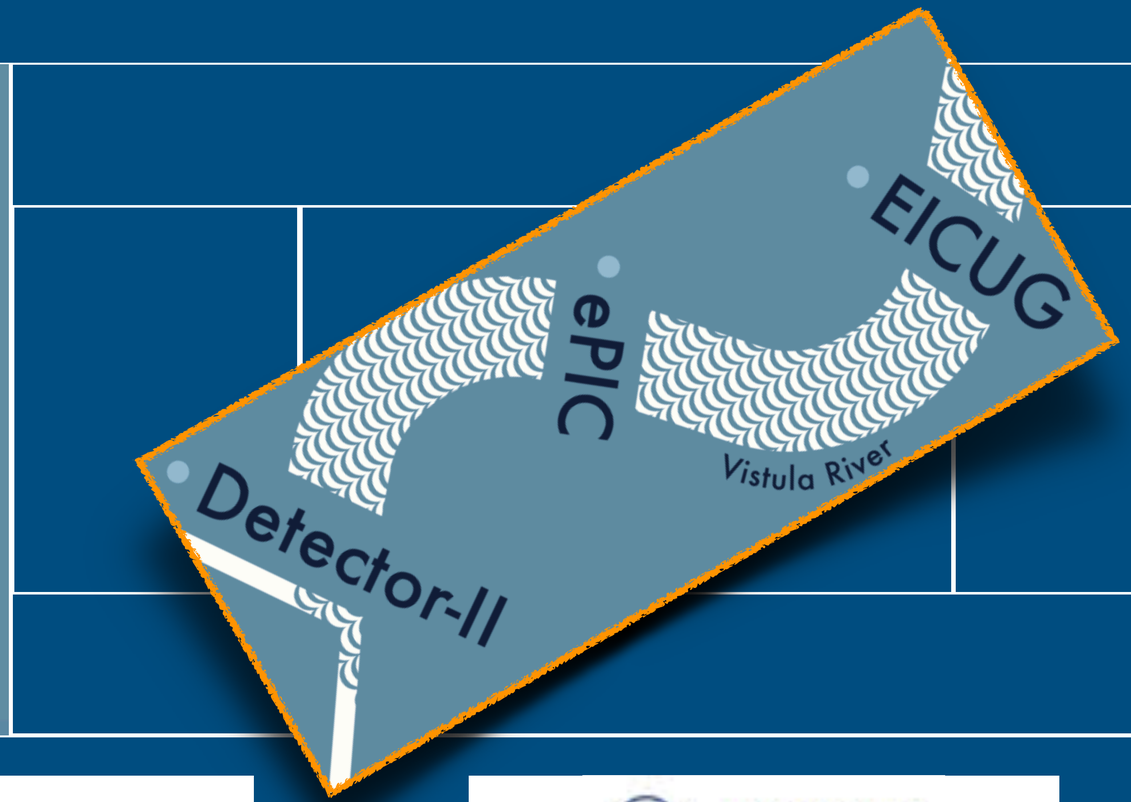
MODELING GLUON TMDS: PERSPECTIVES @EIC

Francesco Giovanni Celiberto, UAH Madrid



Madrid UAH

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1. Opening remarks

Gluon TMD PDFs: A largely unexplored territory

- Theory: different gauge-link structures...

  ...more diversified kind of modified universality!

- Pheno: golden channels for extraction

  of quark TMDs are subleading for gluon TMDs

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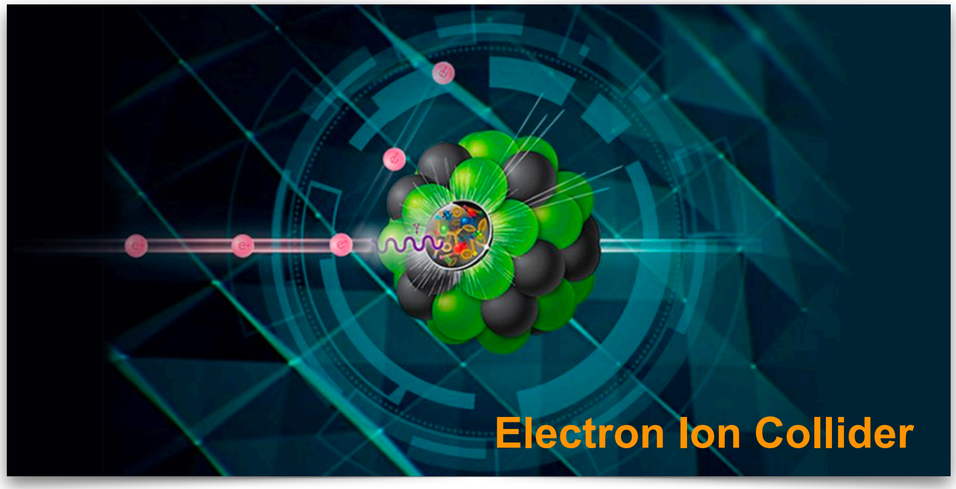

3D proton imaging

- Gluon TMD PDFs ⇒ core sector of EIC studies
- Need for a flexible model, suited to pheno

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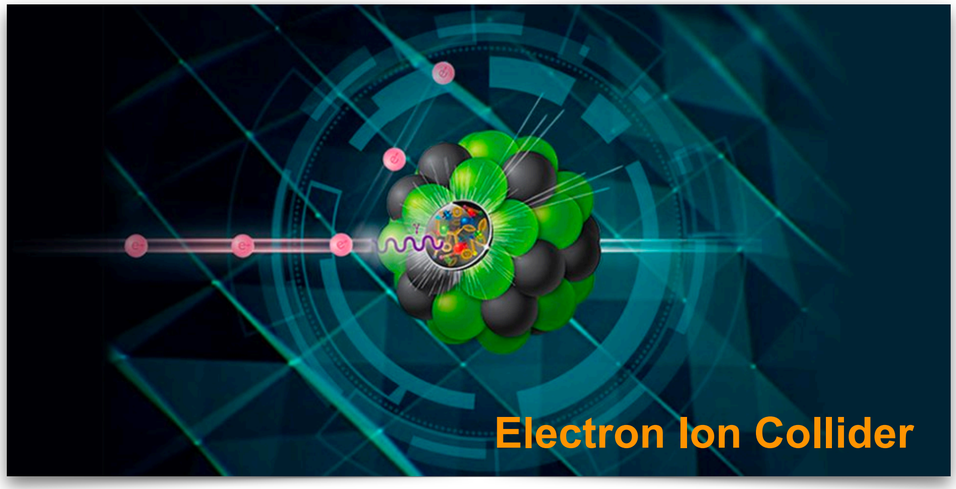


3D proton imaging

- Gluon TMD PDFs ⇒ core sector of EIC studies
- Need for a flexible model, suited to pheno
- Gluon and nucleon polarization at twist-2
- Window of opportunities at ePIC & 2nd detector

Gluon TMD PDFs at leading twist

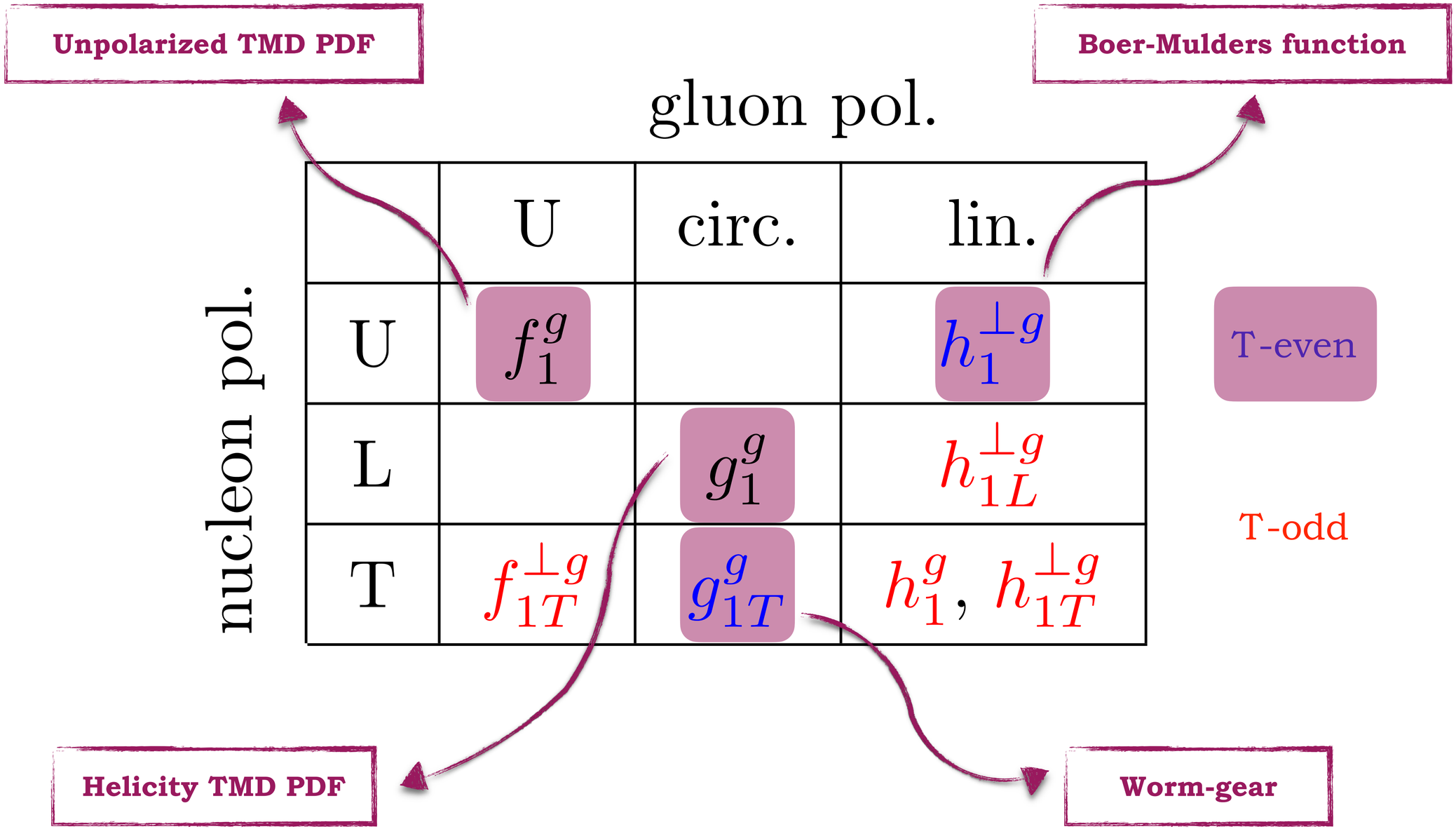
gluon pol.

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

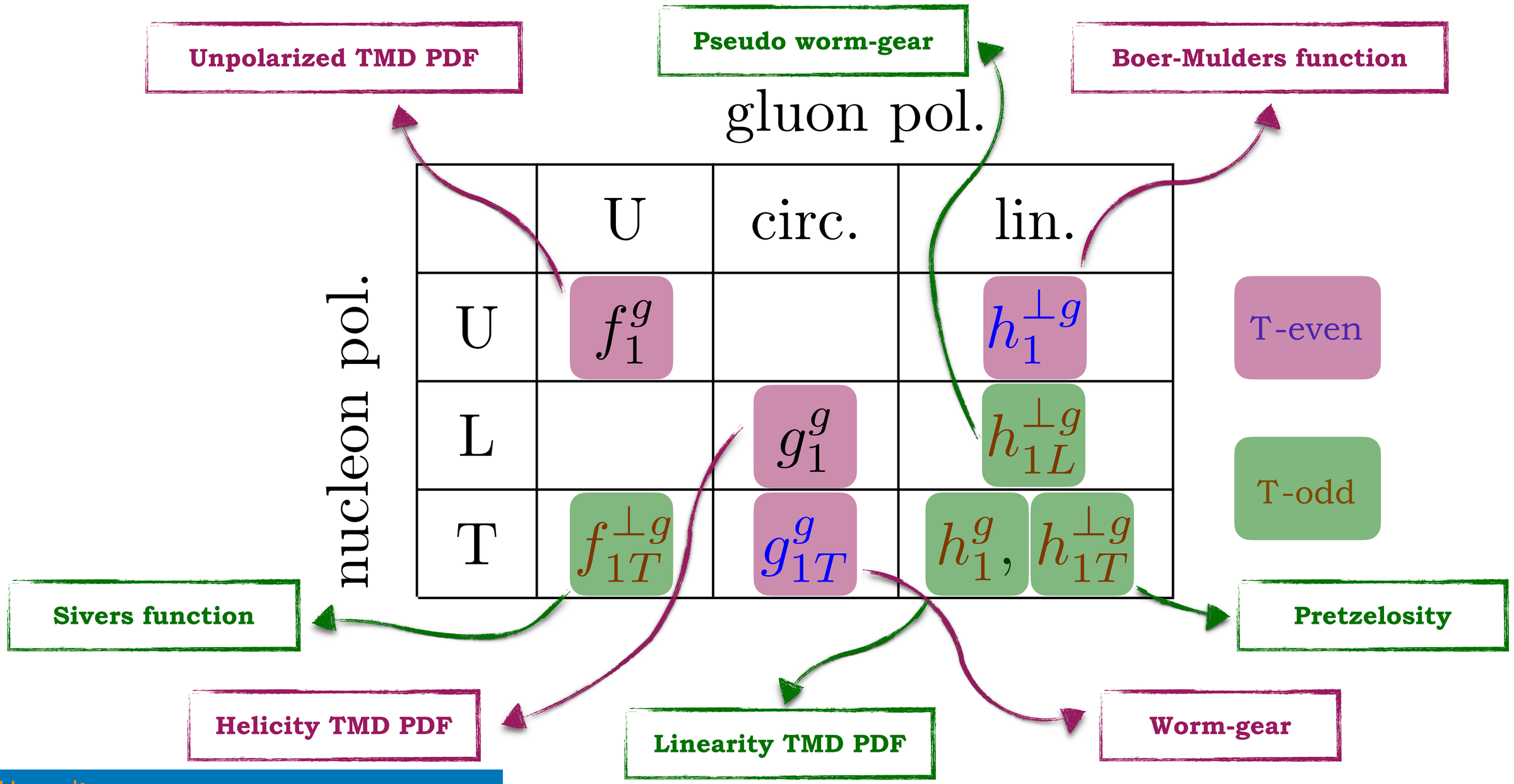
T-even

T-odd

Gluon TMD PDFs at leading twist



Gluon TMD PDFs at leading twist



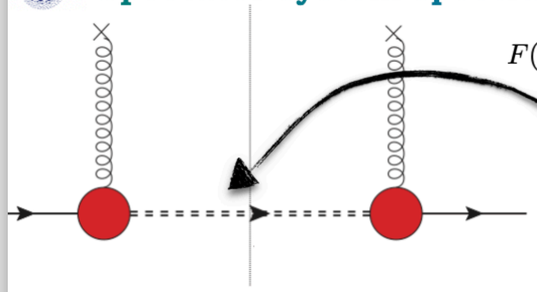
2. Modeling gluon TMDs

Spectator-model gluon TMD PDFs

Our model at a glance

Spectator-system spectral-mass function

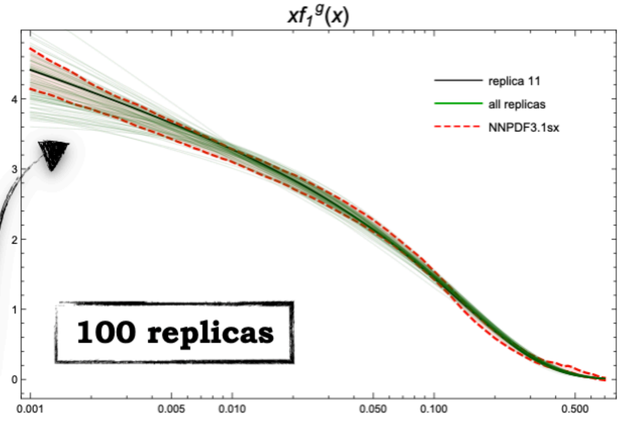
$$F(x, \boldsymbol{p}_T^2) = \int_M^\infty \mathrm{d}M_X \, \rho_X(M_X) \, \hat{F}(x, \boldsymbol{p}_T^2; M_X)$$



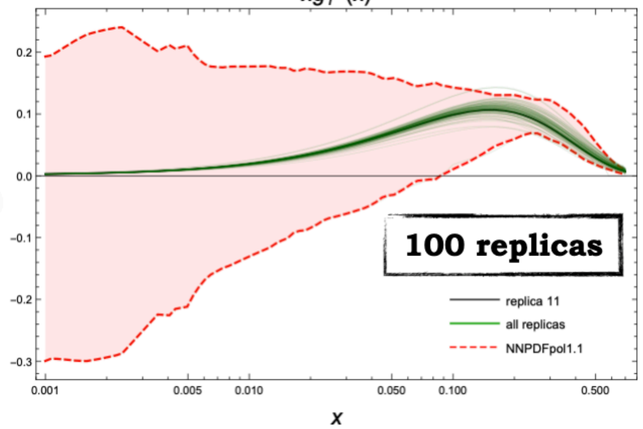
Instead of a single on-shell spectator, a continuum of spectators

Link with collinear factorization

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



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



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

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

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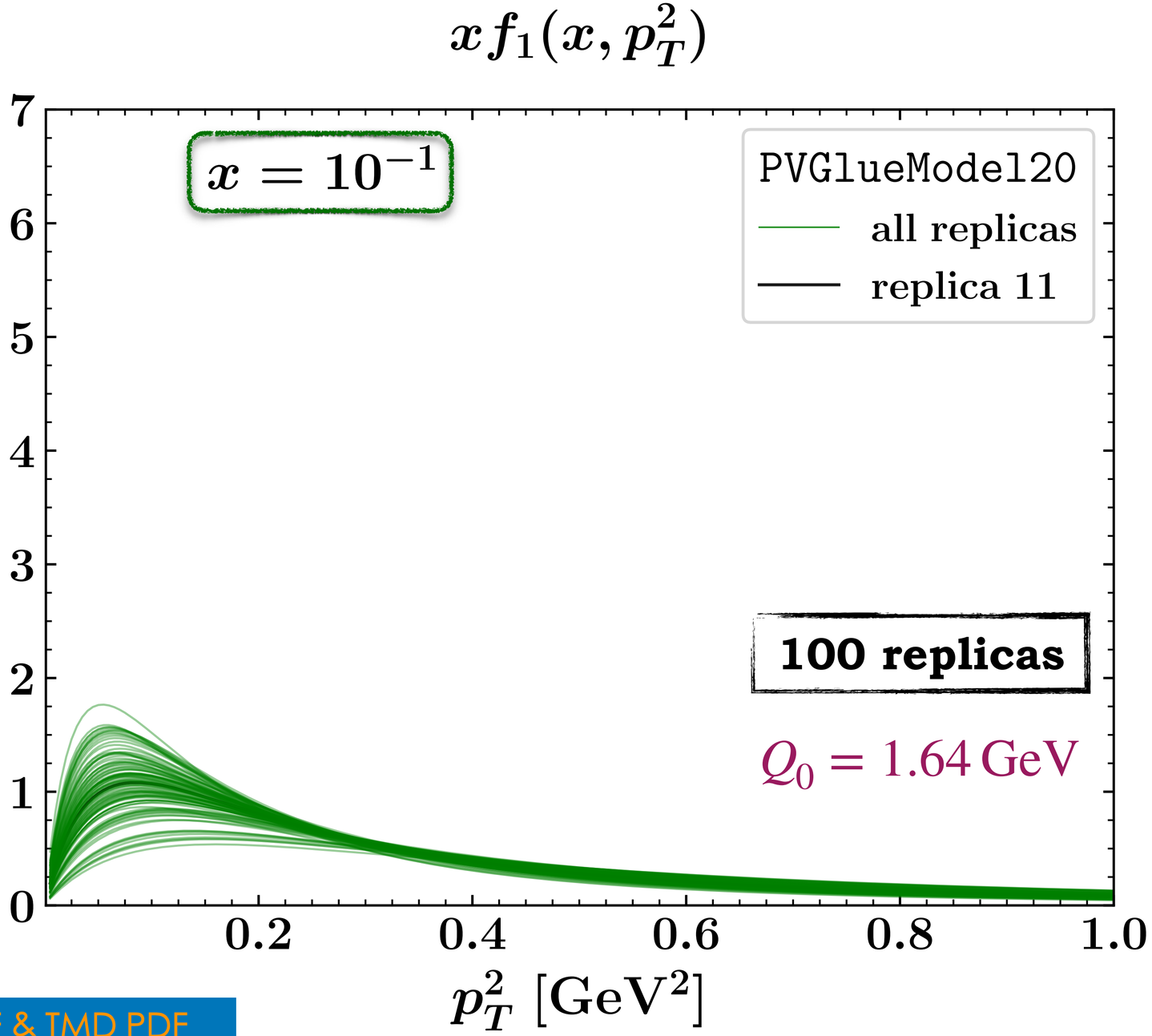
Unpolarized gluon TMD PDF

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



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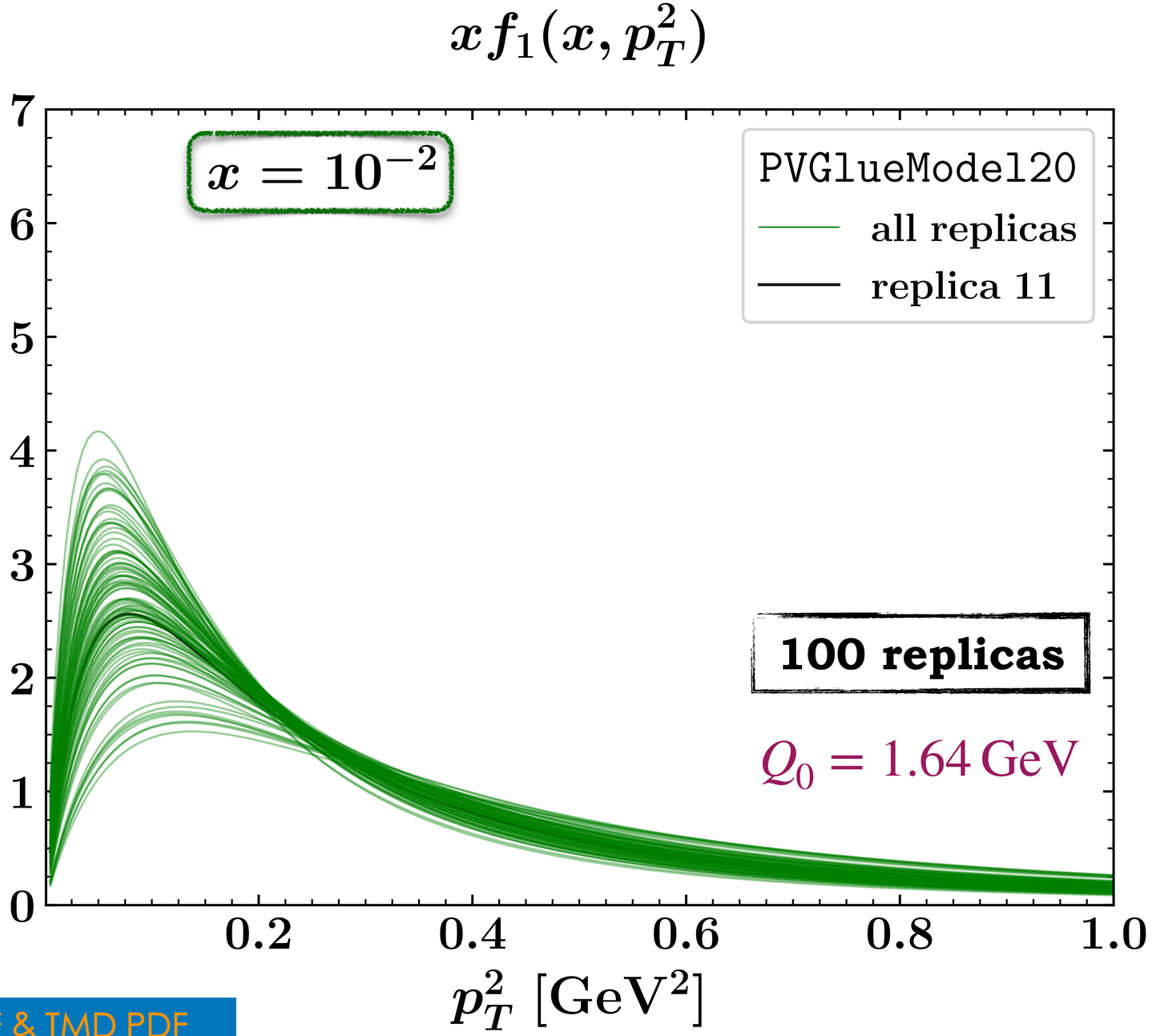

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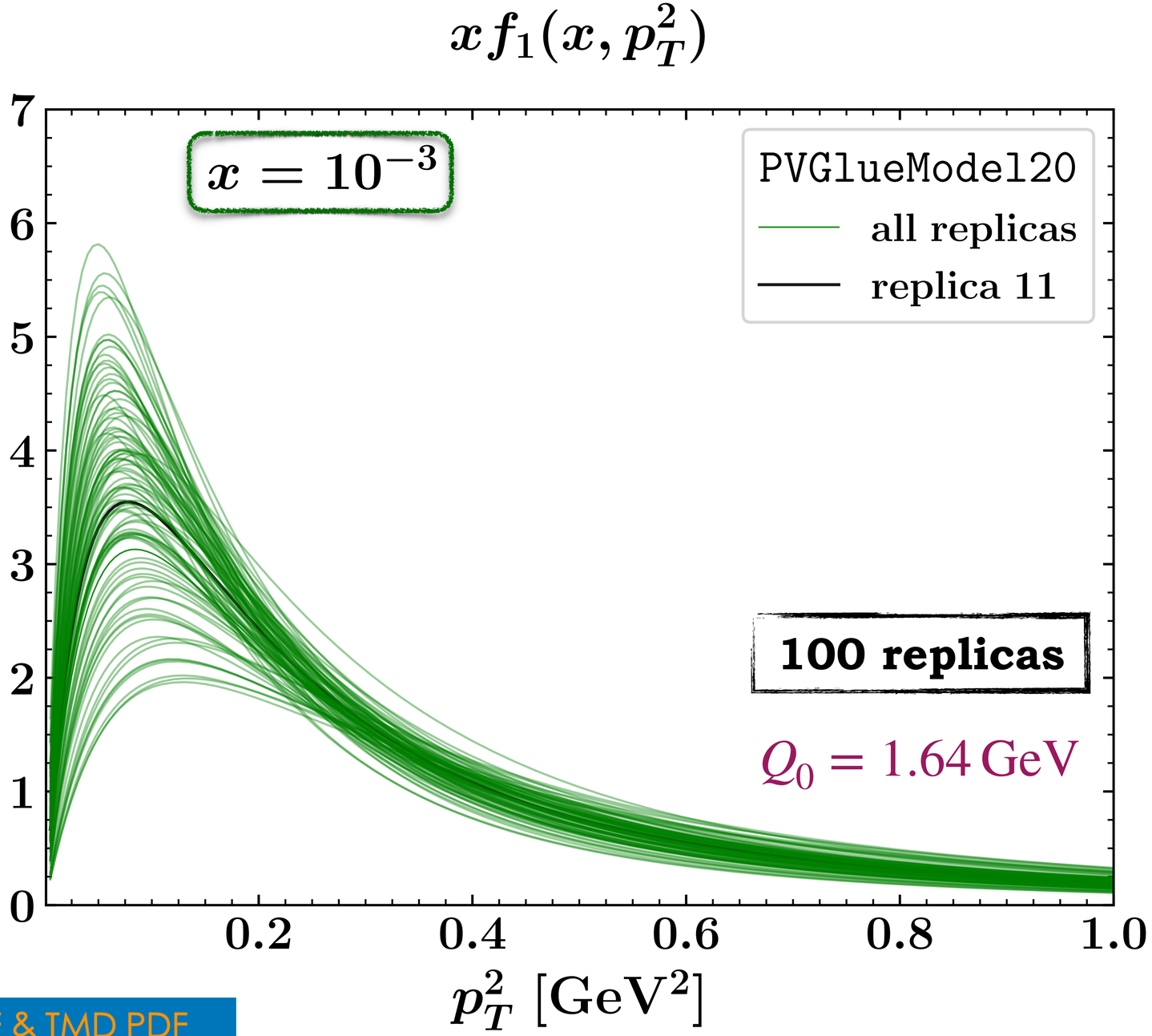
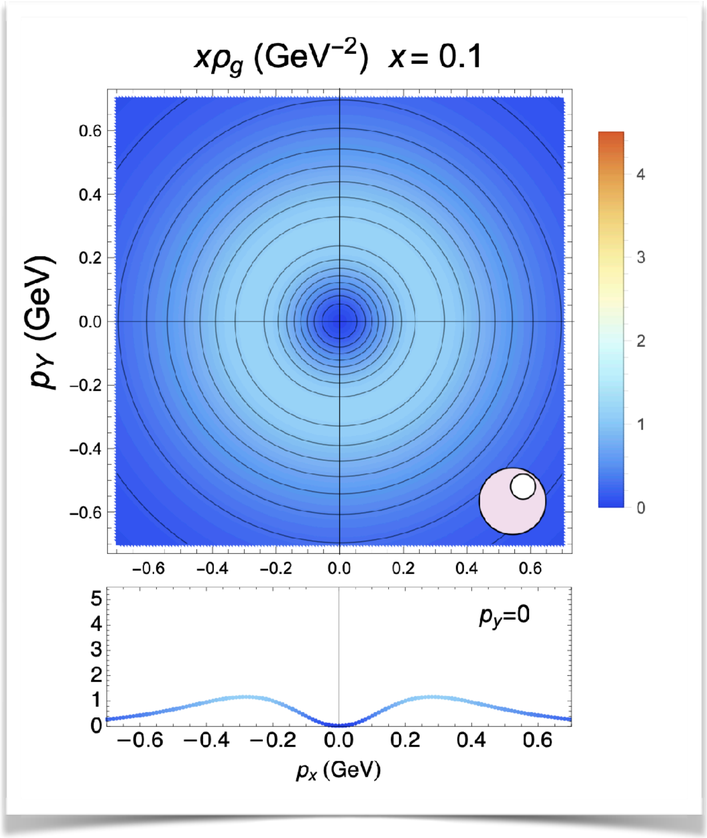


3D proton imaging: Tomographic reconstruction & TMDs

[A. Bacchetta, F.G.C., M. Radici, P. Taels, Eur. Phys. J. C 80 (2020) no.8]

Unpolarized



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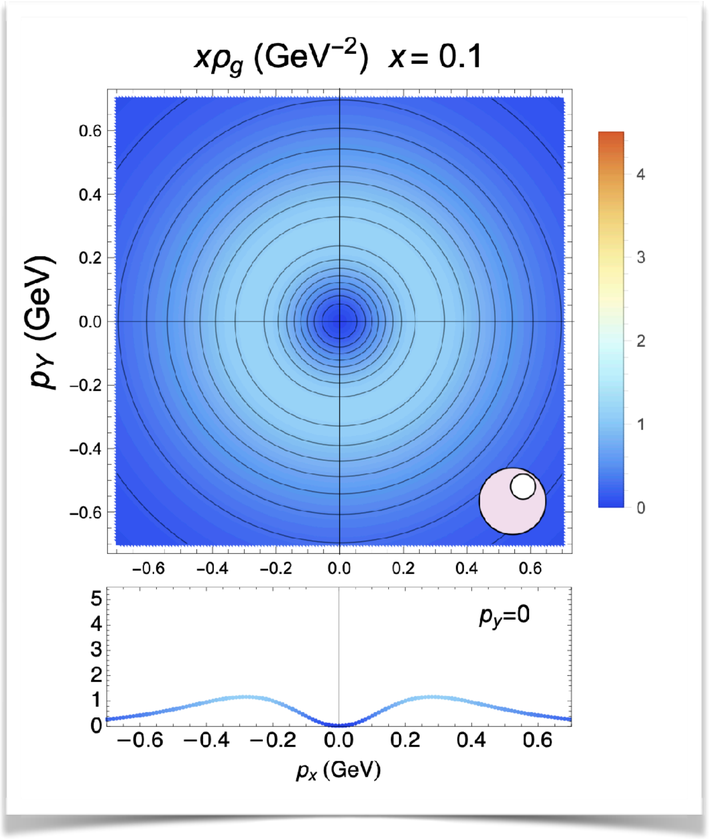
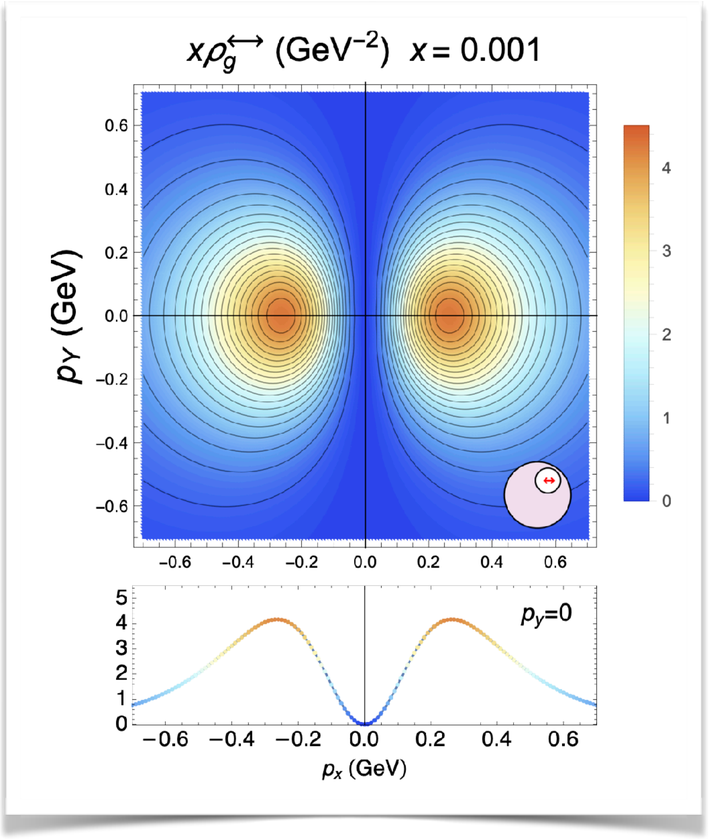


Boer-Mulders



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

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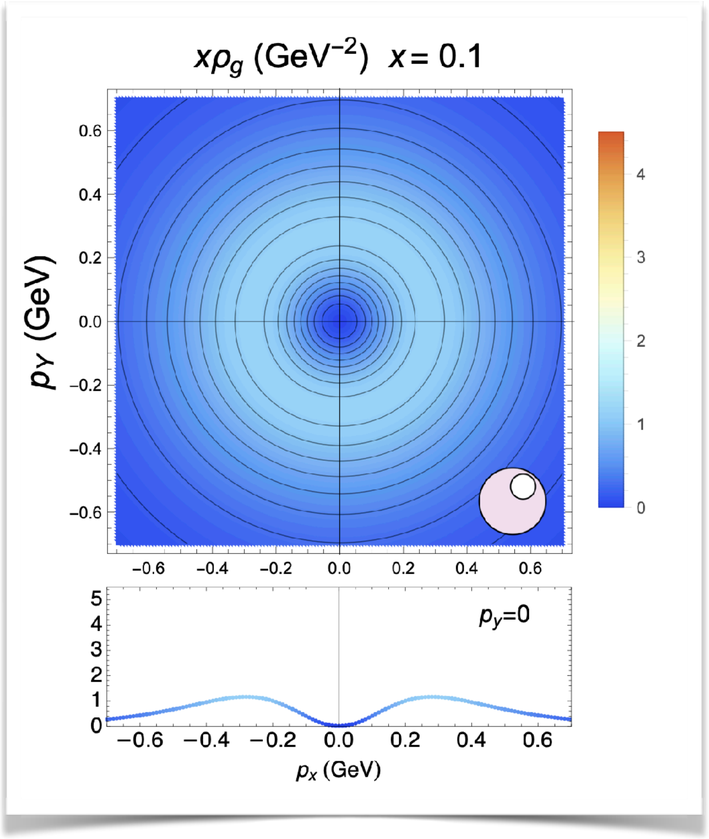

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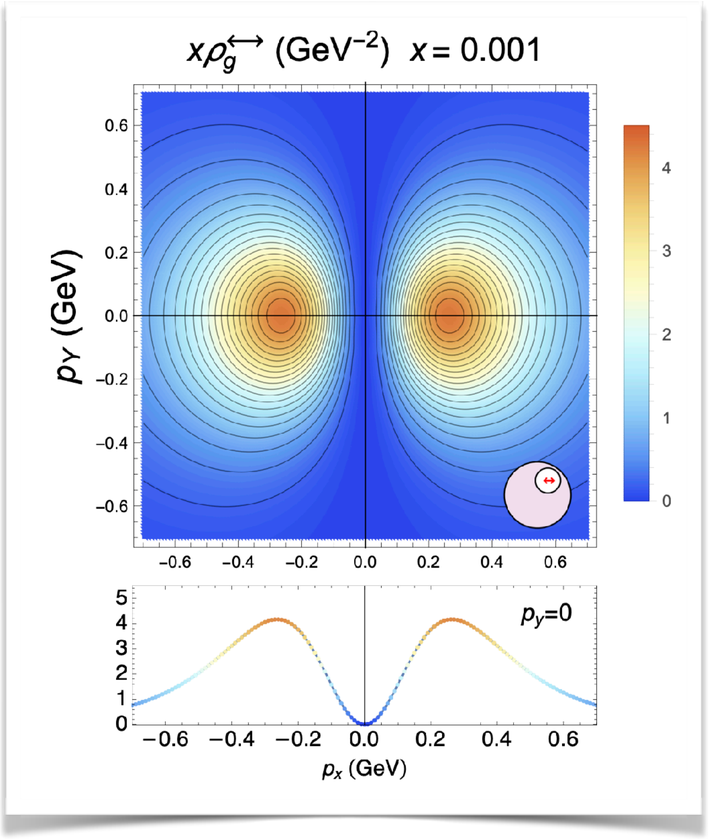
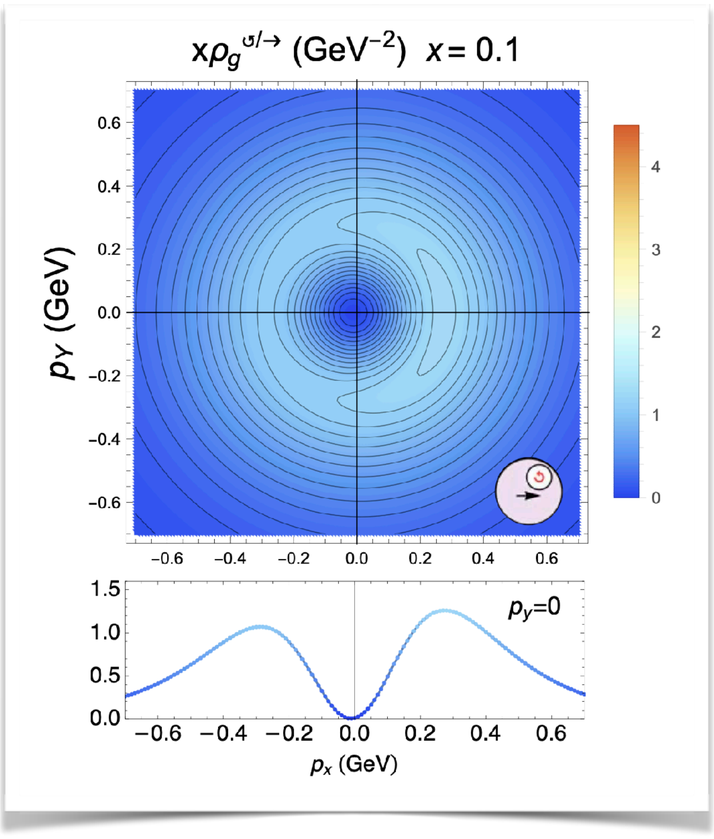


Worm-gear



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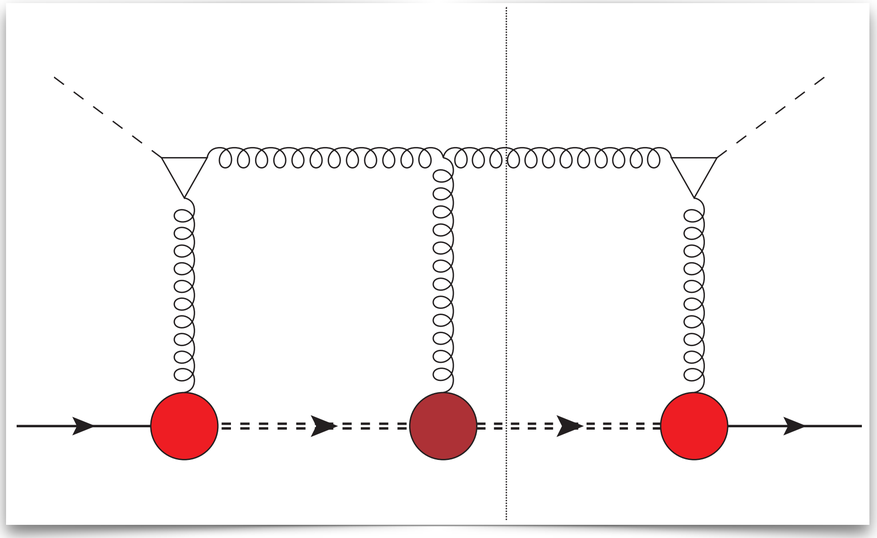
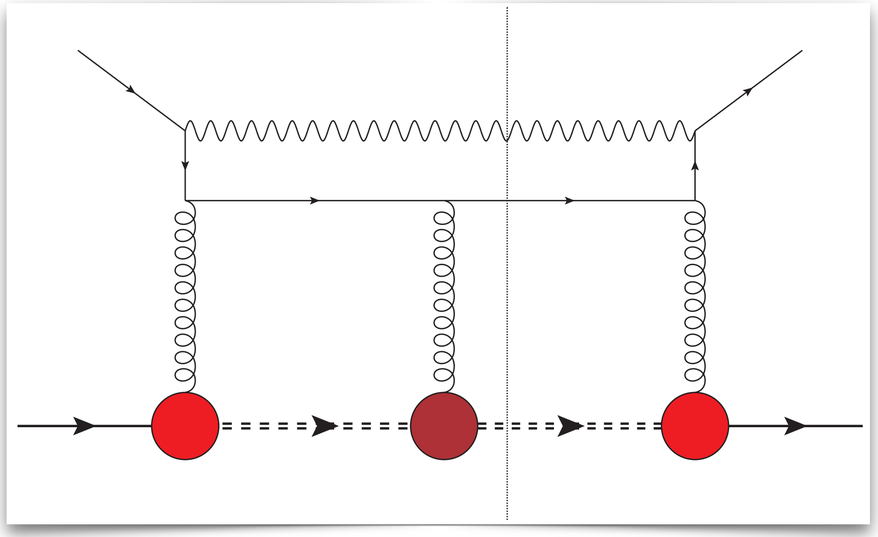
$$x\rho^{\circlearrowleft/\rightarrow}(x, p_x, p_y) = x f_1^g(x, \boldsymbol{p}_T^2) - \frac{p_x}{M}\, x g_{1T}^g(x, \boldsymbol{p}_T^2)$$

T-odd gluon TMDs in a spectator model

Higgs-gluon fusion ⇒ f-type [+ , +]



Photon-jet emission ⇒ d-type [+ , –]



nucleon-gluon-spectator

spectator-gluon-spectator

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

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

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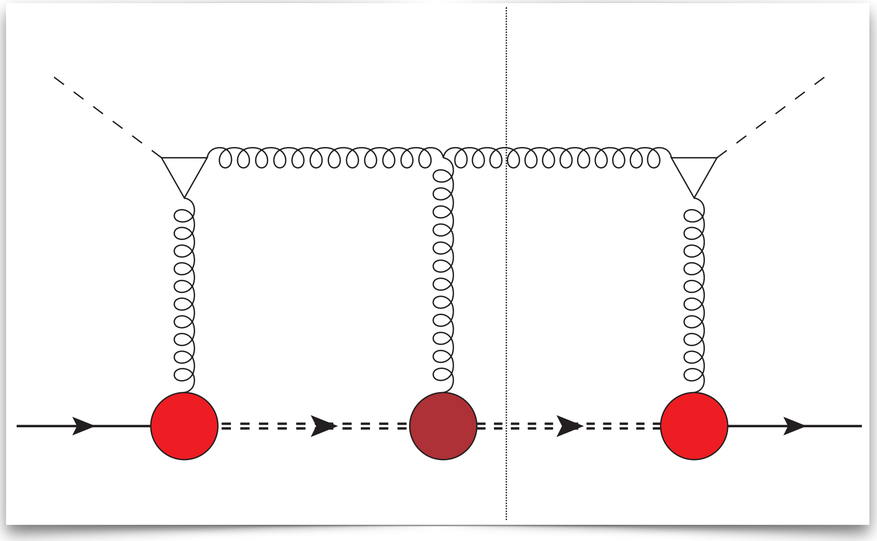

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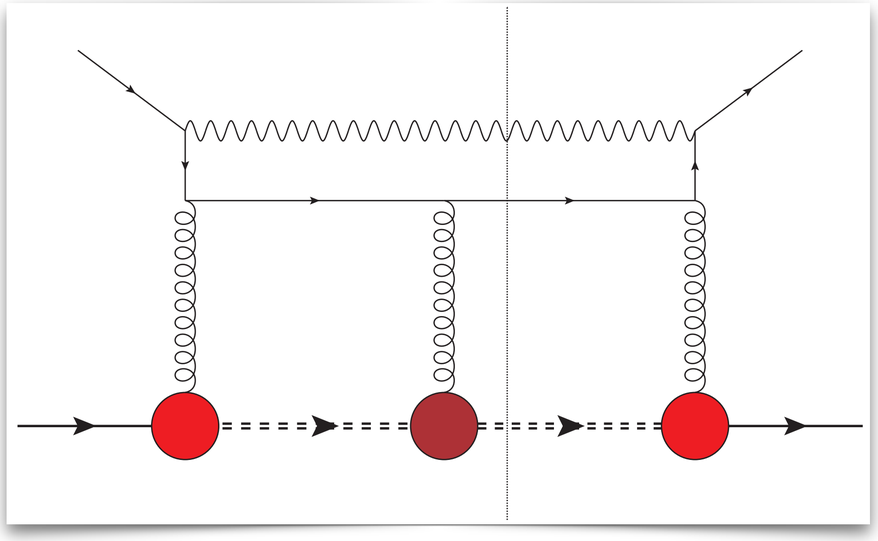

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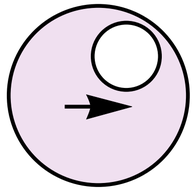
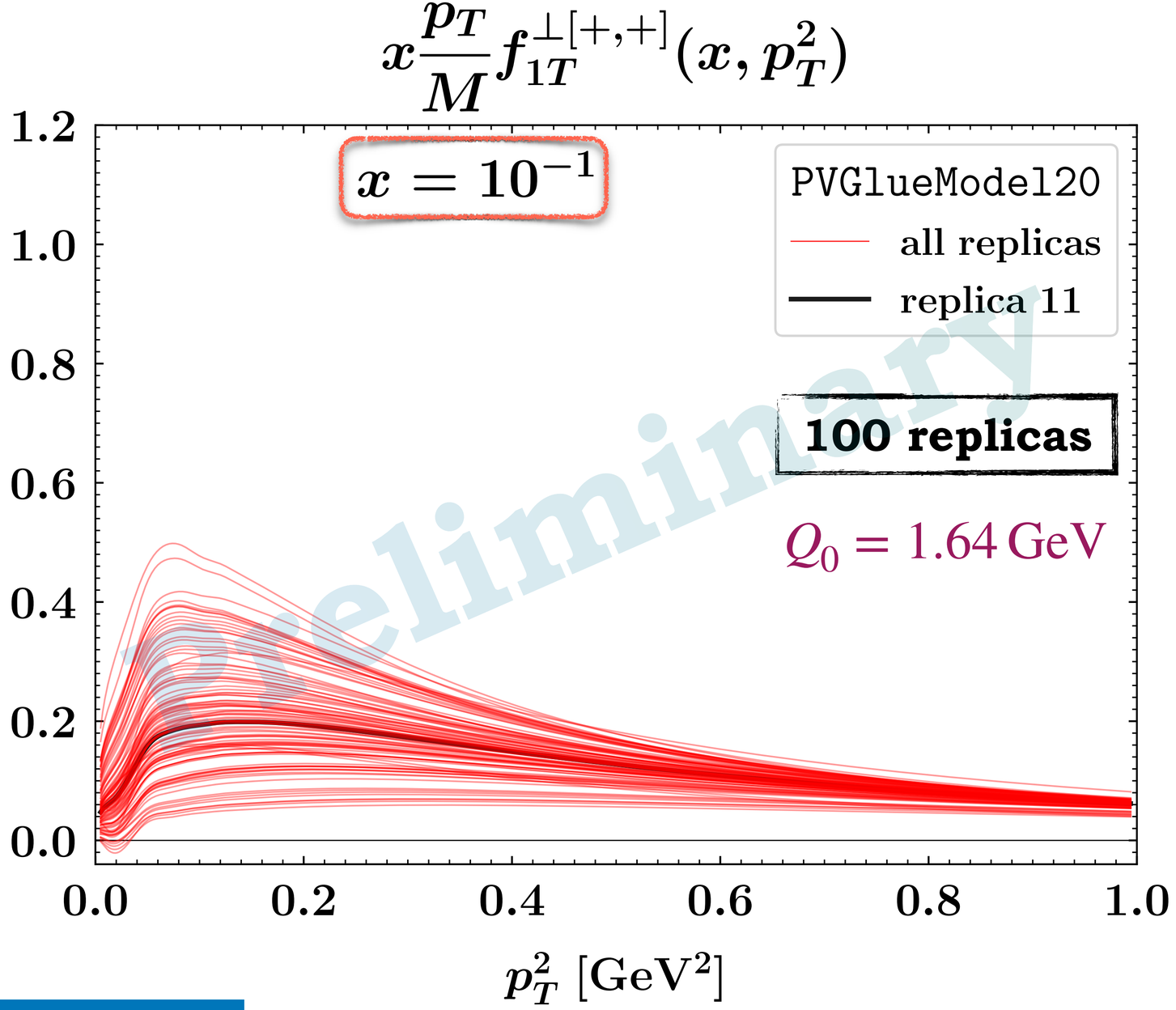
Assumption: $g^d_{1,2}(p^2) = g^f_{1,2}(p^2) \equiv g_{1,2}(p^2)$ ⇔ $f_{1T}^{\perp[+,-]} = \frac{c_{[+,-]}}{c_{[+,+]}} f_{1T}^{\perp[+,+]} \equiv \frac{10}{18} f_{1T}^{\perp[+,+]}$

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

Preliminary results for Sivers

[A. Bacchetta, F.G.C., M. Radici (to appear)]





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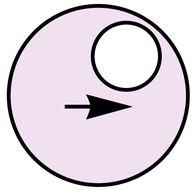

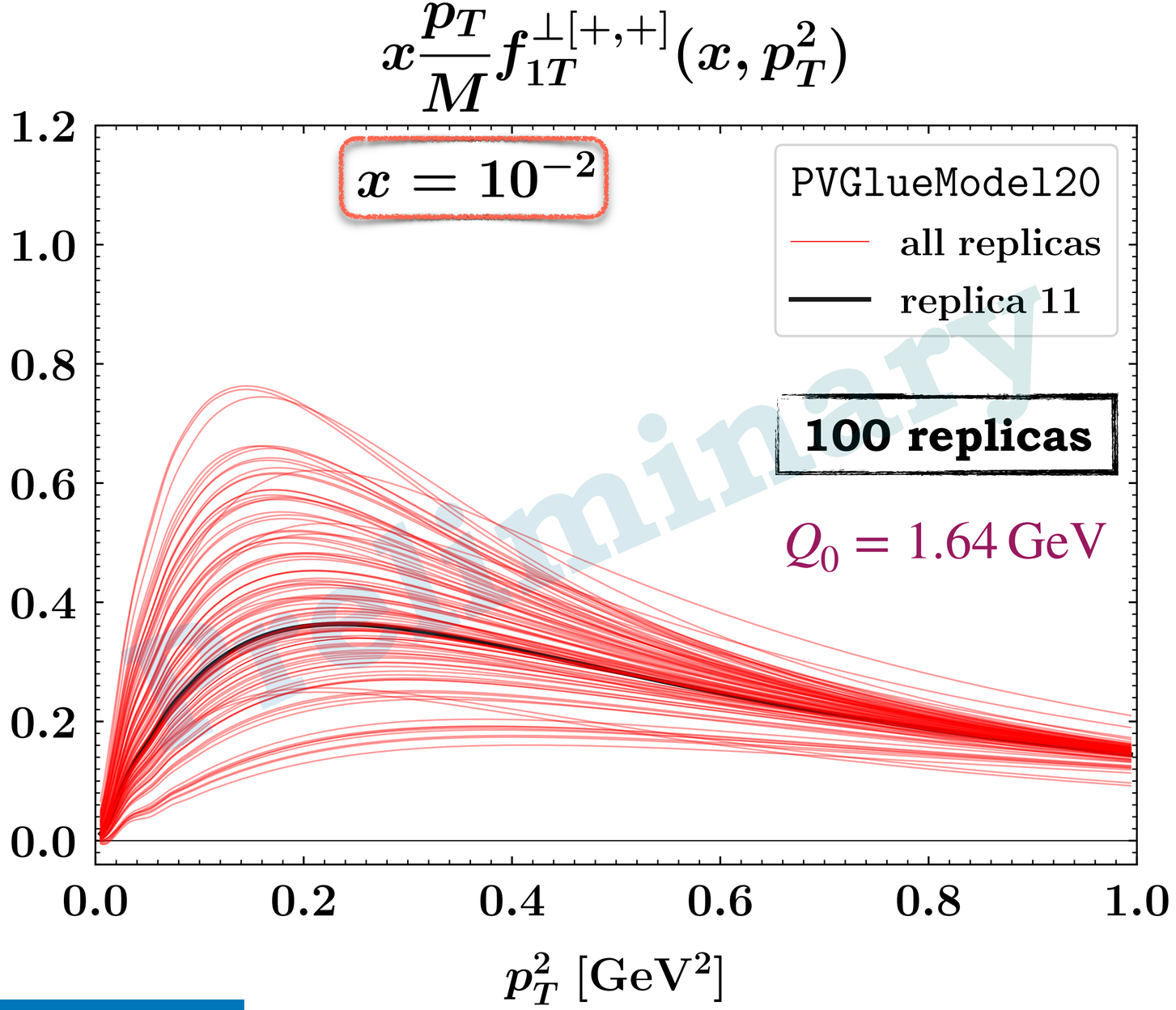

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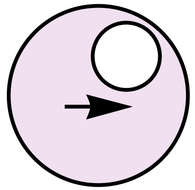
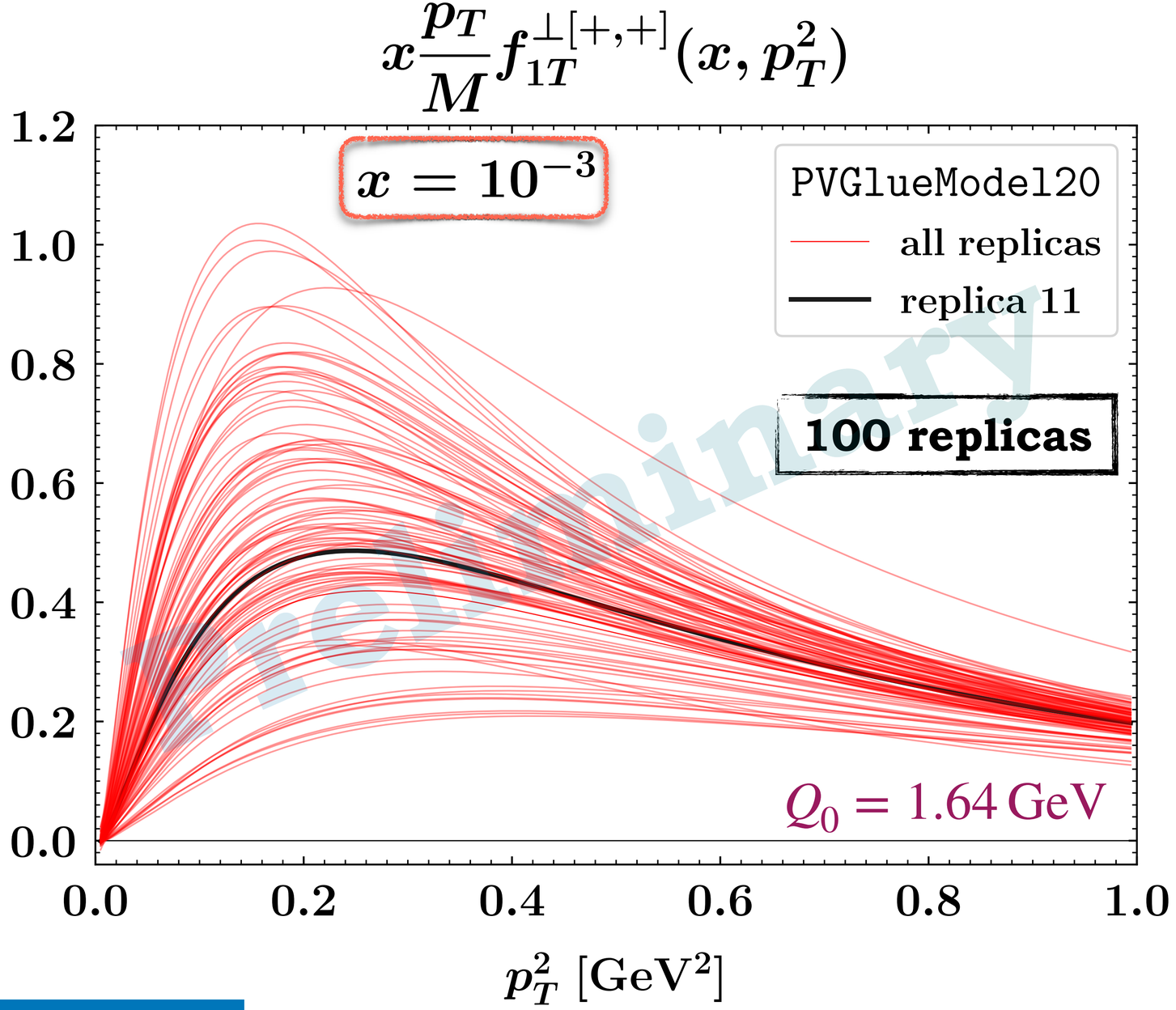
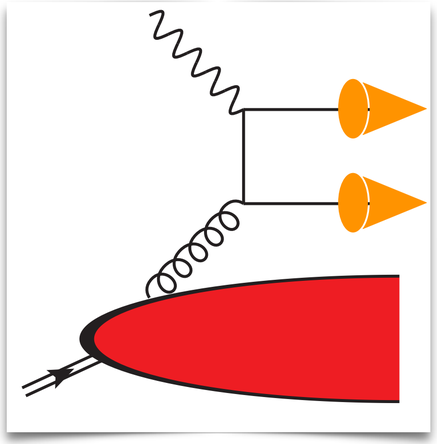




4. Phenomenology

Golden channels for gluon TMD PDFs @EIC

Two-jet SIDIS



jet function

jet function

TMD PDF

Golden channels for gluon TMD PDFs @EIC

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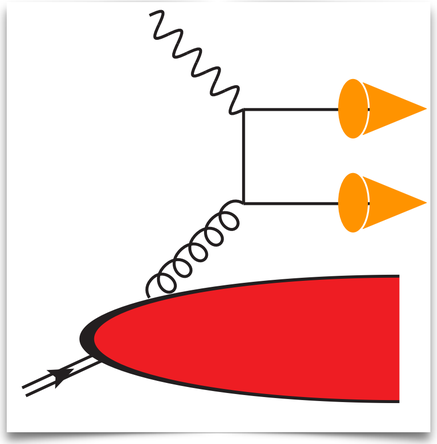

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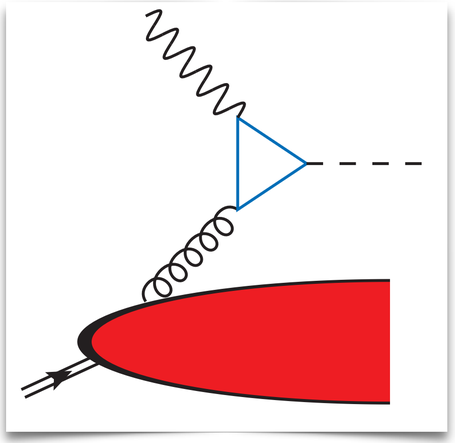
TMD PDF

Higgs in ep collisions



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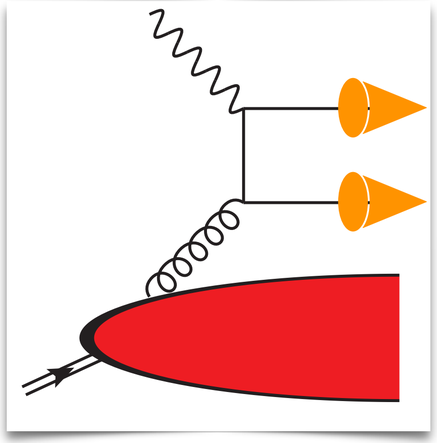

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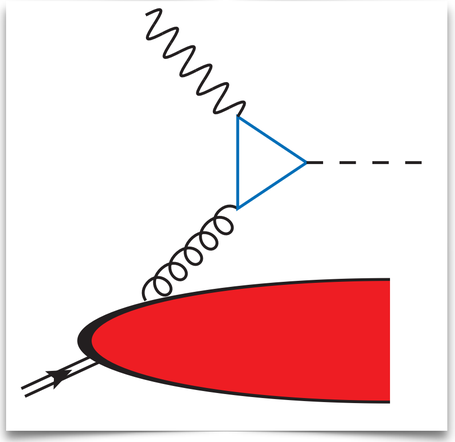
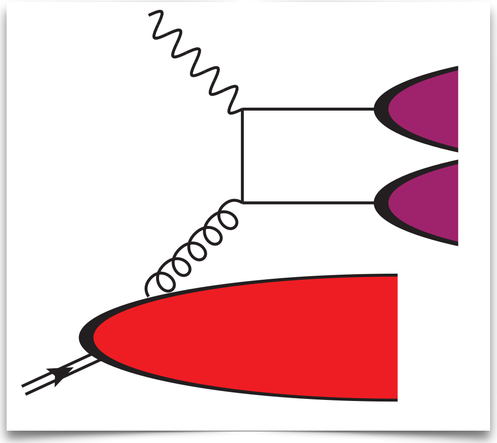


TMD PDF

Double D meson



TMD FF

TMD FF

TMD PDF

Golden channels for gluon TMD PDFs @EIC

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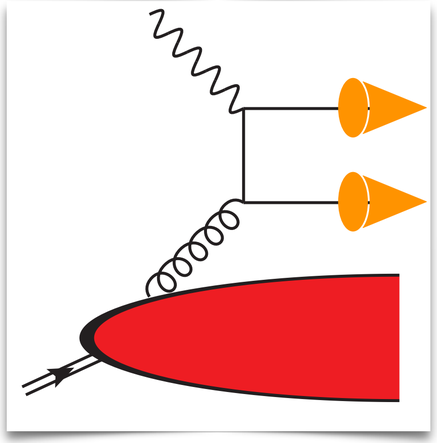

jet function

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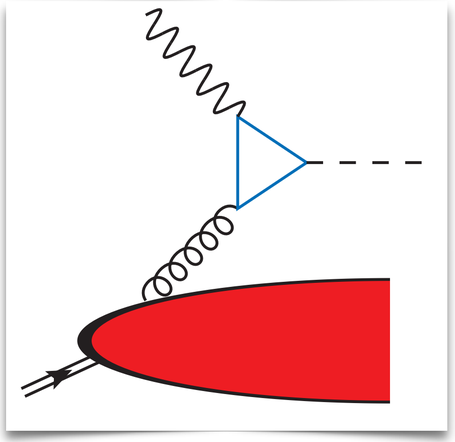
TMD PDF

Higgs in ep collisions



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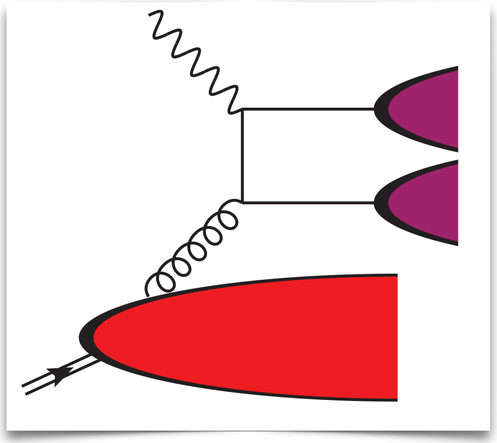
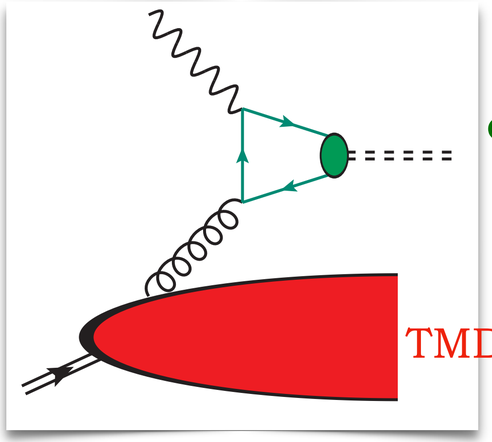


TMD FF

TMD FF

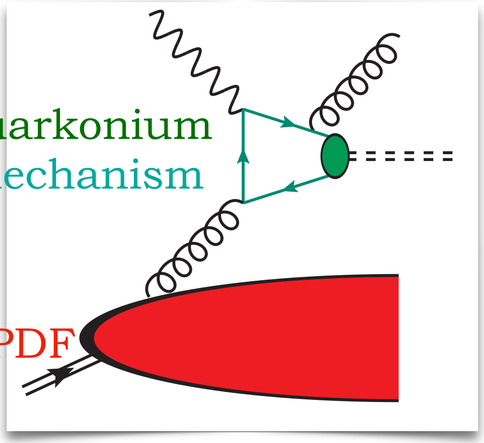
TMD PDF

Quarkonia



TMD PDF

quarkonium mechanism



Quarkonia: A path toward precision

TMD PDFs & shape functions

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

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

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

S-wave quarkonium wave function

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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)]
(unpol. J/ψ) [D. Boer, U. D'Alesio, F. Murgia, C. Pisano, P. Taels (2020)]
(pol. J/ψ) [D. Boer, U. D'Alesio, L. Maxia, F. Murgia, C. Pisano, R. Sangem (2022)]
(unpol. J/ψ) [D. Boer, J. Bor, L. Maxia, C. Pisano, F Yuan (2023)]

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(factorization) 🔗 [M. Garcia Echevarria (2019)]
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Revised TMD shape function in SIDIS

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

Quarkonia: A path toward precision

TMD PDFs & shape functions

- NRQCD ⇒ double expansion: $\alpha_s \oplus v$
- NRQCD ⇒ $\mathrm{d}\sigma(|\mathcal{Q}\rangle) \propto \mathscr{H} \otimes \mathrm{LDME}$

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

S-wave quarkonium wave function

- TMD ⇒ from LDMEs to shape functions (ShFs)
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- 2 mechanisms: bound state + soft-gluon
- Perturbative tail ⊗ LDME
- ShFs and TMD FFs exhibit different divergences

Quarkonia & Gluon TMDs: a path toward precision

TMD PDFs & shape functions

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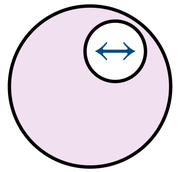
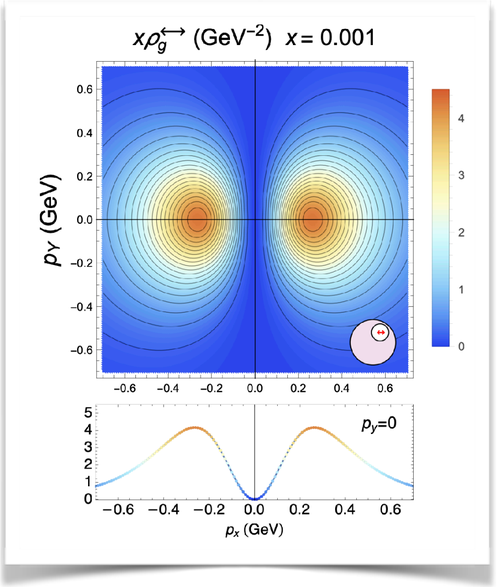
3D proton imaging: LHC & EIC



EIC, LHCb, FT@LHC

Boer-Mulders



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

Quarkonia & Gluon TMDs: a path toward precision

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S-wave quarkonium wave function

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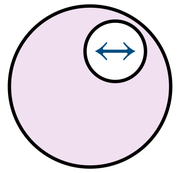

EIC, LHCb, FT@LHC

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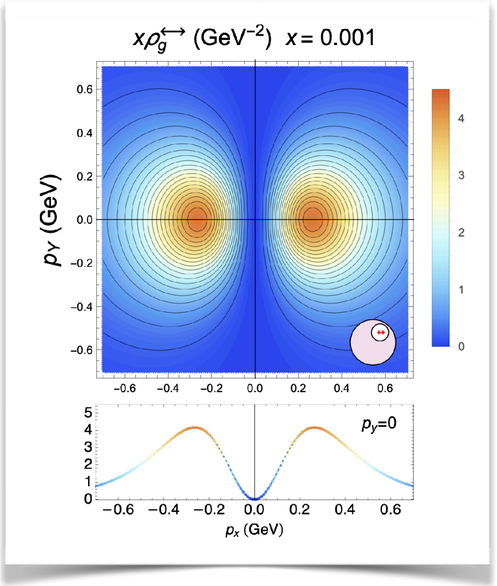
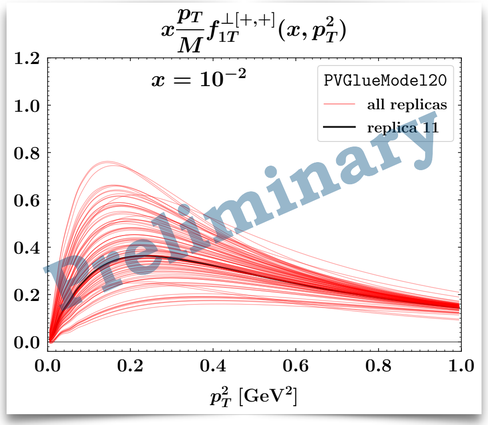
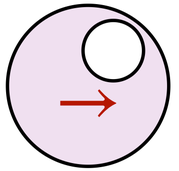


[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]
[A. Bacchetta, F.G. C., M. Radici (to appear)]

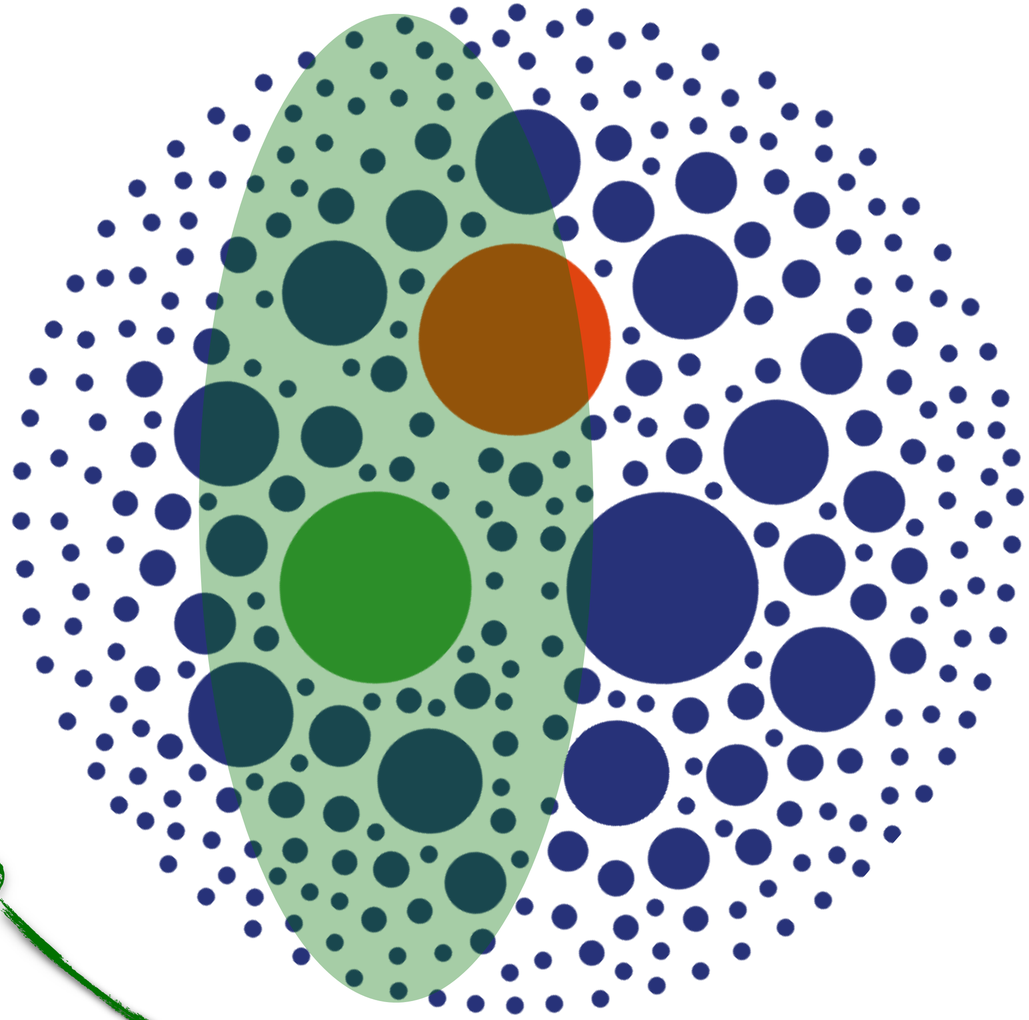




EIC, LHCspin

Sivers

Gluon TMD PDFs @ePIC & @DET-II: A win-win strategy

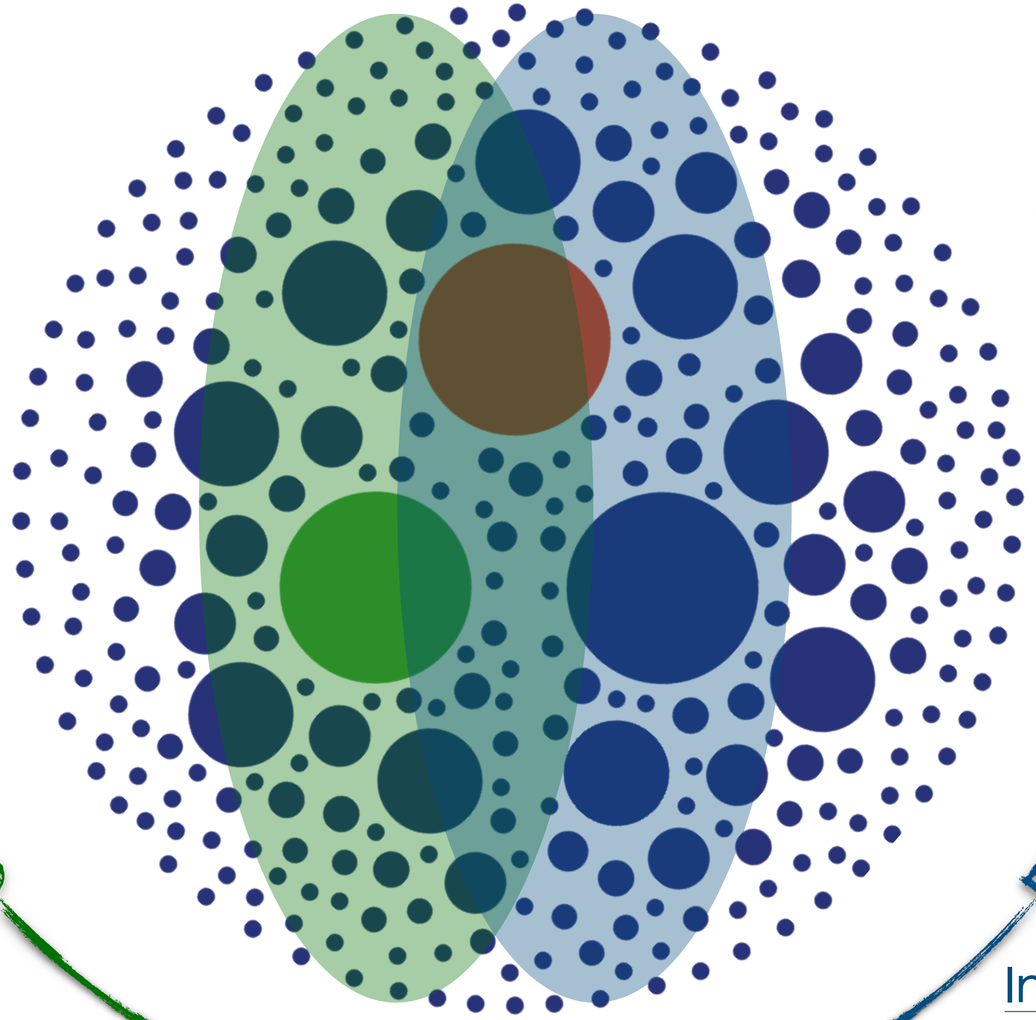


Gluon TMD PDFs

Models & Evolution

Gauge links & polarization

Gluon TMD PDFs @ePIC & @DET-II: A win-win strategy



Gluon TMD PDFs

Models & Evolution

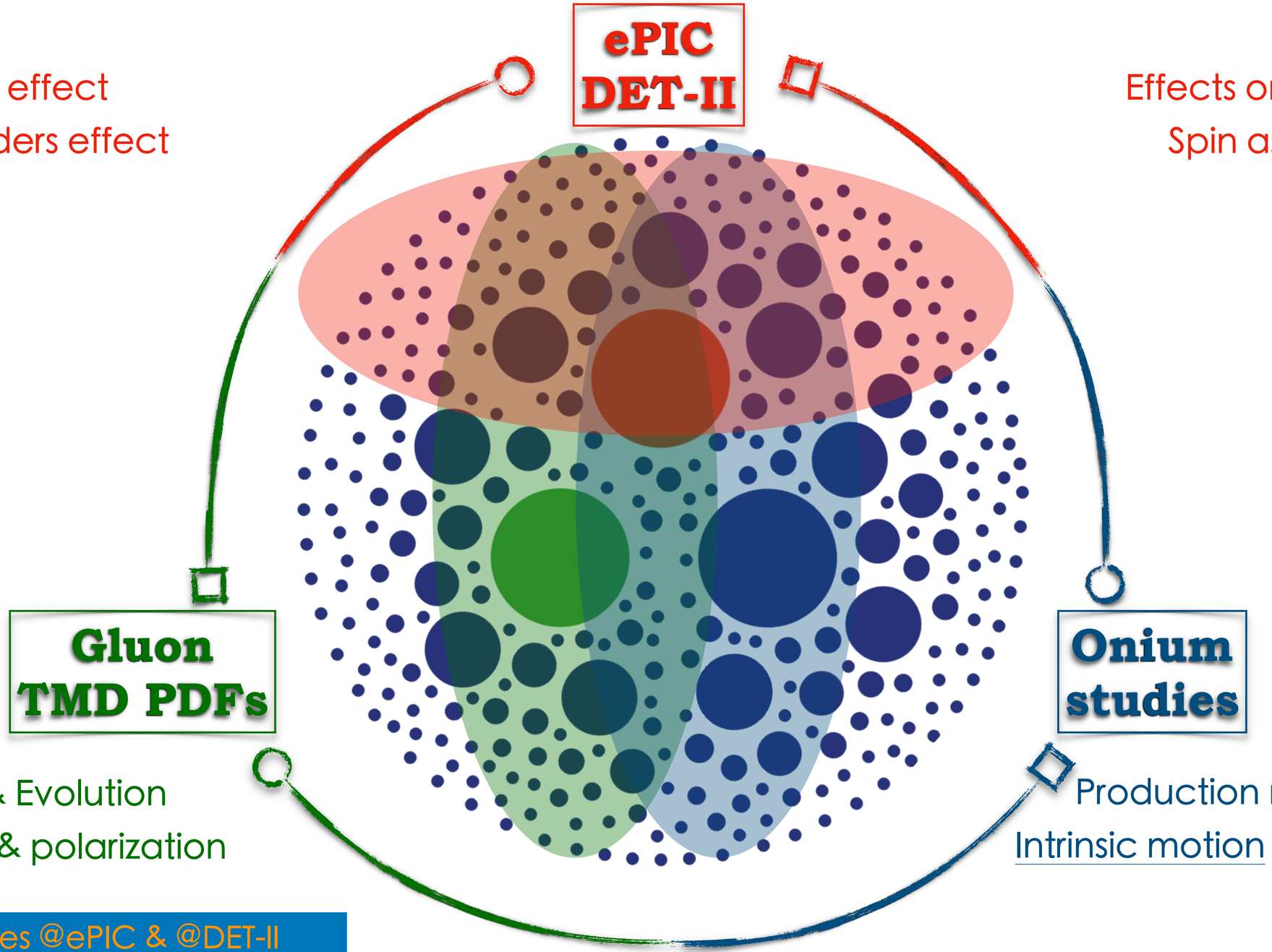
Gauge links & polarization

Onium studies

Production mechanisms

Intrinsic motion & Resummation

Gluon TMD PDFs @ePIC & @DET-II: A win-win strategy



Sivers effect
Boer-Muders effect

Effects on p_T spectrum
Spin asymmetries

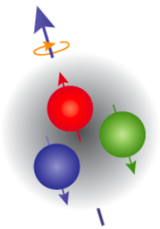
Models & Evolution
Gauge links & polarization

Production mechanisms
Intrinsic motion & Resummation

Extras

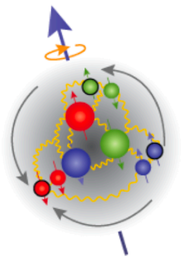
TMD factorization

The proton spin crisis



quarks helicity

~ 30 %



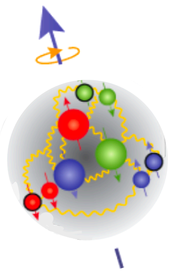
orbital angular momentum

¡ unknown !

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

gluons helicity

~ 20% – 50 % **?**



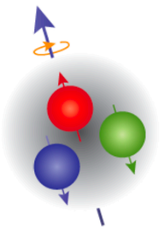
Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description…

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

slide adapted from C. Bissolotti

Backup

The proton spin crisis



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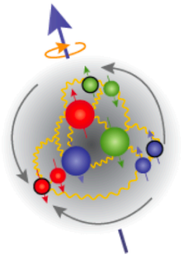

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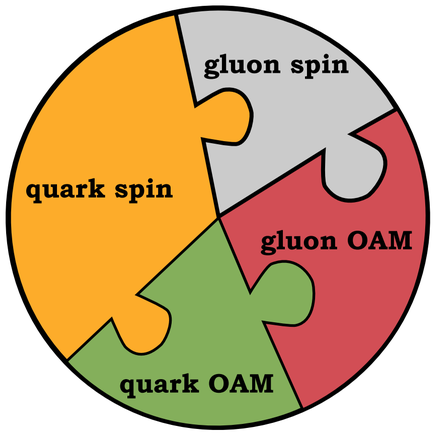

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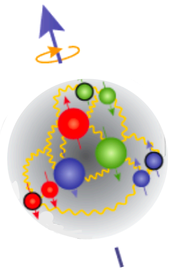

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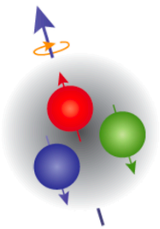

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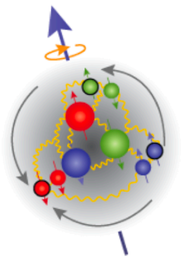

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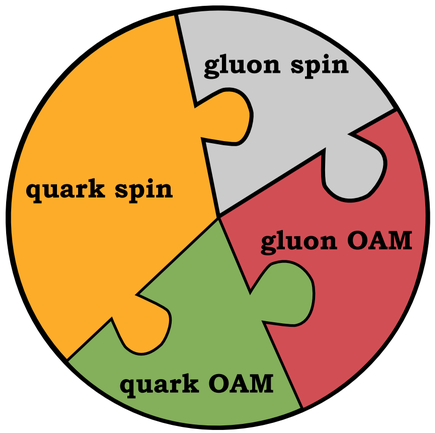

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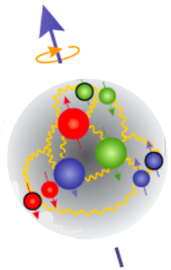

…many other effects in hadronic interactions cannot be understood in the purely collinear approach

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

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slide adapted from C. Bissolotti

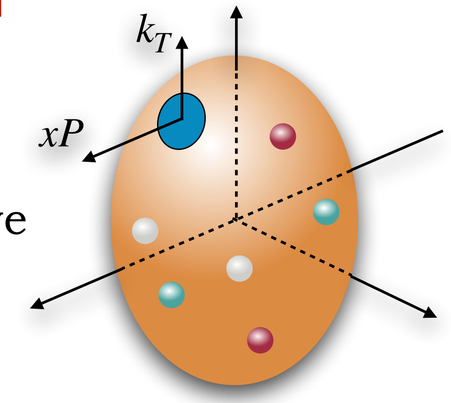
Backup

Parton densities: an incomplete family tree

3D

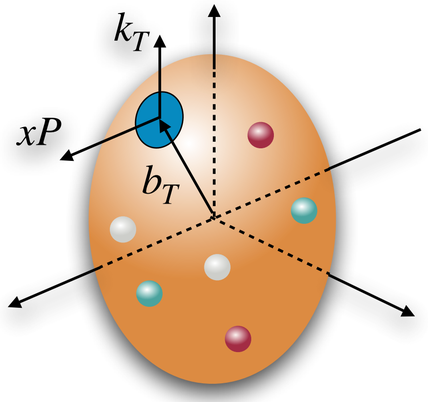
TMDs

(semi-)inclusive



5D

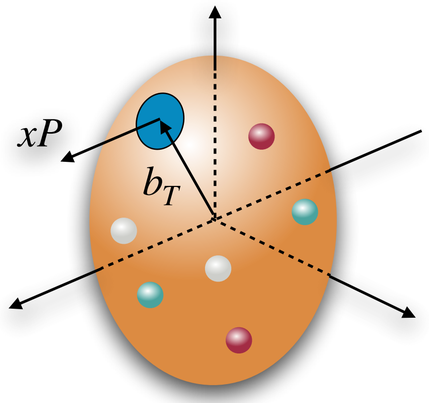
Wigner distributions



3D

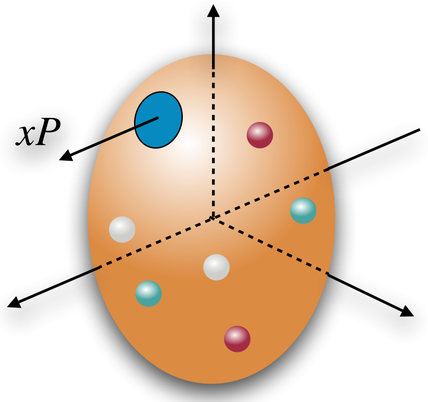
FT of GPDs

exclusive

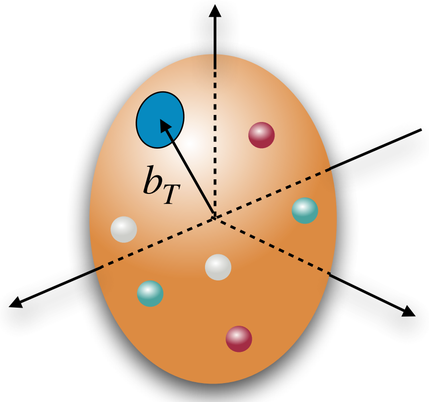


PDFs

(semi-)inclusive



FT of Form Factors



1D

$\vec{b}_\perp$ dependence

$\vec{k}_\perp$ dependence

these two variables are NOT Fourier conjugate

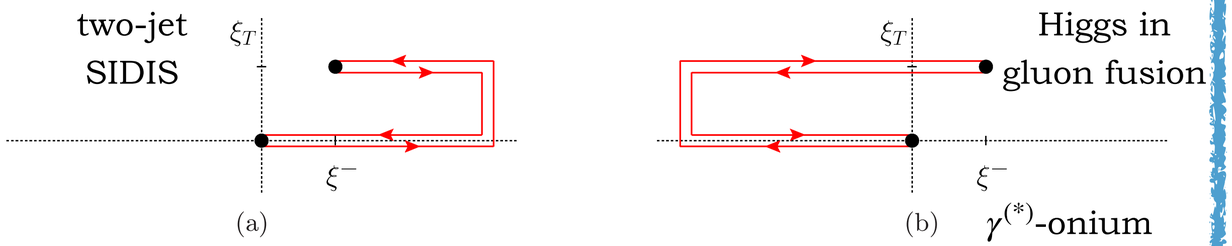
2D

Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

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



Higgs in gluon fusion

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

Backup

Accessing f-type and d-type gluon TMDs

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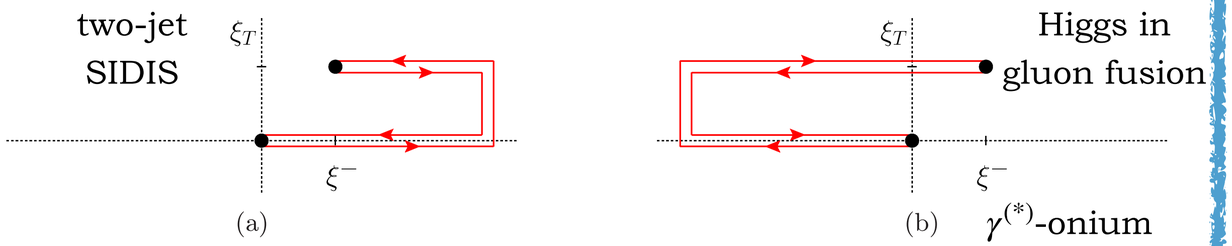
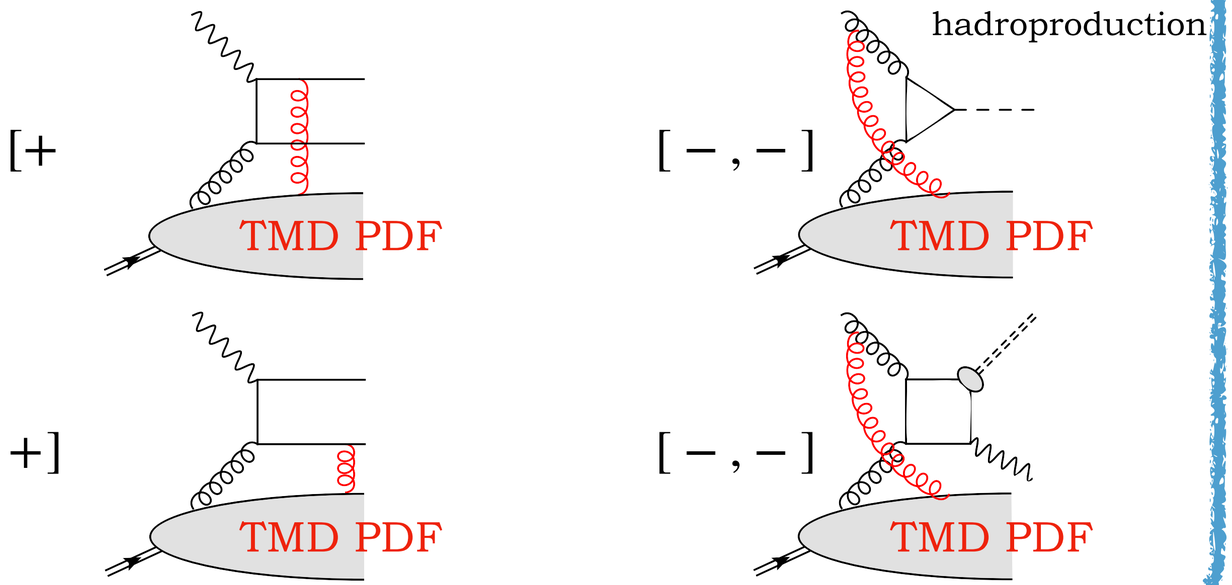




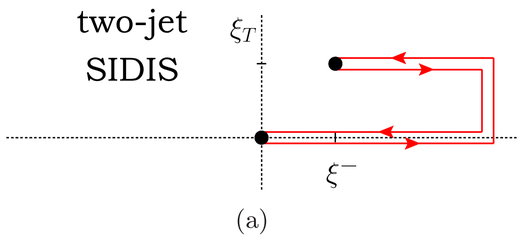
Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

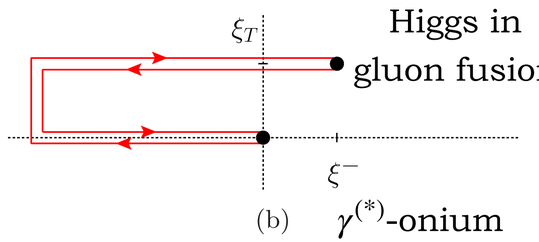
(a) [+ , +] or (b) [− , −]

two-jet SIDIS



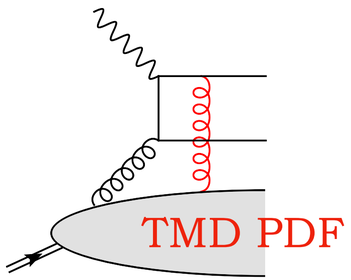
(a)

Higgs in gluon fusion

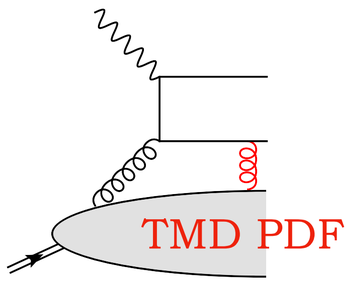


(b)

[+

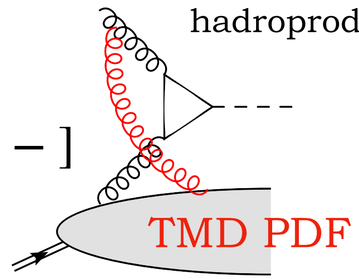


+]

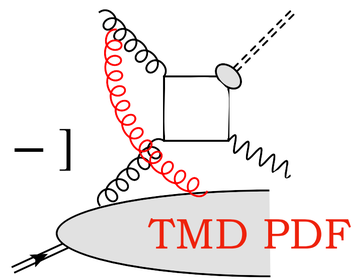


$\gamma^{(*)}$-onium hadroproduction

[− , −]

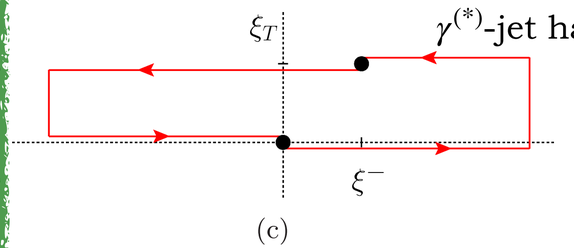


[− , −]



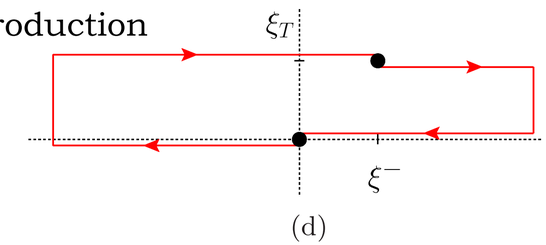
d-type (DP)

(c) [+ , −] or (d) [− , +]



(c)

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



(d)

Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

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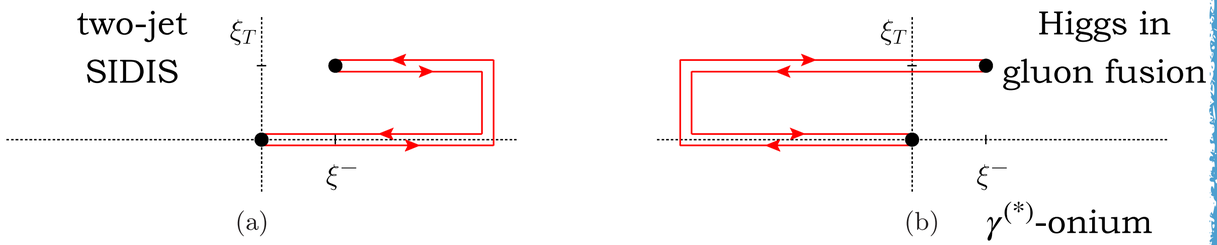

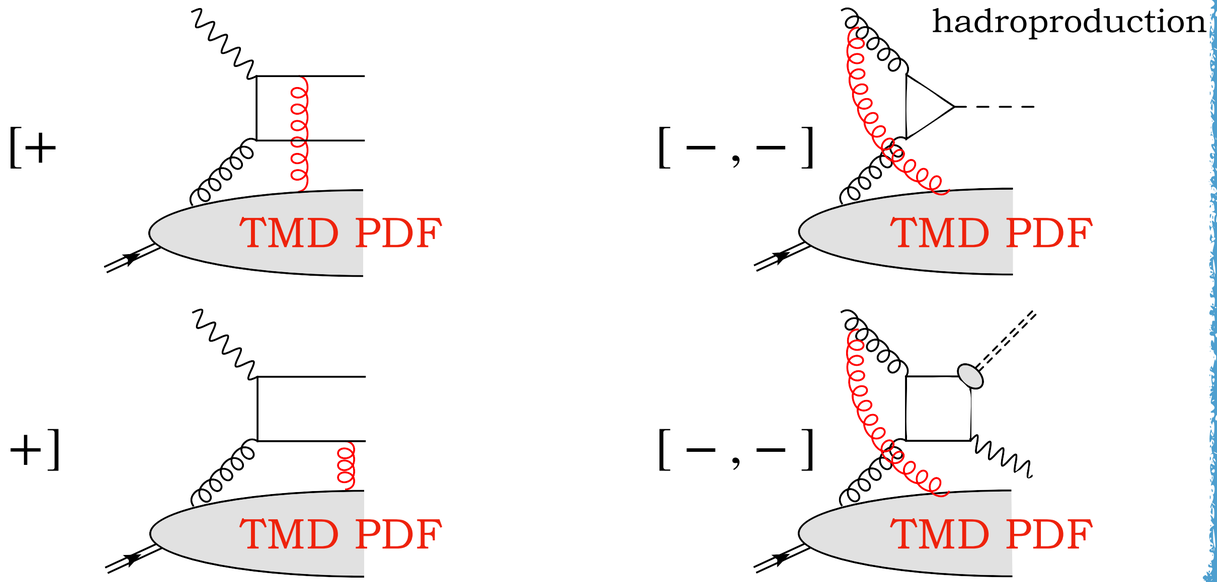

d-type (DP)

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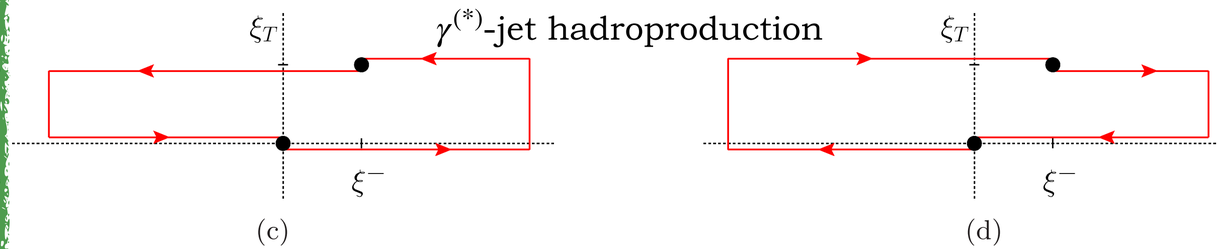
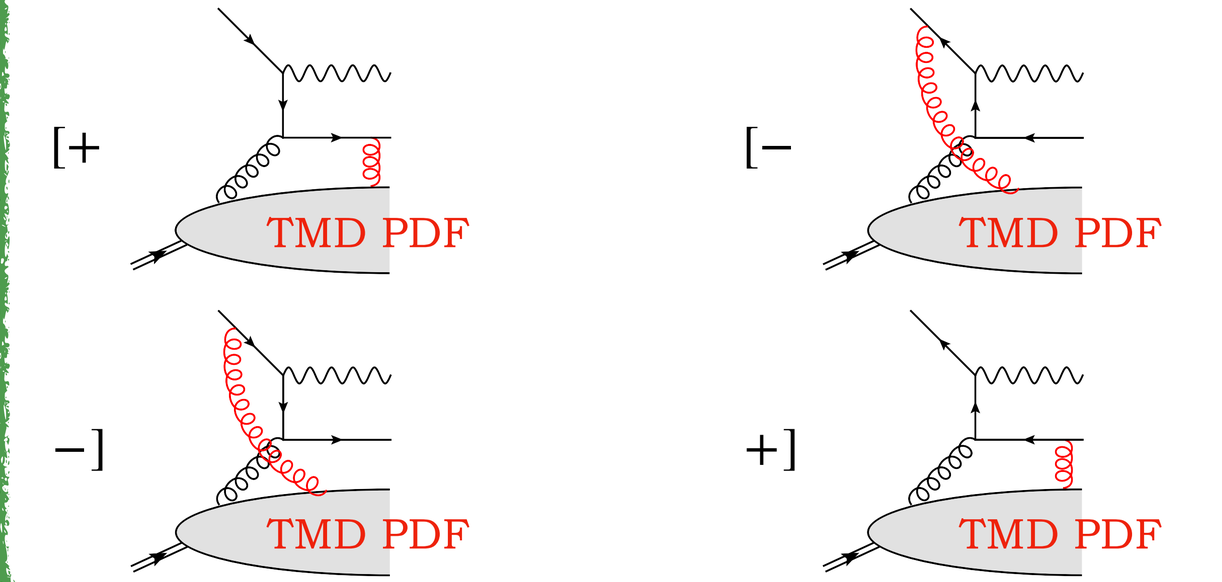


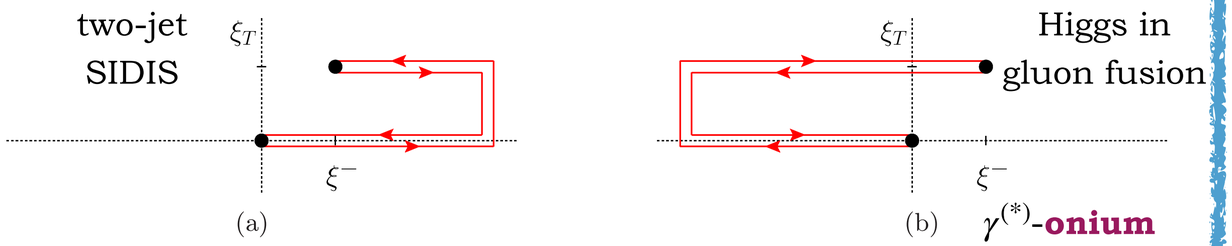


Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

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



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

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

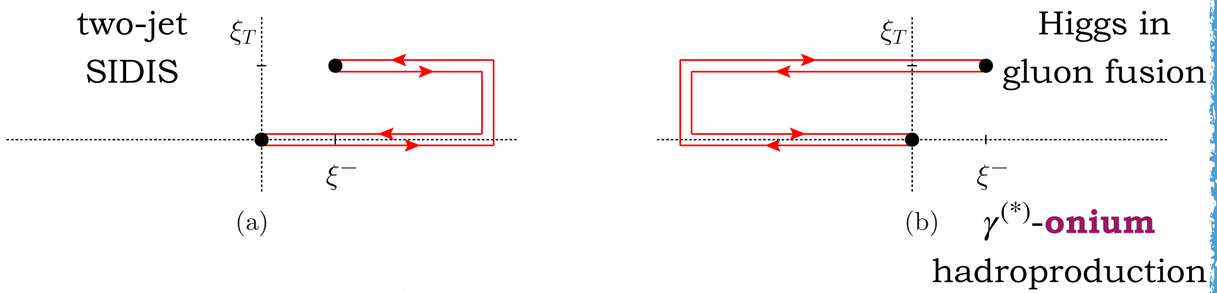
* Phenomenology: Higgs, **quarkonia** or $\gamma\gamma$ in pp, two-jet SIDIS, heavy-quark pair SIDIS

Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

(a) [+ , +] or (b) [− , −]



- Color flow annihilated within final/initial state
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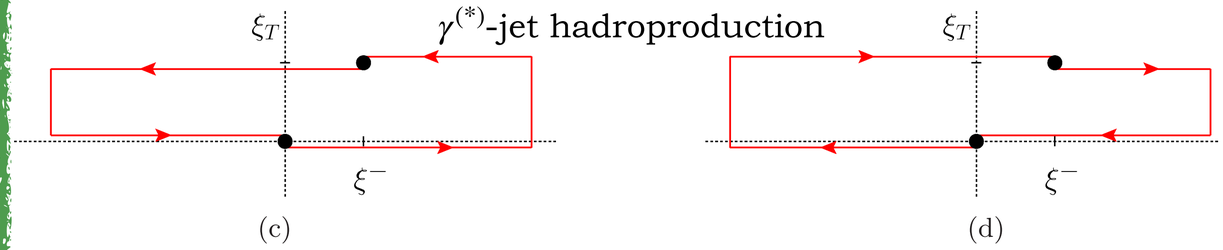
d-type (DP)

(c) [+ , −] or (d) [− , +]



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

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

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

Gauge link → two main independent sets of TMDs, **not related** to each other

Backup

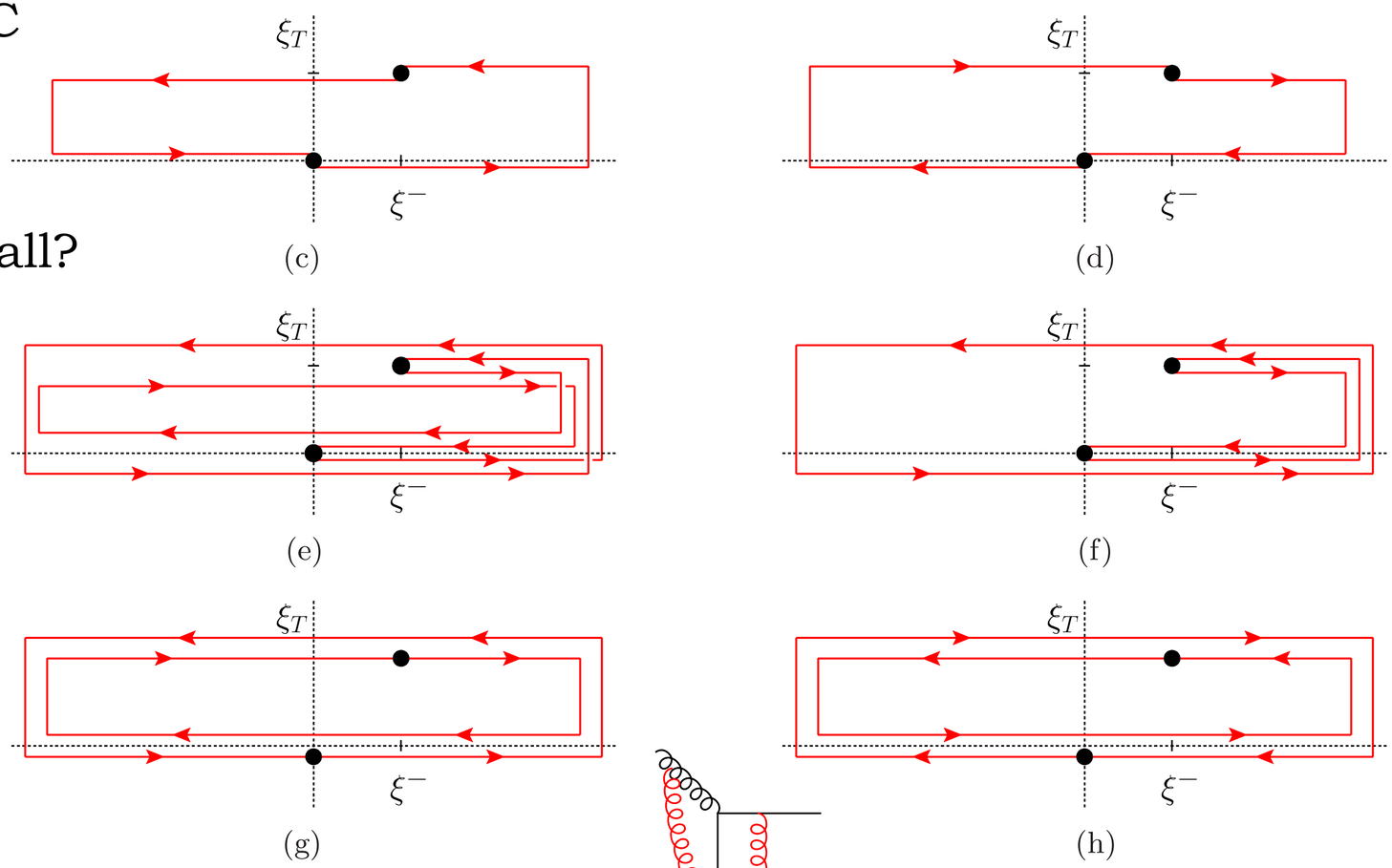
Dihadron hadroproduction and factorization breaking

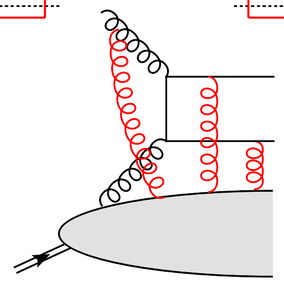
* Proof of factorization violation 🔗 [T. J. Rogers, P. J. Mulders (2010)]
* Assumed factorization in SCET and CGC
* Significance of low-x studies
* Size of factorization-breaking effects small?
* DP TMDs:

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

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

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

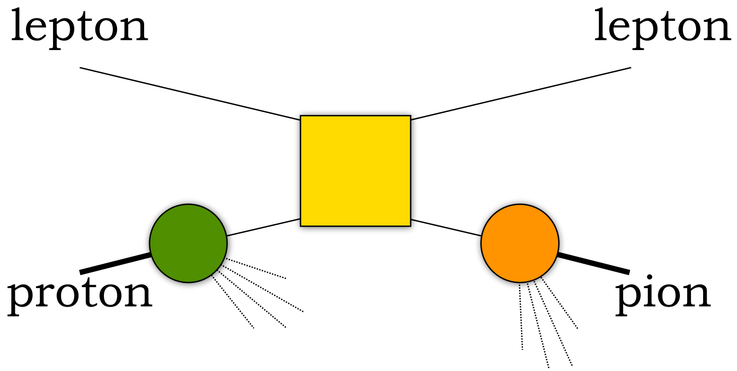




Backup

Factorization and universality

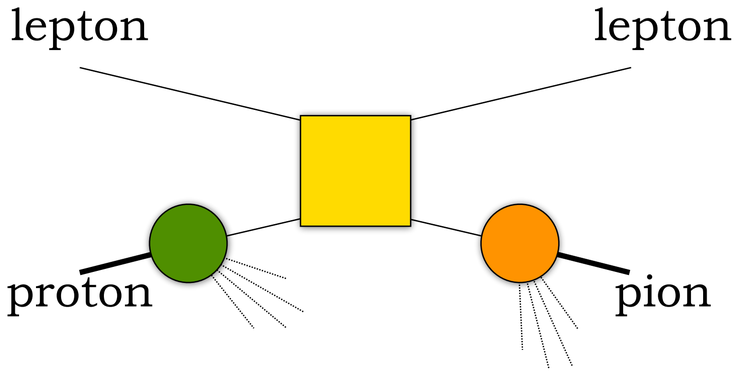
SIDIS



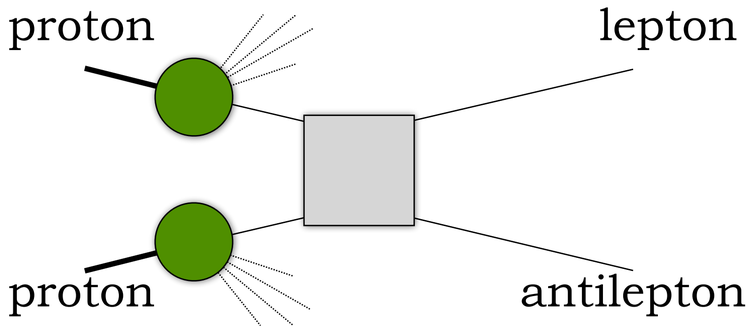
Backup

Factorization and universality

SIDIS



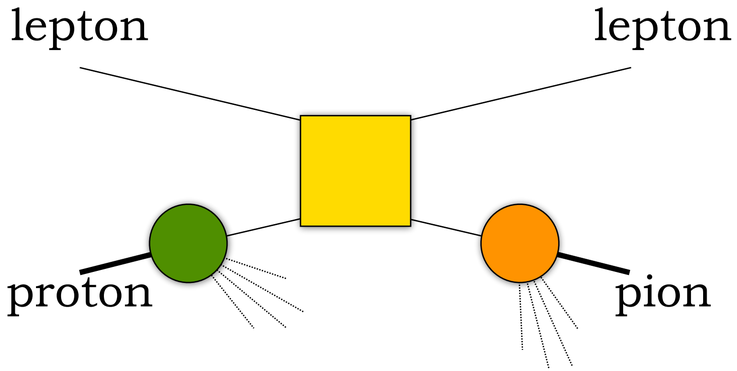
Drell-Yan

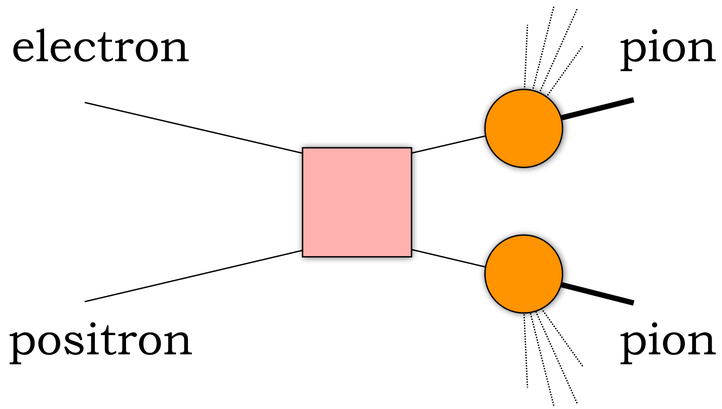


Backup

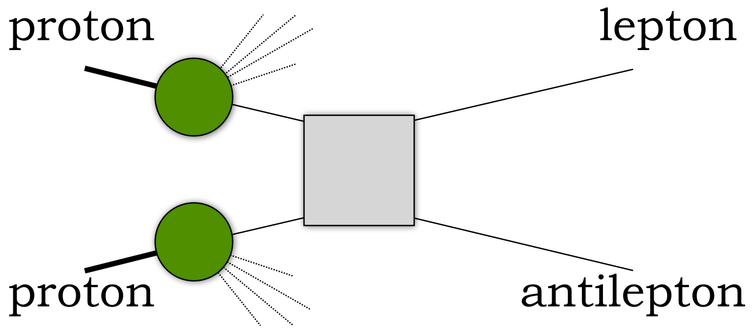
Factorization and universality

SIDIS





Drell-Yan

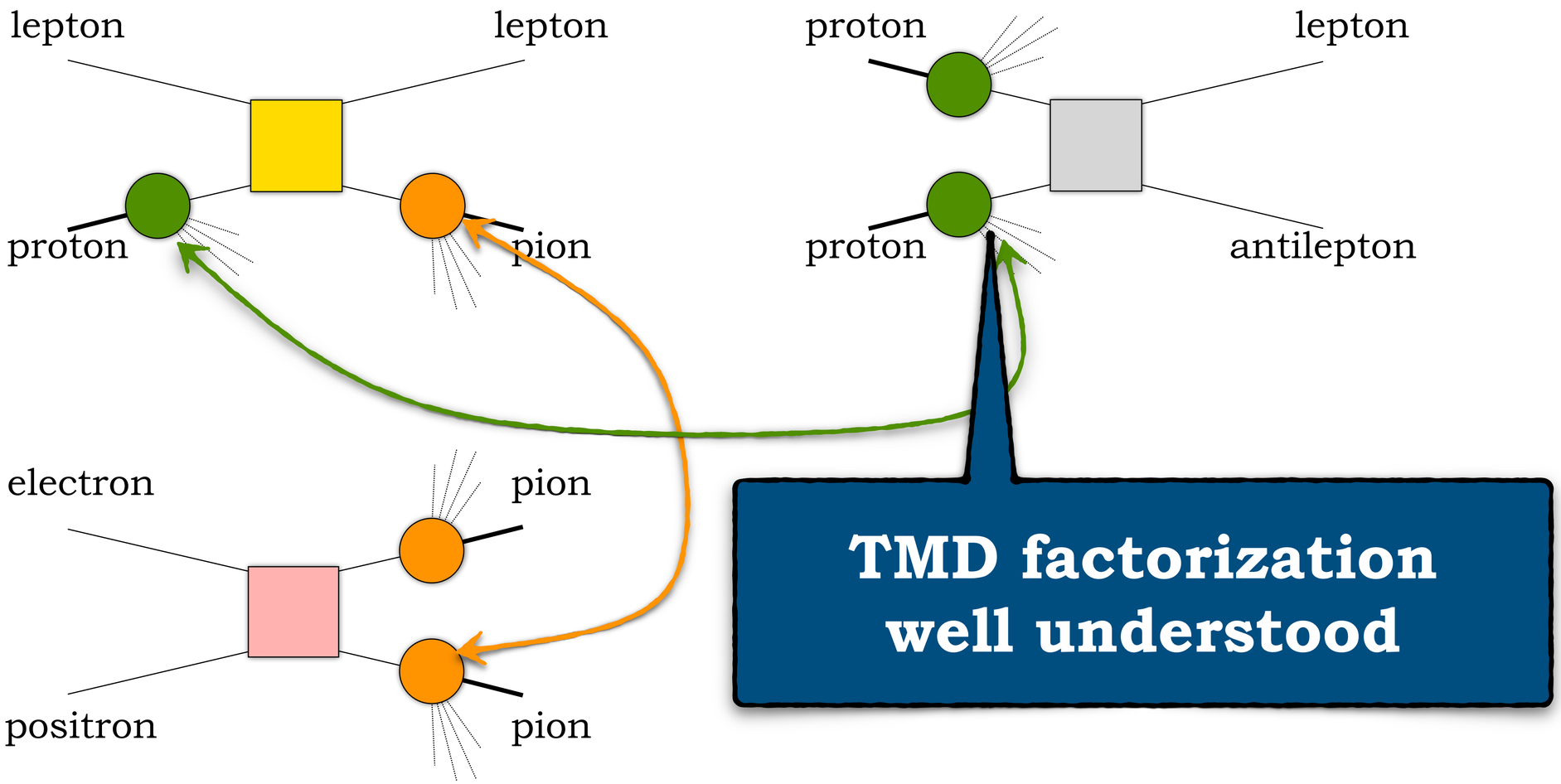


$e^+ + e^- \rightarrow$ **hadrons**

Backup

Factorization and universality

SIDIS **Drell-Yan**



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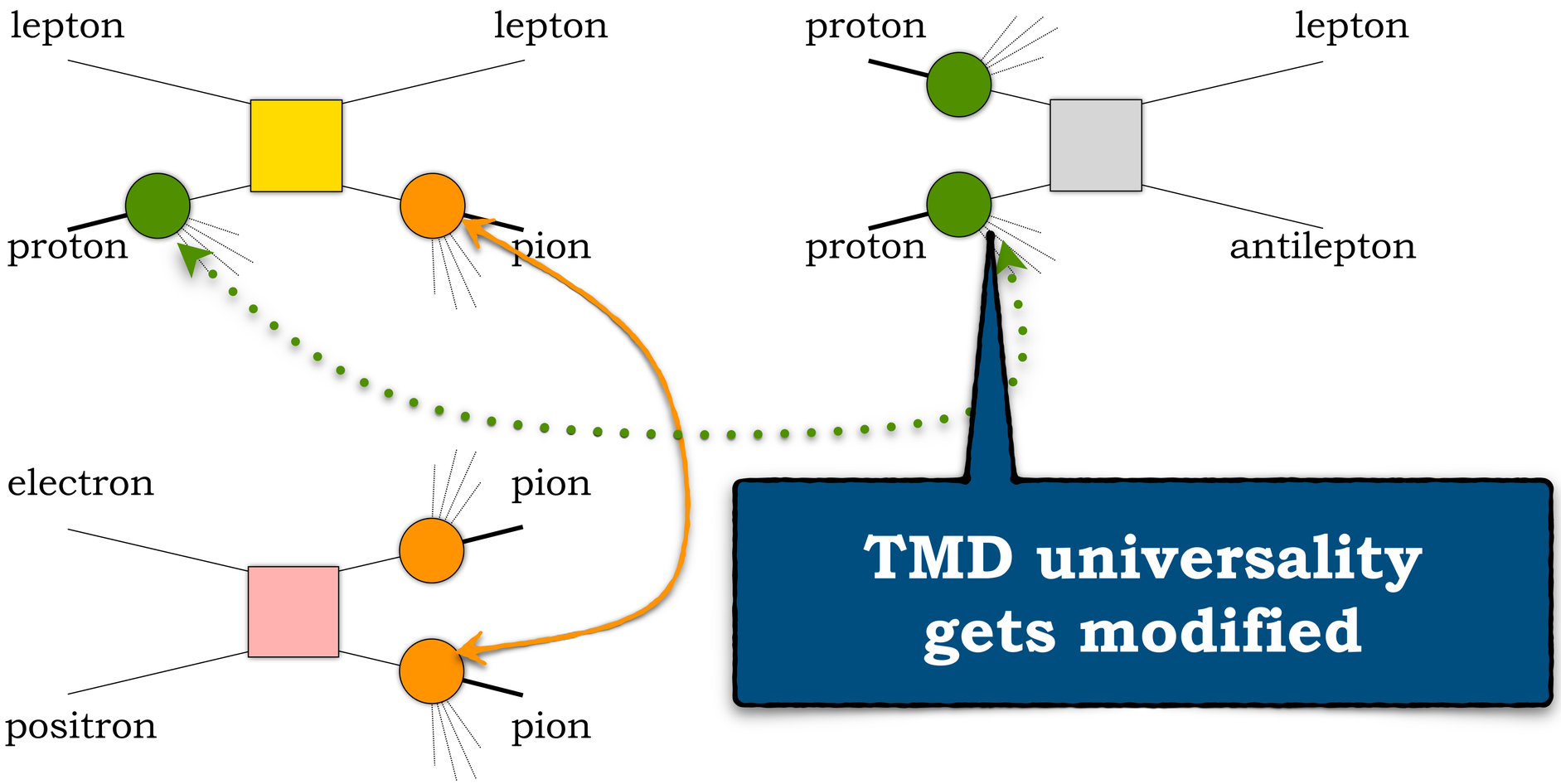
Backup

Factorization and universality

SIDIS **Drell-Yan**

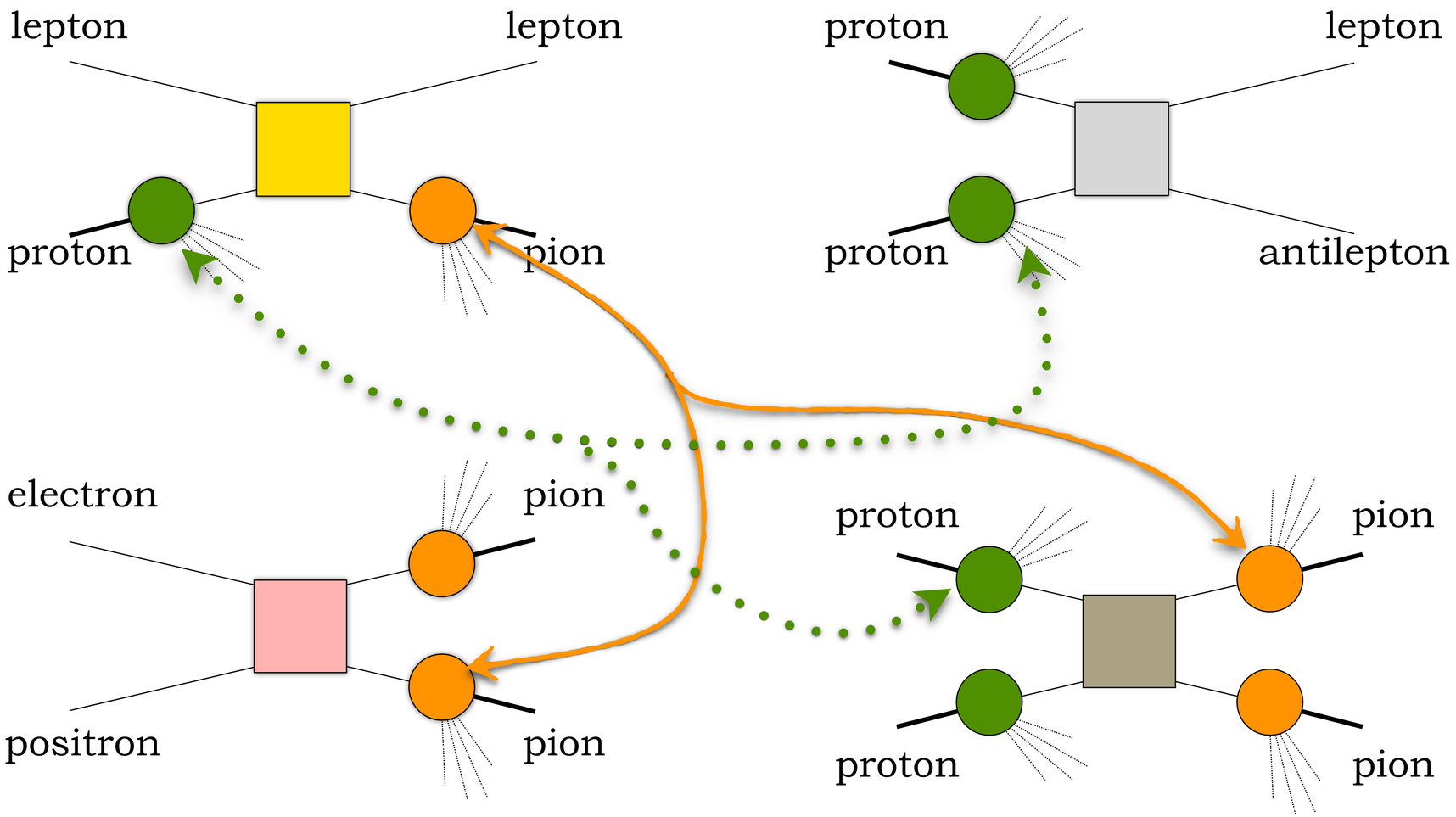


$e^+ + e^- \rightarrow$ **hadrons**

Backup

Factorization and universality

SIDIS **Drell-Yan**



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

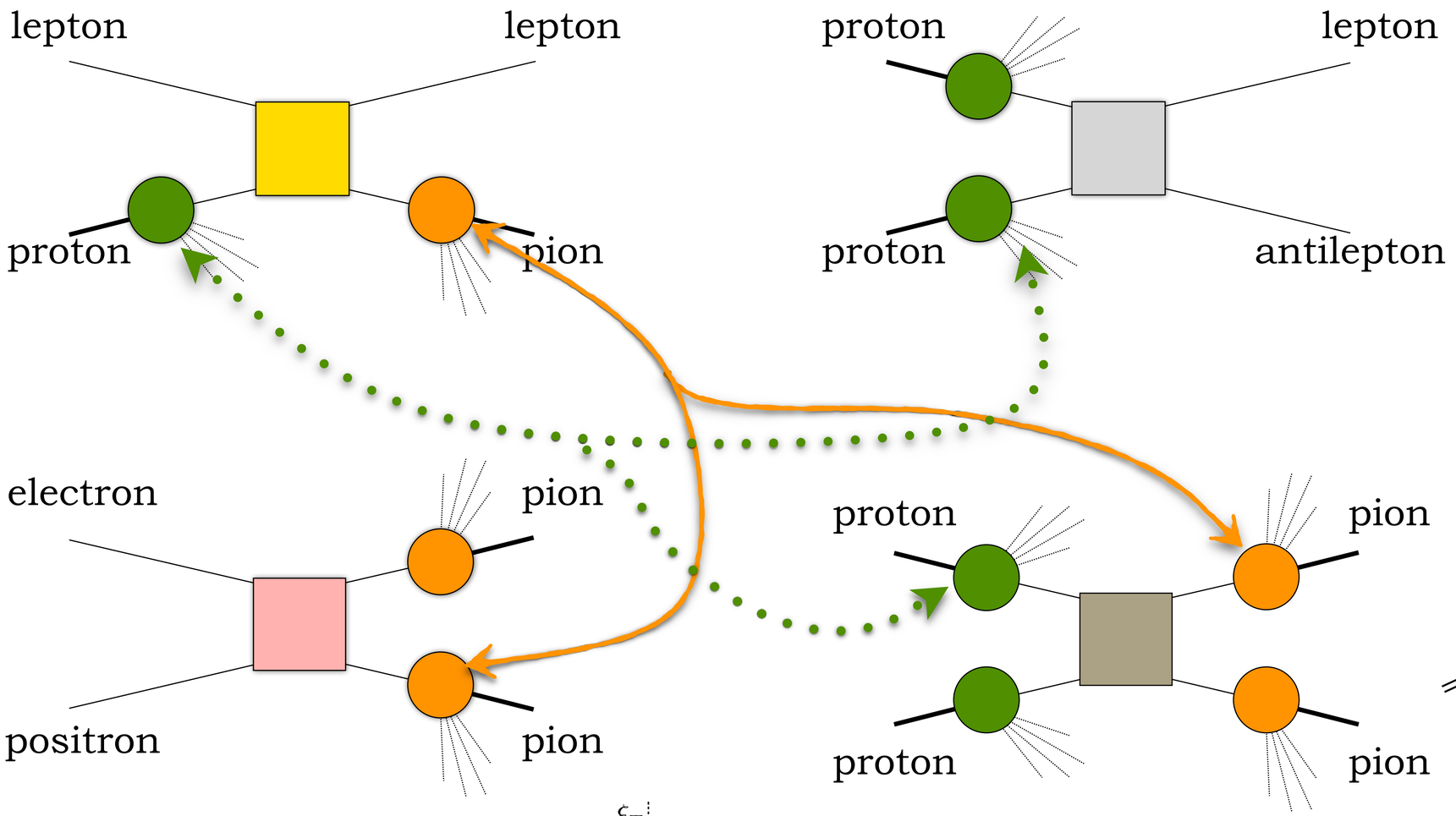
$p + p \rightarrow$ **hadrons**

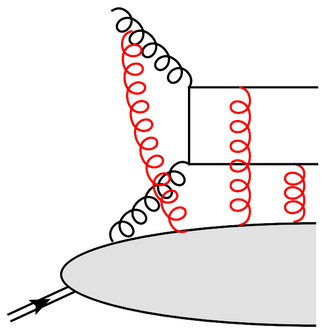
Backup

Factorization and universality

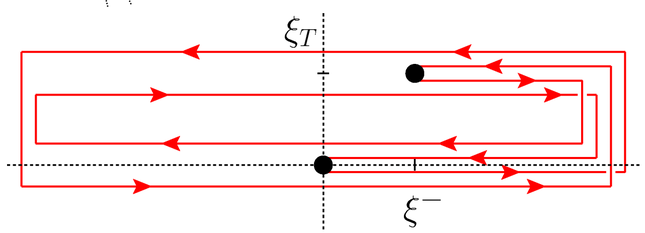
SIDIS

Drell-Yan





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



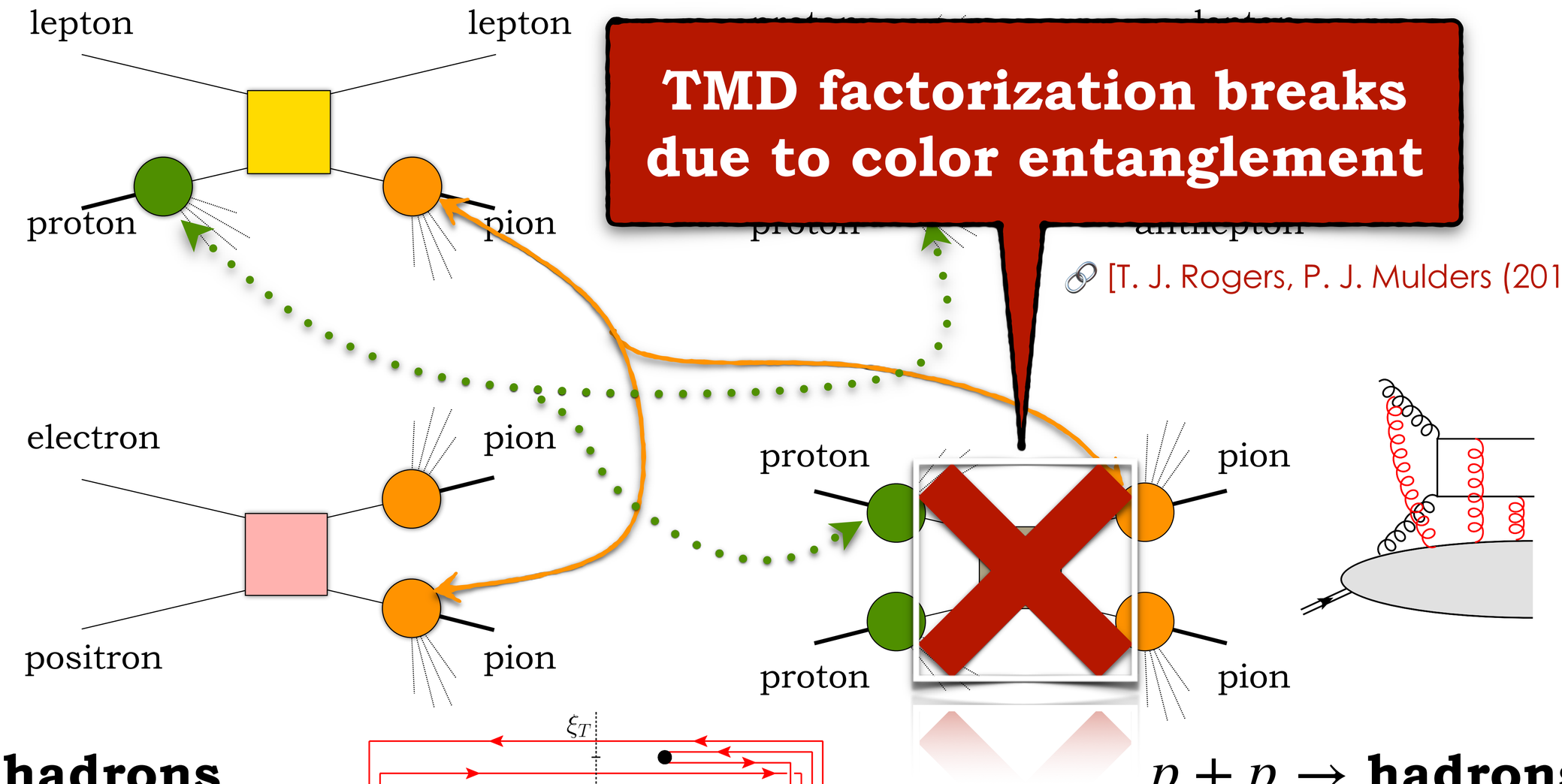
$p + p \rightarrow$ **hadrons**

(also) gluon-induced channel

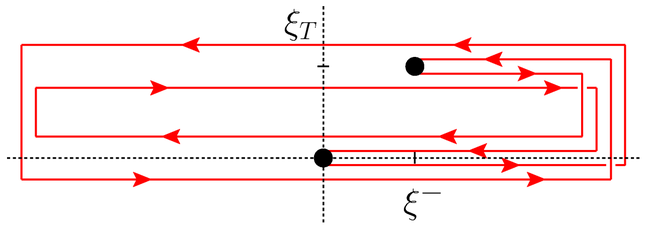
Backup

Factorization and universality

SIDIS **Drell-Yan**



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



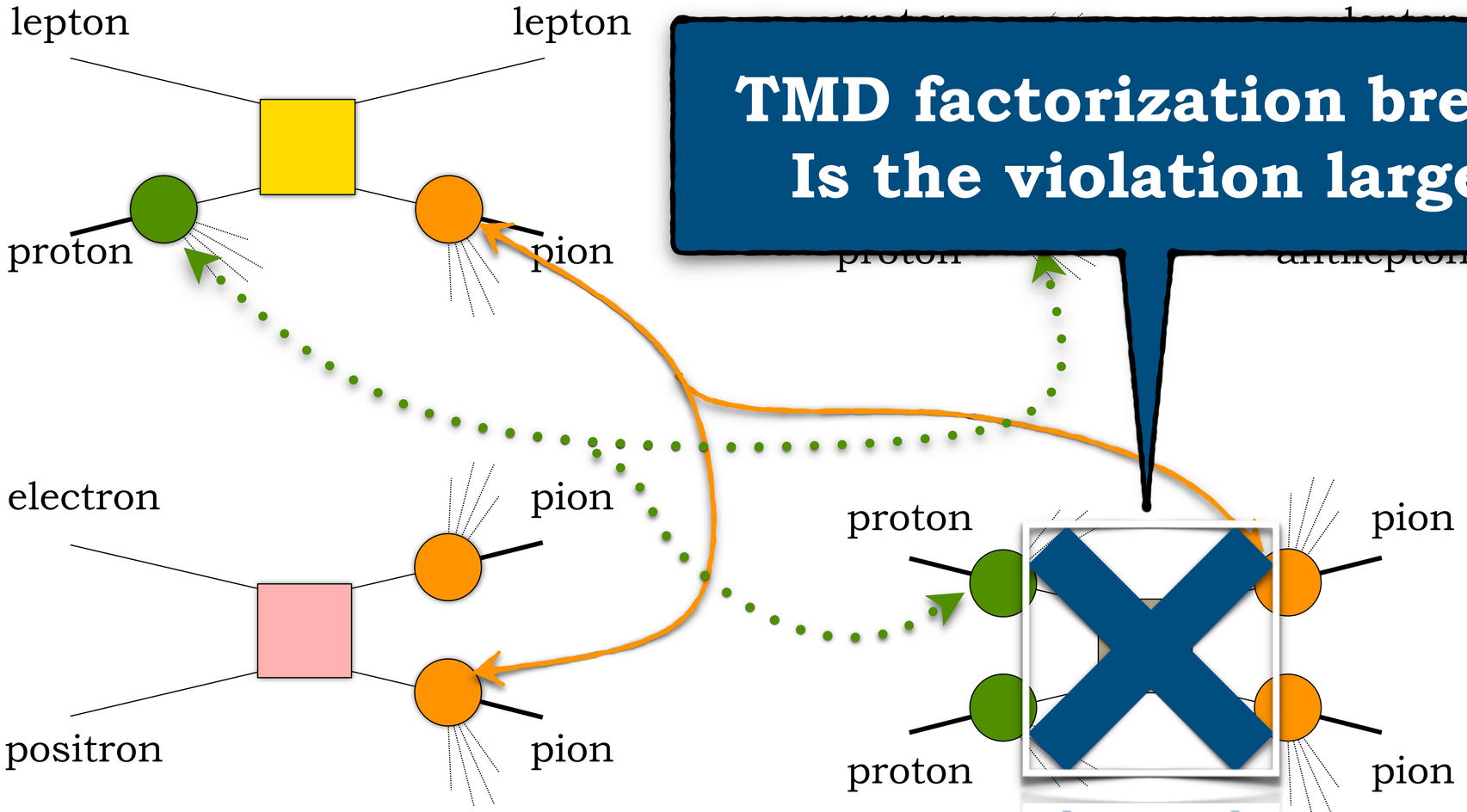
$p + p \to$ **hadrons**

(also) gluon-induced channel

Backup

Factorization and universality

SIDIS **Drell-Yan**



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

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

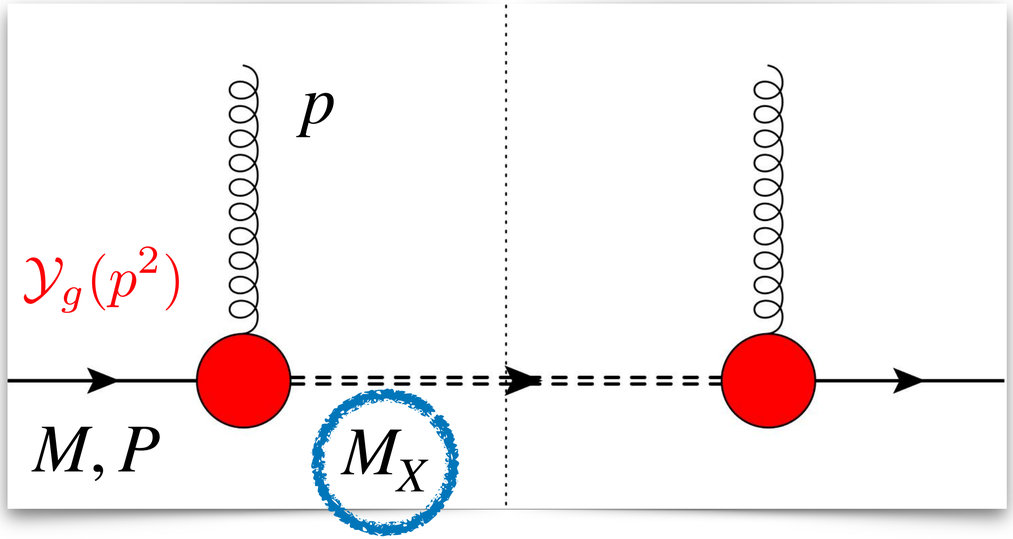
Backup

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 (2020)]

Backup

Spectator-model gluon TMD PDFs

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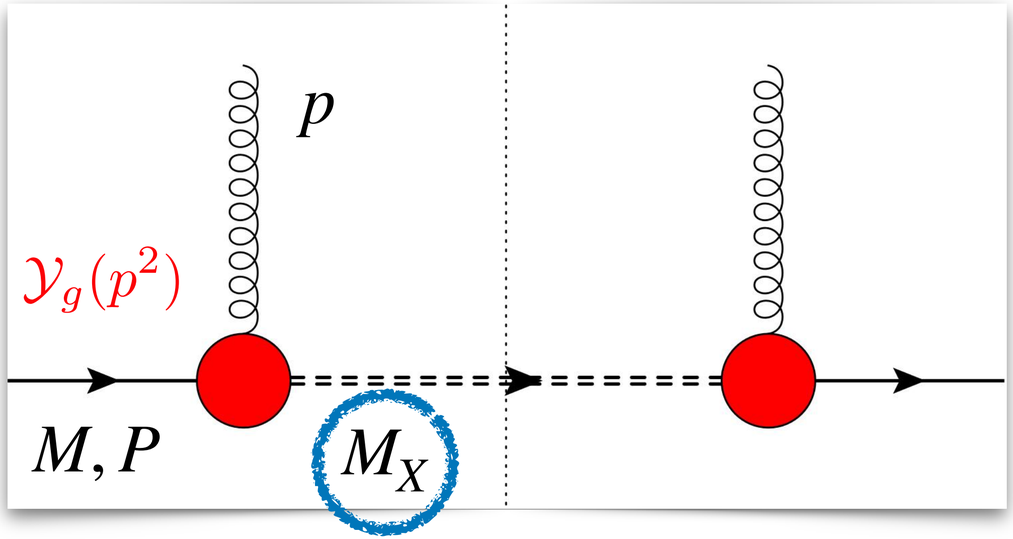

Nucleon-gluon-spectator vertex

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

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

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

[A. Bacchetta, F.G. C., M. Radici, P. Taels (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 (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
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Dipolar form factor(s)

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

1. Cancels singularity of gluon propagator
2. Suppresses effects of high p_T
3. Compensates log divergences arising from p_T-integration
4. Adds three more parameters: $\kappa_{1,2}$ and Λ_X

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

Backup

Assumptions of the model

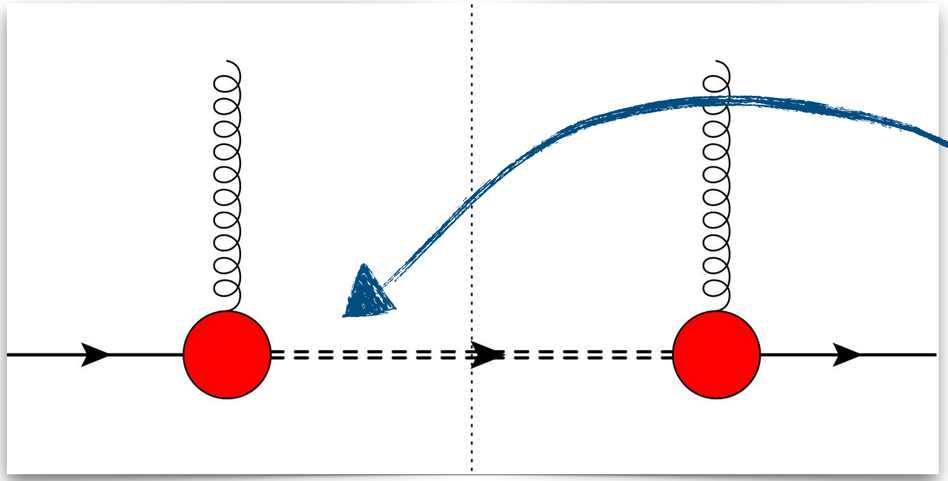
Spectator-system spectral-mass function

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

spectral-mass function

spectator-model TMD

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



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

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

Backup

Assumptions of the model

Spectator-system spectral-mass function

spectral-mass function

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

spectator-model TMD

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

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

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

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

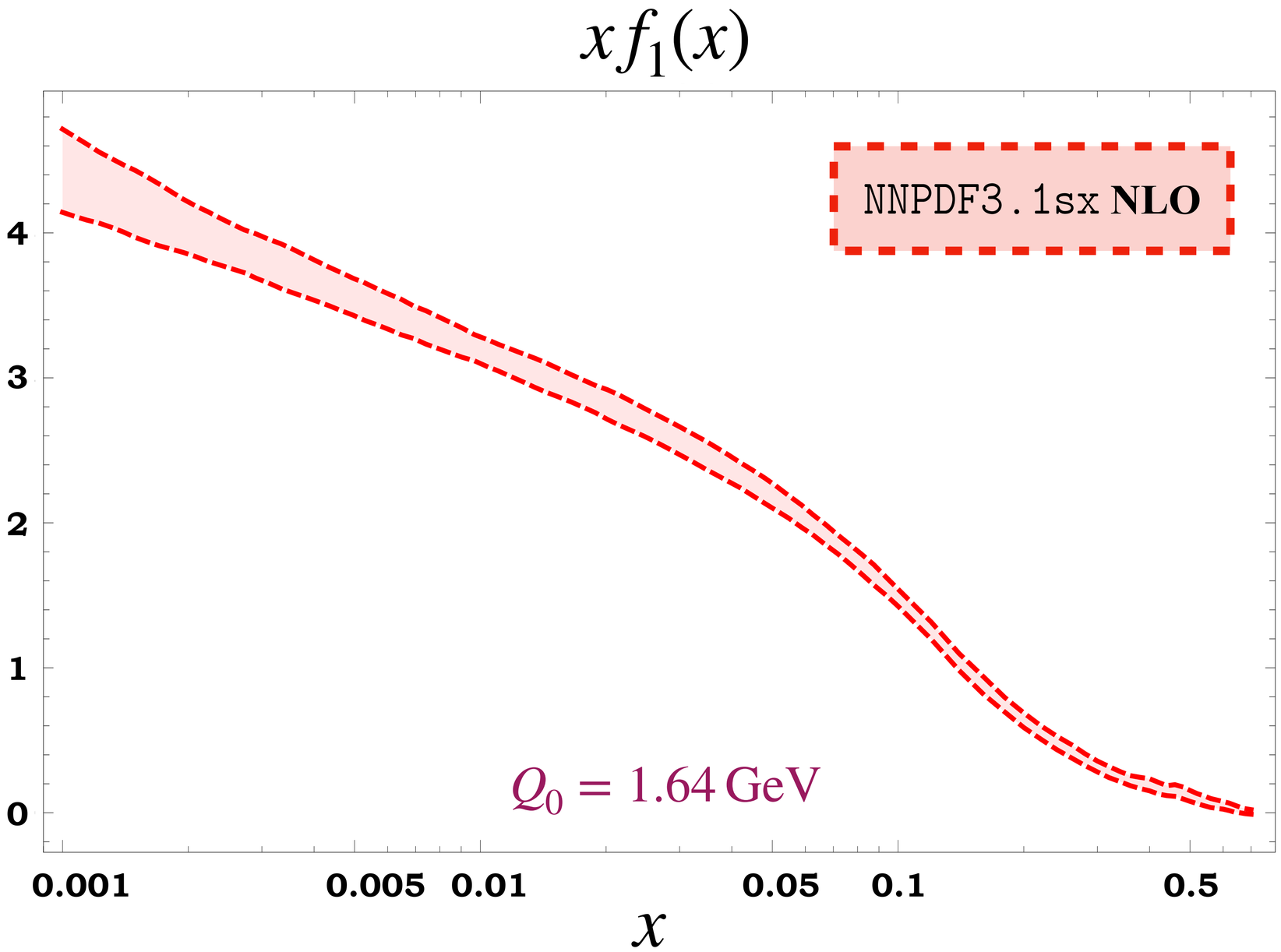
$$\mu^2 = M_X^2 - M^2$$

moderate-x trend

pure tri-quark contribution at low M_X

Backup

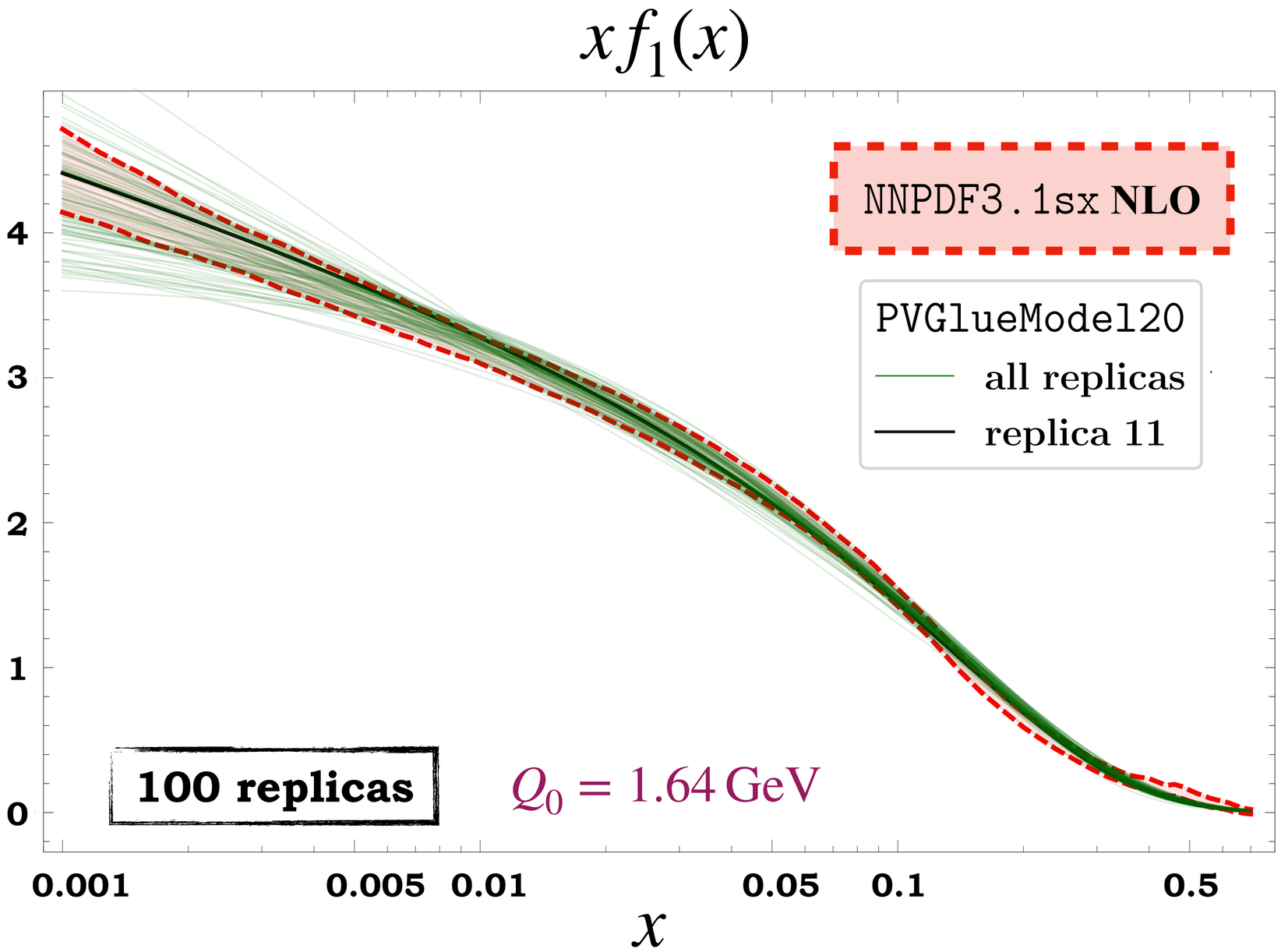
Unpolarized gluon collinear PDF



Backup

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

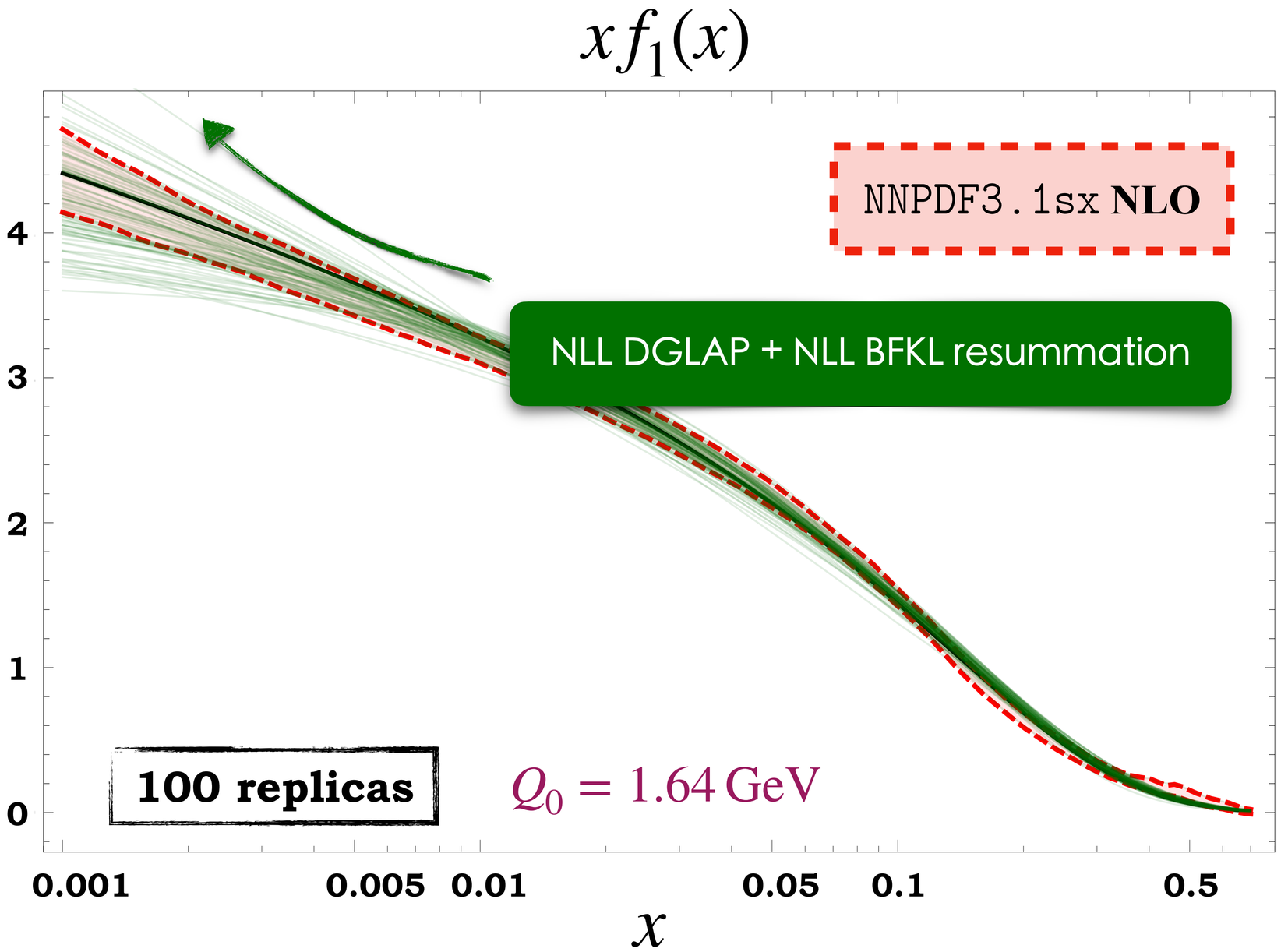
Unpolarized gluon collinear PDF



Backup

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

Unpolarized gluon collinear PDF



Backup

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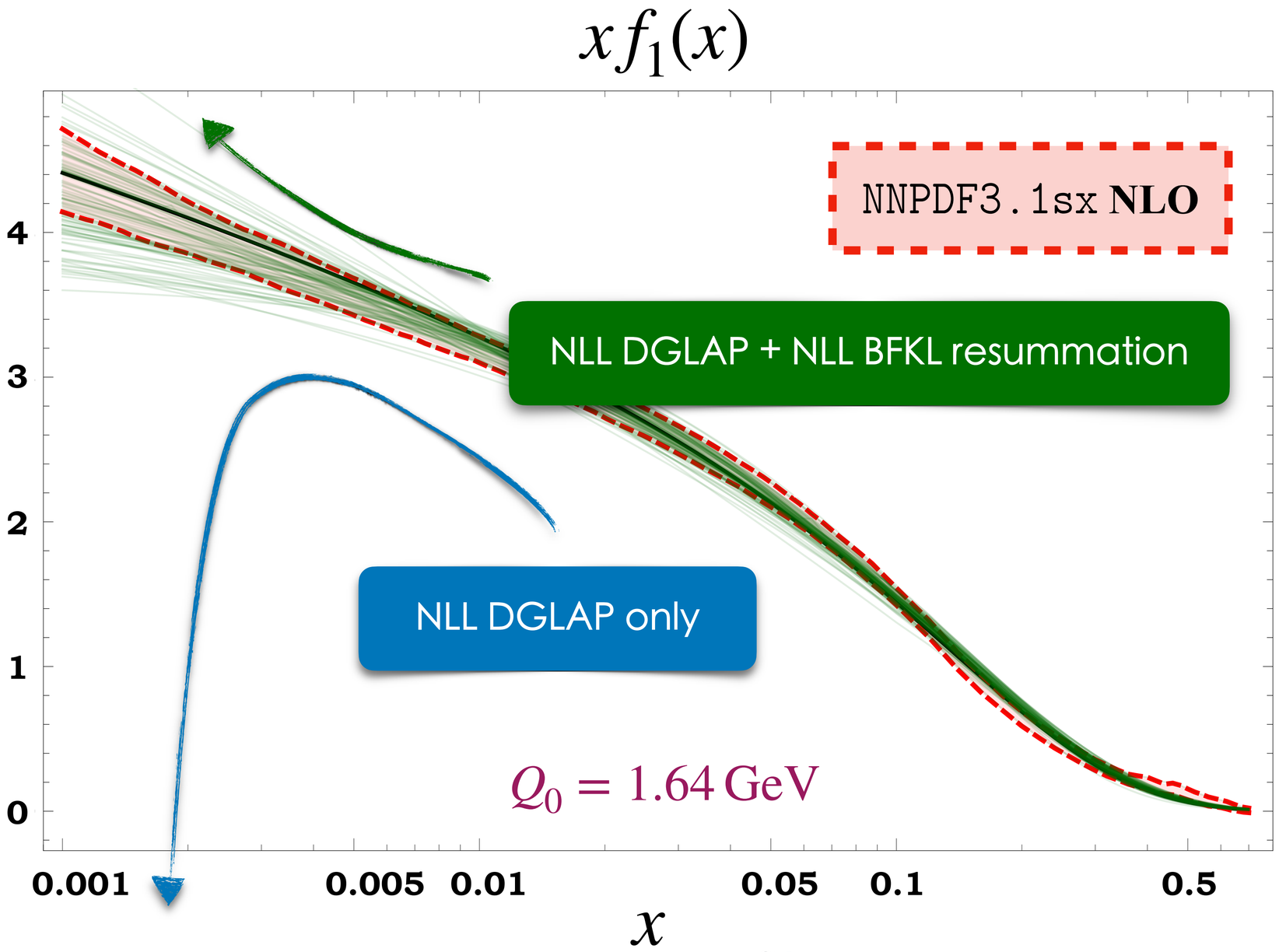
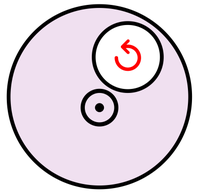
Unpolarized gluon collinear PDF

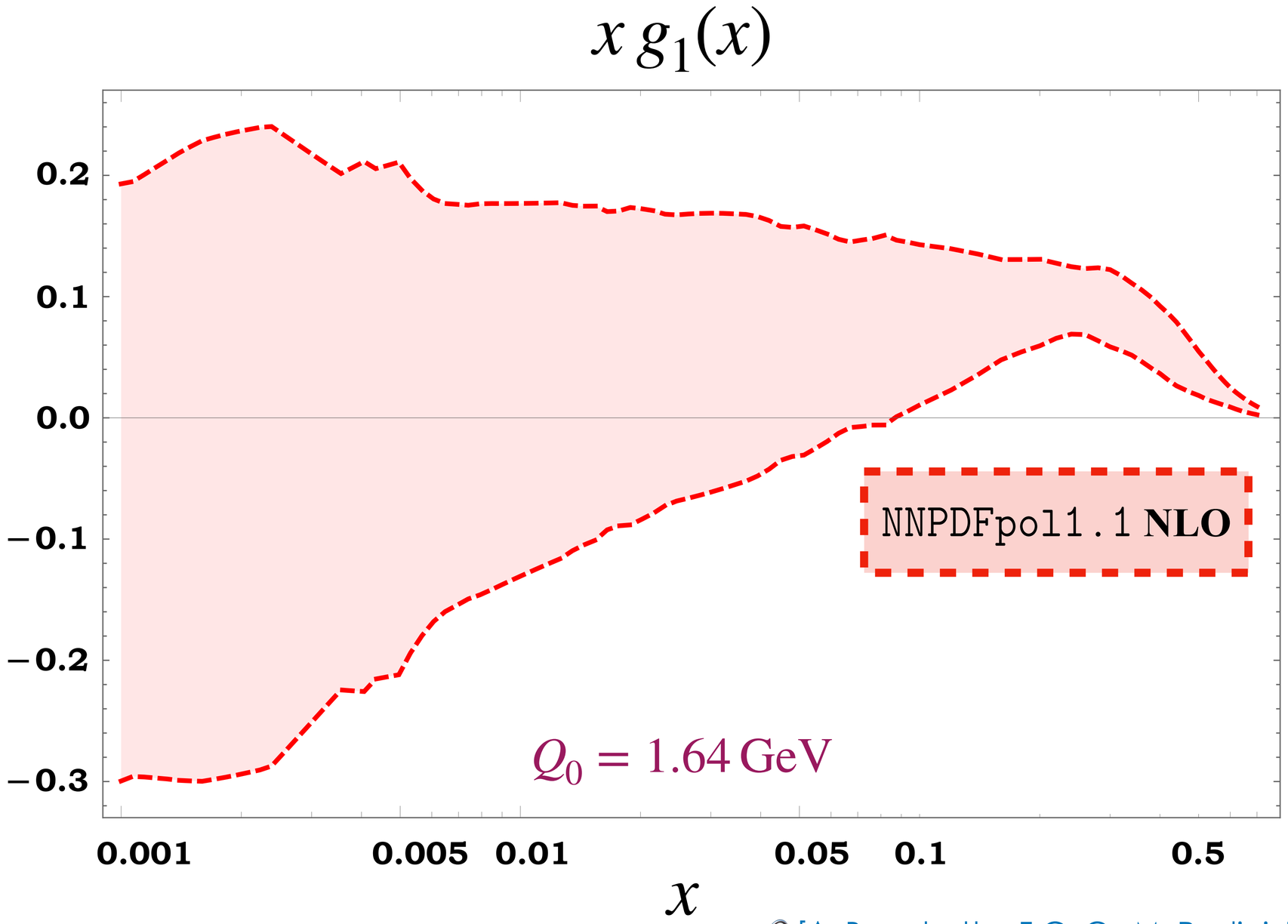


Backup

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

Helicity gluon collinear PDF





Backup

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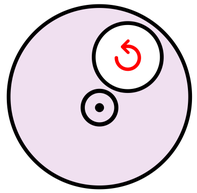
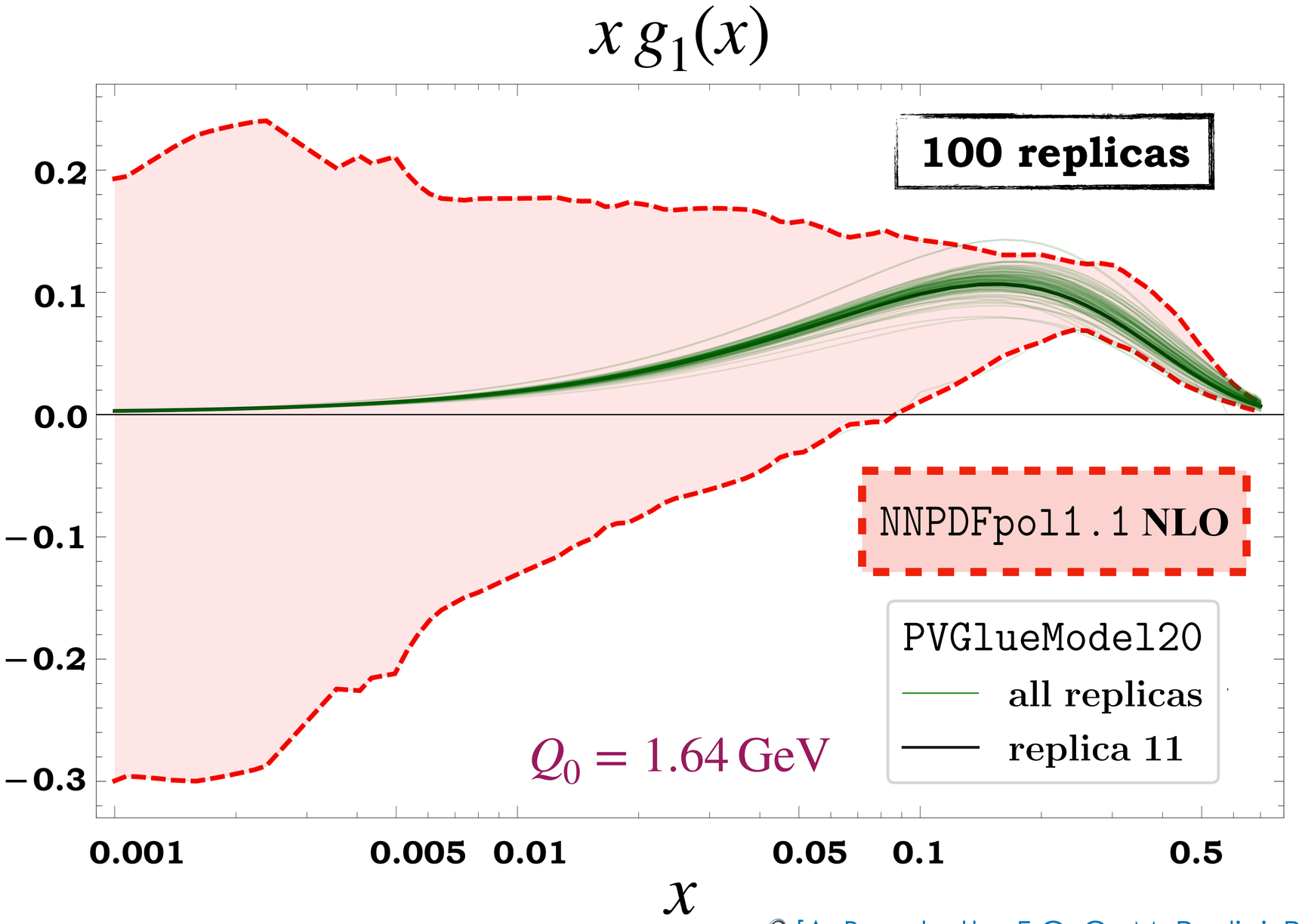




Backup

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

T-odd gluon TMDs in a spectator model

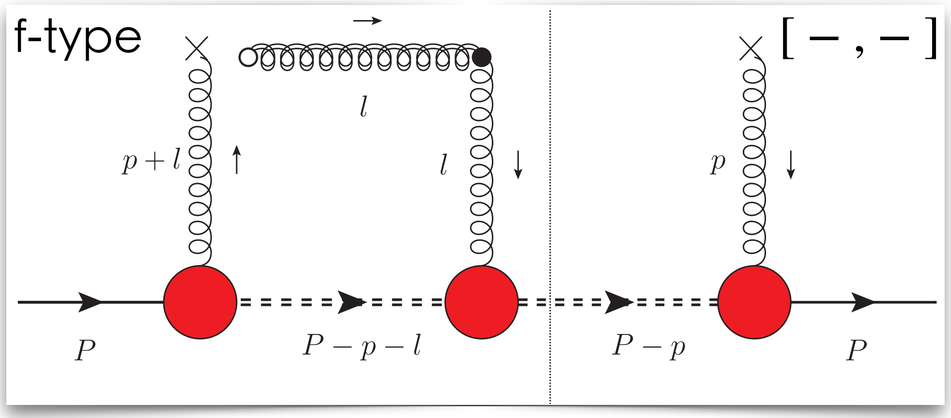
- No residual gluon-spectator interaction at tree level
- Interference with one-gluon exchange (eikonal)

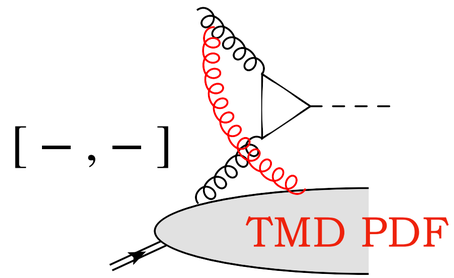
Backup

T-odd gluon TMDs in a spectator model

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

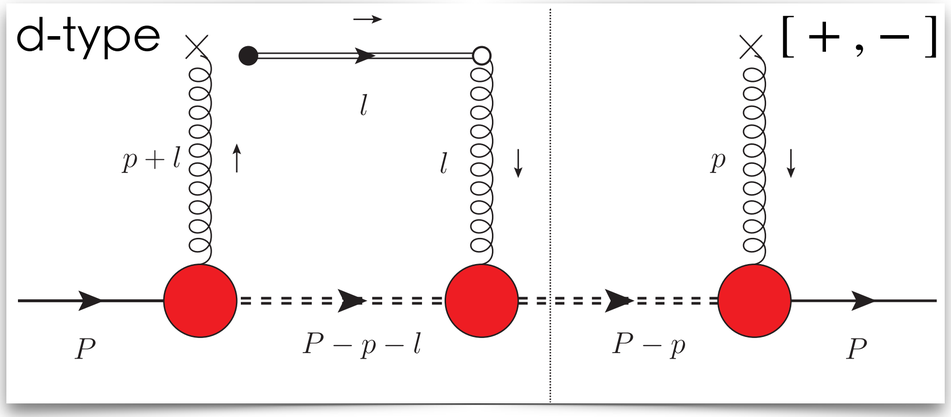
$gg \to H$





f-type (WW) structure

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



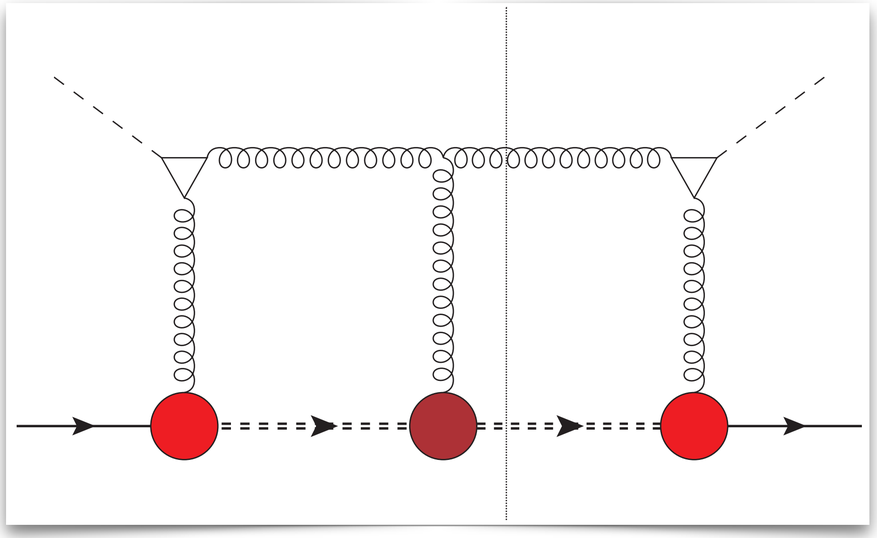
d-type (dipole) structure

Backup

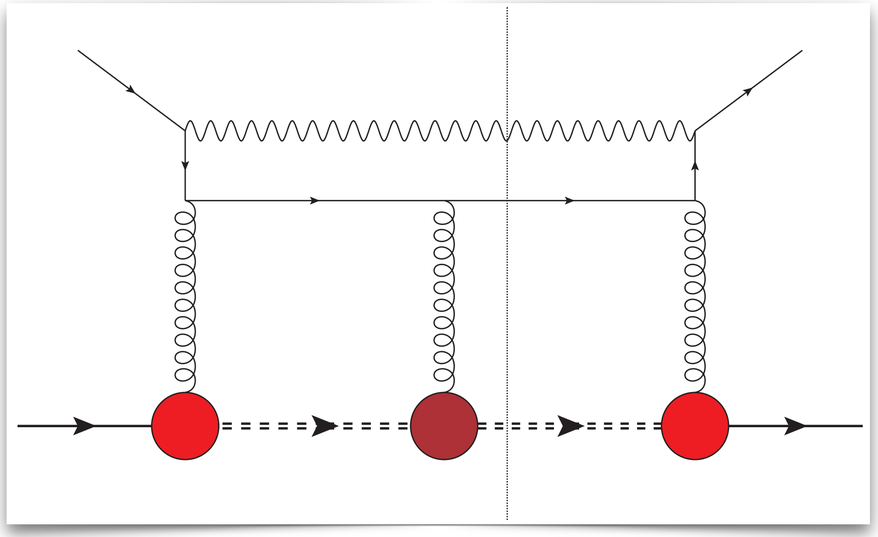
(Sivers & Linearity) [A. Bacchetta, F.G.C., M. Radici, EPS-HEP, PANIC (2021)]

T-odd gluon TMDs in a spectator model

Higgs-gluon fusion ⇒ f-type [+ , +]



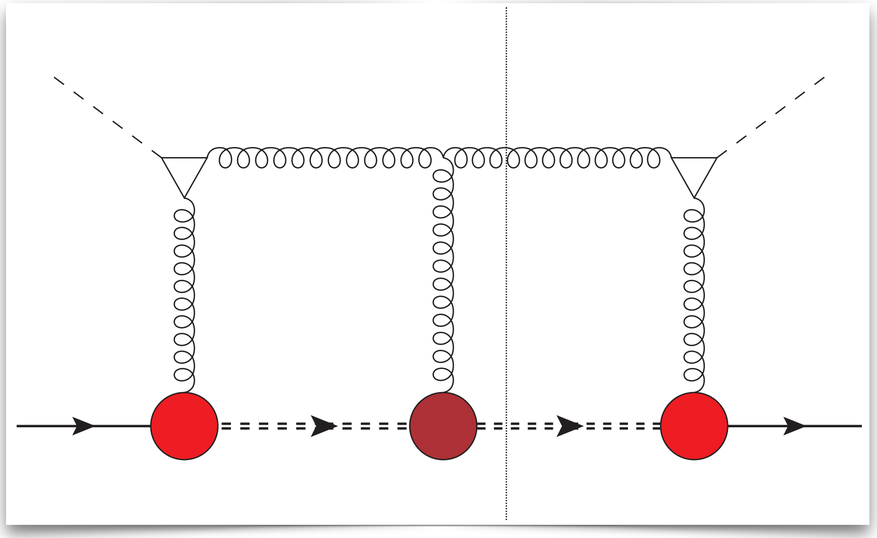
Photon-jet emission ⇒ d-type [+ , –]



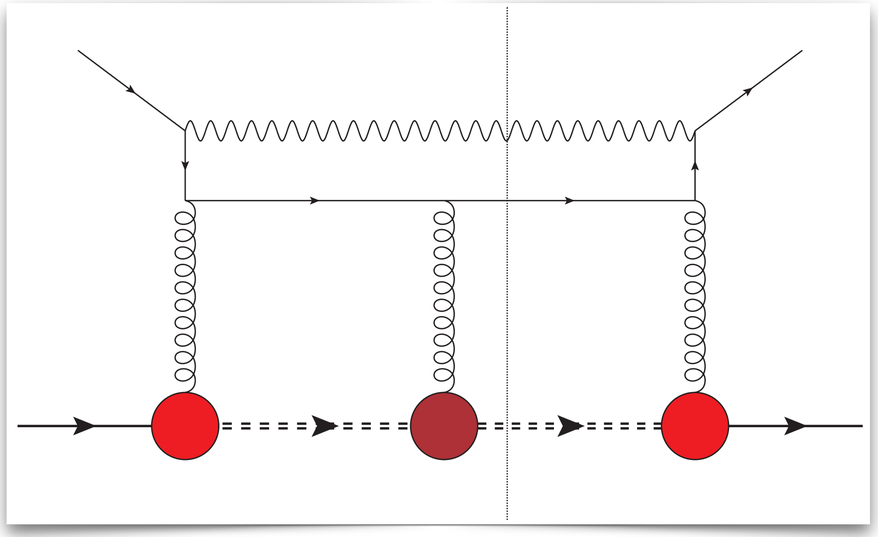
Backup

T-odd gluon TMDs in a spectator model

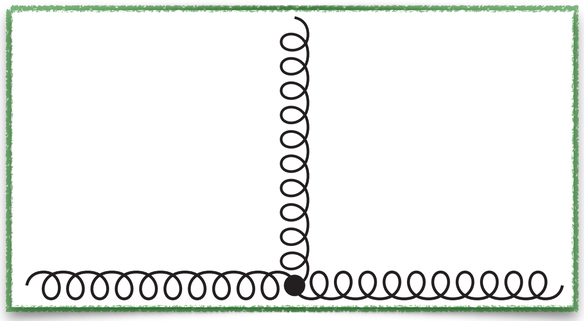
Higgs-gluon fusion ⇒ f-type [+ , +]



Photon-jet emission ⇒ d-type [+ , –]



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

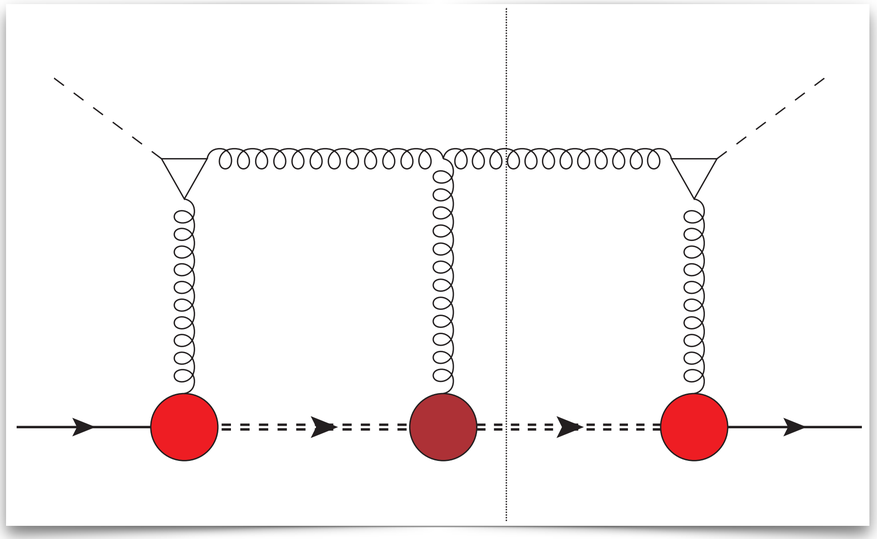


$$-g_s f_{abc}$$

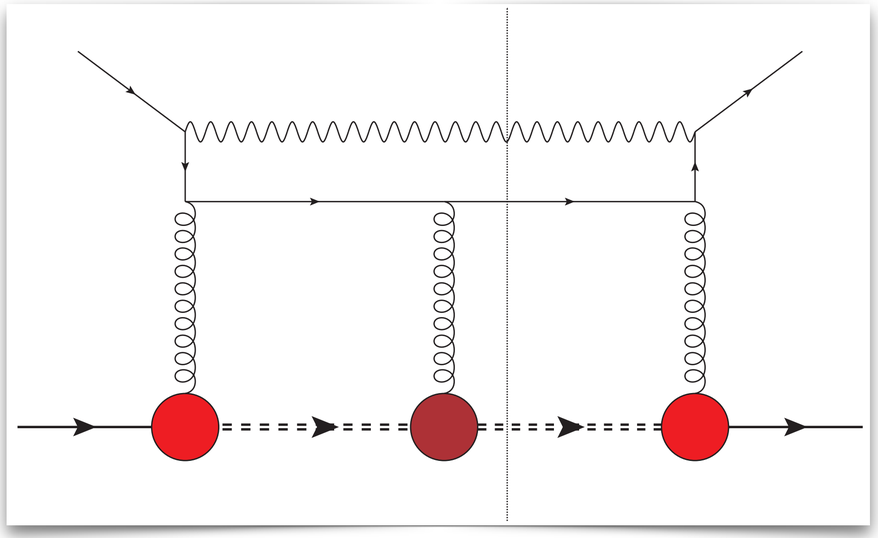
Backup

T-odd gluon TMDs in a spectator model

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



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



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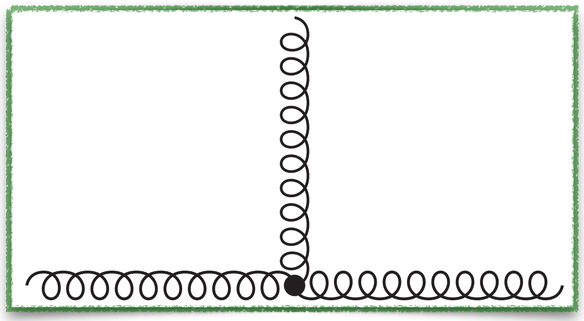
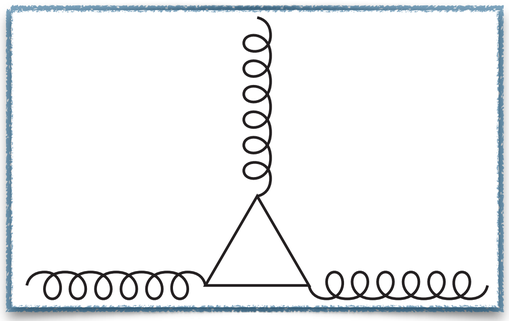


$$-g_s f_{abc}$$

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

$-i t_c$

$-i t_a$

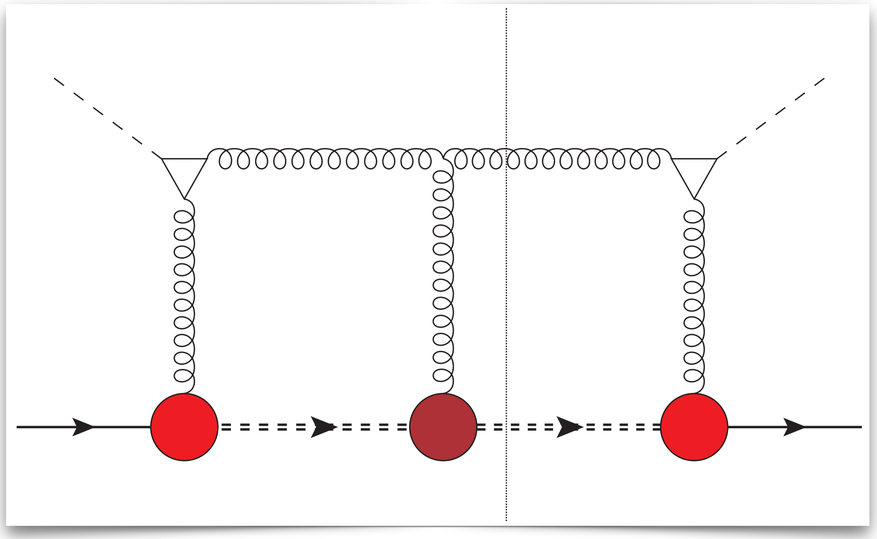


$-i t_b$

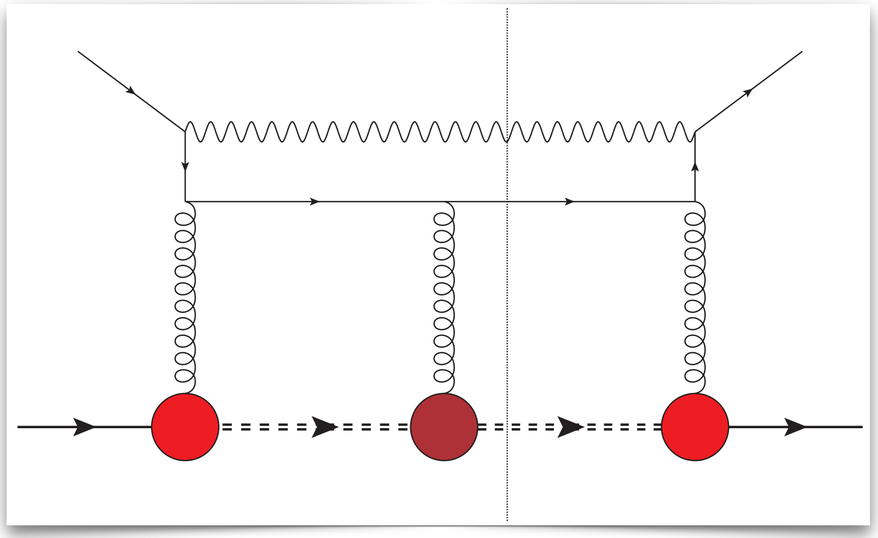
Backup

T-odd gluon TMDs in a spectator model

Higgs-gluon fusion ⇒ f-type [+ , +]



Photon-jet emission ⇒ d-type [+ , –]



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

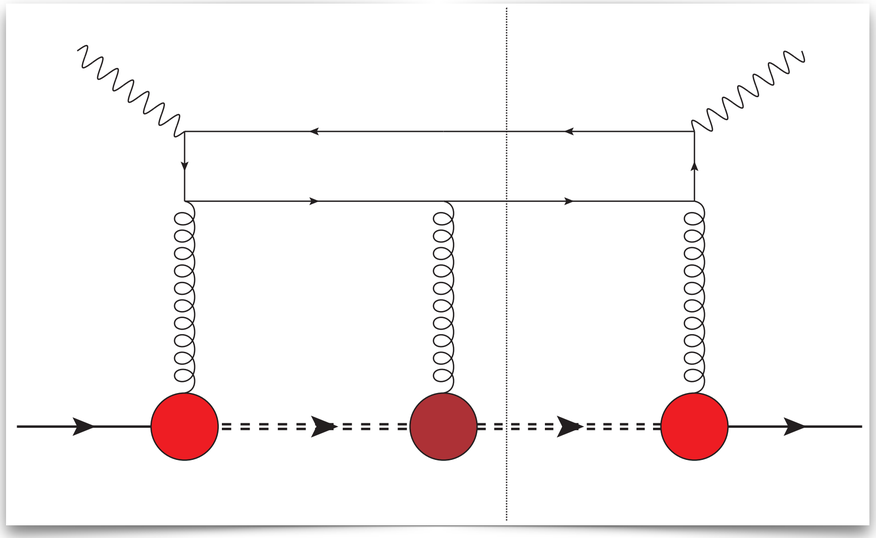
¡ …but the model is not pQCD !

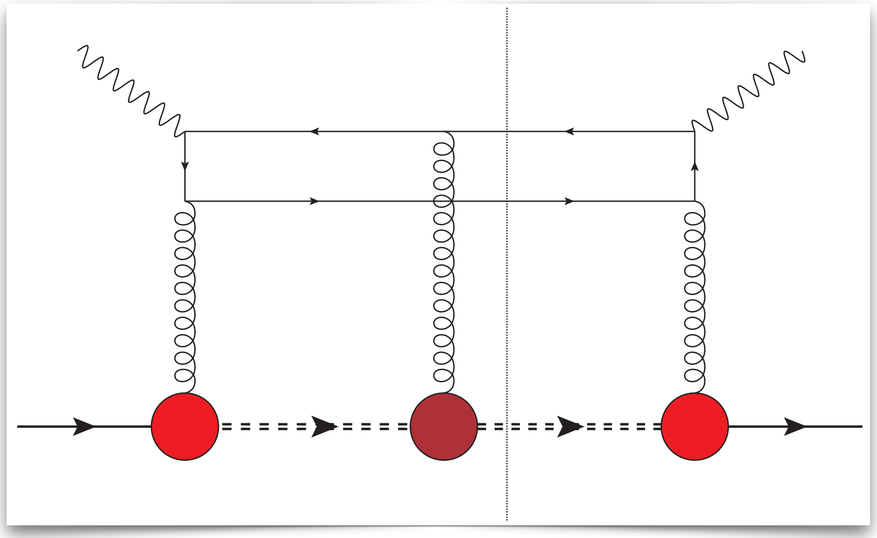
We want to model the nonperturbative content of T-odd TMD PDFs

Backup

Analytic structure of T-odd gluon TMDs

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





nucleon-gluon-spectator

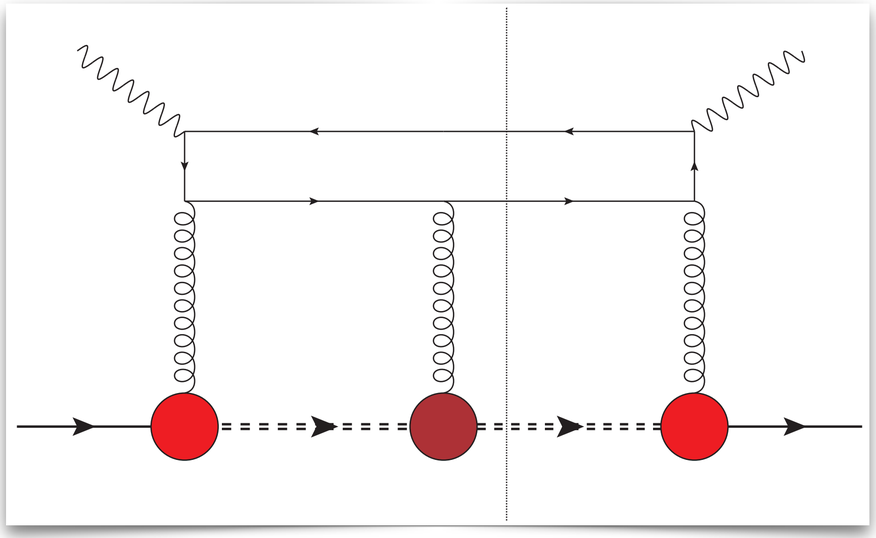
spectator-gluon-spectator

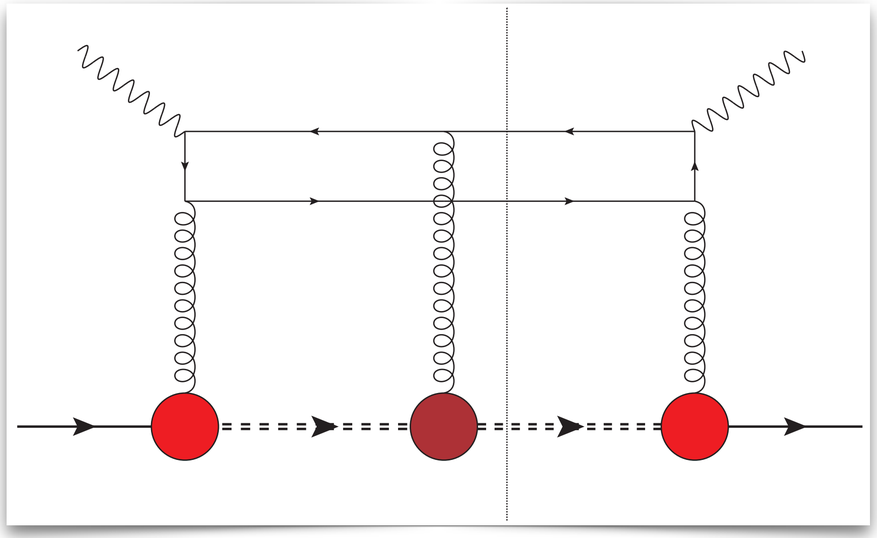
[A. Bacchetta, F.G.C., M. Radici (to appear)]

Backup

Analytic structure of T-odd gluon TMDs

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





nucleon-gluon-spectator

spectator-gluon-spectator

$8 \times 8 \times 4$

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

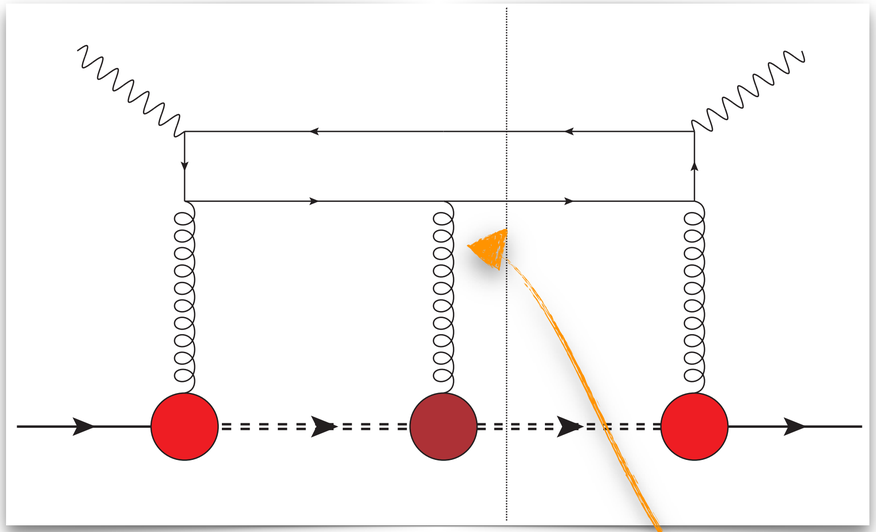
$$C_{ijk}^{(F)}(x, \boldsymbol{p}_T^2) = \sum_{l=1}^{7} \mathcal{C}_{ijk}^{(F),l}(x, \boldsymbol{p}_T^2)\, \mathcal{D}_l(x, \boldsymbol{p}_T^2)$$

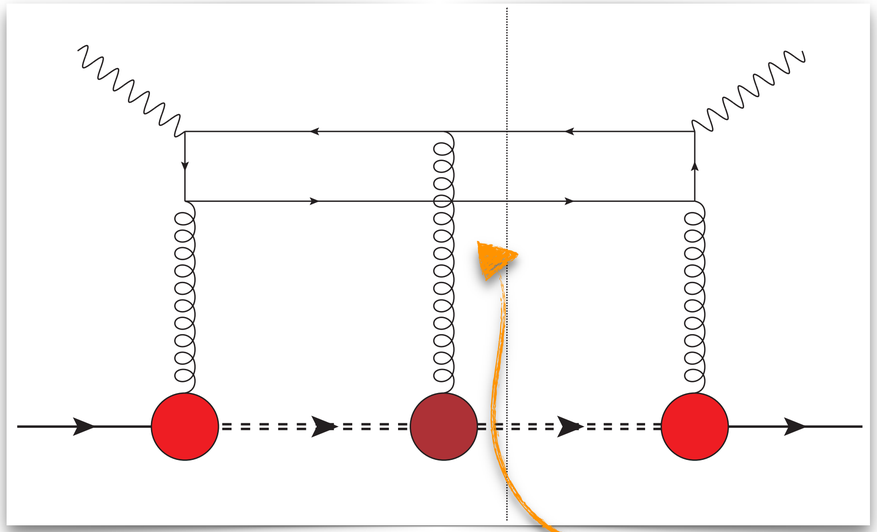
[A. Bacchetta, F.G.C., M. Radici (to appear)]

Backup

Analytic structure of T-odd gluon TMDs

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





nucleon-gluon-spectator

spectator-gluon-spectator

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[A. Bacchetta, F.G.C., M. Radici (to appear)]

Backup

Analytic structure of T-odd gluon TMDs

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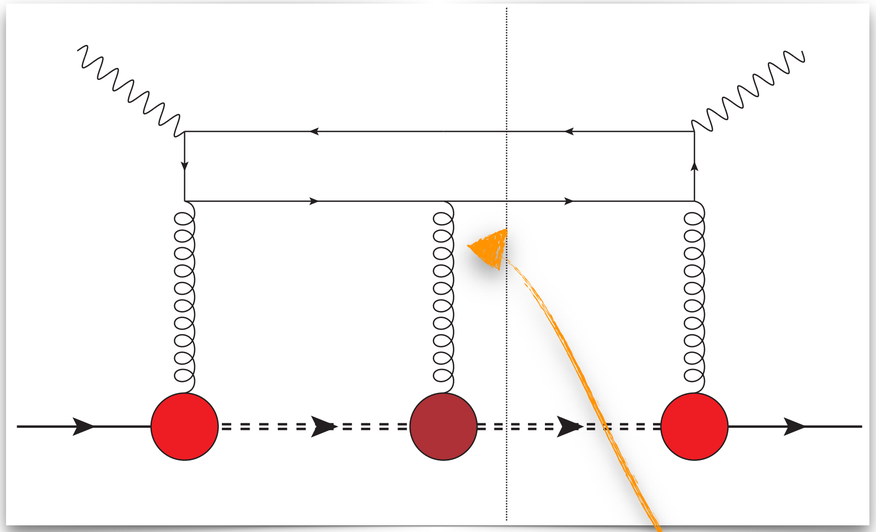

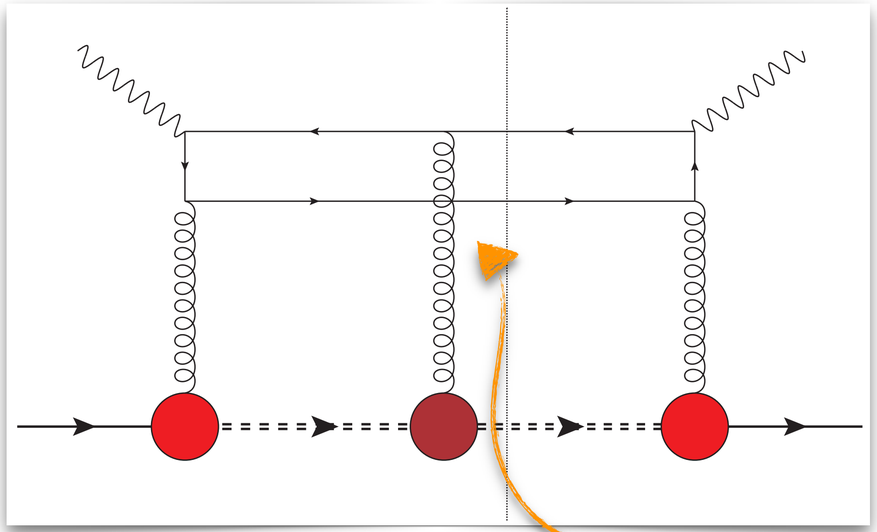

nucleon-gluon-spectator

spectator-gluon-spectator

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$8 \times 8 \times 4$

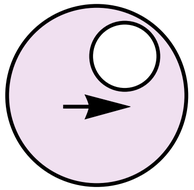
256 coeff. functions

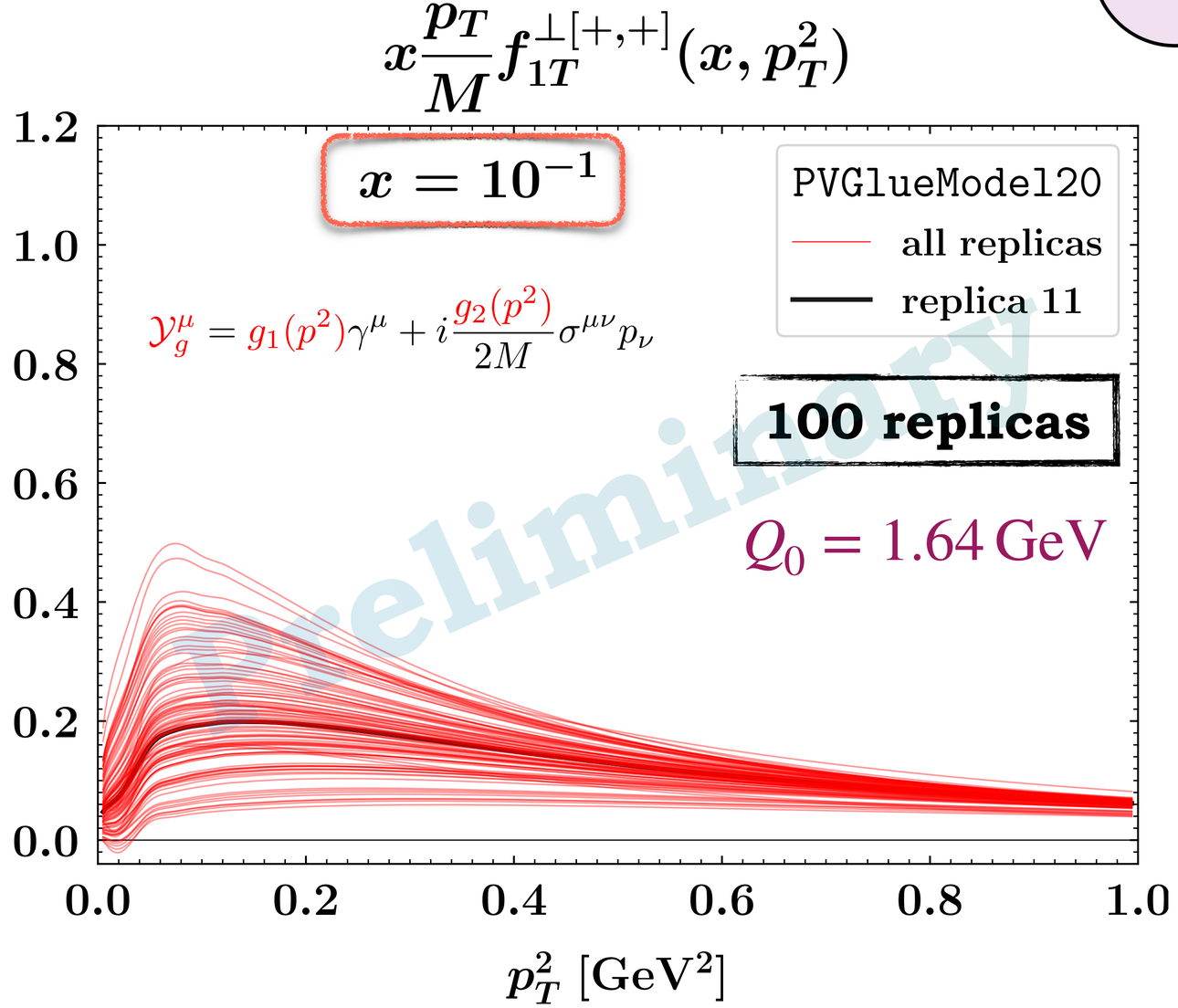
[A. Bacchetta, F.G.C., M. Radici (to appear)]

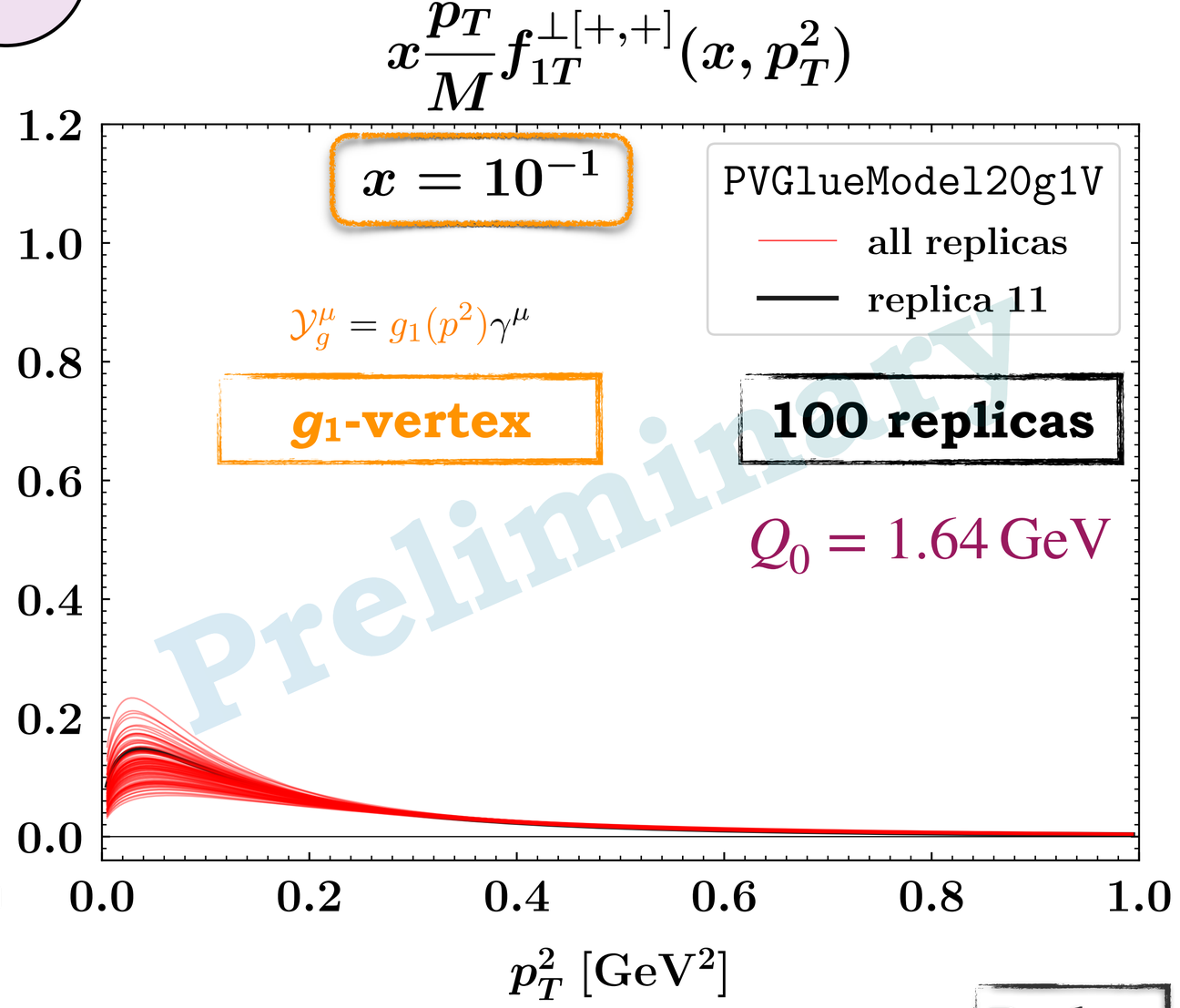
Backup

Preliminary results for Sivers

[A. Bacchetta, F.G.C., M. Radici (to appear)]



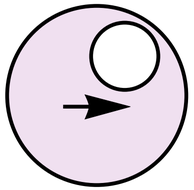


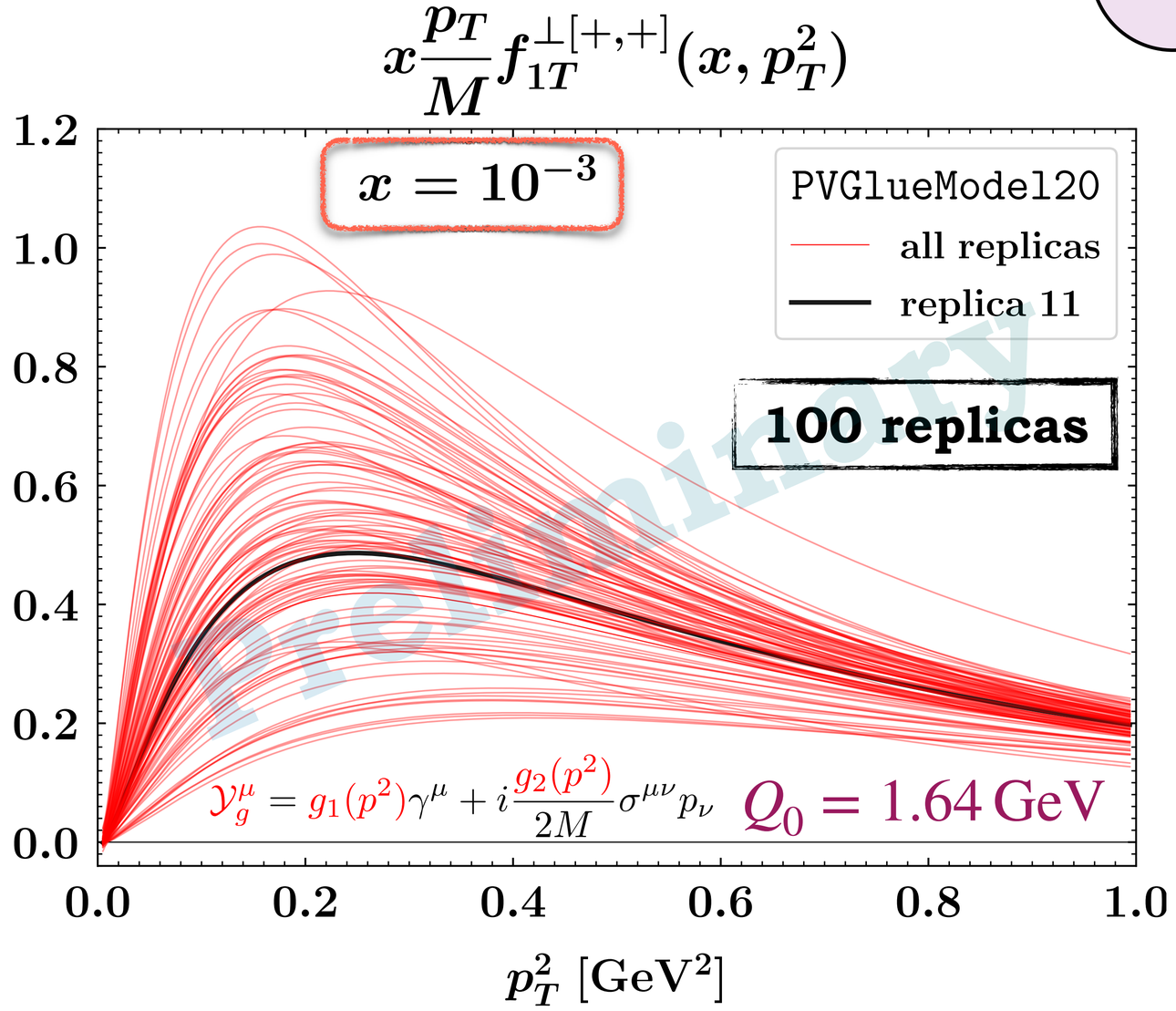


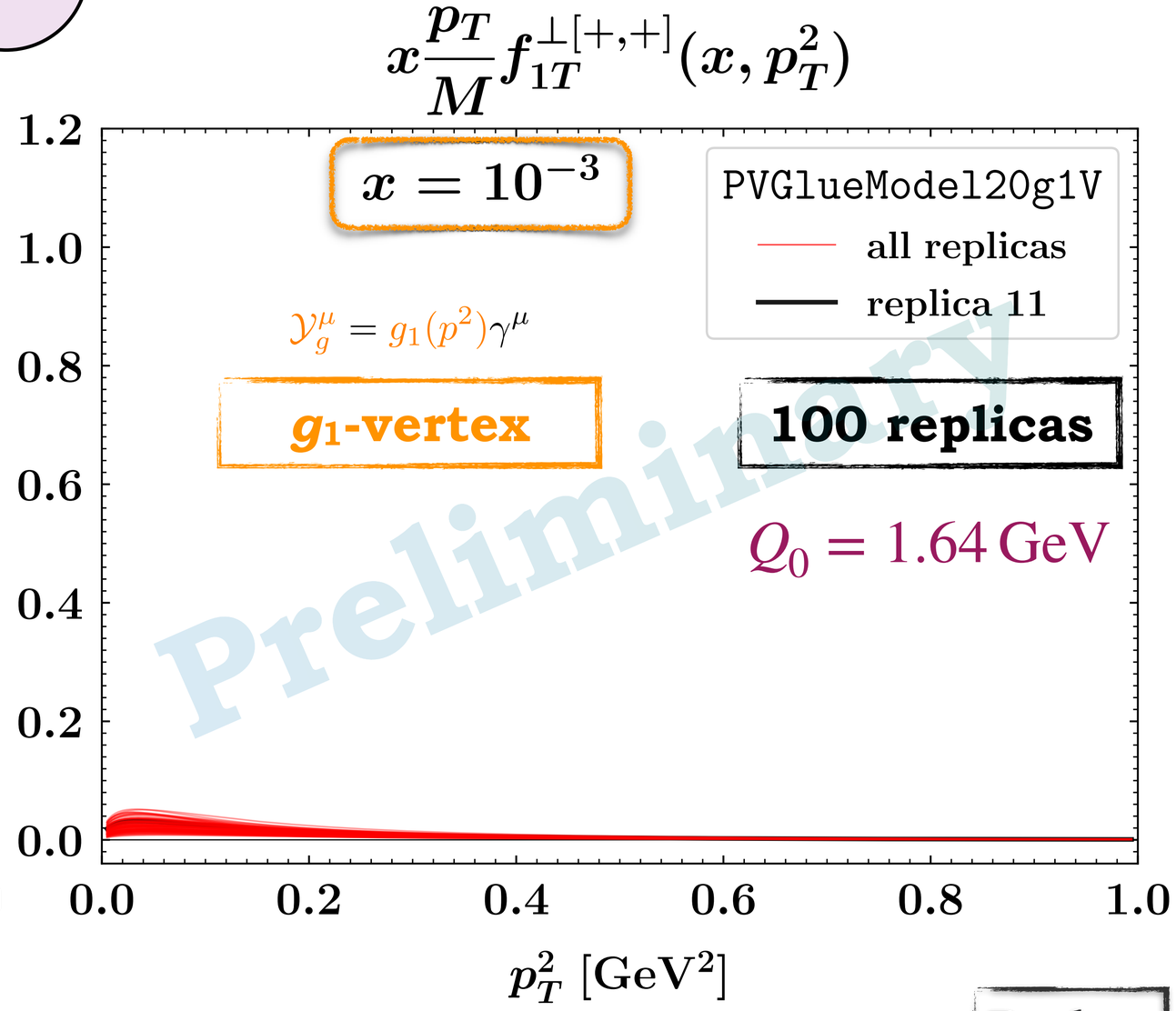
Backup

Preliminary results for Sivers

[A. Bacchetta, F.G.C., M. Radici (to appear)]





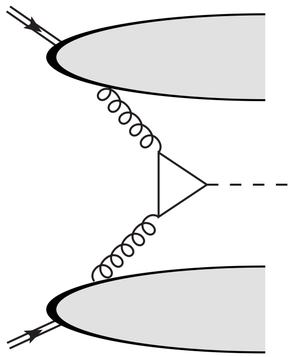


Backup

Gluon TMD phenomenology

Golden channels for gluon TMD PDFs @LHC

Higgs in gluon fusion



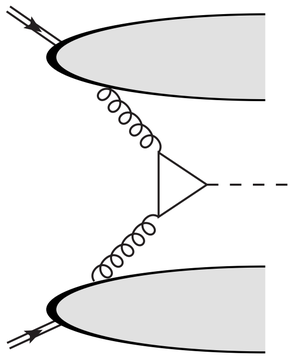
✓ No color entanglement
TMD factorization

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

Backup

Golden channels for gluon TMD PDFs @LHC

Higgs in gluon fusion



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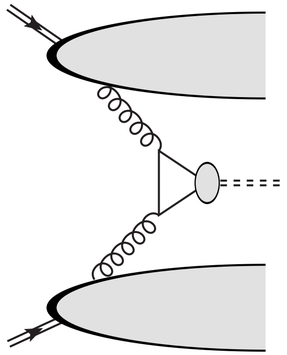
Single quarkonium



✓ $\eta_{c,b}$ ✗ $J/\psi, \Upsilon$

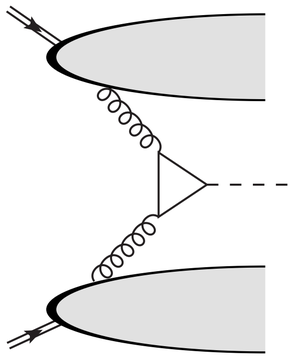
TMD factorization
C-parity selection rules

¡! 🔗 Large-p_T data @LHCb
More data @FT-LHC

Backup

Golden channels for gluon TMD PDFs @LHC

Higgs in gluon fusion



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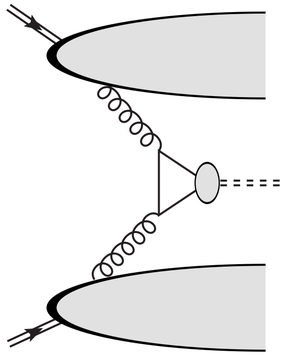
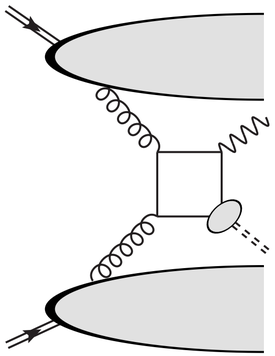
Single quarkonium



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

¡! 🔗 Large-p_T data @LHCb
More data @FT-LHC

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



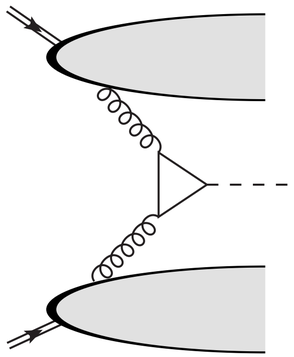
¡✓ Color entanglement
Potential TMD violation (CO)
Back-to-back suppresses CO

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

Backup

Golden channels for gluon TMD PDFs @LHC

Higgs in gluon fusion



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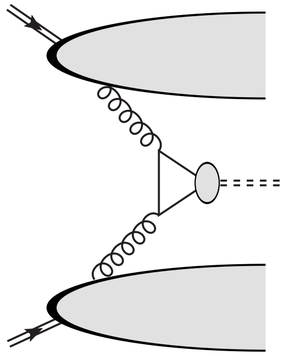
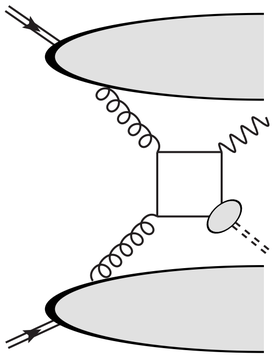


✓ $\eta_{c,b}$ ✗ $J/\psi, \Upsilon$
TMD factorization
C-parity selection rules

¡! 🔗 Large-p_T data @LHCb
More data @FT-LHC

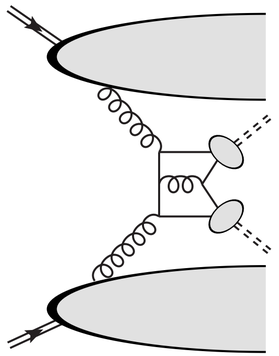
$J/\psi + \gamma^{(*)}$



¡✓ Color entanglement
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- & @FT-LHC

Backup

Quarkonia: Assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs

Initial-state color flow ⇒ [– , –] gauge link

(overview) [D. Boer (2017)]

Sivers	$e\,p^{\uparrow} \to e'\,Q\,\overline{Q}\,X$ $e\,p^{\uparrow} \to e'\,j_1\,j_2\,X$
$f_{1T}^{\perp\,g\,[-,-]}$	√
$f_{1T}^{\perp\,g\,[+,-]}$	×

Boer-Mulders	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$
$h_1^{\perp\,g\,[-,-]}$(WW)	√
$h_1^{\perp\,g\,[+,-]}$ (DP)	×

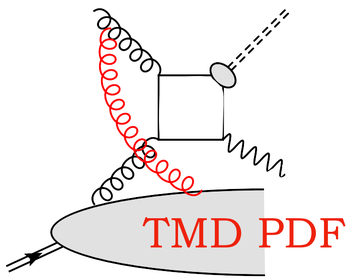
Challenges

Backup

Quarkonia: Assets & challenges

Assets

- Onia ⇒ clean channels of f-type gluon TMDs



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(overview) 🔗 [D. Boer (2017)]

Boer-Mulders	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$
$h_1^{\perp\,g\,[-,-]}$(WW)	√
$h_1^{\perp\,g\,[+,-]}$ (DP)	×

- $\eta_{c,b}$ ⇒ LHC complementarity, TMD factorization

$$\frac{d\sigma}{dq_T} \sim \quad \text{(at low transverse momentum for [pseudo]scalar state)}$$

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

unpolarized gluons — **lin. polarized** gluons

(factorization) 🔗 [M. García Echevarría (2019)]
(pheno) [A. Bacchetta, F.G.C., J.-P. Lansberg, M. Radici, et al. (to appear)]

Challenges

- Precision TMD ⇔ production mechanism(s)

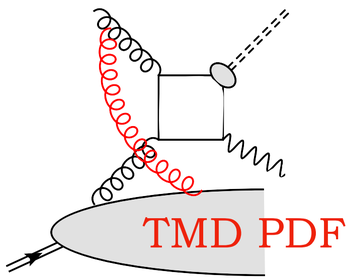
(production mechanisms, LHC pheno) 🔗 [J.-P. Lansberg (2020)]

Backup

Quarkonia: Assets & challenges

Assets

Onia ⇒ clean channels of f-type gluon TMDs



Initial-state color flow ⇒ [– , –] gauge link

Sivers	$e p^{\uparrow} \to e' Q \overline{Q} X$ $e p^{\uparrow} \to e' j_1 j_2 X$
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$f_{1T}^{\perp g\,[+,-]}$	×

(overview) [D. Boer (2017)]

Boer-Mulders	$e p \to e' Q \overline{Q} X$ $e p \to e' j_1 j_2 X$
$h_1^{\perp g\,[-,-]}$(WW)	√
$h_1^{\perp g\,[+,-]}$ (DP)	×

$\eta_{c,b}$ ⇒ LHC complementarity, TMD factorization

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Challenges

Precision TMD ⇔ production mechanism(s)

(production mechanisms, LHC pheno) [J.-P. Lansberg (2020)]

Color Evaporation Model

$(Q\bar{Q})$ decorrelated from onium, semi-soft gluon emissions
Overshoots data at large p_T

Color Singlet Model

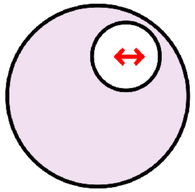
$(Q\bar{Q})$ to onium, no gluon emissions
Fails at large p_T, improves at NLO

NRQCD and Color Octet

Higher Fock states, soft gluon emissions
Problems at low p_T, fails on polarization

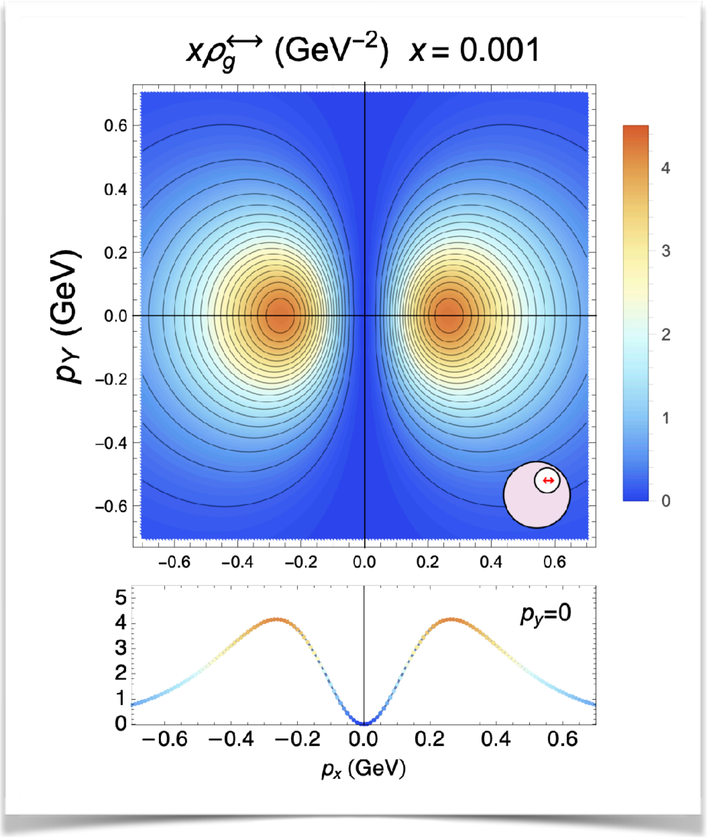
Backup

Boer-Mulders effect in unpolarized pp collisions



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

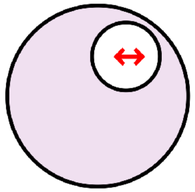
unpol. Boer-Mulders



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

Backup

Boer-Mulders effect in unpolarized pp collisions



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unpol. — Boer-Mulders

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

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

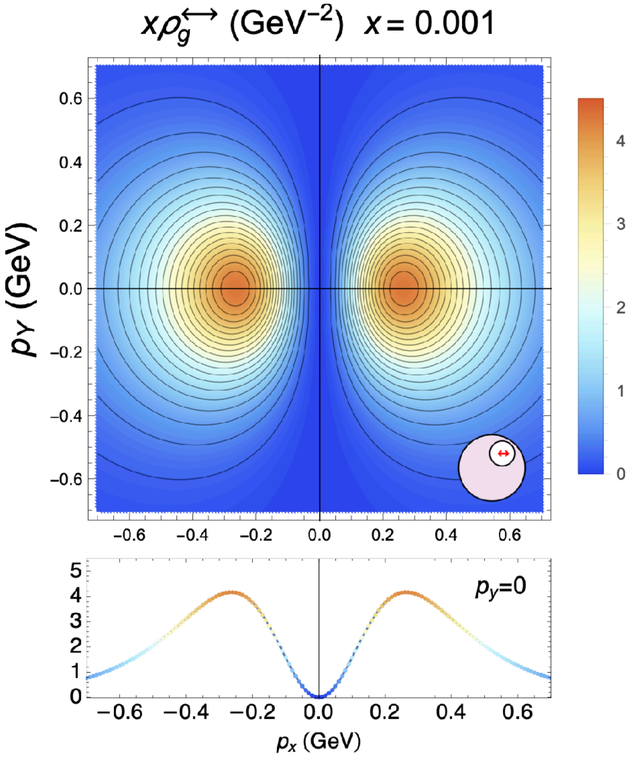
$$\sim \mathcal{C}[\, f_1^{g/A} \, f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \, h_1^{\perp g/B} \,]$$

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

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

NRQCD

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

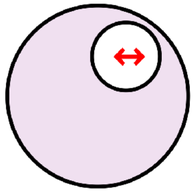


[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]
(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

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

Backup

Boer-Mulders effect in unpolarized pp collisions



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

unpol. Boer-Mulders

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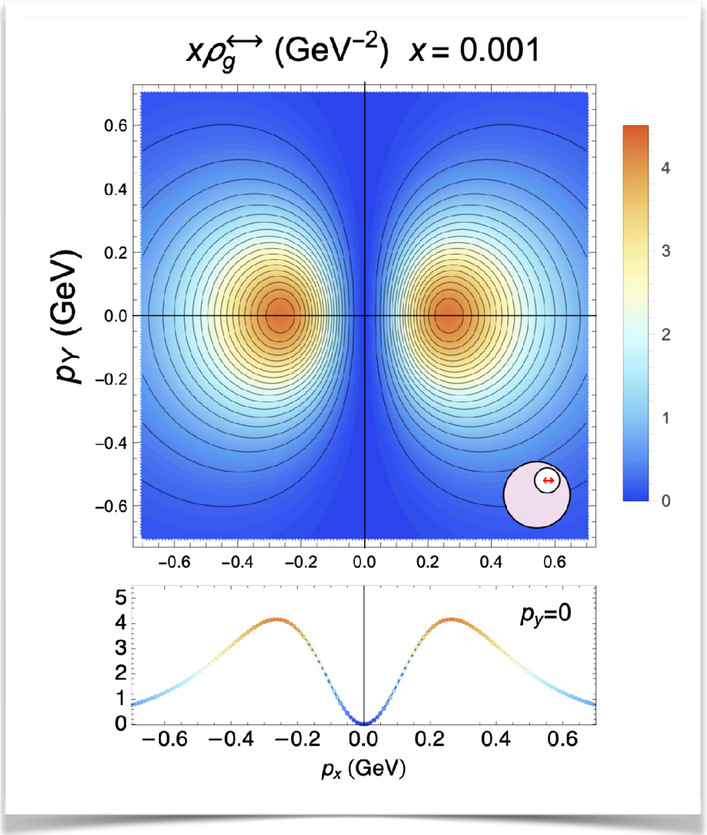
unpolarized gluons — **lin. polarized** gluons

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)]



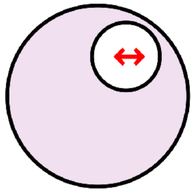
🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

Model prediction at low x

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

Backup

Boer-Mulders effect in unpolarized pp collisions



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

unpol. Boer-Mulders

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

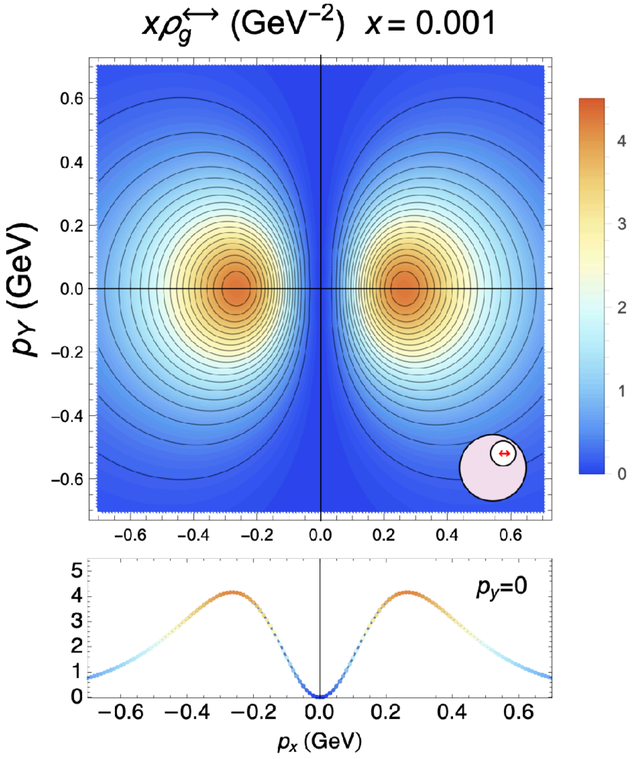
$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \, \Phi_B^U \, |\mathcal{M}|^2 \sim \mathcal{C}[\, f_1^{g/A} \, f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \, h_1^{\perp g/B} \,]$$

at low transverse momentum for (pseudo)scalar state

unpolarized gluons — **lin. polarized** gluons

NRQCD

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



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BFKL regime (linear low-x evolution)

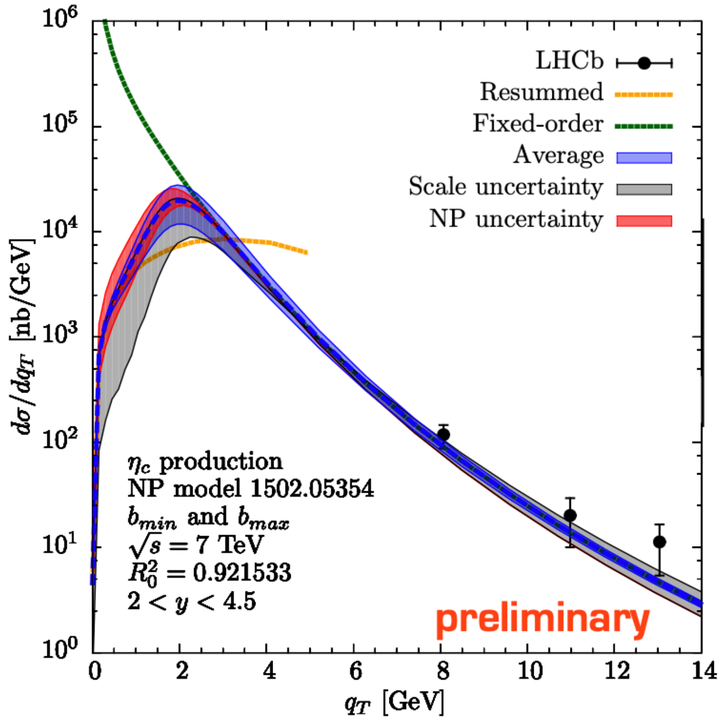
$$f_1^g(x,p_T^2) = h_1^{\perp g}(x,p_T^2) + \text{higher twist}$$

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

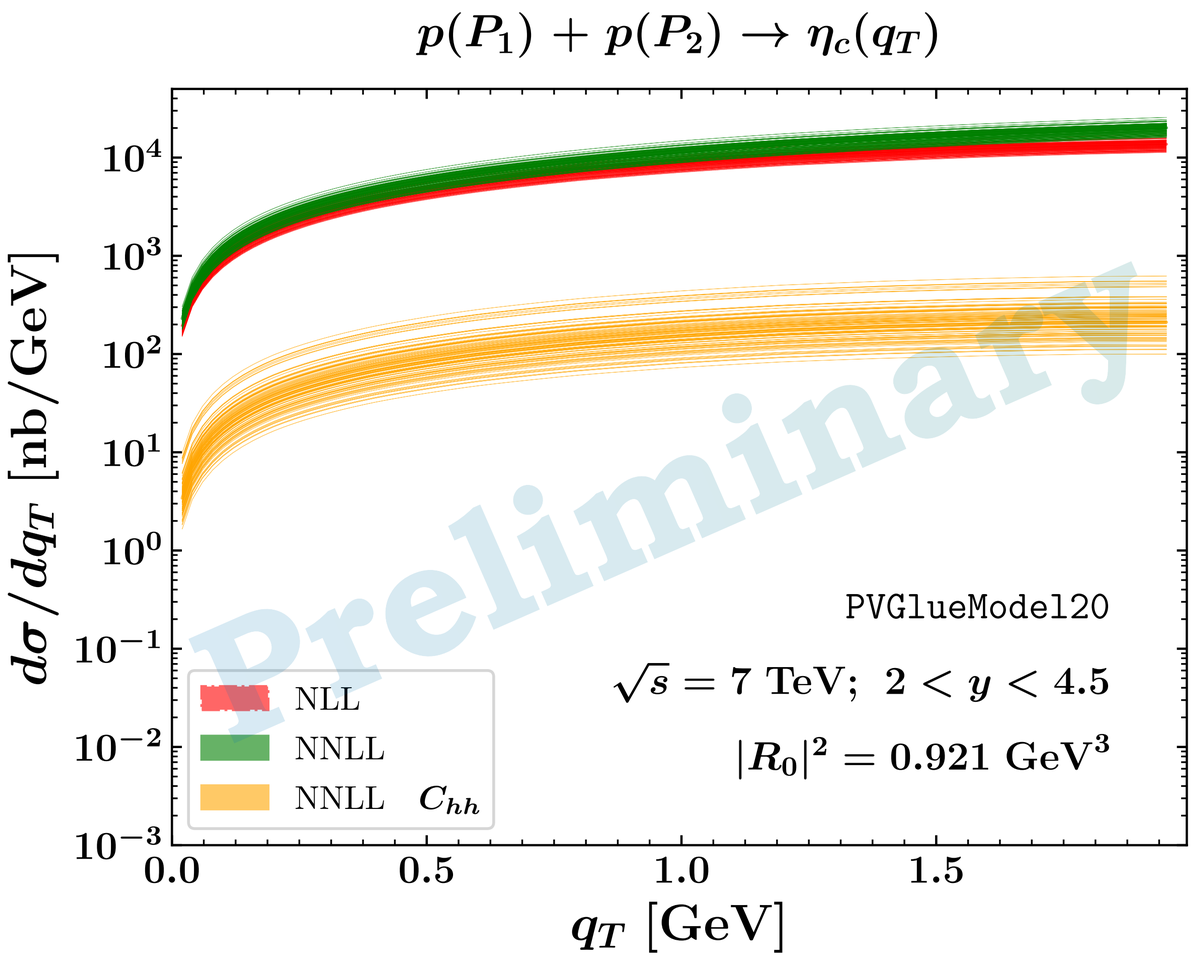
25

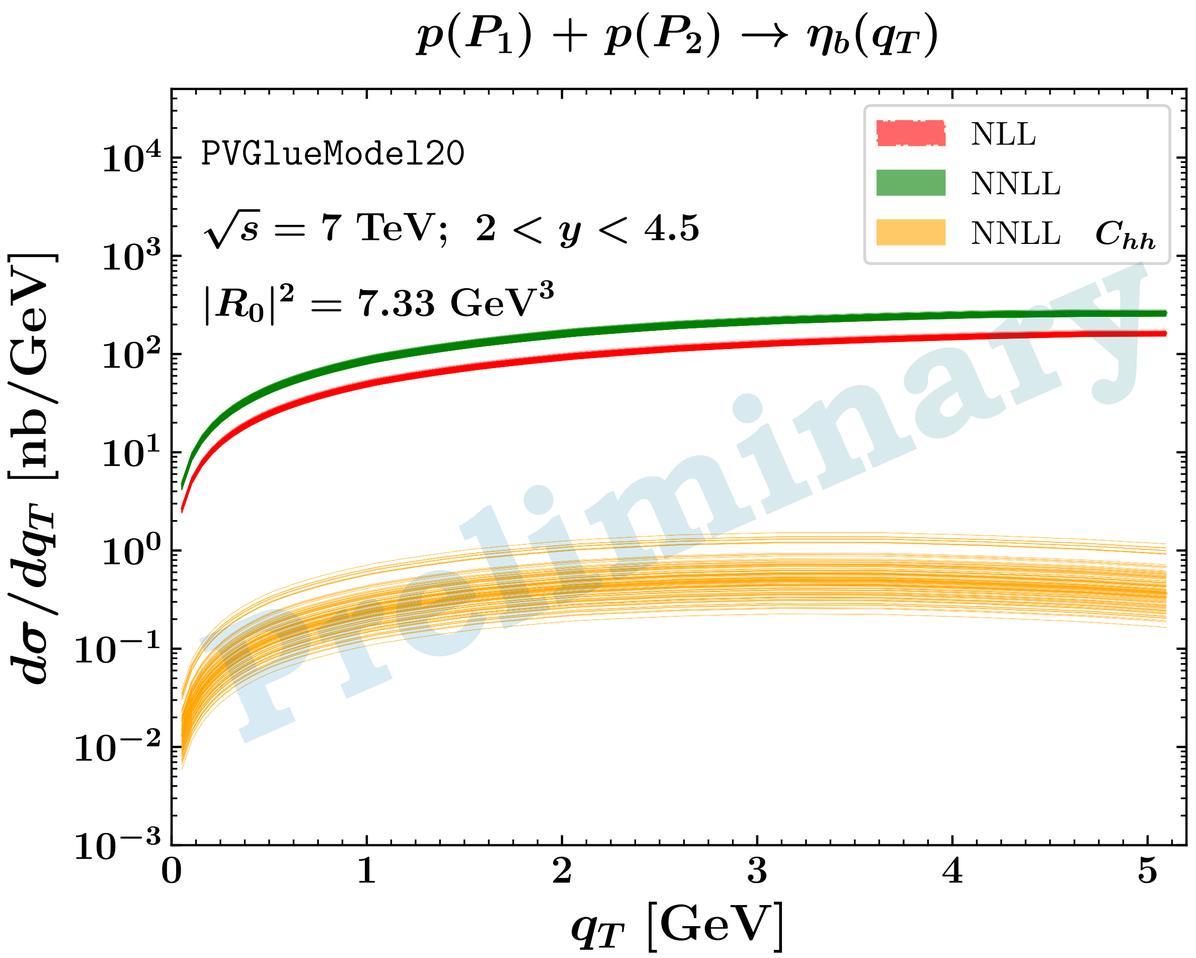
slide by Andrea Signori (INT 2017)

Backup

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

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





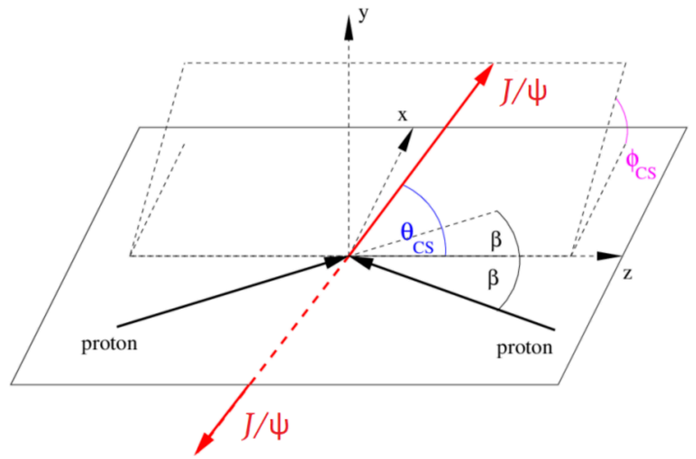
[A. Bacchetta, F.G.C., M.G. Echevarria, J.-P. Lansberg, M. Ozcelik, M. Radici, A. Signori (to appear)]

Backup

Double J/ψ production @(HL-)LHC

- More spin asymmetries, measurable @HL-LHC

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



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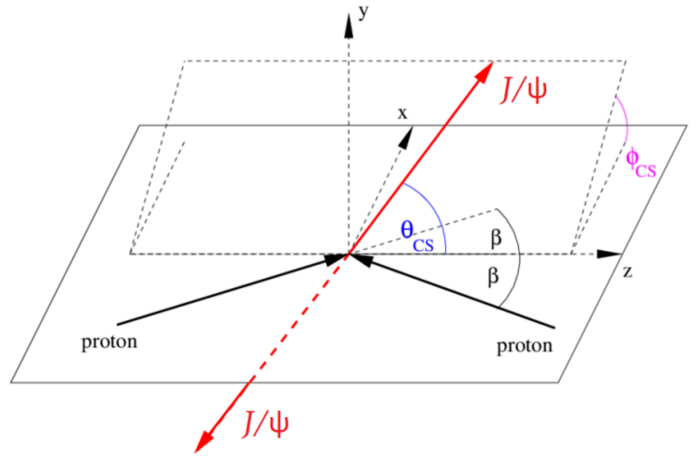

TMD Models

[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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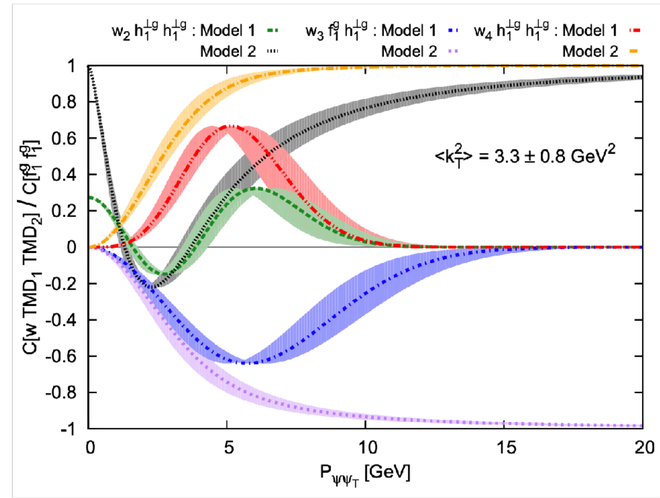

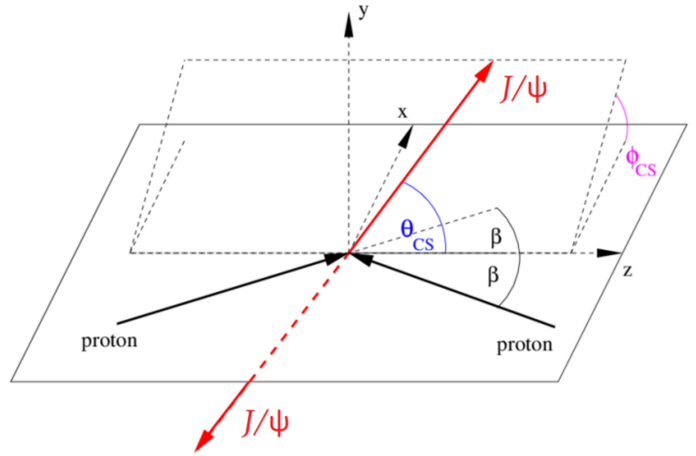

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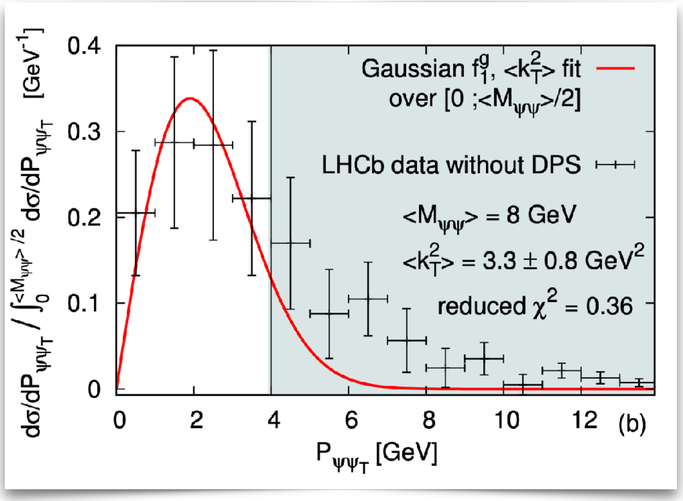

[Model-dependent fit on 13 TeV LHCb data]

Backup

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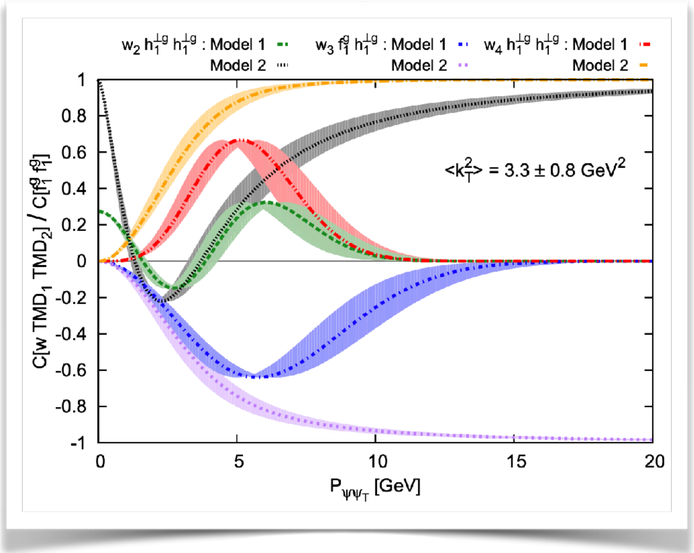

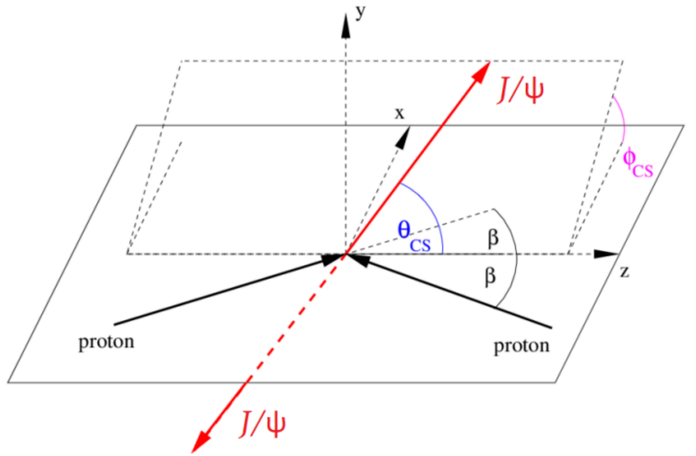

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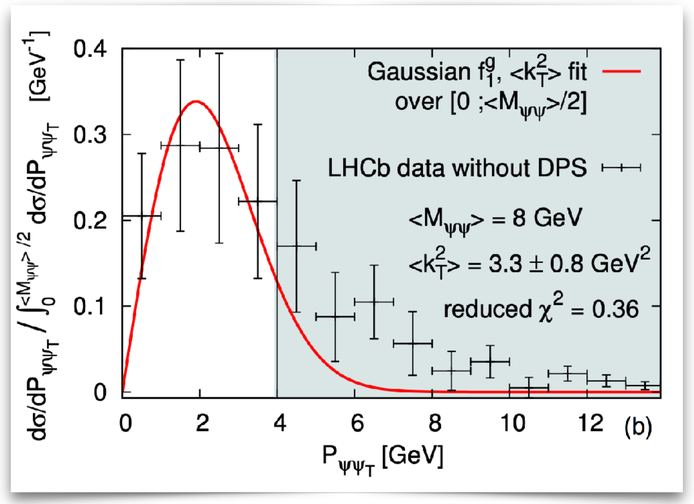
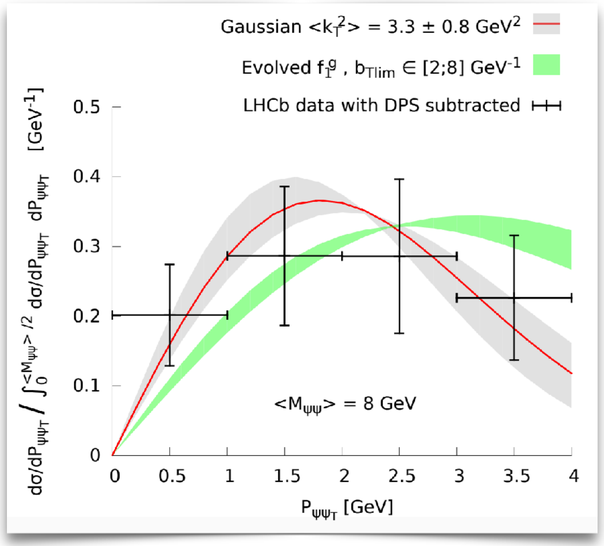


[Model-dependent fit on 13 TeV LHCb data]

NP + TM resummation



[F. Scarpa et al. (2020)]

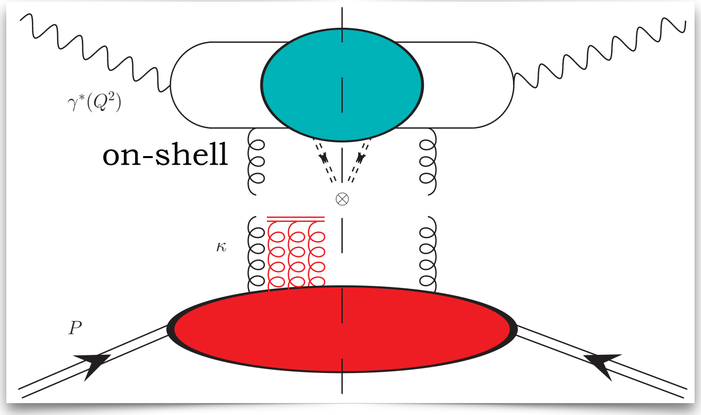
Backup

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

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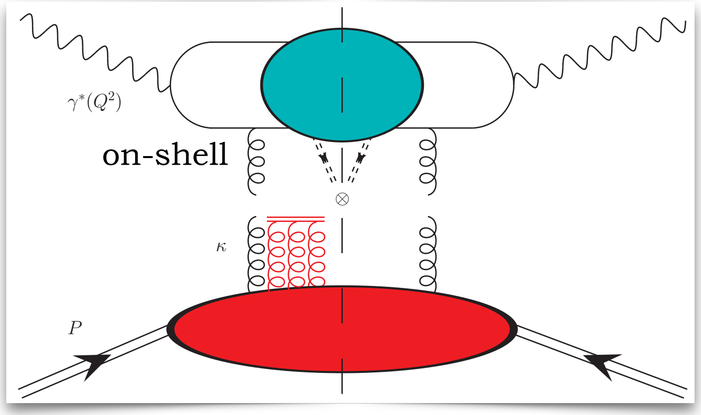
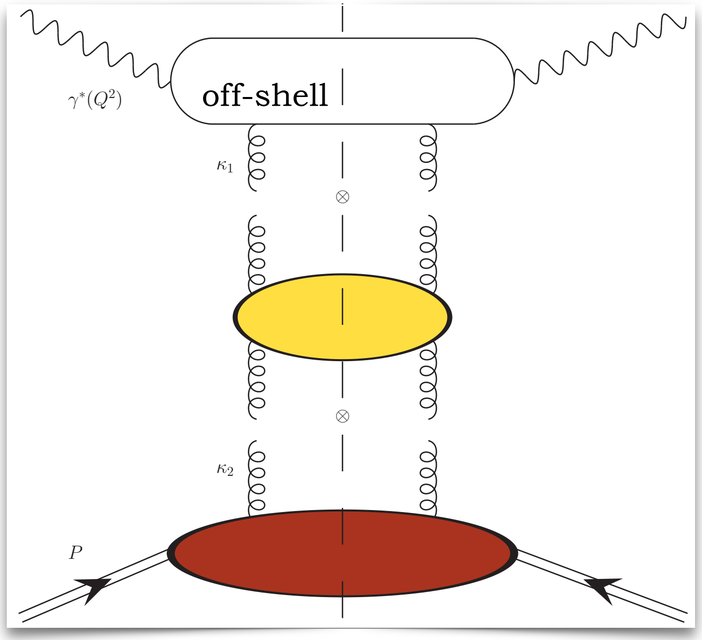


TMD PDF

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)]

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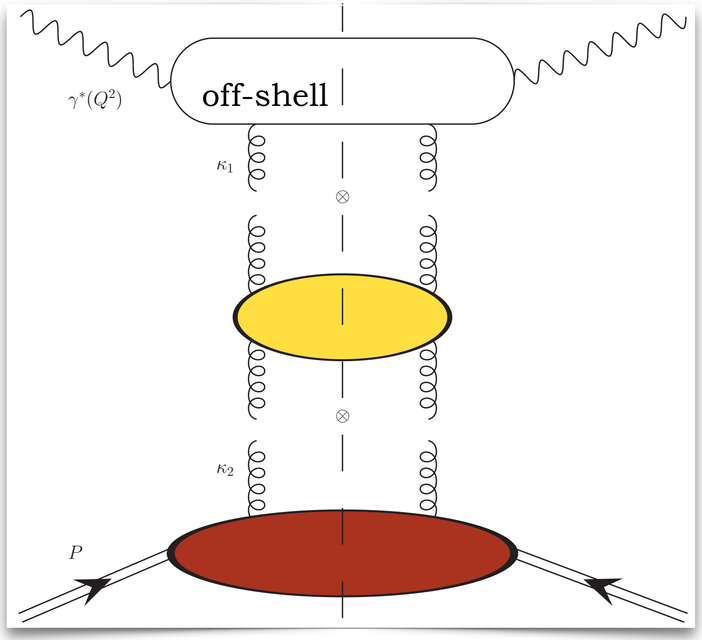

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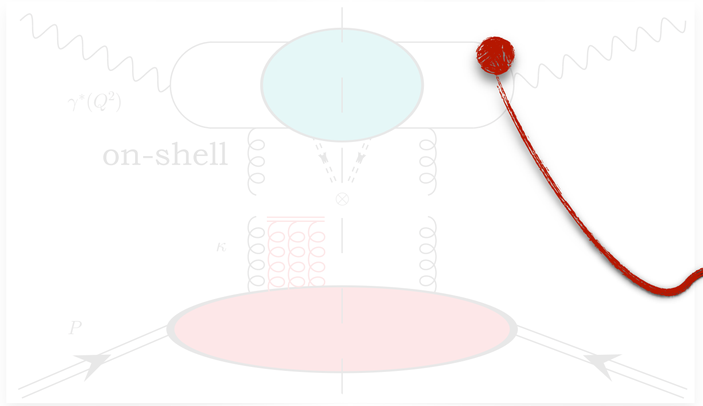
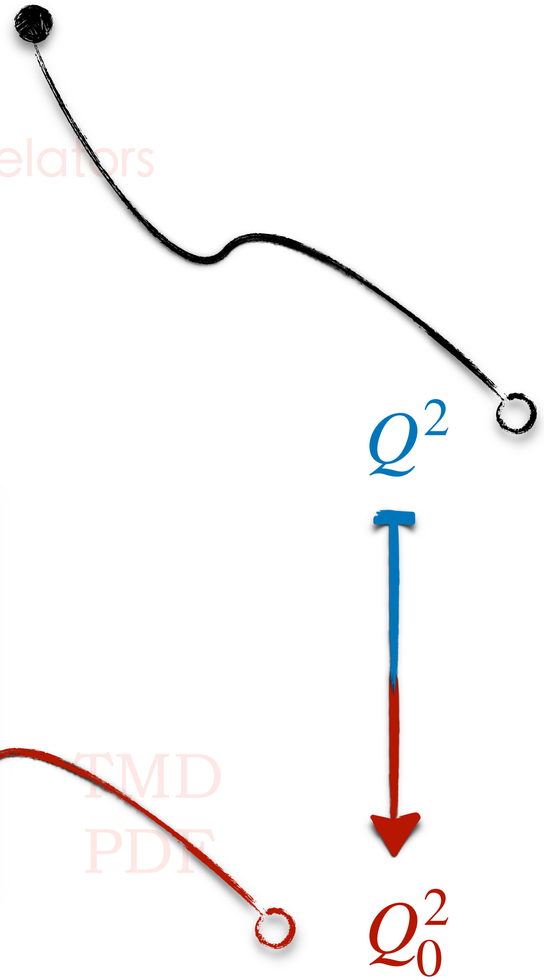
IR diffusion pattern

(Bartels' cigar)

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





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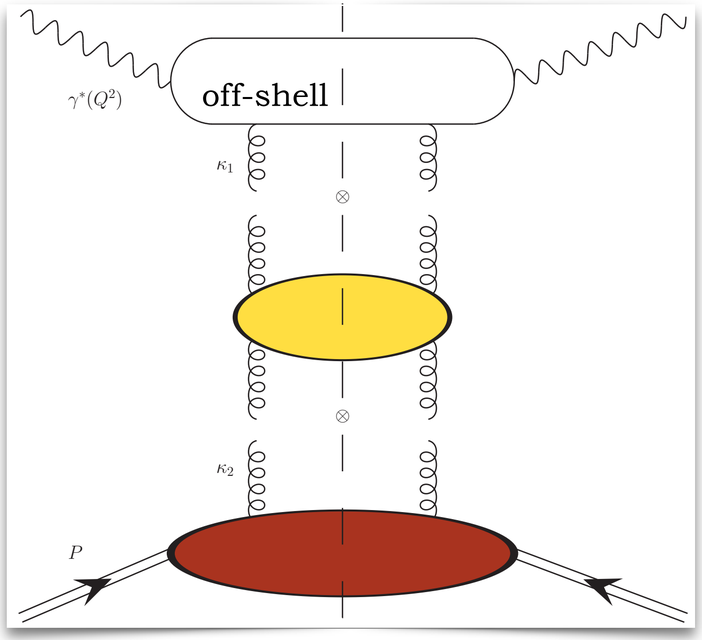

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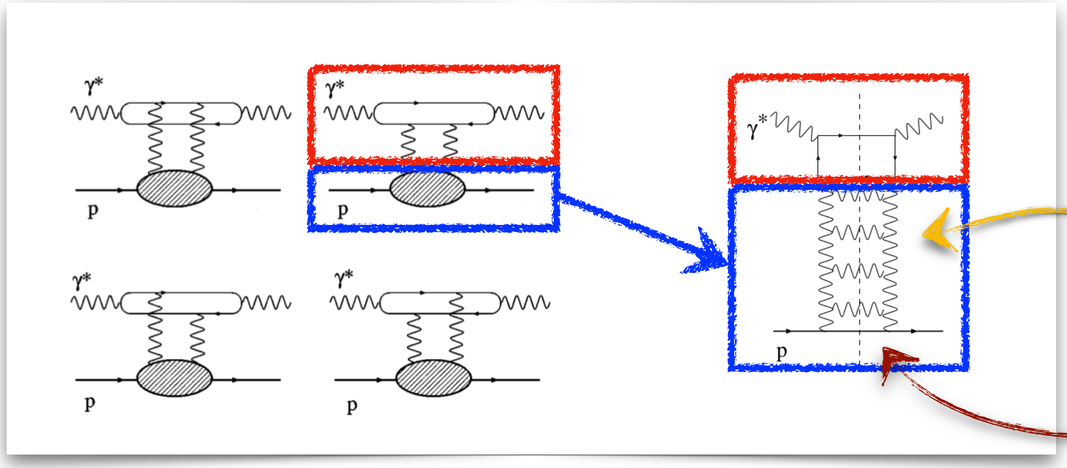
Backup

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!

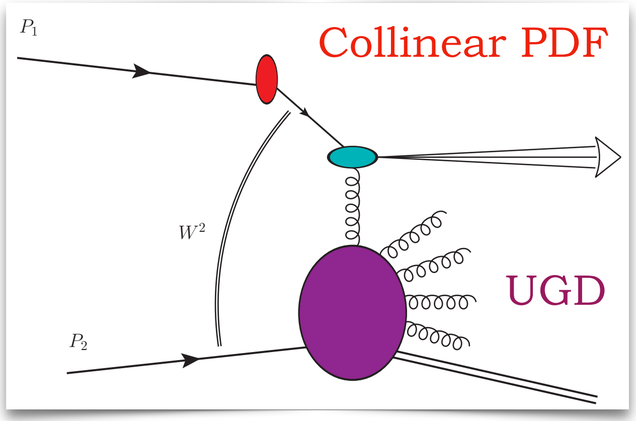
Backup

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

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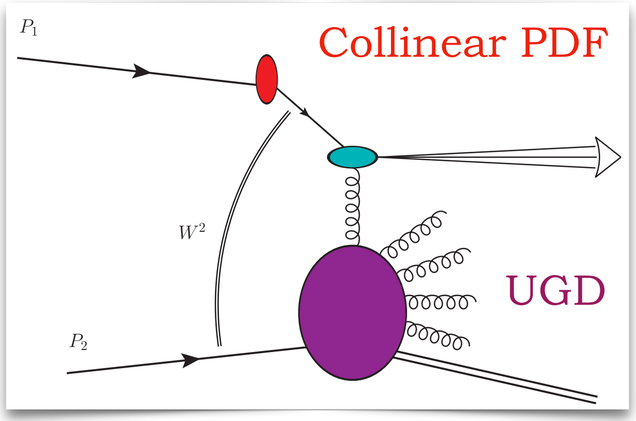

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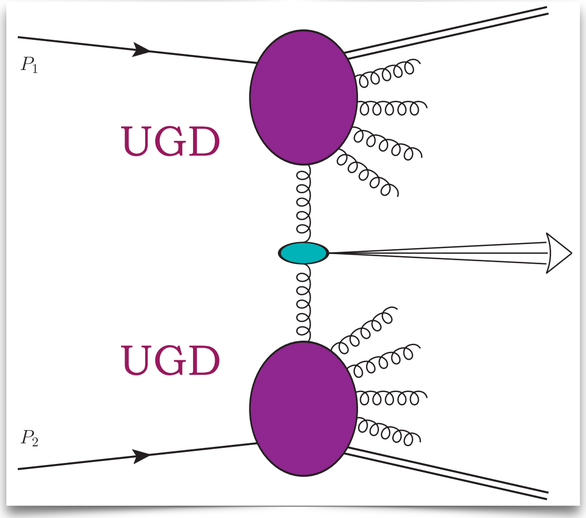
Central emissions

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



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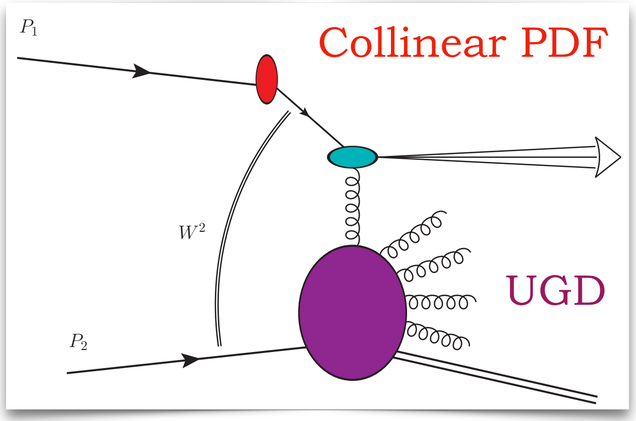

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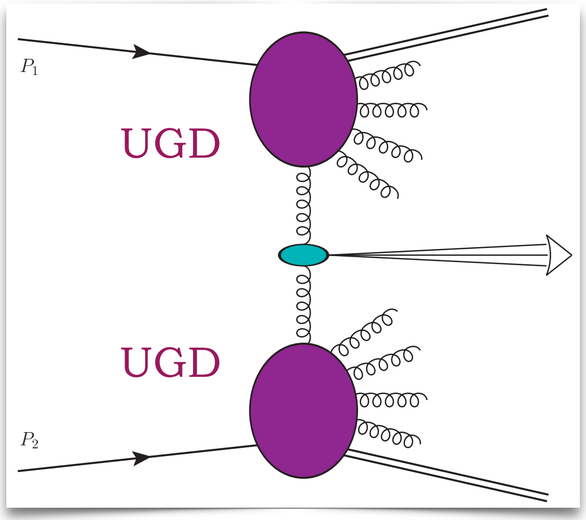

* Small-x dynamics to **enhance** f.o. description
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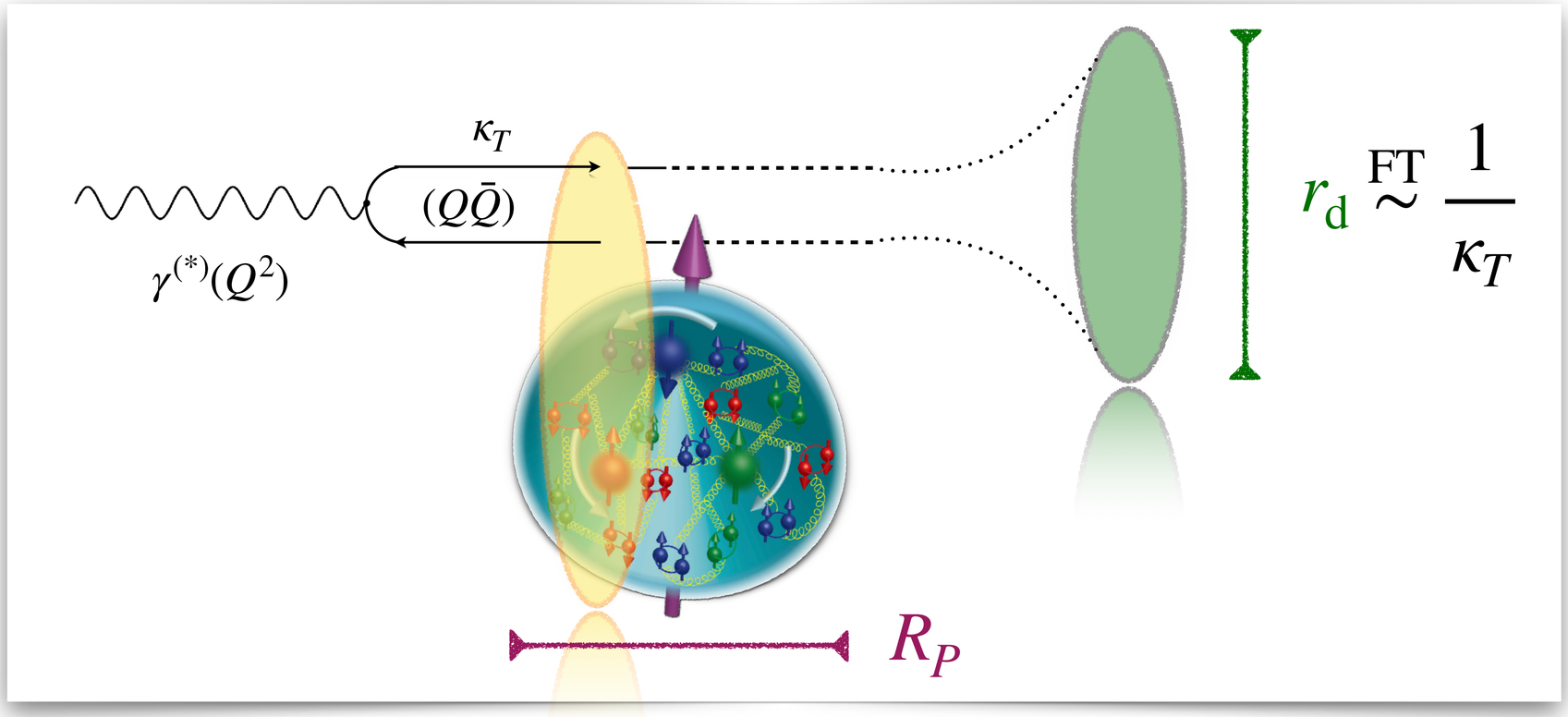
Table complemented by *exclusive* counterparts and *lepto-hadronic* channels

Backup

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



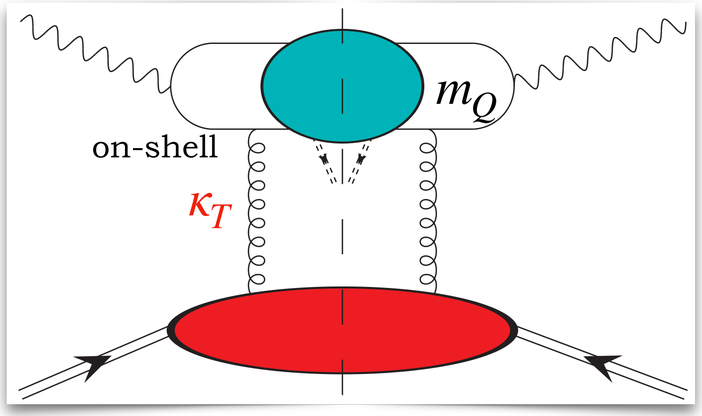
$$W_{\mu\nu} \propto \mathrm{Im}\left\{ i \int \mathrm{d}^4x\, e^{i\,q\cdot x} \langle P | \mathrm{T}\,[J_\mu(x)\, J_\nu(0)] | P \rangle \right\}$$

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

Backup

Inclusive quarkonium production mechanisms

$$\kappa_T \ll Q$$



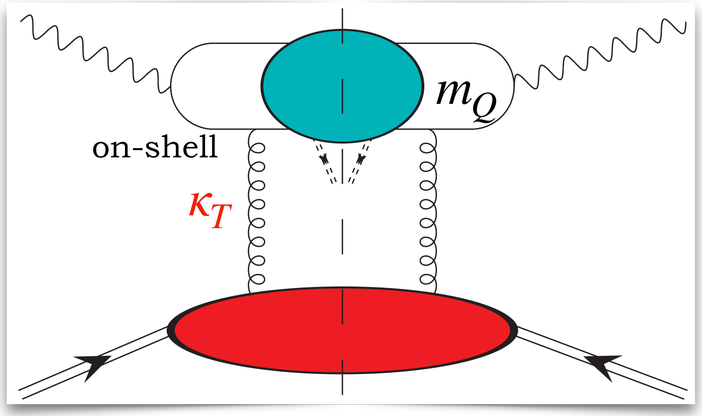
* Gluon TMD PDF
* Short-distance $(Q\bar{Q})$ + ShFs

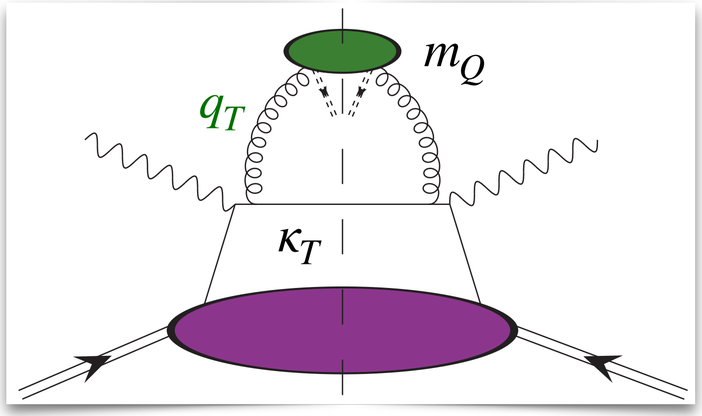
Backup

Inclusive quarkonium production mechanisms

$\kappa_T \ll Q$

$\kappa_T \gg m_Q$





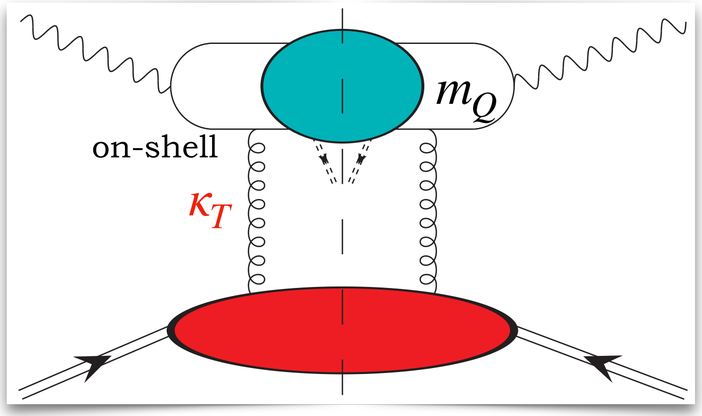
* Gluon TMD PDF
* Short-distance $(Q\bar{Q})$ + ShFs

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

Backup

Inclusive quarkonium production mechanisms

$\kappa_T \ll Q$



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

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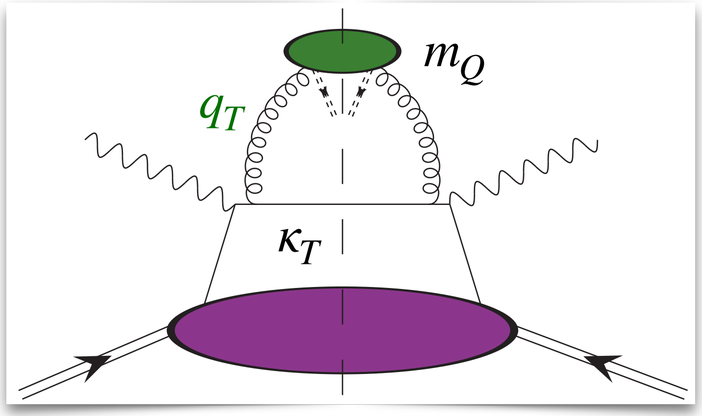
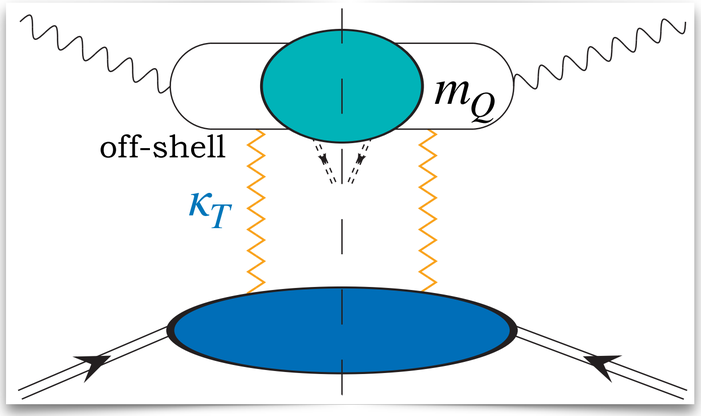


* Quark collinear PDF
* Onium in jet
* Single-quark TMD FF

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…
* HERA indication: no large-r_d dynamics
* LVMs as tools: discrimination among UGD models
* 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