GLUON TMD STUDIES

WITH HEAVY QUARKONIUM STATES

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In collaboration with: A. Bacchetta, M. G. Echevarria, J.-P. Lansberg, M. Ozcelik, M. Radici, A. Signori

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HAS QCD
HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

TIFPA
Trento Institute for Fundamental Physics and Applications

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Programa de atracción de talento investigador
Comunidad de Madrid

Madrid UAH

1. Introductory 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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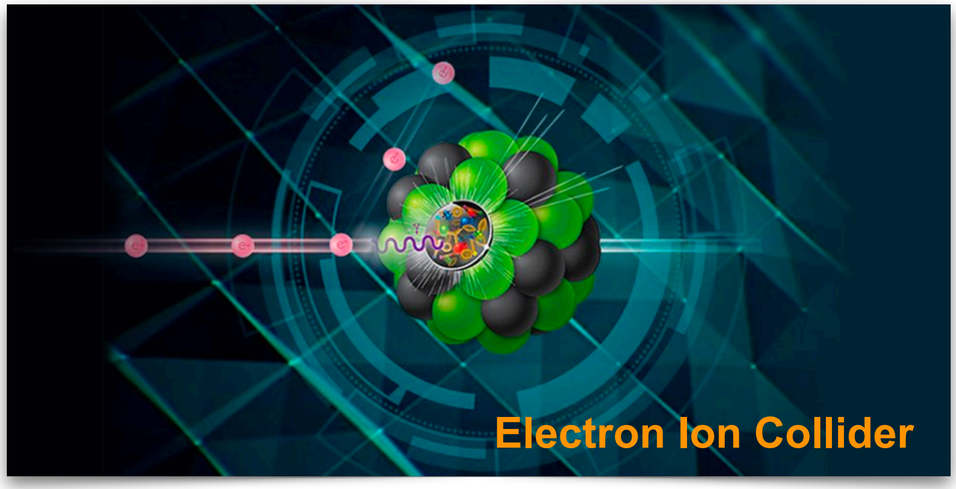

3D proton imaging

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

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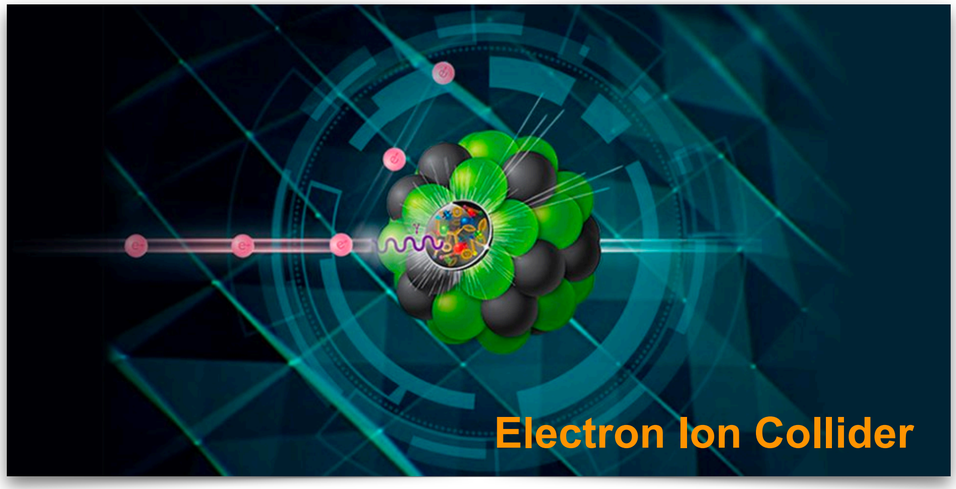


3D proton imaging

- 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 also at a 2nd detector

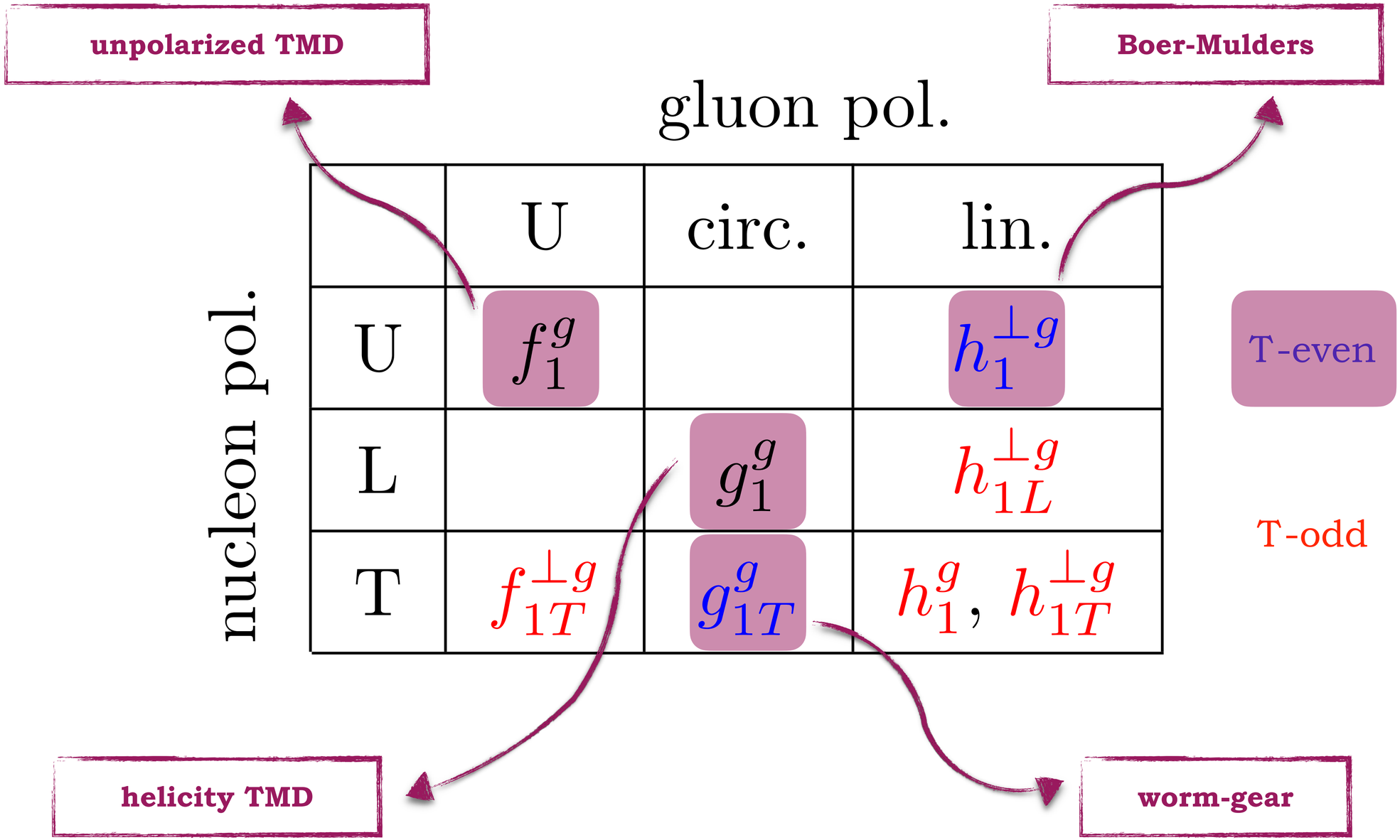
Gluon TMD PDFs at leading twist

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



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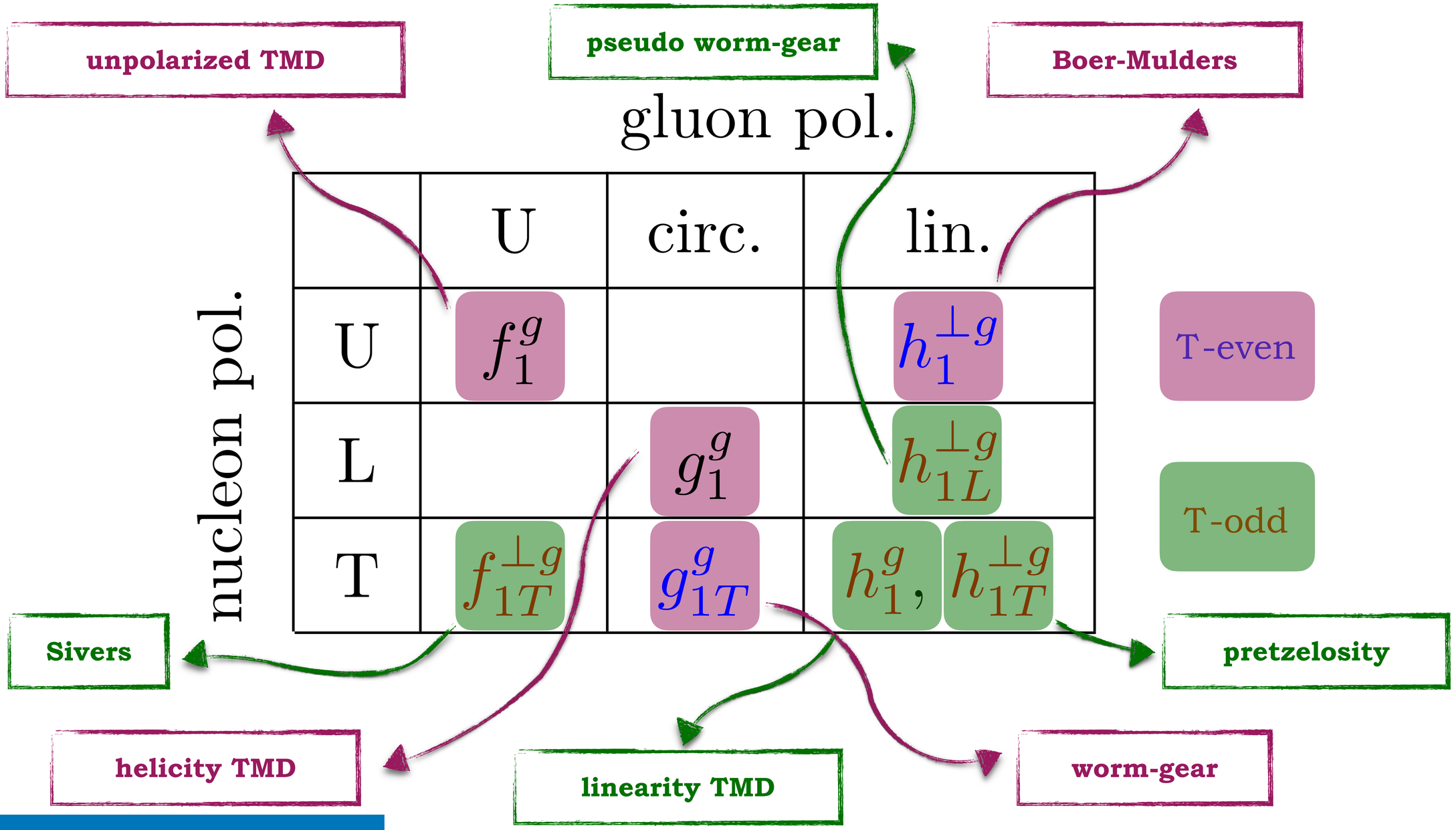


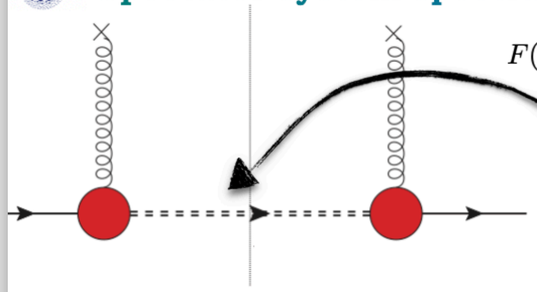
2. Spectator-model gluon TMDs

Spectator-model gluon TMDs

Our model at a glance

Spectator-system spectral-mass function

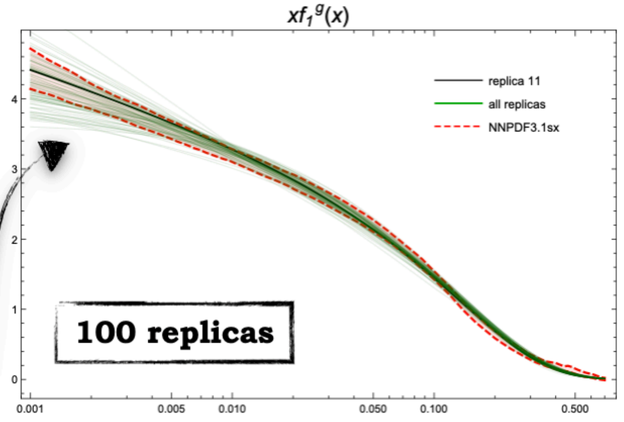
$$F(x, \boldsymbol{p}_T^2) = \int_M^\infty \mathrm{d}M_X \, \rho_X(M_X) \, \hat{F}(x, \boldsymbol{p}_T^2; M_X)$$



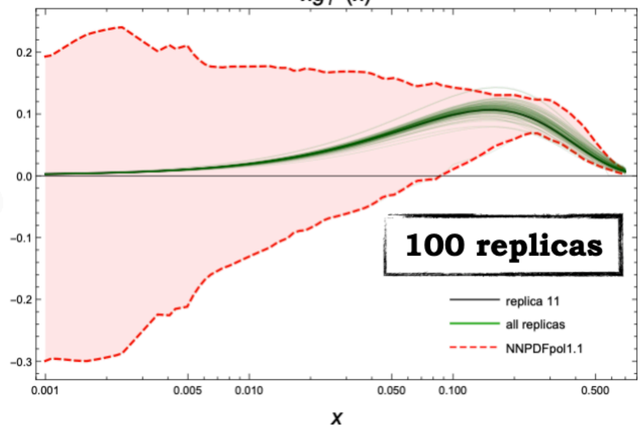
Instead of a single on-shell spectator, a continuum of spectators

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)]

14

T-odd gluon TMDs in a spectator model

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

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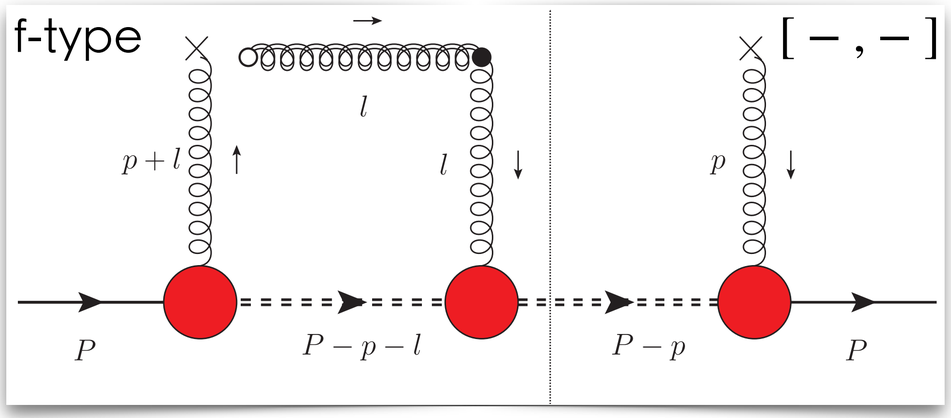
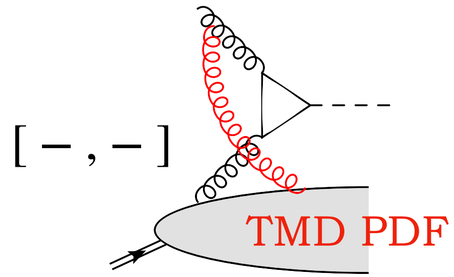
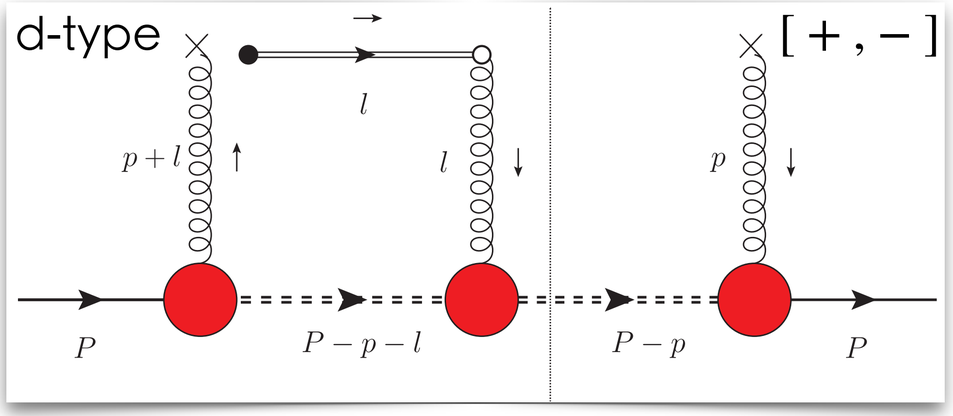
$gg \to H$





f-type (WW) structure

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

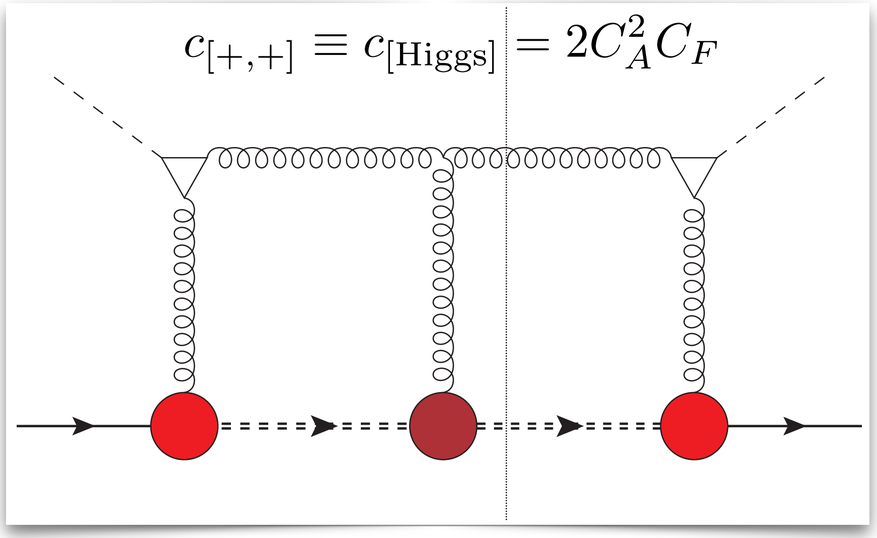


d-type (dipole) structure

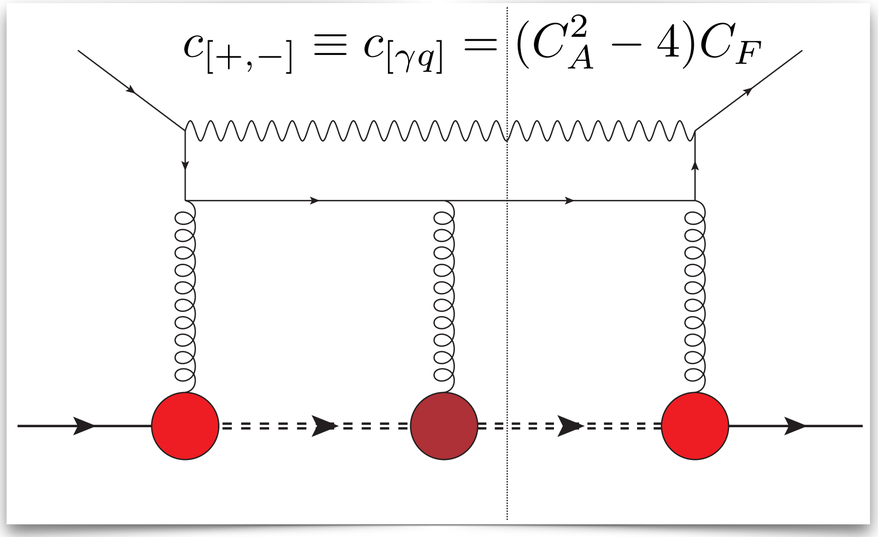
(Sivers & linearity) 🔗🔗 [A. Bacchetta, F.G.C., M. Radici, EPS-HEP, PANIC (2021)]

T-odd gluon TMDs in a spectator model

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



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



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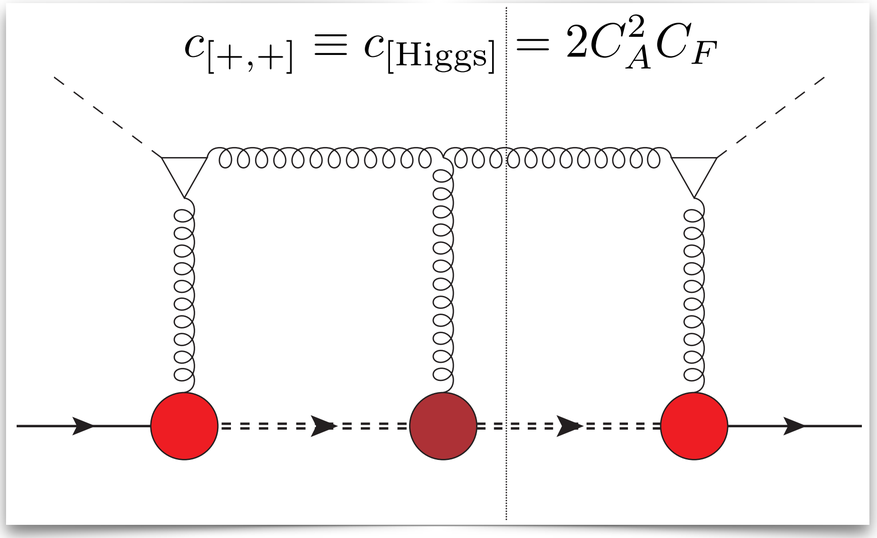

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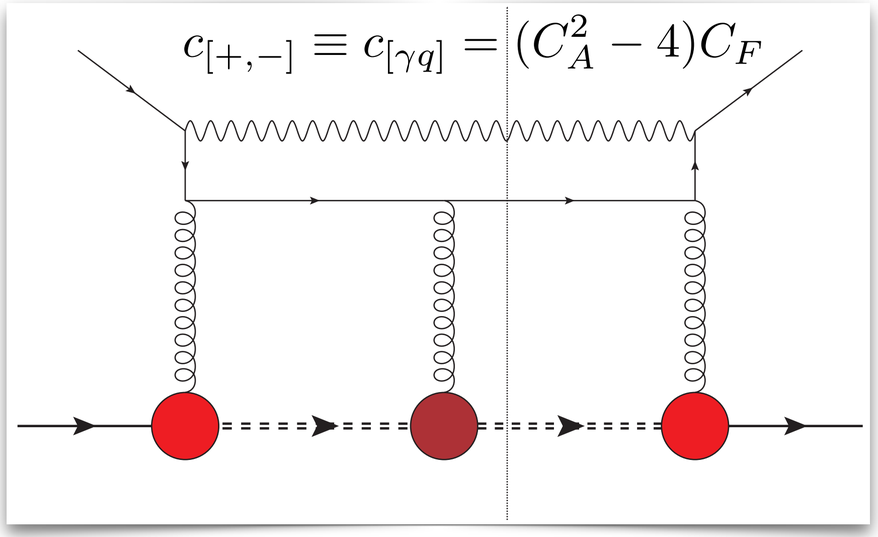

nucleon-gluon-spectator

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

spectator-gluon-spectator

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

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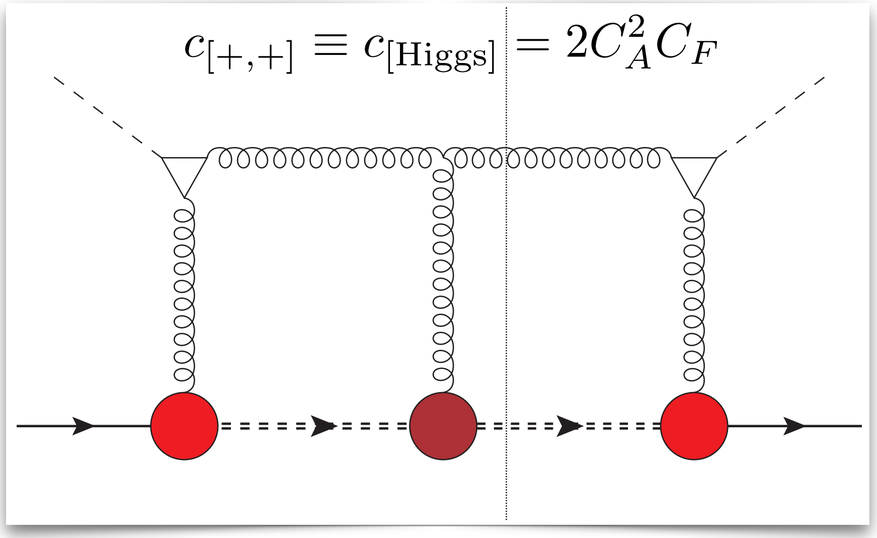

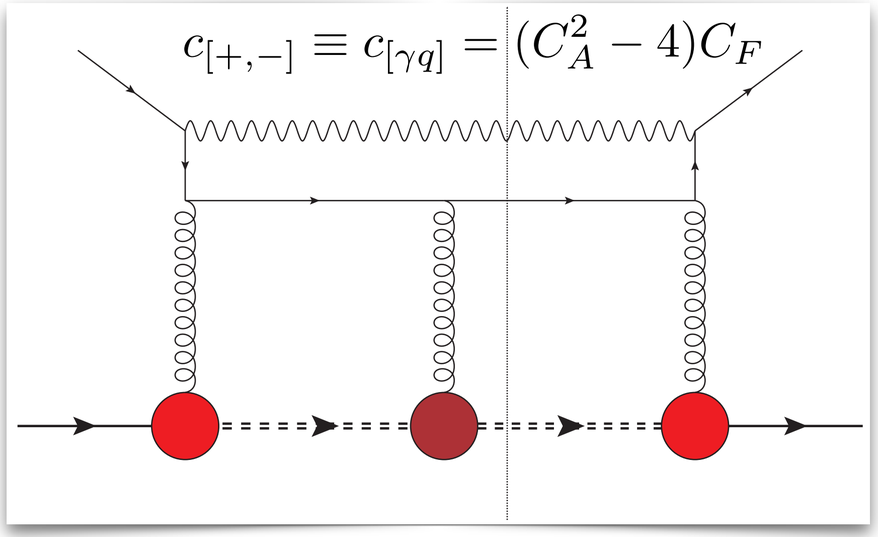

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Assumption: $g^d_{1,2}(p^2) = g^f_{1,2}(p^2) \equiv g_{1,2}(p^2)$ $\Leftrightarrow$ $f_{1T}^{\perp[+,-]} = \dfrac{c_{[+,-]}}{c_{[+,+]}} f_{1T}^{\perp[+,+]} \equiv \dfrac{10}{18} f_{1T}^{\perp[+,+]}$

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

Preliminary results for Sivers

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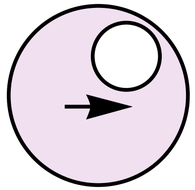

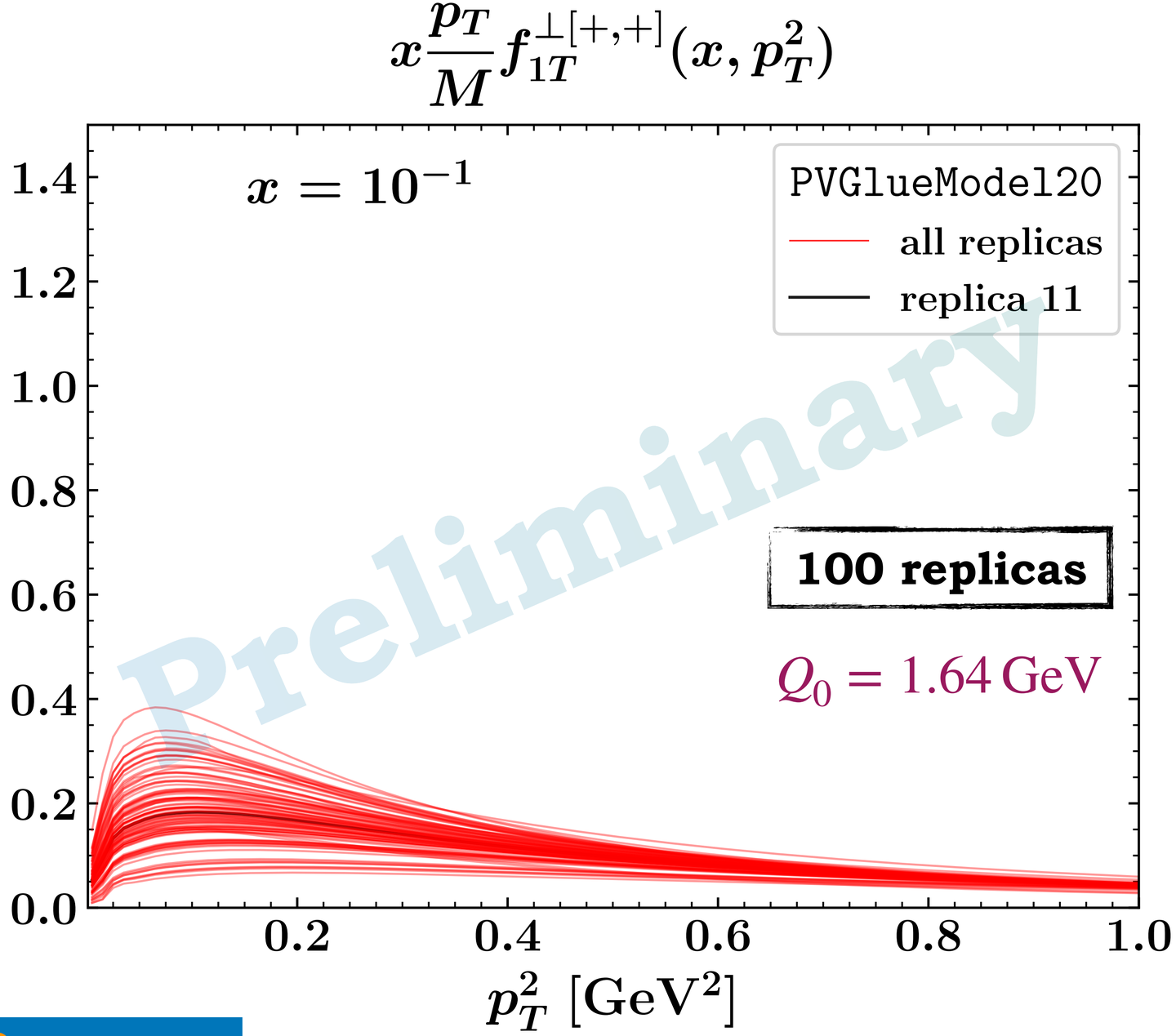

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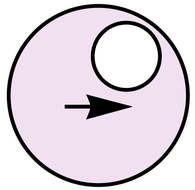
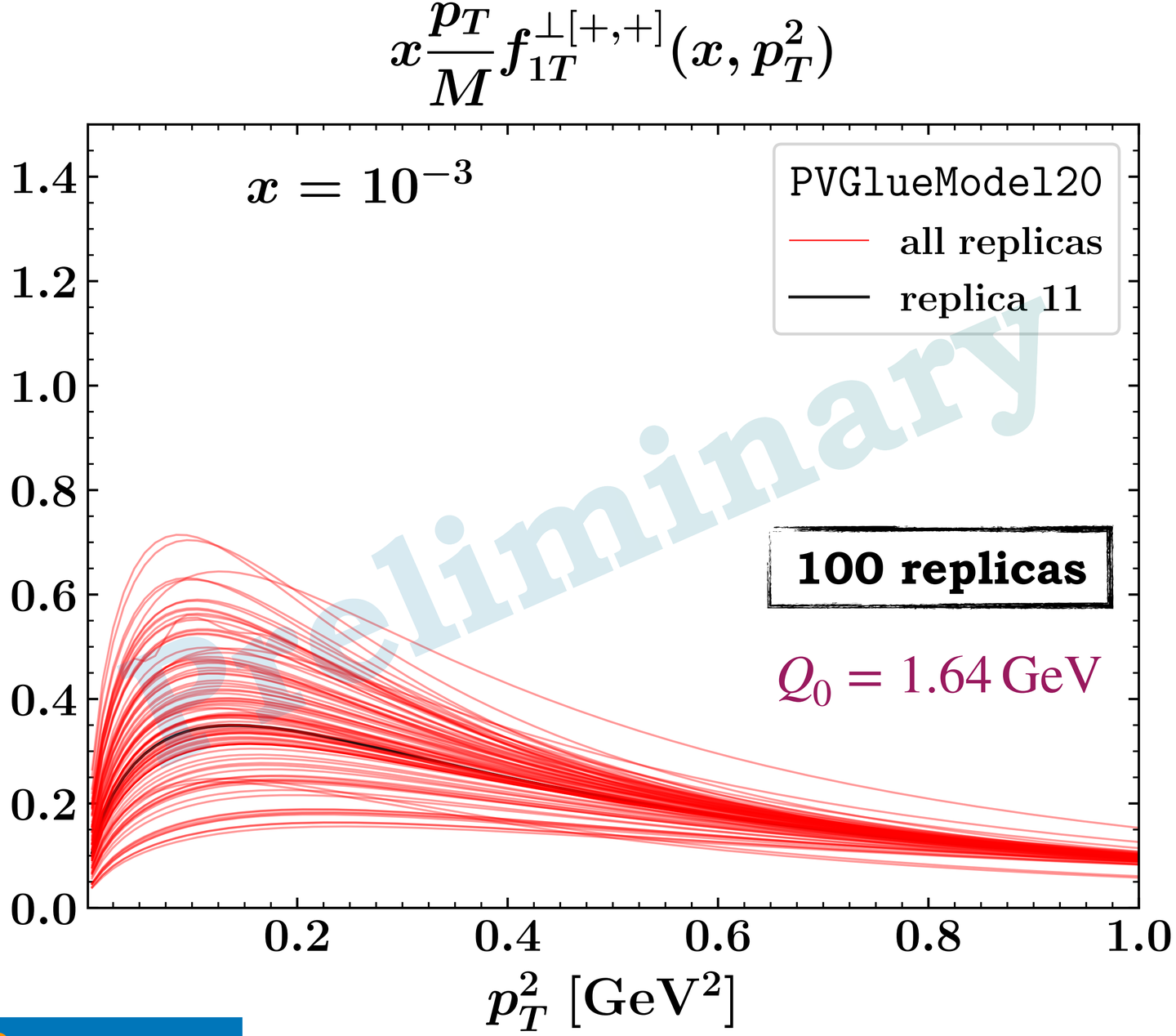


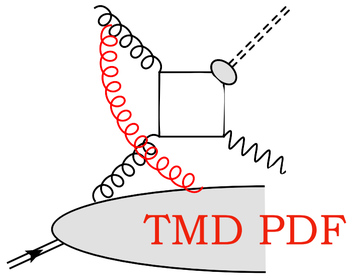


3. Pseudoscalar onium & gluon TMDs

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)	√
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Challenges

Quarkonia: assets & challenges

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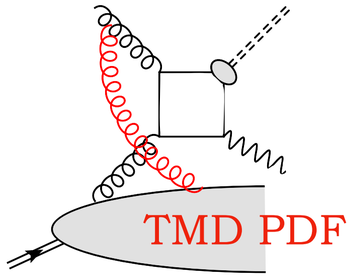

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$\eta_{c,b}$ ⇒ LHC complementarity, TMD factorization

$$\frac{d\sigma}{dq_T} \sim \sim \mathcal{C}[\, f_1^{g/A} \; f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \; h_1^{\perp g/B} \,]$$

at low transverse momentum for (pseudo)scalar state

unpolarized gluons

lin. polarized gluons

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

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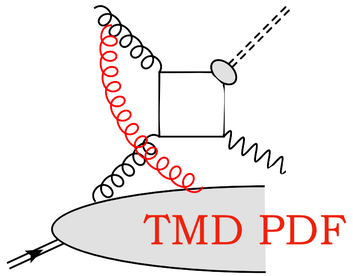

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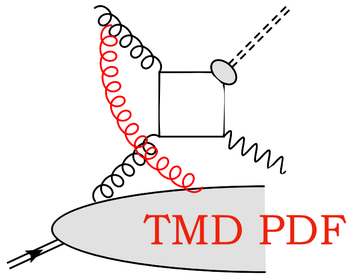

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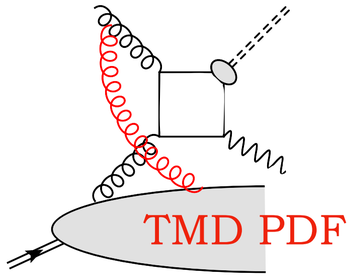

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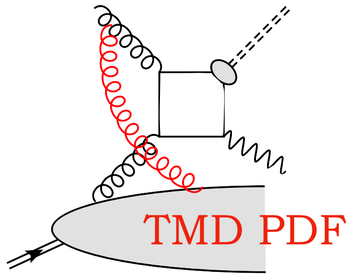

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NRQCD and Color Octet

Higher Fock states, soft gluon emissions

Problems at low p_T, fails on polarization

Quarkonia: a path toward precision

TMD & 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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- 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)]
(pol. J/ψ) [D. Boer, U. D'Alesio, L. Maxia, F. Murgia, C. Pisano, R. Sangem (2022)]

Quarkonia: a path toward precision

TMD & shape functions

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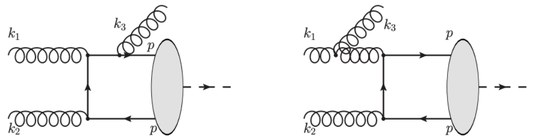
NLO collinear negative distributions

Recap of NLO calculation & origin of negative numbers

$\hat{s}$-dependence only present in real corrections $(g(k_1) + g(k_2) \to \eta_Q(P) + g(k_3))$



- Real-emission corrections are perfect square ($|\mathcal{M}^{(\mathrm{Real})}|^2$) and thus positive
- IR singularities in the real emissions only reveal themselves after taking the phase-space integration: $\overline{\sigma}_{gg}^{\mathrm{NLO},z\neq1}(z) = \int d\hat{t}\, \frac{\overline{\sigma}_{gg}^{\mathrm{NLO},z\neq1}}{d\hat{t}}$

$$\overline{\sigma}_{gg}^{\mathrm{NLO},z\neq1}(z) = -\frac{1}{\epsilon_{\mathrm{IR}}}\frac{\alpha_s}{\pi}\left(\frac{4\pi\mu_R^2}{M_Q^2}\right)^{\epsilon}\Gamma(1+\epsilon)\hat{\sigma}_0^{\mathrm{LO}} z P_{gg}(z) + 2C_A\frac{\alpha_s}{\pi}\hat{\sigma}_0^{\mathrm{LO}}\overline{A}_{gg}(z)$$

- For $\epsilon_{\mathrm{IR}} \to 0^-$, $\overline{\sigma}_{gg}^{\mathrm{NLO},z\neq1} \geq 0$ for all $0 \leq z < 1$ as expected
- Initial-state collinear divergences are absorbed/subtracted into PDF via *process-independent* Altarelli-Parisi counterterm in $\overline{\mathrm{MS}}$-scheme

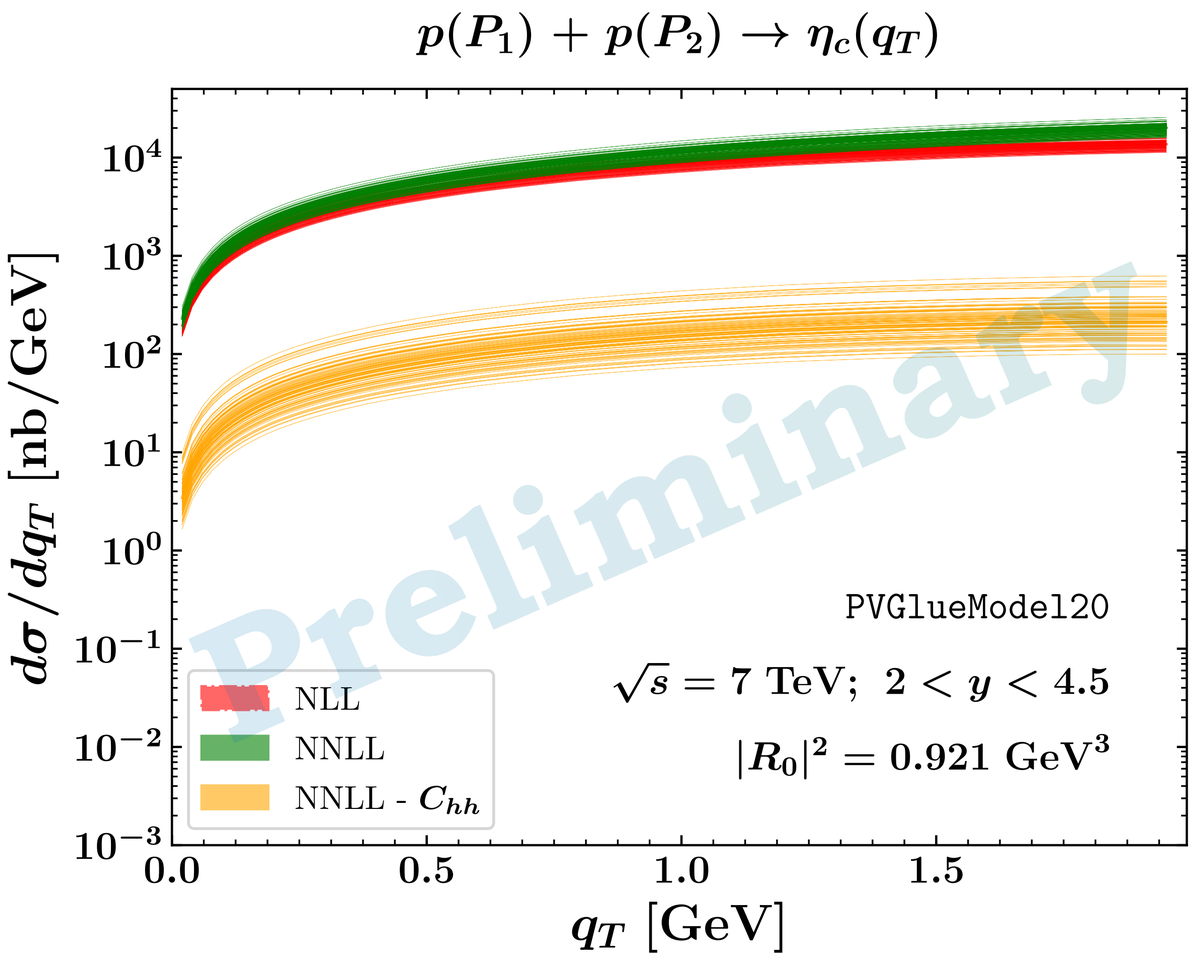
$$\overline{\sigma}_{gg}^{\text{AP-CT}}(z) = \frac{1}{\epsilon_{\mathrm{IR}}}\frac{\alpha_s}{\pi}\left(\frac{4\pi\mu_R^2}{\mu_F^2}\right)^{\epsilon}\Gamma(1+\epsilon)\hat{\sigma}_0^{\mathrm{LO}} z P_{gg}(z)$$

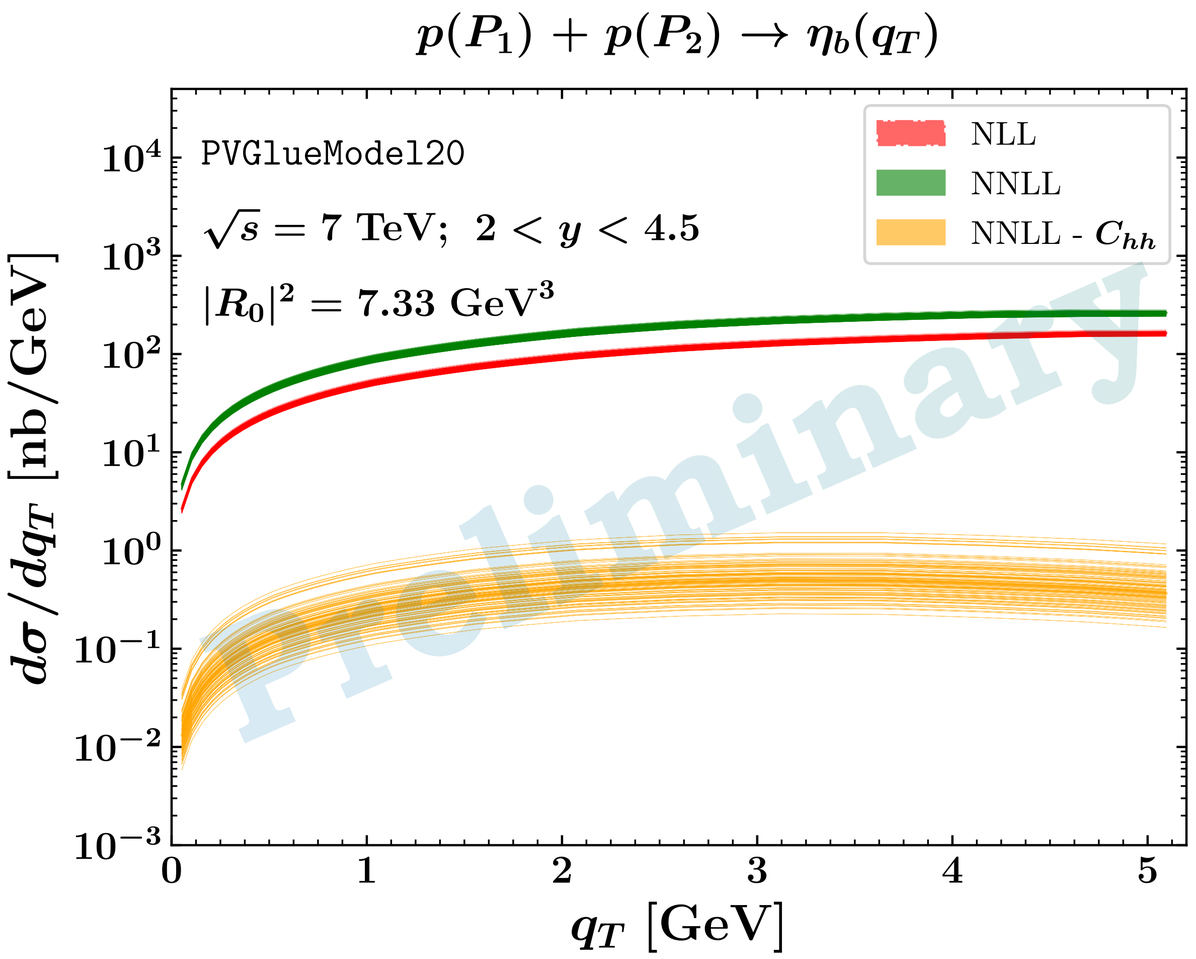
J.P. Lansberg (IJCLab) | Quarkonium production | September 28, 2022 | 5 / 20

(this slide) [Diffraction 2022's talk by Jean-Philippe Lansberg]
(collinear/HEF matching) [J.-P. Lansberg, M. Nefedov, M.A. Ozcelik (2022)]
(scale fixing) [A. Colpani Serri et al. (2021)]

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

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



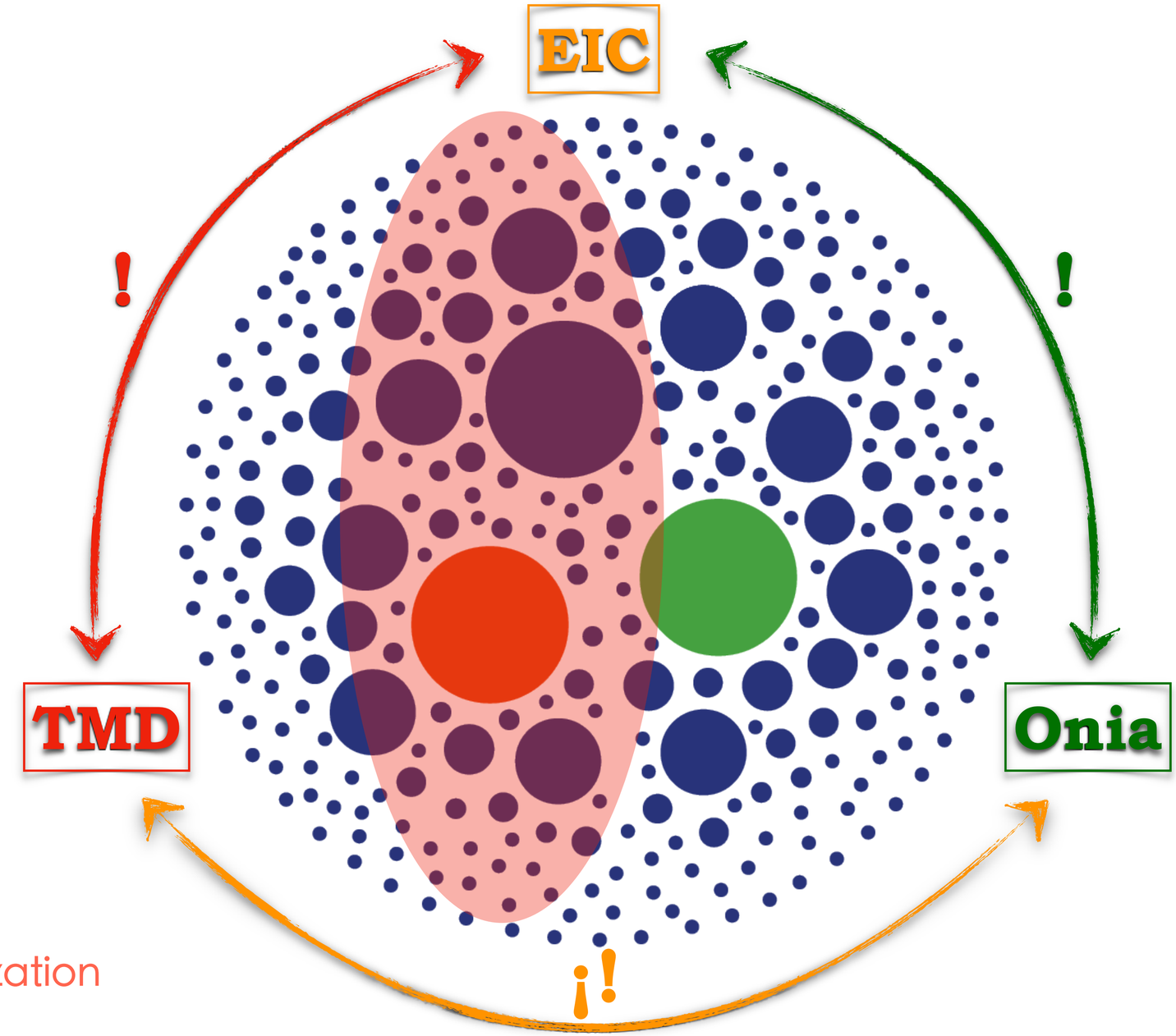


[A. Bacchetta, F.G.C., M.G. Echevarria, J.-P. Lansberg, M. Ozcelik, M. Radici, A. Signori (in preparation)]

Quarkonia & gluon TMDs: a win-win strategy

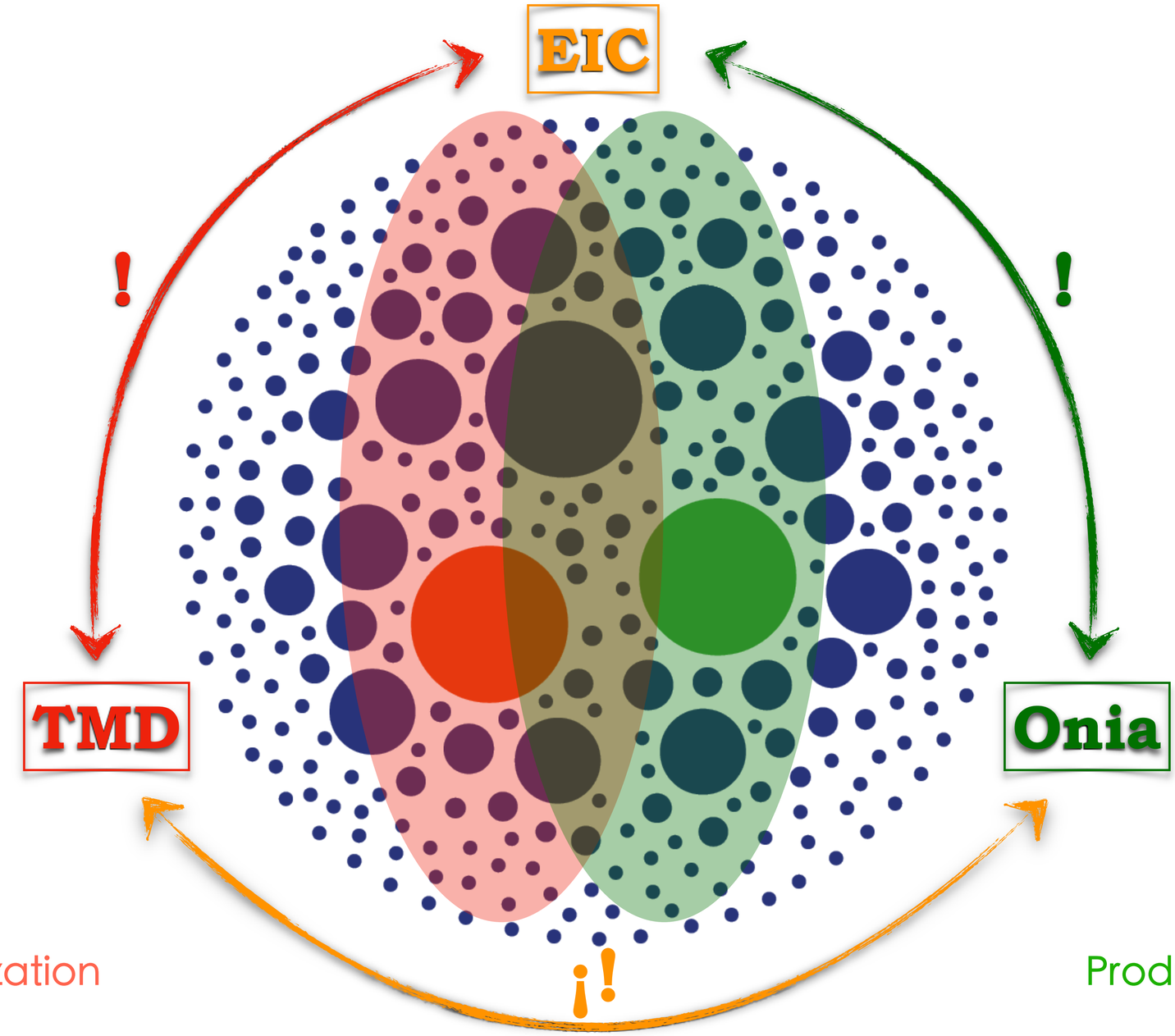
- Onia as Tools ⇒ 3D proton imaging via gluon TMDs
- Gluon TMDs as Tools ⇒ unveil onium production mechamisms

Quarkonia & gluon TMDs: a win-win strategy



Models & polarization

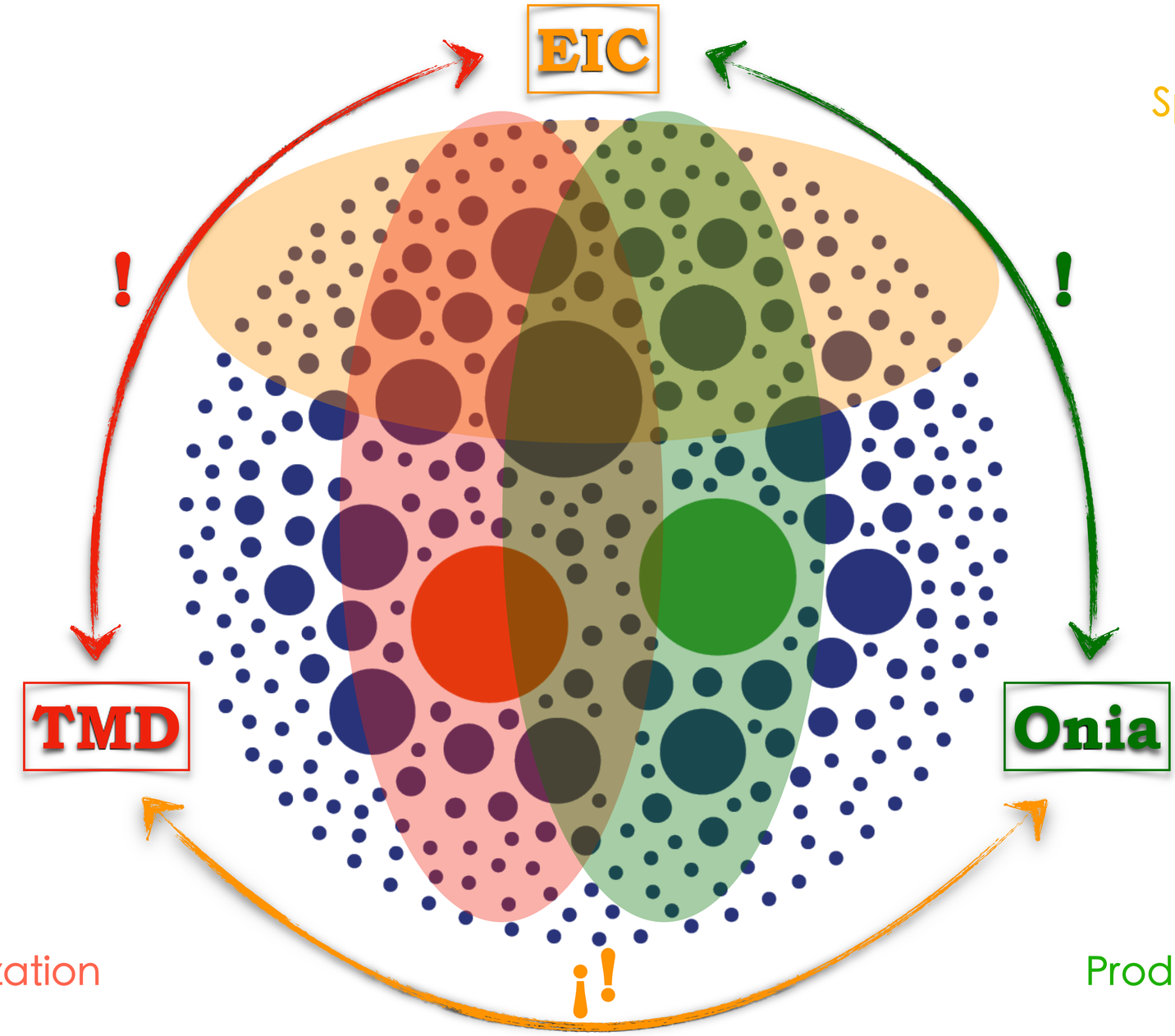
Quarkonia & gluon TMDs: a win-win strategy



Models & polarization

Production mechanisms

Quarkonia & gluon TMDs: a win-win strategy



Spin asymmetries
Impact studies

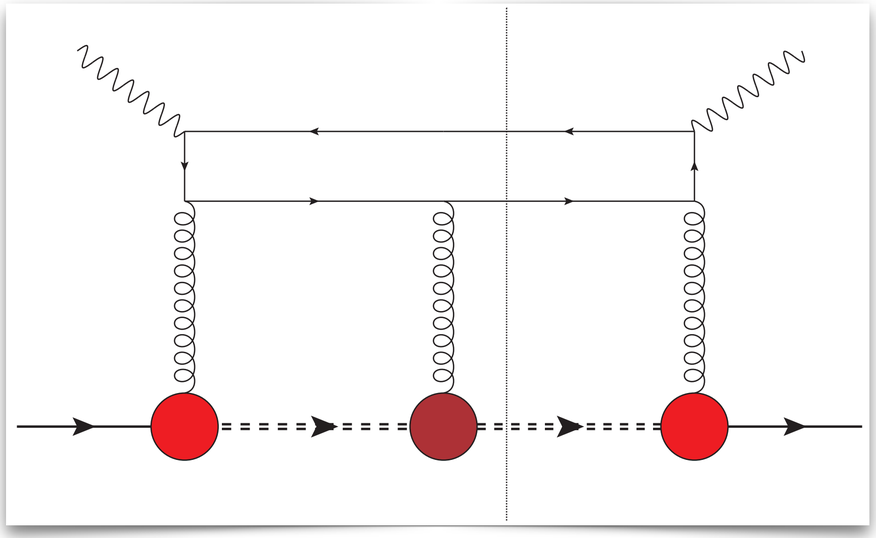
Models & polarization

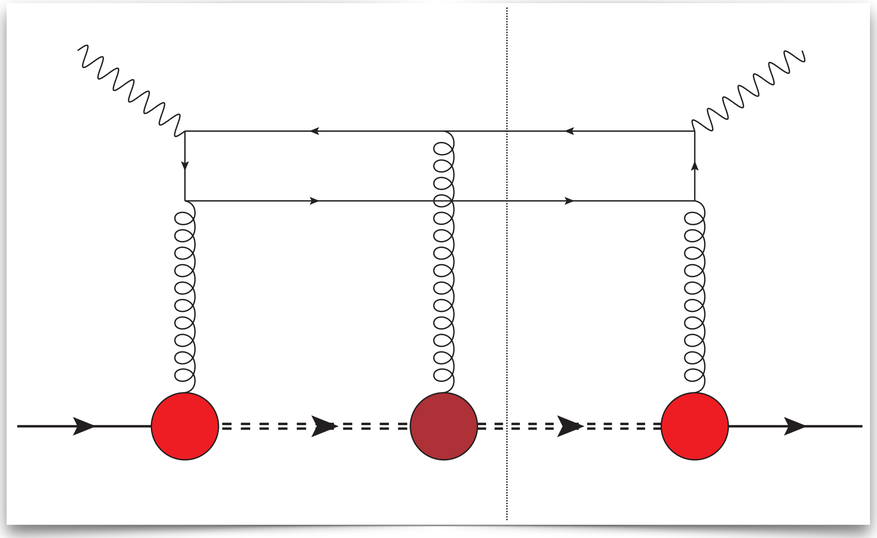
Production mechanisms

Extras

Analytic structure of T-odd gluon TMDs

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





Backup

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

Analytic structure of T-odd gluon TMDs

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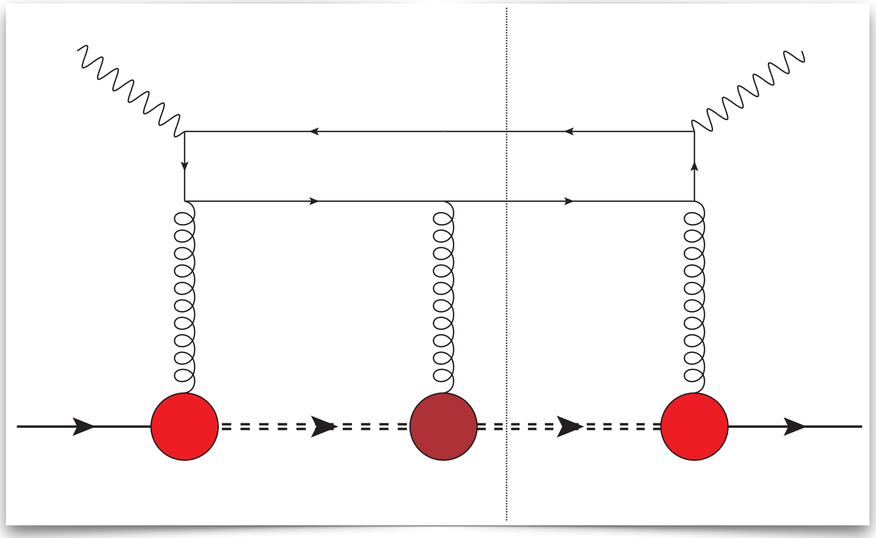

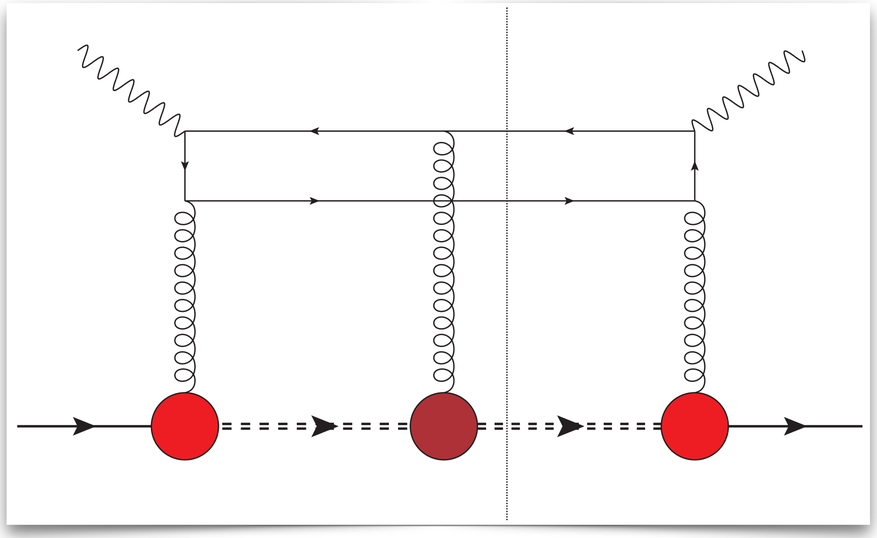

nucleon-gluon-spectator

spectator-gluon-spectator

Backup

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

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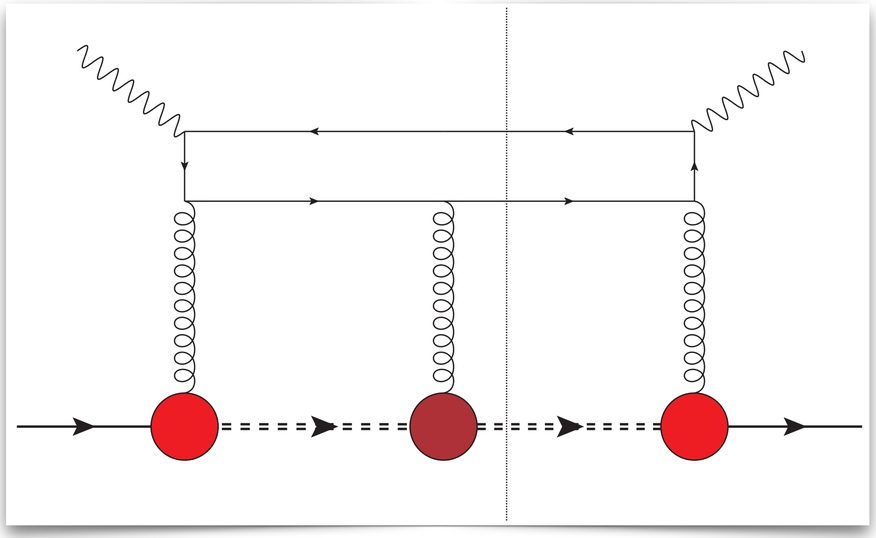

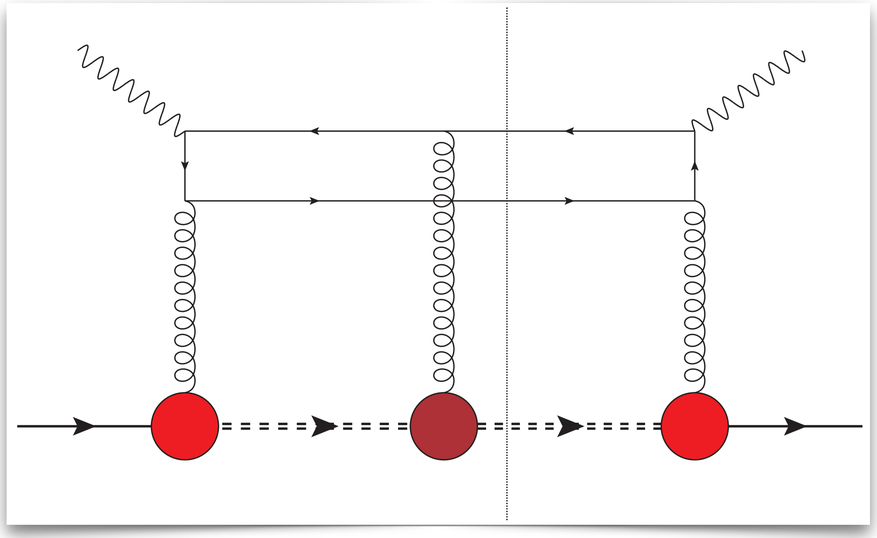

nucleon-gluon-spectator

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

$8 \times 7 \times 4$

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

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Backup

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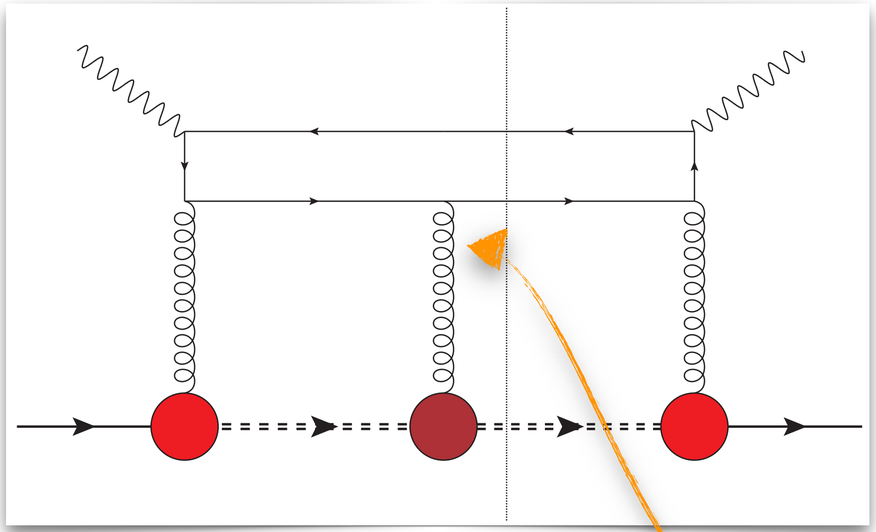

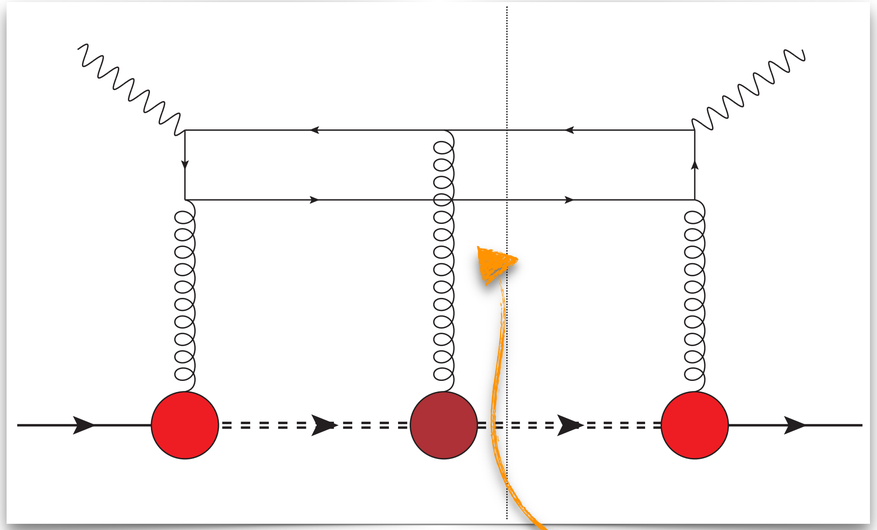

nucleon-gluon-spectator

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Backup

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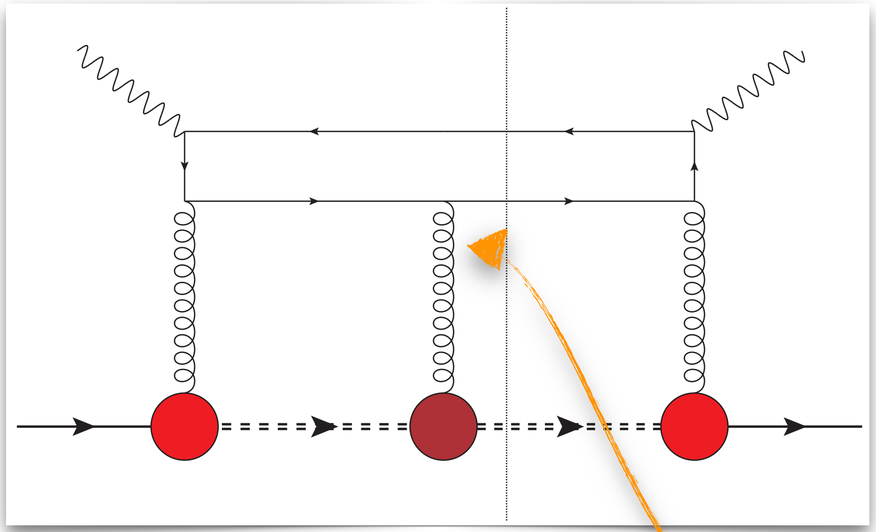

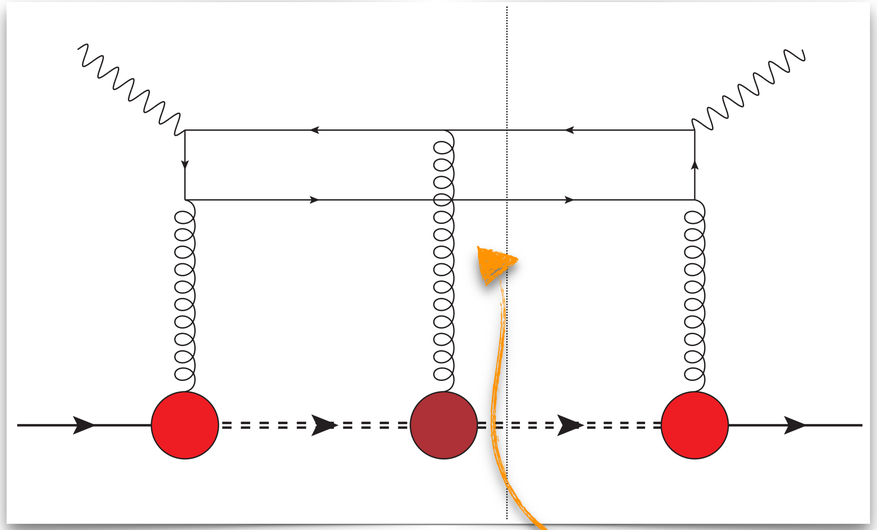

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[A. Bacchetta, F.G.C., M. Radici (in preparation)]

Backup

Anatomy of gluon TMDs

matching coefficients

collinear PDF

nonperturbative Sudakov

nonperturbative TMD function

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

perturbative Sudakov

perturbative expansion in $\alpha_s(\mu)$

resummation of

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

define logarithmic ordering

slide adapted from C. Bissolotti

Backup

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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

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slide adapted from C. Bissolotti

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Backup

¿ Suppression of genuine NP effects ?

TMD factorization

Parton densities: an incomplete family tree

Wigner distributions $\rho\left(x, \mathbf{k}_T, \mathbf{b}_T\right)$ **5D**

$\int d^2\mathbf{k}_T$

$\int d^2\mathbf{b}_T$

Generalized Parton Distributions

GPDs

Transverse Momentum Distributions

TMDs **3D**

$\int d^2\mathbf{k}_T$

Parton Distribution Functions

PDFs **1D**

slide adapted from C. Bissolotti

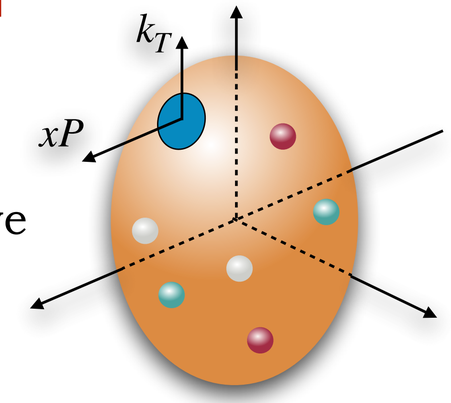
Backup

Parton densities: an incomplete family tree

3D

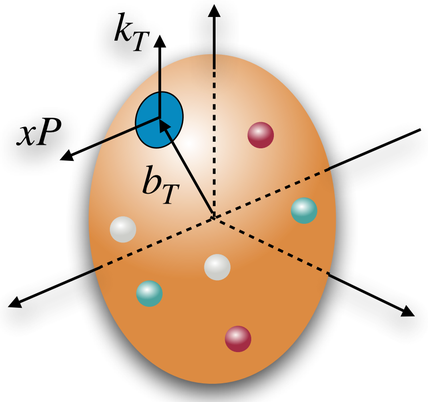
TMDs

(semi-)inclusive



5D

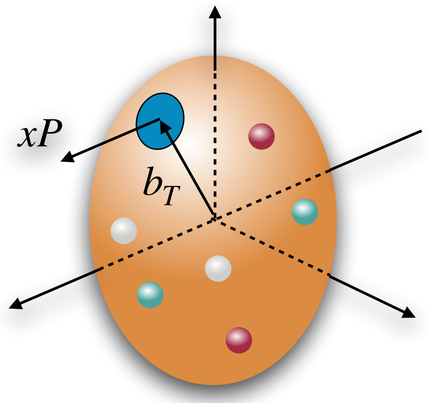
Wigner distributions



3D

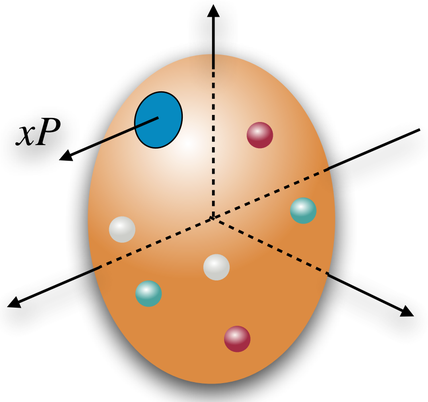
FT of GPDs

exclusive

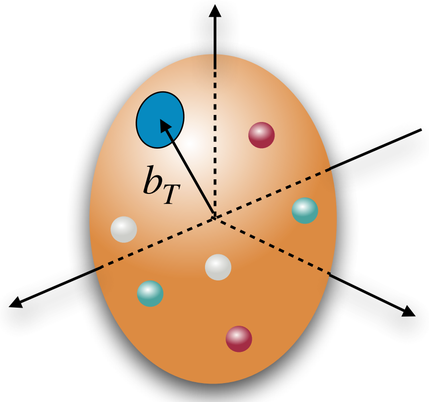


PDFs

(semi-)inclusive



FT of Form Factors



1D

$\vec{b}_\perp$ dependence

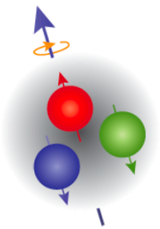
$\vec{k}_\perp$ dependence

these two variables are NOT Fourier conjugate

2D

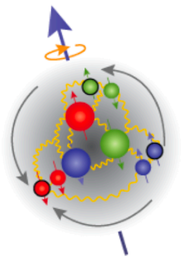
Backup

The proton spin crisis



quarks helicity

~ 30 %



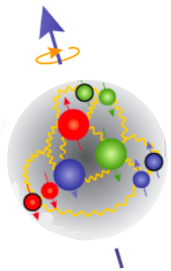
orbital angular momentum

unknown!

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

gluons helicity

~ 20% – 50 % **?**



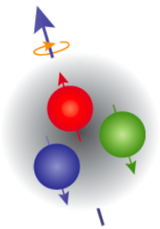
Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description…

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

slide adapted from C. Bissolotti

Backup

The proton spin crisis



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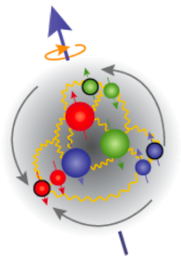

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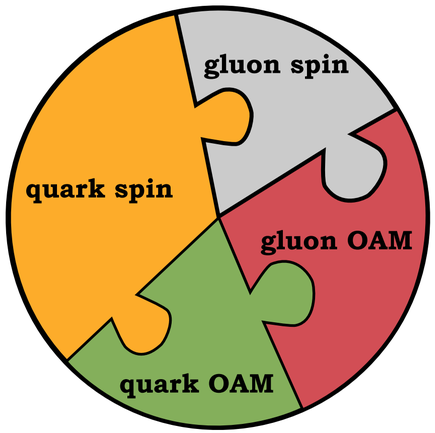

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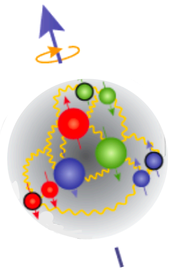

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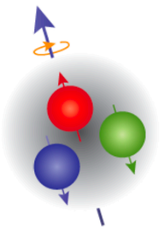
slide adapted from C. Bissolotti

Backup

The proton spin crisis



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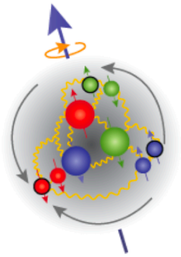

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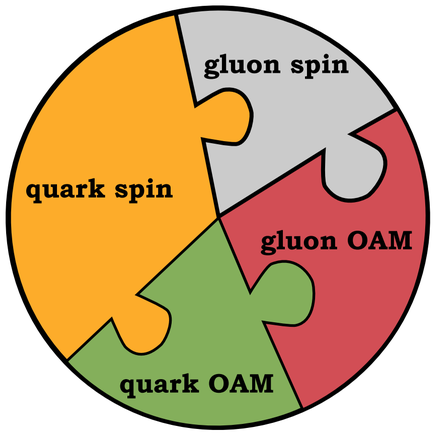

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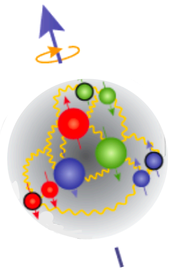

…many other effects in hadronic interactions cannot be understood in the purely collinear approach

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slide adapted from C. Bissolotti

Backup

Gluon TMDs: gauge links and modified universality

* **Single-spin asymmetries** → process dependence of TMDs via **gauge links**
* **Color flow** → integration paths of gauge links calculable
* Gluon TMDs → more complicated structure with respect to quark **staple links**
* **Factorization-preserving** processes → two main kinds of **modified universality**
* Different classes of processes → distinct gluon TMDs, **not related** to each other

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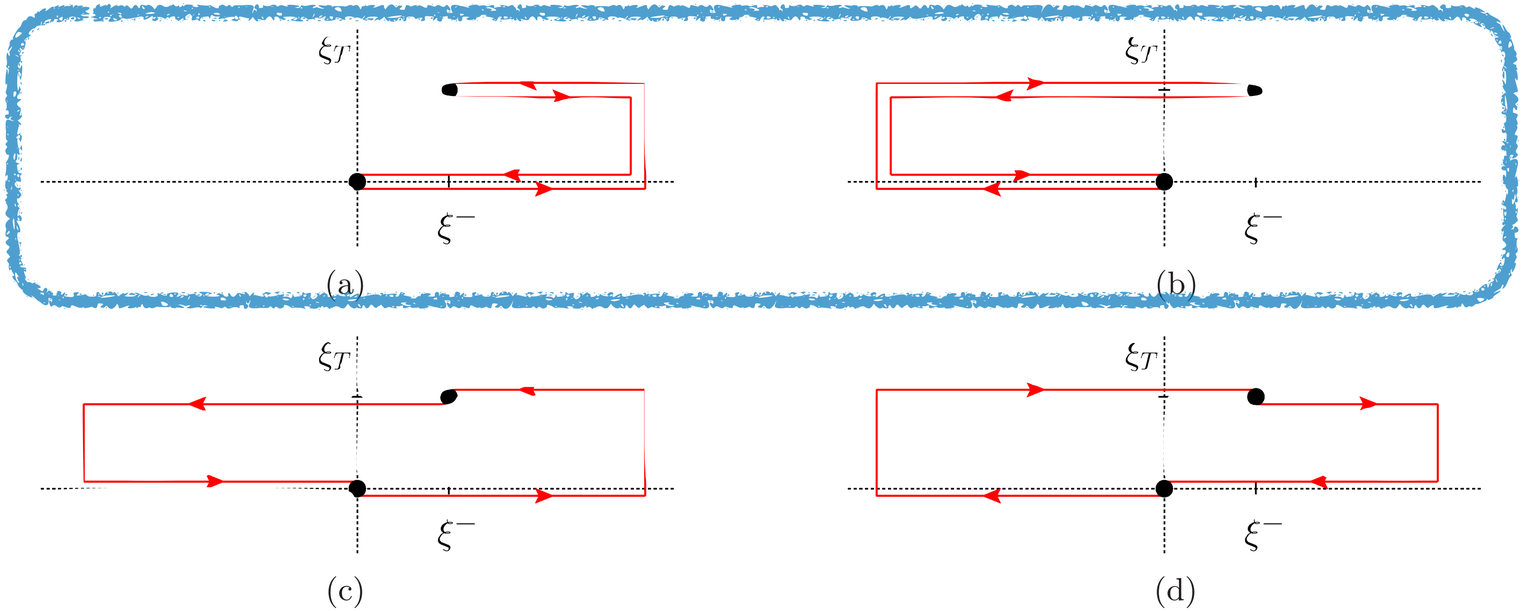
f-type (WW)

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



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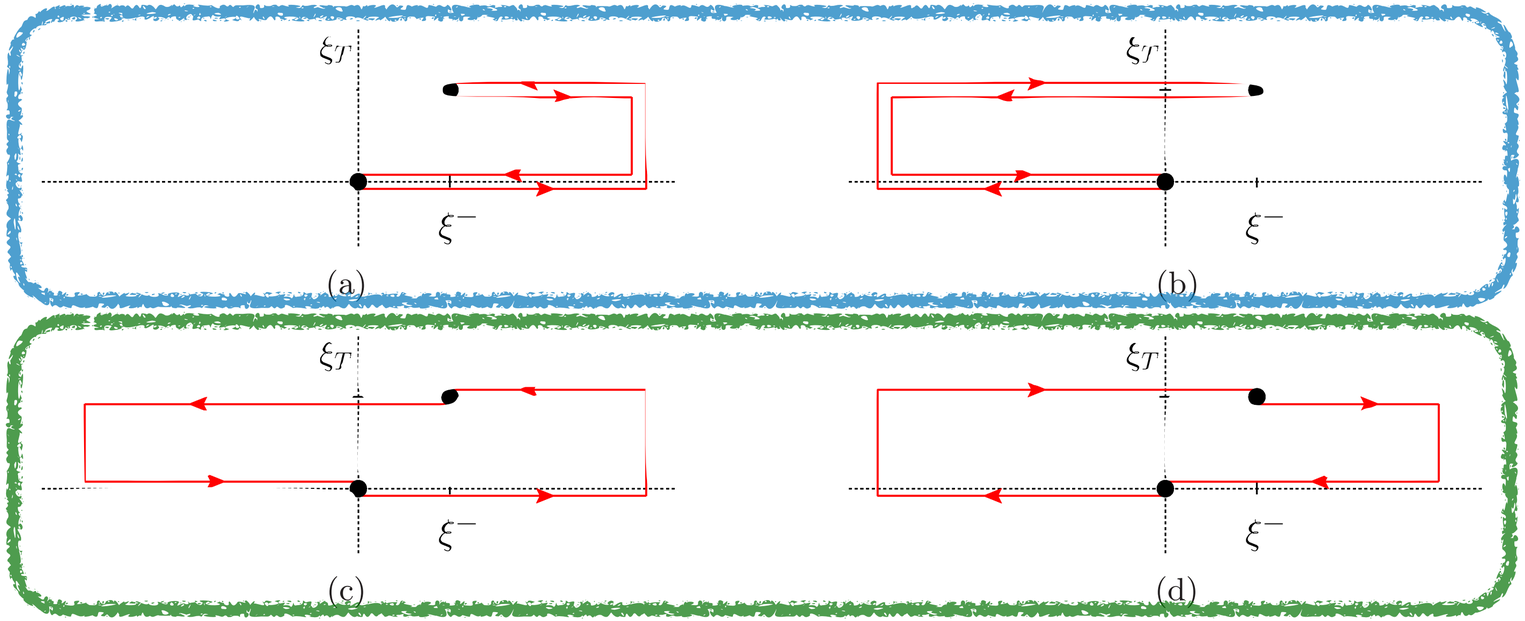
f-type (WW)

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

d-type (dipole)

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

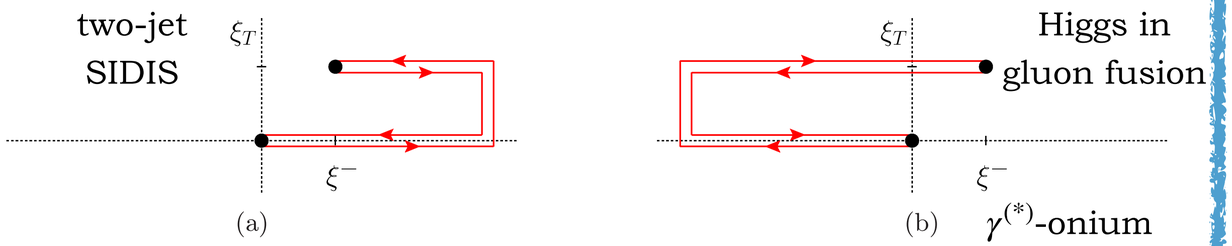


Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

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



Higgs in gluon fusion

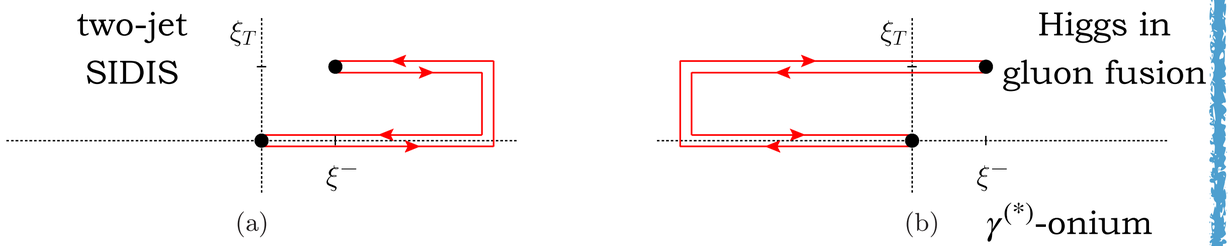
$\gamma^{(*)}$-onium hadroproduction

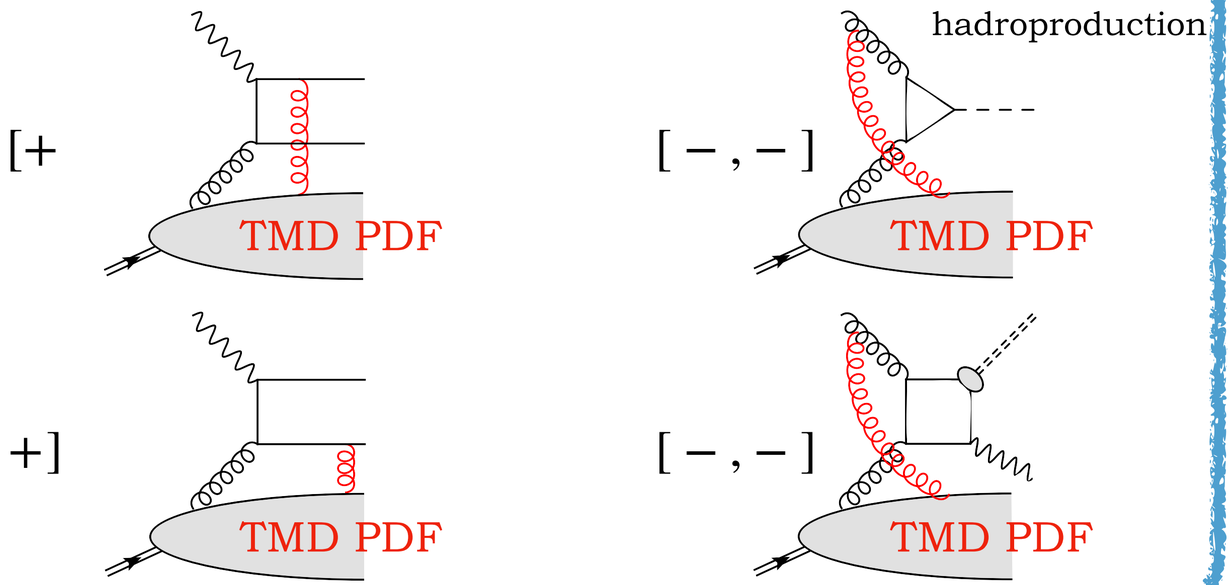
Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

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





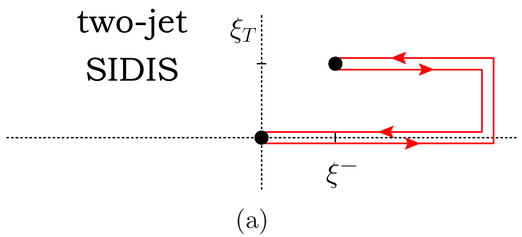
Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

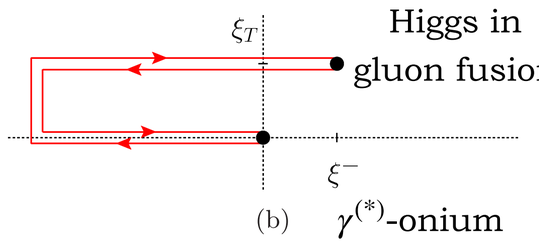
(a) [+ , +] or (b) [− , −]

two-jet SIDIS



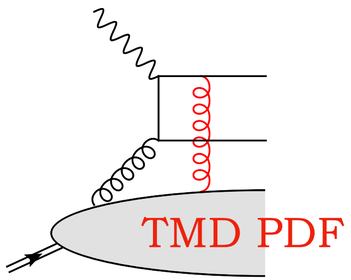
(a)

Higgs in gluon fusion

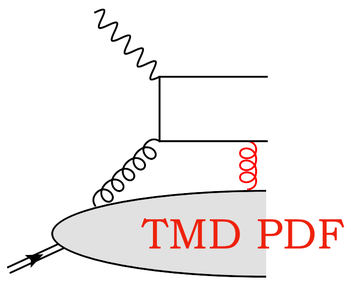


(b)

[+

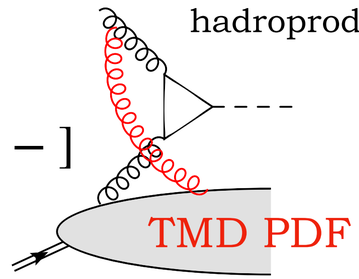


+]

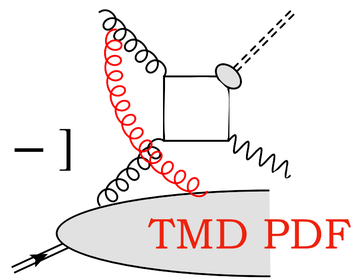


$\gamma^{(*)}$-onium hadroproduction

[− , −]

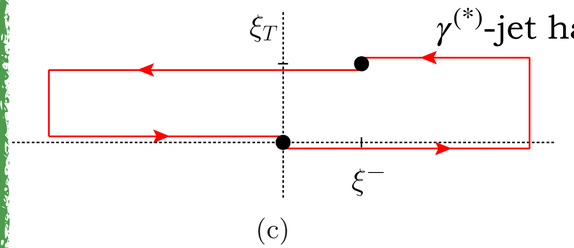


[− , −]



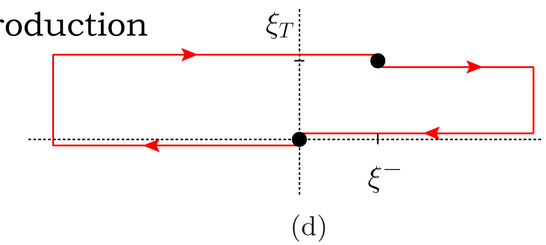
d-type (DP)

(c) [+ , −] or (d) [− , +]



(c)

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



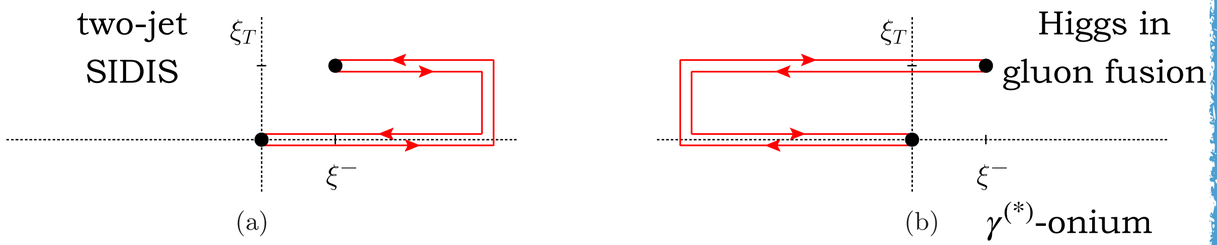
(d)

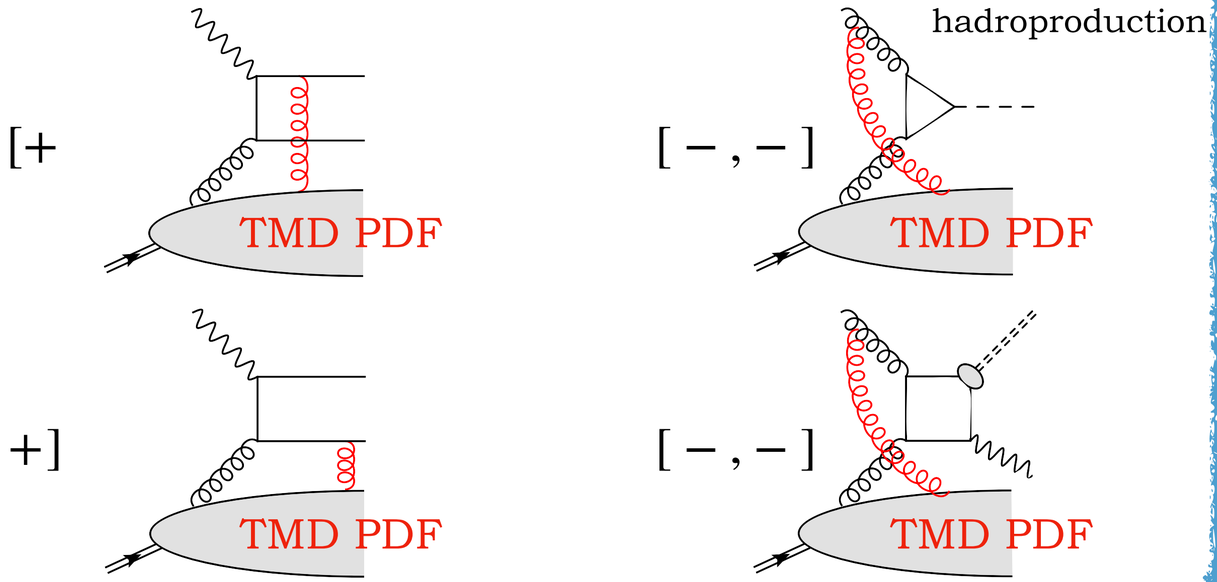
Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

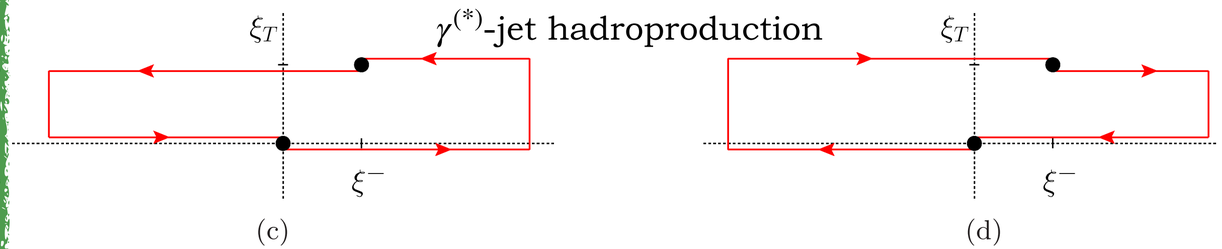
(a) [+ , +] or (b) [− , −]

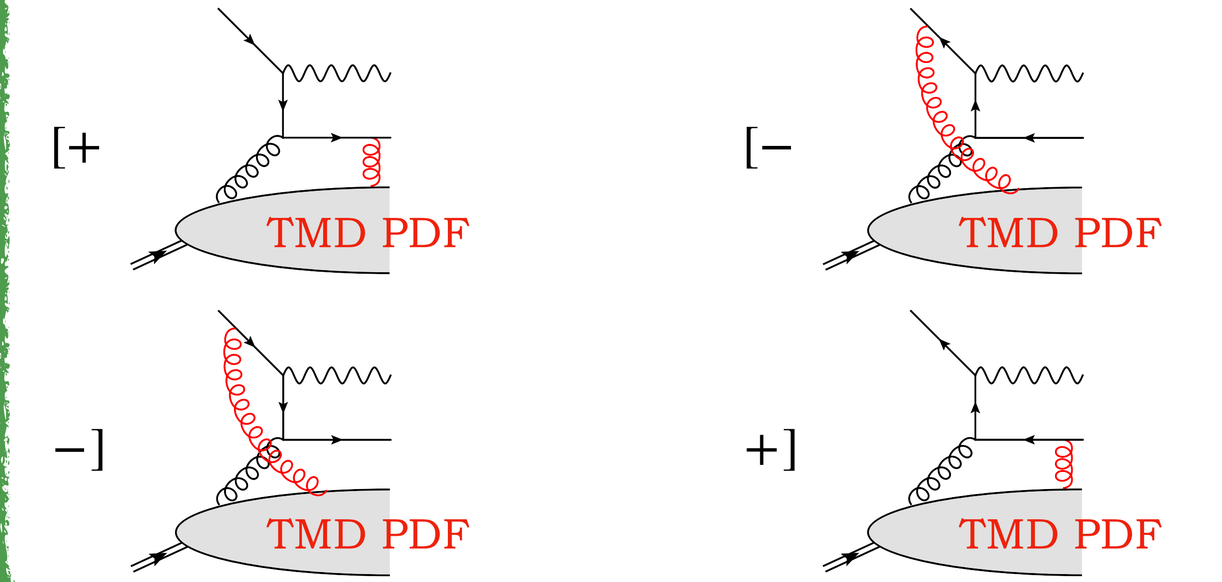




d-type (DP)

(c) [+ , −] or (d) [− , +]



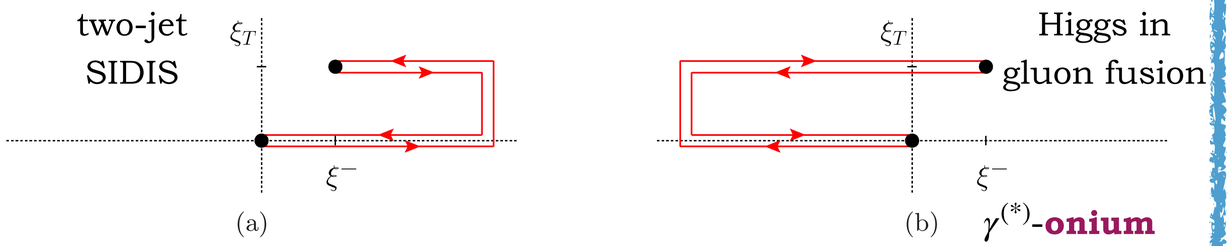


Backup

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:

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

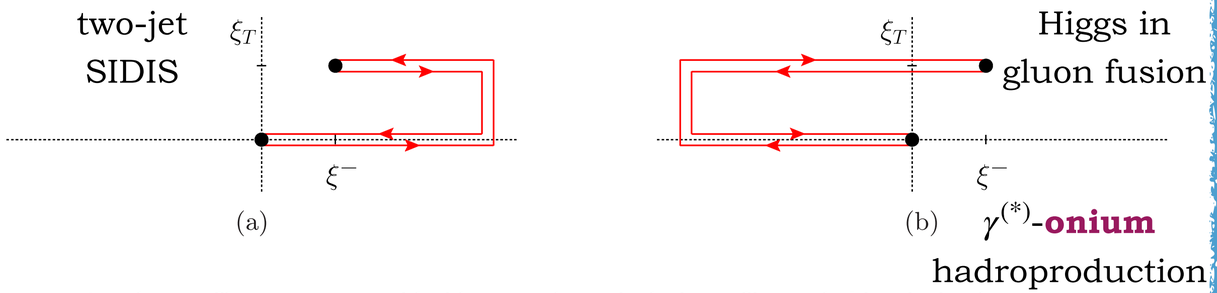
* Phenomenology: Higgs, **quarkonia** or $\gamma\gamma$ in pp, two-jet SIDIS, heavy-quark pair SIDIS

Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

(a) [+ , +] or (b) [− , −]



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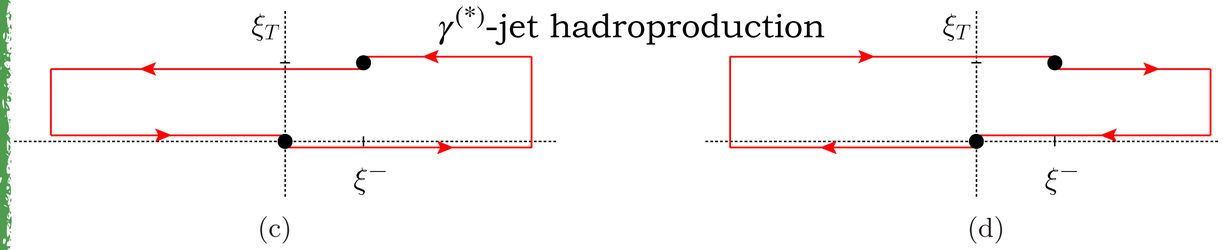
d-type (DP)

(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

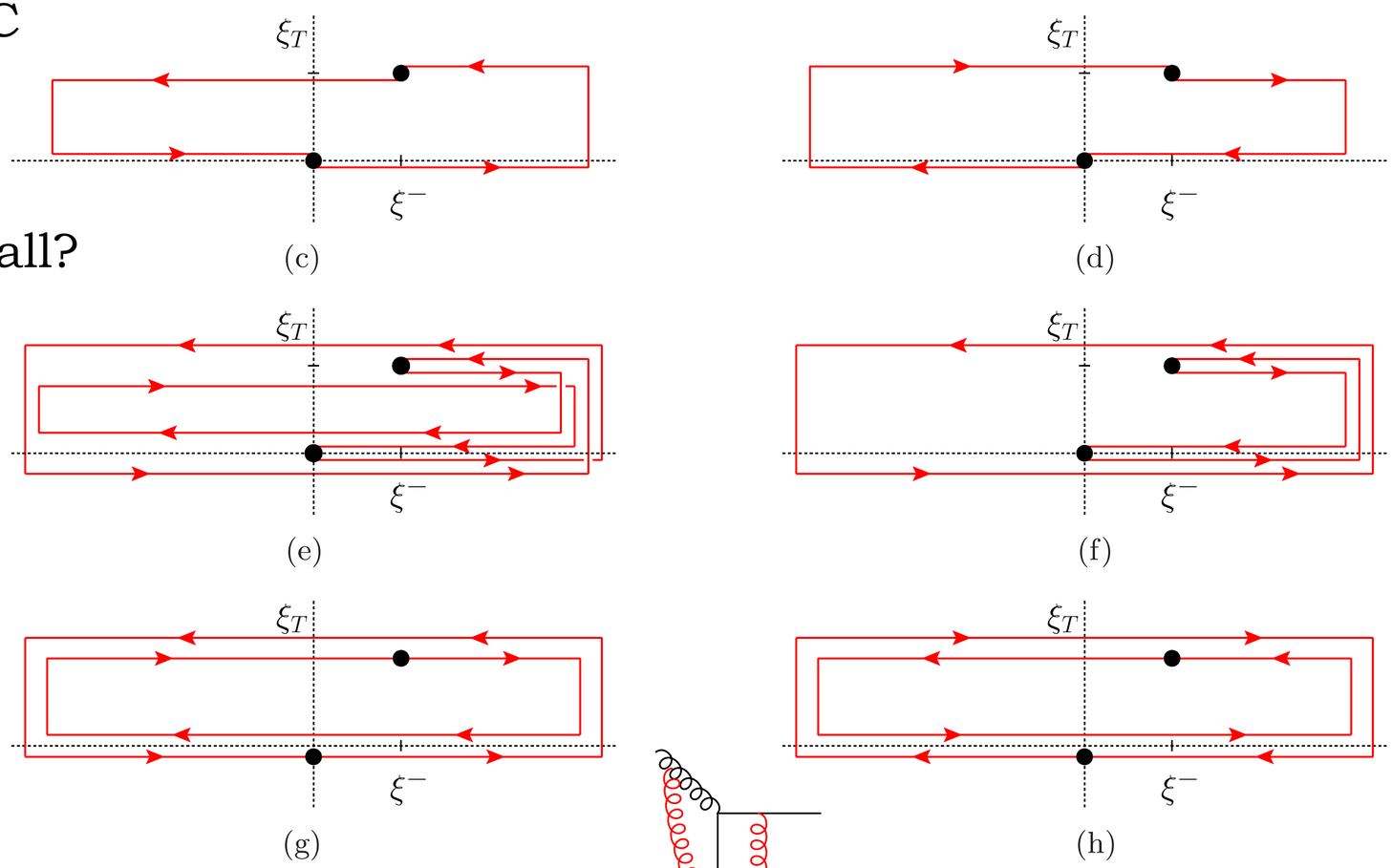
Dihadron hadroproduction and factorization breaking

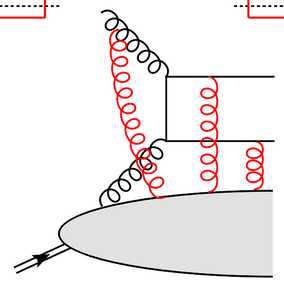
* Proof of factorization violation 🔗 [T. J. Rogers, P. J. Mulders (2010)]
* Assumed factorization in SCET and CGC
* Significance of low-x studies
* Size of factorization-breaking effects small?
* DP TMDs:

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

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

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





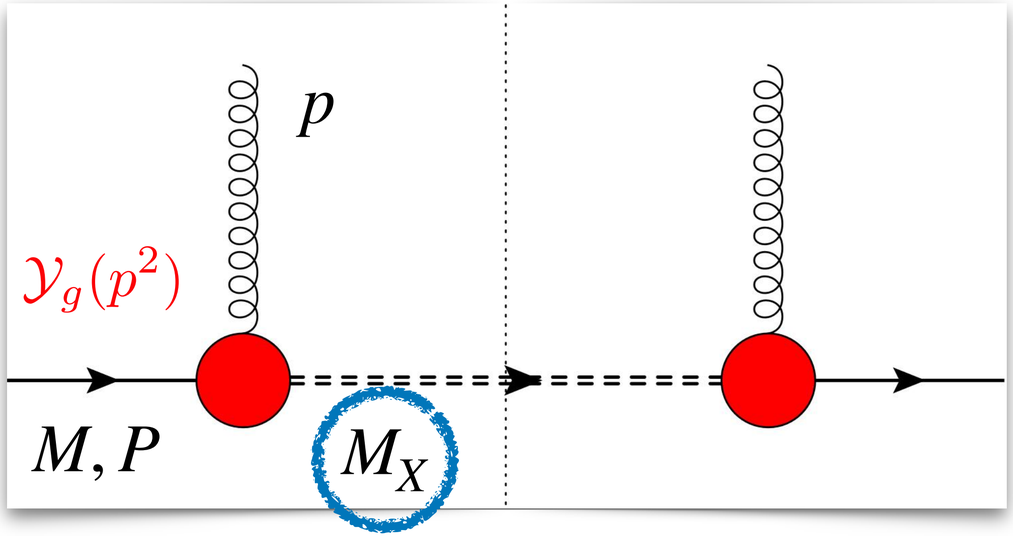
Backup

Small-x improved gluon TMDs

Assumptions of the model

Spin-1/2 spectator

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



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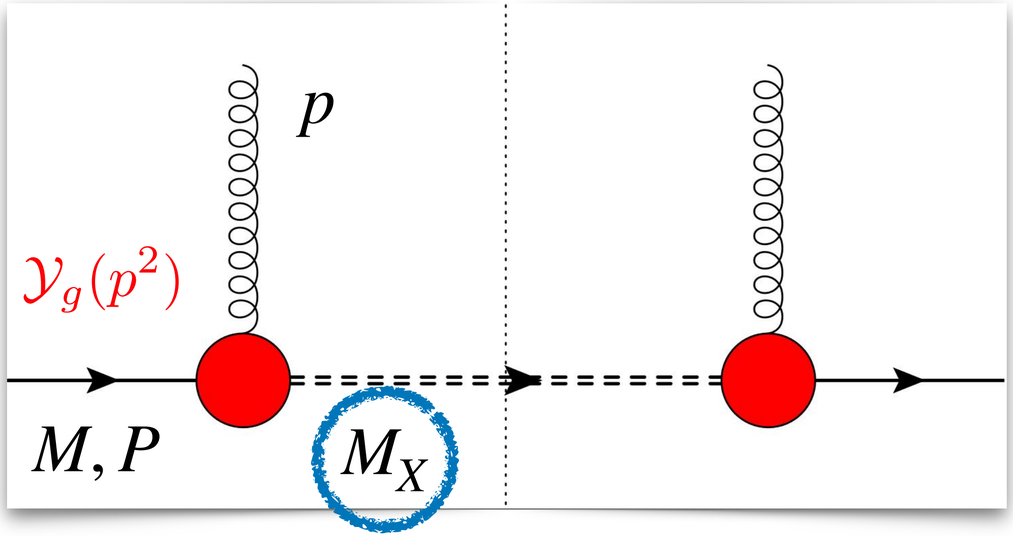


Nucleon-gluon-spectator vertex

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

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

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

Backup

Assumptions of the model

Link with collinear factorization

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

Backup

Assumptions of the model

Link with collinear factorization

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

Dipolar form factor(s)

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

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

Backup

Assumptions of the model

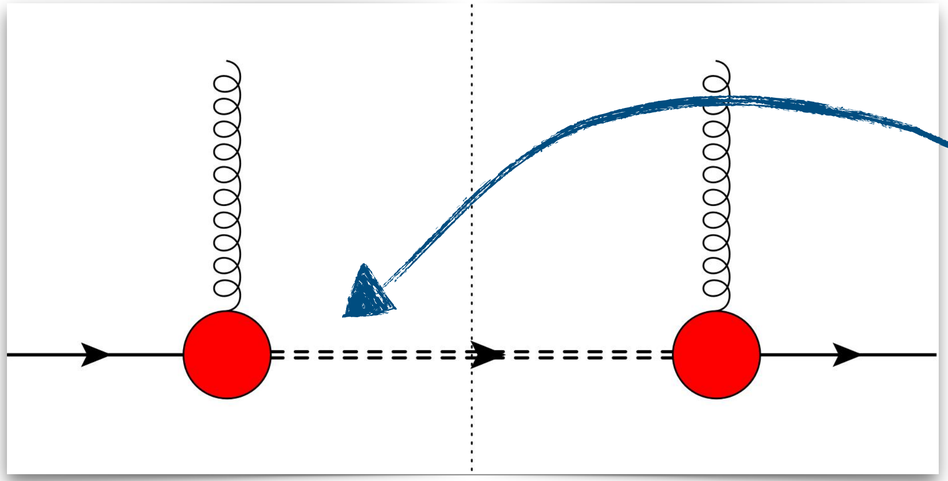
Spectator-system spectral-mass function

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

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

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

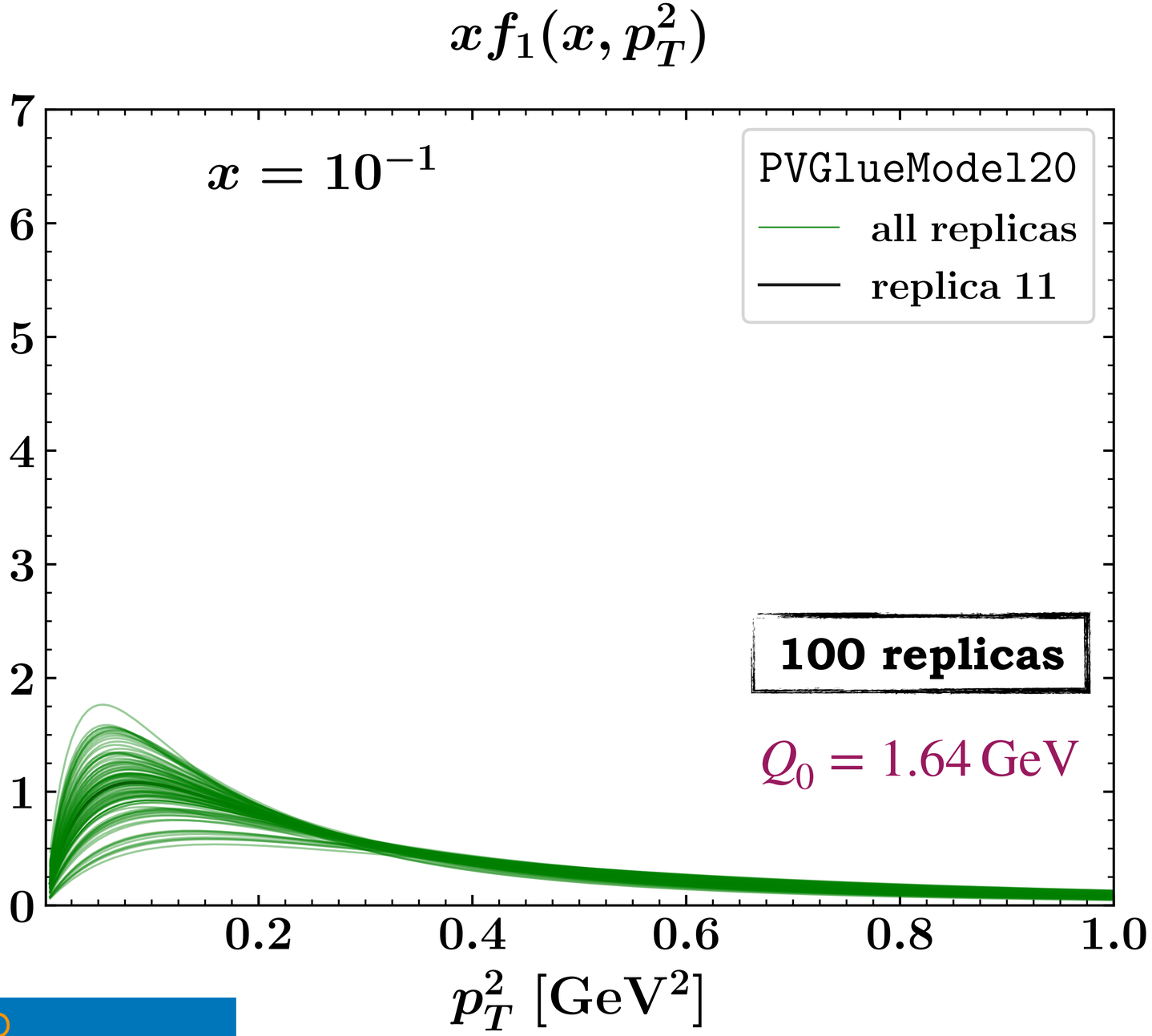
moderate-x trend

pure tri-quark contribution at low M_X

Backup

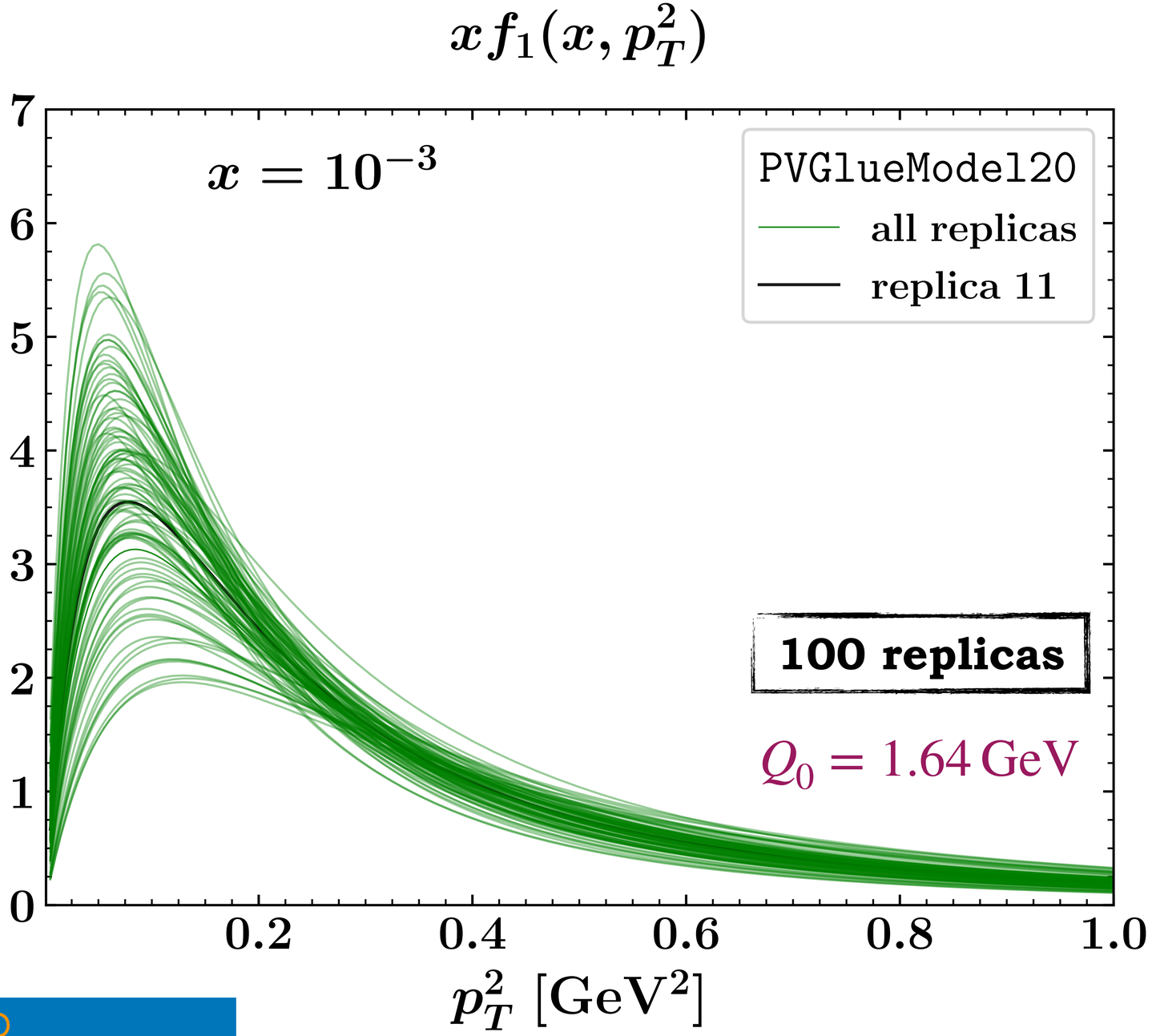
Unpolarized gluon TMD

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



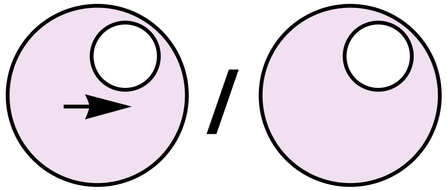
Unpolarized gluon TMD

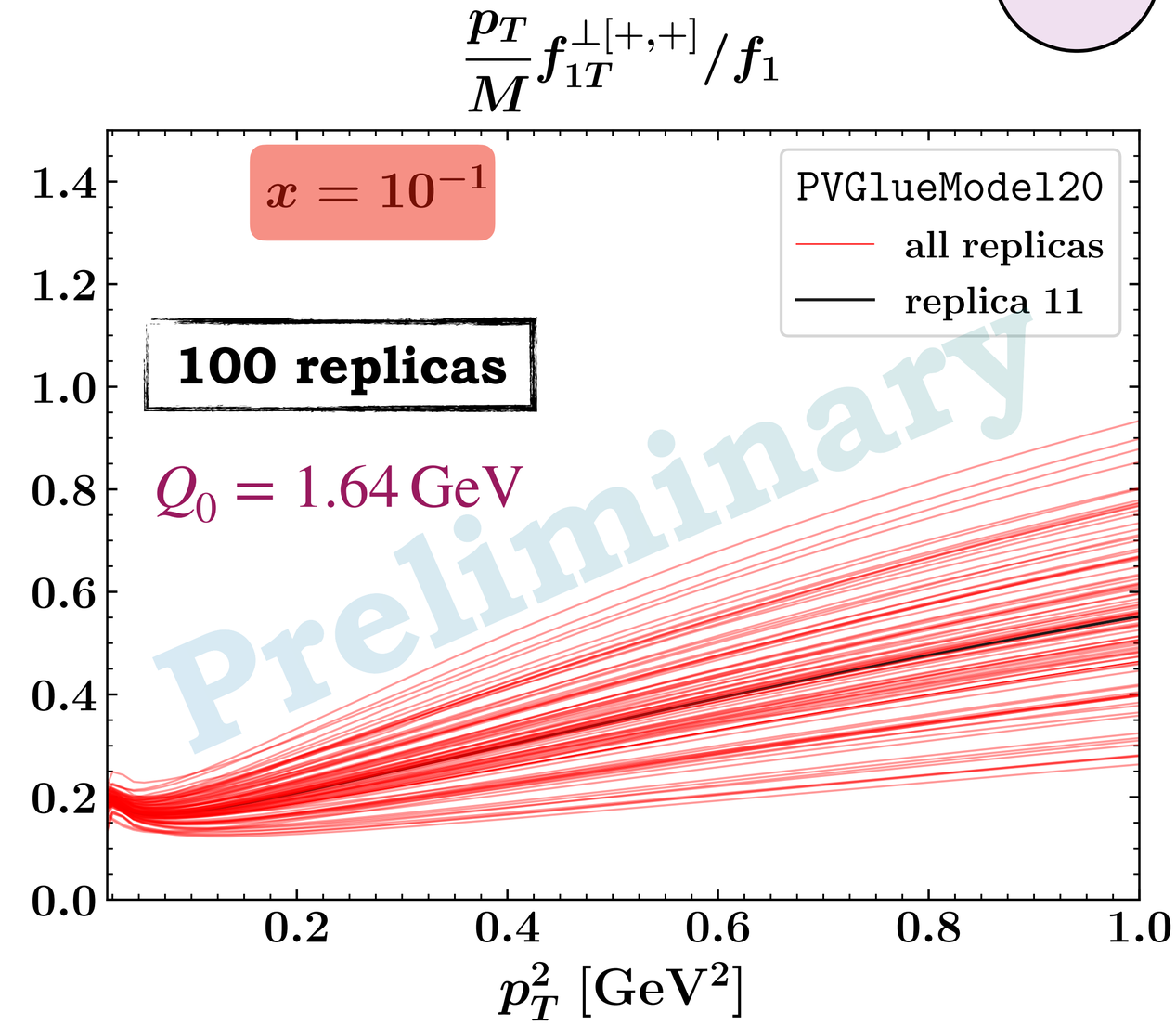
[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

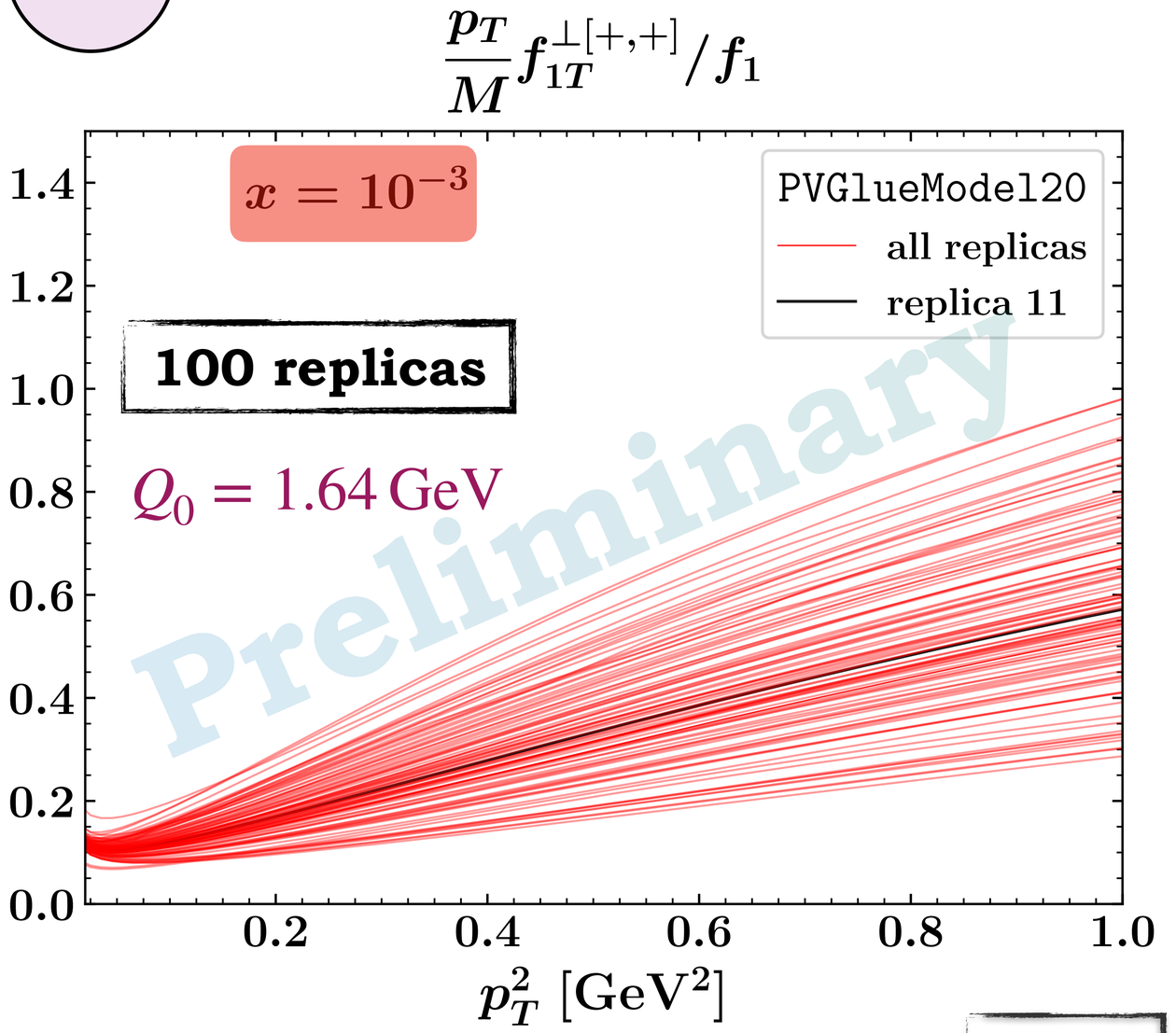


f-type Sivers/unpol.

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







Backup

Gluon TMD correlator and T-odd gluon densities

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

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

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

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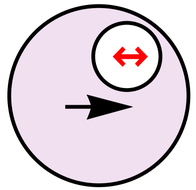
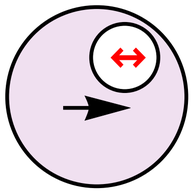
pseudo worm-gear



linearity TMD

pretzelosity



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

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

pseudo worm-gear

linearity TMD

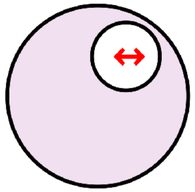
pretzelosity

Sivers

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

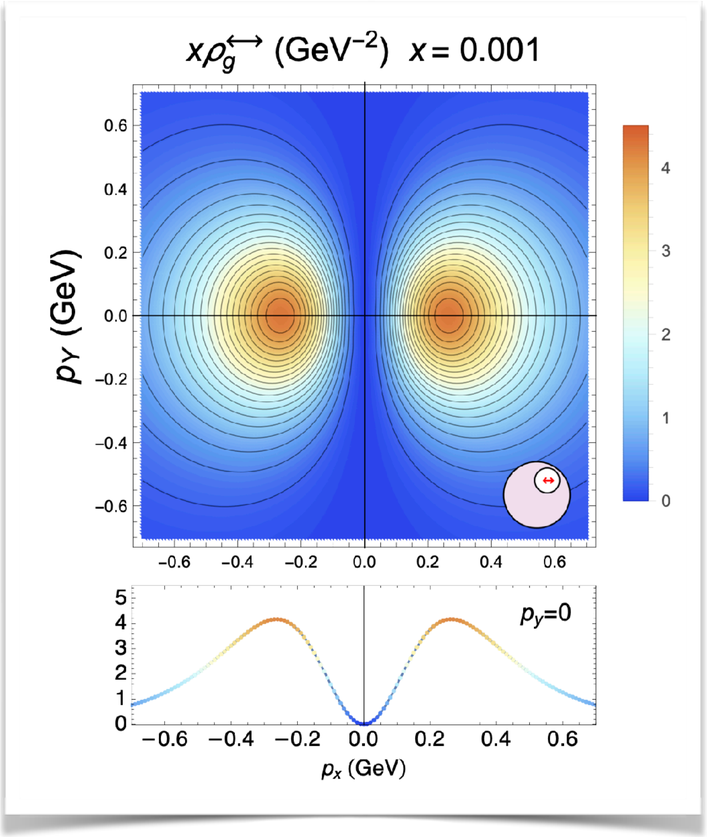
Backup

Boer-Mulders effect in unpolarized pp collisions



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

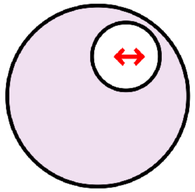
unpol. Boer-Mulders



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

Backup

Boer-Mulders effect in unpolarized pp collisions



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

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

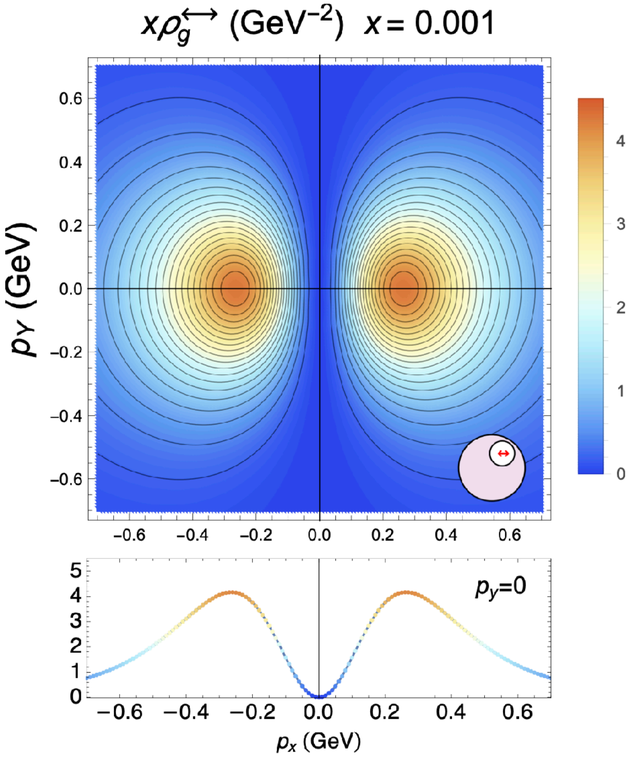
$$\sim \mathcal{C}[\, f_1^{g/A} \, f_1^{g/B} \,] \pm \mathcal{C}[\, h_1^{\perp g/A} \, h_1^{\perp g/B} \,]$$

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

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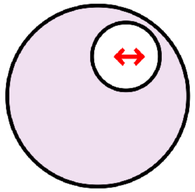

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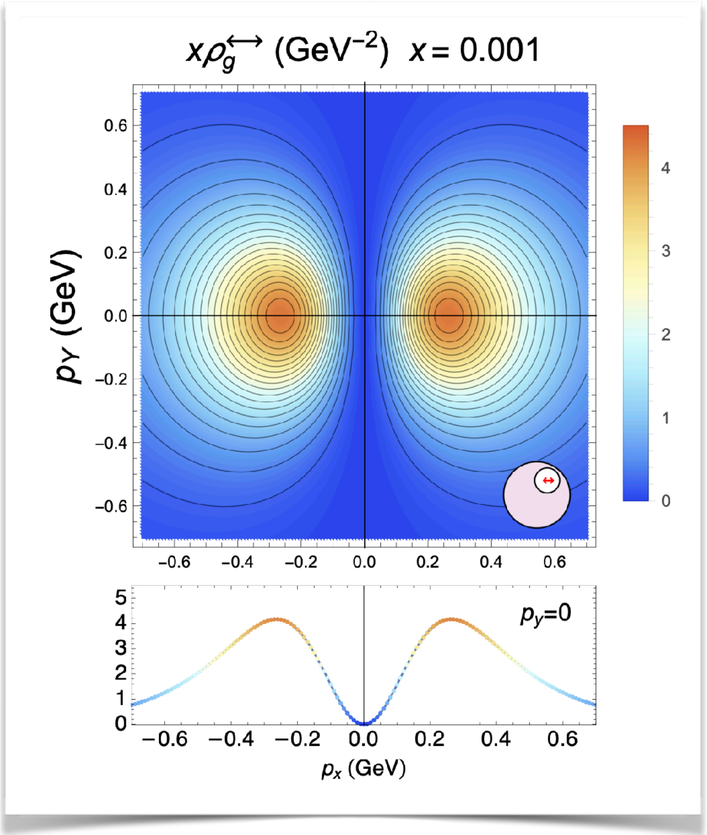

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Model prediction at low-x

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

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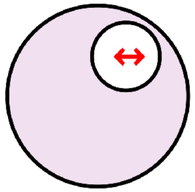

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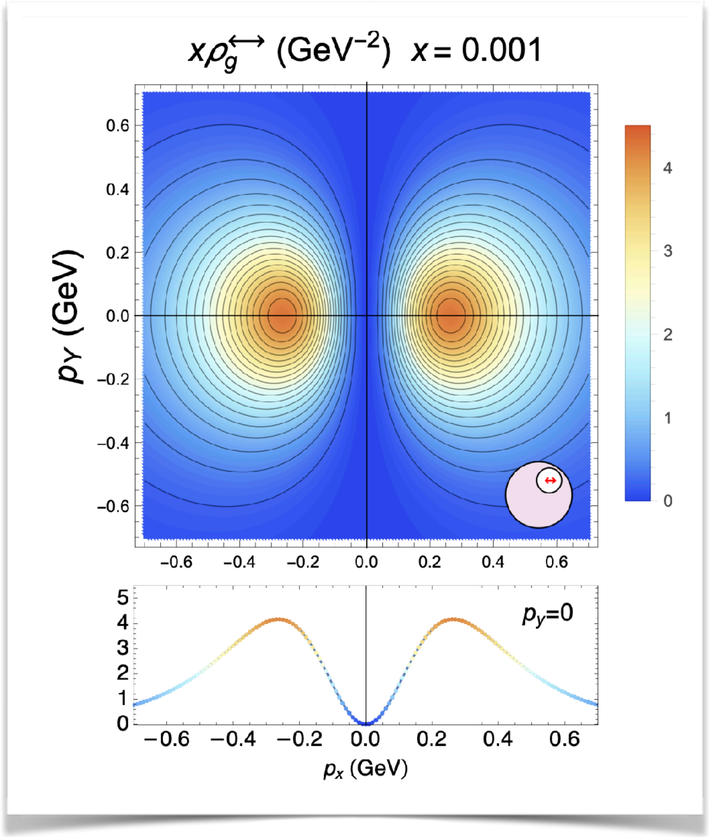

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BFKL regime (linear low-x evolution)

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

Backup

Anatomy of gluon TMDs

matching coefficients

collinear PDF

nonperturbative Sudakov

nonperturbative TMD function

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

perturbative Sudakov

perturbative expansion in $\alpha_s(\mu)$

resummation of

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

define logarithmic ordering

slide adapted from C. Bissolotti

Backup

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

Backup

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

Suppression of genuine NP effects!

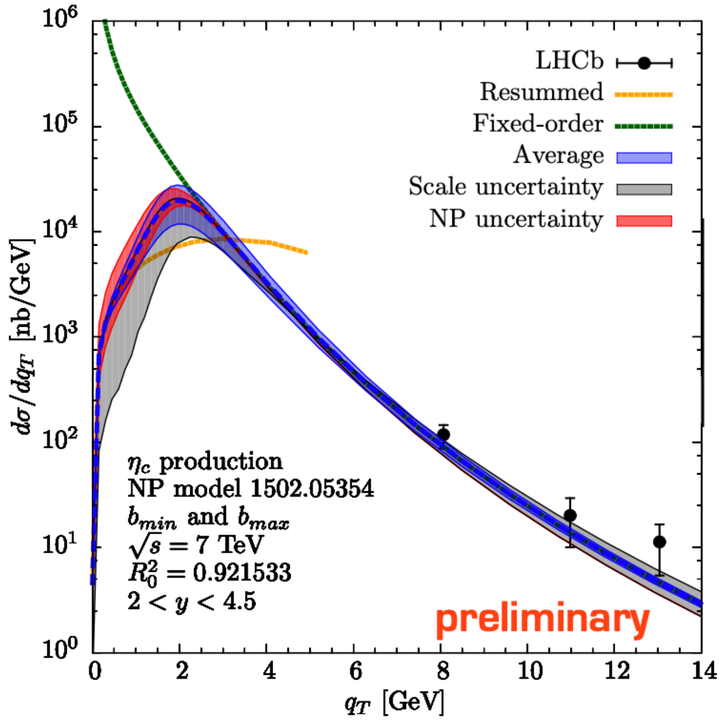
Backup

Gluon TMD phenomenology

$\eta_{c,b}$ 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)

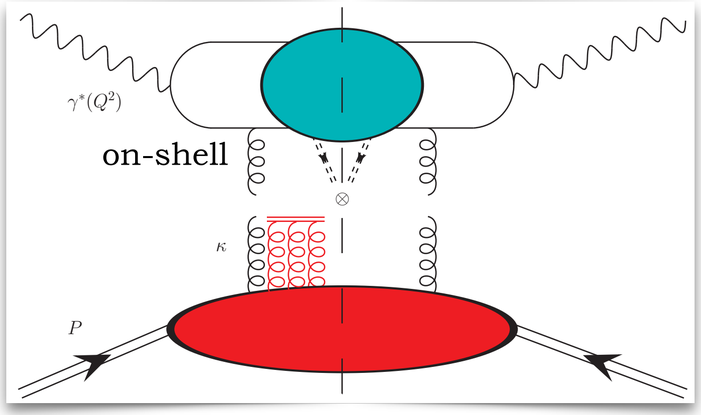
Backup

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

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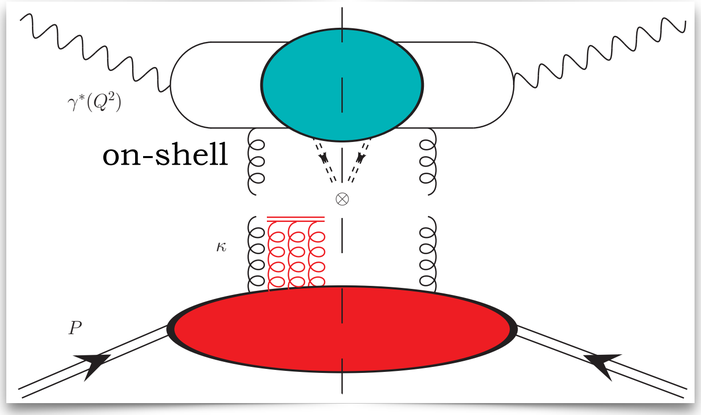
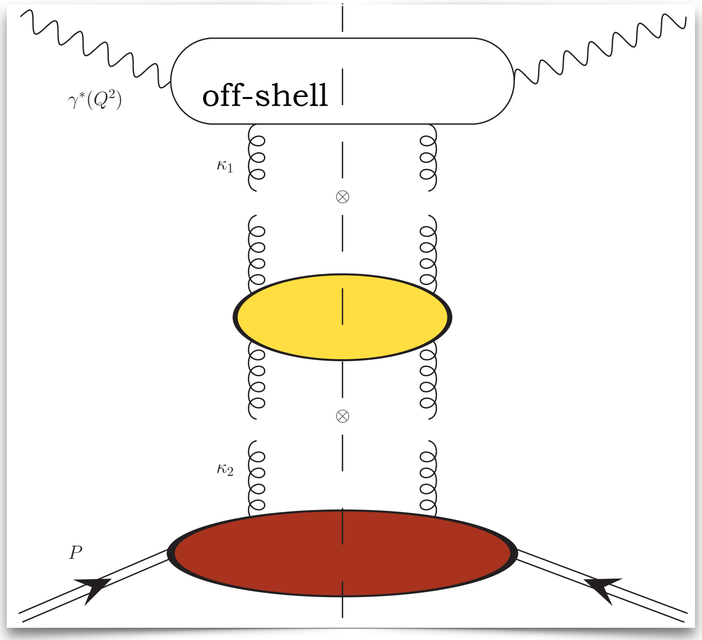


TMD PDF

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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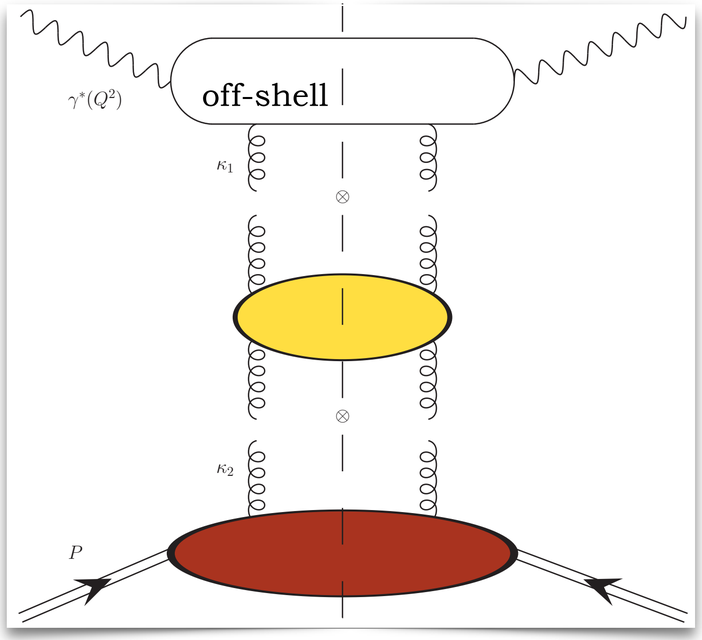

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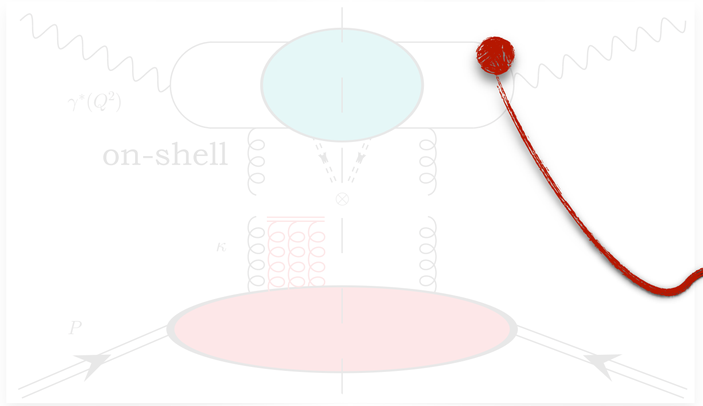
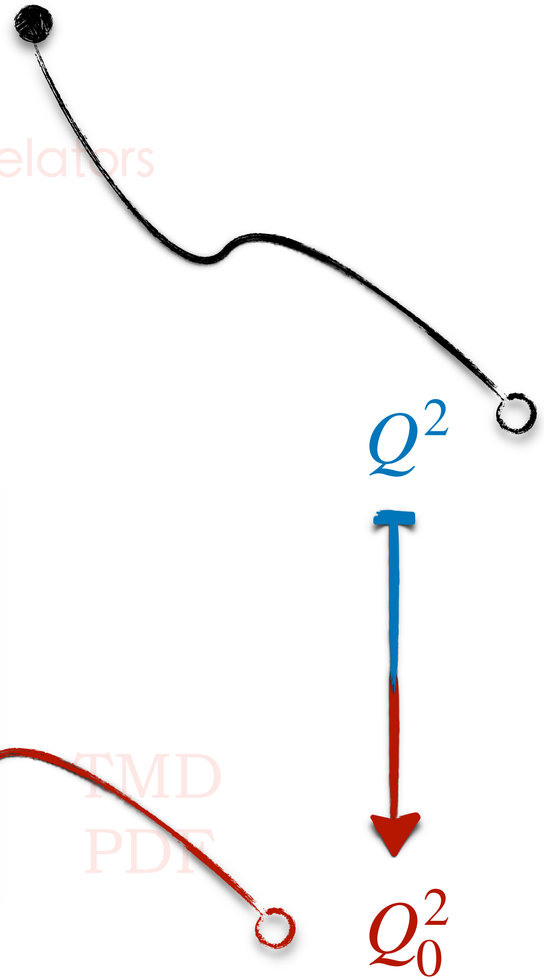
IR diffusion pattern

(Bartels' cigar)

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





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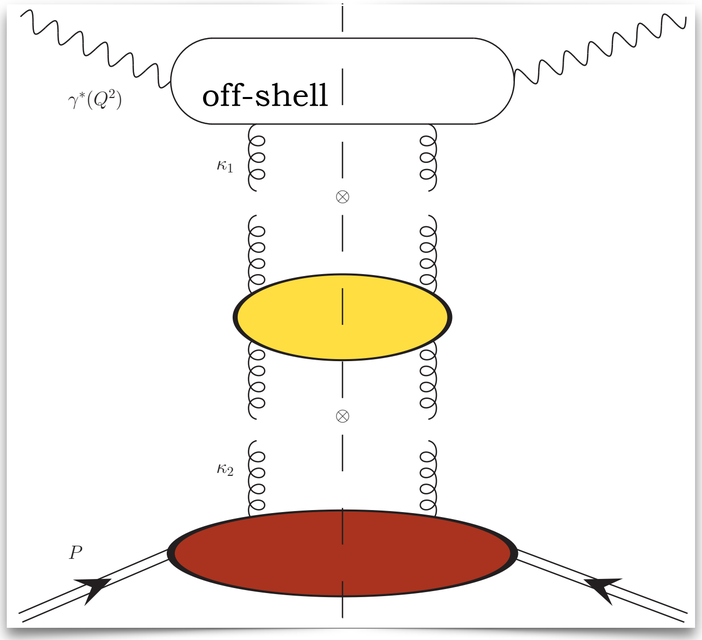

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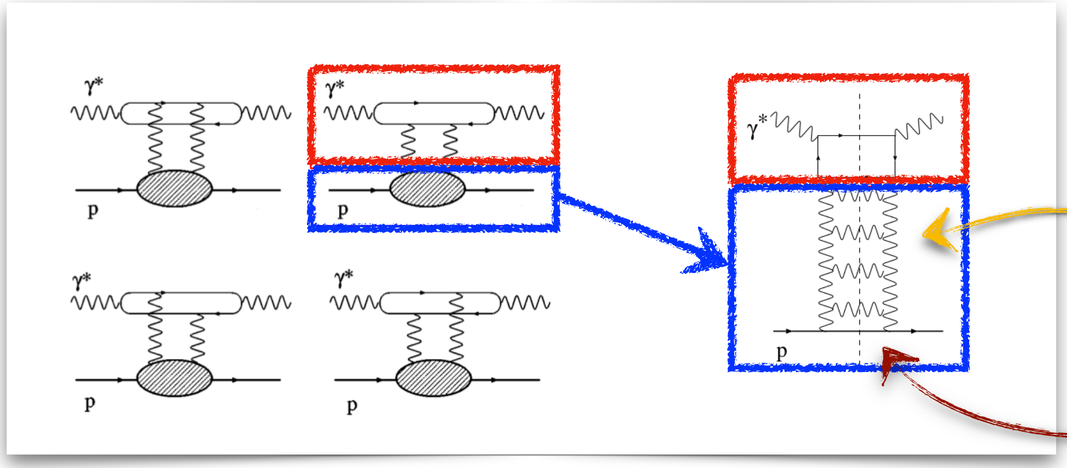
Backup

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!

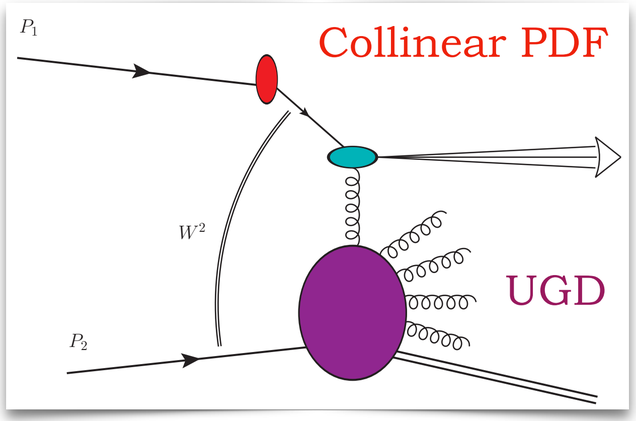
Backup

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:
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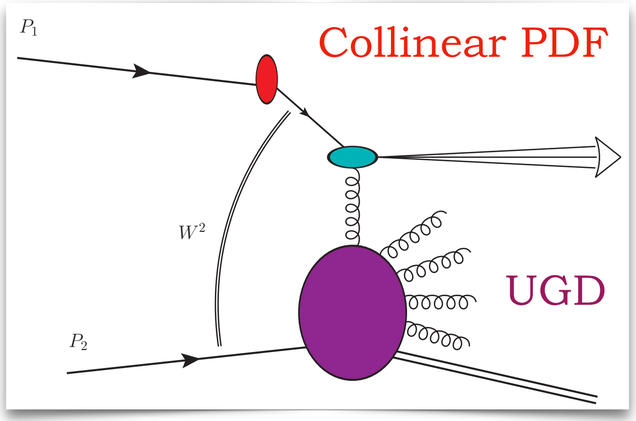

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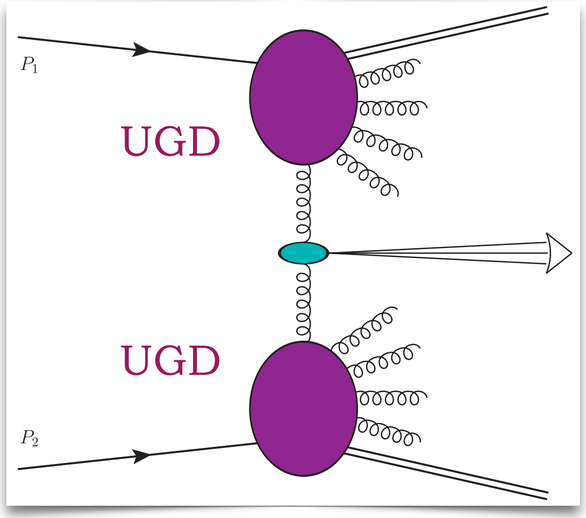
* *Gluon induced* ↔ small-x gluons
* Pure **high-energy** factorization



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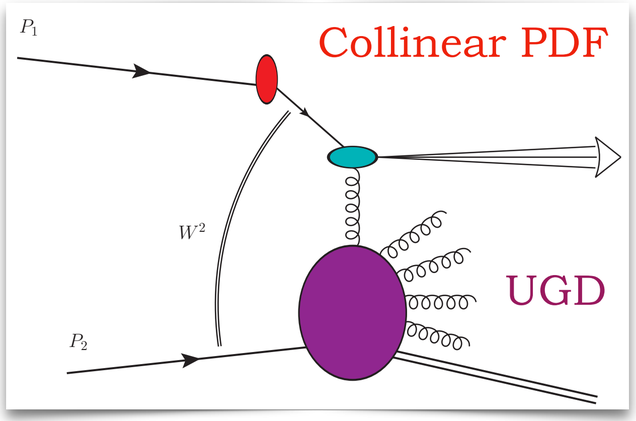

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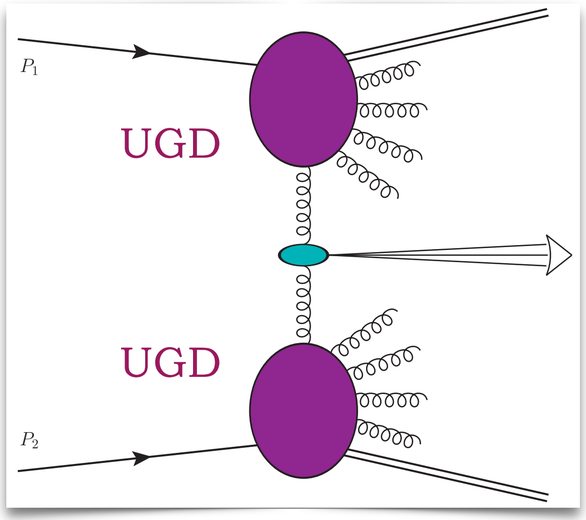

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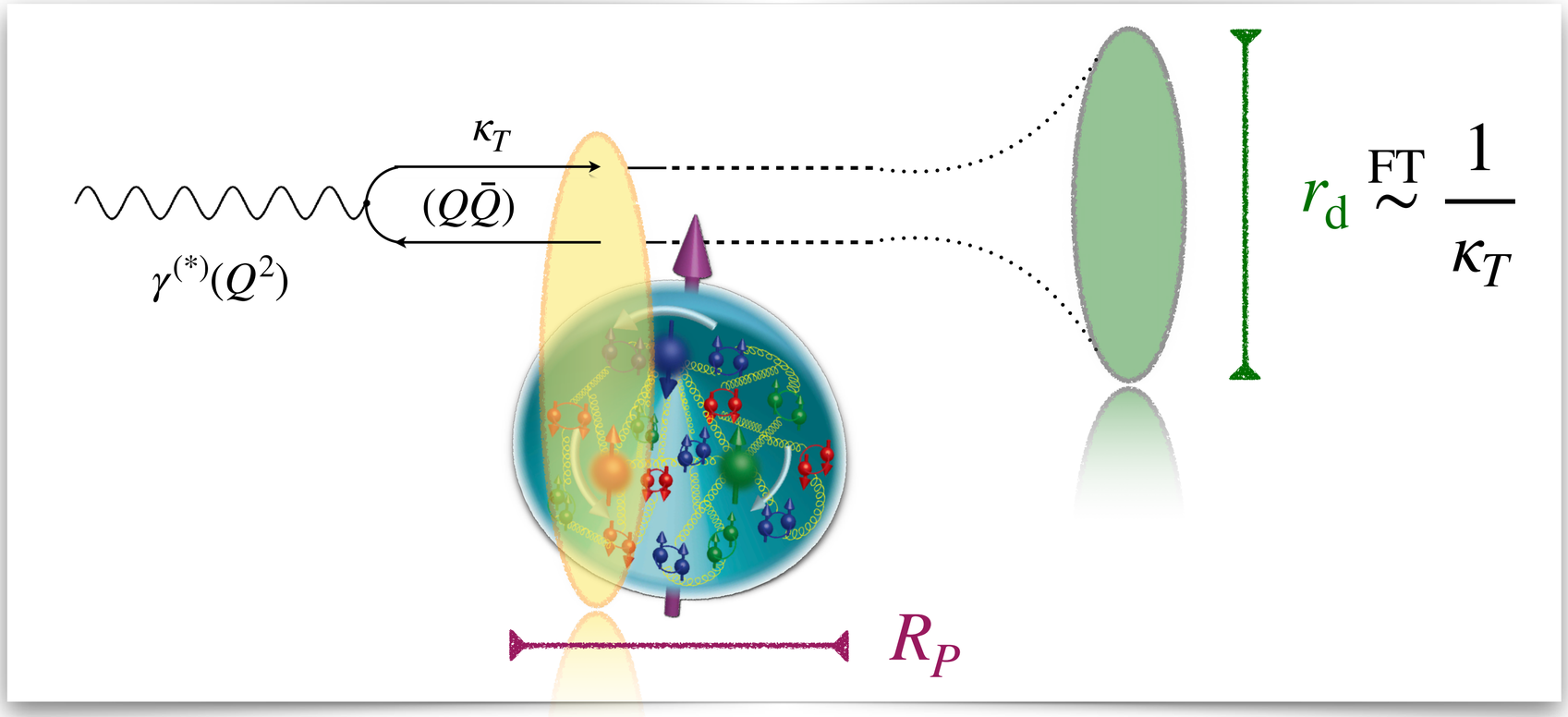
Table complemented by *exclusive* counterparts and *lepto-hadronic* channels

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

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

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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