MPI 2021

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Accessing the proton UGD via exclusive polarized ρ-meson leptoproduction at HERA and the EIC

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

FONDAZIONE BRUNO KESSLER FUTURE BUILT ON KNOWLEDGE

TIFPA Trento Institute for Fundamental Physics and Applications

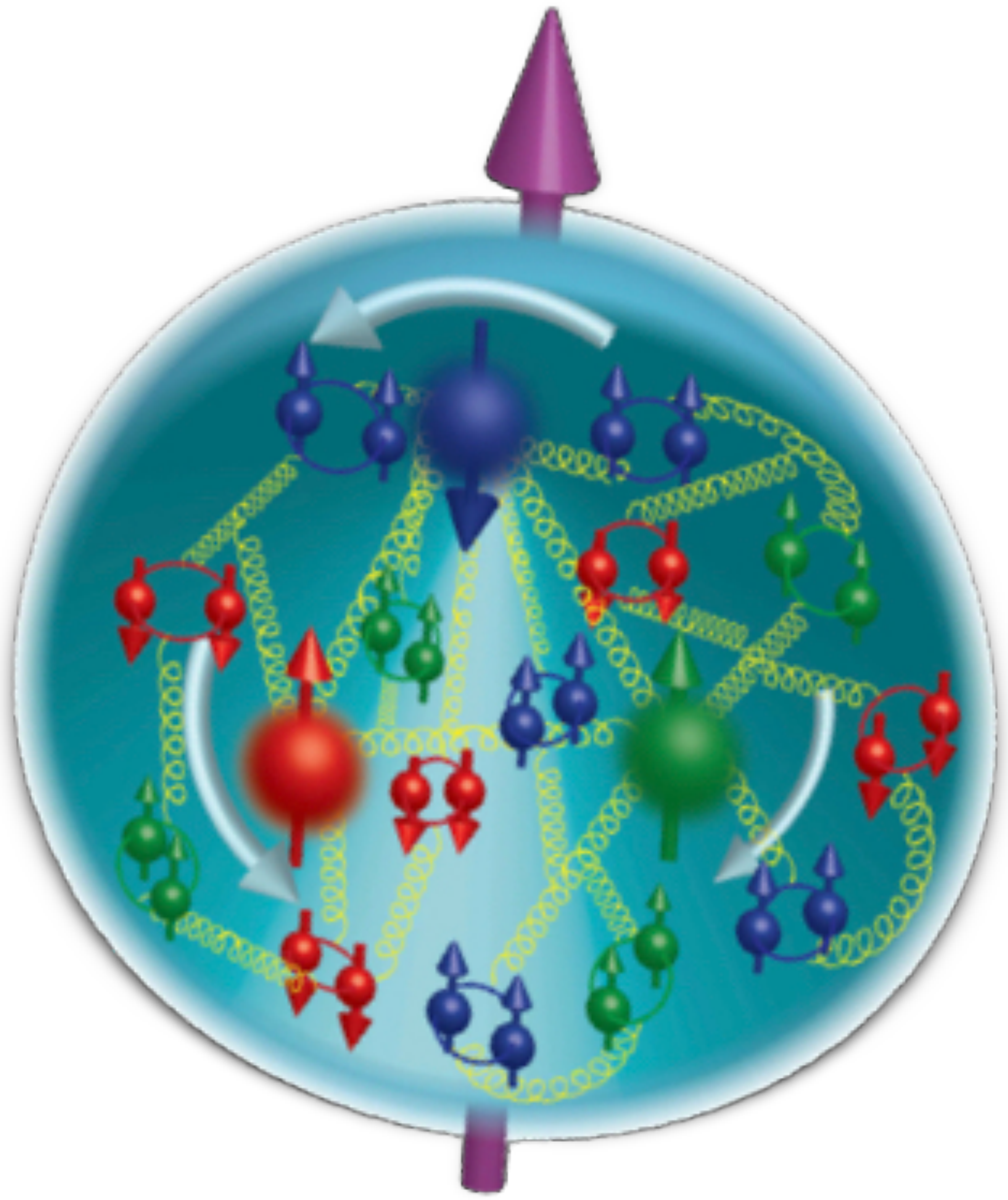
HAS QCD HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

Parton densities: hors d'œuvre

Parton densities → relevant for the search of **New Physics**...

→ ...crucial role in the understanding and exploration of **QCD**

- Describe the internal structure of the nucleon in terms of its elementary constituents (quarks and gluons)
- **Nonperturbative** objects that enter the expression of cross sections
- Can be *extracted* from experiments via *global fits*



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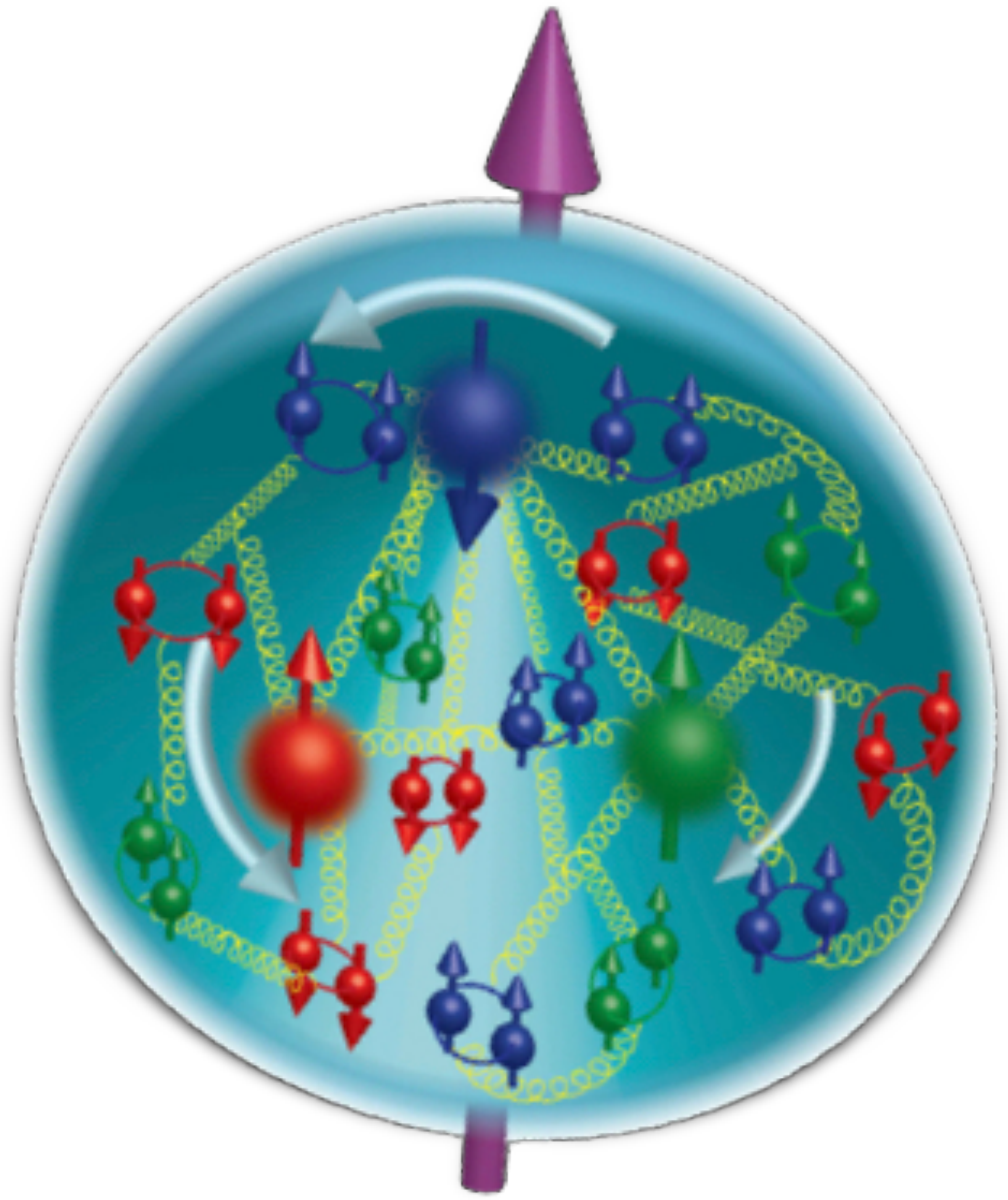
- Several types of distributions…

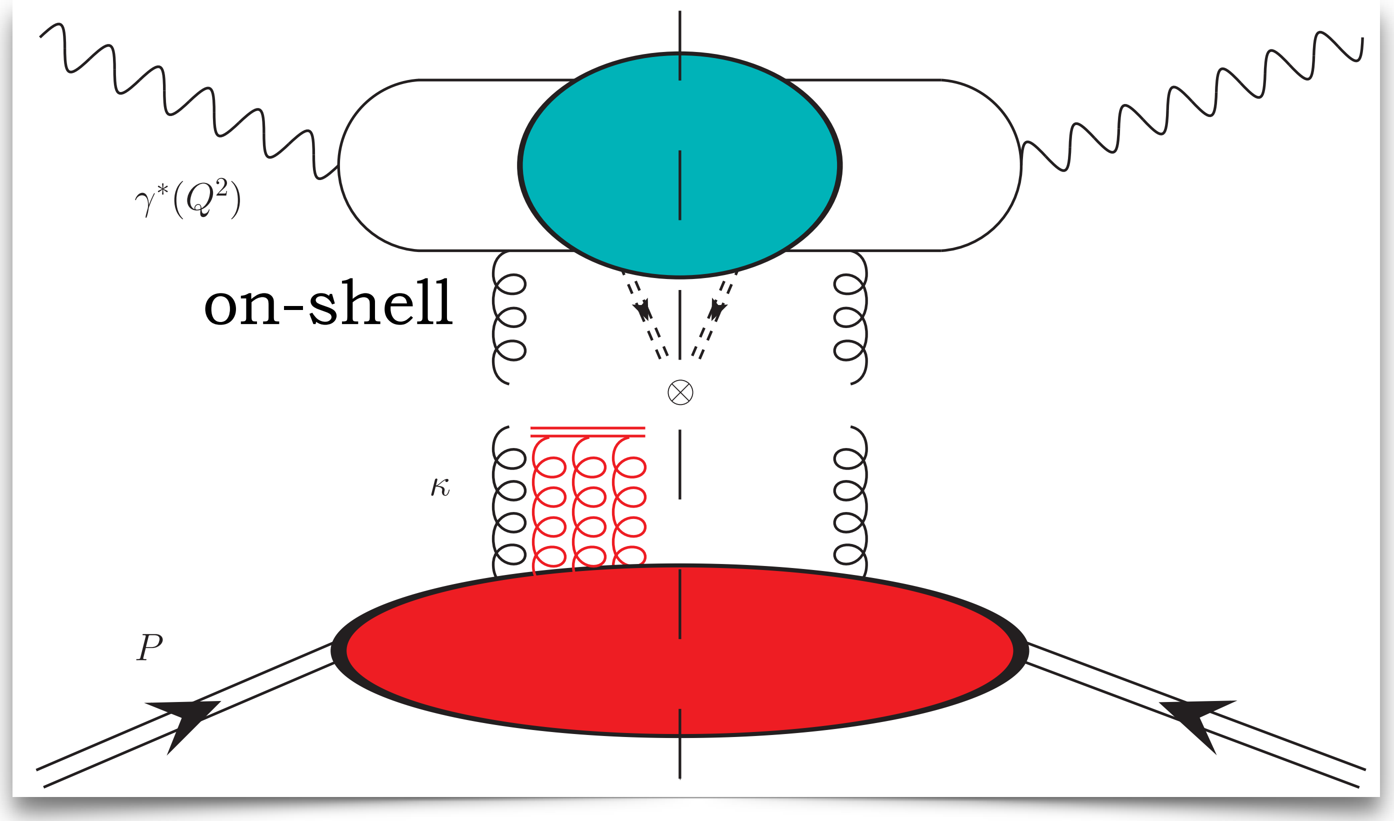
  - Respect different **factorization theorems**
  - Exhibit peculiar **universality properties**
  - Obey distinct **evolution equations**



TMD versus HEF

TMD

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



TMD
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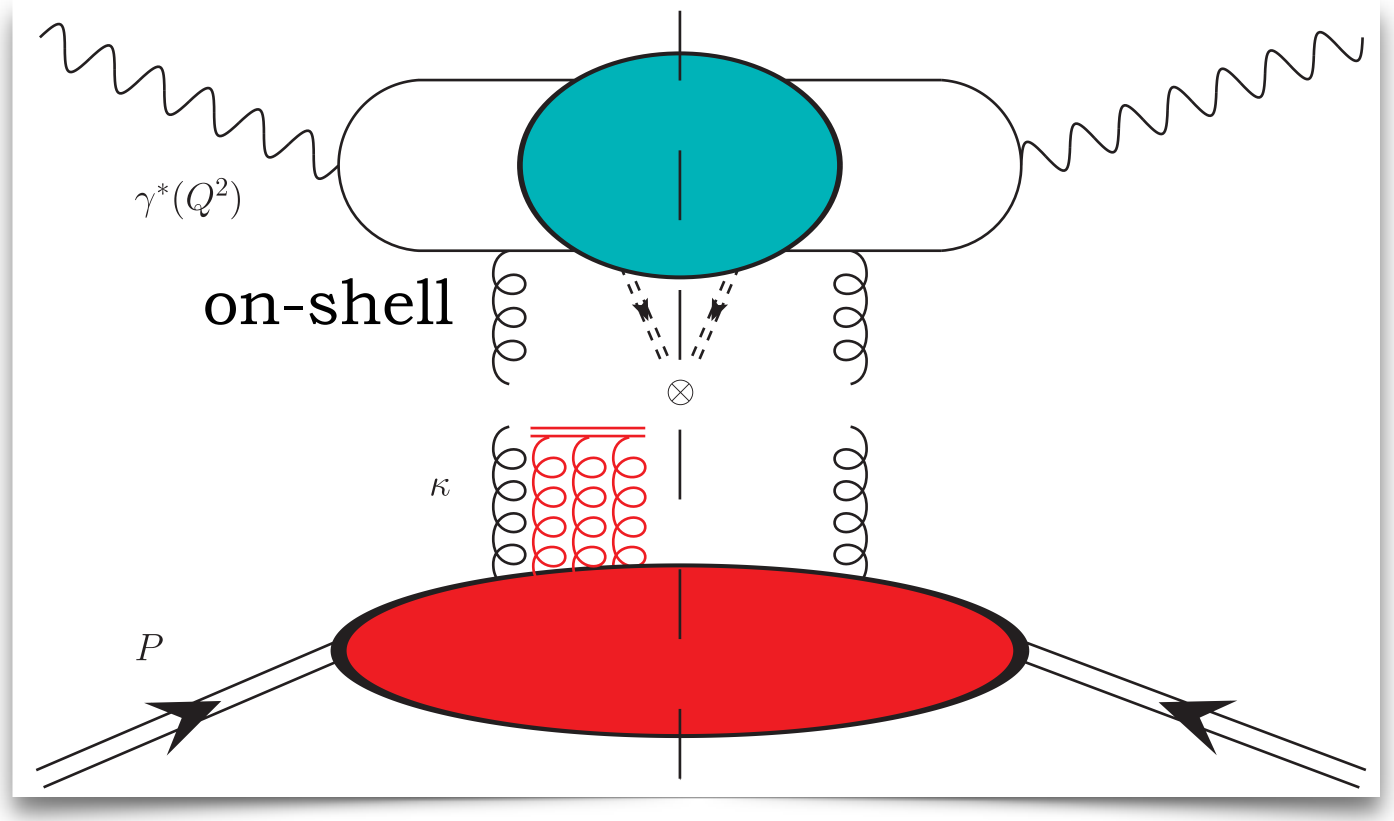

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- Inclusive or exclusive processes **(!)**
- Small x, large κ_T
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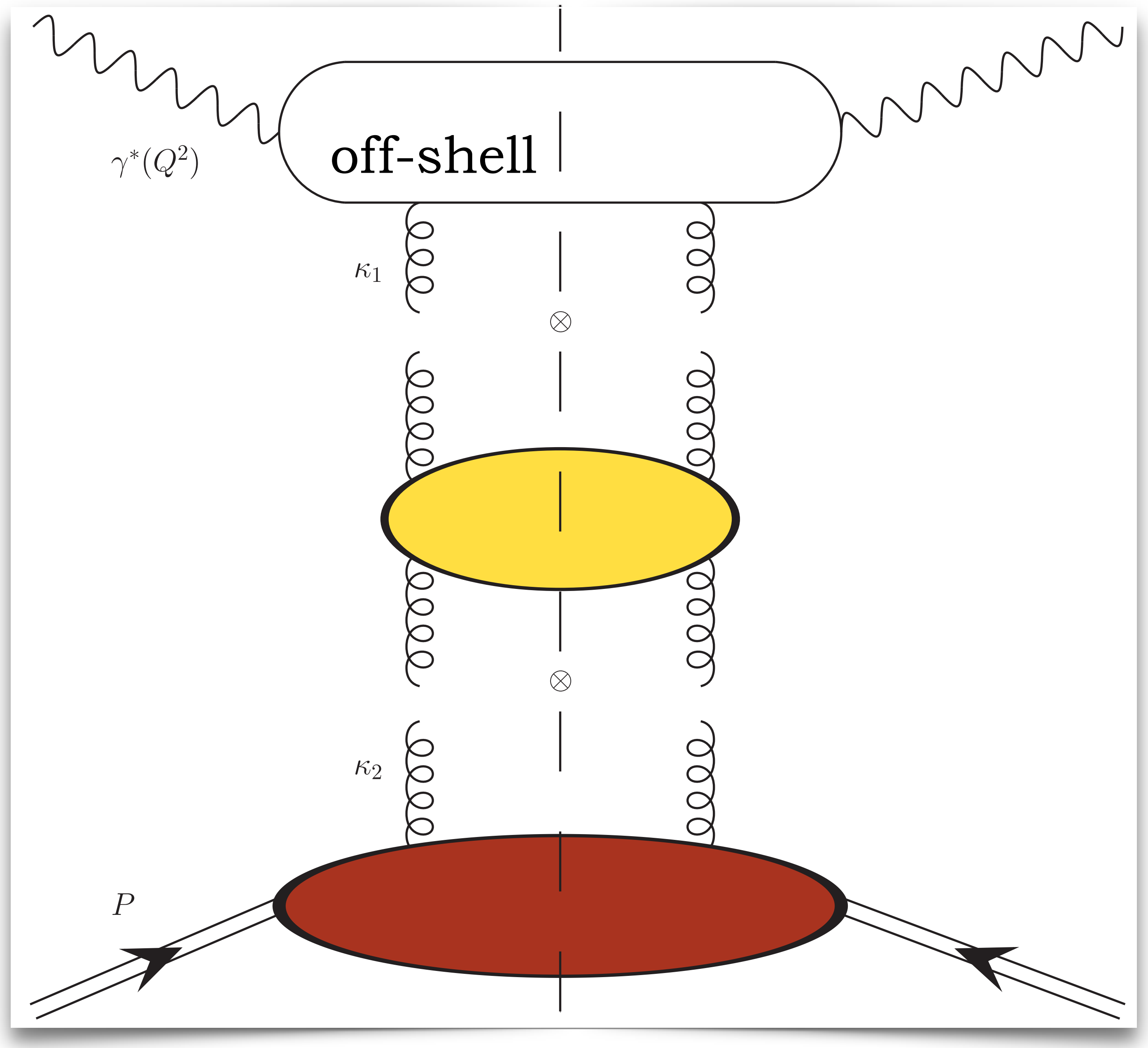

$\Phi^{\gamma^* \to \gamma^*}$

$\otimes$

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

$\otimes$

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

TMD versus HEF

TMD

IR-safe colorless $\{\Phi^{\mathrm{i}\to\mathrm{o}}\}$
(Fadin-Martin theorem)
🔗 [V.S. Fadin, A.D. Martin (1999)]

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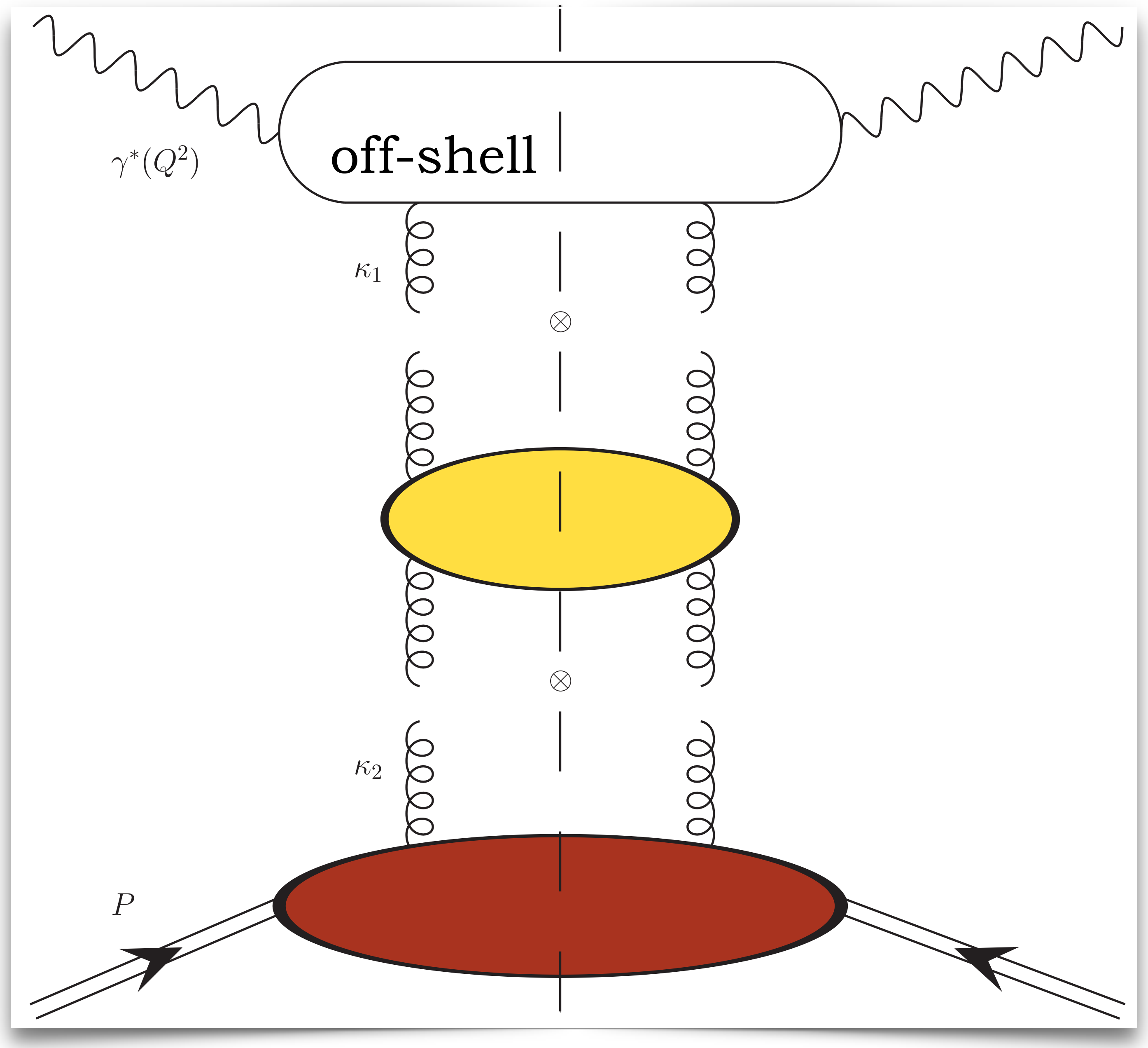

$$\Phi^{\gamma^*\to\gamma^*} \otimes \mathcal{G}_{\mathrm{BFKL}} \otimes \Phi^{P}_{[\mathrm{NP}]}$$

TMD versus HEF

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

IR diffusion pattern

(Bartels' cigar)

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

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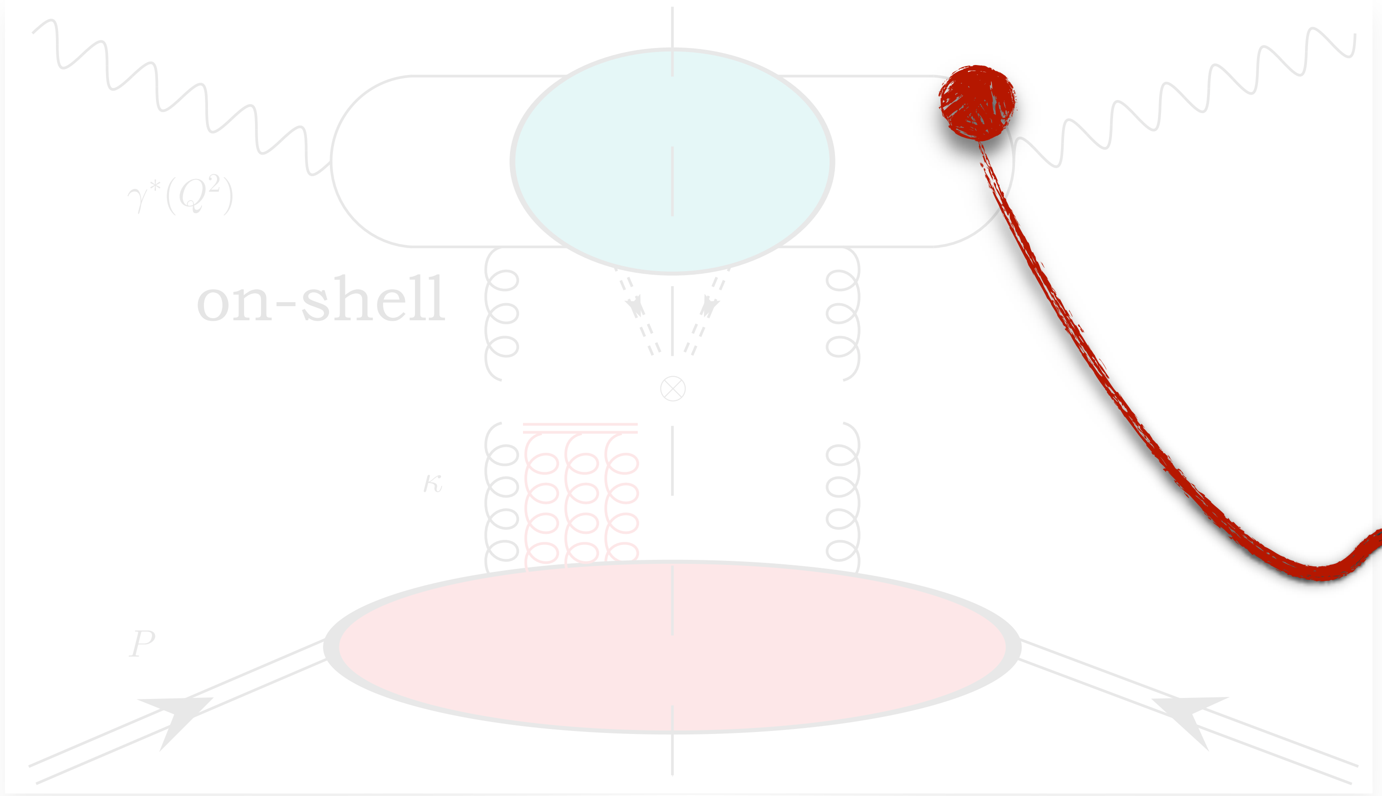

Q^2

Q_0^2

HEF

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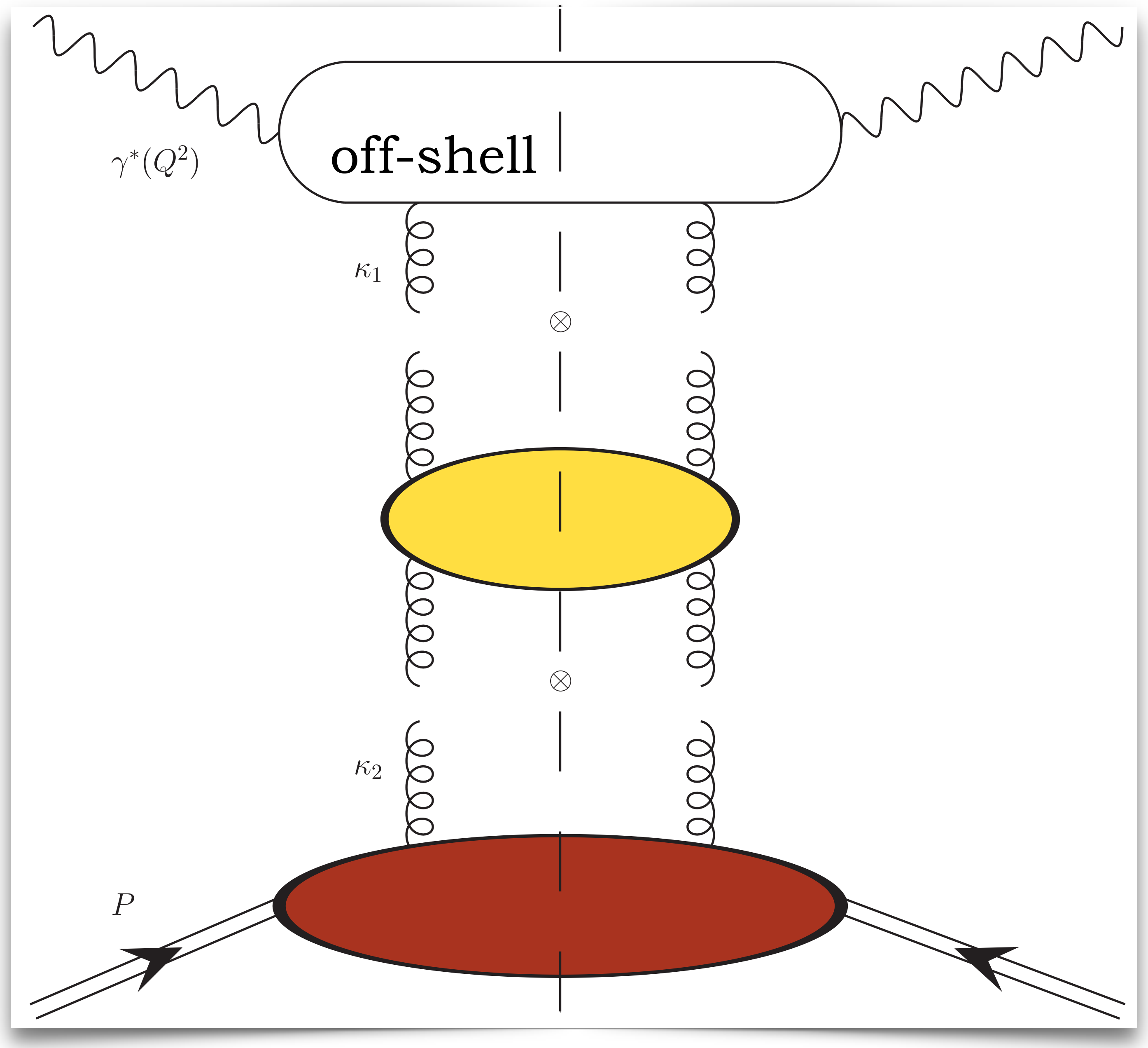

$$\Phi^{\gamma^* \to \gamma^*} \otimes \mathcal{G}_{\rm BFKL} \otimes \Phi^{P}_{\rm [NP]}$$

HEF at work: hybrid or pure factorization?

Forward emissions

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

Central emissions

* *Gluon induced* ↔ small-x gluons

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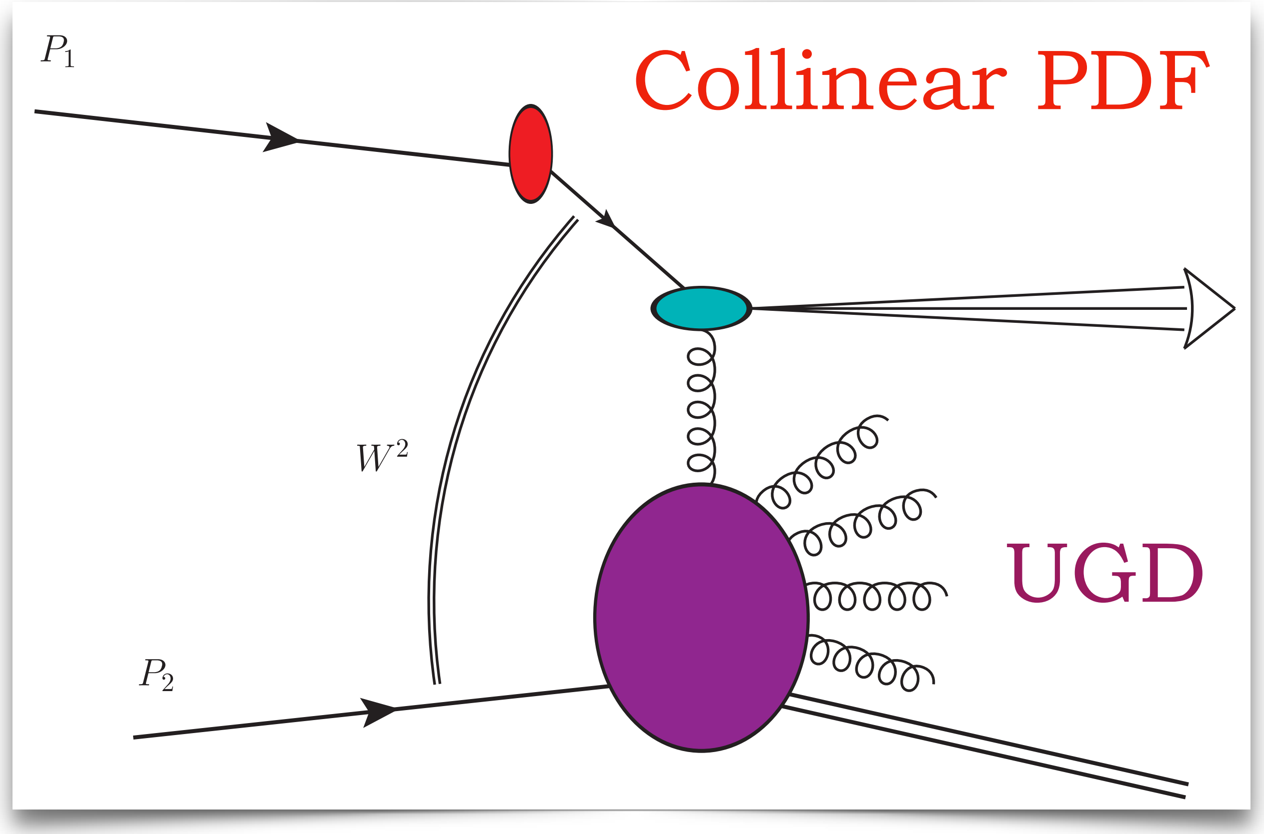

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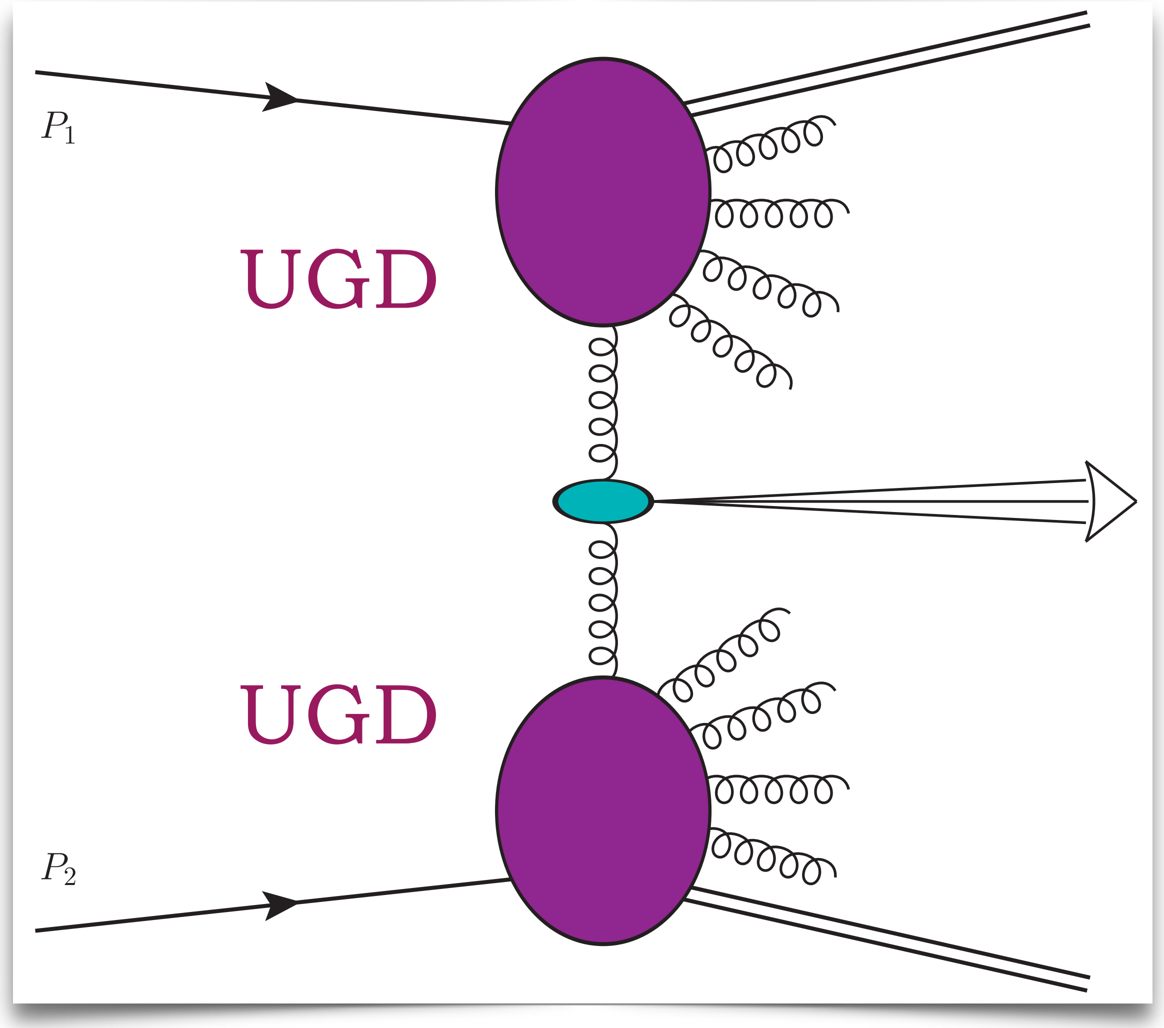

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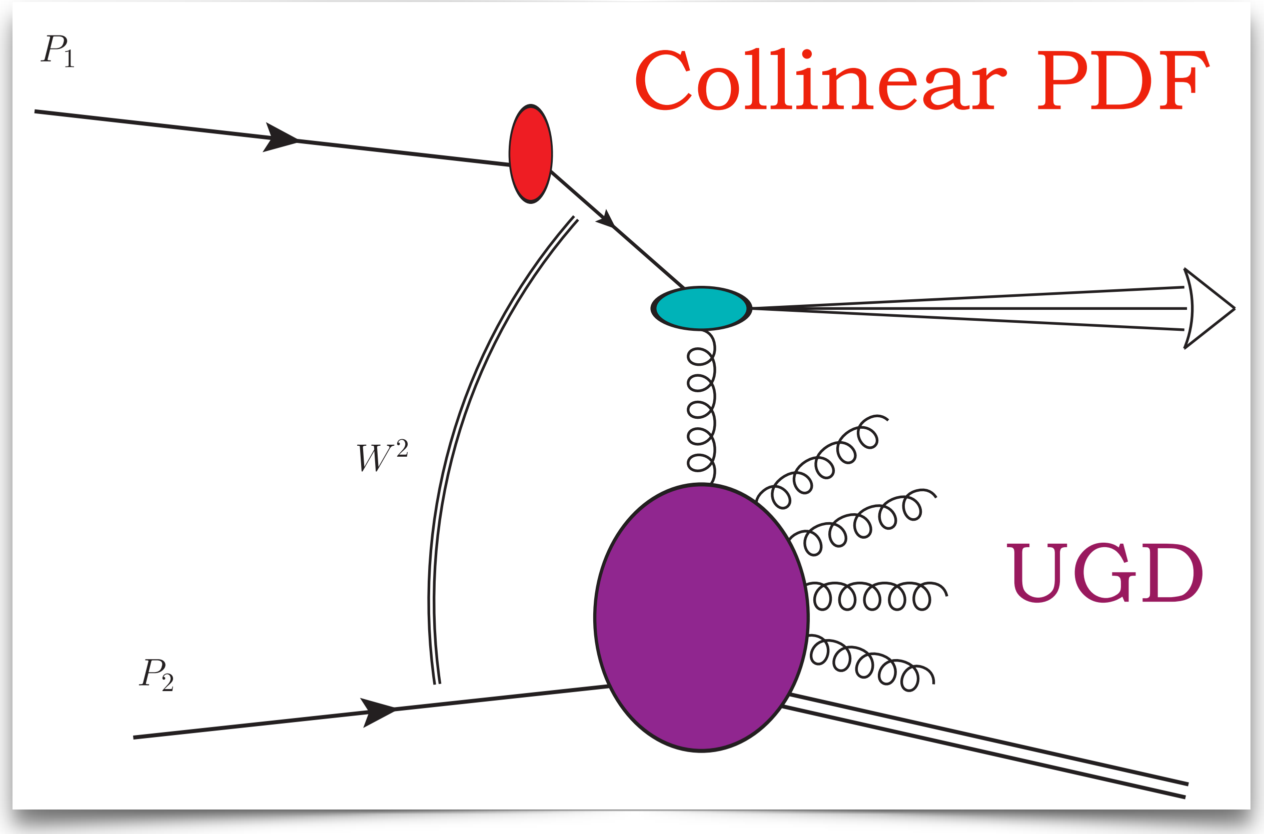

- *Distinctive signals* of small-x dynamics **expected**

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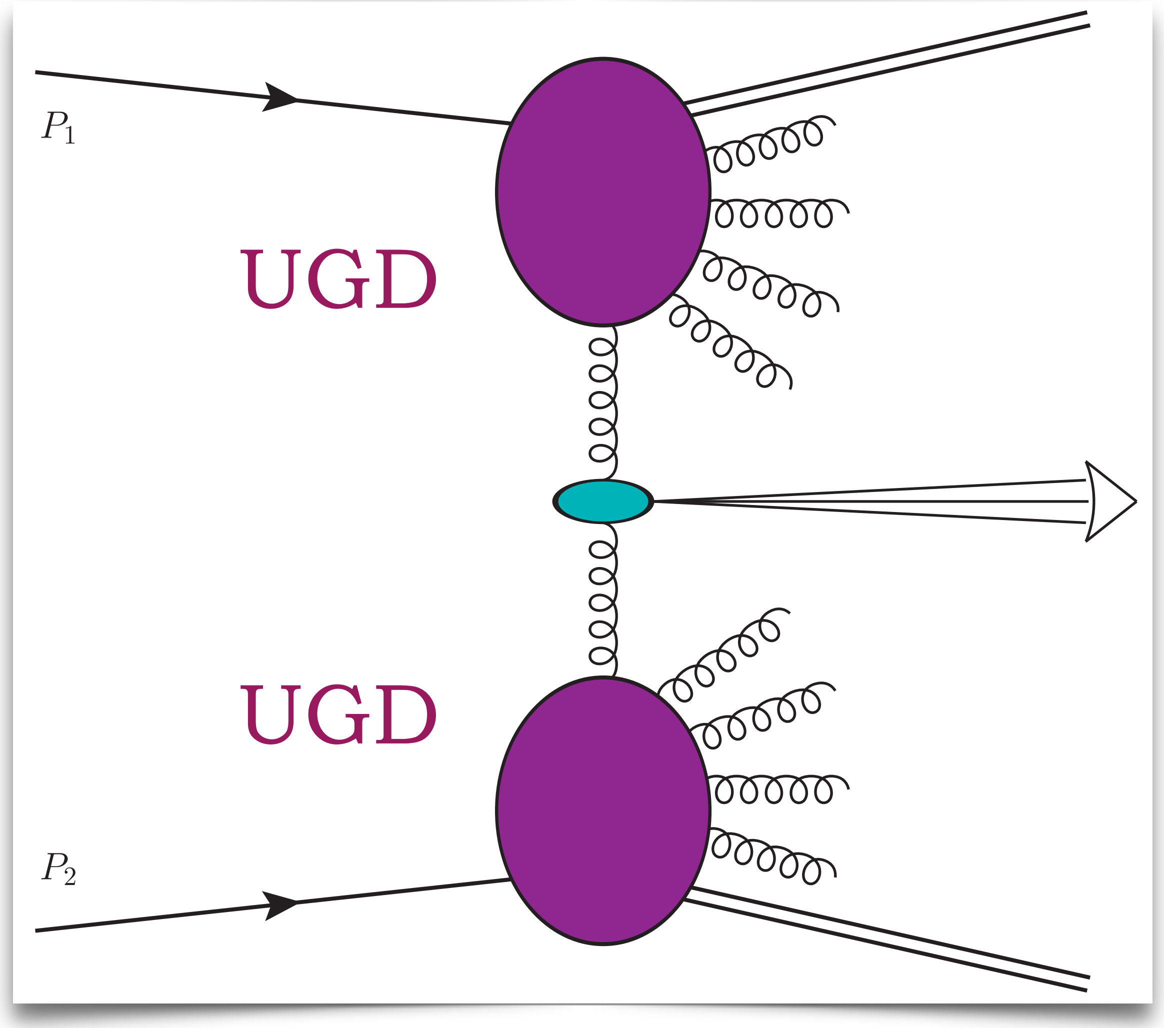

- Small-x dynamics to **enhance** f.o. description

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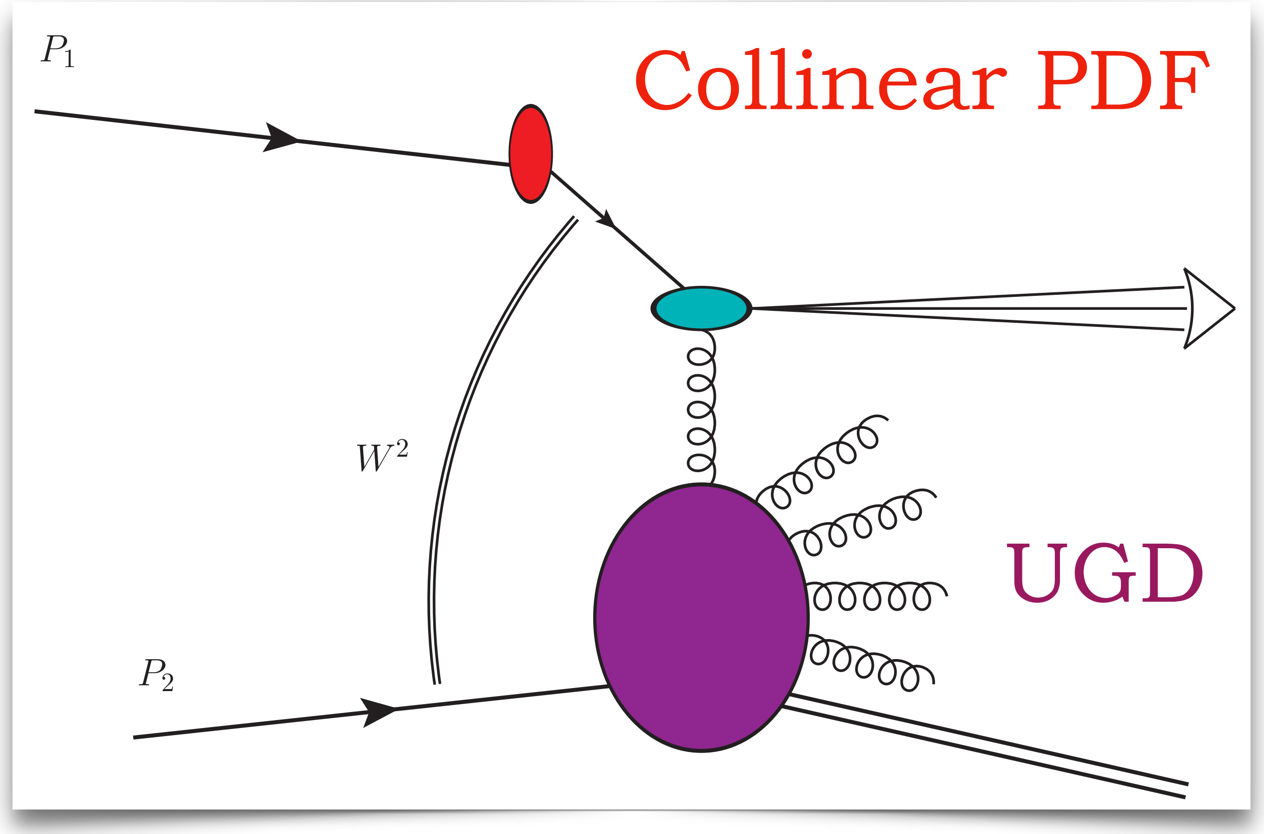

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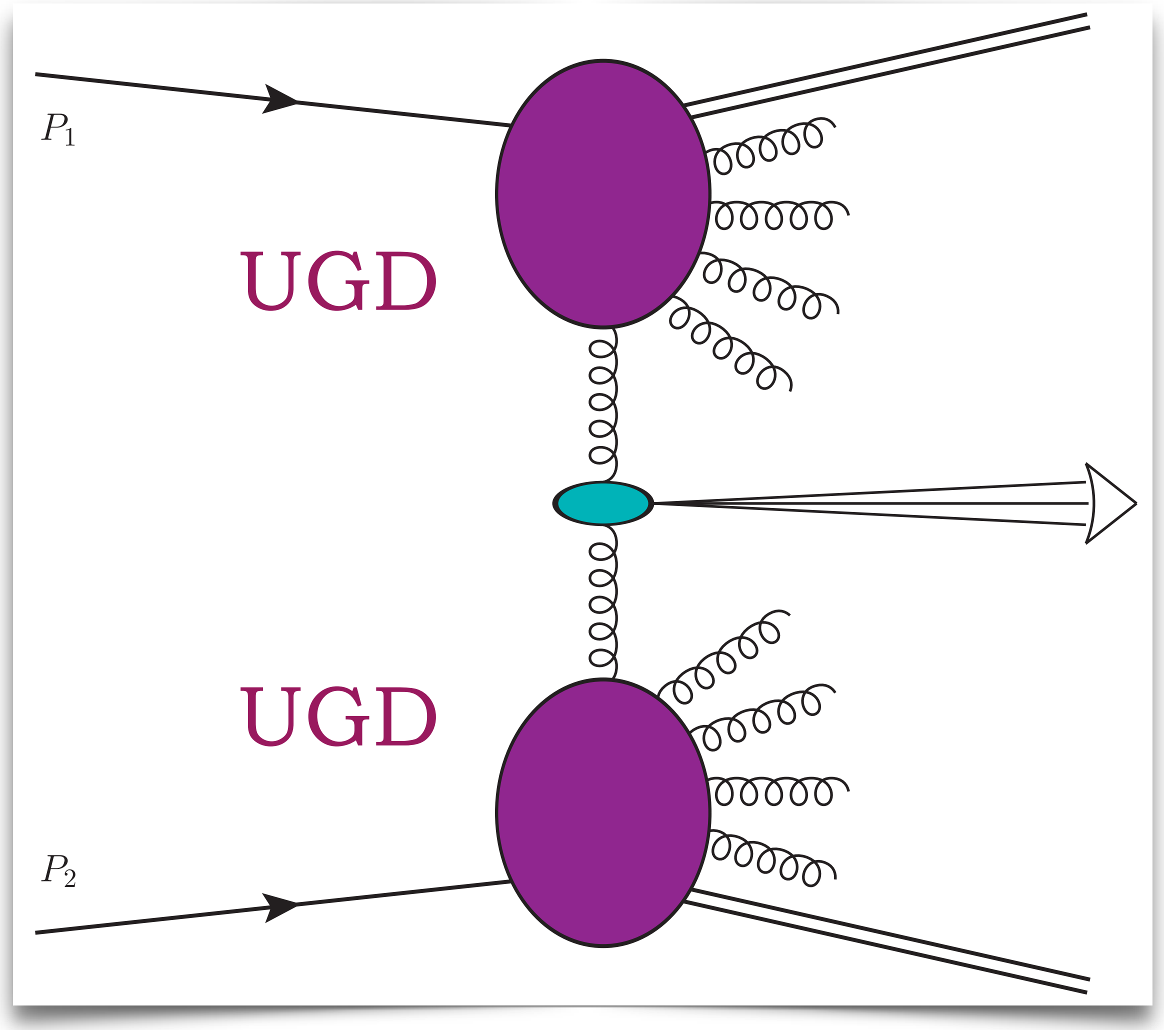

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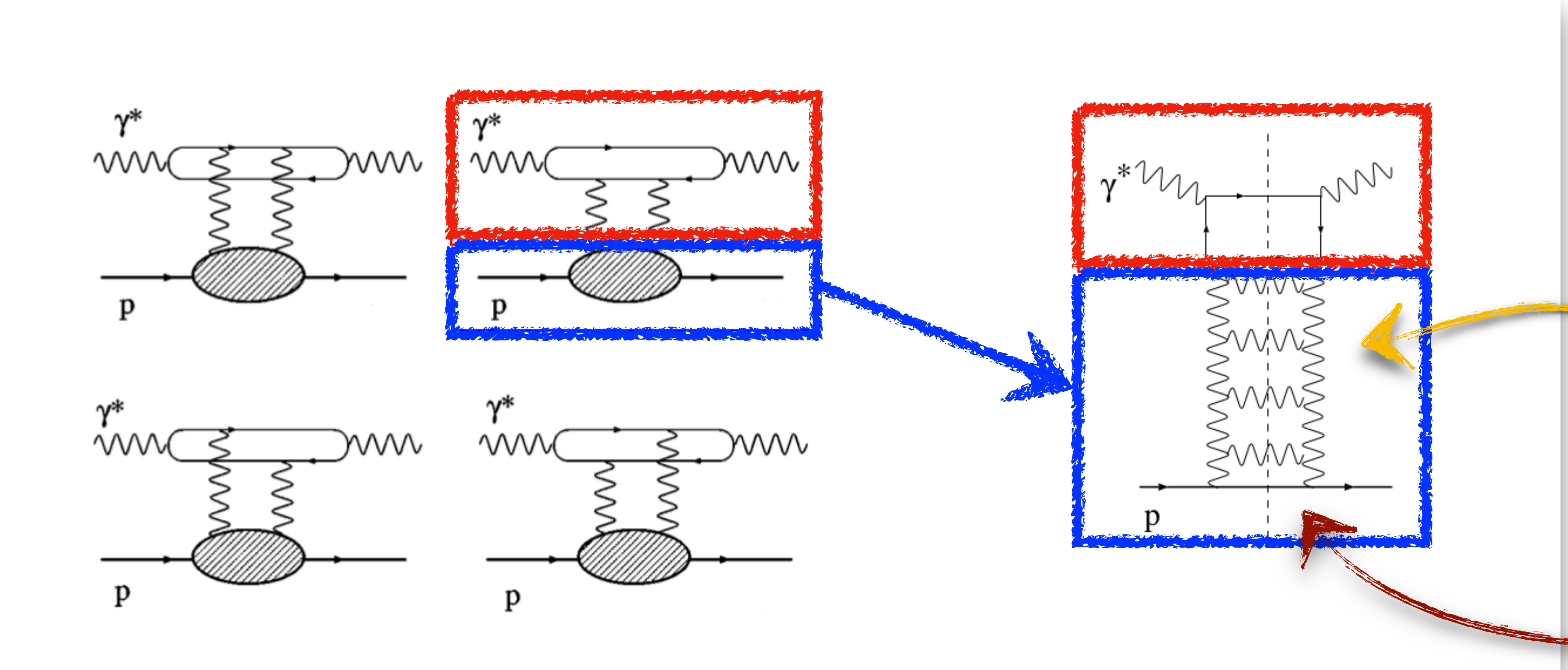
Table complemented by *exclusive* counterparts and *lepto-hadronic* channels

High-energy factorization and the UGD

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

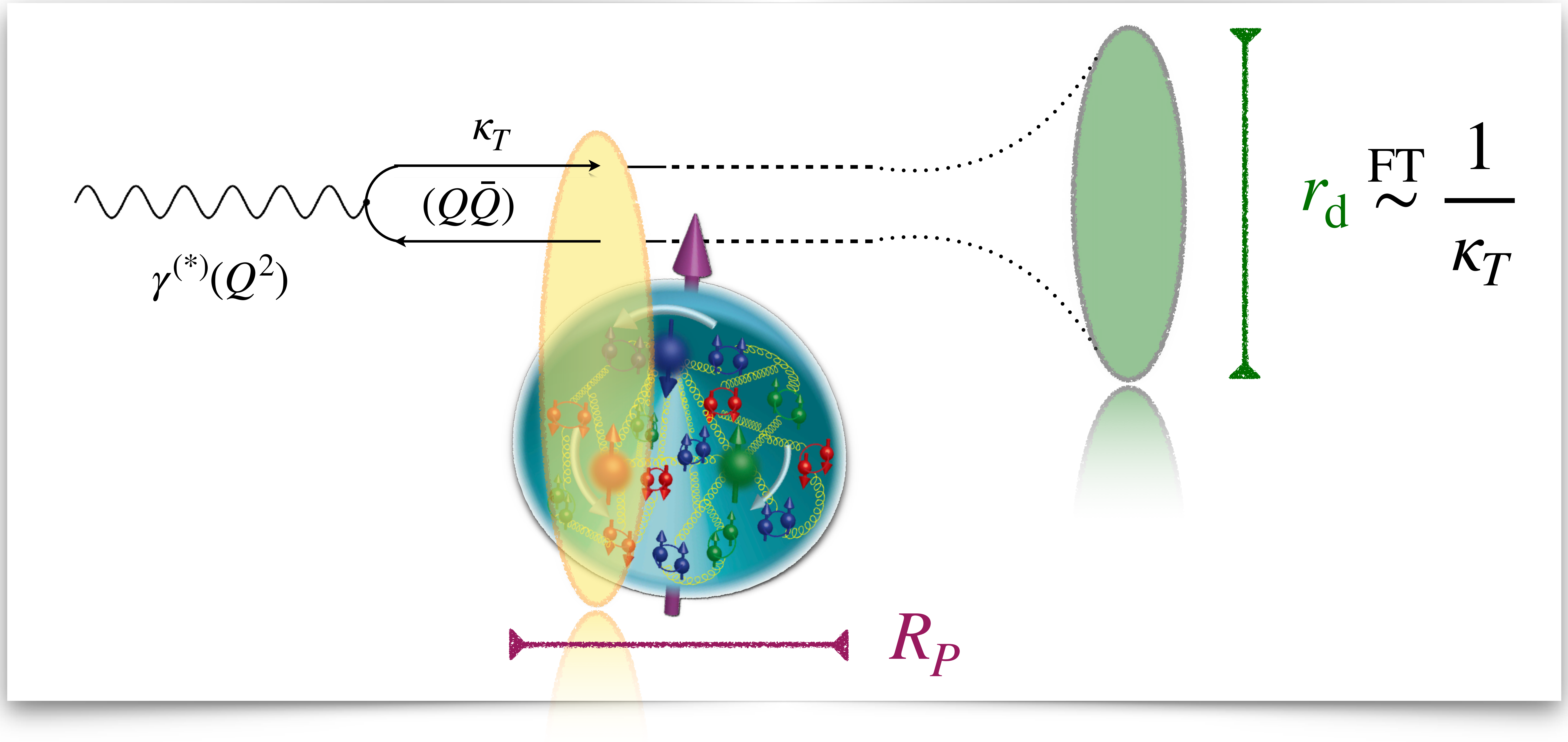
$$\sigma_{\rm tot}(\gamma^* p \to X) \;\propto\; \mathcal{I}m_s\{\mathcal{A}(\gamma^* p \to \gamma^* p)\} \;\equiv\; \Phi_{\gamma^* \to \gamma^*} \circledast \mathcal{F}(x, \kappa^2)$$

◇ $\mathcal{F}(x, \kappa^2)$ 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!

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

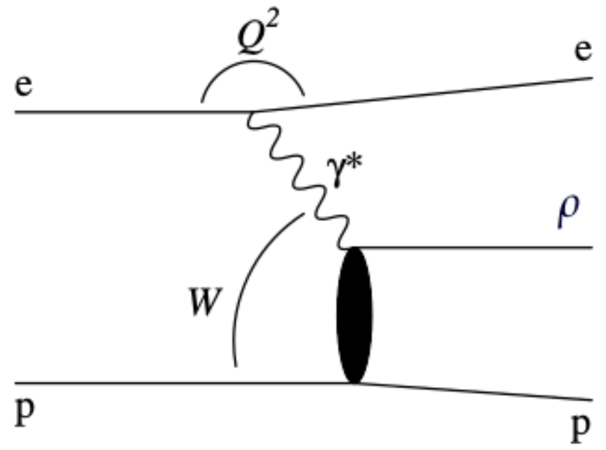


$$W_{\mu\nu} \propto \mathrm{Im}\left\{ i \int \mathrm{d}^4x\, e^{i\,q\cdot x} \langle P|\,\mathrm{T}\,[J_\mu(x)\, J_\nu(0)]\,|P\rangle \right\}$$

- ✱ Small-x ⇒ ***Ioffe time*** ≫ R_P
- ✱ At least one J_μ <u>outside</u> proton…
- ✱ **…color dipole picture!**

Exclusive emissions of forward mesons

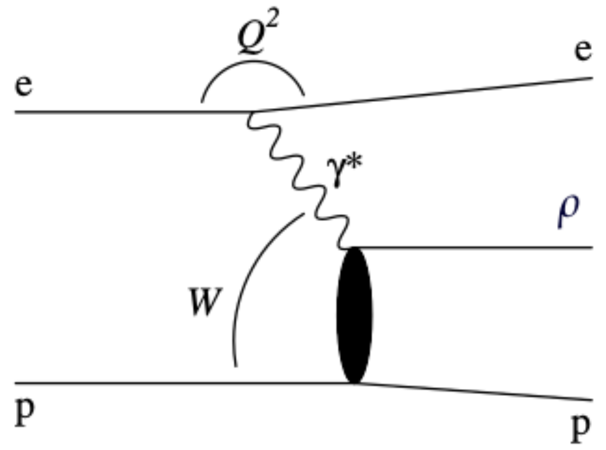
Exclusive forward ρ-meson leptoproduction



- High-energy regime:
  $s \equiv W^2 \gg Q^2 \gg \Lambda^2_{\rm QCD} \implies$ 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

Exclusive forward ρ-meson leptoproduction



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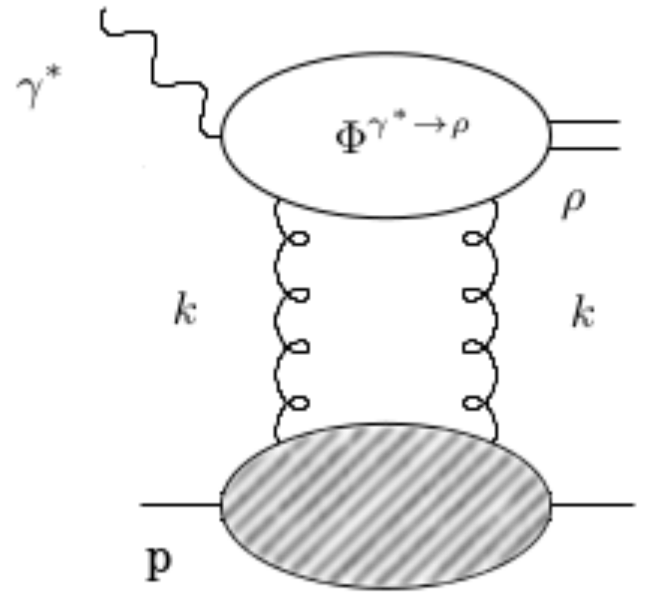
Leading **helicity amplitudes** are known

Assumption:

- $\mathcal{I}m_s\{\mathcal{A}(\gamma^* p \to \rho\, p)\}$
- same W- and t-dependence for T_{11} and T_{00} $\implies$ high-energy factorization
  - $\to$ same physical mechanism, scattering of small transverse size of dipole on the proton target, at work $\Rightarrow$ high-energy factorization

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

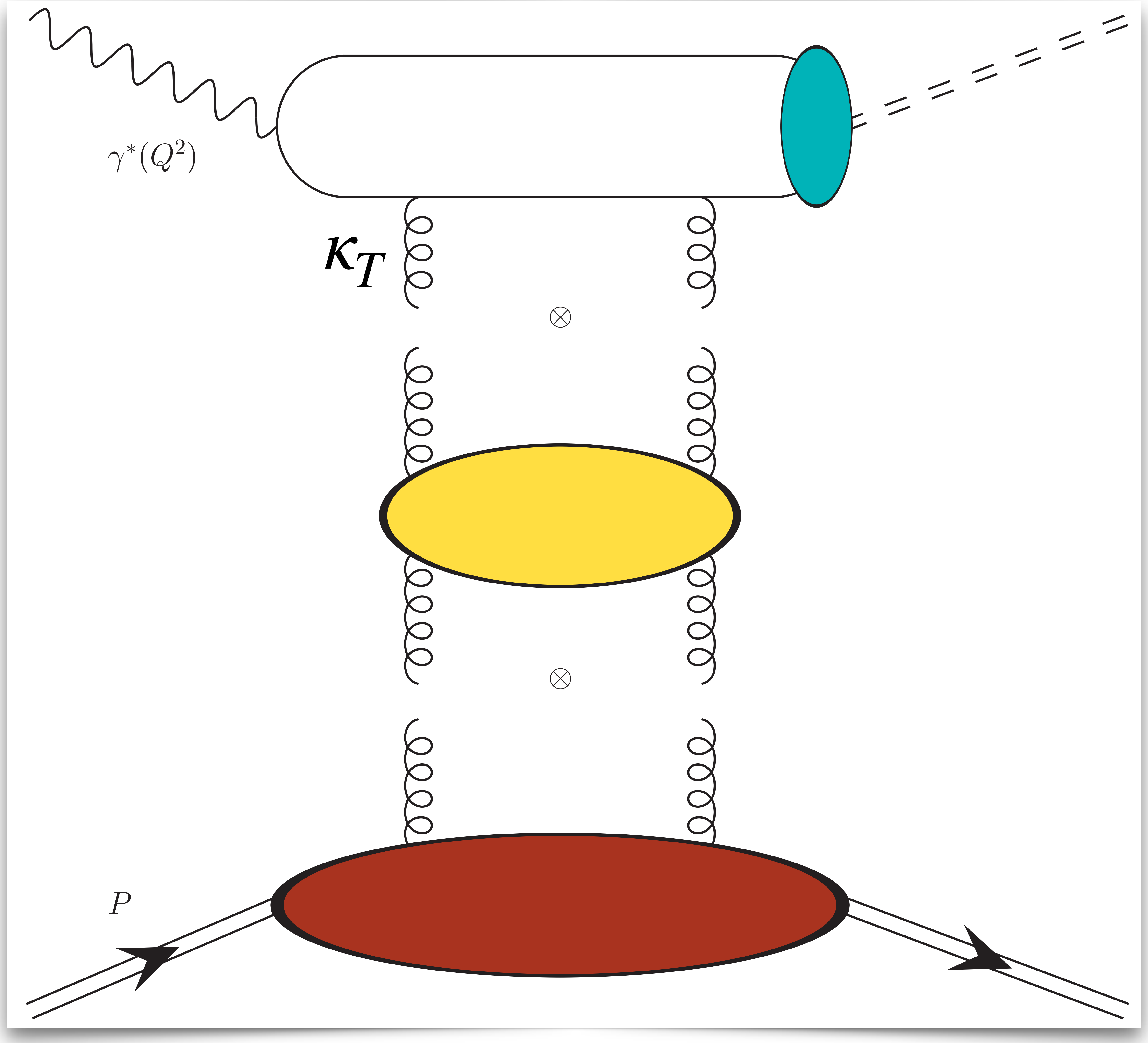


Interesting transitions:

- $\gamma^*_L \to \rho_L \xrightarrow{\text{encoded by}} \Phi^{\gamma^*_L\to\rho_L}$
- $\gamma^*_T \to \rho_T \xrightarrow{\text{encoded by}} \Phi^{\gamma^*_T\to\rho_T}$

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

A factorization…of factorizations



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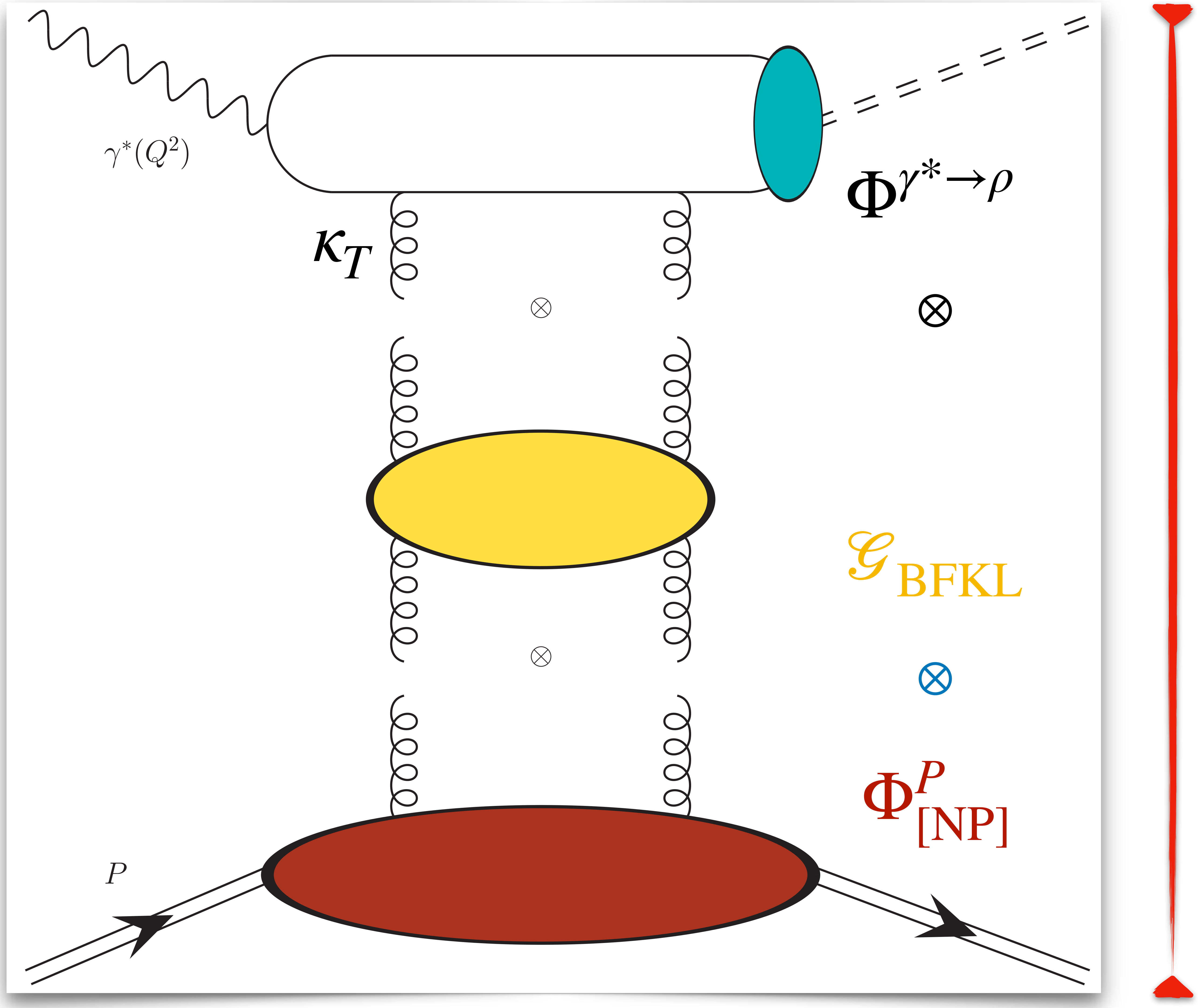

BFKL factorization

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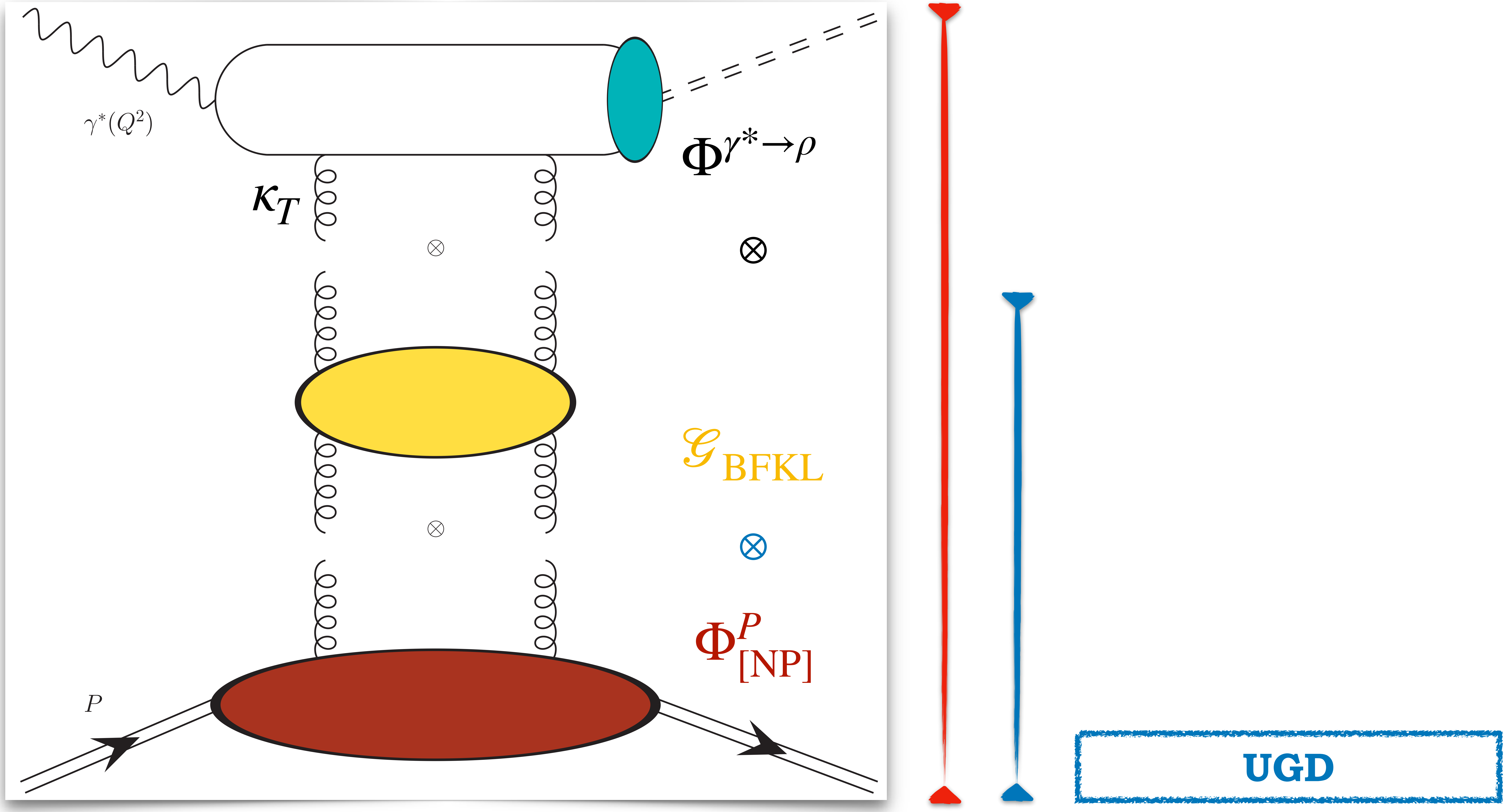

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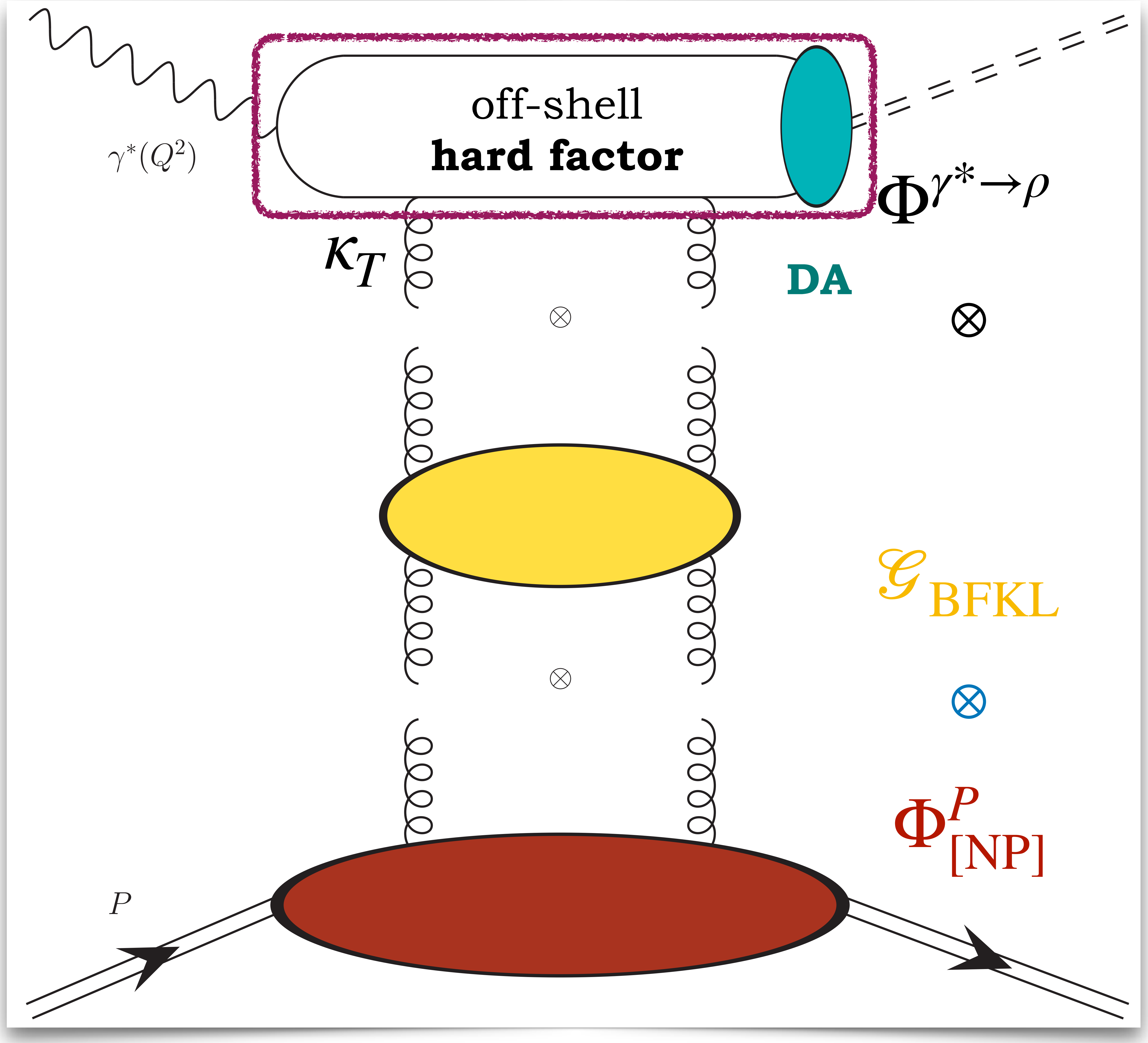

$\gamma \to \rho$ impact factor

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

Collinear convolution $\Leftrightarrow$ large κ_T (!)

UGD

BFKL factorization

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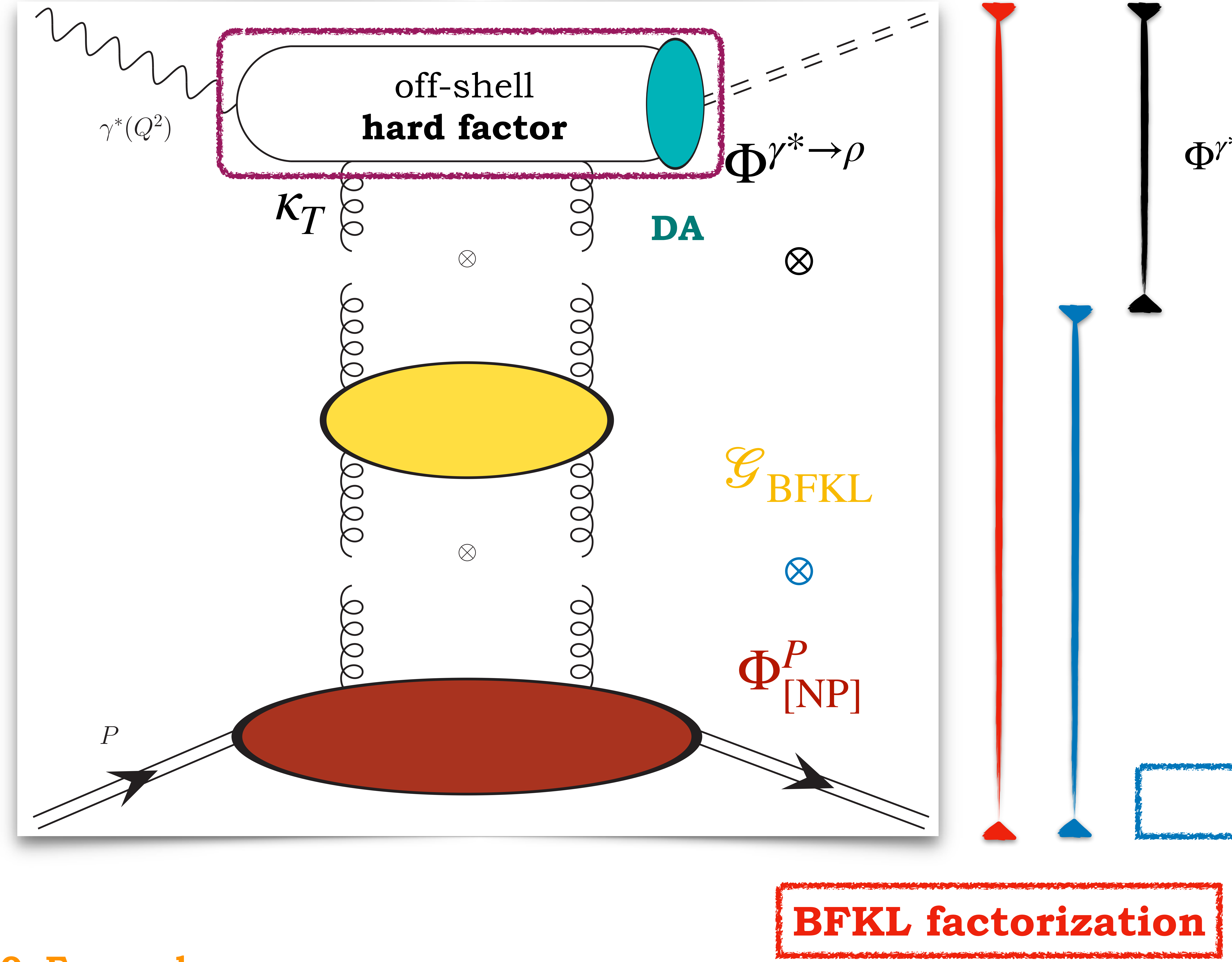

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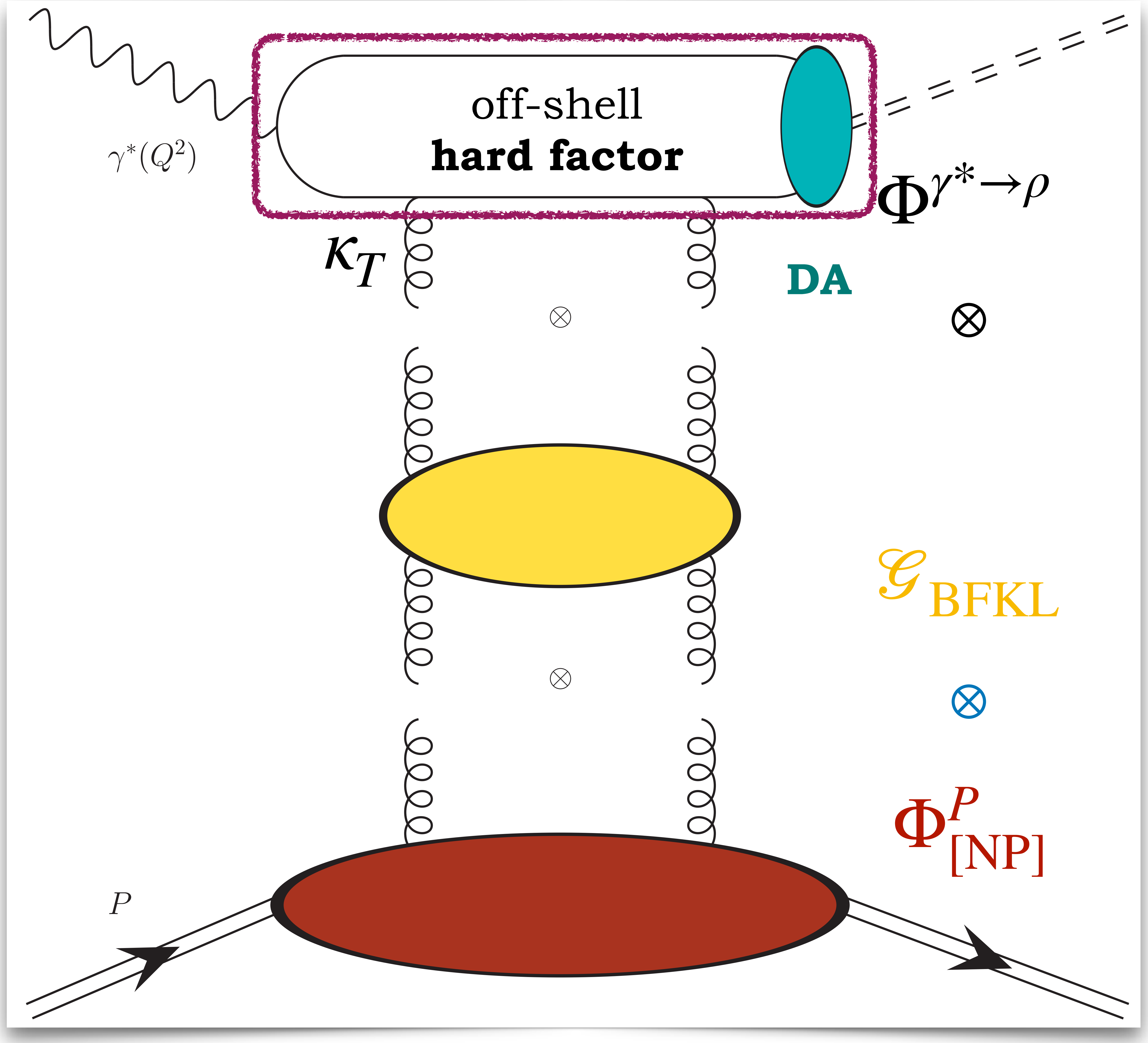
Collinear convolution ⇔ large κ_T (!)

* $\gamma_L^* \to \rho_L$ transition:

$$\frac{1}{\kappa_T^2} \Phi^{\gamma_L^*\to\rho_L} \underset{\kappa_T \to 0^+}{\sim} \text{constant}$$

A factorization...of factorizations



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DA

$\otimes$

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- $\gamma_T^* \to \rho_T$ transition:

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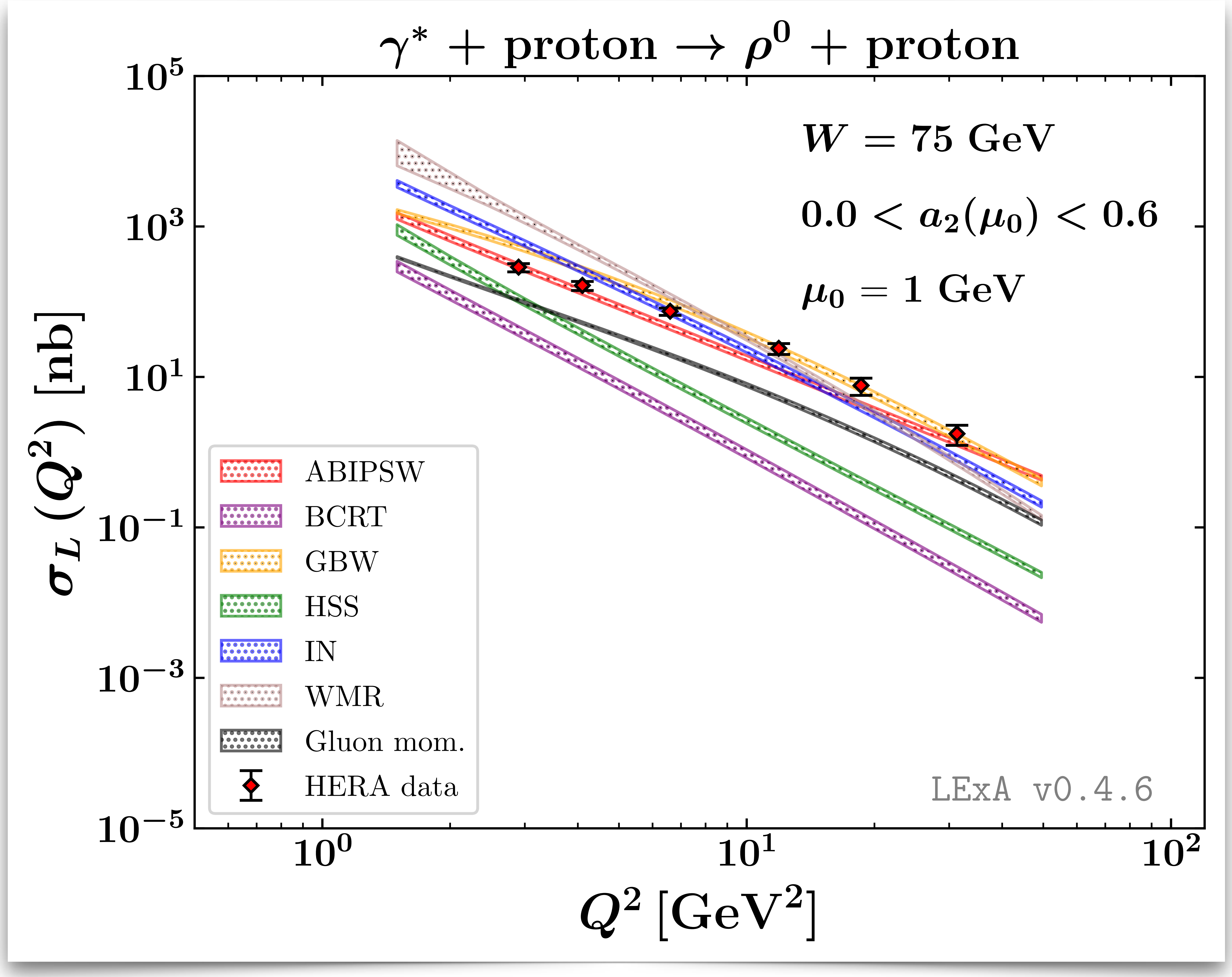
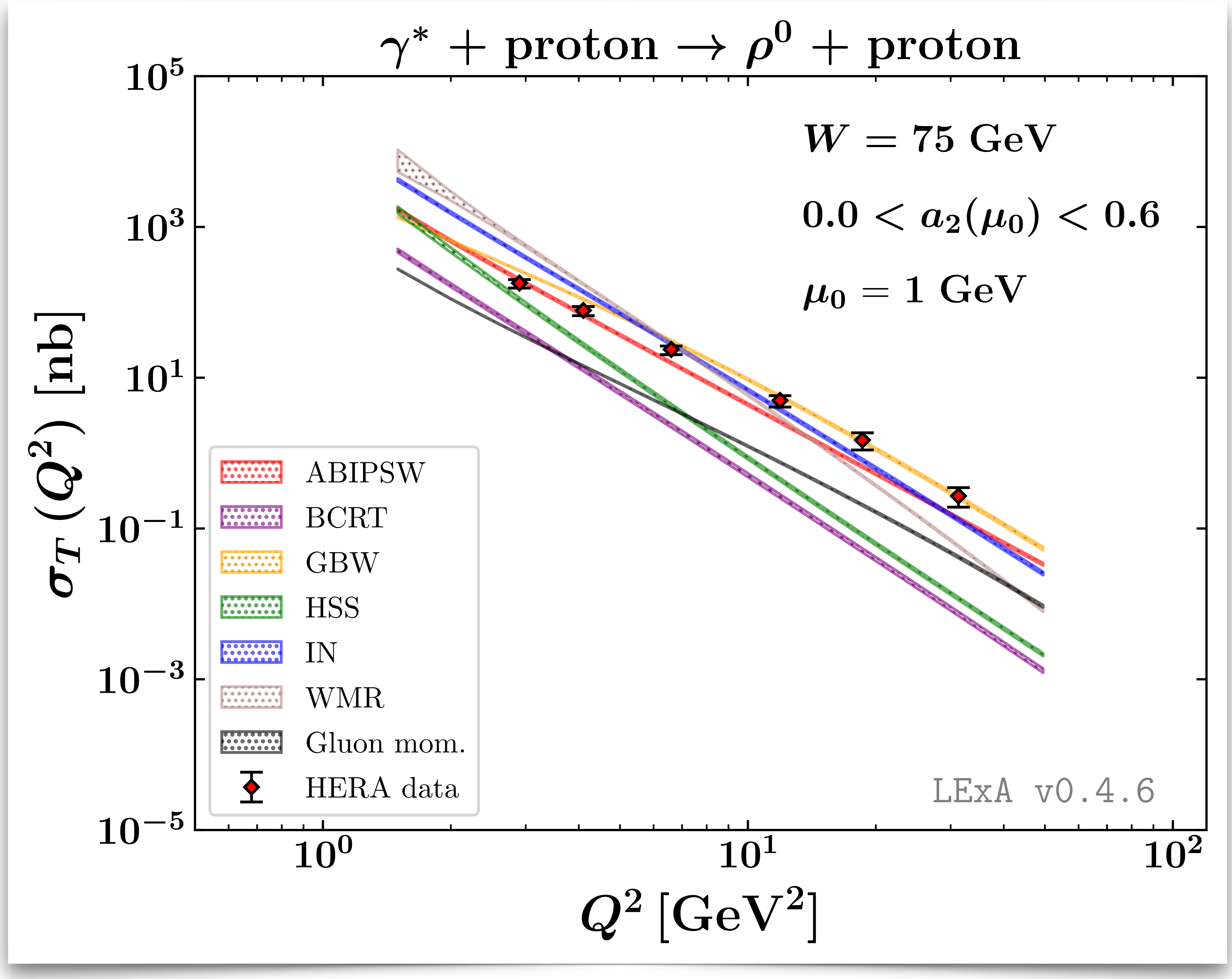
UGD

BFKL factorization

Exclusive forward ρ-meson production at HERA





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

(extension to ϕ-meson emissions) [A.D. Bolognino, A. Szczurek, W. Schäfer (2020)]

[A.D. Bolognino, PhD Thesis (2021)]

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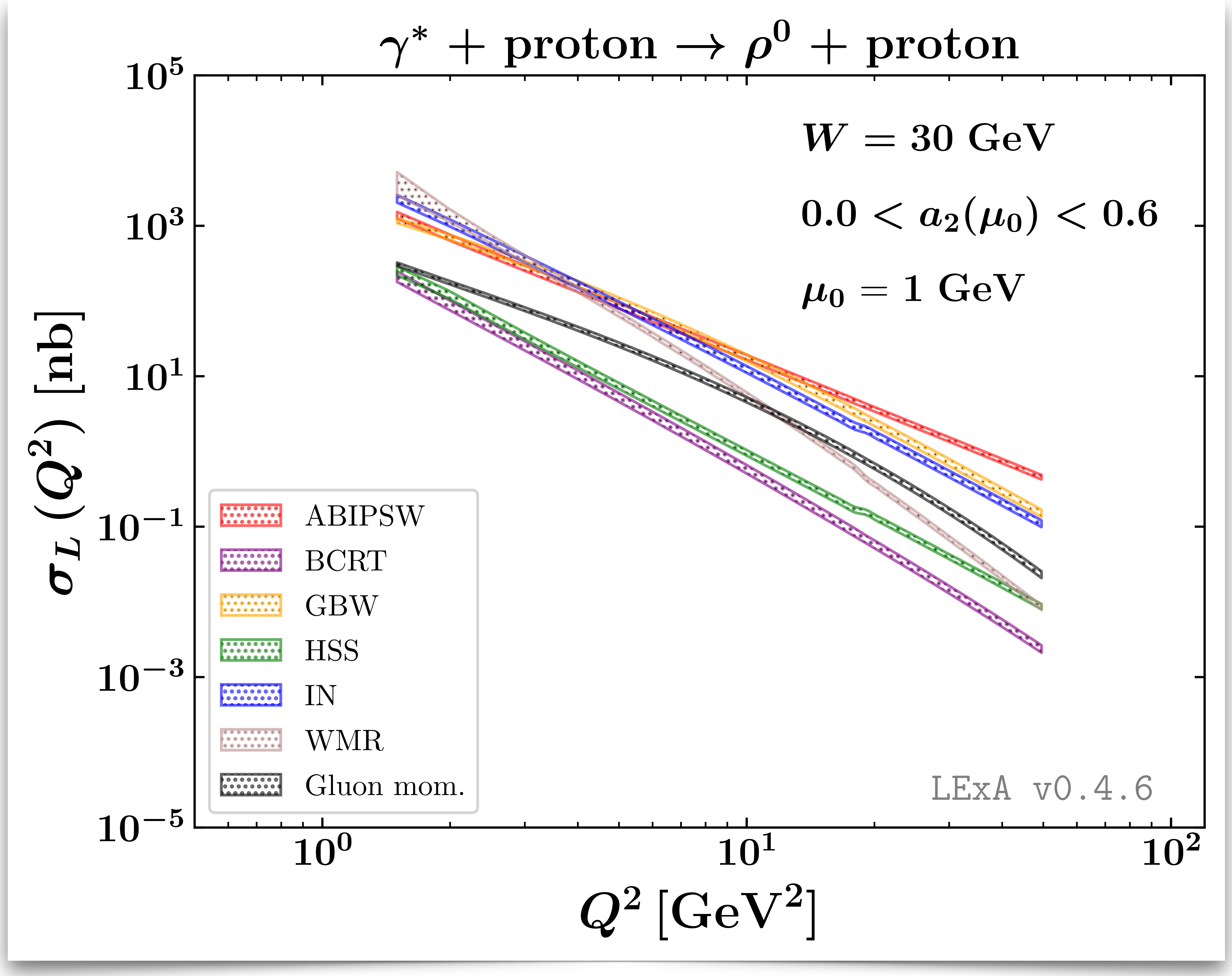
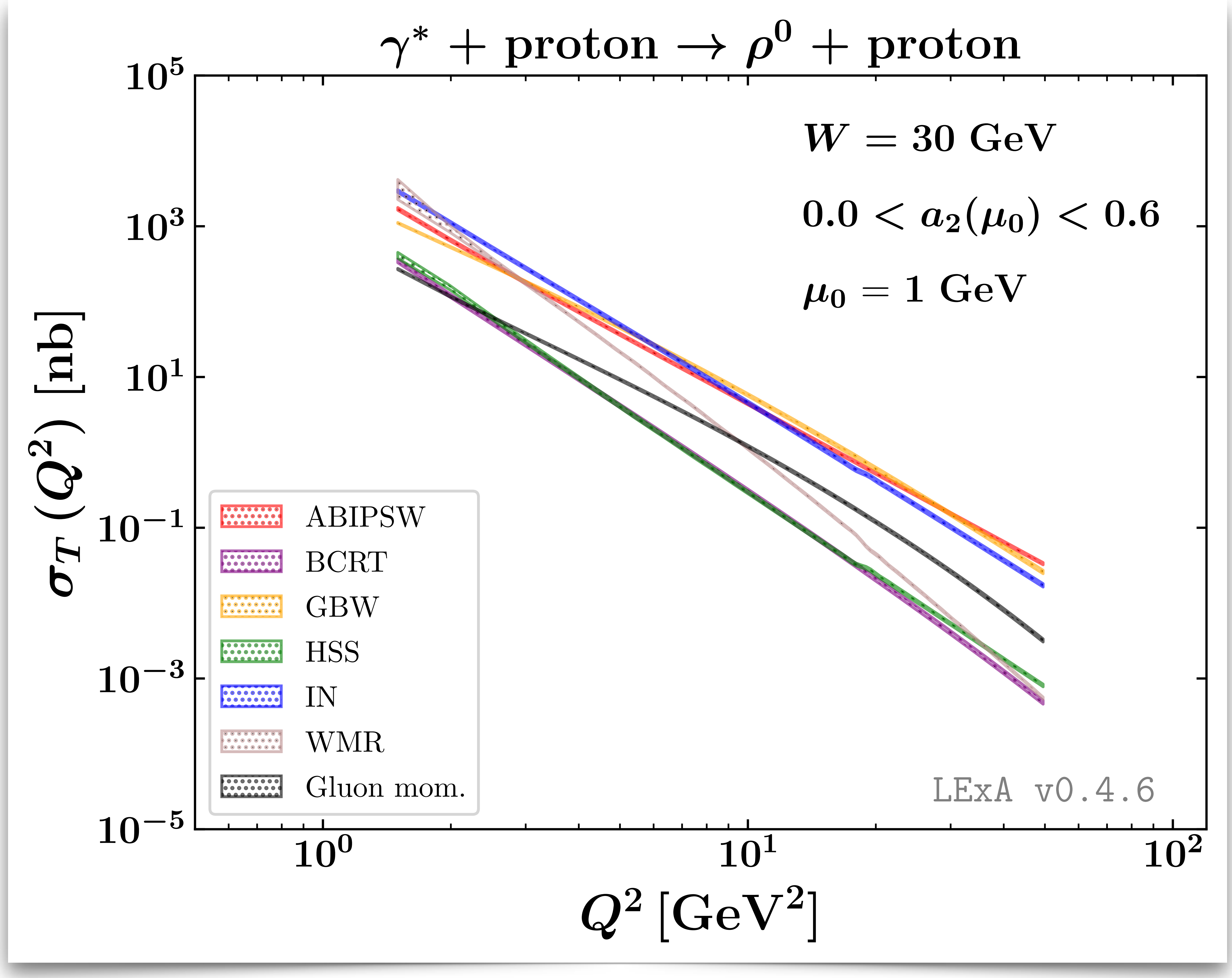
Exclusive forward ρ-meson production at the EIC





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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**

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

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Quarkonia

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

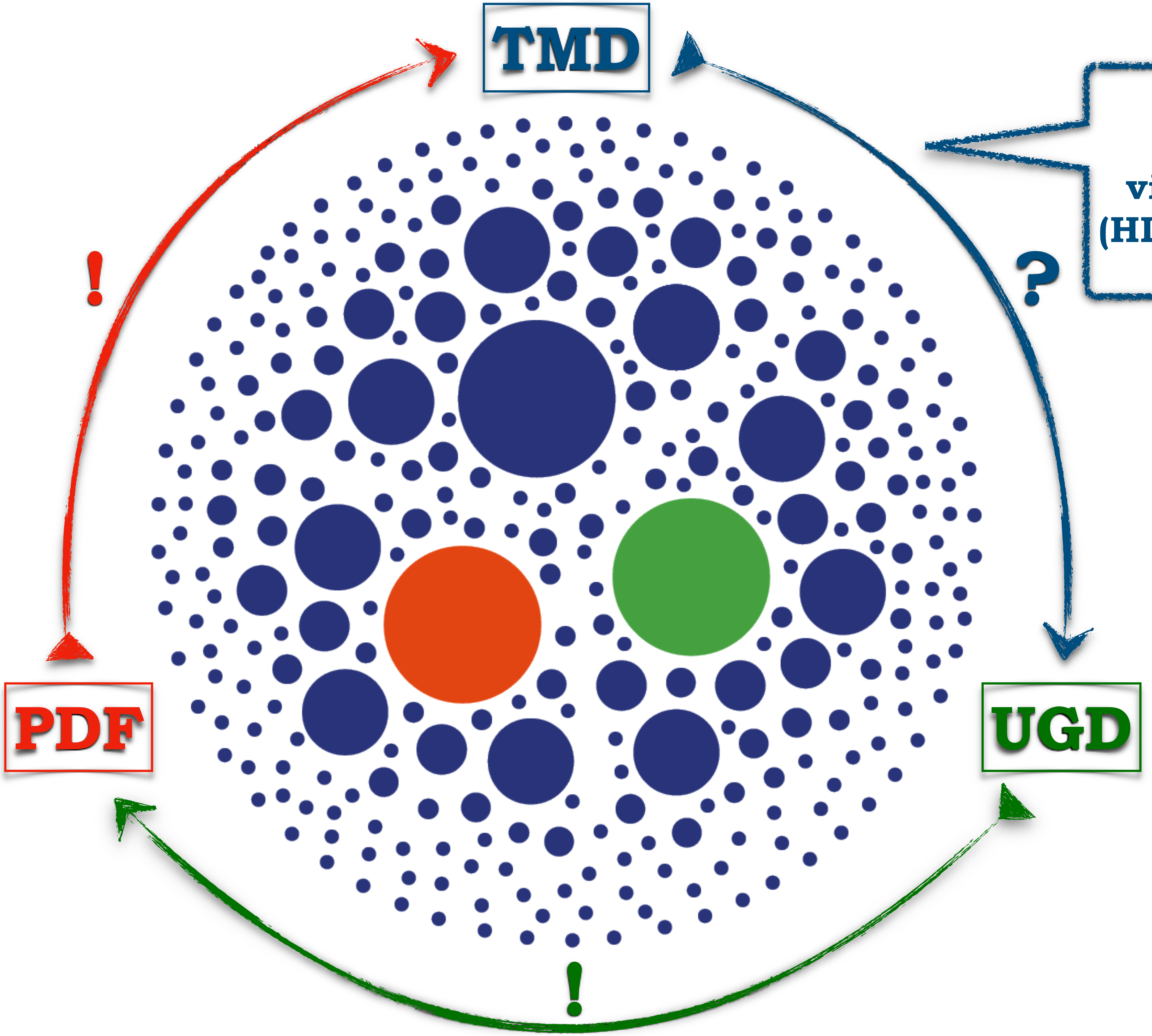
$$\left[\, \mathrm{LFWF} \otimes \mathscr{A}_{\mathrm{dip.}} \right] \overset{\text{dilute}}{\longleftrightarrow} \left[\, \Phi^{\gamma^* \to J/\Psi} \otimes \mathrm{UGD} \right]$$

* 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

Mapping the proton content at small-x



...extensive κ_T *scan*
via forward emissions:
(HL-)LHC, EIC, NICA, FPF

Backup slides

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
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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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Small-x improved gluon TMDs

Nonperturbative content via an enhanced spectator model

- **Pavia model**: initial-scale f_1^g and g_{1L}^g matched to PDFs

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

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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

Small-*x* improved gluon TMDs

Nonperturbative content via an enhanced spectator model

- **Pavia model**: initial-scale f_1^g and g_{1L}^g matched to PDFs

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

Backup

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

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

Small-x improved collinear PDFs

DGLAP description improved via BFKL

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

[R.D. Ball, V. Bertone, M. Bonvini, S. Marzani, J. Rojo, L. Rottoli (2018)]

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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Inclusive forward Drell-Yan dilepton production

- LHC, **forward region** $\rightarrow$ $(\mathrm{l}^+ \mathrm{l}^-)$ produced in the fragmentation region of h_2
  - ◇ Asymmetric configuration: $x_1 \gg x_2$, down to $x_2 \simeq 10^{-6}$

$\Longrightarrow$ **possible small-x resummation effects expected!**

- **small-x** $\rightarrow$ 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** $\rightarrow$ gluon exchange in the t-channel
  - ◇ collinear gluon PDF replaced by κ_T-UGD: $x\,g(x,\mu)$ $\rightarrow$ $\mathcal{F}(x,\kappa_T^2)$

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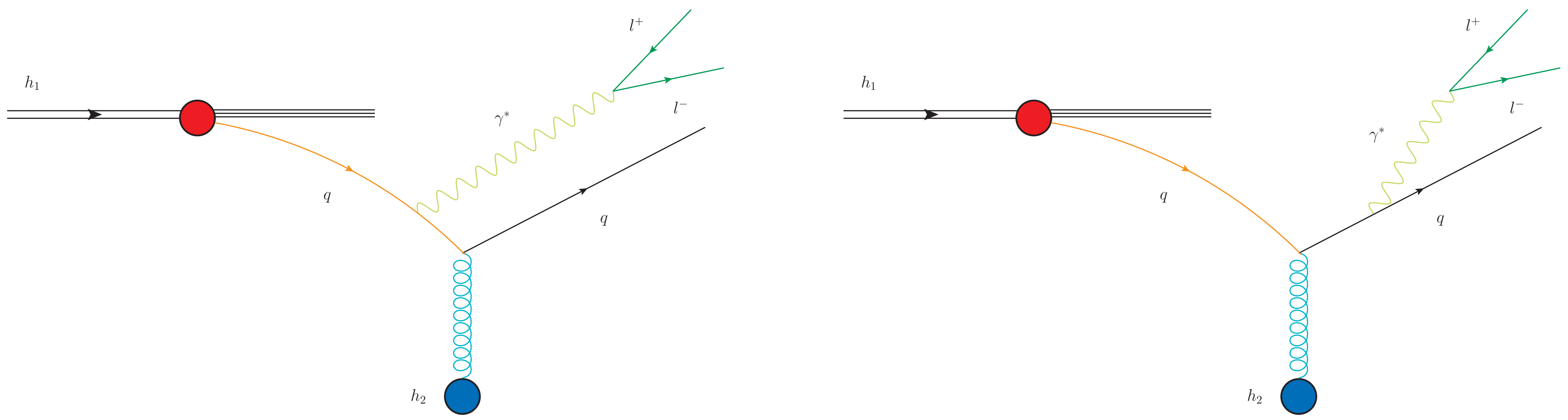

- Helicity structure functions in high-energy factorization:

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

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[D. Brzeminski, L. Motyka, M. Sadzikowski, T. Stebel (2017)]

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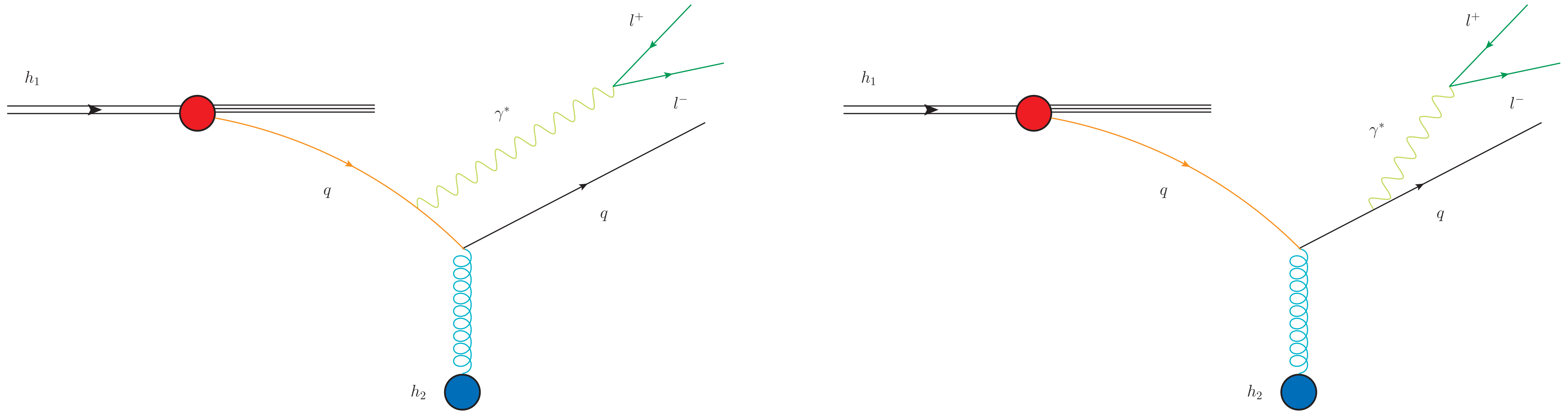

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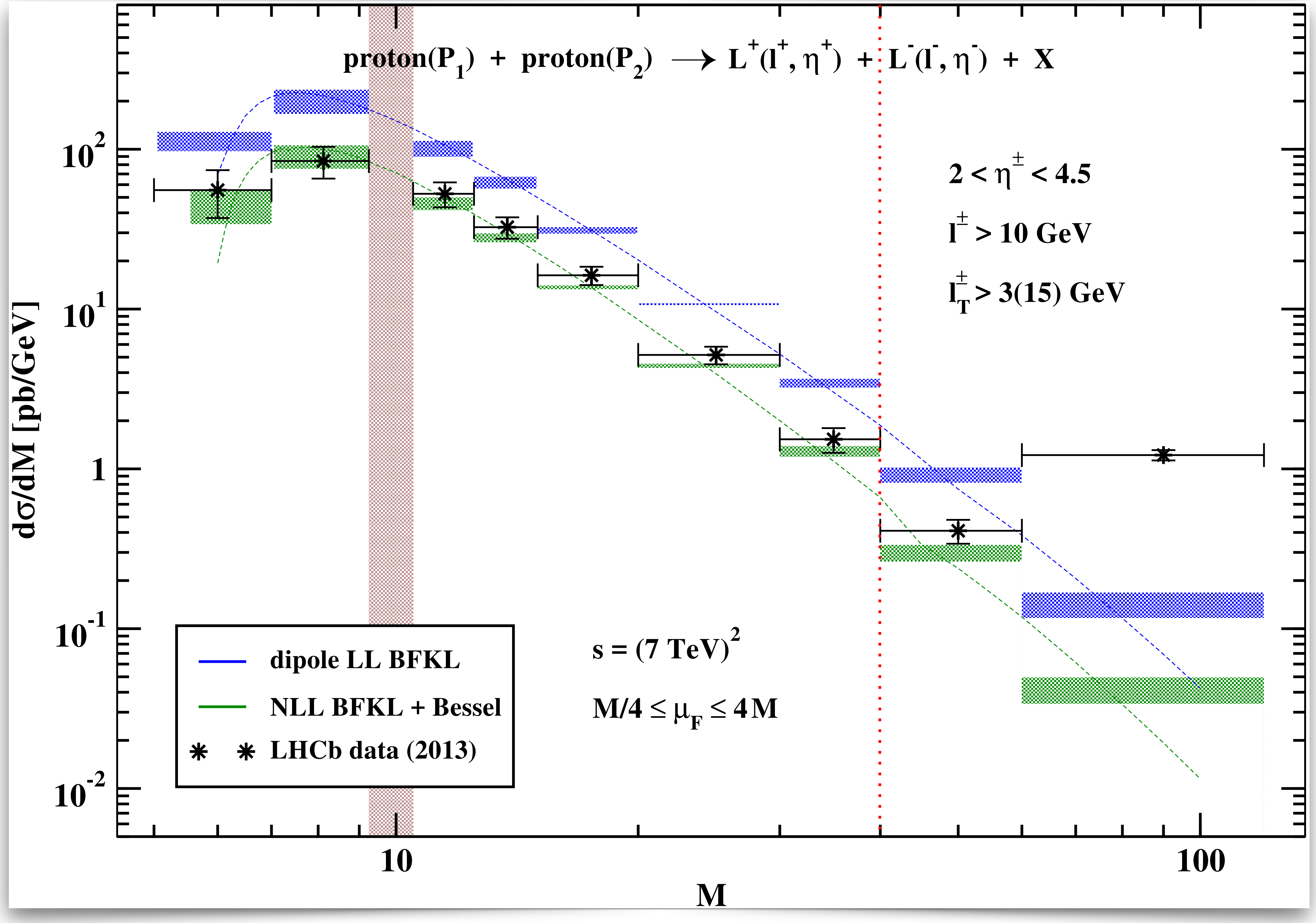

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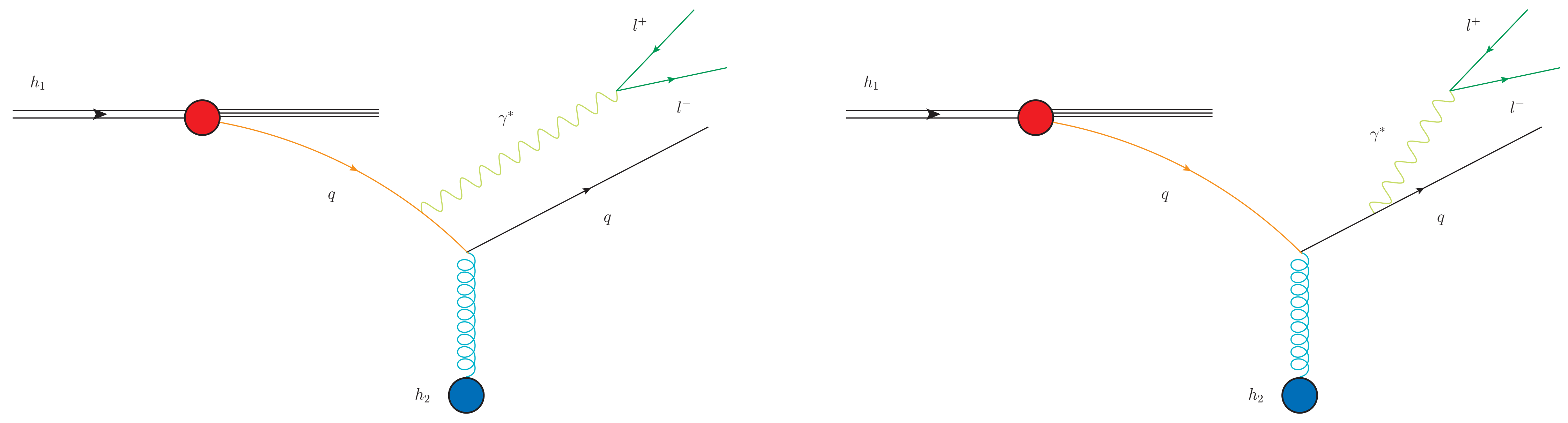

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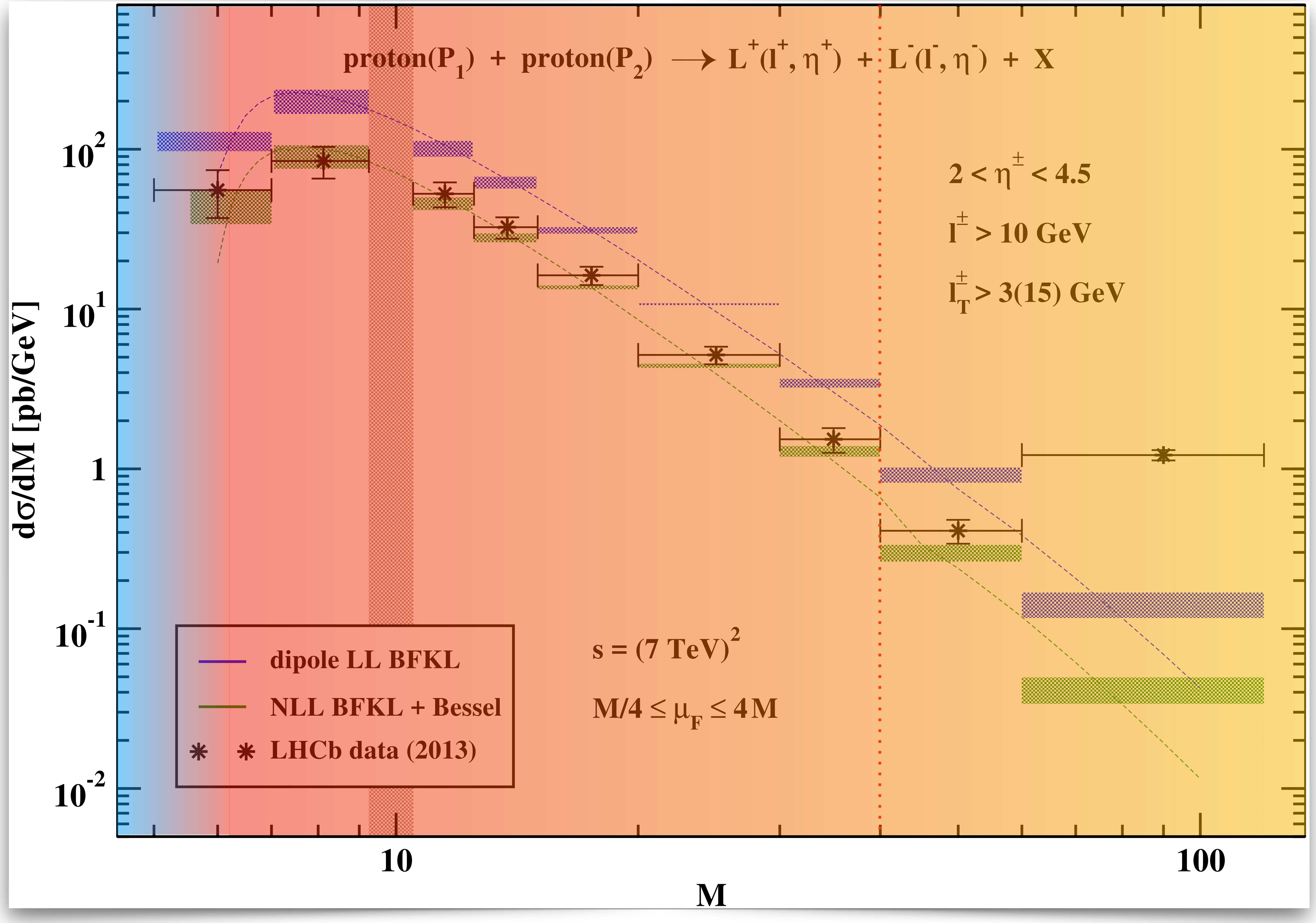
approaching limits of semi-hard regime



Z^0 contribution becoming relevant

Backup

Diffractive slope

Empirical parametrization → introduces *smaller* uncertainties than UGD ones

🔗 [J. Nemchik, N.N. Nikolaev, E. Predazzi, B.G. Zakharov, V. R. Zoller (1998)]

$$b(Q^2) = \beta_0 - \beta_1 \log\left[\frac{Q^2 + m_\rho^2}{m_{J/\psi}^2}\right] + \frac{\beta_2}{Q^2 + m_\rho^2}$$

$$\sigma_L\,(\gamma^* p \to \rho\, p) = \frac{1}{16\pi b(Q^2)}\left|\frac{T_{00}(s, t=0)}{W^2}\right|^2$$

$$\sigma_T\,(\gamma^* p \to \rho\, p) = \frac{1}{16\pi b(Q^2)}\left|\frac{T_{11}(s, t=0)}{W^2}\right|^2$$

$\beta_0 = 6.5\ \mathrm{GeV}^{-2}$, $\beta_1 = 1.2\ \mathrm{GeV}^{-2}$ and $\beta_2 = 1.6$