Diffractive leptoproduction of ρ and ϕ light vector mesons via small-x unintegrated gluon density

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Outline

1. **Introduction**
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   - Unintegrated Gluon Distribution (UGD)
   - Leptoproduction of light vector mesons
2. **Theoretical framework**
   - Helicity Amplitudes in κ_T-factorization
   - UGD models
   - Cross section and $\mathbf{b}(\mathbf{Q}^2)$-slope parametrization
3. **Results**
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4. **Conclusions and Outlook**
   - Conclusions
   - Outlook

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

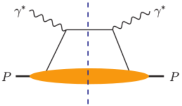
- Several types of distributions...

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

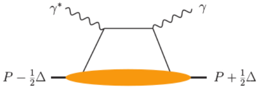
...A brief overview

Integrated parton densities:

- **PDF (or collinear) factorization**
  - inclusive processes
  - $\kappa_T \sim$ hardest scale

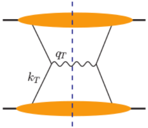


- **GPD factorization**
  - exclusive processes
  - skewness effects

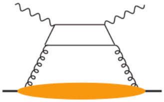


Unintegrated parton densities:

- **TMD factorization**
  - inclusive processes
  - $\kappa_T \ll$ hardest scale



- **κ_T-factorization** (or small-x factorization)
  - inclusive or exclusive processes
  - small-x, large κ_T
  - **Unintegrated gluon distribution**

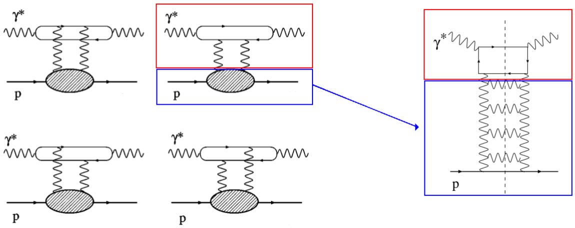


What is the UGD?

- ◇ 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**

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

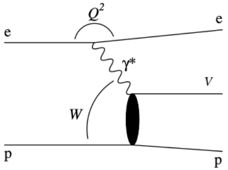
- ◇ $\mathcal{F}(\mathbf{x}, \kappa^2)$ is the **unintegrated gluon distribution** (**UGD**) in the proton
- ▶ small-x limit: UGD = [BFKL gluon ladder] ⊛ [proton impact factor]



Leptoproduction of ρ and ϕ mesons at HERA

$e - p$ collisions provide

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



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

- **Process solved in helicity** $\Longrightarrow$ probe cross sections in the HERA energy range:

H1: $2.5\ \text{GeV}^2 < Q^2 < 60\ \text{GeV}^2$
$35\ \text{GeV} < W < 180\ \text{GeV}$

ZEUS: $2\ \text{GeV}^2 < Q^2 < 60\ \text{GeV}^2$
$32\ \text{GeV} < W < 180\ \text{GeV}$

- HERA data available for σ_L, σ_T, σ_{TOT}

[H1 collaboration: F.D. Aaron et al., *JHEP* 05 032 (2010)]
[ZEUS collaboration: S. Chekanov et al, *Nucl. Phys.* B 718 (2005)]

Helicity Amplitudes in κ_T-factorization

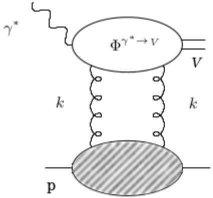
- Leading **helicity amplitudes** are known

Assumption:

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

  → same physical mechanism, scattering of small transverse size of dipole on the proton target, at work $\Longrightarrow$ **κ_T-factorization**

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



Interesting transitions:

- $\gamma_L^* \to V_L \xrightarrow{\text{encoded by}} \Phi^{\gamma_L^* \to V_L}$
- $\gamma_T^* \to V_T \xrightarrow{\text{encoded by}} \Phi^{\gamma_T^* \to V_T}$

$V = \rho,\ \phi$ via **distribution amplitudes (DAs)**: $\varphi(y) = \varphi^{\mathrm{WW}}(y) + \varphi^{\mathrm{gen}}(y)$

$\Longrightarrow$ **DAs** enter $\Phi^{\gamma^*\to V} = [\mathrm{H_{LO}}] \circledast [\mathrm{DA}]$

T_{11} and T_{00}

Assumption:

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

$$T_{11} = is\,\frac{2\,B\,C}{Q^2}\int\frac{d^2\kappa}{(\kappa^2)^2}\mathcal{F}(x,\kappa^2)\int_0^1\frac{dy}{(y\bar{y}+\tau)}\varphi_+^{\rm WW}(y,\mu^2)\frac{\alpha(\alpha+2y\bar{y}+2\tau)}{(\alpha+y\bar{y}+\tau)^2}+o(\tau^2)$$

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

where $B = \frac{\pi\alpha_s f_V e_V}{N_c}$, $\quad C = \sqrt{4\pi\alpha_{\rm em}}$, $\quad \tau = m_q^2/Q^2$, $\quad \alpha = \kappa^2/Q^2$.

- **Generalized massive formula**: $\tau = 0 \longrightarrow$ no quark mass $\Longrightarrow \rho-$production
  $\tau \neq 0 \longrightarrow$ with quark mass $\Longrightarrow \phi-$production

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

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

UGD models

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

Following UGD models are selected:

- **Ivanov-Nikolaev**:

  soft and hard components $\xrightarrow{\text{to probe}}$ different regions of κ

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

- **GBW**:

  FT of dipole cross section

  $\Longrightarrow$ evolution saturation scale is not needed

  $\Downarrow$

  Standard GBW model

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

Cross section and b(Q^2)-slope parametrization

- **Polarized cross sections**:

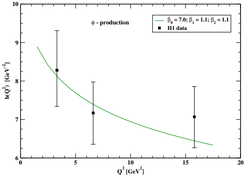
$$\sigma_L\left(\gamma^* p \to V p\right) = \frac{1}{16\pi b(Q^2)} \frac{\left|\mathbf{T}_{00}(\mathbf{s};\mathbf{Q}^2)\right|^2}{W^2}$$

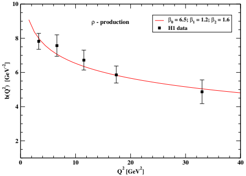
$$\sigma_T\left(\gamma^* p \to V p\right) = \frac{1}{16\pi b(Q^2)} \frac{\left|\mathbf{T}_{11}(\mathbf{s};\mathbf{Q}^2)\right|^2}{W^2}$$

- **b(Q^2)-slope** for light vector mesons:

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

  - for ϕ**-meson**:
    $\beta_0 = 7.0\ \text{GeV}^{-2}$, $\beta_1 = 1.1\ \text{GeV}^{-2}$, $\beta_2 = 1.1$;
  - for ρ**-meson**:
    $\beta_0 = 6.5\ \text{GeV}^{-2}$, $\beta_1 = 1.2\ \text{GeV}^{-2}$, $\beta_2 = 1.6$.





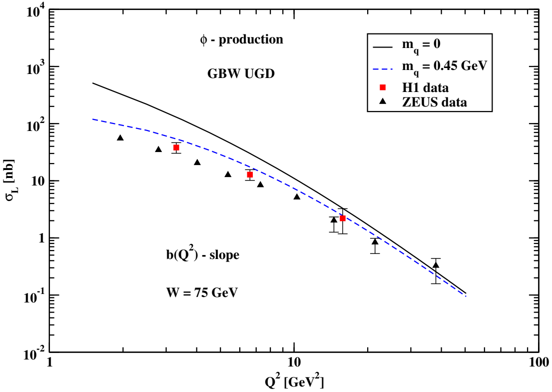
[J. Nemchik et al., *J. Exp. Theor. Phys.* 86 (1998) 1054]

Numerical results

ϕ-production

ϕ-production - Quark mass m_q effect on σ_L

- WW approximation
- **GBW UGD** employed



[A.D. Bolognino, W. Schäfer, A. Szczurek (in progress)]

- Crucial effect of quark mass m_q in order to catch data

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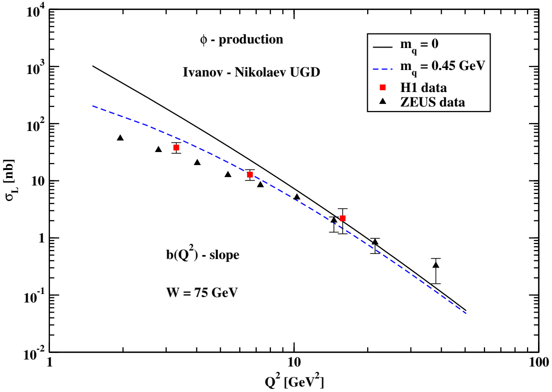
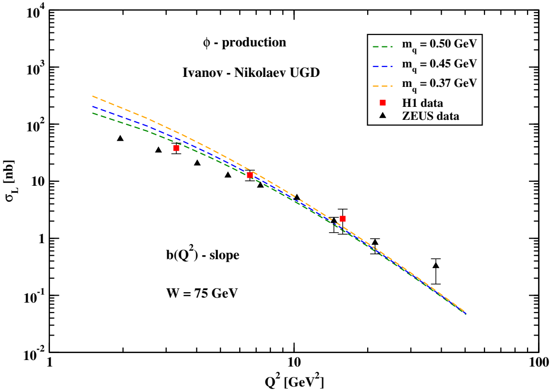


[A.D. Bolognino, W. Schäfer, A. Szczurek (in progress)]

- Crucial effect of quark mass m_q in order to catch data

ϕ-production - Stability of σ_L on m_q values



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ϕ-production - Quark mass m_q effect on σ_T

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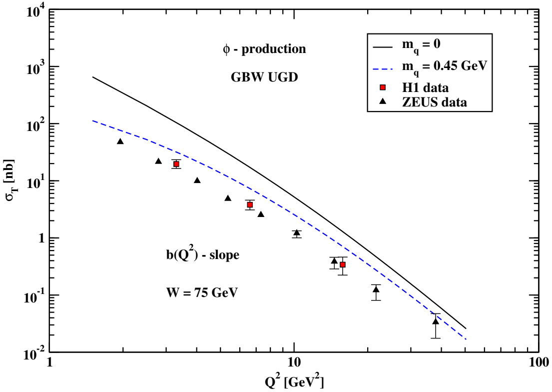

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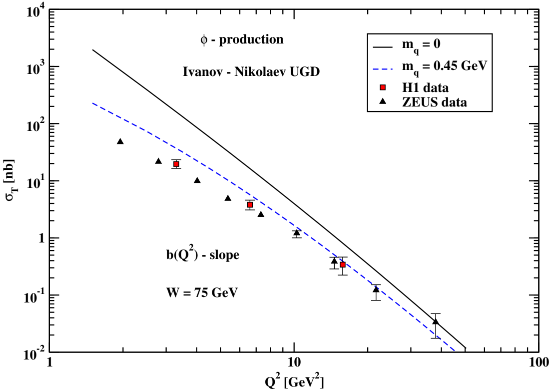

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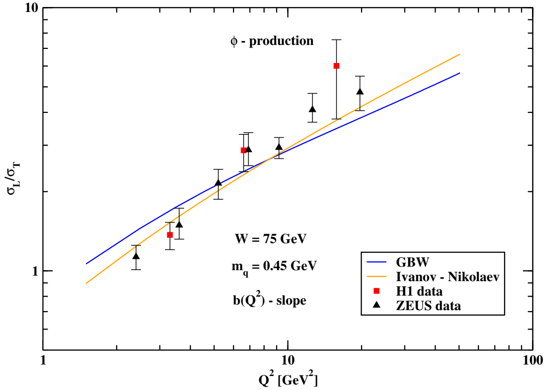
ϕ-production - Cross section ratio σ_L/σ_T

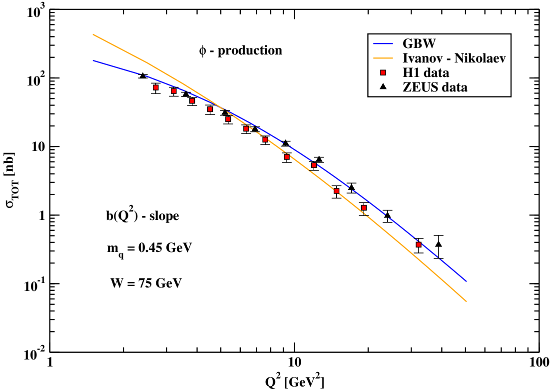
- **GBW** and **Ivanov-Nikolaev** models compared



[A.D. Bolognino, W. Schäfer, A. Szczurek (in progress)]

ϕ-production - Total cross section σ_{TOT}

- **GBW** and **Ivanov-Nikolaev** models compared
- $\sigma_{TOT} = \sigma_L + \epsilon\, \sigma_T$, with $\epsilon \approx 1$ in HERA kinematics



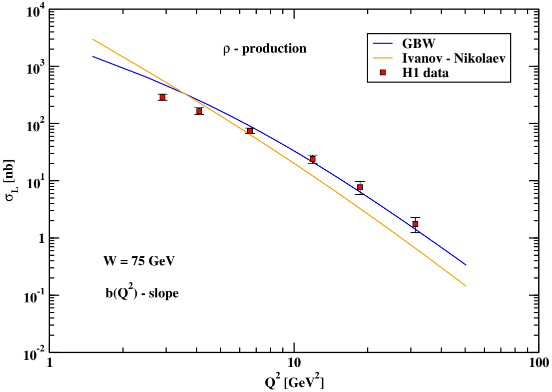
[A.D. Bolognino, W. Schäfer, A. Szczurek (in progress)]

Numerical results

ρ-production

ρ-production - Longitudinal cross section σ_L

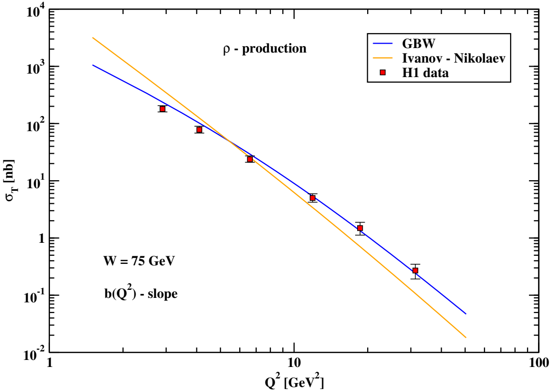
- WW approximation
- **GBW** and **Ivanov-Nikolaev** models compared



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

ρ-production - Transverse cross section σ_T

- WW approximation
- **GBW** and **Ivanov-Nikolaev** models compared



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

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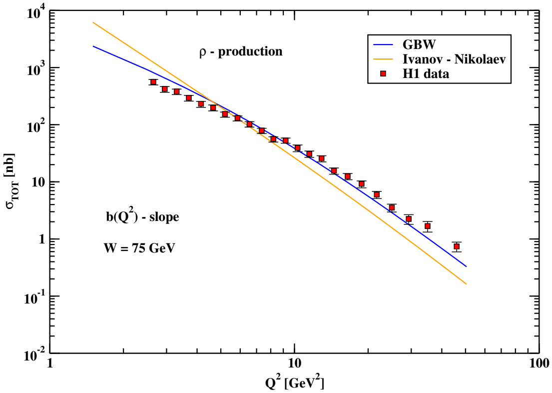

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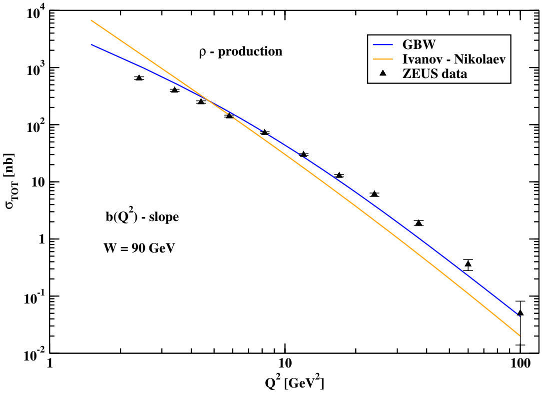


[A.D. Bolognino, F.G. Celiberto, D.Yu. Ivanov, A. Papa, W. Schäfer, A. Szczurek (in progress)]

Conclusions...

Exclusive leptoproduction of **polarized light vector mesons** to describe **cross sections**

- **Exclusive** final state + **small-x** limit $\Longrightarrow$ κ_T**-factorization** allowed
- t-dependence of σ parametrized via $b(Q^2)$-slope:

  $\Longrightarrow$ Improved predictions for ϕ**-production** via quark mass m_q ✓

  $\Longrightarrow$ Standard GBW model able to catch HERA data in ρ**-production** ✓

...Outlook

For ρ**-production**:

- NLO impact factor in ρ-meson leptoproduction $\Longrightarrow \Phi^{\gamma^* \to \rho} = [\mathrm{H}_{\mathrm{NLO}}] \circledast [\mathrm{DA}]$
- Test different UGD models $\xrightarrow{\textit{in order to}}$ calculate cross section

For ϕ**-production**:

- Cross section encoded by non-forward helicity amplitude and spin-flip
- Quark mass m_q in genuine contribution

...And in general

- UGD extraction from different channels:
  - **small-x gluon TMD** $\rightarrow$ **BFKL evolution** + **TMD input**

[A.D. Bolognino, F.G. Celiberto, . . . (in progress)]

- Consider other processes as testfield for UGD:
  - Heavy quark and heavy-meson 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:

◇ $\alpha_s \le 0.82$ (**frozen**)

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

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

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

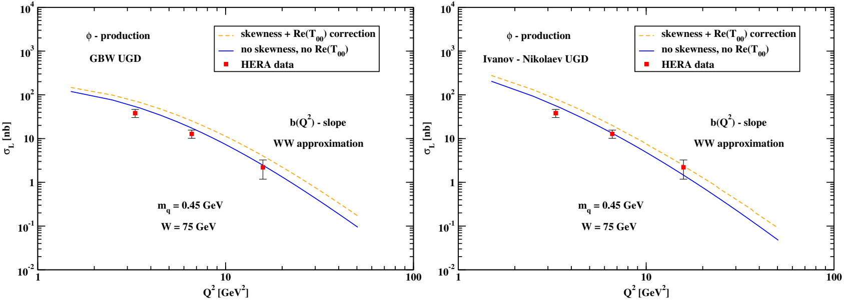
- $R_0^2(x) = \frac{1}{\mathrm{GeV}^2}\left(\frac{x}{x_0}\right)^{\lambda_p}$
- The normalization σ_0 and the parameters x_0 and $\lambda_p > 0$ of $R_0^2(x)$ have been determined by a global fit to $F_2(x)$:

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

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

Skewness effects - ϕ-production

Skewness effects on σ_L



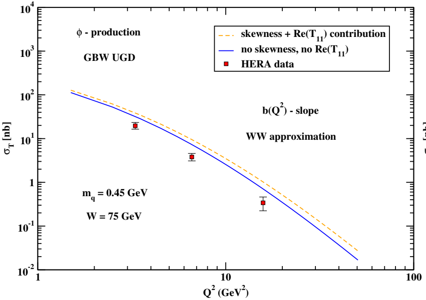
$$\sigma_L = Rg^2(1+\rho^2)\,\tilde{\sigma}_L$$

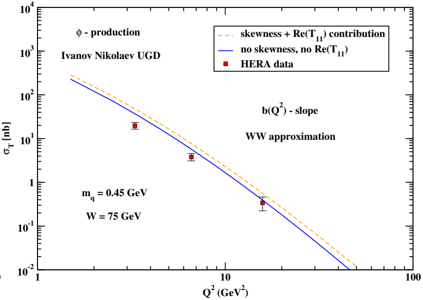
where

- $Rg = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda+5/2)}{\Gamma(\lambda+4)}$ with $\lambda = \frac{\delta \log(1/s\,\Im T_{00})}{\delta \log(1/x)}$
- $\rho = \tan(\frac{\pi\lambda}{2}) = \frac{\Re T_{00}}{\Im T_{00}}$

Skewness effects - ϕ-production

Skewness effects on σ_T





$$\sigma_T = Rg^2 (1+\rho^2)\, \tilde{\sigma}_T$$

where

- $Rg = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda+5/2)}{\Gamma(\lambda+4)}$ with $\lambda = \frac{\delta \log(1/s\, \Im T_{11})}{\delta \log(1/x)}$
- $\rho = \tan(\frac{\pi\lambda}{2}) = \frac{\Re T_{11}}{\Im T_{11}}$