# Leptoproduction of $\rho$-mesons as discriminator for the UGD in the proton

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[arXiv : 1808.02395]

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# Outline

# Motivation

- **Parton densities** are relevant to the search for **new Physics**

  They describe the internal structure of the nucleon in terms of its elementary components (quarks and gluons)

  $\Longrightarrow$ enter the expression for cross sections

  $\Longrightarrow$ nonperturbative objects

  $\Longrightarrow$ can be extracted from experiments through global fits

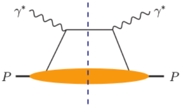
- Several types of distributions...

  - exhibit particular **universality properties**
  - obey distinct **evolution equations**
  - respect different types of **factorization theorems**

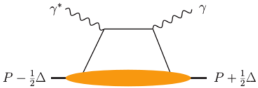
# ...A brief overview

Integrated parton densities:

- **PDF (or collinear) factorization**
  - inclusive processes
  - $\kappa_{\mathrm{T}} \sim$ hardest scale

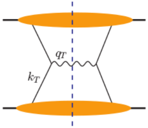



- **GPD factorization**
  - exclusive processes
  - skewness effects

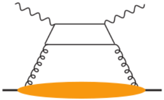



Unintegrated parton densities:

- **TMD factorization**
  - inclusive processes
  - $\kappa_{\mathrm{T}} \ll$ hardest scale




- **$\kappa_{\mathrm{T}}$-factorization** (or small-$x$ factorization)
  - inclusive or exclusive processes
  - small-$x$, large $\kappa_{\mathrm{T}}$
  - **Unintegrated gluon distribution**

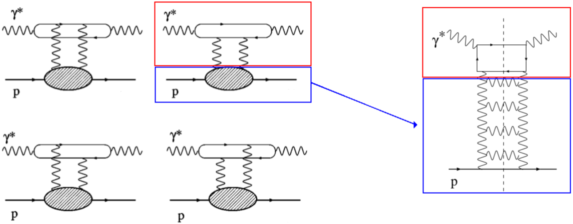


# Unintegrated Gluon Distribution (UGD)

- ◇ DIS: conventionally described in terms of PDFs
- ◇ less inclusive processes: need to use distributions unintegrated over the parton $\kappa_T$
- example: **virtual photoabsorption** in **$\kappa_T$-factorization**

$$\sigma_{\rm tot}(\gamma^* p \to X) \;=\; {\rm Im}_s\left\{\mathcal{A}(\gamma^* p \to \gamma^* p)\right\} \;\equiv\; \Phi_{\gamma^* \to \gamma^*} \circledast \mathcal{F}(x, \kappa^2)$$

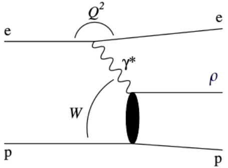
- ◇ $\mathcal{F}(x, \kappa^2)$ is the **unintegrated gluon distribution** (**UGD**) in the proton
- ▶ small-$x$ limit: UGD = [BFKL gluon ladder] $\circledast$ [proton impact factor]



# Leptoproduction of $\rho$ mesons at HERA

$e - p$ collisions provide

$$\gamma^* + \text{proton} \longrightarrow \rho + \text{proton}$$ *...exclusive process!*




- 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

$\implies$ constrain $\kappa_{\rm T}$-dependence of UGD in the HERA energy range

$$2.5 \text{ GeV}^2 < Q^2 < 60 \text{ GeV}^2$$
$$35 \text{ GeV} < W < 180 \text{ GeV}$$

- Hierarchy of helicity amplitudes: $T_{00} \gg T_{11} \gg T_{10} \gg T_{01} \gg T_{1-1}$

[D.Yu. Ivanov and R. Kirschner, *Phys. Rev. D* **58** (1998) 114026]

- HERA data available for $\mathbf{T_{11}/T_{00}}$ [H1 collaboration: F.D. Aaron et al., *JHEP* **05** 032 (2010)]
- $\rho$-meson via **distribution amplitudes (DAs)**: $\varphi(y) = \varphi^{\rm WW}(y) + \varphi^{\rm gen}(y)$

# Helicity Amplitudes in $\kappa_{\mathrm{T}}$-factorization

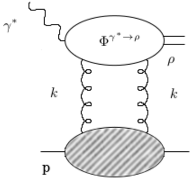
- Leading **helicity amplitudes** are known

**Assumption:**

- $\mathrm{Im}_s \{\mathcal{A}(\gamma^* p \to \rho\, p)\}$
- same $W$- and $t$-dependence for $T_{11}$ and $T_{00}$

  $\to$ same physical mechanism, scattering of small transverse size of dipole on the proton target, at work $\Longrightarrow$ $\kappa_{\mathrm{T}}$**-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:

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

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

# $T_{11}$ and $T_{00}$

**Assumption:**

- **Wandzura-Wilczek (WW) approximation** $\longrightarrow$ genuine terms neglected

$$T_{11} = -is\,(\epsilon_\gamma \cdot \epsilon^*_\rho)\,2\,B\,C\,\frac{m_\rho}{Q^2}\int \frac{d^2\kappa}{(\kappa^2)^2}\mathcal{F}(x,\kappa^2)\int_0^1 dy\;\varphi_+^{\rm WW}(y,\mu^2)\,\frac{\alpha\,(\alpha+2y\bar{y})}{y\bar{y}\,(\alpha+y\bar{y})^2}$$

$$T_{00} = is\frac{4\,B\,C}{Q}\int \frac{d^2\kappa}{(\kappa^2)^2}\mathcal{F}(x,\kappa^2)\int_0^1 dy\;\varphi_1^{\rm as}(y,\mu^2)\left(\frac{\alpha}{\alpha+y\bar{y}}\right)$$

where $\alpha = \frac{\kappa^2}{Q^2}$, $B = 2\pi\alpha_s\frac{e}{\sqrt{2}f_\rho}$, $C = \frac{\delta_{ab}}{2N_c}$

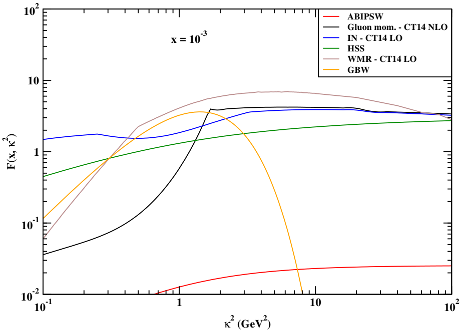
$\Longrightarrow$ $\rho$-**meson DAs** employed:

- **asymptotic** $\varphi_1^{\rm as}(y) \xrightarrow{fixing} a_2(\mu^2) = a_2(\mu_0^2)\,\frac{\alpha_S(\mu^2)}{\alpha_S(\mu_0^2)}^{\gamma_2/b_0} \equiv 0$
- $\varphi_+^{\rm WW}(y,\mu^2) = (2y-1)\varphi_{1T}^{\rm WW}(y,\mu^2) + \varphi_{AT}^{\rm WW}(y,\mu^2)$

$\Longrightarrow$ $\mathcal{F}(x,\kappa^2)$ has to be modeled!

# UGD models

- Existence of several UGD models $\Longrightarrow$ **different behavior** in $\kappa^2$-shape




- **ABIPSW**: $x$-independent model

$$\mathcal{F}(x,\kappa^2) = \frac{A\delta_{ab}}{(2\pi)^2 M^2}\left[\frac{\kappa^2}{M^2+\kappa^2}\right]$$

[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 and hard components $\xrightarrow{\textit{to probe}}$ different regions of $\kappa$

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

- **HSS**: $\mathcal{G}_{\rm BFKL} \otimes$ [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]

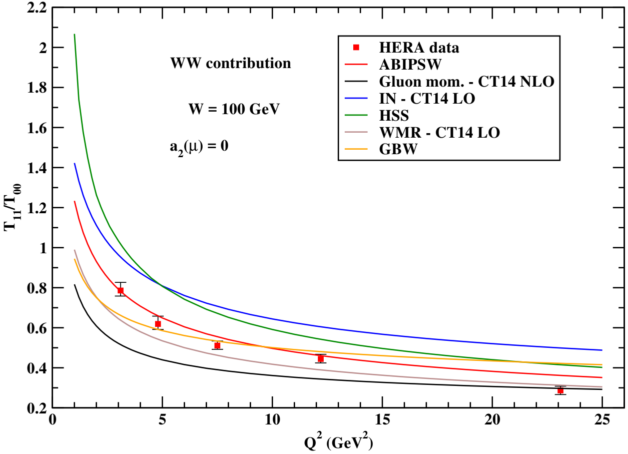
- **WMR**: angular ordering of gluon emissions

[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]

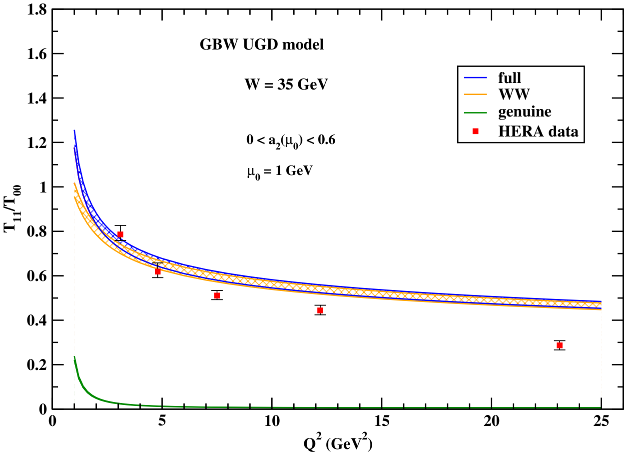
# $T_{11}/T_{00}$ for different UGD models - W = 100 GeV




- None of the models is able to reproduce data over the entire $Q^2$-range
- $x$-independent ABIPSW and GBW $\longrightarrow$ more suitable models

# $T_{11}/T_{00}$ for GBW model - W = 35 GeV

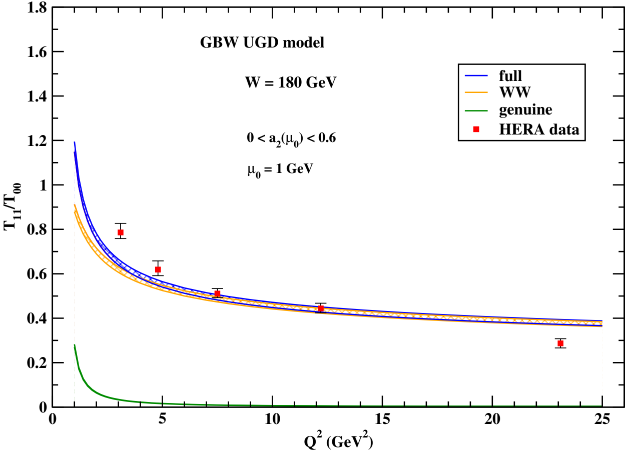
- Genuine twist-3 effect included




- Uncertainty band $\longrightarrow$ variation of $a_2(\mu_0 = 1\text{ GeV})$

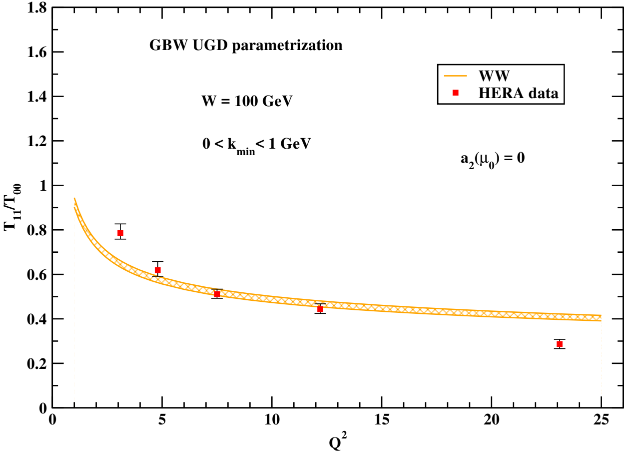
# $T_{11}/T_{00}$ for GBW model - W = 180 GeV

- Genuine twist-3 effect included




- Uncertainty band $\longrightarrow$ variation of $a_2(\mu_0 = 1\ \text{GeV})$

# Stability of $T_{11}/T_{00}$ on $k_{min}$ cutoff




- Uncertainty band $\longrightarrow$ variation of $k_{\rm min}$ between 0 and 1 GeV
- Small shift of $T_{11}/T_{00} \Longrightarrow T_{11}$ and $T_{00}$ dominated by **large** $\kappa$ values

# Conclusions...

Exclusive electroproduction of polarized $\rho$-meson as testing ground for UGD:

- **Exclusive** final state + **small-$x$** limit $\Longrightarrow$ $\kappa_T$-**factorization** allowed
- **Process solved in helicity** $\Longrightarrow$ $T_{11}\,/\,T_{00}$ to constrain the $\kappa_T$-**dependence** of the UGD in the HERA energy range
  - ✓ Importance of the **region of small $\kappa_T$'s checked** via predictions on the **lower cutoff**

$\Longrightarrow$ $T_{11}$ and $T_{00}$ sensitive to large $\kappa_T$ values

# ...Outlook

- Study and test of further UGDs
- Proposal of new UGD models and UGD extraction from different channels
- Consider other processes as testfield for UGD:
  - ◇ Heavy-quark and heavy-meson production
  - ◇ Forward Drell–Yan production

**Thanks for your attention!!**

# BACKUP slides

# UGD models

## Ivanov and Nikolaev' (IN) UGD: a soft-hard model

$$\mathcal{F}(x,\kappa^2) = \mathcal{F}^{(B)}_{\text{soft}}(x,\kappa^2)\frac{\kappa_s^2}{\kappa^2+\kappa_s^2} + \mathcal{F}_{\text{hard}}(x,\kappa^2)\frac{\kappa^2}{\kappa^2+\kappa_h^2}\,,$$

**The soft term:**

◇ $\mathcal{F}^{(B)}_{\text{soft}}(x,\kappa^2) = a_{\text{soft}}\,C_F N_c \frac{\alpha_s(\kappa^2)}{\pi}\left(\frac{\kappa^2}{\kappa^2+\mu^2_{\text{soft}}}\right)^2 V_N(\kappa)$

- $\mu^2_{\text{soft}} \longrightarrow$ soft parameter
- $a_{\text{soft}} \longrightarrow$ weight of soft term compared to the hard one

**The hard term:**

◇ $\mathcal{F}_{\text{hard}}(x,\kappa^2) = \mathcal{F}^{(B)}_{\text{pt}}(\kappa^2)\frac{\mathcal{F}_{\text{pt}}(x,Q_c^2)}{\mathcal{F}^{(B)}_{\text{pt}}(Q_c^2)}\theta(Q_c^2-\kappa^2) + \mathcal{F}_{\text{pt}}(x,\kappa^2)\theta(\kappa^2-Q_c^2)$

- $\mathcal{F}_{\text{pt}}(x,\kappa^2) = \dfrac{\partial xg(x,\kappa^2)}{\partial \ln \kappa^2}$
- $\mathcal{F}^{(B)}_{\text{pt}}(x,\kappa^2) = C_F N_c \frac{\alpha_s(\kappa^2)}{\pi}\left(\frac{\kappa^2}{\kappa^2+\mu^2_{\text{pt}}}\right)^2 V_N(\kappa)$

**The coupling constant:**

◇ $\alpha_s \leq 0.82$ **(frozen)**

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

# UGD models

## Hentschinski-Salas–Sabio Vera' (HSS) model

$$\mathcal{F}(x,\kappa^2,M_h) = \int_{-\infty}^{\infty} \frac{d\nu}{2\pi^2}\, \mathcal{C}\, \frac{\Gamma(\delta - i\nu - \frac{1}{2})}{\Gamma(\delta)} \left(\frac{1}{x}\right)^{\chi\left(\frac{1}{2}+i\nu\right)} \left(\frac{\kappa^2}{Q_0^2}\right)^{\frac{1}{2}+i\nu}$$

$$\times \left\{1 + \frac{\bar{\alpha}_s^2 \beta_0 \chi_0\left(\frac{1}{2}+i\nu\right)}{8N_c} \log\left(\frac{1}{x}\right) \left[-\psi\left(\delta - \frac{1}{2} - i\nu\right) - \log\frac{\kappa^2}{M_h^2}\right]\right\}$$

- $\chi_0(\frac{1}{2}+i\nu) \equiv \chi_0(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma)$ LO eigenvalue of the BFKL kernel
- $\chi(\gamma) = \bar{\alpha}_s\chi_0(\gamma) + \bar{\alpha}_s^2\chi_1(\gamma) - \frac{1}{2}\bar{\alpha}_s^2\chi_0'(\gamma)\,\chi_0(\gamma) + \chi_{RG}(\bar{\alpha}_s,\gamma)$ NLO eigenvalue of the BFKL kernel (**collinearly improved** e **BLM optimized**)
- parametrization for the proton IF:

$$\Phi_p(q,Q_0^2) = \frac{\mathcal{C}}{2\pi\Gamma(\delta)} \left(\frac{q^2}{Q_0^2}\right)^{\delta} e^{-\frac{q^2}{Q_0^2}}$$

- parameters were fitted to the combined HERA data for the $F_2(x)$ proton structure function $\longrightarrow$ **kinematically improved** set chosen:

$$Q_0 = 0.28\,\text{GeV}, \qquad \delta = 6.5, \qquad \mathcal{C} = 2.35$$

[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]

# UGD models

## Watt–Martin–Ryskin' (WMR) model

$$\mathcal{F}(x,\kappa^2,\mu^2) = T_g(\kappa^2,\mu^2)\,\frac{\alpha_s(\kappa^2)}{2\pi}\,\int_x^1 dz\,\left[\sum_q P_{gq}(z)\,\frac{x}{z}q\left(\frac{x}{z},\kappa^2\right) + P_{gg}(z)\,\frac{x}{z}g\left(\frac{x}{z},\kappa^2\right)\,\Theta\left(\frac{\mu}{\mu+\kappa}-z\right)\right]$$

- $T_g(\kappa^2,\mu^2) = \exp\left(-\int_{\kappa^2}^{\mu^2} d\kappa_t^2\,\frac{\alpha_s(\kappa_t^2)}{2\pi}\,\left(\int_{z'_{\rm min}}^{z'_{\rm max}} dz'\;z'\,P_{gg}(z') + N_f\,\int_0^1 dz'\,P_{qg}(z')\right)\right)$

  $\rightarrow$ probability of evolving from the scale $\kappa$ to the scale $\mu$ without parton emission
- $z'_{\rm max} \equiv 1 - z'_{\rm min} = \mu/(\mu+\kappa_t)$
- $\mu$ extra-scale $\xrightarrow{\textit{fixed at}} Q$

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

# UGD models

## Golec-Biernat–Wüsthoff' (GBW) UGD

$$\mathcal{F}(x,\kappa^2) = \kappa^4 \sigma_0 \frac{R_0^2(x)}{2\pi} e^{-\kappa^2 R_0^2(x)}$$

- derives from the effective dipole cross section $\hat{\sigma}(x,r)$ for the scattering of a $q\bar{q}$ pair off a nucleon $\xrightarrow{through}$ a reverse Fourier trasform of

$$\sigma_0 \left\{1 - \exp\left(-\frac{r^2}{4R_0^2(x)}\right)\right\} = \int \frac{d^2\kappa}{\kappa^4} \mathcal{F}(x,\kappa^2) \left(1 - \exp(i\vec{\kappa}\cdot\vec{r})\right) \left(1 - \exp(-i\vec{\kappa}\cdot\vec{r})\right)$$

- $R_0^2(x) = \frac{1}{\mathrm{GeV}^2}\left(\frac{x}{x_0}\right)^{\lambda_p}$
- The normalization $\sigma_0$ and the parameters $x_0$ and $\lambda_p > 0$ of $R_0^2(x)$ have been determined by a global fit to $F_2(x)$:

$$\sigma_0 = 23.03\,\text{mb}, \qquad \lambda_p = 0.288, \qquad x_0 = 3.04 \cdot 10^{-4}\,.$$

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