

Exclusive leptoproduction of the ρ -meson in the high energy limit

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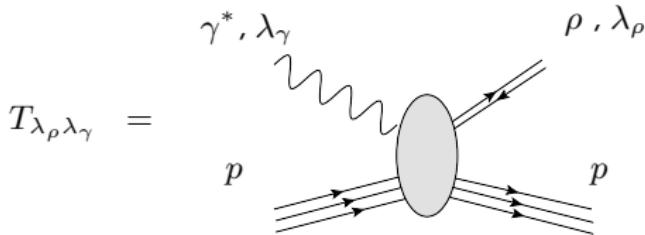
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Introduction

Helicity amplitudes of the diffractive lepto-production of the ρ meson

- **Helicity Amplitudes** $T_{\lambda_\rho \lambda_\gamma}$



Examples :

$$T_{00} \iff \gamma_L^* p \rightarrow \rho_L p$$

$$T_{11} \iff \gamma_T^* p \rightarrow \rho_T p$$

- **Perturbative Regge Limit :**

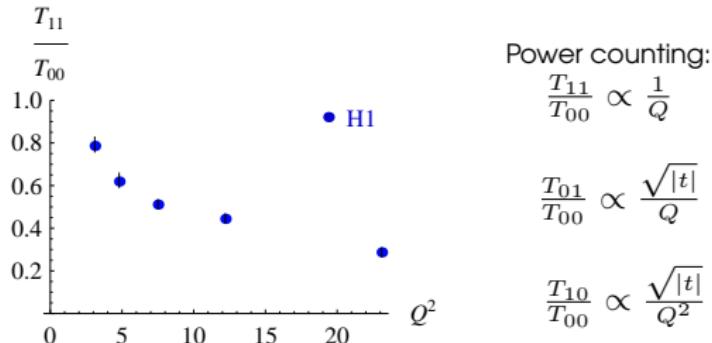
- **Regge Limit** : $s = W^2 \gg Q^2, |t|, M_{\text{hadron}}^2$

- **Hard scale** : $Q \gg \Lambda_{QCD}$

Introduction

Experimental data of helicity amplitudes at high energy

- Helicity amplitudes $T_{\lambda_\rho \lambda_\gamma}$: $\gamma^*_\lambda + p \rightarrow \rho_{\lambda_\rho} + p$
- H1 and ZEUS data for Helicity Amplitudes at HERA:



S. Chekanov et al. (2007), F.D Aaron et al. (2010)

- Kinematics

- High energy in the center of mass $30 \text{ GeV} < W < 180 \text{ GeV}$
- Photon Virtuality $2.5 \text{ GeV}^2 < Q^2 < 60 \text{ GeV}^2$
- $|t| < 1 \text{ GeV}^2$

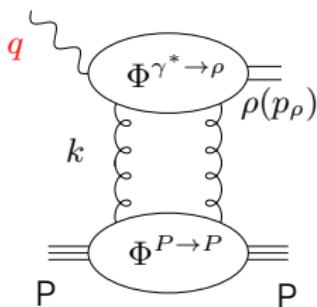
$$\Rightarrow s_{\gamma^* p} = W^2 \gg Q^2 \gg \Lambda_{QCD}^2$$

Introduction

A Theoretical approach within k_T factorisation

k_T factorisation

- Amplitudes with gluons exchange in t -channel dominate at large s ($s = W^2$)



Born order: 2 t -channel gluons

$$T_{\lambda_\rho \lambda_\gamma} = i s \int \frac{d^2 \underline{k}}{(2\pi)^2 (\underline{k}^2)^2} \Phi^{\gamma^*(\lambda_\gamma) \rightarrow \rho(\lambda_\rho)}(\underline{k}) \Phi^{P \rightarrow P}(-\underline{k})$$

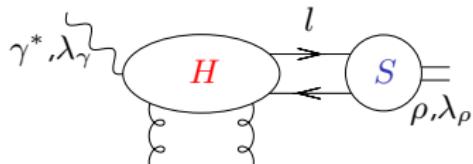
Introduction

A theoretical approach of the $\Phi^{\gamma^* \rightarrow \rho}$ impact factor up to twist 3

Impact factors $\Phi^{\gamma^* \rightarrow \rho}$

- $\Phi^{\gamma^* \rightarrow \rho}$: collinear factorisation

$$Q^2 \gg \Lambda_{QCD}^2$$



- $T_{00} \equiv \gamma_L^* \rightarrow \rho_L$ impact factor : Dominant term at **twist 2** $\equiv 1/Q$
- $T_{11} \equiv \gamma_T^* \rightarrow \rho_T$ impact factor : Dominant term at **twist 3** $\equiv 1/Q^2$

Recently computed at $t = t_{min} \approx 0$

Nucl. Phys. B **828** (2010) 1-68. Anikin, Ivanov, Pire, Szymanowski, Wallon

Introduction

Construction of phenomenological models

Phenomenological models to compare to H1 and ZEUS data:

$$T_{\lambda_\rho \lambda_\gamma} = i s \int \frac{d^2 \underline{k}}{(2\pi)^2 (\underline{k}^2)^2} \Phi^{\gamma^*(\lambda_\gamma) \rightarrow \rho(\lambda_\rho)}(\underline{k}) \Phi^{P \rightarrow P}(-\underline{k})$$

- First approach:

(PhysRevD.84.054004 I. V. Anikin, A. B., D .Yu. Ivanov, B. Pire, L. Szymanowski, S. Wallon)

- Using results for the $\Phi^{\gamma^*(\lambda_\gamma) \rightarrow \rho(\lambda_\rho)}(\underline{k})$ up to twist 3
- Using model for the proton impact factor $\Phi^{P \rightarrow P}$

- Second approach:

- $\Phi^{\gamma^*(\lambda_\gamma) \rightarrow \rho(\lambda_\rho)}$ expressed in coordinate space exhibits the color dipole scattering amplitude with the target.

(arXiv:1204.2281 A. B., L. Szymanowski, S. Wallon)

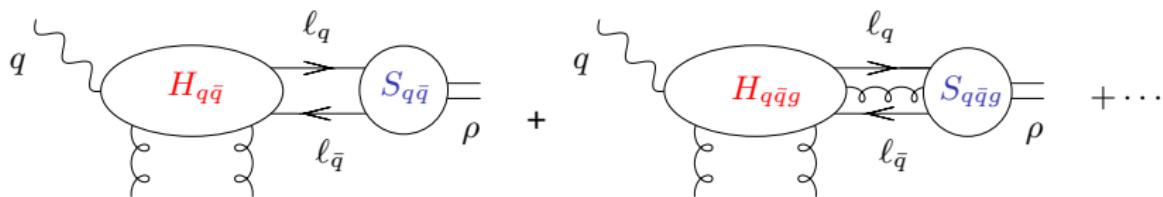
- Using a model for the dipole/target scattering amplitude.

Collinear factorization

Light-Cone Collinear approach

- The impact factor $\Phi^{\gamma^*(\lambda_\gamma) \rightarrow \rho(\lambda_\rho)}$ can be written as

$$\Phi^{\gamma^*(\lambda_\gamma) \rightarrow \rho(\lambda_\rho)} = \int d^4 \ell \cdots \text{tr}[H^{(\lambda_\gamma)}(\ell \cdots) \quad \text{hard part} \quad S^{(\lambda_\rho)}(\ell \cdots)] \quad \text{soft part}$$



Collinear factorization

Light-Cone Collinear approach: 2 steps of factorization (2-parton case)

Collinear factorization

- Momentum factorization:

$$\ell_q = y p_\rho + \ell^\perp + (\ell_q \cdot p_\rho) n \longrightarrow H_{q\bar{q}}(\ell_q) = H_{q\bar{q}}(y p) + \frac{\partial H_{q\bar{q}}(\ell)}{\partial \ell_\alpha} \Big|_{\ell=y p} \ell_\alpha^\perp + \dots$$

- Spinor (and color) factorisation:

$$\Phi_{q\bar{q}}^{\gamma^*(\lambda_\gamma) \rightarrow \rho(\lambda_\rho)} = \int dy \left\{ \text{Tr}[H_{q\bar{q}}(y p) \Gamma] S_{q\bar{q}}^\Gamma(y) + \text{Tr}[\partial_\perp H_{q\bar{q}}(y p) \Gamma] \partial_\perp S_{q\bar{q}}^\Gamma(y) \right\}$$

$$S_{q\bar{q}}^\Gamma(y) = \int \frac{d\lambda}{2\pi} e^{-i\lambda y} \langle \rho(p) | \bar{\psi}(\lambda n) \Gamma \psi(0) | 0 \rangle$$

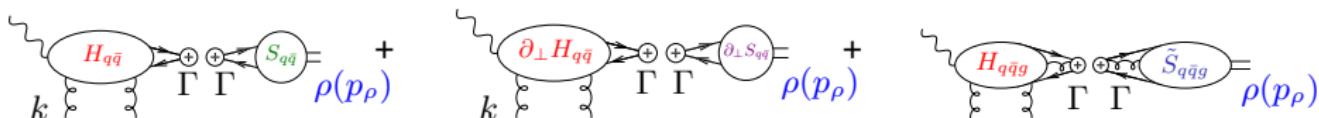
$$\partial_\perp S_{q\bar{q}}^\Gamma(y) = \int \frac{d\lambda}{2\pi} e^{-i\lambda y} \langle \rho(p) | \bar{\psi}(\lambda n) \Gamma i \overleftrightarrow{\partial}_\perp \psi(0) | 0 \rangle$$

Collinear factorization

Light-Cone Collinear approach: Hard parts

Collinear factorization of 2-parton and 3-parton contributions

- Momentum, spinorial and color factorizations



- Hard part diagrams for each Γ

- $H_{q\bar{q}}$ \Rightarrow 6 diagrams
- $\partial_\perp H_{q\bar{q}}$ \Rightarrow 12 diagrams
- $H_{q\bar{q}g}$ \Rightarrow 12 "Abelian" diagrams, 16 "Non-Abelian" diagrams

Collinear factorization

Parametrization of vacuum-to-rho-meson matrix elements (DAs)

• Twist 2 and Twist 3 DAs

Projection on Lorentz tensors built from p_μ , $e_{\perp\mu}^*$, $\epsilon_{\mu\alpha\beta\gamma}$ $e_{\perp}^{*\alpha} p^\beta n^\gamma$

Twist 2	Vector γ_μ
$\langle \bar{\psi}(z) \Gamma \psi(0) \rangle$	$\varphi_1(y)$

Twist 3 (3-parton)	Vector γ_μ	Axial vector $\gamma_5 \gamma_\mu$
$\langle \bar{\psi}(z_1) \Gamma g A_\alpha^T(z_2) \psi(0) \rangle$	$B(y_1, y_2)$	$D(y_1, y_2)$

Twist 3 (2-parton)	Vector γ_μ	Axial vector $\gamma_5 \gamma_\mu$
$\langle \bar{\psi}(z) \Gamma \psi(0) \rangle$	$\varphi_3(y)$	$\varphi_A(y)$
$\langle \bar{\psi}(z) \Gamma i \not{\partial}_\perp \psi(0) \rangle$	$\varphi_1^T(y)$	$\varphi_A^T(y)$

• Relations between DAs

- Equation of motion $\langle \bar{\psi}(\lambda n) \not{D} \psi(0) \rangle = 0$
- n -independence $(\ell_q = \textcolor{green}{y} p_\rho + \textcolor{violet}{\ell}^\perp + (\ell_q \cdot p_\rho) \textcolor{red}{n}) \quad \frac{d\mathcal{A}}{dn^\mu} = 0$

Collinear factorization

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$\langle \bar{\psi}(z_1) \Gamma g A_\alpha^T(z_2) \psi(0) \rangle$	$B(y_1, y_2)$	$D(y_1, y_2)$

Twist 3 (2-parton)	Vector γ_μ	Axial vector $\gamma_5 \gamma_\mu$
$\langle \bar{\psi}(z) \Gamma \psi(0) \rangle$	$\varphi_3^{WW}(y) + \varphi_3^{gen}(y)$	$\varphi_A^{WW}(y) + \varphi_A^{gen}(y)$
$\langle \bar{\psi}(z) \Gamma i \not{\partial}_\perp \psi(0) \rangle$	$\varphi_1^{TWW}(y) + \varphi_1^{Tgen}(y)$	$\varphi_A^{TWW}(y) + \varphi_A^{Tgen}(y)$

• Relations between DAs

- Equation of motion $\langle \bar{\psi}(\lambda n) \not{D} \psi(0) \rangle = 0$
- n -independence $(\ell_q = \textcolor{green}{y} p_\rho + \textcolor{violet}{\ell}^\perp + (\ell_q \cdot p_\rho) \textcolor{red}{n}) \quad \frac{d\mathcal{A}}{dn^\mu} = 0$

Collinear factorization

Explicit solutions for the DAs

- Evolution of the DAs

P. Ball, V.M Braun, Y. Koike, K. Tanaka

$$\varphi_1(y, \mu_F^2) = 6y\bar{y}(1 + a_2(\mu_F^2)\frac{3}{2}(5(y - \bar{y})^2 - 1)) \xrightarrow{\mu_F^2 \rightarrow \infty} 6y\bar{y}$$

$$B(y_1, y_2; \mu_F^2) = -5040y_1\bar{y}_2(y_1 - \bar{y}_2)(y_2 - y_1)$$

$$D(y_1, y_2; \mu_F^2) = -360y_1\bar{y}_2(y_2 - y_1)(1 + \frac{\omega_{\{1,0\}}^A(\mu_F^2)}{2}(7(y_2 - y_1) - 3))$$

with μ_F the collinear factorization scale.

$$\varphi(y, \mu_F) \propto \int_0^{|\ell_\perp| < \mu_F} d^2\ell_\perp \Phi(y, \ell_\perp)$$

Impact factors in momentum space

- Some results in momentum space

- Twist 2 $\gamma_L^* \rightarrow \rho_L$ impact factor:

$$\Phi^{\gamma_L^* \rightarrow \rho_L}(y, \underline{k}) \propto e \alpha_s \frac{f_\rho}{Q} \int_0^1 dy \varphi_1(y, \mu_F^2) \frac{\underline{k}^2}{\underline{k}^2 + y\bar{y}Q^2}$$

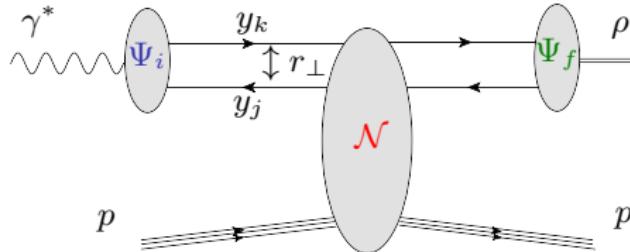
- Twist 3 $\gamma_T^* \rightarrow \rho_T$ impact factor in WW approximation

$$\Phi^{\gamma_T^* \rightarrow \rho_T, WW}(y, \underline{k}) \propto e \alpha_s \frac{m_\rho f_\rho}{Q^2} \int_0^1 du \frac{\varphi_1(u; \mu_F^2)}{u} \int_0^u dy \frac{\underline{k}^2(\underline{k}^2 + 2y\bar{y}Q^2)}{(\underline{k}^2 + y\bar{y}Q^2)^2}$$

Dipole Models

Dipole model picture

- Factorization of a high energy scattering amplitude into:



- Initial Ψ_i and final Ψ_f states wave functions.
- Universal scattering amplitude $\mathcal{N} \equiv \mathcal{N}_{\text{dipole-target}}$.
- In the impact factors "Target" = the two t -channel gluons:

$$\mathcal{N}(\underline{r}, \underline{k}) = \frac{4\pi\alpha_s}{N_c} \left(1 - e^{i\underline{k} \cdot \underline{r}}\right) \left(1 - e^{-i\underline{k} \cdot \underline{r}}\right)$$

The 2-parton Impact factor

Fourier transform of the $\gamma^* \rightarrow \rho$ impact factor

- Impact factors $\Phi_{q\bar{q}}^{\gamma^* \rightarrow \rho} = -\frac{1}{4} \int d^4 \ell \text{Tr}(\mathbf{H}_{q\bar{q}} \Gamma)(\ell) S_{q\bar{q}\Gamma}(\ell)$

- Collinear approximation \Rightarrow expansion around $\ell_\perp = 0$:

$$\text{Tr}(\mathbf{H}_{q\bar{q}} \Gamma)(\ell) = \int \frac{d^2 r_\perp}{2\pi} \tilde{H}_{q\bar{q}}^\Gamma(y, r_\perp) e^{-i\ell_\perp \cdot r_\perp} = \int \frac{d^2 r_\perp}{2\pi} \tilde{H}_{q\bar{q}}^\Gamma(y, r_\perp) (1 - i\ell_\perp \cdot r_\perp + \dots)$$

- 2-parton impact factor in transverse coordinate space:

$$\begin{aligned} \Phi_{q\bar{q}}^{\gamma^* \rightarrow \rho} = & -\frac{1}{4} m_\rho f_\rho \int dy \int \frac{d^2 r_\perp}{(2\pi)} \left\{ \tilde{H}_{q\bar{q}}^{\gamma, \mu}(y, \underline{r}) \left(\varphi_3(y) \mathbf{e}_{\rho\mu}^* + i\varphi_{1T}(y) \mathbf{p}_{1\mu} (\mathbf{e}_\rho^* \cdot \underline{r}) \right) \right. \\ & \left. + \tilde{H}_{q\bar{q}}^{\gamma_5 \gamma, \mu}(y, \underline{r}) \left(i\varphi_A(y) \varepsilon_{\mu e_\rho^* p_1 n} + \varphi_{AT}(y) p_{1\mu} \varepsilon_{r_\perp e_\rho^* p_1 n} \right) \right\} \end{aligned}$$

The 2-parton impact factor

Role of the equation of motion of QCD

- Hard parts Fourier transforms: $\mathcal{N}(\underline{r}, \underline{k}) \propto (1 - e^{i\underline{k} \cdot \underline{r}})(1 - e^{-i\underline{k} \cdot \underline{r}})$

$$\tilde{H}_{q\bar{q}}^{\gamma, \mu}(y, \underline{r}) \propto -y\bar{y}K_0(\mu|\underline{r}|)e_\gamma^\mu + i(y - \bar{y})\mu \frac{\underline{e} \cdot \underline{r}}{|\underline{r}|} K_1(\mu|\underline{r}|) \times (\mathcal{N}(\underline{r}, \underline{k}) - 1) \frac{p_2^\mu}{s}$$

$$\tilde{H}_{q\bar{q}}^{\gamma\gamma_5, \mu}(y, \underline{r}) \propto \epsilon^{\mu\nu\rho\sigma}(e_{\gamma\nu} \frac{\underline{r}_\perp \rho}{|\underline{r}|} \frac{p_{2\sigma}}{s}) \mu K_1(\mu|\underline{r}|) \times (\mathcal{N}(\underline{r}, \underline{k}) - 1)$$

- Equations of motion of QCD:

$$\begin{aligned} \Phi_{q\bar{q}}^{\gamma^* \rightarrow \rho} &= \int dy \int d\underline{r} \psi_{(q\bar{q})}^{\gamma^* \rightarrow \rho_T} \times \mathcal{N}(\underline{r}, \underline{k}) \\ &+ \text{Hard Terms} \times \underbrace{(2y\bar{y}\varphi_3(y) + (y - \bar{y})\varphi_{1T}(y) + \varphi_{AT}(y))}_{=0 \text{ in the Wandzura Wilczek approximation}} \end{aligned}$$

The 2-parton impact factor

Results in the WW approximation

Twist 3, 2-parton impact factors in WW approximation:

$$\Phi_{q\bar{q}}^{\gamma_T^* \rightarrow \rho_T \text{ WW}} = \int dy \int d^2 \underline{r} \, \mathcal{N}(\underline{r}, \underline{k}) \underbrace{\sum_h \phi_{\lambda_\rho, h}^{WW} \times \Psi_{\lambda_\gamma, h}^{\gamma_T^*}}_{\psi_{q\bar{q}}^{WW}}$$

with :

$$\Psi_{\lambda_\gamma, h}^{\gamma_T^*}(y, \underline{r}) = i \frac{e}{2\pi} \sqrt{\frac{N_c}{\pi}} (y \delta_{h, \lambda_\gamma} + \bar{y} \delta_{h, -\lambda_\gamma}) \frac{\underline{e}^{(\lambda_\gamma)} \cdot \underline{r}}{|\underline{r}|} \mu K_1(\mu |\underline{r}|)$$

$$\phi_{\lambda_\rho, h}^{WW} = -i \frac{m_\rho f_\rho}{\sqrt{2}} (\underline{e}_\rho^{\lambda_\rho *} \cdot \underline{r}) \sqrt{\frac{\pi}{4N_c}} (\varphi_A^{TWW} + (\delta_{h, \lambda_\rho} - \delta_{h, -\lambda_\rho}) \varphi_1^{TWW})$$

The WW-result

Interpretation

- Schematic interpretation:

$$\int d^2\underline{r} \quad \text{wavy line} \times \left(\underline{r} \cdot \partial_z \right) \text{z-axis dipole} + \dots \Big|_{z=0} \times \text{rho meson wave function} \mathcal{N}(\underline{r}, \underline{k})$$

$\Psi_{\lambda_\gamma, h}^{\gamma^*_T}$ $\phi_{\lambda_\rho, h}^{WW}$ $\mathcal{N}(\underline{r}, \underline{k})$

- Compare with ρ -meson wave function models

- Expressing DAs in terms of the ρ -meson wave function
- Implement the models in our result

$$\phi_{\lambda_\rho, h}^{WW} \propto (\varphi_A^{TWW} + (\delta_{h, \lambda_\rho} - \delta_{h, -\lambda_\rho}) \varphi_1^{TWW})$$

The 3-parton impact factor

Expression and kinematics

- The 3-parton amplitude in transverse coordinate space after collinear approximation

$$\Phi_{3\text{-parton}}^{\gamma^* \rightarrow \rho} = -\frac{im_\rho f_\rho}{4} \int dy_1 dy_g \int \frac{d^2 r_{1\perp}}{(2\pi)^2} \frac{d^2 r_{g\perp}}{(2\pi)^2}$$

$$\left(\zeta_{3\rho}^V B(y_1, y_2) p_\mu e_{\rho\perp\alpha} \tilde{H}_{q\bar{q}g}^{\alpha, \gamma^\mu} (y_1, y_g, r_{1\perp}, r_{g\perp}) \right.$$

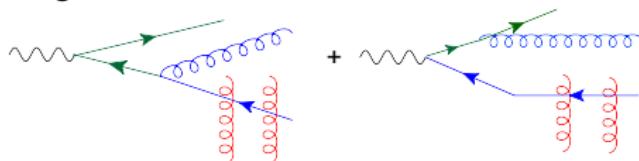
$$\left. + \zeta_{3\rho}^A i D(y_1, y_2) p_\mu \epsilon_{\alpha e_{\rho\perp} p n} \tilde{H}_{q\bar{q}g}^{\alpha, \gamma^\mu \gamma_5} (y_1, y_g, r_{1\perp}, r_{g\perp}) \right)$$

The 3-parton impact factor

Dynamics of the dipoles

Example: $\{\bar{q}g\}$ system

- Diagrams associated:



- Partons kinematics in transverse space \leftrightarrow nonrelativistic 2D mechanics of an equivalent system of masses $m_i \equiv y_i Q$

- Center of mass G of $\{\bar{q}g\} \leftrightarrow$ spectator dipole:

$$\underline{\ell}_G \mapsto 0$$

- Reduced particle of $\{\bar{q}g\} \leftrightarrow$ interacting dipole:

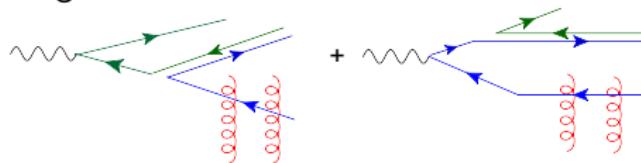
$$\underline{\ell} = \frac{y_g \underline{\ell}_{\bar{q}} - y_{\bar{q}} \underline{\ell}_g}{y_g + y_{\bar{q}}} \mapsto \underline{r}$$

The 3-parton impact factor

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The 3-parton impact factor

Results form of the 3-parton impact factor

- 3-partons results:

$$\Phi_{q\bar{q}g}^{\gamma_T^* \rightarrow \rho_T} \propto \int dy_1 \int dy_2 \int d^2 \underline{r} \psi_{(q\bar{q}g)}^{\gamma_T^* \rightarrow \rho_T}(y_1, y_2, \underline{r}) \times \mathcal{N}(\underline{r}, \underline{k}) + \int dy_1 dy_2 \frac{2S(y_1, y_2)}{\bar{y}_1}$$

$$\text{with } S(y_1, y_2) = \zeta_\rho^V(\mu^2)B(y_1, y_2; \mu^2) + \zeta_\rho^A(\mu^2)D(y_1, y_2; \mu^2)$$

- Impact factor 2-parton+3-parton:

$$\begin{aligned} \Phi^{\gamma_T^* \rightarrow \rho_T} &\propto \int dy_i \int d^2 \underline{r} \mathcal{N}(\underline{r}, \underline{k}) \left(\psi_{(q\bar{q})}^{\gamma_T^* \rightarrow \rho_T}(y, \underline{r}) + \psi_{(q\bar{q}g)}^{\gamma_T^* \rightarrow \rho_T}(y_1, y_2, \underline{r}) \right) \\ &+ \underbrace{\int \frac{dy}{y\bar{y}} \left(2y\bar{y}\varphi_3(y) + (y - \bar{y})\varphi_1^T(y) + \varphi_A^T(y) \right)}_{=0 \text{ due to EOM of QCD}} + \int dy_1 dy_2 \frac{2S(y_1, y_2)}{\bar{y}_1} \end{aligned}$$

Helicity amplitudes

Dipole cross-section

- Dipole-target cross-section:

$$\hat{\sigma}(x, \underline{r}) = \frac{N_c^2 - 1}{4} \int \frac{d^2 \underline{k}}{\underline{k}^4} \mathcal{F}(x, \underline{k}) \mathcal{N}(\underline{k}, \underline{r})$$

- Helicity amplitudes:

$$\begin{aligned} T_{00} &= s \int dy \int d\underline{r} \psi_{(q\bar{q})}^{\gamma_L^* \rightarrow \rho_L}(y, \underline{r}; Q, \mu_F) \hat{\sigma}(x, \underline{r}) \\ T_{11} &= s \int dy \int d\underline{r} \psi_{(q\bar{q})}^{\gamma_T^* \rightarrow \rho_T}(y, \underline{r}; Q, \mu_F) \hat{\sigma}(x, \underline{r}) \\ &+ s \int dy_2 \int dy_1 \int d\underline{r} \psi_{(q\bar{q}g)}^{\gamma_T^* \rightarrow \rho_T}(y_1, y_2, \underline{r}; Q, \mu_F) \hat{\sigma}(x, \underline{r}), \end{aligned}$$

Helicity amplitudes

A model for the dipole cross-section

Model for the dipole cross-section $\hat{\sigma}$

- rc-BK numerical solution (Albacete, Armesto, Milhano, Quiroga Arias, Salgado)
 - fitting DIS data with light quarks u, d, s
 - including heavy quarks c, b contribution to DIS data
 - GBW-like and MV-like initial conditions
- Good description of inclusive and longitudinal structure functions.

Polarized cross-sections

- Differential cross-sections

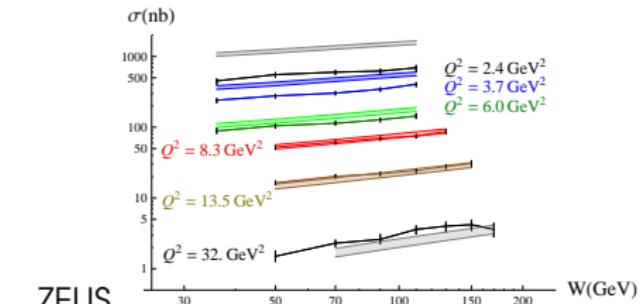
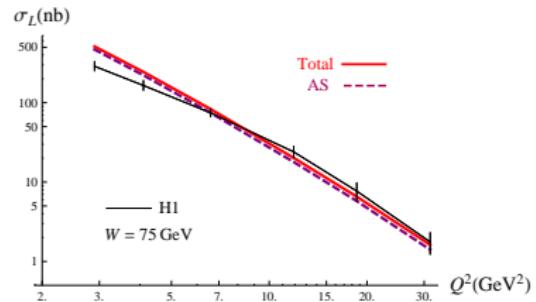
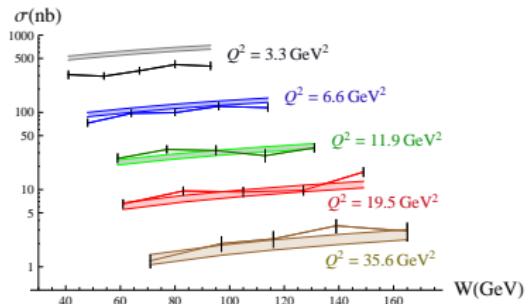
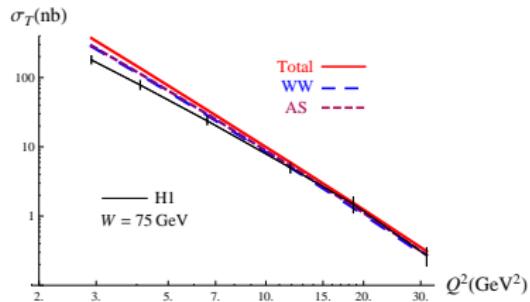
$$\frac{d\sigma_{L,T}}{dt}(t) = e^{-b(Q^2)t} \frac{d\sigma_{L,T}}{dt}(t=0),$$

- Polarized cross-sections

$$\begin{aligned}\sigma_L &= \frac{1}{b(Q^2)} \frac{T_{00}(s, t=0)^2}{16\pi s^2} \\ \sigma_T &= \frac{1}{b(Q^2)} \frac{T_{11}(s, t=0)^2}{16\pi s^2}.\end{aligned}$$

Results

Comparison with H1 and ZEUS data

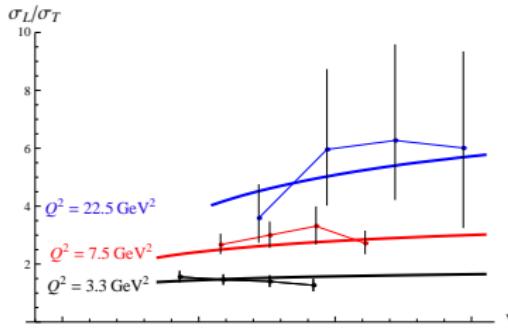


H1

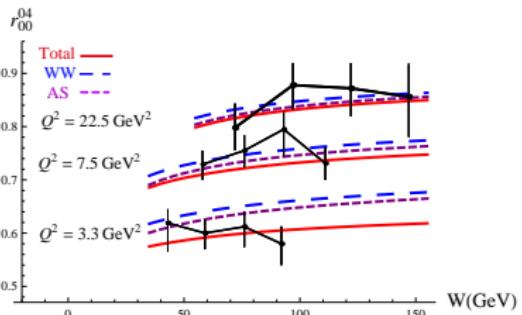
ZEUS

Results

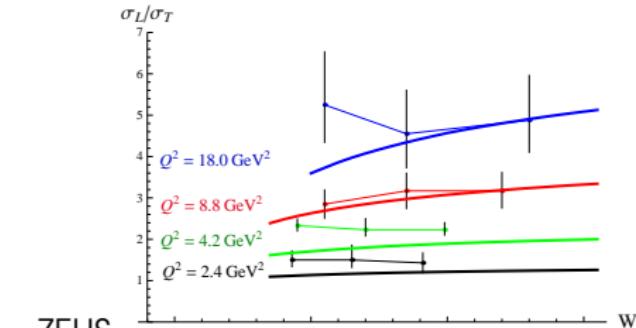
Comparison with H1 and ZEUS data



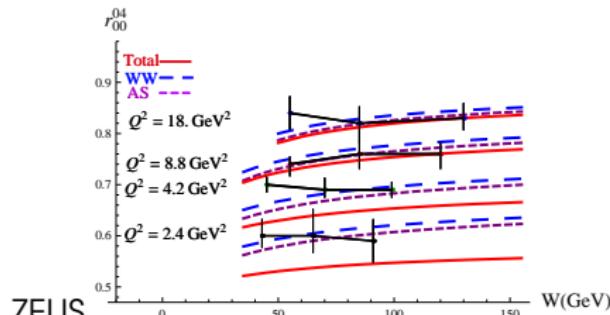
H1



H1



ZEUS



ZEUS

Conclusion

- Inclusion of saturation effects in the diffractive meson production up to twist 3 accuracy for the $\gamma^* \rightarrow \rho$ impact factor
- Results
 - Predictions with normalizations in good agreement with HERA data for Q^2 larger than $\approx 6 - 8 \text{ GeV}^2$
 - Predictions not really dependent on the choice of the collinear factorization scale μ_F
- Some perspectives
 - Implementing existing models for the ρ meson wave function through the DAs
 - Extending the kinematics at $t \neq 0 \Rightarrow T_{01}$, etc...
 - Higher twist contributions of the impact factor

Results

the μ_F dependence

