

Quarkonia As Tools 2021

March 24th, 2021

Quarkonium emissions as probes of the hadronic structure at small- x

Francesco Giovanni Celiberto

ECT*/FBK Trento & INFN-TIFPA

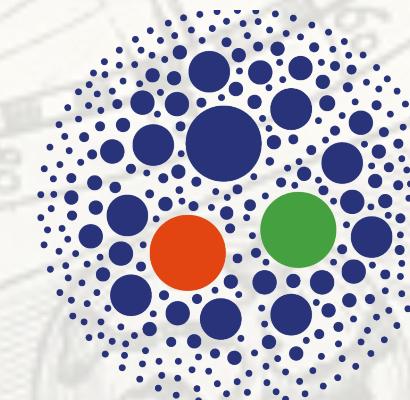
ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

FONDAZIONE
BRUNO KESSLER
FUTURE BUILT
ON KNOWLEDGE



Trento Institute for
Fundamental Physics
and Applications



HAS QCD

HADRONIC STRUCTURE AND
QUANTUM CHROMODYNAMICS

Omnes viae small- x ducunt

Incomplete list of small- x formalisms \rightarrow *linear* (BFKL) or *saturation* (BK/JIMWLK) effects embodied



Unintegrated parton densities

A (hybrid) high-energy factorization established

- * **BFKL UGD**: pure small- x evolution, Reggeons
- * HEF, CCFM, PRA **uPDFs**: BFKL + collinear matching

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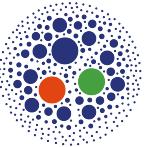
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Small- x improved collinear PDFs

DGLAP description improved via BFKL

* **ABF approach**: PDFs + small- x resummed splitting

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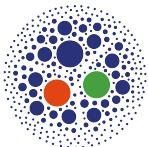
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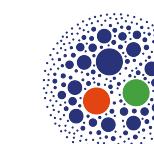
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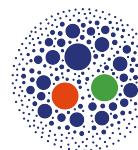
Small- x improved gluon TMDs

Nonperturbative content via an enhanced spectator model

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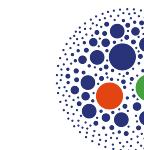
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Helicity and OAM at small- x

Need for sub-eikonal corrections, neglected by BFKL

* **BER**: DLA, flavor singlet and nonsinglet

* **KPS**: evolution via Wilson lines, saturation



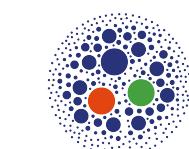
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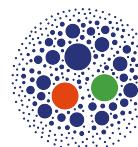
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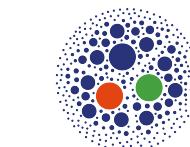
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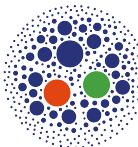


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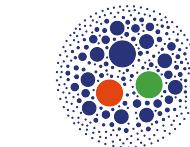


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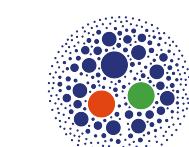


CGC/JIMWLK gluon TMDs

Gluon-recombination effects encoded

* **WW vs DP** gluon TMDs, **GTMDs**

* **iTMD**: interpolating between TMD and BFKL regimes



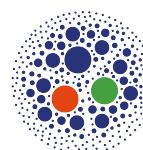
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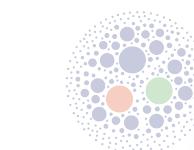
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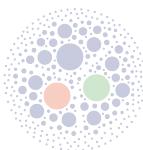


All-Twist High-Energy Factorization

AT_HEF

x

ited by BFKL
singlet
uration

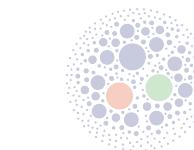


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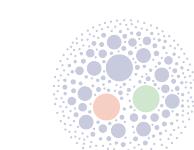


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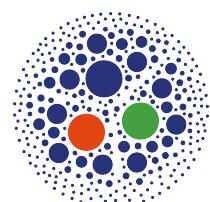


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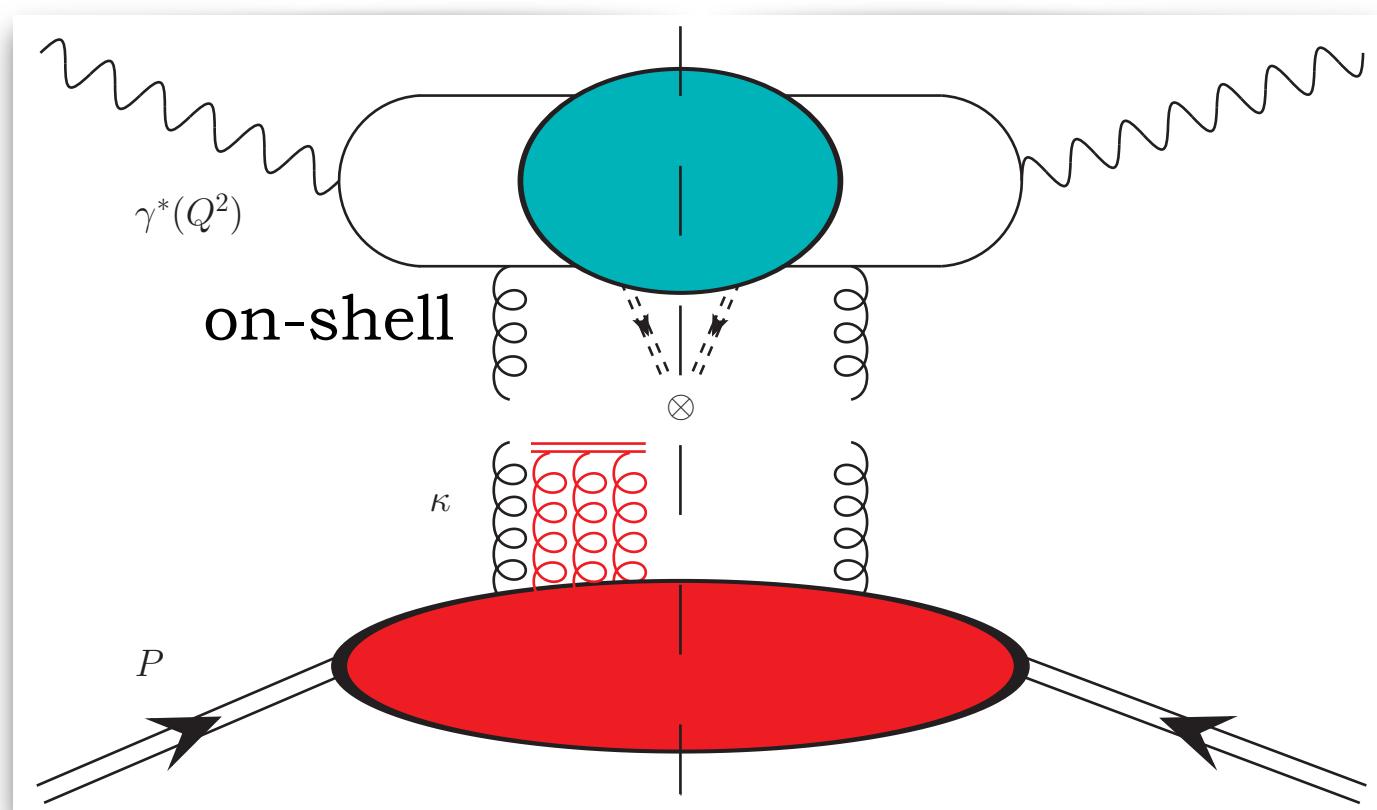
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TMD versus AT_HEF



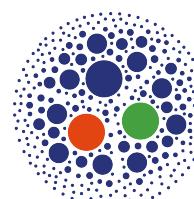
TMD

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

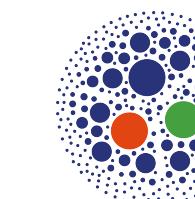


TMD
PDF

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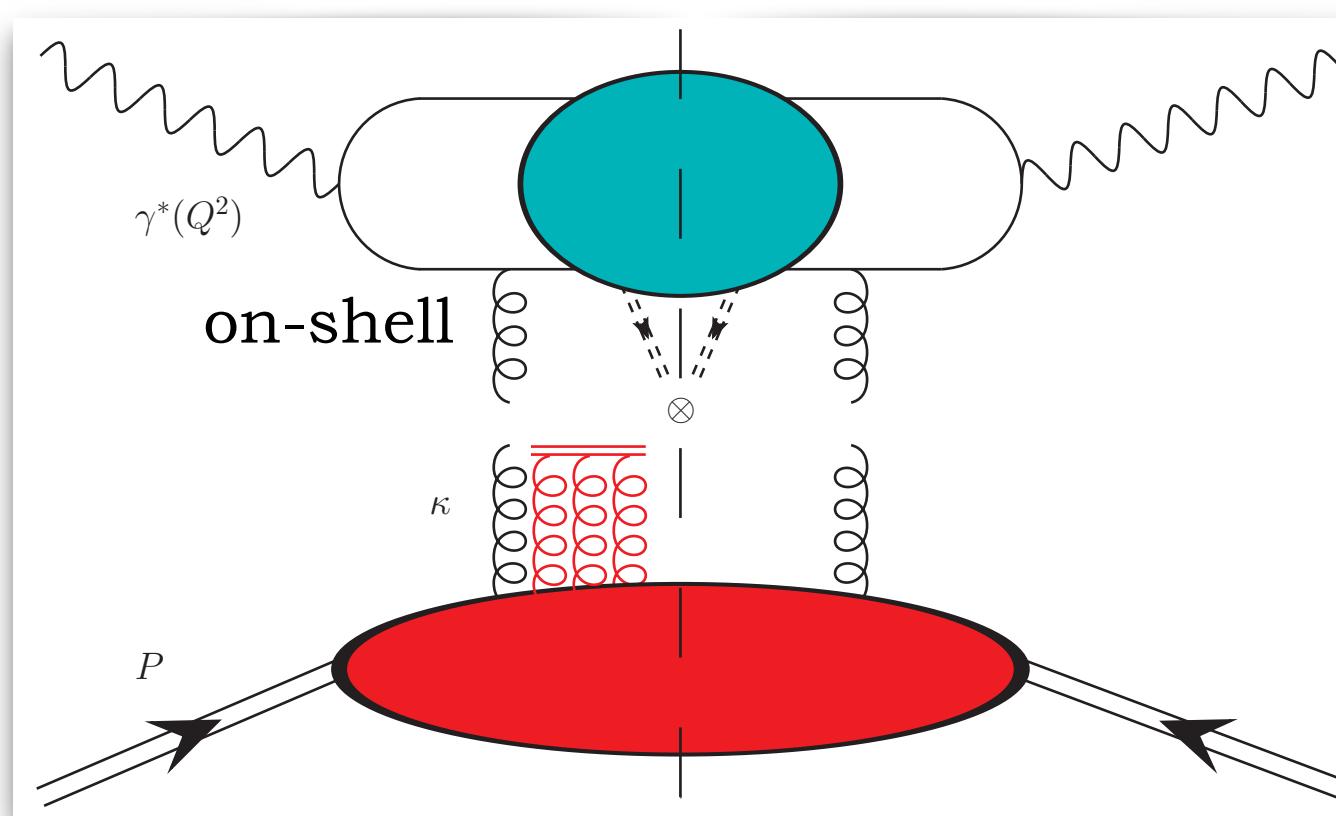


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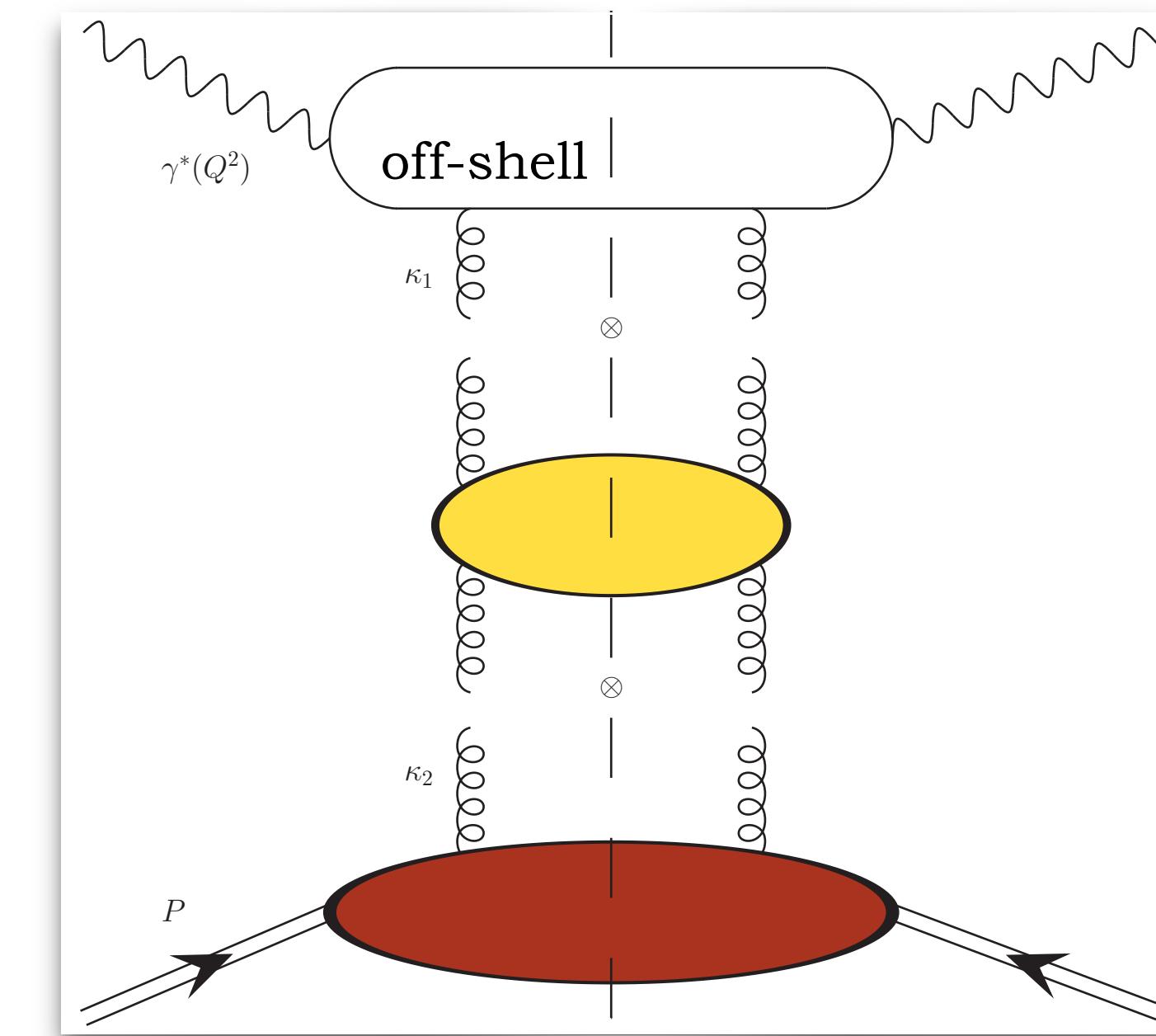


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**TMD
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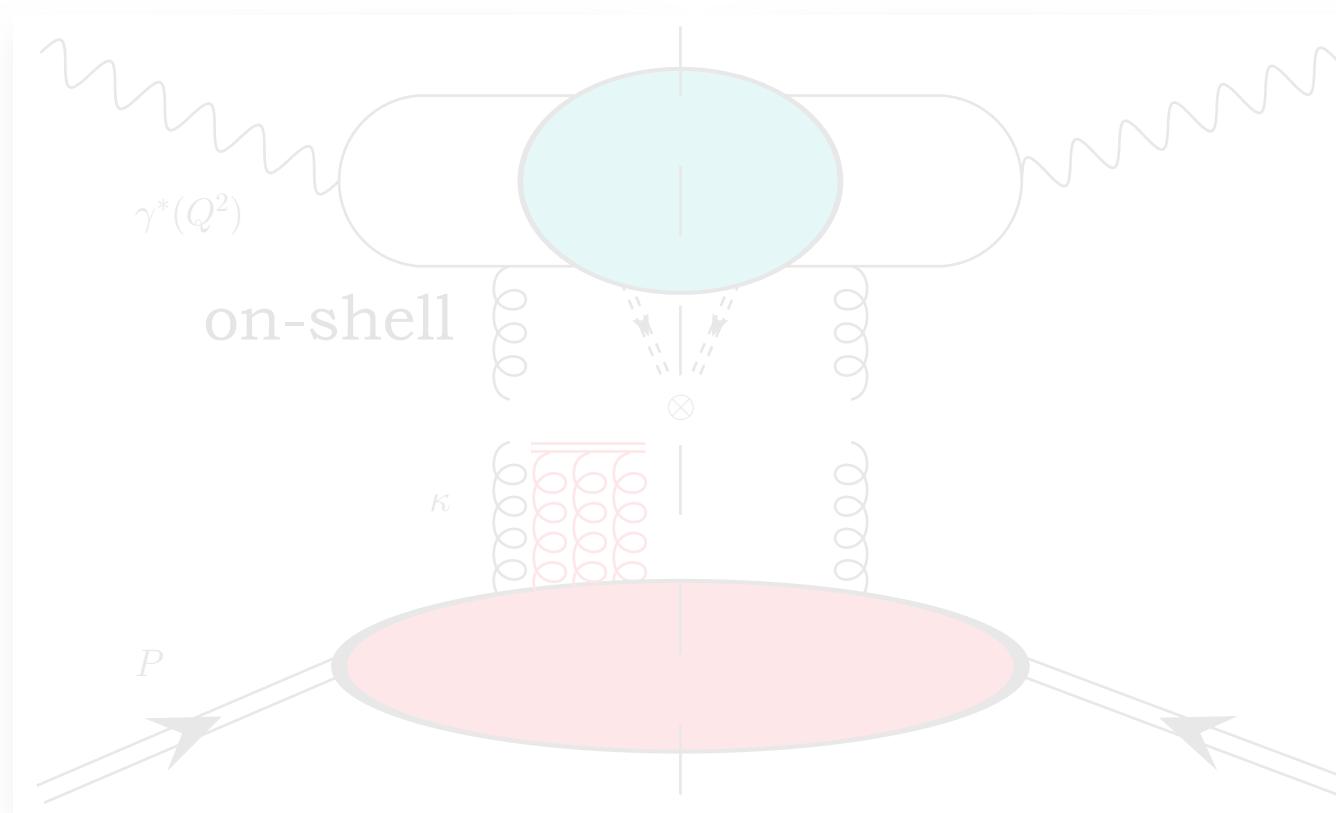


$\Phi^{\gamma^*\rightarrow\gamma^*}$
 \otimes
 $\mathcal{G}_{\text{BFKL}}$
 \otimes
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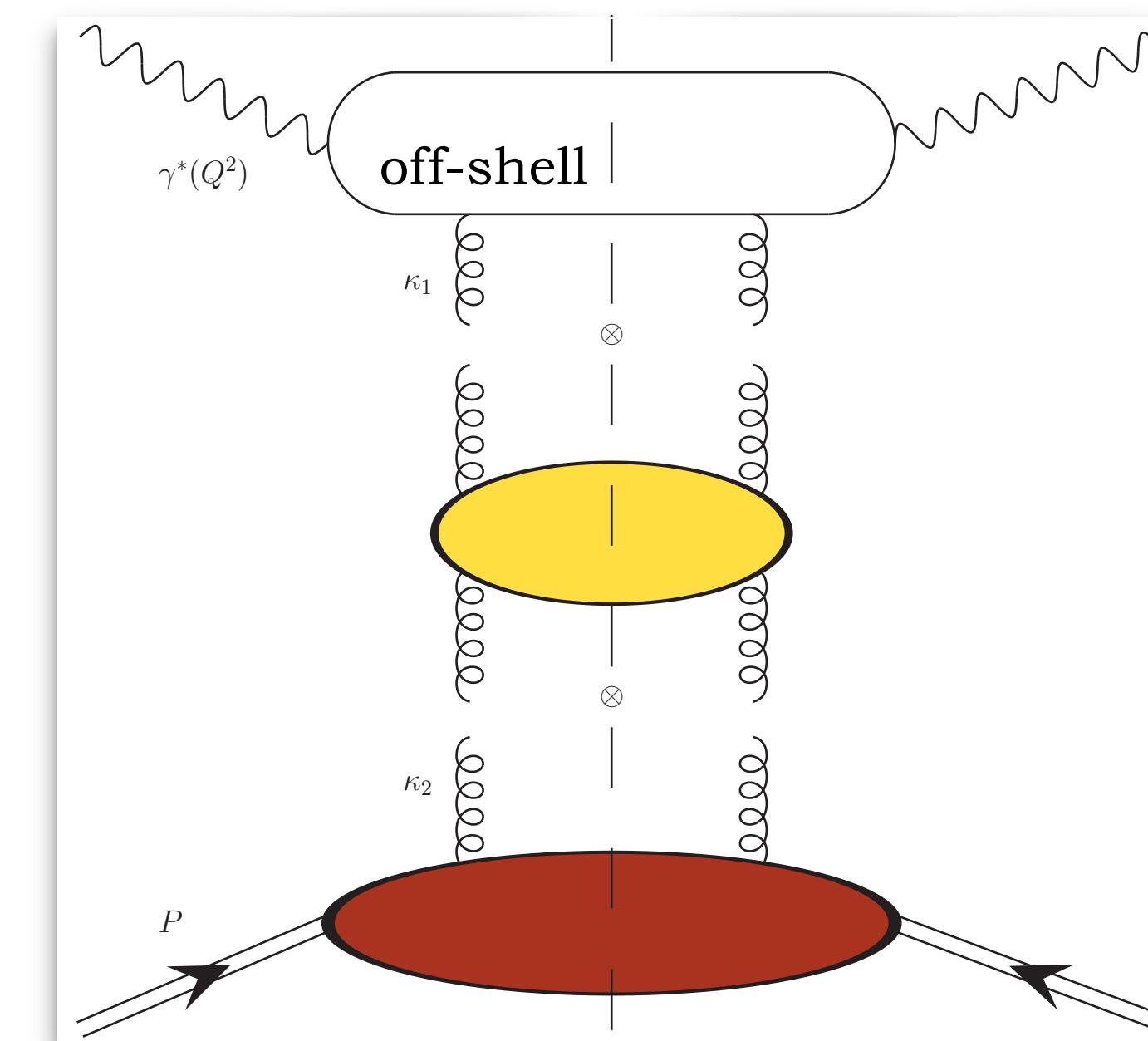
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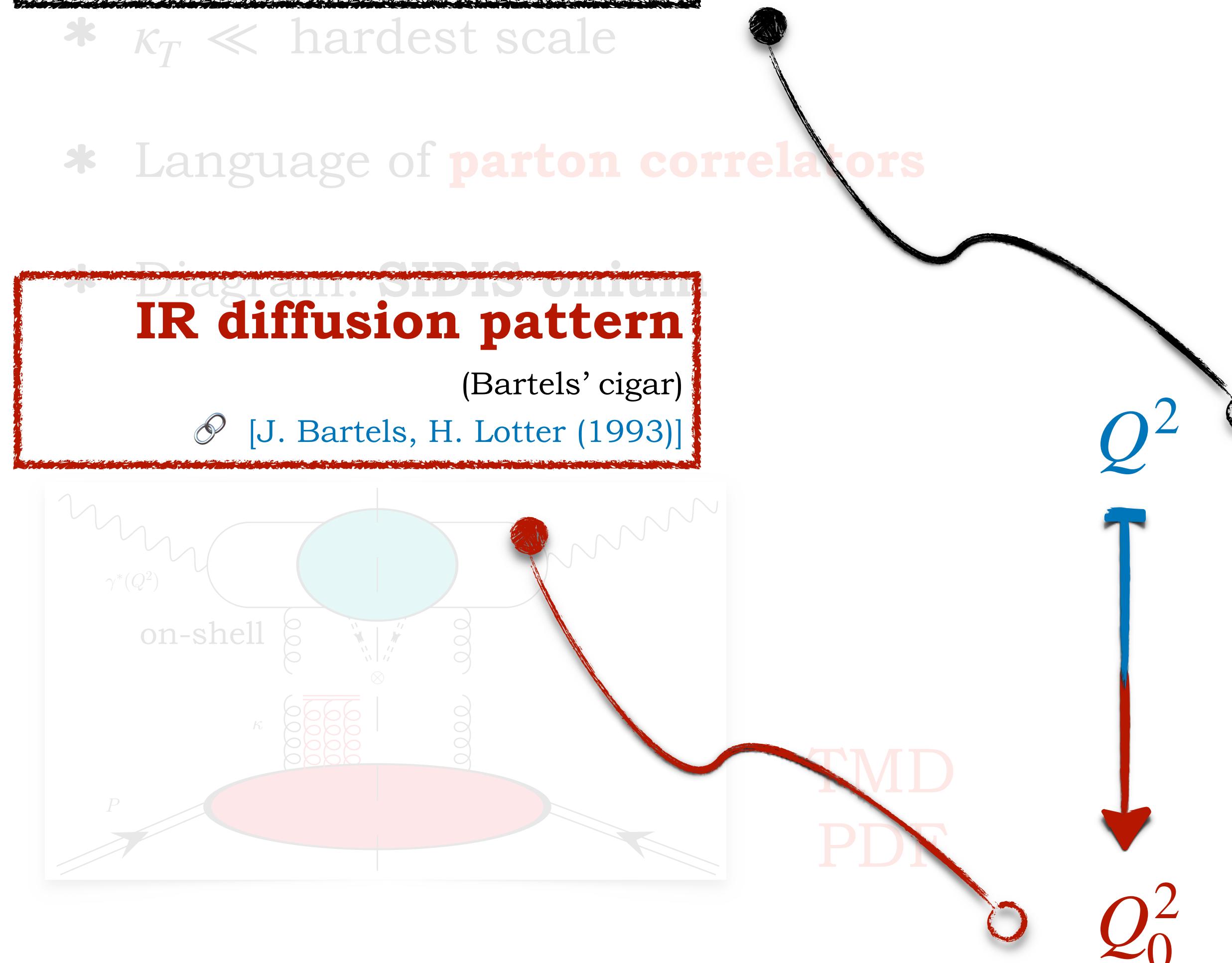


- * Inclusive or exclusive processes (!)
- * Small x , large κ_T
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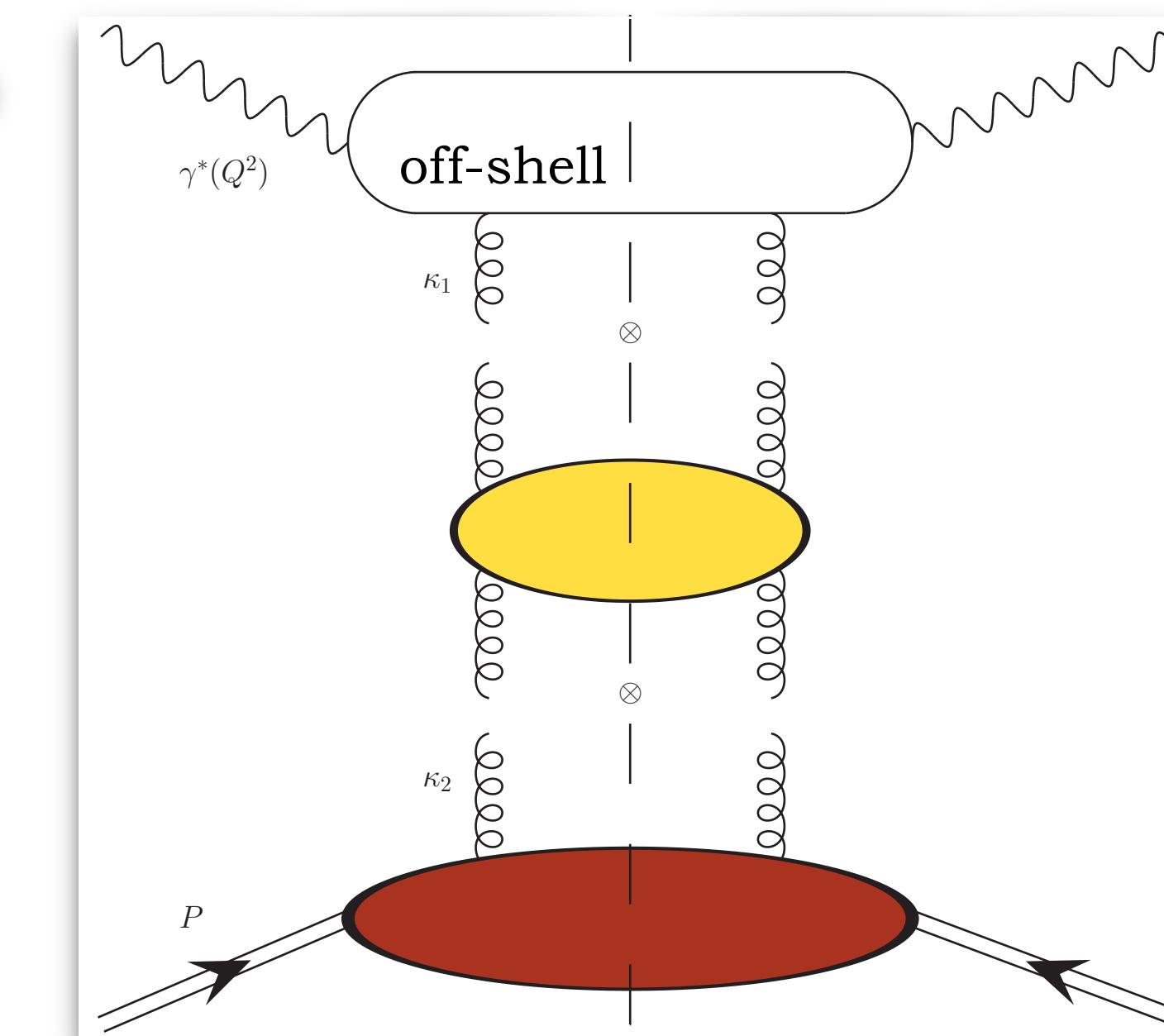


$$\begin{aligned} & \Phi^{\gamma^* \rightarrow \gamma^*} \\ & \otimes \\ & \mathcal{G}_{\text{BFKL}} \\ & \otimes \\ & \Phi_{[\text{NP}]}^P \end{aligned}$$

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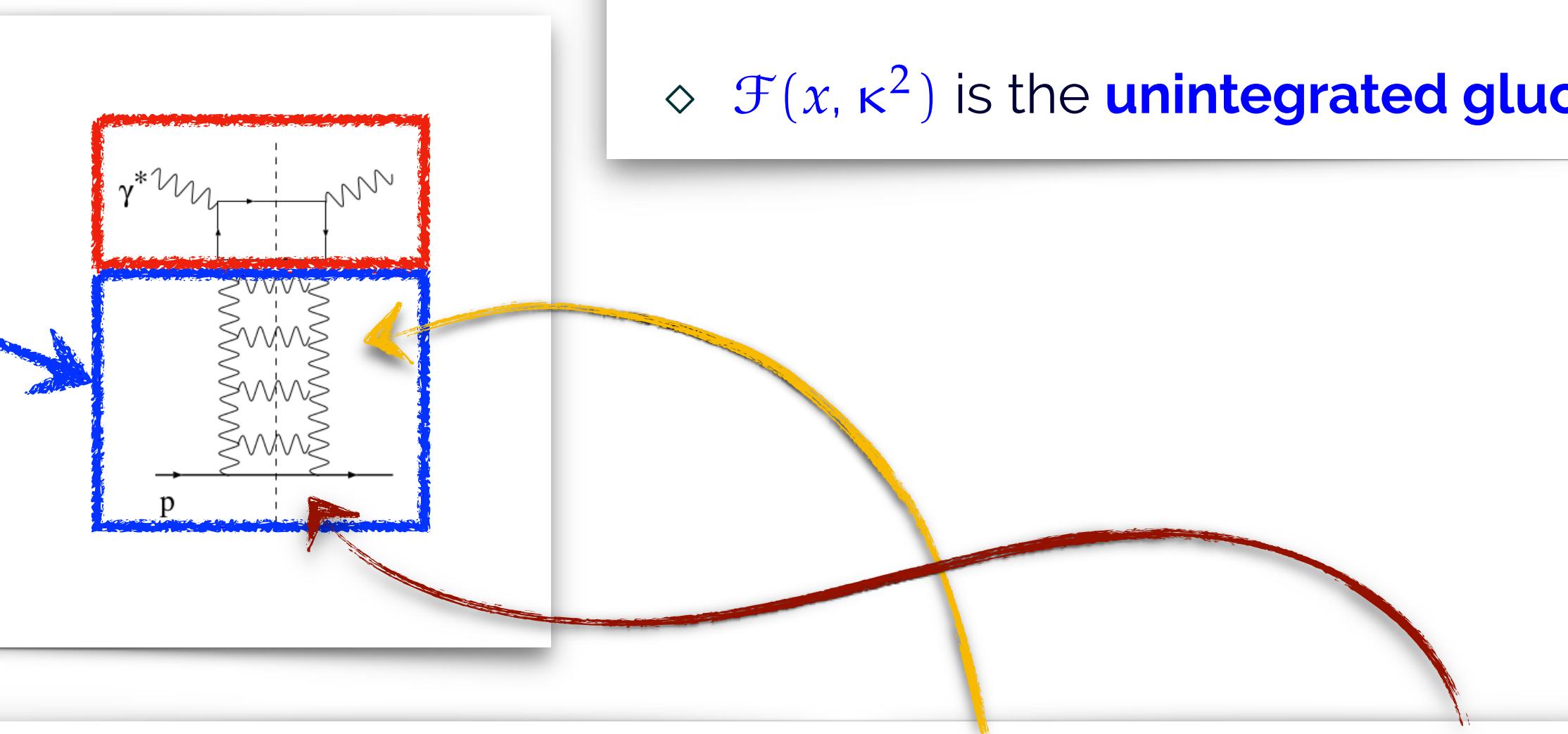
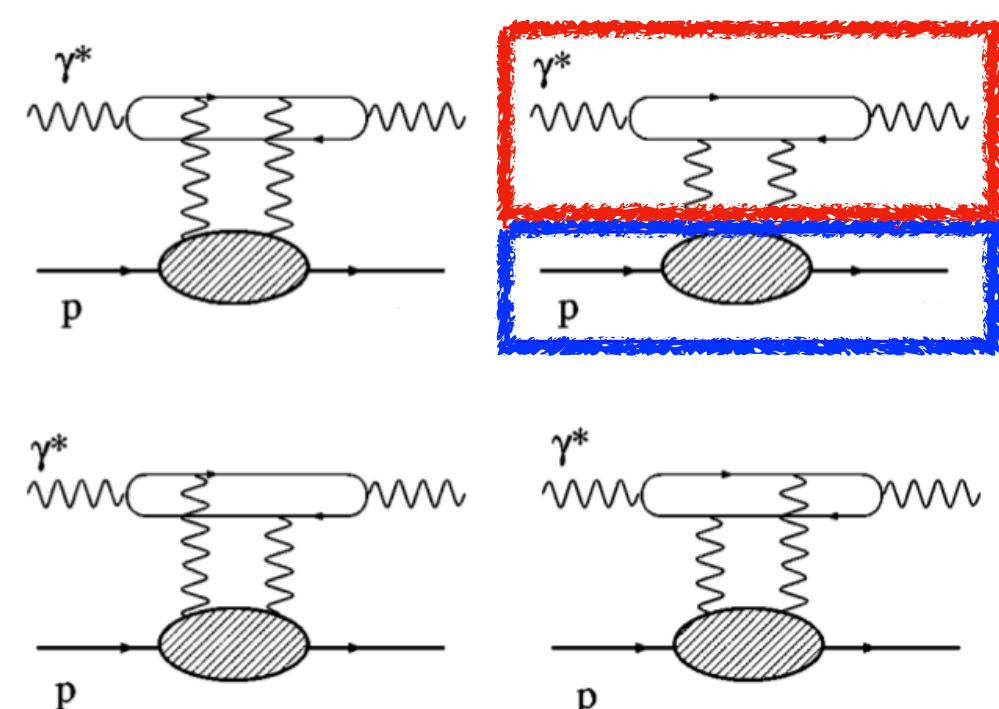
$$\Phi^{\gamma^* \rightarrow \gamma^*} \otimes \mathcal{G}_{\text{BFKL}} \otimes \Phi_{[\text{NP}]}^P$$

High-energy factorization and the UGD

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

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

- ◊ $\mathcal{F}(x, \kappa^2)$ 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 \implies UGD needs to be modeled!

Hybrid or pure factorization?

Forward emissions

- * Asymmetric config. \leftrightarrow fast parton + small- x gluon

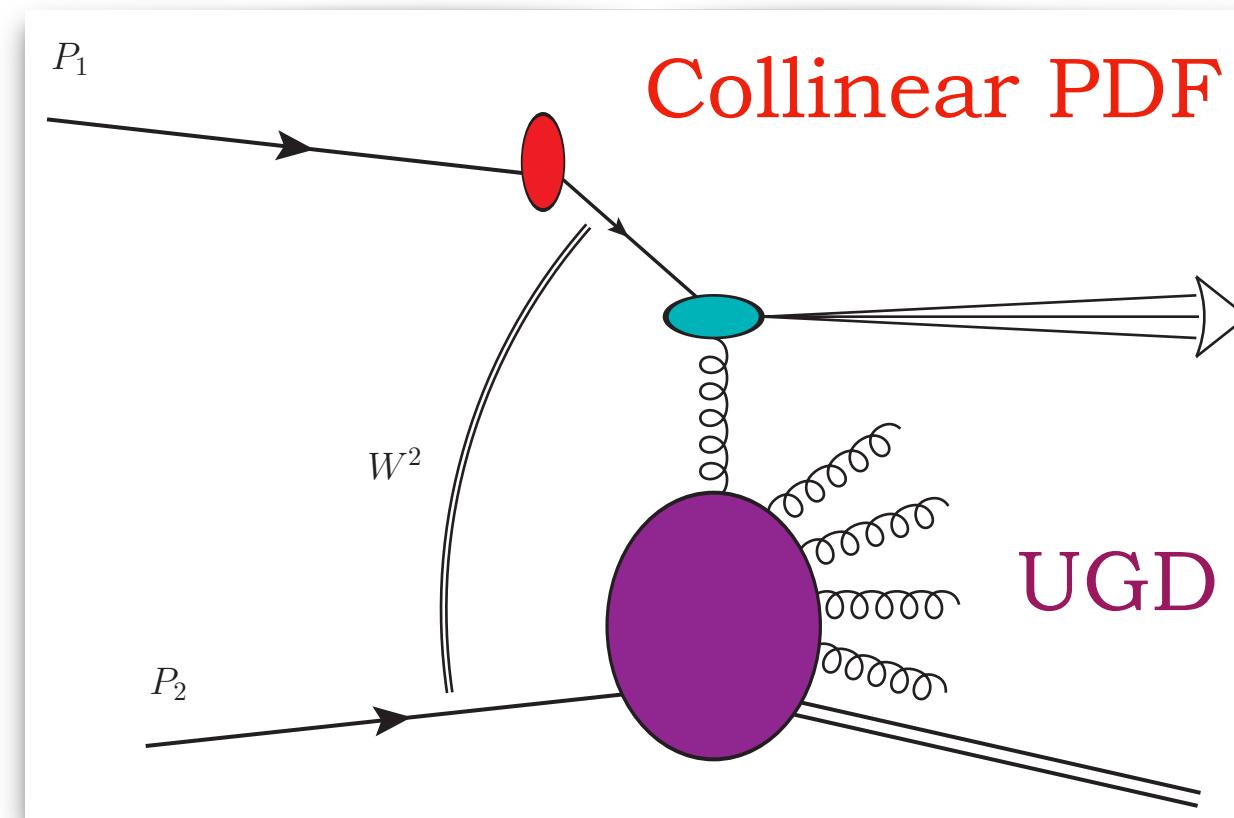
Central emissions

- * Gluon induced \leftrightarrow small- x gluons

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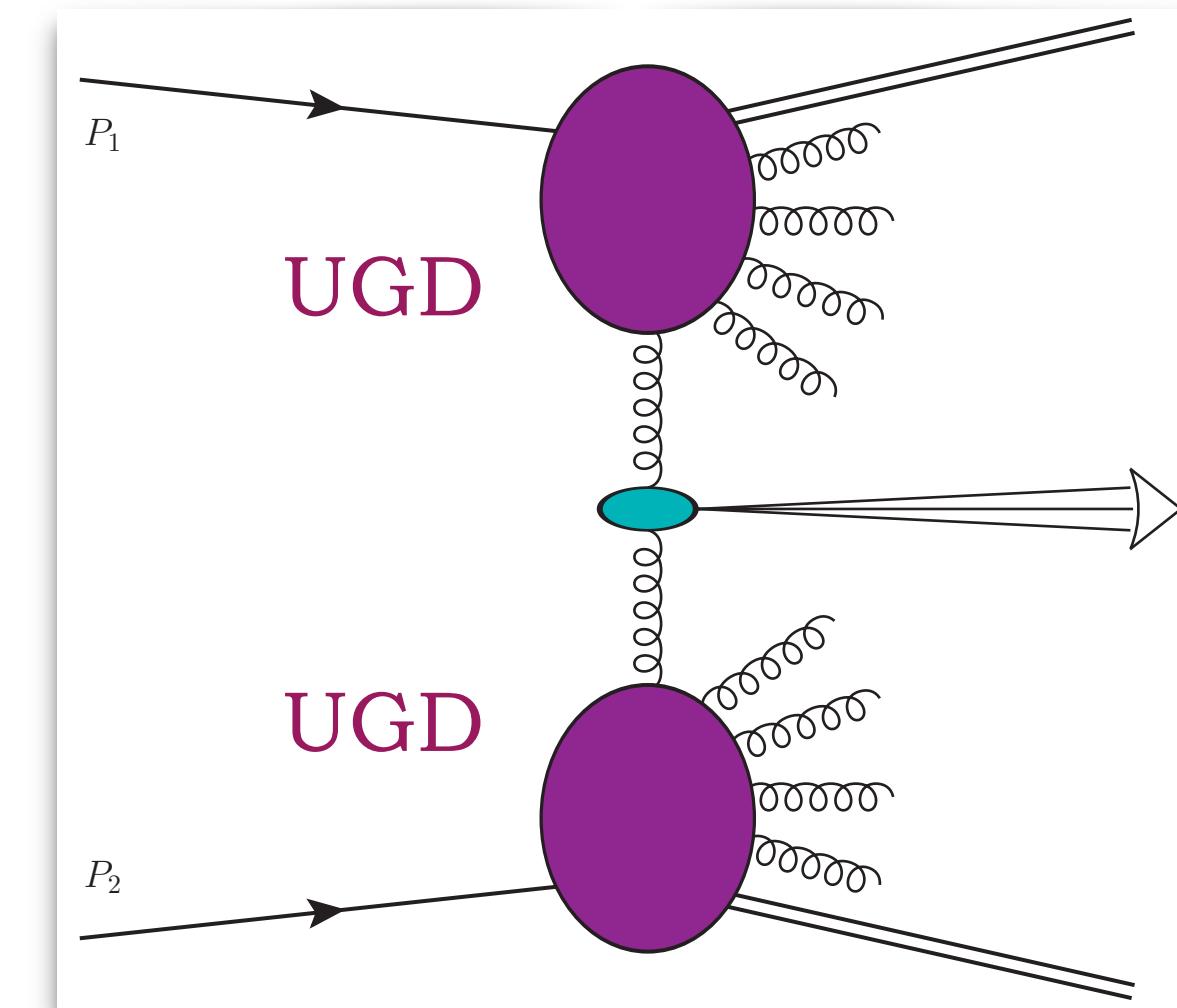
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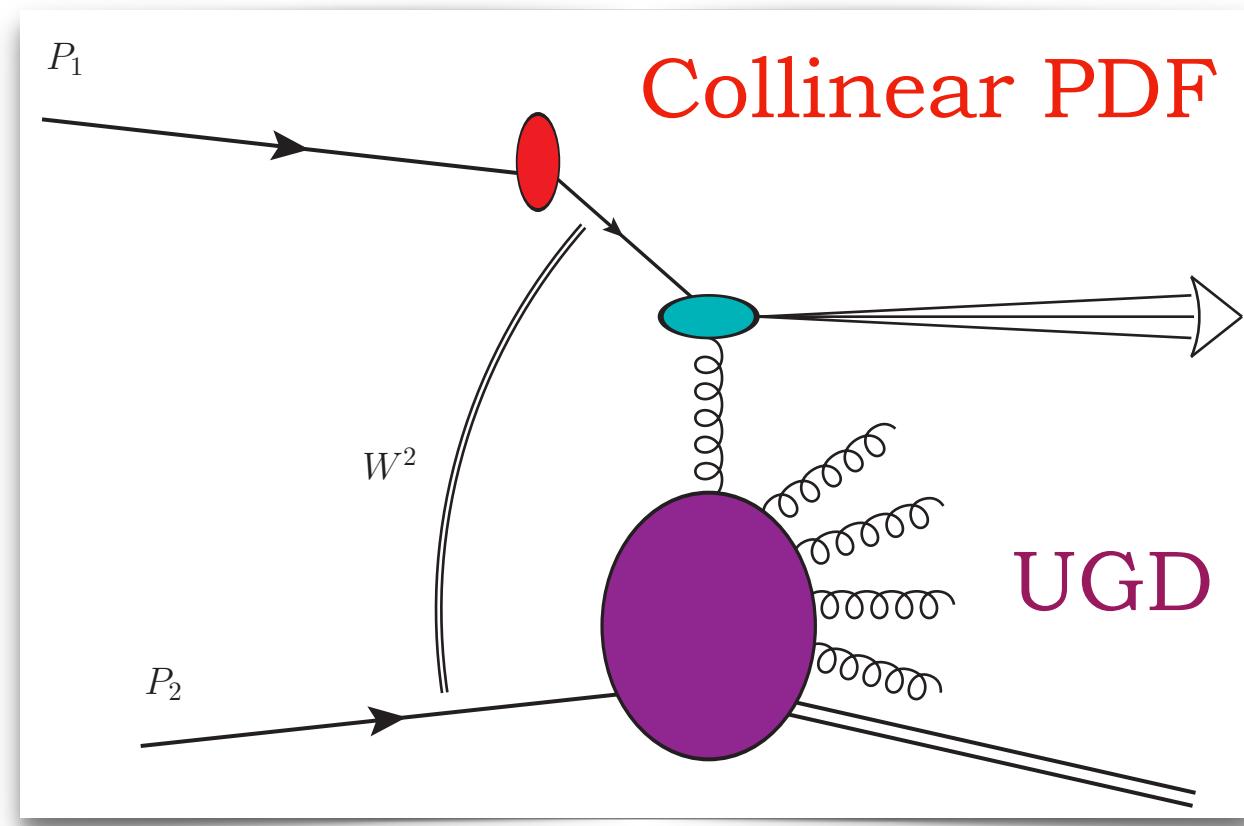
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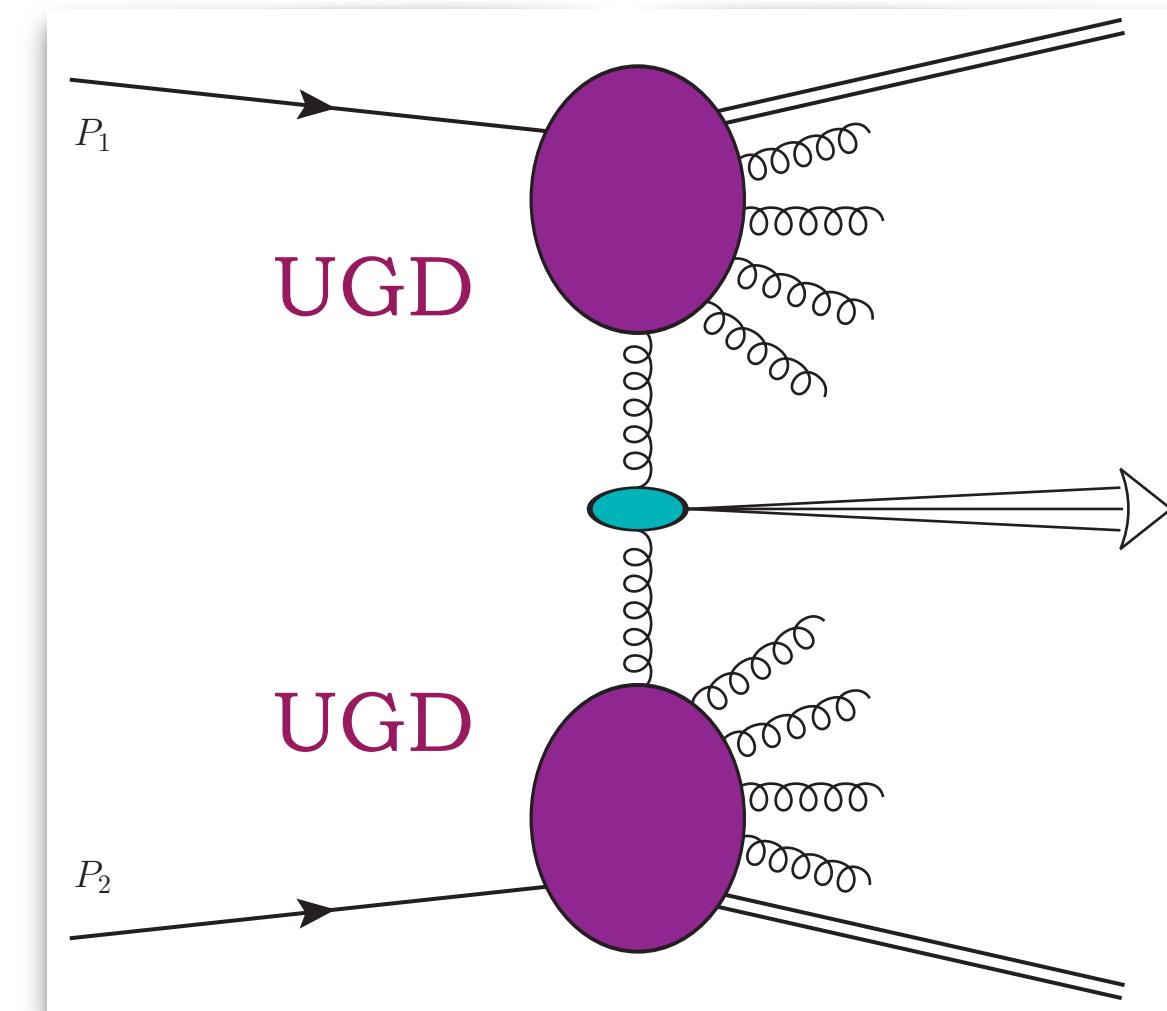
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- * Distinctive signals of small- x dynamics **expected**

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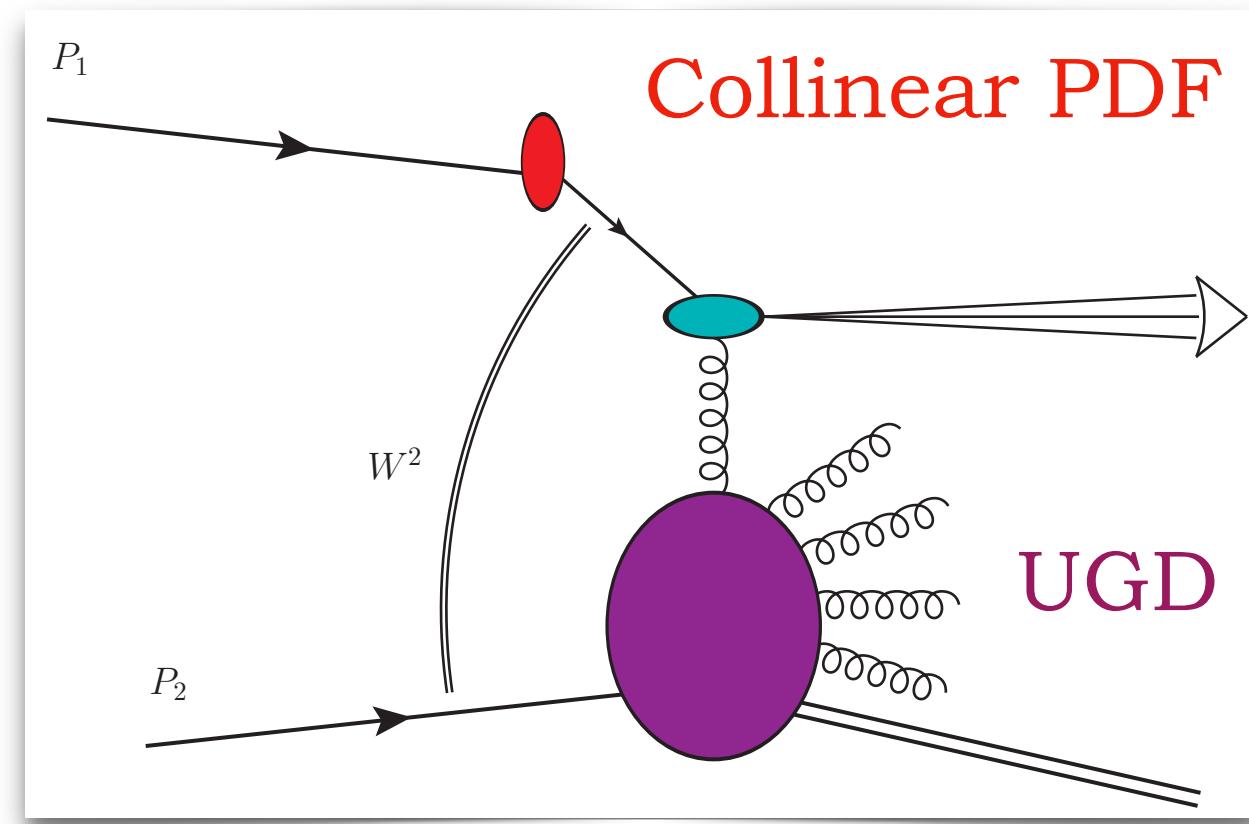


- * Small- x dynamics to **enhance** f.o. description

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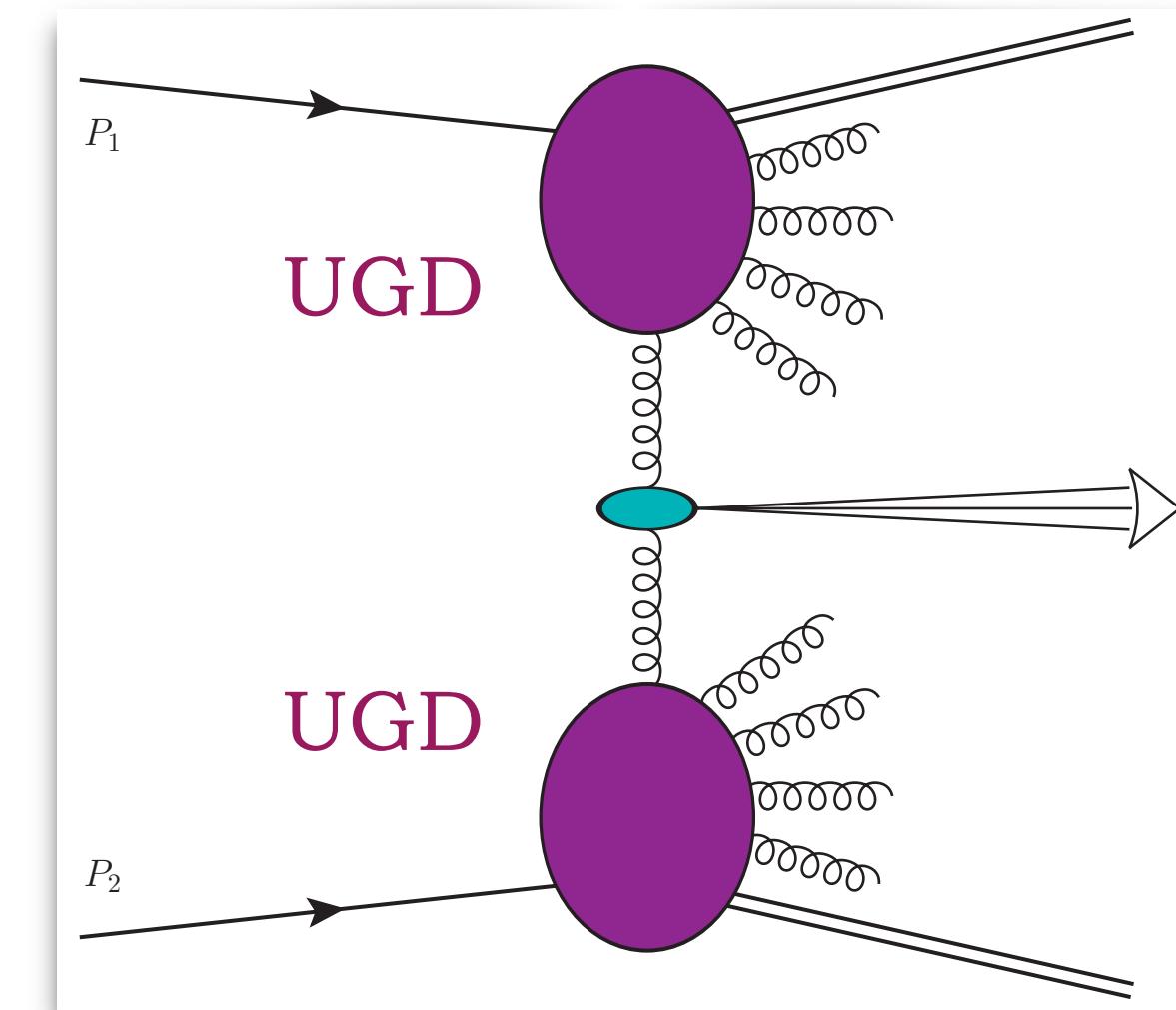
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- * Phenomenology:
forward jet, Drell-Yan, Higgs or vector meson

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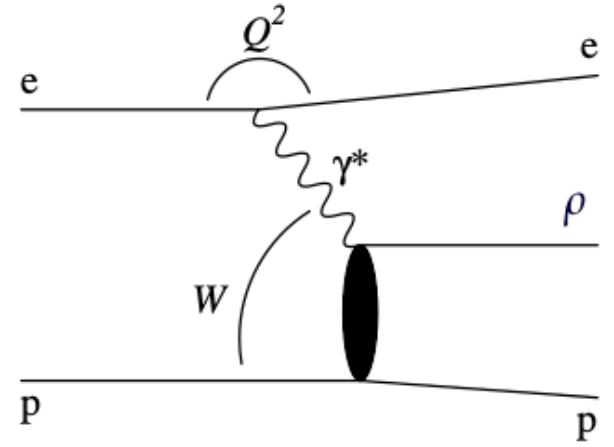
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Table complemented by *exclusive* counterparts and *lepto-hadronic* channels

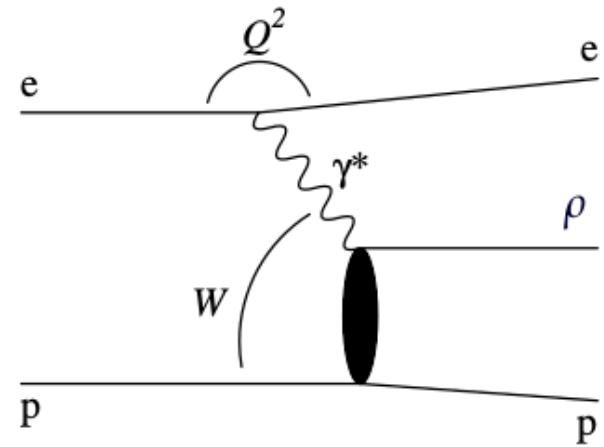
Exclusive forward ρ -meson leptoproduction



- High-energy regime:
 $s \equiv W^2 \gg Q^2 \gg \Lambda_{\text{QCD}}^2 \implies \text{small } x = \frac{Q^2}{W^2}$
- photon virtuality Q is the **hard scale** of the process

► **Process solved in helicity** \implies so far **unexplored testfield** for UGD

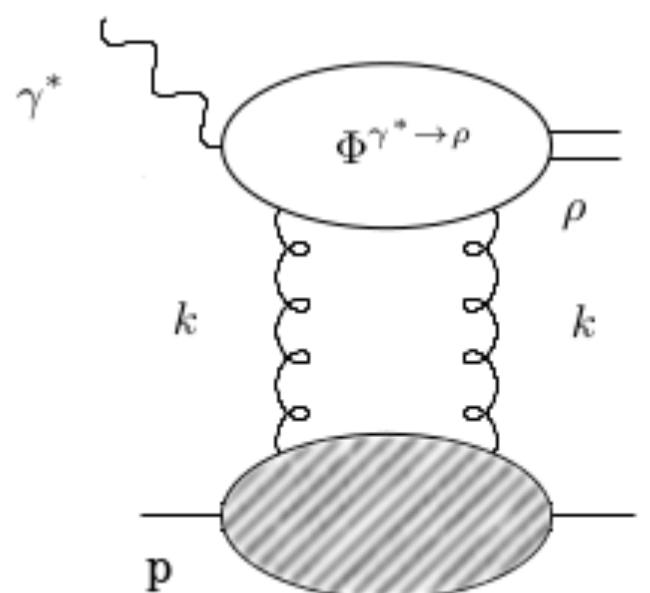
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$$T_{\lambda_\rho \lambda_\gamma}(s; Q^2) = i s \int \frac{d^2 \kappa}{(\kappa^2)^2} \Phi^{\gamma^* \rightarrow \rho}(\lambda_\gamma) (\kappa^2, Q^2) \mathcal{F}(x, \kappa^2), \quad x = \frac{Q^2}{s}$$

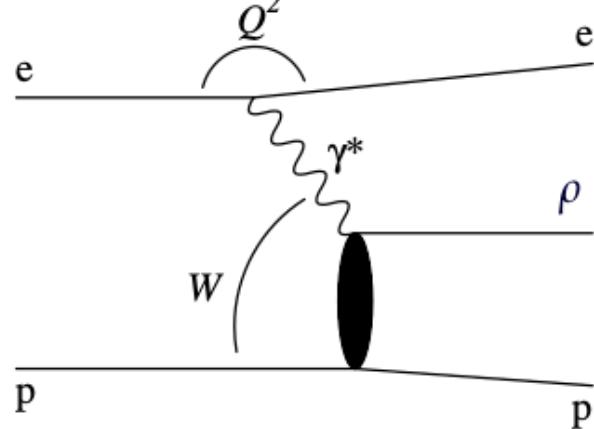


Interesting transitions:

- $\gamma_L^* \rightarrow \rho_L \xrightarrow{\text{encoded by}} \Phi^{\gamma_L^* \rightarrow \rho_L}$
- $\gamma_T^* \rightarrow \rho_T \xrightarrow{\text{encoded by}} \Phi^{\gamma_T^* \rightarrow \rho_T}$

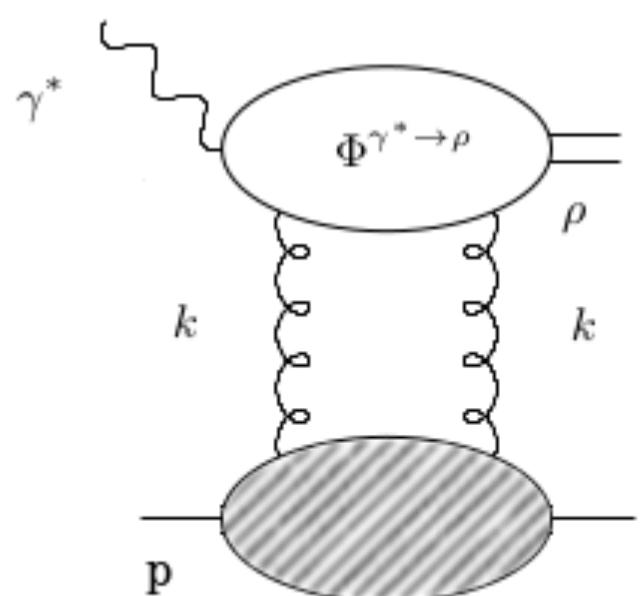
\implies **DAs** enter in $\Phi^{\gamma^* \rightarrow \rho}$

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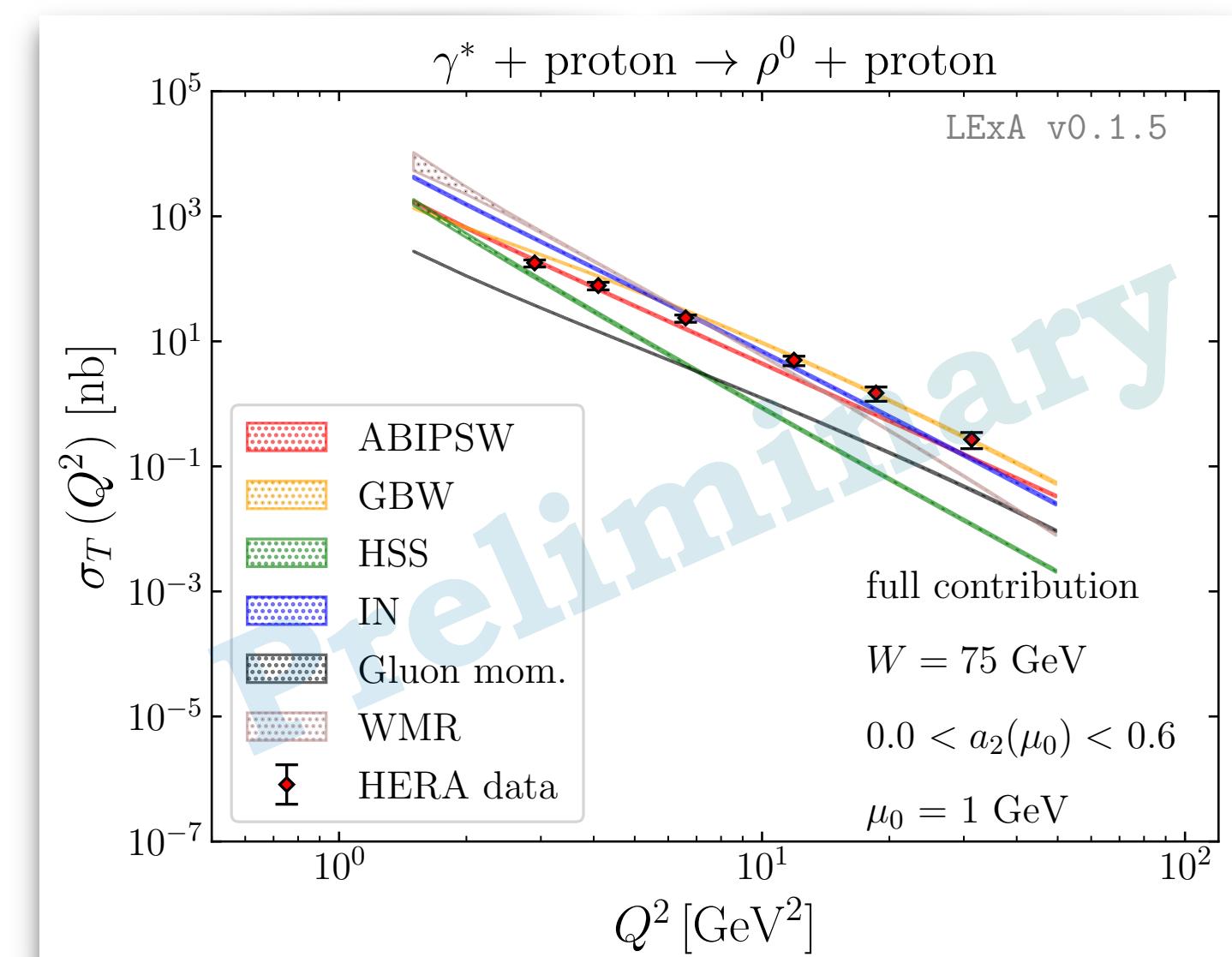
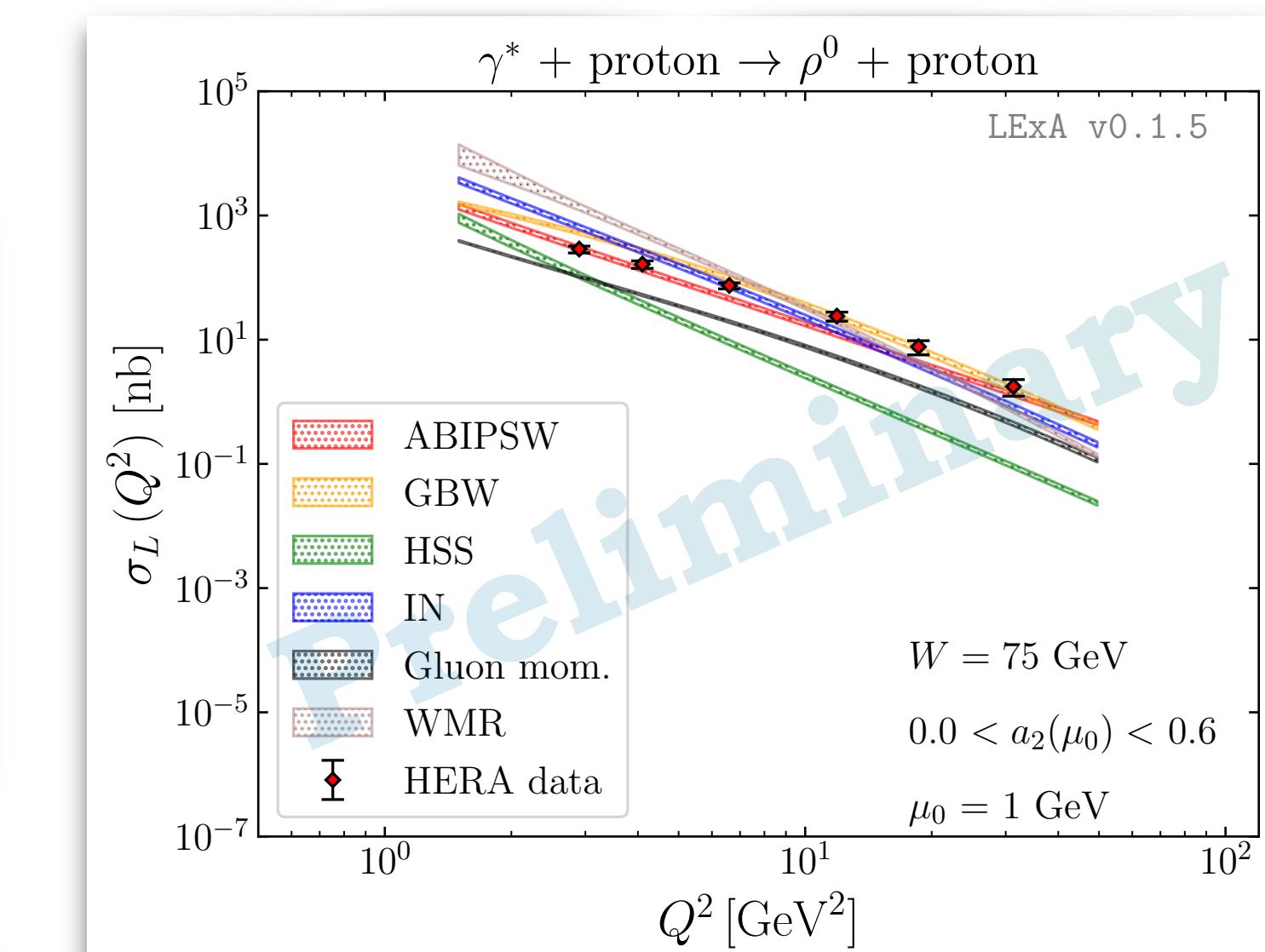
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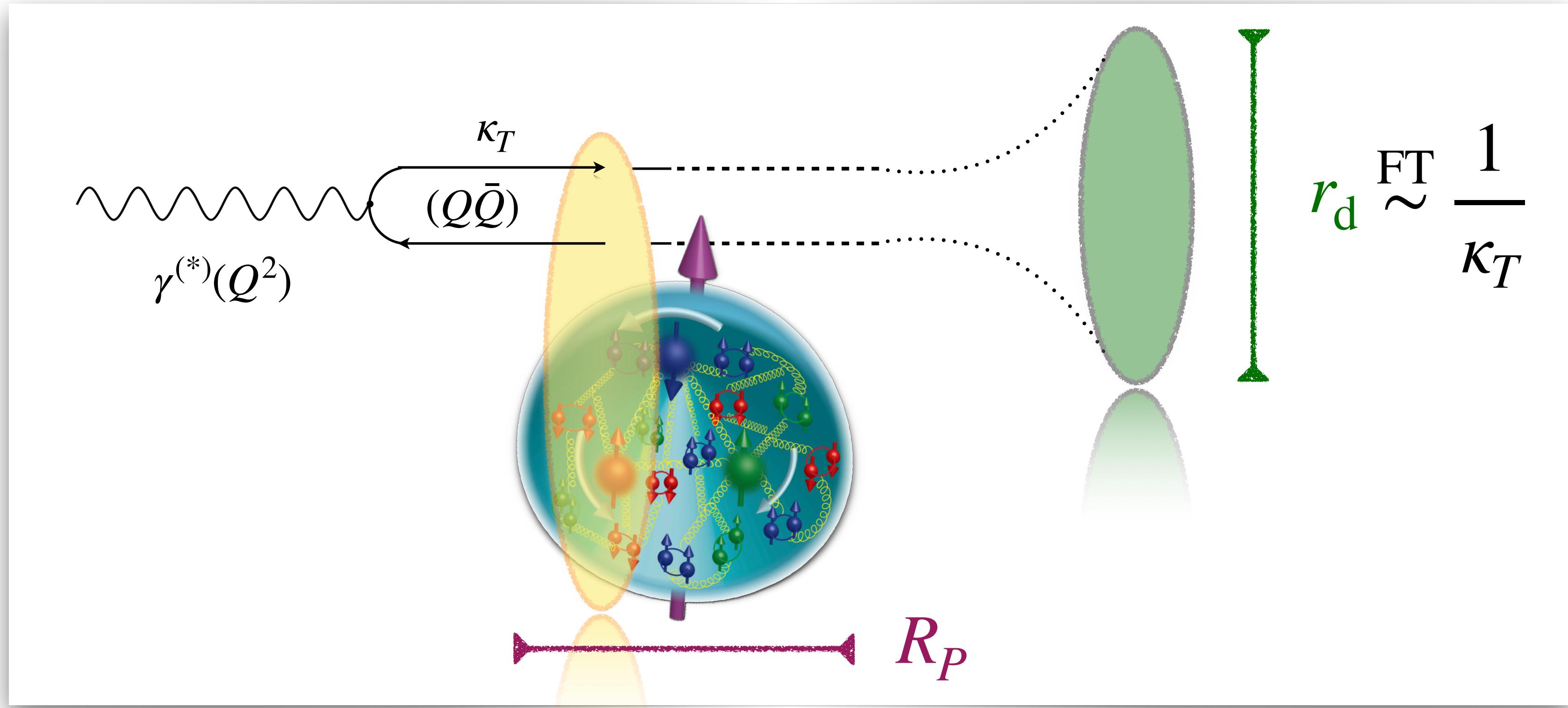
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- \implies **DAs** enter in $\Phi^{\gamma^* \rightarrow \rho}$



🔗 [A.D. Bolognino, F.G.C., D.Yu. Ivanov, A. Papa (2018)]

[A.D. Bolognino, F.G.C., D.Yu. Ivanov, A. Papa, W. Schäfer, A. Szczerba (in preparation)]

Diffractive $\gamma^{(*)}P$ scattering and color dipoles



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

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

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**

$$\Phi^{r^* \rightarrow \rho} \propto \int_0^1 dz T_H(z, \kappa_T, Q, \mu_R, \mu_F) \phi(z, \mu_F)$$

- * Significance of small κ_T under investigation...
- * HERA indication: no large- r_d dynamics
- * Pheno outcome: sensitivity to **intermediate** κ_T
- * LVMs as tools: discrimination among UGD models

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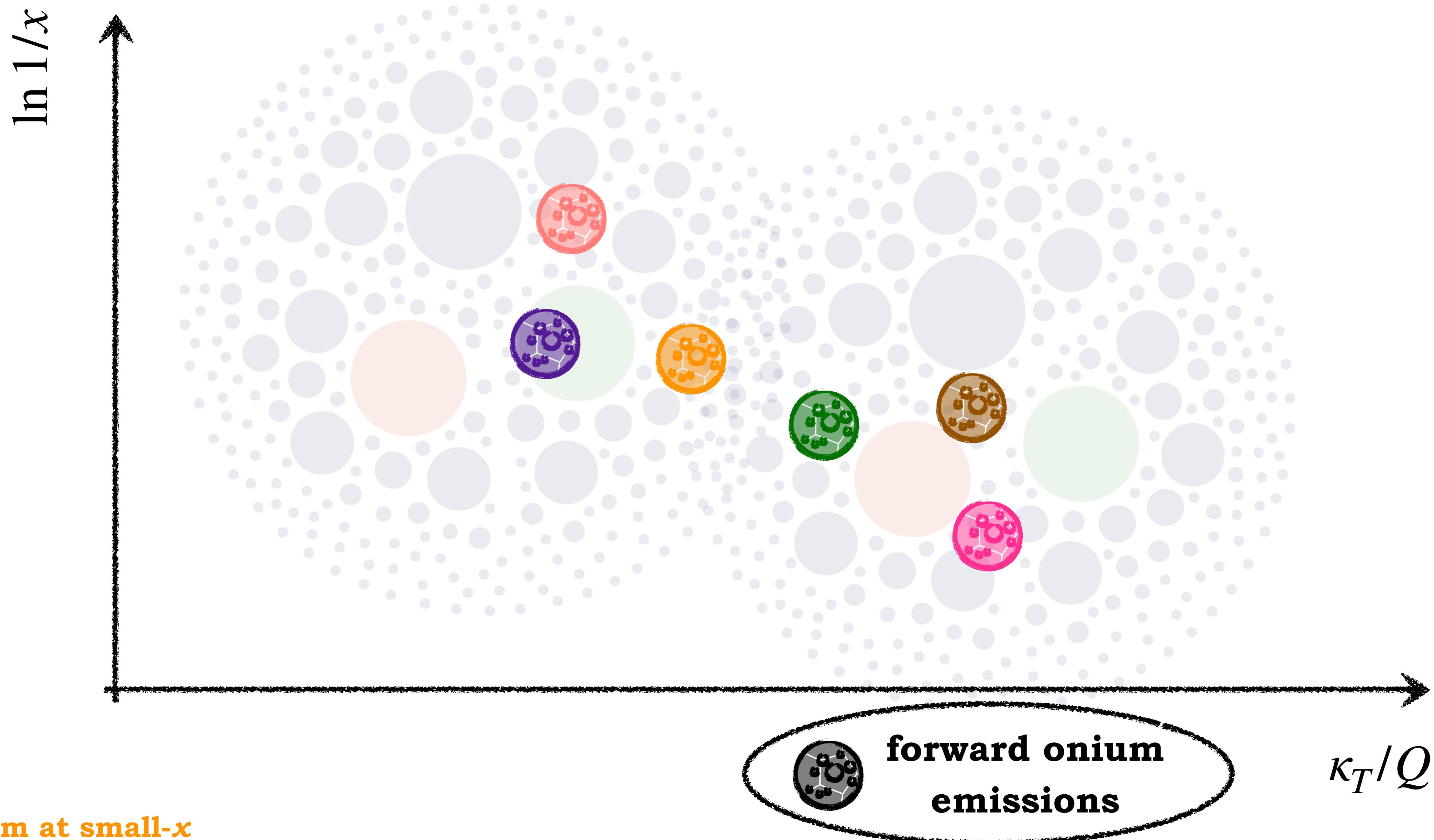
- * Size of dipoles \Rightarrow wide range of κ_T
- * Description: **NRQCD** (combined with LFWFs)

$$[\text{LFWF} \otimes \mathcal{A}_{\text{dip.}}] \xrightleftharpoons{\text{dilute}} [\Phi^{\gamma^* \rightarrow J/\Psi} \otimes \text{UGD}]$$

- * Validity of *small-size* dipoles questionable...
 - * NRQCD: large- r_d dynamics for $\Psi(2s)$ ($\Upsilon(2s)$?)
- \circlearrowleft [K. Suzuki *et al.* (2000)]; \circlearrowleft [J. Cepila *et al.* (2019)]; \circlearrowleft [M. Hentschinski *et al.* (2020)]
- * **Onia as tools**: scan of TMD/HEF intersection range

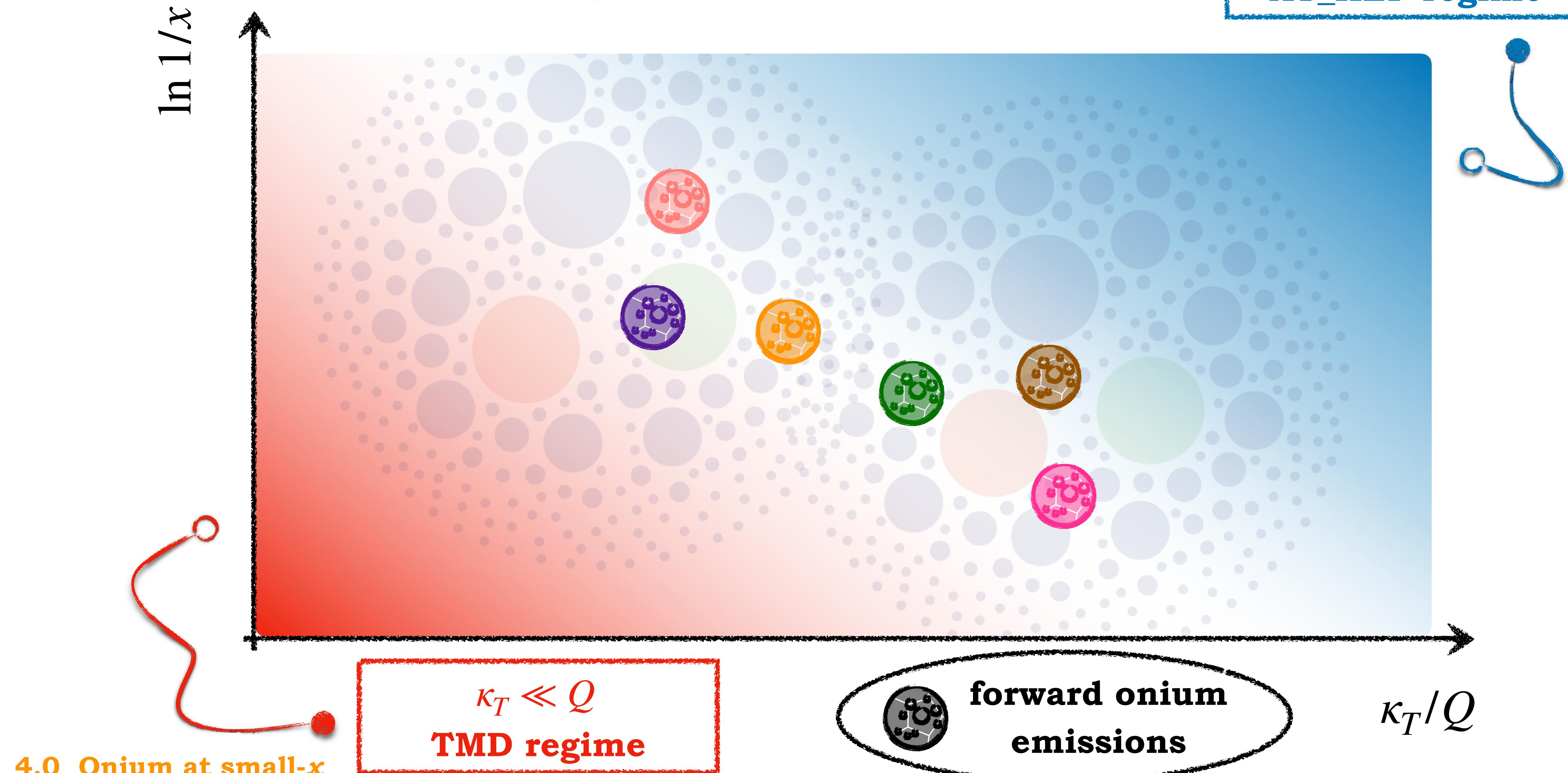
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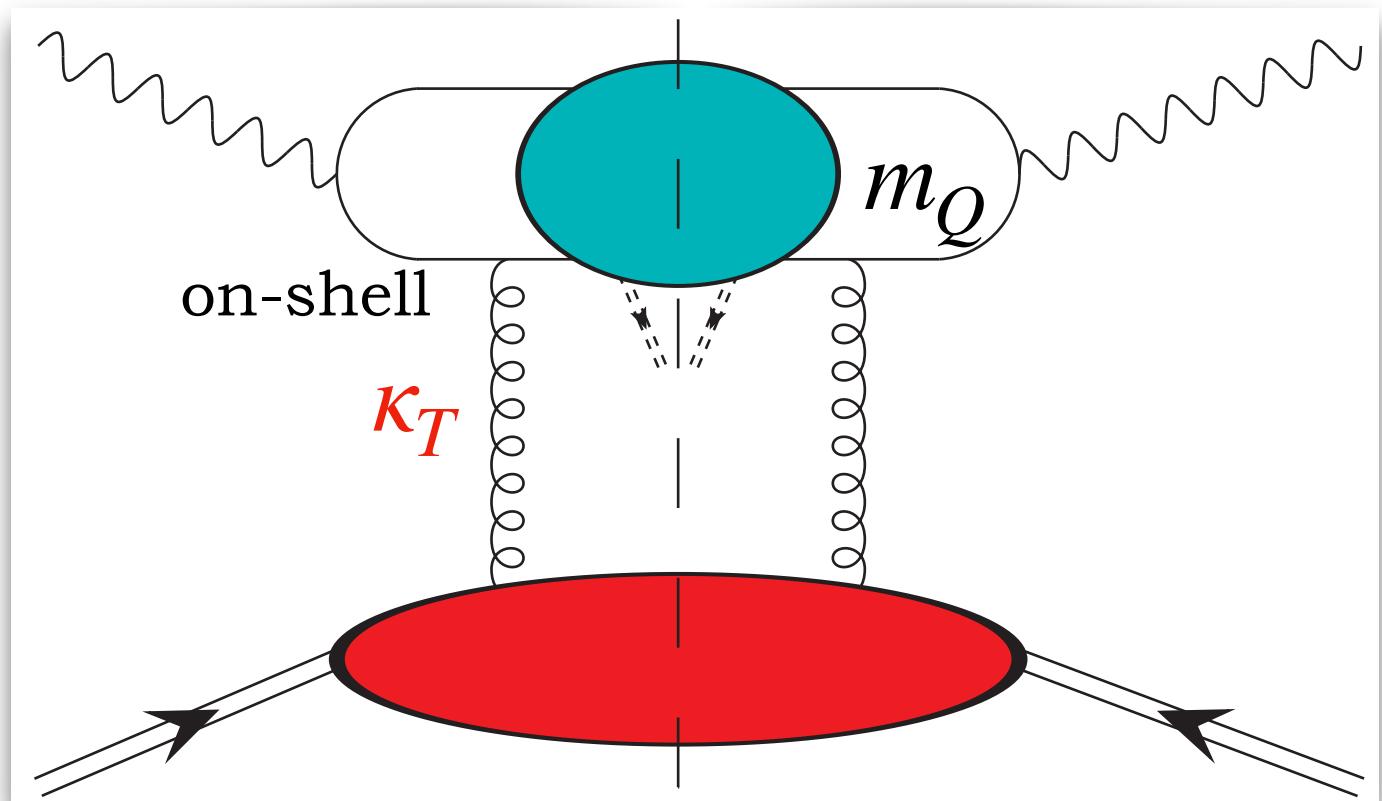
Hadronic structure and quarkonia

$x \ll 1; \kappa_T \approx Q \gg \Lambda_{\text{QCD}}$
AT_HEF regime



Inclusive quarkonium emissions

$$\kappa_T \ll Q$$

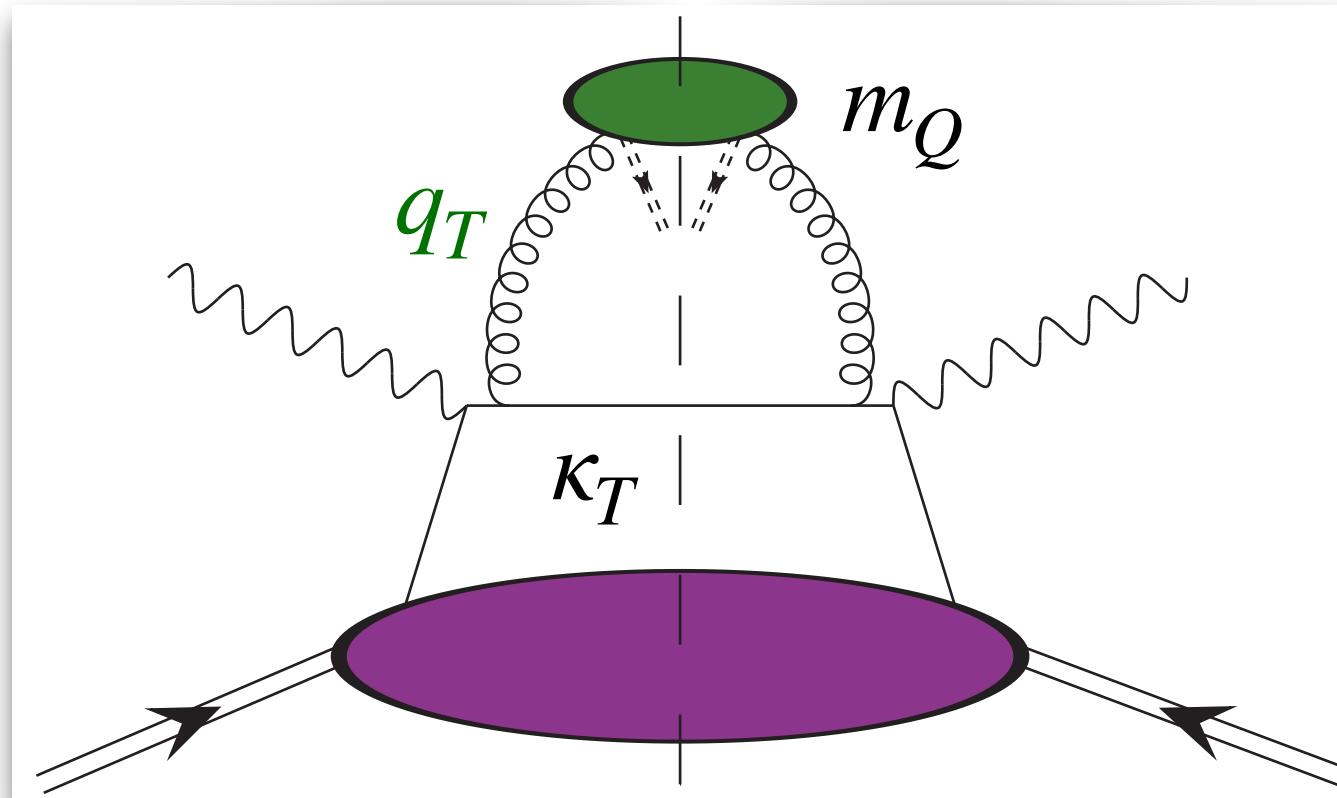
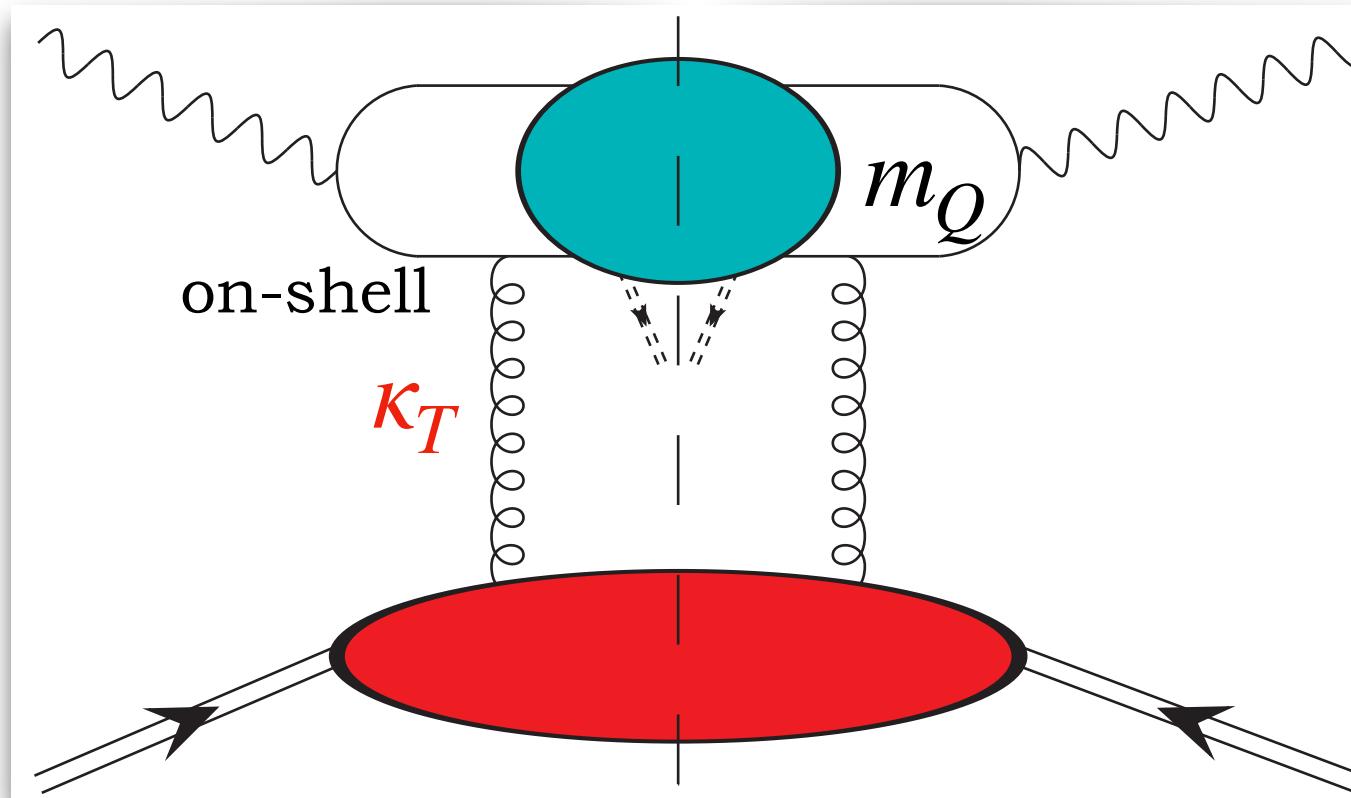


- * Gluon TMD PDF
- * Double-parton fragment.

Inclusive quarkonium emissions

$$\kappa_T \ll Q$$

$$\kappa_T \gg m_Q$$



- * Gluon TMD PDF

- * Double-parton fragment.

- * Quark collinear PDF

- * Onium in jet

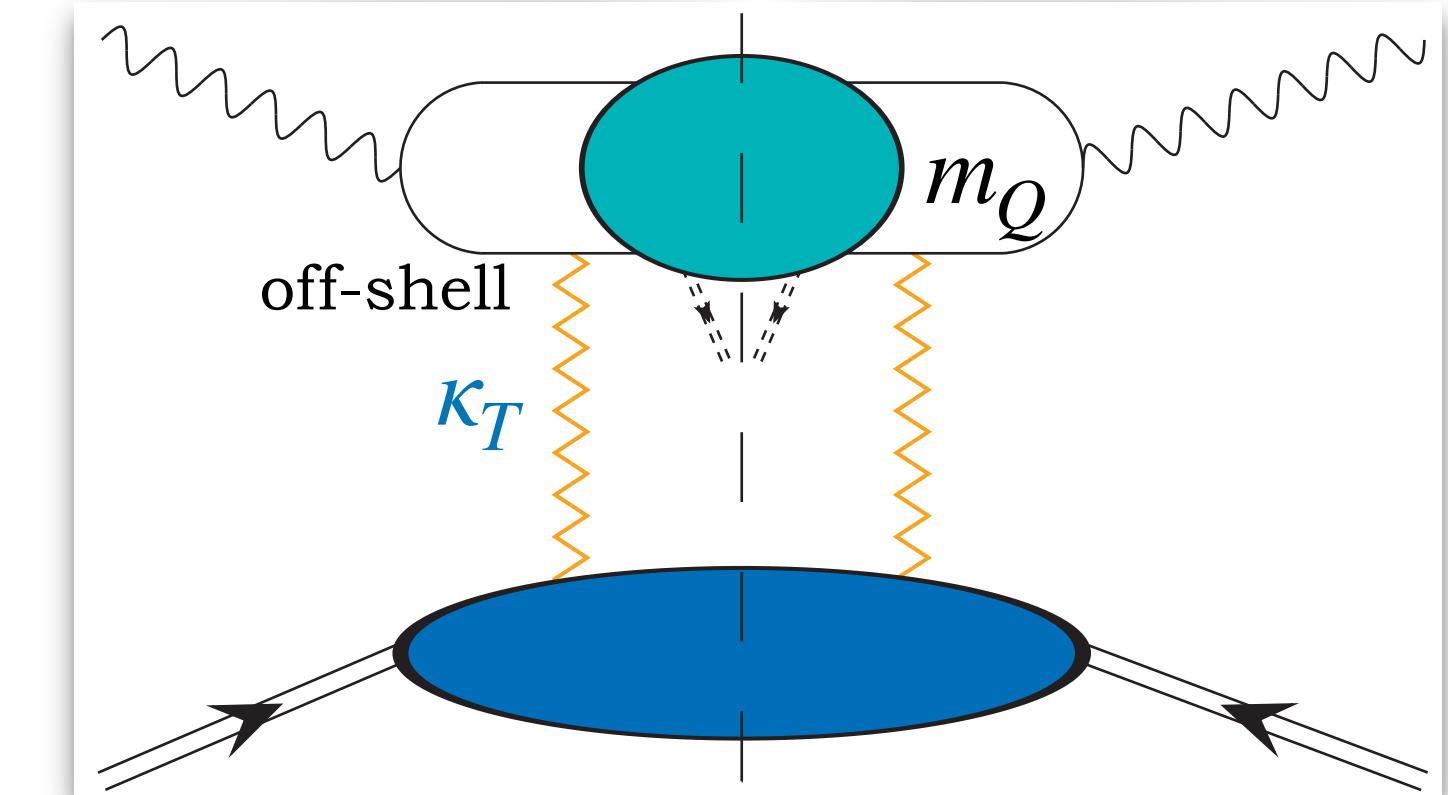
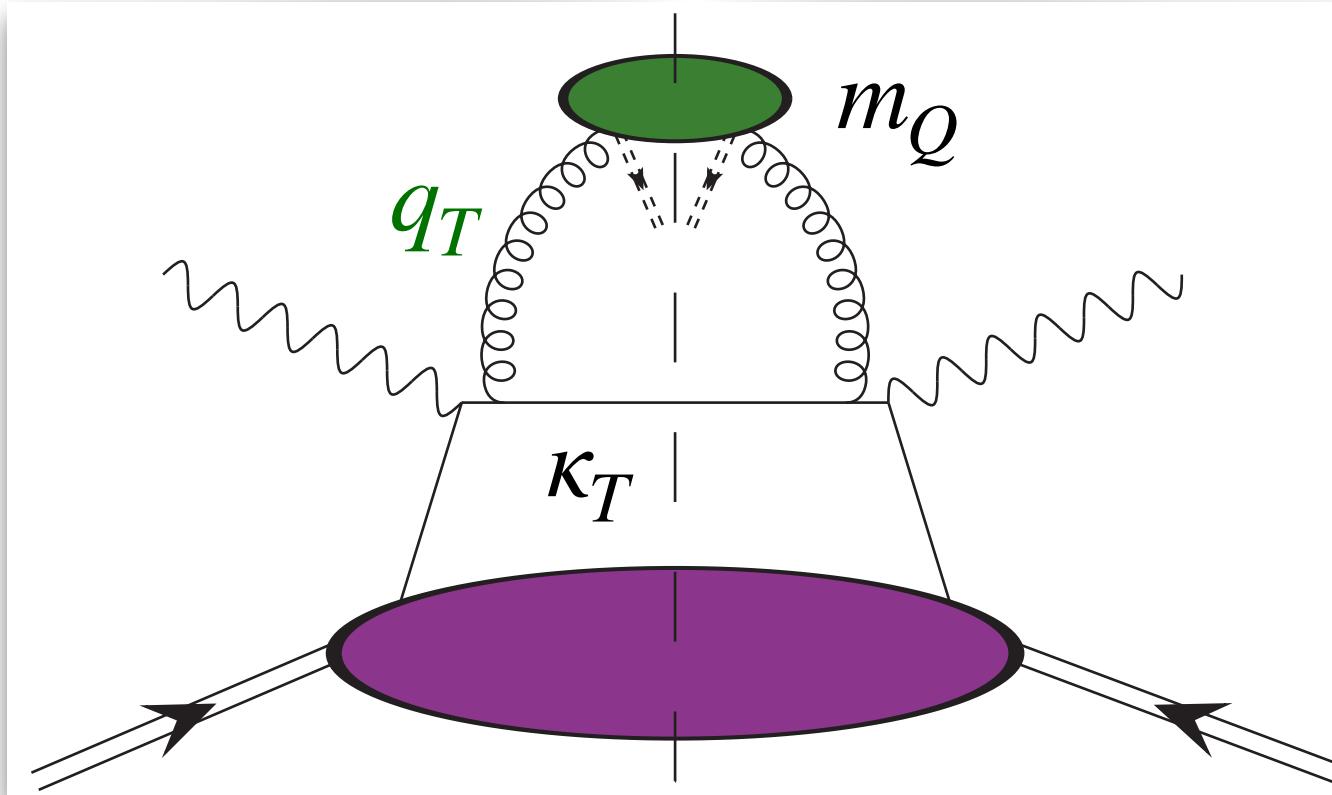
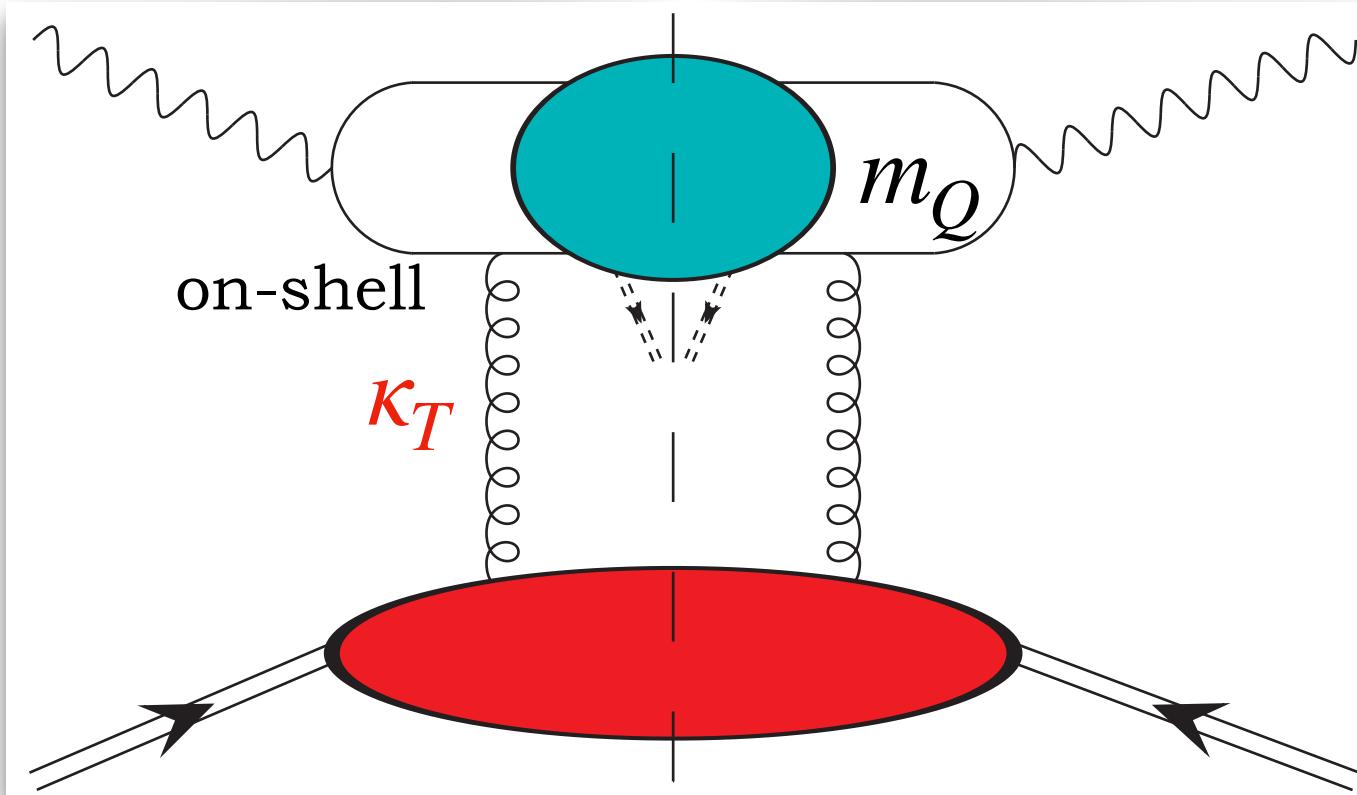
- * Single-quark TMD FF

Inclusive quarkonium emissions

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HEF



* Gluon TMD PDF

* Double-parton fragment.

* Quark collinear PDF

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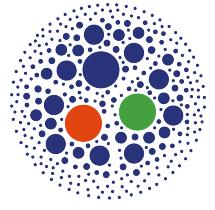
* Single-quark TMD FF

* BFKL UGD

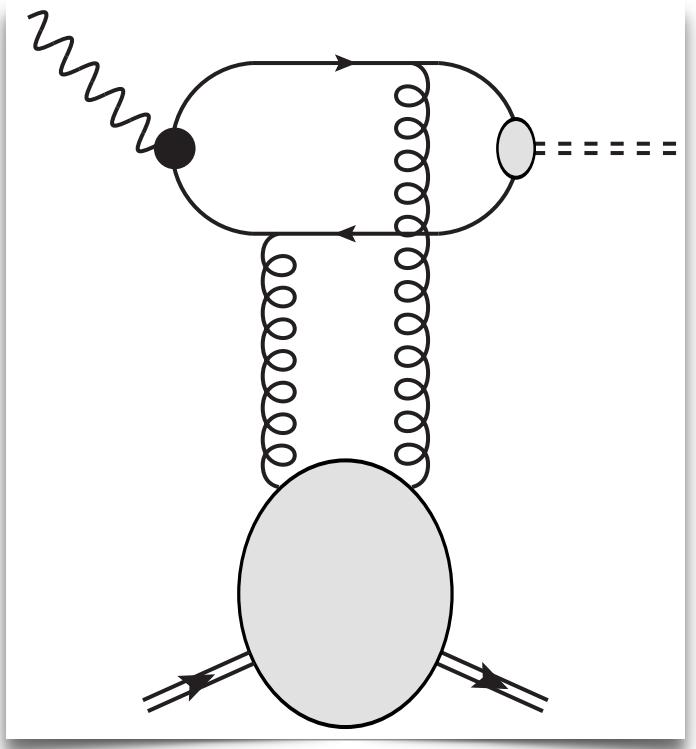
* Reggeized gluons

* Dipole mechanism

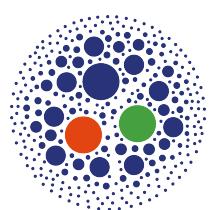
Small- x and quarkonia



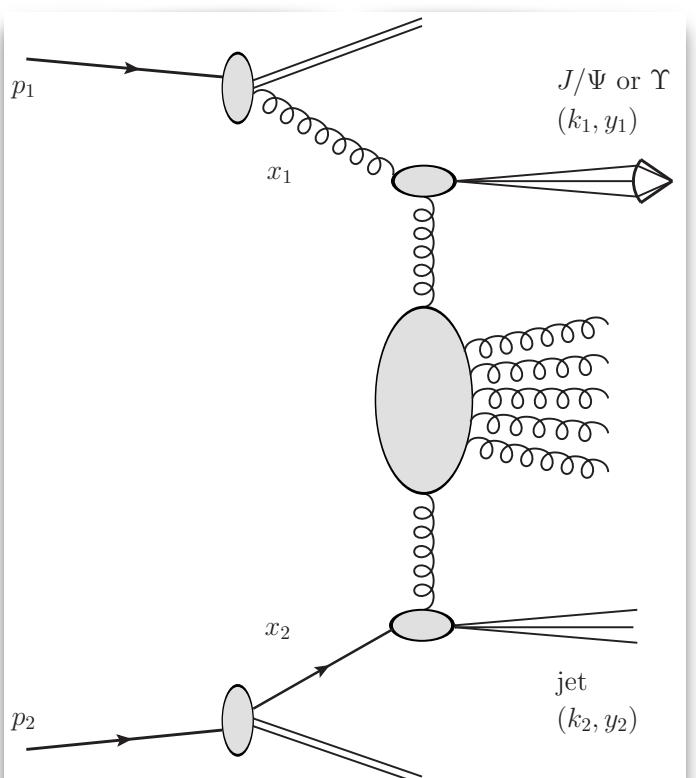
Exclusive photoproduction



CS

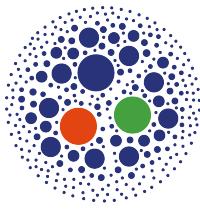


Hadroproduction

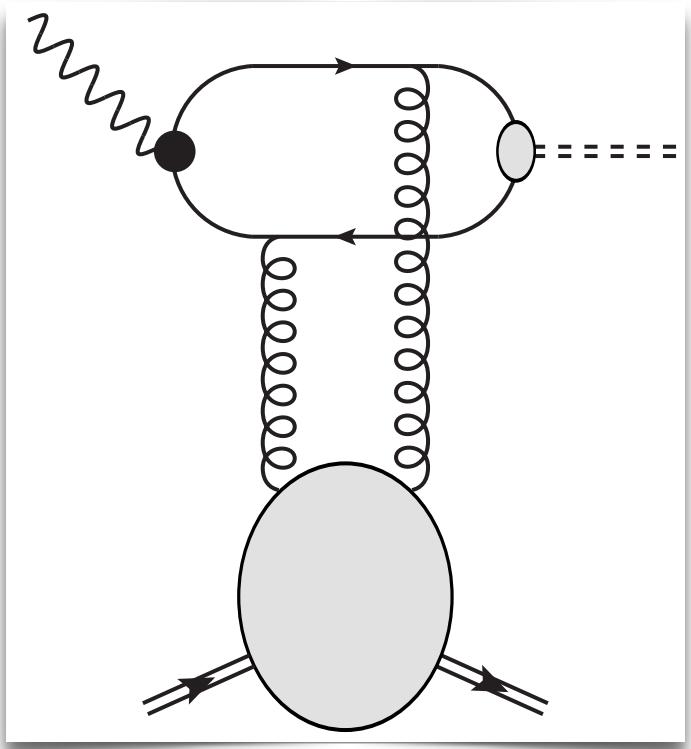


CO + CS

Small- x and quarkonia



Exclusive photoproduction



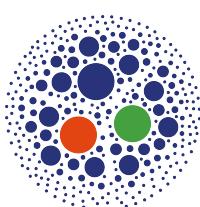
CS

Exclusive single forward J/Ψ , $\Psi(2s)$, Υ emissions

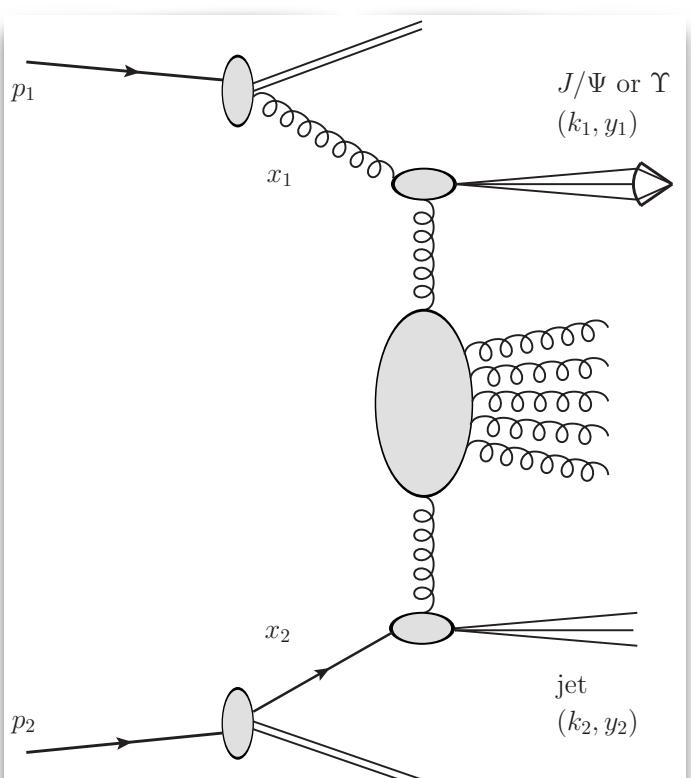
(BFKL growth with energy with HSS UGD) [I. Bautista, A. Fernandez Tellez, M. Hentschinski (2017)]

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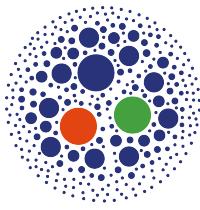


Hadroproduction

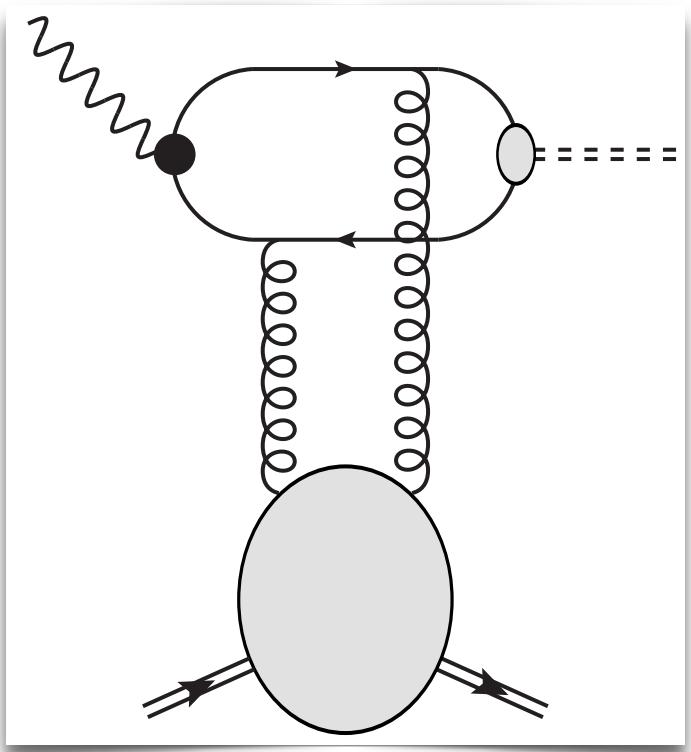


CO + CS

Small- x and quarkonia



Exclusive photoproduction



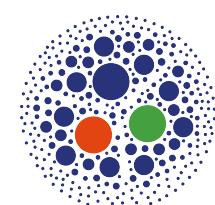
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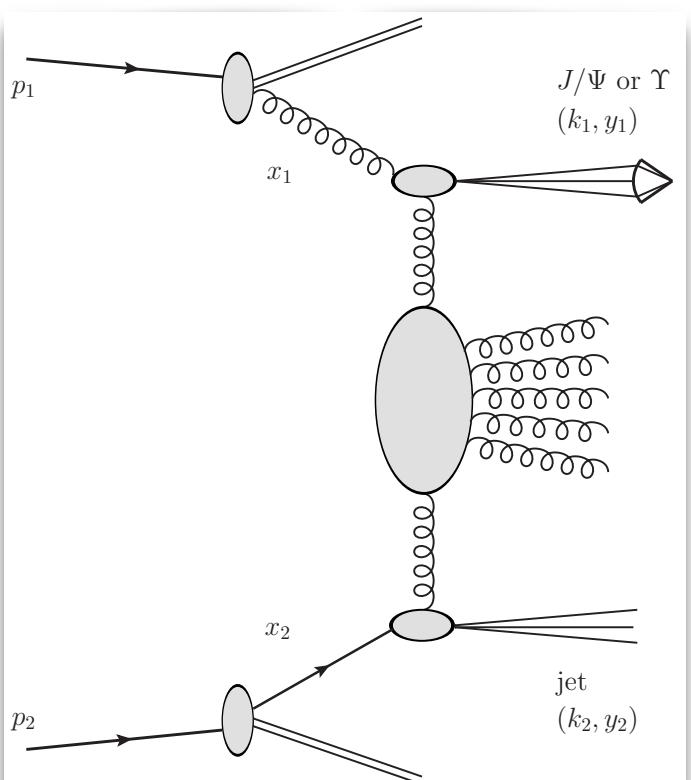
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Hadroproduction



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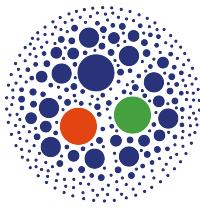
Inclusive single/double central quarkonium emissions

($\Psi(2s)$, $\Psi(3s)$: PRA + NRQCD LDME + fragmentation) [B.A. Kniehl, M. Nefedov, V. Saleev (2016)]

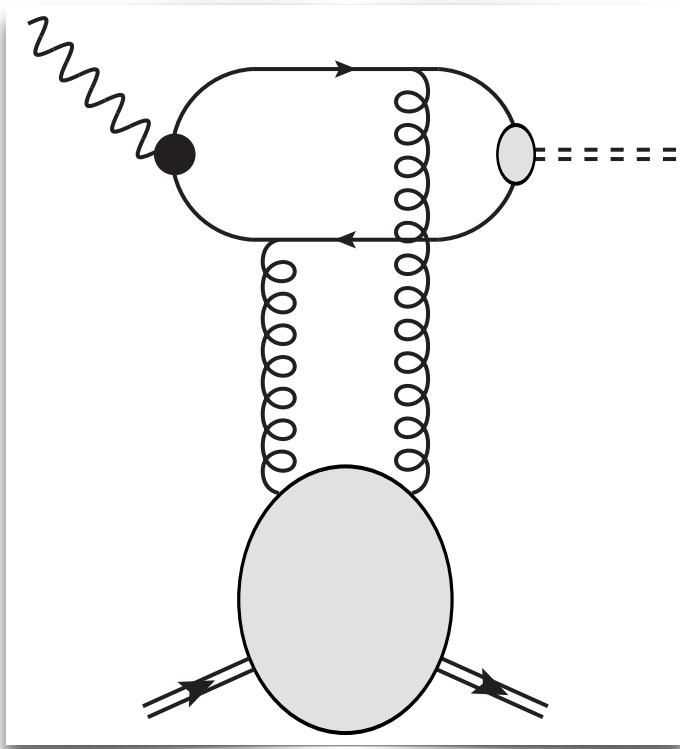
($\chi_c(J)$ pairs with large ΔY : HEF with KMR-type UGD + CS NRQCD) [A. Cisek, W. Schäfer, A. Szczurek (2018)]

(J/Ψ pairs: HEF with CCFM uPDFs + NRQCD LDME) [A.A. Prokhorov, A.V. Lipatov, M.A. Malyshev, S.P. Baranov (2020)]

Small- x and quarkonia



Exclusive photoproduction



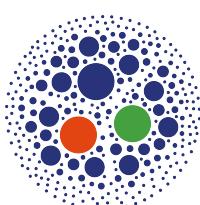
CS

Exclusive single forward J/Ψ , $\Psi(2s)$, Υ emissions

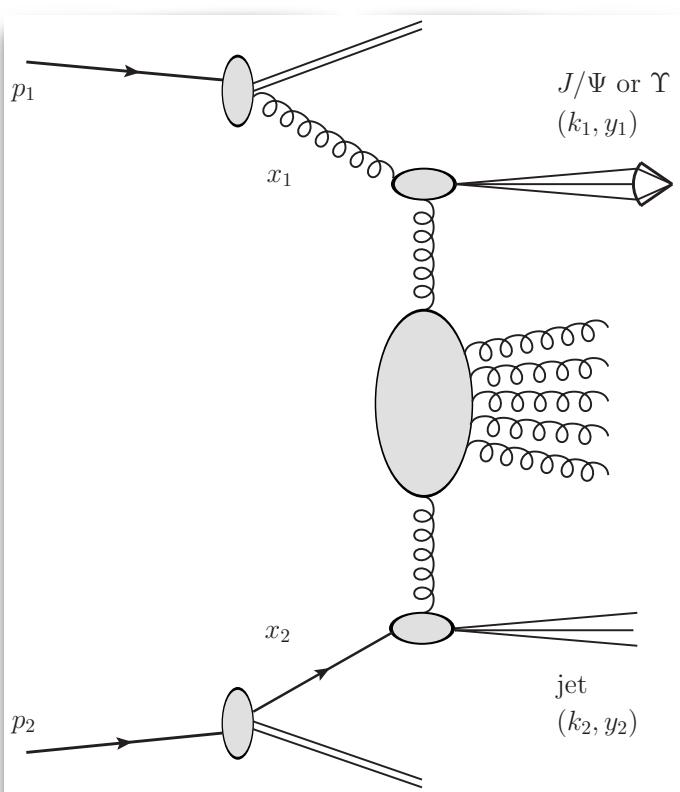
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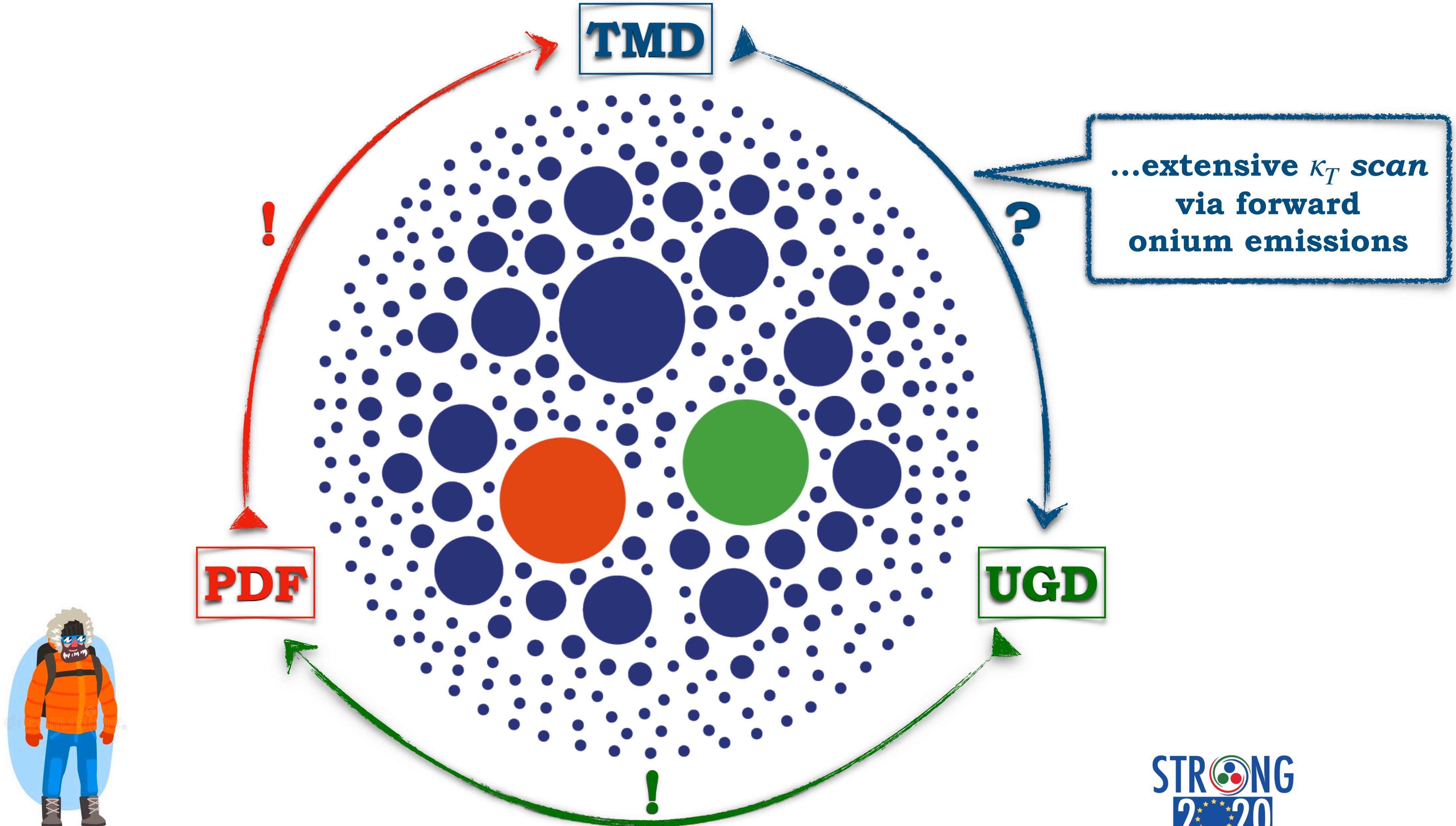
Inclusive forward/backward quarkonium emissions

(J/Ψ + jet: hybrid HEF with PDFs and BFKL + NRQCD/CEM) [R. Boussarie, B. Ducloué, L. Szymanowski, S. Wallon (2018)]

(LO forward $Q\bar{Q}$ impact factor: ongoing program to quarkonia) [A.D. Bolognino, F.G.C., M. Fucilla, D.Yu. Ivanov, A. Papa (2019)]

...Monday's talk by **Michael Fucilla**

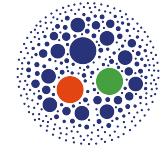
Mapping the proton content at small- x



**Backup
slides**

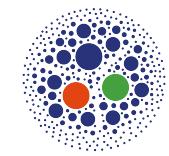
Hadronic structure at small- x

Forward physics and the hadronic structure

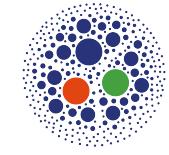


Forward emissions → *golden channels* to access the **nucleon structure** at small- x

Forward physics and the hadronic structure



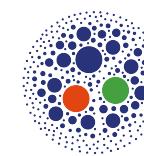
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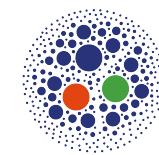
Several formalisms developed → various kinds of **parton distribution functions**

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

Forward physics and the hadronic structure



Forward emissions → *golden channels* to access the **nucleon structure** at small- x



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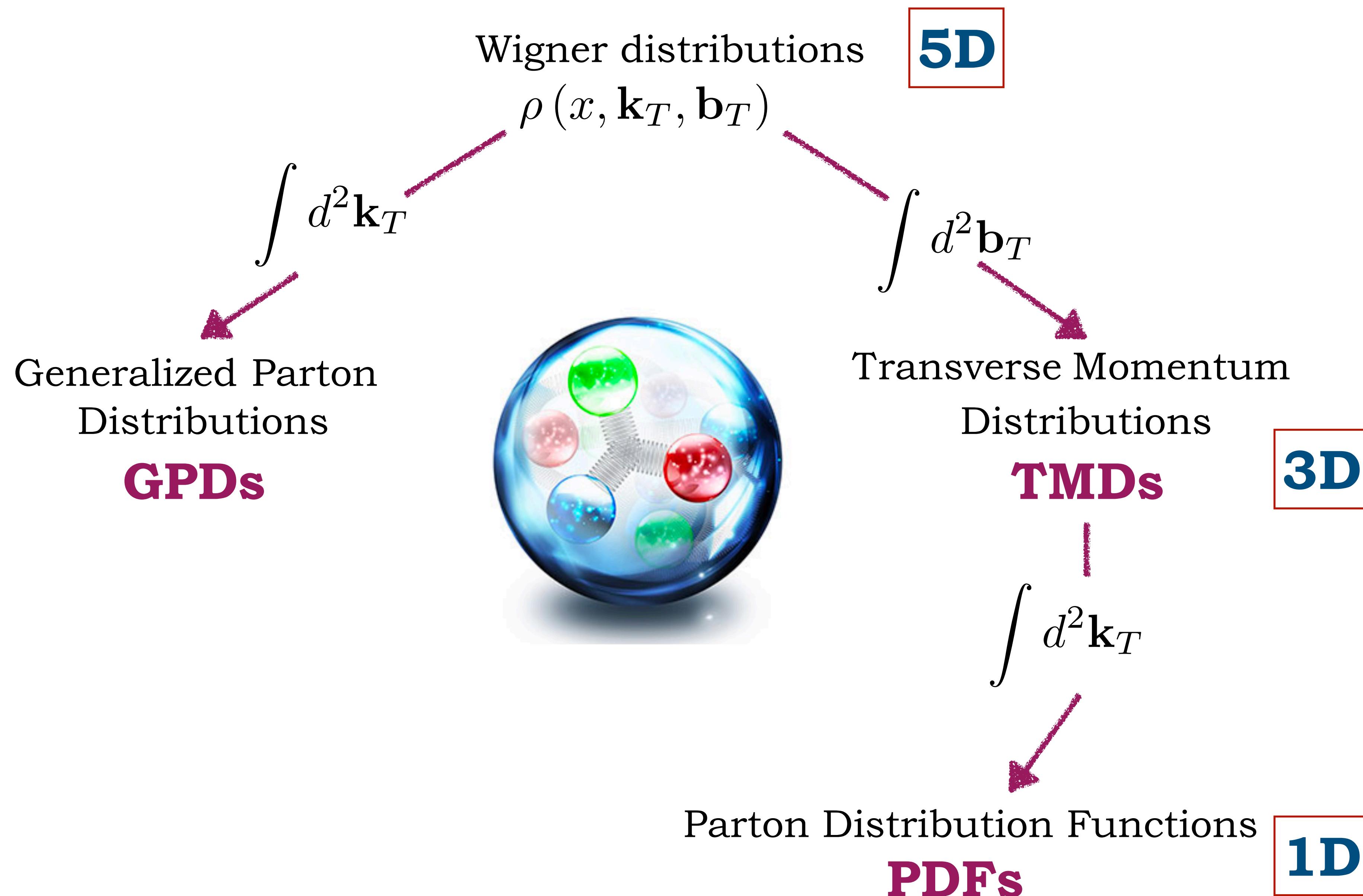
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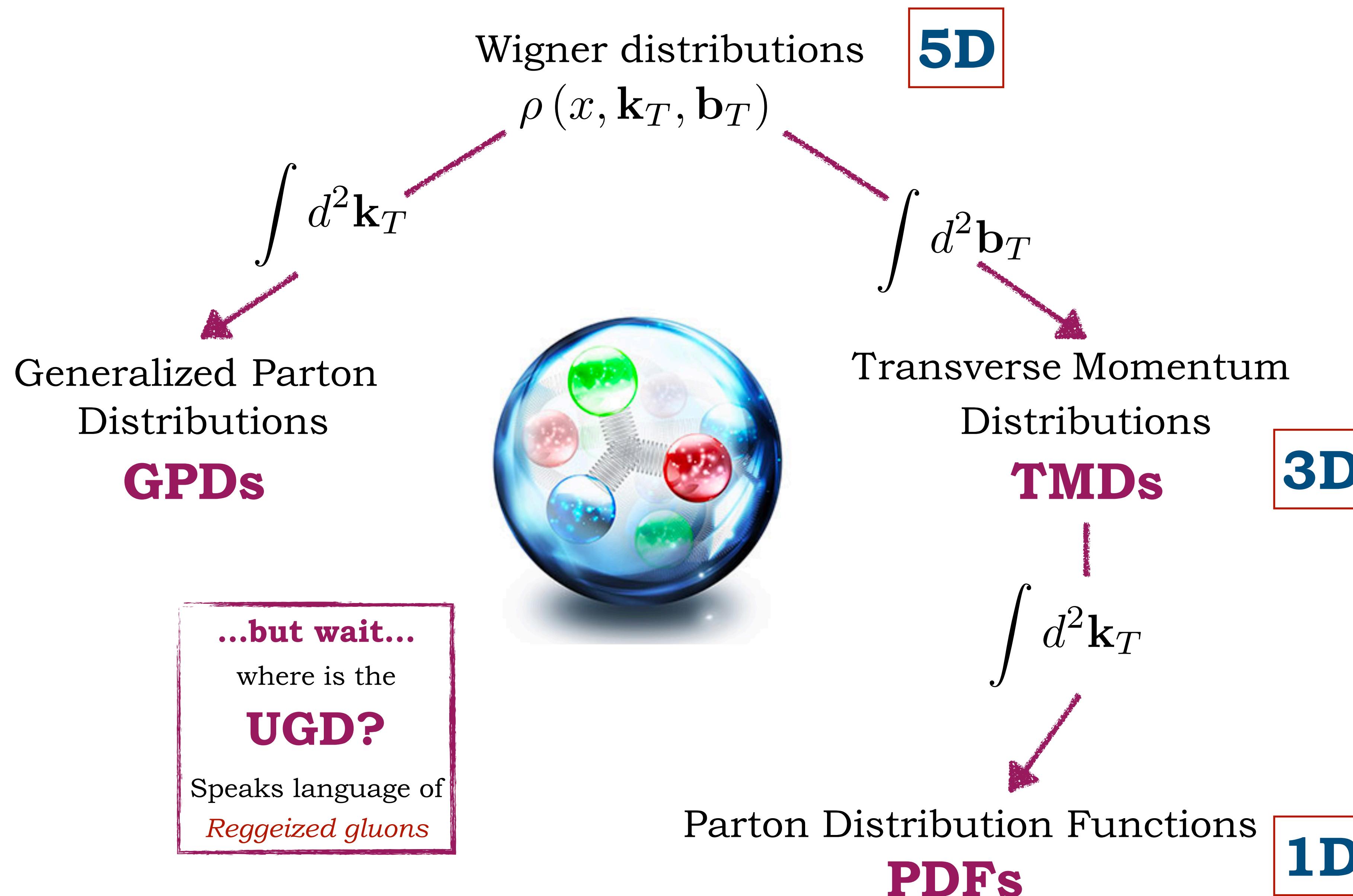
Pheno studies → kinematic ranges in the *intersection corner* of different approaches

- * Some approaches are directly connected to each other, other ones not...
- * Need for a **unified description** by the hand of a *transversal formalism!*

Parton densities: an incomplete family tree



Parton densities: an incomplete family tree



BFKL UGD

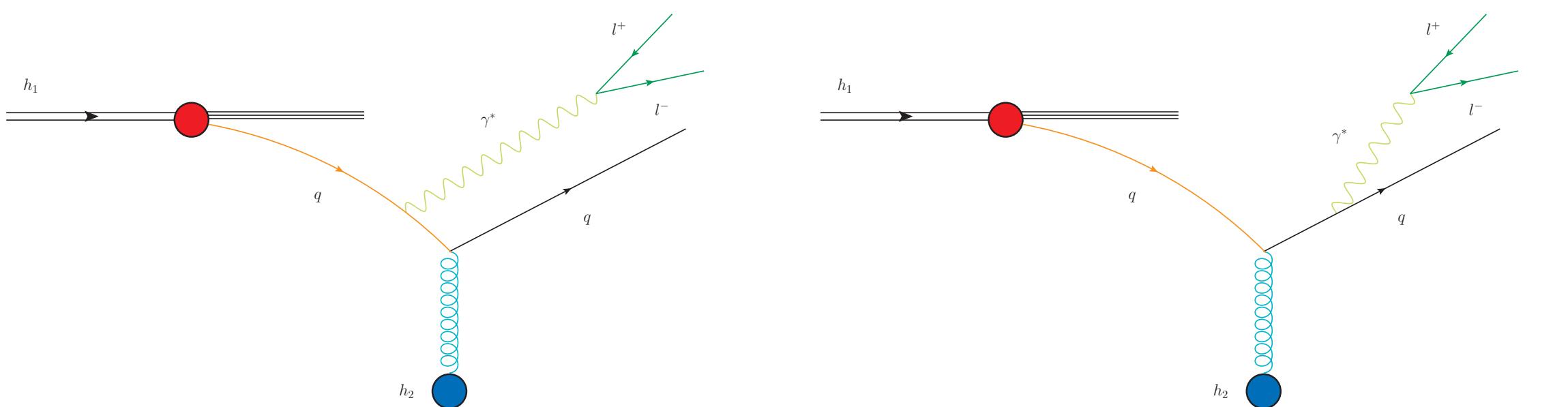
Inclusive forward Drell-Yan dilepton production

- LHC, **forward region** → $(1^+ 1^-)$ produced in the fragmentation region of h_2
 - ◊ Asymmetric configuration: $x_1 \gg x_2$, down to $x_2 \simeq 10^{-6}$
 - ⇒ **possible small- x resummation effects expected!**
- **small- x** → evolution of sea $q(\bar{q})$ inside h_2 driven by gluon evolution
 - ◊ Dominance of sea $q(\bar{q})$ emerging in the last splitting (suppression of quark propagator at large rapidity)
- **high-energy factorization** → gluon exchange in the t -channel
 - ◊ collinear gluon PDF replaced by κ_T -UGD: $xg(x, \mu) \rightarrow \mathcal{F}(x, \kappa_T^2)$

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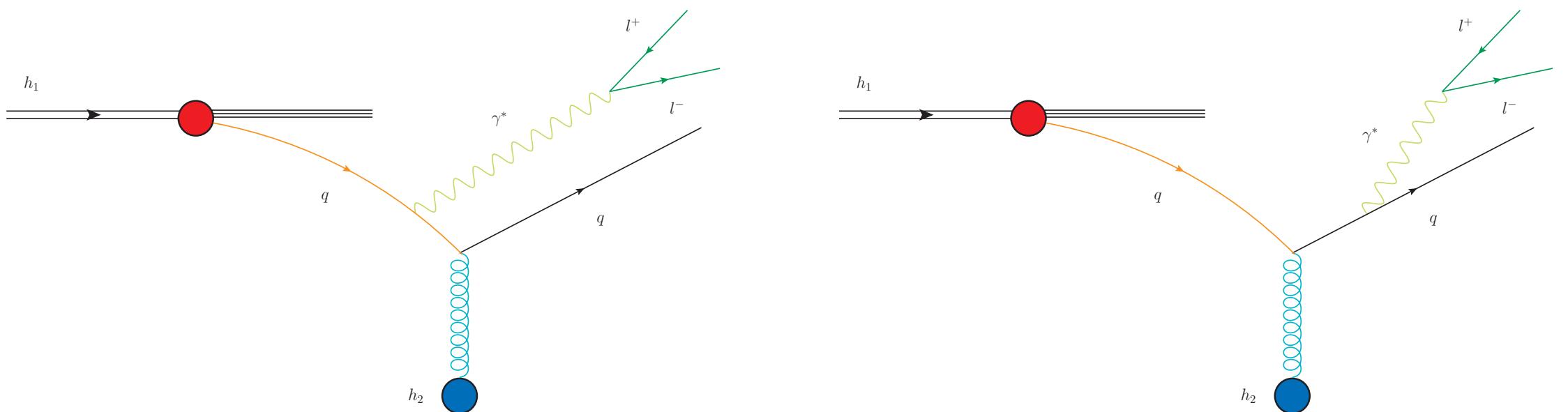


- Helicity structure functions in high-energy factorization:

$$\mathcal{W}_{[\textcolor{blue}{Y}]} = \frac{2\pi M^2}{3} \int_{x_F}^1 \frac{dz}{z^2} \sum_{r=q,\bar{q}} f_r \left(\frac{x_F}{z}, \mu_F \right) \int \frac{d\kappa_T d\Phi_{\kappa_T}}{\left(\kappa_T^2 \right)^2} \alpha_s(\mu_R) \mathcal{F}(x_g, \kappa_T^2) \Phi_{[\textcolor{blue}{Y}]}(q_T, \kappa_T, z)$$

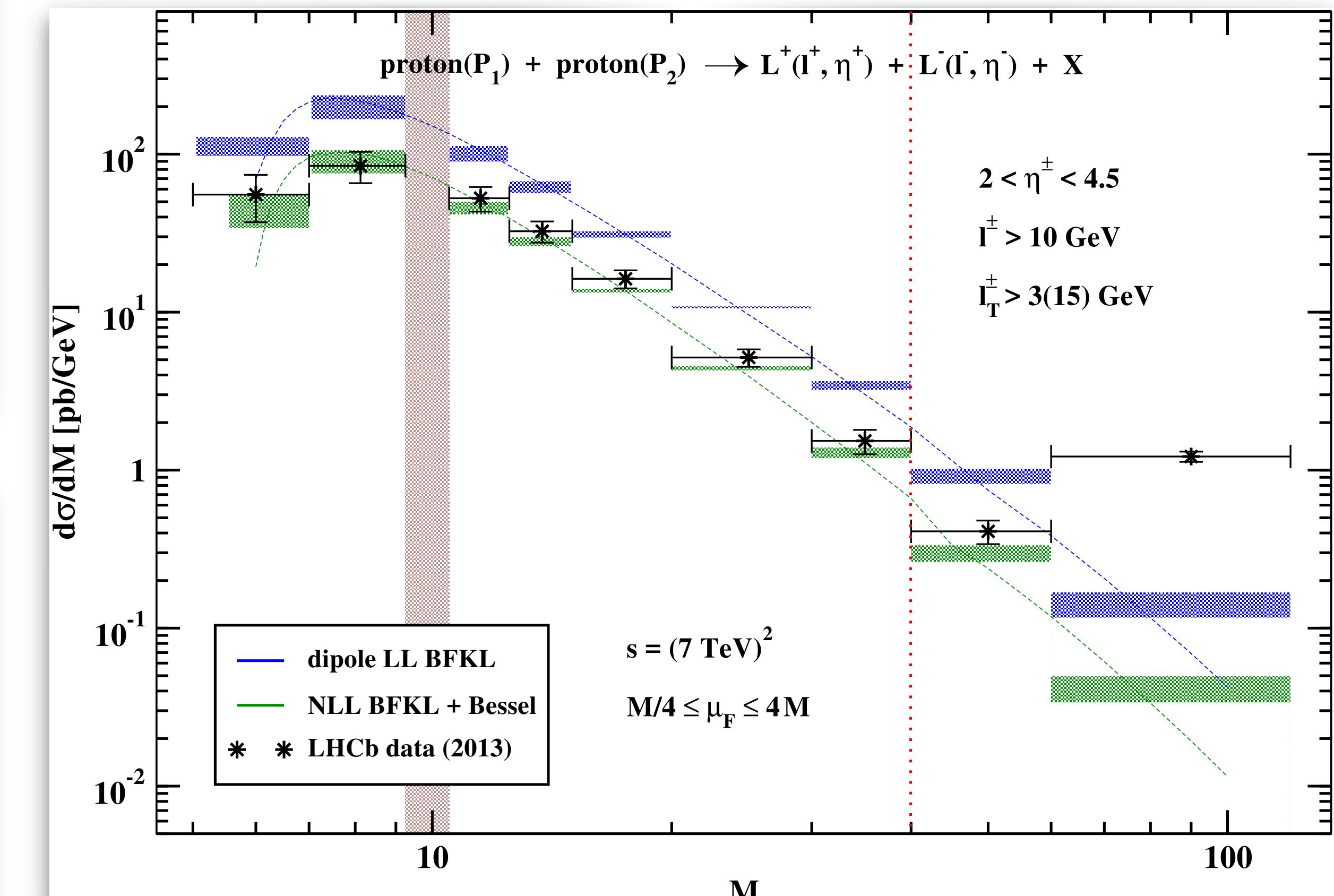
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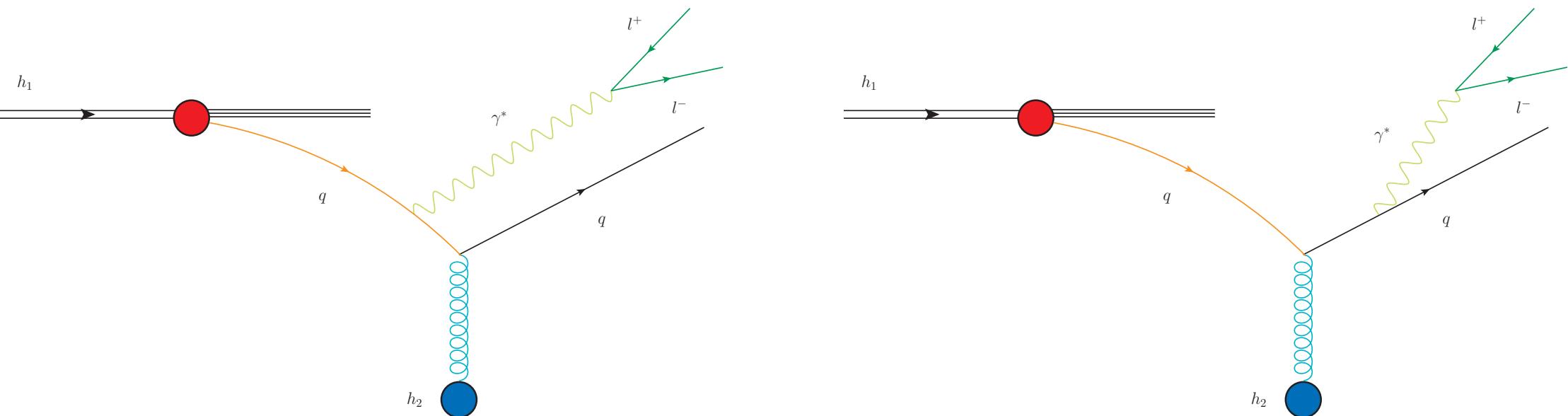
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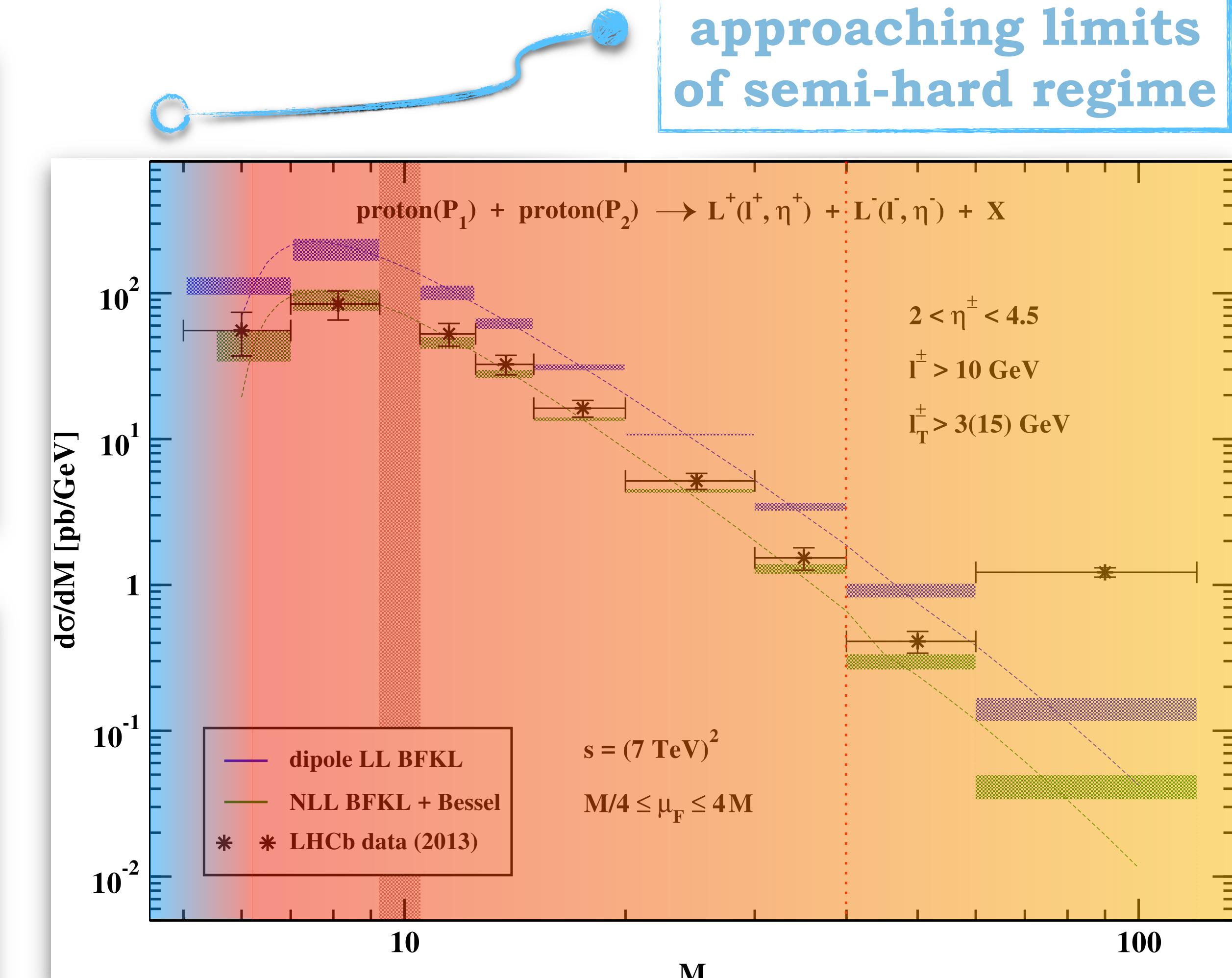


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🔗 [D. Brzemiński, L. Motyka, M. Sadzikowski, T. Stebel (2017)]
 ↪ [F.G.C., D. Gordo Gómez, A. Sabio Vera (2018)]

**approaching limits
of semi-hard regime**



**Z⁰ contribution
becoming relevant**



Backup

UGD pheno: partial conclusions

Summary...

Exclusive polarized ρ -leptoproduction

[A.D. Bolognino, F.G. C., D.Yu. Ivanov, A. Papa, arXiv:1808.02395, to appear in *Eur. Phys. J. C*]

- ▼ T_{11}/T_{00} helicity-amplitude ratio to constrain the **UGD** in the HERA range
- High sensitivity to **distinct UGD models**
- Low sensitivity to **region of small- κ_T values**
→ dominance of **small-size dipoles**

Forward Drell-Yan dilepton production

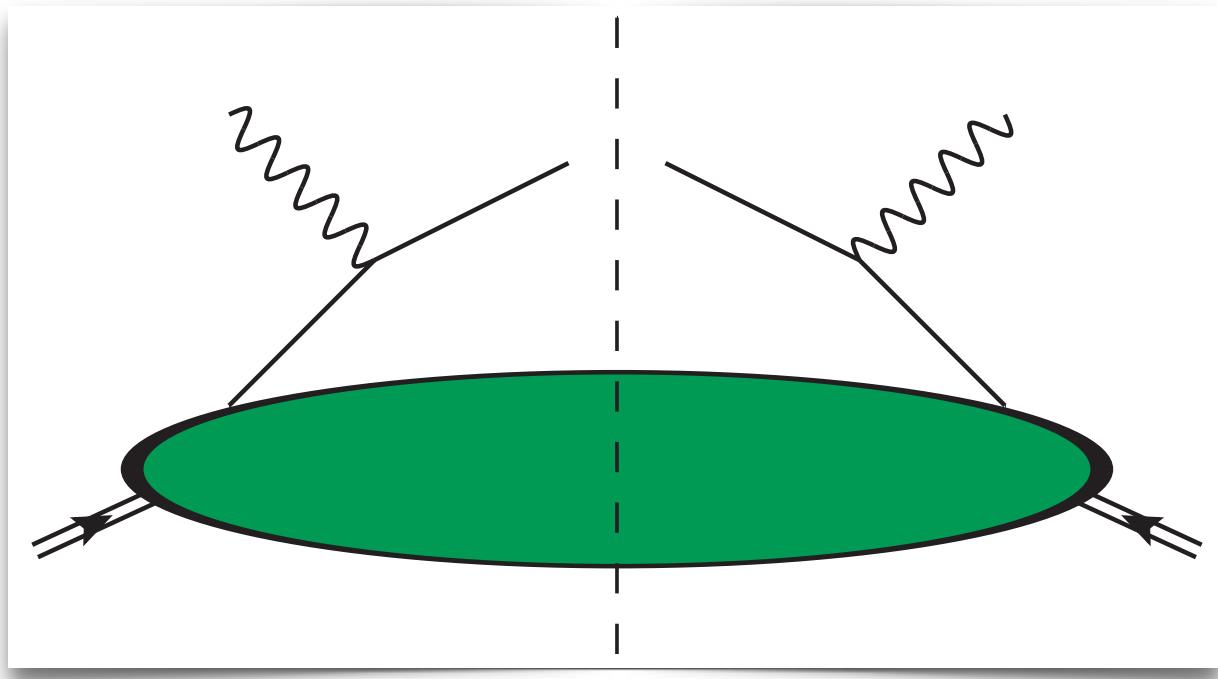
[F.G. C., D. Gordo Gómez, A. Sabio Vera, *Phys. Lett. B* **786** (2018) 201]

- ▼ Good description of $d\sigma/dM$ in the **BFKL approach** at the LHC
- Same observable well described also by **fixed-order** calculations

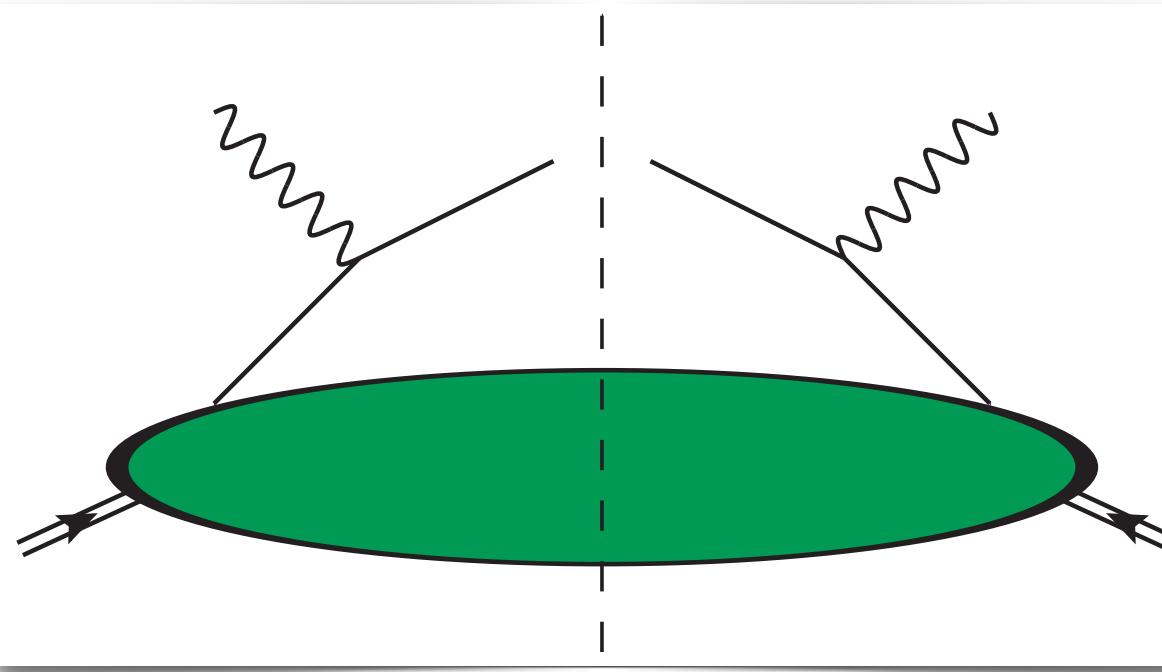
[LHCb Coll.: LHCb-CONF-2012-013, CERN-LHCb-CONF-2012-013]; [ATLAS Coll.: G. Aad et al., *JHEP* **1406** (2014) 112]

- Future data for Drell-Yan production in **forward directions**
→ gauge need for **high-energy resummation**

Gauge links and process dependence



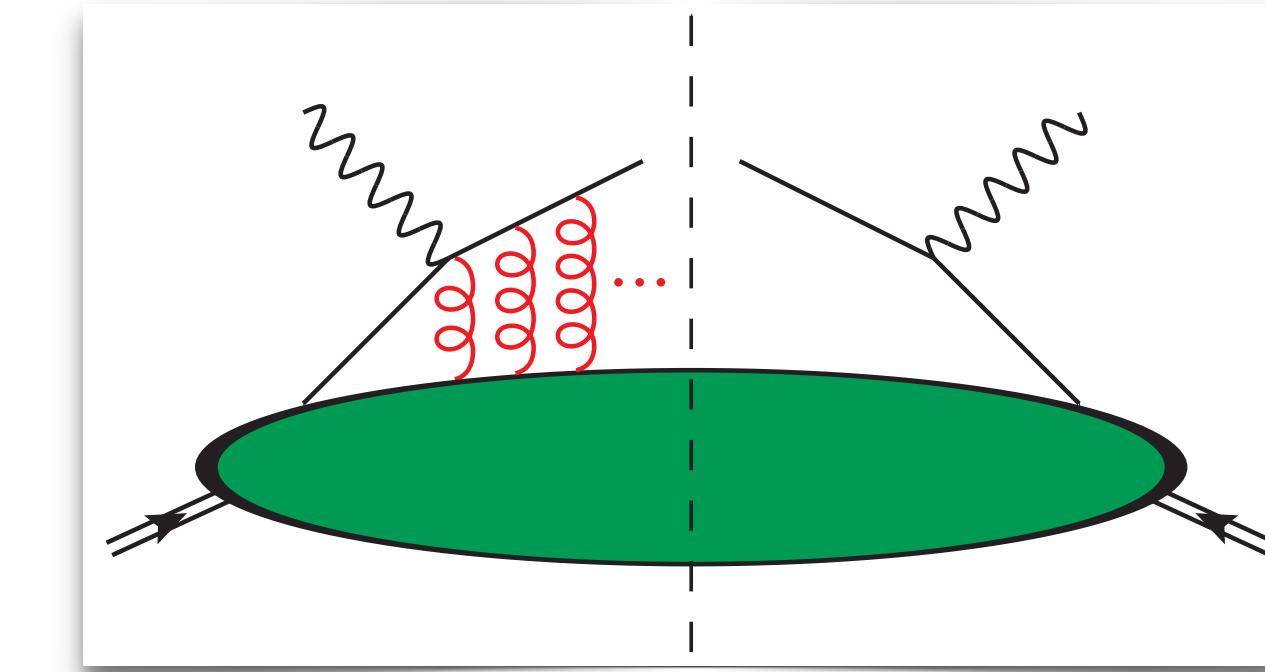
Gauge links and process dependence



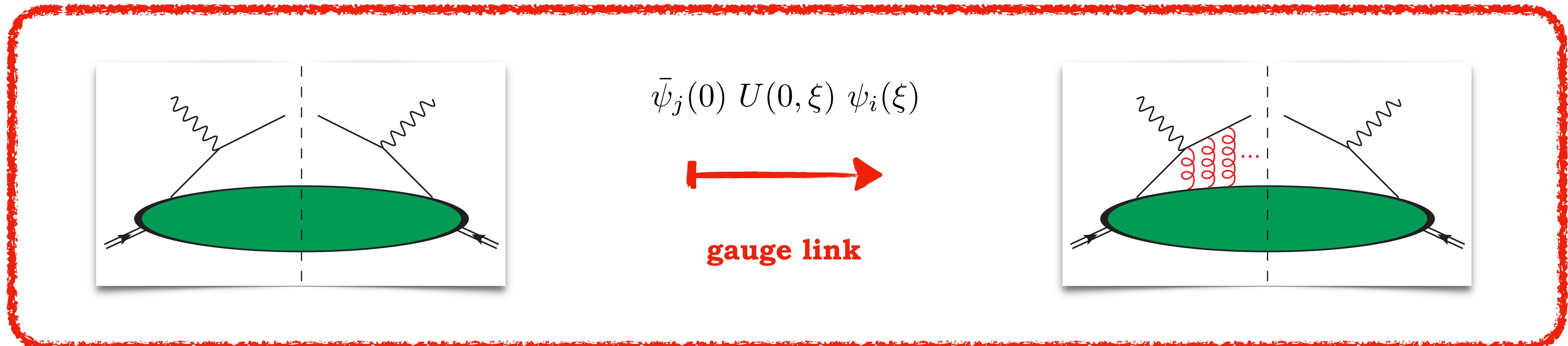
$$\bar{\psi}_j(0) \ U(0, \xi) \ \psi_i(\xi)$$



gauge link



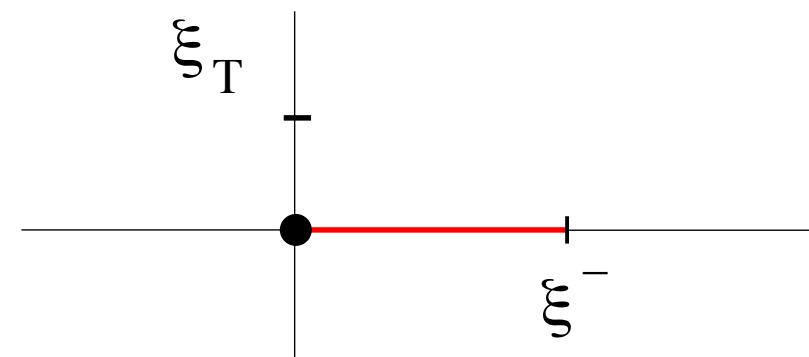
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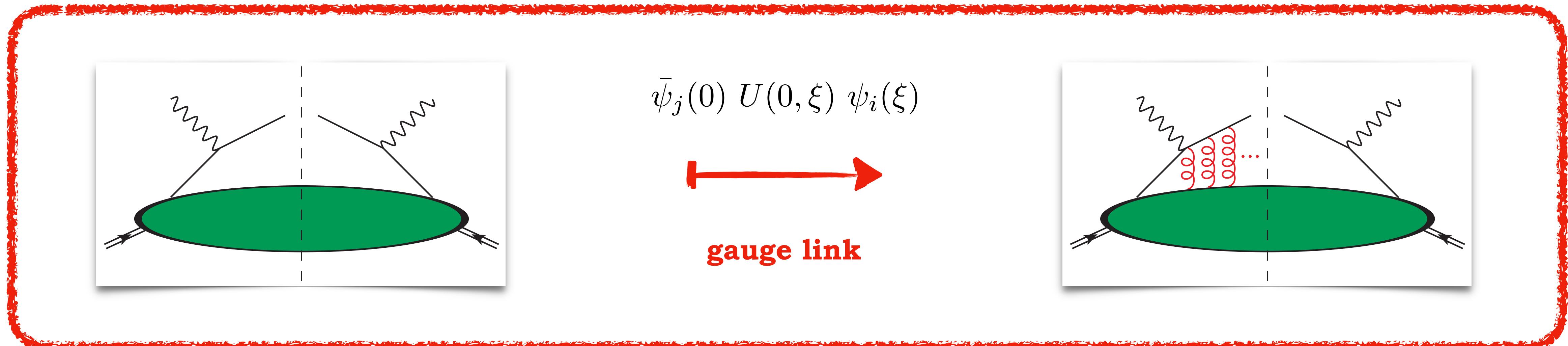
Collinear PDFs

$$\Phi_{ij}(x) \doteq \int d^2 p_T \Phi_{ij}(x, p_T) = \int \frac{d\xi^-}{2\pi} e^{ip \cdot \xi} \langle P | \bar{\psi}_j(0) \psi_i(\xi) | P \rangle|_{\xi^+ = 0, \xi_T = 0}$$

- Light-cone: $\xi^+ = 0, \xi = 0$
- **Straight** gauge link (unique!)
- $(A^+ = 0)$ light-cone: WL = $\hat{1}$
- ✓ **Universality warranted**



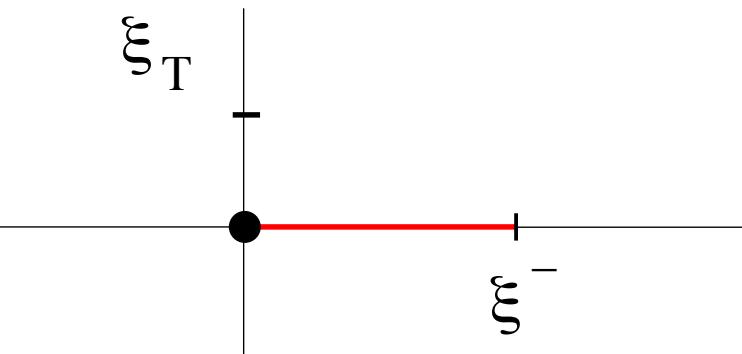
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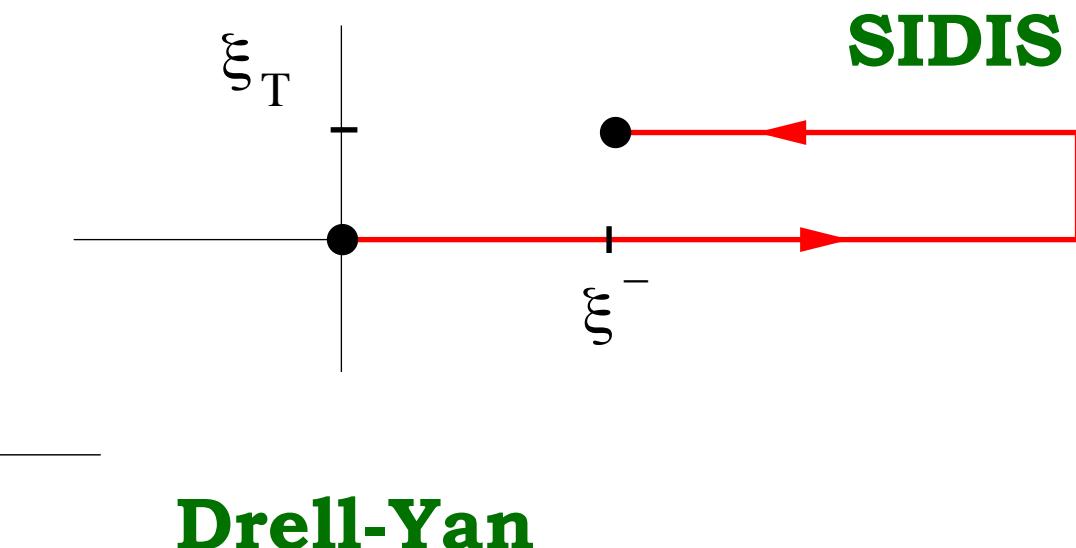
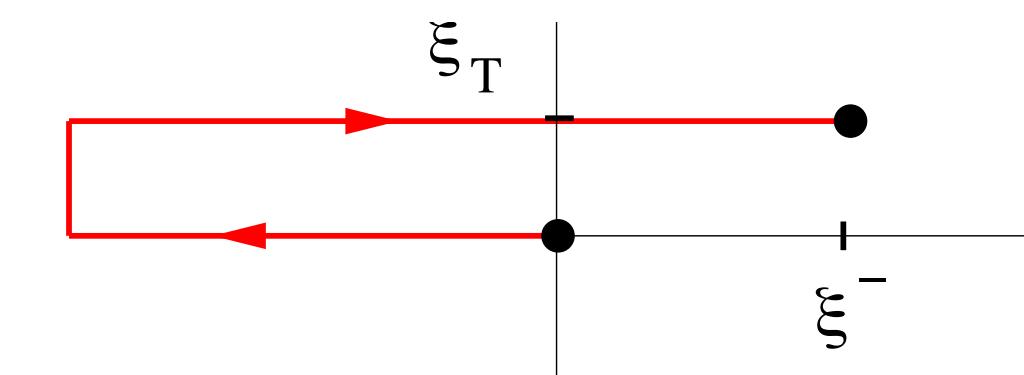
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TMD PDFs

- Transverse gauge link not eliminated by gauge choice
- Staple-like gauge link (not unique!)
- Process dependence**



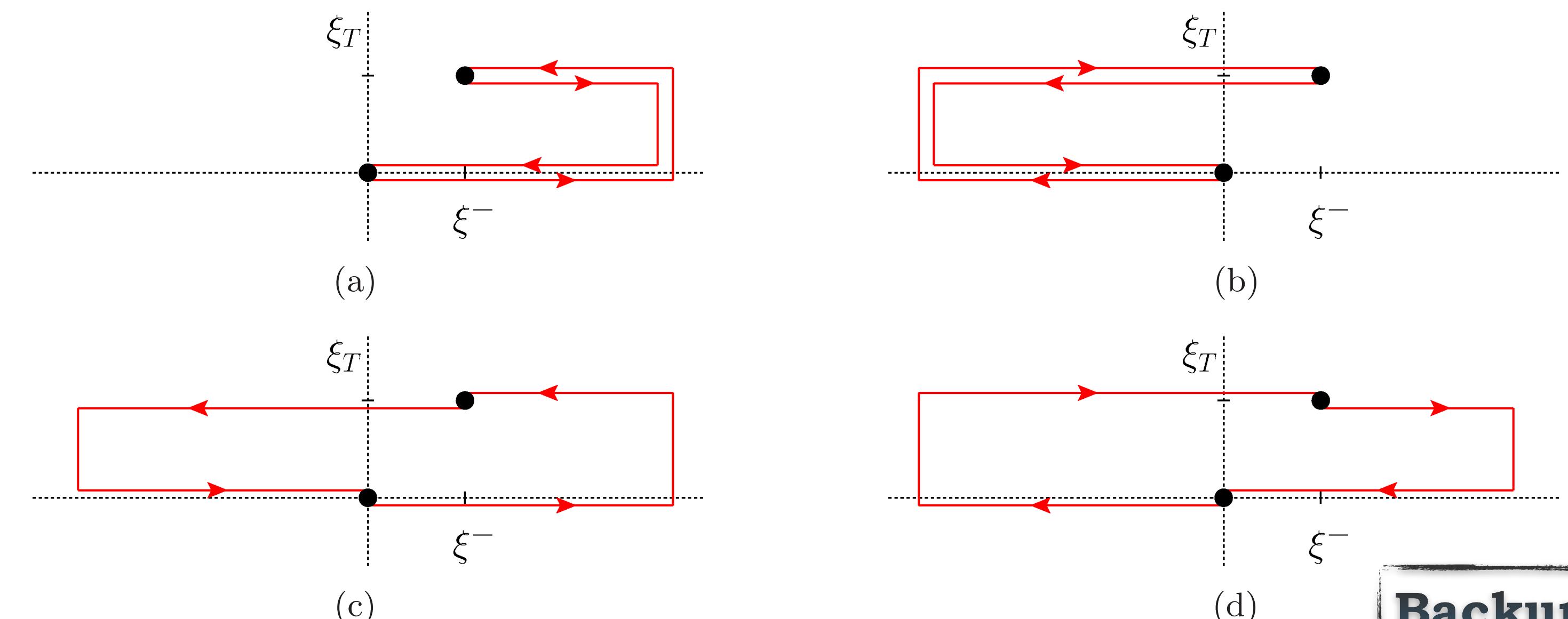
Small- x improved gluon TMDs

Gluon TMDs: gauge links and modified universality

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

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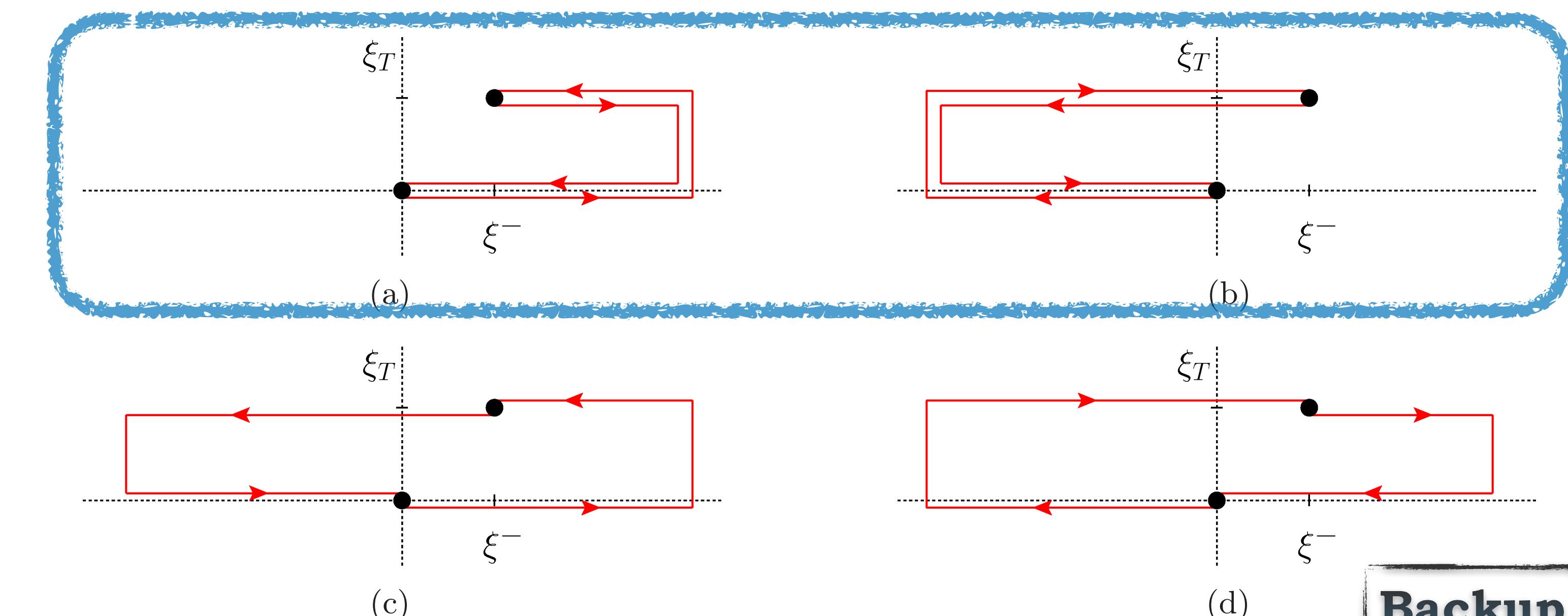


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Weiszäcker-Williams (WW)

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

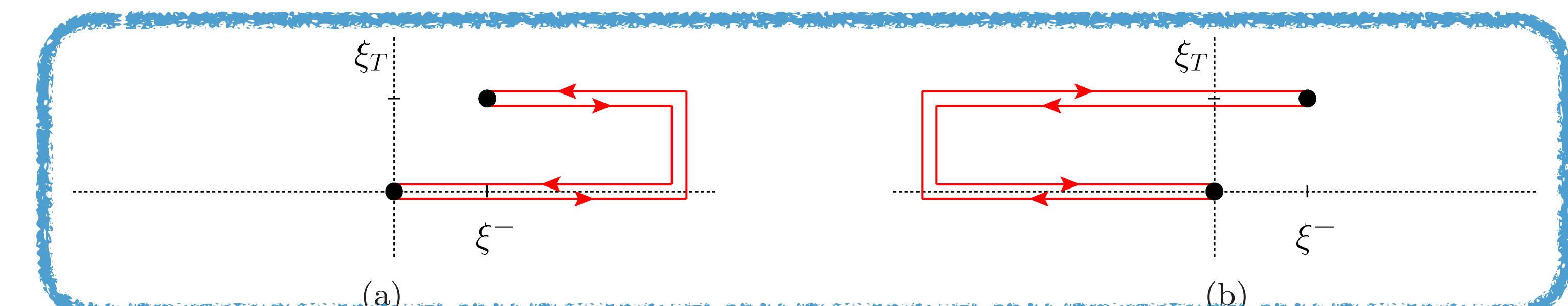


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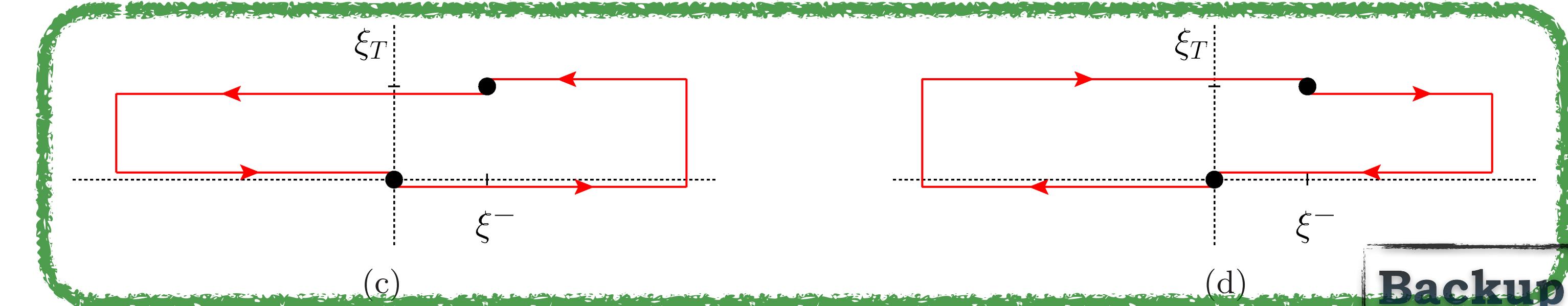
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(a) [+ , +] or (b) [- , -]



Dipole (DP)

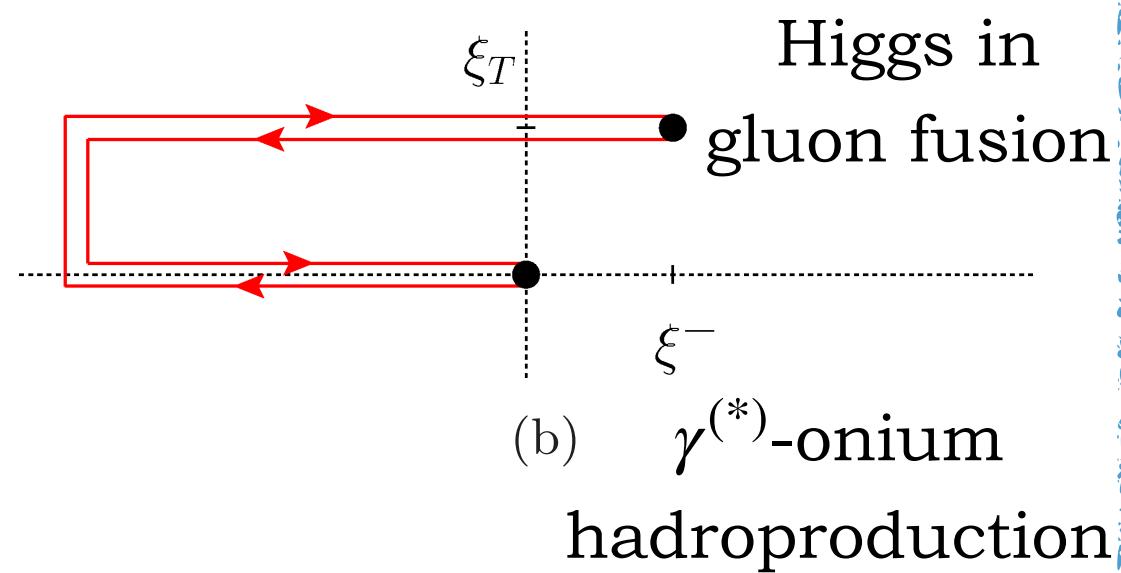
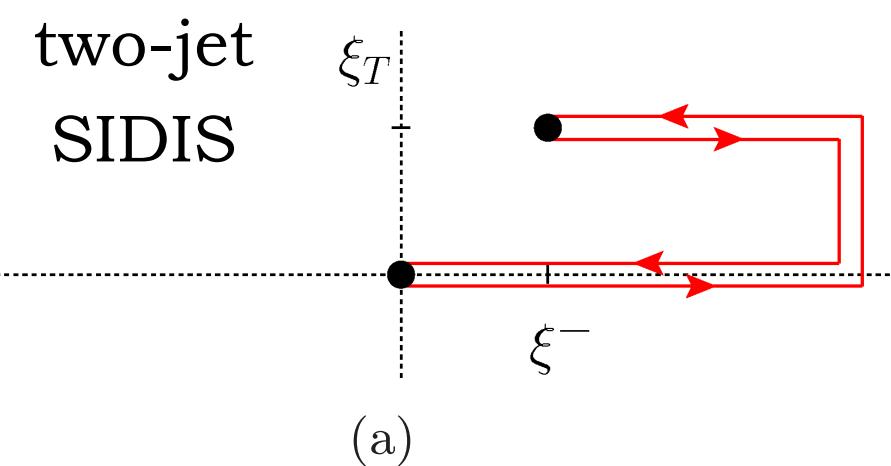
(c) [+ , -] or (d) [- , +]



Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

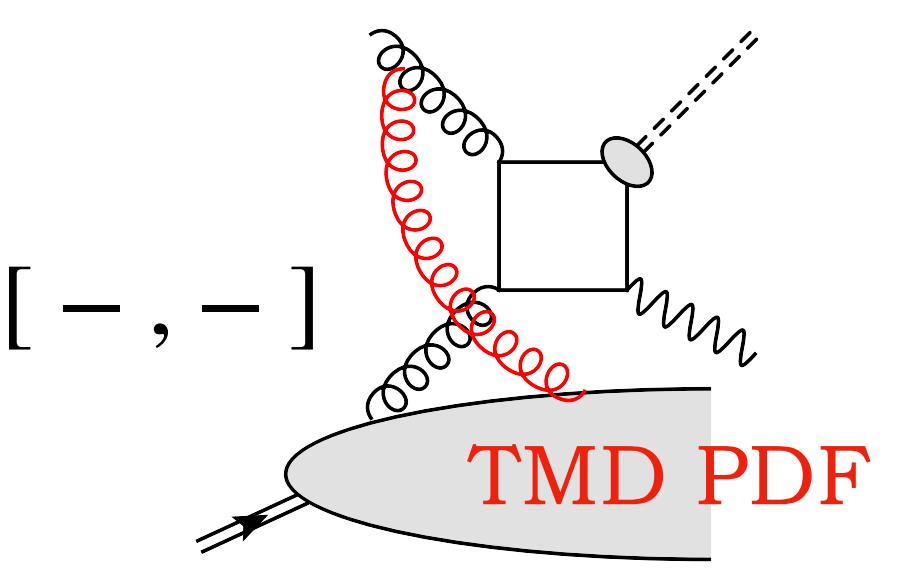
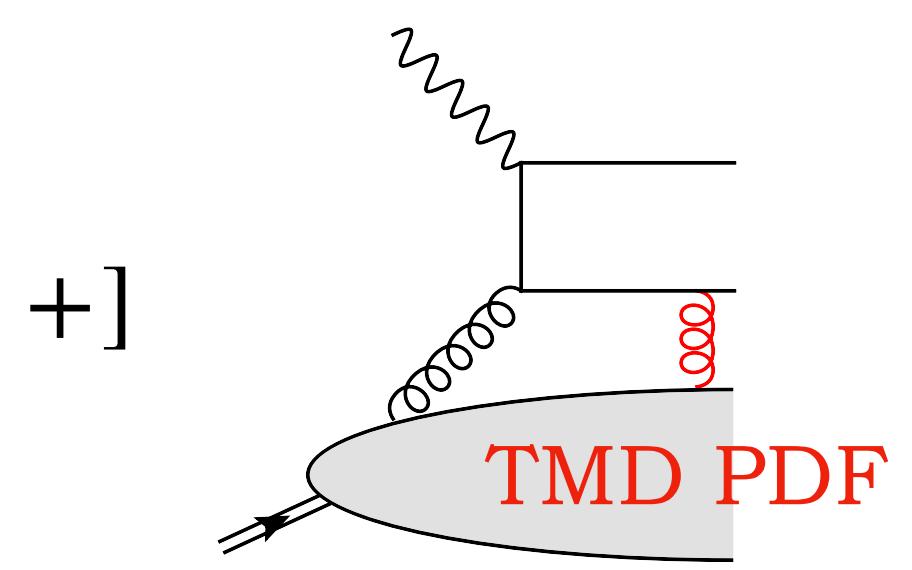
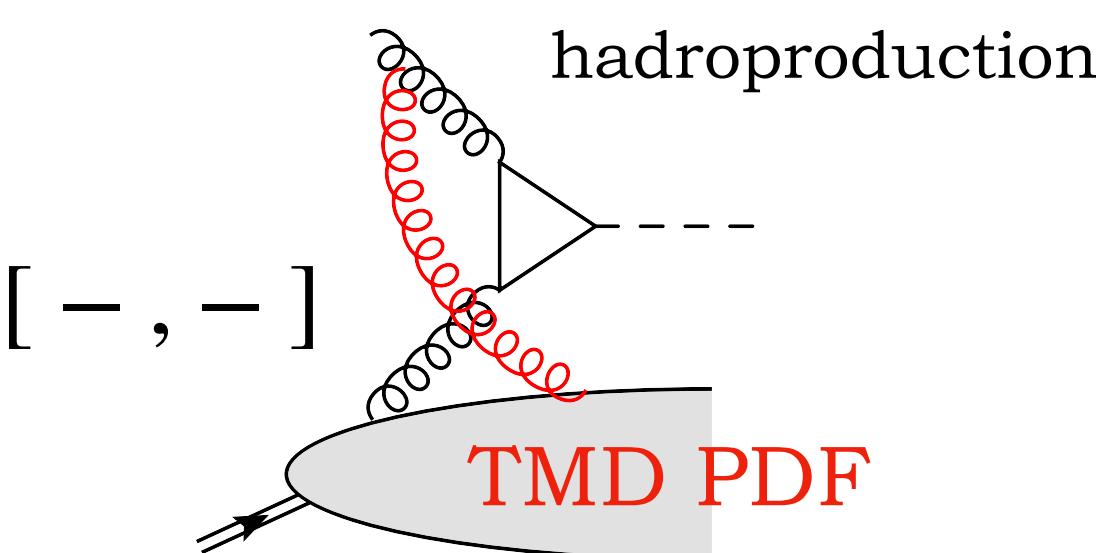
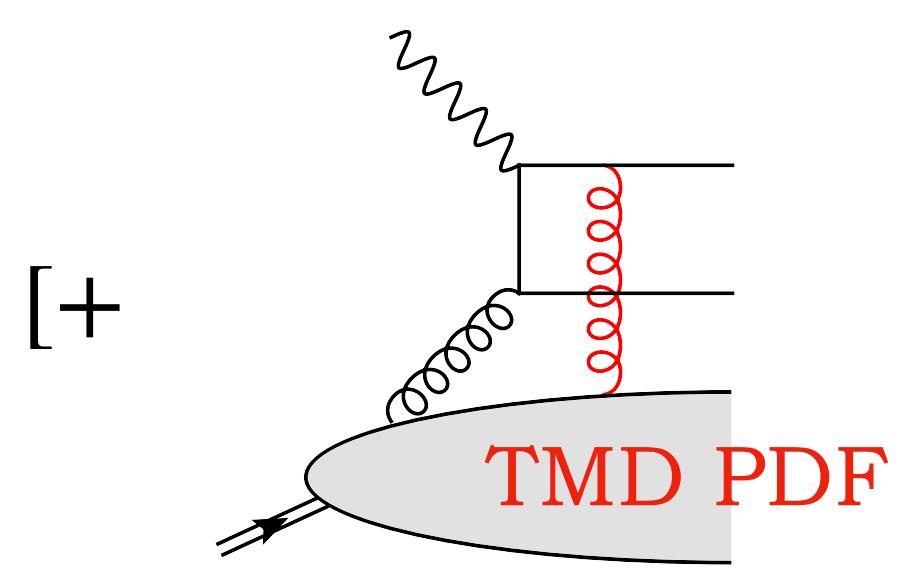
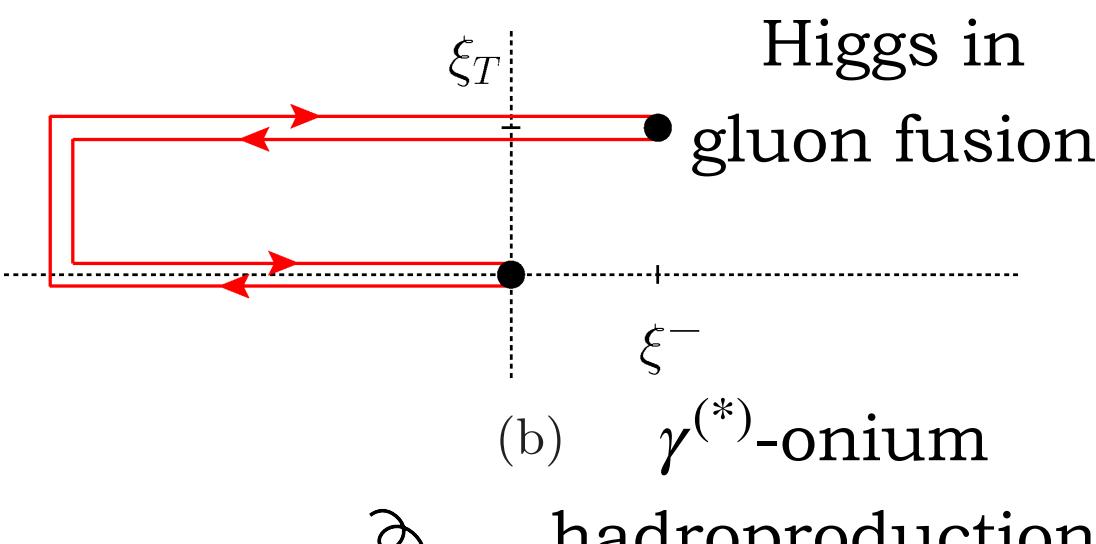
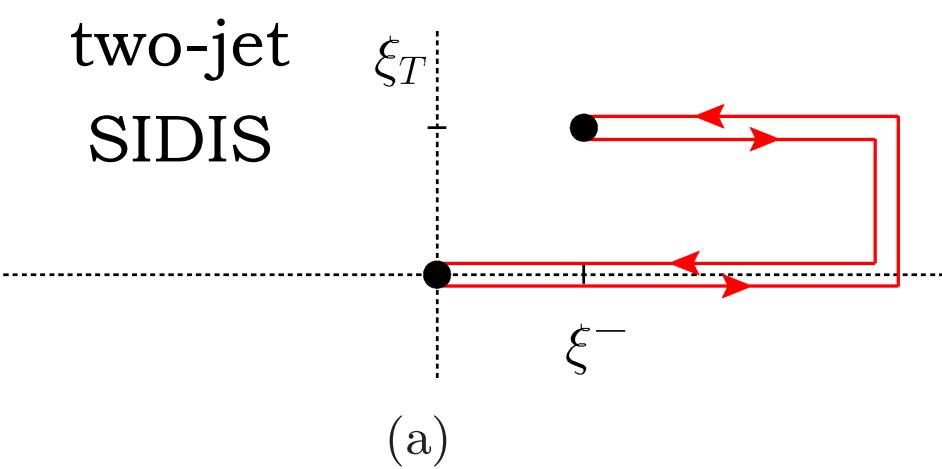
(a) [+ , +] or (b) [- , -]



Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

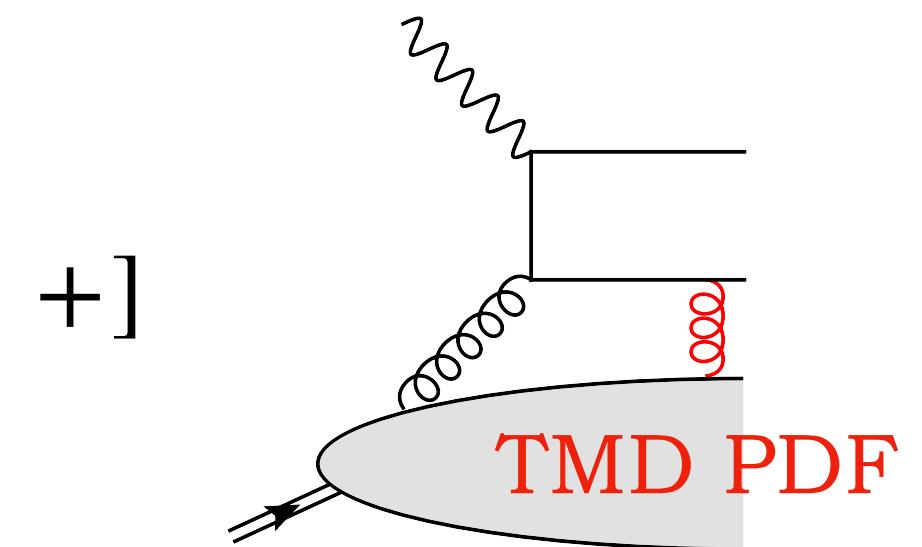
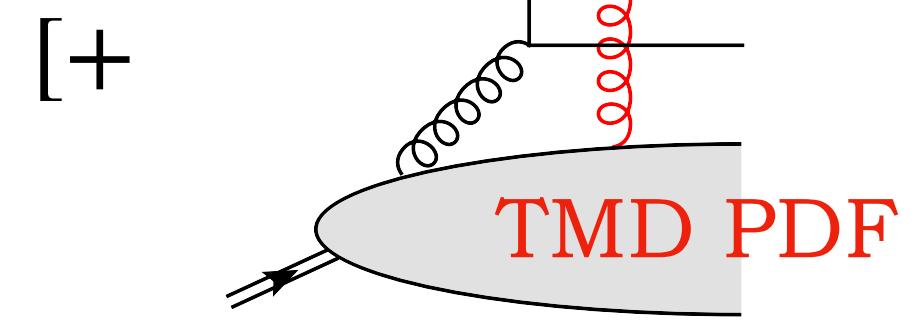
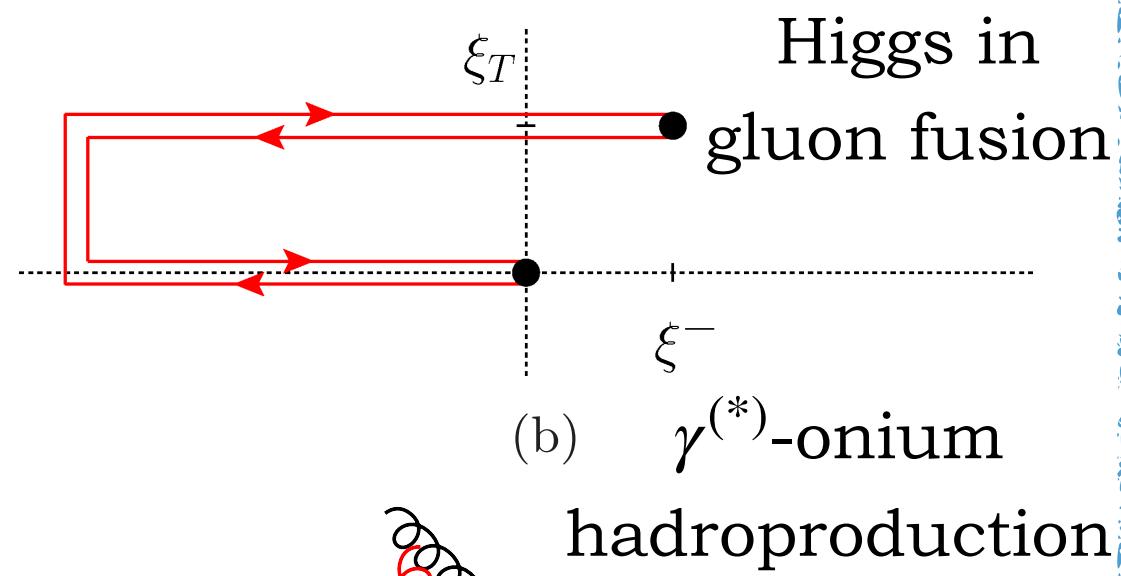
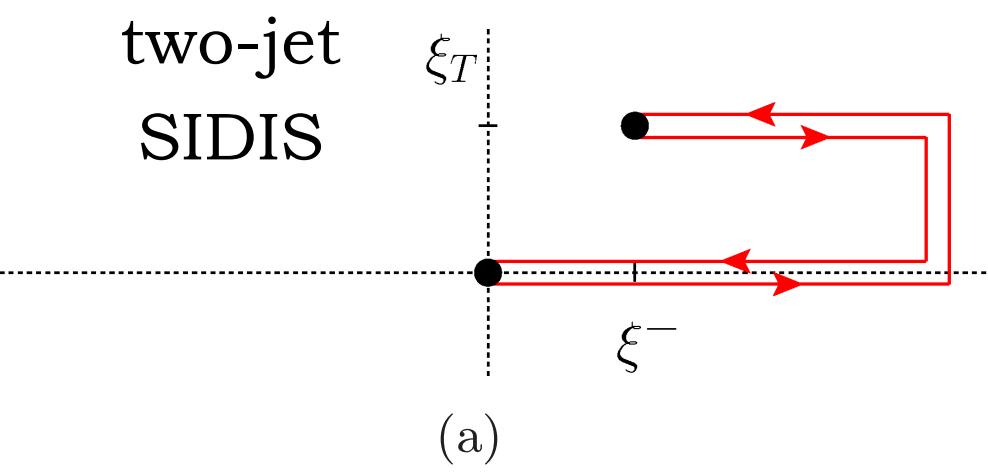
(a) [+ , +] or (b) [- , -]



Accessing WW and DP gluon TMDs

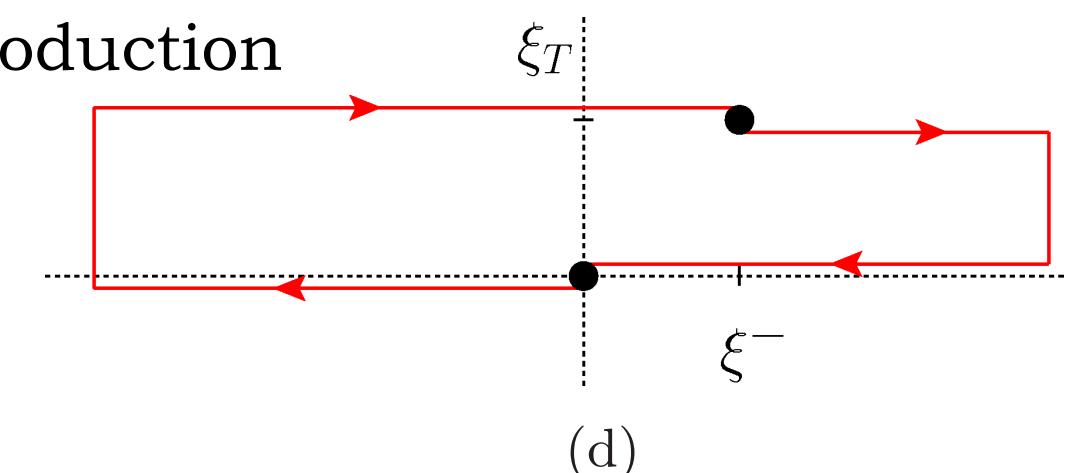
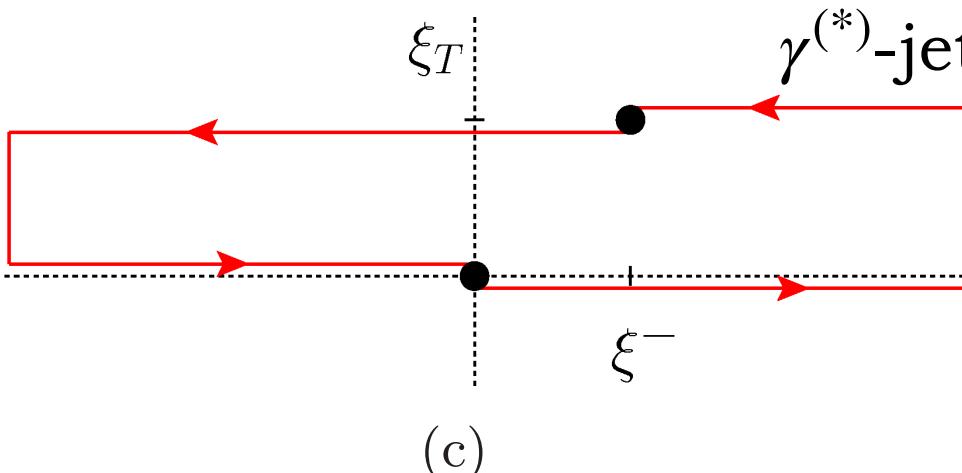
Weiszäcker-Williams (WW)

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



Dipole (DP)

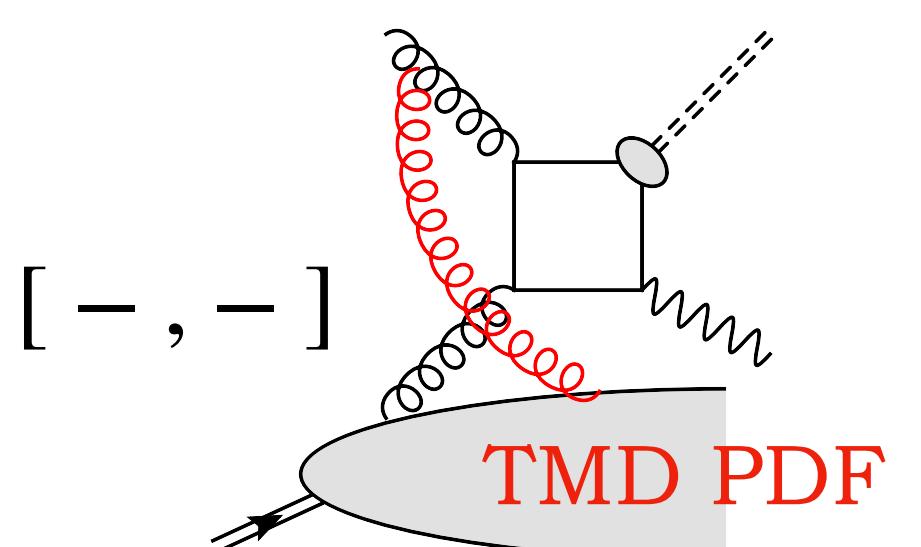
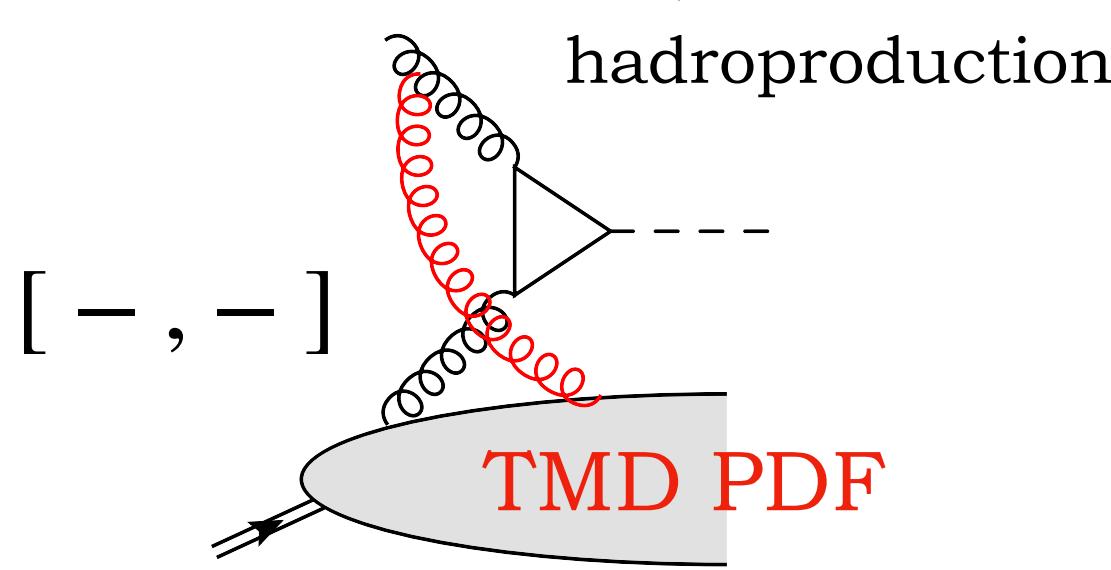
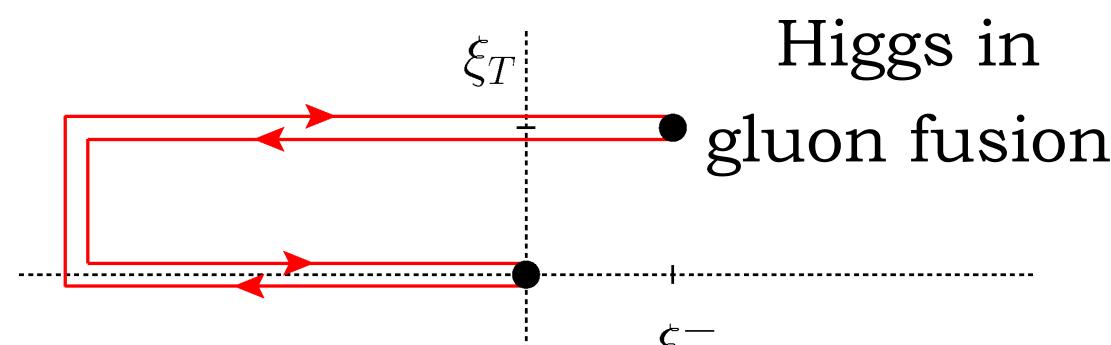
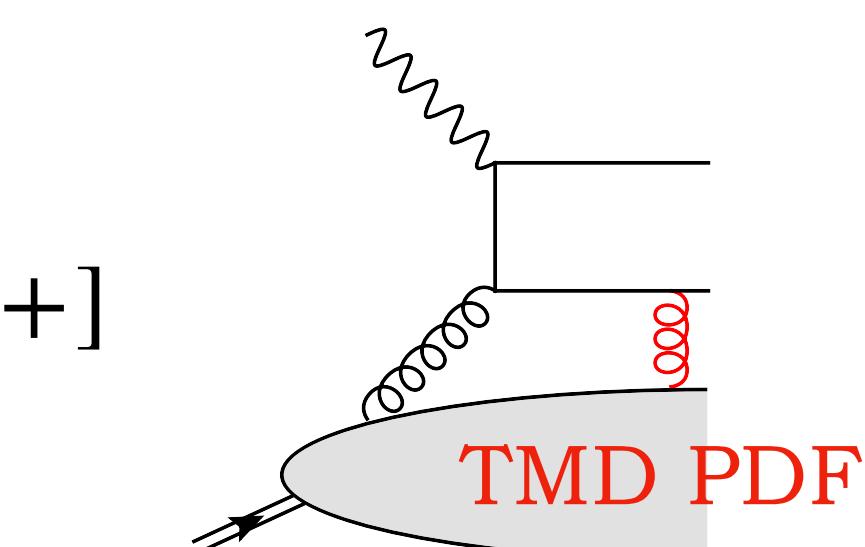
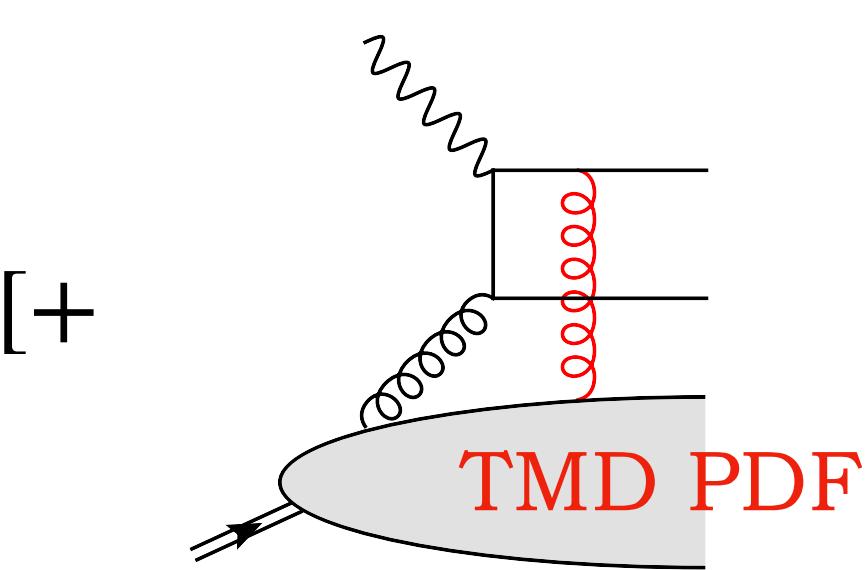
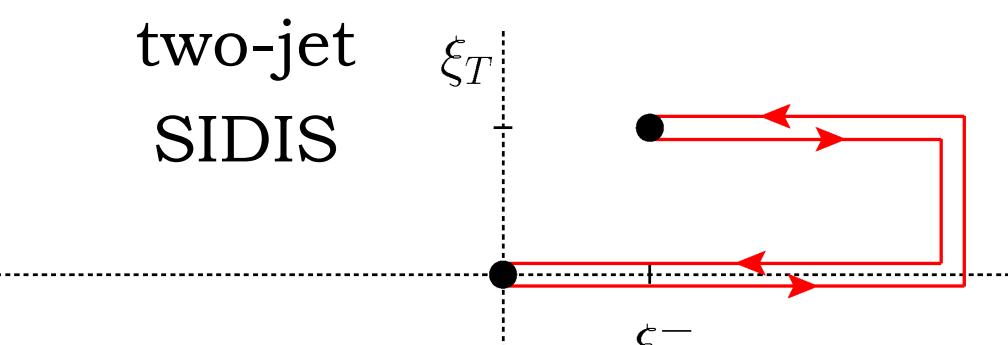
(c) [+ , -] or (d) [- , +]



Accessing WW and DP gluon TMDs

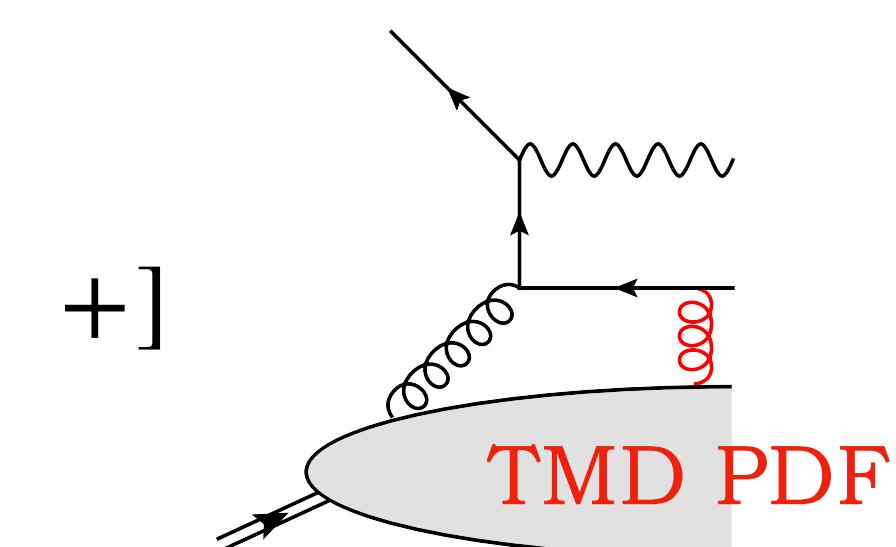
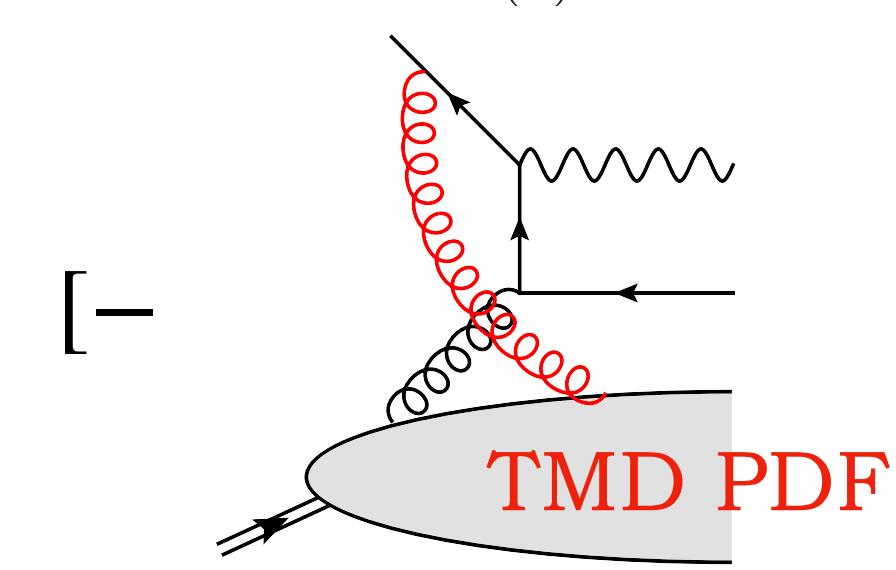
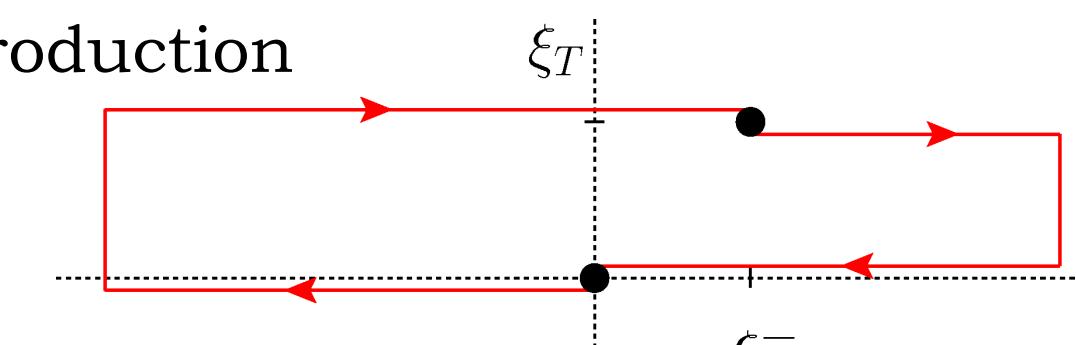
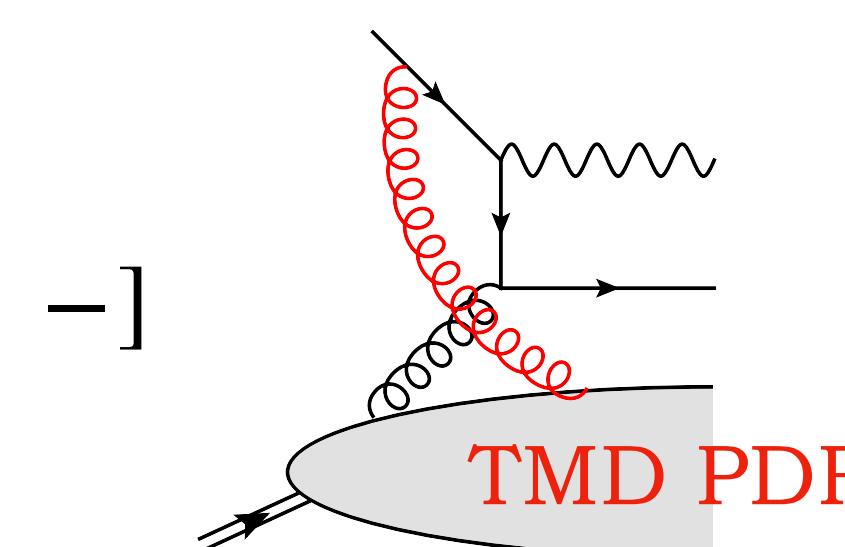
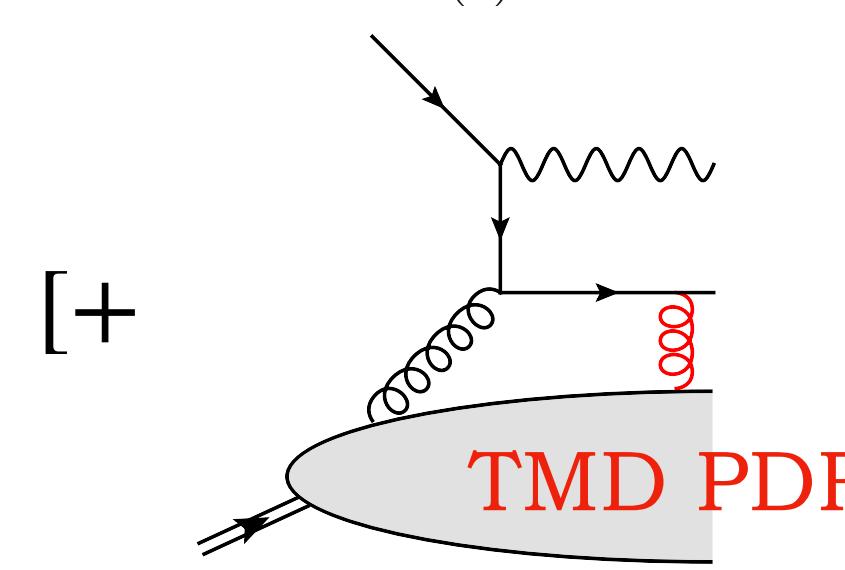
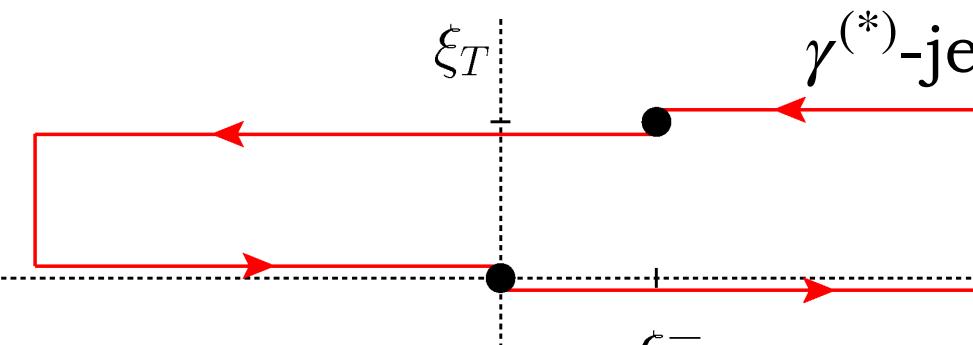
Weiszäcker-Williams (WW)

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



Dipole (DP)

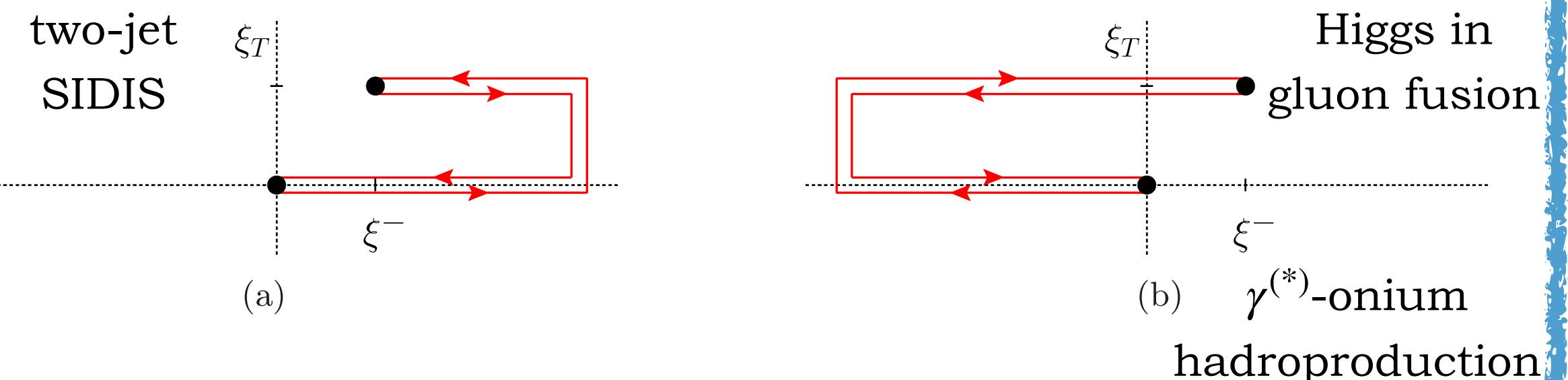
(c) [+ , -] or (d) [- , +]



Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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



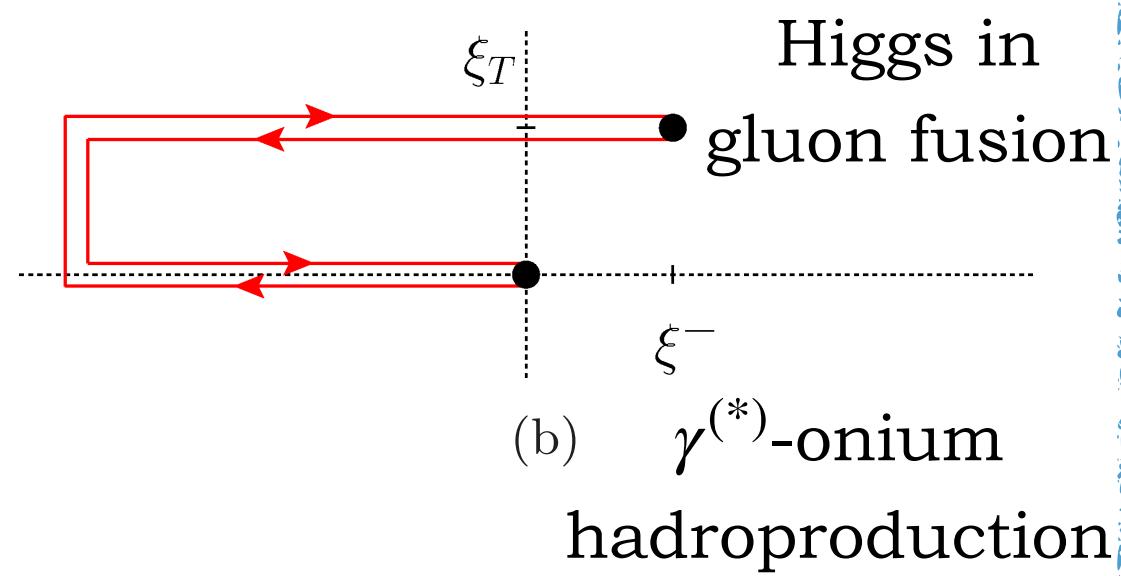
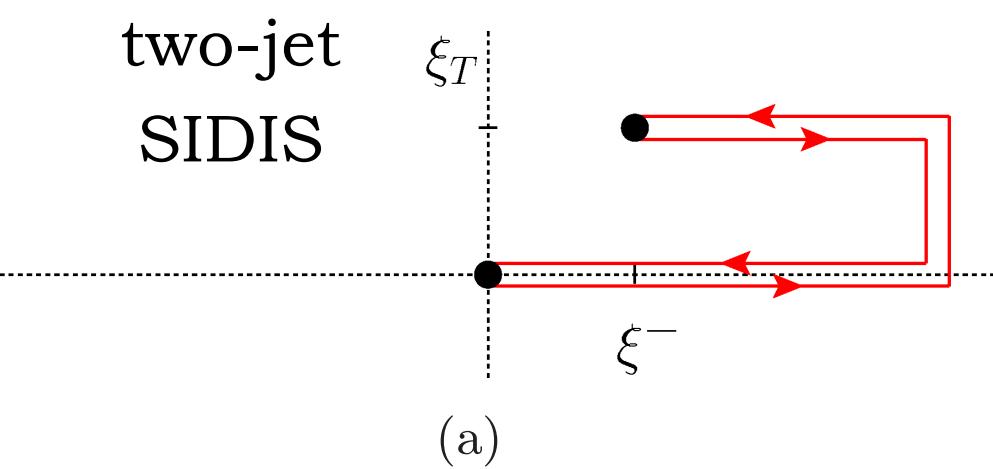
- * Color flow annihilated within final/initial state
- * f -type gluon TMDs $\rightarrow f^{abc}$ color structure
- * Modified universality:

$$f_1^{[+,+]} = f_1^{[-,-]},$$
$$f_{1T}^{\perp[+,+]} = -f_{1T}^{\perp[-,-]}$$
- * Phenomenology: Higgs, quarkonia or $\gamma\gamma$ in pp , two-jet SIDIS, heavy-quark pair SIDIS

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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



- * Color flow annihilated within final/initial state

- * f -type gluon TMDs $\rightarrow f^{abc}$ color structure

- * Modified universality:

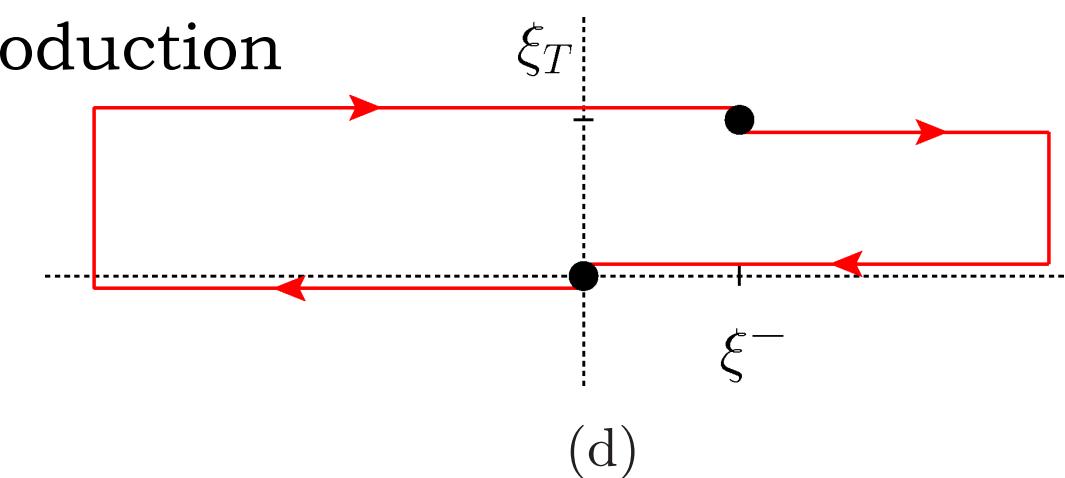
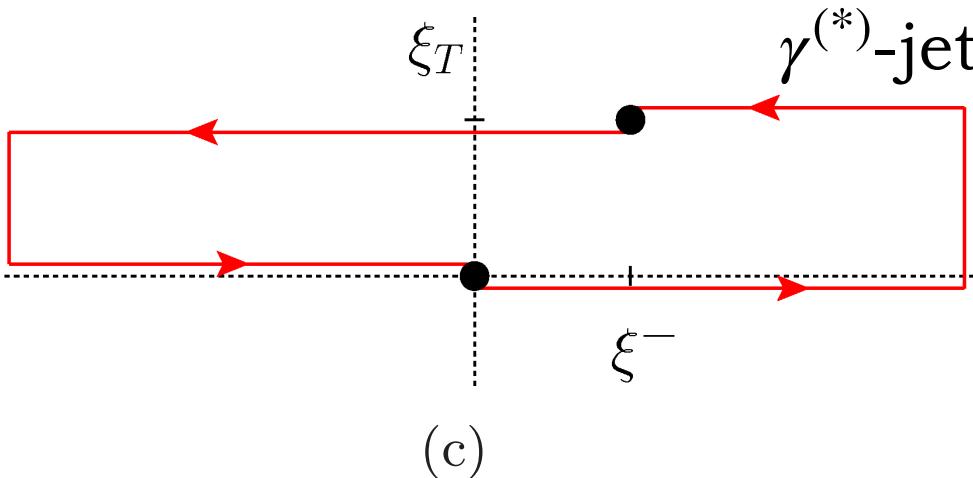
$$f_1^{[+,-]} = f_1^{[-,+]},$$

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

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

Dipole (DP)

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



- * Color flow involving both initial and final states

- * d -type gluon TMDs $\rightarrow d^{abc}$ color structure

- * Modified universality:

$$f_1^{[+,-]} = f_1^{[-,+]},$$

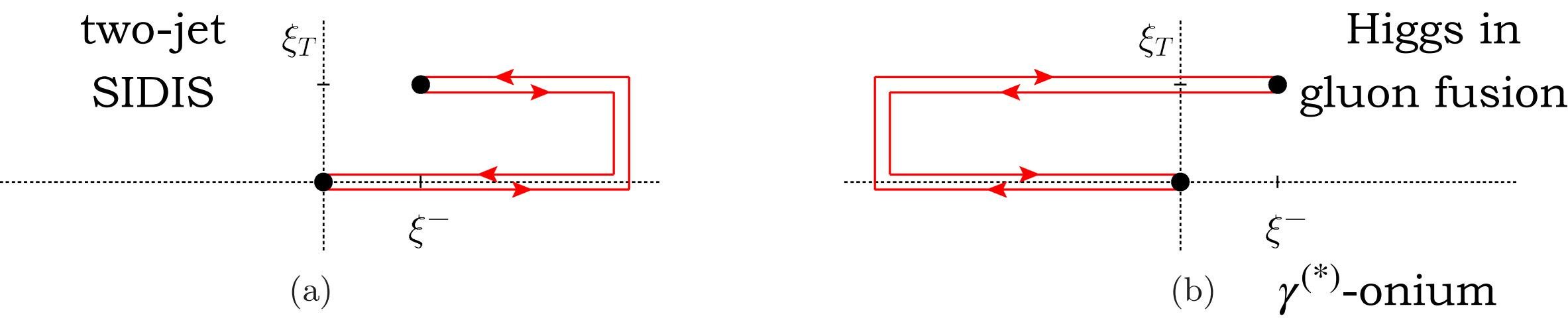
$$f_{1T}^{\perp[+,-]} = -f_{1T}^{\perp[-,+]}$$

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

Accessing WW and DP gluon TMDs

Weiszäcker-Williams (WW)

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



- * Color flow annihilated within final/initial state

- * f -type gluon TMDs $\rightarrow f^{abc}$ color structure

- * Modified universality:

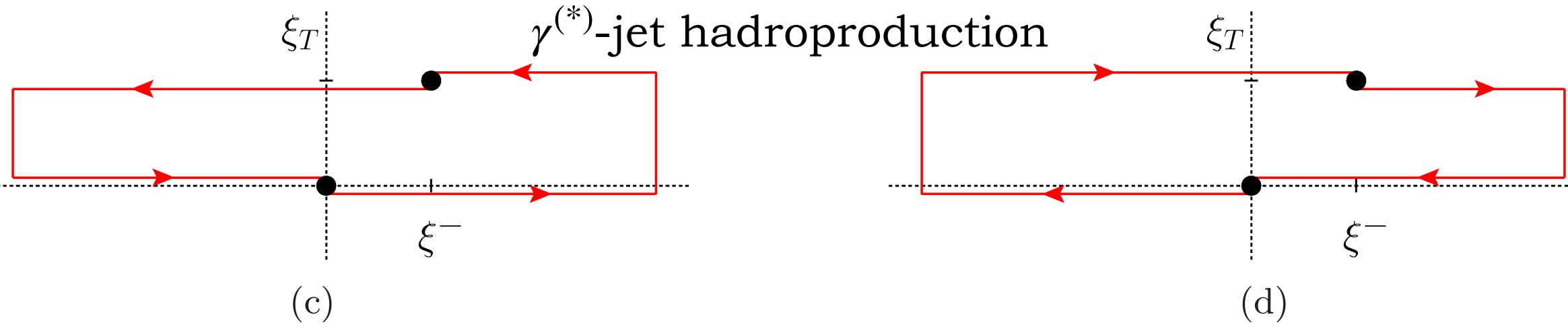
$$f_1^{[+,-]} = f_1^{[-,+]},$$

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

Dipole (DP)

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



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- * d -type gluon TMDs $\rightarrow d^{abc}$ color structure

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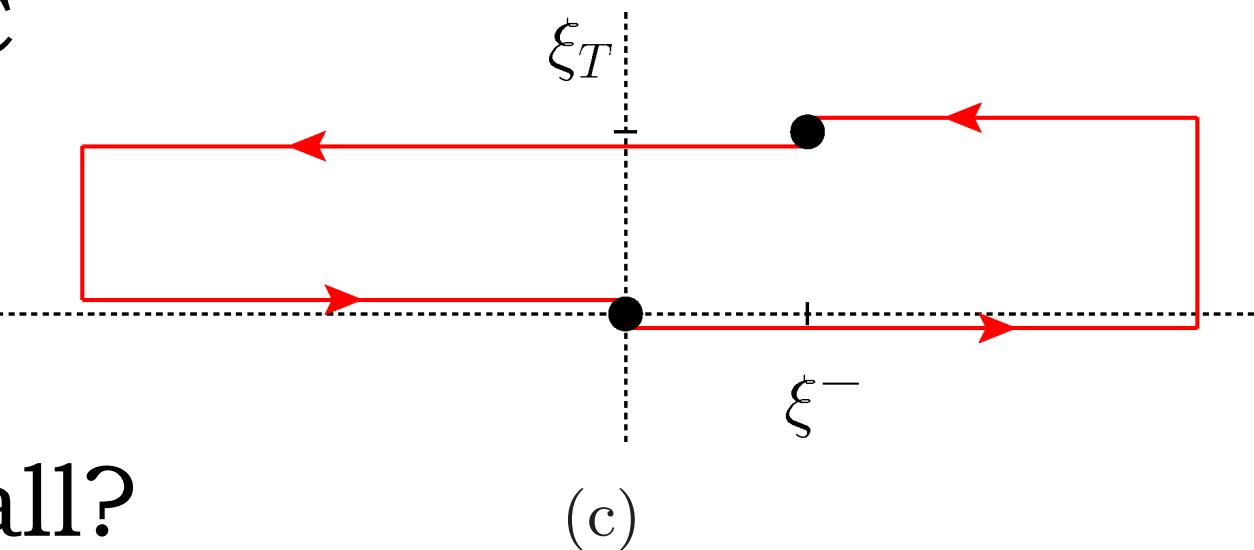
- * Phenomenology: single hadron or $\gamma^{(*)}$ -jet hadroproduction, SIDIS or Drell-Yan (subleading)

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

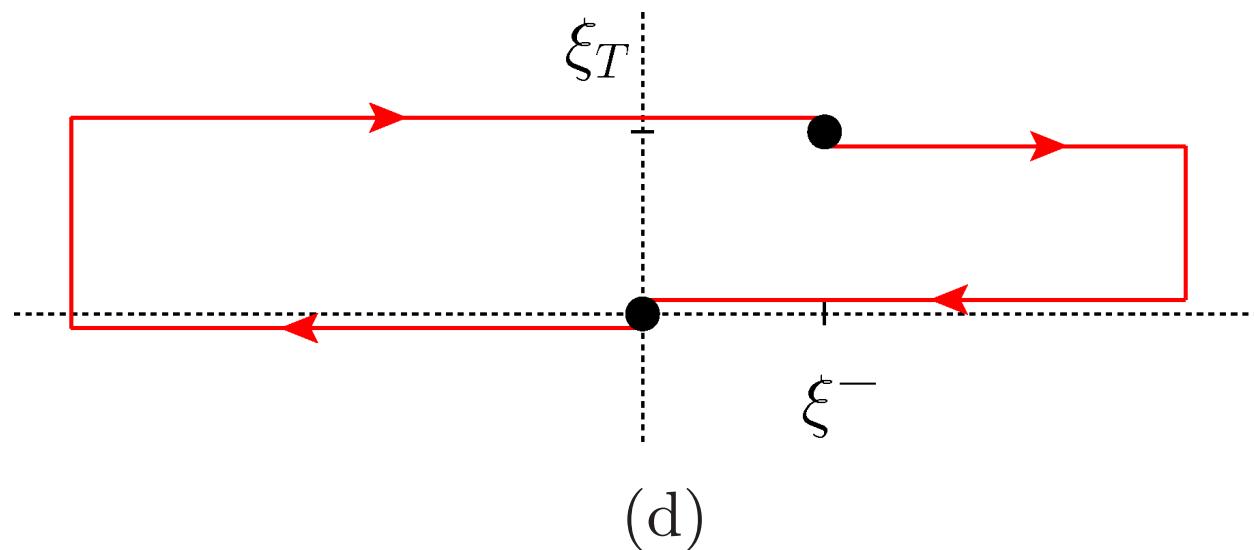
Dihadron hadroproduction and factorization breaking

- * Proof of factorization violation  [T.J. Rogers, P.J. Mulders (2010)]

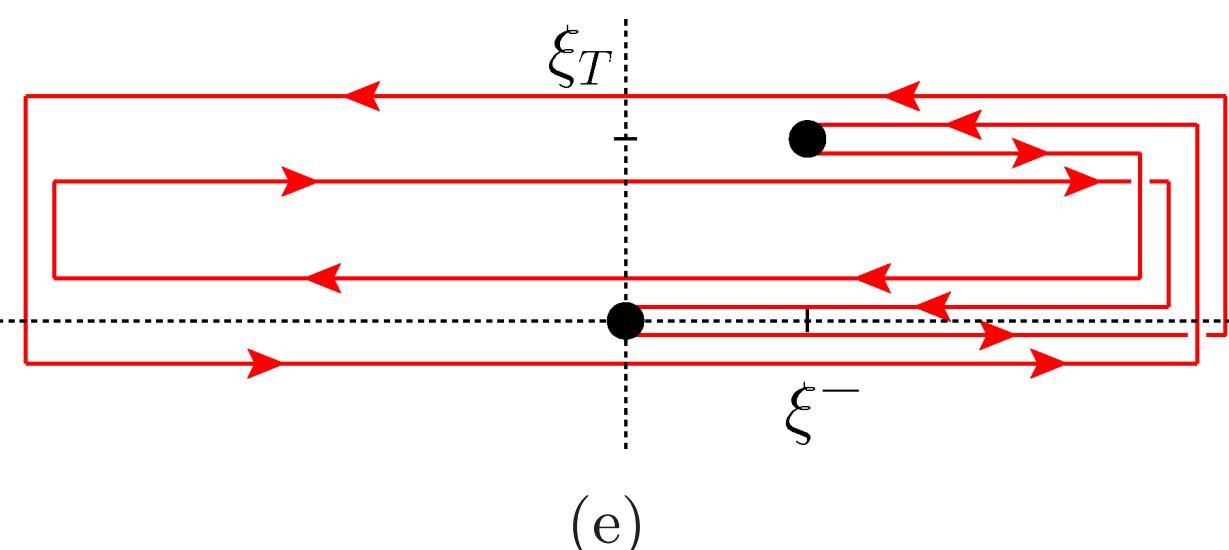
- * Assumed factorization in SCET and CGC



- * Significance of low- x studies

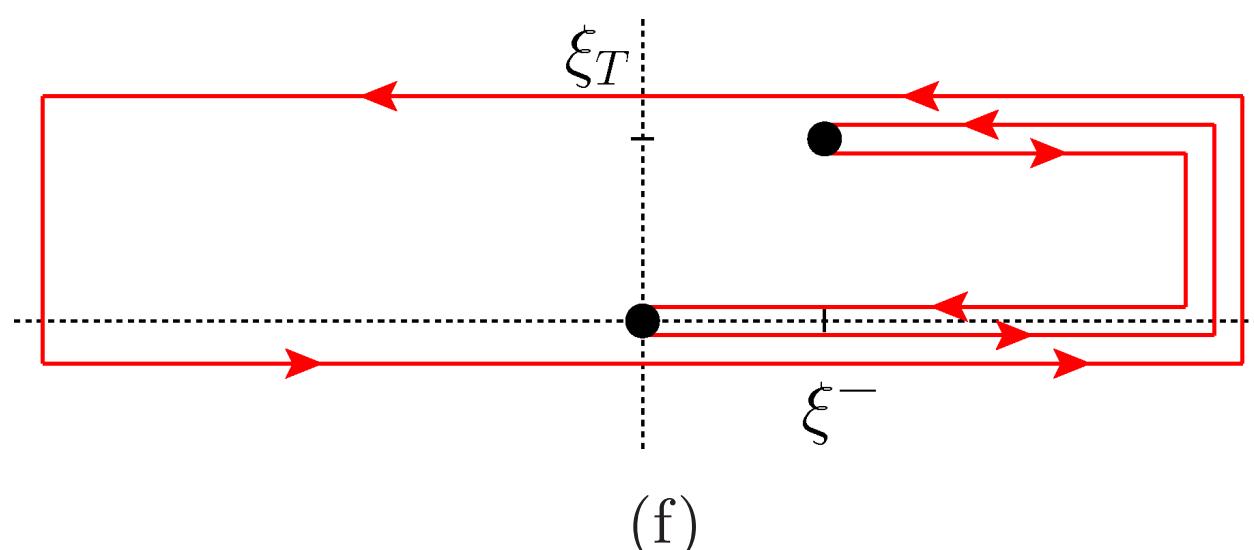


- * Size of factorization-breaking effects small?



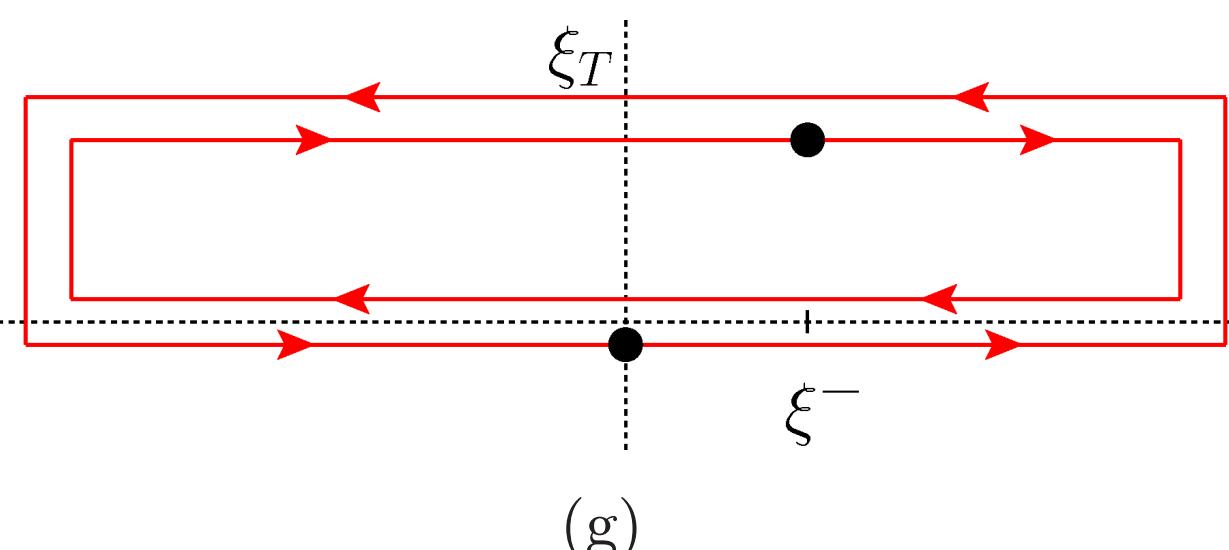
- * DP TMDs:

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

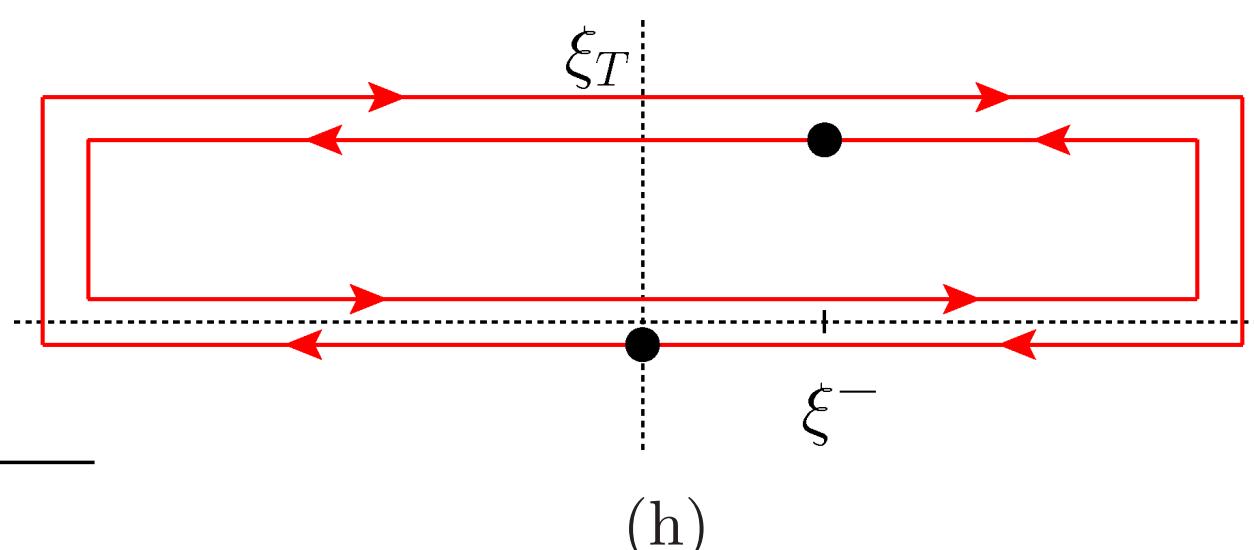
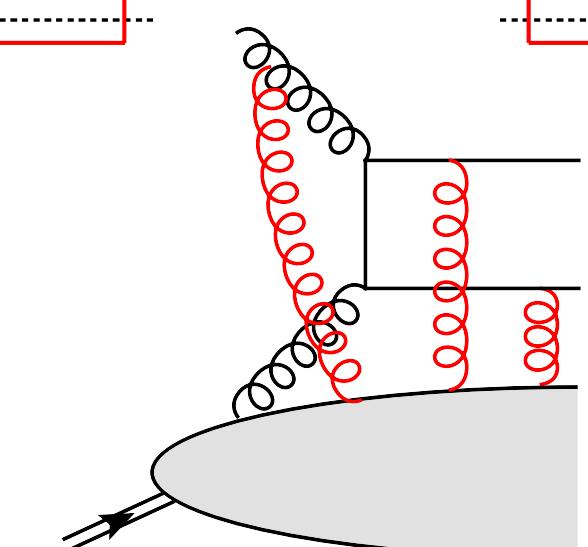


- * Appearance of new gauge **loop links**:

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



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



	$e p^\uparrow \rightarrow e' Q \bar{Q} X$ $e p^\uparrow \rightarrow e' j_1 j_2 X$	$p^\uparrow A \rightarrow h X$ ($x_F < 0$)	$p^\uparrow A \rightarrow \gamma^{(*)} \text{jet } X$	$p^\uparrow p \rightarrow \gamma \gamma X$ $p^\uparrow p \rightarrow J/\psi \gamma X$ $p^\uparrow p \rightarrow J/\psi J/\psi X$
$f_{1T}^{\perp g [+,+]}$	✓	✗	✗	✓
$f_{1T}^{\perp g [+,-]}$	✗	✓	✓	✗

Boer-Mulders

credits: D. Boer

	$pp \rightarrow \gamma \gamma X$	$pA \rightarrow \gamma^* \text{jet } X$	$ep \rightarrow e' Q \bar{Q} X$ $ep \rightarrow e' j_1 j_2 X$	$pp \rightarrow \eta_{c,b} X$ $pp \rightarrow H X$	$pp \rightarrow J/\psi \gamma X$ $pp \rightarrow \Upsilon \gamma X$
$h_1^{\perp g [+,+]} (\text{WW})$	✓	✗	✓	✓	✓
$h_1^{\perp g [+,-]} (\text{DP})$	✗	✓	✗	✗	✗

	$e p^\uparrow \rightarrow e' Q \bar{Q} X$ $e p^\uparrow \rightarrow e' j_1 j_2 X$	$p^\uparrow A \rightarrow h X$ ($x_F < 0$)	$p^\uparrow A \rightarrow \gamma^{(*)} \text{jet } X$	$p^\uparrow p \rightarrow \gamma \gamma X$ $p^\uparrow p \rightarrow J/\psi \gamma X$ $p^\uparrow p \rightarrow J/\psi J/\psi X$
$f_{1T}^{\perp g} [+,-]$	✓	✗	✗	✓
$f_{1T}^{\perp g} [+,-]$	✗	✓	✓	✗

Boer-Mulders

credits: D. Boer

	$pp \rightarrow \gamma \gamma X$	$pA \rightarrow \gamma^* \text{jet } X$	$ep \rightarrow e' Q \bar{Q} X$ $ep \rightarrow e' j_1 j_2 X$	$pp \rightarrow \eta_{c,b} X$ $pp \rightarrow H X$	$pp \rightarrow J/\psi \gamma X$ $pp \rightarrow \Upsilon \gamma X$
$h_1^{\perp g} [+,-]$ (WW)	✓	✗	✓	✓	✓
$h_1^{\perp g} [+,-]$ (DP)	✗	✓	✗	✗	✗

(pheno overview)  [D. Boer (2017)](azimuthal asym. in $J/\Psi + \text{jet}$ SIDIS at the EIC)  [U. D'Alesio, F. Murgia, C. Pisano, P. Taels (2019)](matching high and low p_T in J/Ψ SIDIS)  [D. Boer, U. D'Alesio, F. Murgia, C. Pisano, P. Taels (2020)](gluon TMDs and NRQCD in J/Ψ at the EIC)  [A. Bacchetta, D. Boer, C. Pisano, P. Taels (2020)]

T-even and T-odd gluon TMD PDFs at twist-2

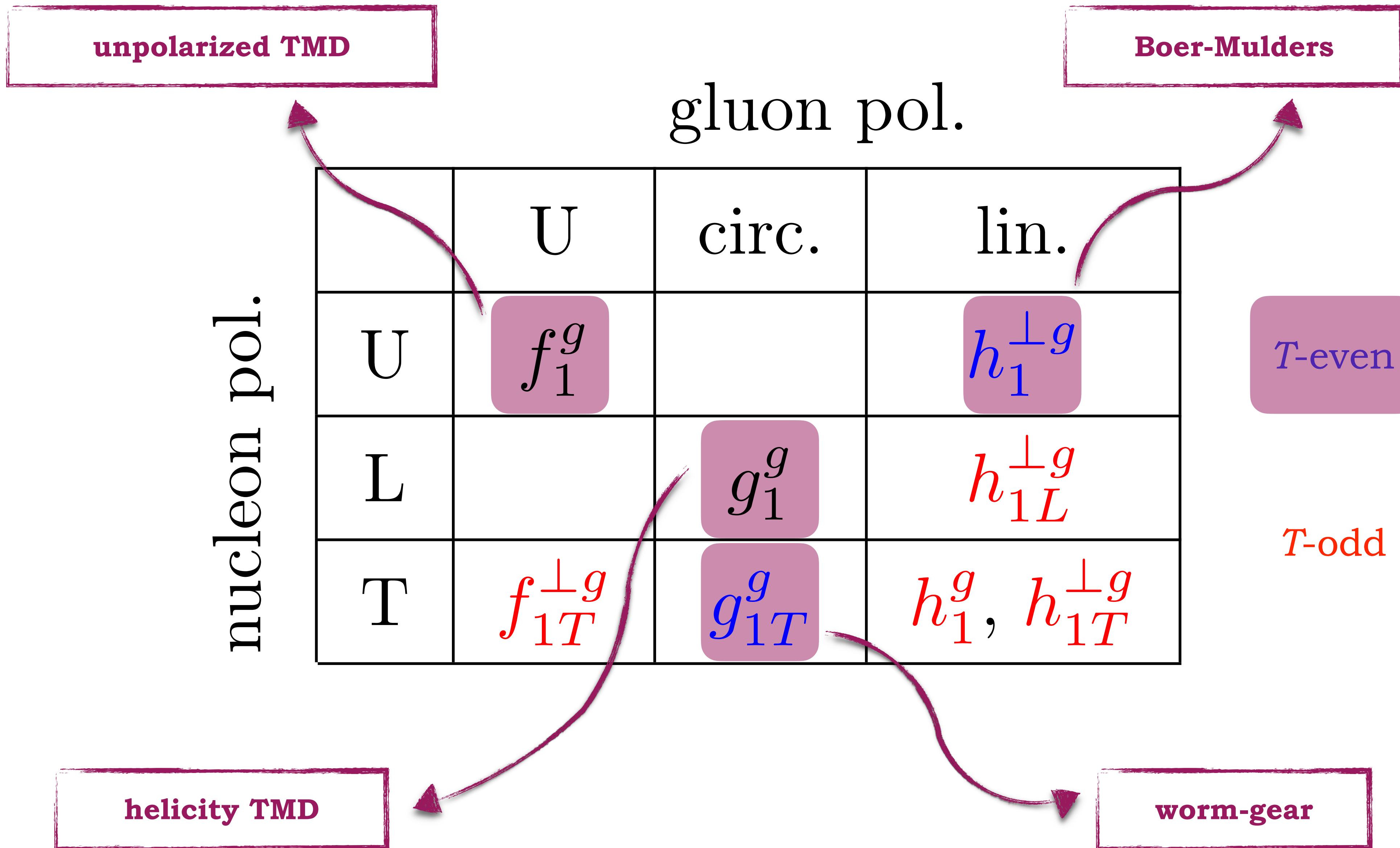
gluon pol.

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

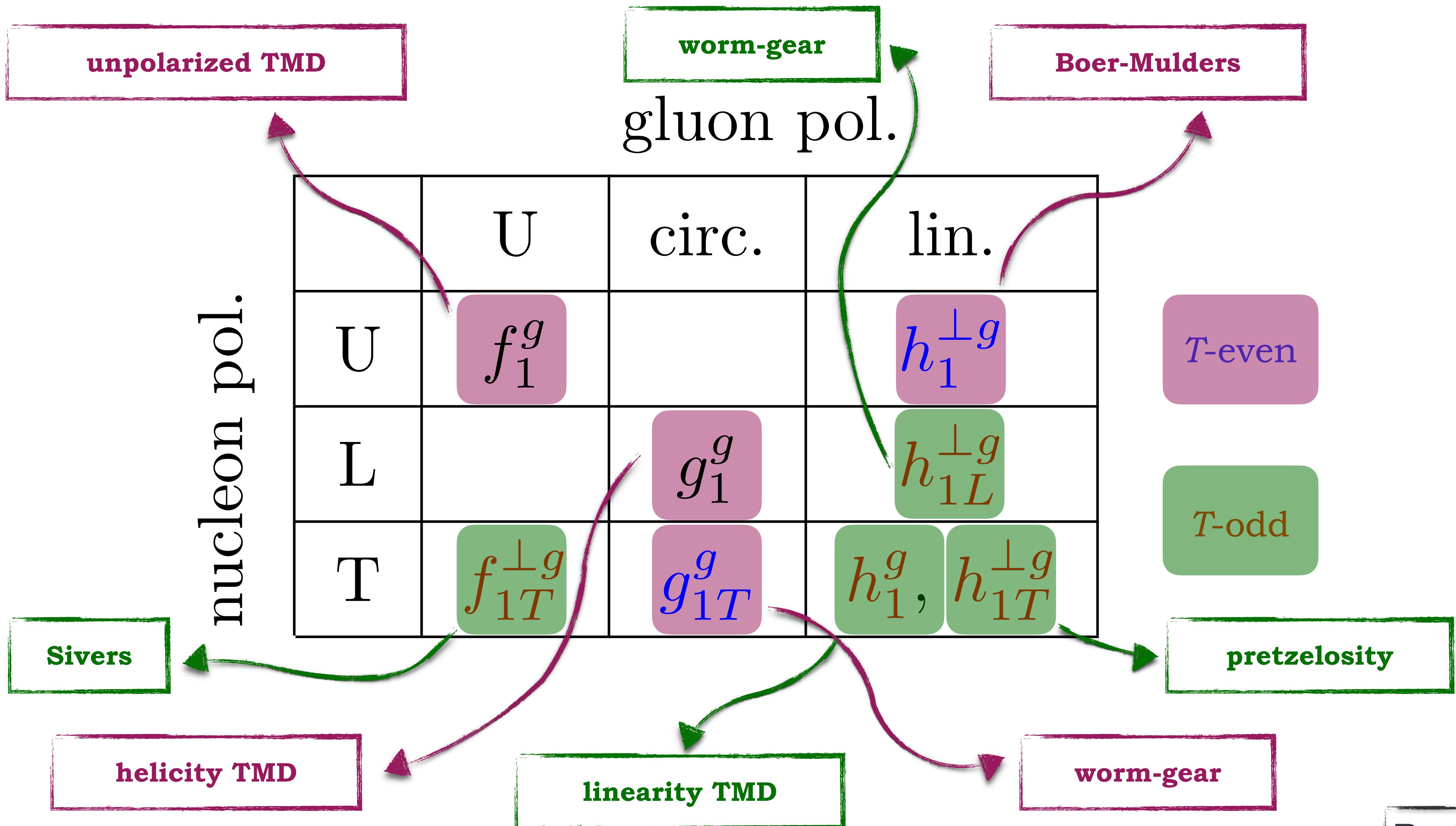
T-even

T-odd

T-even and T-odd gluon TMD PDFs at twist-2



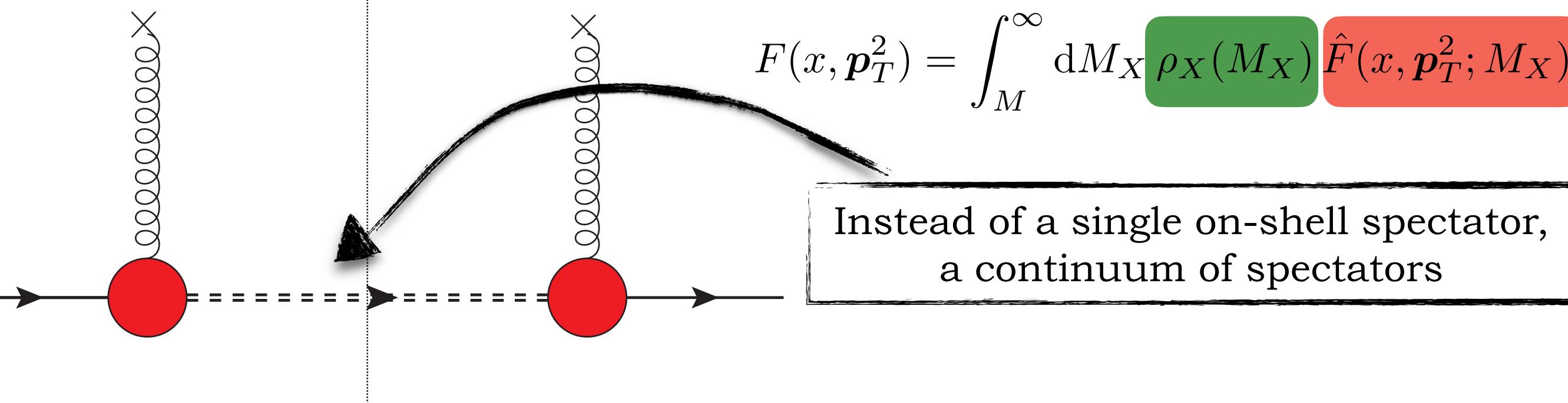
T-even and T-odd gluon TMD PDFs at twist-2



Our model at a glance

Backup

Spectator-system spectral-mass function



Spectral function **learns** small- and moderate- x info
encoded in **NNPDF** collinear parametrizations

(NNPDF3.1sx + NNPDFpol1.1)

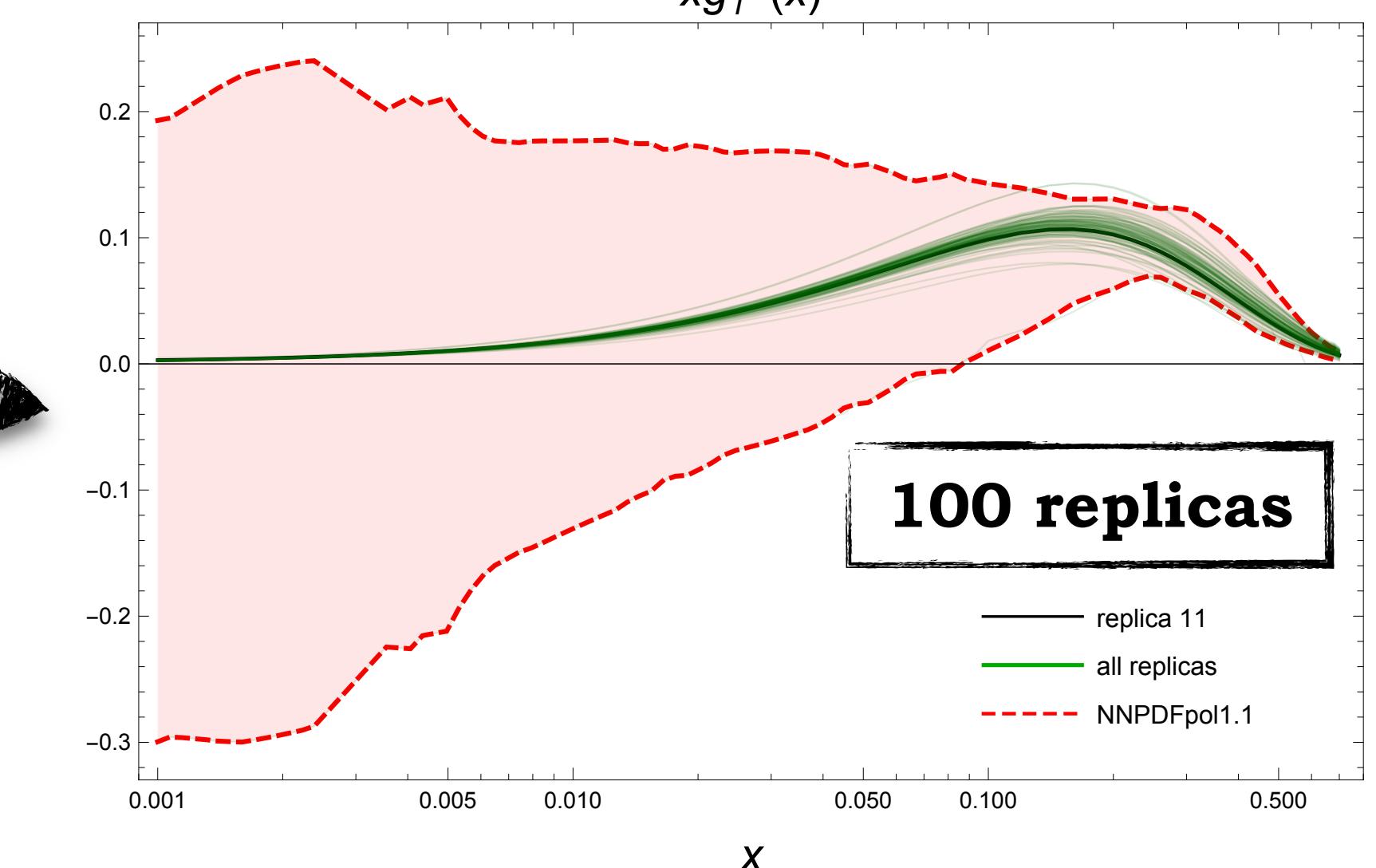
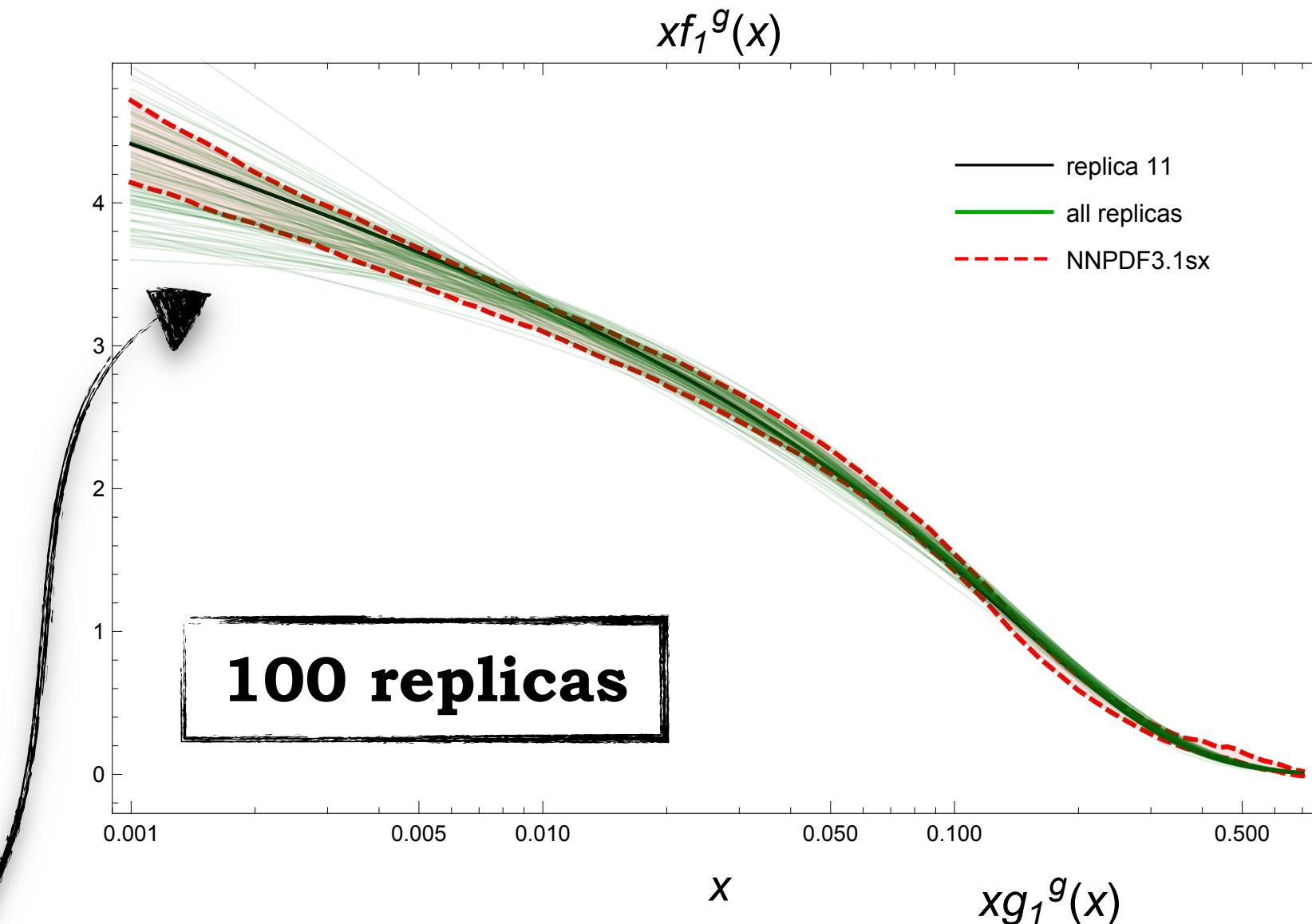
Simultaneous fit of f_1 and g_1 PDFs

Inclusion of small- x resummation effects (**BFKL**)

Calculation of all twist-2 T -even gluon TMDs

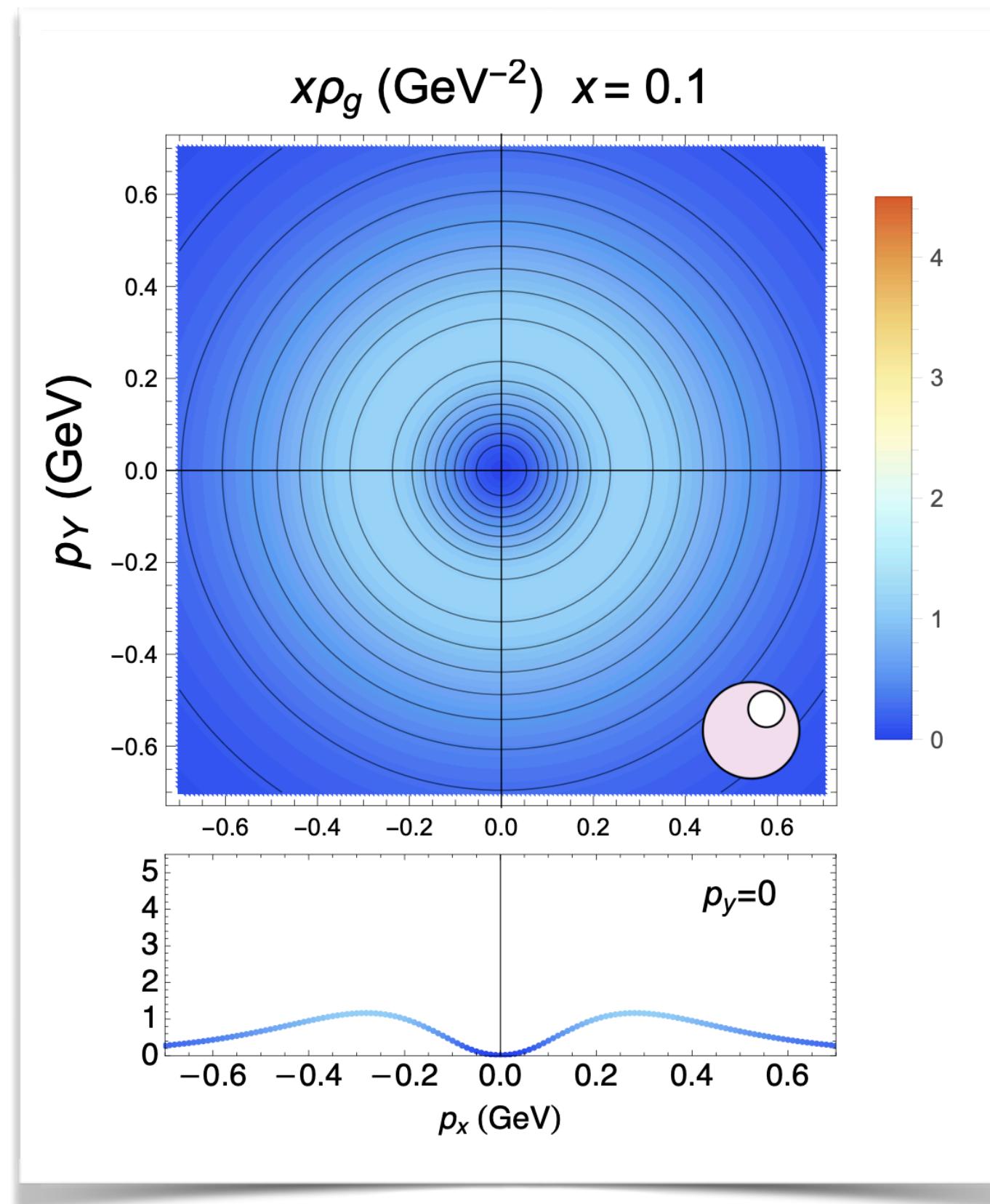
Link with collinear factorization

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



3D tomography: the gluon content in the proton

unpolarized TMD

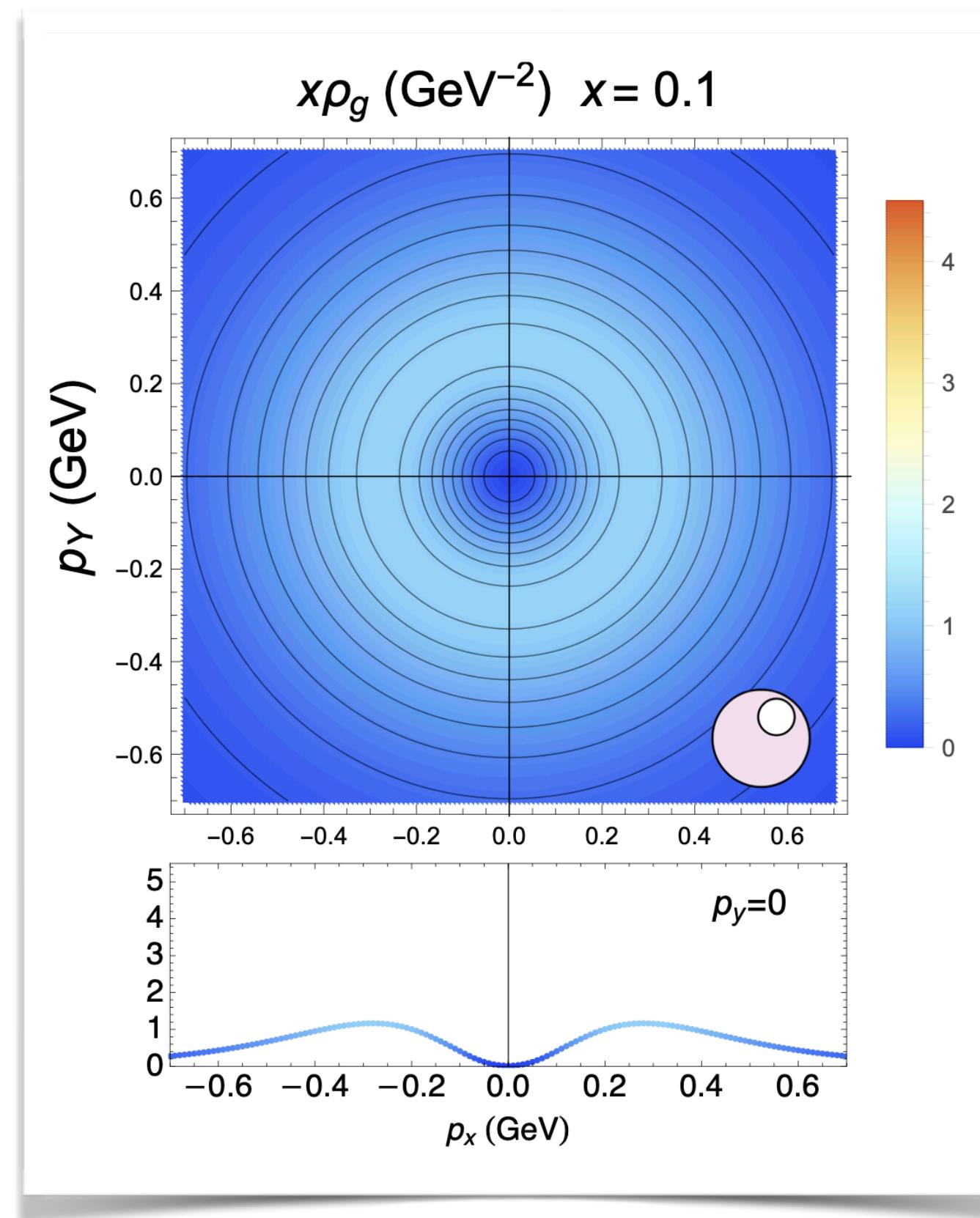


[A. Bacchetta, F.G.C., M. Radici, P. Taels, *Eur. Phys. J. C* **80** (2020) no.8 [[arXiv:2005.02288](https://arxiv.org/abs/2005.02288)]]

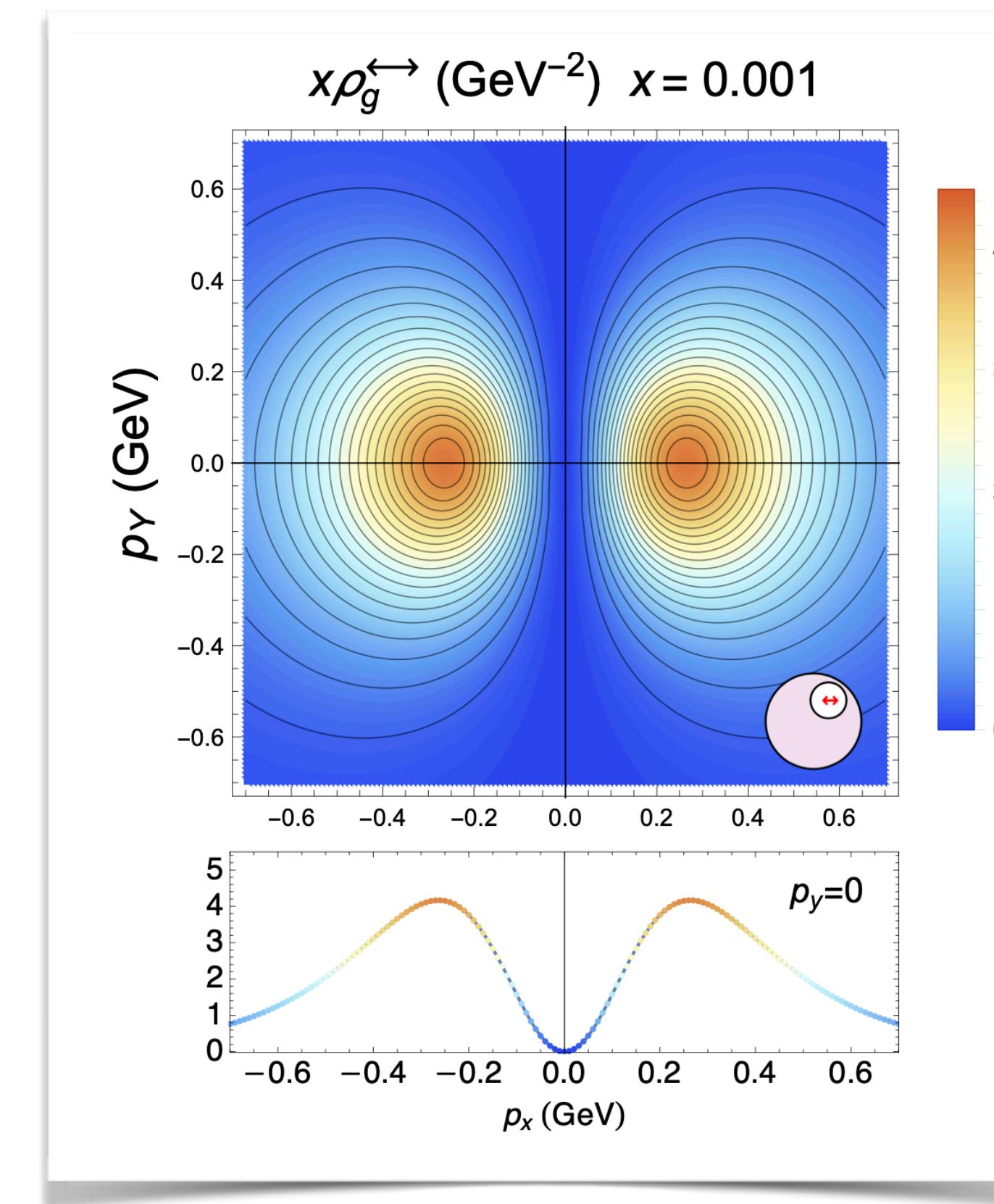
Backup

3D tomography: the gluon content in the proton

unpolarized TMD



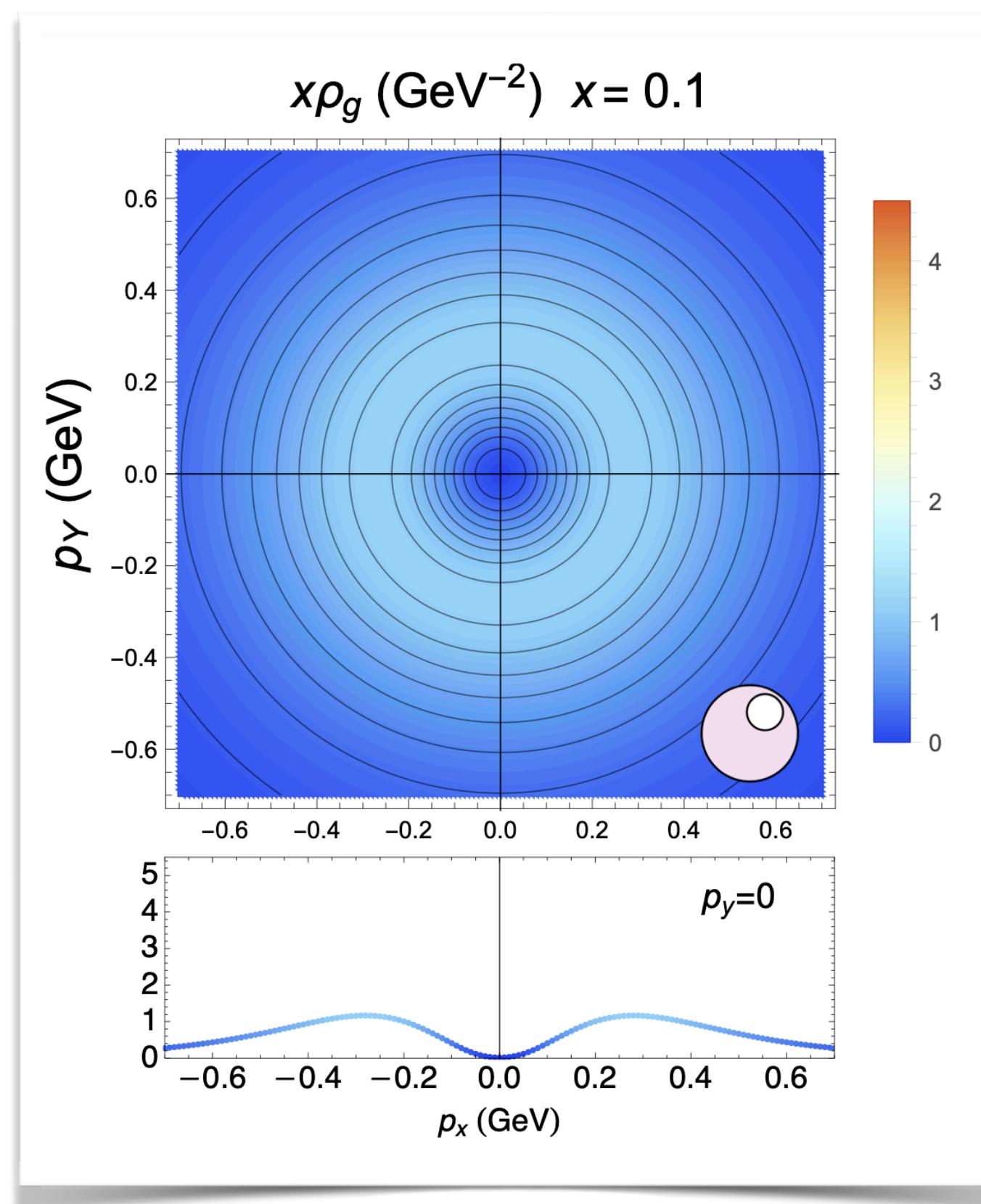
Boer-Mulders



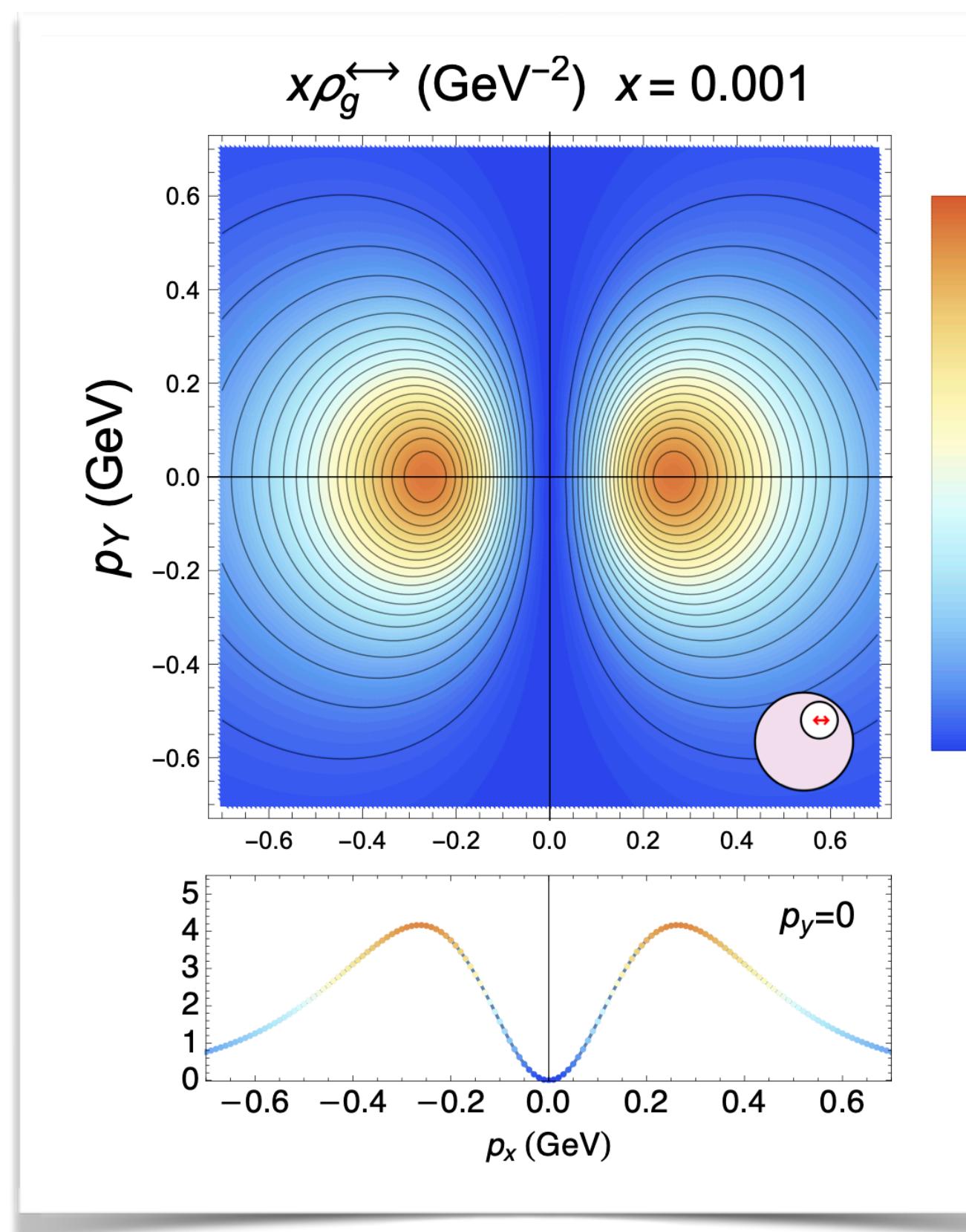
[A. Bacchetta, F.G.C., M. Radici, P. Taels, *Eur. Phys. J. C* **80** (2020) no.8 [[arXiv:2005.02288](https://arxiv.org/abs/2005.02288)]]

3D tomography: the gluon content in the proton

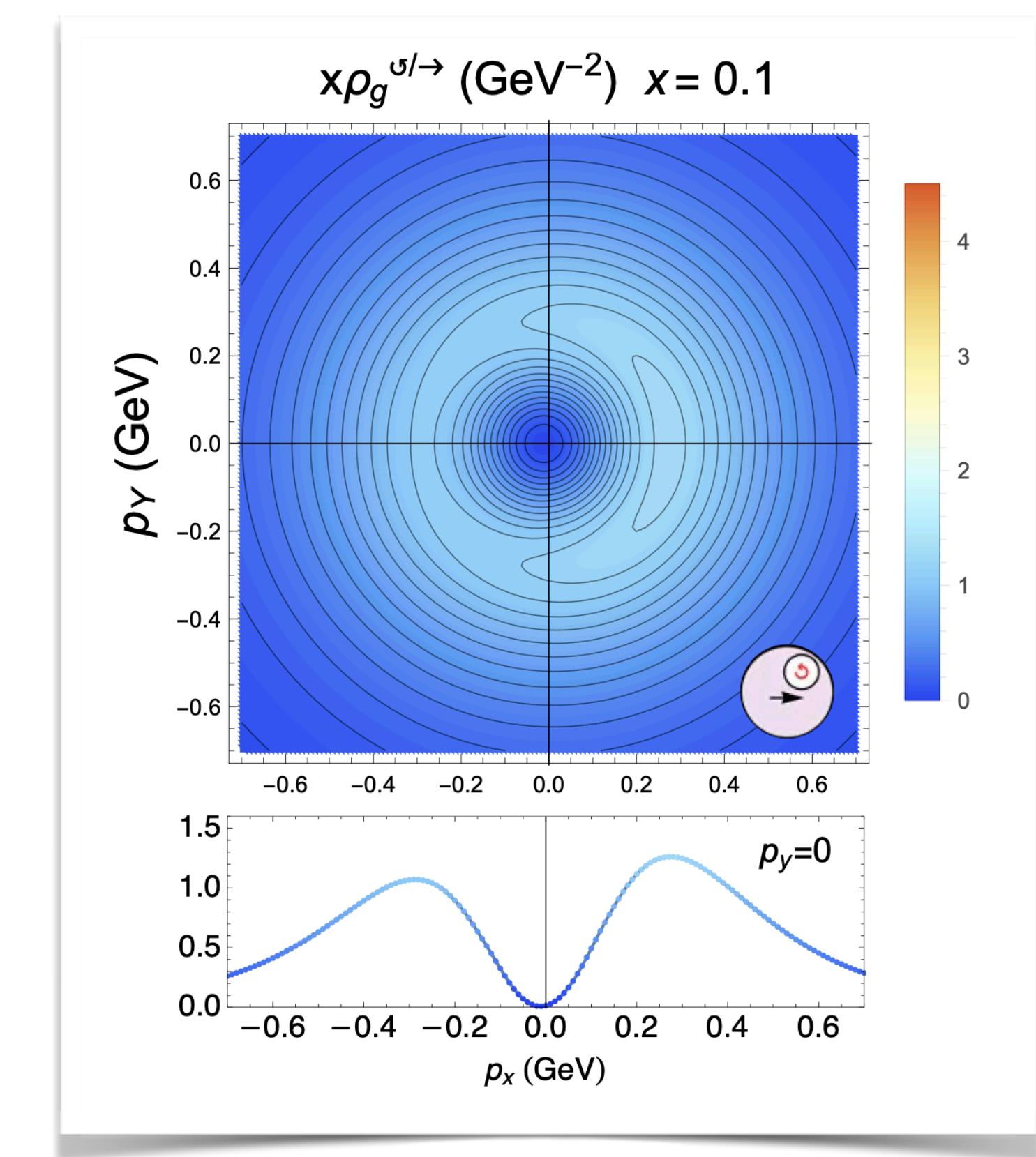
unpolarized TMD



Boer-Mulders



worm-gear



[A. Bacchetta, F.G.C., M. Radici, P. Taels, *Eur. Phys. J. C* **80** (2020) no.8 [[arXiv:2005.02288](https://arxiv.org/abs/2005.02288)]]