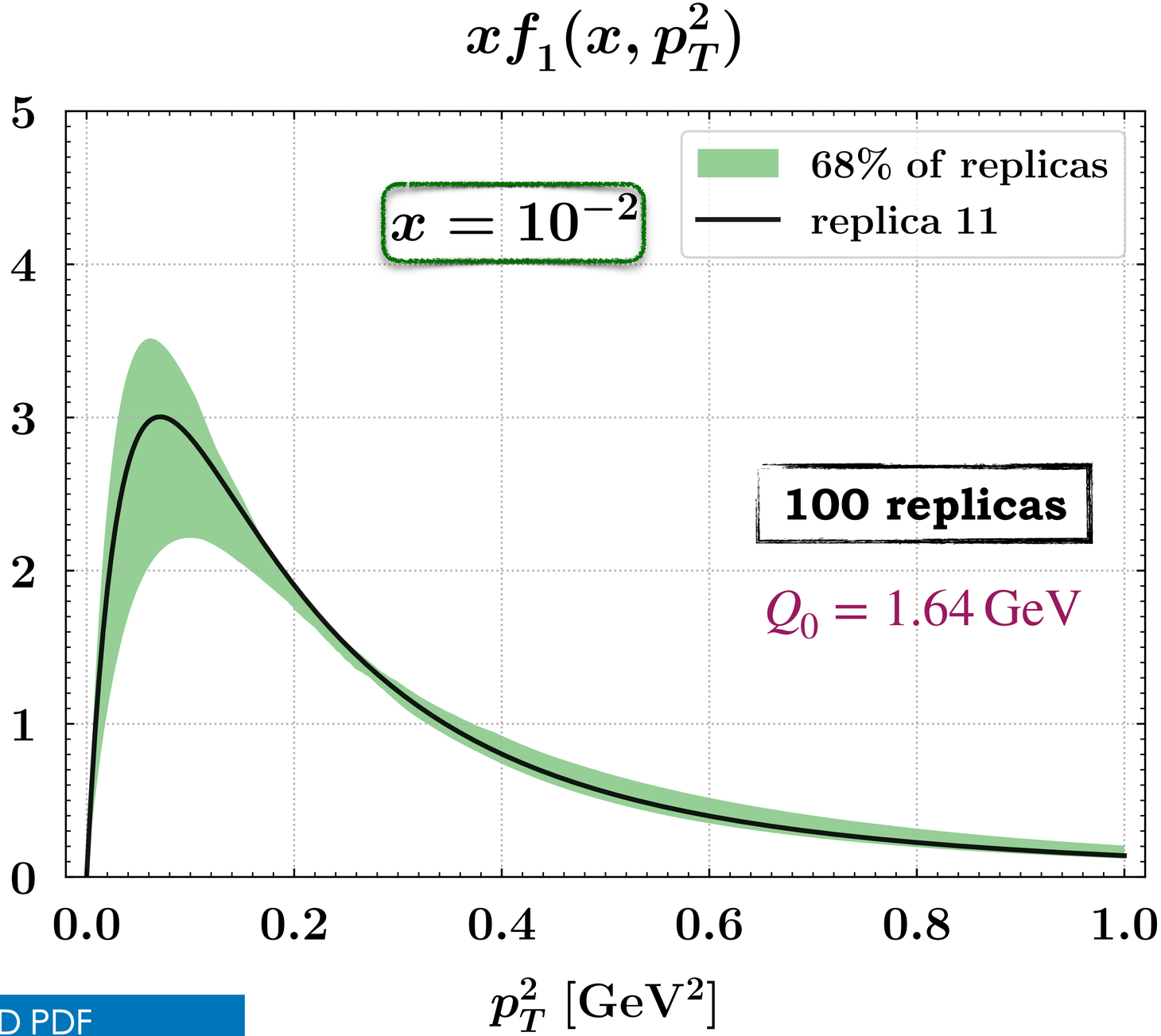
Unpolarized gluon TMD PDF

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



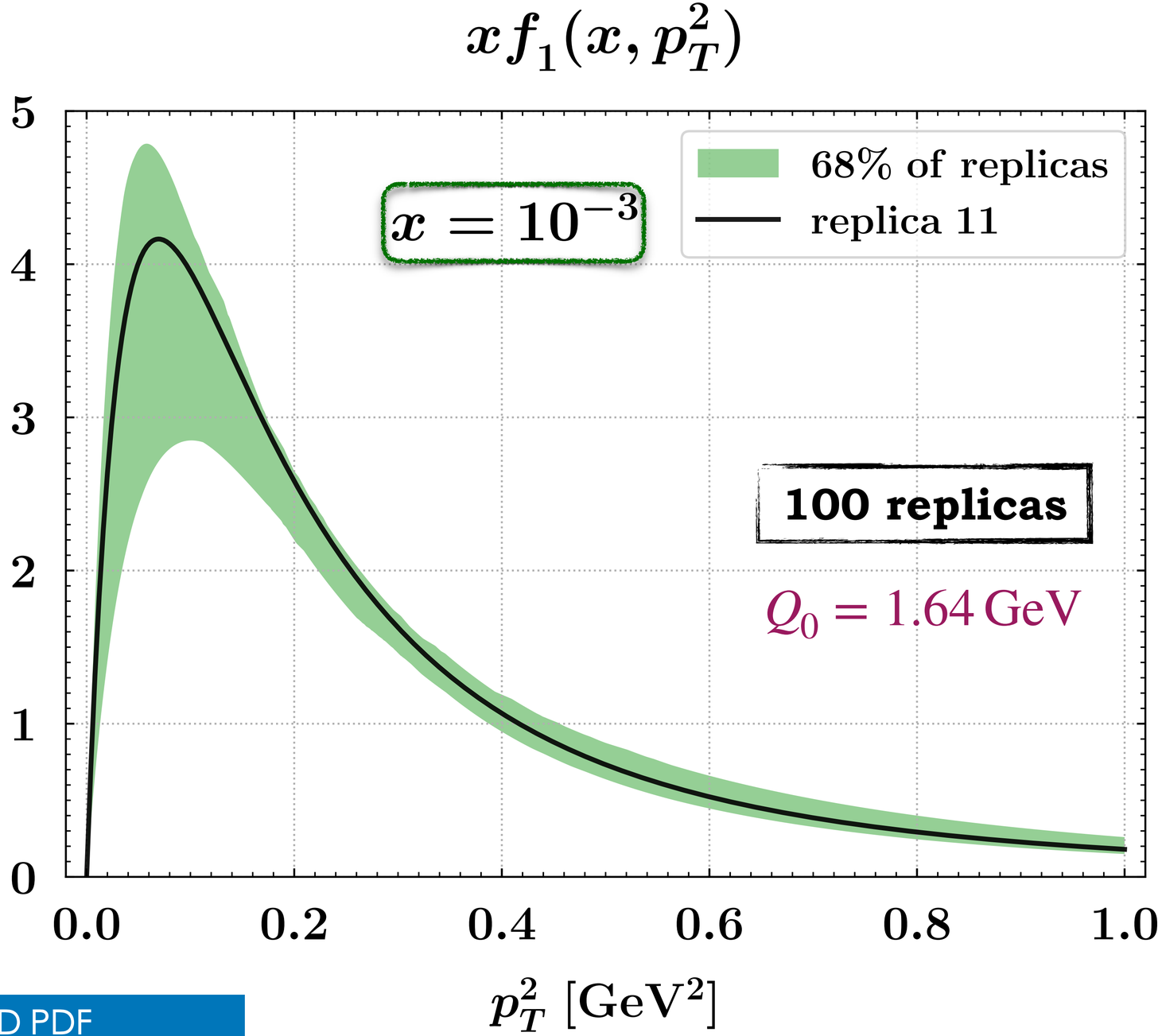
Unpolarized gluon TMD PDF

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



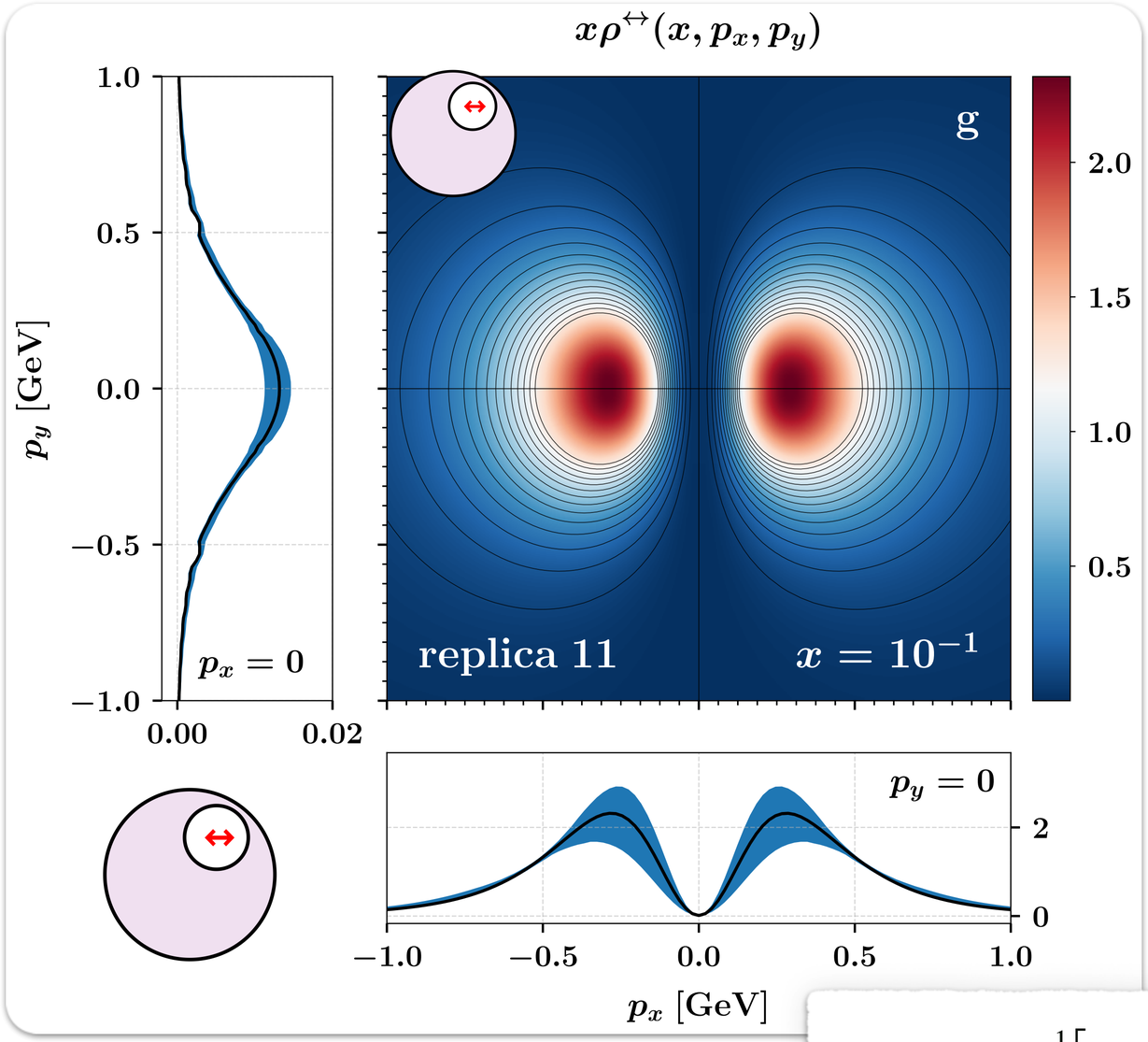
Unpolarized gluon TMD PDF

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



Gluon Boer-Mulders effect

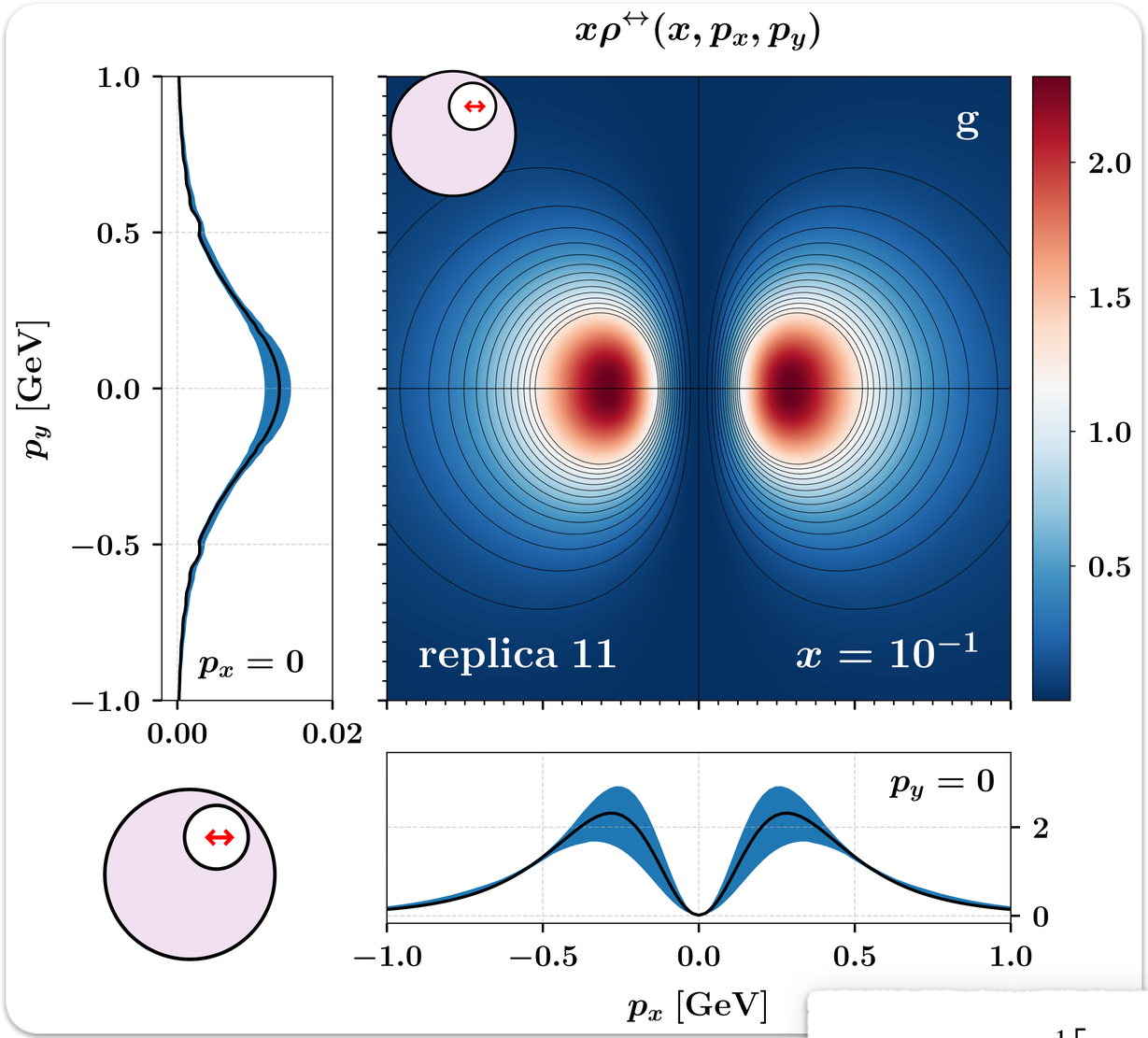
[A. Bacchetta, F.G.C., M. Radici, P. Taels (EPJC 2020)]

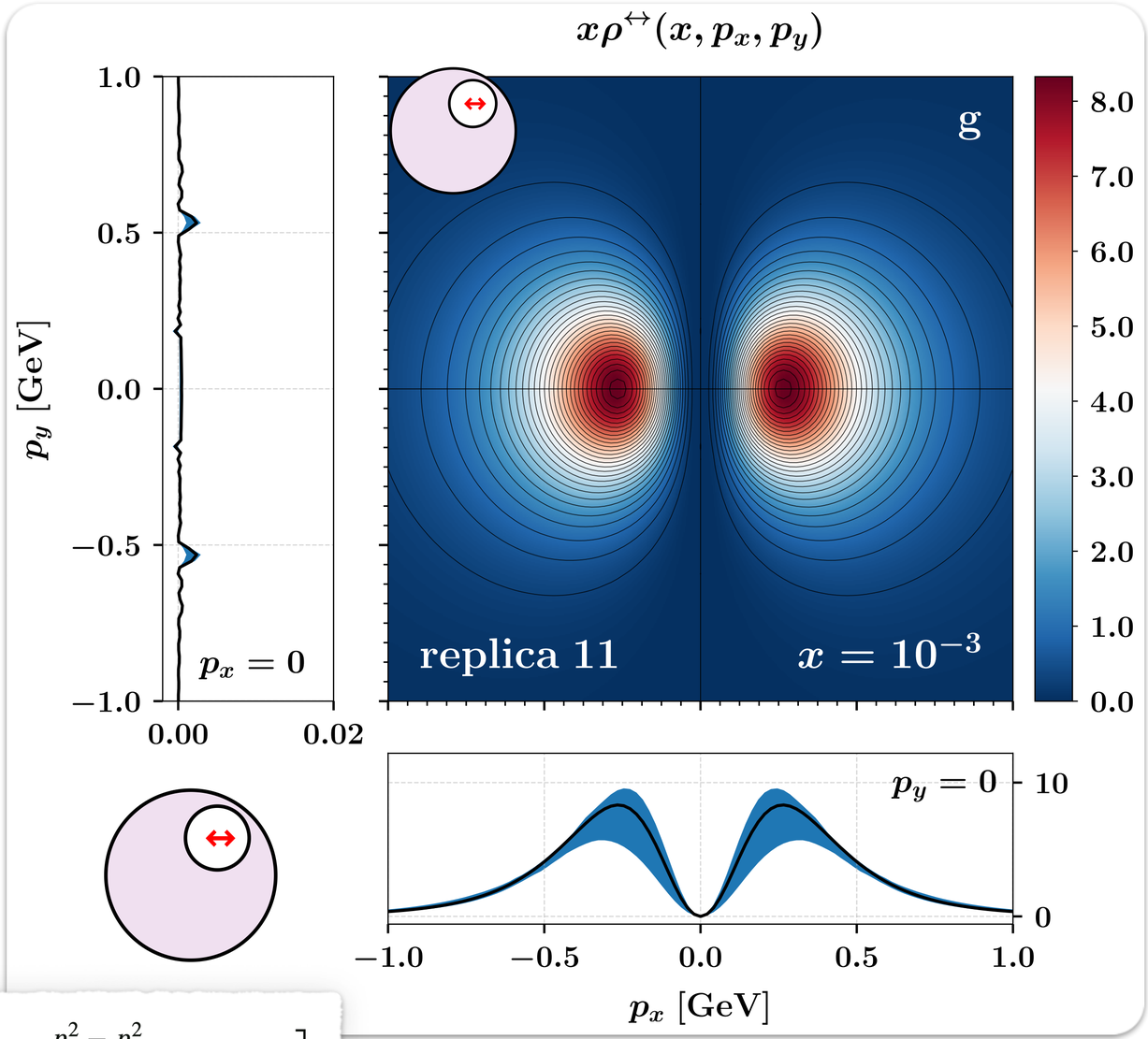


$$x\rho^{\leftrightarrow}(x, p_x, p_y) = \frac{1}{2}\left[x f_1^g(x, \boldsymbol{p}_T^2) + \frac{p_x^2 - p_y^2}{2M^2}\, x h_1^{\perp g}(x, \boldsymbol{p}_T^2)\right]$$

Gluon Boer-Mulders effect

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





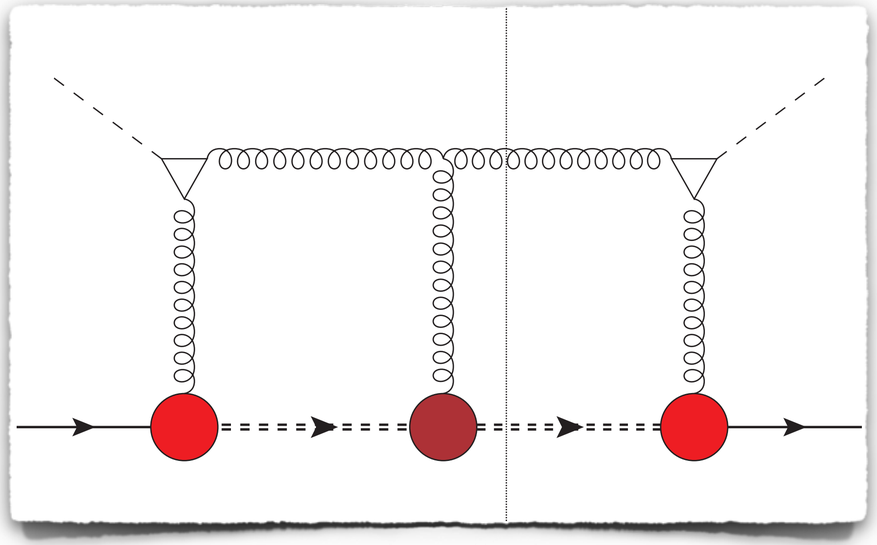
$$x\rho^{\leftrightarrow}(x, p_x, p_y) = \frac{1}{2}\left[x f_1^g(x, \boldsymbol{p}_T^2) + \frac{p_x^2 - p_y^2}{2M^2}\, x h_1^{\perp g}(x, \boldsymbol{p}_T^2)\right]$$

3. BUILDING T-ODD STRUCTURES

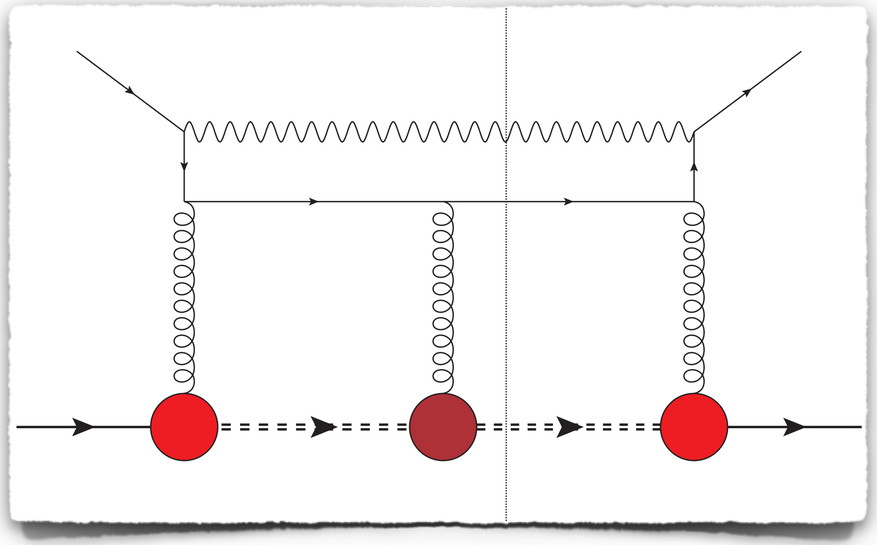


T-odd gluon TMD PDFs in a spectator model

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

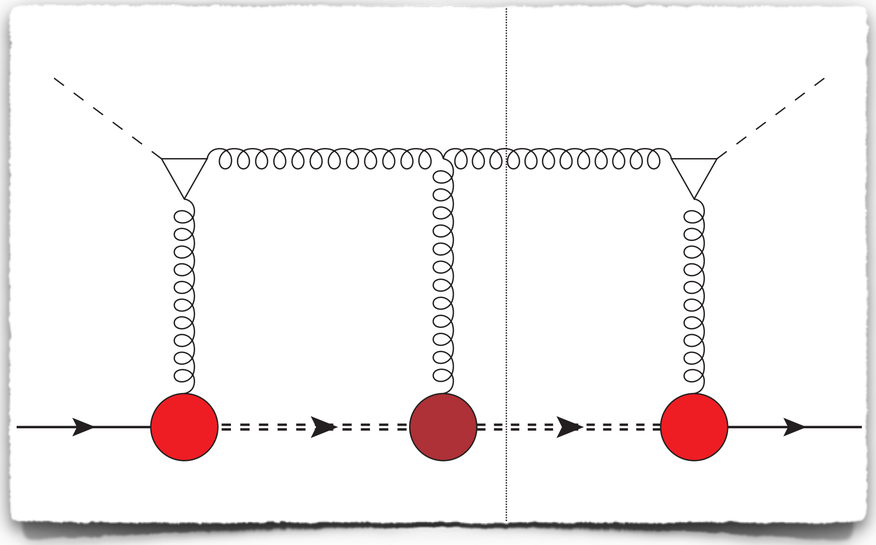


Photon-jet emission $\Rightarrow$ d-type $[+,-]$

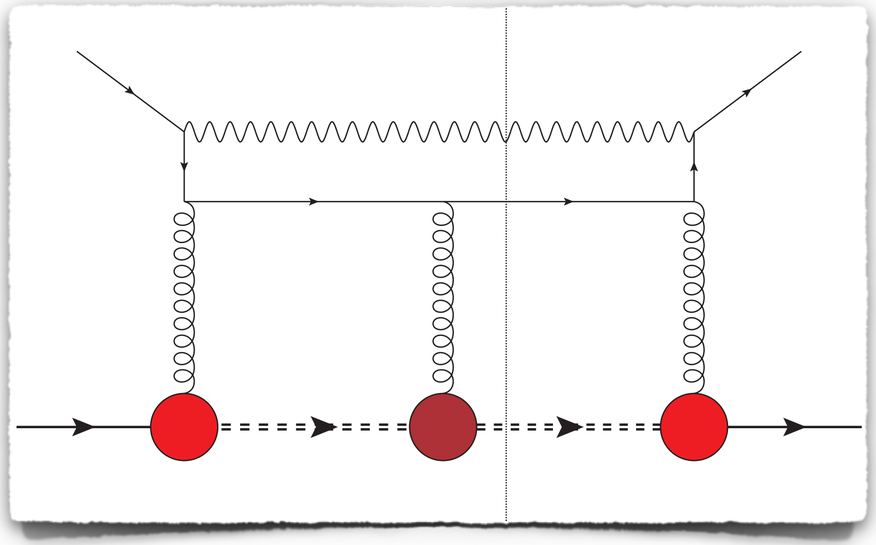


T-odd gluon TMD PDFs in a spectator model

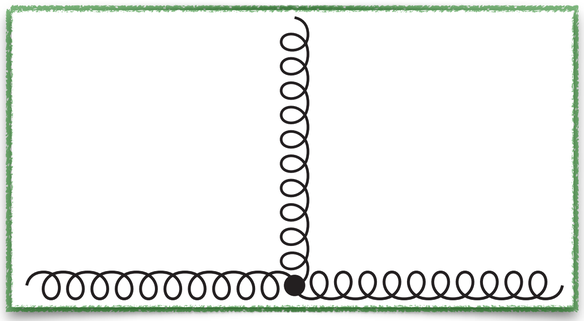
Higgs-gluon fusion $\Rightarrow$ f-type $[+,+]$



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



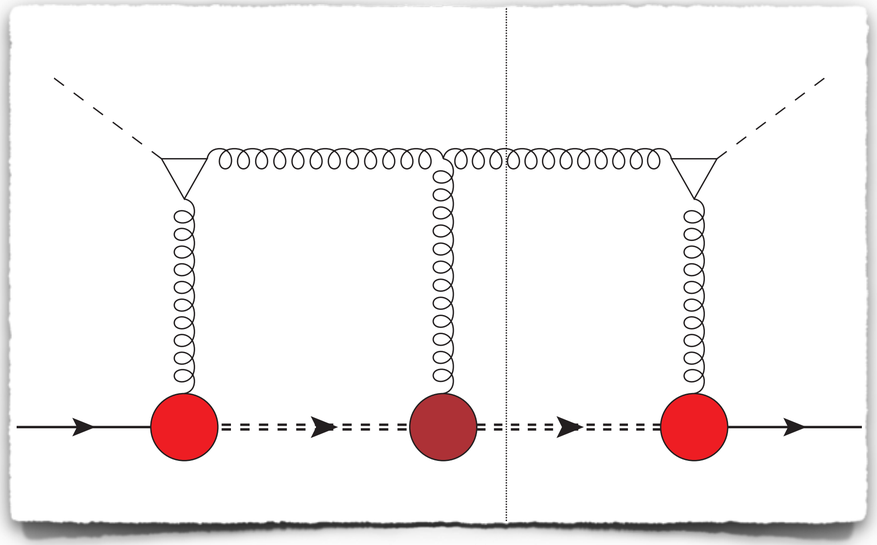
* If the model were pQCD, say a gluon-target model…



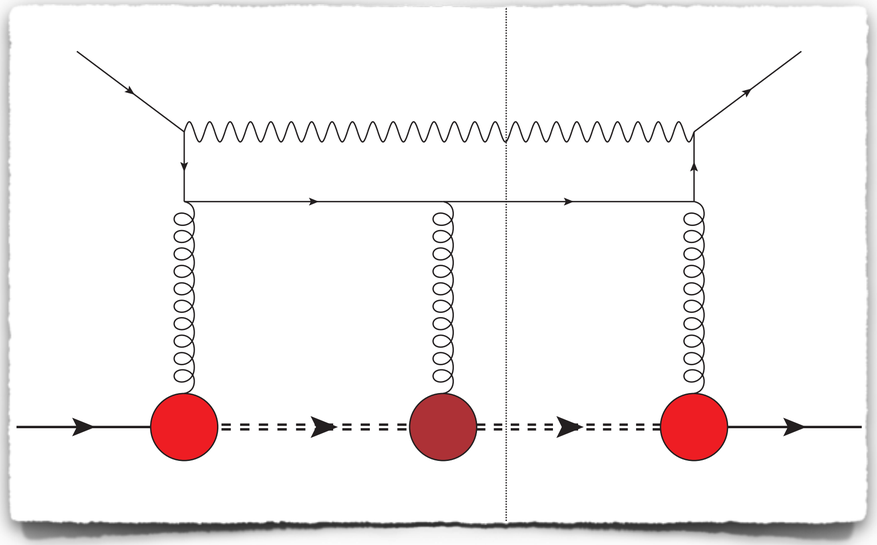
$$-g_s f_{abc}$$

T-odd gluon TMD PDFs in a spectator model

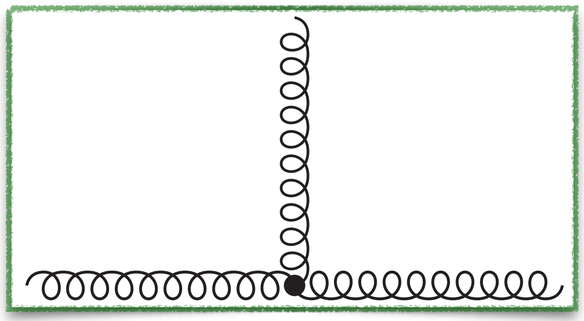
Higgs-gluon fusion $\Rightarrow$ f-type $[+,+]$



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

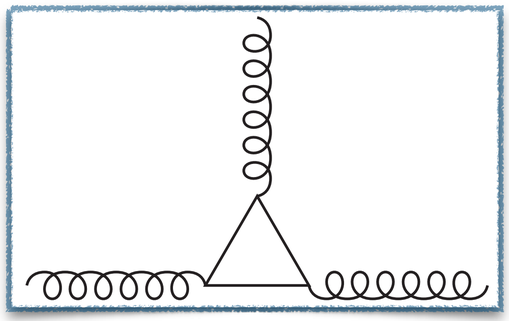


* If the model were pQCD, say a gluon-target model...



$$-g_s f_{abc}$$

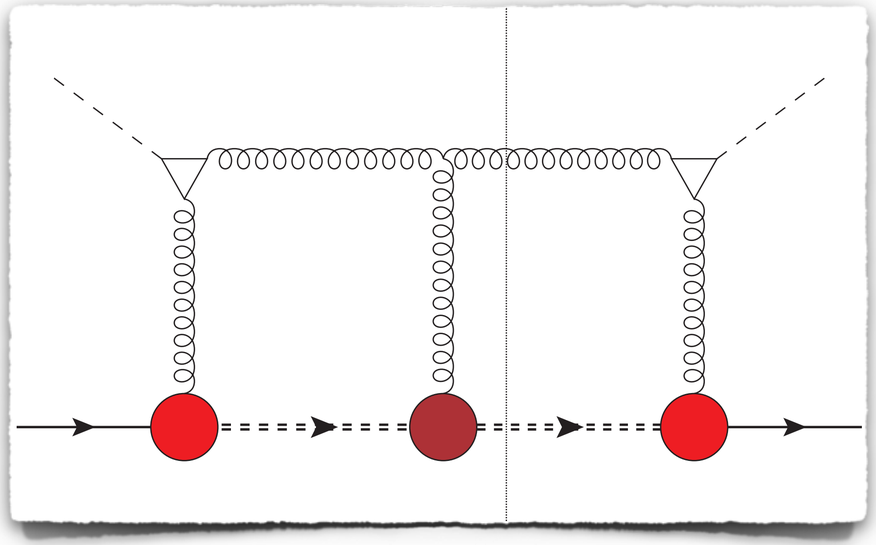
$$i g_s^3 d_{abc}$$



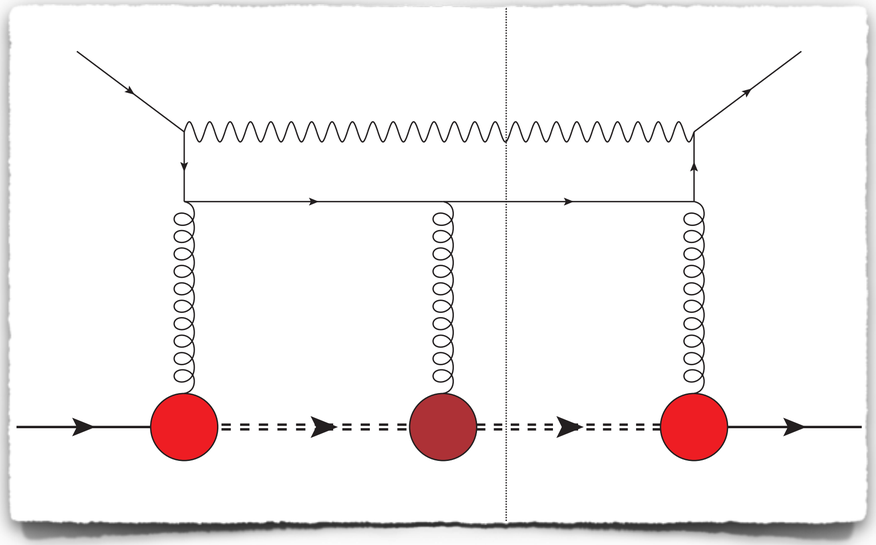
$-i t_a$ $-i t_b$ $-i t_c$

T-odd gluon TMD PDFs in a spectator model

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



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



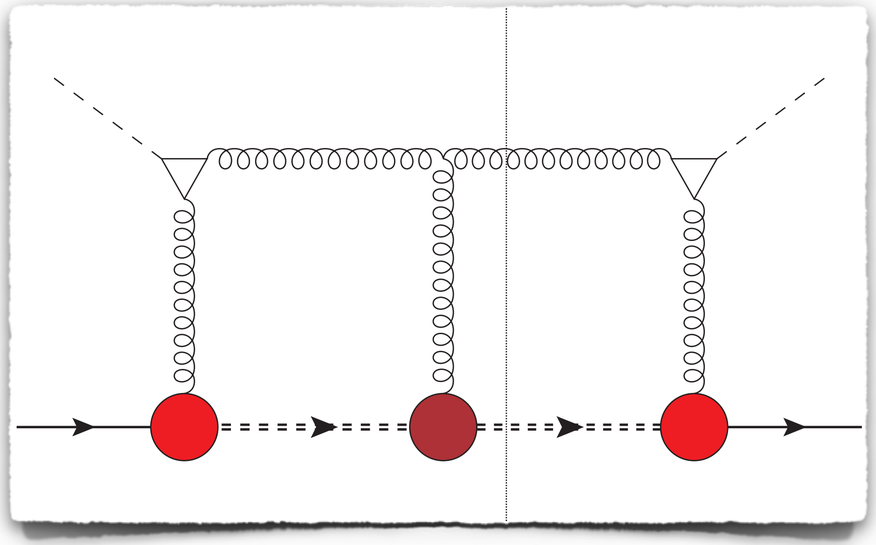
* If the model were pQCD, say a gluon-target model…

¡ …but the model is not pQCD !

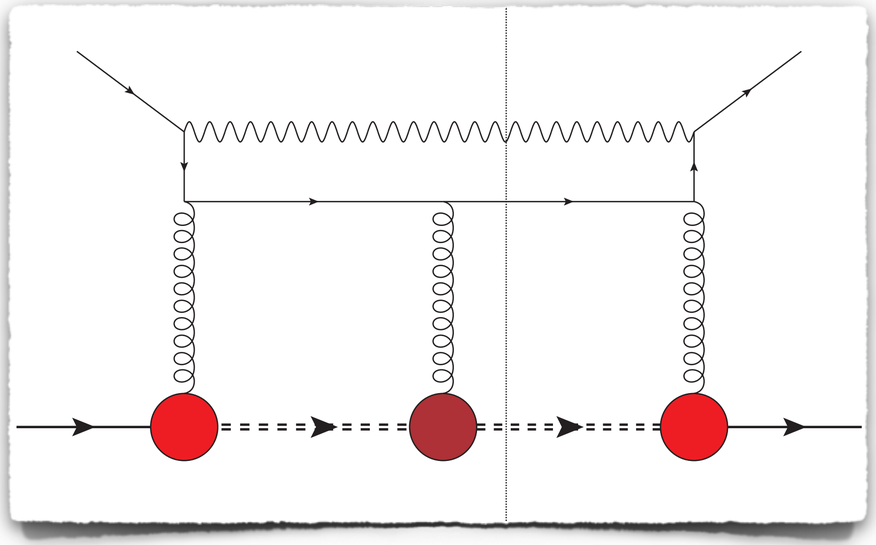
We want to model the nonperturbative content of T-odd TMD PDFs

T-odd gluon TMD PDFs in a spectator model

Higgs-gluon fusion ⇒ f-type [+ , +]



Photon-jet emission ⇒ d-type [+ , –]



nucleon-gluon-spectator

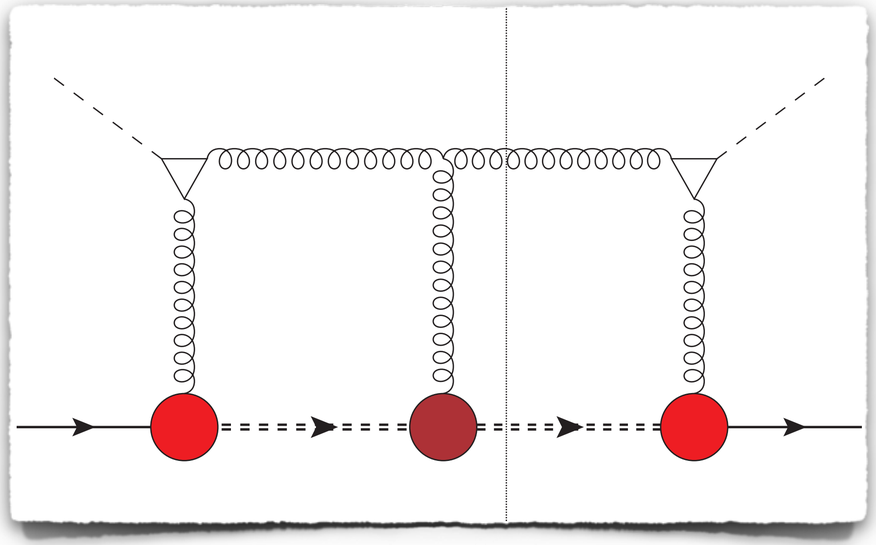
spectator-gluon-spectator

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

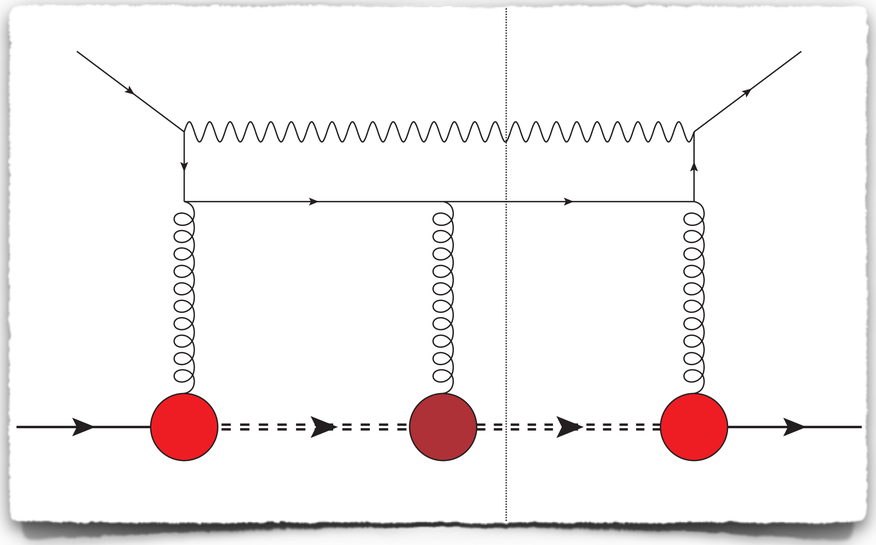
$$\mathcal{X}^{\mu}_{abc}(p^2) = f^{abc}\left[g^f_1(p^2)\,\gamma^\mu + g^f_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right] - i\,d^{abc}\left[g^d_1(p^2)\,\gamma^\mu + g^d_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$$

T-odd gluon TMD PDFs in a spectator model

Higgs-gluon fusion ⇒ f-type [+ , +]



Photon-jet emission ⇒ d-type [+ , –]



nucleon-gluon-spectator

spectator-gluon-spectator

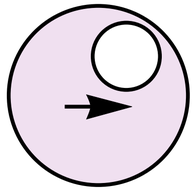
$$\mathcal{Y}^{\mu}_{bc}(p^2) = \delta_{bc}\left[g_1(p^2)\,\gamma_\mu + g_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$$

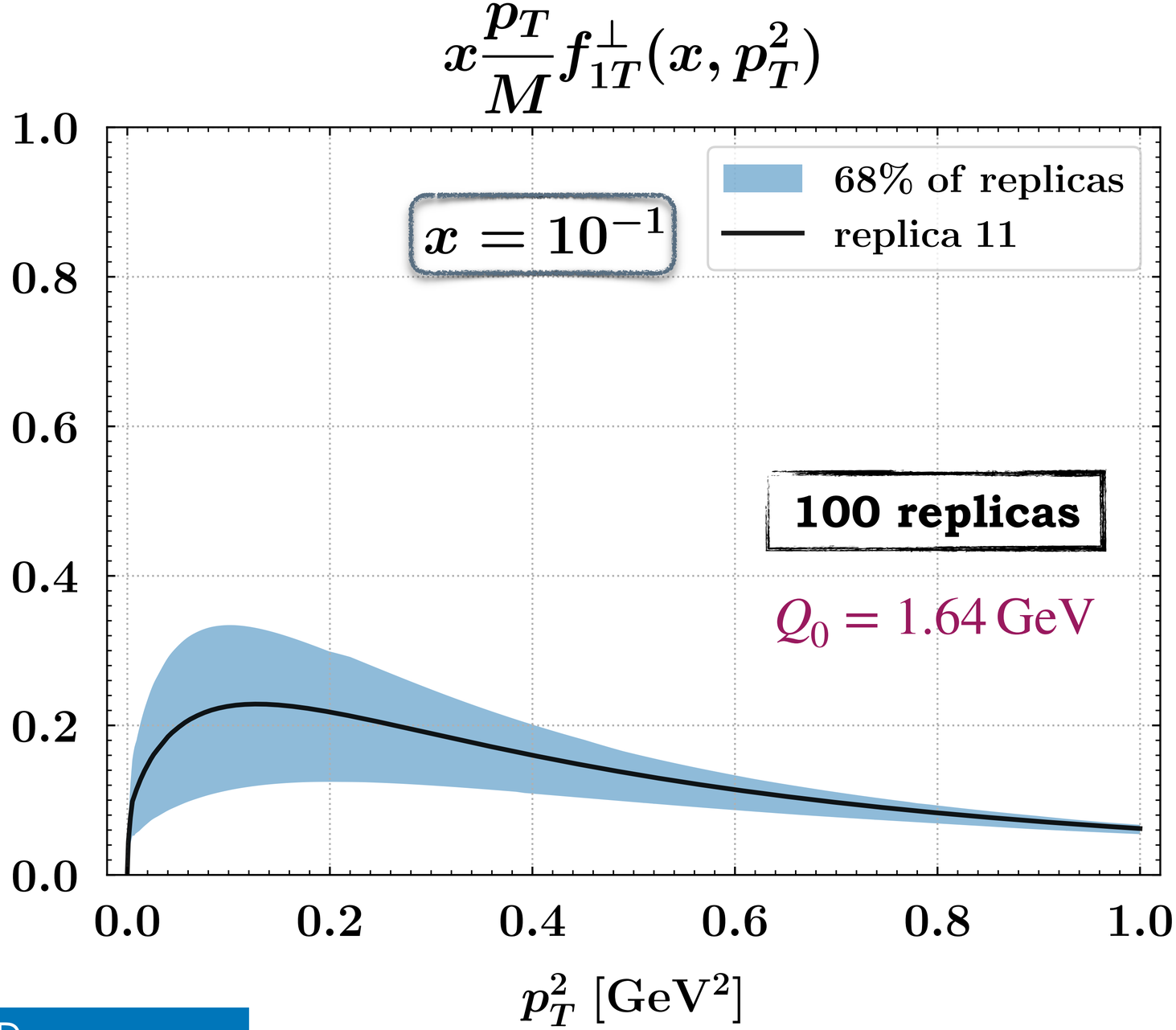
$$\mathcal{X}^{\mu}_{abc}(p^2) = f^{abc}\left[g^f_1(p^2)\,\gamma^\mu + g^f_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right] - i\,d^{abc}\left[g^d_1(p^2)\,\gamma^\mu + g^d_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$$

Assumption: $g^d_{1,2}(p^2) = g^f_{1,2}(p^2) \equiv g_{1,2}(p^2)$ $\Leftrightarrow$ $f_{1T}^{\perp[+,-]} = \frac{c_{[+,-]}}{c_{[+,+]}} f_{1T}^{\perp[+,+]} \equiv \frac{10}{18} f_{1T}^{\perp[+,+]}$

f-type Sivers gluon TMD

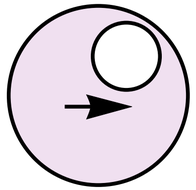
[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

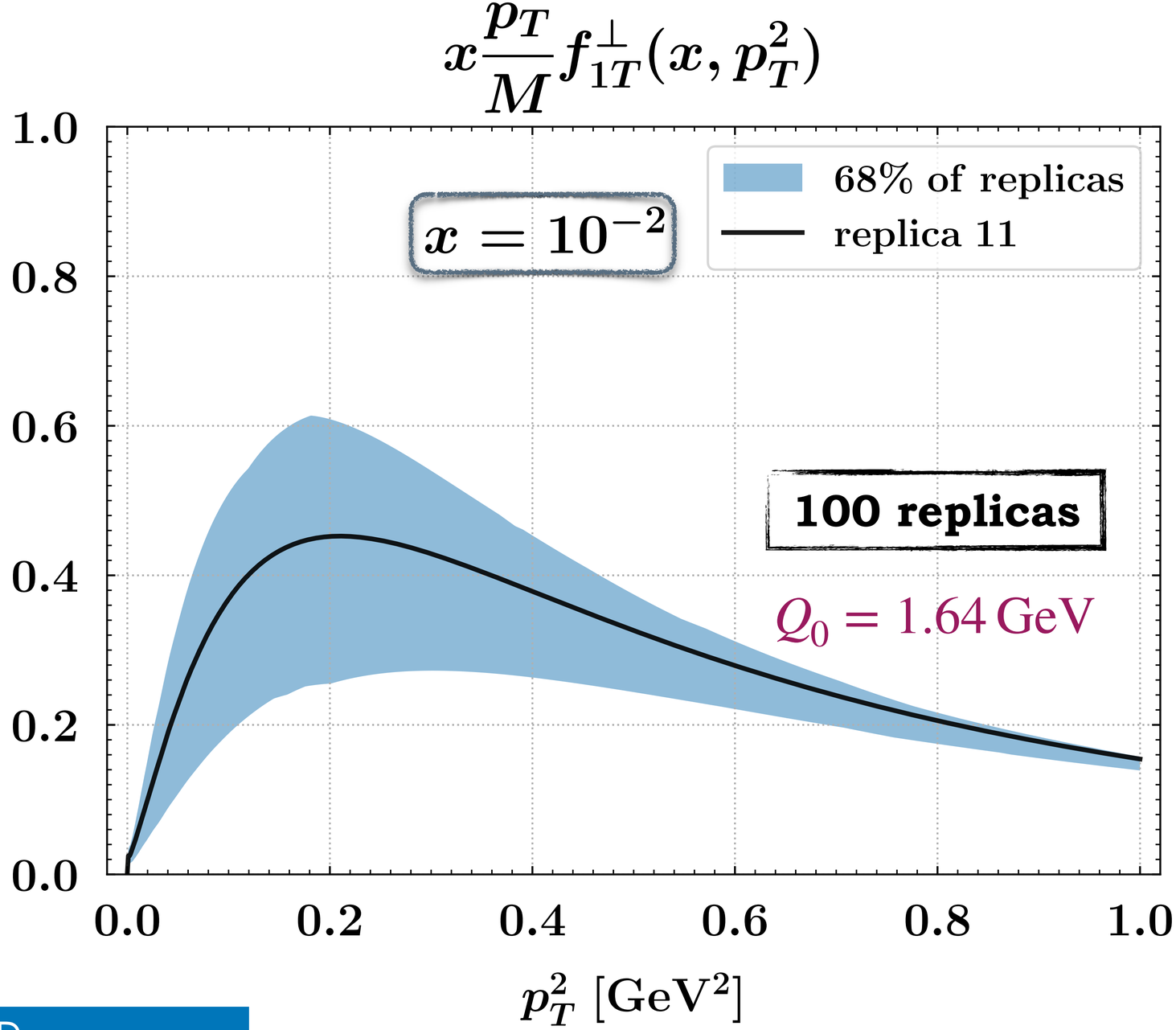




f-type Sivers gluon TMD

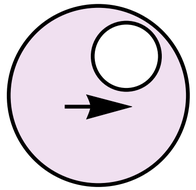
[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

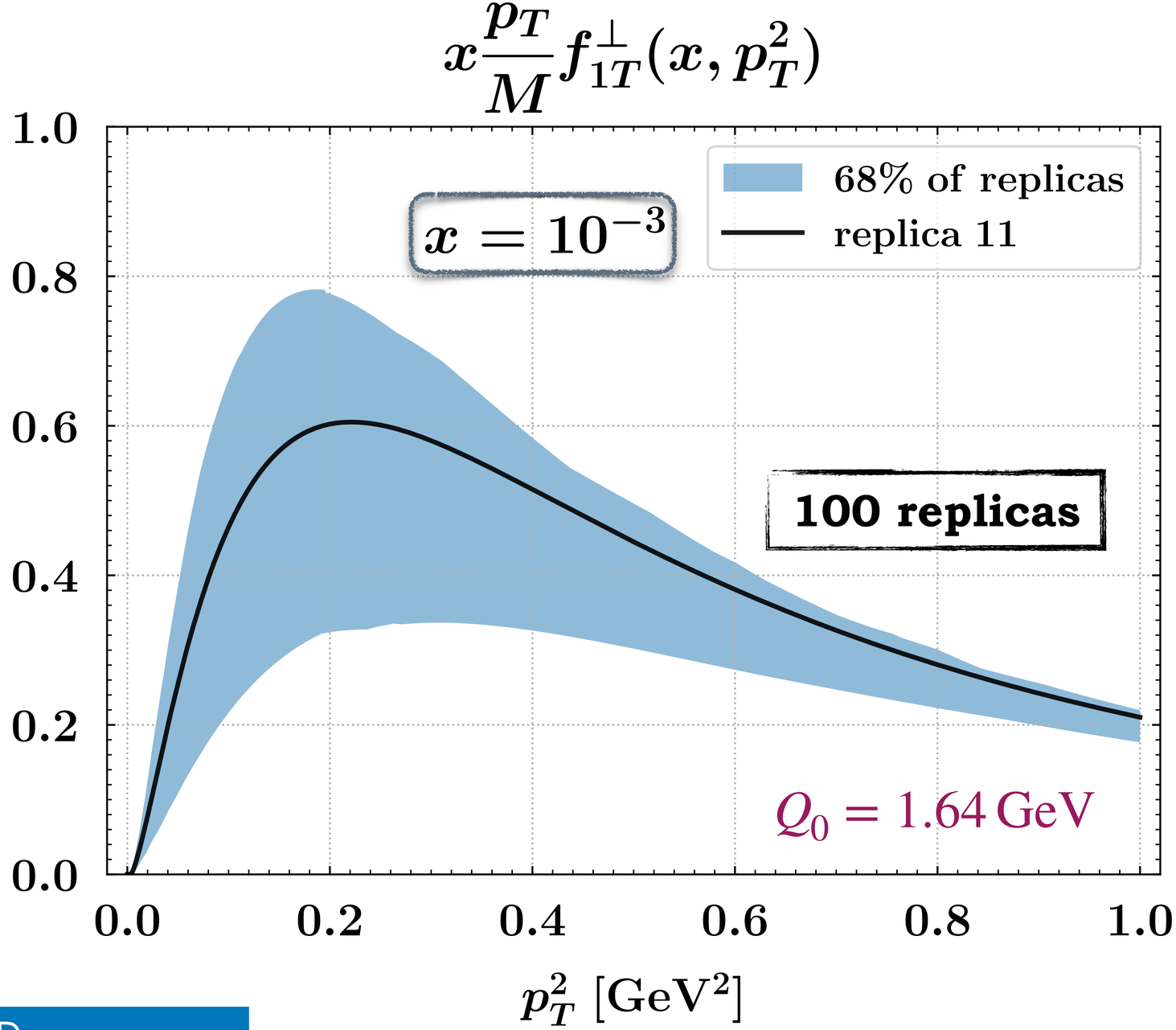




f-type Sivers gluon TMD

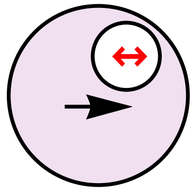
[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

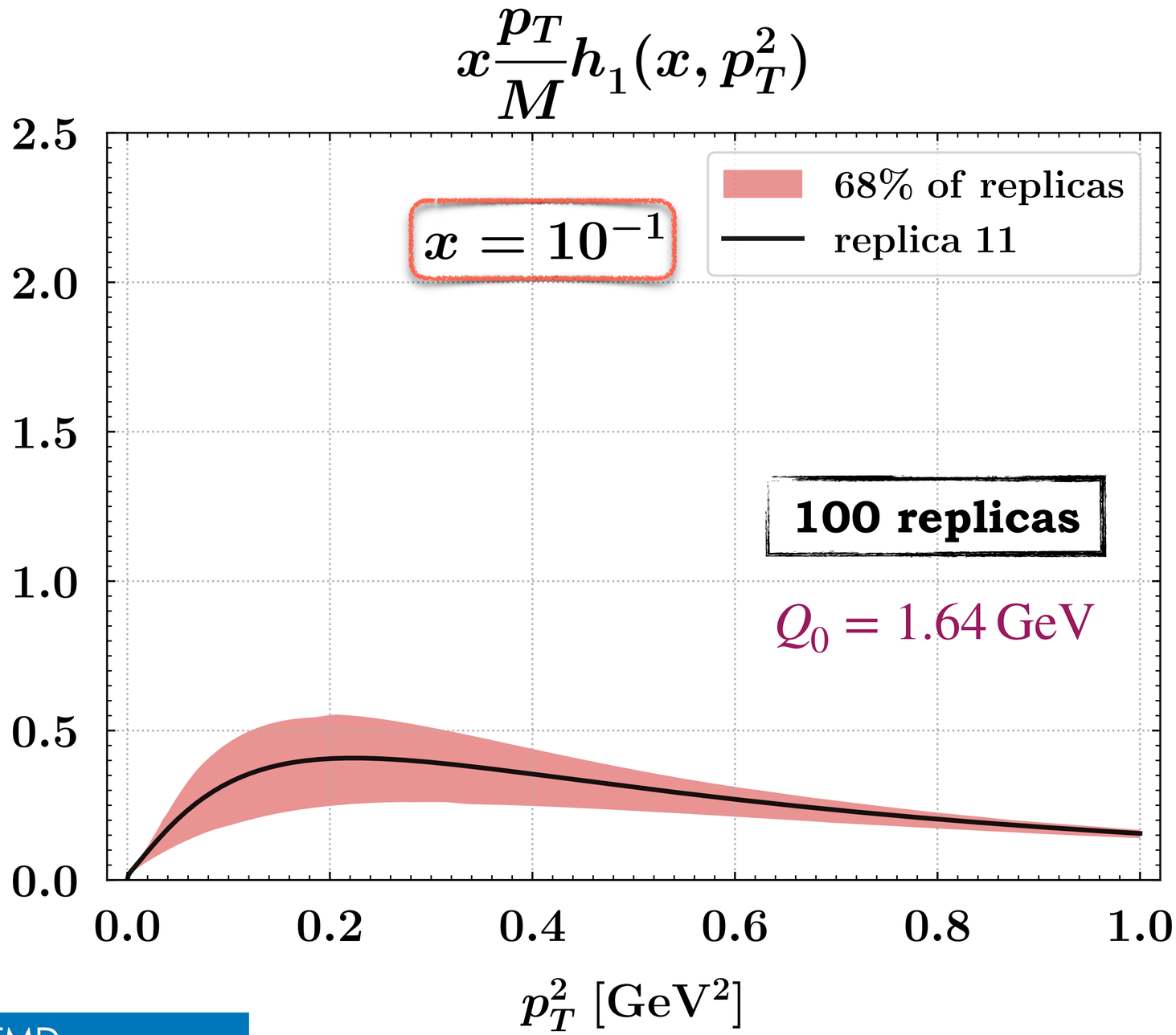




f-type linearity gluon TMD

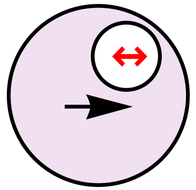
[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

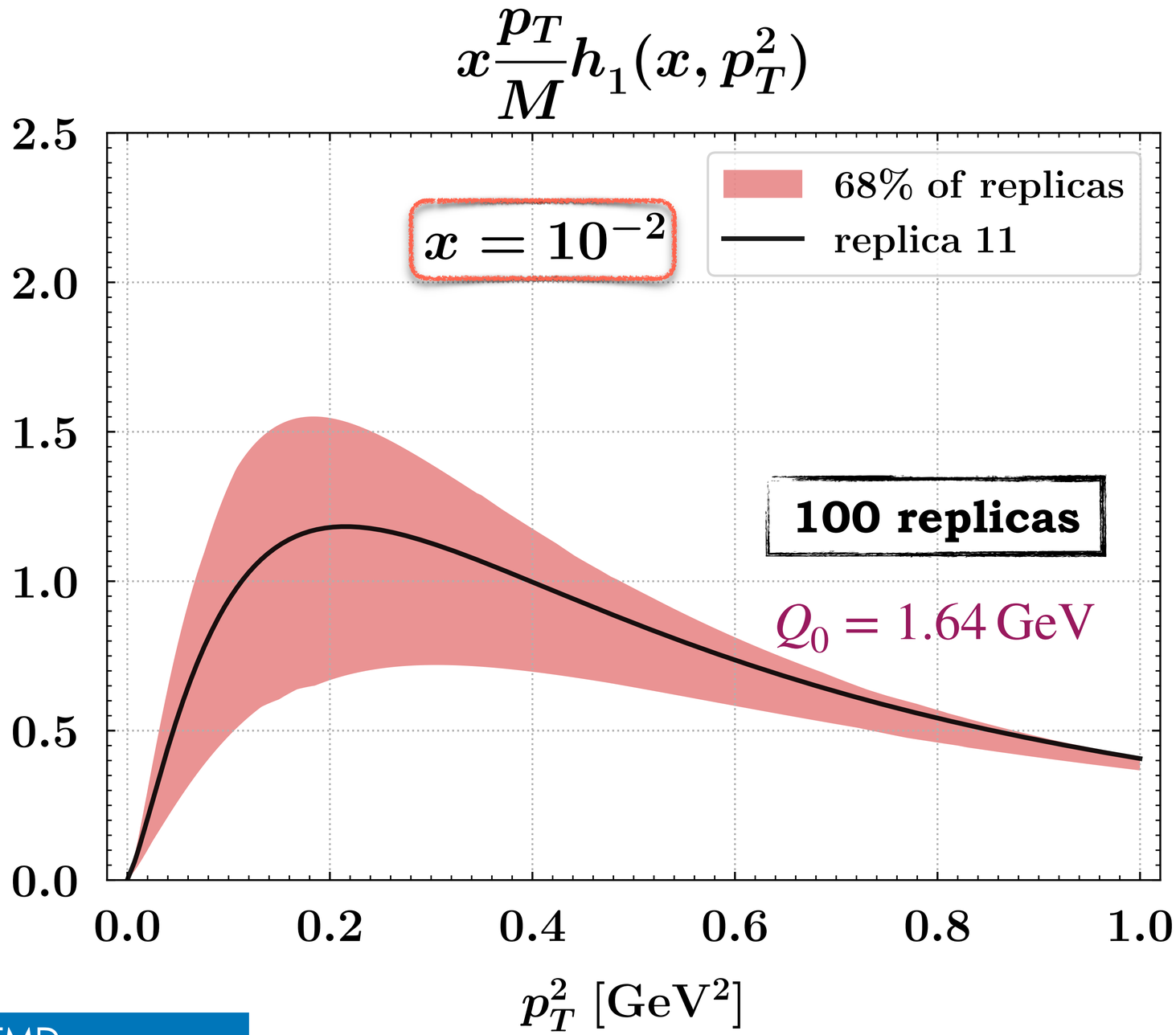




f-type linearity gluon TMD

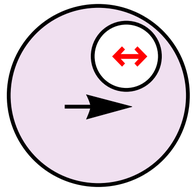
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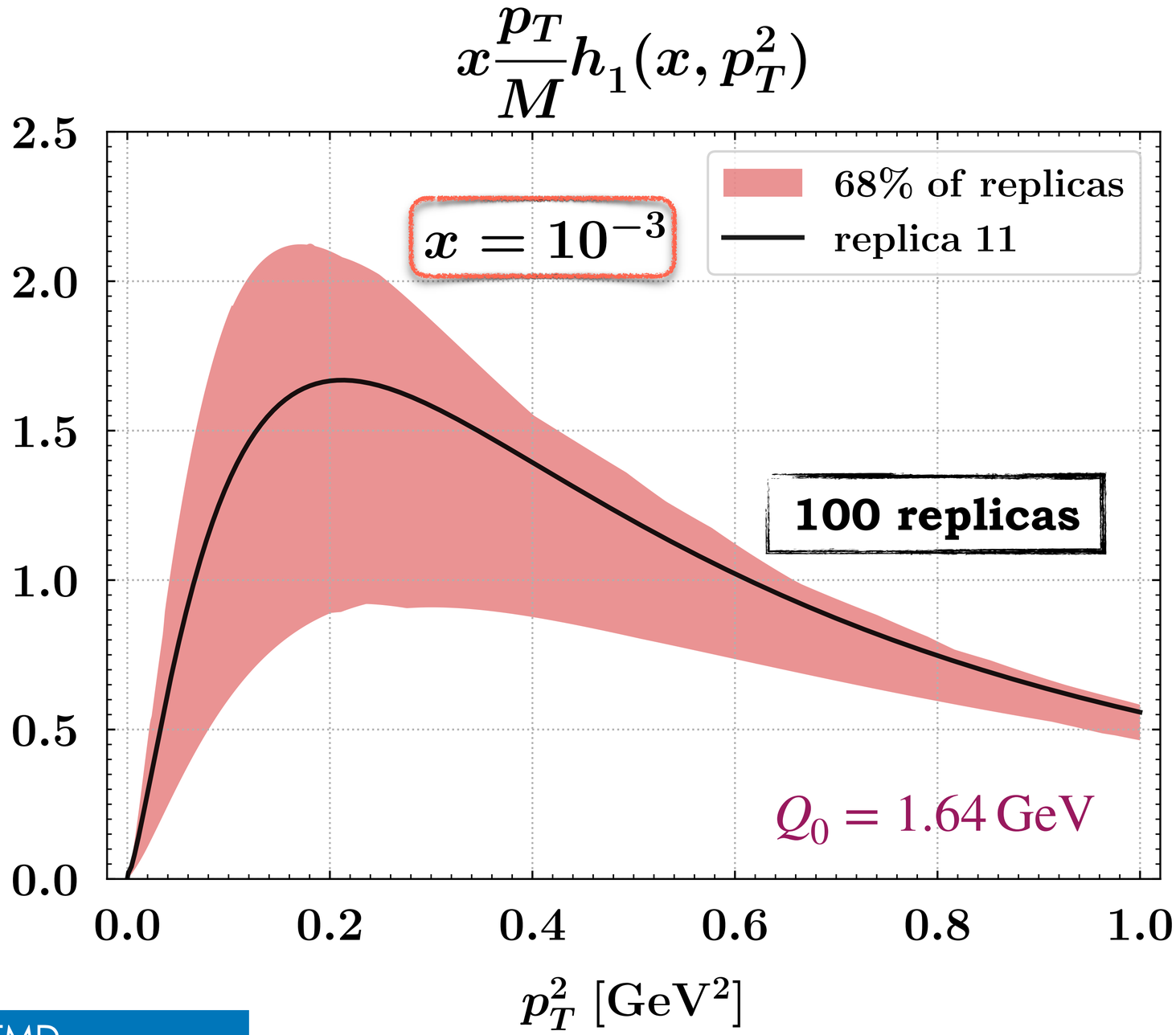




f-type linearity gluon TMD

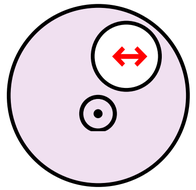
[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

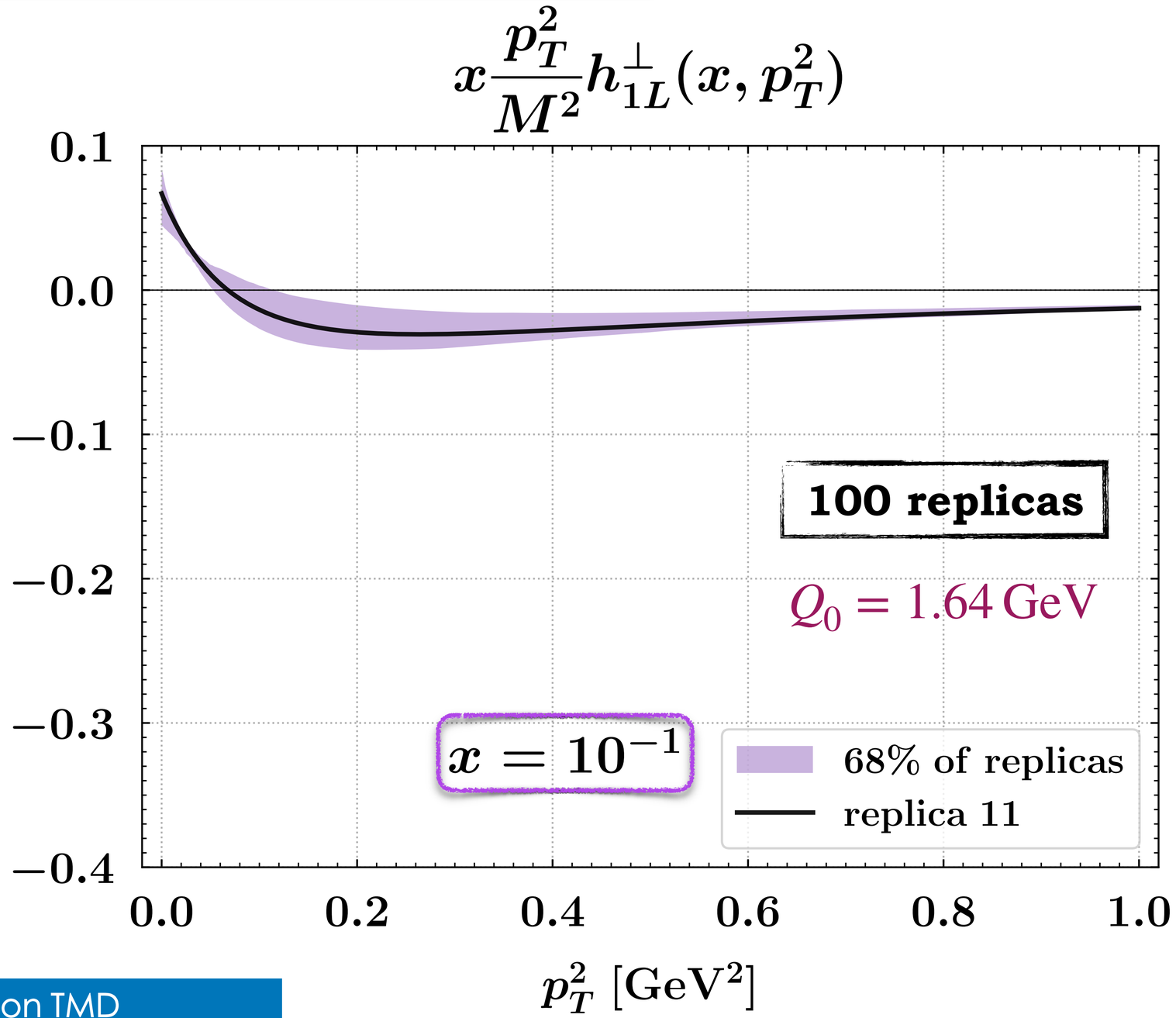




f-type propeller gluon TMD

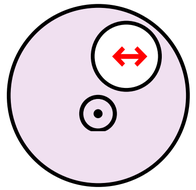
[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

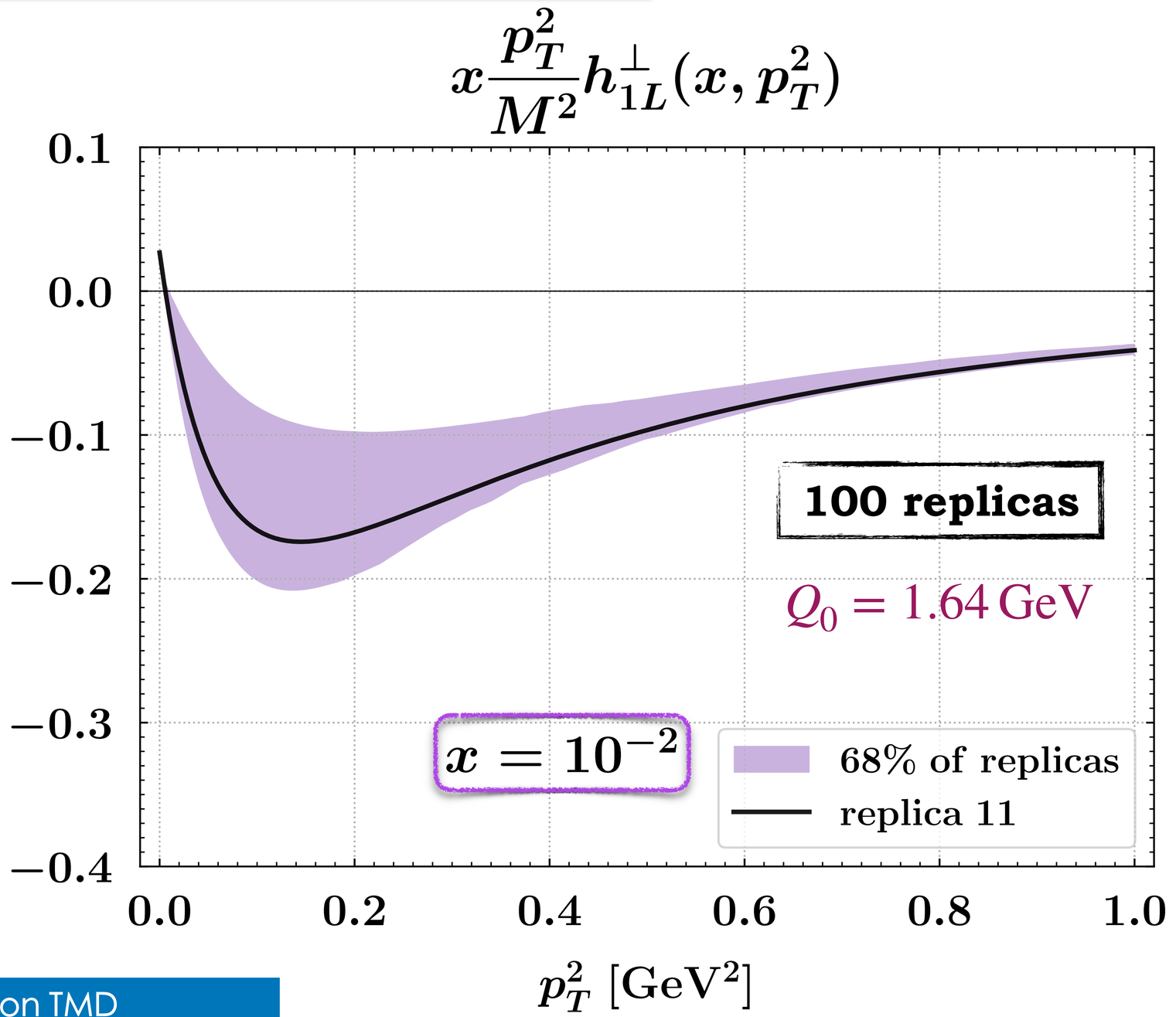




f-type propeller gluon TMD

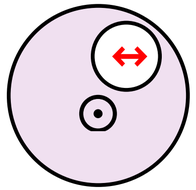
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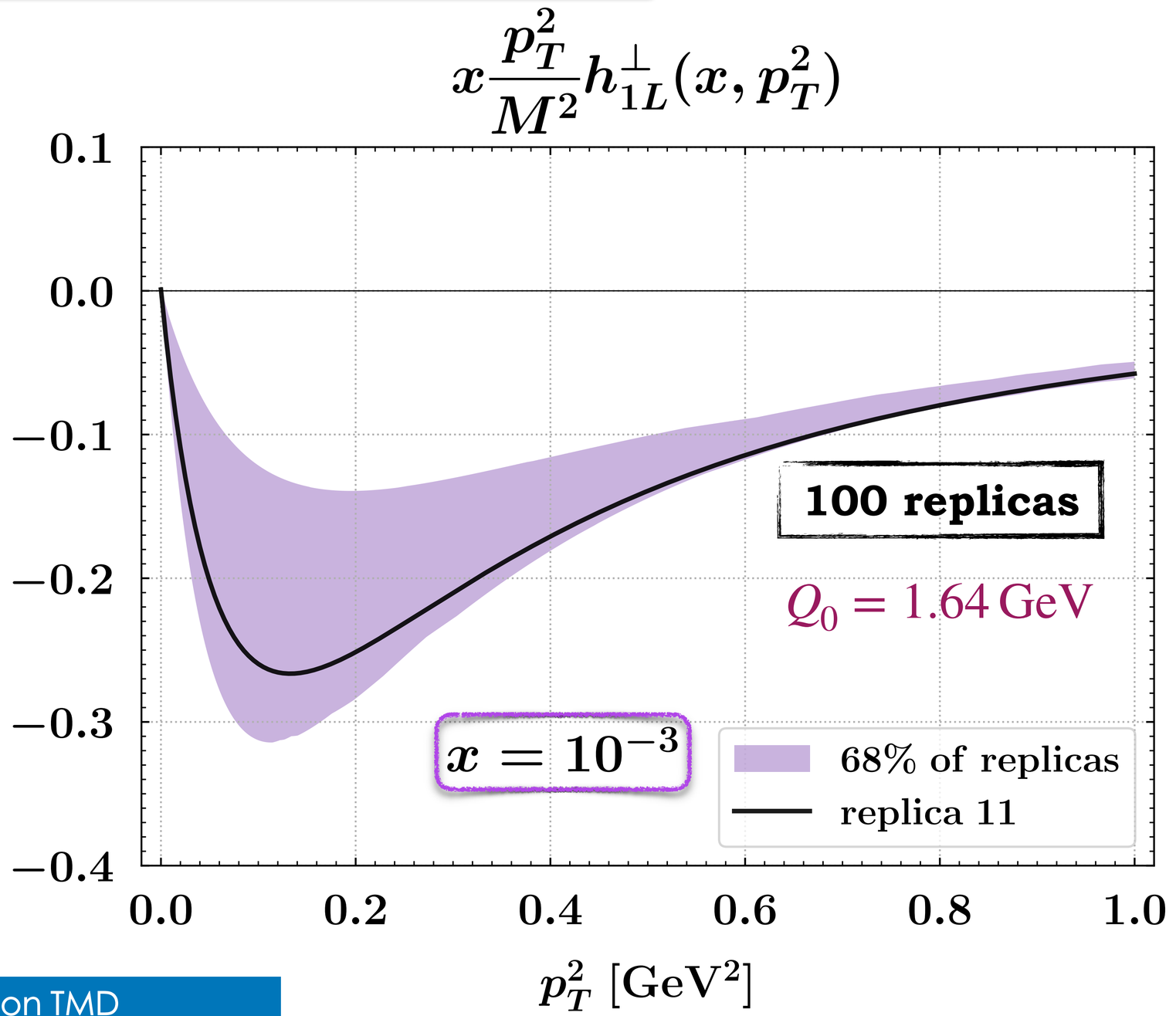




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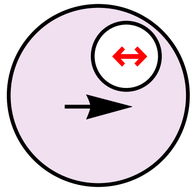
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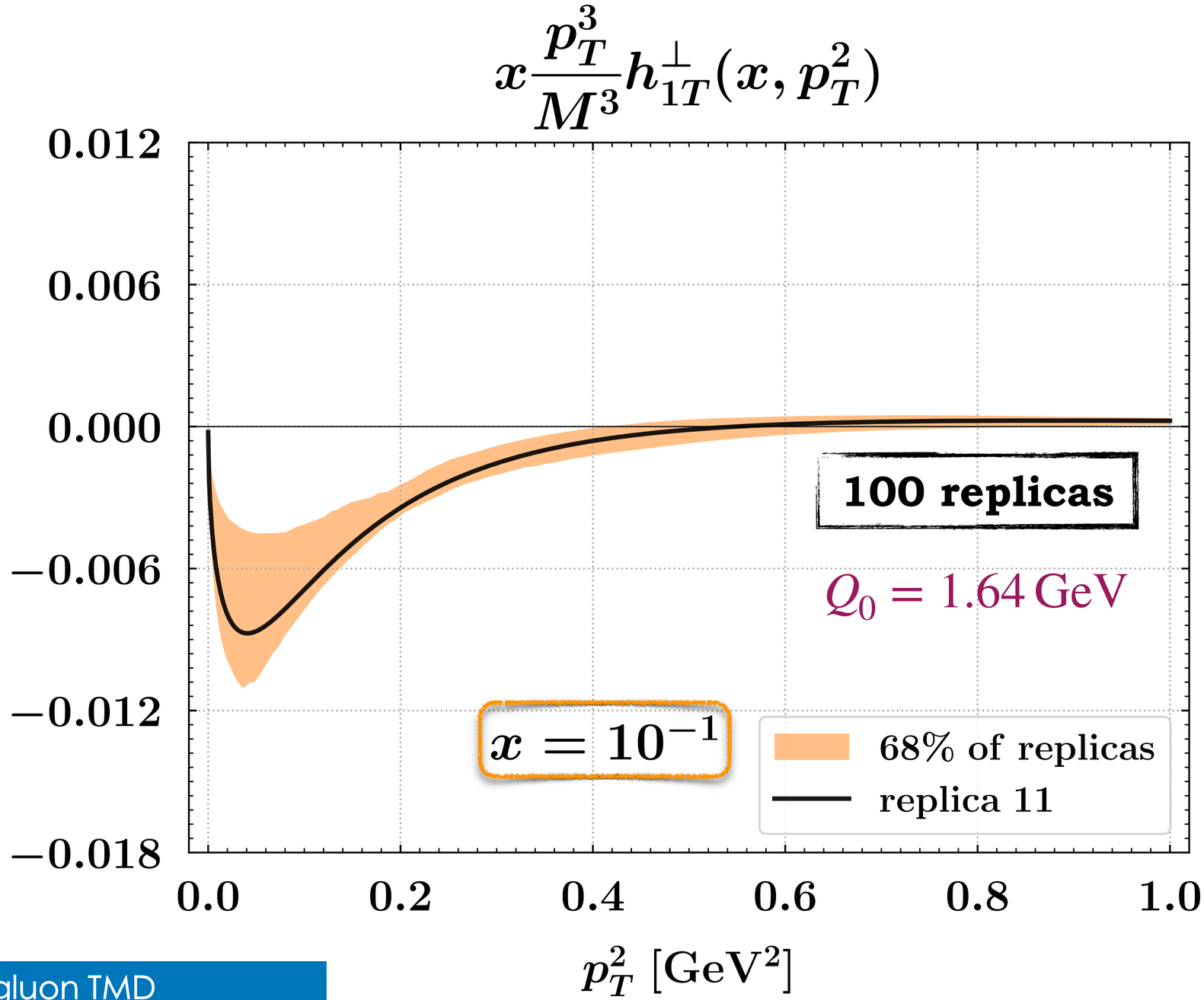




f-type butterfly gluon TMD

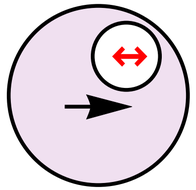
[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

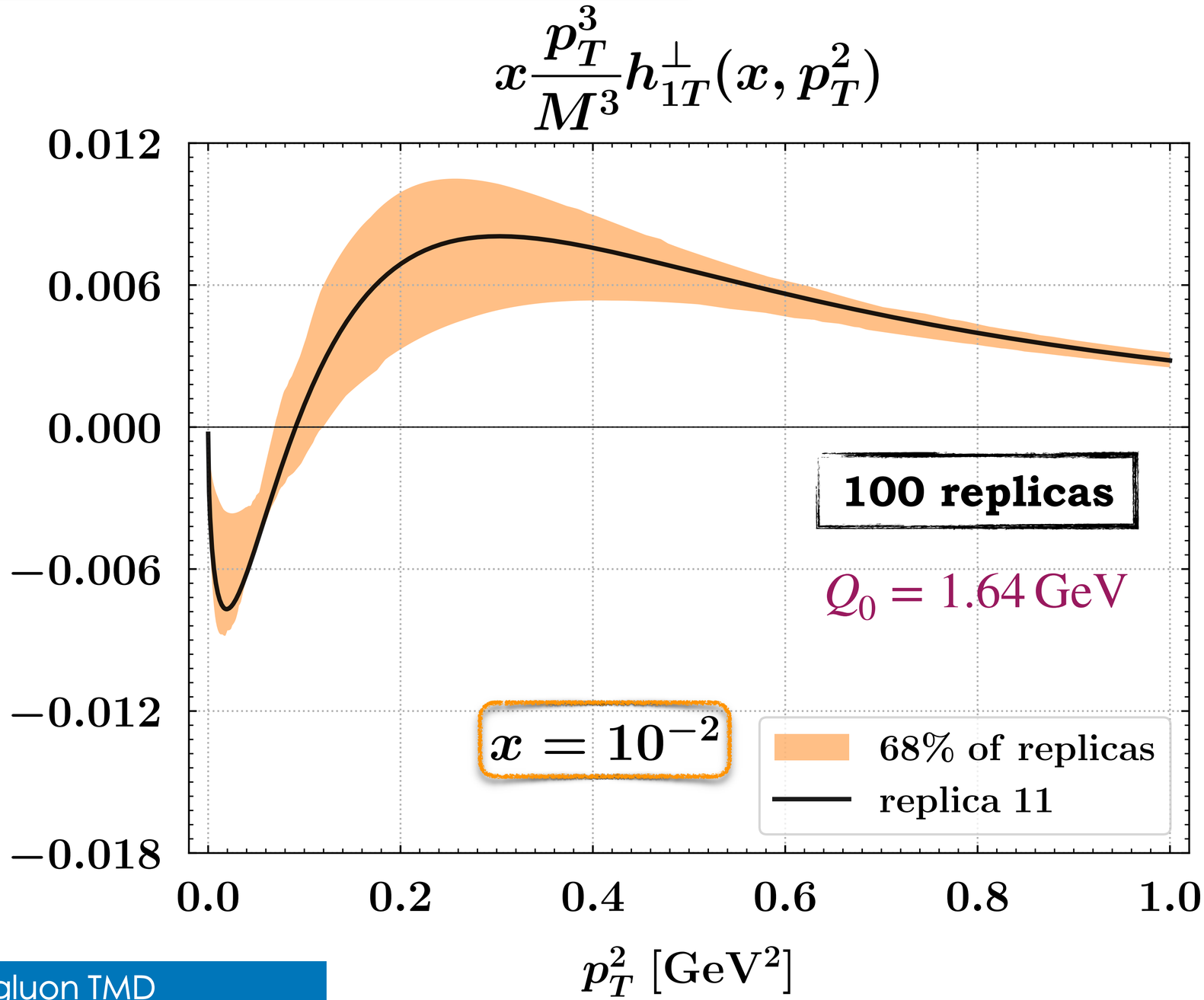




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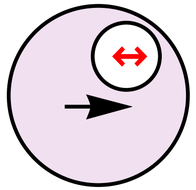
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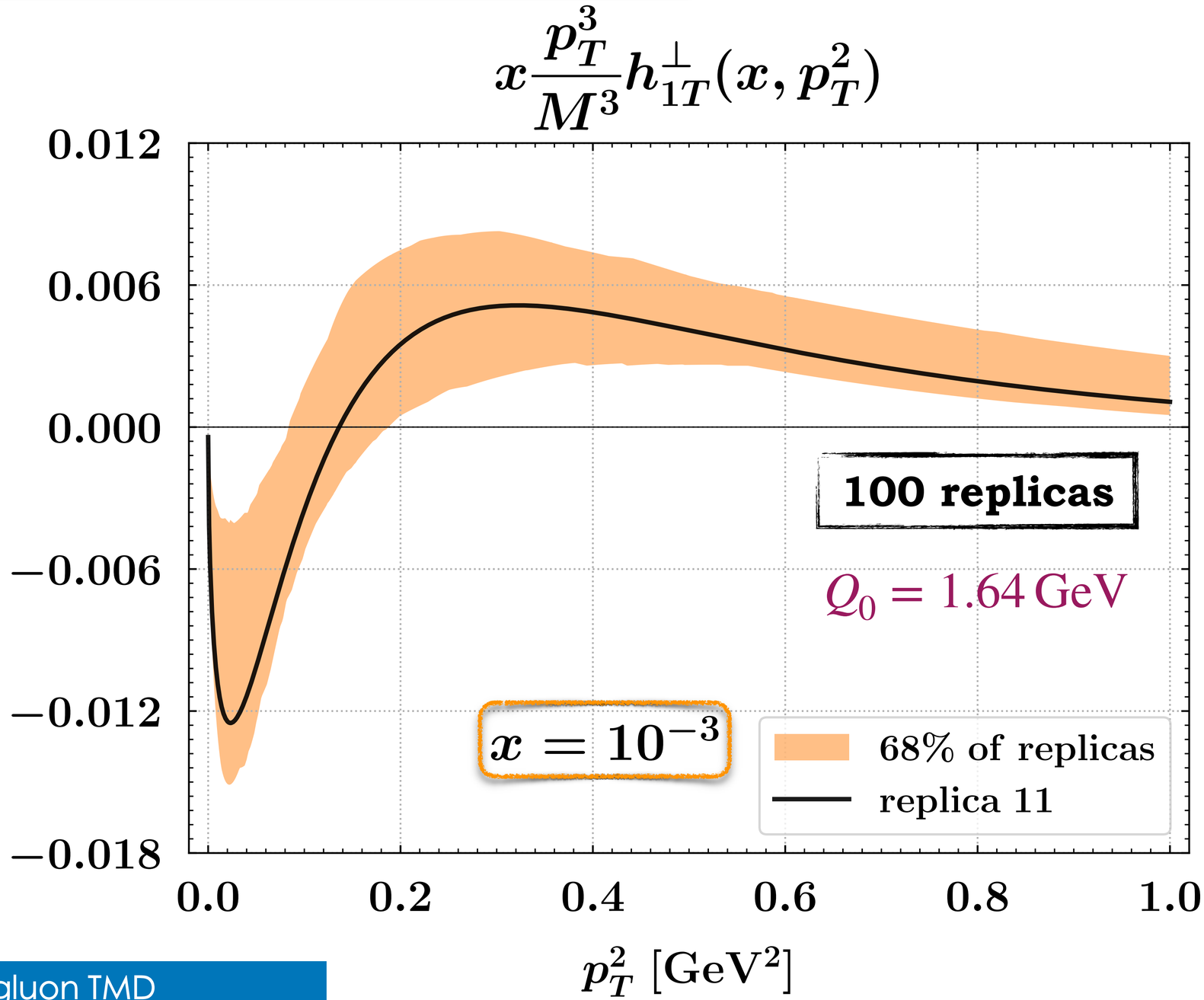




f-type butterfly gluon TMD

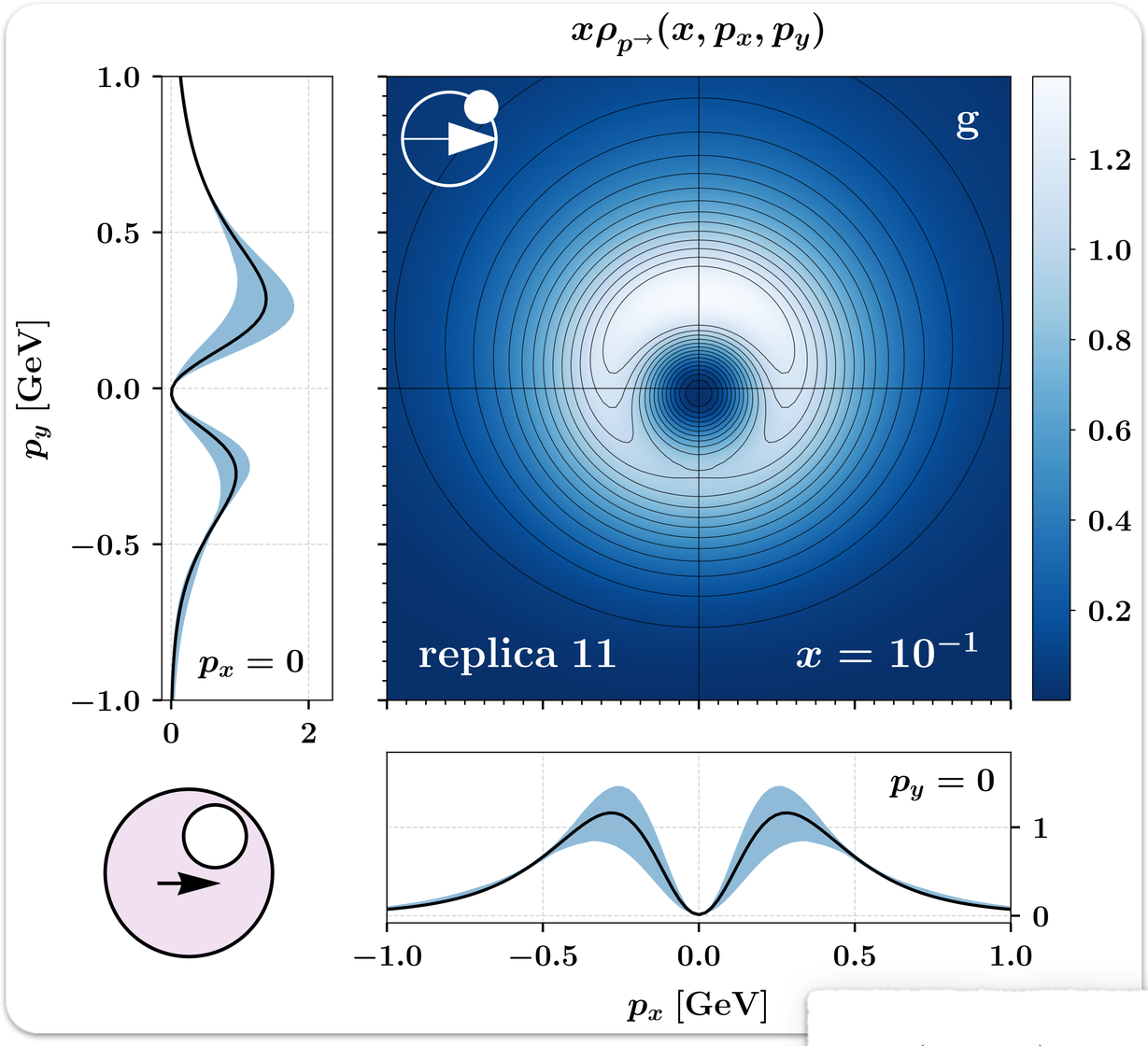
[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]





Gluon Sivers effect

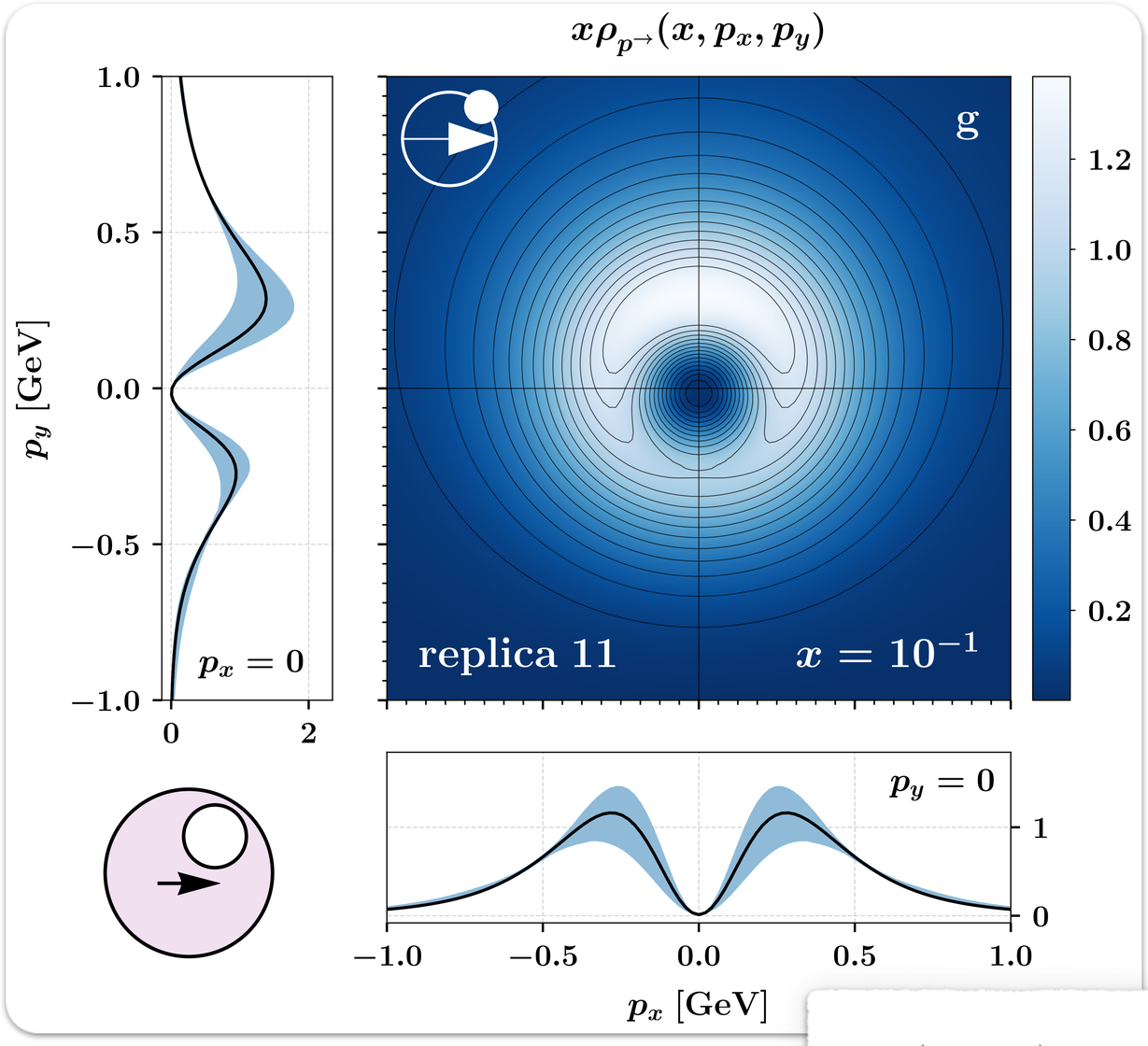
🔗 [A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

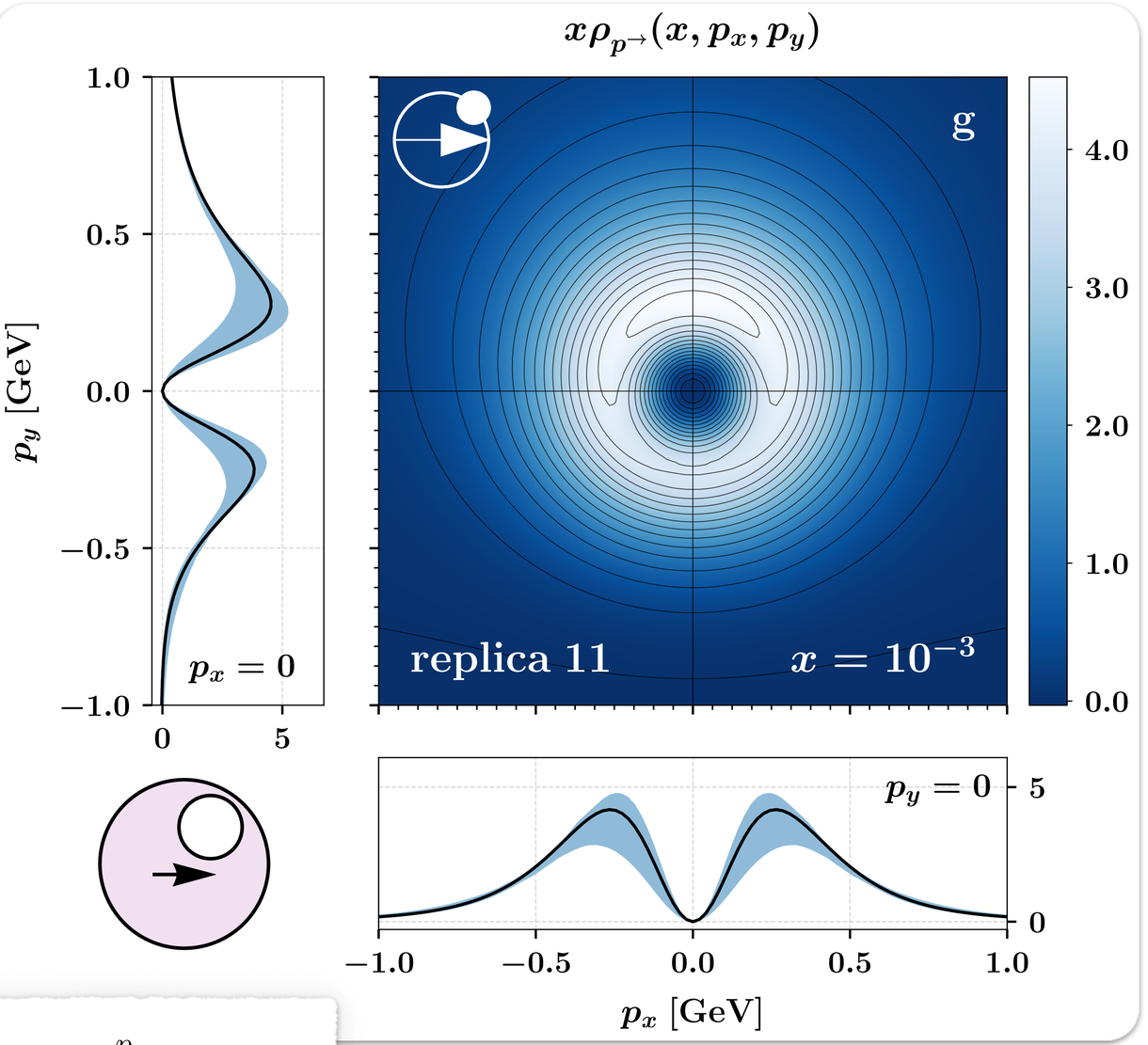


$$x\rho_{p^\rightarrow}(x, p_x, p_y) = x\, f_1(x, \boldsymbol{p}_T^2) + x\frac{p_y}{M}\, f_{1T}^\perp(x, \boldsymbol{p}_T^2)$$

Gluon Sivers effect

[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

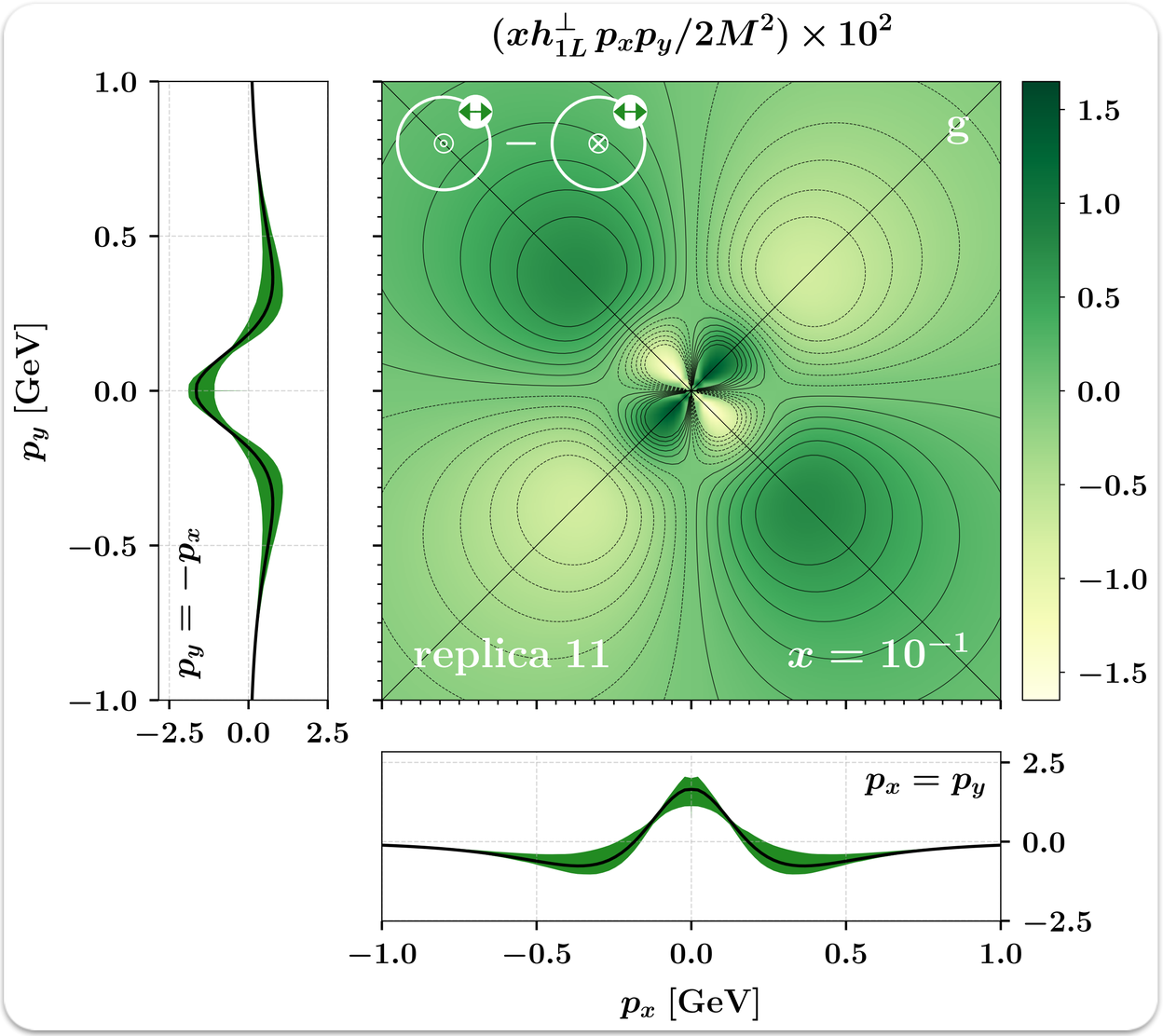


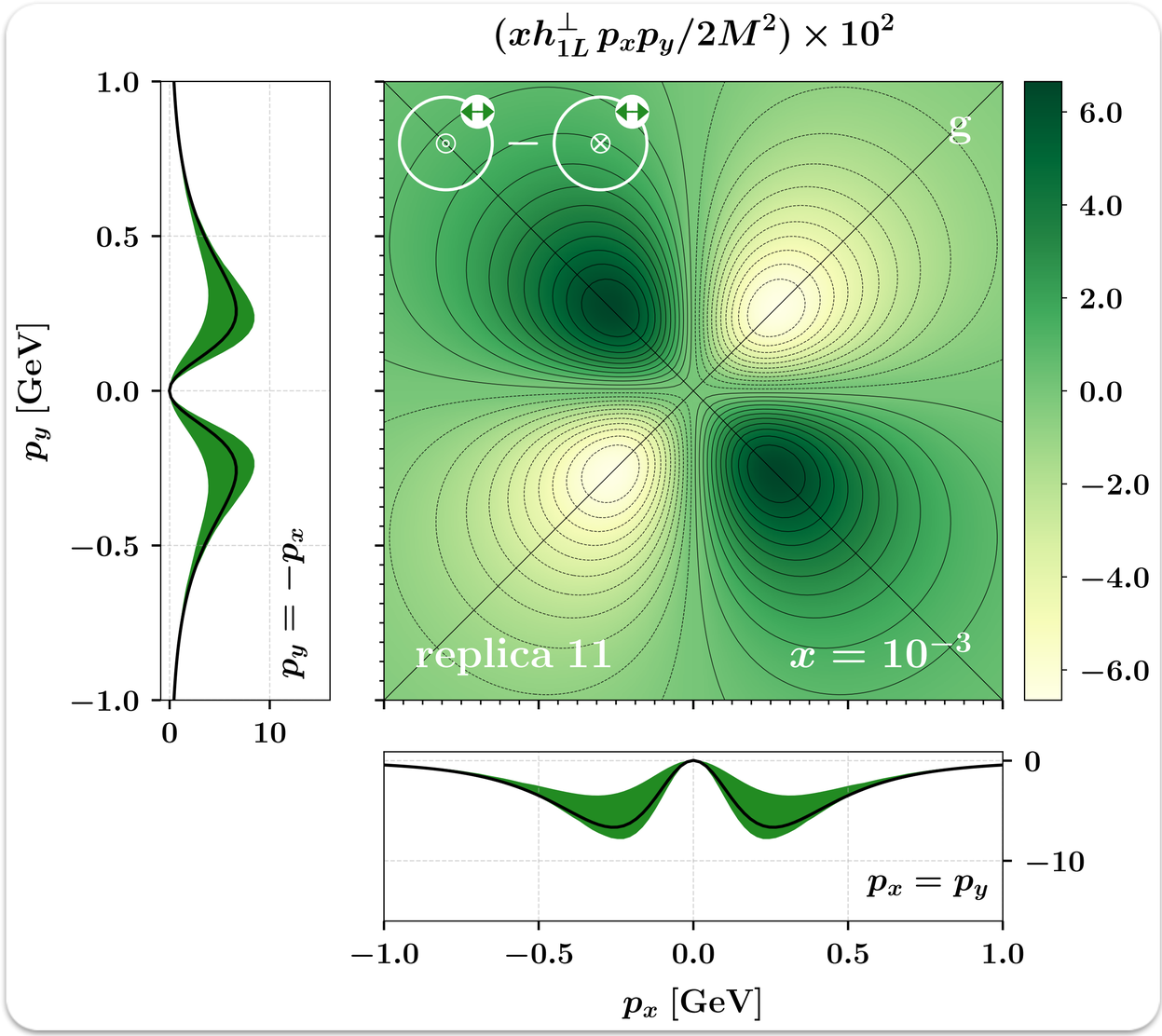


$$x\rho_{p^\rightarrow}(x, p_x, p_y) = x\, f_1(x, \boldsymbol{p}_T^2) + x\frac{p_y}{M}\, f_{1T}^\perp(x, \boldsymbol{p}_T^2)$$

Gluon propeller effect

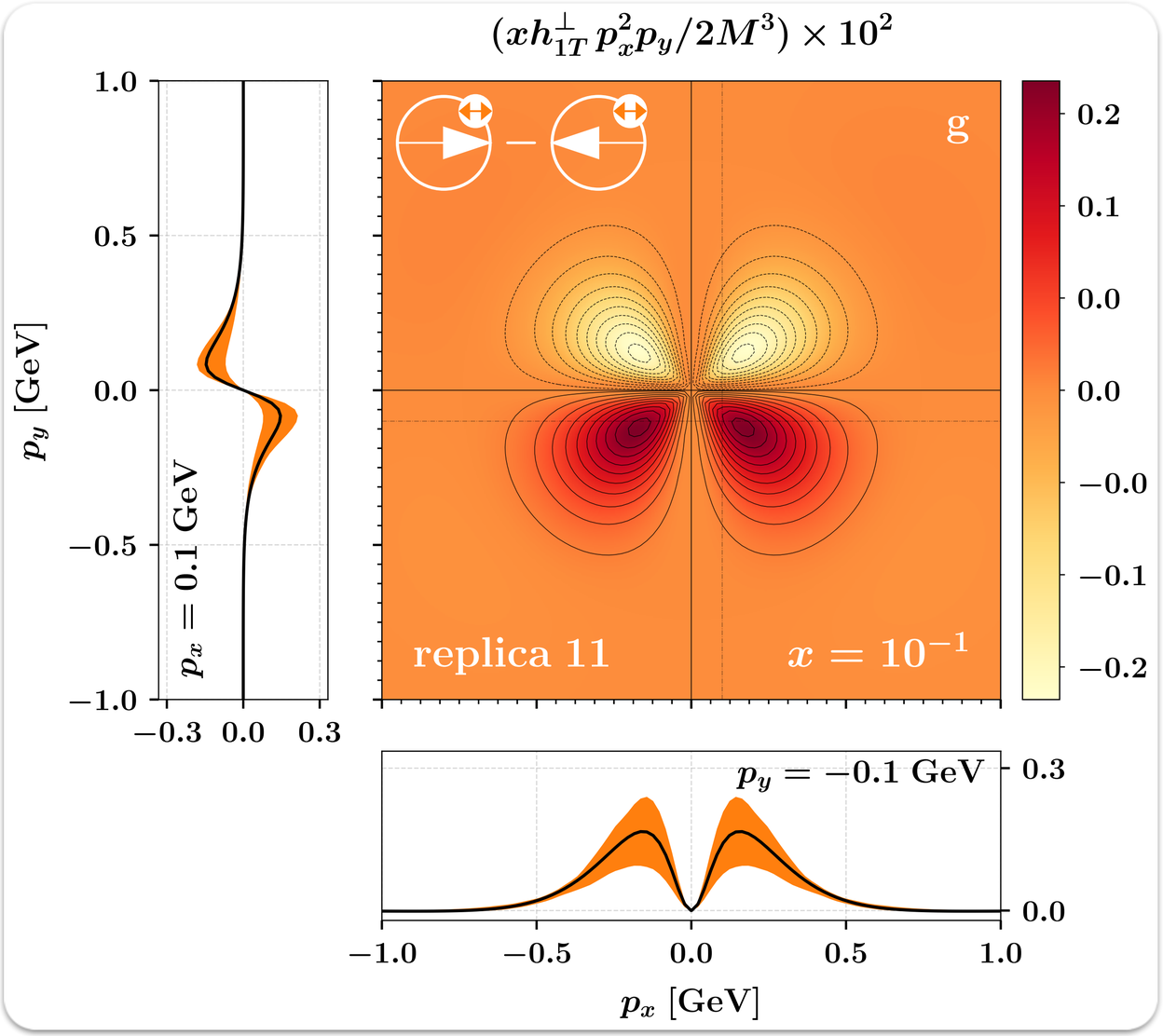
🔗 [A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

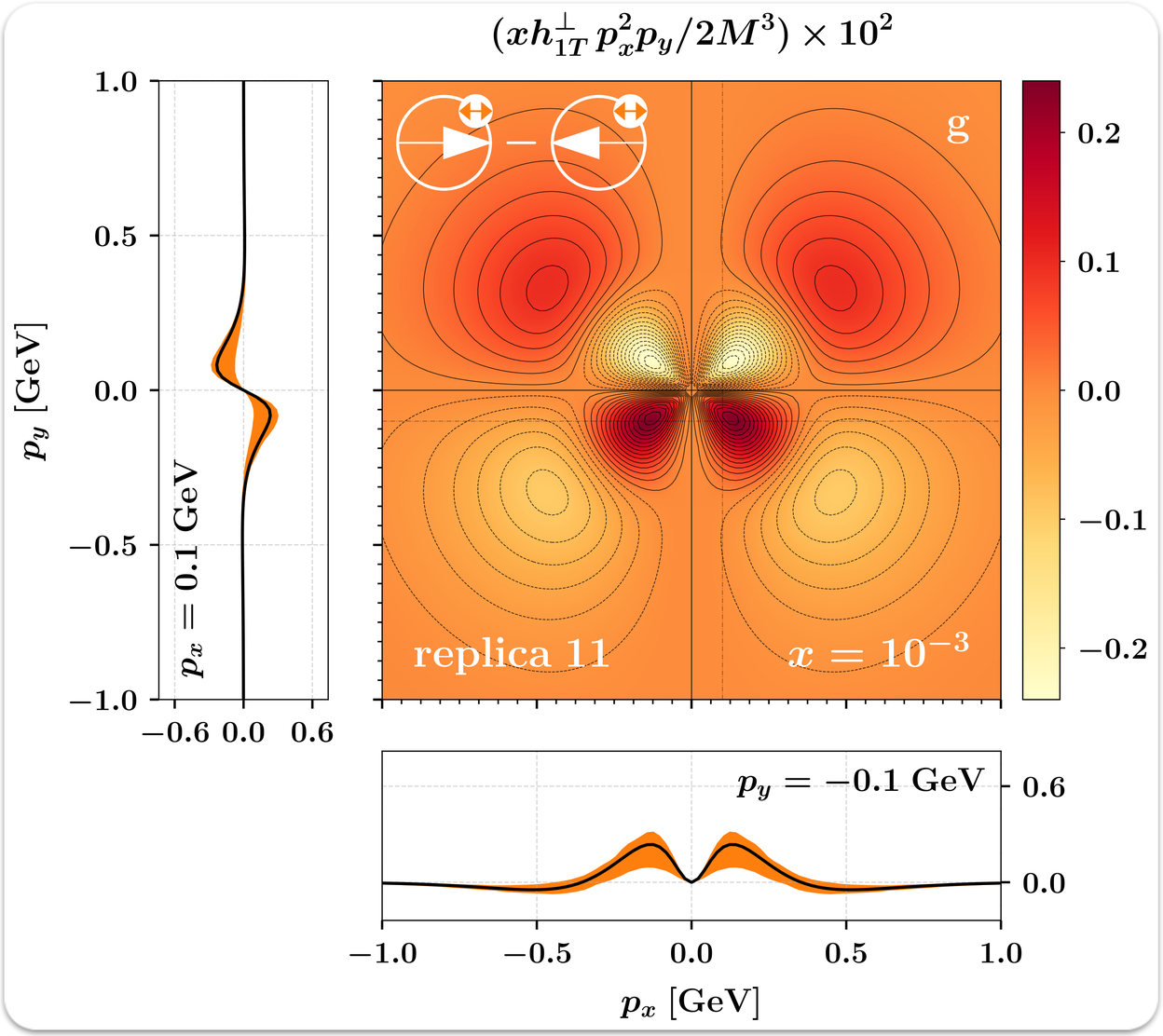




Gluon butterfly effect

[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]



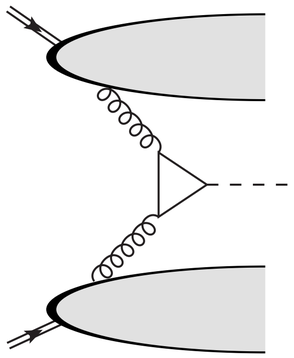


4. GLUON TMD PHENO OPPORTUNITIES



Gluon TMD pheno from the LHC to the EIC

Higgs in gluon fusion

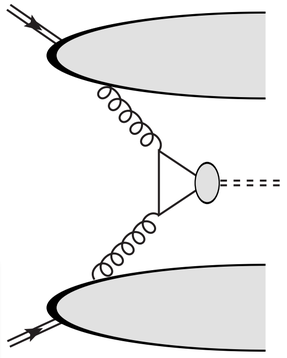


✓ No color entanglement
TMD factorization

¡! 🔗 Large low-p_T bin @CMS
More data @HL-LHC

LHC

Single quarkonium

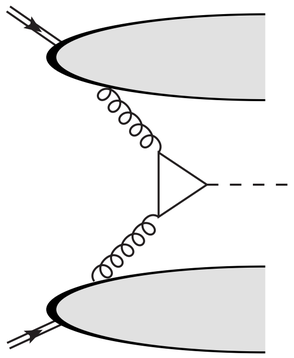


✓ $\eta_{c,b}$ ✗ $J/\psi, \Upsilon$
TMD factorization
C-parity selection rules

¡! 🔗 Large-p_T data @LHCb
More data @LHCspin

Gluon TMD pheno from the LHC to the EIC

Higgs in gluon fusion

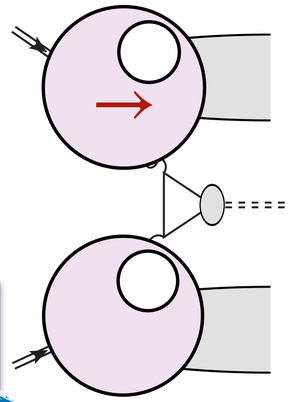


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LHC

Single quarkonium

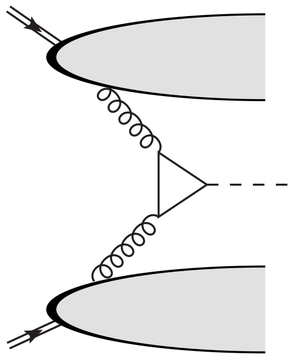


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Gluon TMD pheno from the LHC to the EIC

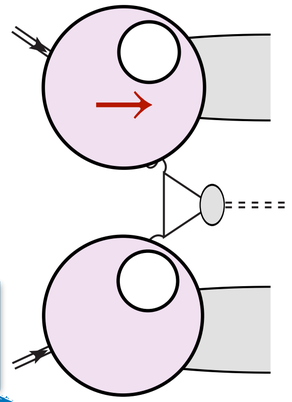
Higgs in gluon fusion



✓ No color entanglement
TMD factorization

¡! 🔗 Large low-p_T bin @CMS
More data @HL-LHC

Single quarkonium



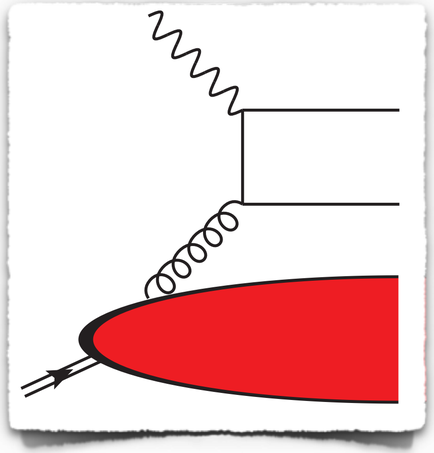
✓ $\eta_{c,b}$ ✗ $J/\psi, \Upsilon$
TMD factorization
C-parity selection rules

¡! 🔗 Large-p_T data @LHCb
More data @LHCspin

LHC

EIC

Two-jet SIDIS

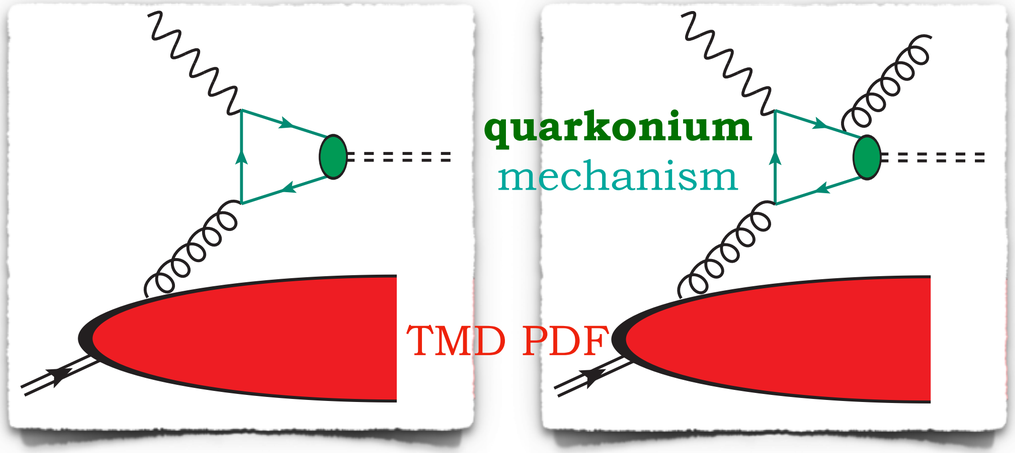


jet function

jet function

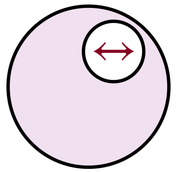
TMD PDF

Quarkonia



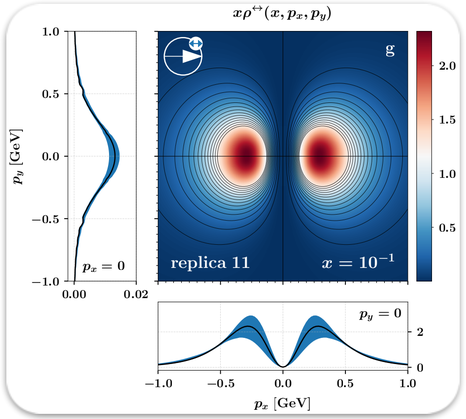
Quarkonia: Precision & Exploration

TMD exploration: Assets



EIC, LHCb, LHCspin

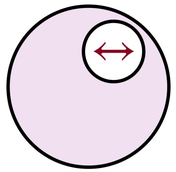
Boer-Mulders



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

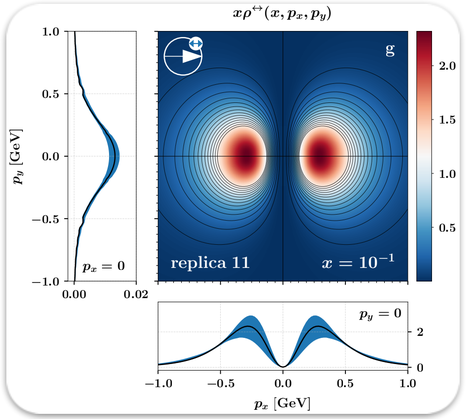
Quarkonia: Precision & Exploration

TMD exploration: Assets



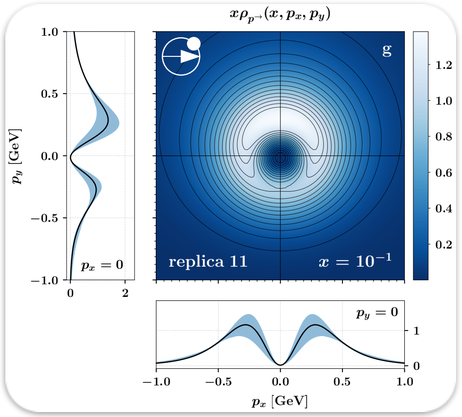
EIC, LHCb, LHCspin

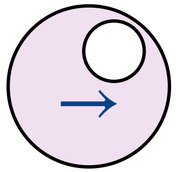
Boer-Mulders



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

[A. Bacchetta, F.G. C., M. Radici (EPJC 2024)]



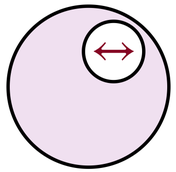


EIC, LHCspin

Sivers

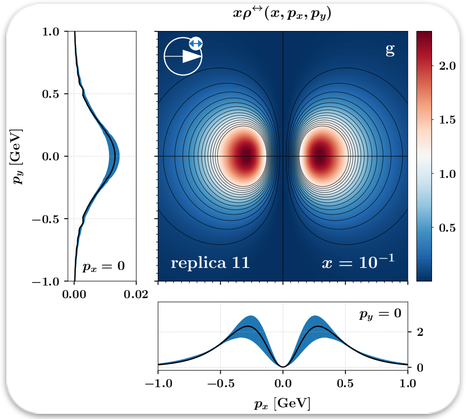
Quarkonia: Precision & Exploration

TMD exploration: Assets

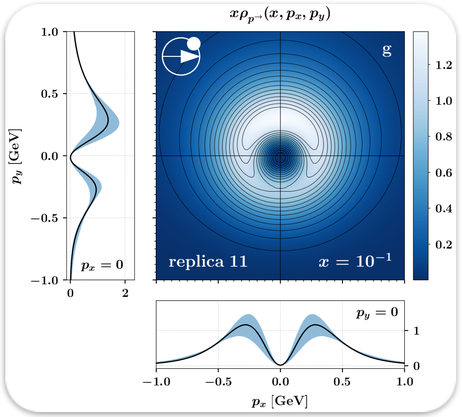


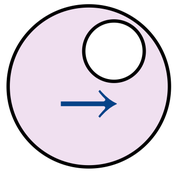
EIC, LHCb, LHCspin

Boer-Mulders



🔗 [A. Bacchetta, F.G. C., M. Radici, P. Taels (EPJC 2020)]
🔗 [A. Bacchetta, F.G. C., M. Radici (EPJC 2024)]



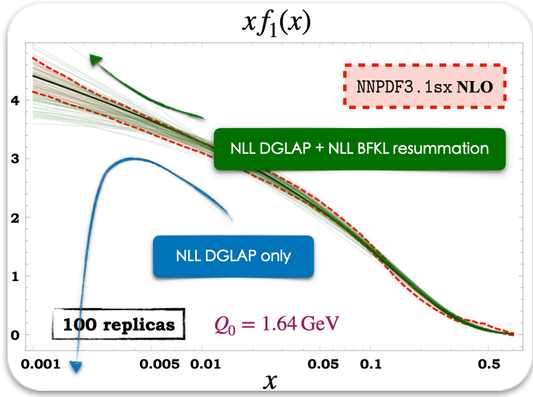


EIC, LHCspin

Sivers

Precision QCD: Challenges

Forward Onia ⇒ Gluon PDF & TMD Positivity

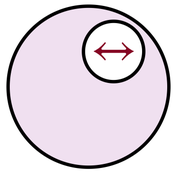


Low x and low Q^2

🔗 [G. Altarelli et al. (1998)]
🔗 [A. Candido et al. (2020)]
🔗 [J. Collins et al. (2022)]
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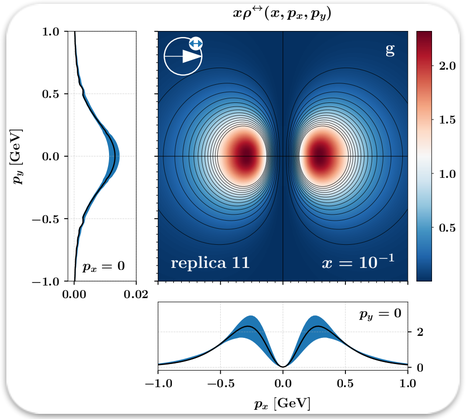
Quarkonia: Precision & Exploration

TMD exploration: Assets

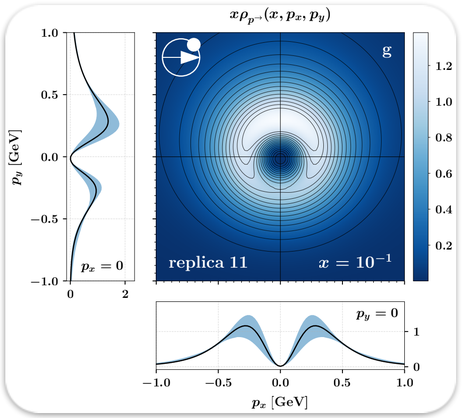


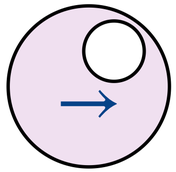
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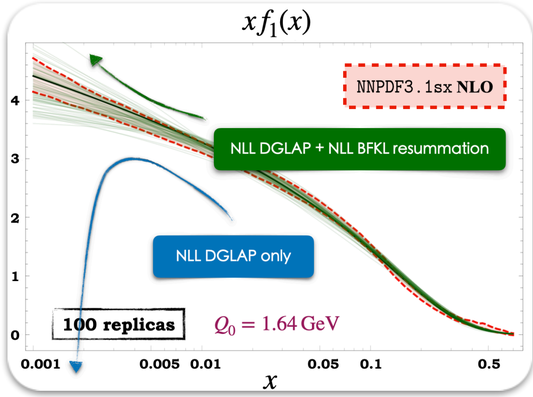


EIC, LHCspin

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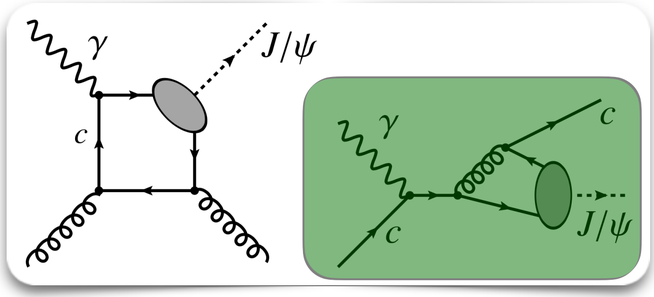


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🔗 [A. Candido et al. (2023)]

$\gamma + g \rightarrow J/\psi + c$ ⇒ Valence Intrinsic Charm @EIC

Large x
Moderate to large p_T



(J/ψ @EIC) 🔗 [C. Flore, J.-P. Lansberg, H.-S. Shao, Y. Yedelkina (2020)]
(Intrinsic Charm + valence) studies 🔗🔗 [NNPDF Collaboration (2022, 2023)]

Checkpoints & Perspectives

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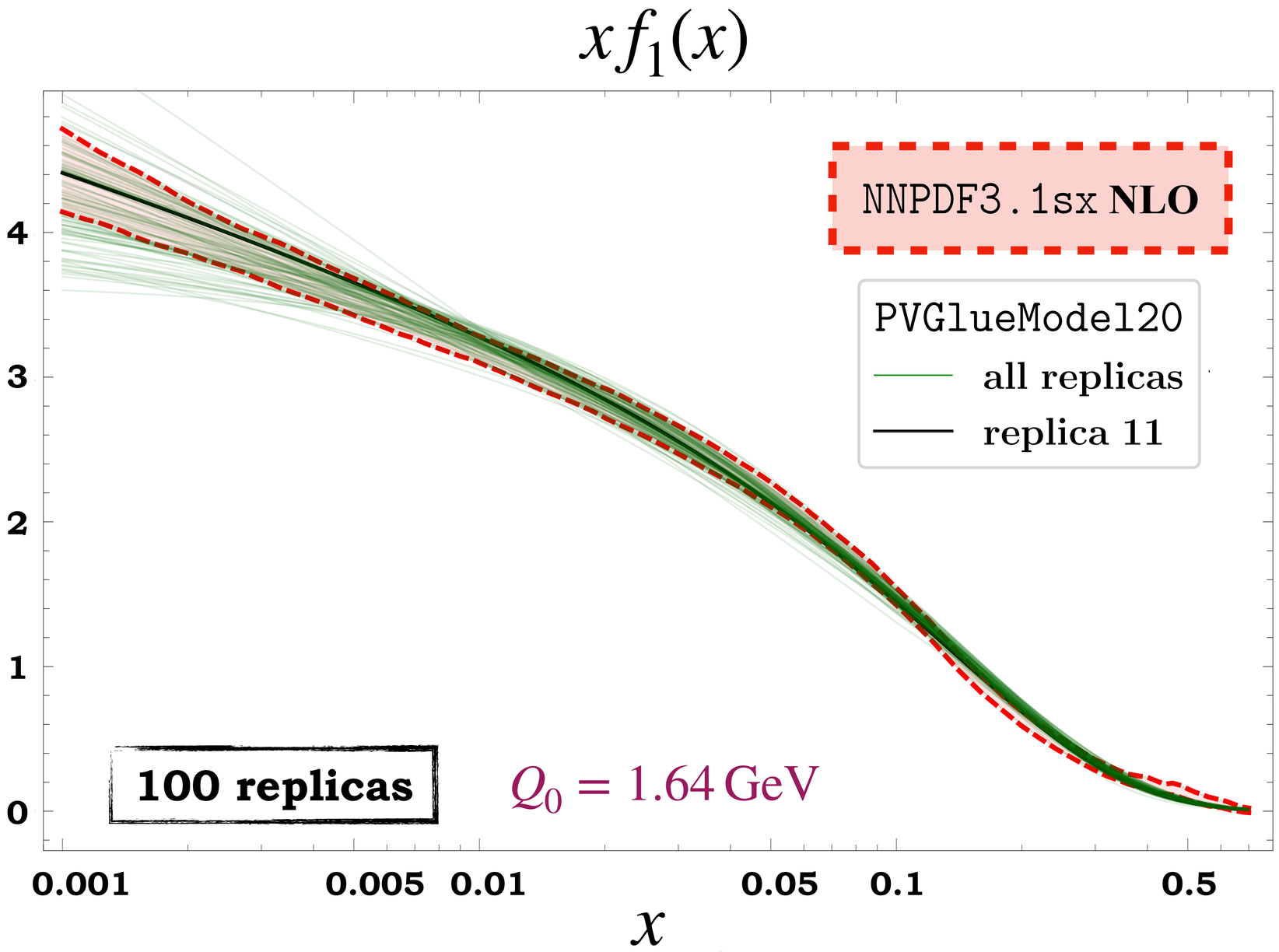
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¡ Thanks for the attention !

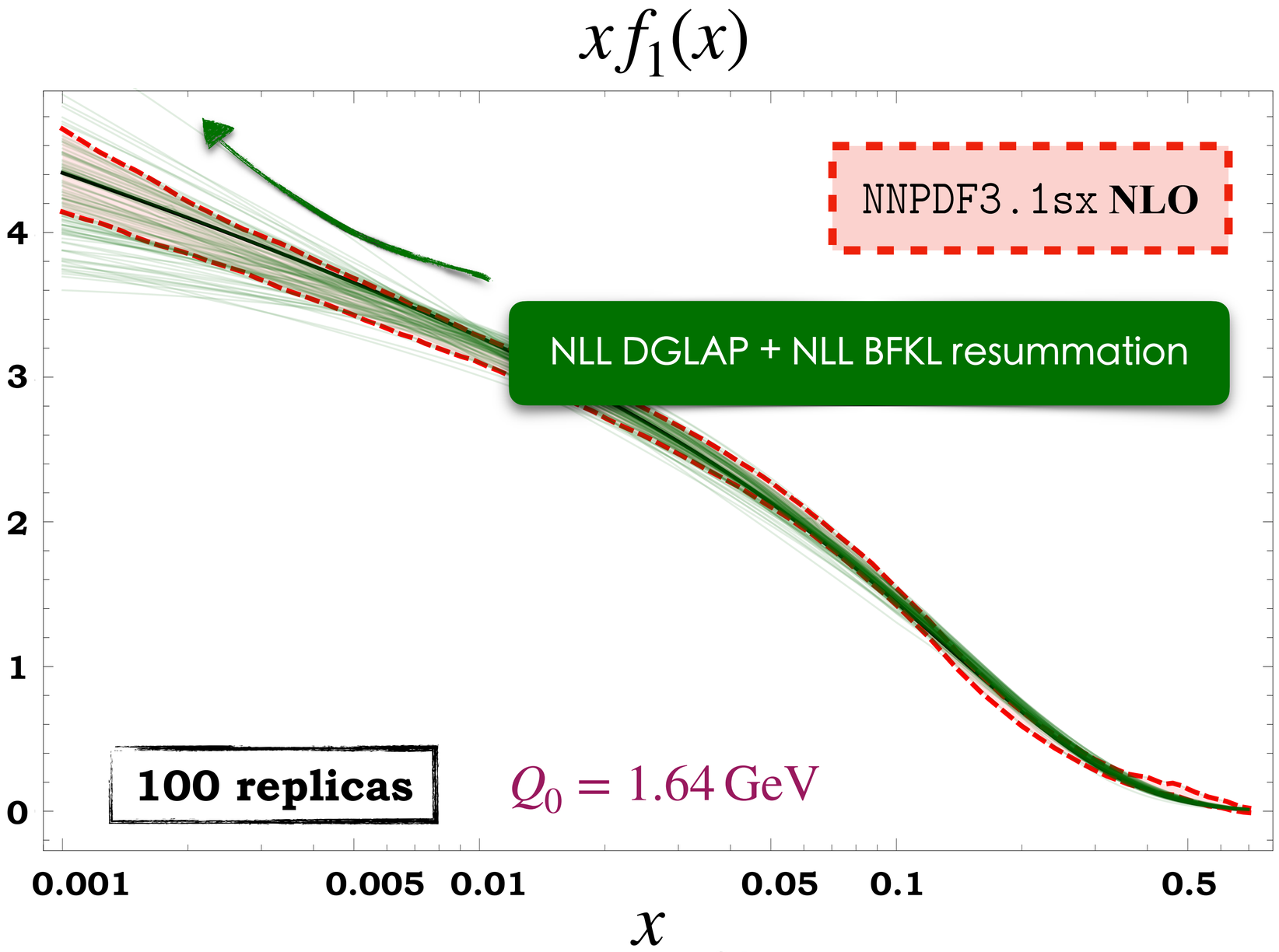
EXTRAS

Unpolarized gluon collinear PDF



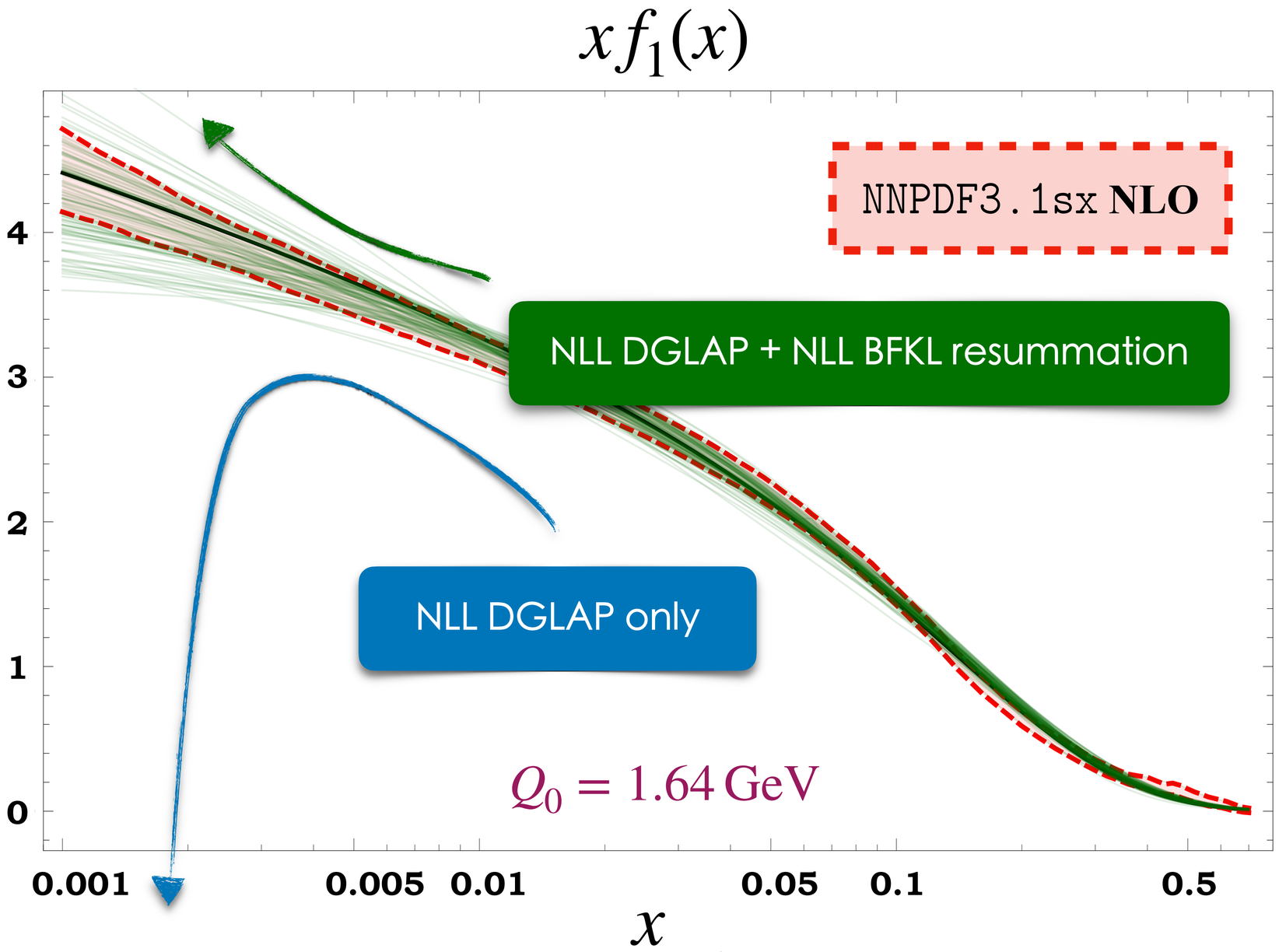
[A. Bacchetta, F.G.C., M. Radici, P. Taels (EPJC 2020)]

Unpolarized gluon collinear PDF



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

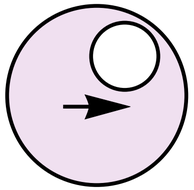
Unpolarized gluon collinear PDF

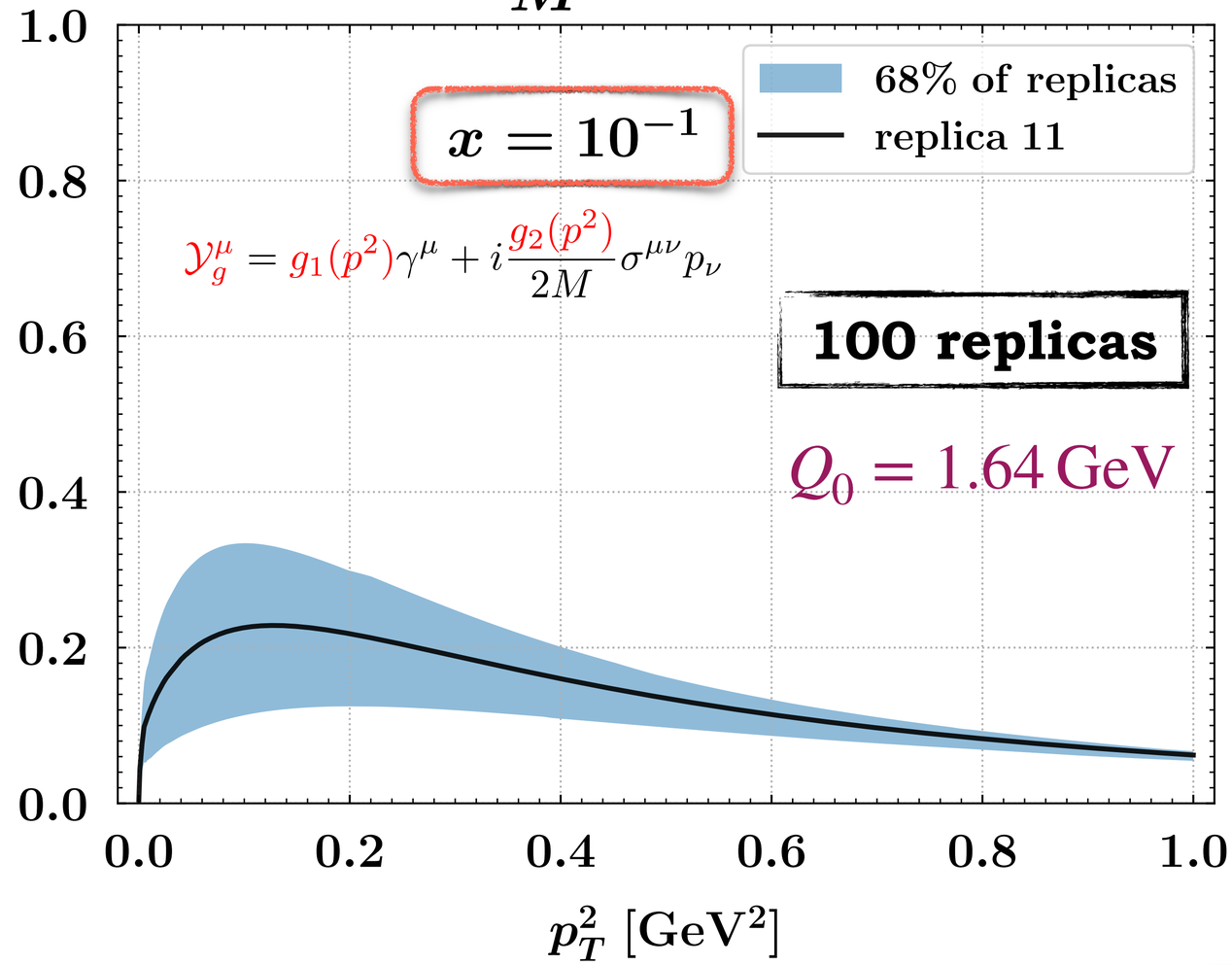


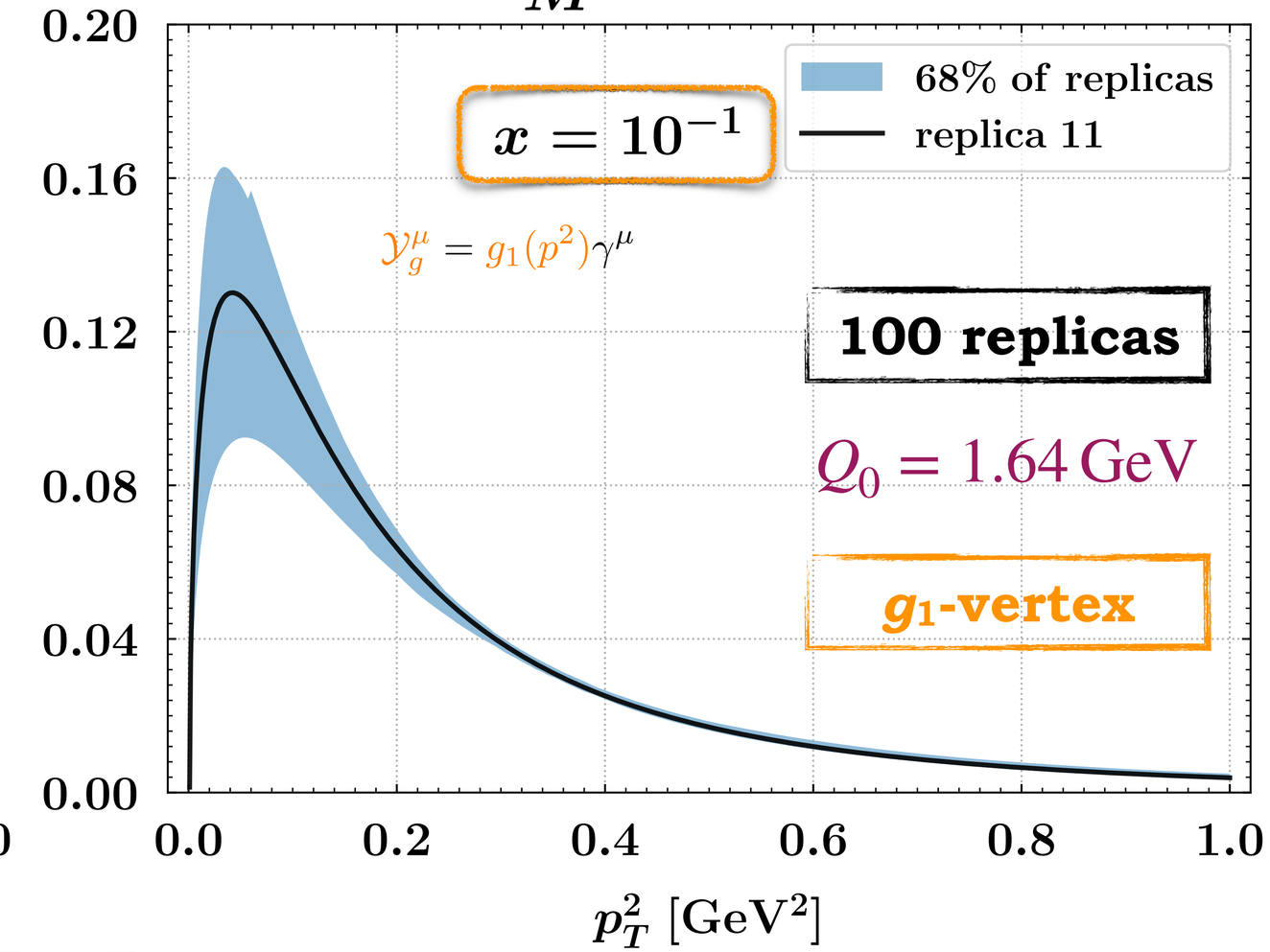
[A. Bacchetta, F.G.C., M. Radici, P. Taels (EPJC 2020)]

f-type Sivers gluon TMD

[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]



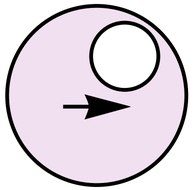


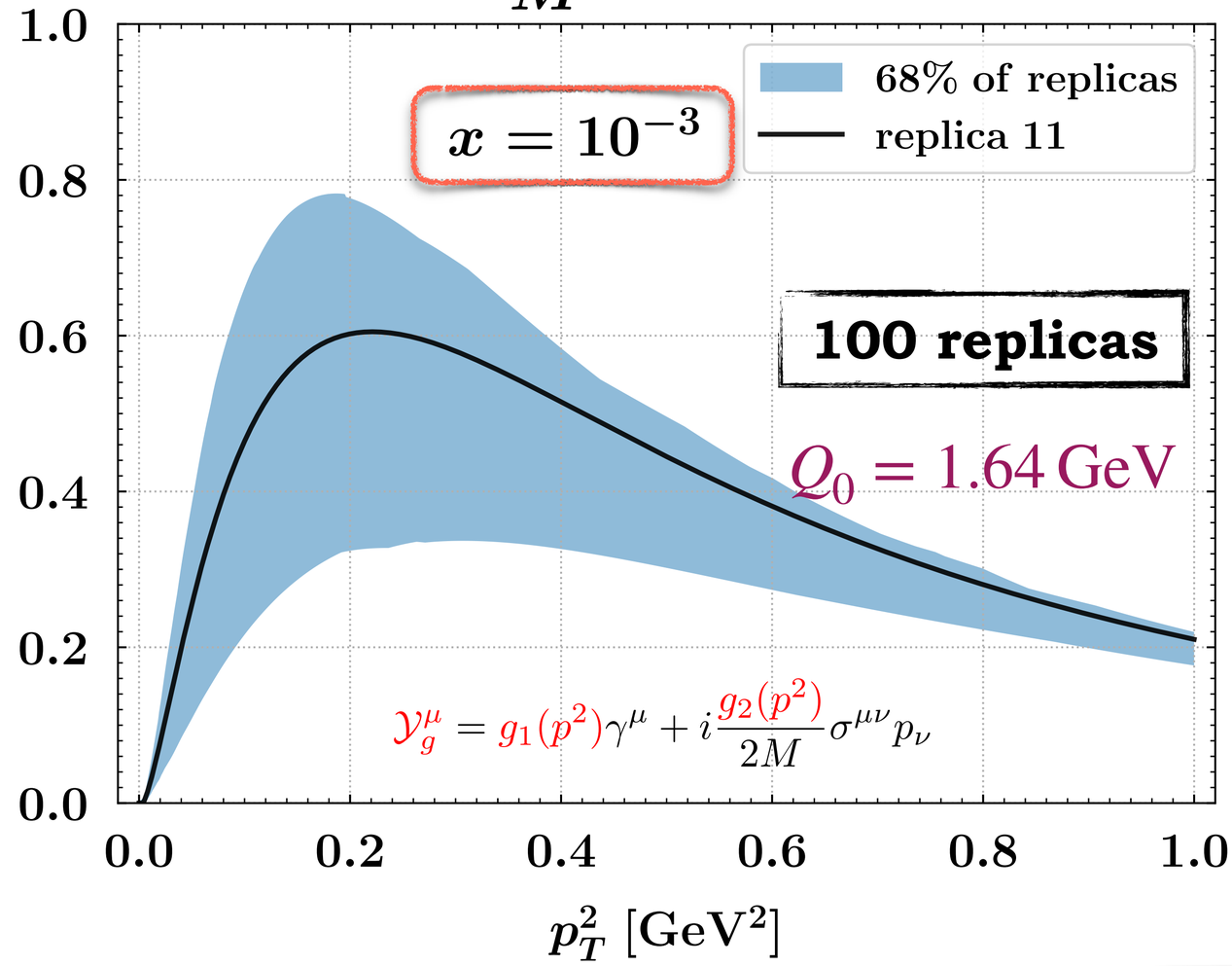


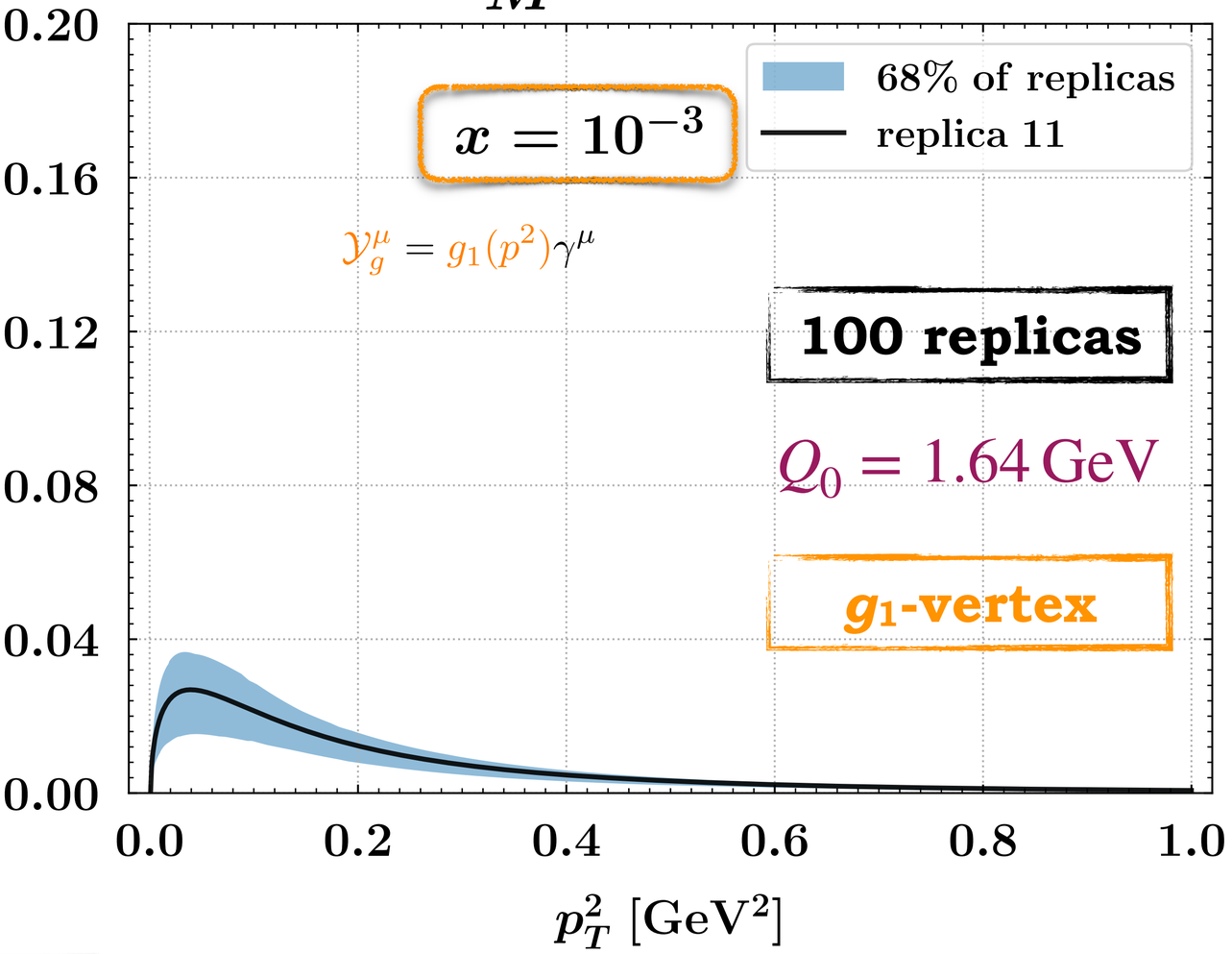
Backup

f-type Sivers gluon TMD

[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]



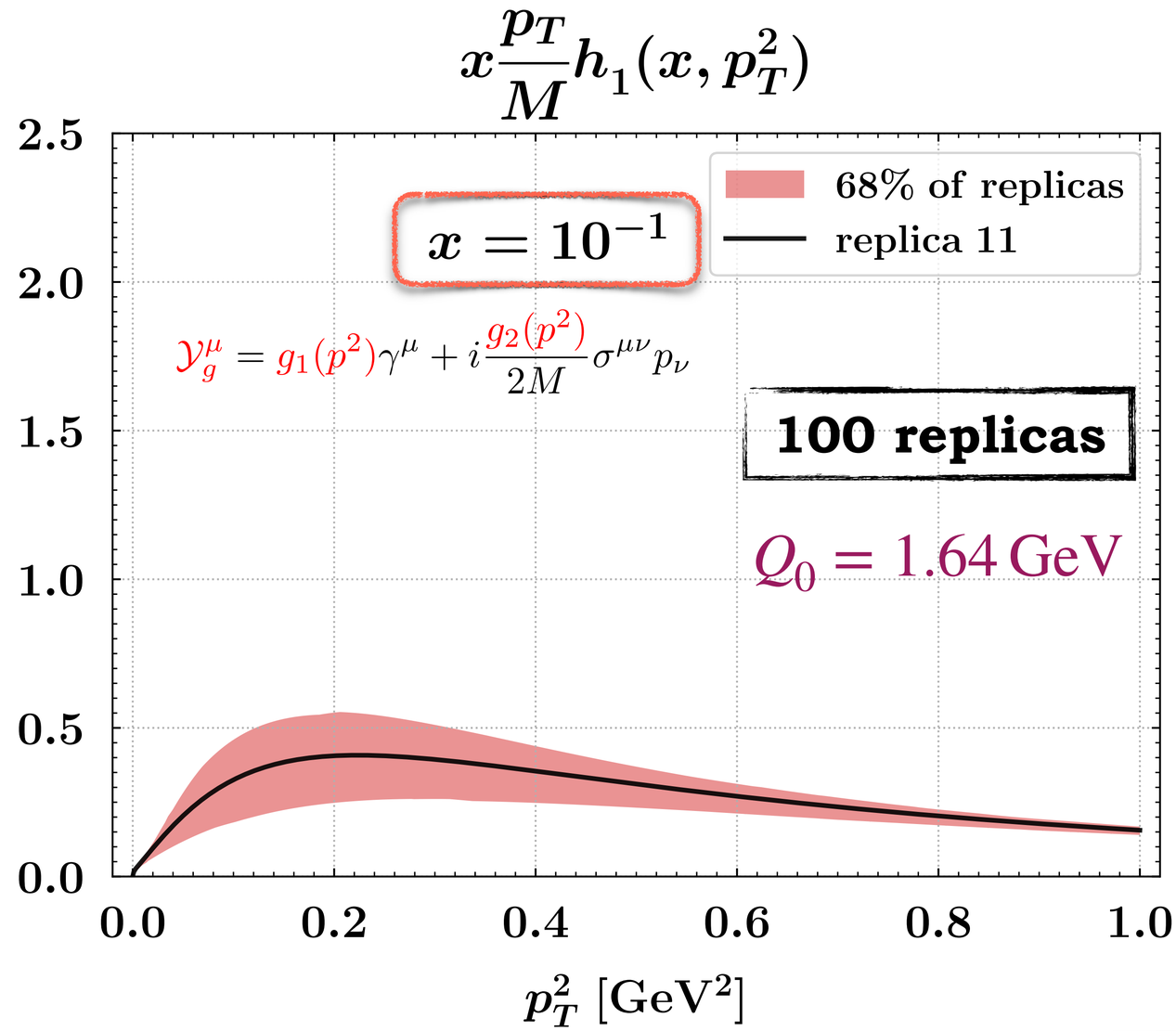


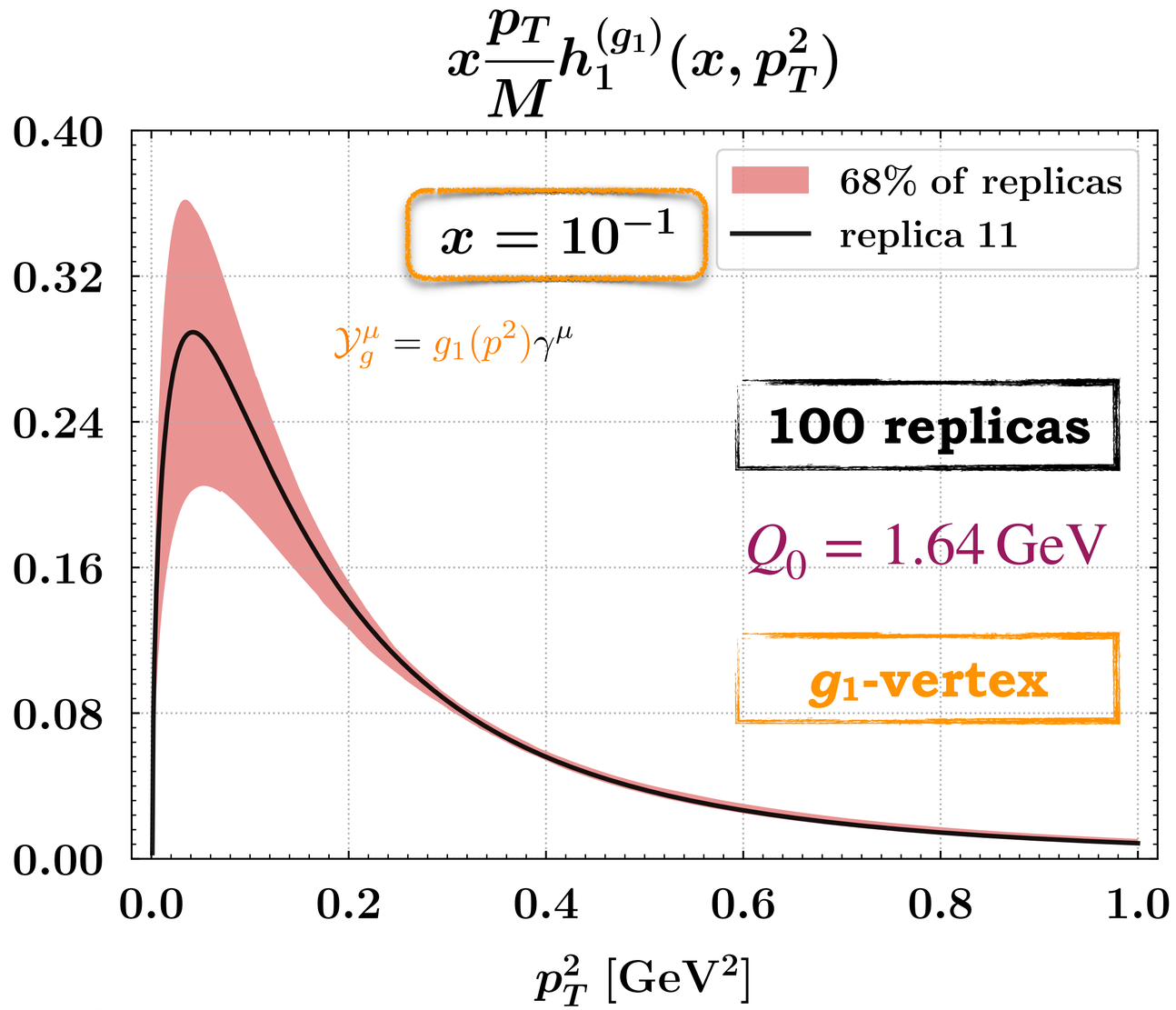


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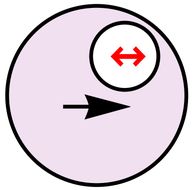


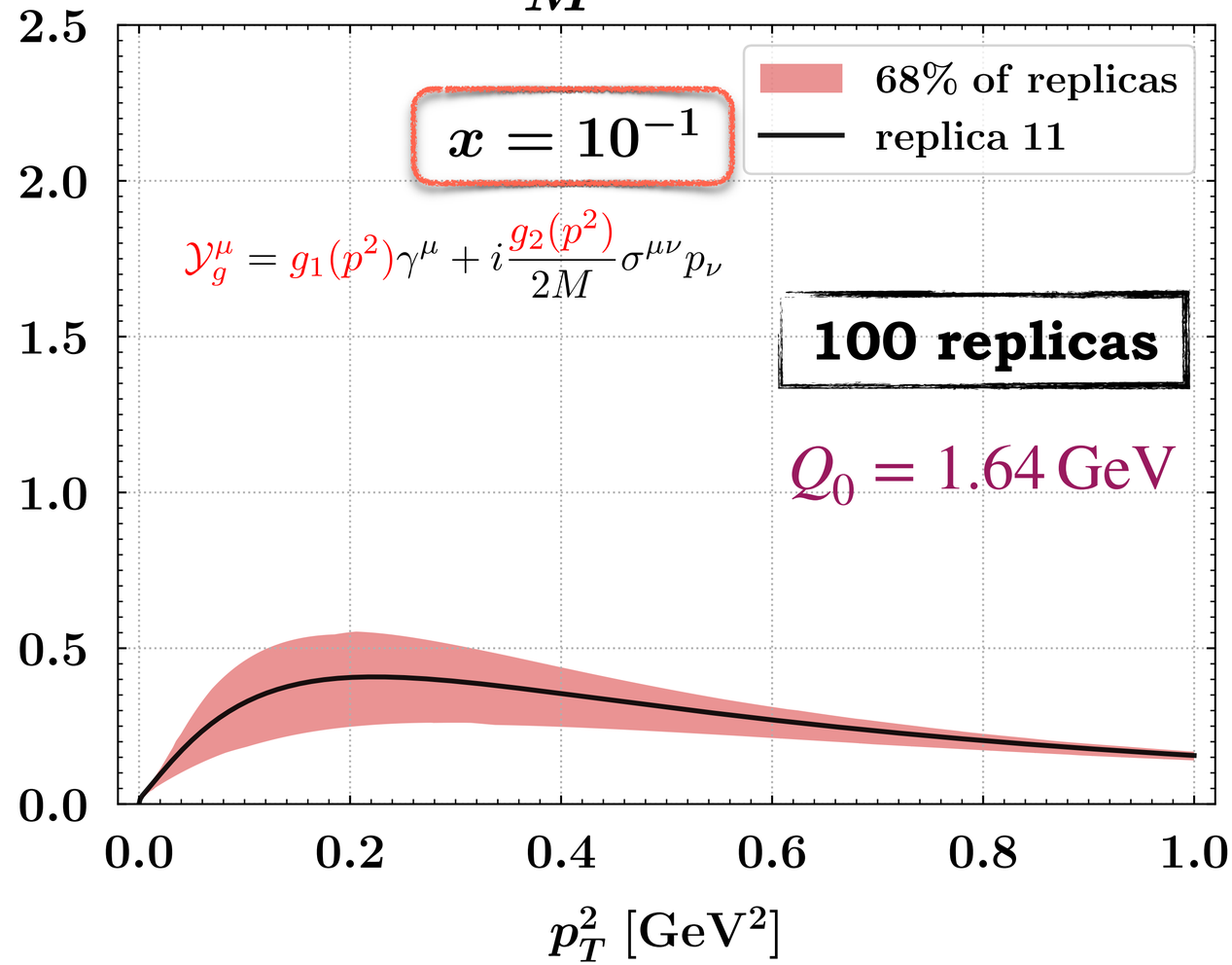


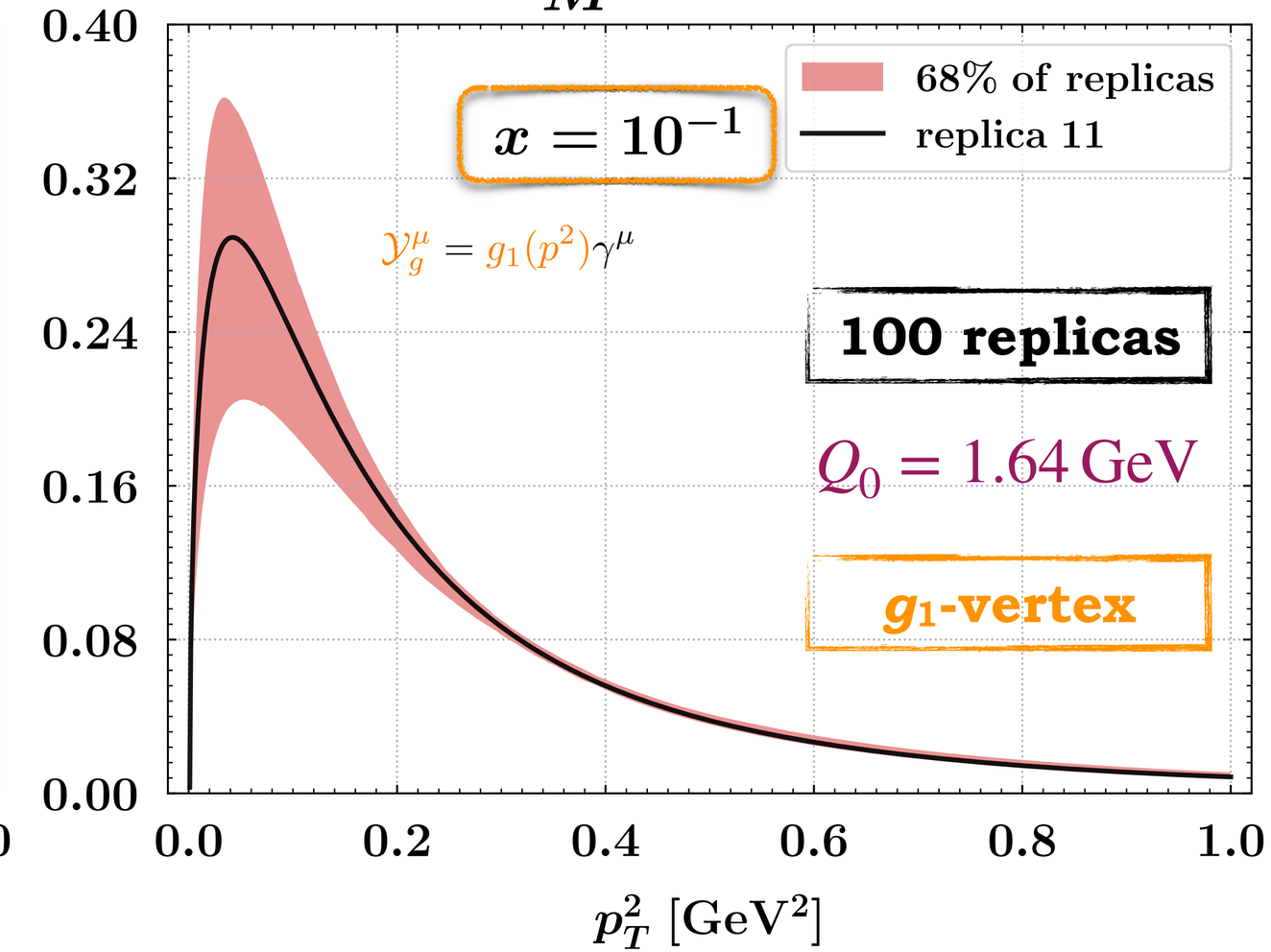
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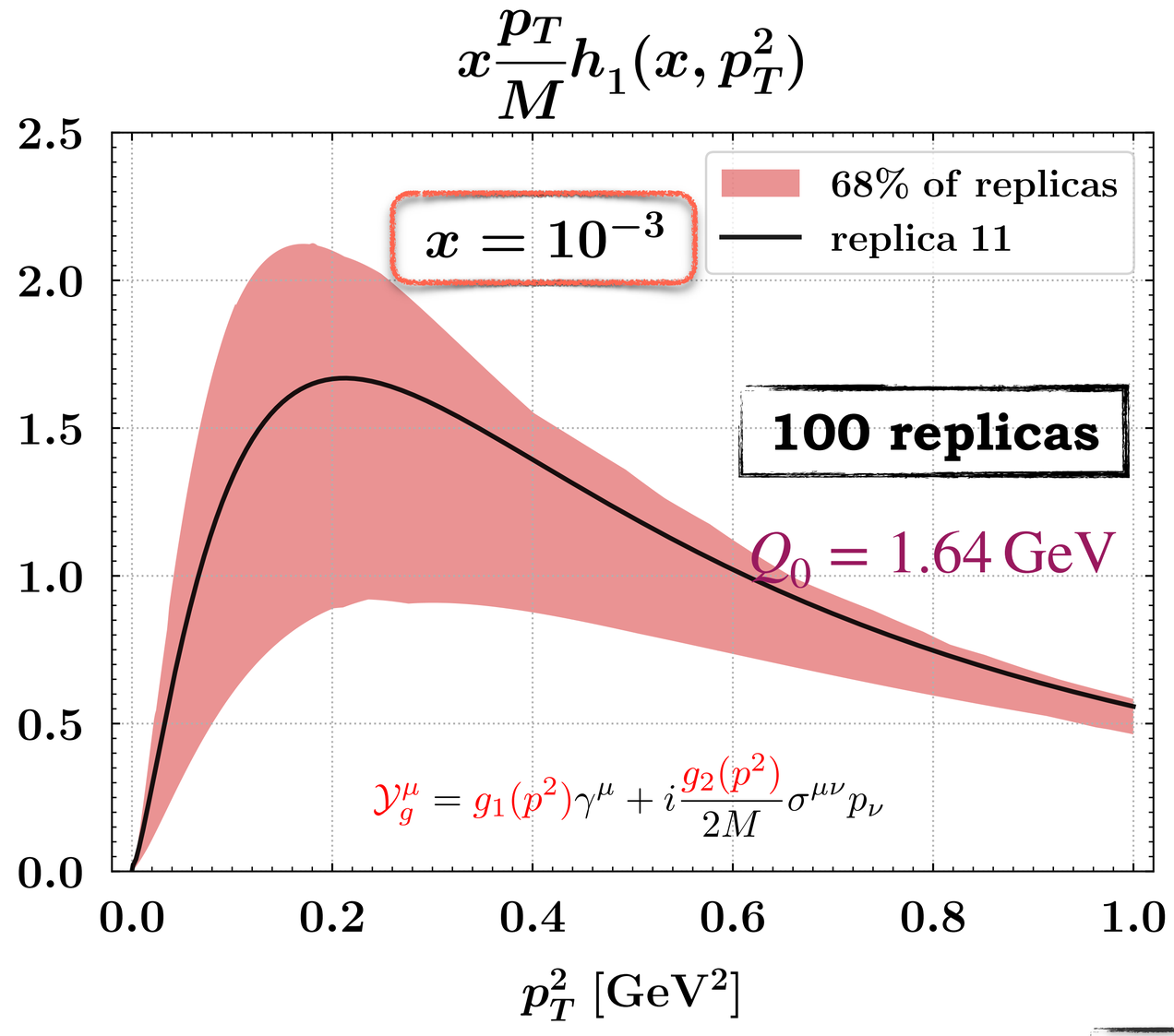


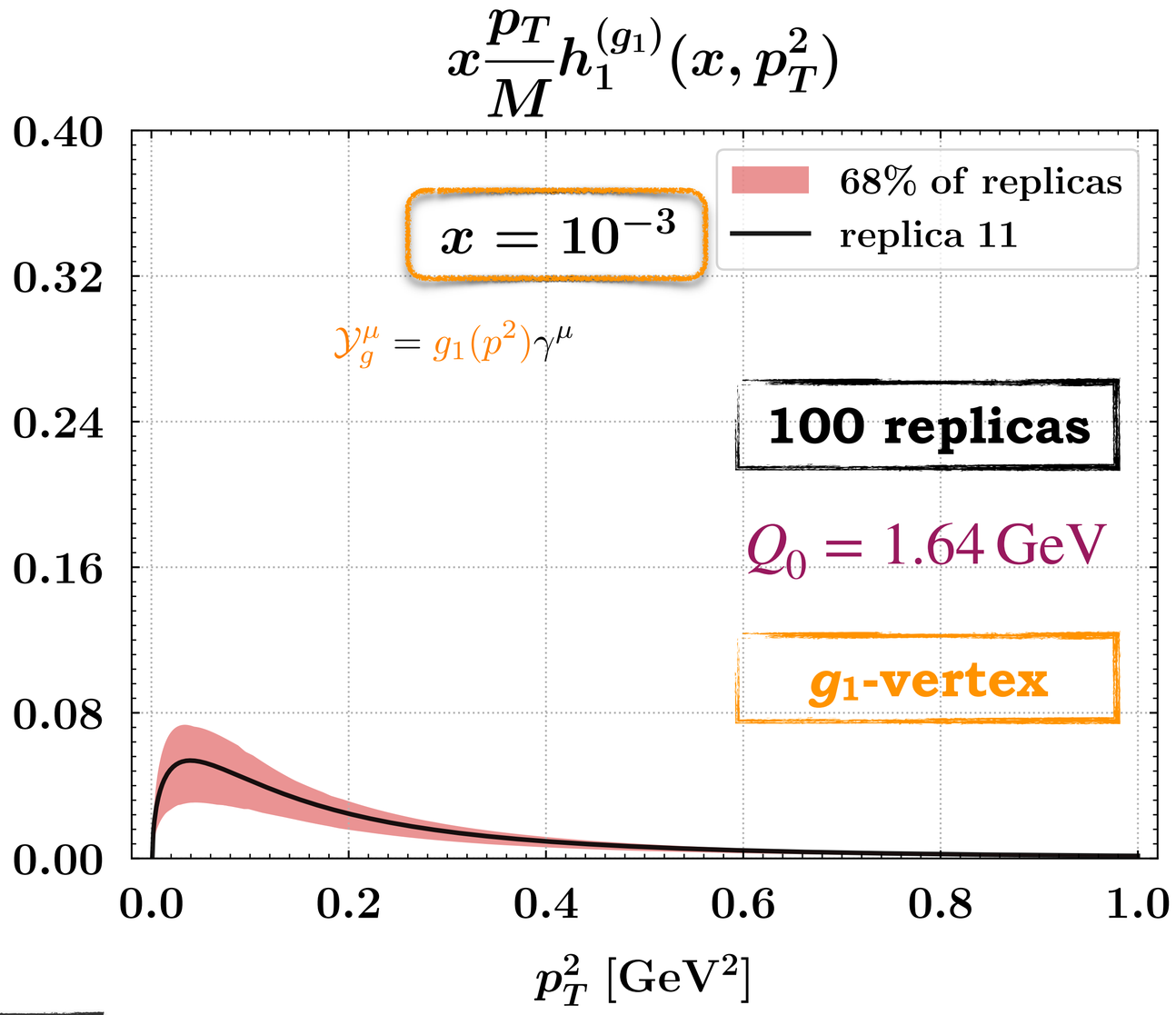


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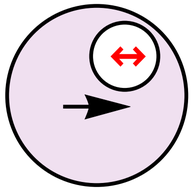


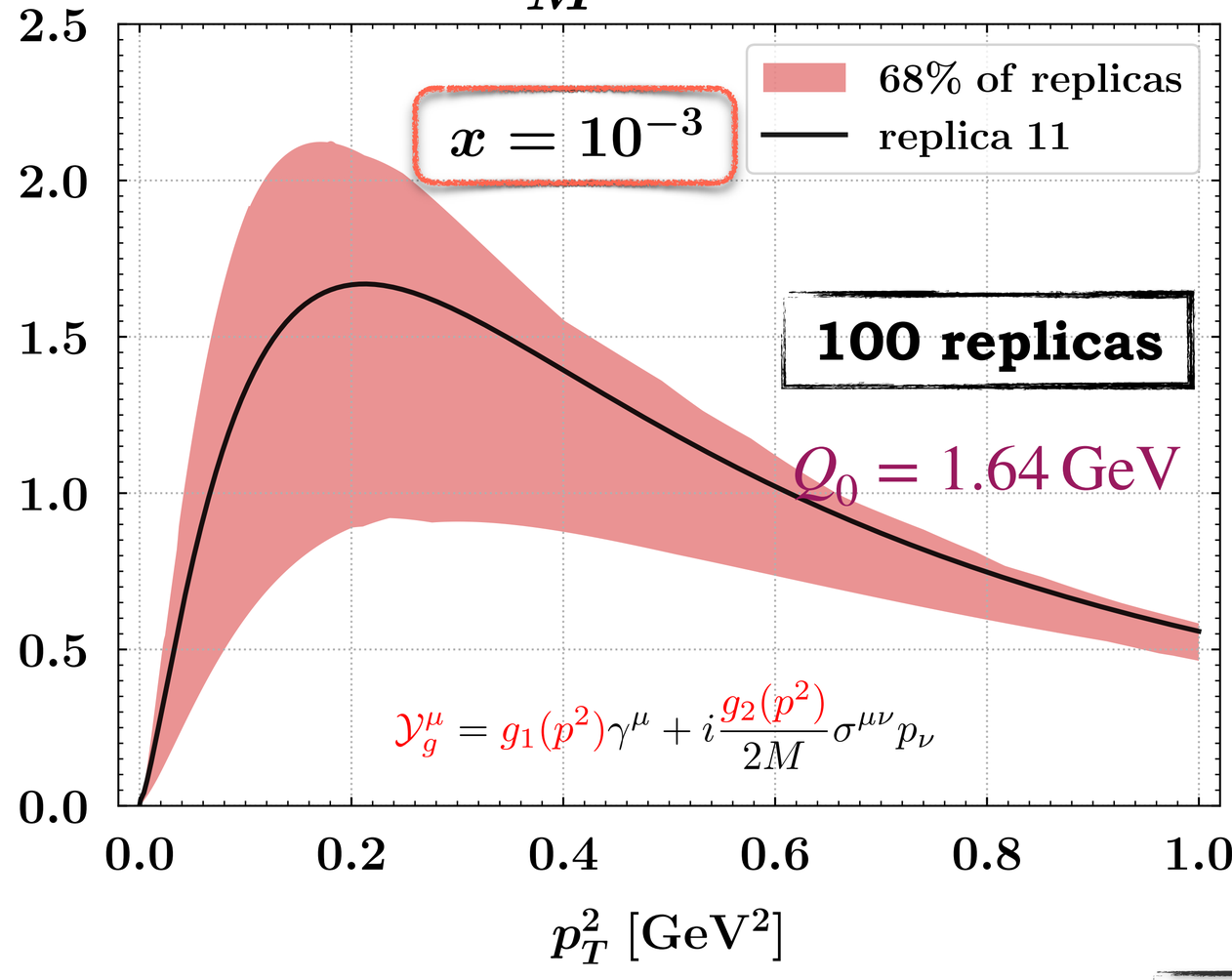


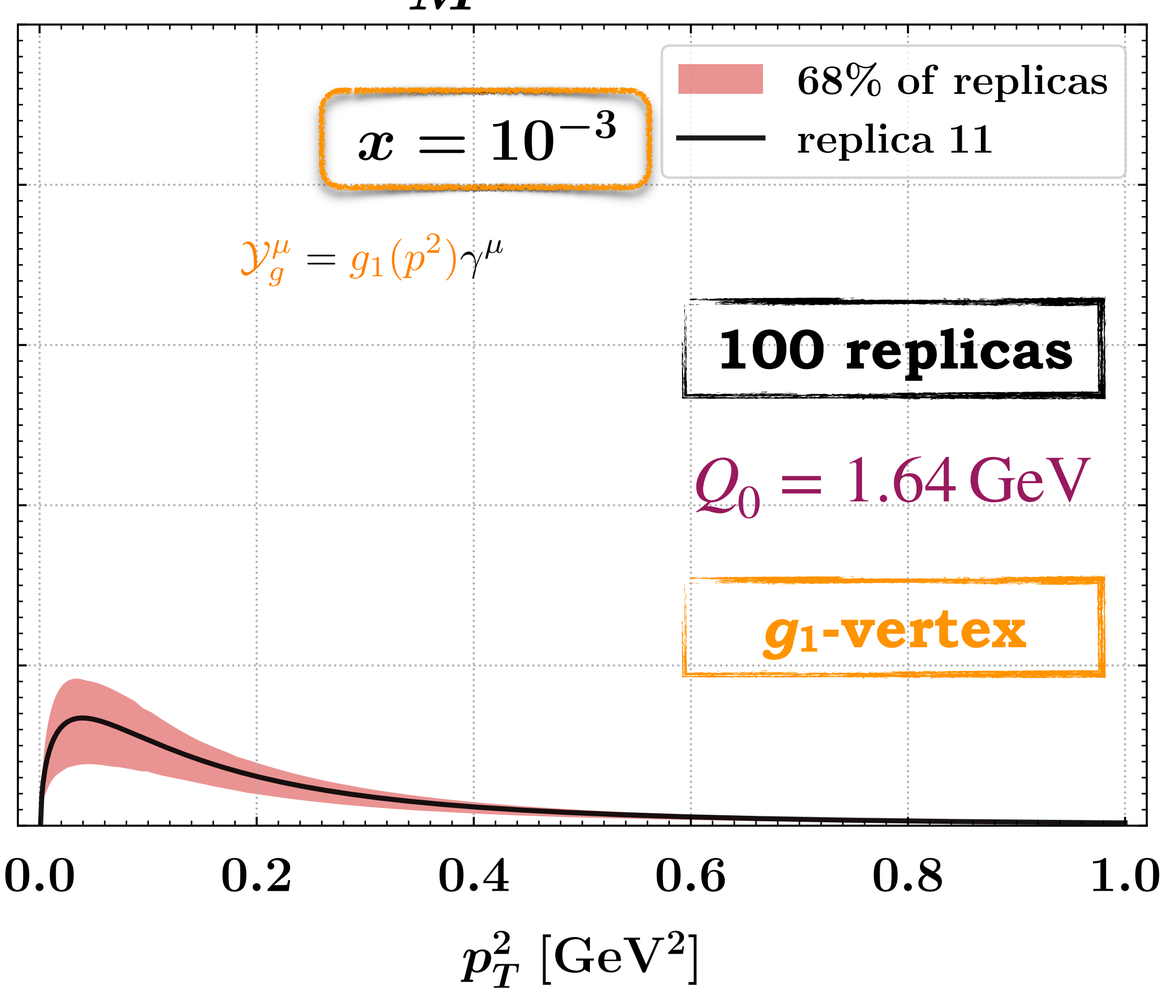
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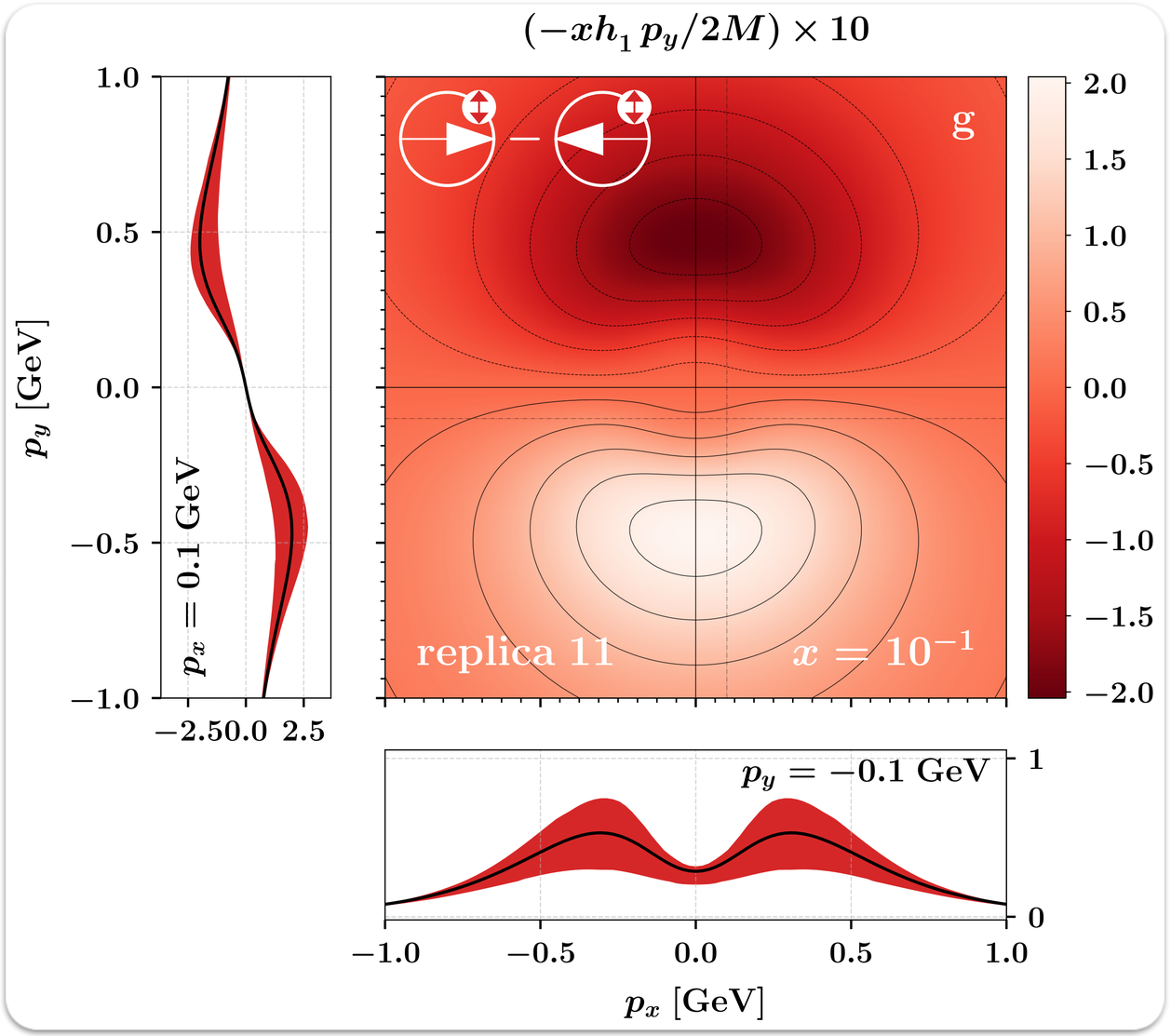


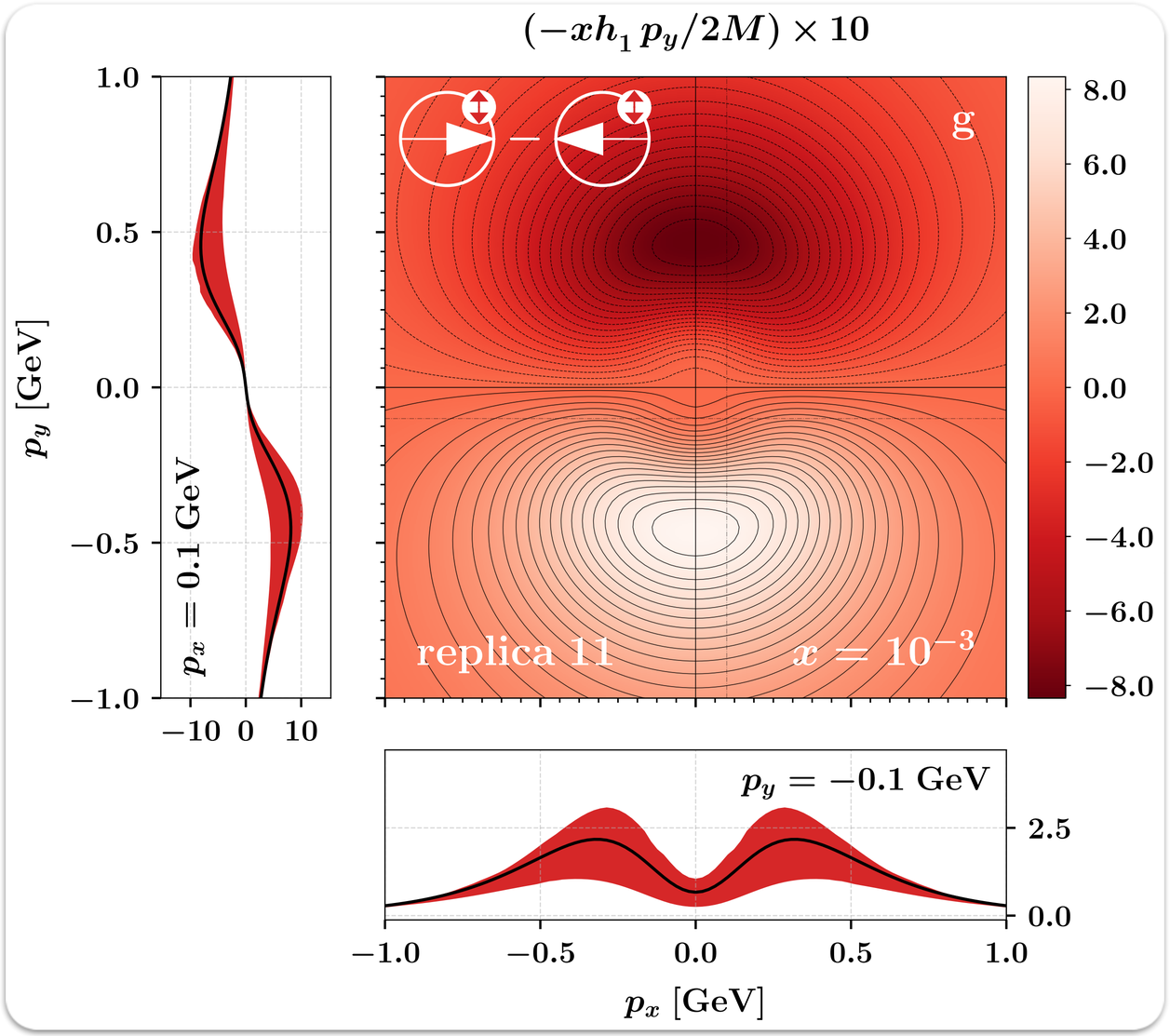


Backup

Gluon linearity effect

[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

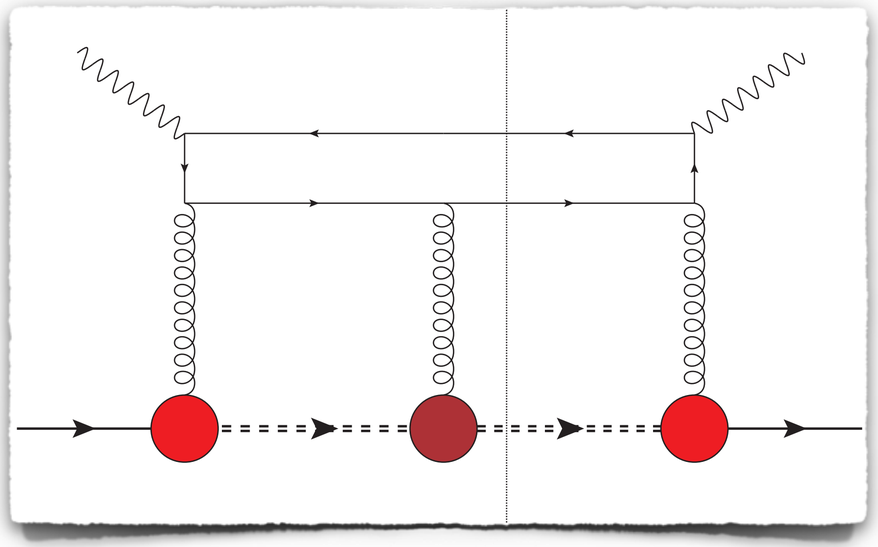


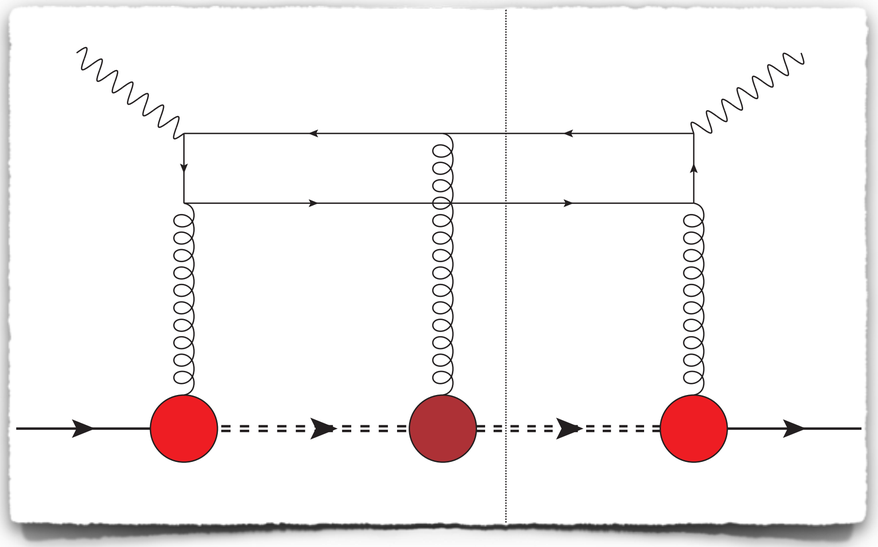


Backup

Analytic structure of T-odd gluon TMDs

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





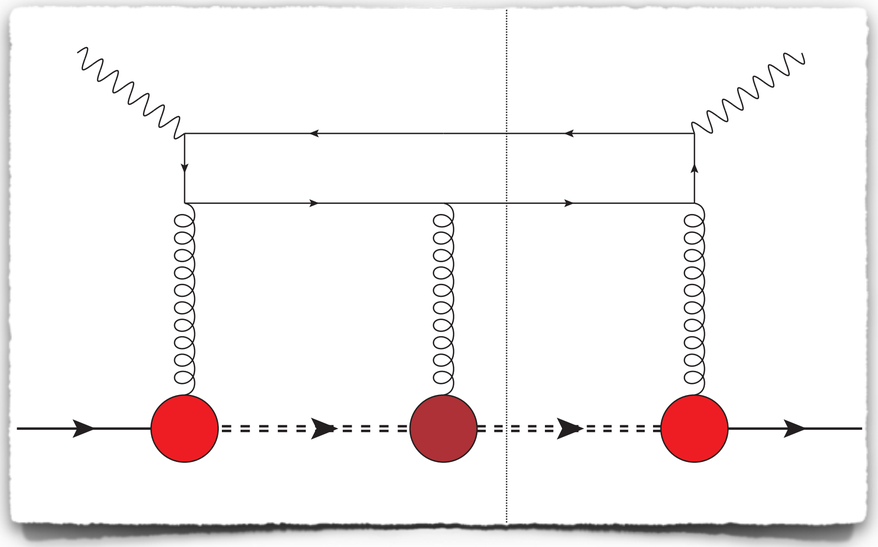
nucleon-gluon-spectator

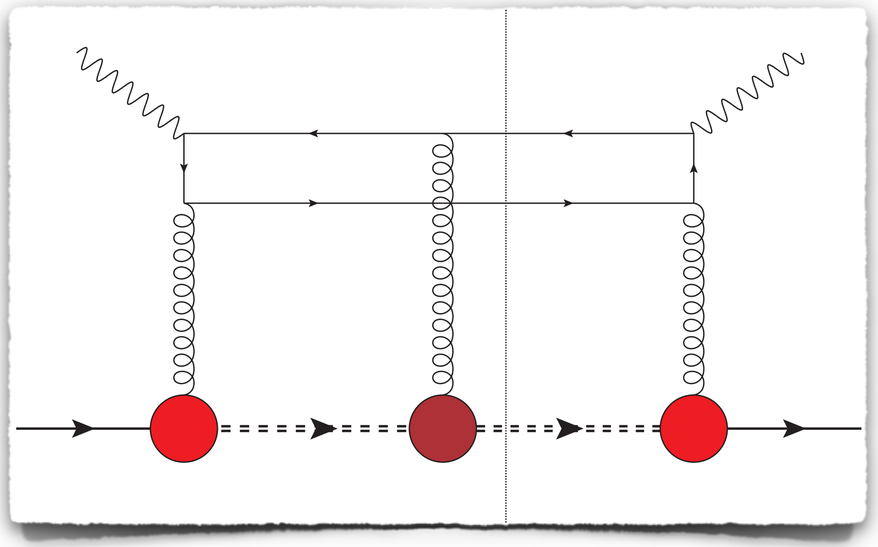
spectator-gluon-spectator

[A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

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





nucleon-gluon-spectator

spectator-gluon-spectator

$8 \times 8 \times 4$

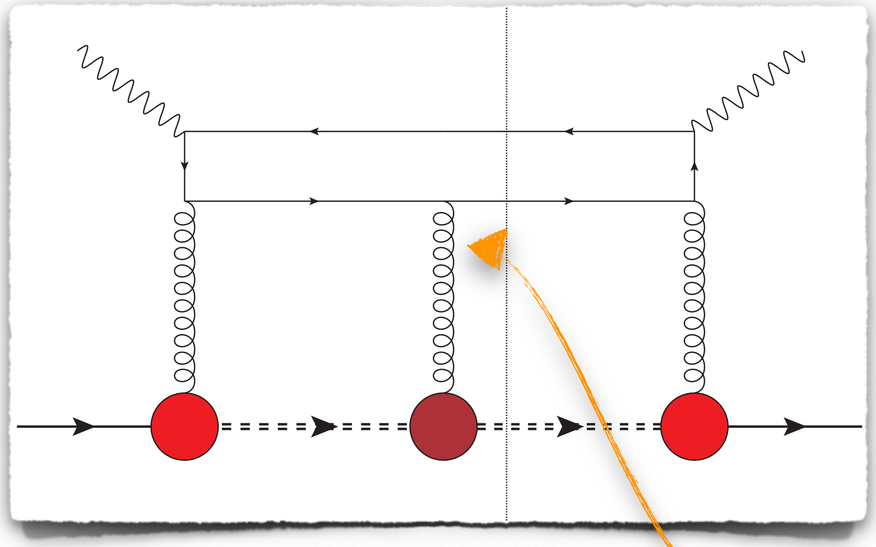
$$F(x, \boldsymbol{p}_T^2) = \sum_{i,j,k}^{1,2} C_{ijk}^{(F)}(x, \boldsymbol{p}_T^2)\, g_i(\boldsymbol{p}_T^2)\, g_j(\boldsymbol{p}_T^2)\, g_k(\boldsymbol{p}_T^2)$$

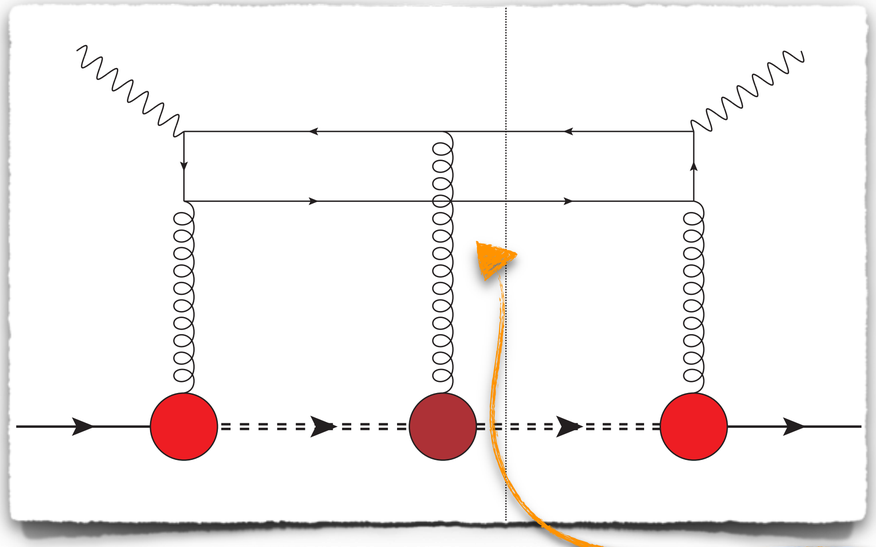
$$C_{ijk}^{(F)}(x, \boldsymbol{p}_T^2) = \sum_{l=1}^{7} \mathcal{C}_{ijk}^{(F),l}(x, \boldsymbol{p}_T^2)\, \mathcal{D}_l(x, \boldsymbol{p}_T^2)$$

🔗 [A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

Analytic structure of T-odd gluon TMDs

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





nucleon-gluon-spectator

spectator-gluon-spectator

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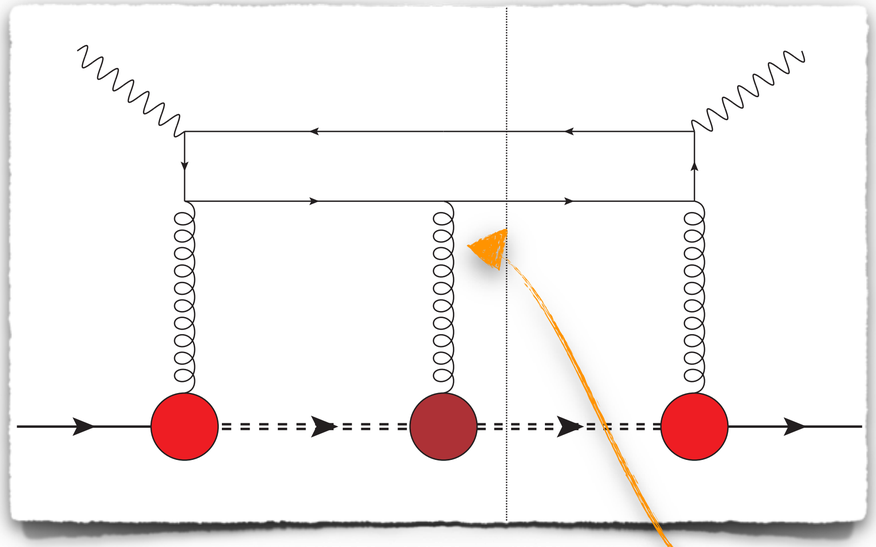
$8 \times 8 \times 4$

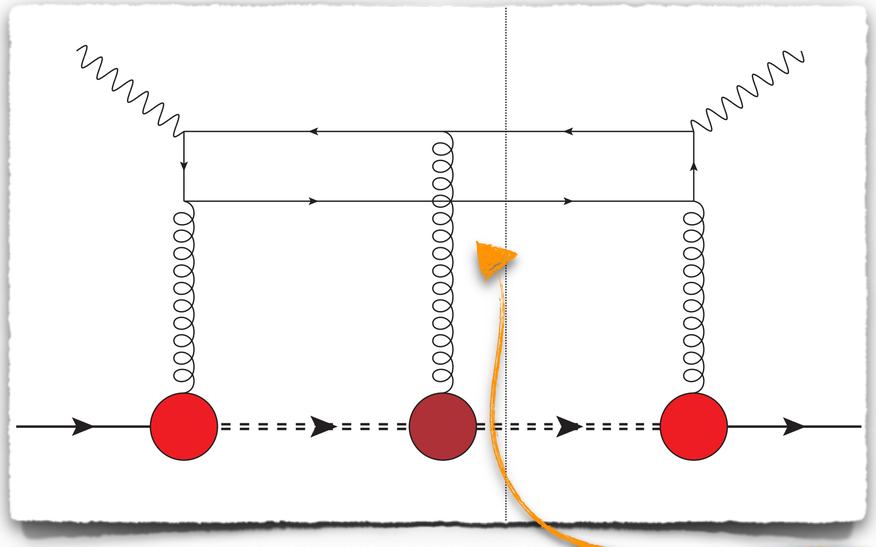
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🔗 [A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

Analytic structure of T-odd gluon TMDs

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





nucleon-gluon-spectator

spectator-gluon-spectator

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$8 \times 8 \times 4$

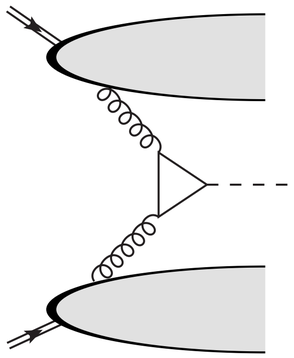
256 coeff. functions

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

🔗 [A. Bacchetta, F.G.C., M. Radici (EPJC 2024)]

Golden channels for gluon TMD PDFs in $\mathscr{H}\mathscr{H}$

Higgs in gluon fusion



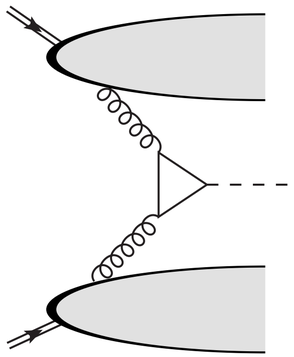
✓ No color entanglement
TMD factorization

¡! 🔗 Large low-p_T bin @CMS
More data @HL-LHC

Backup

Golden channels for gluon TMD PDFs in $\mathscr{H}\,\mathscr{H}$

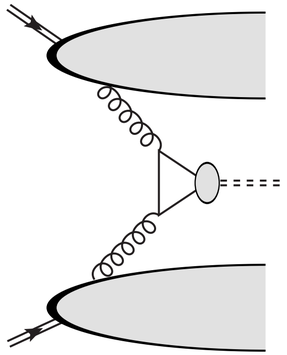
Higgs in gluon fusion



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Single quarkonium



✔ $\eta_{c,b}$ ✗ $J/\psi, \Upsilon$

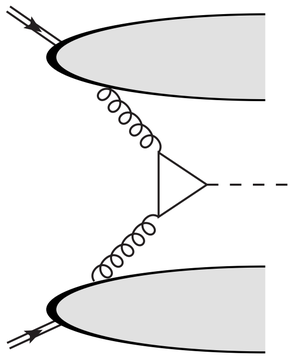
TMD factorization
C-parity selection rules

¡! 🔗 Large-p_T data @LHCb
More data @LHCspin

Backup

Golden channels for gluon TMD PDFs in $\mathscr{H}\,\mathscr{H}$

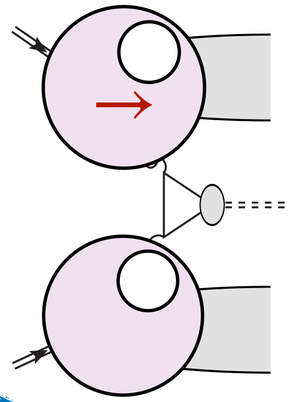
Higgs in gluon fusion



✔ No color entanglement
TMD factorization

¡! 🔗 Large low-p_T bin @CMS
More data @HL-LHC

Single quarkonium



✔ $\eta_{c,b}$ ✗ $J/\psi, \Upsilon$

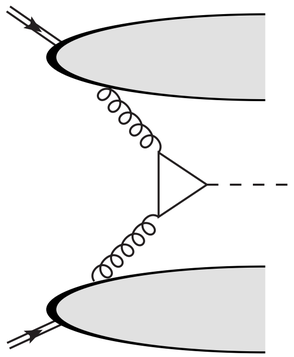
TMD factorization
C-parity selection rules

¡! 🔗 Large-p_T data @LHCb
More data @LHCspin

Backup

Golden channels for gluon TMD PDFs in $\mathscr{H}\,\mathscr{H}$

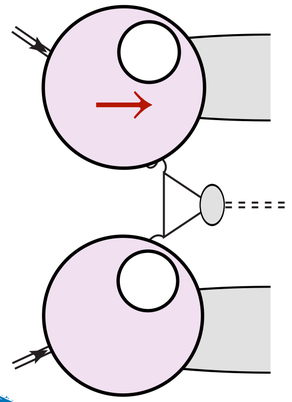
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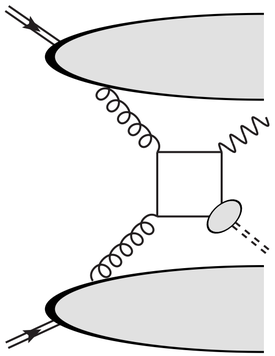
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More data @LHCspin

$J/\psi + \gamma^{(*)}$



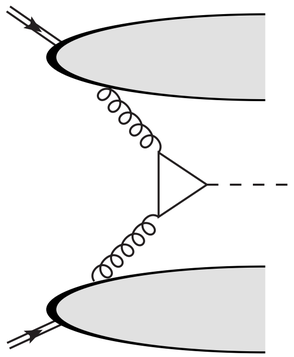
¡✓ Color entanglement
Potential TMD violation (CO)
Back-to-back suppresses CO

✓! Possible studies @HL-LHC
Currently no low-p_T data

Backup

Golden channels for gluon TMD PDFs in $\mathscr{H}\,\mathscr{H}$

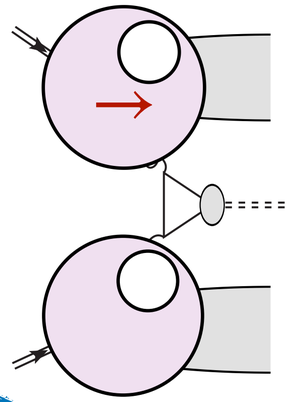
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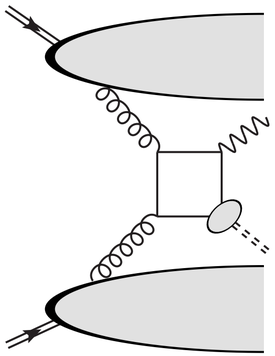
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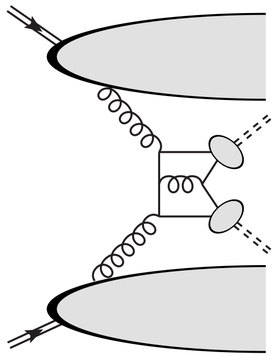
$J/\psi + \gamma^{(*)}$



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Potential TMD violation (CO)
Back-to-back suppresses CO

✓! Possible studies @HL-LHC
Currently no low-p_T data

$J/\psi + J/\psi$



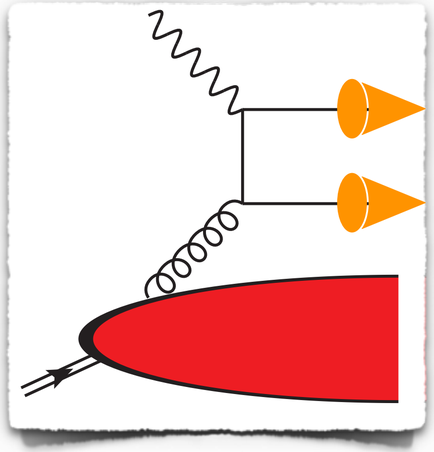
¡✓ No color entanglement
TMD factorization (CSM)

✓ 🔗 Low-p_T data @LHCb
Opportunities @HL- & @LHCSpin

Backup

Golden channels for gluon TMD PDFs @EIC

Two-jet SIDIS



jet function

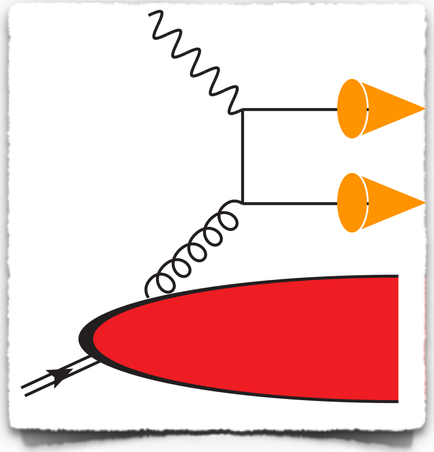
jet function

TMD PDF

Backup

Golden channels for gluon TMD PDFs @EIC

Two-jet SIDIS

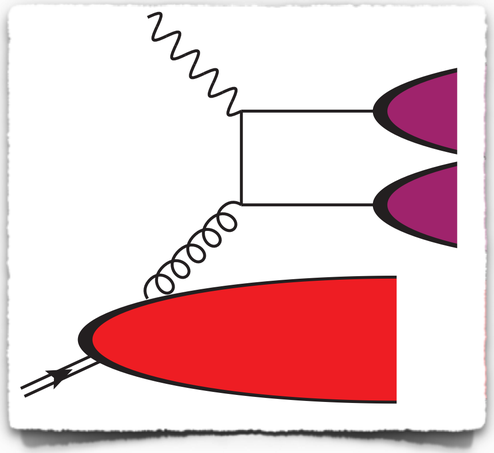


jet function

jet function

TMD PDF

Double D meson



TMD FF

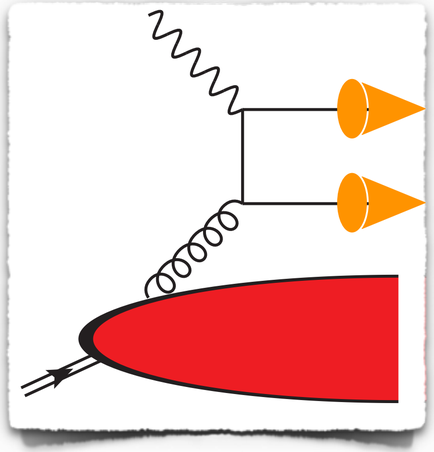
TMD FF

TMD PDF

Backup

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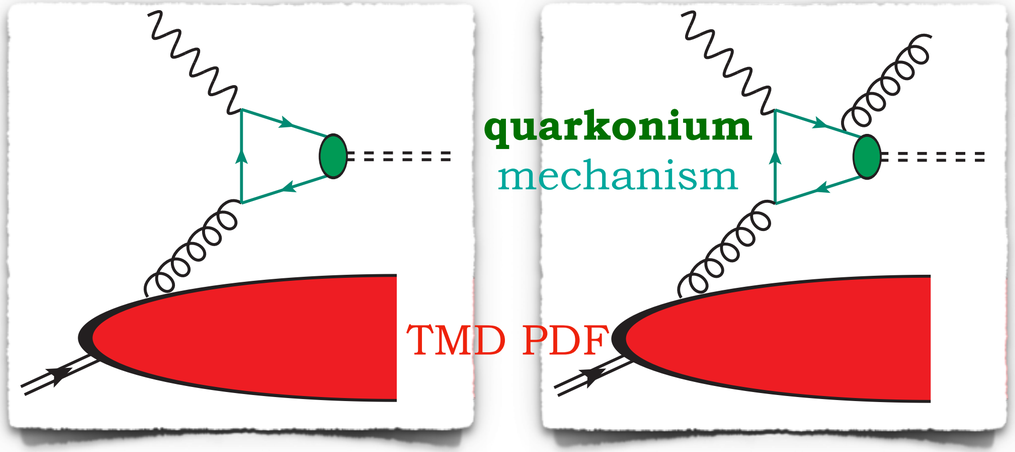


jet function

jet function

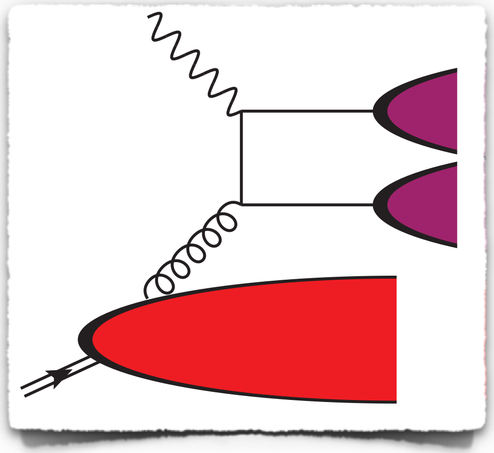
TMD PDF

Quarkonia



quarkonium
mechanism

Double D meson



TMD FF

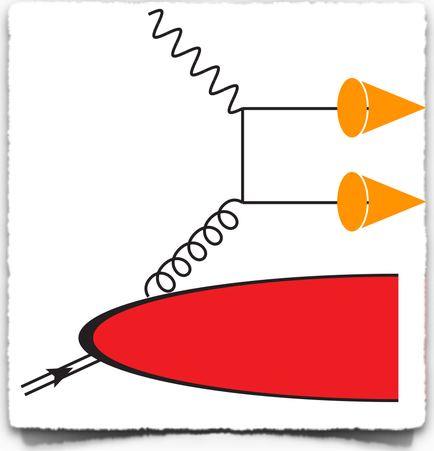
TMD FF

TMD PDF

Backup

Golden channels for gluon TMD PDFs @EIC

Two-jet SIDIS

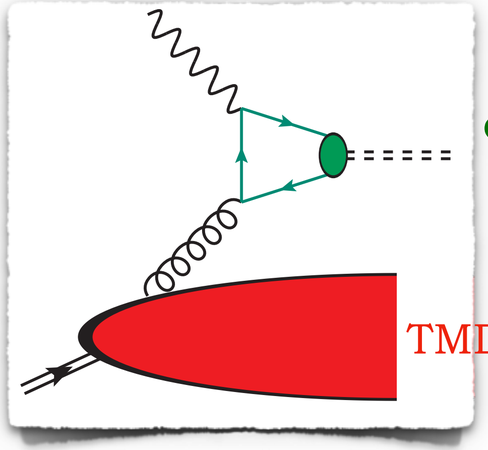


jet function

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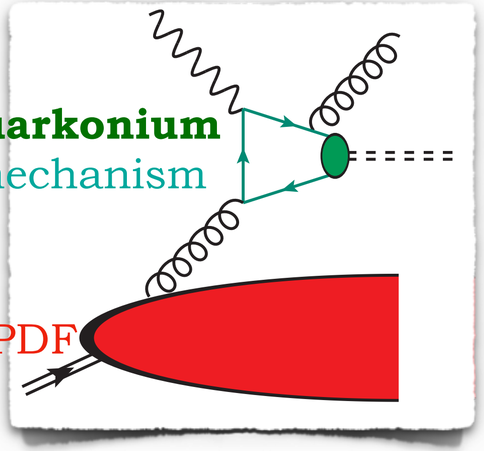
TMD PDF

Quarkonia

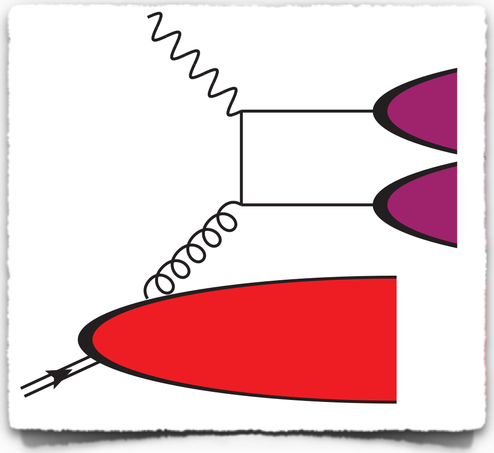


TMD PDF

quarkonium
mechanism



Double D meson

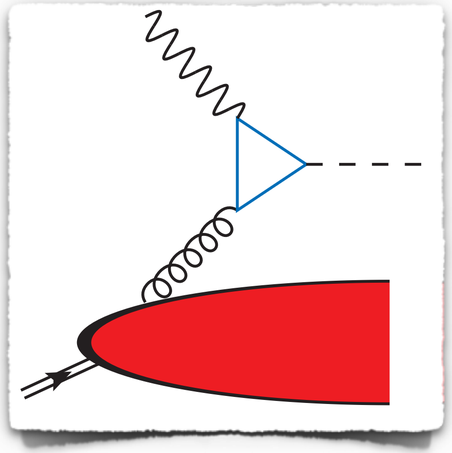


TMD FF

TMD FF

TMD PDF

…an EIC theorist's dream



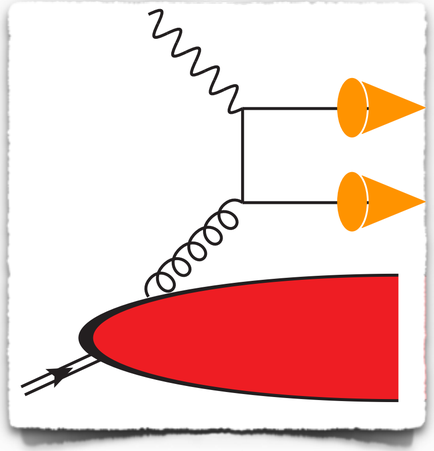
Higgs

TMD PDF

Backup

Golden channels for gluon TMD PDFs @EIC

Two-jet SIDIS

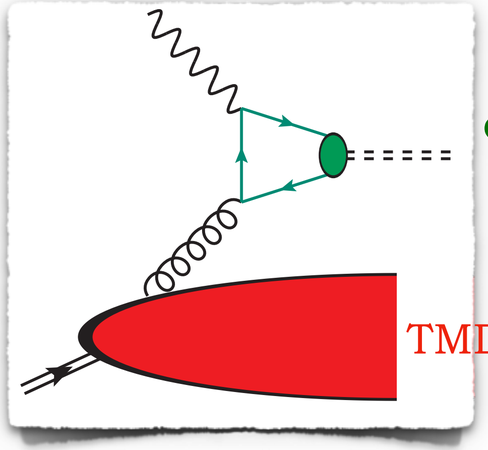


jet function

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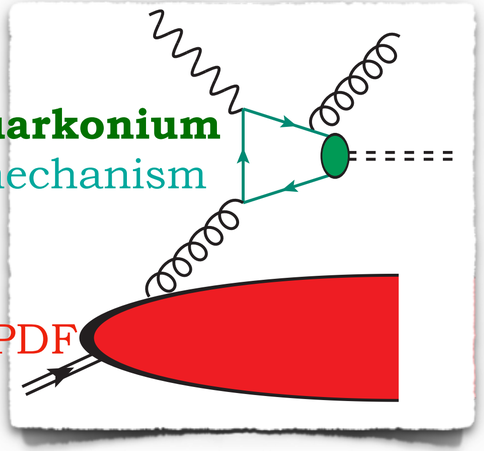
TMD PDF

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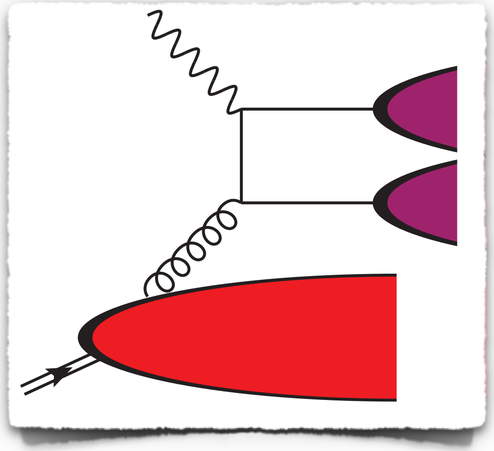


TMD PDF

quarkonium mechanism



Double D meson

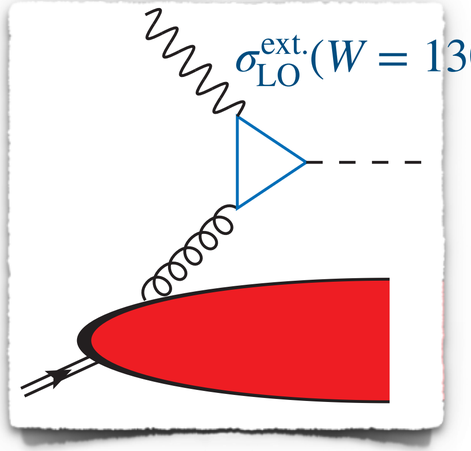


TMD FF

TMD FF

TMD PDF

...an EIC theorist's dream



$\sigma_{\mathrm{LO}}^{\mathrm{ext.}}(W = 130\,\mathrm{GeV}) \sim 110\,\mathrm{pb}$

Higgs

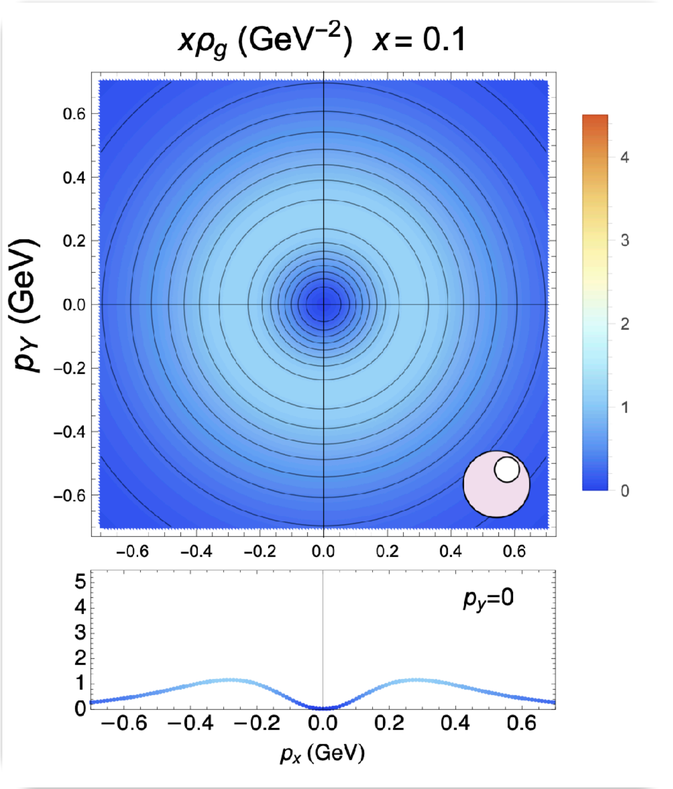
TMD PDF

Backup

3D proton imaging: Tomographic reconstruction & TMDs

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

Unpolarized

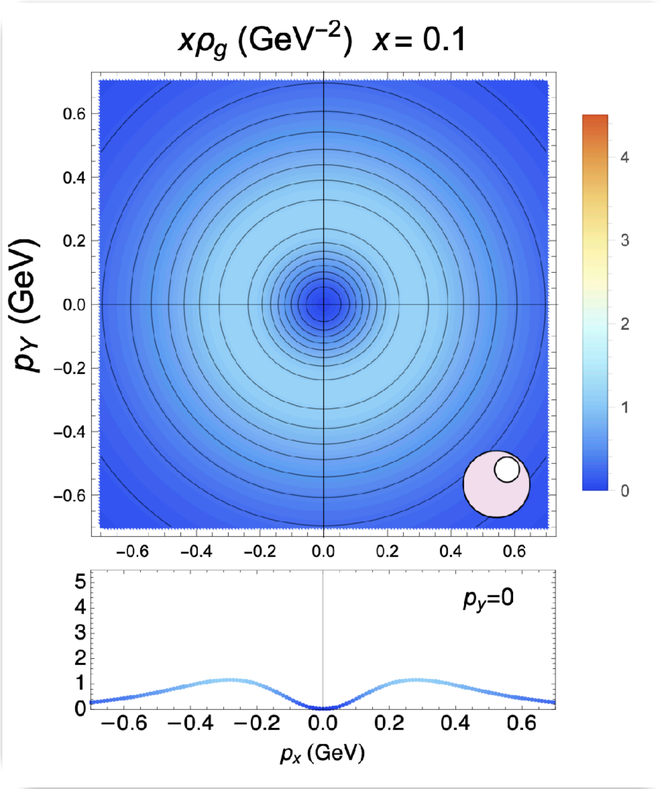


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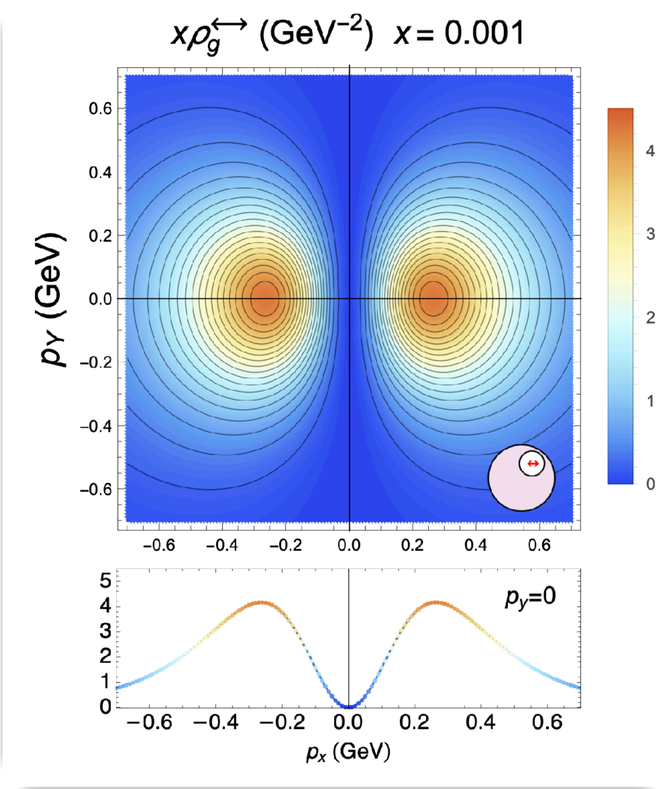
3D proton imaging: Tomographic reconstruction & TMDs

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

Unpolarized



Boer-Mulders



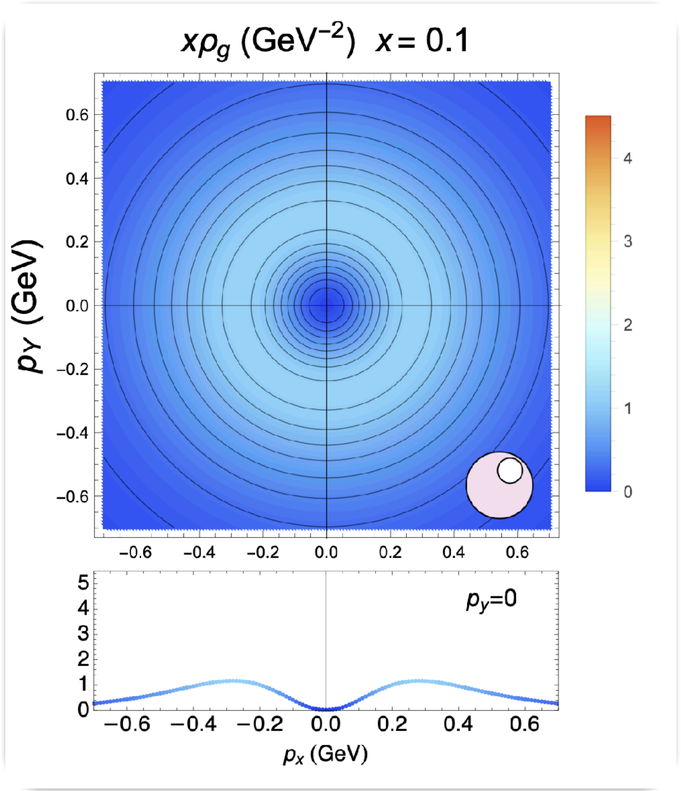
$$x\rho^{\leftrightarrow}(x, p_x, p_y) = \frac{1}{2}\left[x f_1^g(x, \boldsymbol{p}_T^2) + \frac{p_x^2 - p_y^2}{2M^2}\, x h_1^{\perp g}(x, \boldsymbol{p}_T^2)\right]$$

Backup

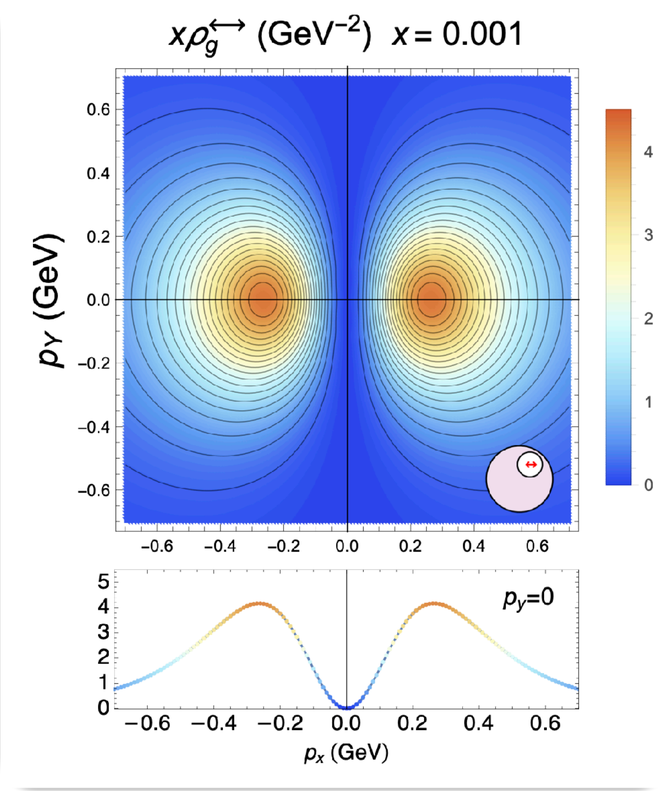
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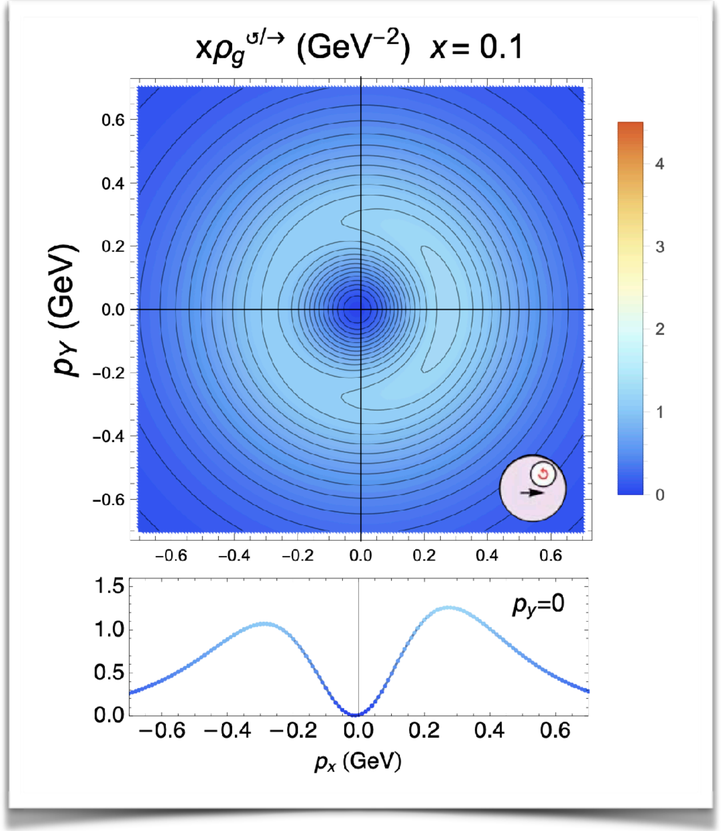
Unpolarized



Boer-Mulders



Worm-gear



$$x\rho^{\leftrightarrow}(x, p_x, p_y) = \frac{1}{2}\left[x f_1^g(x, \boldsymbol{p}_T^2) + \frac{p_x^2 - p_y^2}{2M^2}\, x h_1^{\perp g}(x, \boldsymbol{p}_T^2)\right]$$

$$x\rho^{\circlearrowleft/\rightarrow}(x, p_x, p_y) = x f_1^g(x, \boldsymbol{p}_T^2) - \frac{p_x}{M}\, x g_{1T}^g(x, \boldsymbol{p}_T^2)$$

Backup

Anatomy of gluon TMD PDFs

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

Backup

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Model input

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Backup

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perturbative expansion in $\alpha_s(\mu)$

perturbative Sudakov

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

Model input

define logarithmic ordering

slide adapted from C. Bissolotti

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

Backup

Anatomy of gluon TMD PDFs

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nonperturbative Sudakov

nonperturbative TMD function

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

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Model input

define logarithmic ordering

slide adapted from C. Bissolotti

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

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

¿ Suppression of genuine NP effects ?

Backup

Quarkonia & Gluon TMDs: A path toward precision

TMD PDFs & shape functions

NRQCD ⇒ double expansion: $\alpha_s \oplus v$

NRQCD ⇒ $\mathrm{d}\sigma(|\mathcal{Q}\rangle) \propto \mathscr{H} \otimes \mathrm{LDME}$

$$|\mathcal{Q}\rangle = \mathcal{O}(1)\,|Q\bar{Q}[^3S_1^{(1)}]\rangle + \mathcal{O}(v)\,|Q\bar{Q}[^3P_J^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^1S_0^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3S_1^{(1,8)}gg]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3D_J^{(1,8)}gg]\rangle + \dots .$$

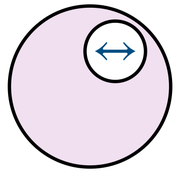
S-wave quarkonium wave function

TMD ⇒ from LDMEs to shape functions (ShFs)

2 mechanisms: bound state + soft-gluon

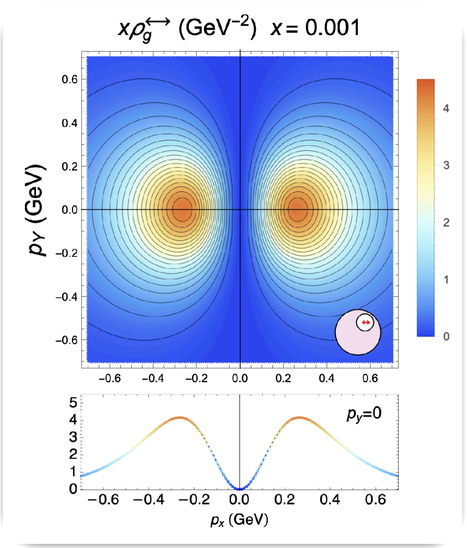
(factorization) [M. Garcia Echevarria (2019)]
(SCET) [S. Fleming, Y. Makris, T. Mehen (2020)]
(unpol. J/ψ) [D. Boer, U. D'Alesio, F. Murgia, C. Pisano, P. Taels (2020)]
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3D proton imaging: LHC & EIC



EIC, LHCb, FT@LHC

Boer-Mulders



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

Backup

Quarkonia & Gluon TMDs: A path toward precision

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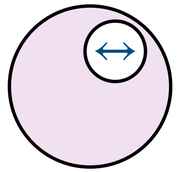
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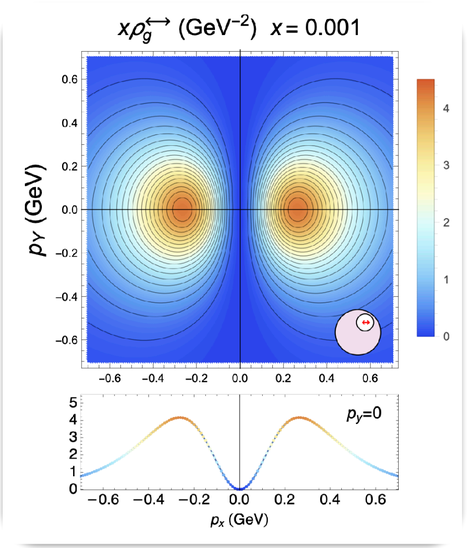
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3D proton imaging: LHC & EIC

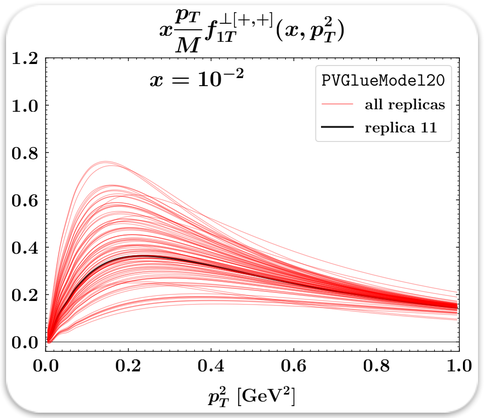


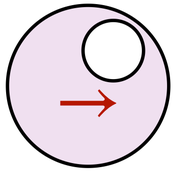
EIC, LHCb, FT@LHC

Boer-Mulders



[A. Bacchetta, F.G. C., M. Radici, P. Taels (EPJC 2020)]
[A. Bacchetta, F.G. C., M. Radici (EPJC 2024)]





EIC, LHCspin

Sivers

Backup

Quarkonia: A path toward precision

TMD PDFs & shape functions

NRQCD $\Rightarrow$ double expansion: $\alpha_s \oplus v$

NRQCD $\Rightarrow$ $\mathrm{d}\sigma(|\mathcal{Q}\rangle) \propto \mathscr{H} \otimes \mathrm{LDME}$

$$|\mathcal{Q}\rangle = \mathcal{O}(1)\,|Q\bar{Q}[^3S_1^{(1)}]\rangle + \mathcal{O}(v)\,|Q\bar{Q}[^3P_J^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^1S_0^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3S_1^{(1,8)}gg]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3D_J^{(1,8)}gg]\rangle + \ldots.$$

S-wave quarkonium wave function

Backup

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S-wave quarkonium wave function

- TMD ⇒ from LDMEs to shape functions (ShFs)
- 2 mechanisms: bound state + soft-gluon

(factorization) 🔗 [M. Garcia Echevarria (2019)]
(SCET) 🔗 [S. Fleming, Y. Makris, T. Mehen (2020)]
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Backup

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Revised TMD shape function in SIDIS

$$\Delta^{[n]}(\boldsymbol{\kappa_T}^2) \propto \frac{\alpha_s}{2\pi^2 \boldsymbol{\kappa_T}^2} C_A \left(1 + \ln \frac{M_{\mathbb{Q}}^2}{M_{\mathbb{Q}}^2 + Q^2}\right) \langle O[n] \rangle$$

Backup

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- 2 mechanisms: bound state + soft-gluon
- Perturbative tail ⊗ LDME
- ShFs and TMD FFs exhibit different divergences

Backup

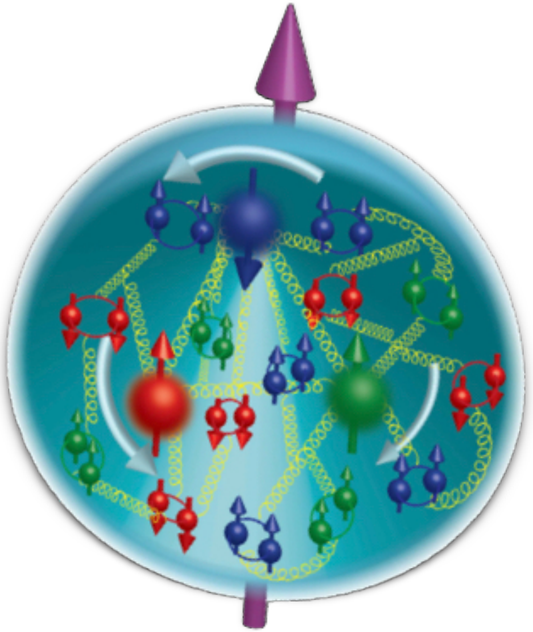
TMD FACTORIZATION

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

Parton densities: Hors d'œuvre

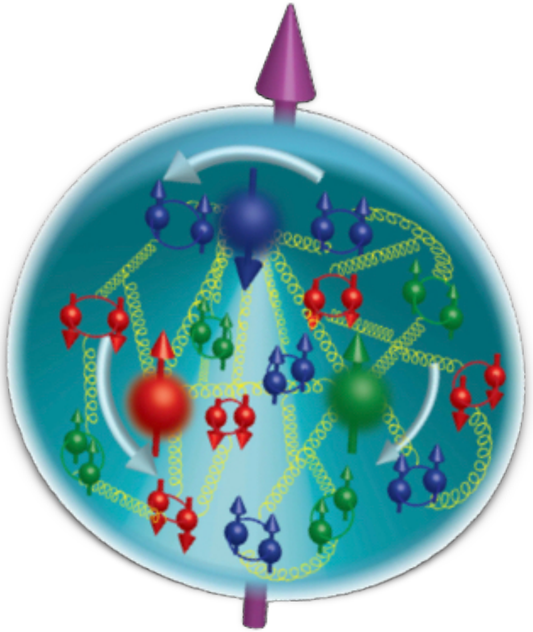
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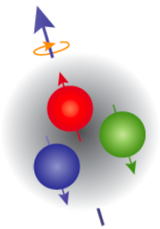
Several types of distributions (1D collinear, **3D TMD**, **3D GPD**, …)

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



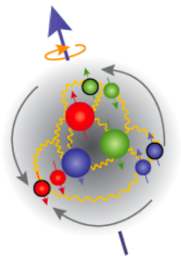
Backup

The proton spin crisis



quarks helicity

~ 30 %



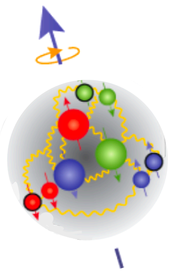
orbital angular momentum

¡ unknown !

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

gluons helicity

~ 20% – 50 % **?**



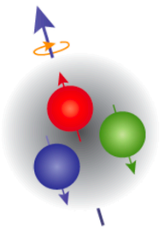
Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description…

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

slide adapted from C. Bissolotti

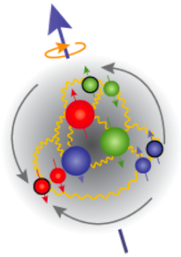
Backup

The proton spin crisis



quarks helicity

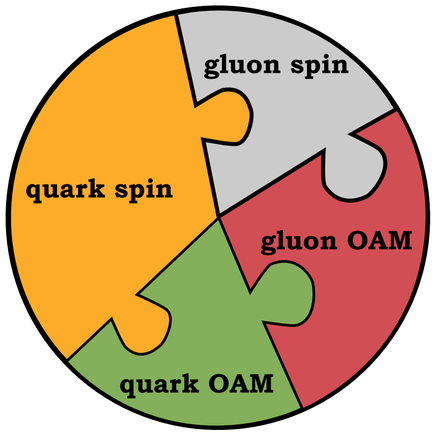
~ 30 %



orbital angular momentum

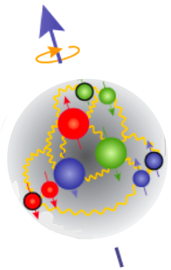
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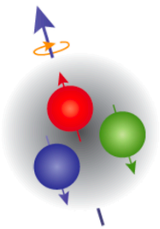
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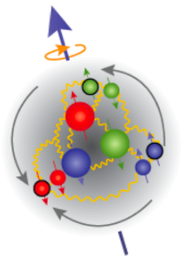
Backup

The proton spin crisis



quarks helicity

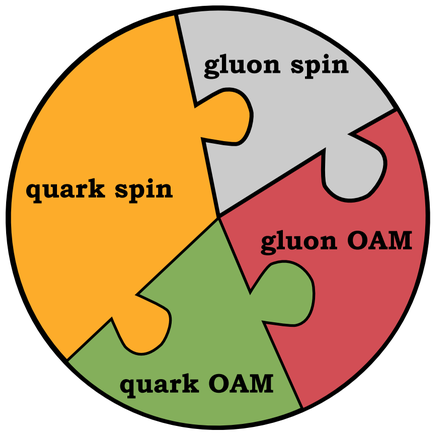
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orbital angular momentum

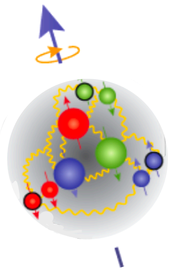
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…many other effects in hadronic interactions cannot be understood in the purely collinear approach

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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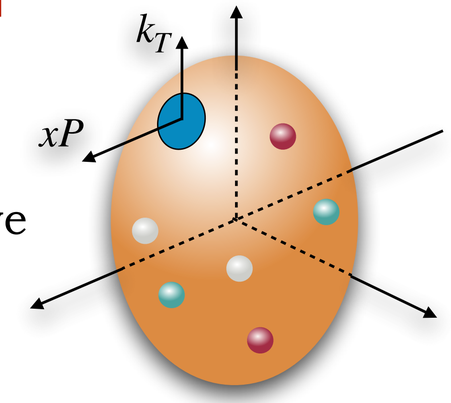
Backup

Parton densities: an incomplete family tree

3D

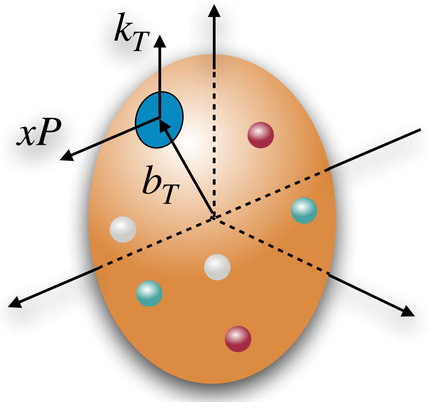
TMDs

(semi-)inclusive



5D

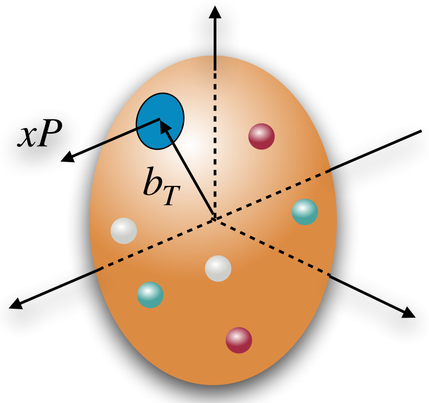
Wigner distributions



3D

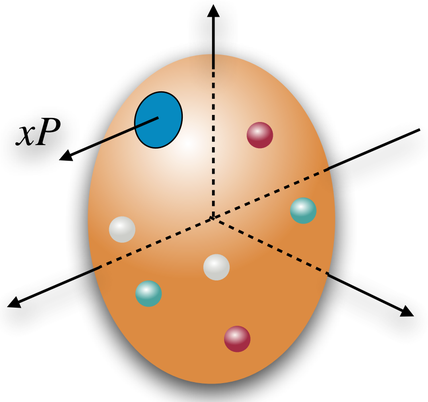
FT of GPDs

exclusive

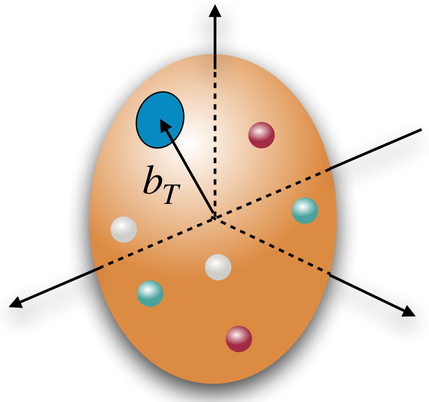


PDFs

(semi-)inclusive



FT of Form Factors



1D

$\vec{b}_\perp$ dependence

$\vec{k}_\perp$ dependence

these two variables are NOT Fourier conjugate

2D

Backup

Gluon TMD PDFs: Gauge links & modified universality

* 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

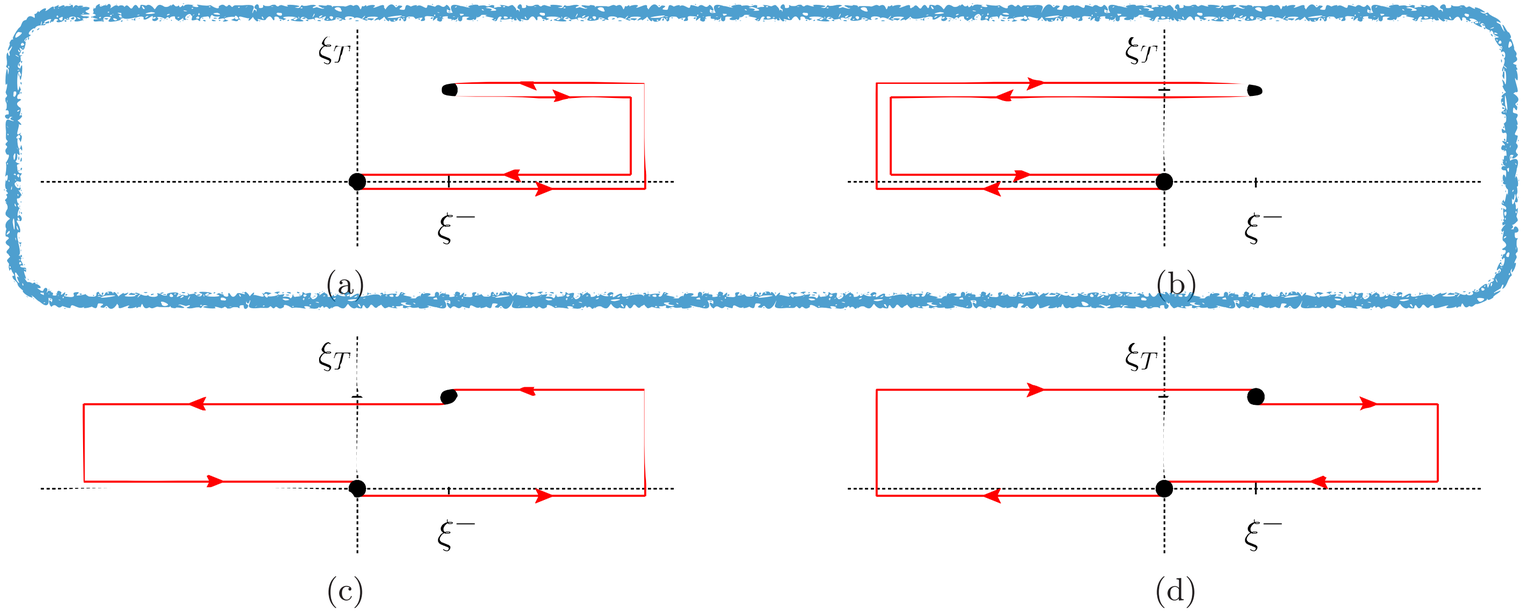
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f-type (WW)

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



Backup

Gluon TMD PDFs: Gauge links & modified universality

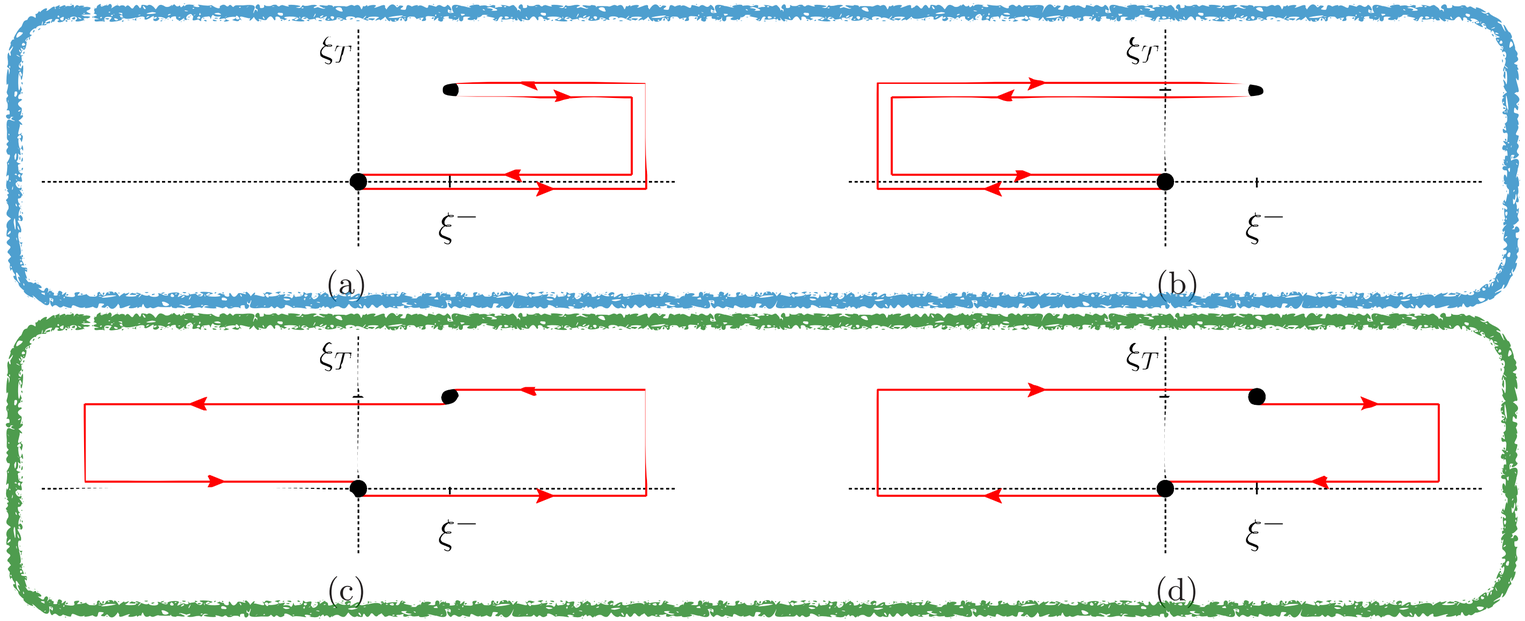
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f-type (WW)

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

d-type (dipole)

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



Backup

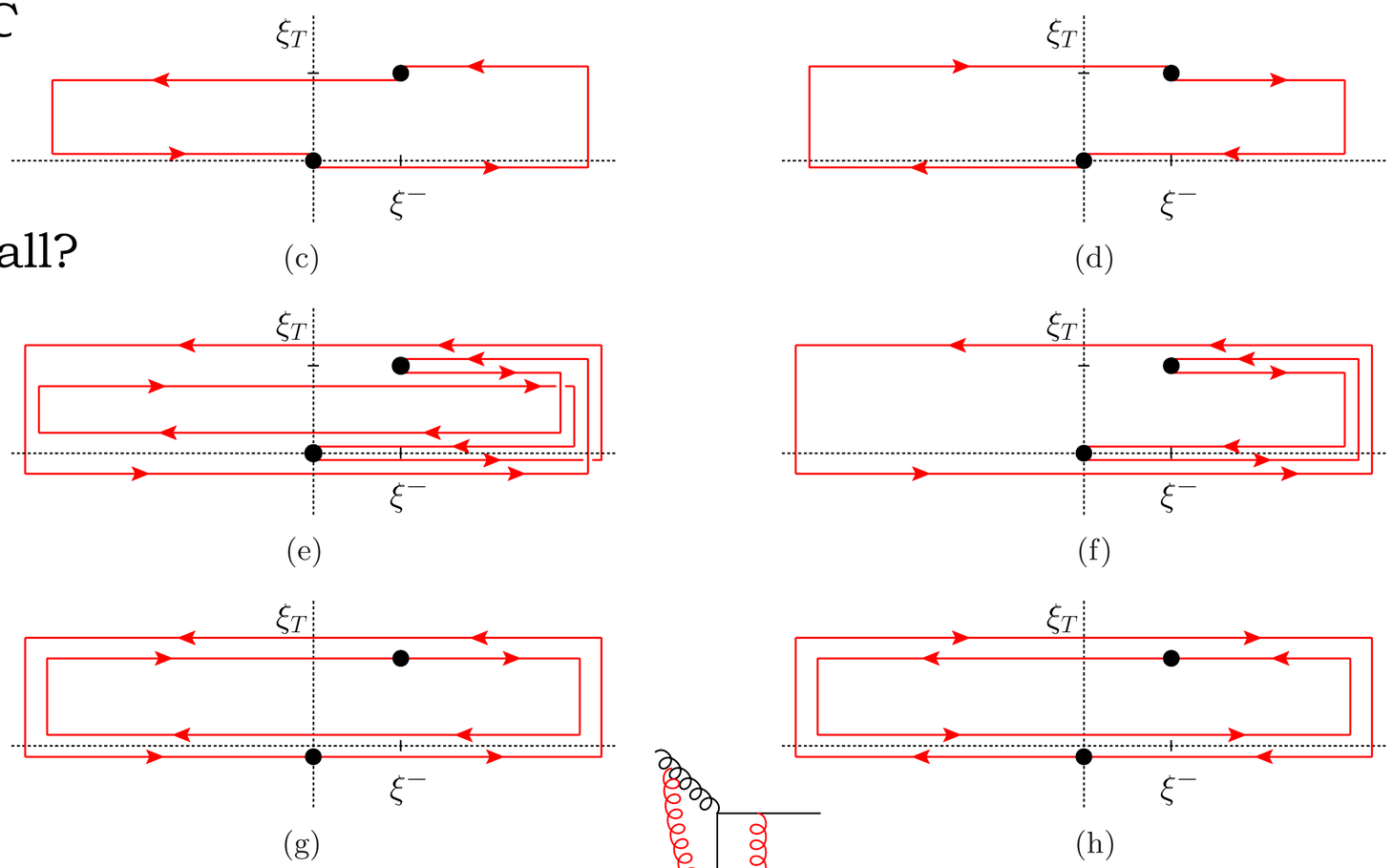
Dihadron hadroproduction and factorization breaking

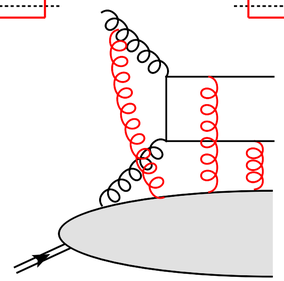
* Proof of factorization violation 🔗 [T. J. Rogers, P. J. Mulders (2010)]
* Assumed factorization in SCET and CGC
* Significance of low-x studies
* Size of factorization-breaking effects small?
* DP TMDs:

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

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

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

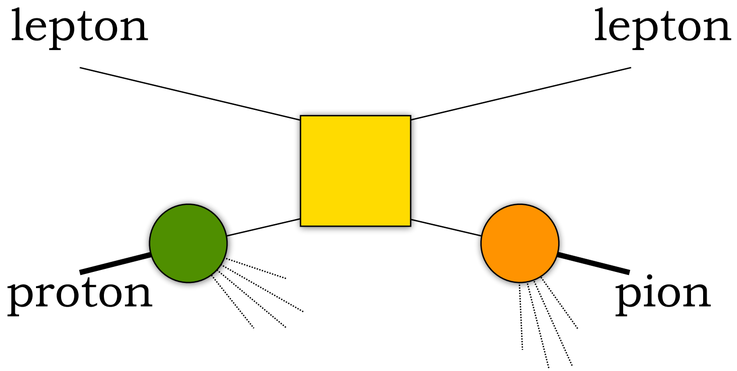




Backup

Factorization and universality

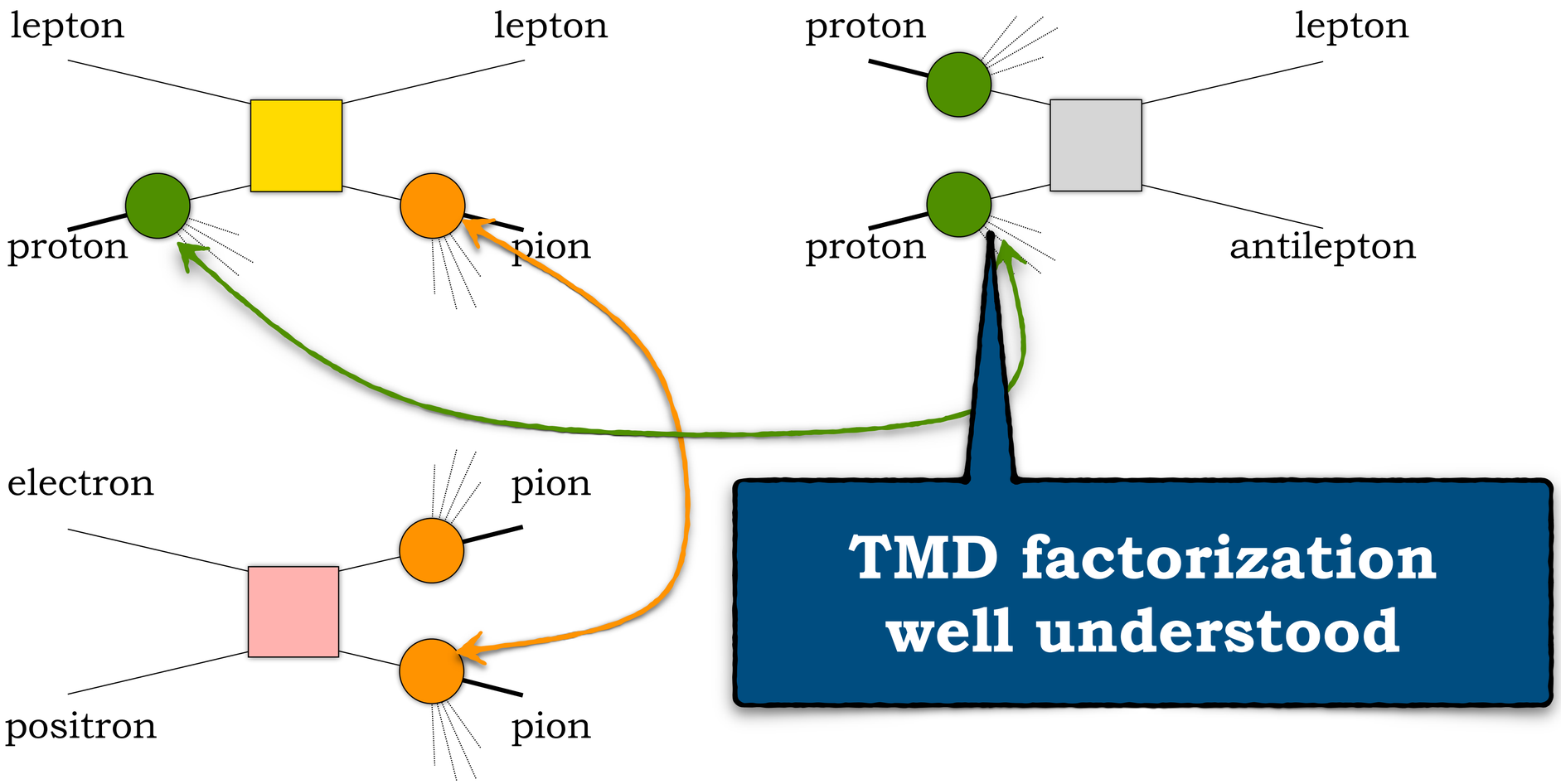
SIDIS



Backup

Factorization and universality

SIDIS **Drell-Yan**

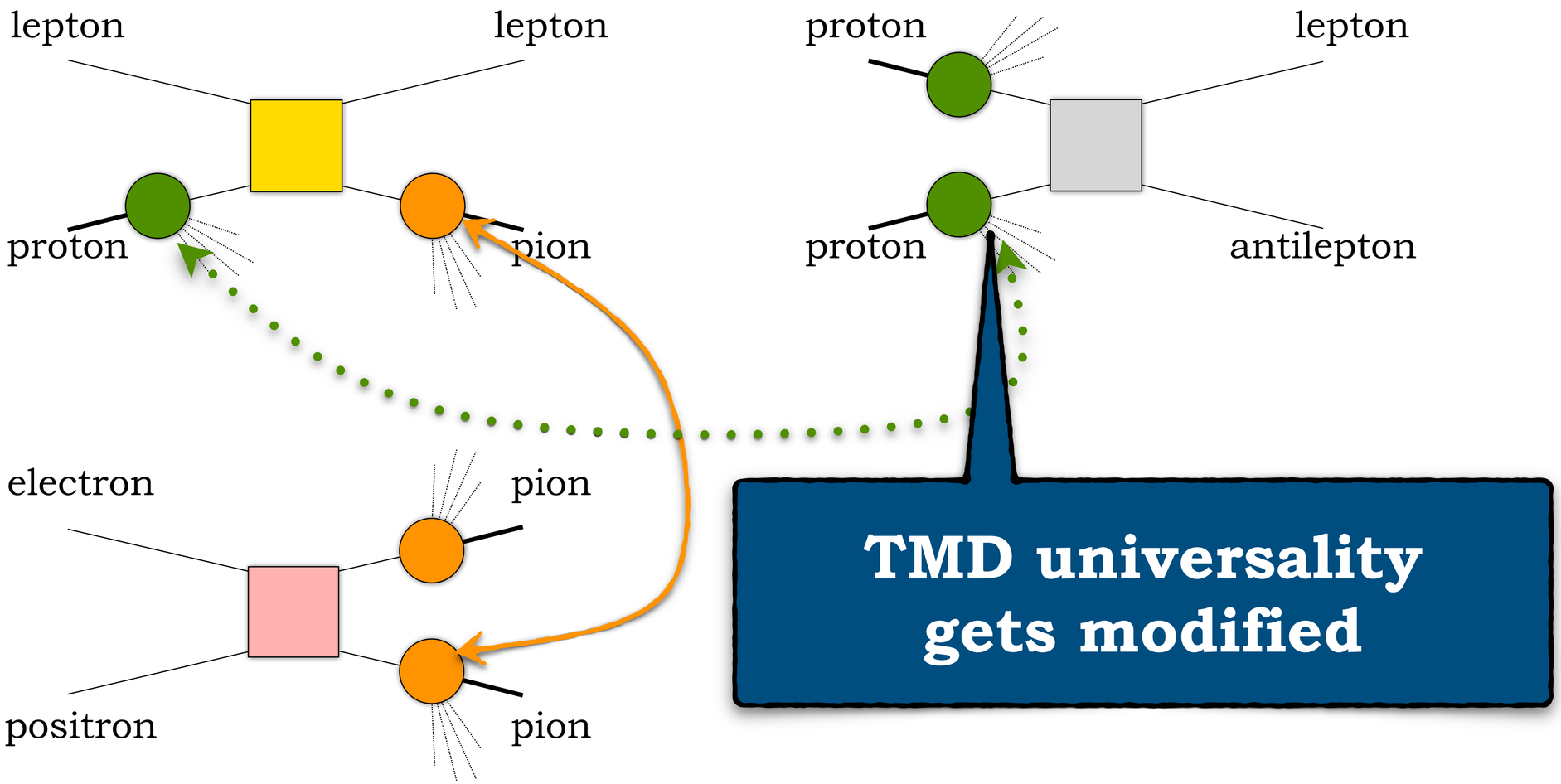


$e^+ + e^- \rightarrow$ **hadrons**

Backup

Factorization and universality

SIDIS **Drell-Yan**

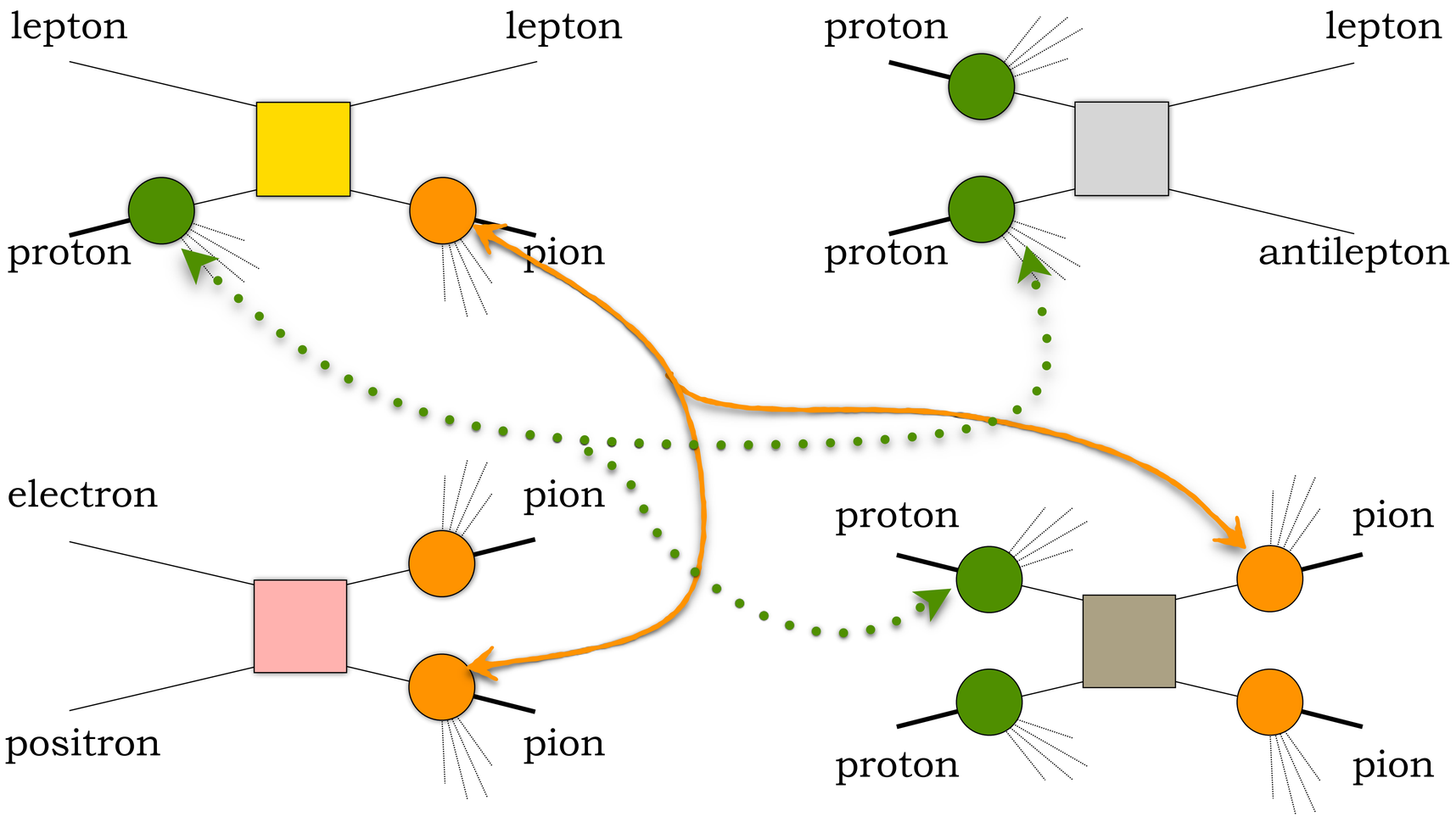


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Backup

Factorization and universality

SIDIS **Drell-Yan**



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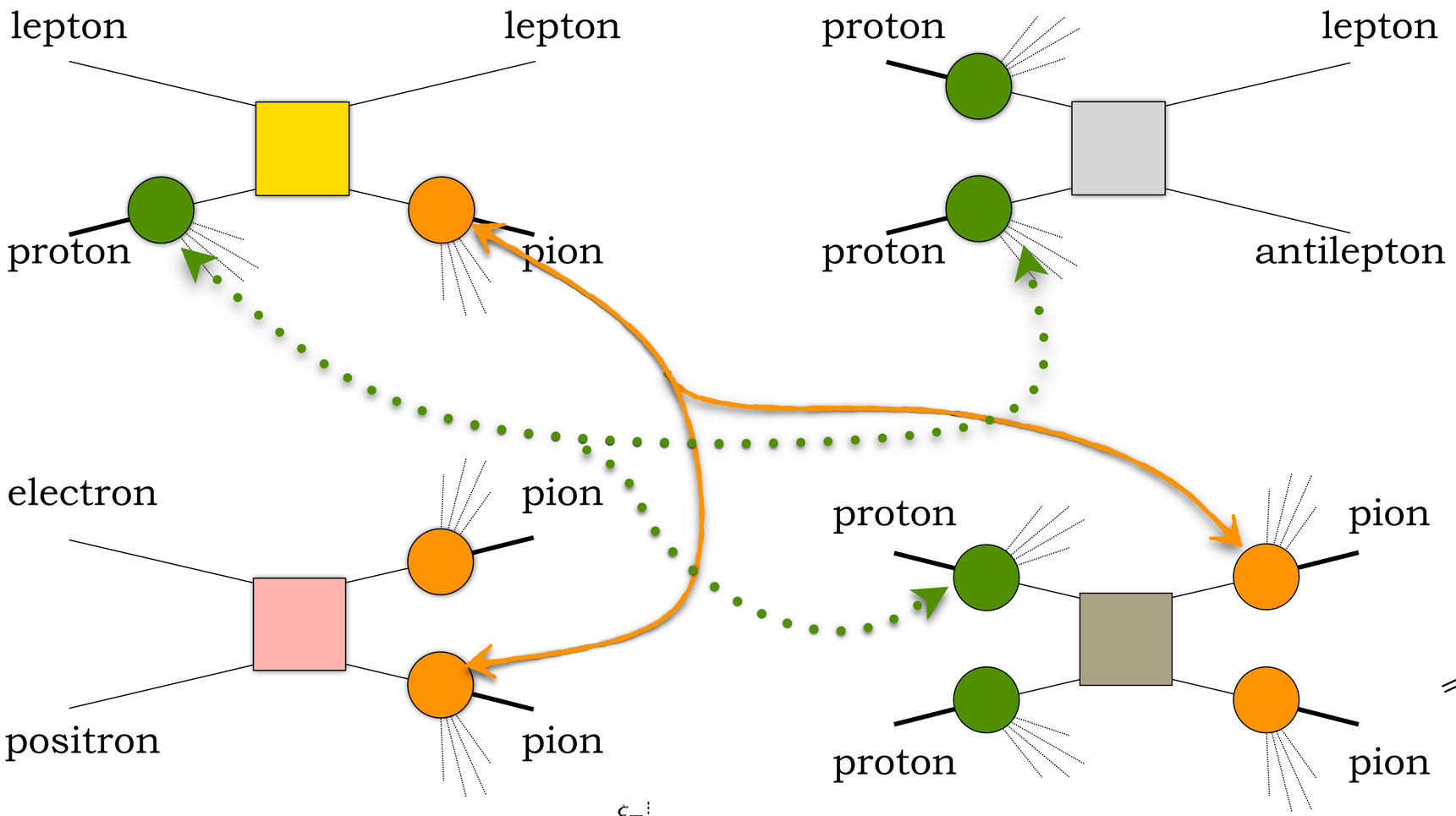
$p + p \rightarrow$ **hadrons**

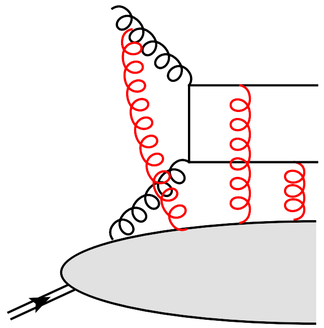
Backup

Factorization and universality

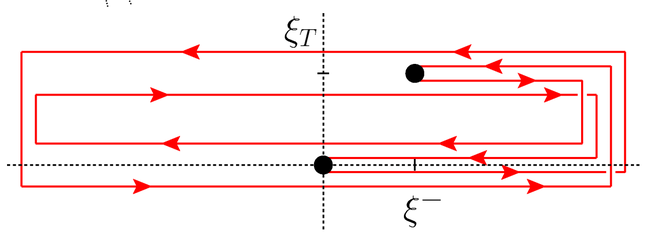
SIDIS

Drell-Yan





$e^+ + e^- \rightarrow$ **hadrons**



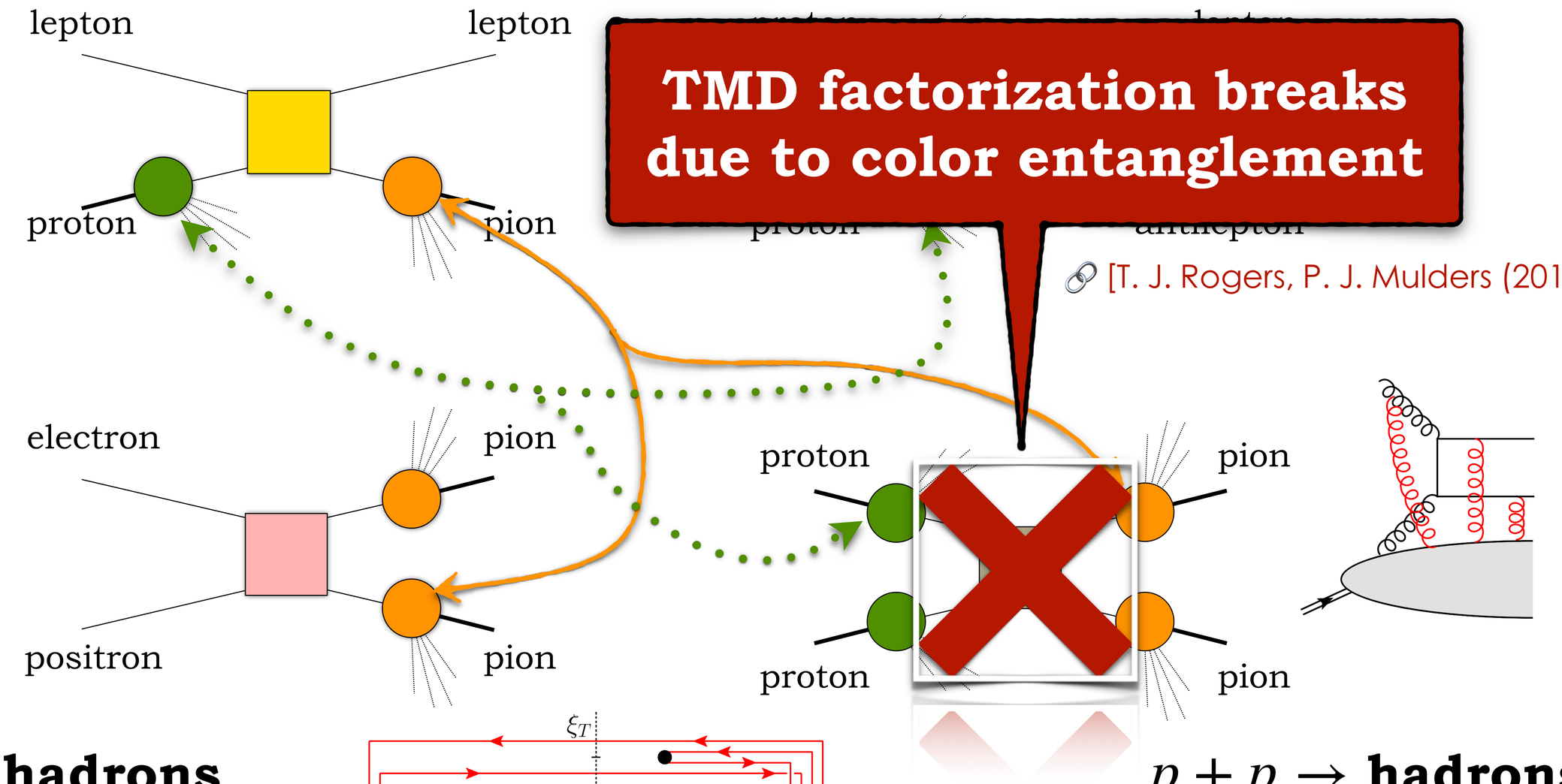
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(also) gluon-induced channel

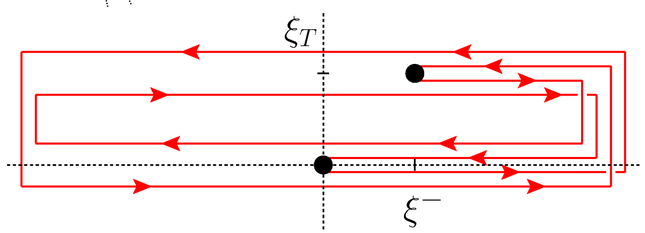
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Factorization and universality

SIDIS **Drell-Yan**



$e^+ + e^- \to$ **hadrons**



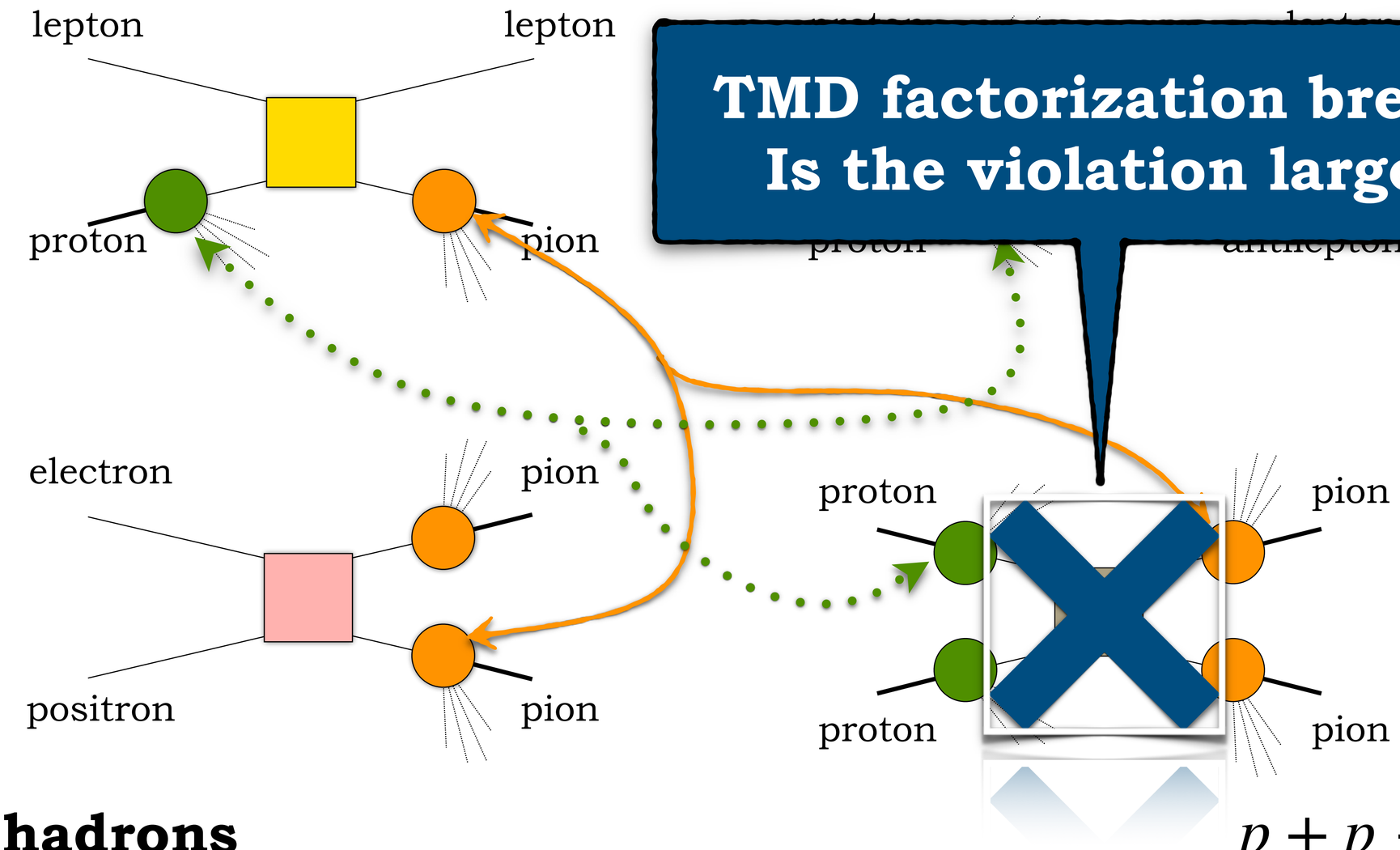
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(also) gluon-induced channel

Backup

Factorization and universality

SIDIS **Drell-Yan**



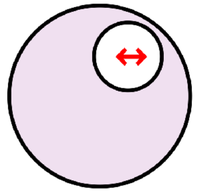
$e^+ + e^- \rightarrow$ **hadrons**

$p + p \rightarrow$ **hadrons**

Backup

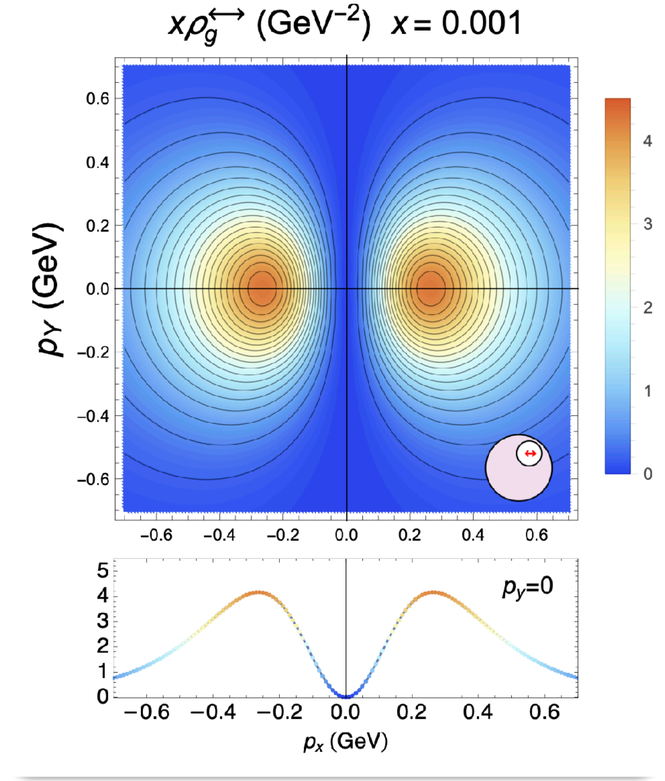
ACCESSING GLUON TMDS @LHC

Boer-Mulders effect in unpolarized pp collisions



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

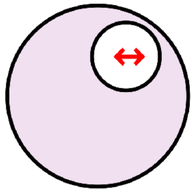
unpol. Boer-Mulders



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

Backup

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

$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \, \Phi_B^U \, |\mathcal{M}|^2 \qquad \text{at low transverse momentum for (pseudo)scalar state}$$

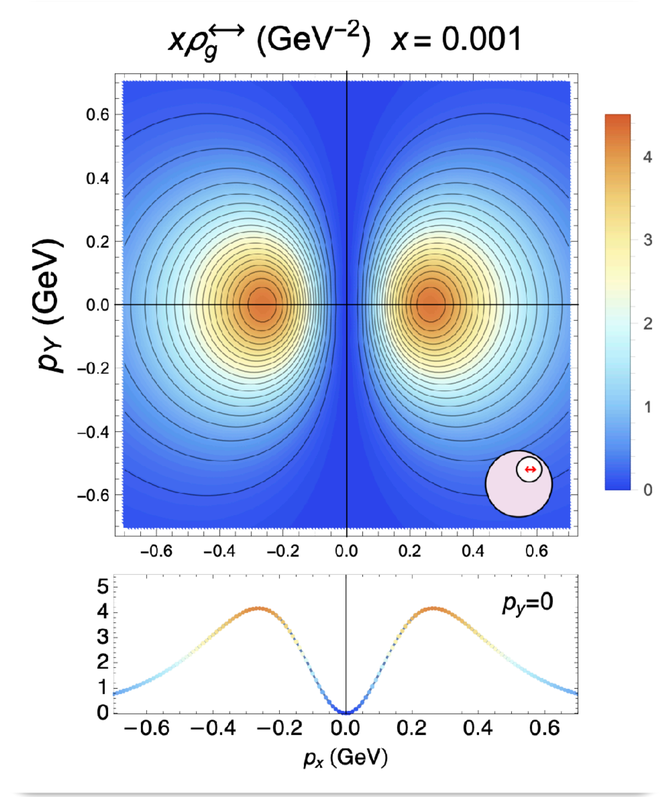
$$\sim \mathcal{C}[\, f_1^{g/A} \, f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \, h_1^{\perp g/B} \,]$$

$\mathcal{C}[\, f_1^{g/A} \, f_1^{g/B} \,]$: **unpolarized** gluons

$\mathcal{C}[\, h_1^{\perp g/A} \, h_1^{\perp g/B} \,]$: **lin. polarized** gluons

NRQCD

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

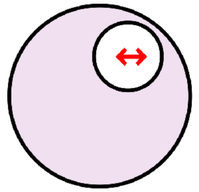


[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

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

Backup

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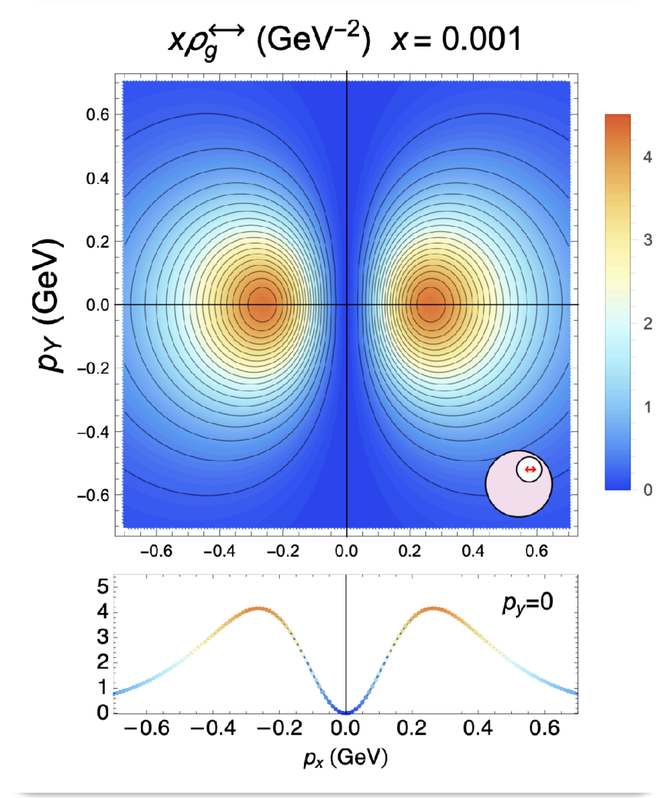
at low transverse momentum for (pseudo)scalar state

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

unpolarized gluons — **lin. polarized** gluons

NRQCD

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



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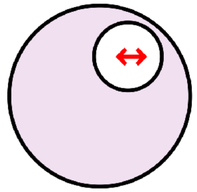
[A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

Model prediction at low x

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

Backup

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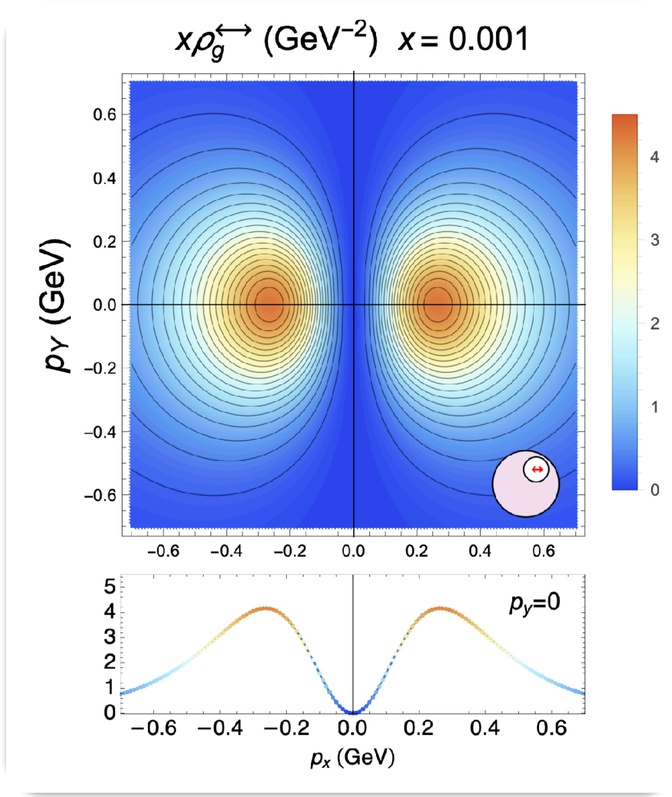
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BFKL regime (linear low-x evolution)

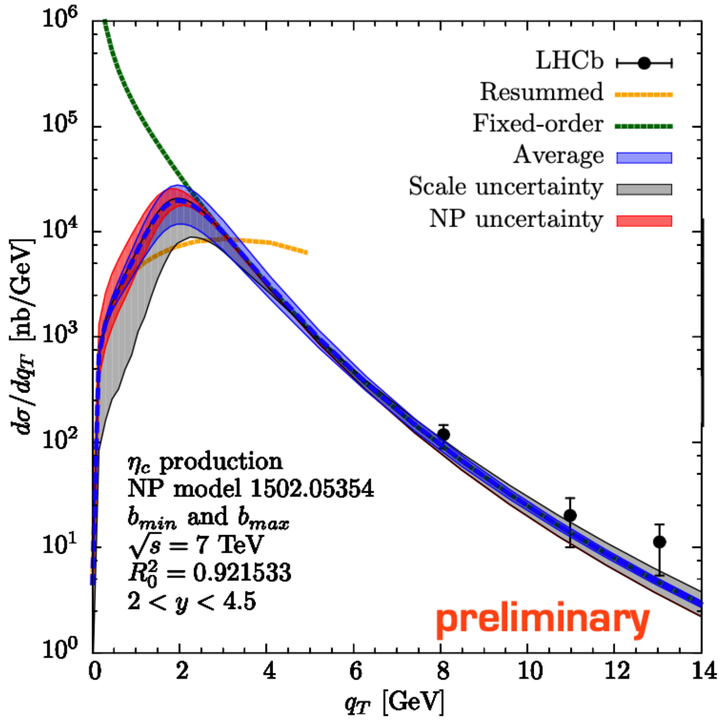
$$f_1^g(x,p_T^2) = h_1^{\perp g}(x,p_T^2) + \text{higher twist}$$

Backup

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

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

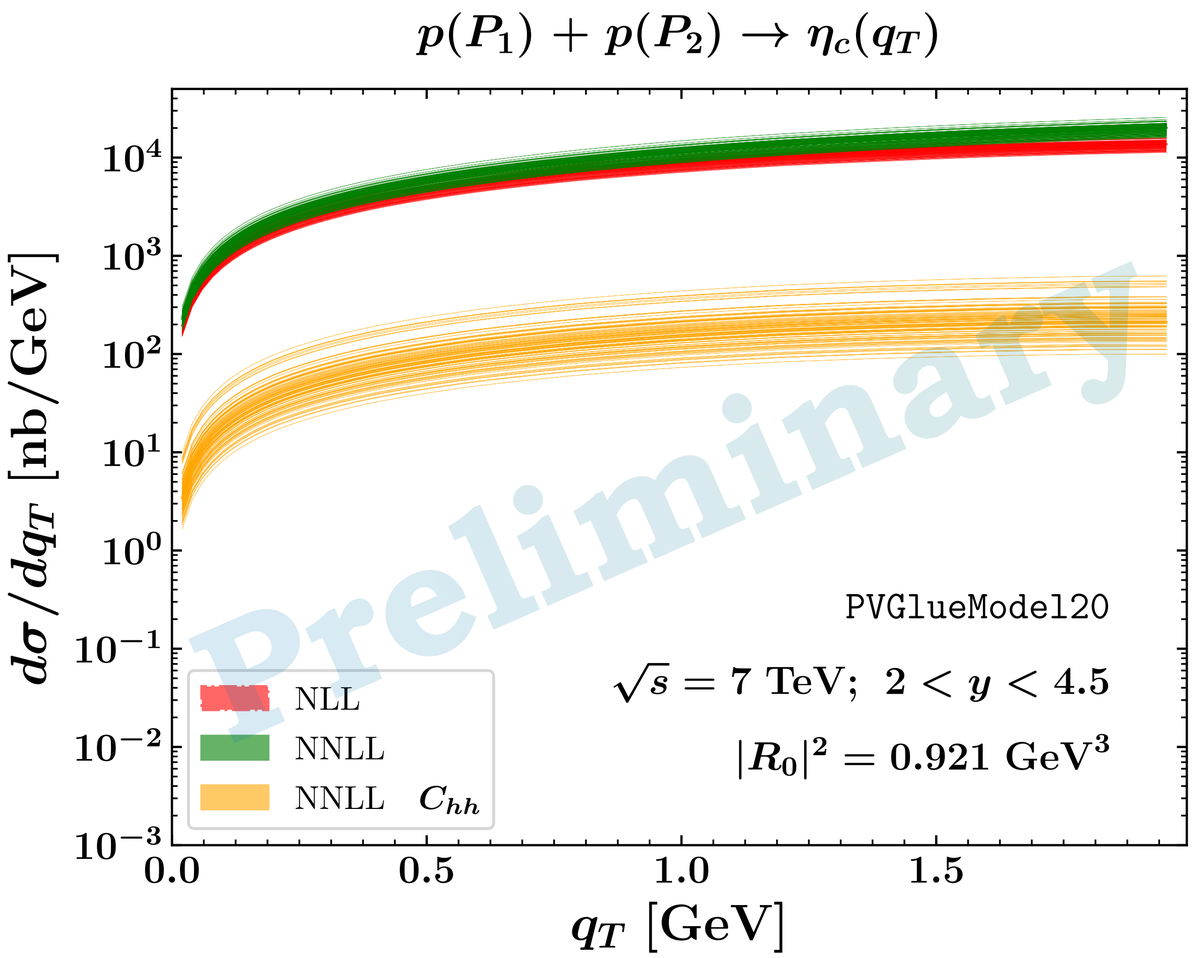
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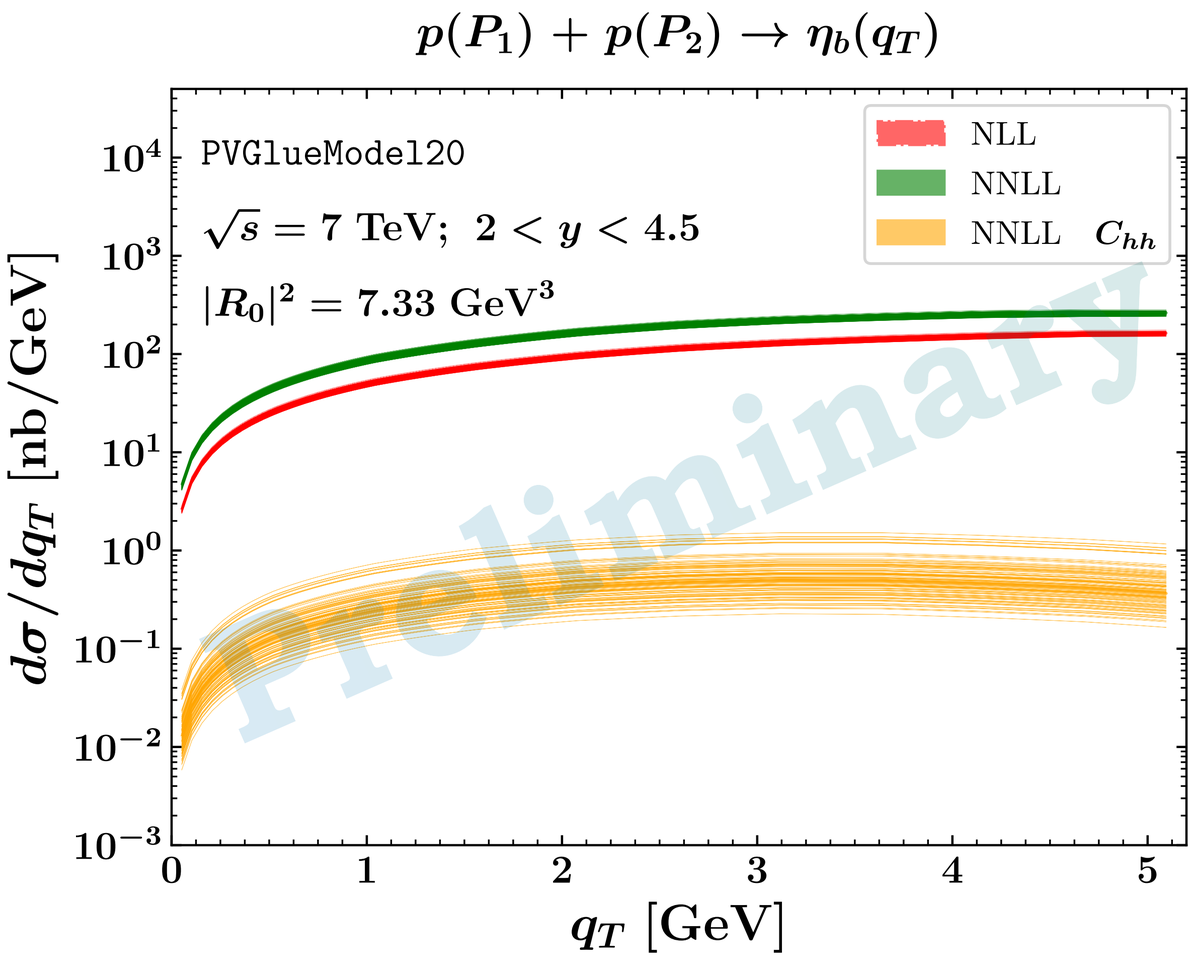
slide by Andrea Signori (INT 2017)

Backup

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

Perturbative scales fixed, NP-evolution parameters fixed, TMD 100-replica analysis, NRQCD w/o ShFs





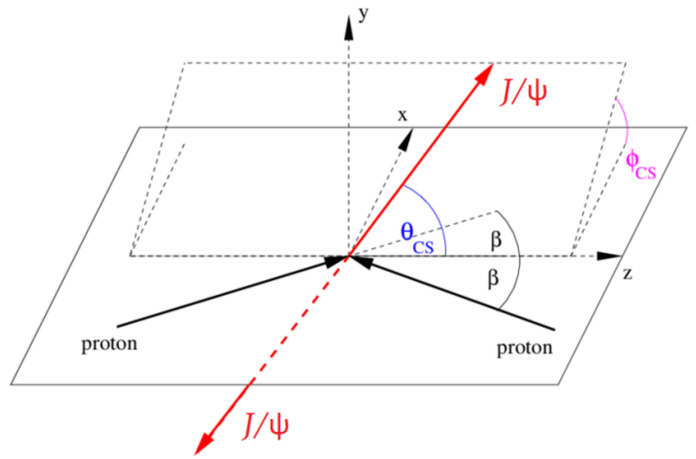
[A. Bacchetta, F.G.C., M.G. Echevarria, J.-P. Lansberg, M. Ozcelik, M. Radici, A. Signori (to appear)]

Backup

Double J/ψ production @(HL-)LHC

- More spin asymmetries, measurable @HL-LHC

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{QQ}\mathrm{d}Y_{QQ}\mathrm{d}^2\boldsymbol{P}_{QQ_T}\mathrm{d}\Omega} = \frac{\sqrt{Q^2-4M_Q^2}}{(2\pi)^2 8s\,Q^2}\Big\{F_1\,C\Big[f_1^g f_1^g\Big] + F_2\,C\Big[w_2 h_1^{\perp g} h_1^{\perp g}\Big] + \cos 2\phi_{\mathrm{CS}}\Big(F_3 C\Big[w_3 f_1^g h_1^{\perp g}\Big] + F_3' C\Big[w_3' h_1^{\perp g} f_1^g\Big]\Big) + \cos 4\phi_{\mathrm{CS}} F_4 C\Big[w_4 h_1^{\perp g} h_1^{\perp g}\Big]\Big\},$$

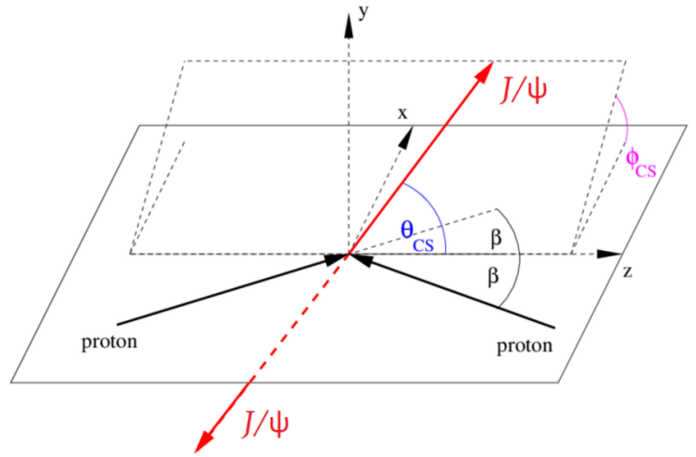


Backup

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TMD Models

[J.-P. Lansberg et al. (2018)]

$$f_1^g(x,\boldsymbol{k}_T^2,\mu) = \frac{g(x,\mu)}{\pi\langle k_T^2\rangle}\exp\Big(-\frac{\boldsymbol{k}_T^2}{\langle k_T^2\rangle}\Big)$$

¿ $f_1^g / h_1^{\perp g}\,(p_T \to 0)$? $\Rightarrow$ $|h_1^{\perp g}| \le f_1^g$

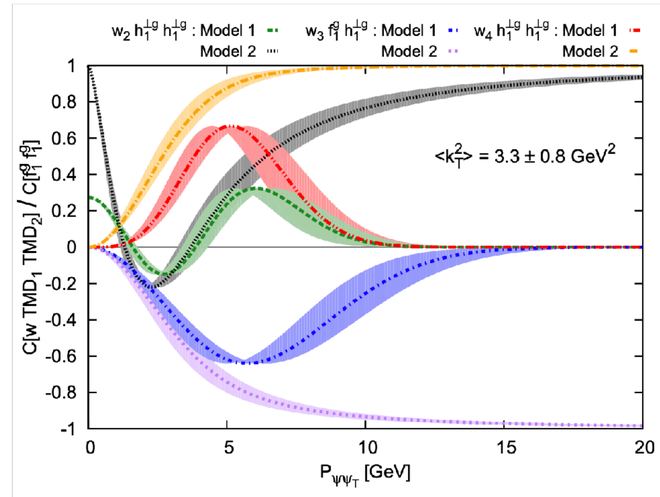
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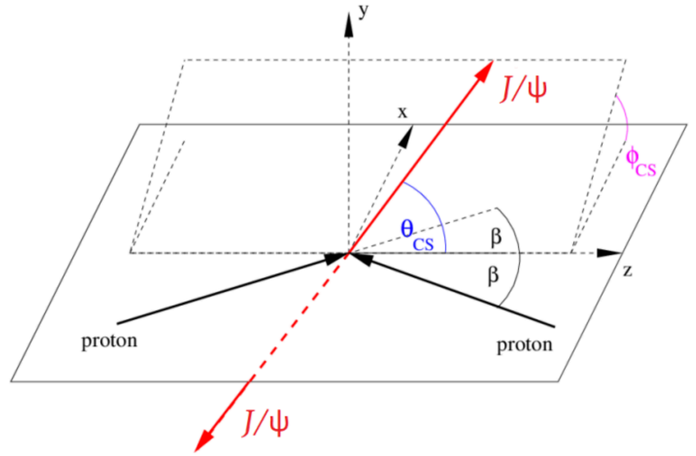
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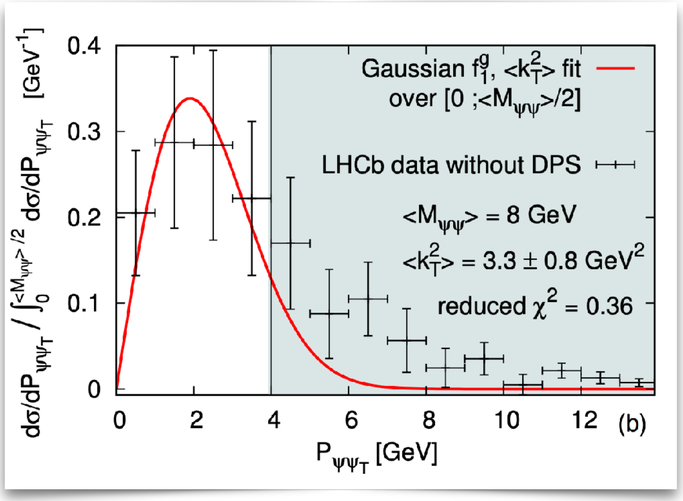
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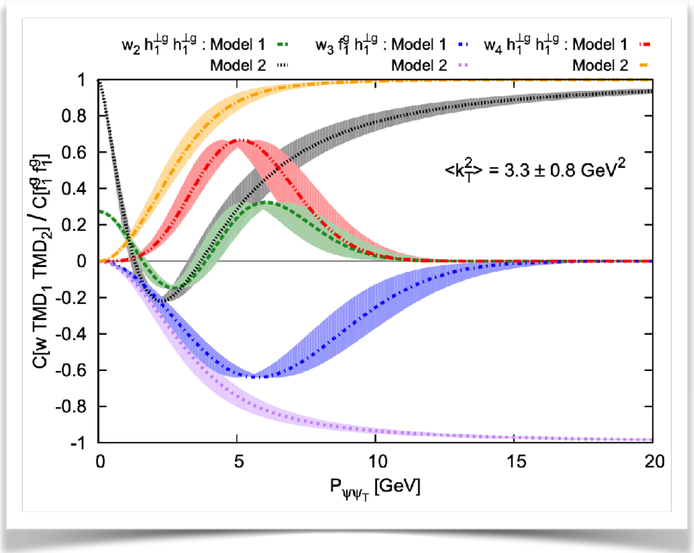
[Model-dependent fit on 13 TeV LHCb data]

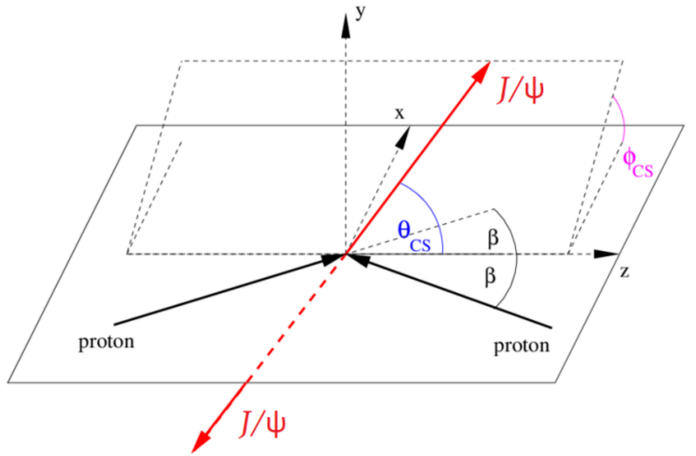
Backup

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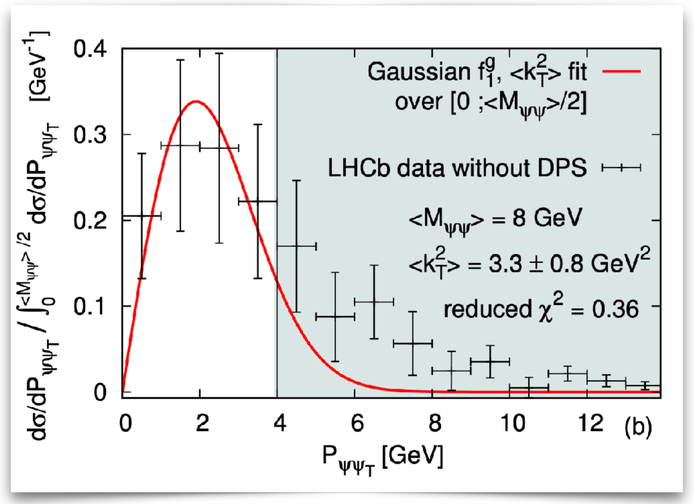
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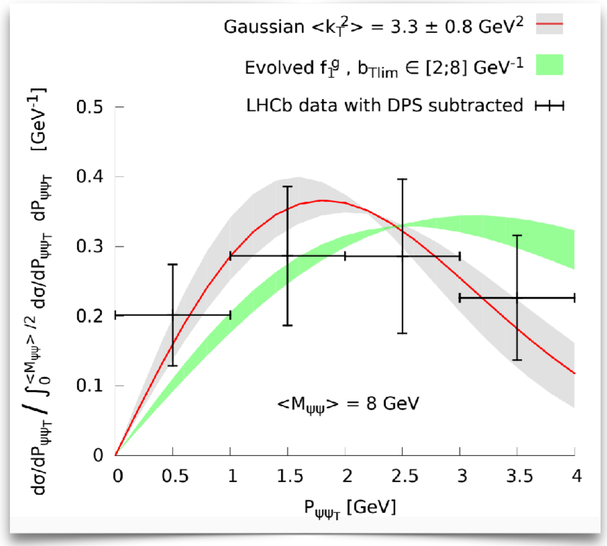
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[Model-dependent fit on 13 TeV LHCb data]

NP + TM resummation



[F. Scarpa et al. (2020)]

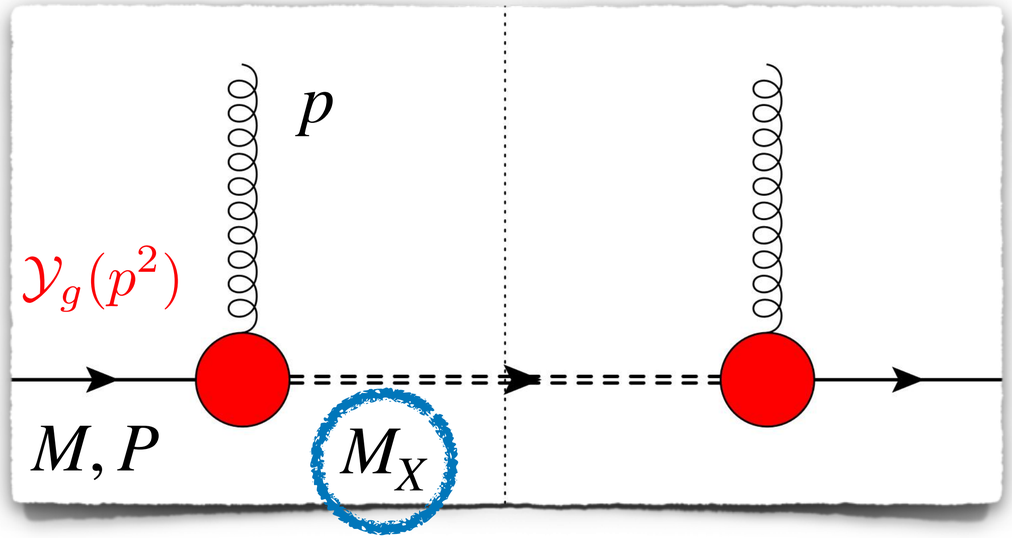
Backup

SPECTATOR-MODEL GLUON TMDS

Spectator-model gluon TMD PDFs

Spin-1/2 spectator

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



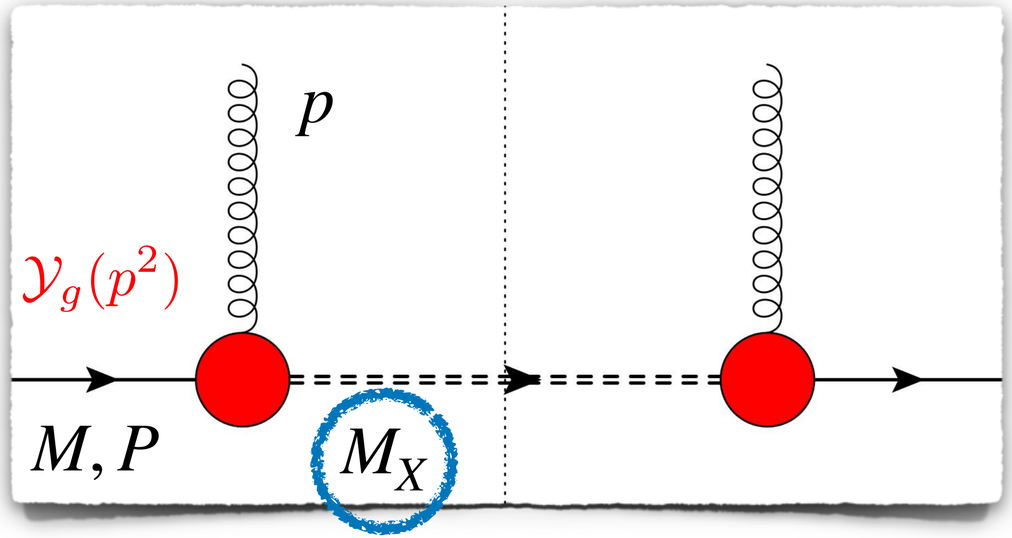
[A. Bacchetta, F.G.C., M. Radici, P. Taels (EPJC 2020)]

Backup

Spectator-model gluon TMD PDFs

Spin-1/2 spectator

Lowest Fock state:
tri-quark spectator
on-shell and
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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)

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

Backup

Spectator-model gluon TMD PDFs



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

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

Backup

Spectator-model gluon TMD PDFs

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

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

Backup

Assumptions of the model

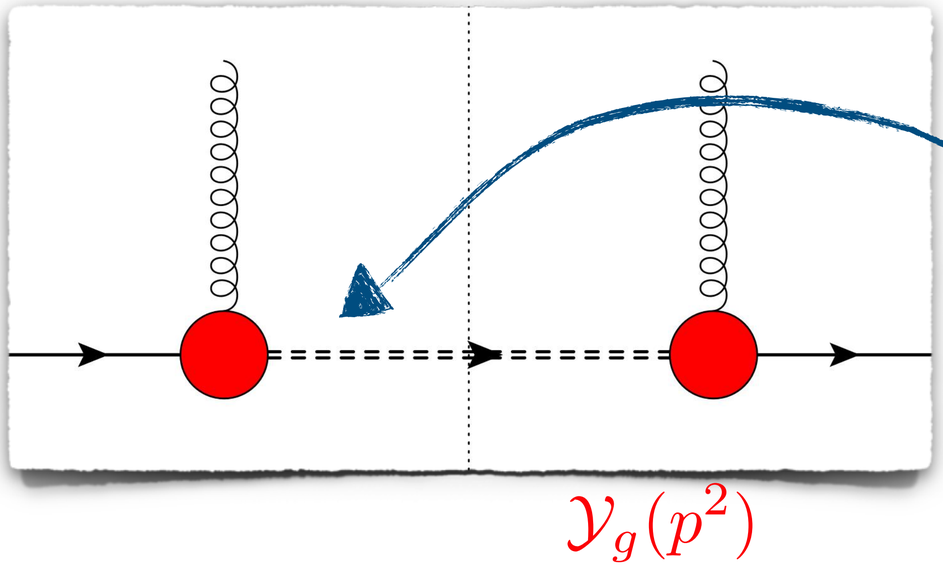
Spectator-system spectral-mass function

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

spectral-mass function

spectator-model TMD

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



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

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

Backup

Assumptions of the model

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



Spectator-system spectral-mass function

spectral-mass function

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spectator-model TMD

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

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

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

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

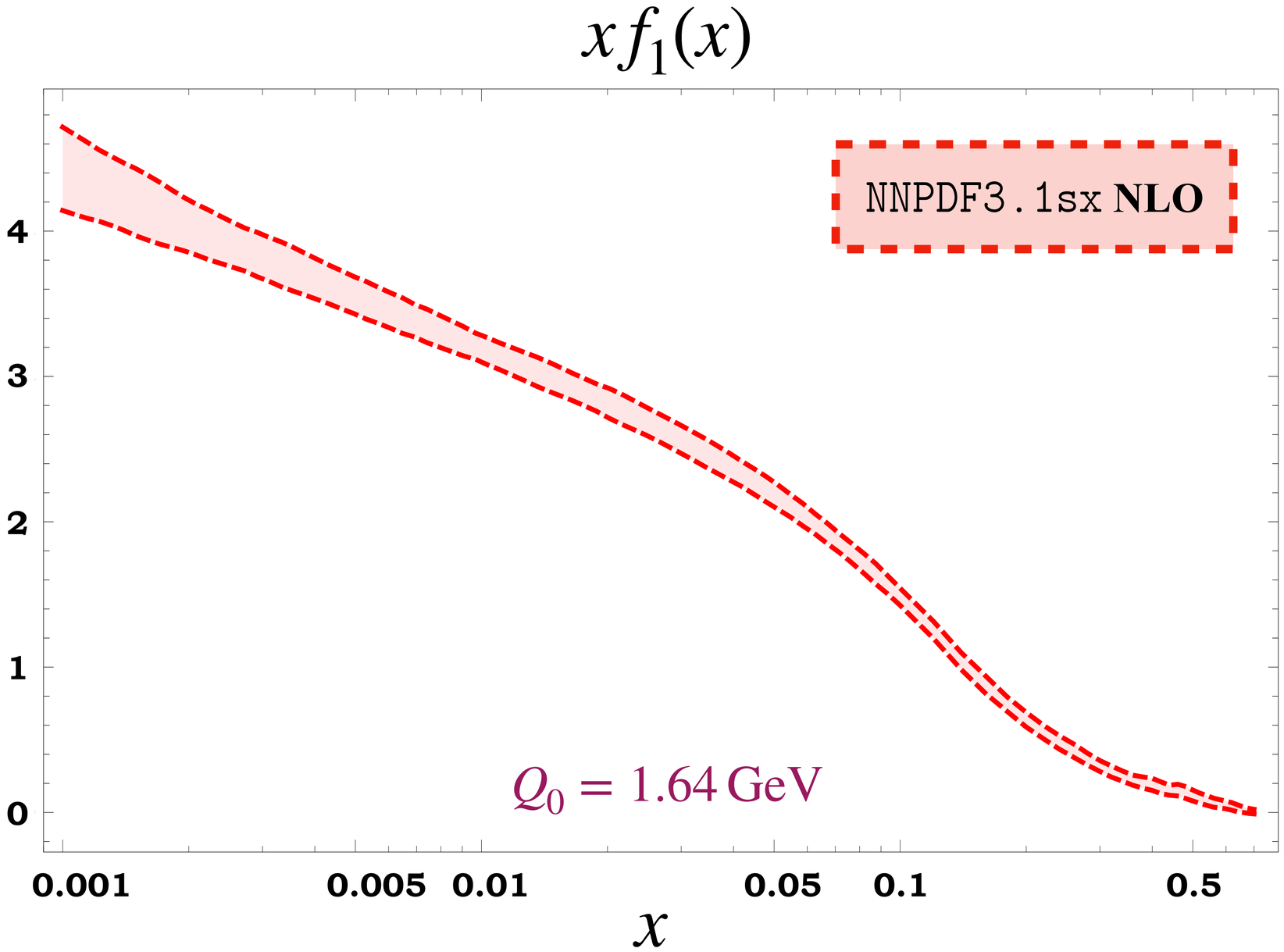
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

Backup

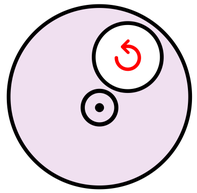
Unpolarized gluon collinear PDF

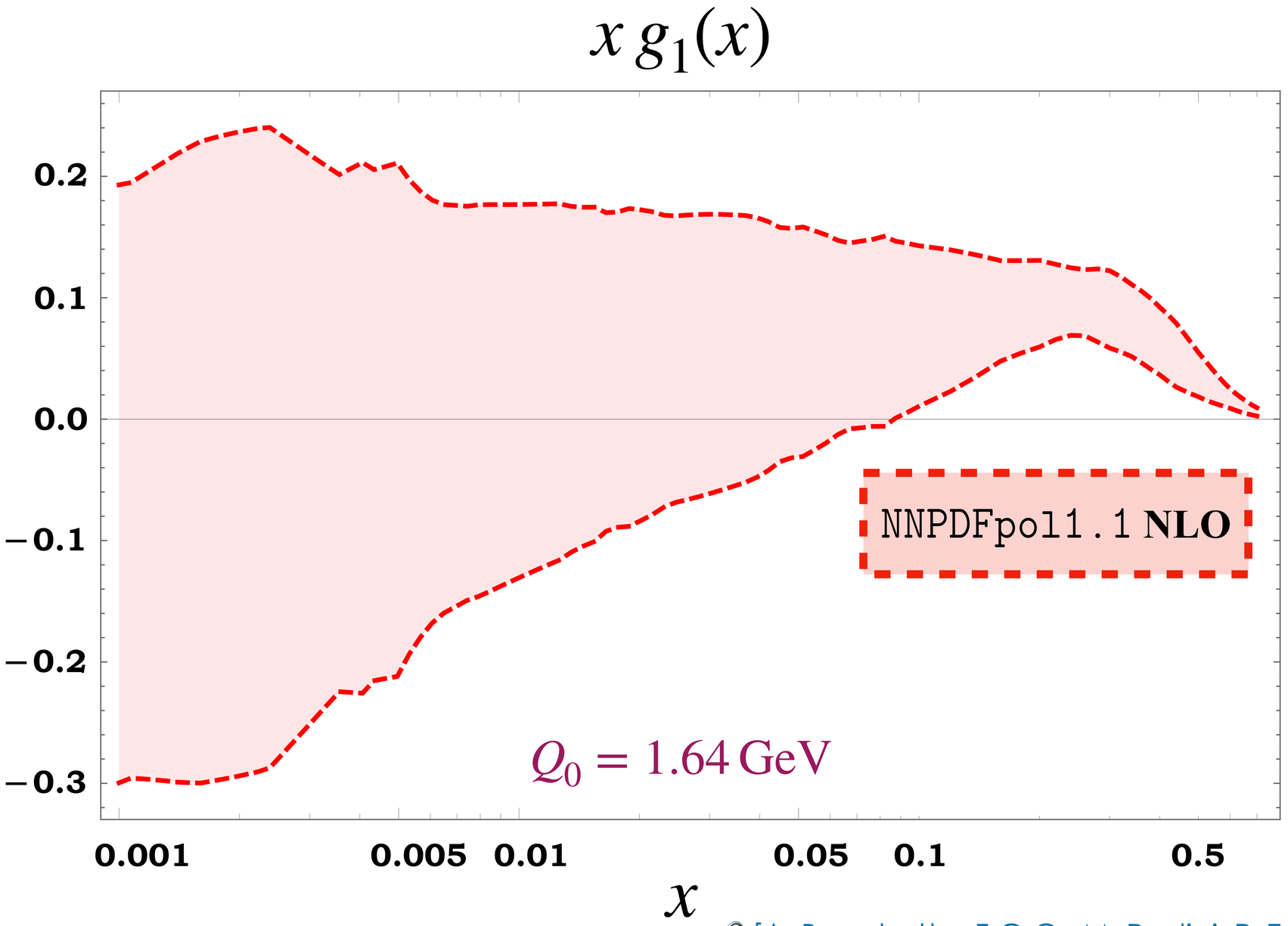


Backup

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

Helicity gluon collinear PDF

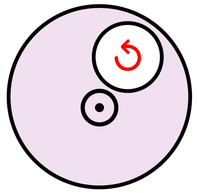


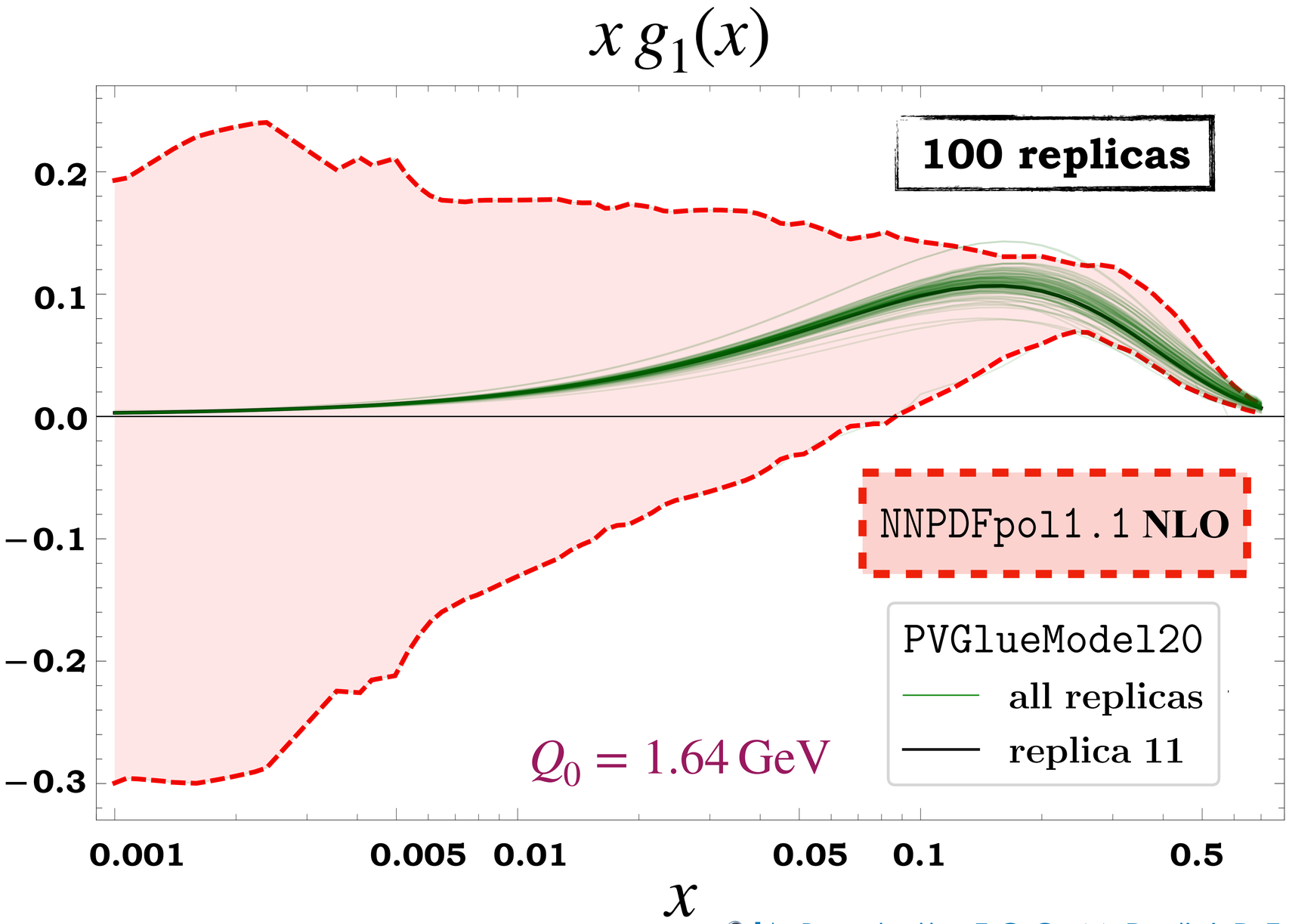


Backup

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

Helicity gluon collinear PDF





Backup

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

T-odd gluon TMDs in a spectator model

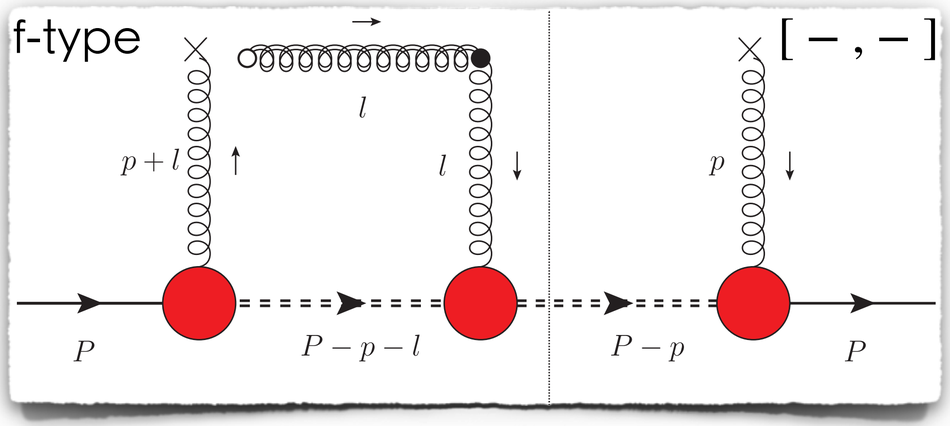
- No residual gluon-spectator interaction at tree level
- Interference with one-gluon exchange (eikonal)

Backup

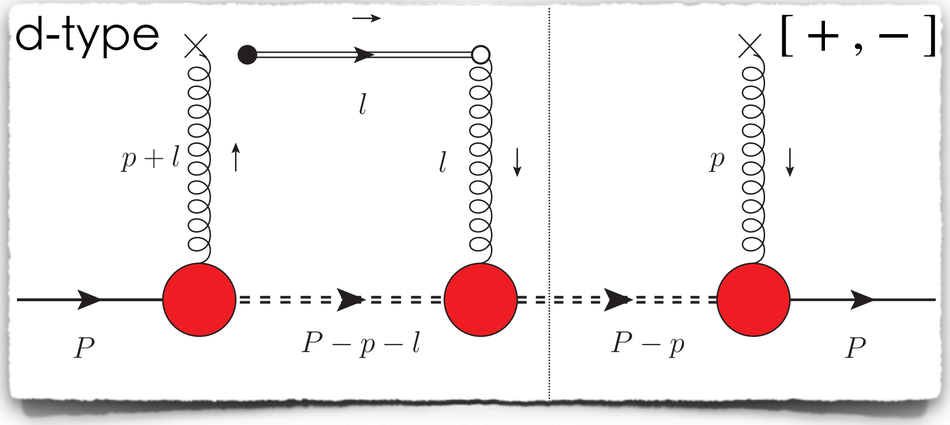
T-odd gluon TMDs in a spectator model

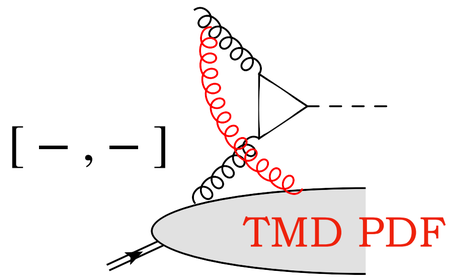
- No residual gluon-spectator interaction at tree level
- Interference with one-gluon exchange (eikonal)

$gg \to H$



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





f-type (WW) structure



d-type (dipole) structure

Backup

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

Gluon TMD correlator and T-odd gluon densities

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

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

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

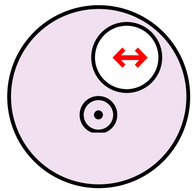
Backup

Gluon TMD correlator and T-odd gluon densities

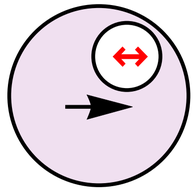
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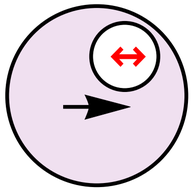


pseudo worm-gear



linearity TMD

pretzelosity



Backup

Gluon TMD correlator and T-odd gluon densities

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

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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

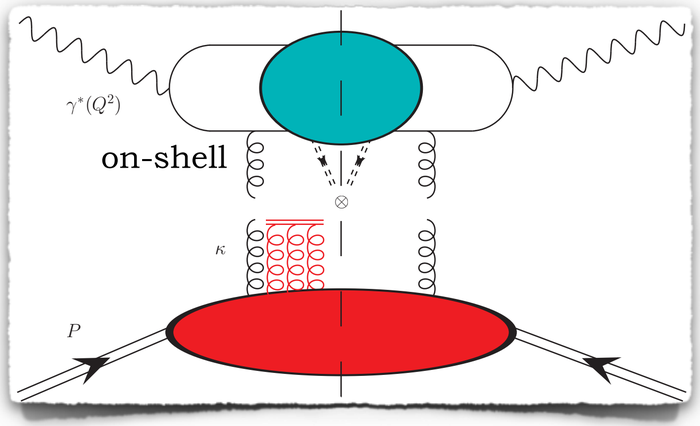
HEF AND THE UGD

TMD versus high-energy factorization



TMD

* Semi-inclusive processes
* $\kappa_T \ll$ hardest scale
* Language of parton correlators
* Diagram: SIDIS onium



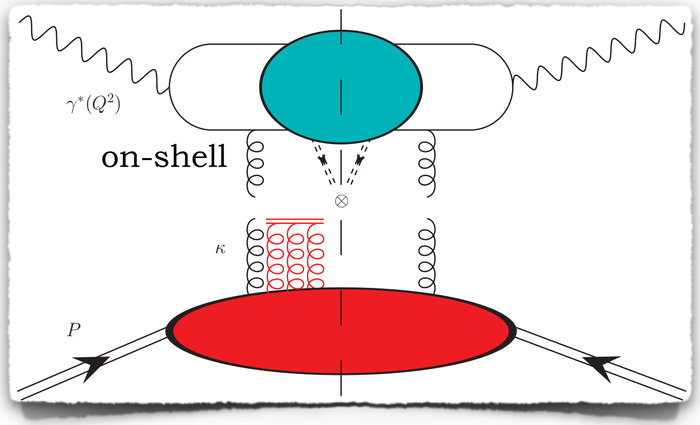
TMD
PDF

Backup

TMD versus high-energy factorization

TMD

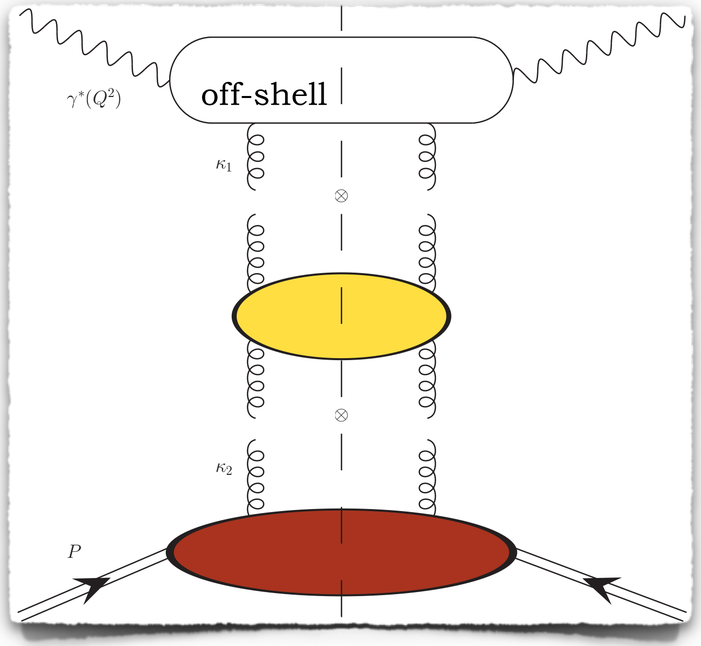
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TMD PDF

HEF

* Inclusive or exclusive processes (!)
* Small x, large κ_T
* Language of Reggeized gluons
* Diagram: DIS



$$\Phi^{\gamma^*\to\gamma^*} \otimes \mathcal{G}_{\mathrm{BFKL}} \otimes \Phi^{P}_{[\mathrm{NP}]}$$

Backup

TMD versus high-energy factorization

TMD

IR-safe colorless $\{\Phi^{i\to o}\}$

(Fadin-Martin theorem)

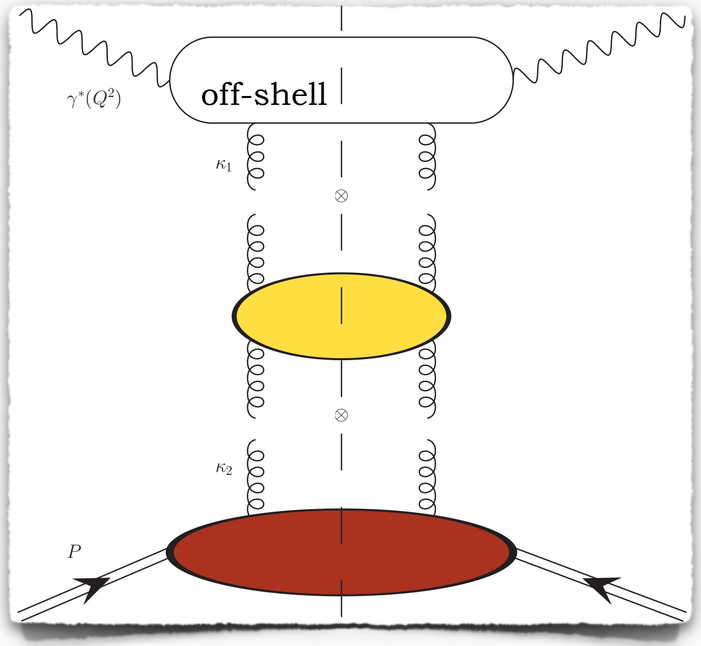
[V.S. Fadin, A.D. Martin (1999)]

* Semi-inclusive processes
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TMD PDF

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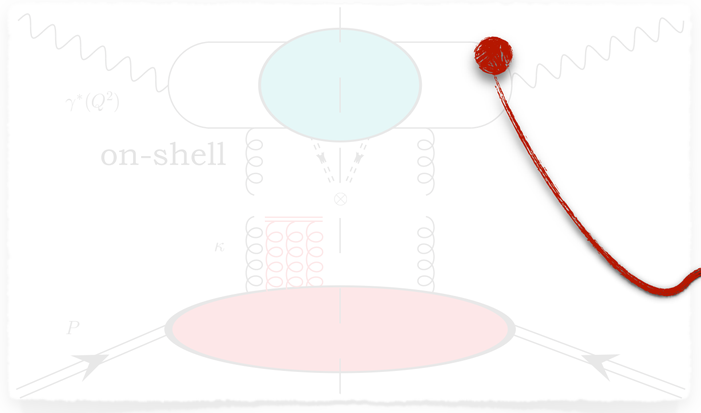
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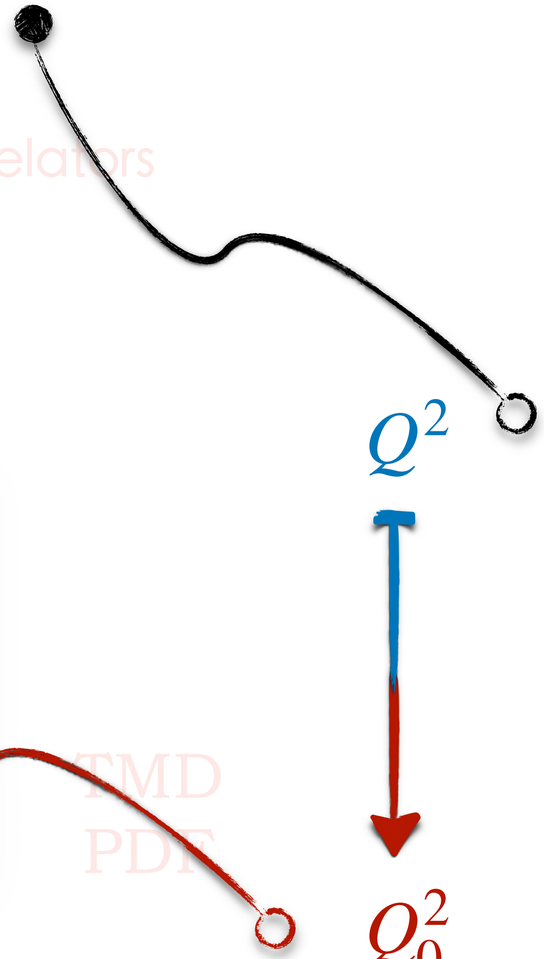
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IR diffusion pattern

(Bartels' cigar)

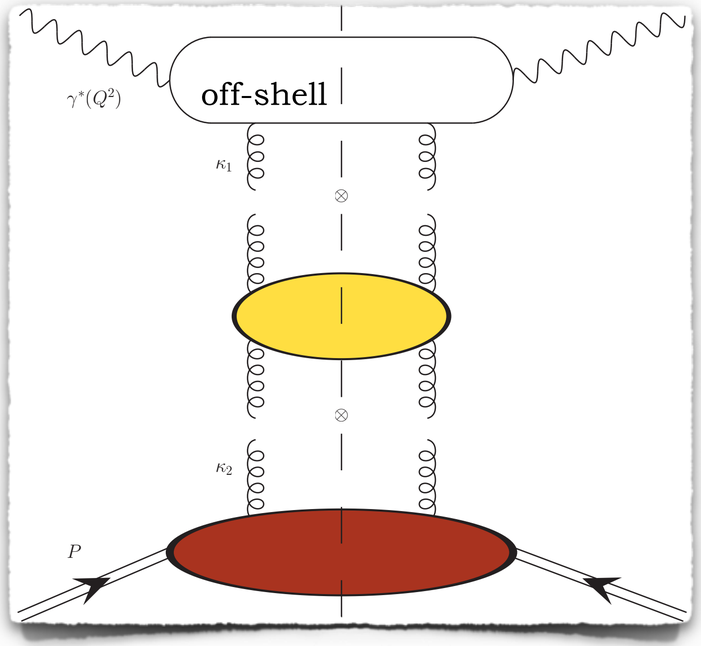
[J. Bartels, H. Lotter (1993)]





HEF

* Inclusive or exclusive processes (!)
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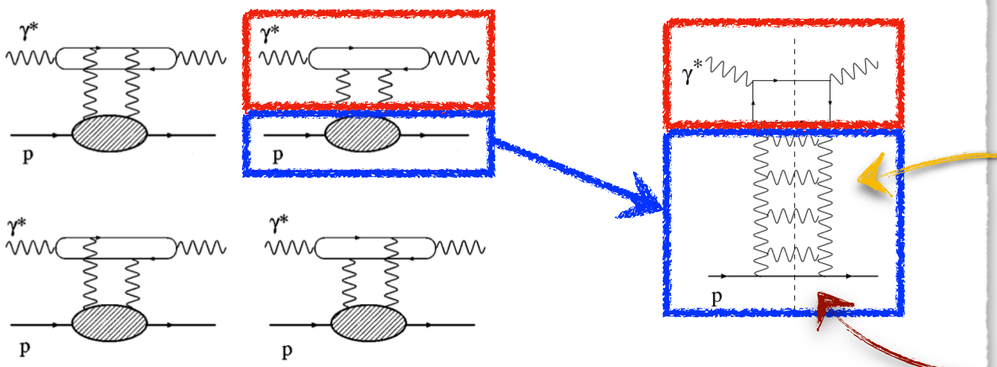
Backup

High-energy factorization and the UGD

- example: **virtual photoabsorption** in **high-energy factorization**

$$\sigma_{\text{tot}}(\gamma^* p \to X) \propto \mathcal{I}m_s\{\mathcal{A}(\gamma^* p \to \gamma^* p)\} \equiv \Phi_{\gamma^* \to \gamma^*} \circledast \mathcal{F}(x, \kappa^2)$$

◇ $\mathcal{F}(x, \kappa^2)$ is the **unintegrated gluon distribution** (**UGD**) in the proton



▶ Small-x limit: **UGD** = [**BFKL gluon ladder**] $\circledast$ [**proton impact factor**]

◇ Takes into account the resummation of high-energy logs

◇ Describes the coupling of the gluon Green's function to the proton

▶ Proton impact factor is non-perturbative $\Longrightarrow$ UGD needs to be modeled!

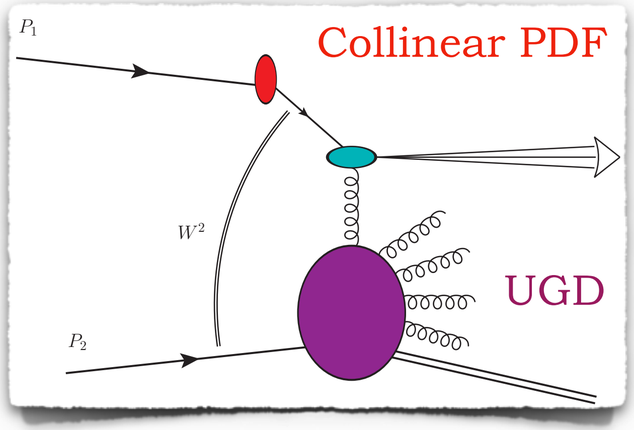
Backup

Hybrid or pure factorization?

Forward emissions

* *Asymmetric* config. ↔ fast parton + small-x gluon

* Hybrid **high-energy**/**collinear** factorization



* *Distinctive signals* of small-x dynamics **expected**

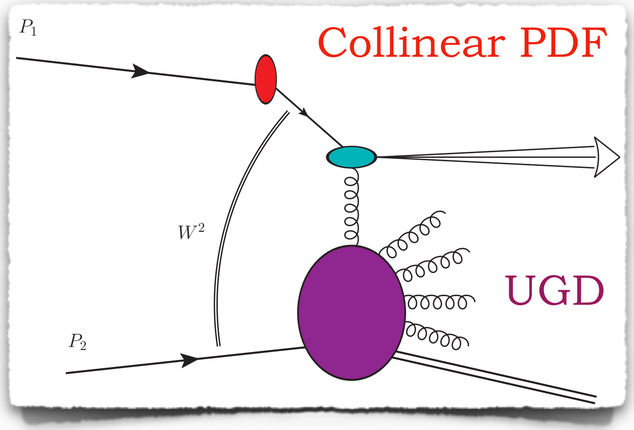
* Phenomenology:
  forward jet, Drell-Yan, Higgs or vector meson

Backup

Hybrid or pure factorization?

Forward emissions

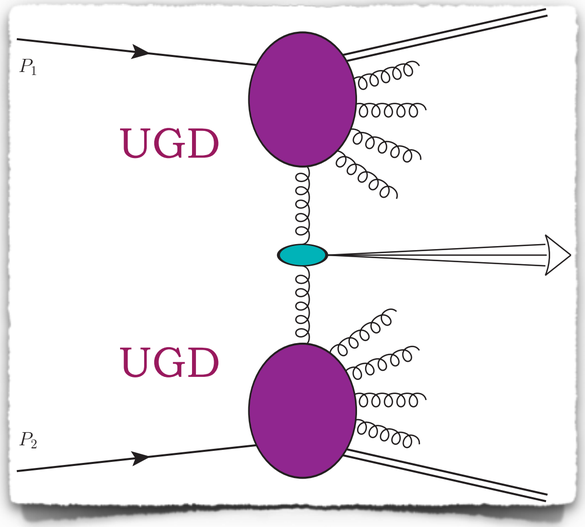
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Central emissions

* *Gluon induced* ↔ small-x gluons
* Pure **high-energy** factorization



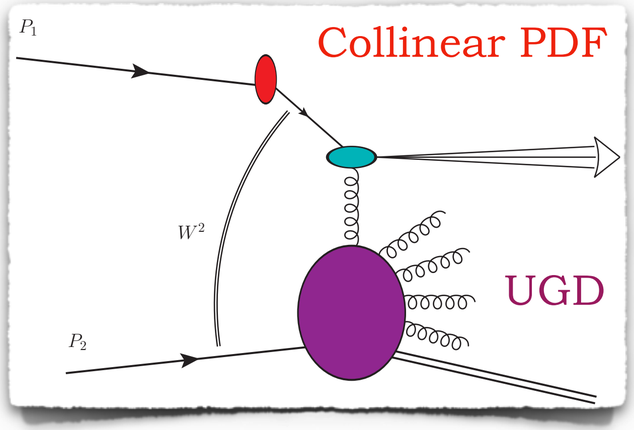
* Small-x dynamics to **enhance** f.o. description
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Backup

Hybrid or pure factorization?

Forward emissions

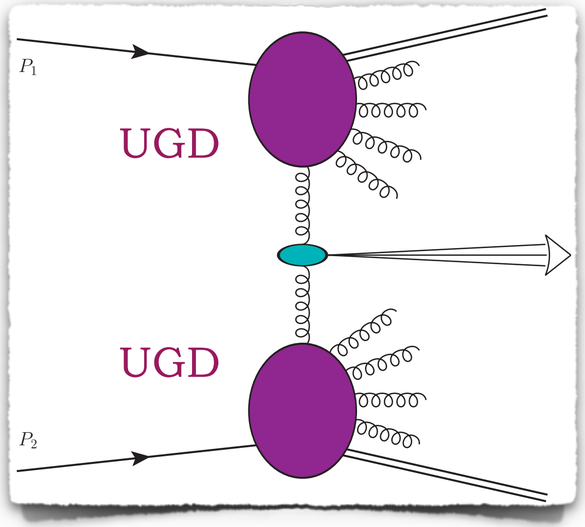
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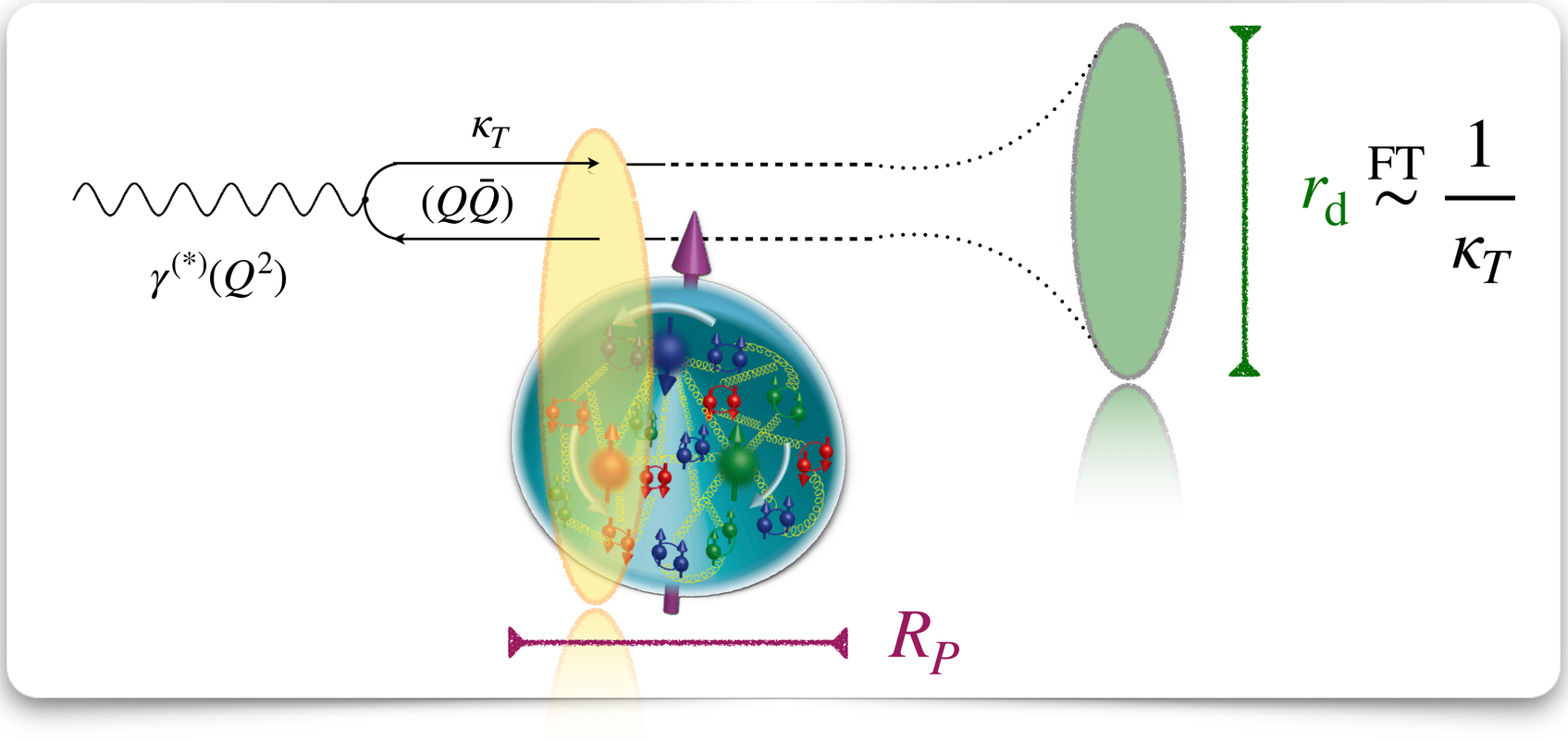


* Small-x dynamics to **enhance** f.o. description
* Phenomenology:
  central jet, Higgs or vector meson

Table complemented by *exclusive* counterparts and *lepto-hadronic* channels

Backup

Diffractive $\gamma^* P$ scatterings and color dipoles



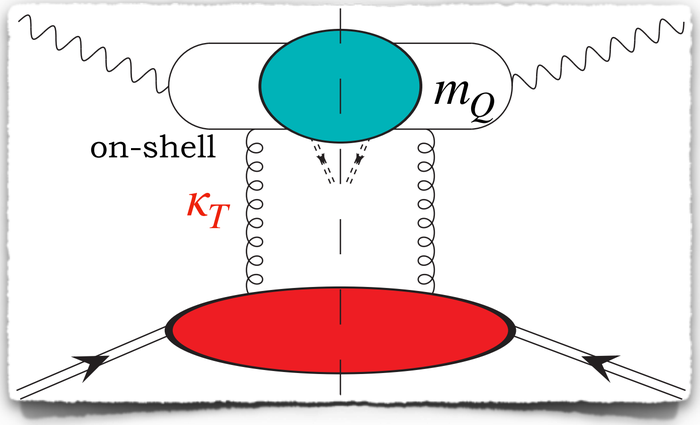
$$W_{\mu\nu} \propto \mathrm{Im}\left\{ i \int \mathrm{d}^4x\, e^{i\,q\cdot x} \langle P | \mathrm{T}\,[J_\mu(x)\, J_\nu(0)] | P \rangle \right\}$$

- Small-x $\Rightarrow$ Ioffe time $\gg R_P$
- At least one J_μ outside proton…
- …color dipole picture!

Backup

Inclusive quarkonium production mechanisms

$$\kappa_T \ll Q$$

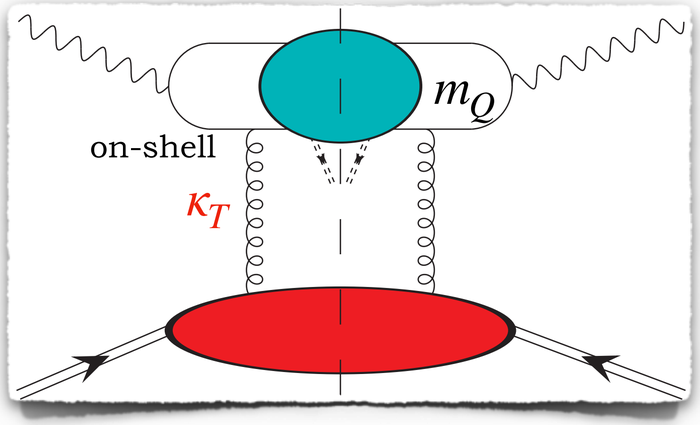


* Gluon TMD PDF
* Short-distance $(Q\bar{Q})$ + ShFs

Backup

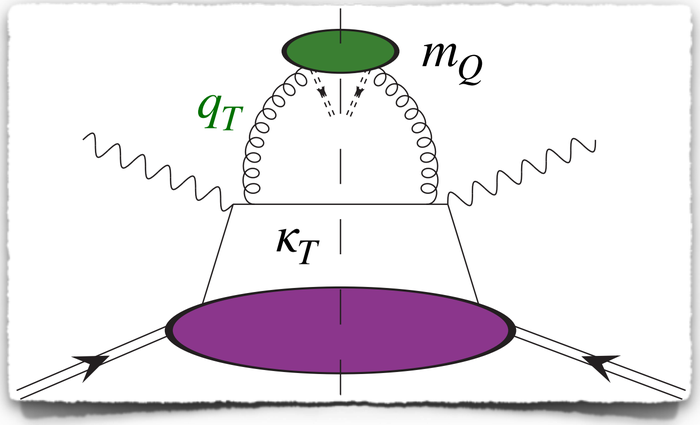
Inclusive quarkonium production mechanisms

$\kappa_T \ll Q$



* Gluon TMD PDF
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$\kappa_T \gg m_Q$

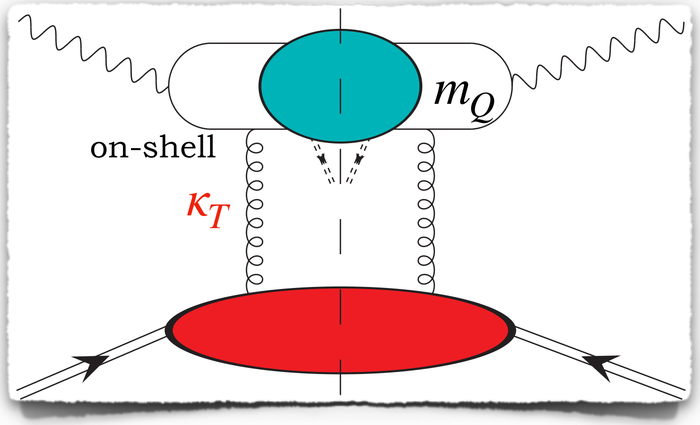


* Quark collinear PDF
* Onium in jet
* Single-quark TMD FF

Backup

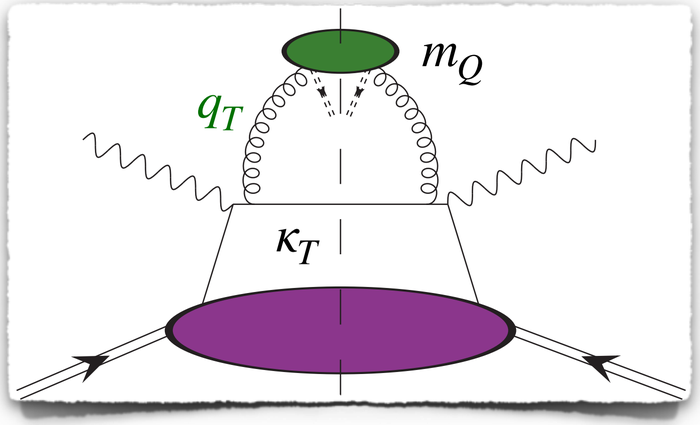
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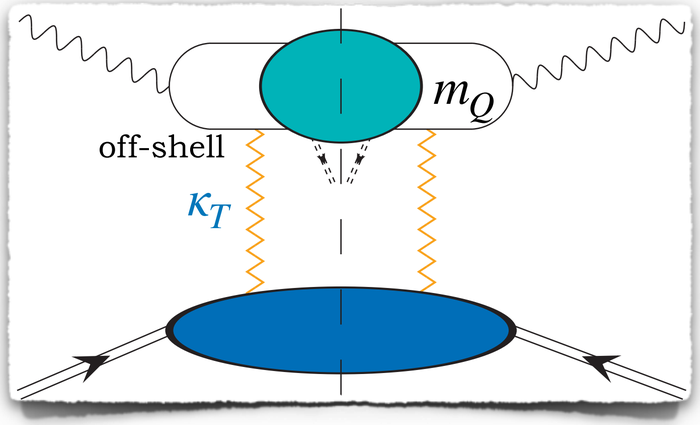
* Gluon TMD PDF
* Short-distance $(Q\bar{Q})$ + ShFs

$\kappa_T \gg m_Q$



* Quark collinear PDF
* Onium in jet
* Single-quark TMD FF

HEF



* BFKL UGD
* Reggeized gluons
* Dipole mechanism

Backup

EXCLUSIVE FORWARD

ρ MESON LEPTOPRODUCTION

Single forward emissions

Exclusive light VM: ρ^0, ω, ϕ

* *Small-size* dipoles $\Rightarrow$ large κ_T
* Collinear description: twist-2/-3 LVM NP **DAs**

$$\Phi^{\gamma^* \to \rho} \propto \int_0^1 \mathrm{d}z \, T_H^{\gamma^* \to \rho}(z, \kappa_T, Q, \mu_R, \mu_F) \, \phi^{\lambda_\rho}(z, \mu_F)$$

* Significance of small κ_T under investigation…
* HERA indication: no large-r_d dynamics
* LVMs as tools: discrimination among UGD models
* LVMs as tools: UGD extraction $\Leftarrow$ HERA + EIC fits

Backup

Single forward emissions

Exclusive light VM: ρ^0, ω, ϕ

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* Significance of small κ_T under investigation…
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* LVMs as tools: UGD extraction ⇐ HERA + EIC fits

Quarkonia

* Size of dipoles ⇒ wide range of κ_T
* Description: **NRQCD** (combined with LFWFs)

$$\left[\mathrm{LFWF} \otimes \mathscr{A}_{\mathrm{dip.}} \right] \overset{\text{dilute}}{\longleftrightarrow} \left[\Phi^{\gamma^* \to J/\Psi} \otimes \mathrm{UGD} \right]$$

* Validity of *small-size* dipoles questionable…
* NRQCD: large-r_d dynamics for $\Psi(2s)$ ($\Upsilon(2s)$?)

🔗 [K. Suzuki *et al.* (2000)]; 🔗 [J. Cepila *et al.* (2019)]; 🔗 [M. Hentschinski *et al.* (2020)]

* Onia as tools: scan of TMD/HEF intersection range

Backup