Model calculations of gluon TMDs
Applications to quarkonium @EIC

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

FBK FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

TIFPA Trento Institute for Fundamental Physics and Applications

HAS QCD HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

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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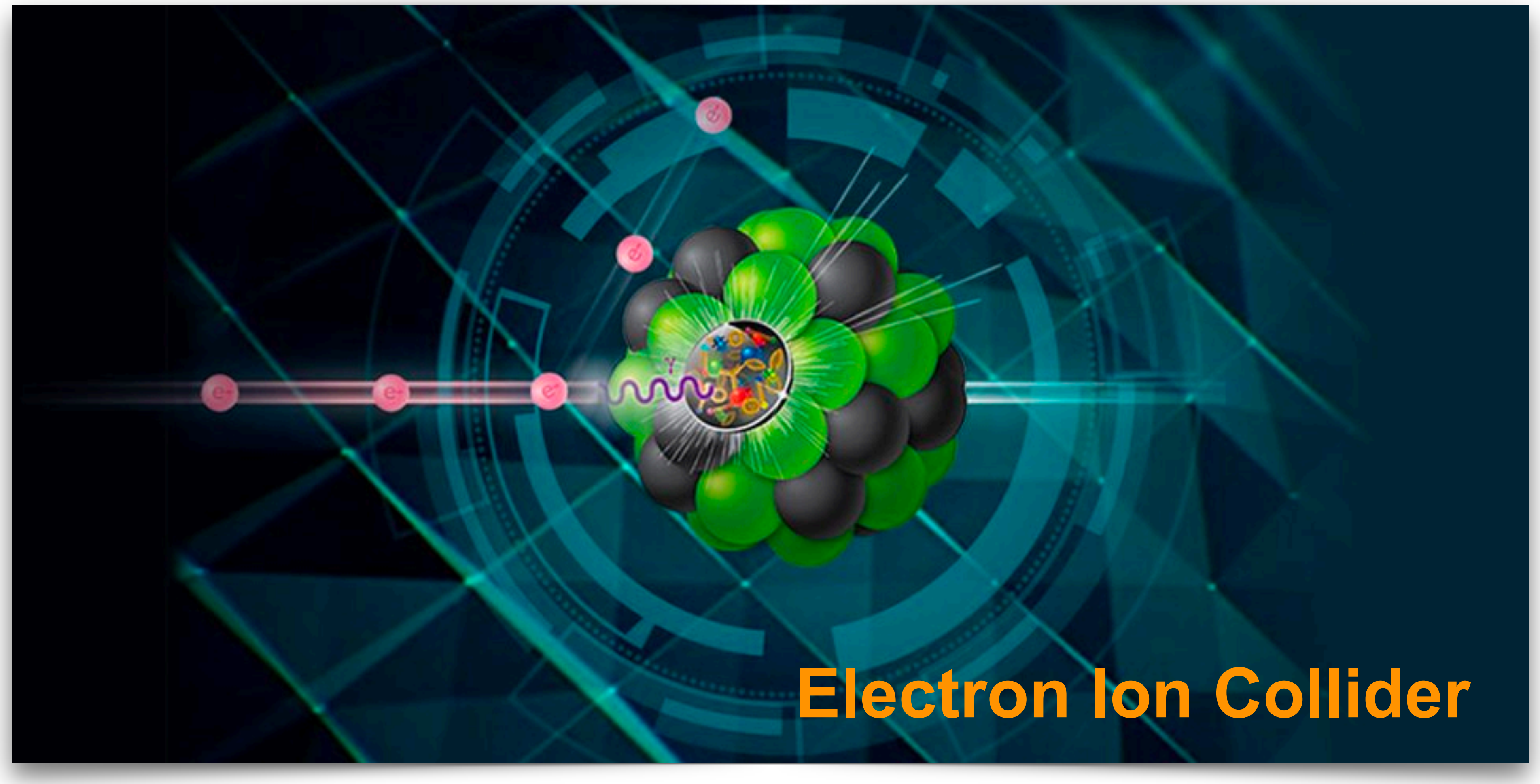

3D proton imaging

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

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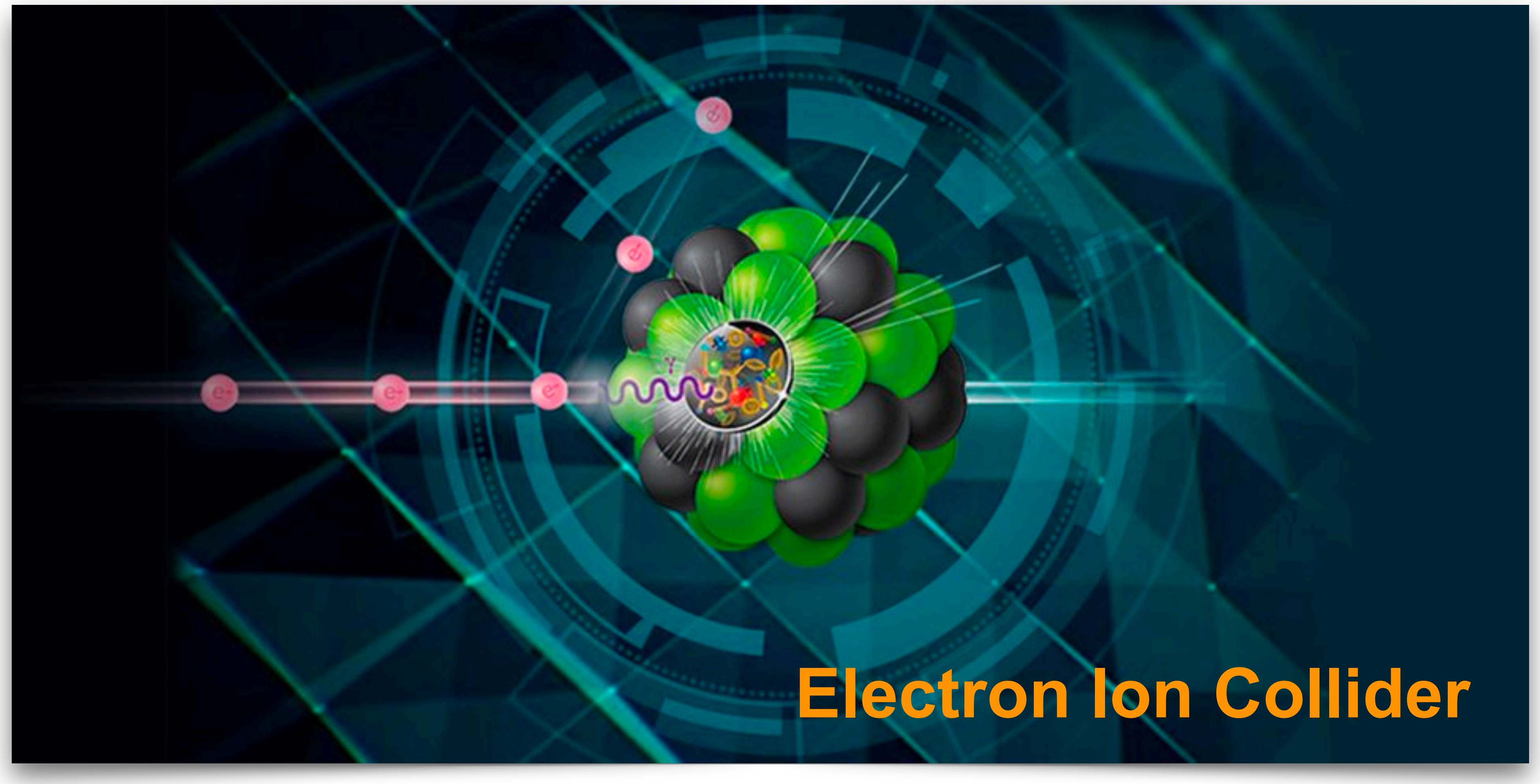

3D proton imaging

- Gluon TMD PDFs $\Rightarrow$ 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

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

unpolarized TMD

Boer-Mulders

gluon pol.

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T-even

T-odd

helicity TMD

worm-gear

Gluon TMD PDFs at leading twist

unpolarized TMD

pseudo worm-gear

Boer-Mulders

gluon pol.

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T-even

T-odd

Sivers

pretzelosity

helicity TMD

linearity TMD

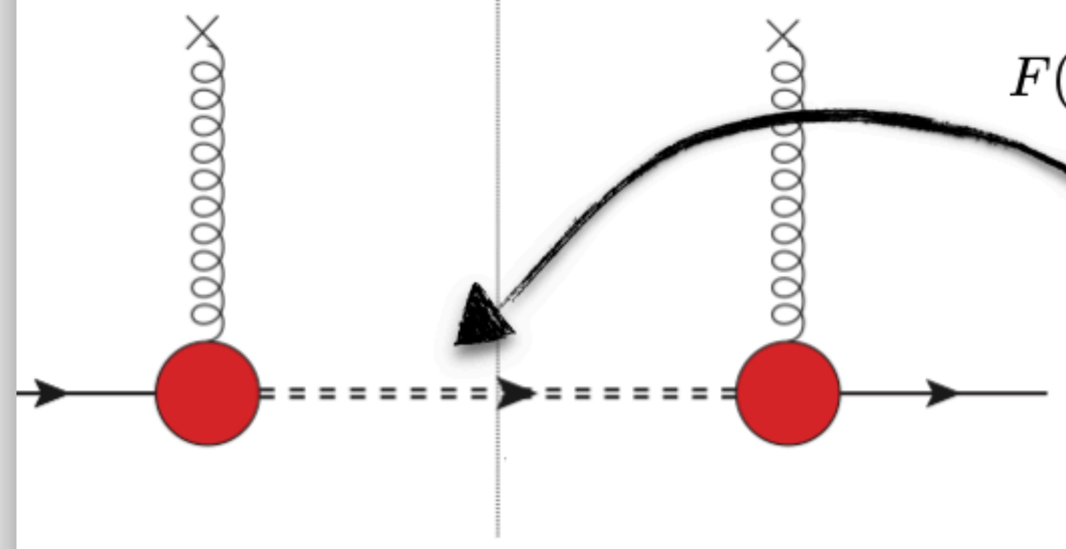
worm-gear

2. Spectator-model gluon TMDs

Spectator-model gluon TMDs

Our model at a glance

Spectator-system spectral-mass function



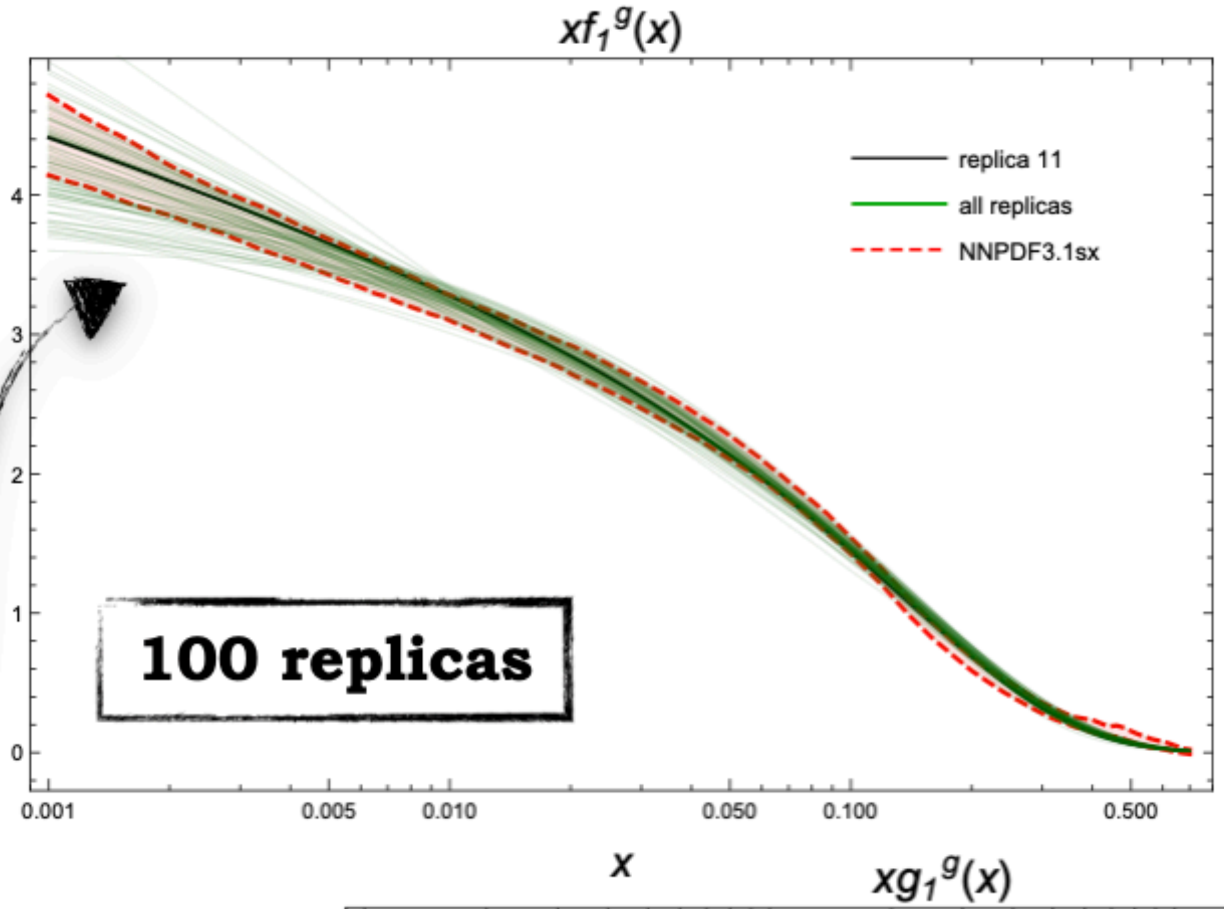
$$F(x, \boldsymbol{p}_T^2) = \int_M^\infty \mathrm{d}M_X \, \rho_X(M_X) \, \hat{F}(x, \boldsymbol{p}_T^2; M_X)$$

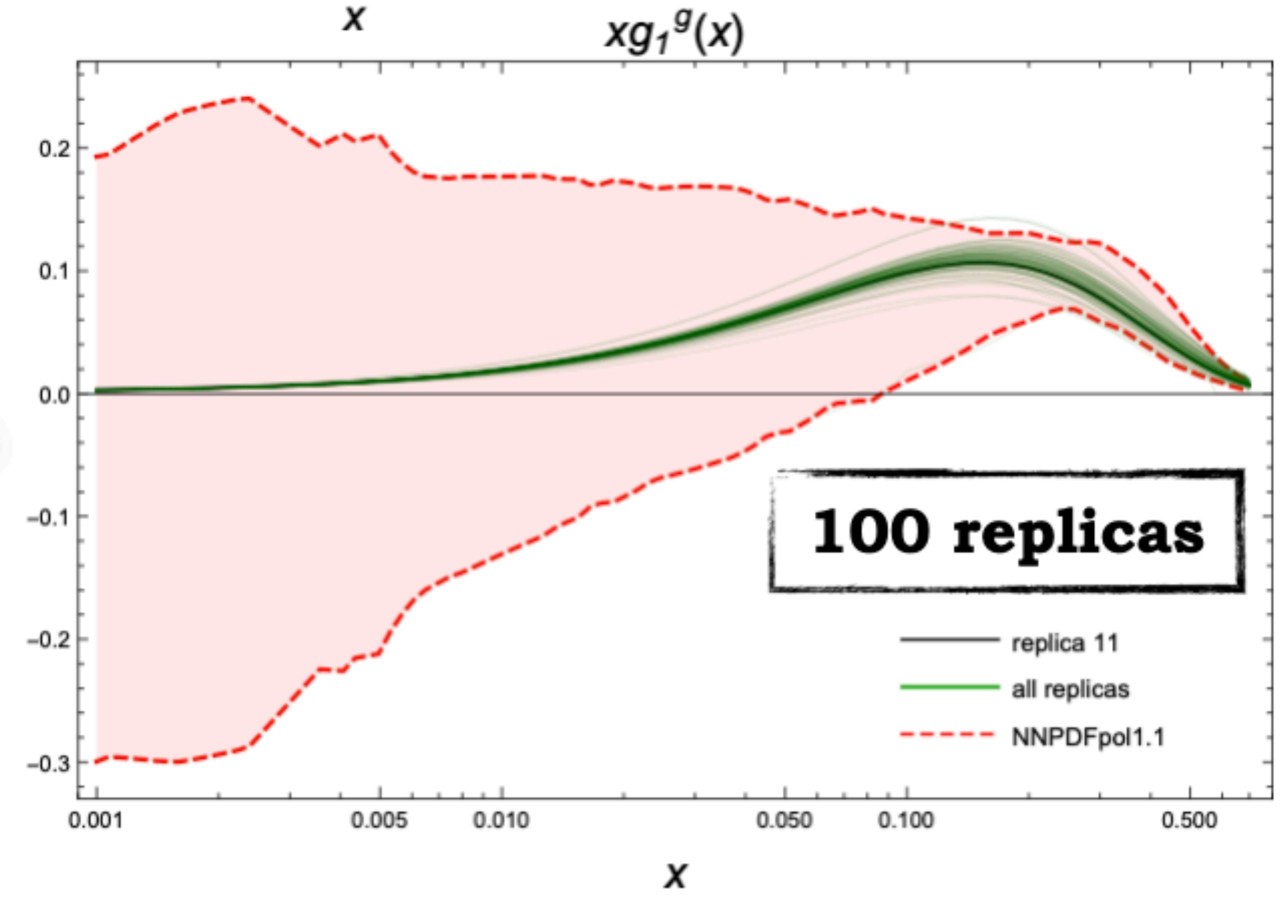
Instead of a single on-shell spectator, a continuum of spectators

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

Link with collinear factorization

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





- ☑ **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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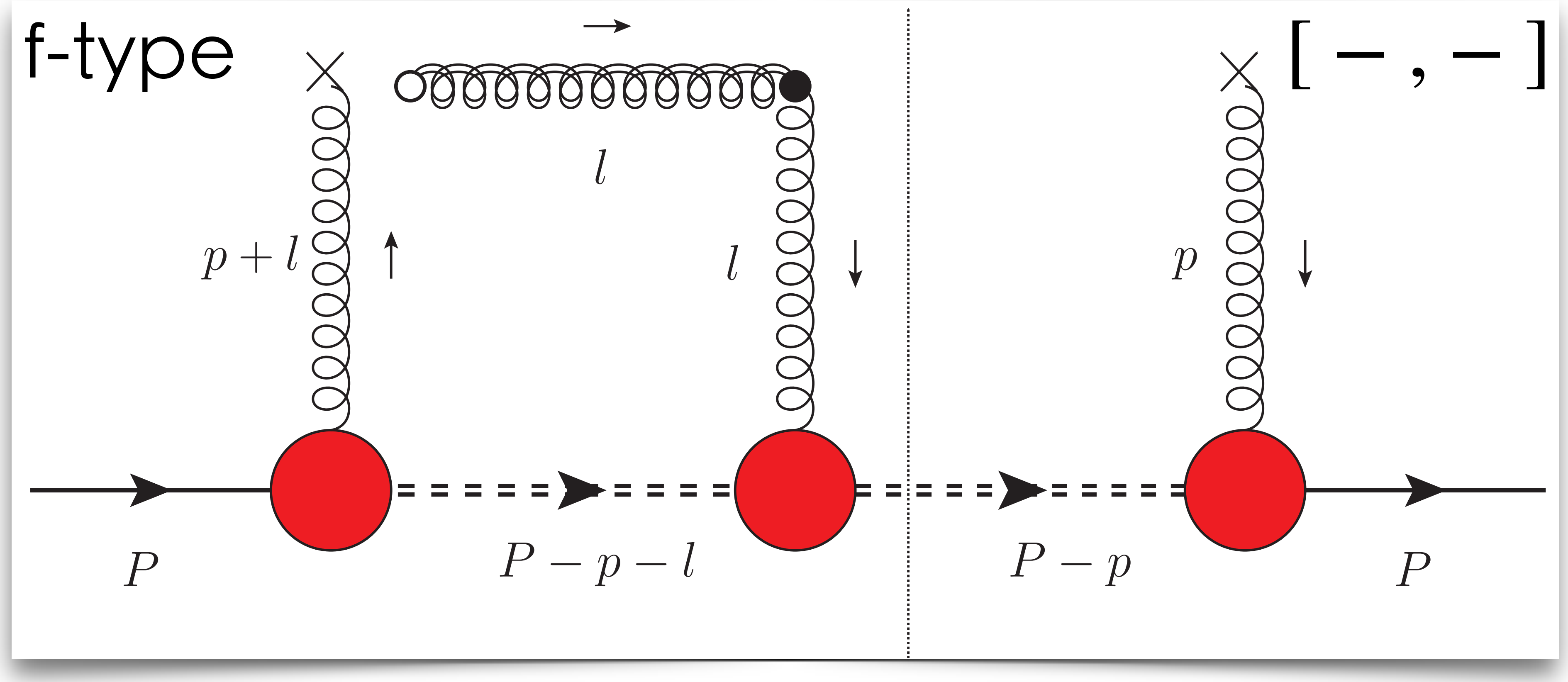
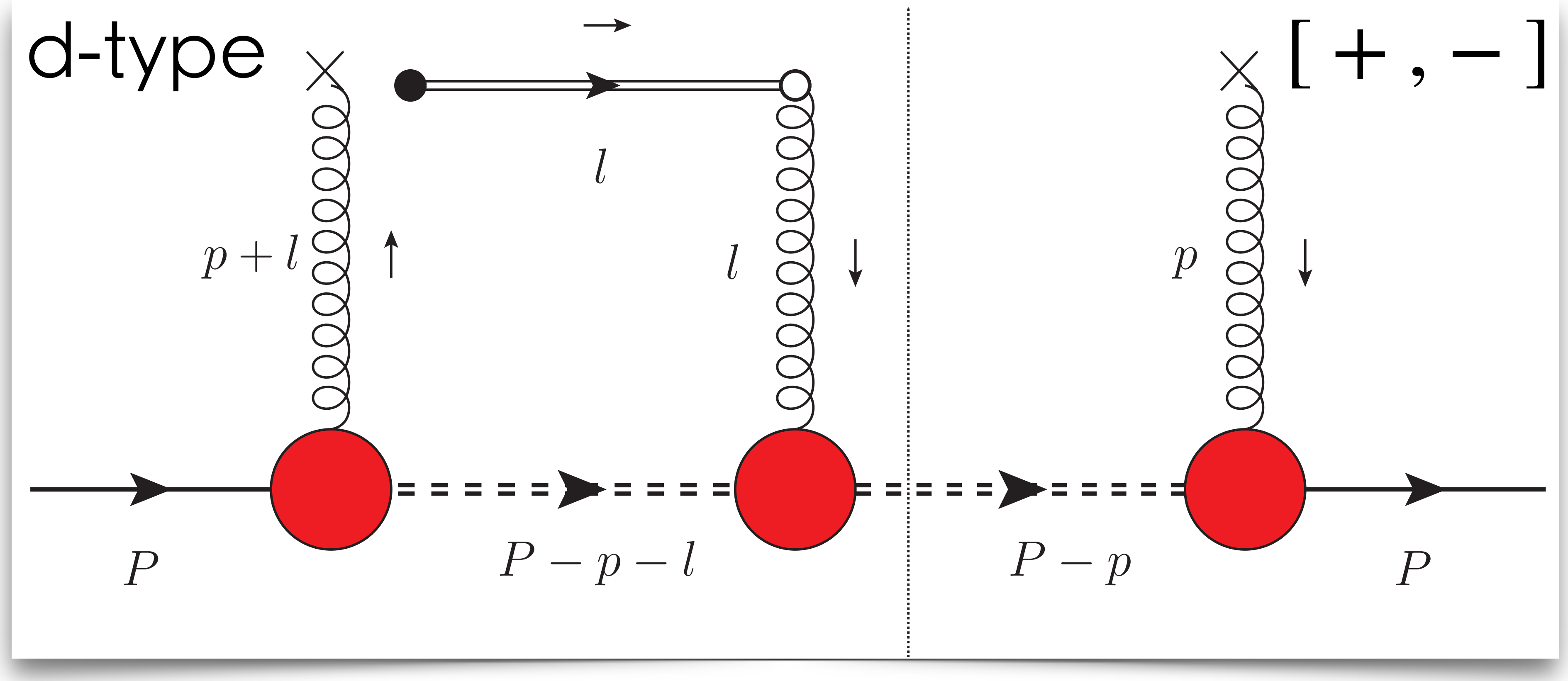
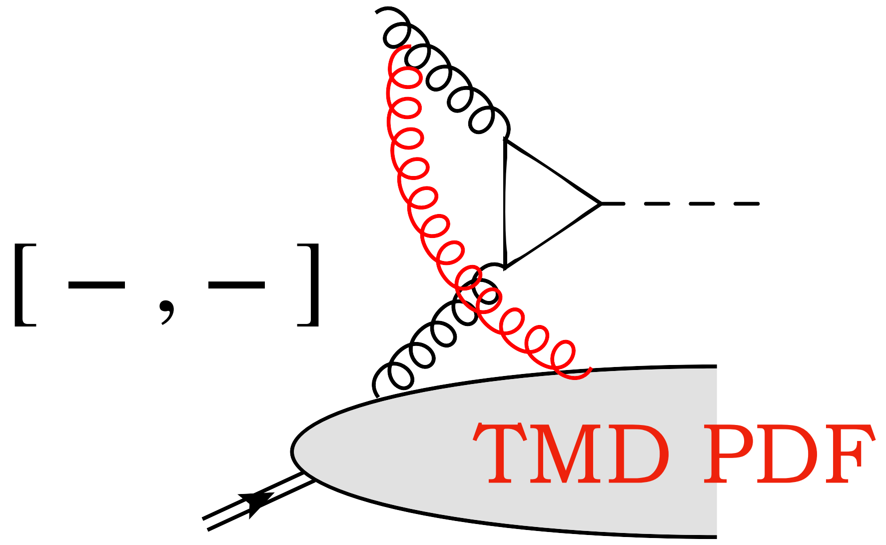
$gg \to H$

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







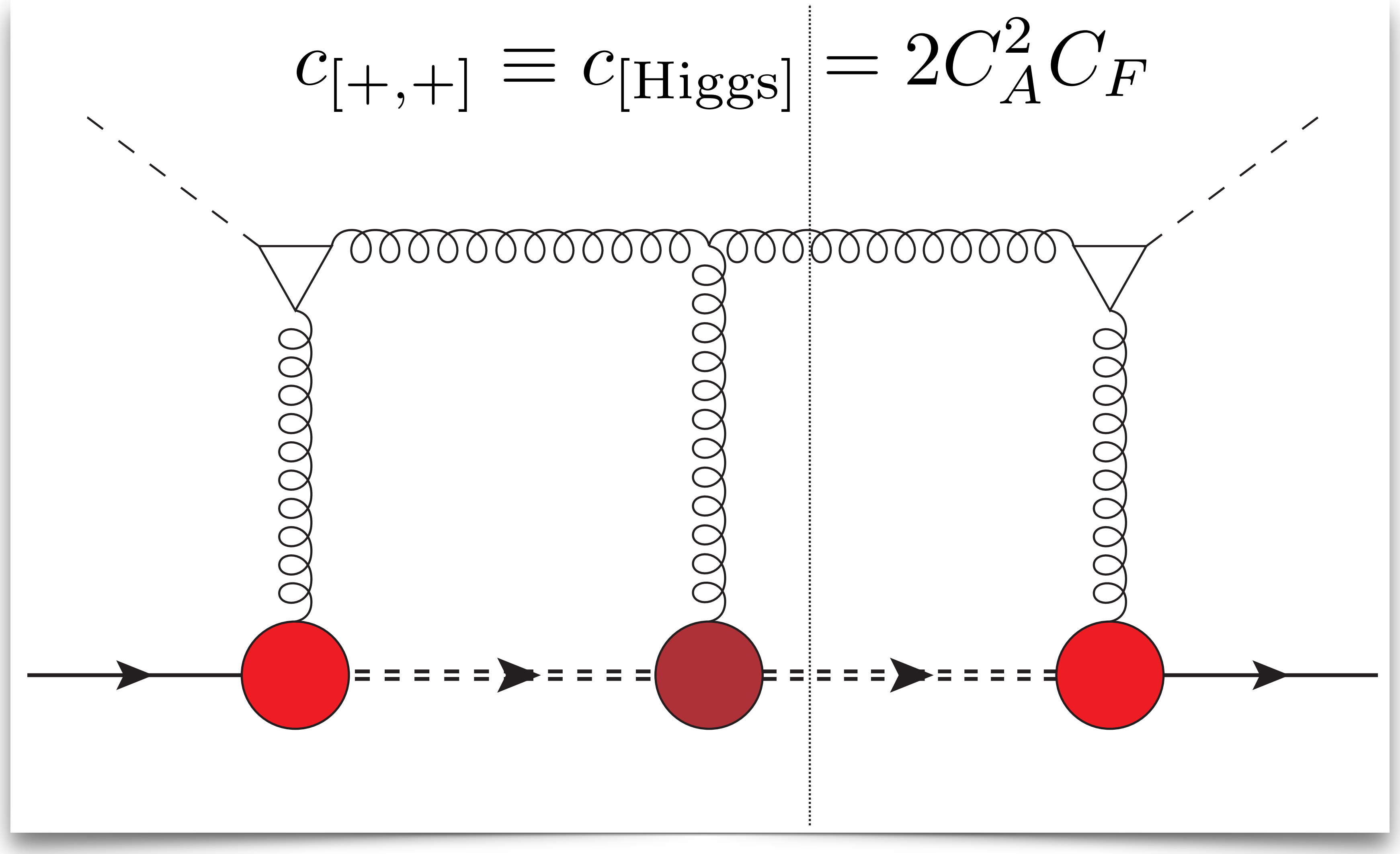
f-type (WW) structure

d-type (dipole) structure

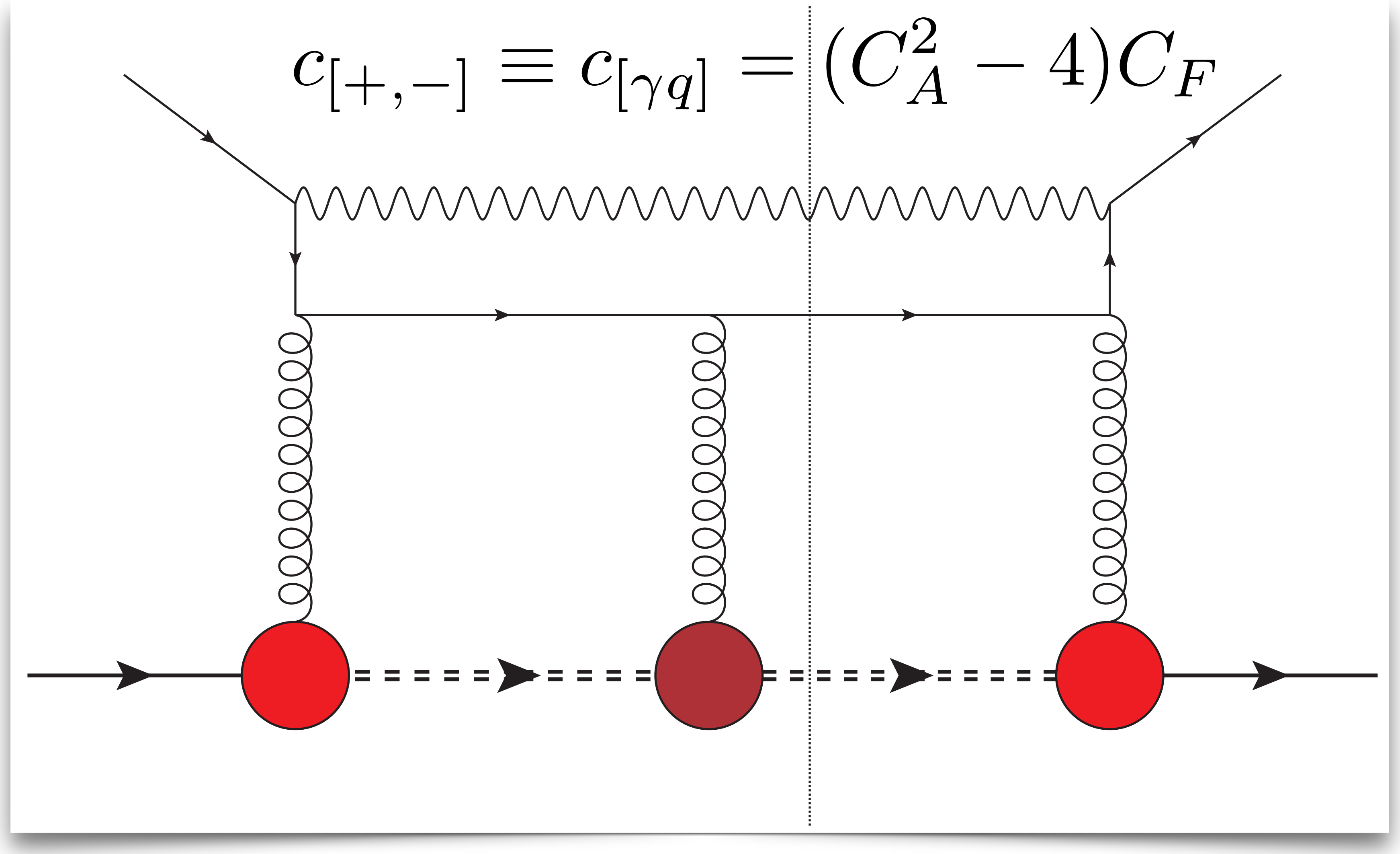
(Sivers & linearity) 🔗 🔗 [A. Bacchetta, F.G.C., M. Radici, EPS-HEP, PANIC (2021)]

T-odd gluon TMDs in a spectator model

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



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



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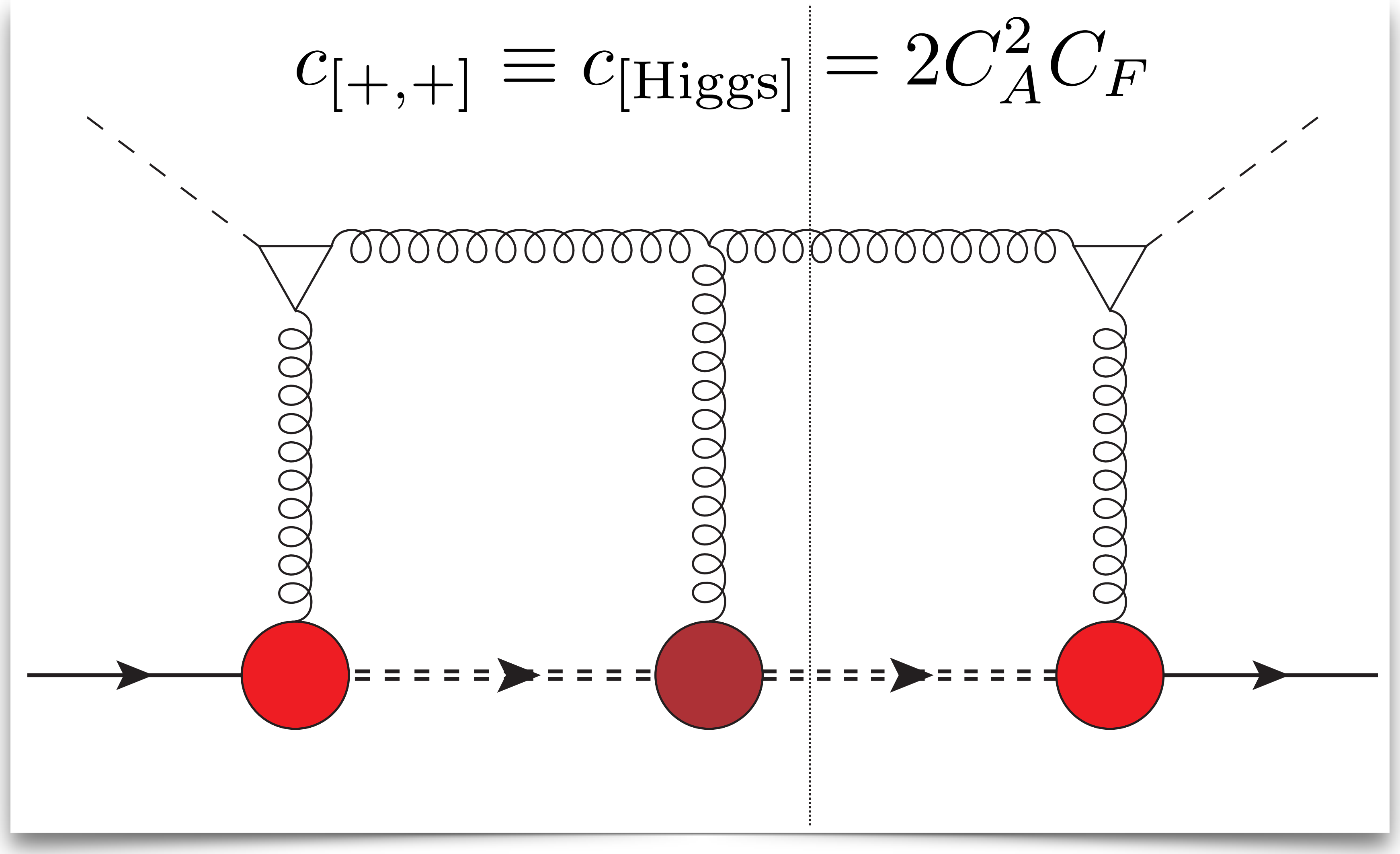

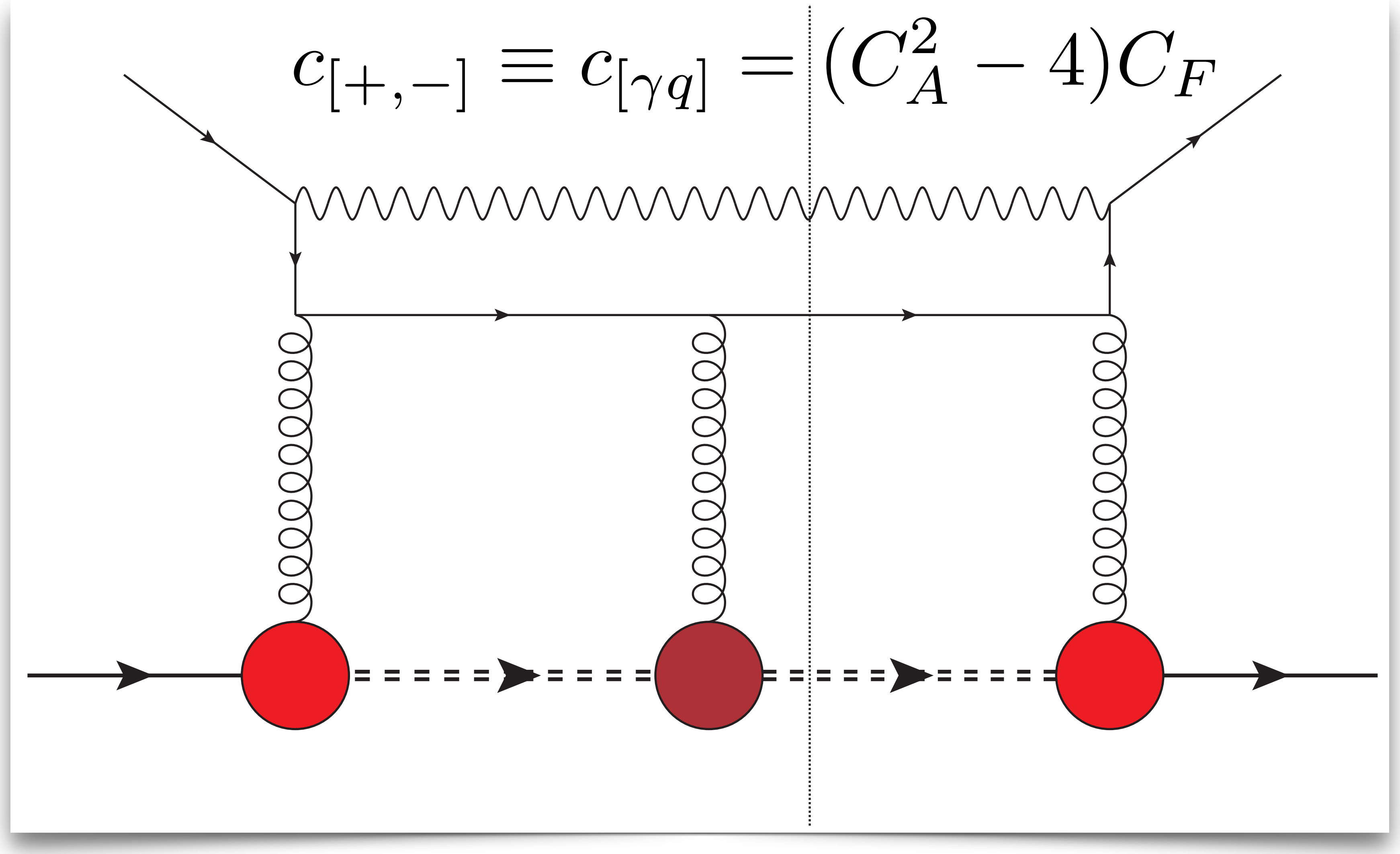

nucleon-gluon-spectator

spectator-gluon-spectator

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

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

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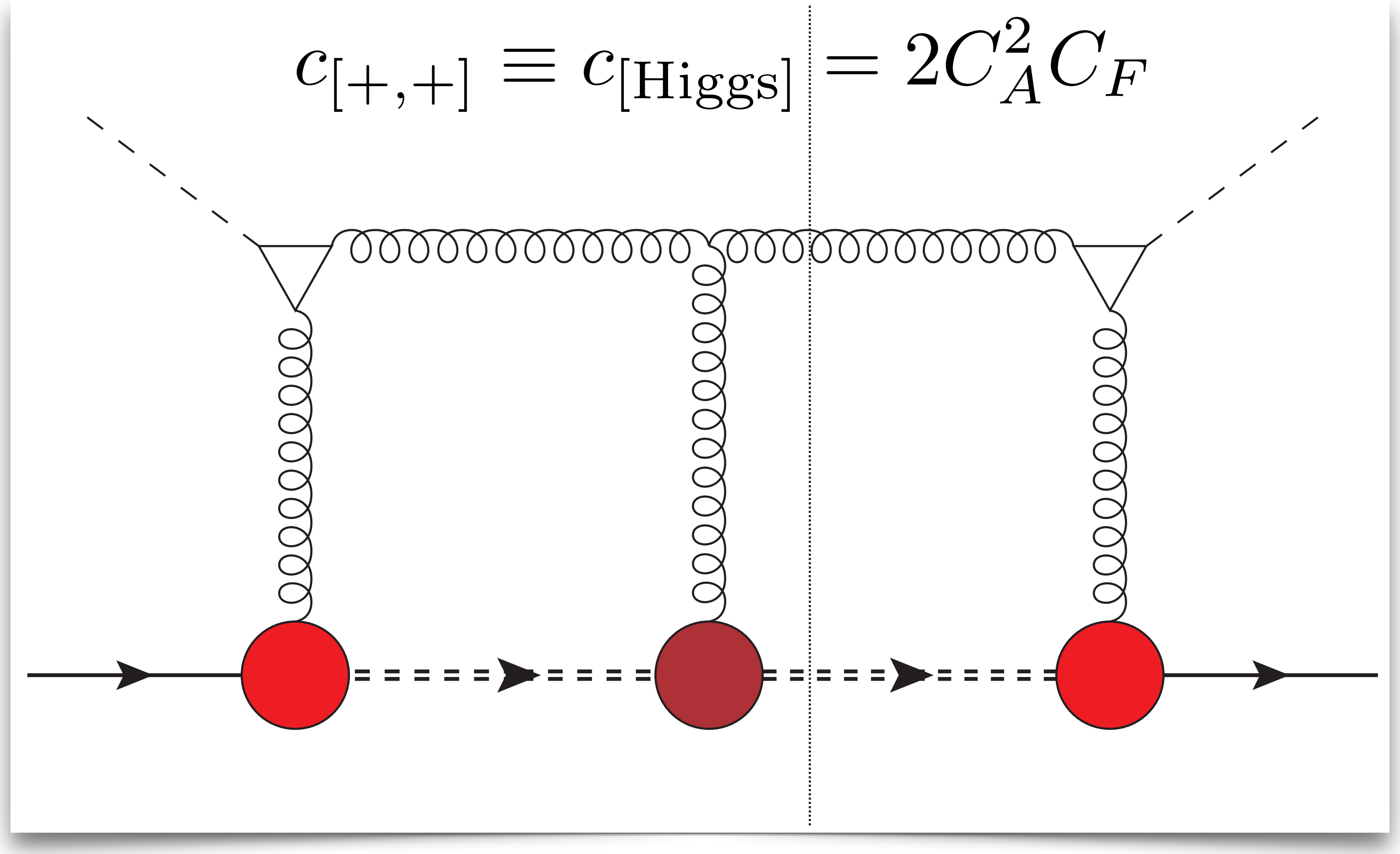

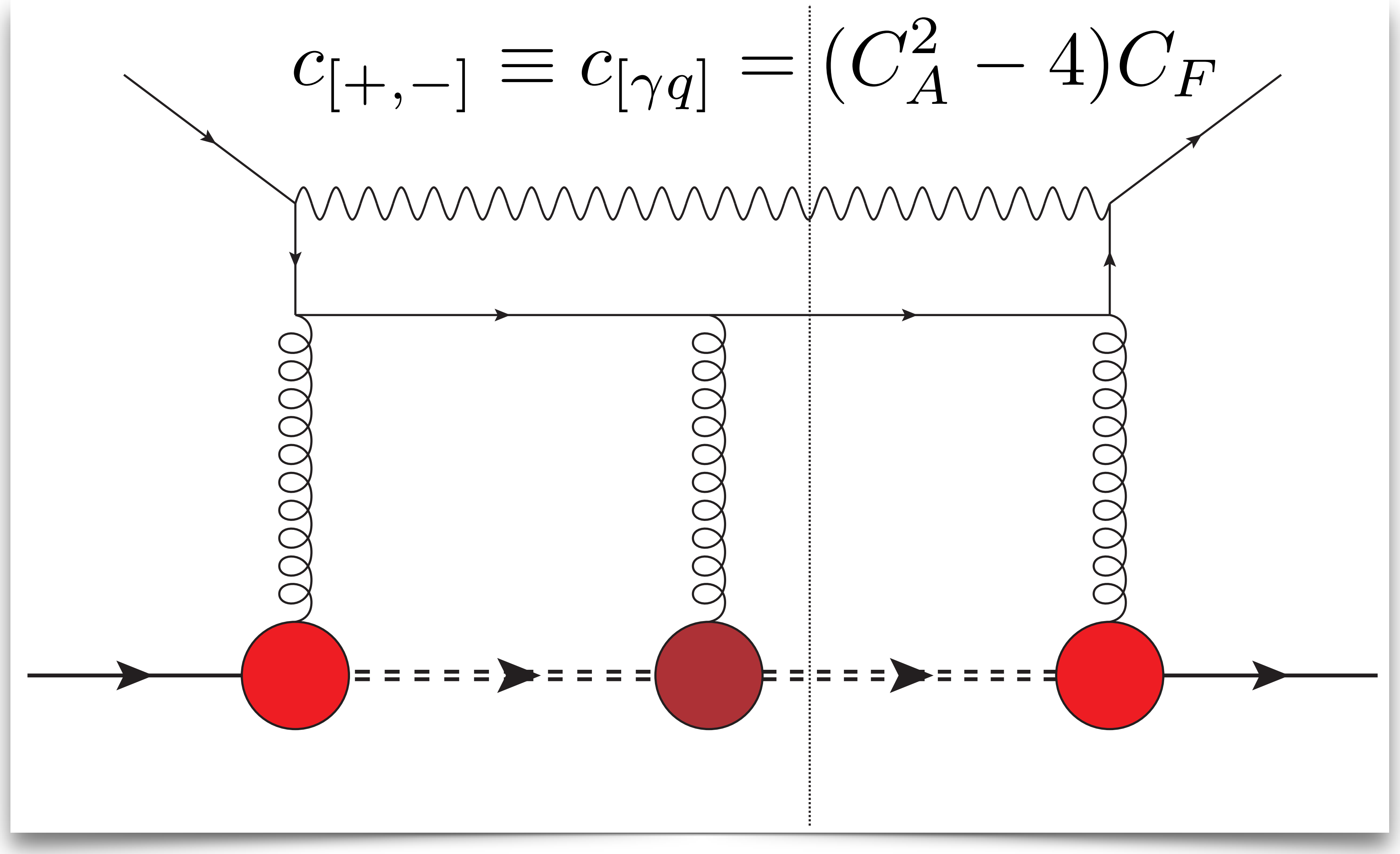

nucleon-gluon-spectator $\quad \mathcal{Y}^{\mu}_{bc}(p^2) = \delta_{bc}\left[g_1(p^2)\,\gamma_\mu + g_2(p^2)\,\frac{i}{2M}\,\sigma^{\mu\nu}\,p_\nu\right]$

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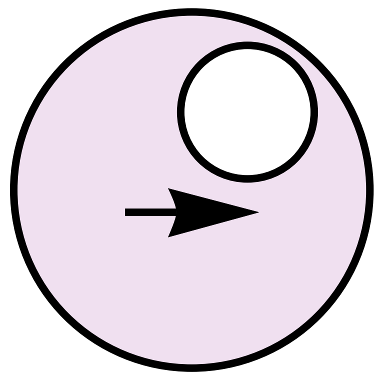
Assumption: $\quad g^d_{1,2}(p^2) = g^f_{1,2}(p^2) \equiv g_{1,2}(p^2) \quad \Leftrightarrow \quad f_{1T}^{\perp[+,-]} = \frac{c_{[+,-]}}{c_{[+,+]}}\,f_{1T}^{\perp[+,+]} \equiv \frac{5}{18}\,f_{1T}^{\perp[+,+]}$

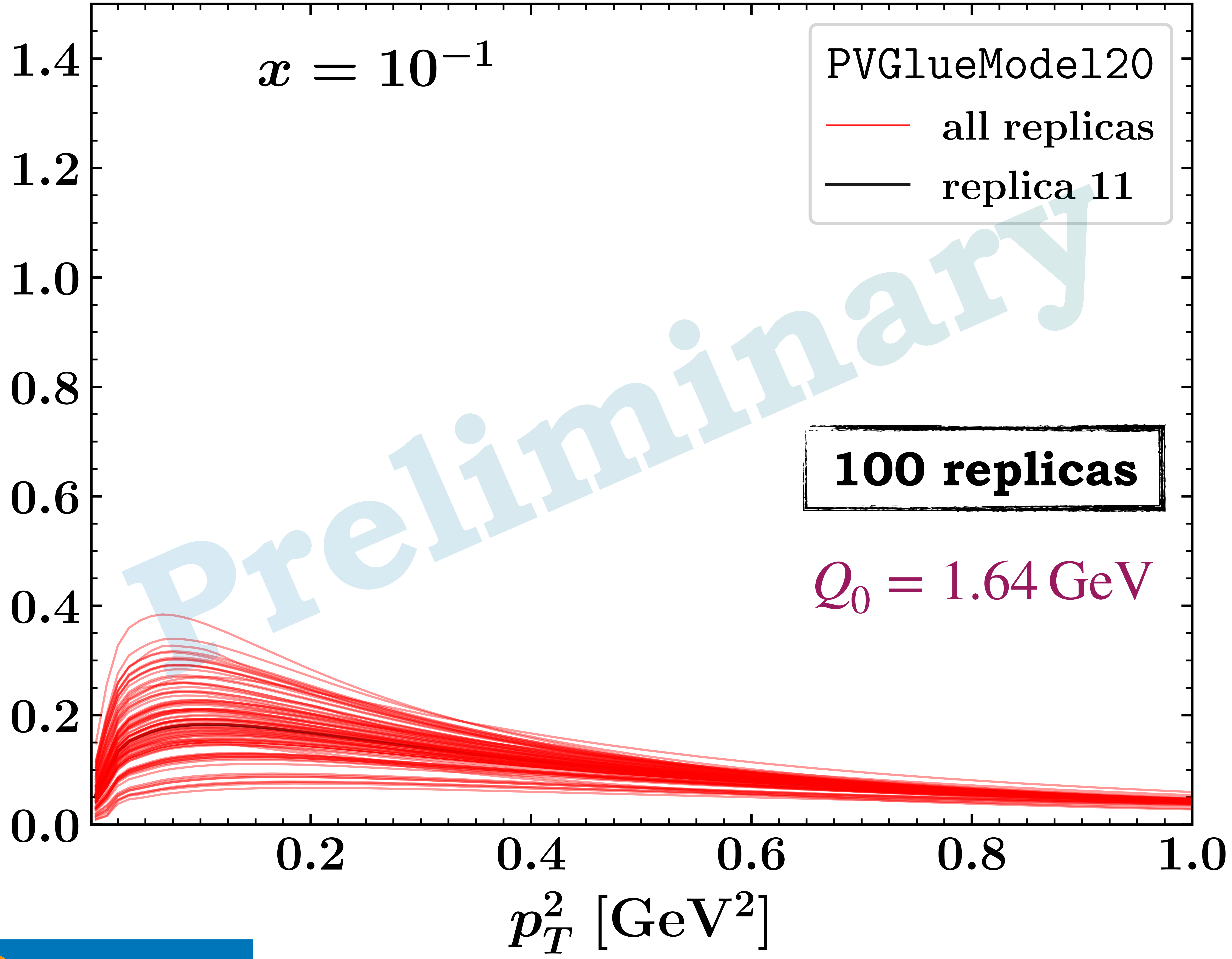
[A. Bacchetta, F.G.C., M. Radici (in preparation)]

Preliminary results for Sivers

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



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



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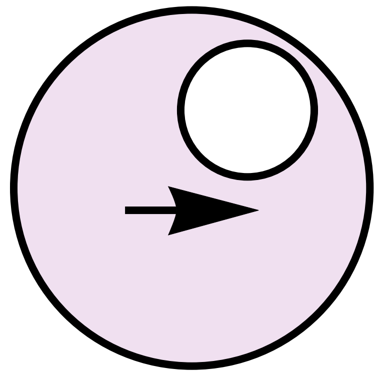

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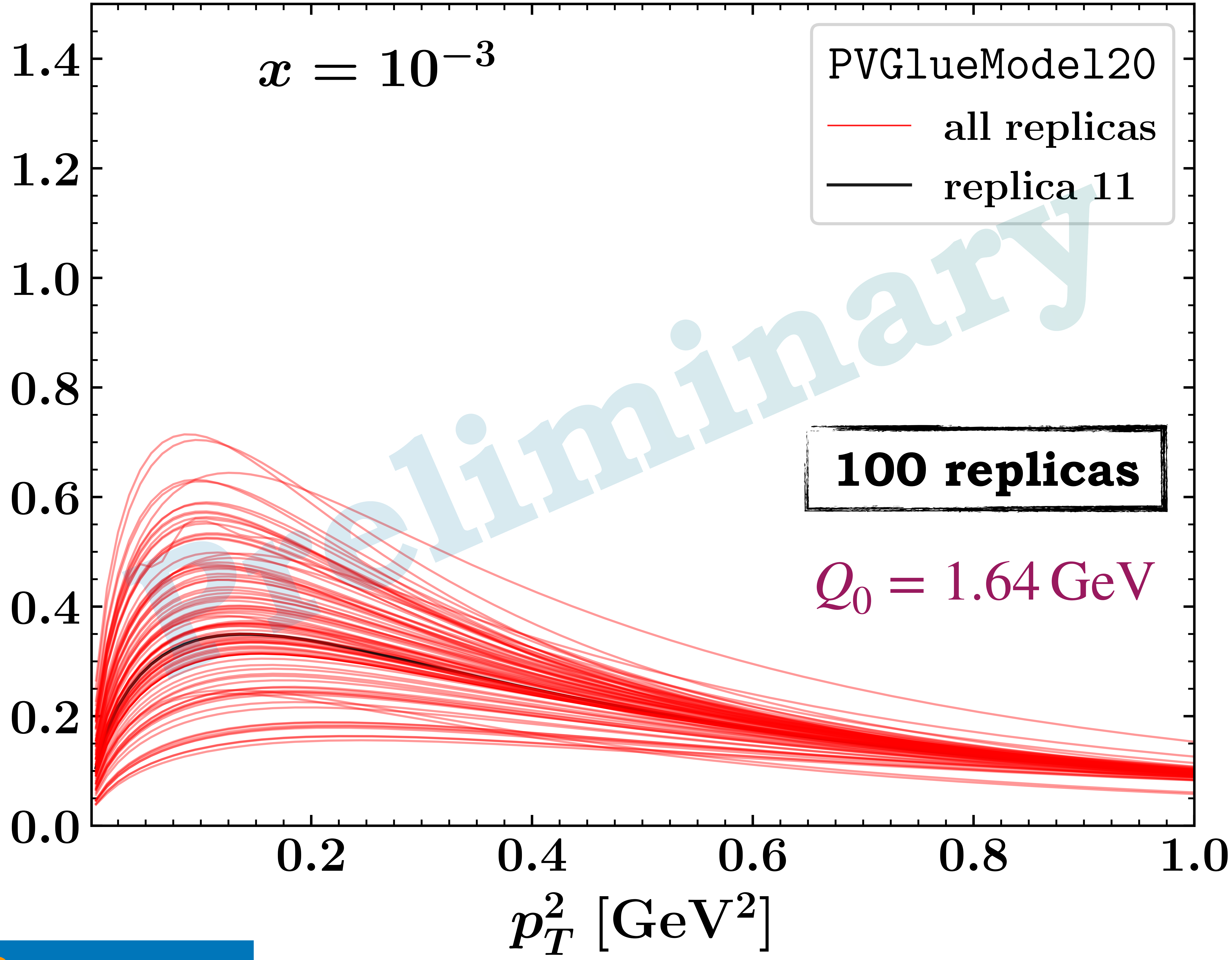
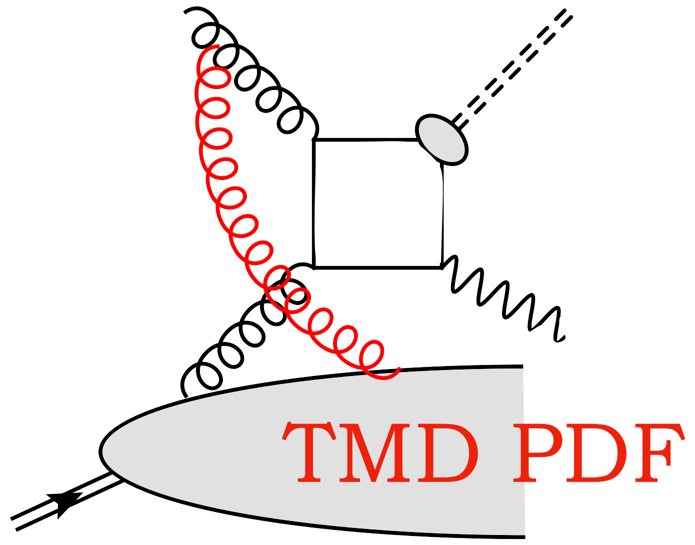


3. Gluon TMDs and quarkonium @EIC

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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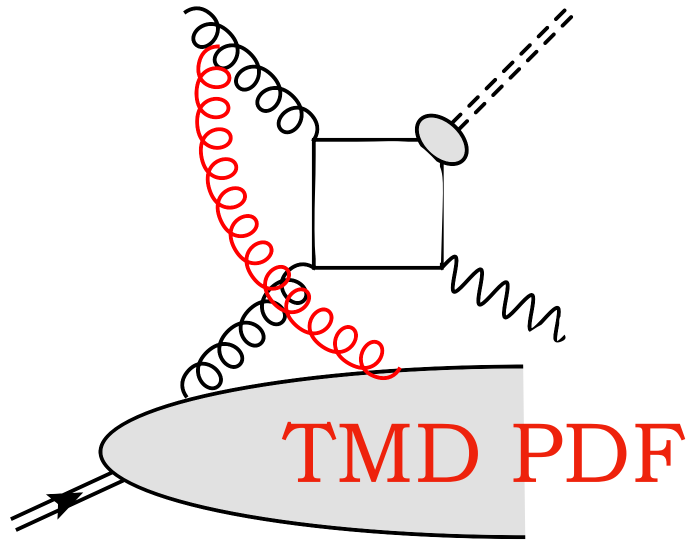

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$\eta_{c,b}$ $\Rightarrow$ LHC complementarity, TMD factorization

at low transverse momentum
for (pseudo)scalar state

$$\frac{d\sigma}{dq_T} \sim$$

$$\sim \underbrace{\mathcal{C}[\ f_1^{g/A}\ \ f_1^{g/B}\ ]}_{\text{unpolarized gluons}} \pm \underbrace{\mathcal{C}[\ h_1^{\perp g/A}\ \ h_1^{\perp g/B}\ ]}_{\text{lin. polarized gluons}}$$

(factorization) 🔗 [M. García Echevarría (2019)]

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

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Quarkonia: assets & challenges

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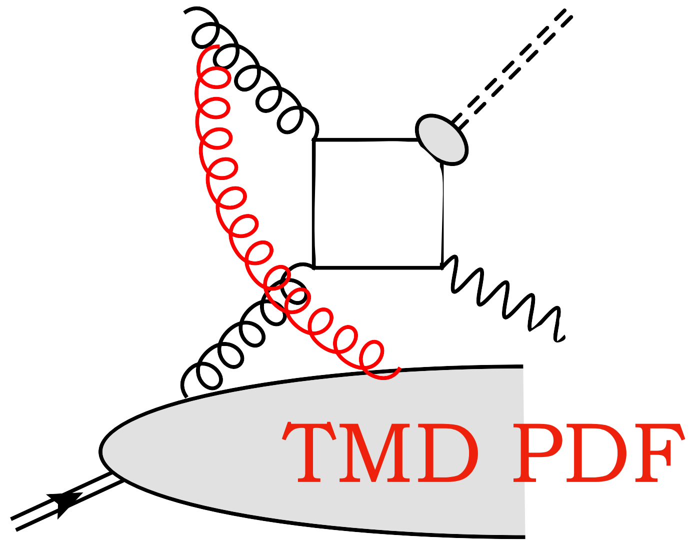

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Challenges

- Precision TMD ⇔ production mechanism(s)

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

Quarkonia: assets & challenges

Assets

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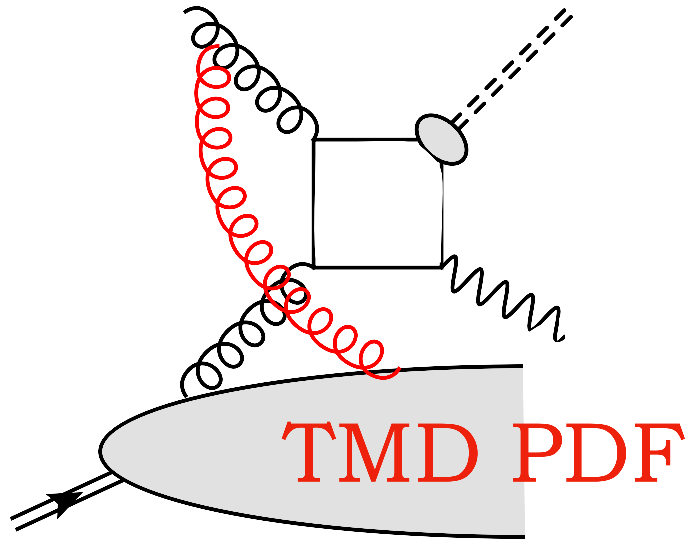

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unpolarized gluons — **lin. polarized** gluons

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Challenges

Precision TMD ⇔ production mechanism(s)

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Color Evaporation Model

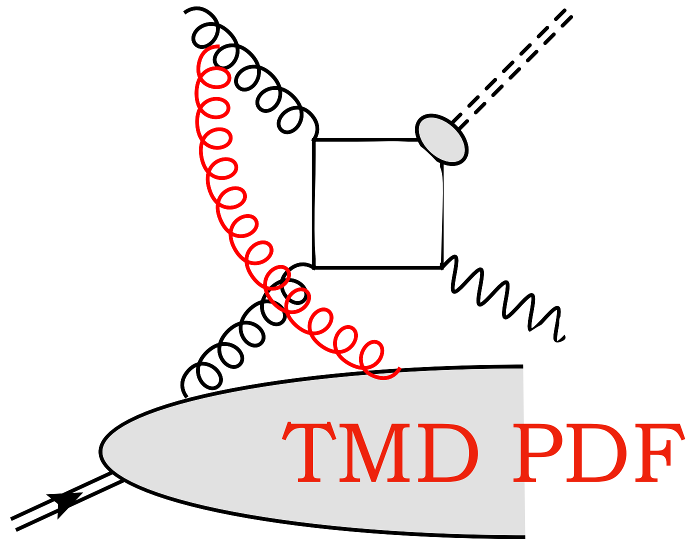
$(Q\bar{Q})$ decorrelated from onium, semi-soft gluon emissions

Overshoots data at large p_T

Quarkonia: assets & challenges

Assets

- Onia $\Rightarrow$ clean channels of f-type gluon TMDs



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Quarkonia: assets & challenges

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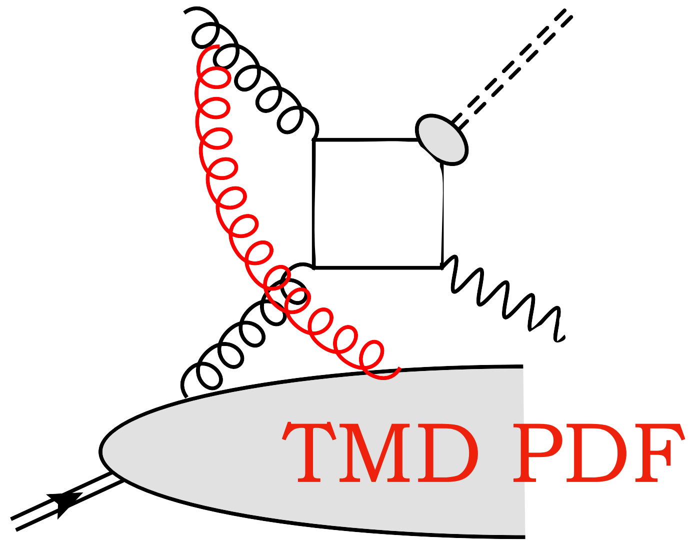

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NRQCD and Color Octet

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

TMD & shape functions

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

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

S-wave quarkonium wave function

TMD & shape functions

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S-wave quarkonium wave function

- TMD ⇒ from LDMEs to shape functions
- 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) 🔗 [, U. D'Alesio, L. Maxia, F. Murgia, C. Pisano, R. Sangem (2022)]

Quarkonium production @EIC

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

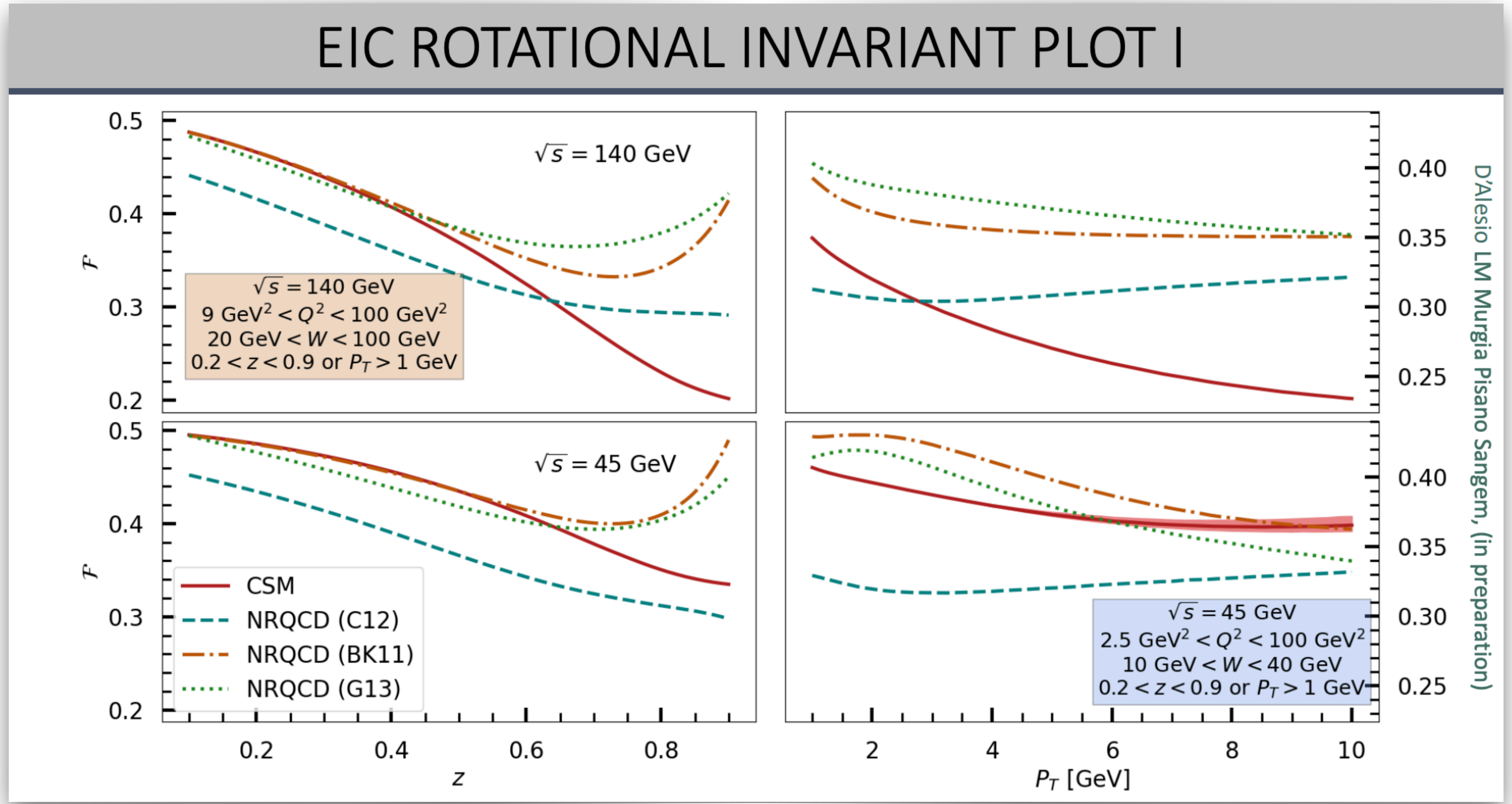
$$|\mathcal{Q}\rangle = \mathcal{O}(1)\,|Q\bar{Q}[^3S_1^{(1)}]\rangle + \mathcal{O}(v)\,|Q\bar{Q}[^3P_J^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^1S_0^{(8)}g]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3S_1^{(1,8)}gg]\rangle + \mathcal{O}(v^2)\,|Q\bar{Q}[^3D_J^{(1,8)}gg]\rangle + \ldots\,.$$

S-wave quarkonium wave function

- TMD $\Rightarrow$ from LDMEs to shape functions
- 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) [, U. D'Alesio, L. Maxia, F. Murgia, C. Pisano, R. Sangem (2022)]

Voices from our ECW22



$$\mathcal{F} = \frac{1 + \lambda_\theta + \nu_{\theta\phi}}{3 + \lambda_\theta}$$

λ_θ and $\nu_{\theta\phi}$ are angular parameters

Plot in this slide:
Polarization phenomenology for J/ψ @EIC
[talk by Luca Maxia]

EIC studies: a win-win strategy

- Onia as Tools $\Rightarrow$ 3D proton imaging via gluon TMDs
- Gluon TMDs as Tools $\Rightarrow$ unveil onium production mechamisms
- [EIC p_T domain] $<$ [HERA p_T domain] $\Rightarrow$ TMD factorization needed (¡!)

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Relevant studies

* Vectors & pseudoscalars ($J/\psi, \eta_c, \chi_c$)
* Lepto & photoproduction
* Inclusive UPCs

[D. Boer, et al. [Quarkonia At Tools Community],
Physics case for quarkonium studies
at the Electron Ion Collider (in preparation)]

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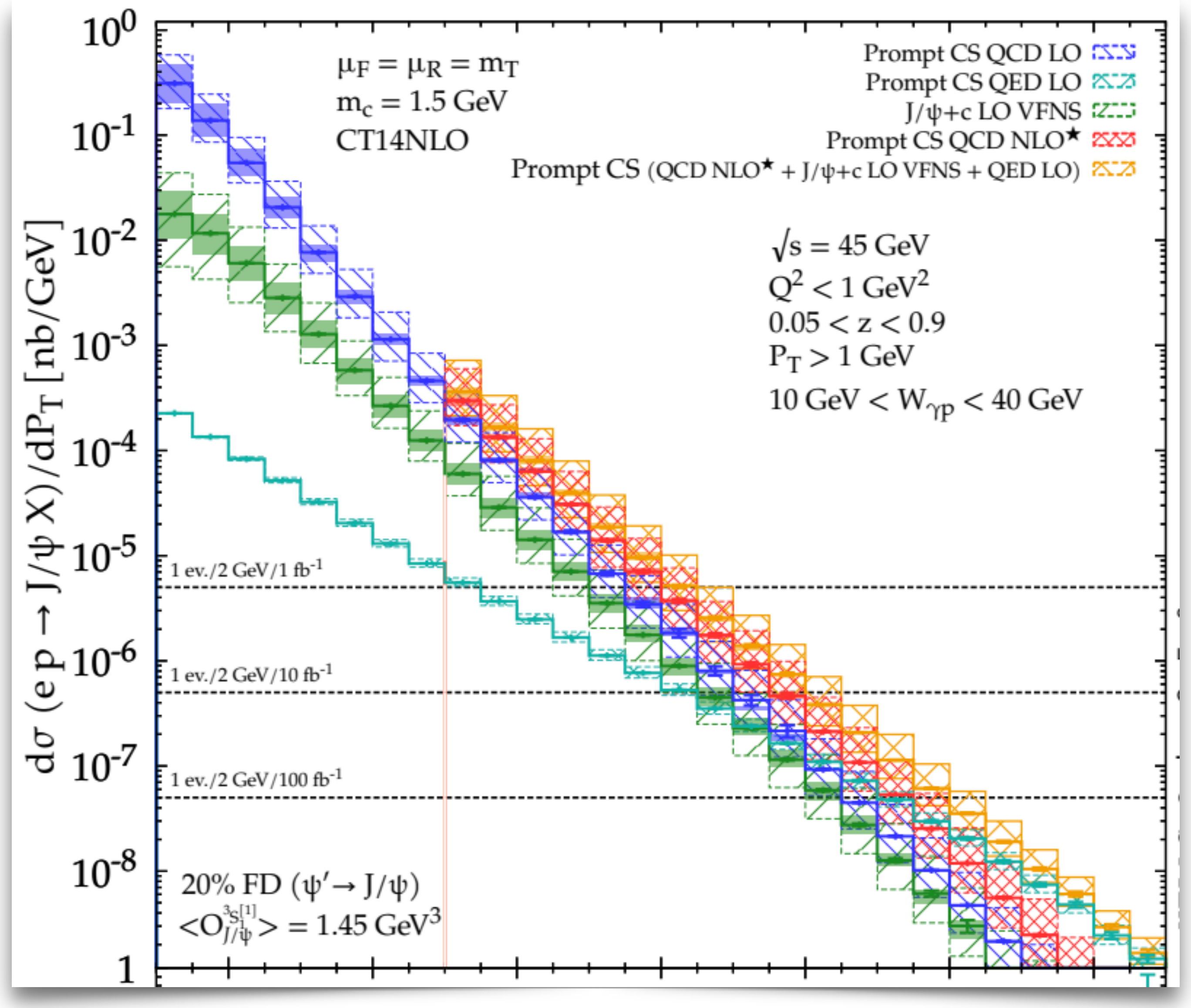
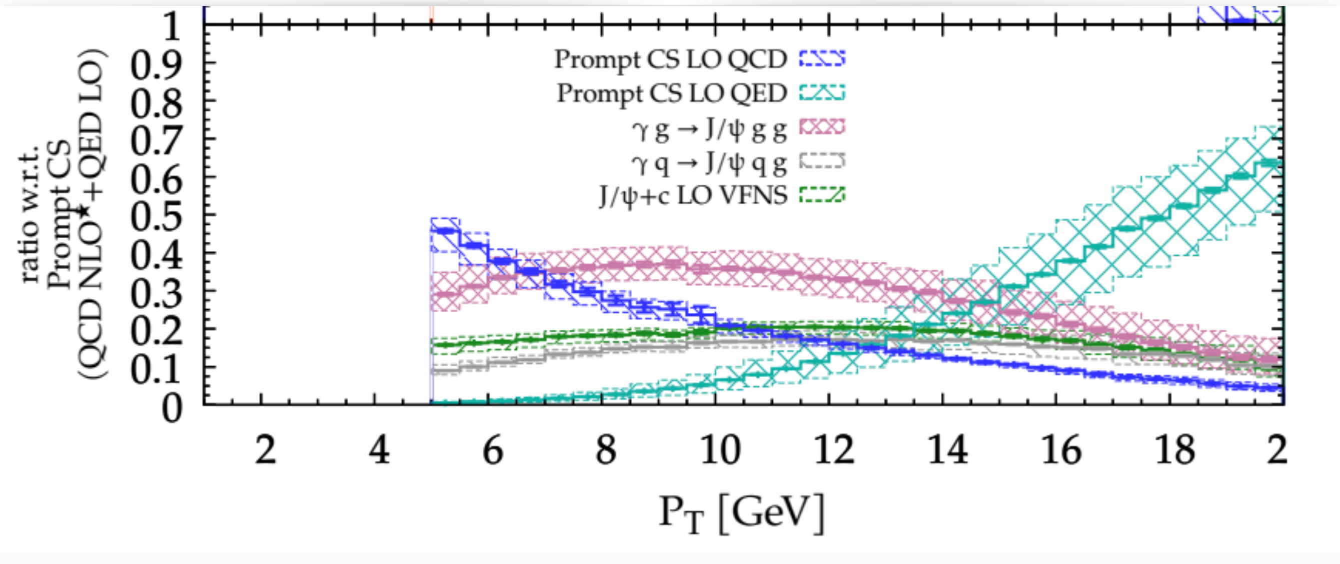
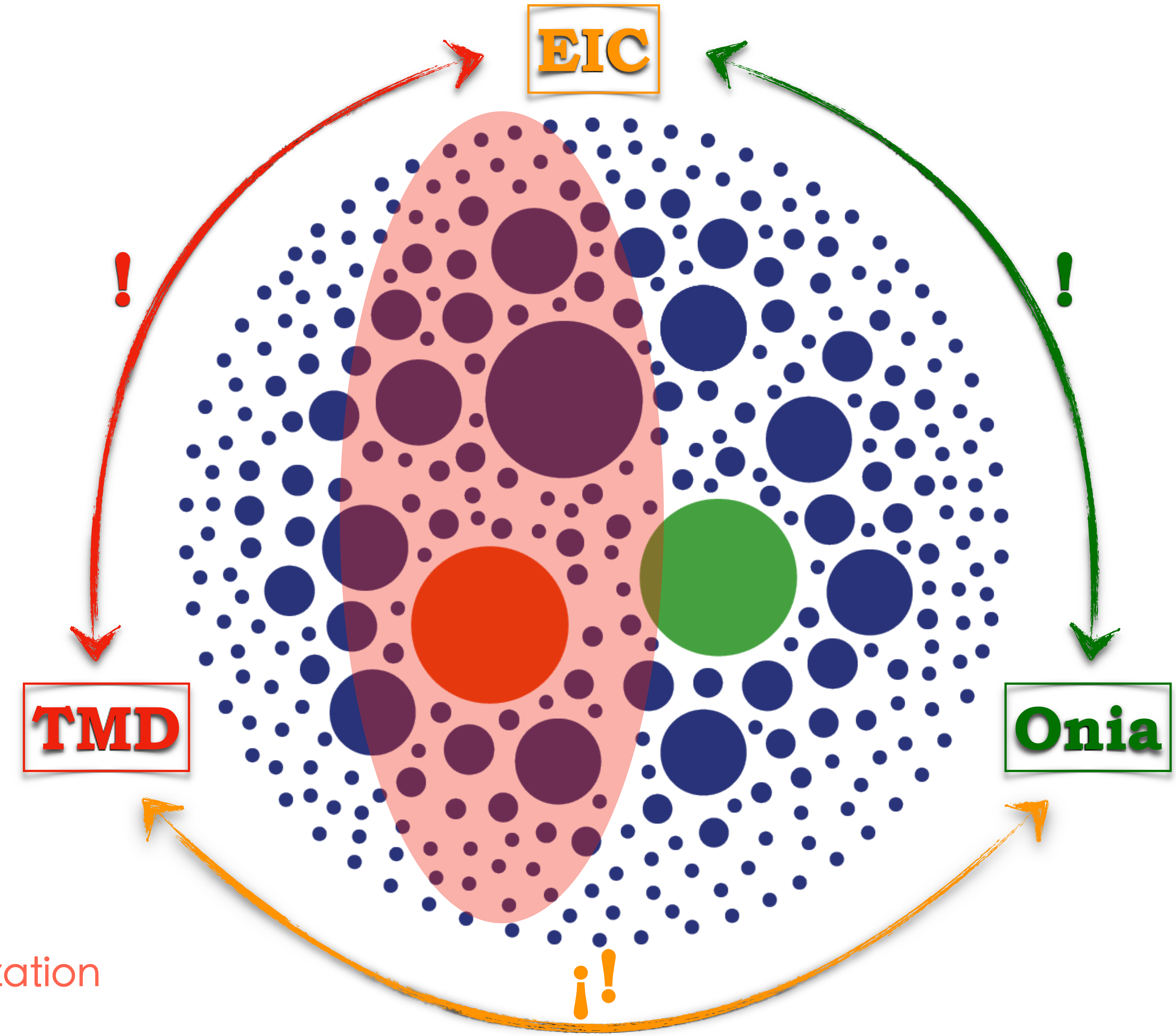




Plots in this slide:
NLO $J/\psi + X$ at 45 GeV EIC
[talk by Yelyzaveta Yedelkina]

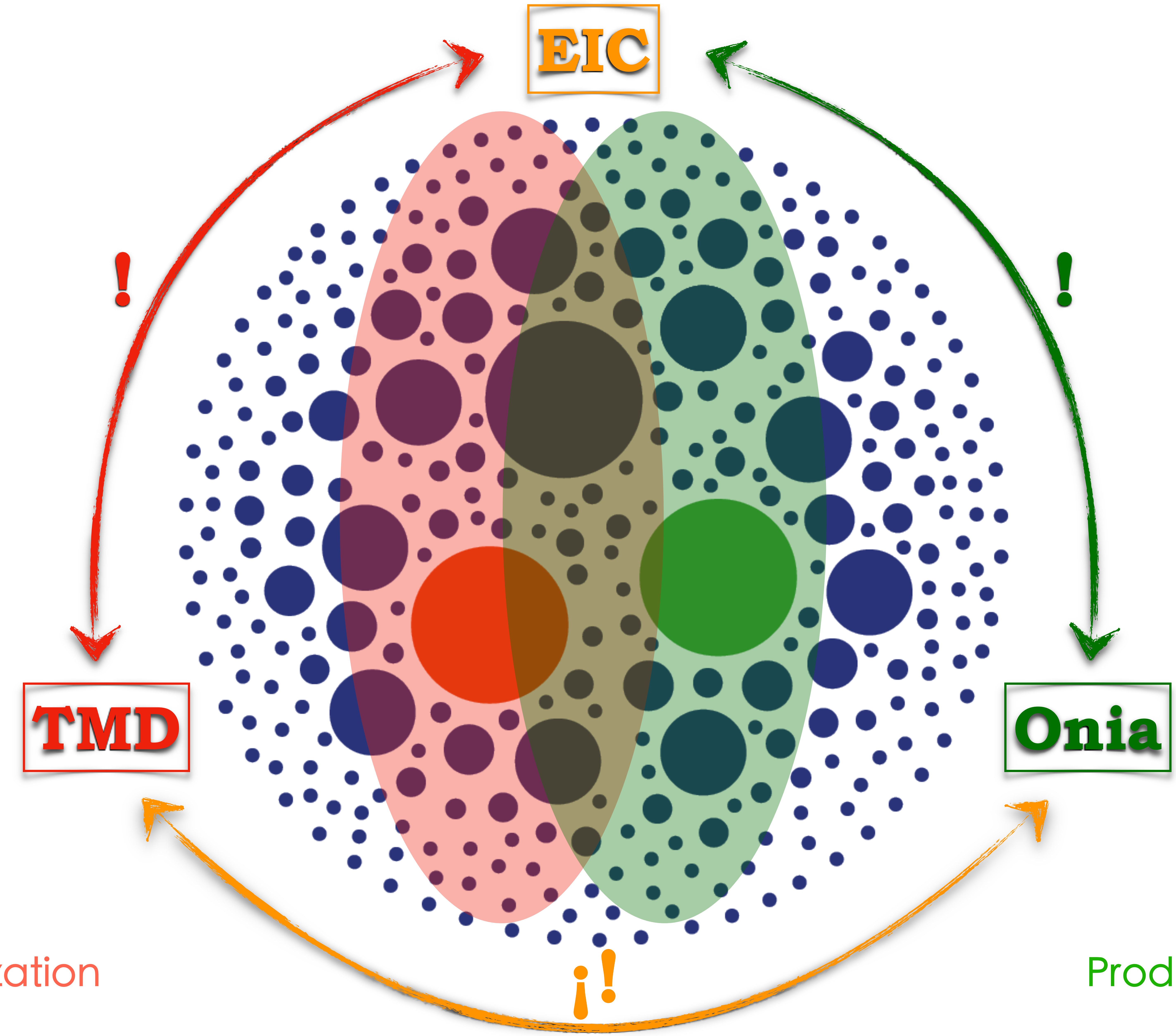
Inclusive onium in UPCs
[talk by Kate Lynch]

Gluon TMD & quarkonium opportunities @EIC



Models & polarization

Gluon TMD & quarkonium opportunities @EIC



Models & polarization

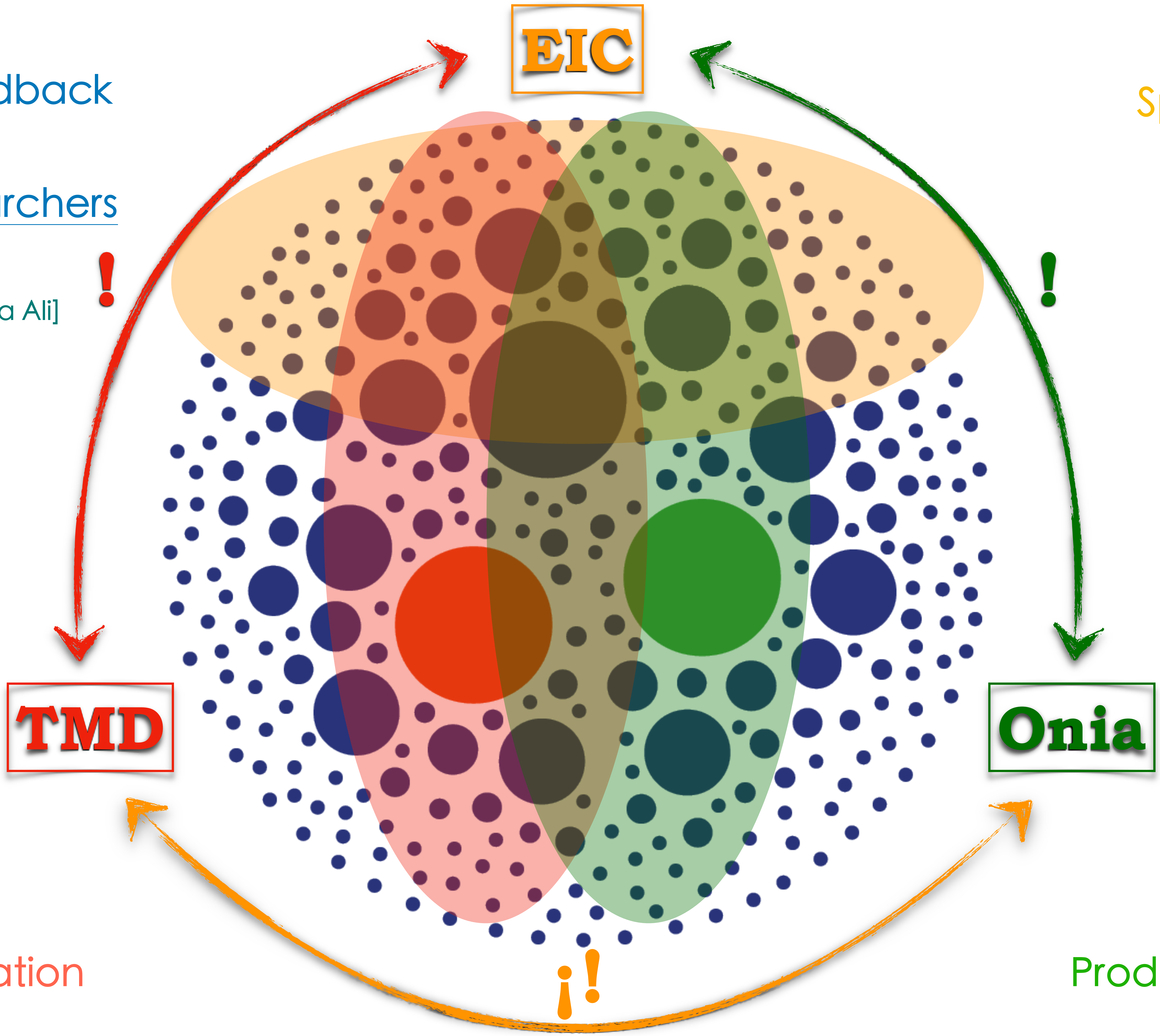
Production mechanisms

Gluon TMD & quarkonium opportunities @EIC

Enthusiasm & Feedback
from our
Early Career Researchers

[ECW Summary by Salina Ali]

Spin asymmetries
Impact studies

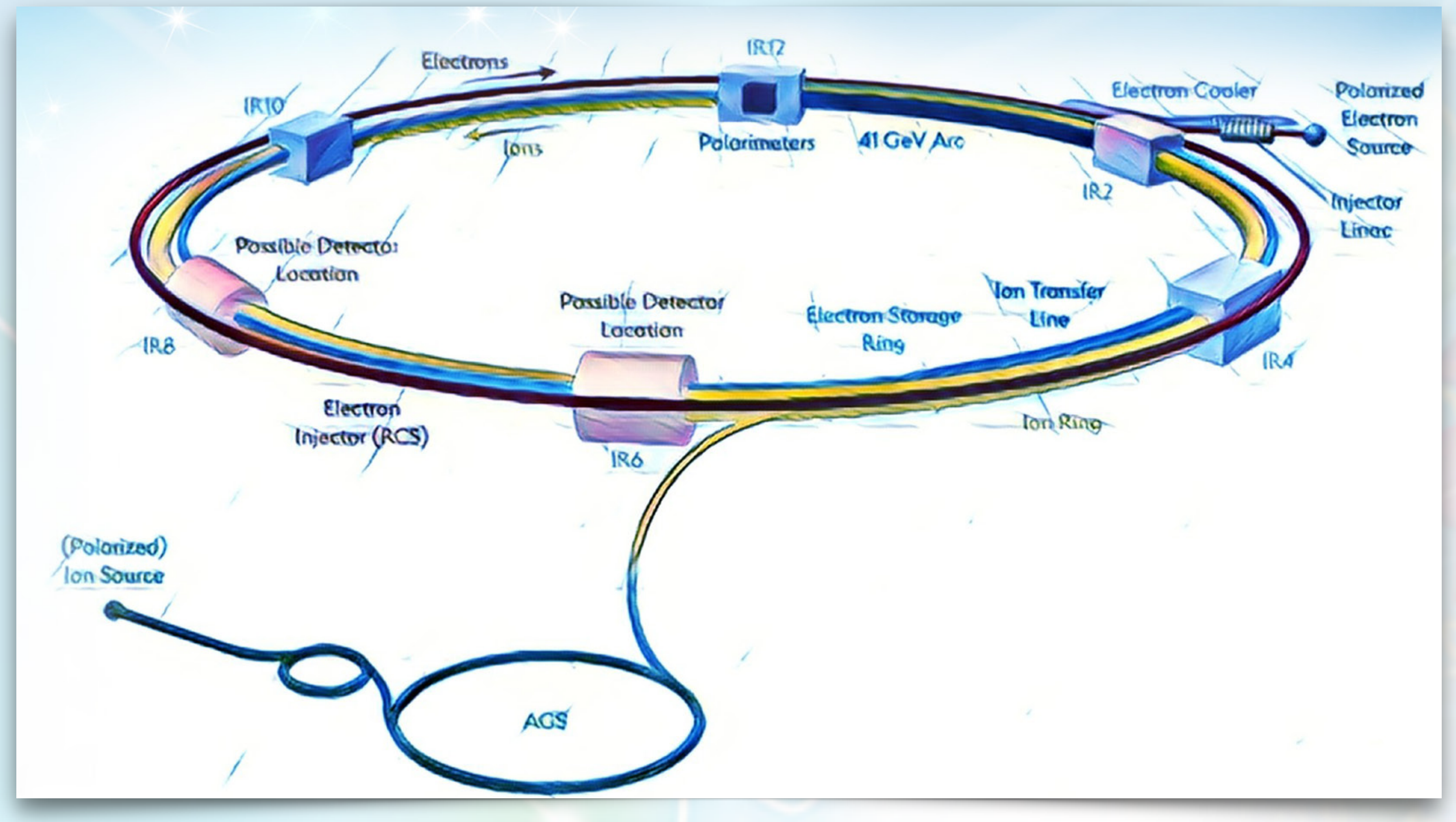


Models & polarization

Production mechanisms

Extras

Quarkonium studies at new-generation colliders

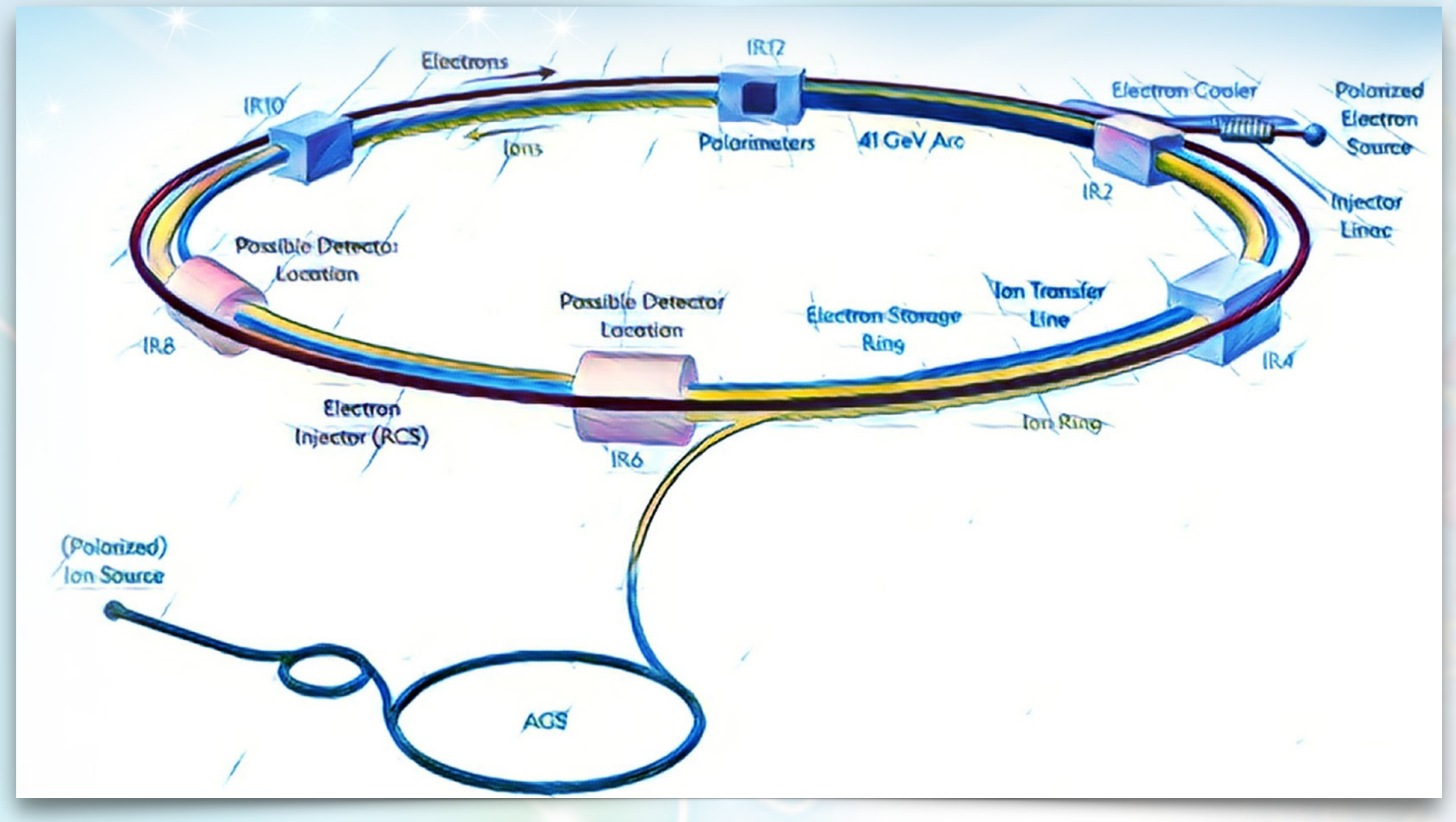


EIC Yellow Report 🔗 [EICUG [arXiv:2103.05419]]

EIC

Accessing the proton content

Quarkonium studies at new-generation colliders



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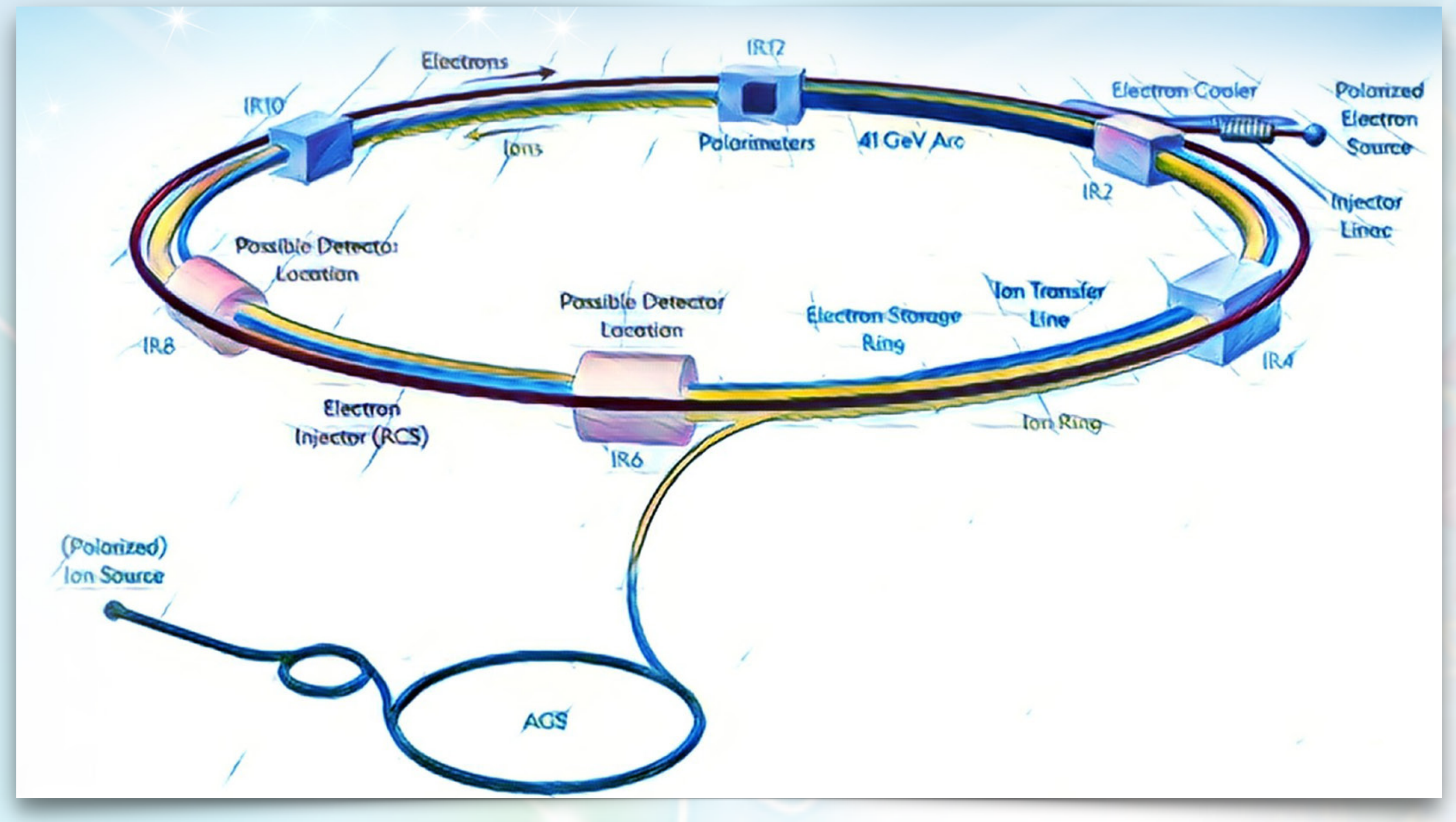
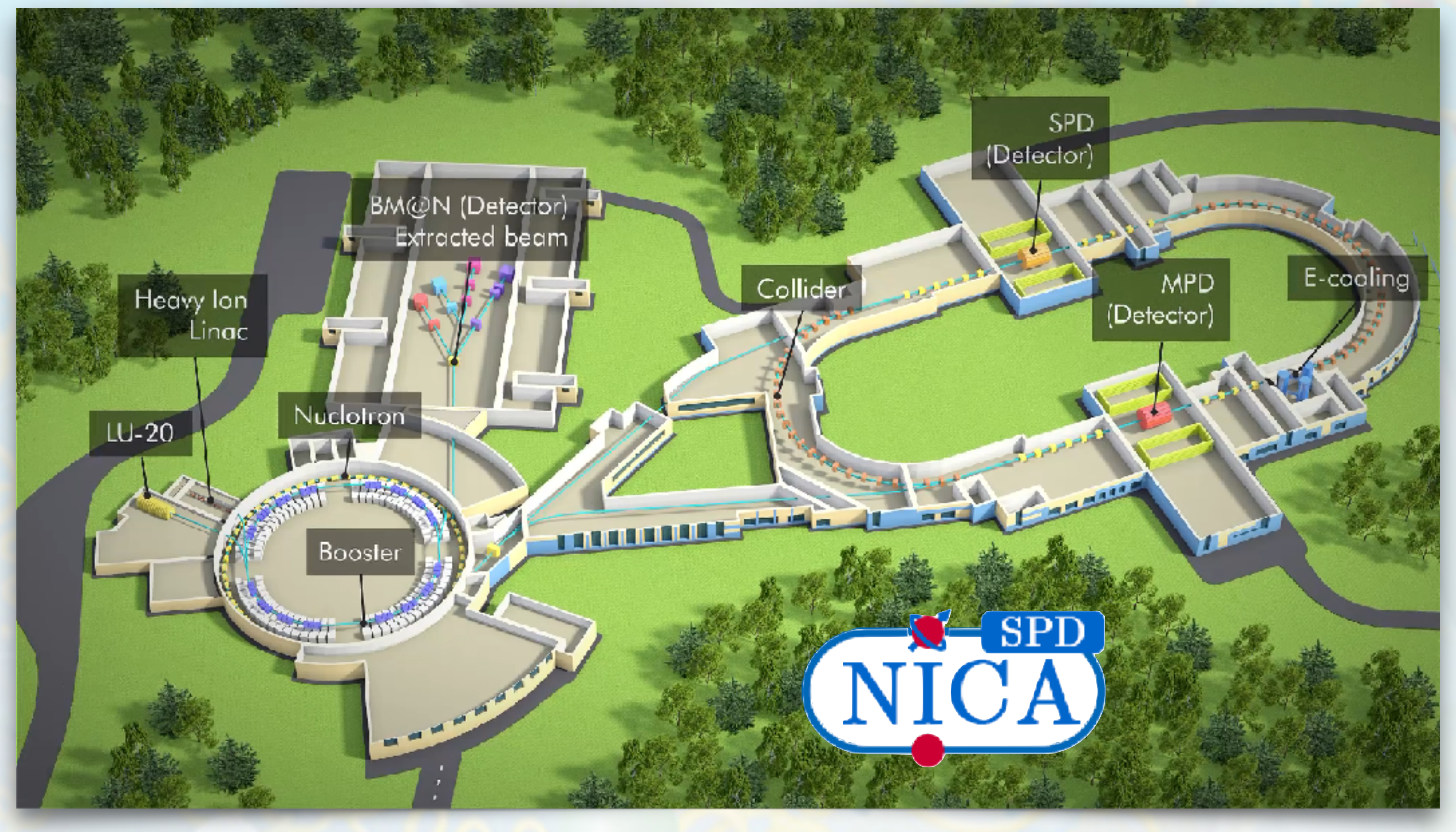
Accessing the proton content

Core sector of EIC analyses

Quarkonium studies at new-generation colliders





EIC

NICA-SPD

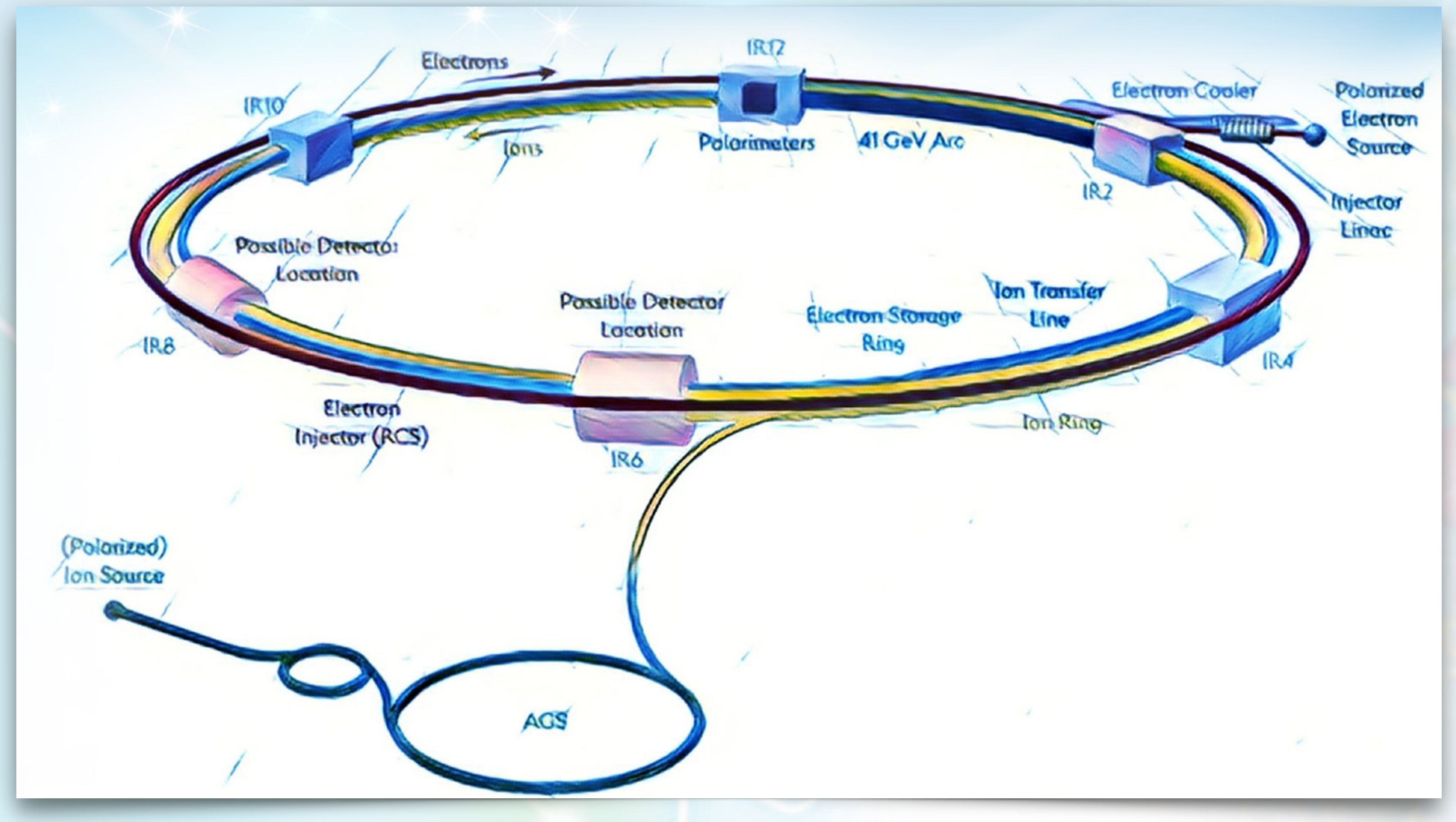
EIC Yellow Report 🔗 [EICUG [arXiv:2103.05419]]

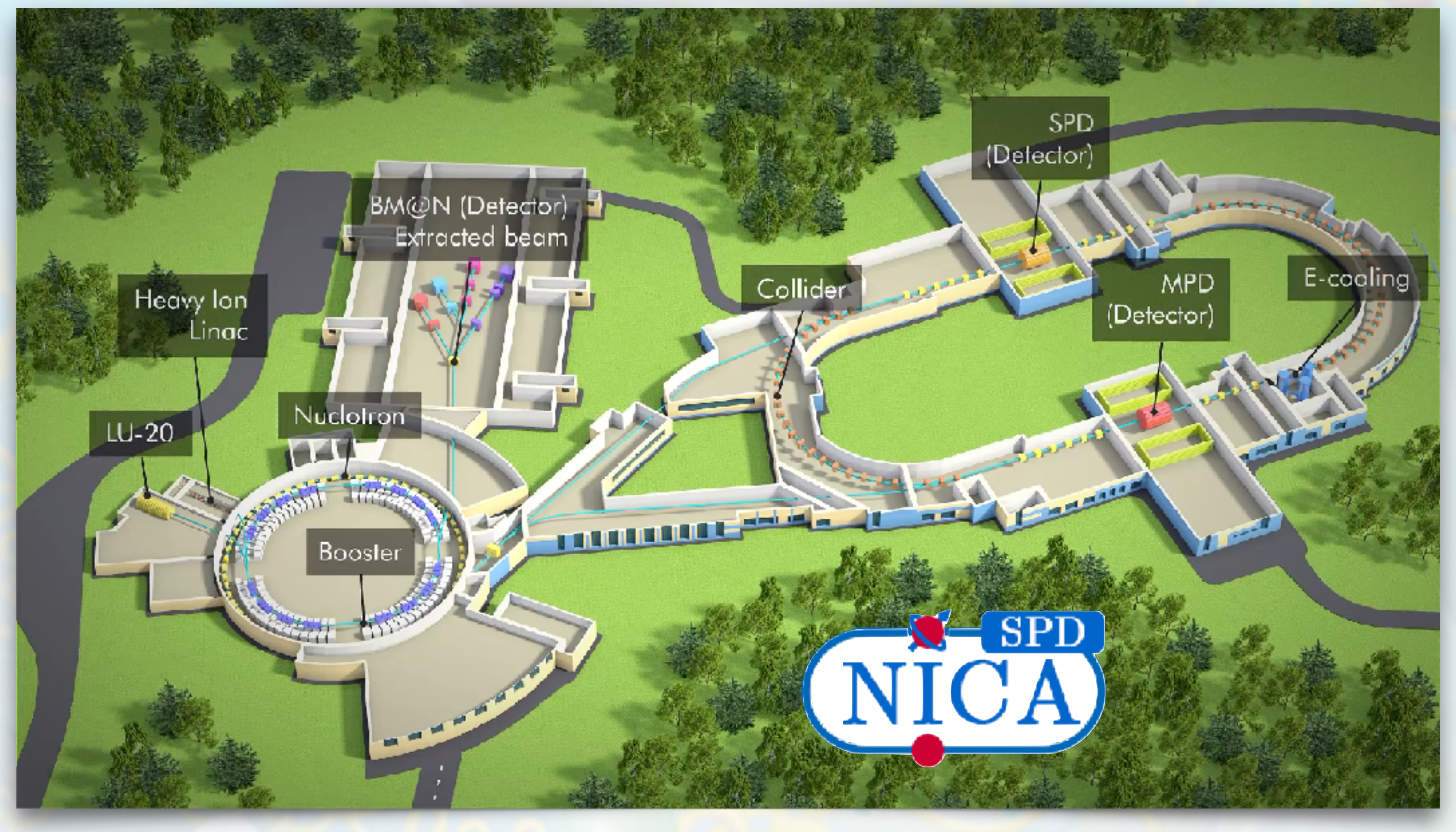
Gluons at NICA-SPD 🔗 [Prog. Part. Nucl. Phys. 119 (2021) 103858]

Accessing the proton content

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

Quarkonium studies at new-generation colliders





EIC

NICA-SPD

HL-LHC, FPF

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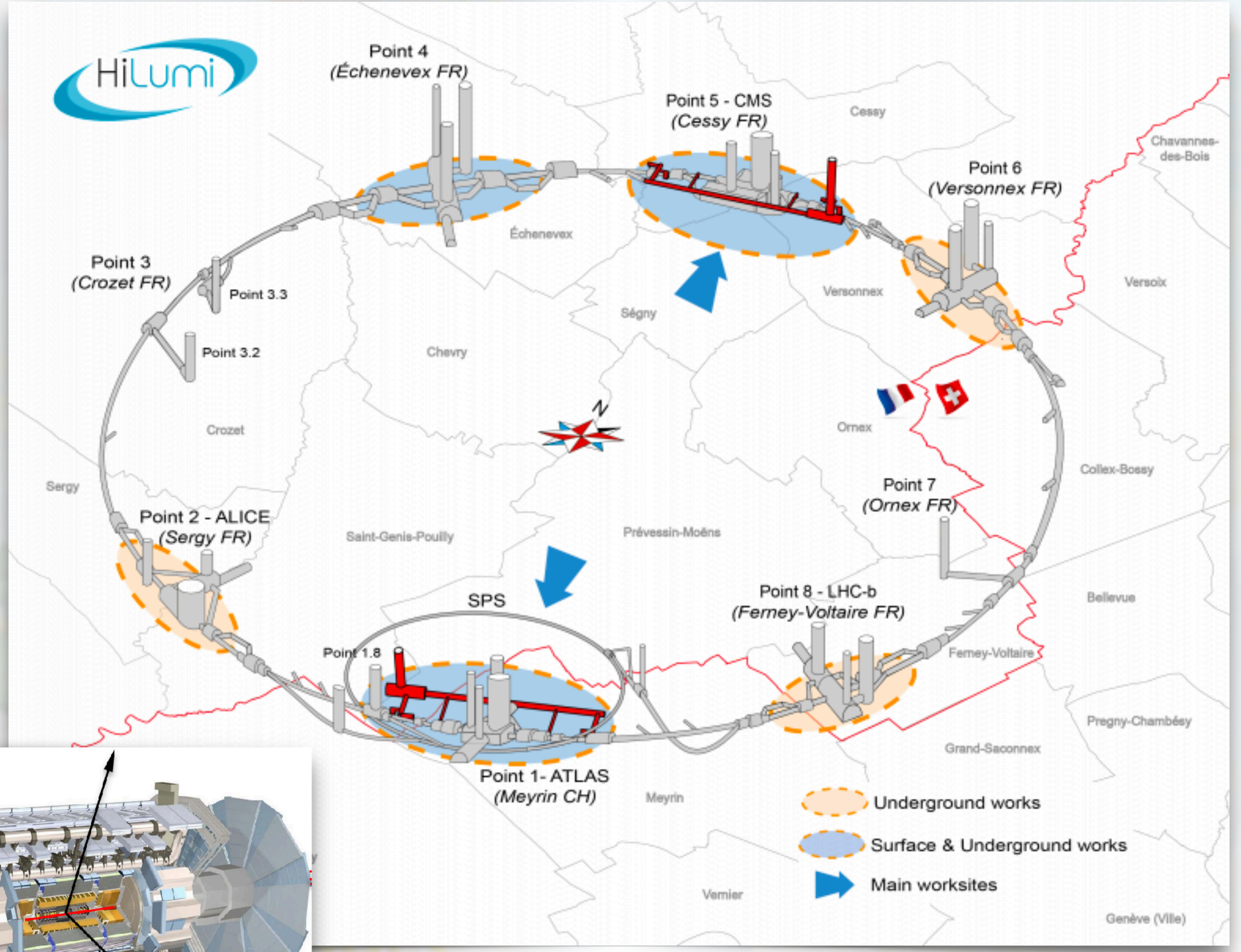
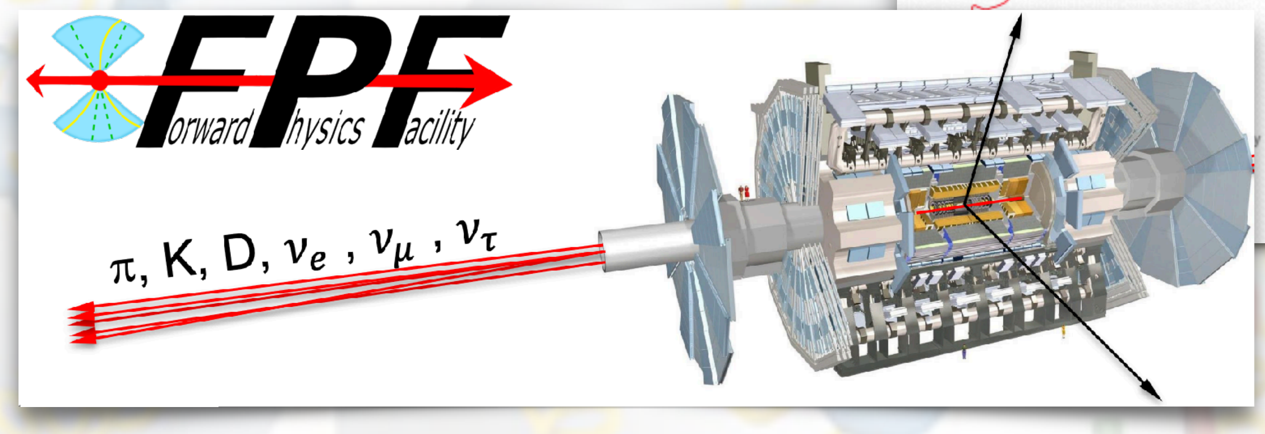
Accessing the proton content

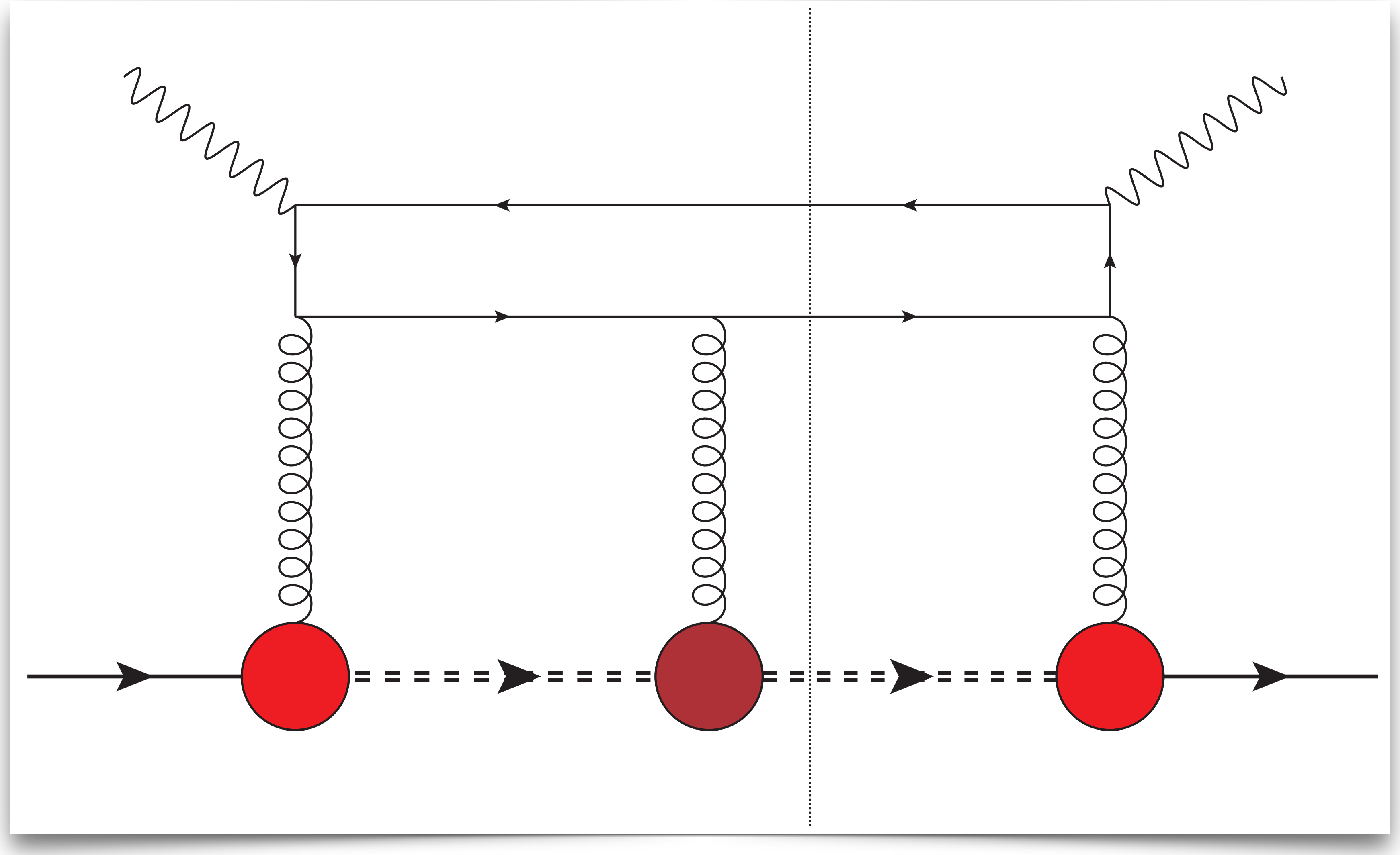
- Core sector of EIC analyses
- Significance of large-x studies at NICA-SPD
- Intrinsic gluon polarization at HL-LHC (+ FPF)

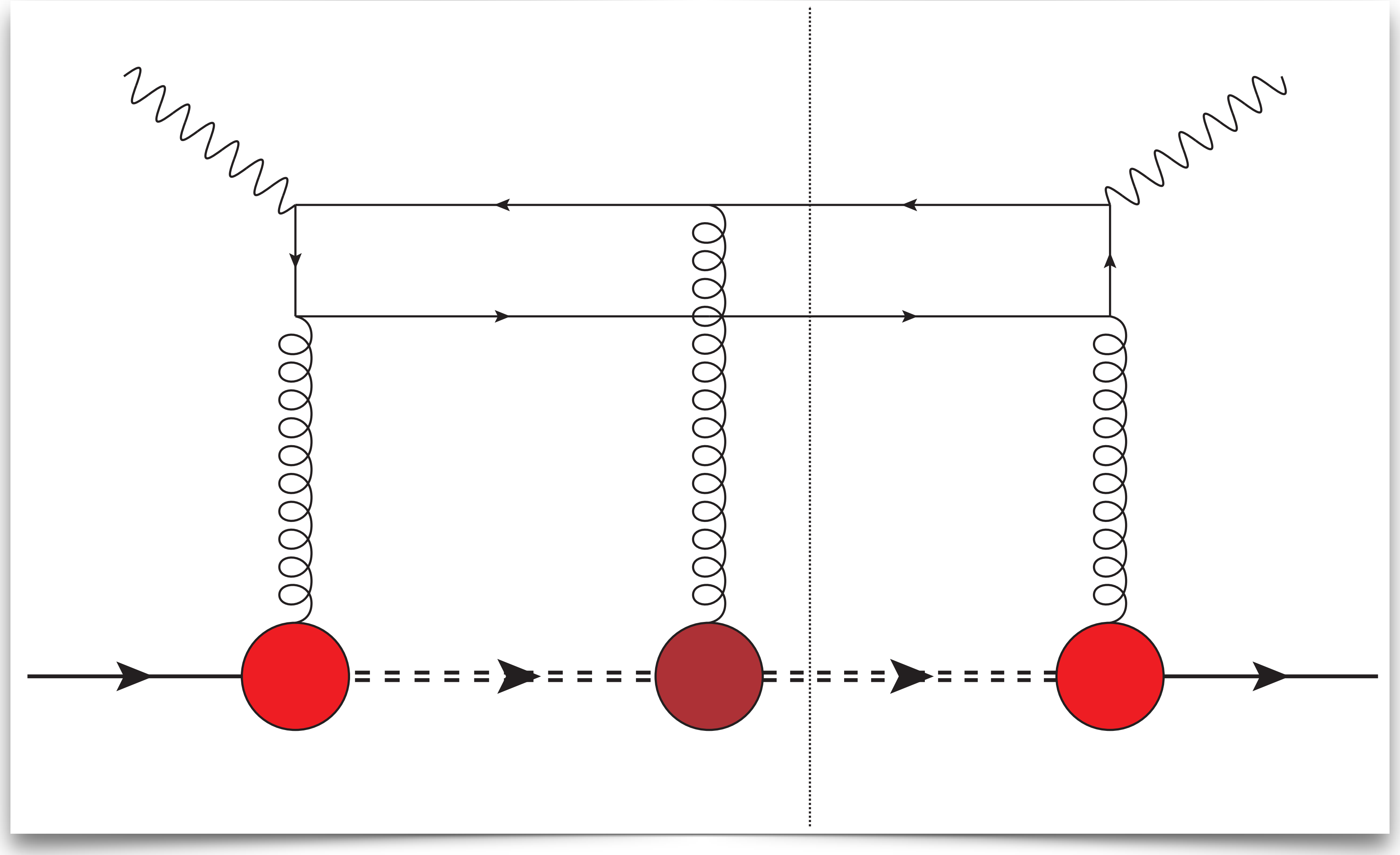




Analytic structure of T-odd gluon TMDs

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





Backup

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

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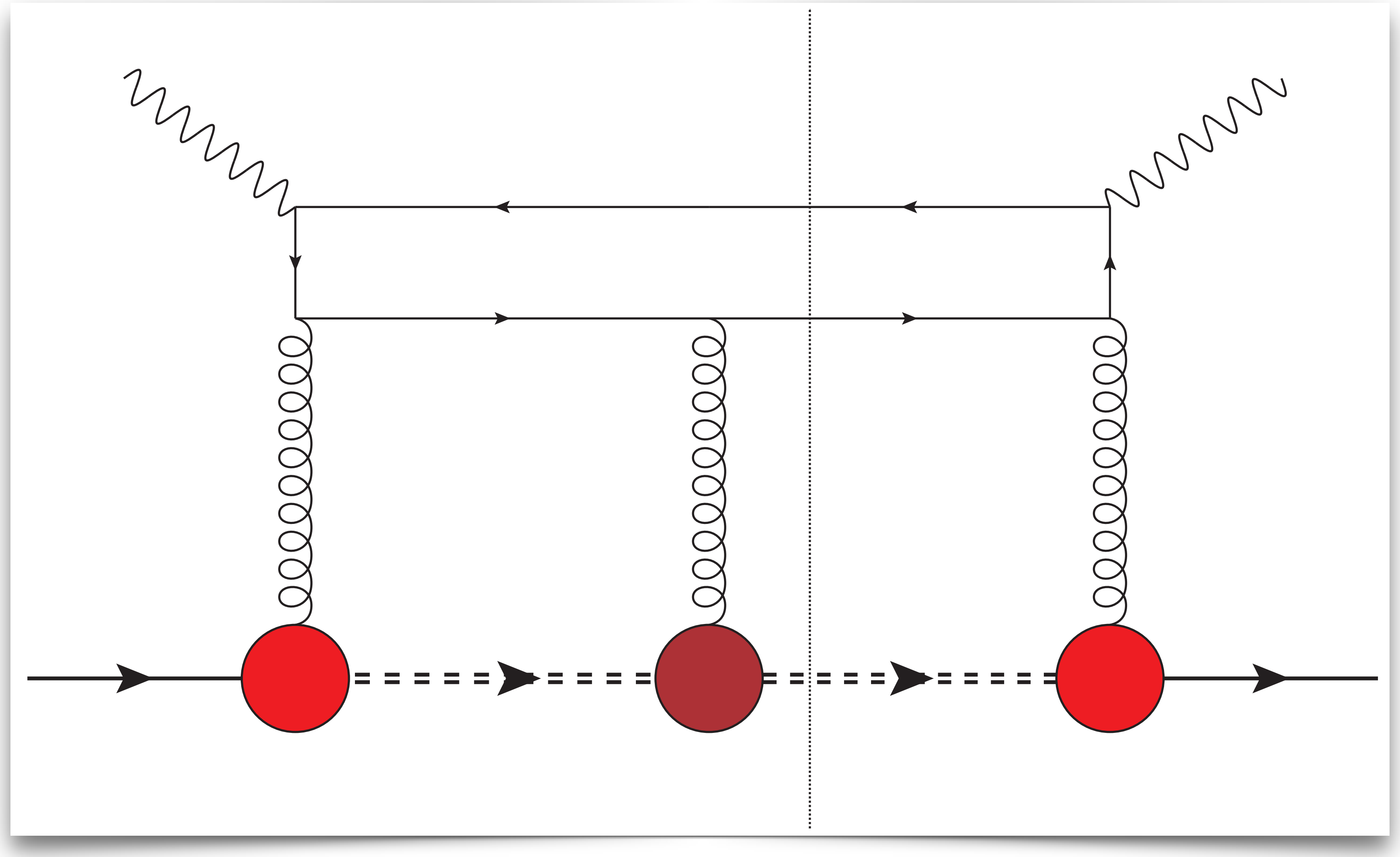

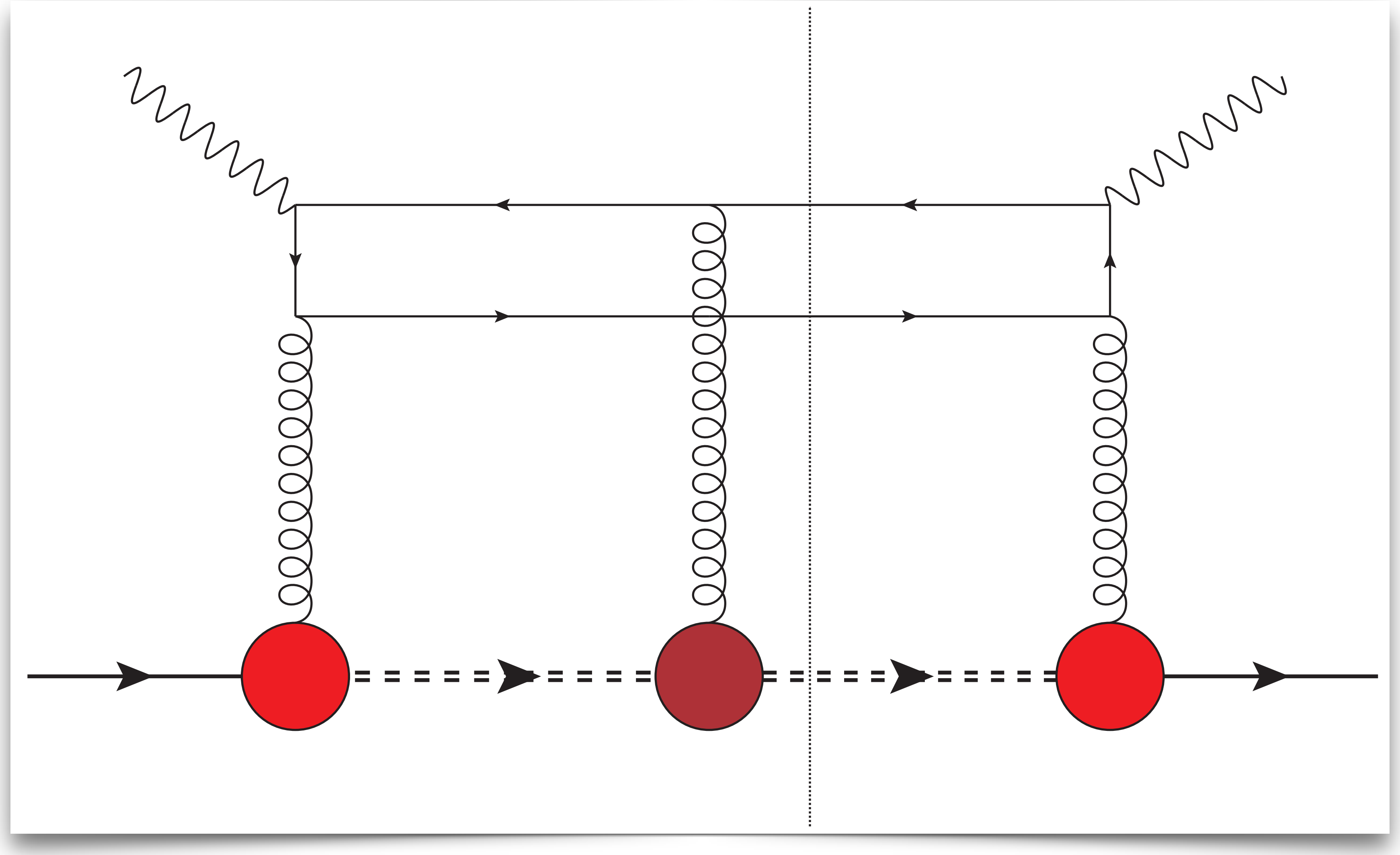

nucleon-gluon-spectator

spectator-gluon-spectator

Backup

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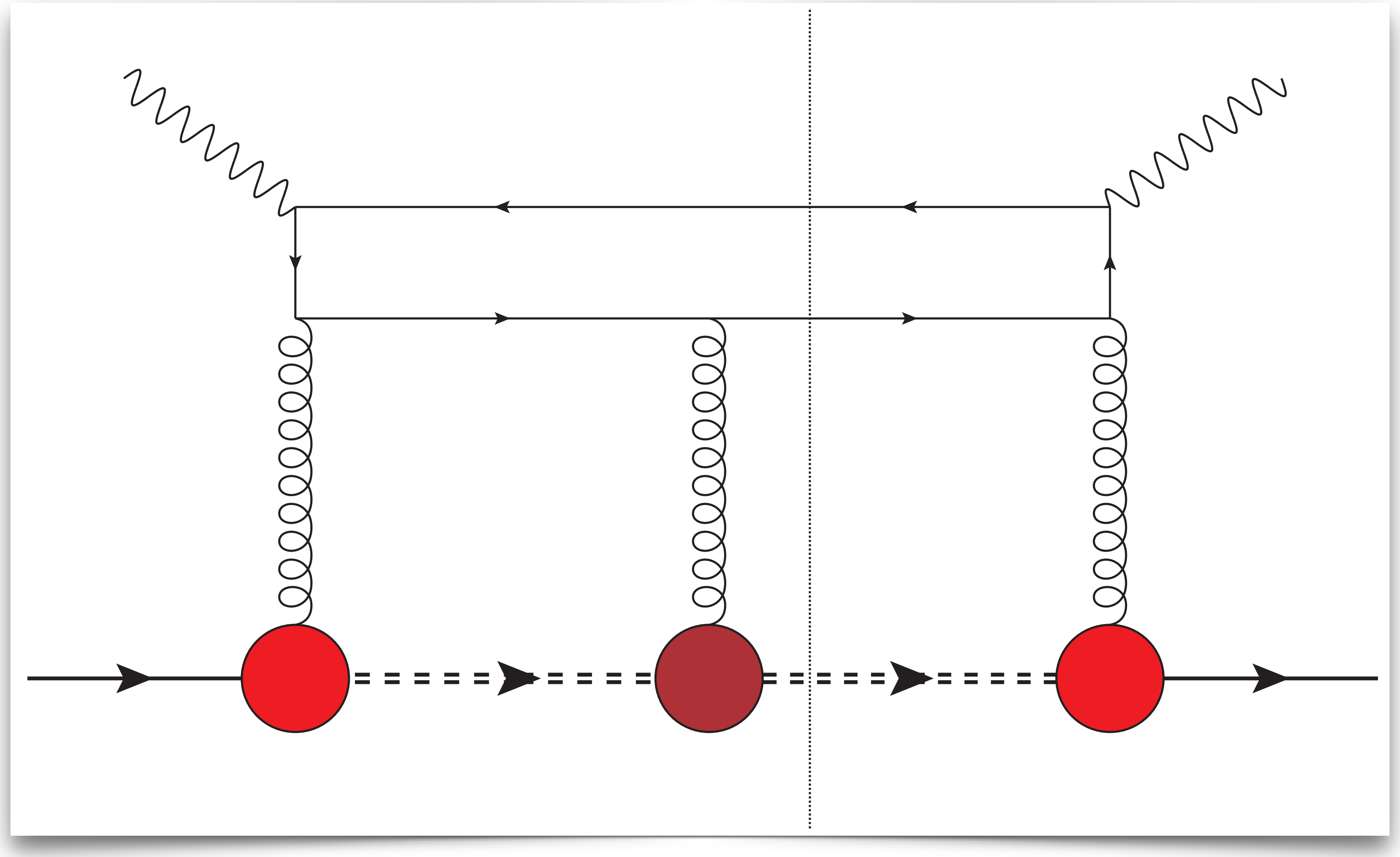

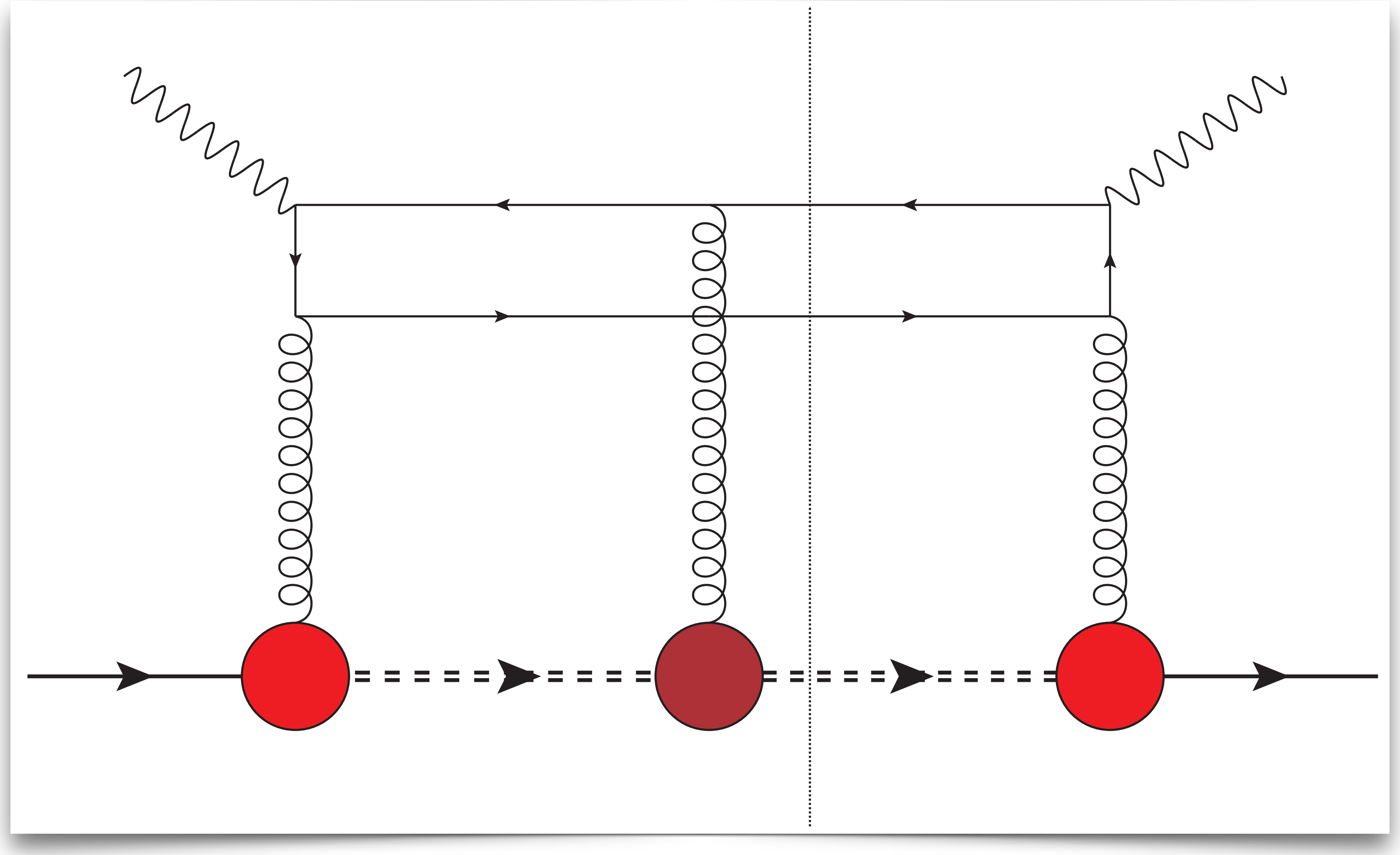

nucleon-gluon-spectator

spectator-gluon-spectator

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

$8 \times 7 \times 4$

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

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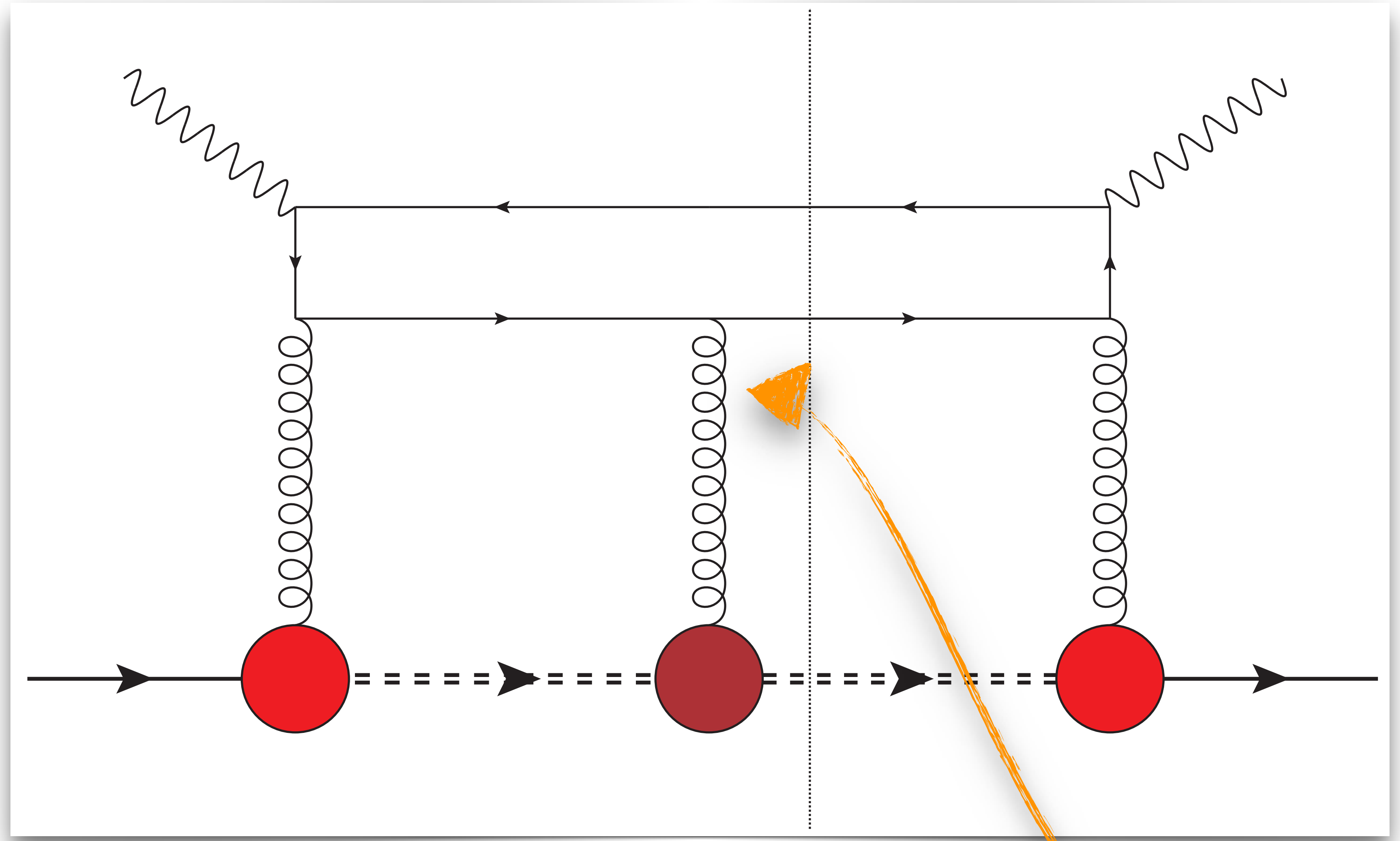

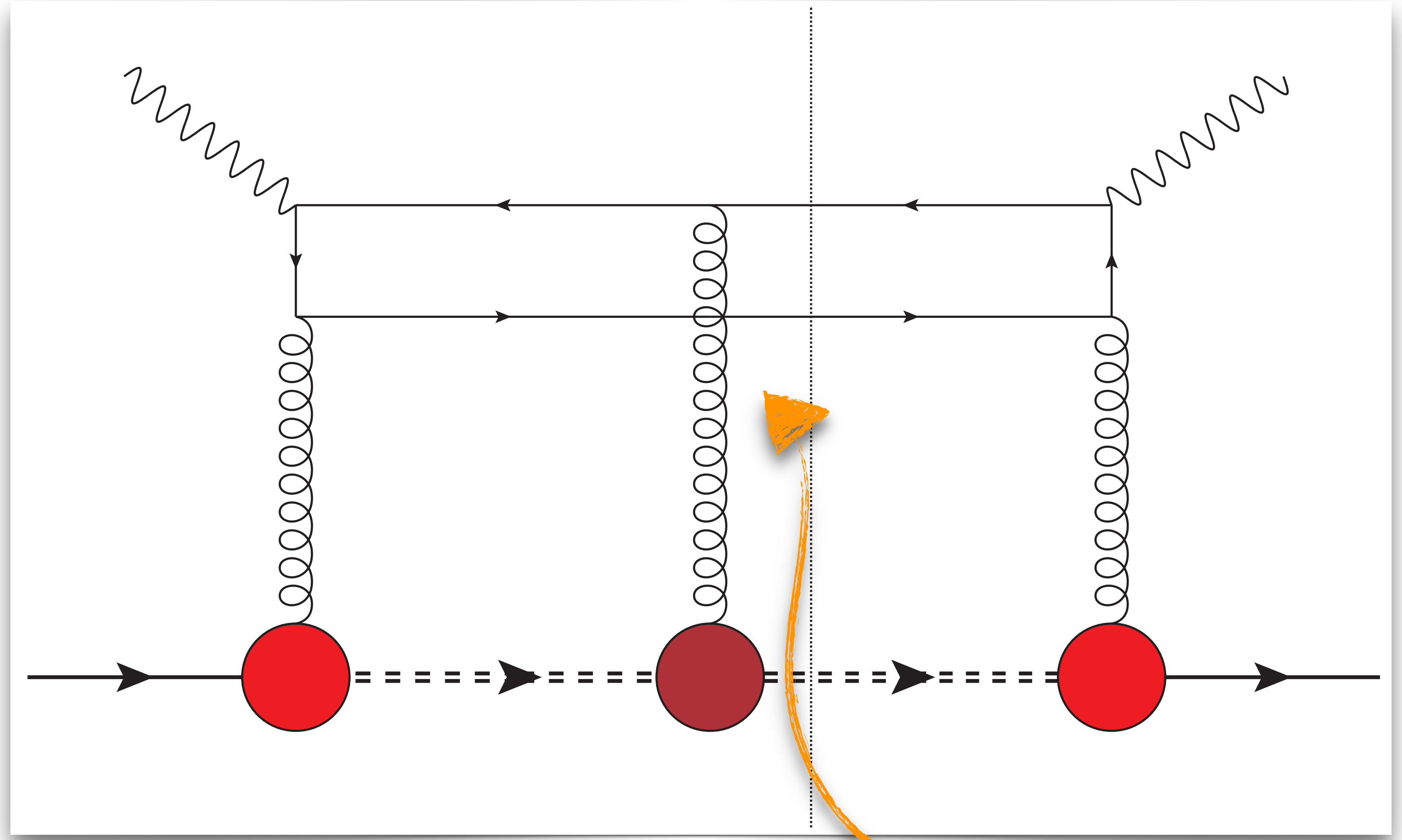

nucleon-gluon-spectator

spectator-gluon-spectator

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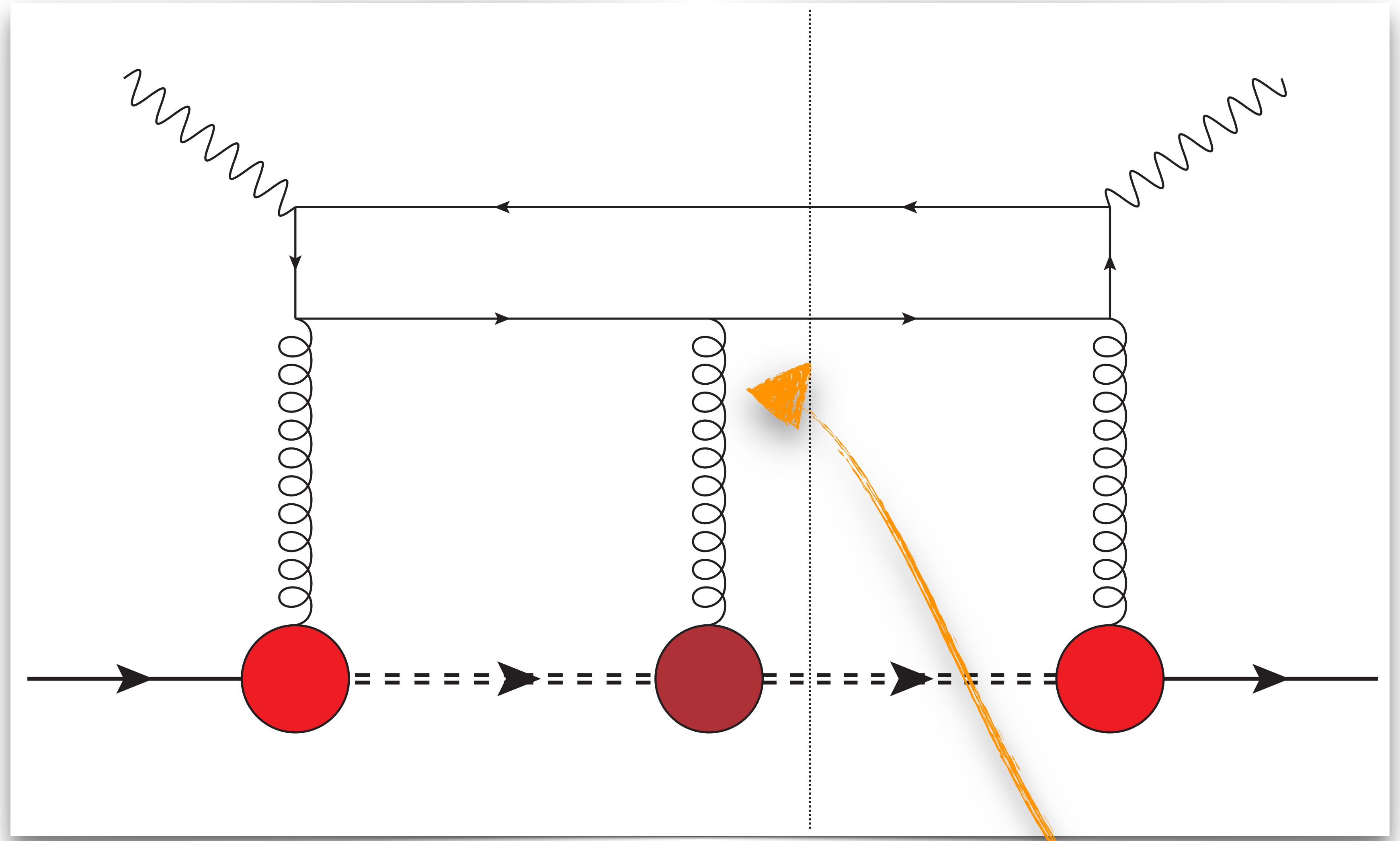

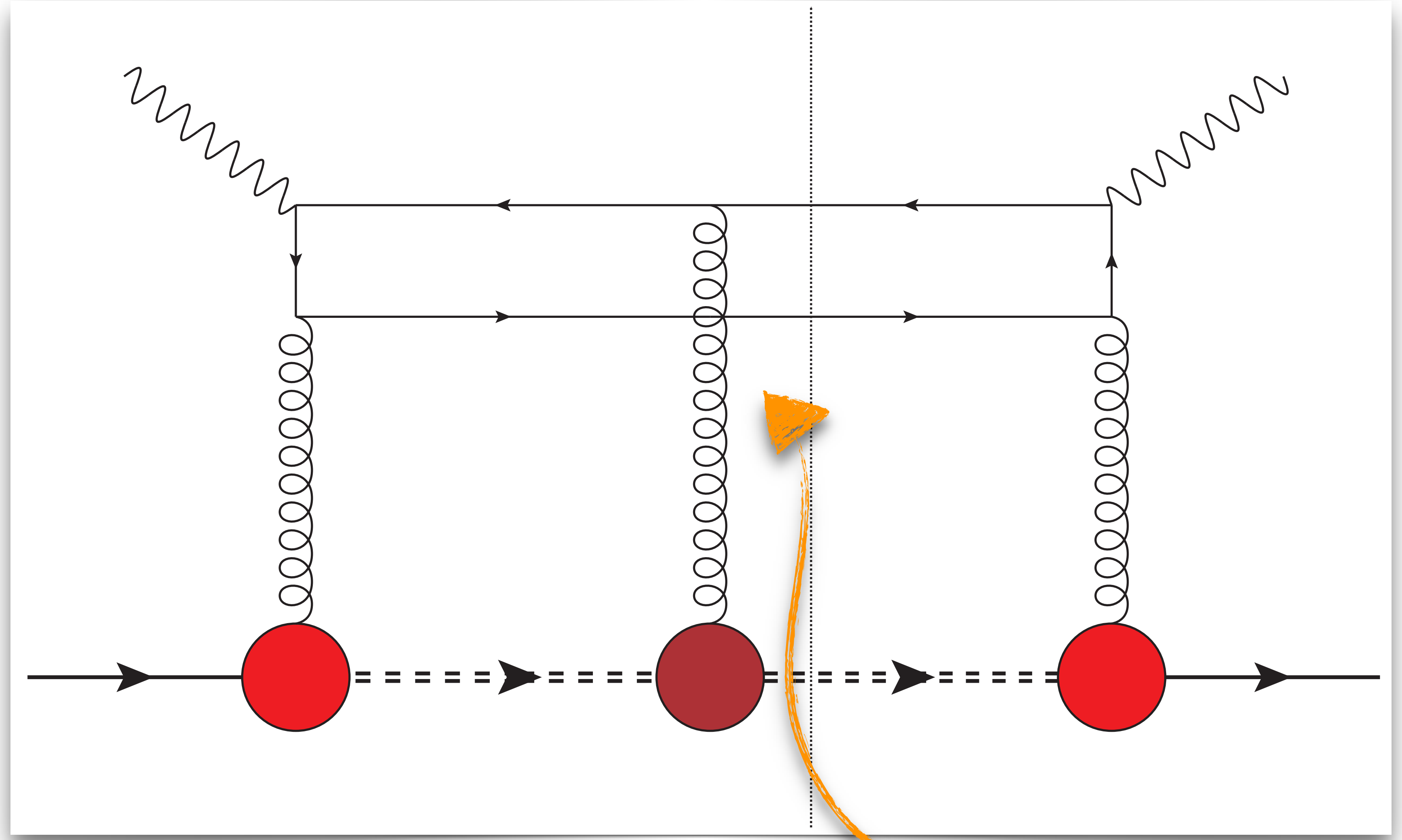

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[A. Bacchetta, F.G.C., M. Radici (in preparation)]

TMD factorization

Parton densities: an incomplete family tree

Wigner distributions **5D**

$\rho\left(x, \mathbf{k}_T, \mathbf{b}_T\right)$

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

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

Generalized Parton Distributions

GPDs

Transverse Momentum Distributions

TMDs **3D**

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

Parton Distribution Functions **1D**

PDFs

slide adapted from C. Bissolotti

Backup

Parton densities: an incomplete family tree

3D

TMDs

(semi-)inclusive

5D

Wigner distributions

3D

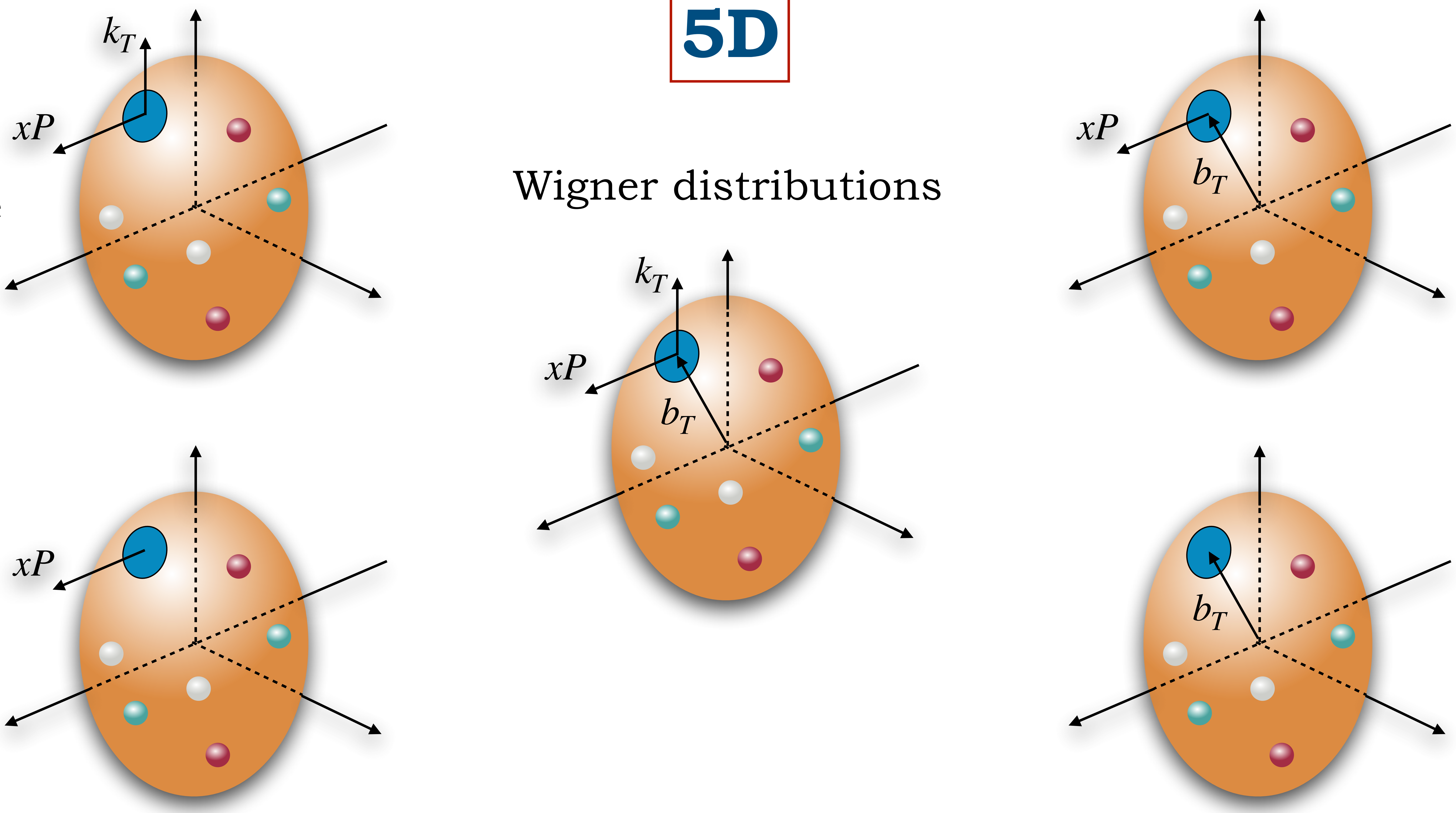
FT of GPDs

exclusive

PDFs

(semi-)inclusive

FT of Form Factors



1D

2D

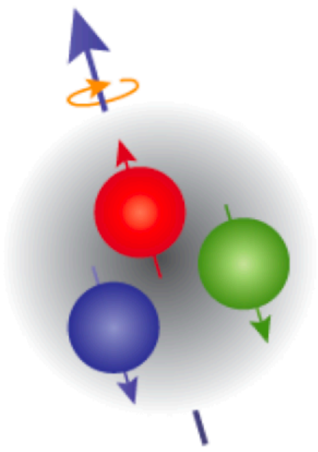
$\vec{b}_\perp$ dependence

$\vec{k}_\perp$ dependence

these two variables are NOT Fourier conjugate

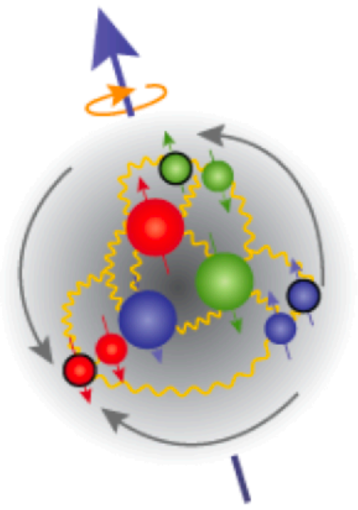
Backup

The proton spin crisis



quarks helicity

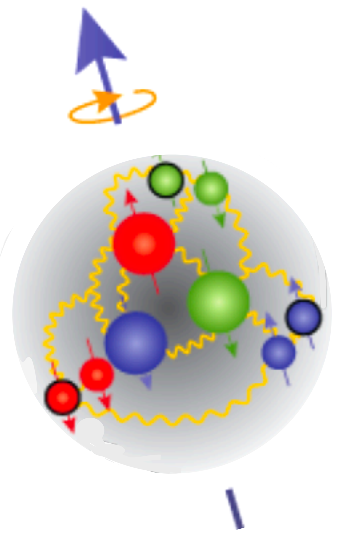
~ 30 %



orbital angular momentum

unknown!

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



gluons helicity

~ 20% – 50 % ?

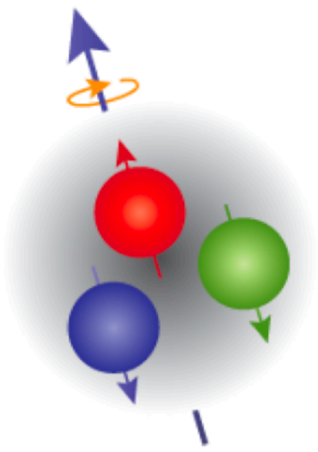
Total spin carried by quarks and gluons does not amount to 1/2, one needs orbital angular momentum, then a 3D description…

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

slide adapted from C. Bissolotti

Backup

The proton spin crisis



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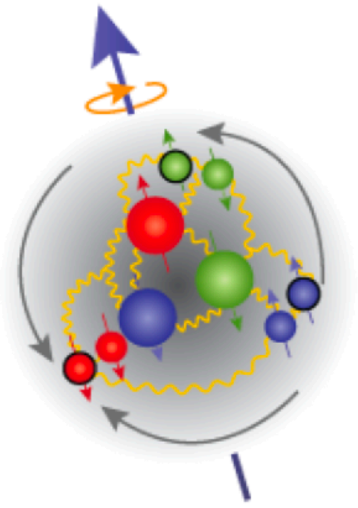

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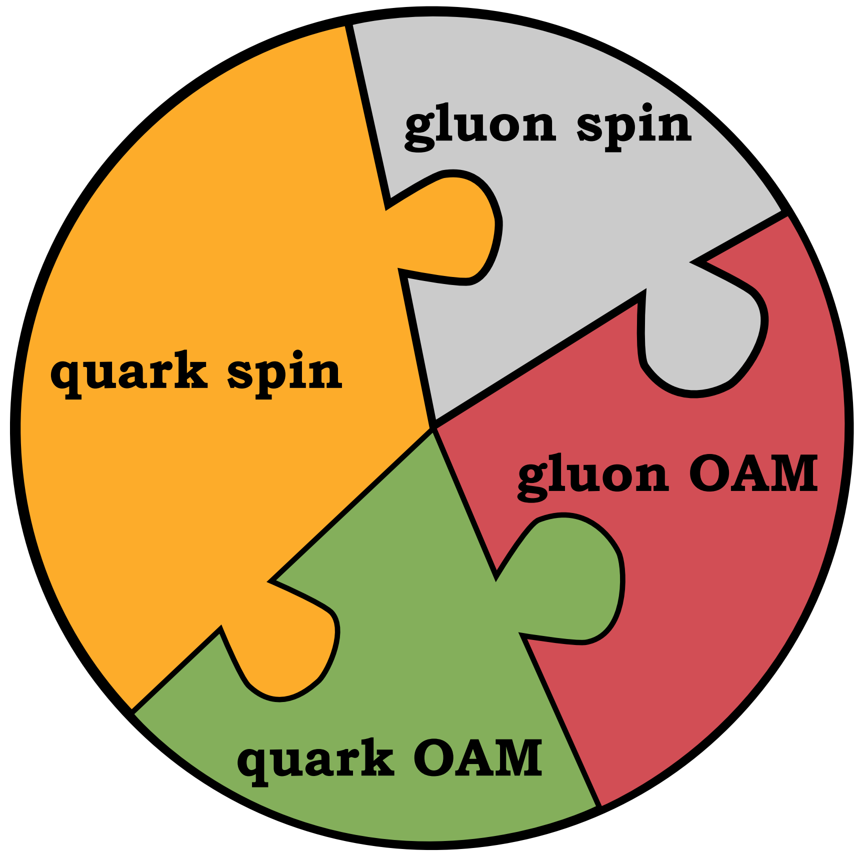

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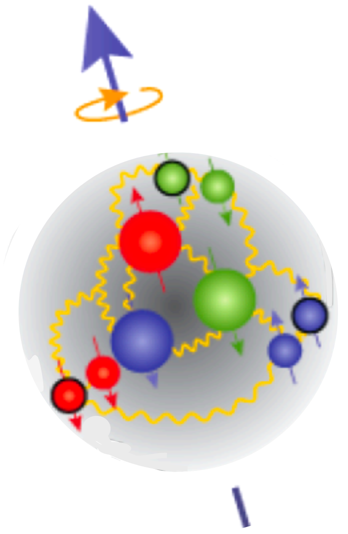

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Backup

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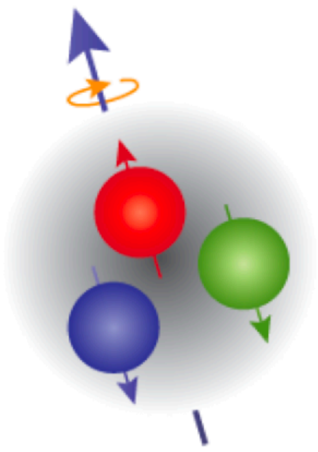
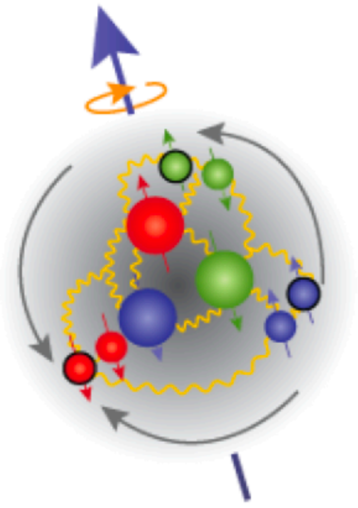


quarks helicity

$\sim 30\ \%$

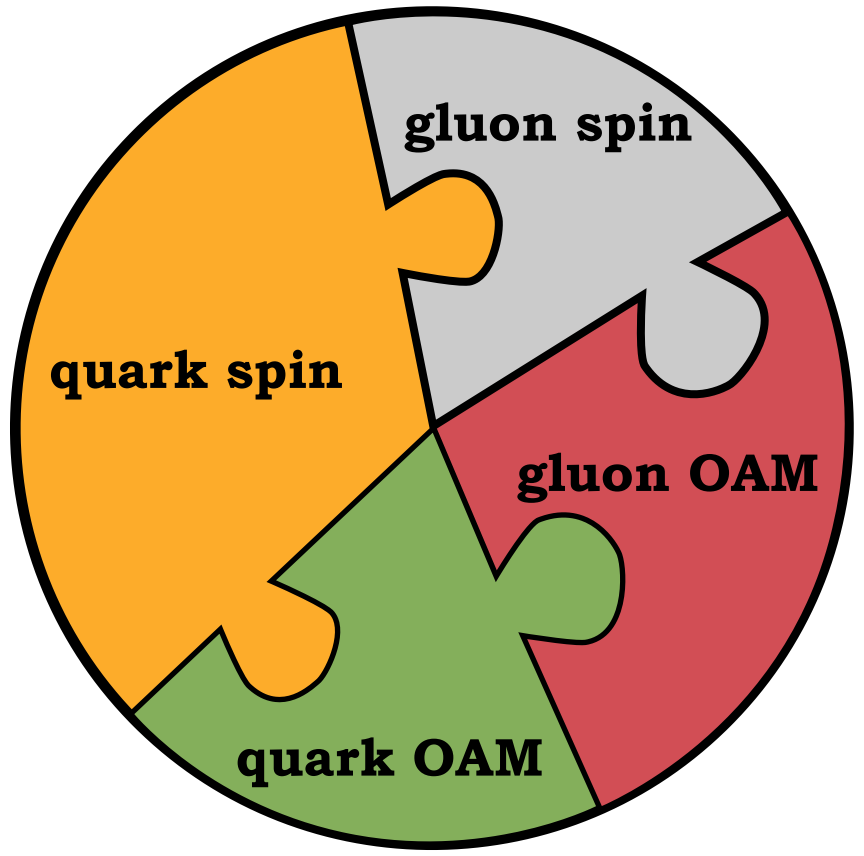


orbital angular momentum

$\boxed{\text{unknown!}}$

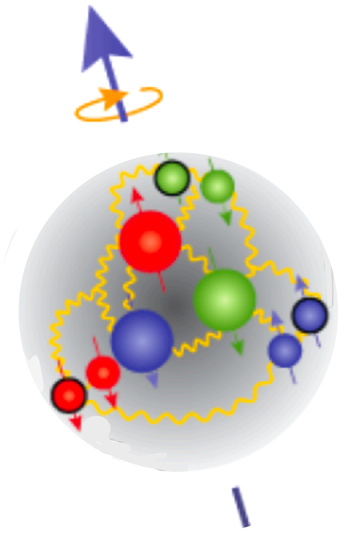
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

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



gluons helicity

$\sim\ 20\% - 50\ \%$ **?**



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Backup

Gluon TMDs: gauge links and modified universality

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

Backup

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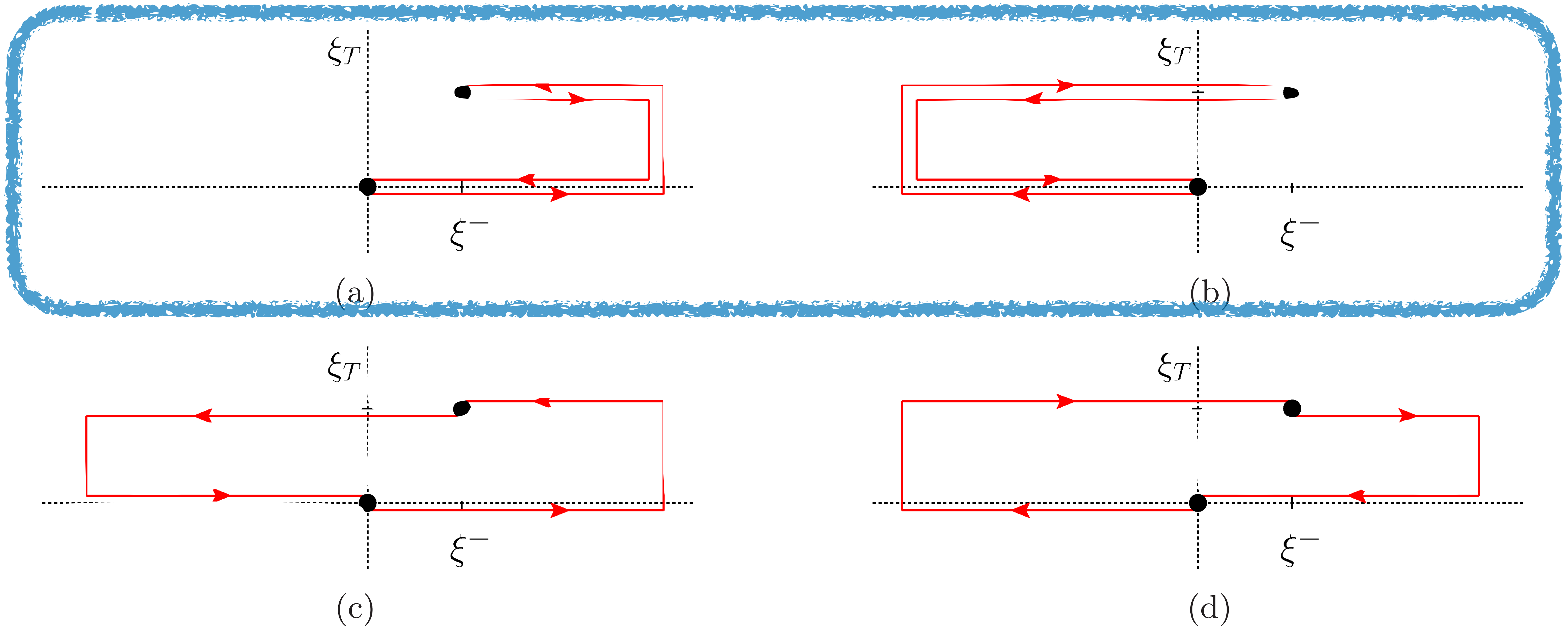
f-type (WW)

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



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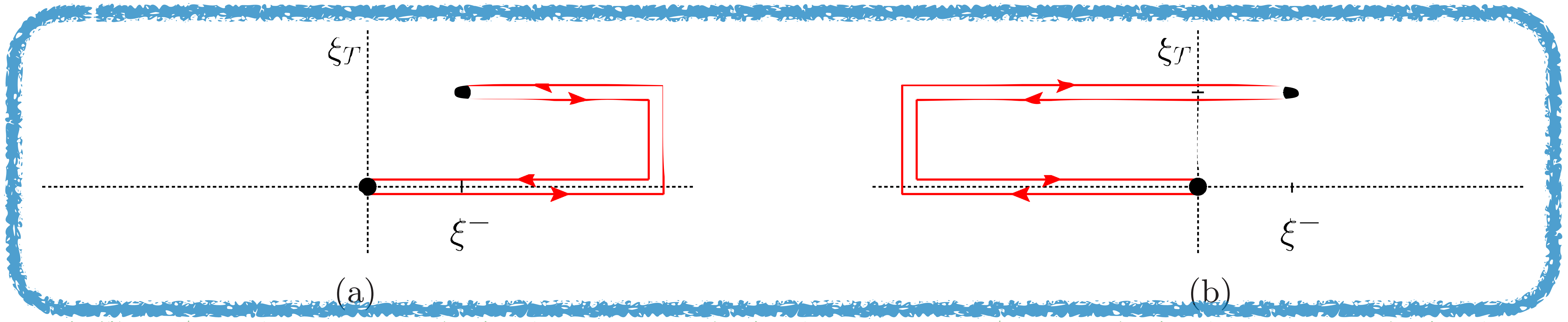
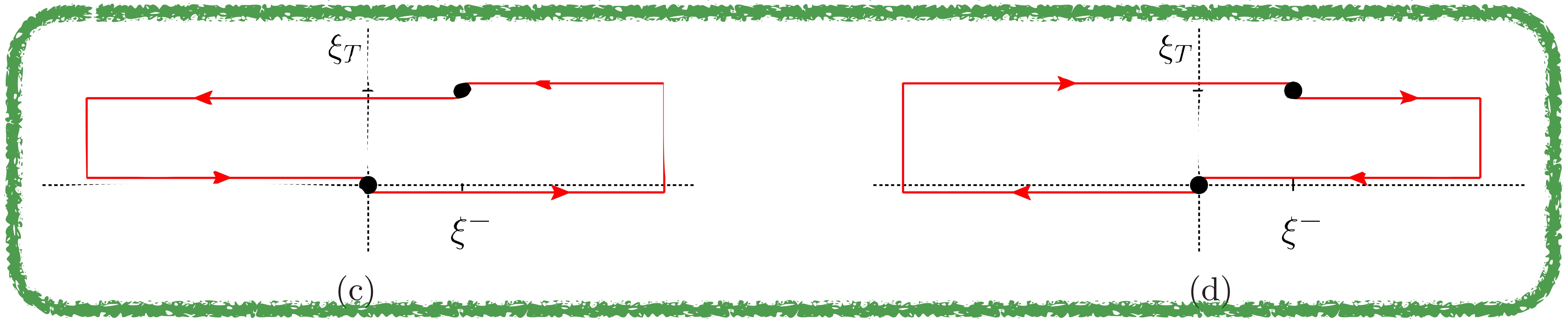


d-type (dipole)

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



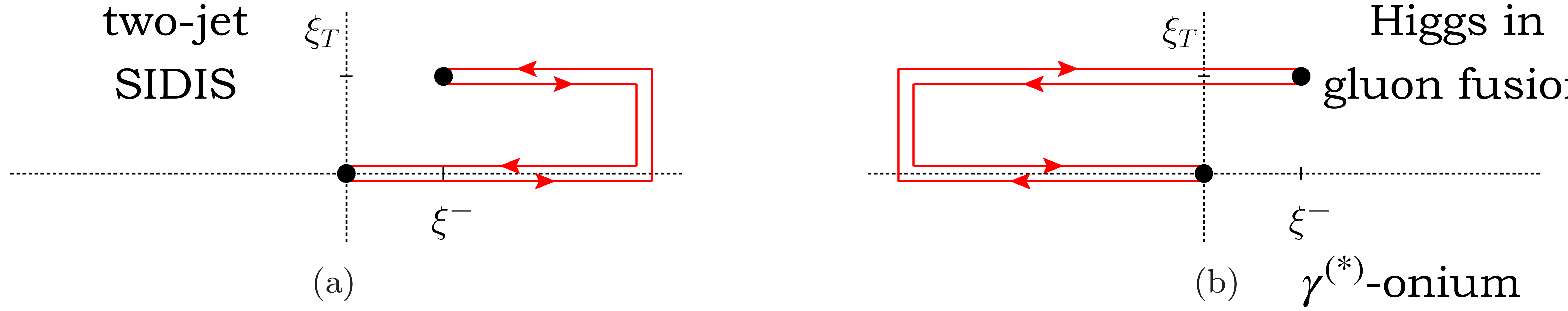
Backup

Accessing f-type and d-type gluon TMDs

f-type (WW)

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

two-jet
SIDIS



Higgs in
gluon fusion

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

Backup

Accessing f-type and d-type gluon TMDs

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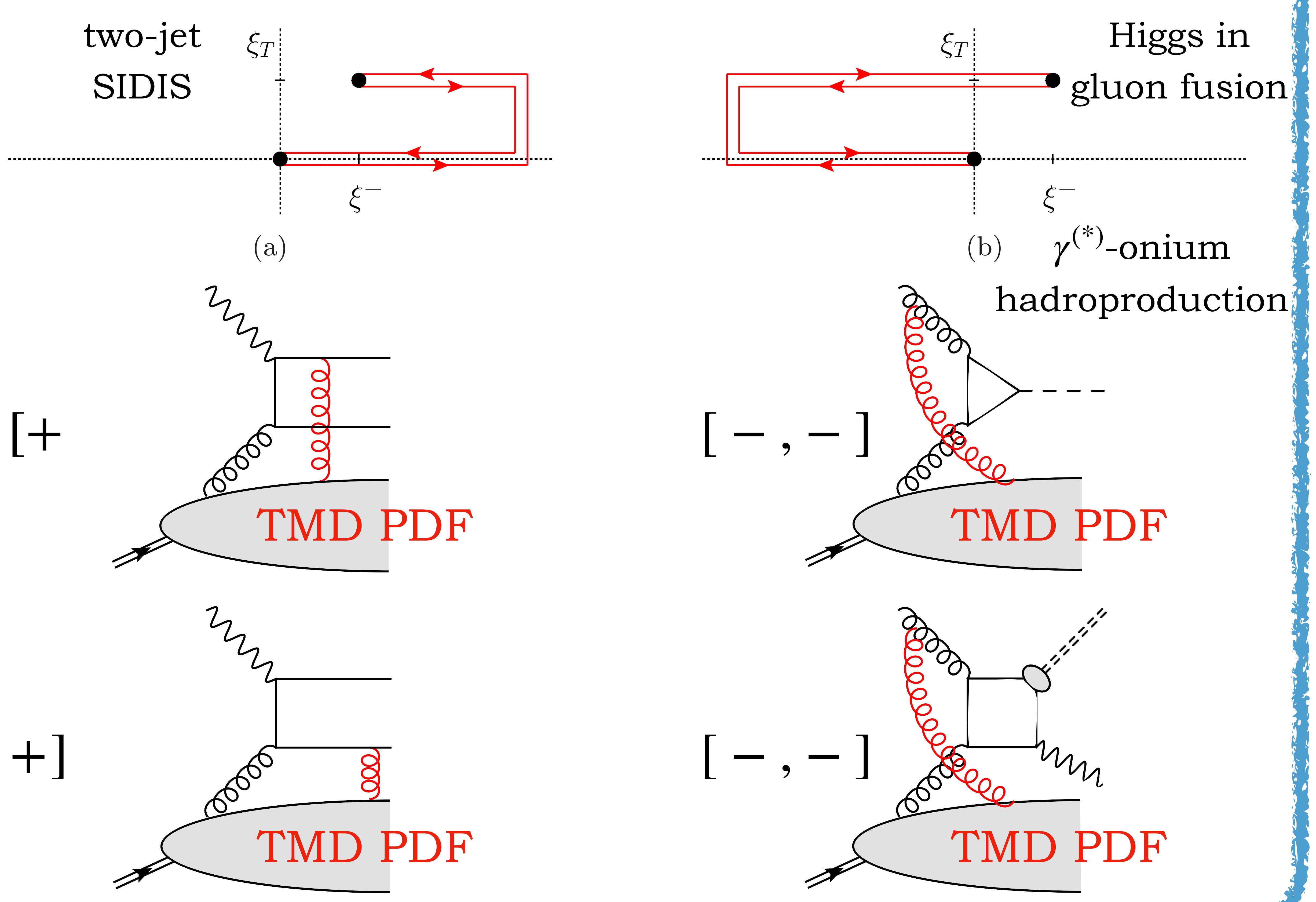

Backup

Accessing f-type and d-type gluon TMDs

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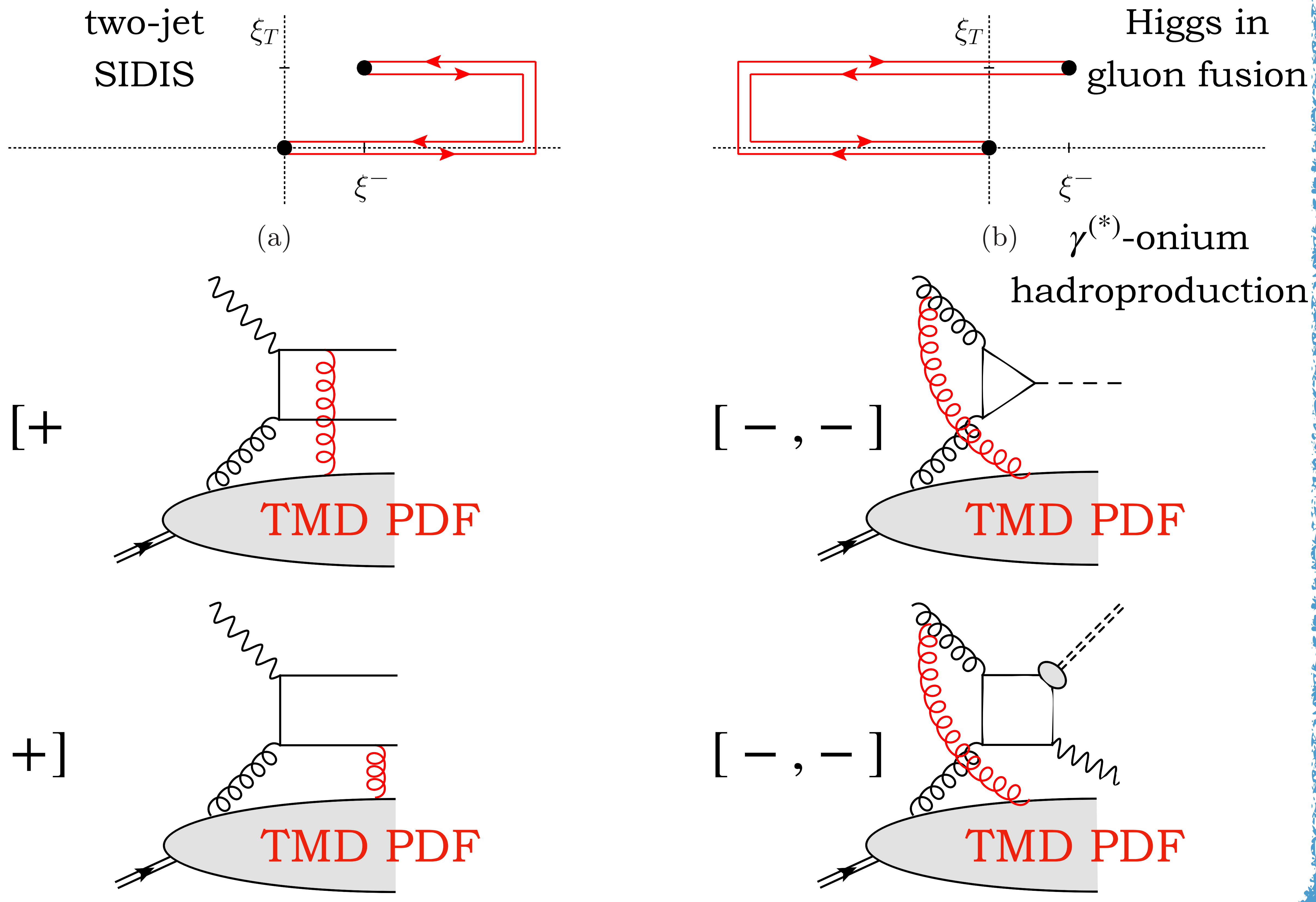
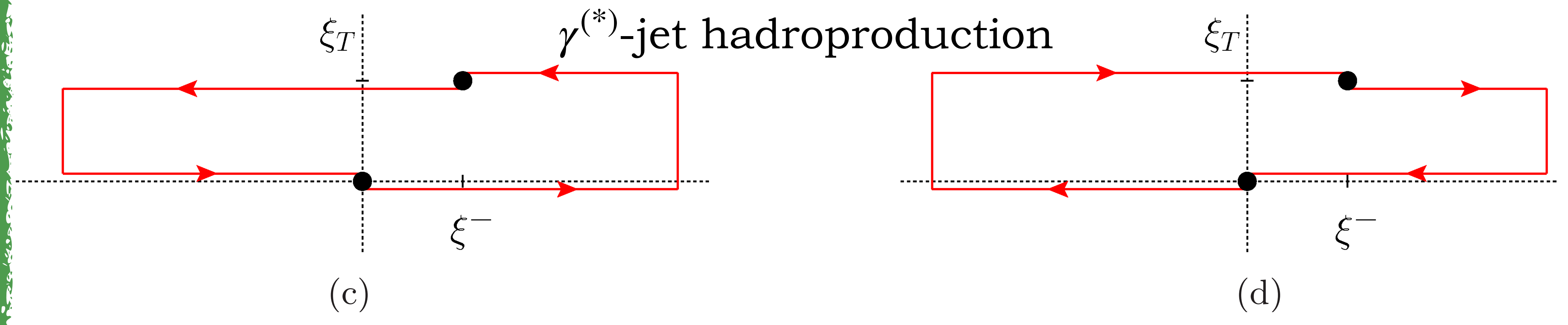


d-type (DP)

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

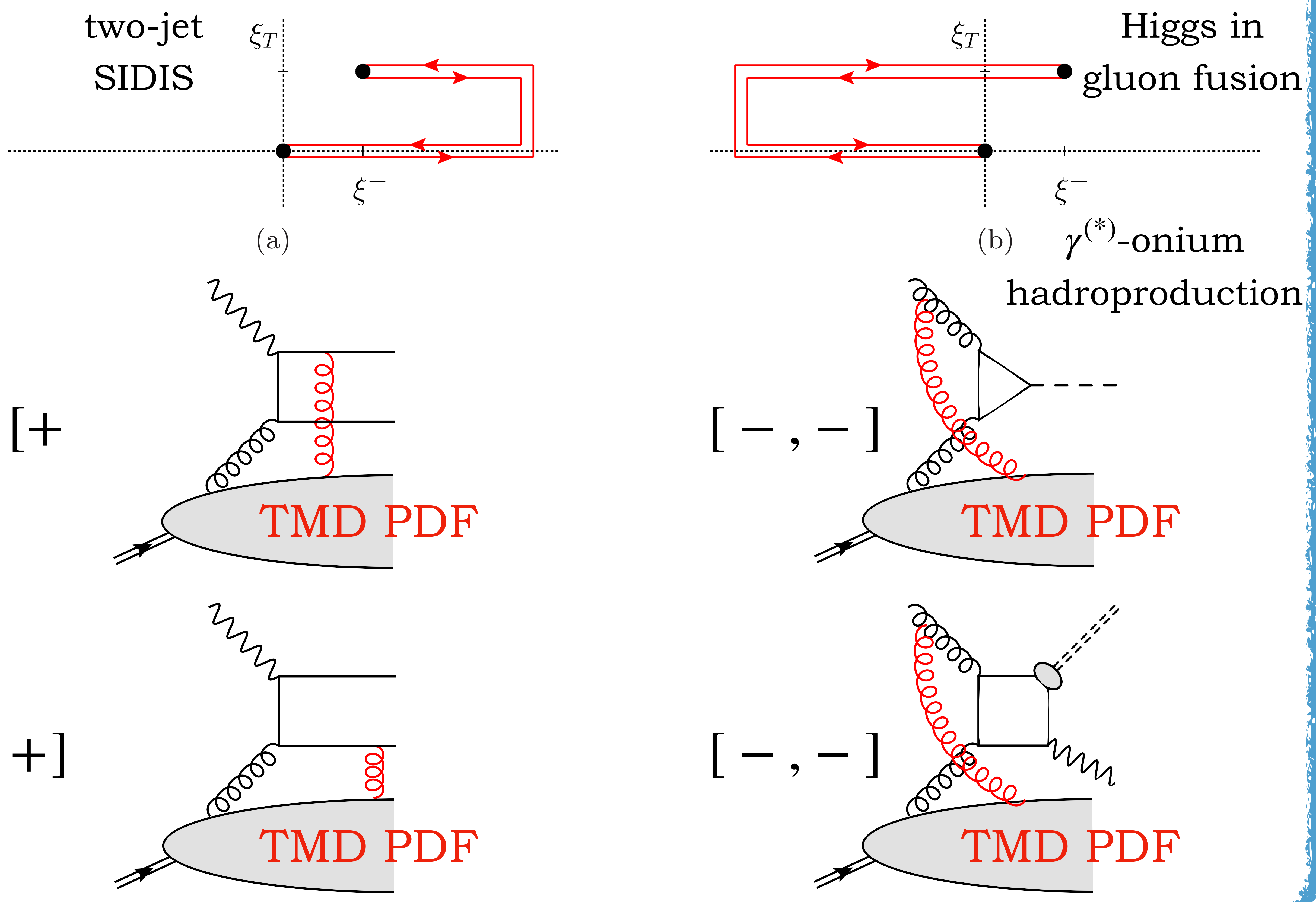


Backup

Accessing f-type and d-type gluon TMDs

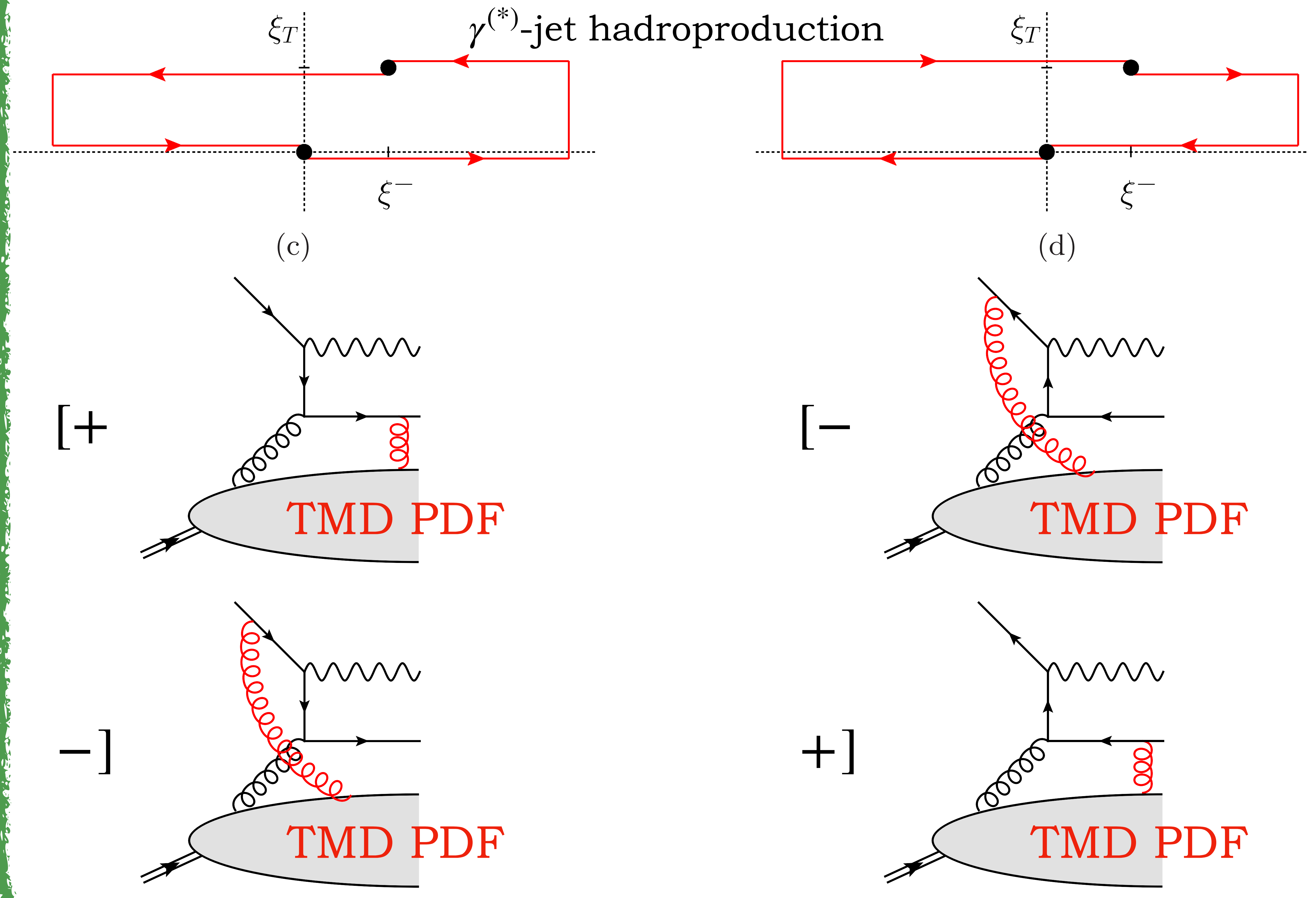
f-type (WW)

(a) [+ , +] or (b) [− , −]



d-type (DP)

(c) [+ , −] or (d) [− , +]

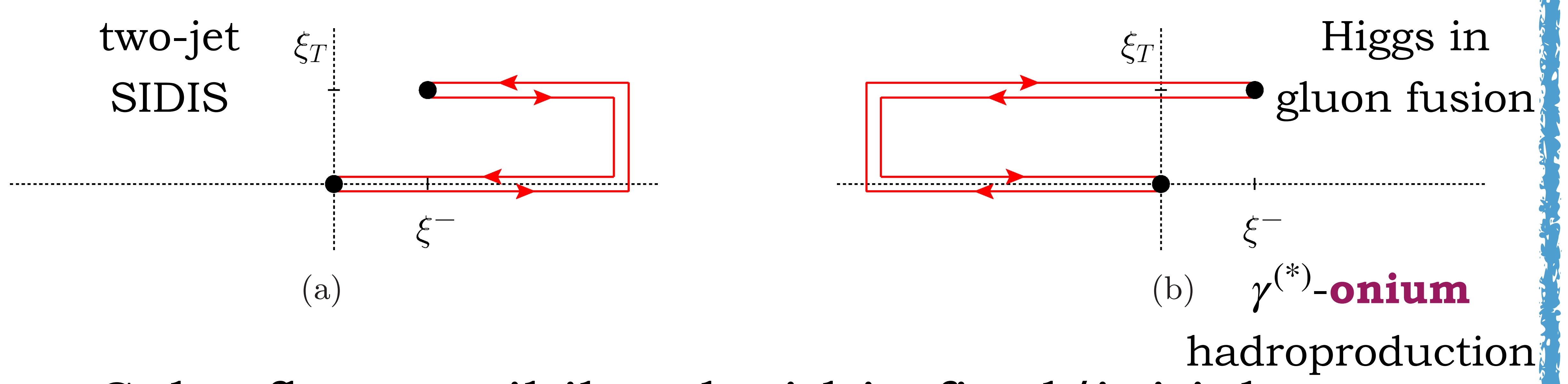


Backup

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

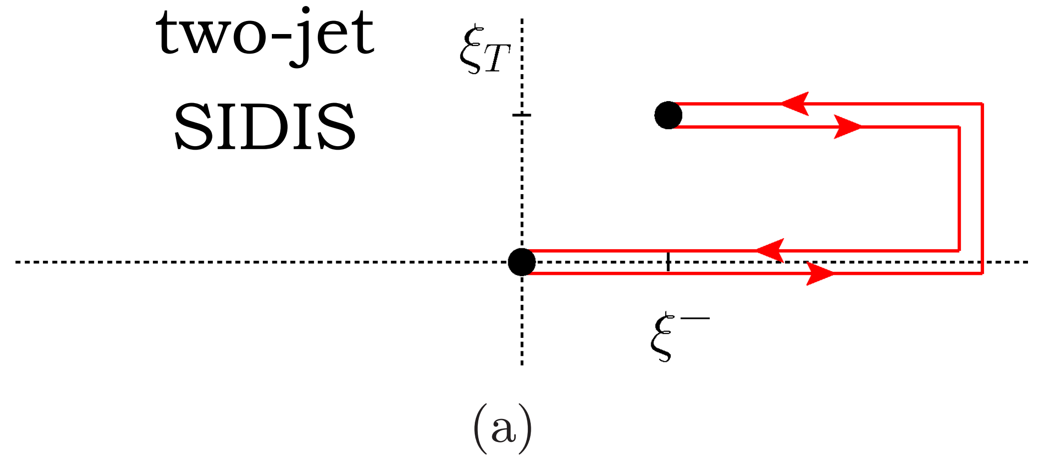
Backup

Accessing f-type and d-type gluon TMDs

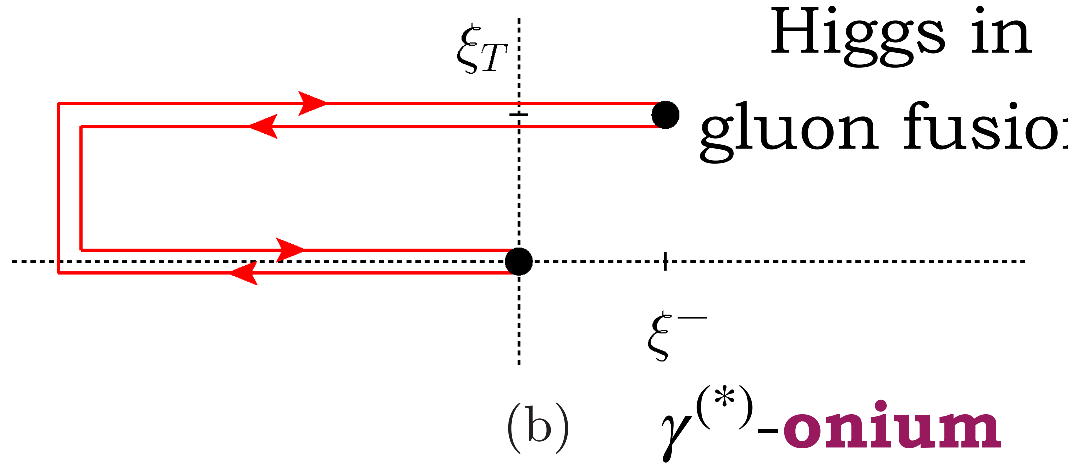
f-type (WW)

(a) [+ , +] or (b) [− , −]

two-jet SIDIS



Higgs in gluon fusion



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

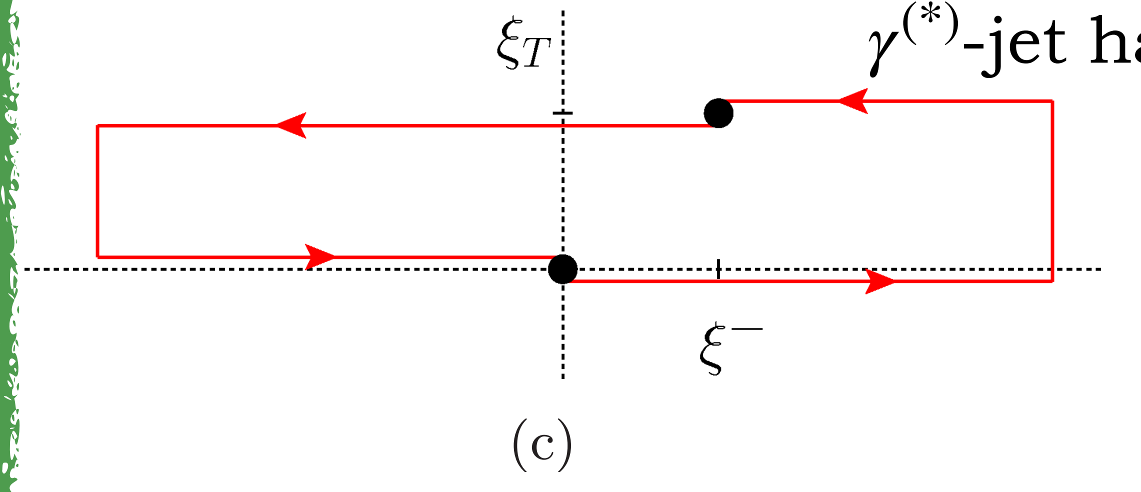
- Color flow annihilated within final/initial state
- *f*-type gluon TMDs $\rightarrow$ f^{abc} color structure
- Modified universality:

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

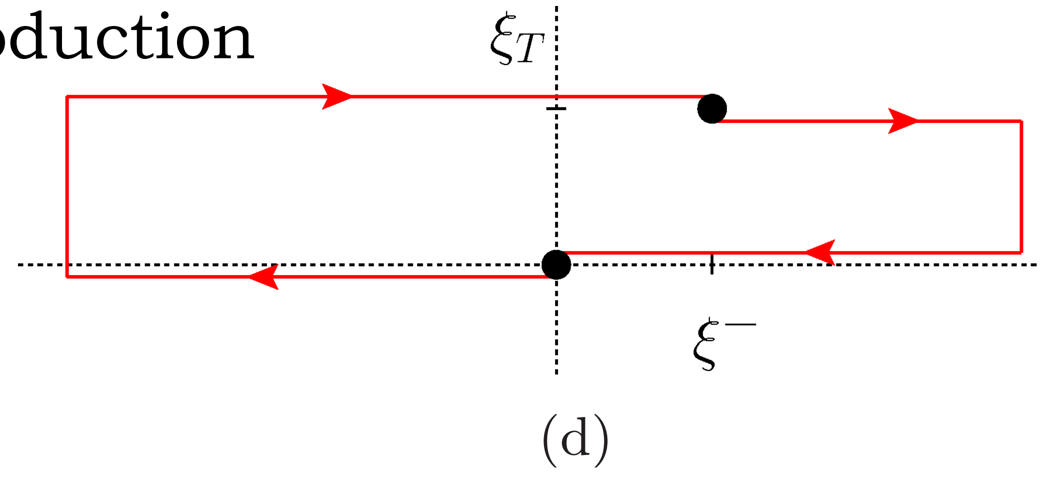
- Phenomenology: Higgs, **quarkonia** or $\gamma\gamma$ in pp, two-jet SIDIS, heavy-quark pair SIDIS

d-type (DP)

(c) [+ , −] or (d) [− , +]



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



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

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

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

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

Backup

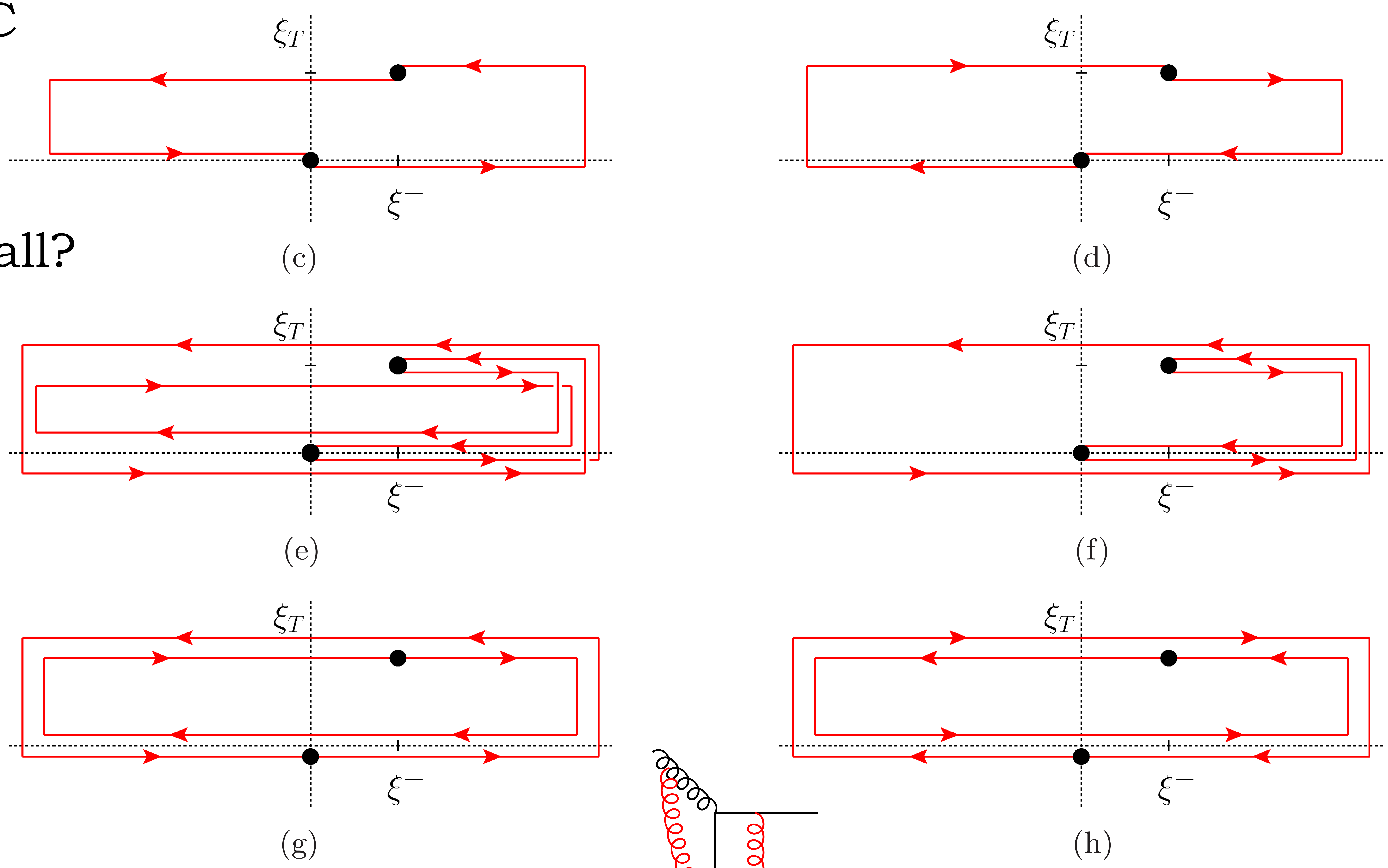
Dihadron hadroproduction and factorization breaking

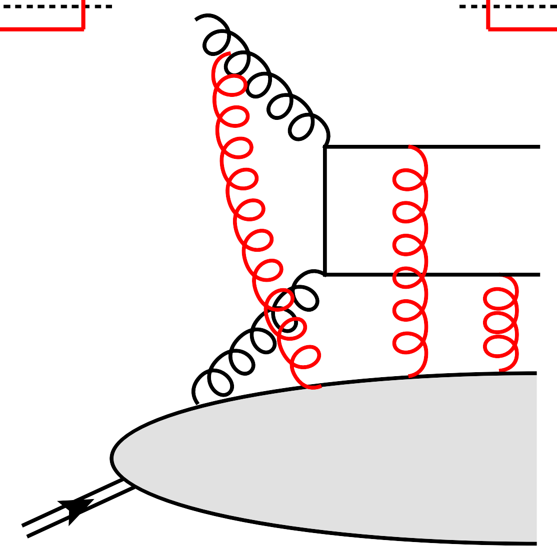
- Proof of factorization violation [T. J. Rogers, P. J. Mulders (2010)]
- Assumed factorization in SCET and CGC
- Significance of low-x studies
- Size of factorization-breaking effects small?
- DP TMDs:

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

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

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





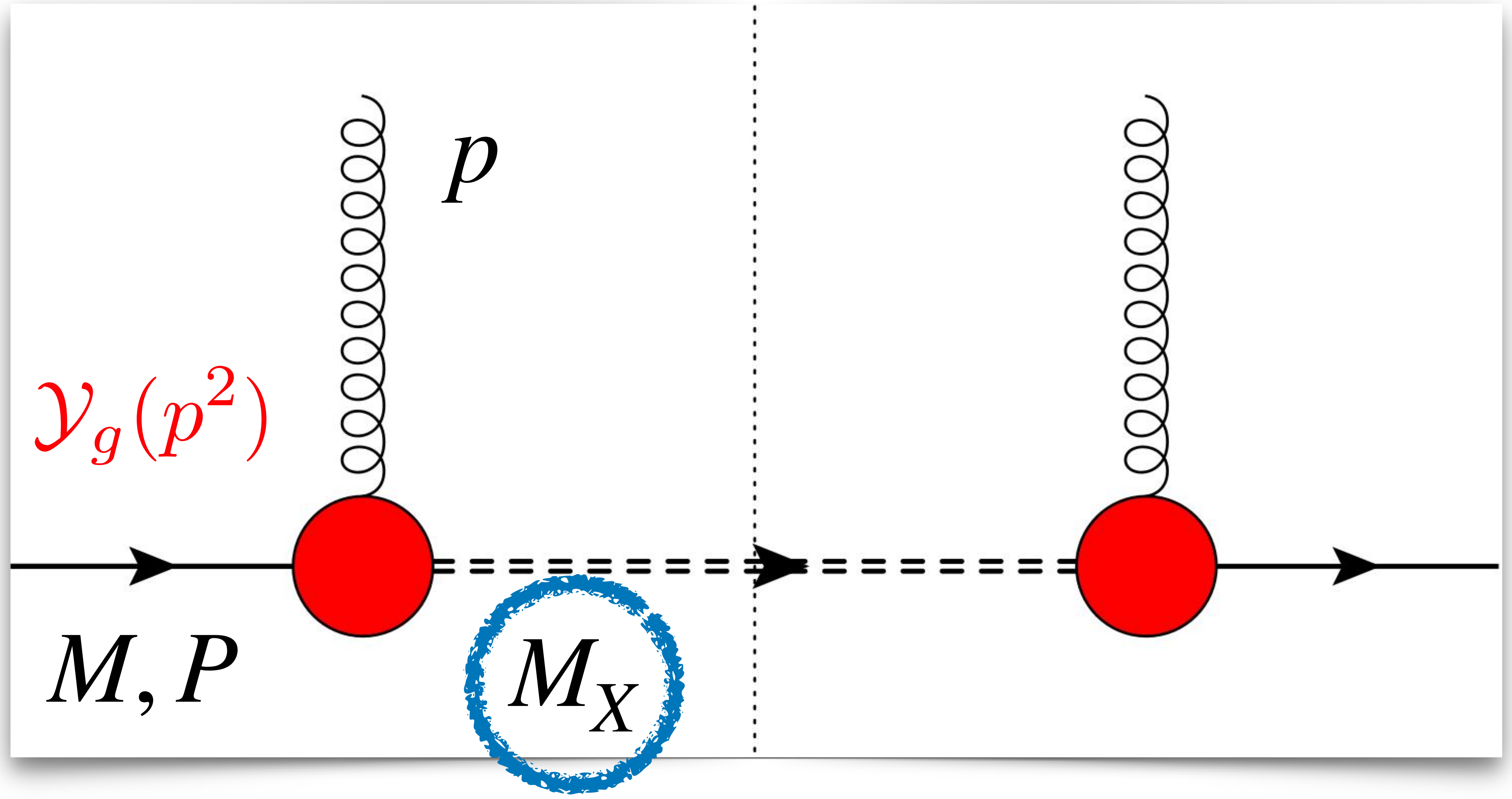
Backup

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



Backup

Assumptions of the model

Spin-1/2 spectator

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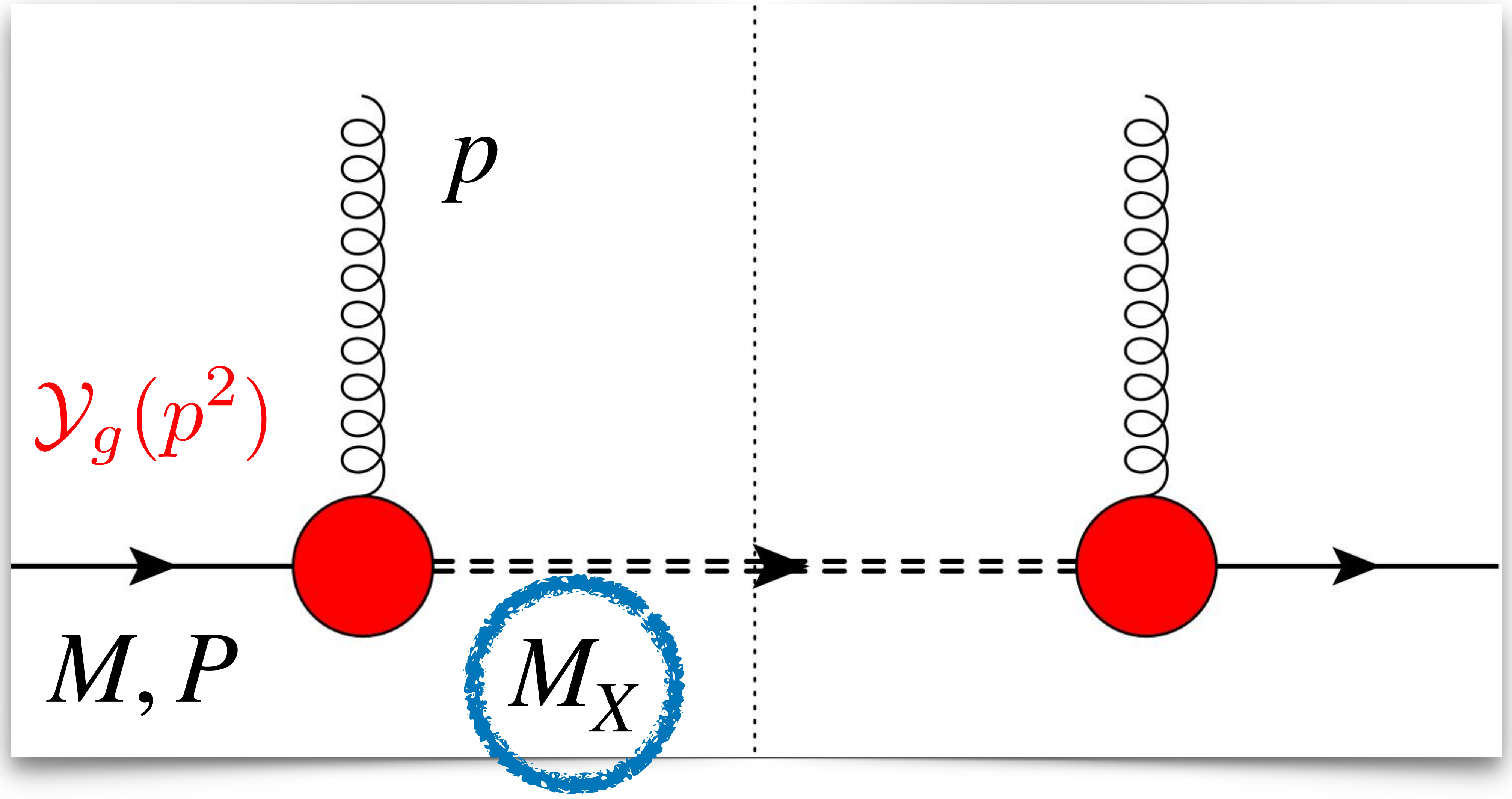


Nucleon-gluon-spectator vertex

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

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

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

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

Dipolar form factor(s)

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

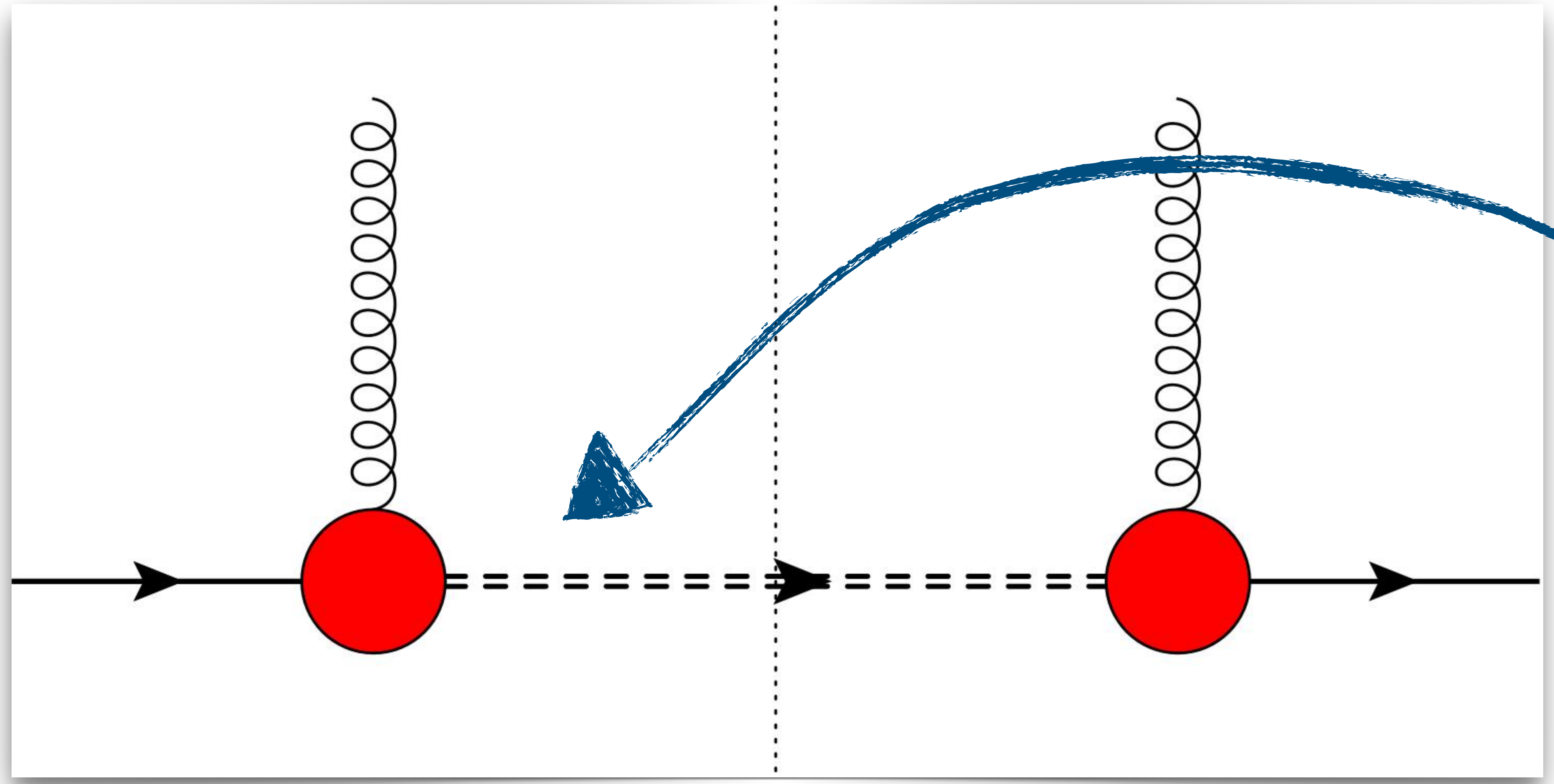
Spectator-system spectral-mass function

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

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

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

spectral-mass function

spectator-model TMD

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

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

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

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

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

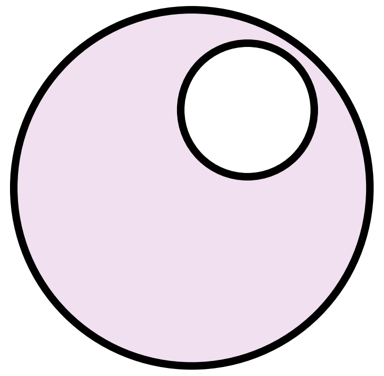
moderate-x trend

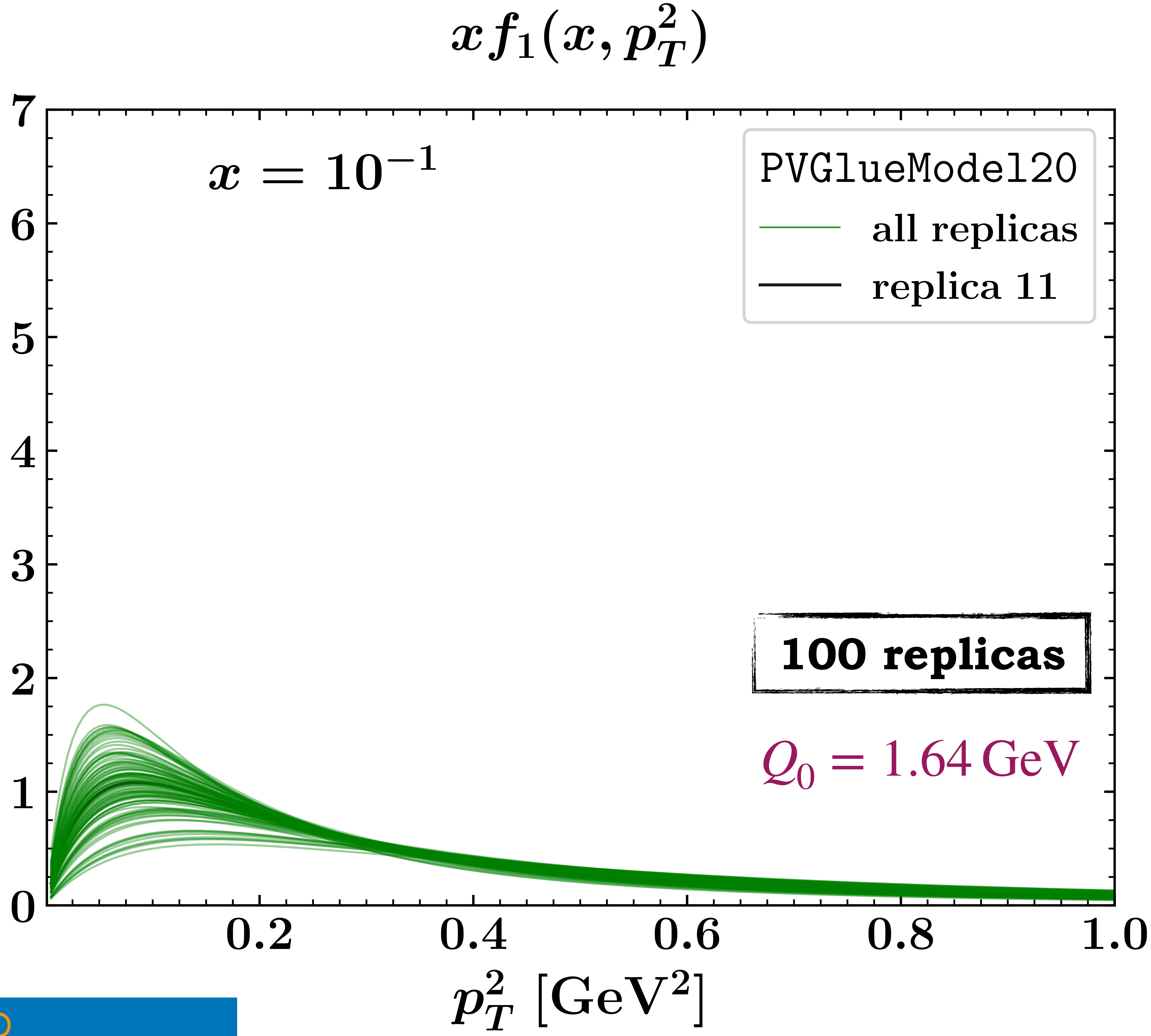
pure tri-quark contribution at low M_X

Backup

Unpolarized gluon TMD

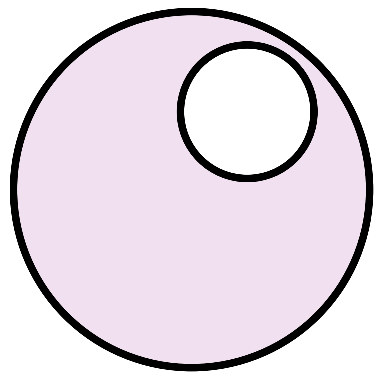
[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

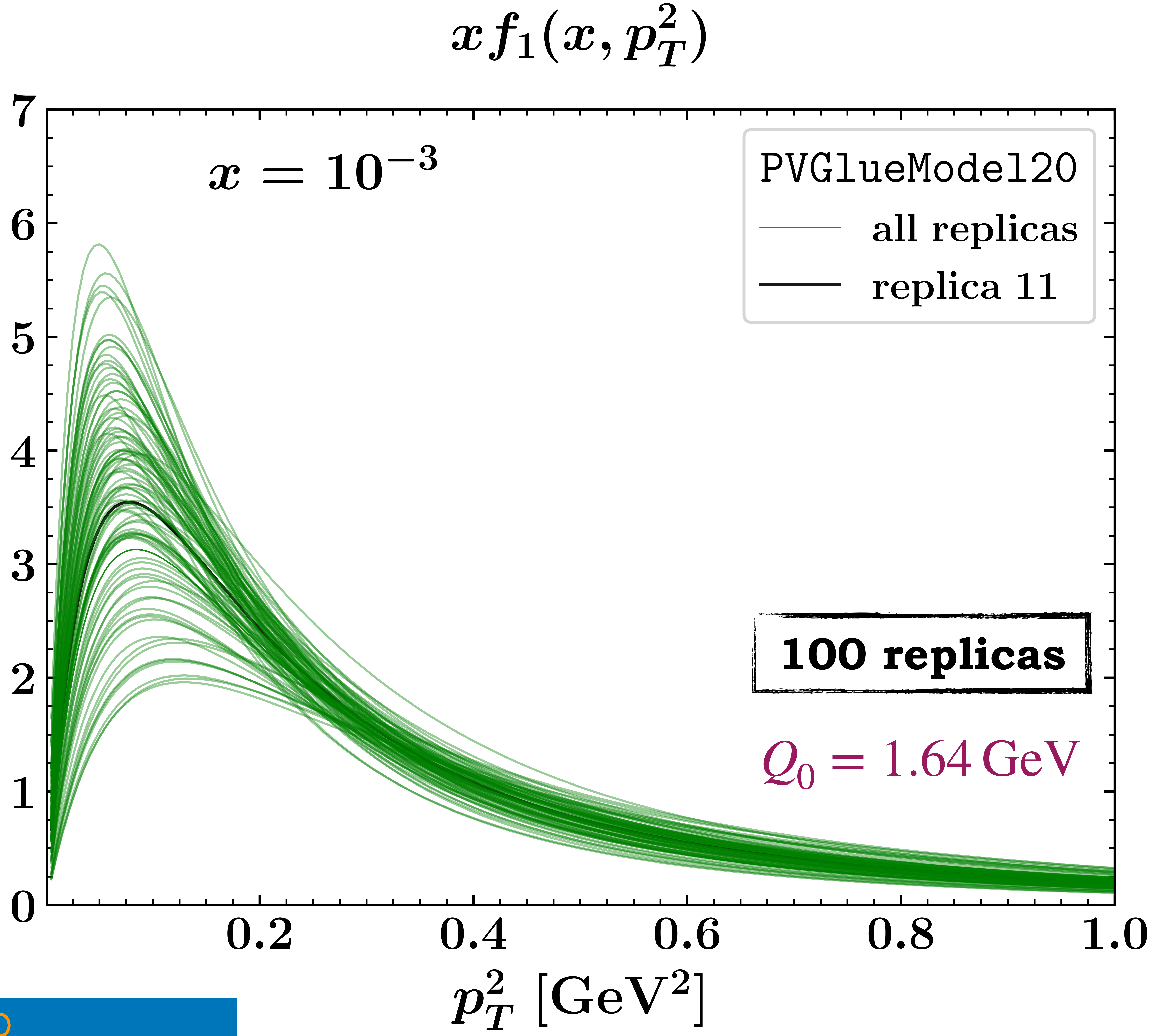




Unpolarized gluon TMD

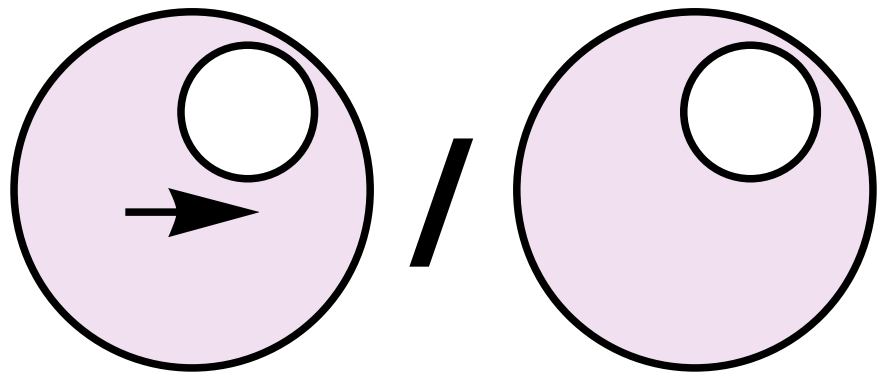
[A. Bacchetta, F.G. C., M. Radici, P. Taels (2020)]

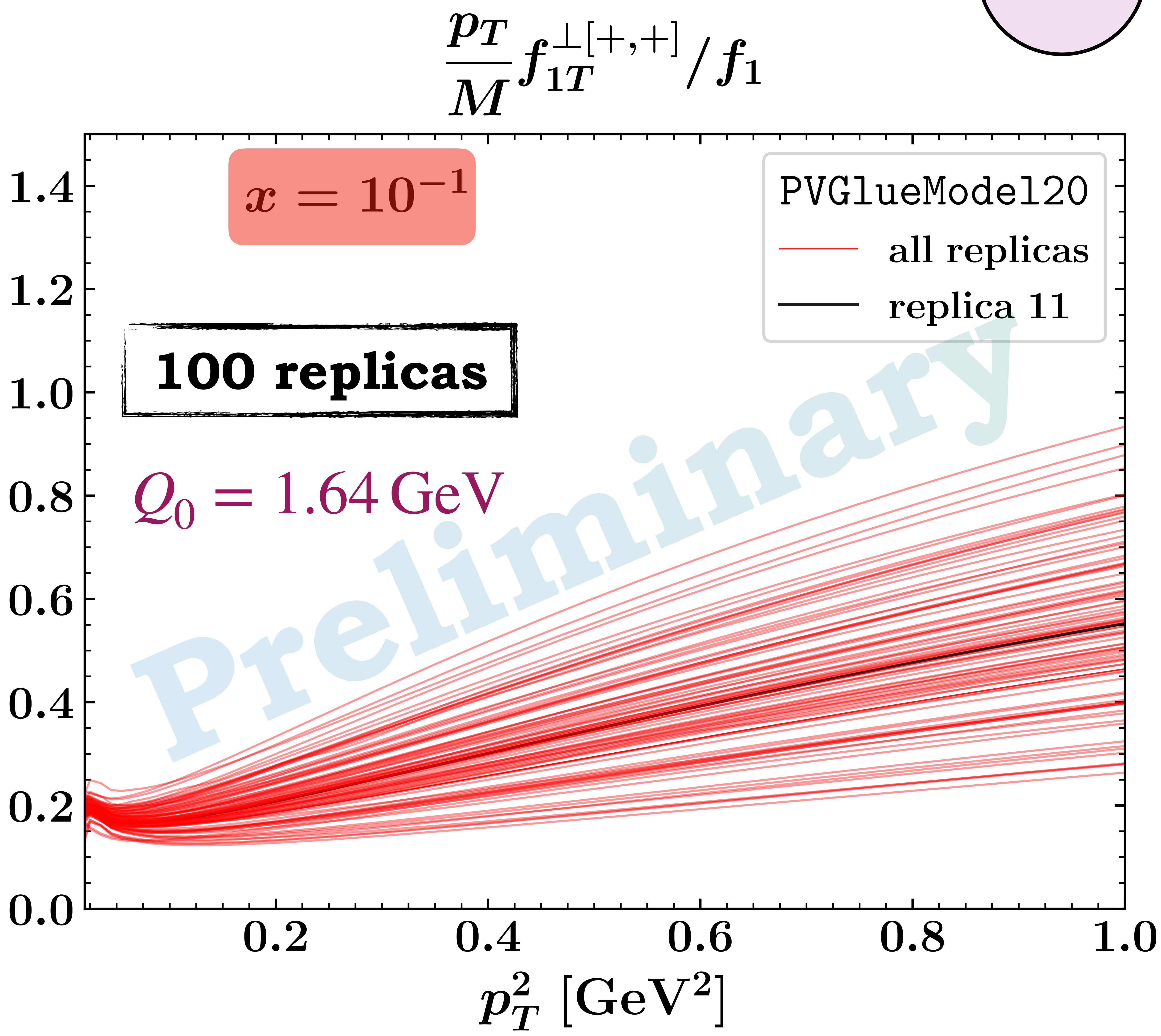


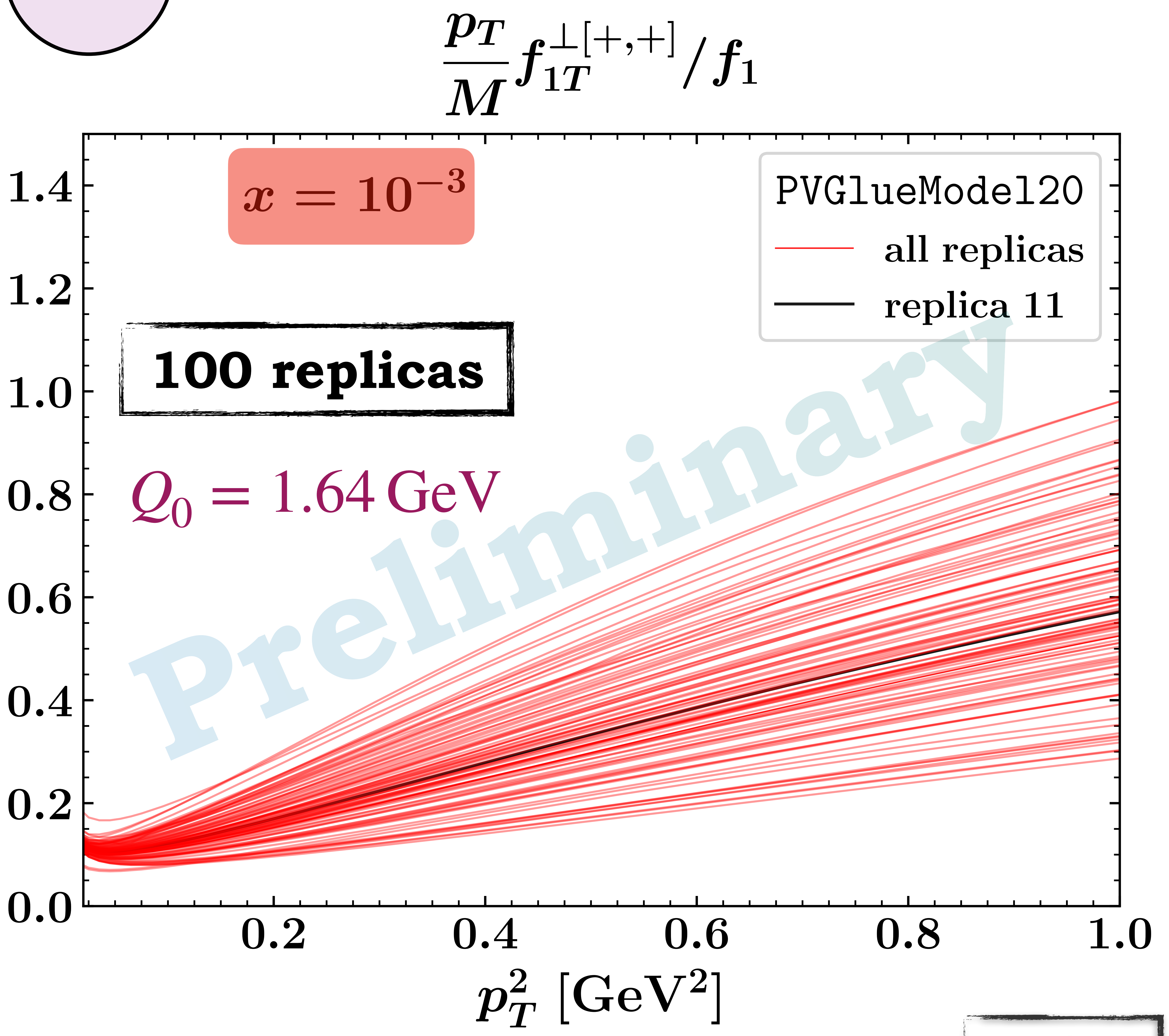


f-type Sivers/unpol.

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







Backup

Gluon TMD correlator and T-odd gluon densities

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

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

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

Backup

Gluon TMD correlator and T-odd gluon densities

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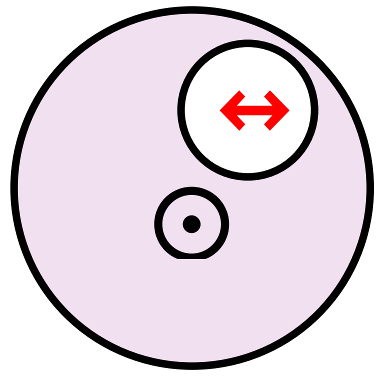
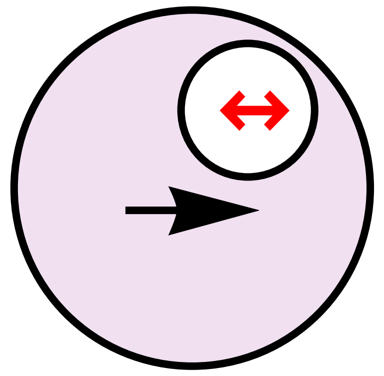
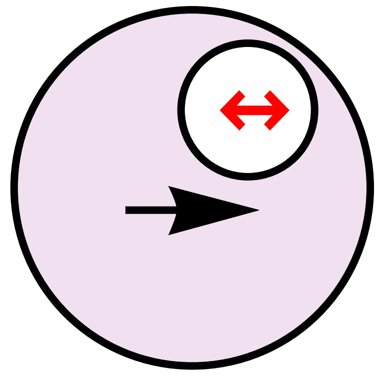


pseudo worm-gear



linearity TMD

pretzelosity



Backup

Gluon TMD correlator and T-odd gluon densities

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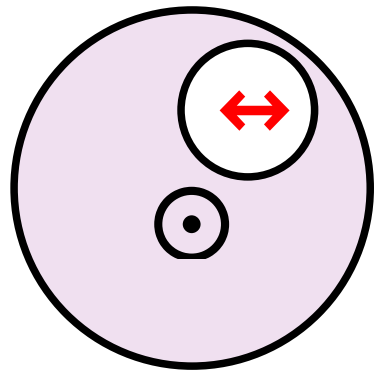
$$\Gamma_L^{ij}(x,\boldsymbol{k}) = x\left[i\epsilon_T^{ij} S_L\, g_1(x,\boldsymbol{k}^2) + \frac{\epsilon_T^{\{i}{}_{\alpha} k_T^{j\}\alpha} S_L}{2M^2}\, h_{1L}^{\perp}(x,\boldsymbol{k}^2)\right]$$

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



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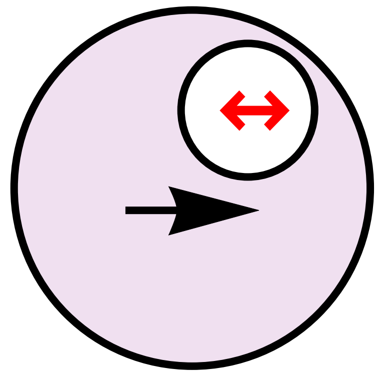
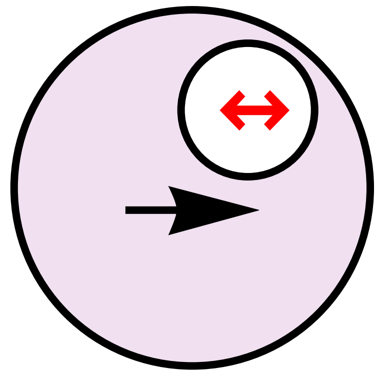
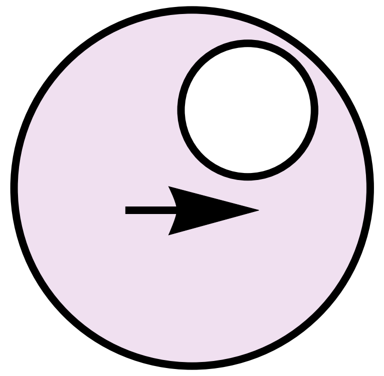


linearity TMD

pretzelosity



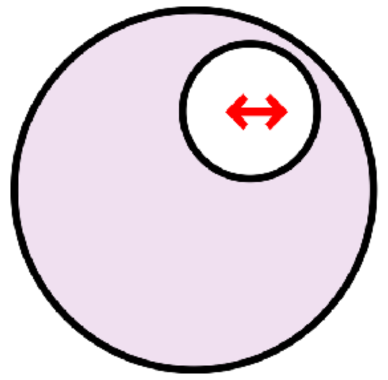
Sivers



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

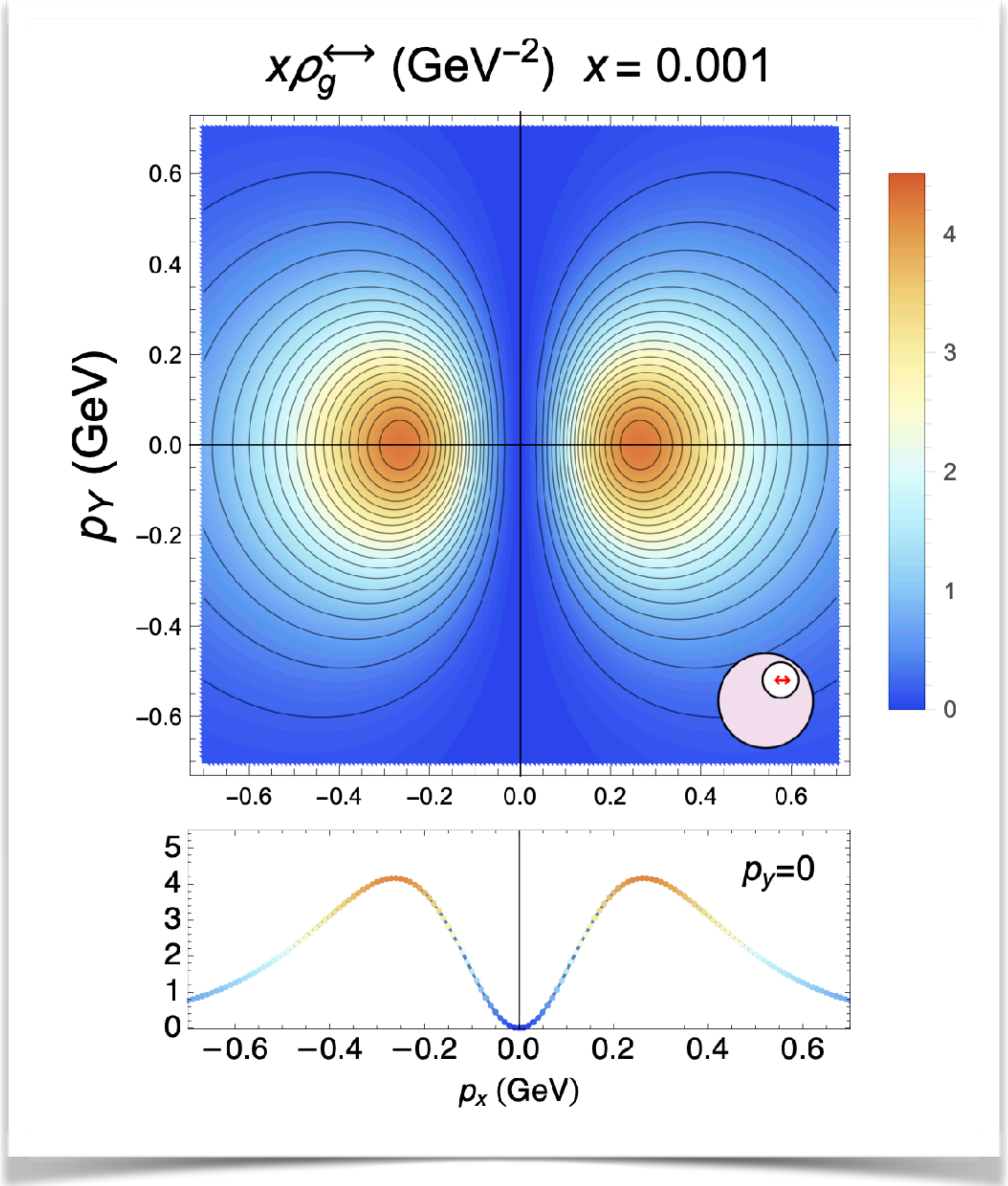
Backup

Boer-Mulders effect in unpolarised pp collisions



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

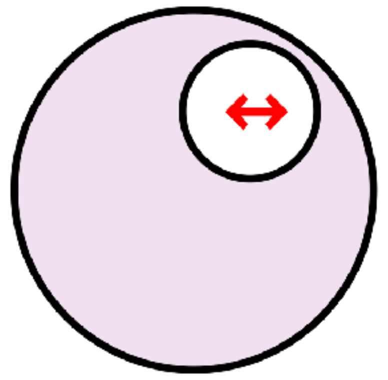
unpol. Boer-Mulders



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

Backup

Boer-Mulders effect in unpolarised pp collisions



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

unpol. Boer-Mulders

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

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

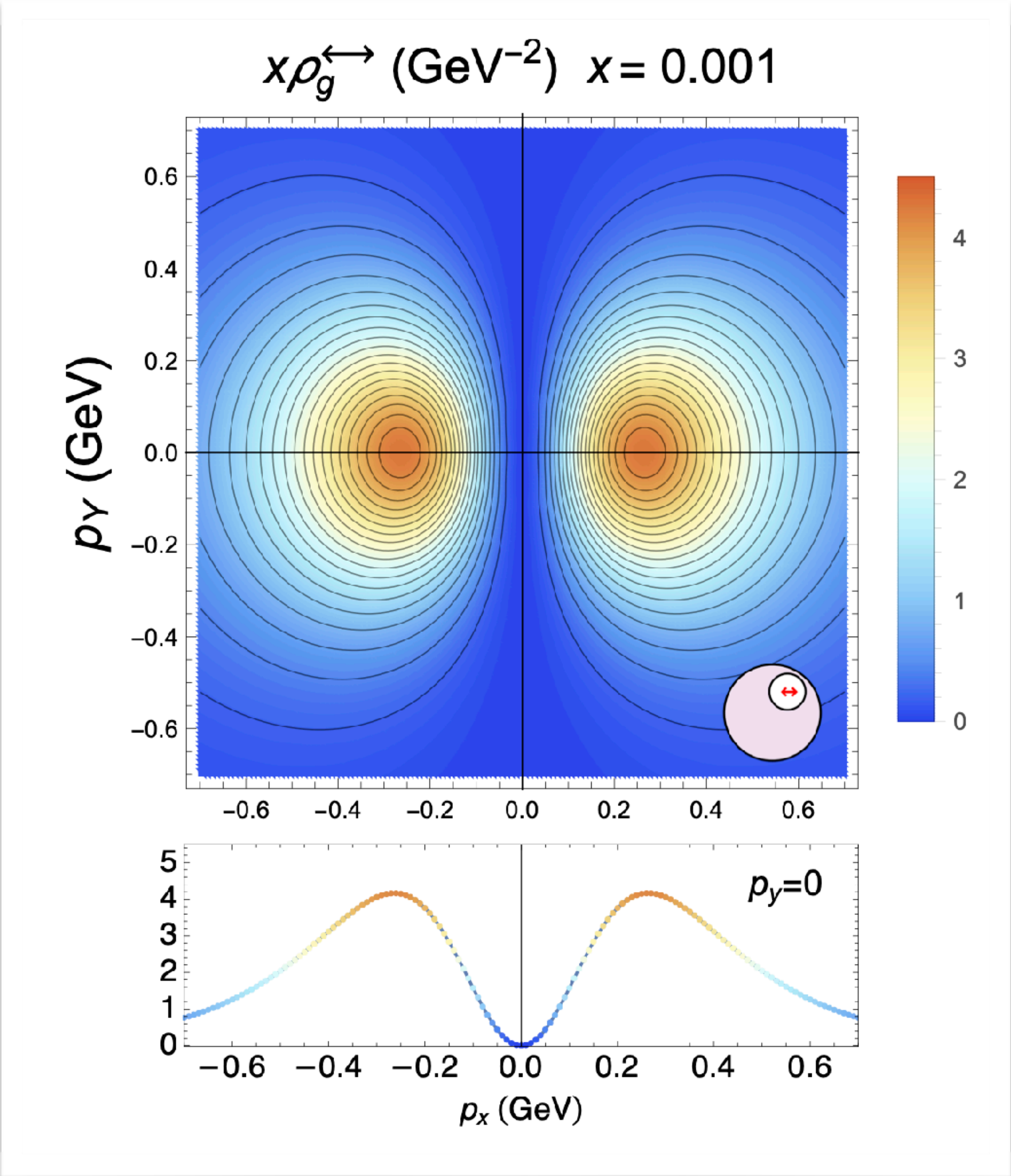
at low transverse momentum for (pseudo)scalar state

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

unpolarized gluons **lin. polarized** gluons

NRQCD

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



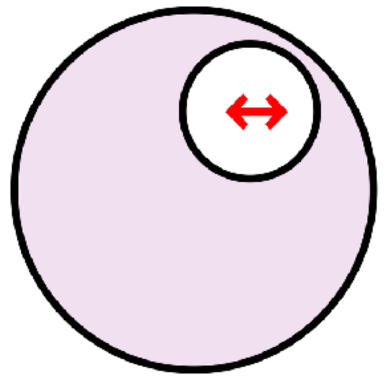
[D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]

(Higgs+jet angular distributions) [D. Boer, C. Pisano (2015)]

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

Backup

Boer-Mulders effect in unpolarised pp collisions



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

unpol. Boer-Mulders

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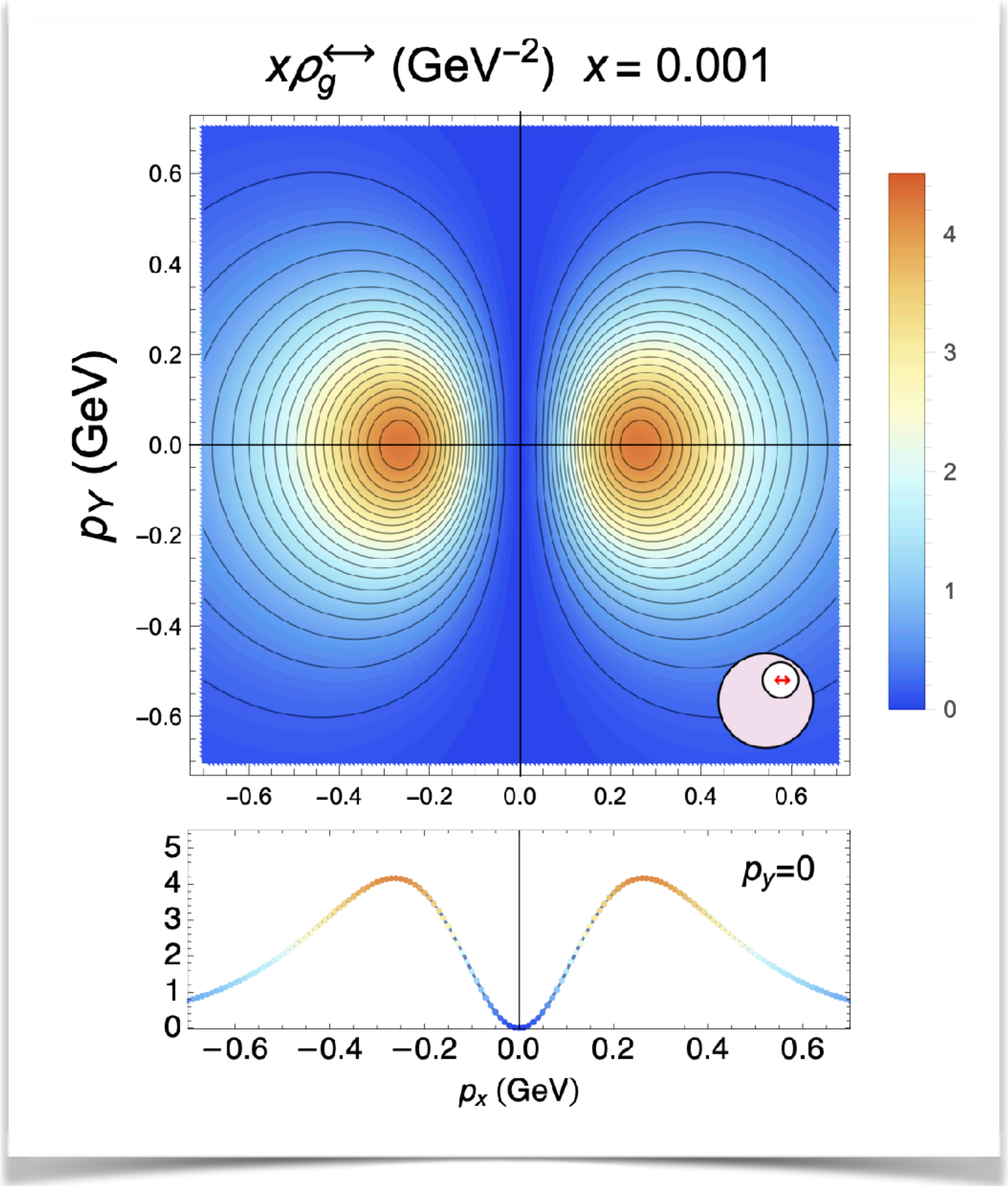
🔗 [D. Boer, W.J. den Dunnen, C. Pisano, M. Schlegel, W. Vogelsang (2012)]

(Higgs+jet angular distributions) 🔗 [D. Boer, C. Pisano (2015)]



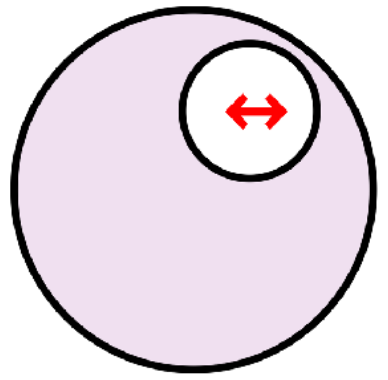
🔗 [A. Bacchetta, F.G.C., M. Radici, P. Taels (2020)]

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 unpolarised pp collisions



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unpol. Boer-Mulders

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unpolarized gluons | **lin. polarized** gluons

NRQCD

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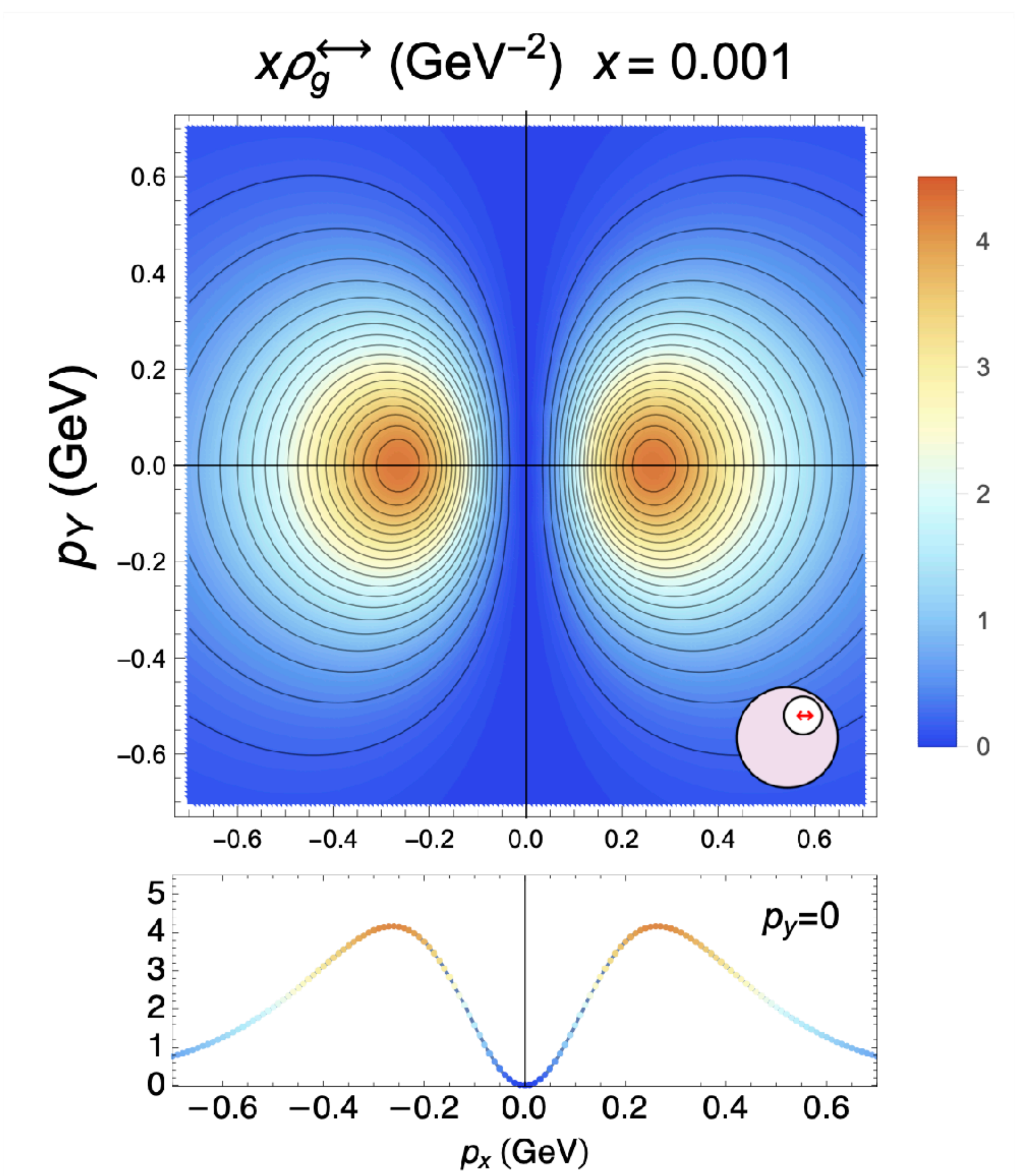

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Model prediction at low-x

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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

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

perturbative Sudakov

perturbative expansion in $\alpha_s(\mu)$

resummation of

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

define $\boxed{\text{logarithmic ordering}}$

slide adapted from C. Bissolotti

Backup

Anatomy of gluon TMDs

matching coefficients

collinear PDF

nonperturbative Sudakov

nonperturbative TMD function

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

perturbative Sudakov

perturbative expansion in $\alpha_s(\mu)$

resummation of

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

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

Suppression of genuine NP effects!

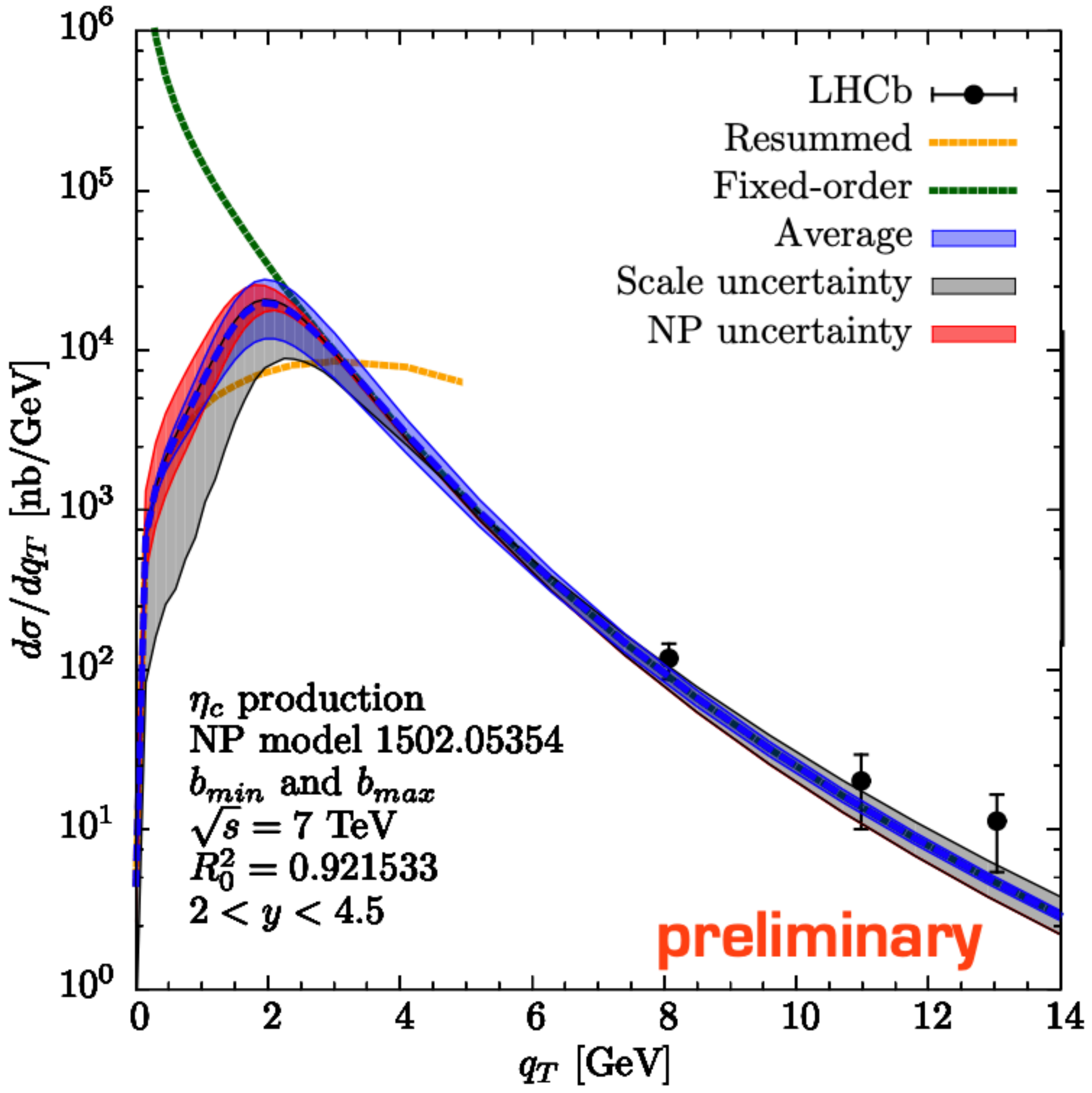
Backup

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

$$S_{NP}(\bar{b}_T) = -\left[\frac{a_1}{2} + \frac{a_2}{2}\ \ln Q^2\right]\ \bar{b}_T^2$$

$a_i = 0.5\ \text{GeV}^2$, var. 50%, envelope

both for unpolarized and
linearly polarized distributions

the formalism is in good shape!
we need the data at low qT

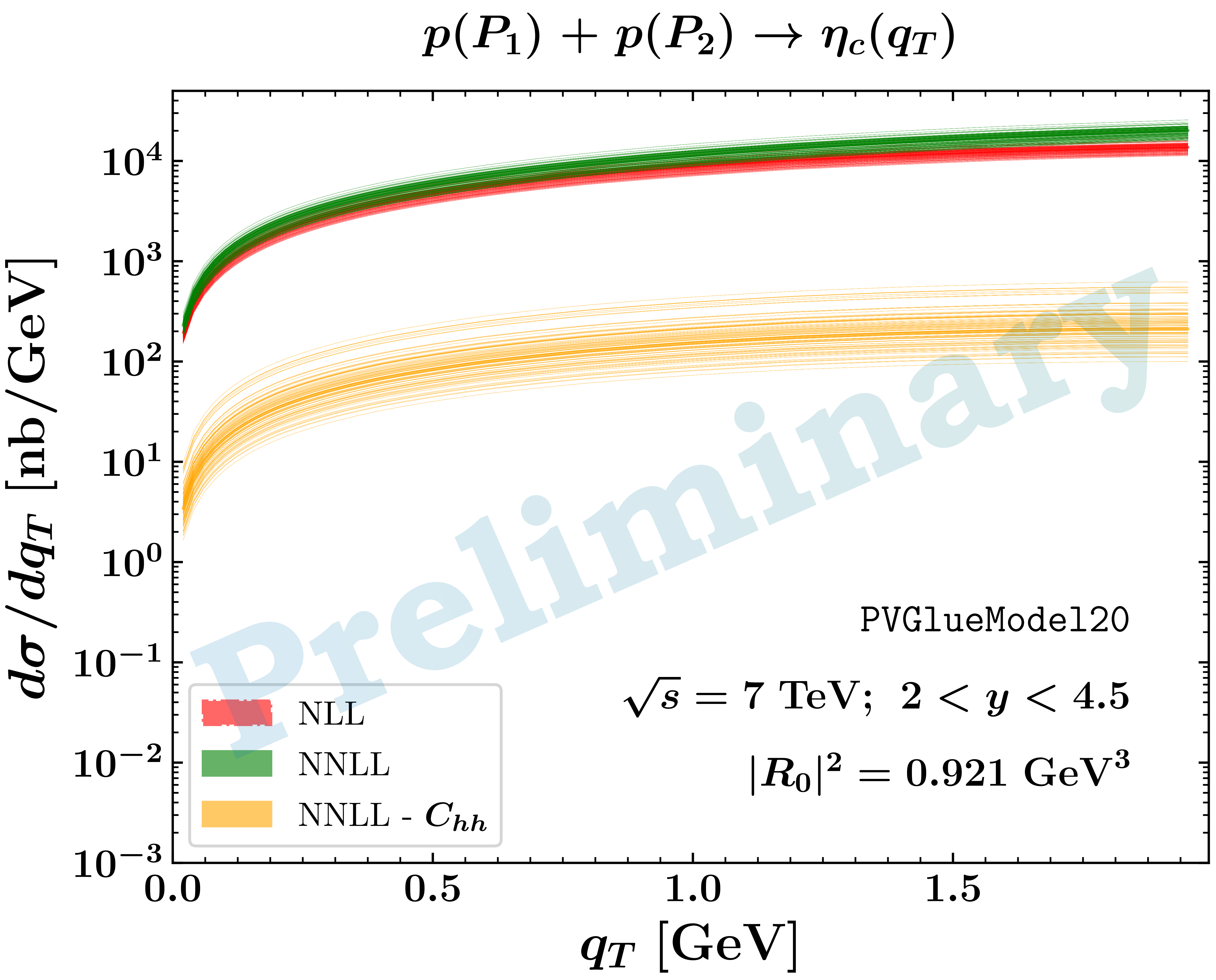
Jefferson Lab

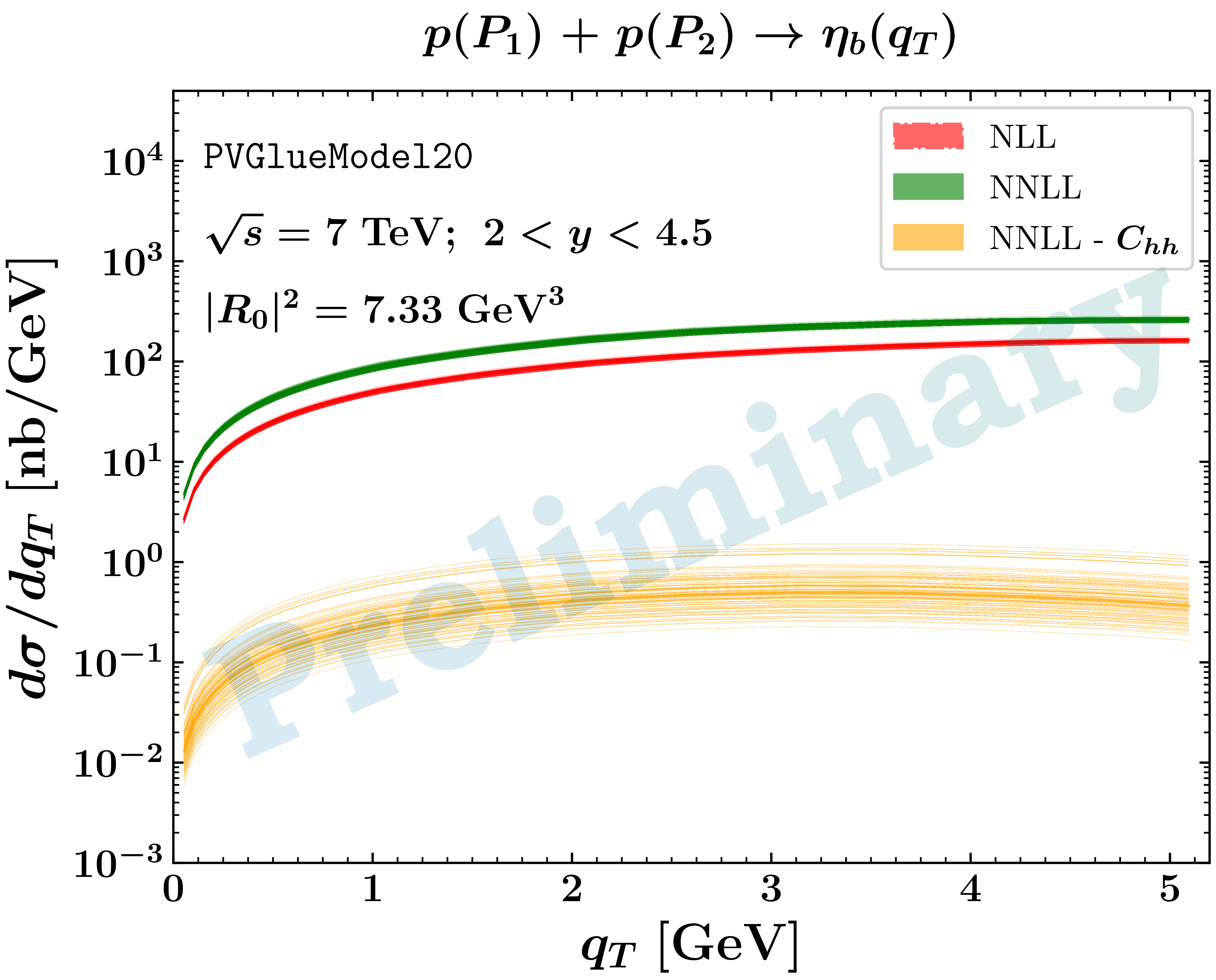
slide by Andrea Signori (INT 2017)

Backup

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

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





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

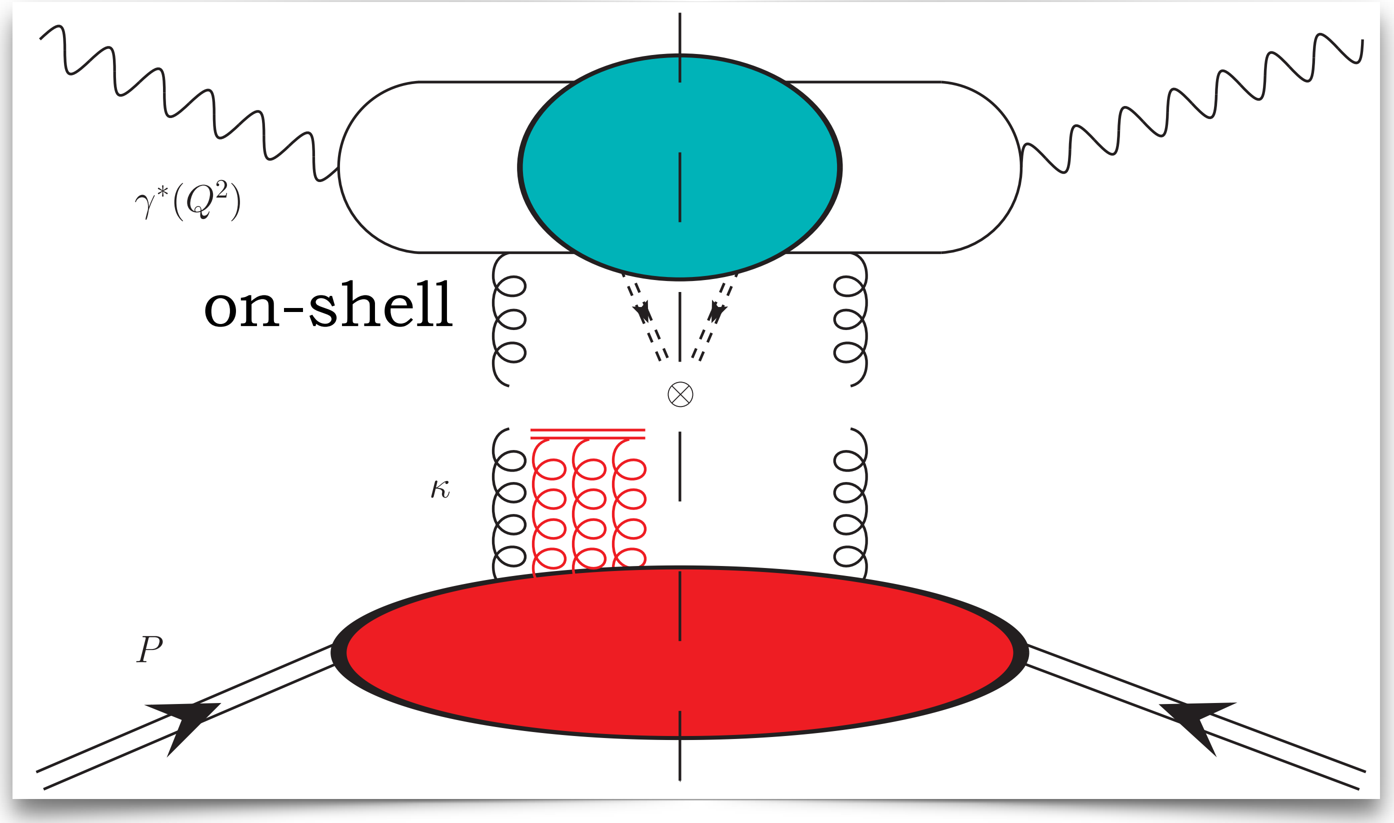
Backup

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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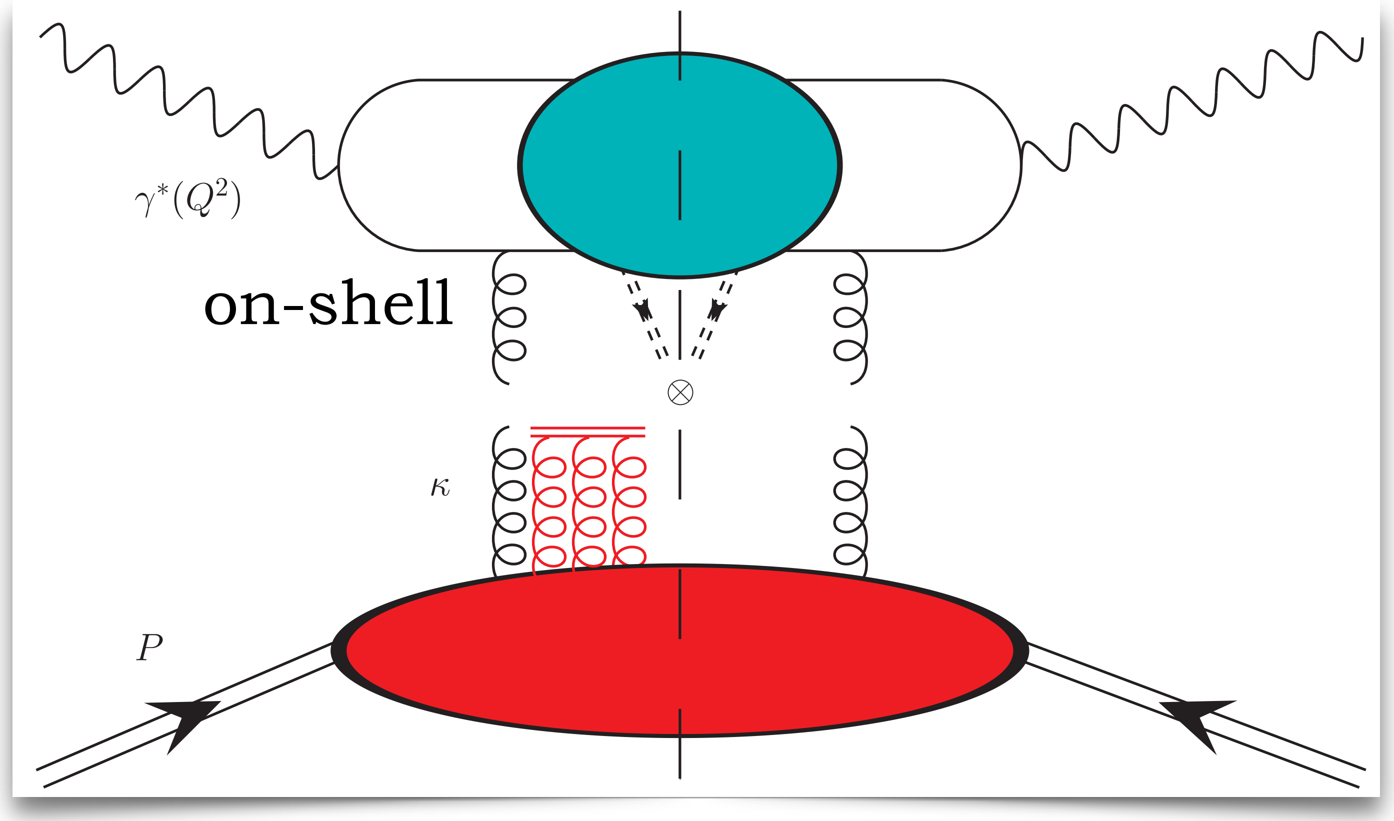
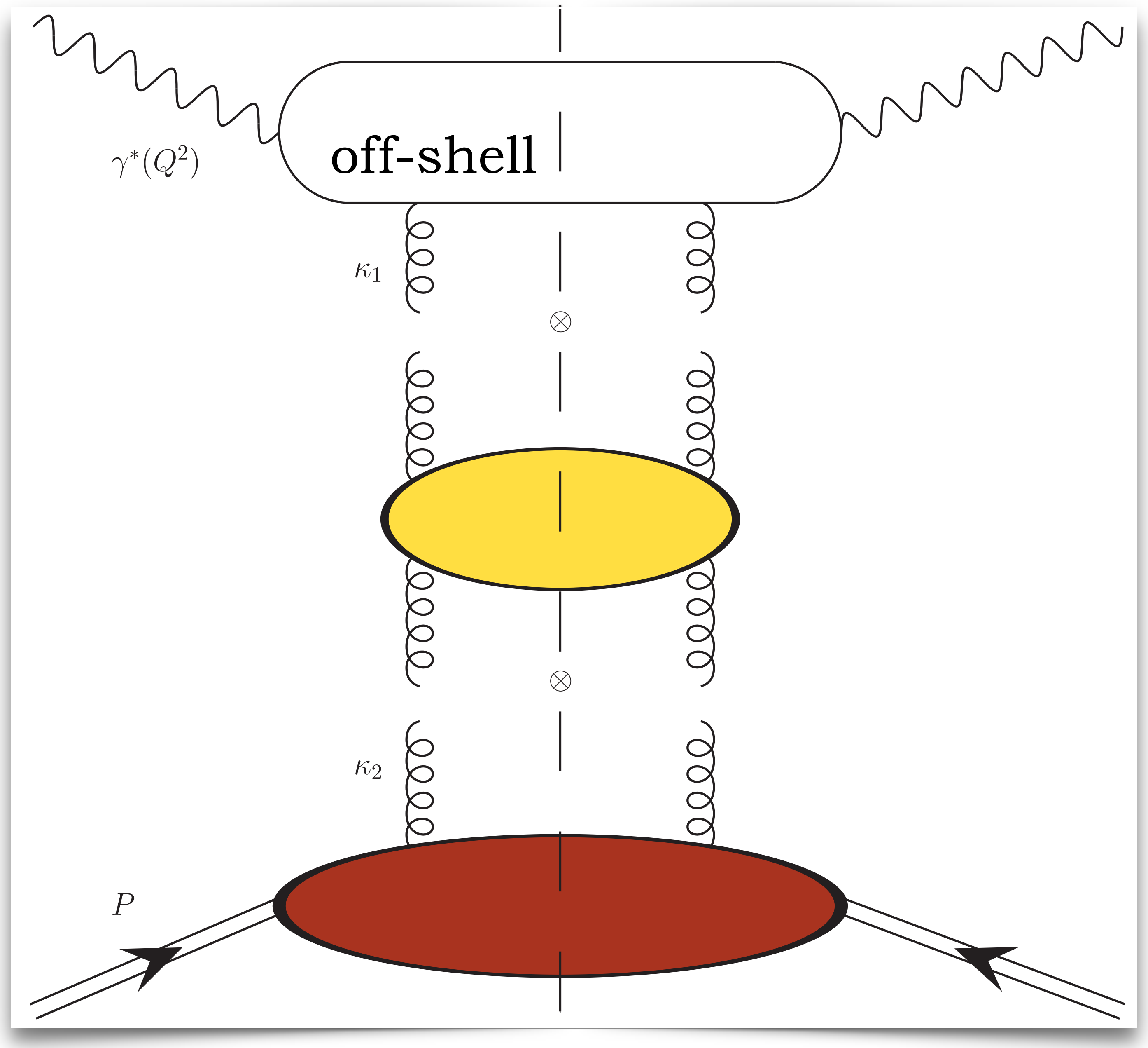


TMD
PDF

HEF

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



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

Backup

TMD versus high-energy factorization

TMD

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

(Fadin-Martin theorem)

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

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TMD PDF

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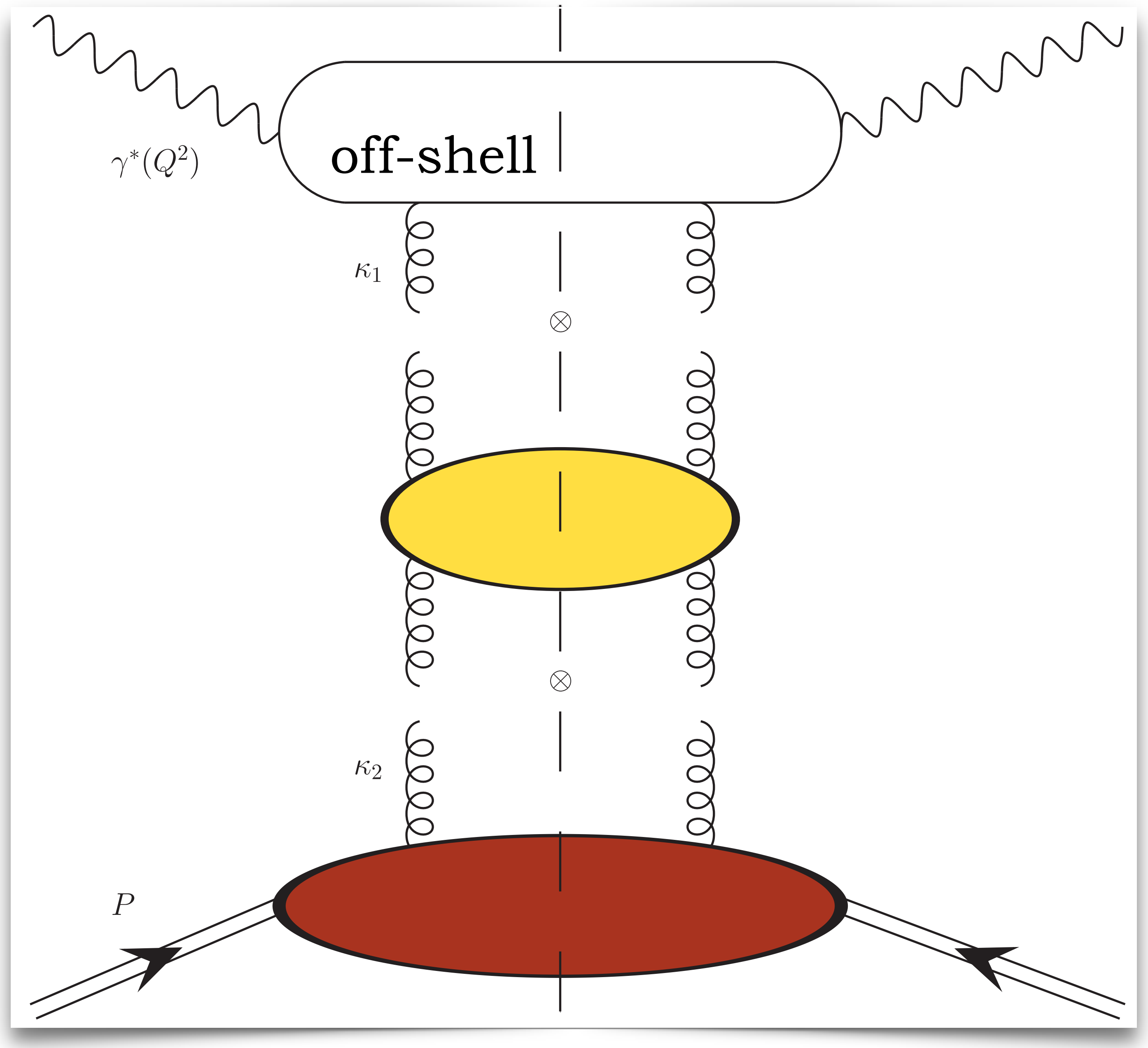

$$\Phi^{\gamma^*\to\gamma^*} \otimes \mathcal{G}_{\mathrm{BFKL}} \otimes \Phi^{P}_{[\mathrm{NP}]}$$

Backup

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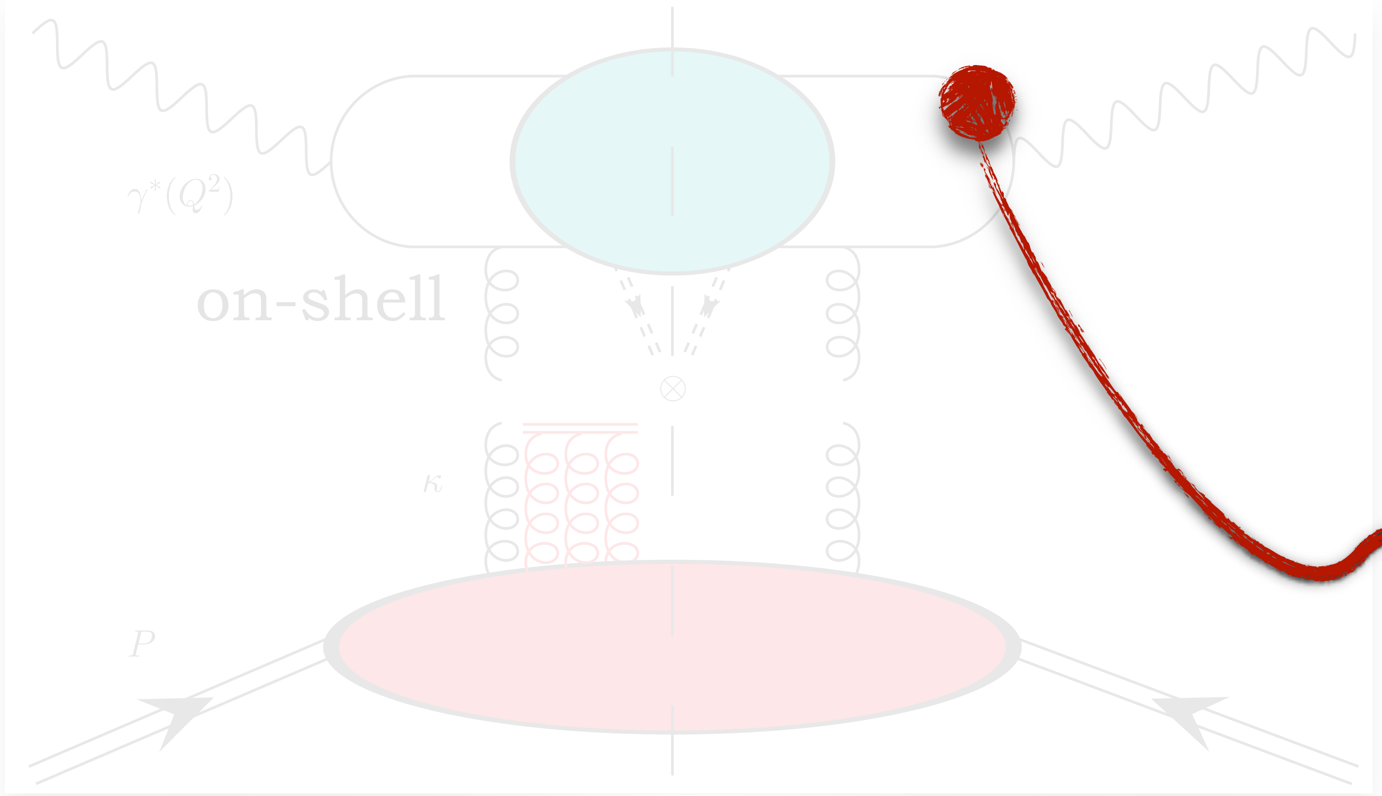
IR diffusion pattern

(Bartels' cigar)

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



Q^2

Q_0^2

HEF

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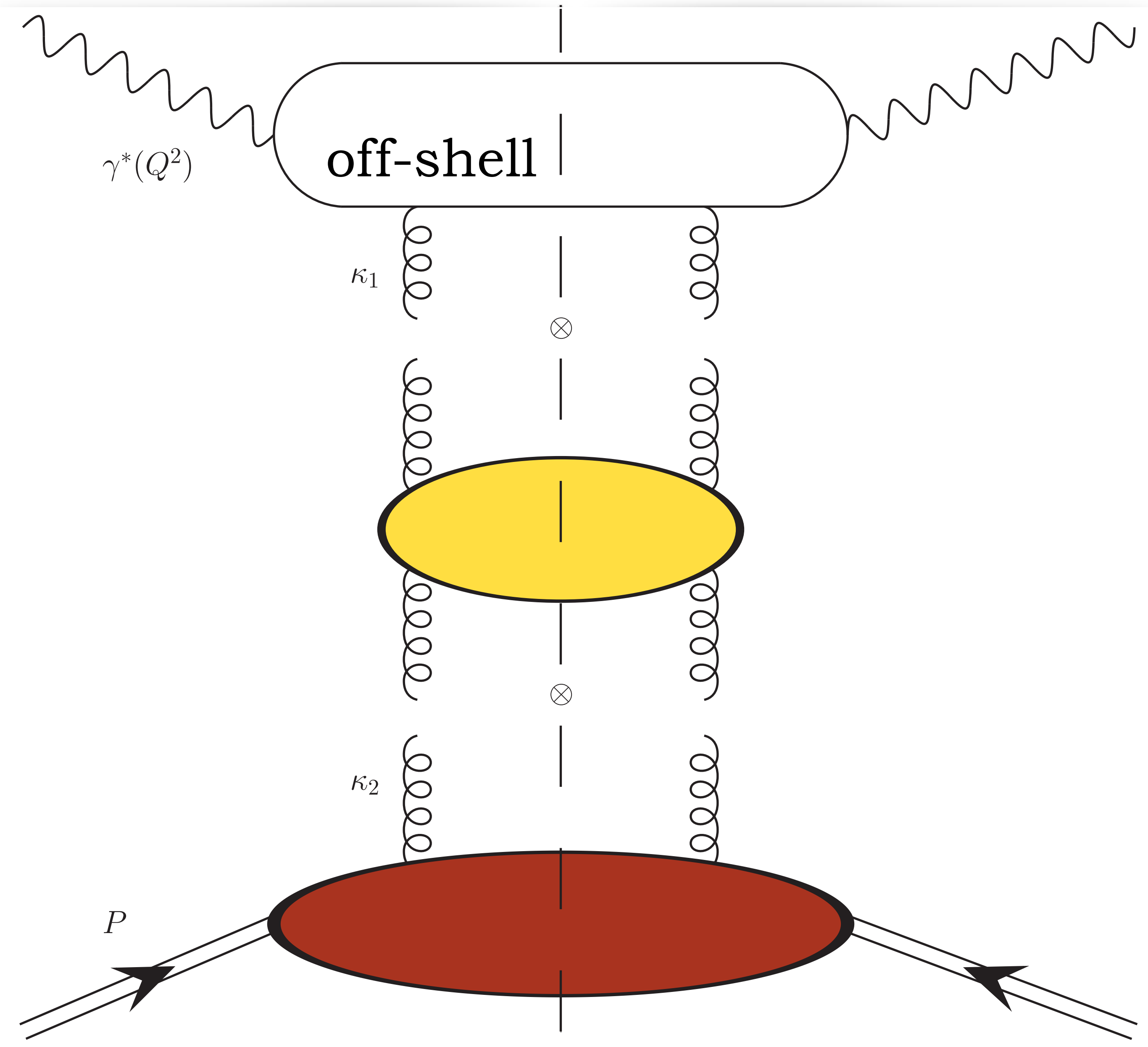


$\Phi^{\gamma^*\to\gamma^*}$

$\otimes$

$\mathcal{G}_{\mathrm{BFKL}}$

$\otimes$

$\Phi^{P}_{[\mathrm{NP}]}$

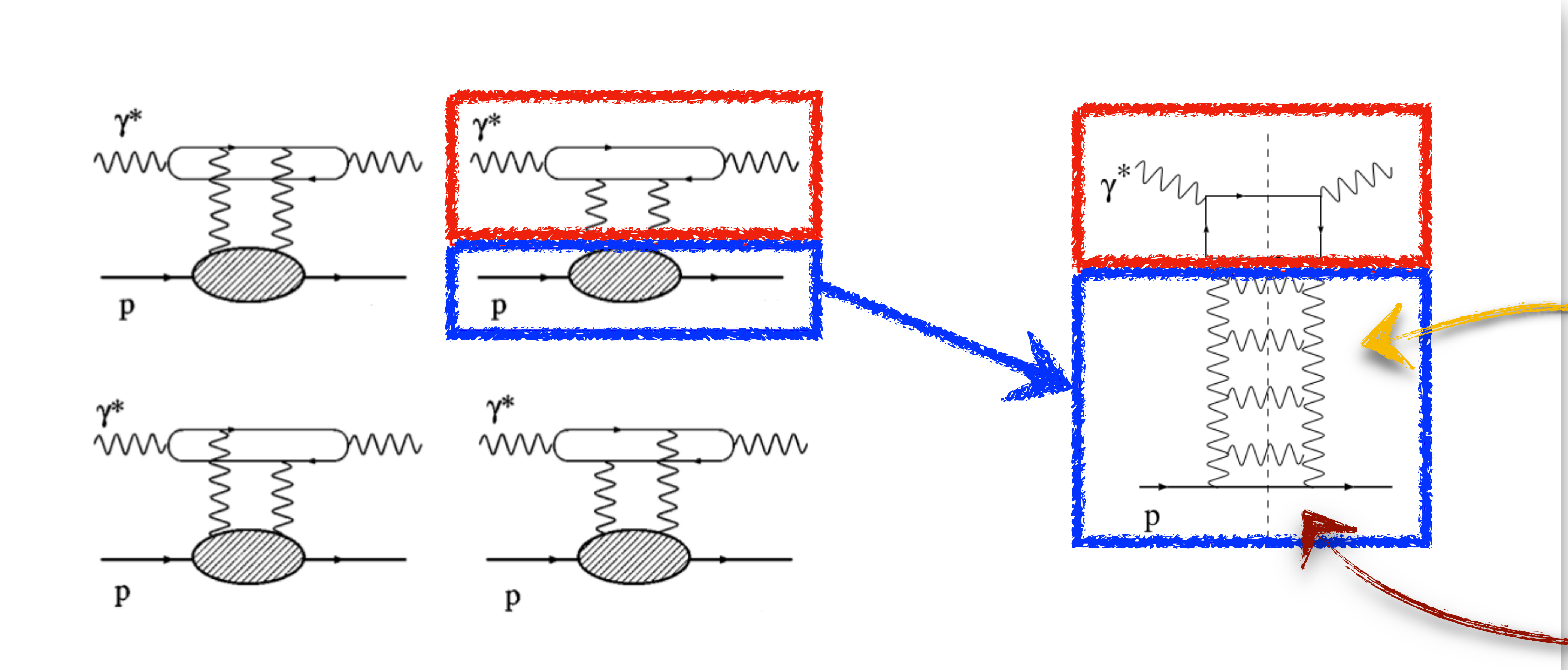
Backup

High-energy factorization and the UGD

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

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

◇ $\mathcal{F}(x, \kappa^2)$ 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!

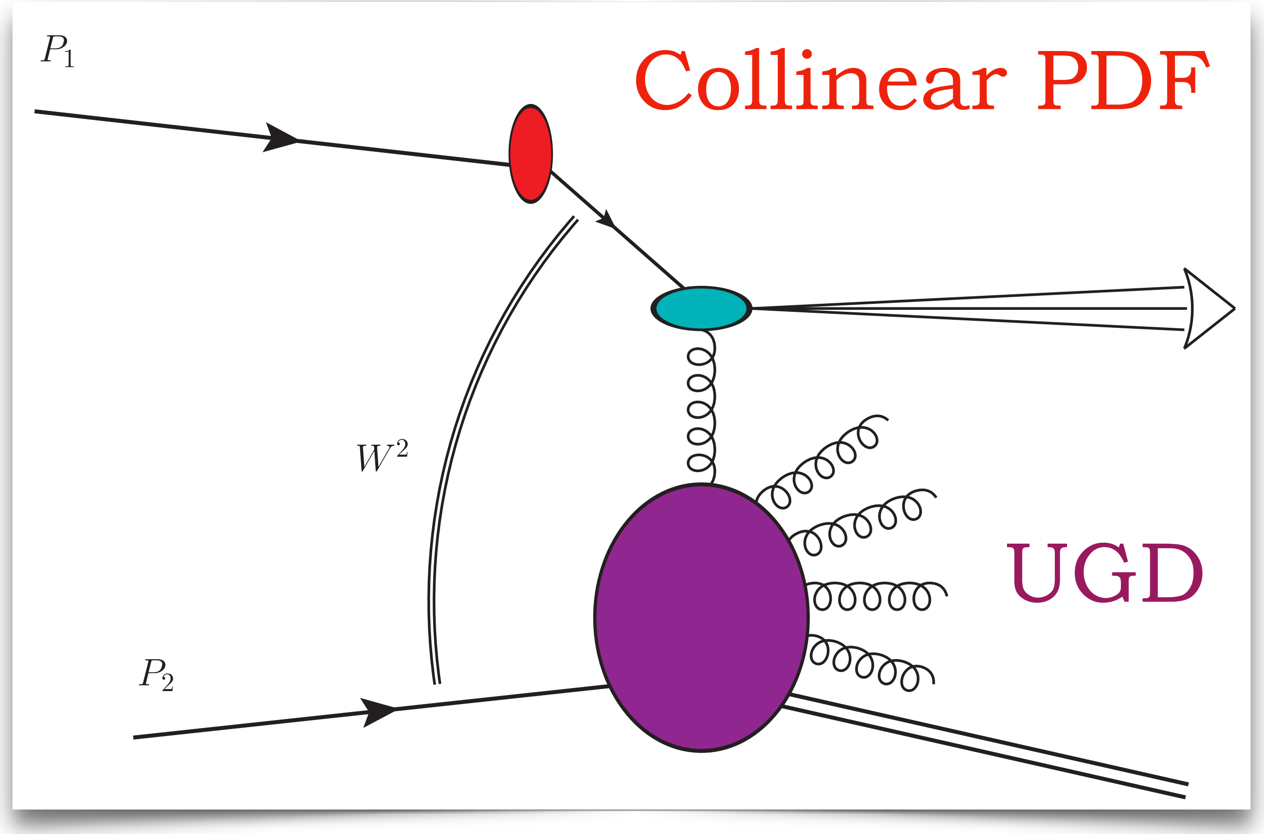
Backup

Hybrid or pure factorization?

Forward emissions

* *Asymmetric* config. $\leftrightarrow$ 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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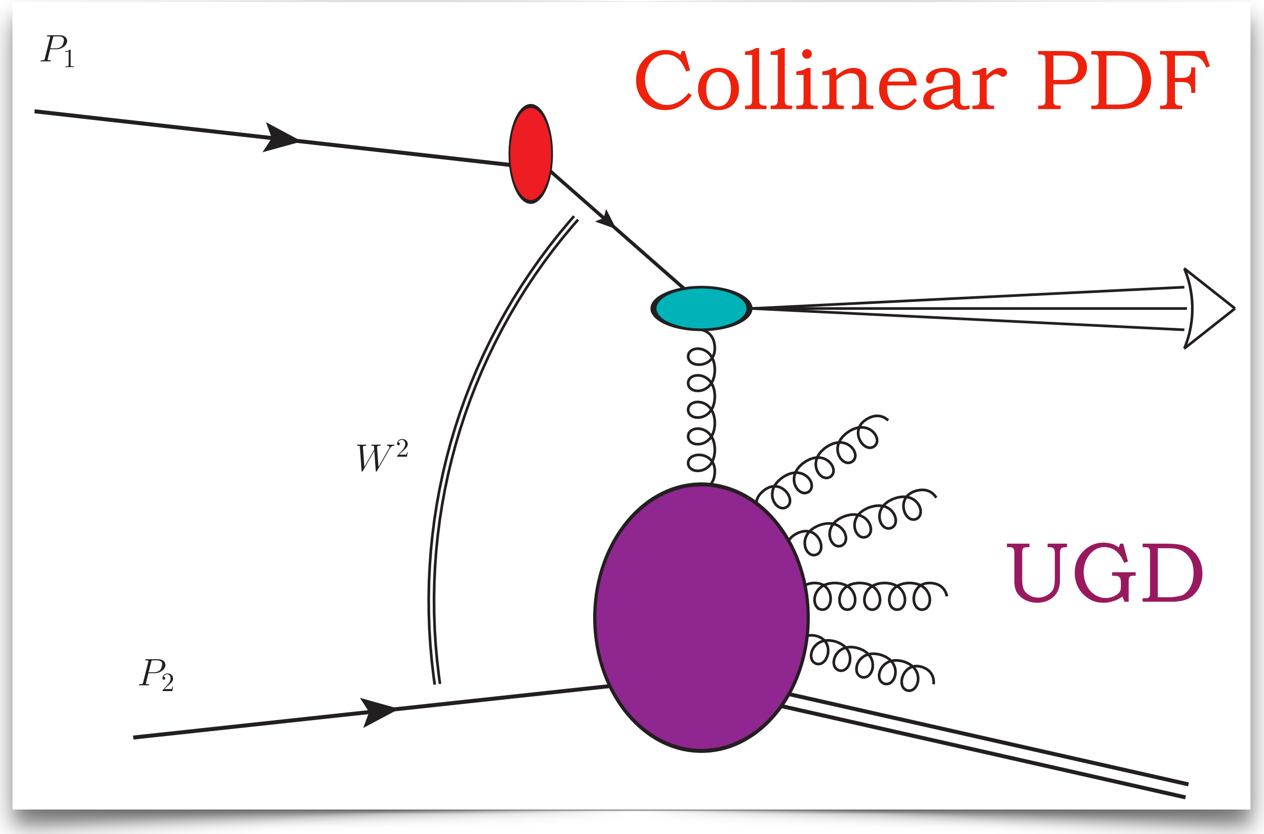

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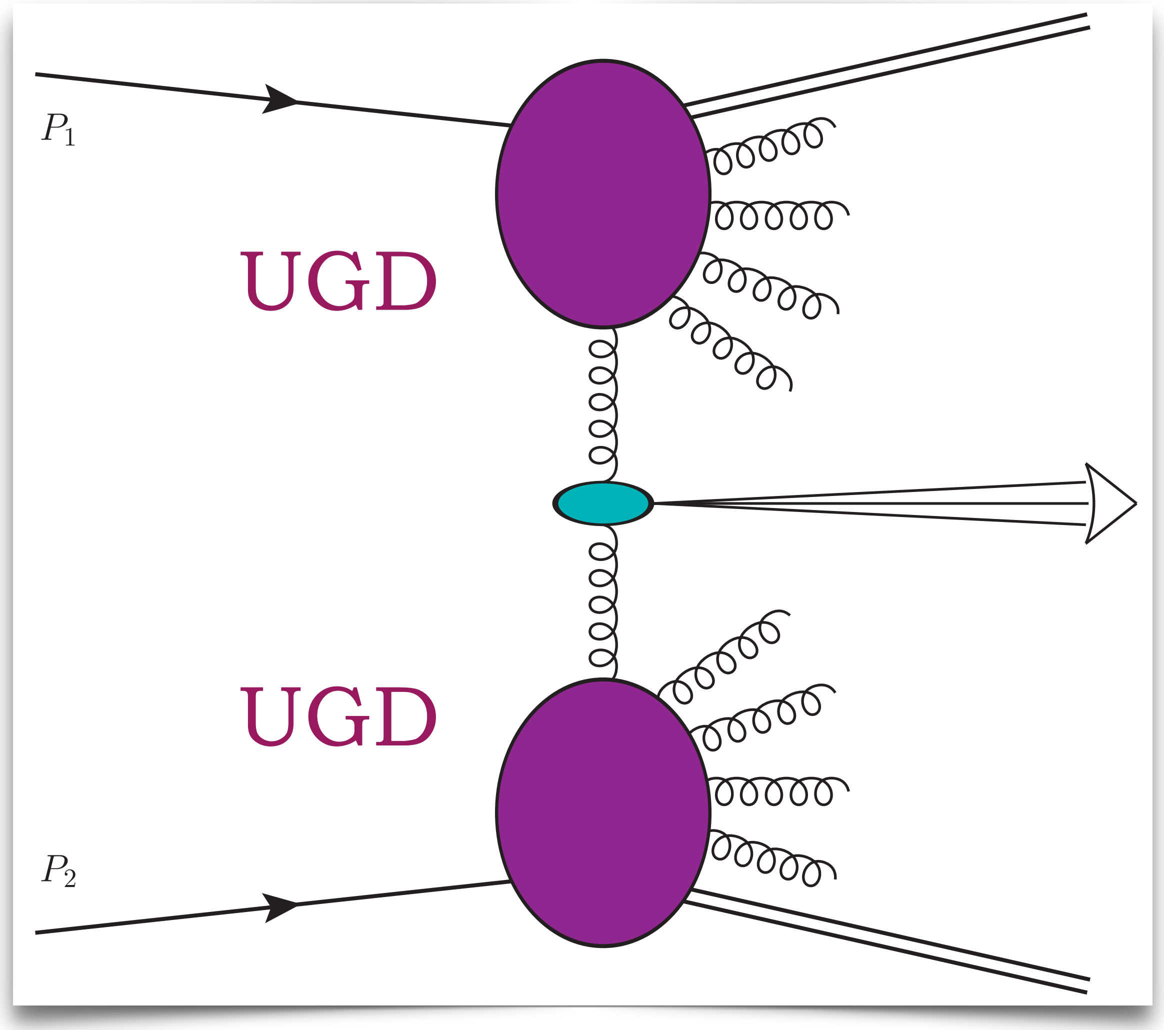
Central emissions

* *Gluon induced* $\leftrightarrow$ small-x gluons
* Pure **high-energy** factorization



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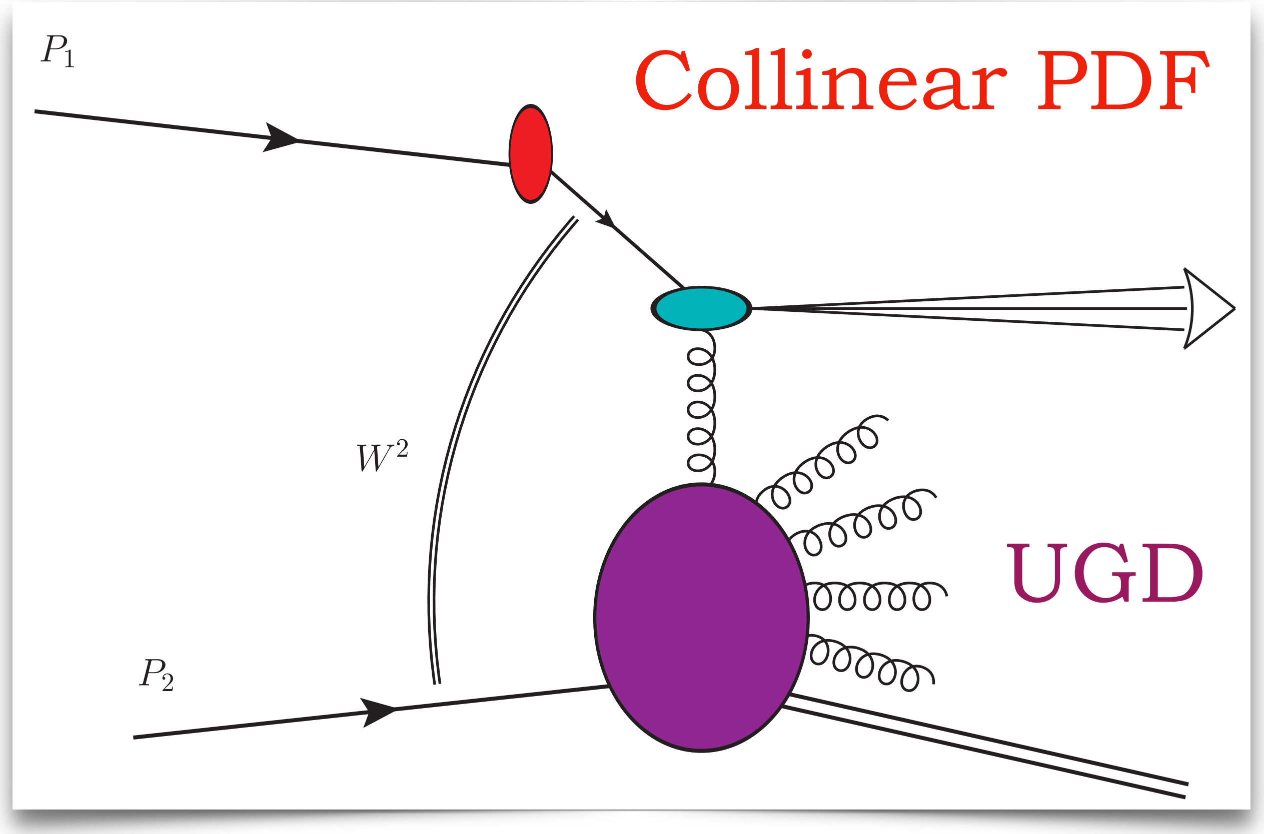

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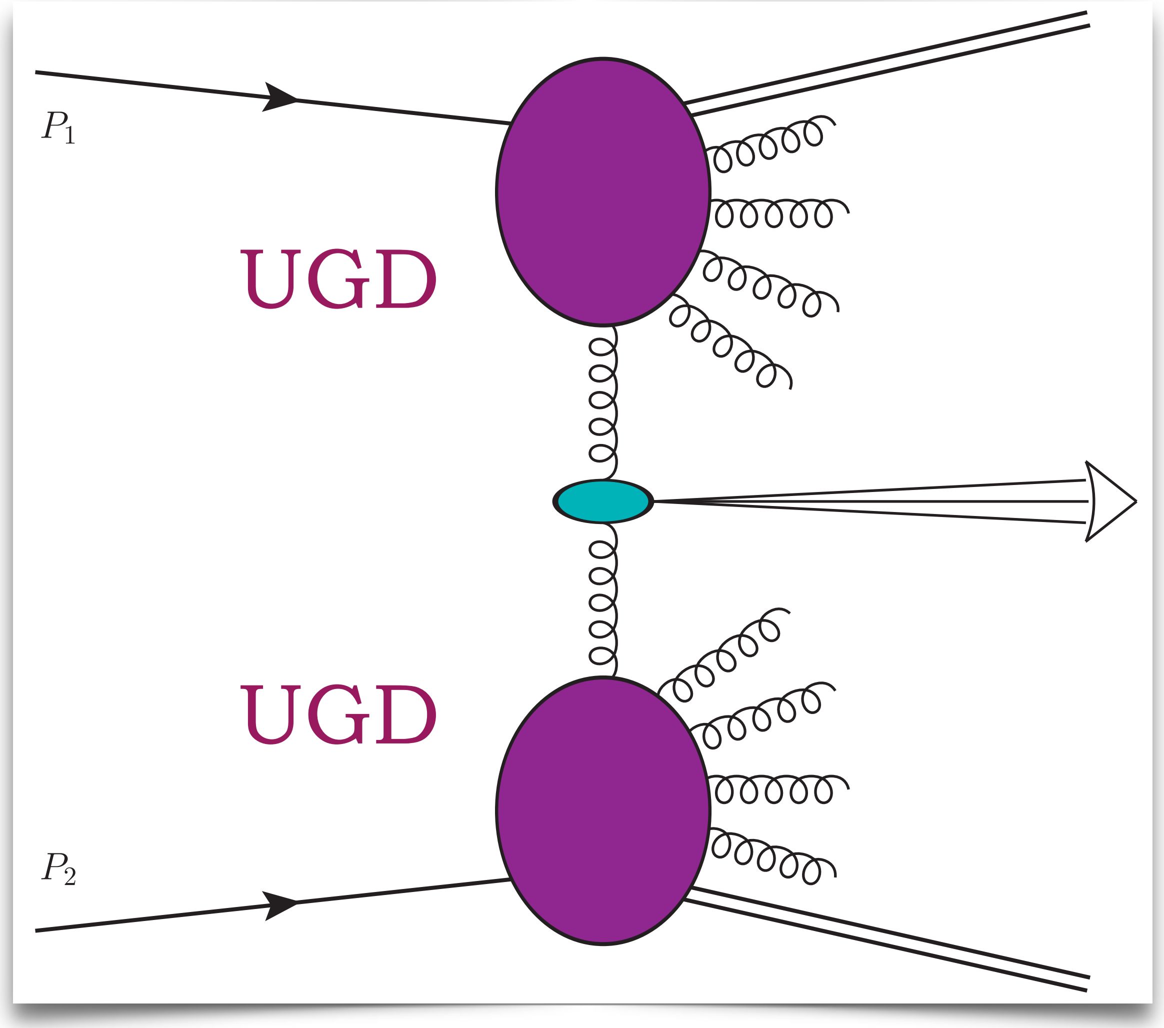

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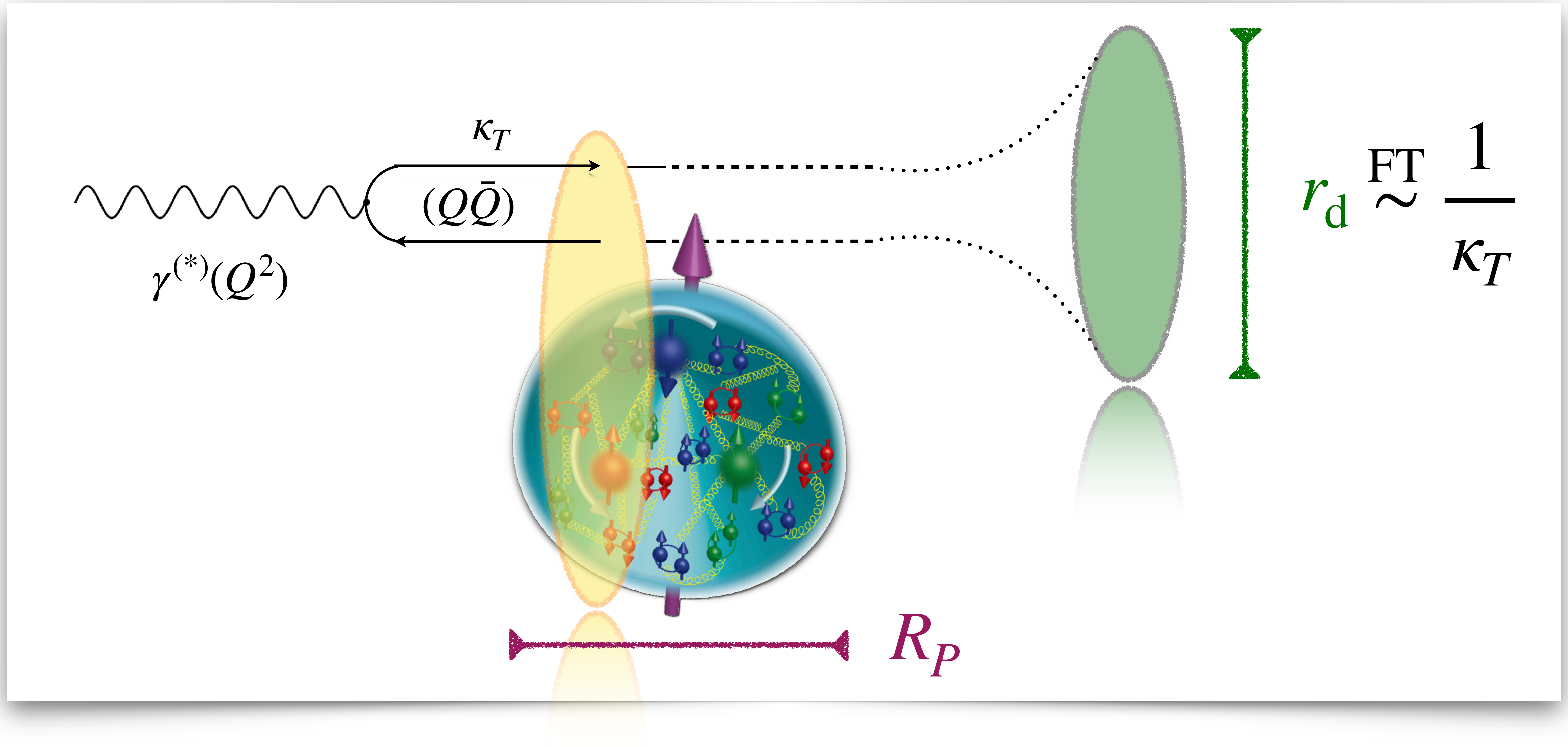
Table complemented by *exclusive* counterparts and *lepto-hadronic* channels

Backup

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



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

- 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

Backup

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Quarkonia

* Size of dipoles $\Rightarrow$ 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