κ_T-dependence of the UGD in the ρ-meson leptoproduction

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Outline

1. **Introduction**
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   - Unintegrated Gluon Distribution (UGD)
   - Leptoproduction of ρ mesons
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   - UGD models
3. **Results**
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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

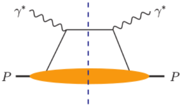
  $\Longrightarrow$ can be extracted from experiments through global fits

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

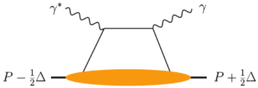
...A brief overview

Integrated parton densities:

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

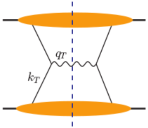


- **GPD factorization**
  - exclusive processes
  - skewness effects

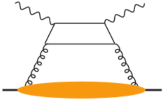


Unintegrated parton densities:

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



- **κ_{T}-factorization** (or small-x factorization)
  - inclusive or exclusive processes
  - small-x, large κ_{T}
  - **Unintegrated gluon distribution**

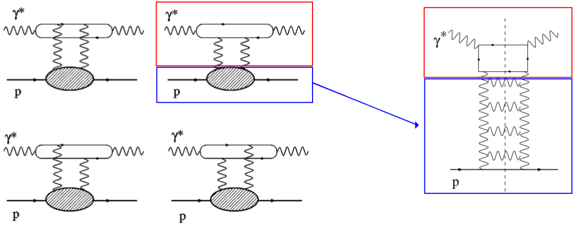


Unintegrated Gluon Distribution (UGD)

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

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

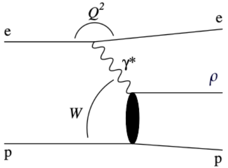
- ◇ $\mathcal{F}\,(\mathbf{x}, \kappa^2)$ is the **unintegrated gluon distribution** (**UGD**) in the proton
- ▶ small-x limit: UGD = [BFKL gluon ladder] ⊛ [proton impact factor]



Leptoproduction of ρ mesons at HERA

$e - p$ collisions provide

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



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

- **Process solved in helicity** $\Longrightarrow$ so far **unexplored testfield** for UGD

  $\Longrightarrow$ constrain κ_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)]**

- ρ-meson via **distribution amplitudes (DAs)**: $\varphi(y) = \varphi^{\text{WW}}(y) + \varphi^{\text{gen}}(y)$

Helicity Amplitudes in κ_T-factorization

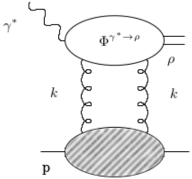
- Leading **helicity amplitudes** are known

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 $\Longrightarrow$ **κ_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 $\Phi^{\gamma^*\to\rho} = [\mathrm{H_{LO}}] \circledast [\mathrm{DA}]$

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

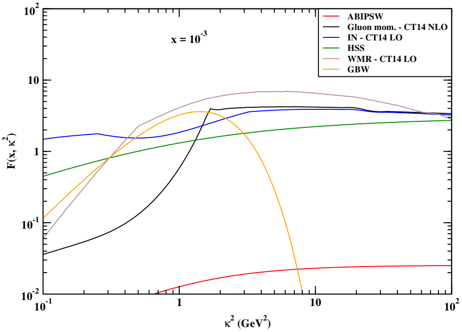
$\Longrightarrow$ ρ-**meson DAs** employed:

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

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

UGD models

- Existence of several UGD models $\Longrightarrow$ **different behavior** in κ^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 $\xrightarrow{\text{to probe}}$ different regions of κ

[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]

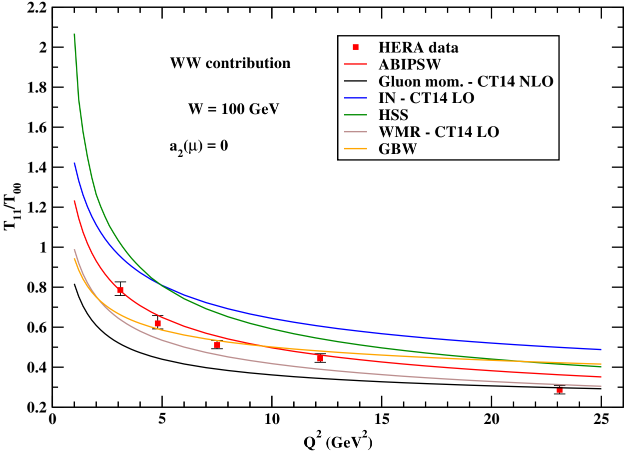
- **WMR**: angular ordering of gluon emissions

[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]

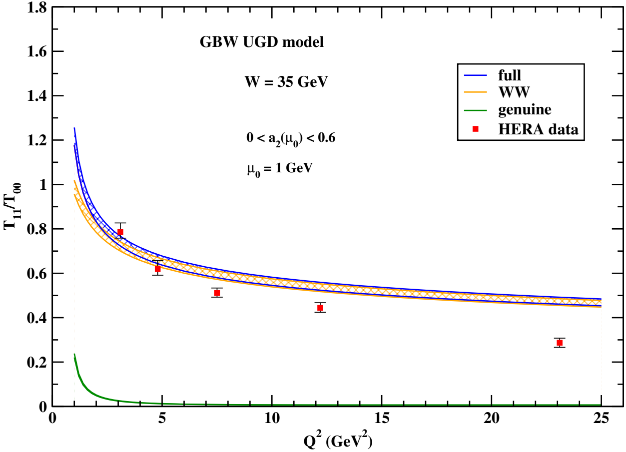
T_{11}/T_{00} for different UGD models - W = 100 GeV



- 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

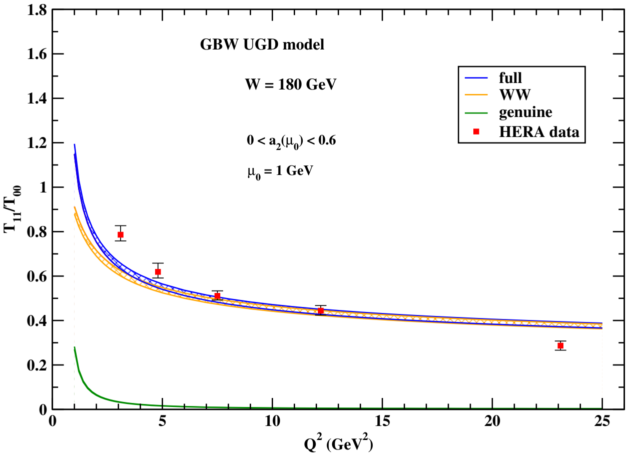
- Genuine twist-3 effect included



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

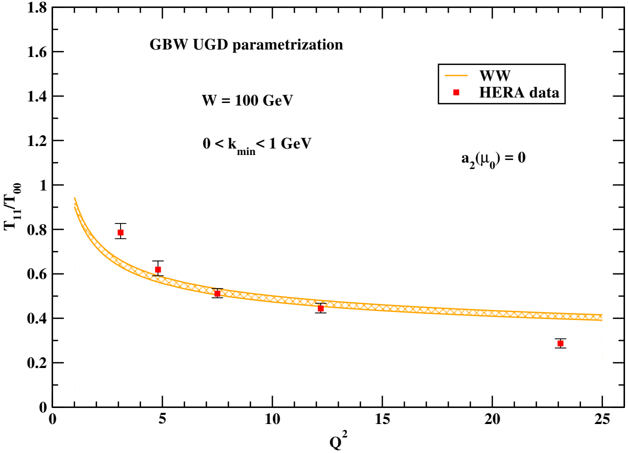
T_{11}/T_{00} for GBW model - $W = 180$ GeV

- 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_{min} between 0 and 1 GeV
- Small shift of $T_{11}/T_{00} \Longrightarrow T_{11}$ and T_{00} dominated by **large** κ values

Conclusions...

Exclusive electroproduction of polarized ρ-meson as testing ground for UGD:

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

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

...Outlook

- NLO impact factor in ρ-meson leptoproduction $\Longrightarrow$ $\Phi^{\gamma^* \to \rho} = [\mathrm{H_{NLO}}] \circledast [\mathrm{DA}]$
- 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 (talk by F.G. Celiberto on Thursday!)

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

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** and **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 κ to the scale μ without parton emission
- $z'_{\rm max} \equiv 1 - z'_{\rm min} = \mu / (\mu + \kappa_t)$
- μ 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 σ_0 and the parameters x_0 and $\lambda_p > 0$ of $R_0^2(x)$ have been determined by a global fit to $F_2(x)$:

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

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