DIS 2021

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Exclusive emissions of ρ-mesons and the unintegrated gluon distribution

Francesco Giovanni Celiberto

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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

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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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

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Need for sub-eikonal corrections, neglected by BFKL

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

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- **WW** vs **DP** gluon TMDs, **GTMDs**
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All-Twist High-Energy Factorization

AT_HEF

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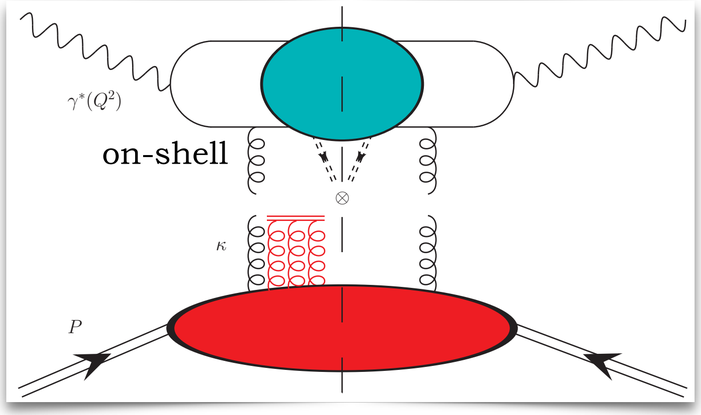
TMD versus AT_HEF

TMD

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



TMD
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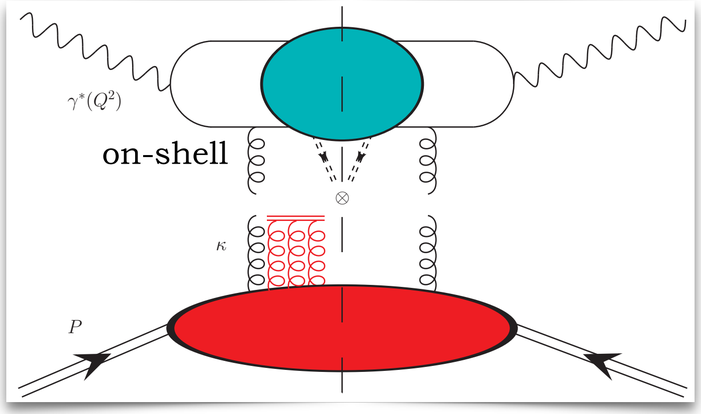

TMD PDF

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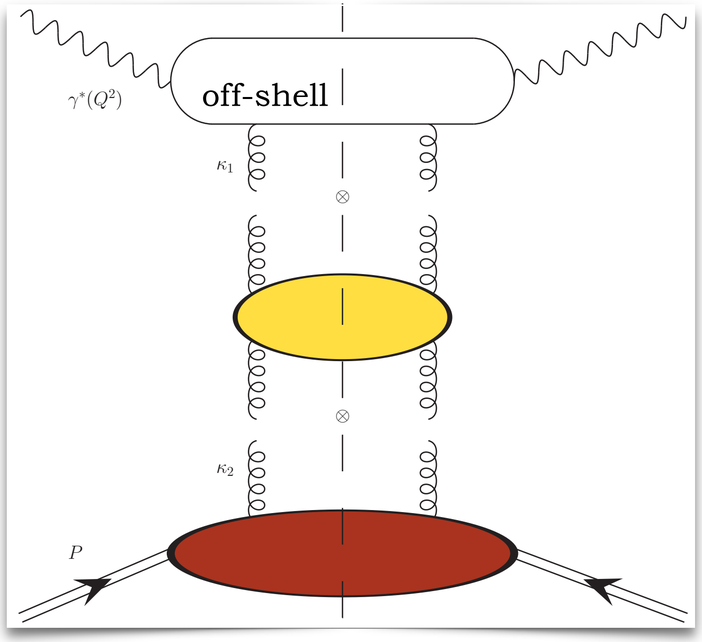

$$\Phi^{\gamma^*\to\gamma^*} \otimes \mathcal{G}_{\text{BFKL}} \otimes \Phi^P_{[\text{NP}]}$$

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

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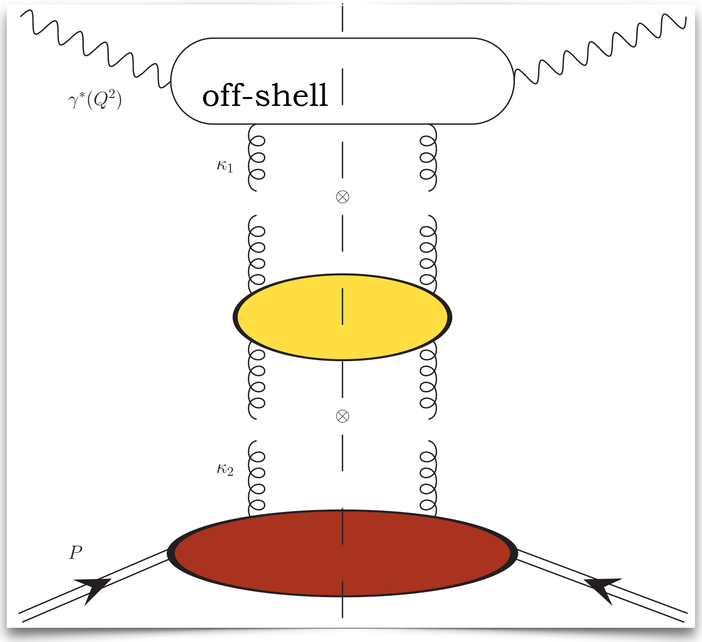

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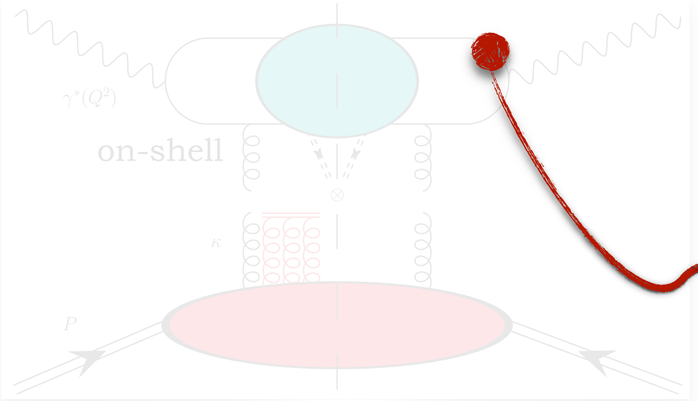
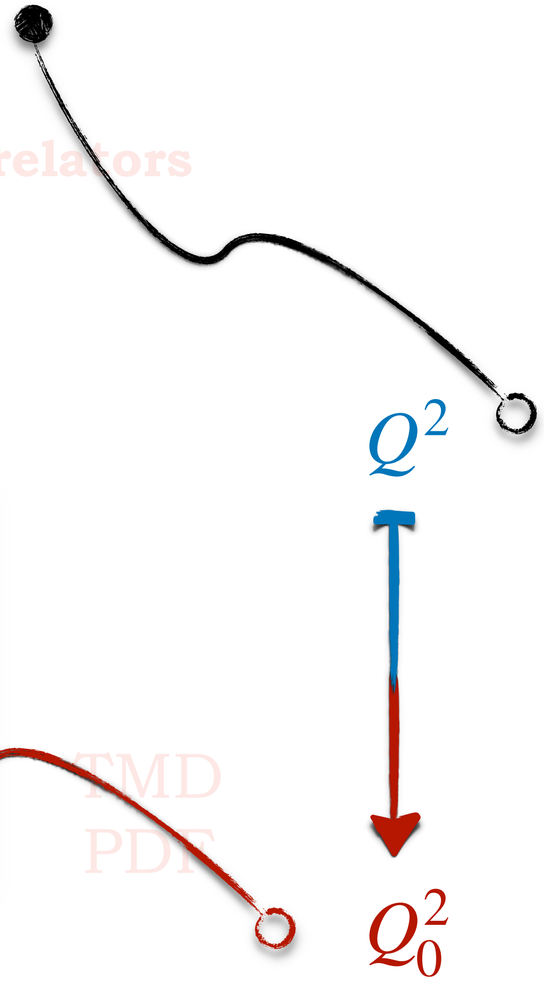
IR diffusion pattern
(Bartels' cigar)
[J. Bartels, H. Lotter (1993)]





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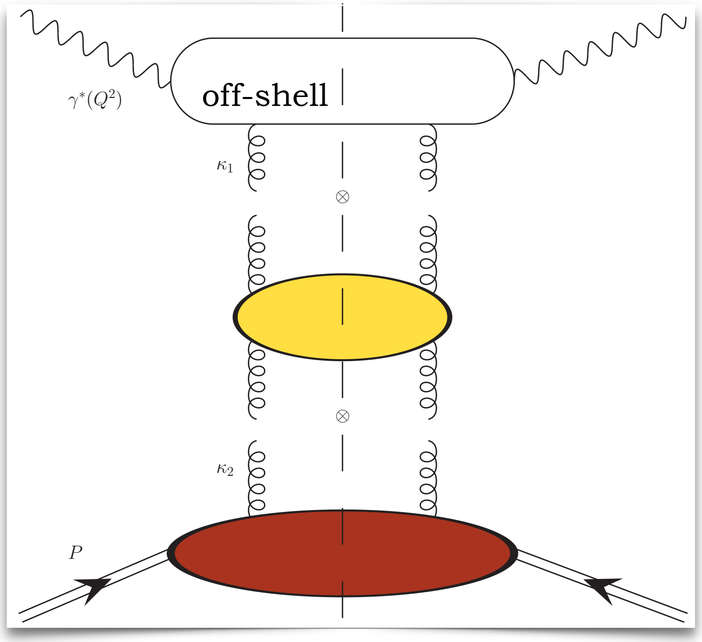

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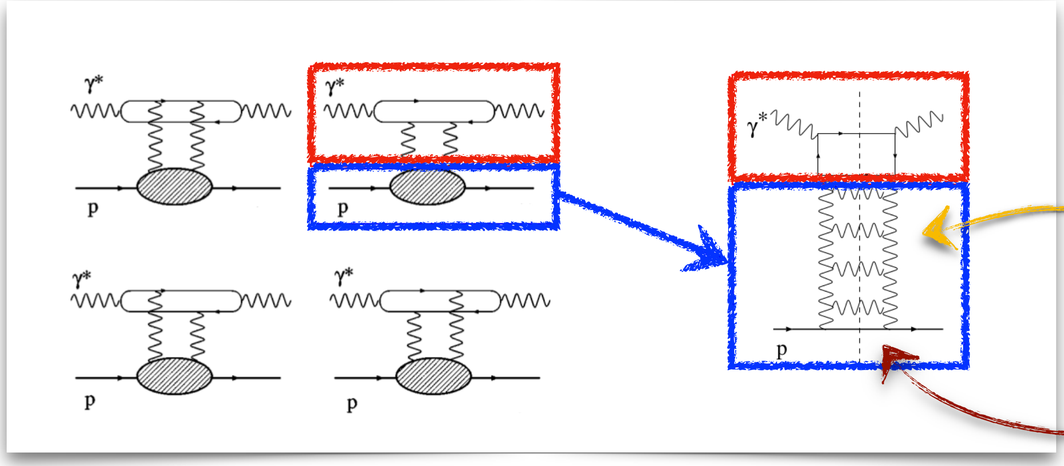
High-energy factorization and the UGD

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

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

◇ $\mathcal{F}(x, \kappa^2)$ is the **unintegrated gluon distribution** (**UGD**) in the proton



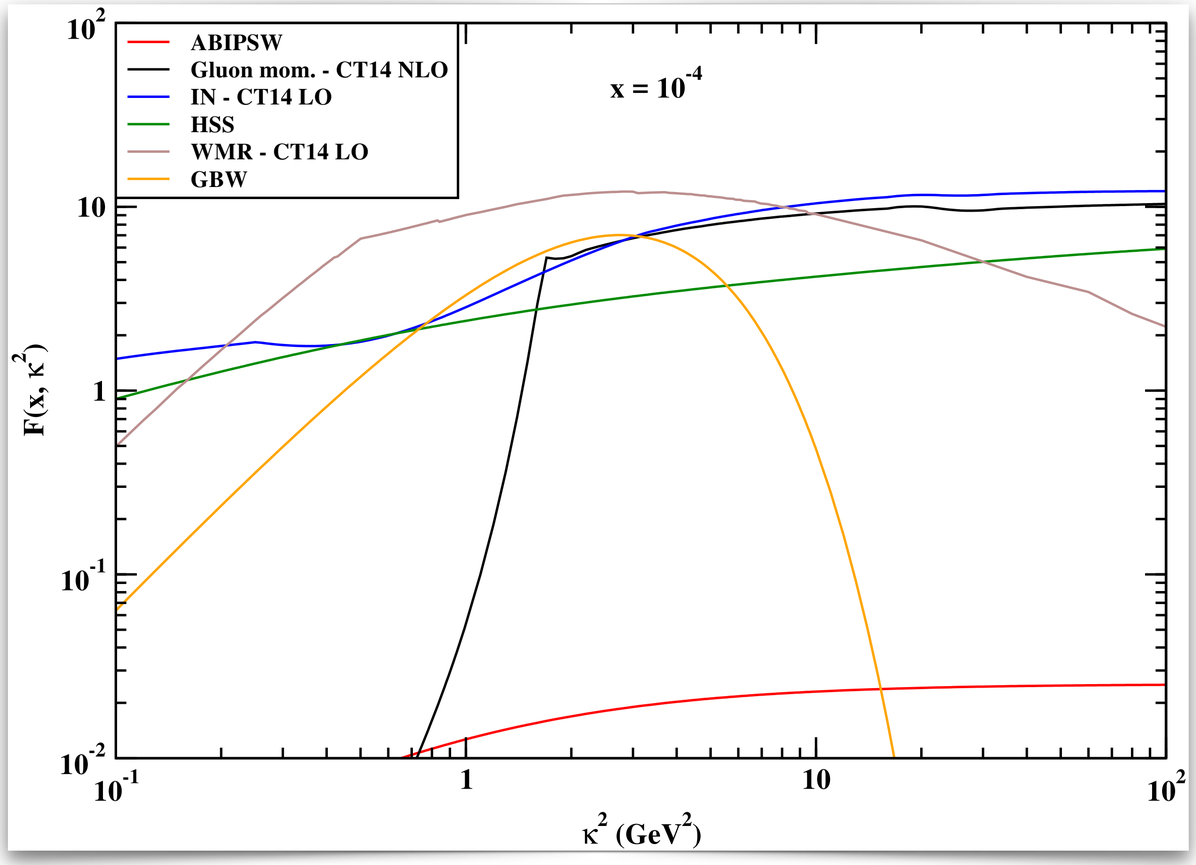
▶ Small-x limit: **UGD** = [**BFKL gluon ladder**] $\circledast$ [**proton impact factor**]

◇ Takes into account the resummation of high-energy logs

◇ Describes the coupling of the gluon Green's function to the proton

▶ Proton impact factor is non-perturbative $\Longrightarrow$ UGD needs to be modeled!

UGD models



- **ABIPSW**: x-independent model

  [I. V. Anikin et al., *Phys. Rev. D* **84** (2011)]

- **Gluon mom. derivative**:

$$\mathcal{F}(x, \kappa^2) = \frac{d\, xg(x, \kappa^2)}{d \ln \kappa^2}$$

- **IN**: soft + hard component $\xrightarrow{\text{to probe}}$ different regions of κ

  [I. P. Ivanov and N. N. Nikolaev, *Phys. Rev. D* **65** (2002)

- **HSS**: $\mathcal{G}_{\mathrm{BFKL}} \otimes$ [proton IF]

  [I. Bautista, A. Fernandez Tellez, M. Hentschinski, *Phys. Rev. D* **94** (2016) no.5, 054002]
  [G. Chachamis, M. Deák, M. Hentschinski, G. Rodrigo and A. Sabio Vera, *JHEP* **1509** (2015) 123]

- **WMR**: angular ordering of gluon emissions

  [G. Watt, A.D. Martin, M.G. Ryskin, *Eur. Phys. J. C* **31** (2003) 73]

- **GBW**: FT of dipole cross section

  [K.J. Golec-Biernat, M. Wüsthoff, *Phys. Rev. D* **59** (1998) 014017]

Hybrid or pure factorization?

Forward emissions

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

Central emissions

* *Gluon induced* ↔ small-x gluons

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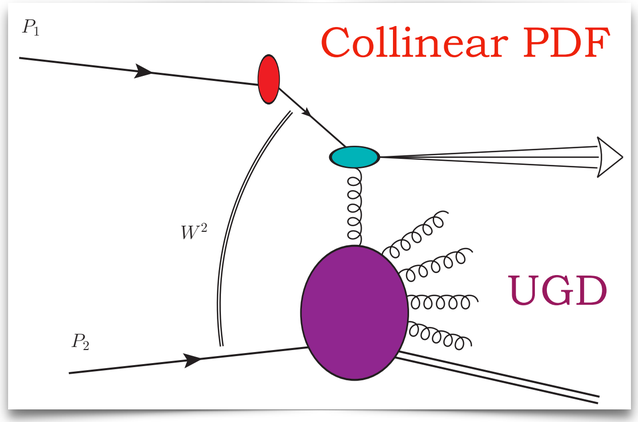

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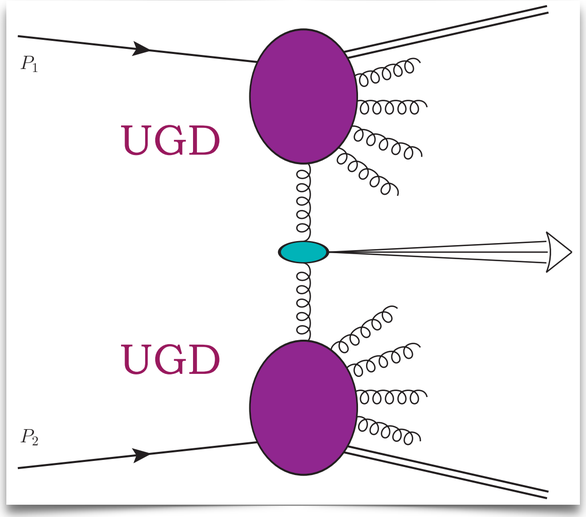

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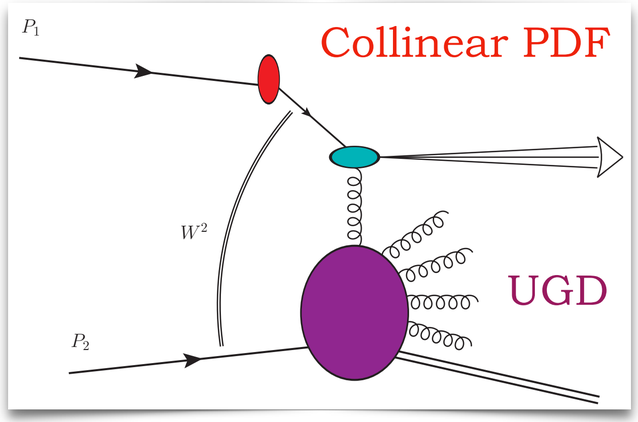

* *Distinctive signals* of small-x dynamics **expected**

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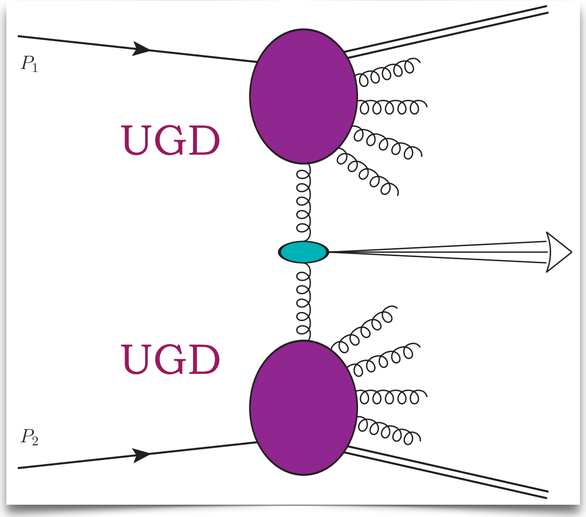

* Small-x dynamics to **enhance** f.o. description

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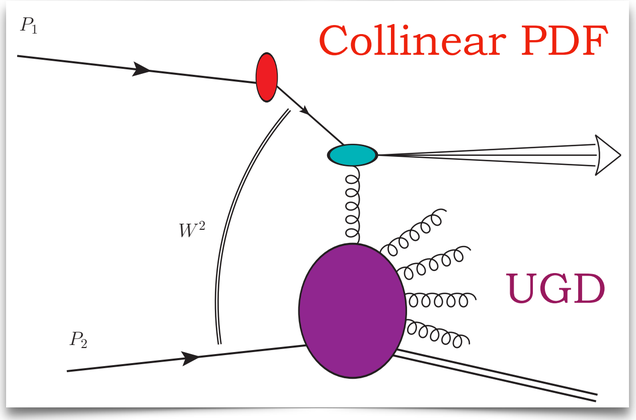

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* Phenomenology:
  forward jet, Drell-Yan, Higgs or vector meson

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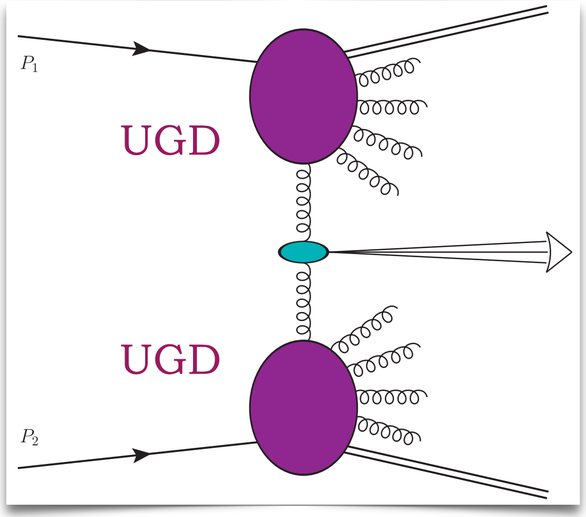

* Small-x dynamics to **enhance** f.o. description
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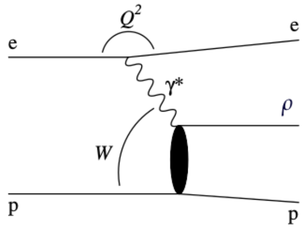
Table complemented by *exclusive* counterparts and *lepto-hadronic* channels

Exclusive forward ρ-meson leptoproduction



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

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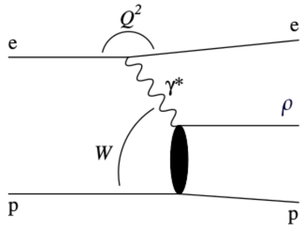

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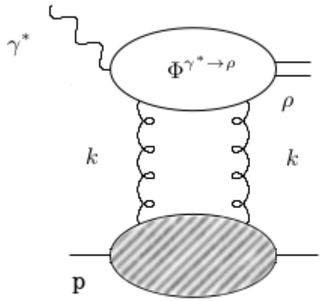
Leading **helicity amplitudes** are known

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

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

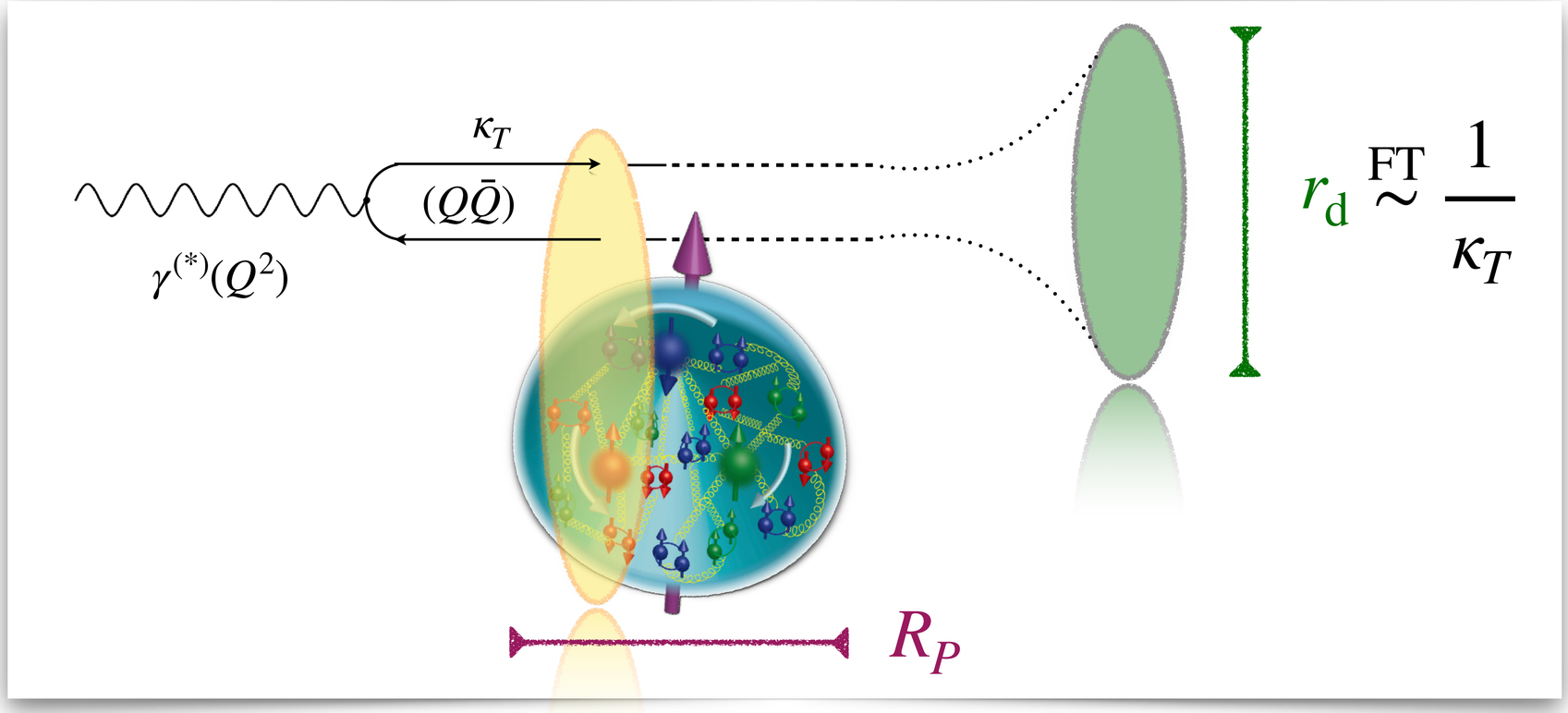


Interesting transitions:

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

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

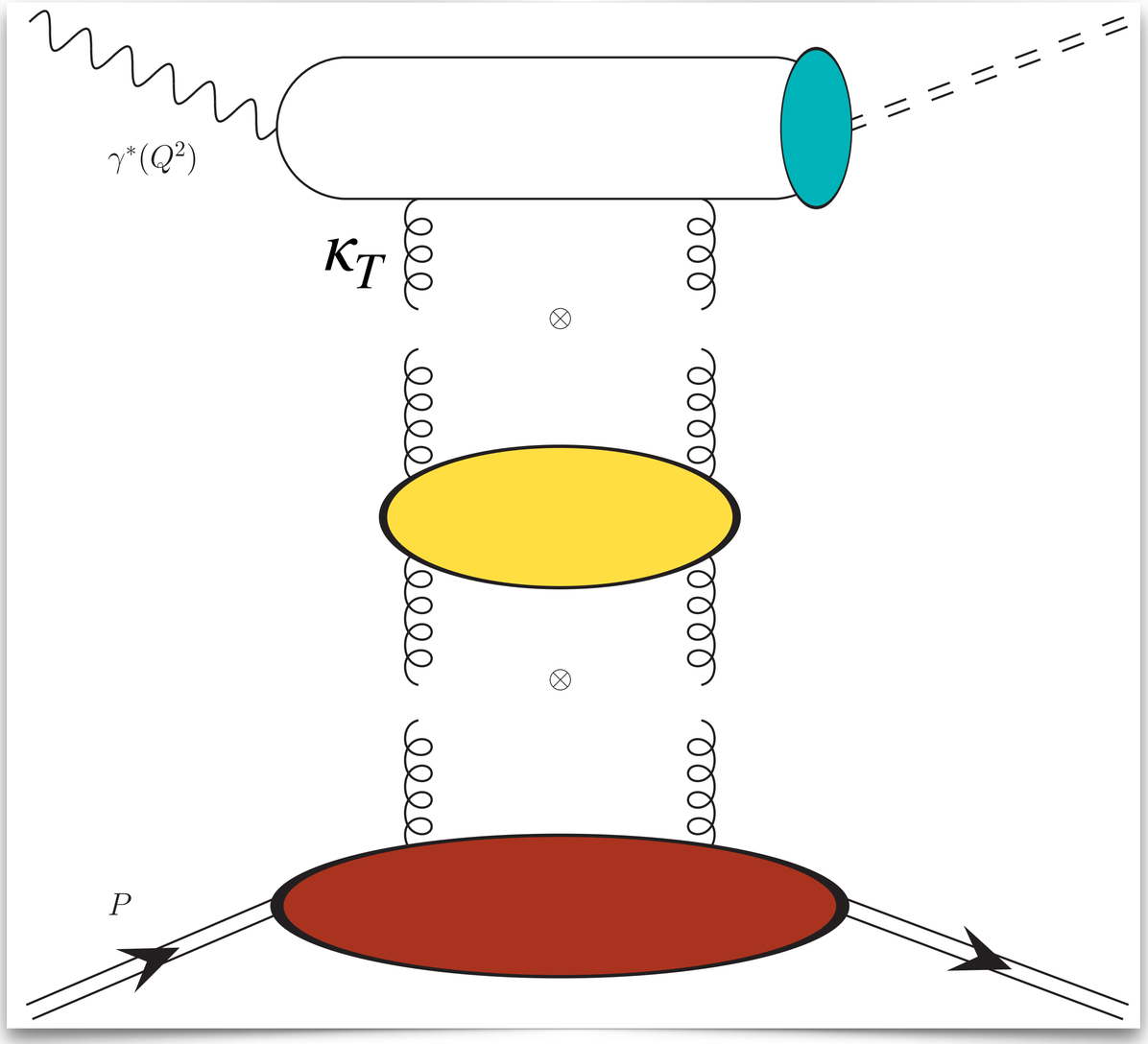
Diffractive $\gamma^{(*)}P$ scattering and color dipoles



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

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

A factorization...of factorizations



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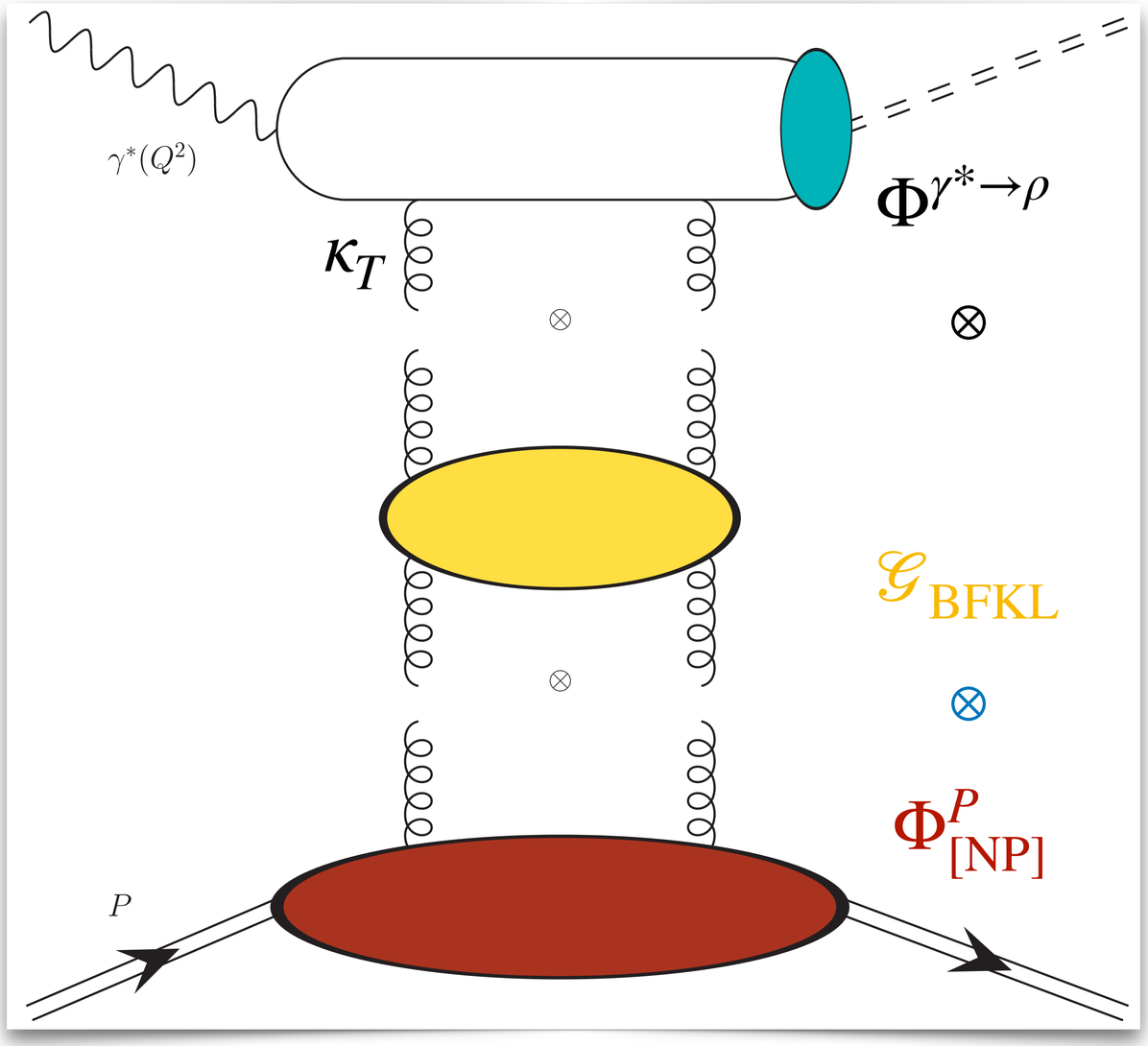

BFKL factorization

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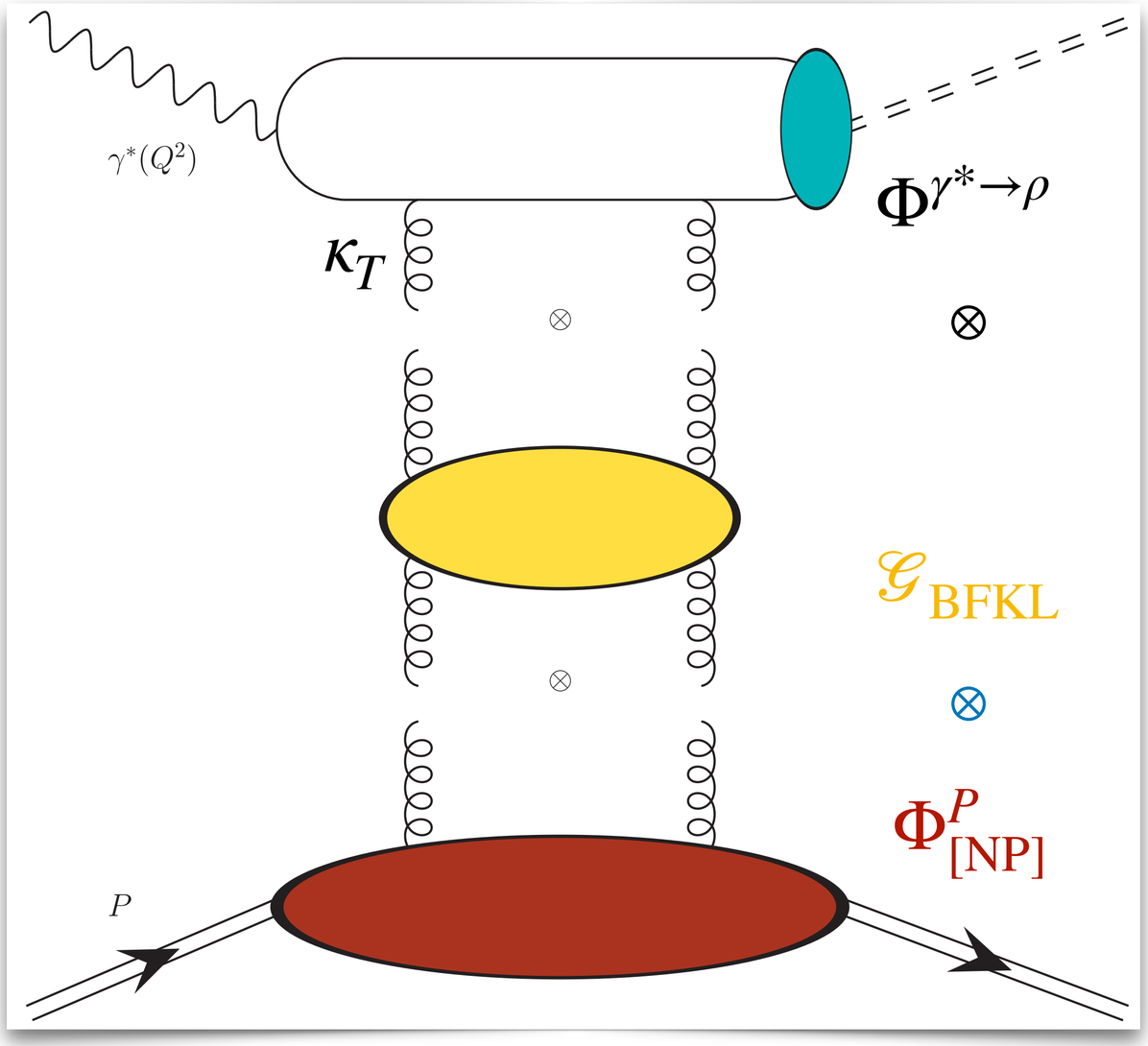

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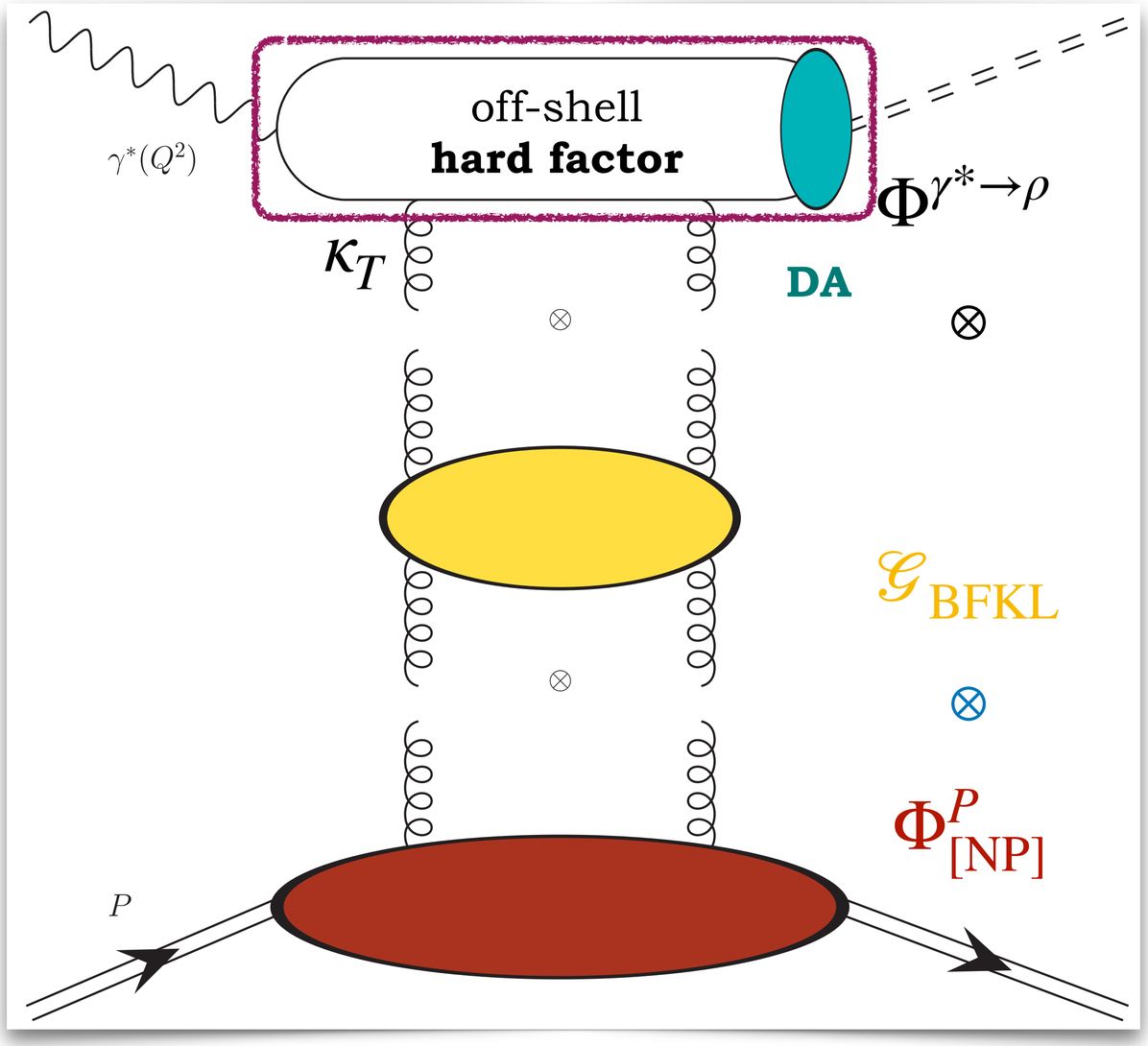

$\gamma \to \rho$ impact factor

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

Collinear convolution $\Leftrightarrow$ large κ_T (!)

UGD

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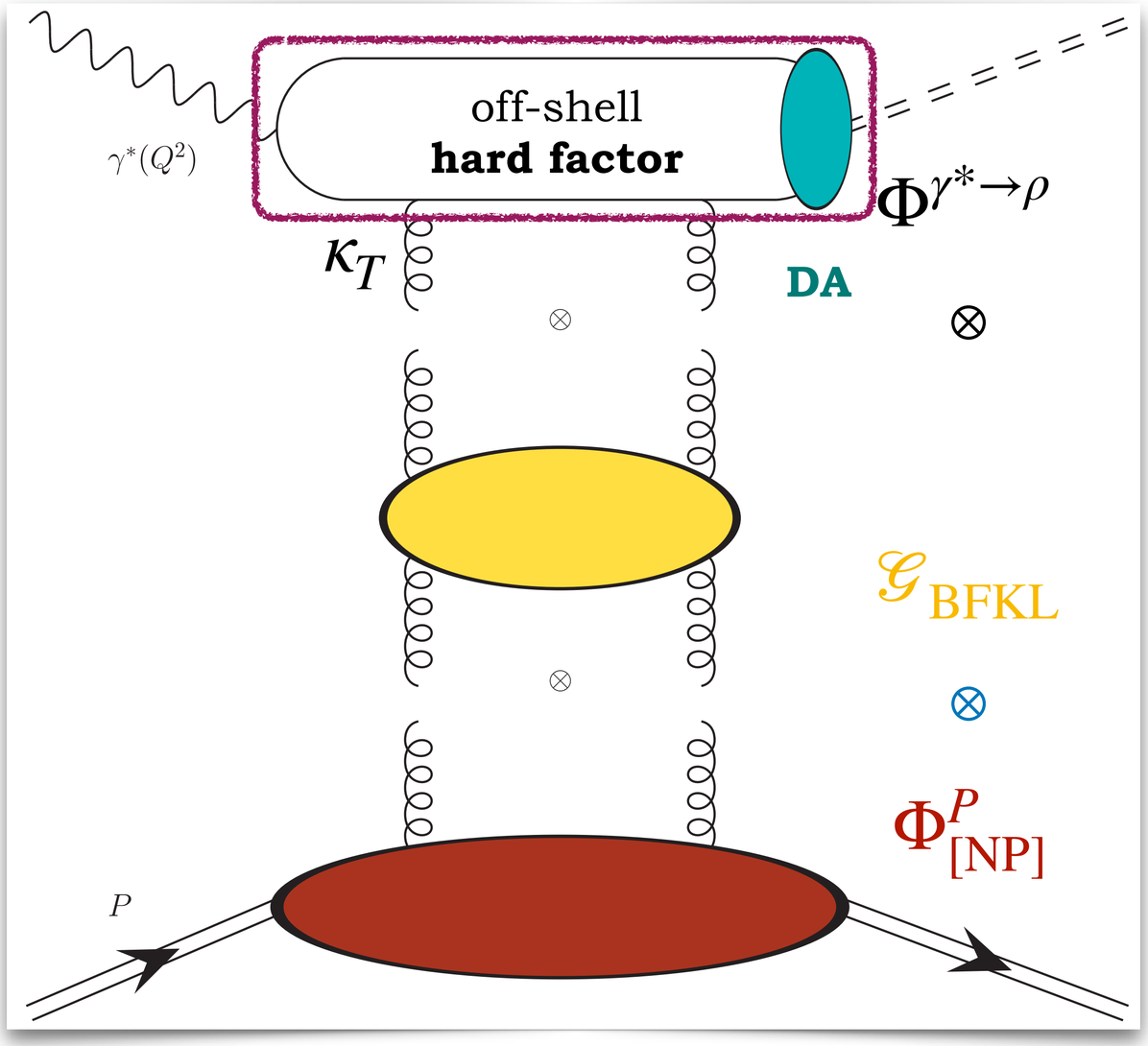
A factorization...of factorizations



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

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

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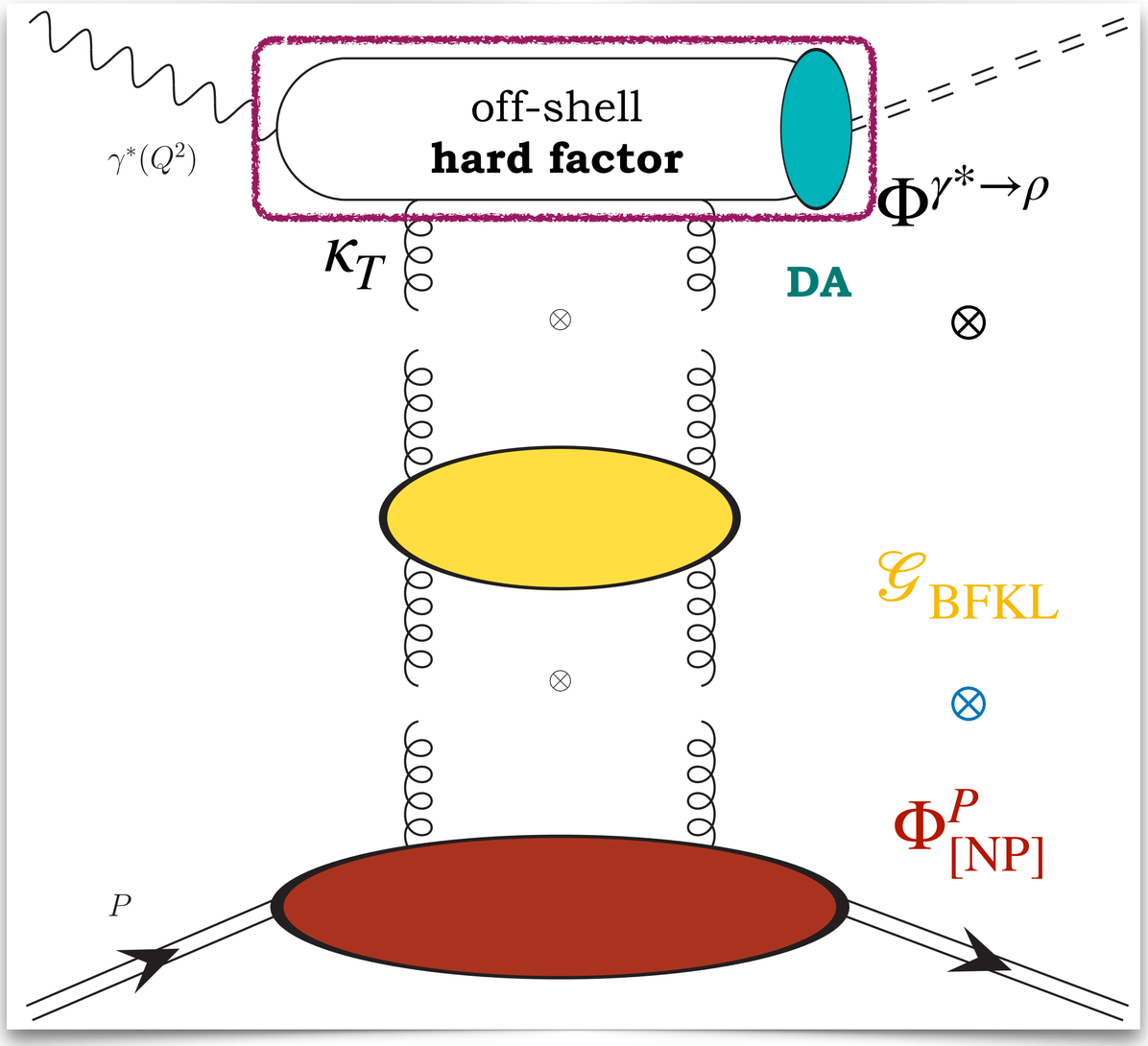

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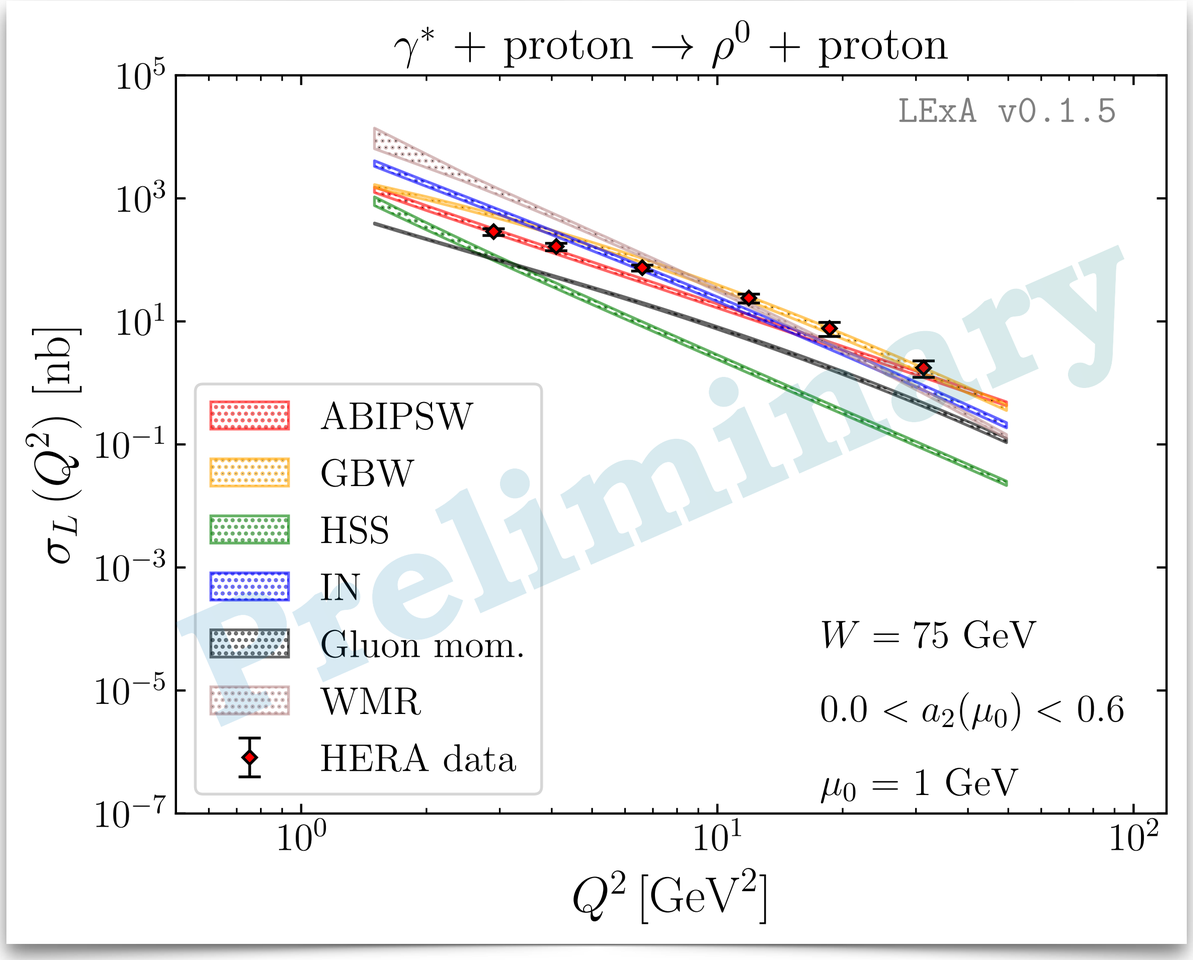
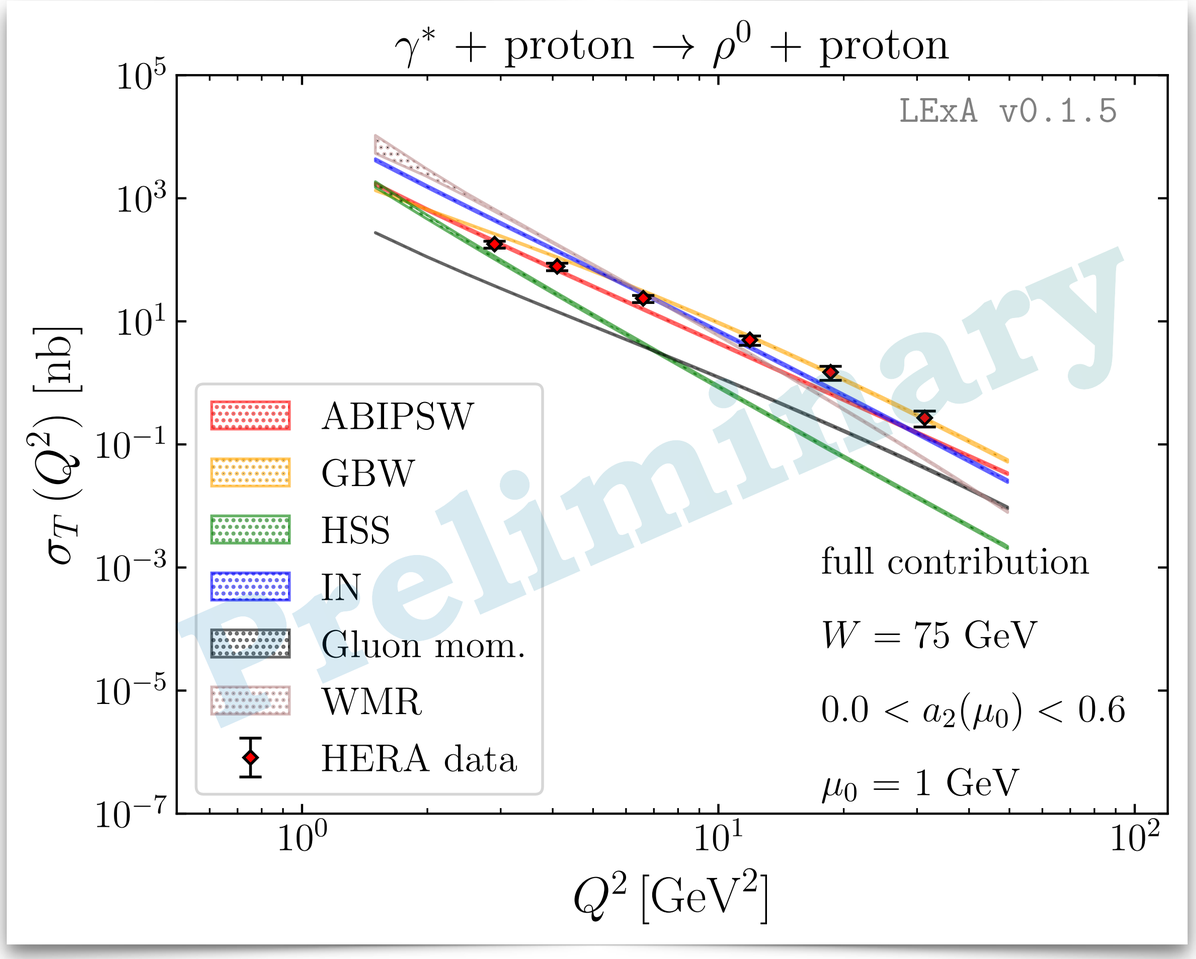
BFKL factorization

Exclusive forward ρ-meson leptoproduction





[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)]

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

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
* Pheno outcome: sensitivity to **intermediate** κ_T
* LVMs as tools: discrimination among UGD models

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- LVMs as tools: discrimination among UGD models

Quarkonia

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

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

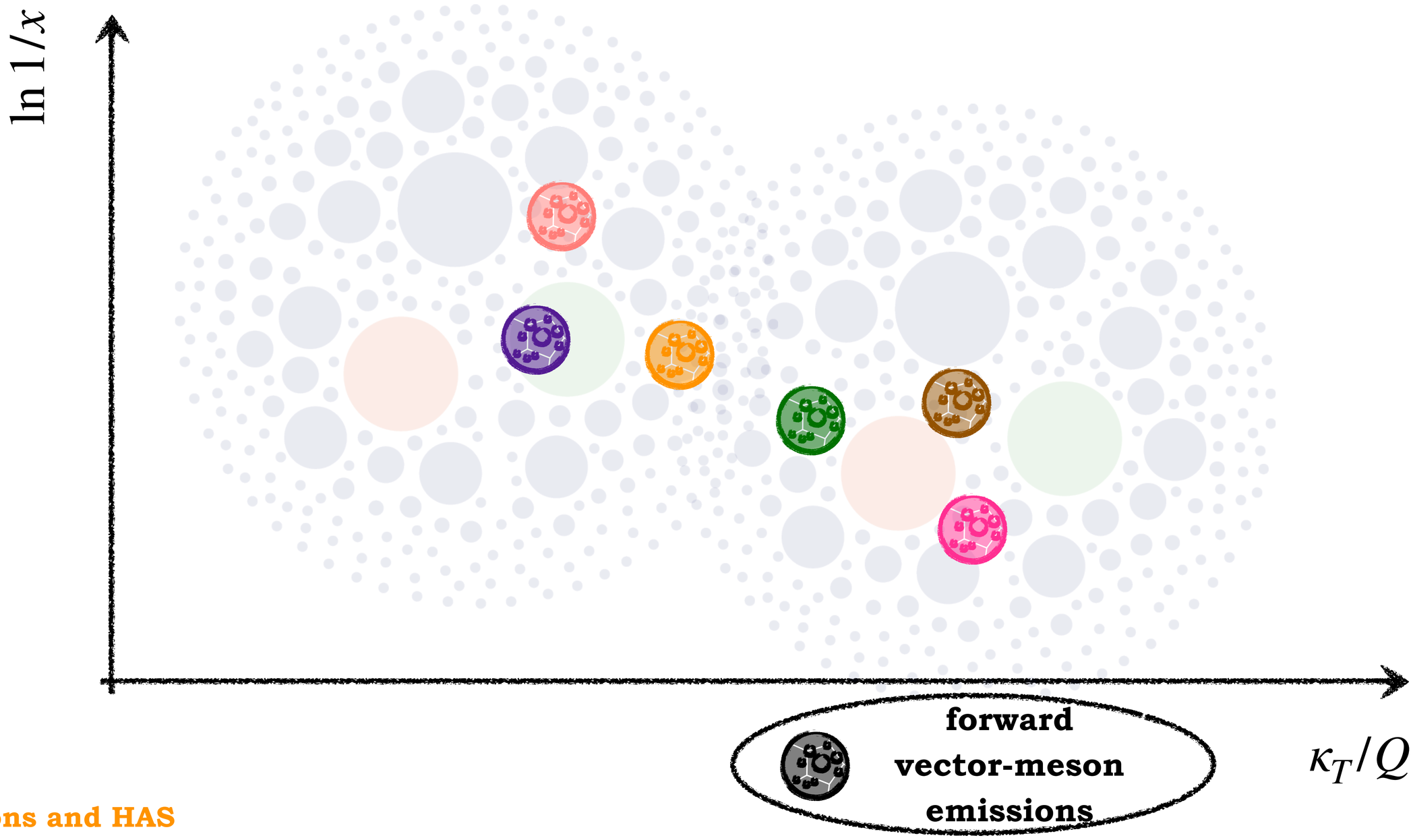
- Validity of *small-size* dipoles questionable…
- NRQCD: large-r_d dynamics for $\Psi(2s)$ ($\Upsilon(2s)$?)

[K. Suzuki *et al.* (2000)]; [J. Cepila *et al.* (2019)]; [M. Hentschinski *et al.* (2020)]

- Onia as tools: scan of TMD/HEF intersection range

Hadronic structure and vector mesons

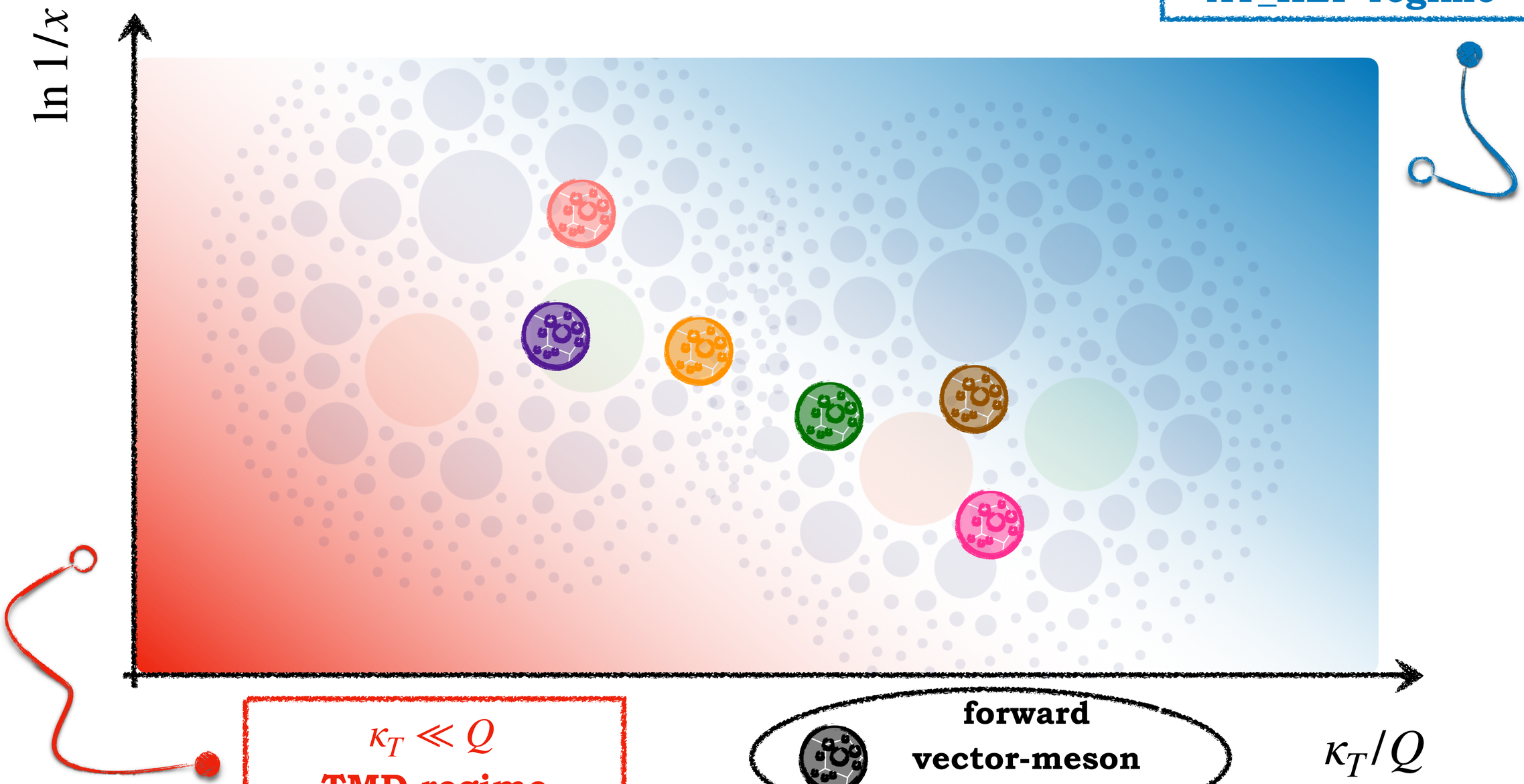
Hadronic structure and vector mesons



Hadronic structure and vector mesons

$x \ll 1;\ \kappa_T \approx Q \gg \Lambda_{\mathrm{QCD}}$

AT_HEF regime

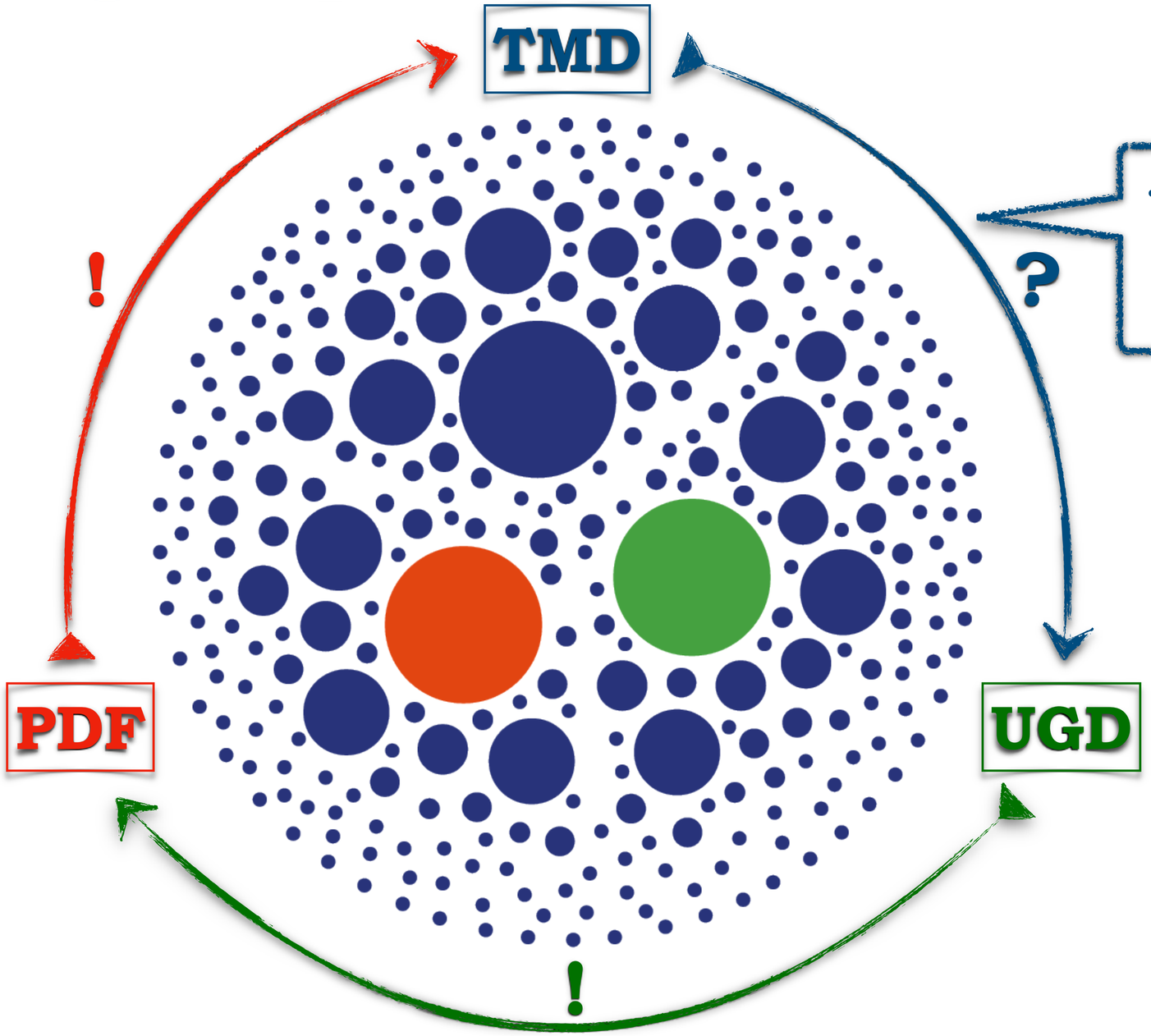


$\kappa_T \ll Q$

TMD regime

forward vector-meson emissions

Mapping the proton content at small-x



...extensive κ_T *scan* via forward vector-meson emissions

Backup slides

Hadronic structure at small-x

Backup

Forward physics and the hadronic structure

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

Backup

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**

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Forward physics and the hadronic structure

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

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

  - Respect different **factorization theorems**

  - Exhibit peculiar **universality properties**

  - Obey distinct **evolution equations**

- 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!*

Backup

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

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PDFs

...but wait...

where is the

UGD?

Speaks language of

Reggeized gluons

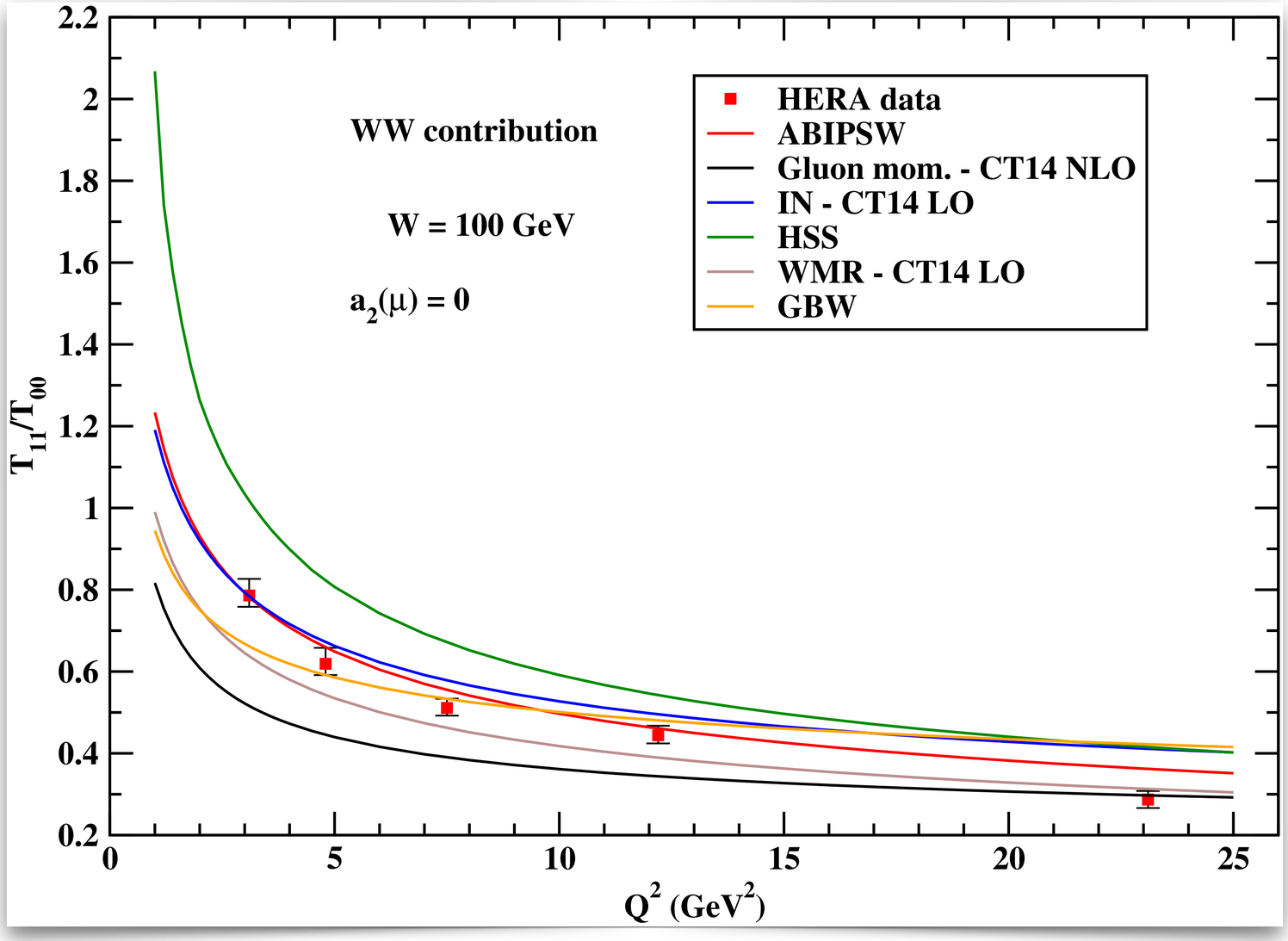
slide adapted from C. Bissolotti

Backup

BFKL UGD

Backup

Exclusive forward ρ-meson leptoproduction



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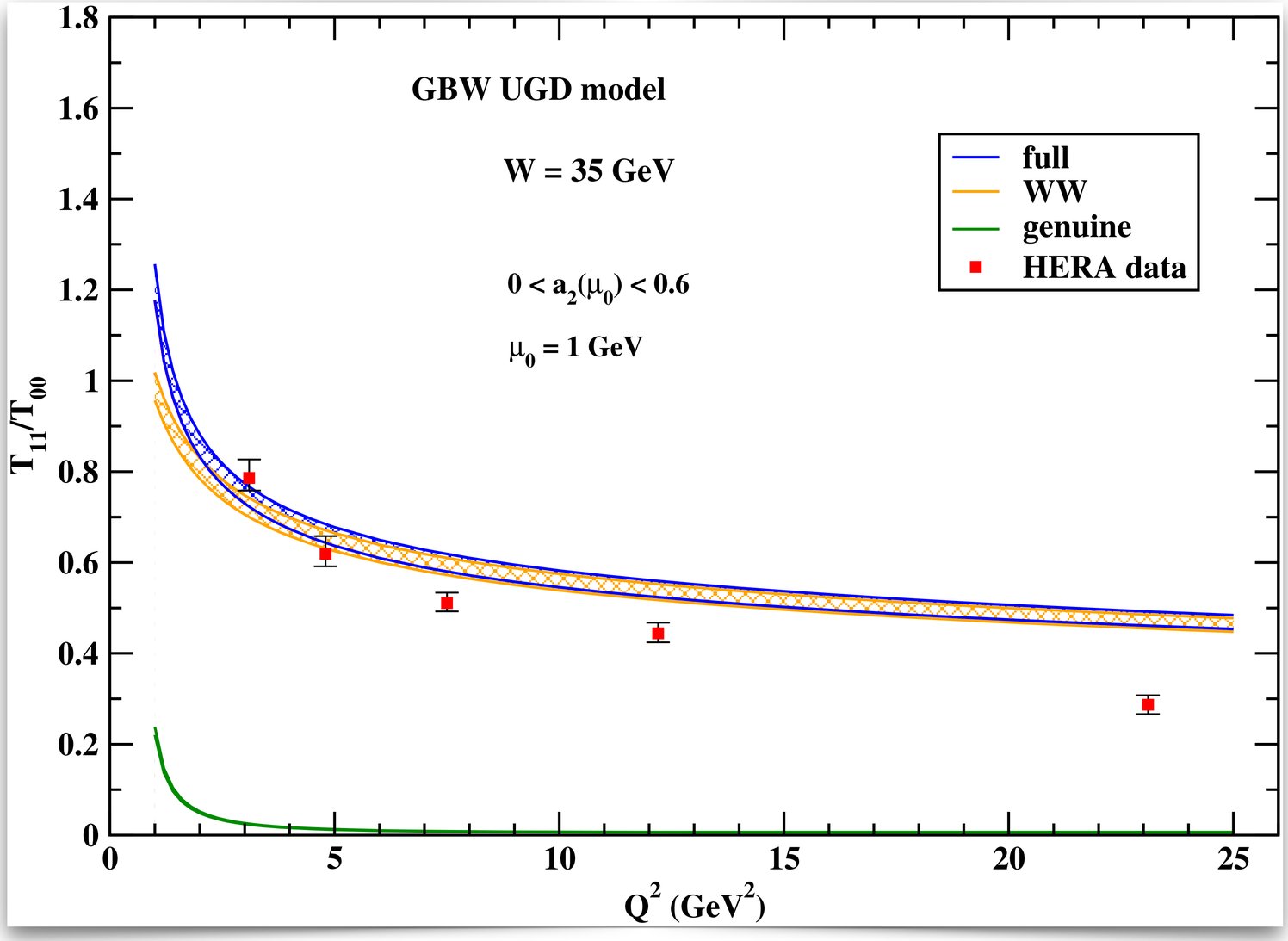

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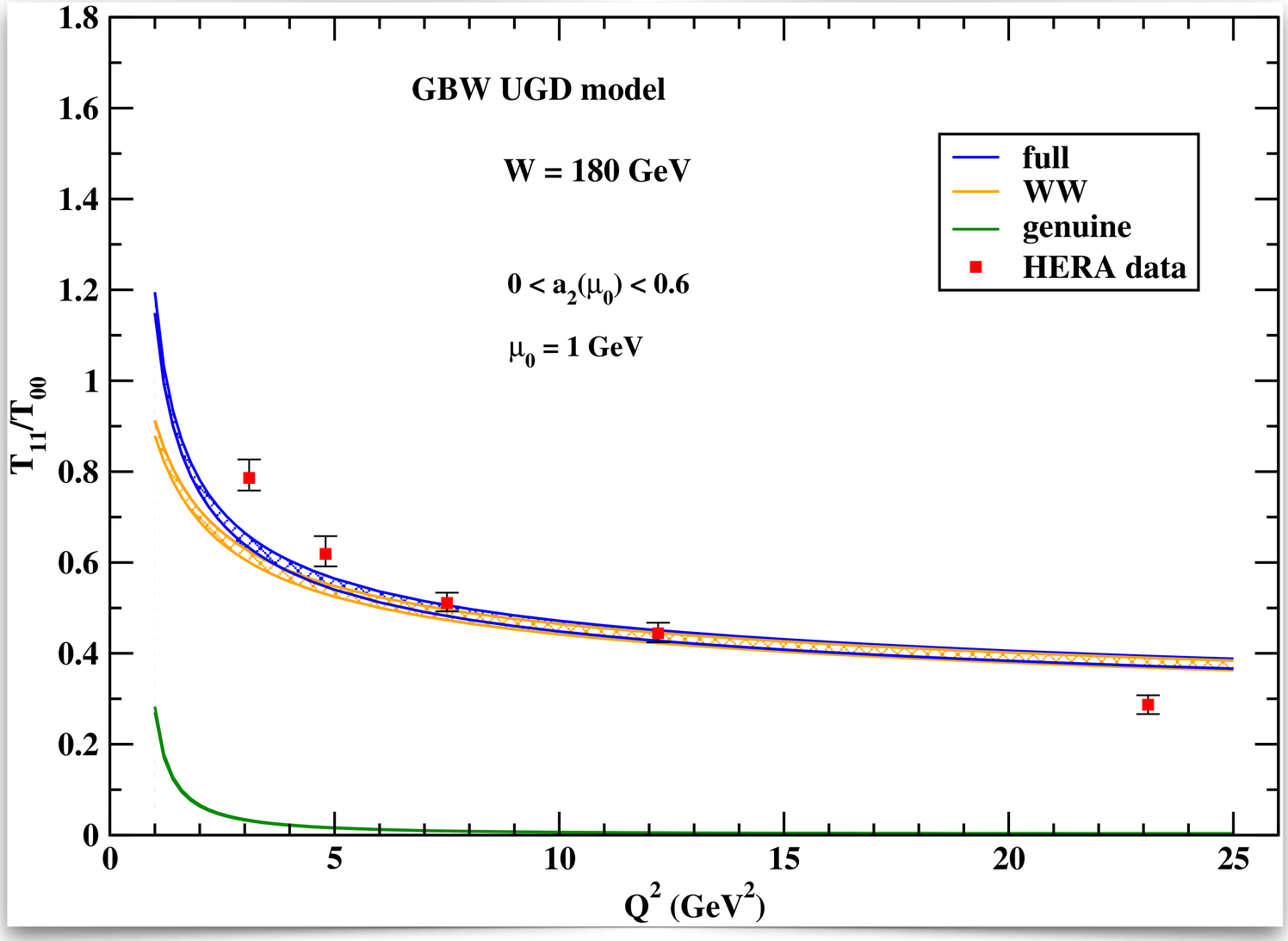

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Backup

Inclusive forward Drell-Yan dilepton production

- LHC, **forward region** $\rightarrow$ $(l^+ l^-)$ 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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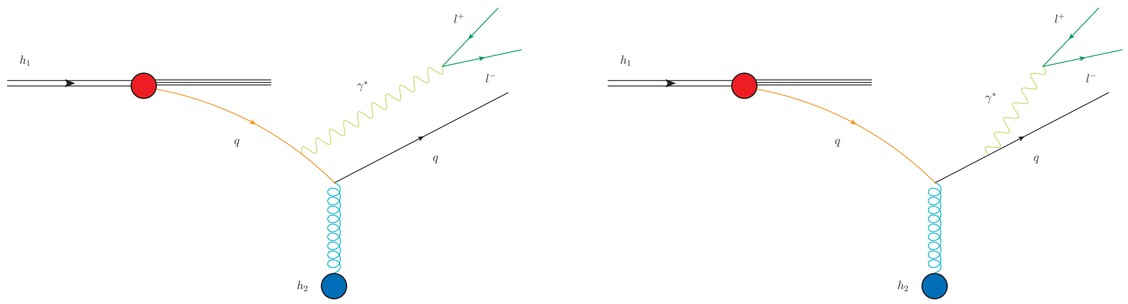

- Helicity structure functions in high-energy factorization:

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

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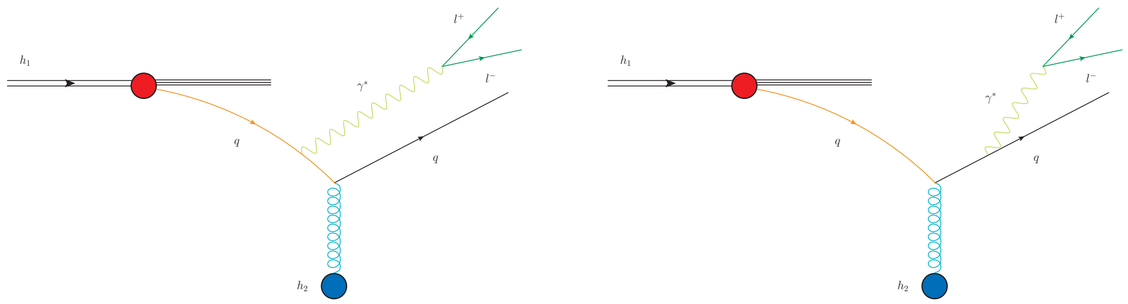

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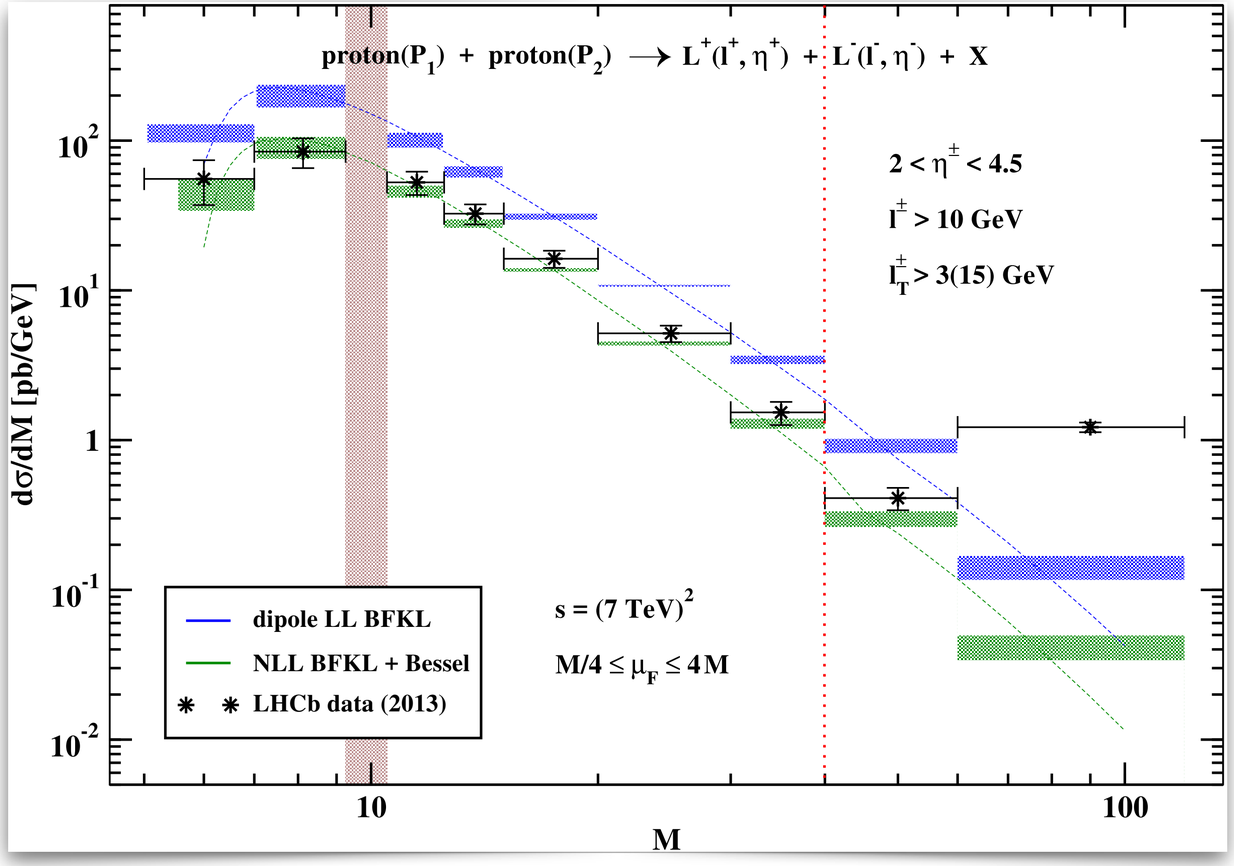

🔗 [D. Brzeminski, L. Motyka, M. Sadzikowski, T. Stebel (2017)]

🔗 [F.G.C., D. Gordo Gómez, A. Sabio Vera (2018)]

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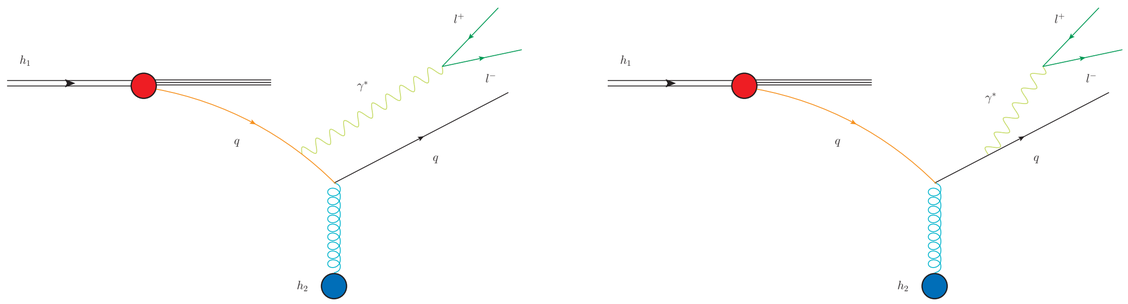

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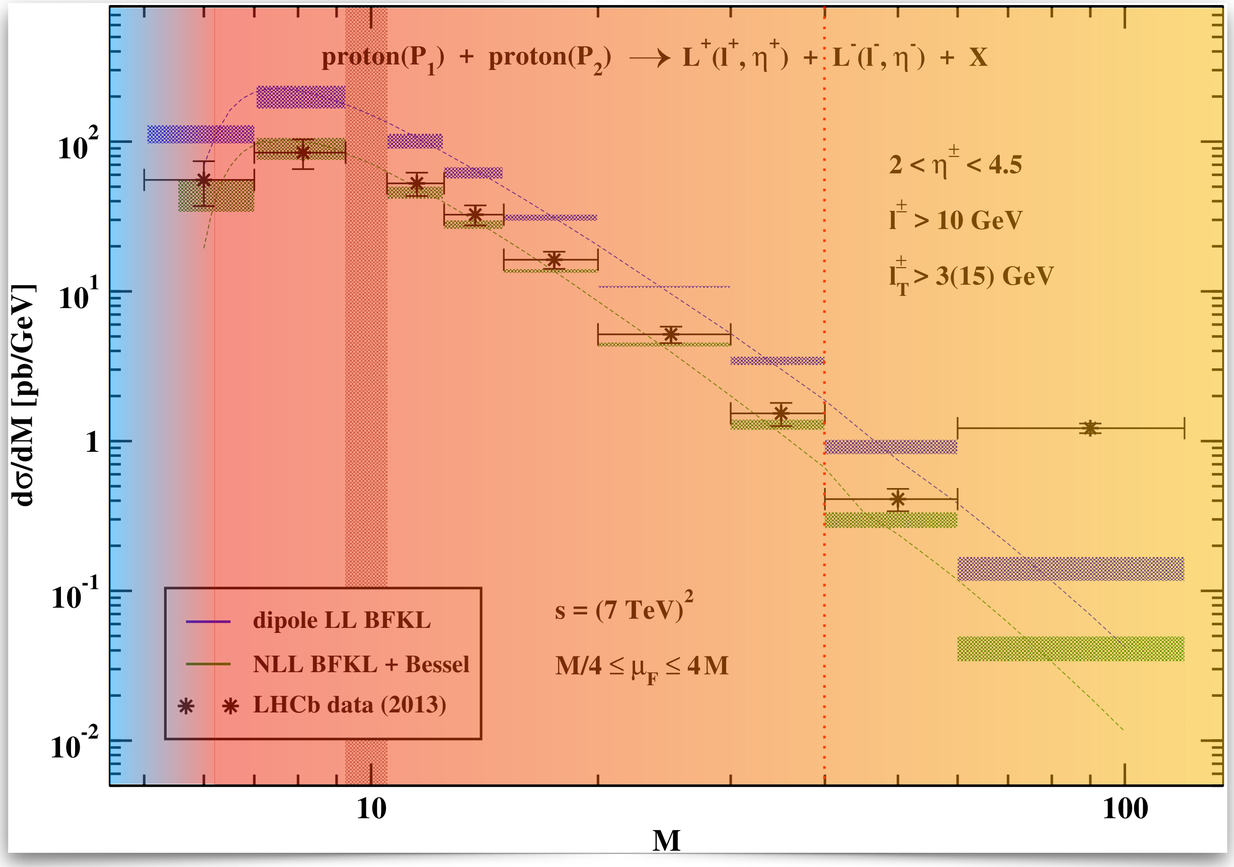
🔗 [F.G.C., D. Gordo Gómez, A. Sabio Vera (2018)]

approaching limits of semi-hard regime



Z^0 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**

  $\xrightarrow{\text{effect of}}$ 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 $\mathrm{d}\sigma/\mathrm{d}M$ 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]

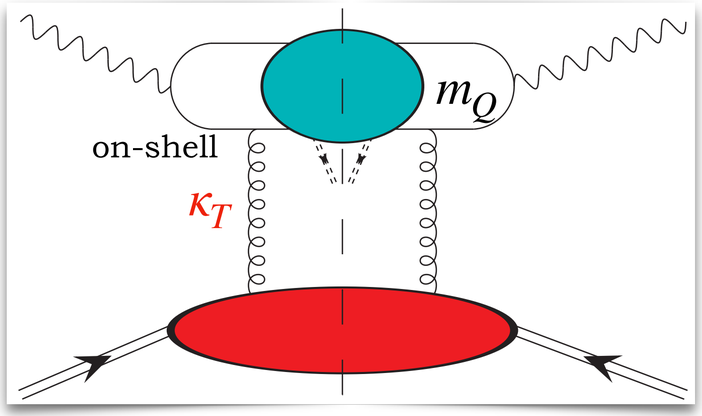
- ● Future data for Drell–Yan production in **forward directions**

  $\xrightarrow{\text{peerless to}}$ gauge need for **high-energy resummation**

Backup

Inclusive quarkonium emissions

$$\kappa_T \ll Q$$



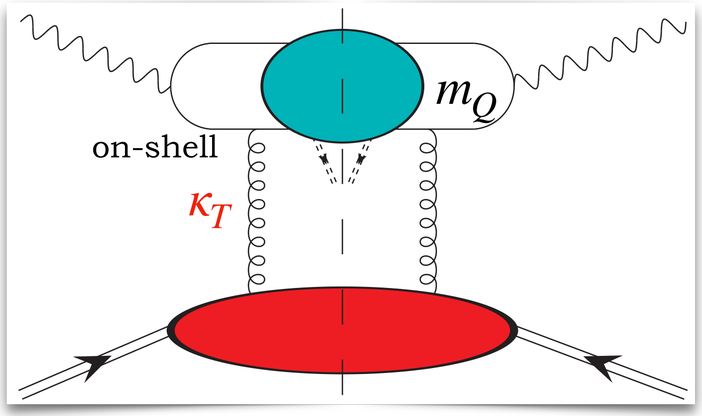
* Gluon TMD PDF
* Double-parton fragment.

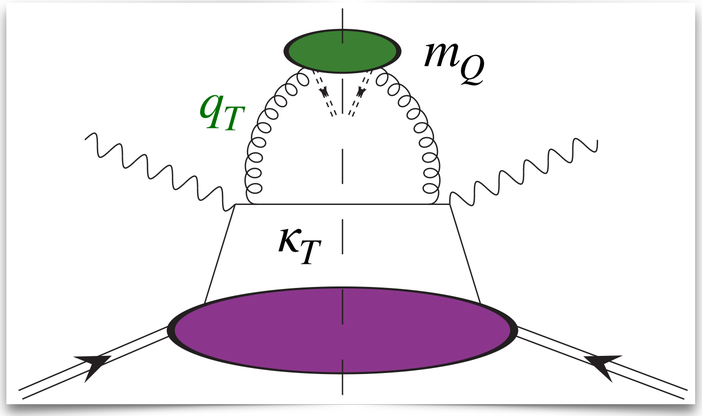
Backup

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

Backup

Inclusive quarkonium emissions

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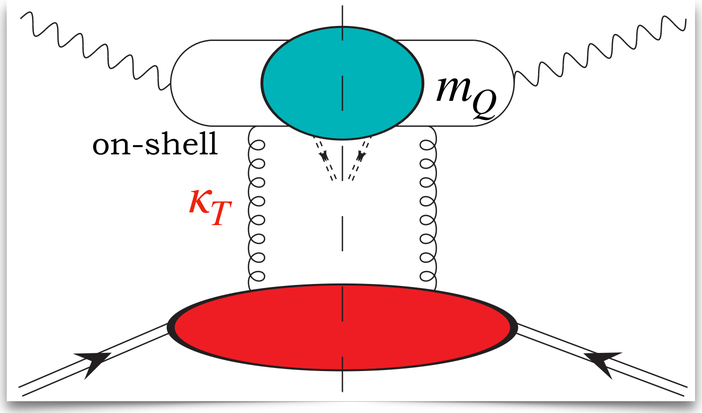

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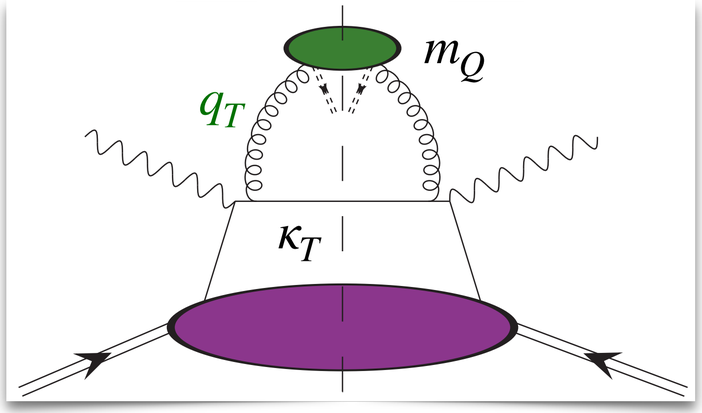

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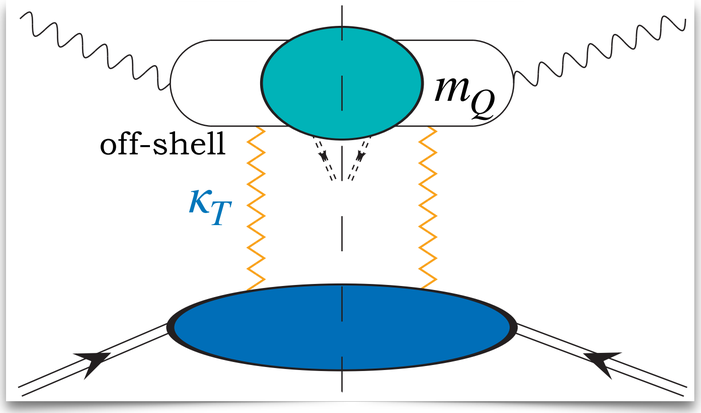
HEF

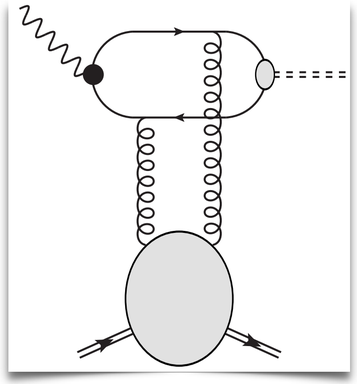


* BFKL UGD
* Reggeized gluons
* Dipole mechanism

Backup

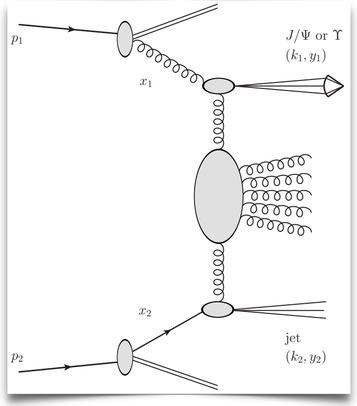
Small-x and quarkonia

Exclusive photoproduction



CS

Hadroproduction



CO + CS

Backup

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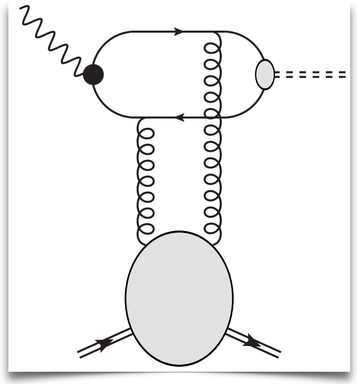

CS

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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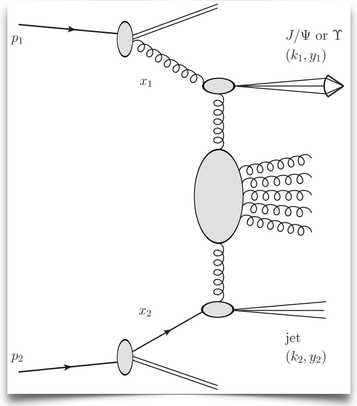

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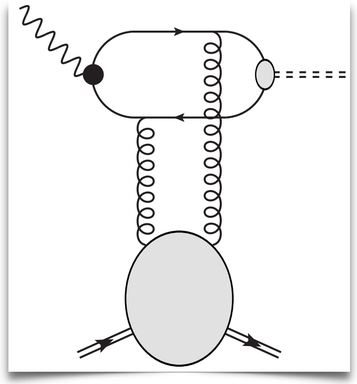

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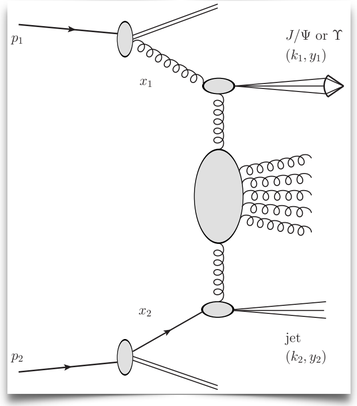
Hadroproduction

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)]



CO + CS

Backup

Small-x and quarkonia

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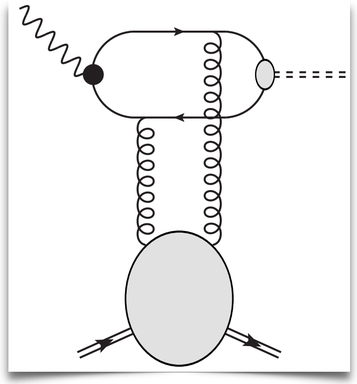

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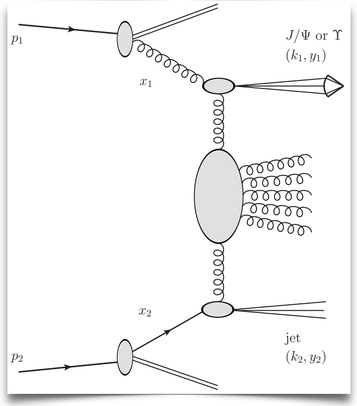
Inclusive single/double central quarkonium emissions

($\Psi(2s)$, $\Psi(3s)$: 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)]



CO + CS

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)]

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