LUND UNIVERSITY
Faculty of Science

Theoretical High Energy Physics

Inclusive and Exclusive Processes with a Leading Neutron in ep and pp collisions

Victor P. Goncalves

High and Medium Energy Group - UFPel - Brazil

Based on PLB 572 (2016) 76, PRD93 (2016) 054025 and PRD94 (2016) 014009

In collaboration with D. Spiering, B. Moreira, F. Navarra and F. Carvalho.

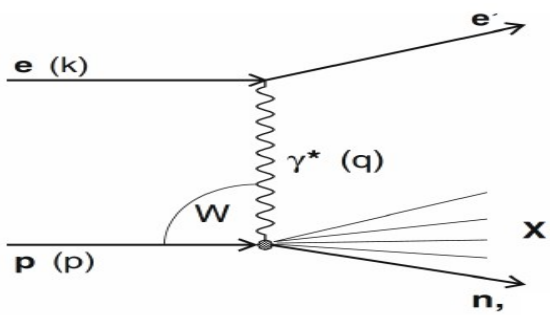
Lund
01 Dec
2016

Motivation

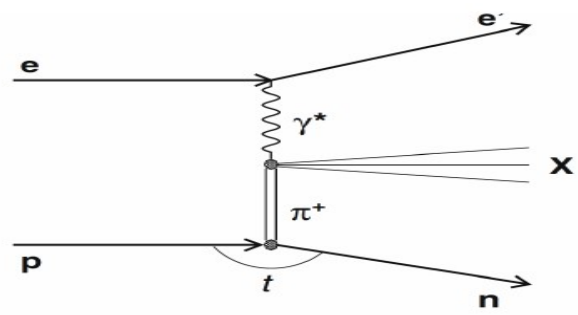
- High precision data on leading neutrons produced in electron - proton reaction at HERA at high energies became available.

Motivation

- High precision data on leading neutrons produced in electron - proton reaction at HERA at high energies became available.



normal DIS
with quark fragmentation



pion emission

Forward neutrons
$\eta > 7.9$
$0.1 < x_F < 0.94$
$0 < p_T^* < 0.6$ GeV

Motivation

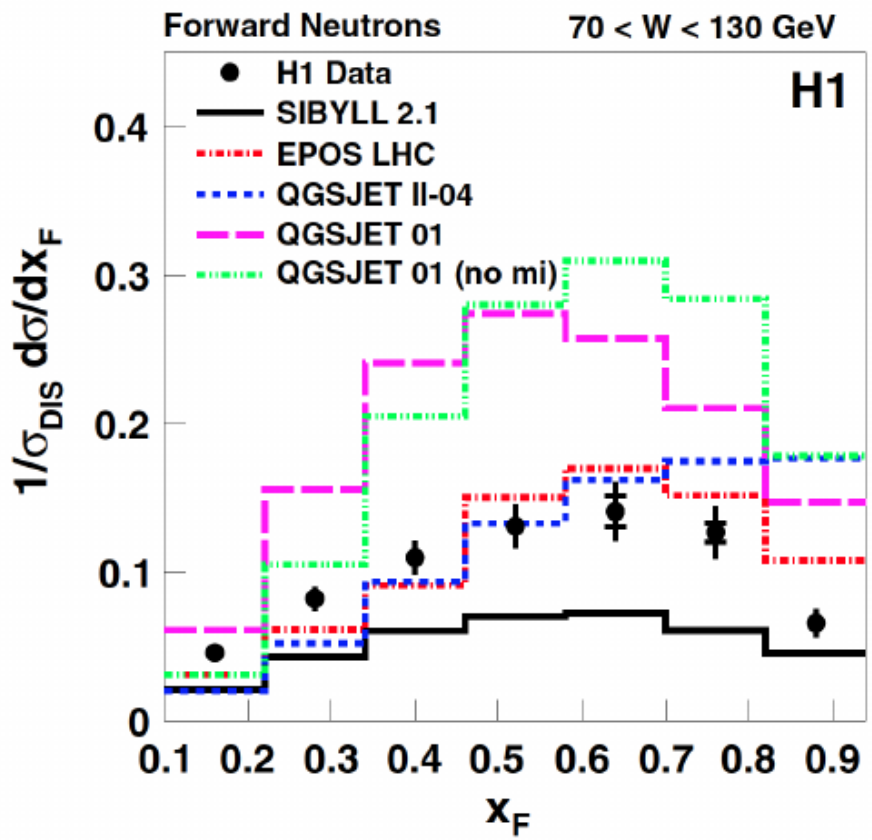
- High precision data on leading neutrons produced in electron – proton reaction at HERA at high energies became available.
- In spite of intense experimental and theoretical efforts (*), the Feynman momentum distribution of the leading neutrons remains without a satisfactory theoretical description.

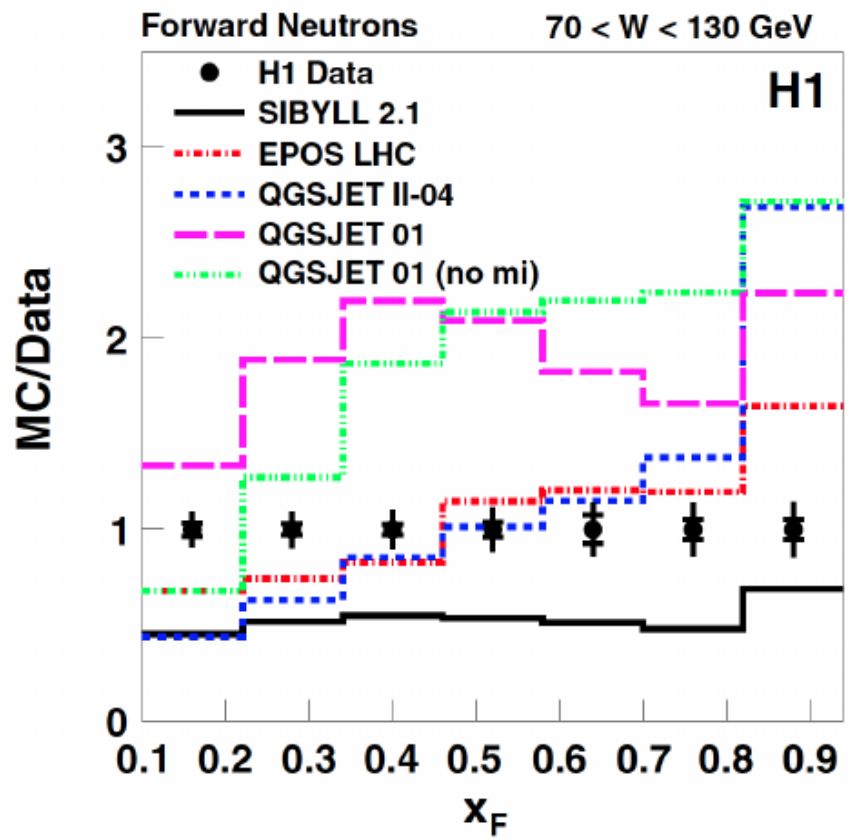
(*) D´Alesio, Holtmann, Kaidalov, Khoze, Kopeliovich, Martin, Melnitchouk, Nikolaev, Pirner, Ryskin, Sczureck, Schäfer, Speth, Thomas, …

Motivation

- High precision data on leading neutrons produced in electron – proton reaction at HERA at high energies became available.
- In spite of intense experimental and theoretical efforts, the Feynman momentum distribution of the leading neutrons remains without a satisfactory theoretical description.
- The interpretation of cosmic ray data depends on the accurate knowledge of the leading baryon momentum spectrum and its energy dependence.

Motivation

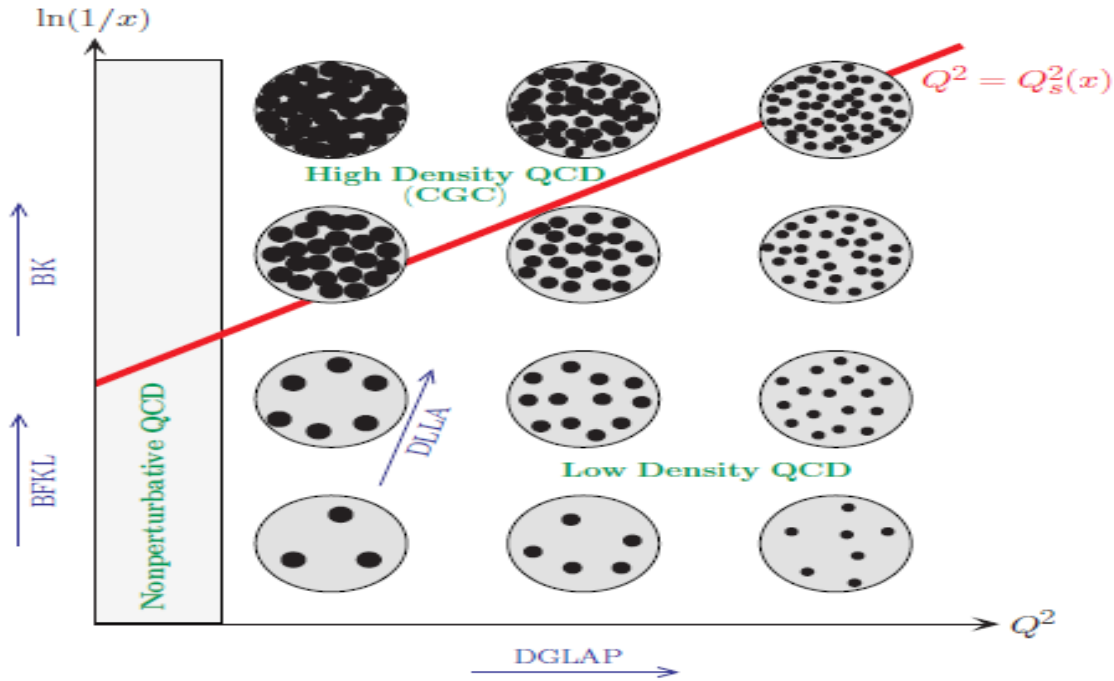

Forward Neutrons
70 < W < 130 GeV
H1 Data
SIBYLL 2.1
EPOS LHC
QGSJET II-04
QGSJET 01
QGSJET 01 (no mi)
H1
$1/\sigma_{DIS}\, d\sigma/dx_F$
x_F


Forward Neutrons
70 < W < 130 GeV
H1 Data
SIBYLL 2.1
EPOS LHC
QGSJET II-04
QGSJET 01
QGSJET 01 (no mi)
H1
MC/Data
x_F

Motivation

- High precision data on leading neutrons produced in electron – proton reaction at HERA at high energies became available.
- In spite of intense experimental and theoretical efforts, the Feynman momentum distribution of the leading neutrons remains without a satisfactory theoretical description.
- The interpretation of cosmic ray data depends on the accurate knowledge of the leading baryon momentum spectrum and its energy dependence.
- Leading neutron production at high energies probes the low – x component of the target wave function, where nonlinear effects are expected to be present in the description of the QCD dynamics.

Motivation



- Linear QCD evolution equations predict a power growth of gluon distribution as $x \to 0$ (violates unitarity).
- Number of gluons in the nucleon becomes so large that gluon recombine $\Rightarrow$ Nonlinear effects
- Saturation scale Q_s (energy and atomic number dependent) defines the onset of nonlinear QCD dynamics.

Our goal

- Treat the inclusive and exclusive processes with a leading neutron in ep collision using the color dipole formalism (*).

(*) Largely used to successfully describe the HERA data w/o a leading neutron.

Our goal

- Treat the inclusive and exclusive processes with a leading neutron in ep collision using the color dipole formalism.
- Describe the current high precision HERA data.

Our goal

- Treat the inclusive and exclusive processes with a leading neutron in ep collision using the color dipole formalism.
- Describe the current high precision HERA data.
- Estimate the impact of the nonlinear effects.

Our goal

- Treat the inclusive and exclusive processes with a leading neutron in ep collision using the color dipole formalism.
- Describe the current high precision HERA data.
- Estimate the impact of the nonlinear effects.
- Predict the magnitude of the cross sections for inclusive and exclusive processes with a leading neutron in future electron – proton colliders and in exclusive processes at the LHC.

Leading Neutron Processes at HERA

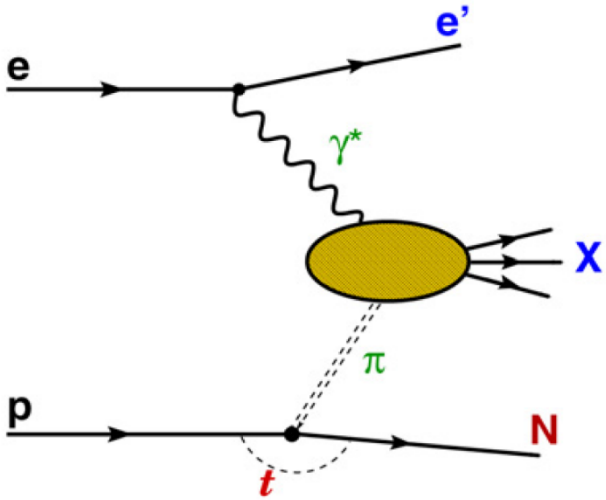
Inclusive process:

$$e + p \rightarrow e + n + X$$

Leading Neutron Processes at HERA

Inclusive process:

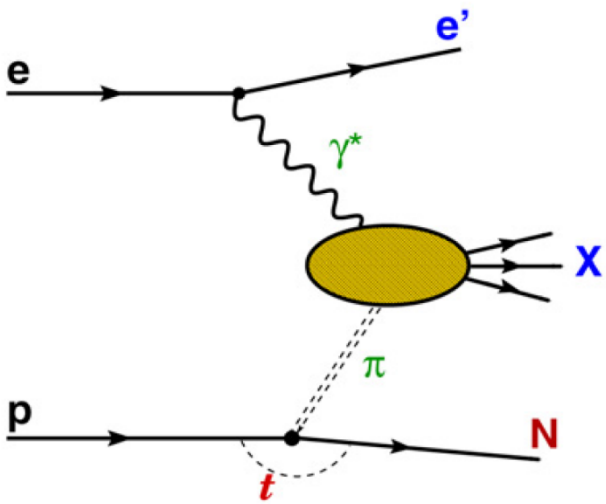
$$e + p \rightarrow e + n + X$$



Leading Neutron Processes at HERA

Inclusive process:

$$e + p \rightarrow e + n + X$$

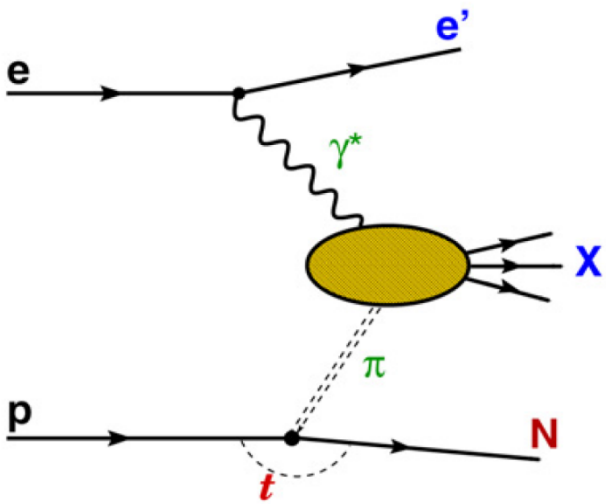


Forward neutrons
$\eta > 7.9$
$0.1 < x_F < 0.94$
$0 < p_T^* < 0.6$ GeV

Leading Neutron Processes at HERA

Inclusive process:

$$e + p \rightarrow e + n + X$$



Forward neutrons
$\eta > 7.9$
$0.1 < x_F < 0.94$
$0 < p_T^* < 0.6$ GeV

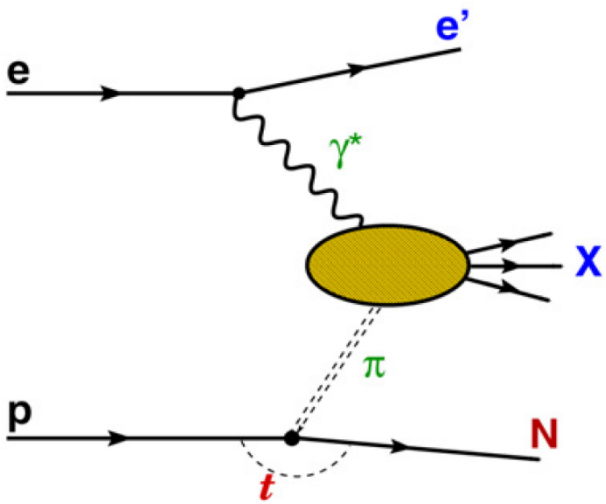
Exclusive process:

$$\gamma p \rightarrow \rho^0 \pi^+ n$$

Leading Neutron Processes at HERA

Inclusive process:

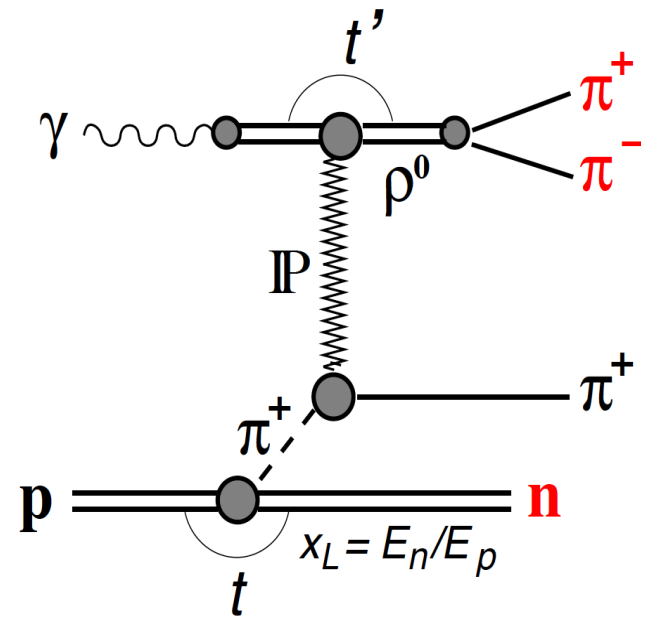
$$e + p \rightarrow e + n + X$$



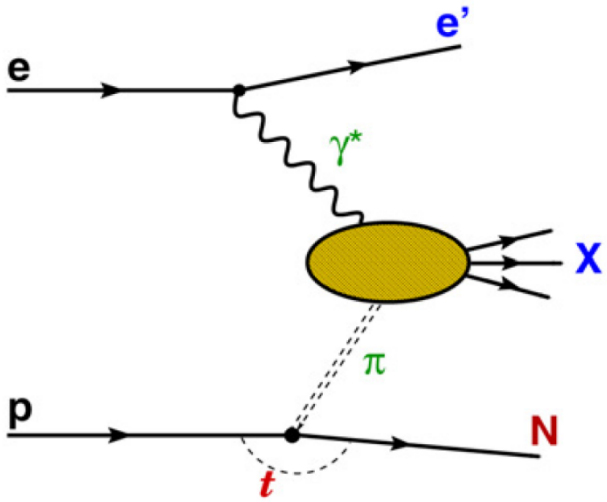
Forward neutrons
$\eta > 7.9$
$0.1 < x_F < 0.94$
$0 < p_T^* < 0.6$ GeV

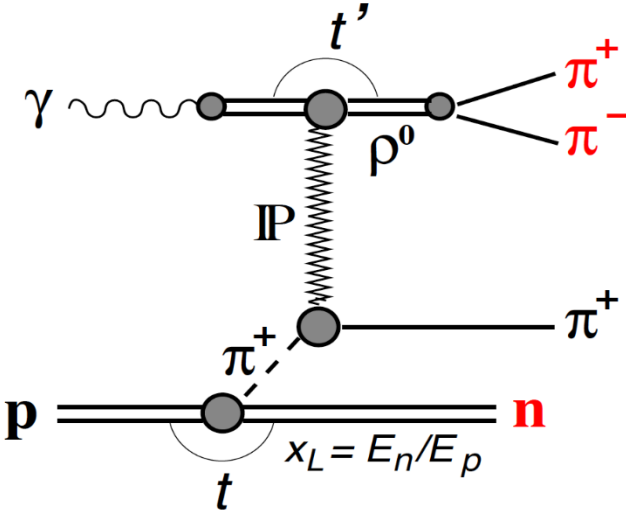
Exclusive process:

$$\gamma p \rightarrow \rho^0 \pi^+ n$$



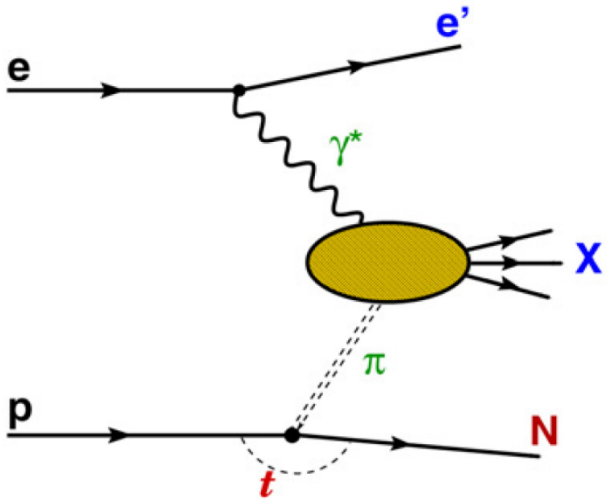
Leading Neutron Processes at HERA

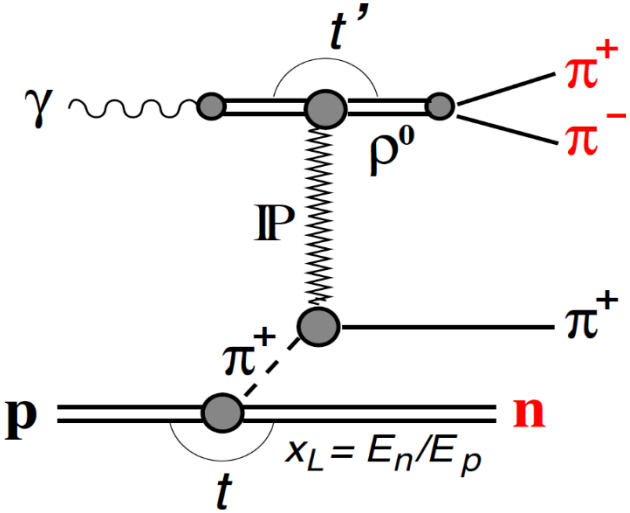




$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L\, dt} = f_{\pi/p}(x_L, t)\,\sigma_{\gamma^*\pi}(\hat{W}^2, Q^2)$$

Leading Neutron Processes at HERA

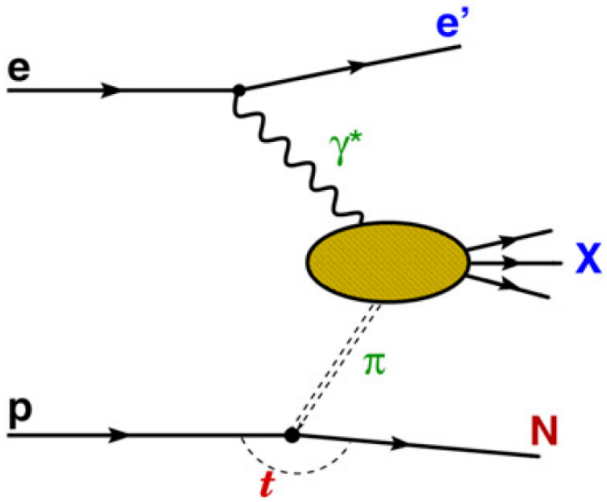


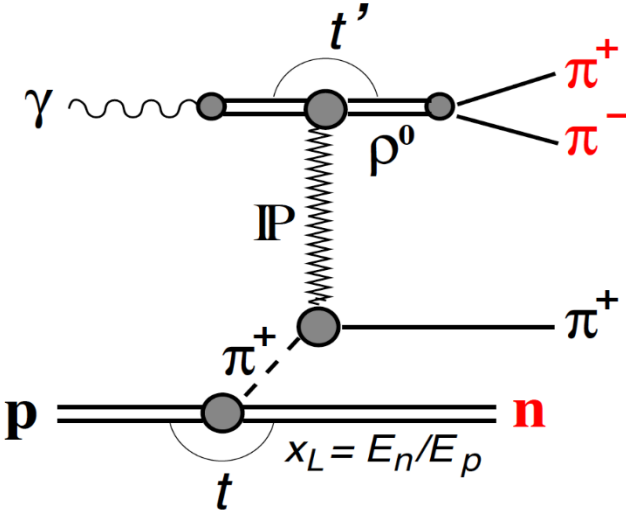


$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L\, dt} = f_{\pi/p}(x_L, t)\,\sigma_{\gamma^*\pi}(\hat{W}^2, Q^2)$$

Photon - pion cross section at energy $\hat{W}^2 = (1 - x_L)\, W^2$

Leading Neutron Processes at HERA





$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L\, dt} = f_{\pi/p}(x_L, t)\,\sigma_{\gamma^*\pi}(\hat{W}^2, Q^2)$$

Pion flux / Pion splitting function

Leading Neutron Processes at HERA

Pion flux / Pion splitting function:

$$f_{\pi/p}(x_L,t) = \frac{1}{4\pi}\frac{2g^2_{p\pi p}}{4\pi}\frac{-t}{(t-m^2_\pi)^2}(1-x_L)^{1-2\alpha(t)}[F(x_L,t)]^2$$

Form factors:

$$F_1(x_L,t) = exp[R^2\frac{(t-m^2_\pi)}{(1-x_L)}] \quad , \quad \alpha(t)=0$$

light cone

$$F_2(x_L,t) = 1 \quad , \quad \alpha(t)=\alpha(t)_\pi$$

reggeized pion

$$F_3(x_L,t) = exp[b(t-m^2_\pi)] \quad , \quad \alpha(t)=\alpha(t)_\pi$$

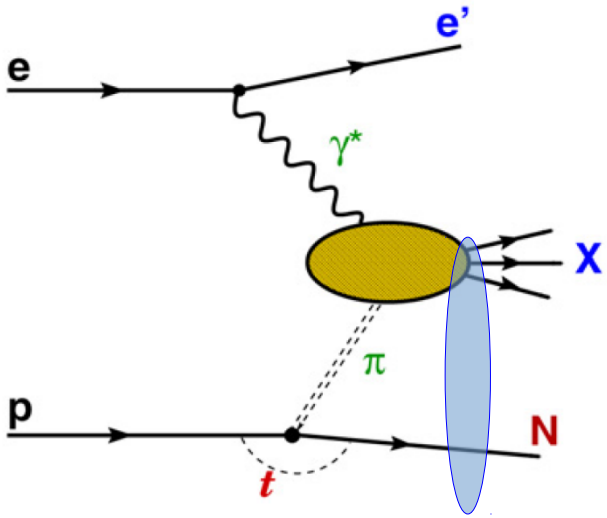
$$F_4(x_L,t) = \frac{(\Lambda^2-m^2_\pi)}{(\Lambda^2-t^2)} \quad , \quad \alpha(t)=0$$

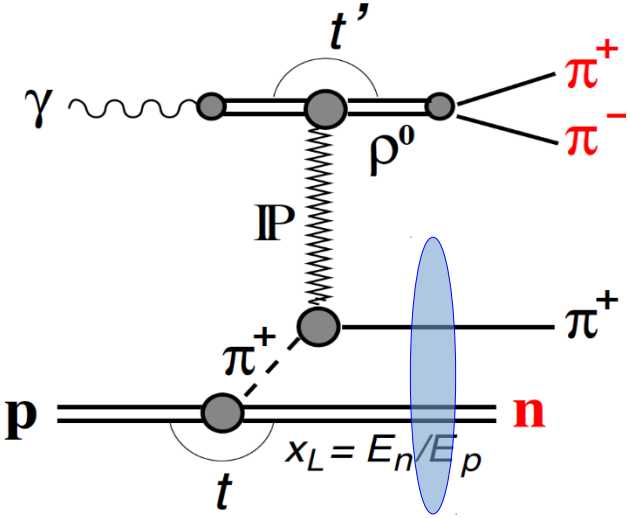
monopole

$$F_5(x_L,t) = [\frac{(\Lambda^2-m^2_\pi)}{(\Lambda^2-t^2)}]^2 \quad , \quad \alpha(t)=0$$

dipole

Leading Neutron Processes at HERA



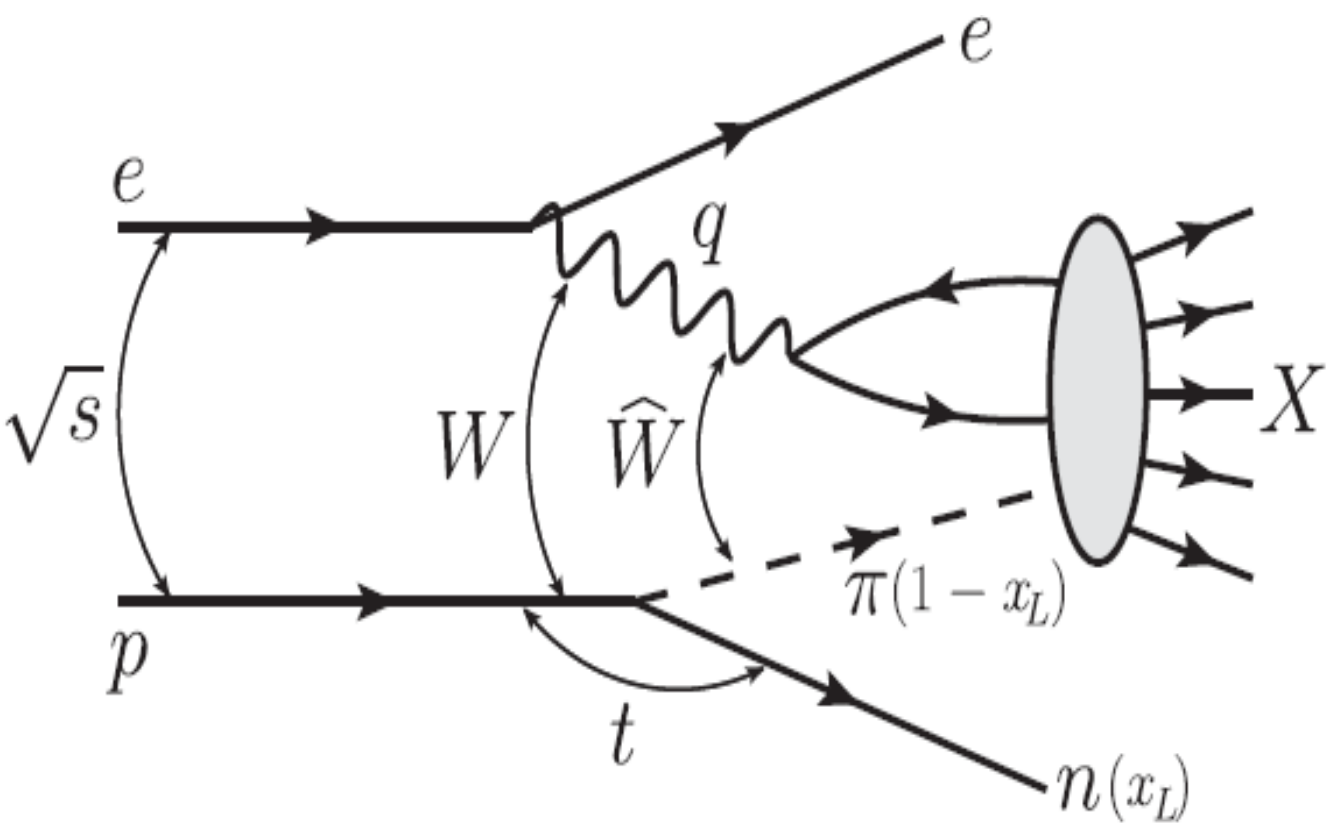


$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L\, dt} = f_{\pi/p}(x_L, t)\,\sigma_{\gamma^*\pi}(\hat{W}^2, Q^2)$$

Theoretical and experimental analysis indicate that absorptive effects should be taken into account in order to describe the experimental data.

Leading Neutron Processes in the Color Dipole Formalism

Inclusive processes:



Leading Neutron Processes in the Color Dipole Formalism

Inclusive processes:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left| \Psi_{T,L}(z, \boldsymbol{r}, Q^2) \right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

Photon wave function:

$$|\psi_L(z,r)|^2 = \frac{3\alpha_{em}}{\pi^2} \sum_f e_f^2 4Q^2 z^2 (1-z)^2 K_0^2(\epsilon r)$$

$$|\psi_T(z,r)|^2 = \frac{3\alpha_{em}}{2\pi^2} \sum_f e_f^2 \left\{ [z^2 + (1-z^2]\epsilon^2 K_1^2(\epsilon r) + m_f^2 K_0^2(\epsilon r) \right\}$$

Dipole cross section:

$$\sigma_{d\pi}(\hat{x}, \boldsymbol{r}) = 2 \int d^2\boldsymbol{b} \mathcal{N}^{\pi}(\hat{x}, \boldsymbol{r}, \boldsymbol{b})$$

$$\hat{x} = \frac{Q^2 + m_f^2}{\hat{W}^2 + Q^2} = \frac{Q^2 + m_f^2}{(1-x_L)W^2 + Q^2}$$

Leading Neutron Processes in the Color Dipole Formalism

Inclusive processes:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \underbrace{\sigma_{d\pi}(\hat{x}, \boldsymbol{r})}$$

Photon wave function:

$$|\psi_L(z,r)|^2 = \frac{3\alpha_{em}}{\pi^2} \sum_f e_f^2 4Q^2 z^2 (1-z)^2 K_0^2(\epsilon r)$$

$$|\psi_T(z,r)|^2 = \frac{3\alpha_{em}}{2\pi^2} \sum_f e_f^2 \left\{[z^2 + (1-z^2]\epsilon^2 K_1^2(\epsilon r) + m_f^2 K_0^2(\epsilon r)\right\}$$

Dipole cross section:

$$\sigma_{d\pi}(\hat{x}, \boldsymbol{r}) = 2 \int d^2\boldsymbol{b}\, \mathcal{N}^{\pi}(\hat{x}, \boldsymbol{r}, \boldsymbol{b})$$

$$\hat{x} = \frac{Q^2 + m_f^2}{\hat{W}^2 + Q^2} = \frac{Q^2 + m_f^2}{(1-x_L)W^2 + Q^2}$$

Leading Neutron Processes in the Color Dipole Formalism

Inclusive processes:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

Photon wave function:

$$|\psi_L(z,r)|^2 = \frac{3\alpha_{em}}{\pi^2} \sum_f e_f^2 4Q^2 z^2 (1-z)^2 K_0^2(\epsilon r)$$

$$|\psi_T(z,r)|^2 = \frac{3\alpha_{em}}{2\pi^2} \sum_f e_f^2 \left\{[z^2 + (1-z^2]\epsilon^2 K_1^2(\epsilon r) + m_f^2 K_0^2(\epsilon r)\right\}$$

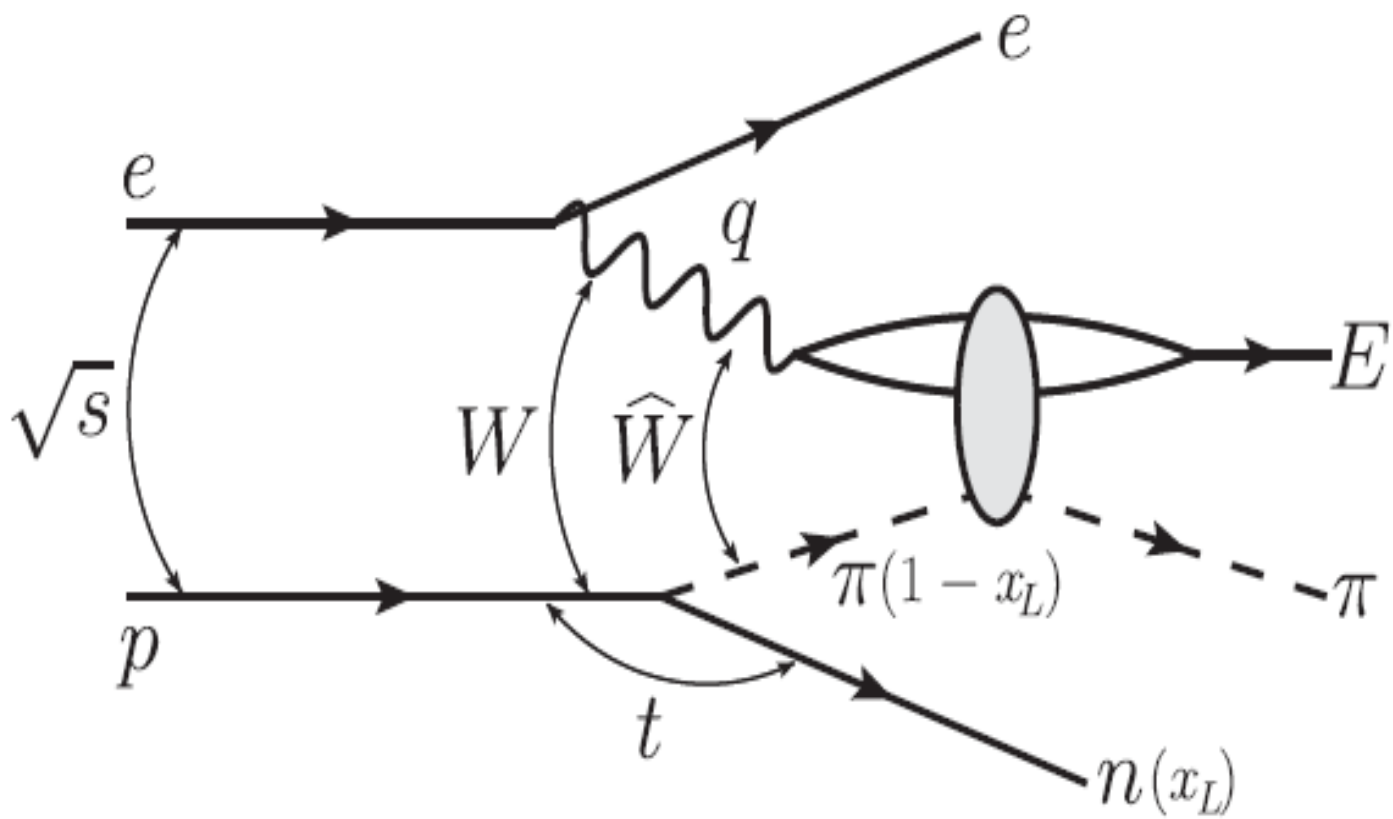
Dipole cross section:

$$\sigma_{d\pi}(\hat{x}, \boldsymbol{r}) = 2 \int d^2\boldsymbol{b} \mathcal{N}^{\pi}(\hat{x}, \boldsymbol{r}, \boldsymbol{b})$$

$$\hat{x} = \frac{Q^2 + m_f^2}{\hat{W}^2 + Q^2} = \frac{Q^2 + m_f^2}{(1-x_L)W^2 + Q^2}$$

Leading Neutron Processes in the Color Dipole Formalism

Exclusive processes: $E = \rho,\ \phi,\ J/\Psi,\ \gamma$



Leading Neutron Processes in the Color Dipole Formalism

Exclusive processes: $E = \rho,\ \phi,\ J/\Psi,\ \gamma$

$$\sigma(\gamma^*\pi \to E\pi) = \sum_{i=L,T} \int_{-\infty}^{0} \frac{d\sigma_i}{d\hat{t}}\, d\hat{t} = \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi\to E\pi}(x,\Delta)|^2\, d\hat{t}$$

Scattering amplitude:

$$\mathcal{A}_{T,L}^{\gamma^*\pi\to E\pi}(\hat{x},\Delta) = i \int dz\, d^2\boldsymbol{r}\, d^2\boldsymbol{b} e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}].\boldsymbol{\Delta}}\ (\Psi^{E*}\Psi)_{T,L}\ 2\mathcal{N}_\pi(\hat{x},\boldsymbol{r},\boldsymbol{b})$$

Leading Neutron Processes in the Color Dipole Formalism

Exclusive processes: $E = \rho,\ \phi,\ J/\Psi,\ \gamma$

$$\sigma(\gamma^*\pi \to E\pi) = \sum_{i=L,T} \int_{-\infty}^{0} \frac{d\sigma_i}{d\hat{t}}\, d\hat{t} = \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi\to E\pi}(x,\Delta)|^2\, d\hat{t}$$

Scattering amplitude:

$$\mathcal{A}_{T,L}^{\gamma^*\pi\to E\pi}(\hat{x},\Delta) = i \int dz\, d^2\boldsymbol{r}\, d^2\boldsymbol{b} e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}].\boldsymbol{\Delta}} \underbrace{(\Psi^{E*}\Psi)_{T,L}}\, 2\mathcal{N}_\pi(\hat{x},\boldsymbol{r},\boldsymbol{b})$$

Overlap functions for Vector Mesons:

$$(\Psi_V^*\Psi)_T = \frac{\hat{e}_f e}{4\pi} \frac{N_c}{\pi z(1-z)} \{m_f^2 K_0(\epsilon r)\phi_T(r,z) - [z^2 + (1-z)^2]\epsilon K_1(\epsilon r)\partial_r \phi_T(r,z)\}$$

$$(\Psi_V^*\Psi)_L = \frac{\hat{e}_f e}{4\pi} \frac{N_c}{\pi} 2Qz(1-z)K_0(\epsilon r)\left[M_V\phi_L(r,z) + \delta \frac{m_f^2 - \nabla_r^2}{M_V z(1-z)}\phi_L(r,z)\right]$$

Leading Neutron Processes in the Color Dipole Formalism

Exclusive processes: $E = \rho,\ \phi,\ J/\Psi,\ \gamma$

$$\sigma(\gamma^*\pi \to E\pi) = \sum_{i=L,T} \int_{-\infty}^{0} \frac{d\sigma_i}{d\hat{t}}\, d\hat{t} = \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi\to E\pi}(x,\Delta)|^2\, d\hat{t}$$

Scattering amplitude:

$$\mathcal{A}_{T,L}^{\gamma^*\pi\to E\pi}(\hat{x},\Delta) = i \int dz\, d^2\boldsymbol{r}\, d^2\boldsymbol{b} e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}].\boldsymbol{\Delta}} \underbrace{(\Psi^{E*}\Psi)_{T,L}}\, 2\mathcal{N}_\pi(\hat{x},\boldsymbol{r},\boldsymbol{b})$$

Overlap functions for Deeply Virtual Compton Scattering (DVCS):

$$(\Psi_\gamma^*\Psi)_T^f = \frac{N_c \alpha_{\rm em} e_f^2}{2\pi^2} \{[z^2+\bar{z}^2]\varepsilon_1 K_1(\varepsilon_1 r)\varepsilon_2 K_1(\varepsilon_2 r) + m_f^2 K_0(\varepsilon_1 r) K_0(\varepsilon_2 r)\}$$

Leading Neutron Processes in the Color Dipole Formalism

Exclusive processes: $E = \rho,\ \phi,\ J/\Psi,\ \gamma$

$$\sigma(\gamma^*\pi \to E\pi) = \sum_{i=L,T} \int_{-\infty}^{0} \frac{d\sigma_i}{d\hat{t}}\, d\hat{t} = \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi\to E\pi}(x,\Delta)|^2\, d\hat{t}$$

Scattering amplitude:

$$\mathcal{A}_{T,L}^{\gamma^*\pi\to E\pi}(\hat{x},\Delta) = i \int dz\, d^2\boldsymbol{r}\, d^2\boldsymbol{b} e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}].\boldsymbol{\Delta}}\ (\Psi^{E*}\Psi)_{T,L}\ 2\mathcal{N}_\pi(\hat{x},\boldsymbol{r},\boldsymbol{b})$$

Overlap functions for Deeply Virtual Compton Scattering (DVCS):

$$(\Psi_\gamma^*\Psi)_T^f = \frac{N_c \alpha_{\rm em} e_f^2}{2\pi^2}\{[z^2+\bar{z}^2]\varepsilon_1 K_1(\varepsilon_1 r)\varepsilon_2 K_1(\varepsilon_2 r) + m_f^2 K_0(\varepsilon_1 r) K_0(\varepsilon_2 r)\}$$

Leading Neutron Processes in the Color Dipole Formalism

Main assumption:

$$\mathcal{N}^{\pi}(\hat{x}, \boldsymbol{r}, \boldsymbol{b}) = R_q \cdot \mathcal{N}^{p}(\hat{x}, \boldsymbol{r}, \boldsymbol{b})$$

Leading Neutron Processes in the Color Dipole Formalism

Main assumption:

$$\mathcal{N}^{\pi}(\hat{x}, \boldsymbol{r}, \boldsymbol{b}) = R_q \cdot \mathcal{N}^{p}(\hat{x}, \boldsymbol{r}, \boldsymbol{b})$$

Constrained by HERA data for inclusive and exclusive processes (w/o a leading neutron)

Leading Neutron Processes in the Color Dipole Formalism

Main assumption:

$$\mathcal{N}^{\pi}(\hat{x}, \boldsymbol{r}, \boldsymbol{b}) = R_q \cdot \mathcal{N}^{p}(\hat{x}, \boldsymbol{r}, \boldsymbol{b})$$

With : R_q = cte $\qquad 1/3 \leq R_q \leq 2/3$

Leading Neutron Processes in the Color Dipole Formalism

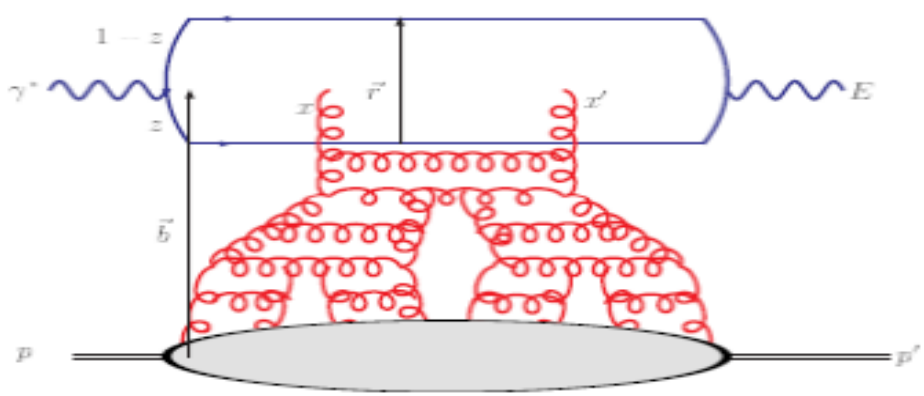
Main assumption:

$$\mathcal{N}^{\pi}(\hat{x}, \boldsymbol{r}, \boldsymbol{b}) = R_q \cdot \mathcal{N}^{p}(\hat{x}, \boldsymbol{r}, \boldsymbol{b})$$

With : R_q = cte

Constrained by HERA data for inclusive and exclusive processes (w/o a leading neutron)

- bCGC :



Leading Neutron Processes in the Color Dipole Formalism

Main assumption:

$$\mathcal{N}^{\pi}(\hat{x}, \boldsymbol{r}, \boldsymbol{b}) = R_q \cdot \mathcal{N}^{p}(\hat{x}, \boldsymbol{r}, \boldsymbol{b})$$

With : R_q = cte

Constrained by HERA data for inclusive and exclusive processes (w/o a leading neutron)

- bCGC : $$\mathcal{N}^{p}(\hat{x}, \boldsymbol{r}, \boldsymbol{b}) = \begin{cases} \mathcal{N}_0 \left(\frac{rQ_s(b)}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/rQ_s(b))}{\kappa\lambda Y}\right)} & rQ_s(b) \leq 2 \\ 1 - e^{-A\ln^2(BrQ_s(b))} & rQ_s(b) > 2 \end{cases}$$

$$Q_s(b) \equiv Q_s(\hat{x}, b) = \left(\frac{x_0}{\hat{x}}\right)^{\frac{\lambda}{2}} \left[\exp\left(-\frac{b^2}{2B_{\mathrm{CGC}}}\right)\right]^{\frac{1}{2\gamma_s}}.$$

Leading Neutron Processes in the Color Dipole Formalism

Dipole – proton scattering amplitude:

$$\mathcal{N}^p(\hat{x}, \boldsymbol{r}, \boldsymbol{b}) = \mathcal{N}^p(\hat{x}, \boldsymbol{r}) S(\boldsymbol{b})$$

- Golec- Biernat – Wusthoff (GBW) :

$$\mathcal{N}^p(x, \boldsymbol{r}) = 1 - \exp\left[-\frac{Q_s^2 r^2}{4}\right]$$

- Iancu – Itakura – Munier – Soyez (IIMS):

$$\mathcal{N}^p(x, \boldsymbol{r}) = \begin{cases} \mathcal{N}_0 \left(\frac{r\,Q_s}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/r\,Q_s)}{\kappa\,\lambda\,Y}\right)}, & \text{for } r\,Q_s(x) \leq 2, \\ 1 - e^{-a\,\ln^2(b\,r\,Q_s)}, & \text{for } r\,Q_s(x) > 2, \end{cases}$$

- Running coupling Balitsky- Kovchegov equation (rcBK)

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \mathcal{K}_{inc} \cdot \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \mathcal{K}_{inc} \cdot \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

$$\sigma(\gamma^*\pi \to E\pi) = \mathcal{K}_{exc} \cdot \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi \to E\pi}(x, \Delta)|^2 \, d\hat{t}$$

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \mathcal{K}_{inc} \cdot \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

$$\sigma(\gamma^*\pi \to E\pi) = \mathcal{K}_{exc} \cdot \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi \to E\pi}(x, \Delta)|^2 \, d\hat{t}$$

Open questions:

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \mathcal{K}_{inc} \cdot \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

$$\sigma(\gamma^*\pi \to E\pi) = \mathcal{K}_{exc} \cdot \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi \to E\pi}(x, \Delta)|^2 \, d\hat{t}$$

Open questions:

- $\mathcal{K}_{inc} = \mathcal{K}_{exc} = \mathcal{K}$??

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \mathcal{K}_{inc} \cdot \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

$$\sigma(\gamma^*\pi \to E\pi) = \mathcal{K}_{exc} \cdot \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi \to E\pi}(x, \Delta)|^2 \, d\hat{t}$$

Open questions:

- $\mathcal{K}_{inc} = \mathcal{K}_{exc} = \mathcal{K}$??
- $\mathcal{K}_{inc} = \mathcal{K}_{inc}(\hat{W}, x_L, Q^2)$??

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \mathcal{K}_{inc} \cdot \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

$$\sigma(\gamma^*\pi \to E\pi) = \mathcal{K}_{exc} \cdot \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi \to E\pi}(x, \Delta)|^2 \, d\hat{t}$$

Open questions:

- $\mathcal{K}_{inc} = \mathcal{K}_{exc} = \mathcal{K}$??
- $\mathcal{K}_{inc} = \mathcal{K}_{inc}(\hat{W}, x_L, Q^2)$??
- $\mathcal{K}_{exc} = \mathcal{K}_{exc}(\hat{W}, x_L, Q^2)$??

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \mathcal{K}_{inc} \cdot \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

$$\sigma(\gamma^*\pi \to E\pi) = \mathcal{K}_{exc} \cdot \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi \to E\pi}(x, \Delta)|^2 \, d\hat{t}$$

Open questions:

- $\mathcal{K}_{inc} = \mathcal{K}_{exc} = \mathcal{K}$??
- $\mathcal{K}_{inc} = \mathcal{K}_{inc}(\hat{W}, x_L, Q^2)$??
- $\mathcal{K}_{exc} = \mathcal{K}_{exc}(\hat{W}, x_L, Q^2)$??

Our assumption:

- $\mathcal{K}$ = cte

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) = \mathcal{K}_{inc} \cdot \int_0^1 dz \int d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z, \boldsymbol{r}, Q^2)\right|^2 \sigma_{d\pi}(\hat{x}, \boldsymbol{r})$$

$$\sigma(\gamma^*\pi \to E\pi) = \mathcal{K}_{exc} \cdot \frac{1}{16\pi} \sum_{i=L,T} \int_{-\infty}^{0} |\mathcal{A}_i^{\gamma^*\pi \to E\pi}(x, \Delta)|^2 \, d\hat{t}$$

Consequently :

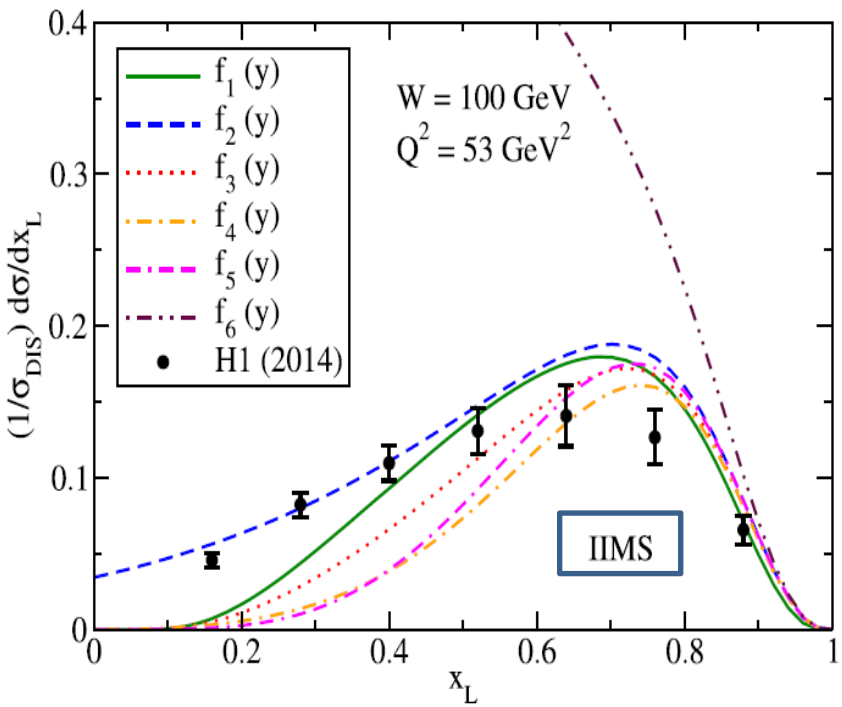
$$\sigma_{\gamma^*\pi}(\hat{x}, Q^2) \propto \mathcal{K}_{inc} \cdot R_q$$

$$\sigma(\gamma^*\pi \to E\pi) \propto \mathcal{K}_{exc} \cdot {R_q}^2$$

Results for Inclusive Processes

$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L dt} = f_{\pi/p}(x_L, t)\sigma_{\gamma^*\pi}(\hat{W}^2, Q^2)$$

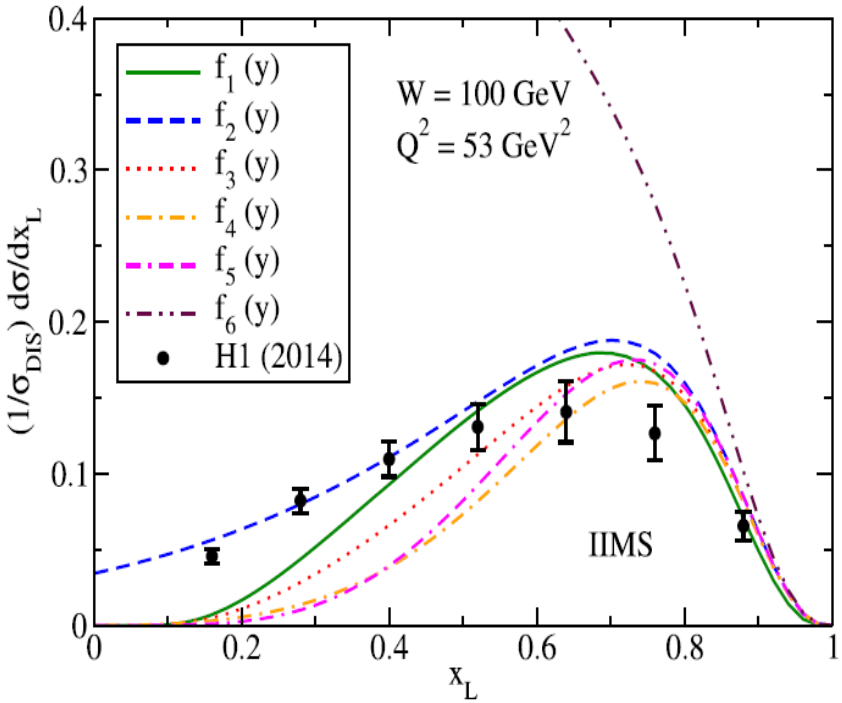
$R_q = 2/3$; K = 1

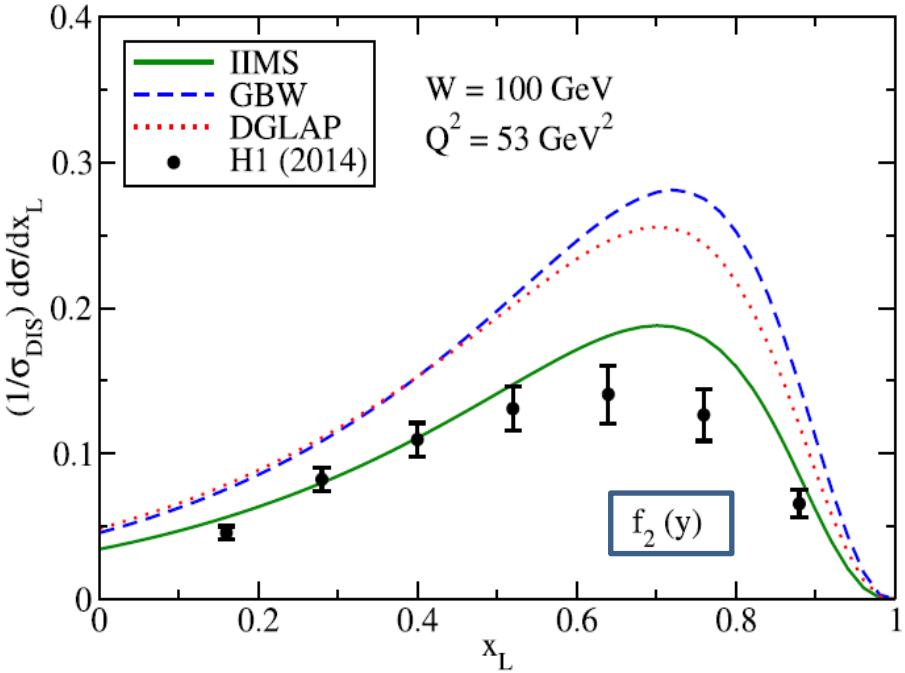


Results for Inclusive Processes

$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L dt} = f_{\pi/p}(x_L, t)\sigma_{\gamma^*\pi}(\hat{W}^2, Q^2)$$

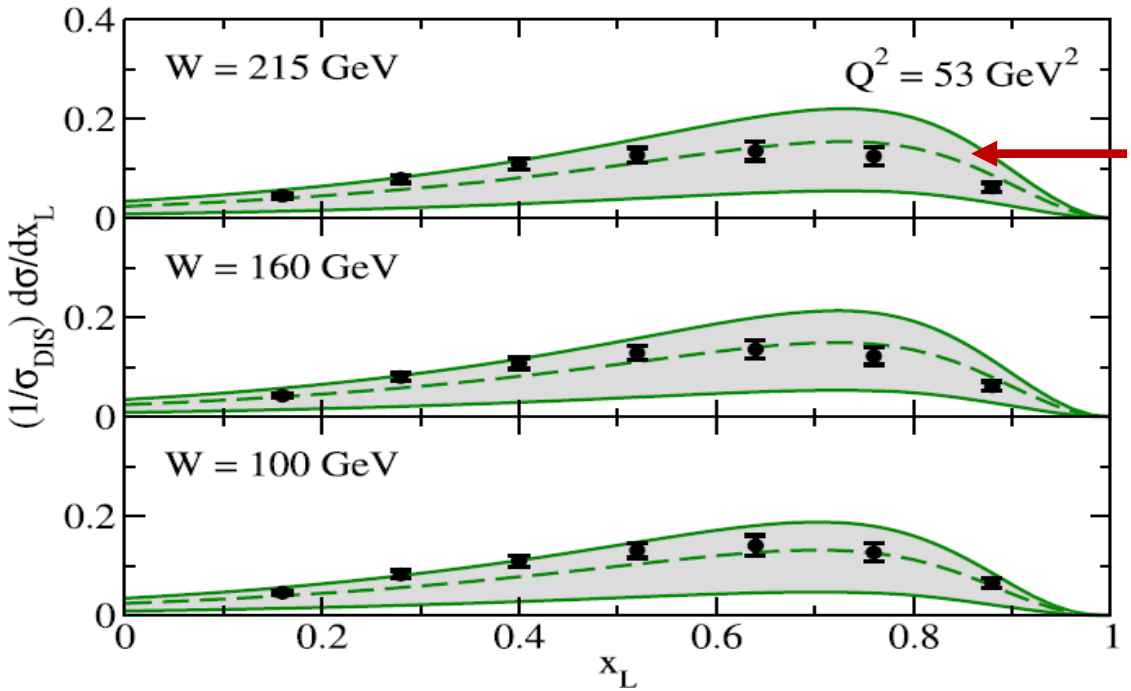
$R_q = 2/3$; K = 1





Results for Inclusive Processes

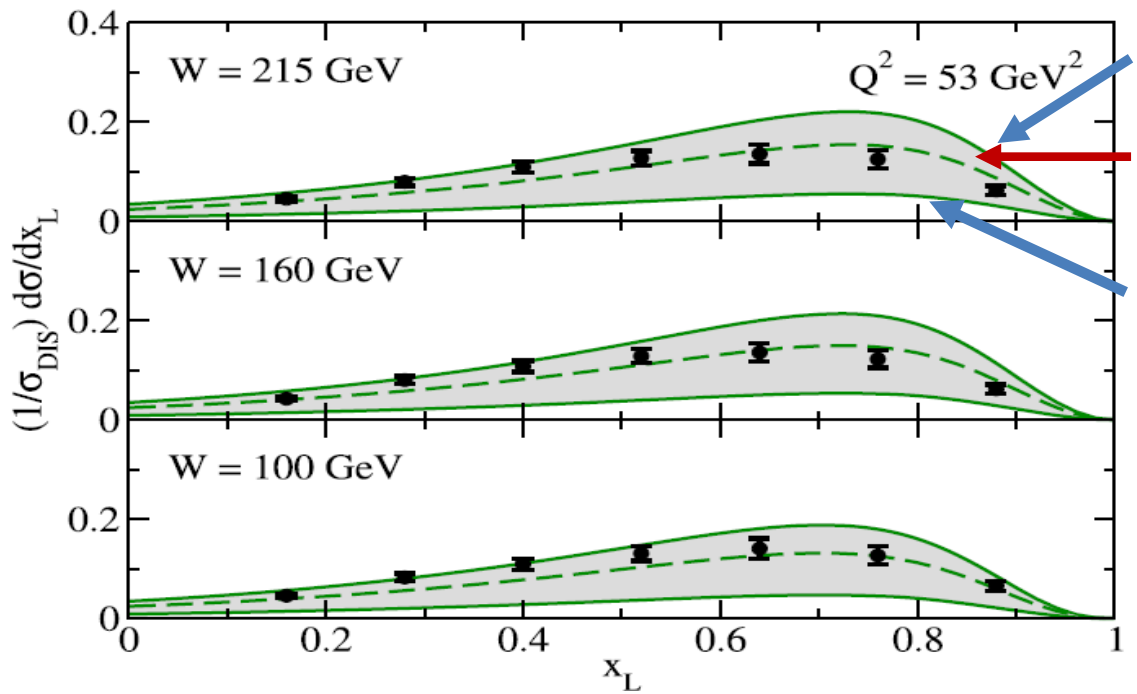
$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L dt} = f_{\pi/p}(x_L, t)\sigma_{\gamma^*\pi}(\hat{W}^2, Q^2)$$



Rq . K = 0.5

Results for Inclusive Processes

$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L dt} = f_{\pi/p}(x_L, t)\sigma_{\gamma^*\pi}(\hat{W}^2, Q^2)$$



Rq = 2/3; K = 1

Rq . K = 0.5

Rq = 1/3; K = 0.5

Results for Exclusive Processes

$$\gamma p \rightarrow \rho^0 \pi^+ n$$

Initially, we will assume that: $R_q = 2/3$

Results for Exclusive Processes

$$\gamma p \to \rho^0 \pi^+ n$$

Initially, we will assume that: $R_q = 2/3$

Our strategy to constrain the K-factor: For a given model of the pion flux, Rq and dipole scattering amplitude, we estimate the total cross section. The value of K will be the value necessary to make our predictions consistent with the HERA data.

Results for Exclusive Processes

$$\gamma p \to \rho^0 \pi^+ n$$

Initially, we will assume that: $R_q = 2/3$

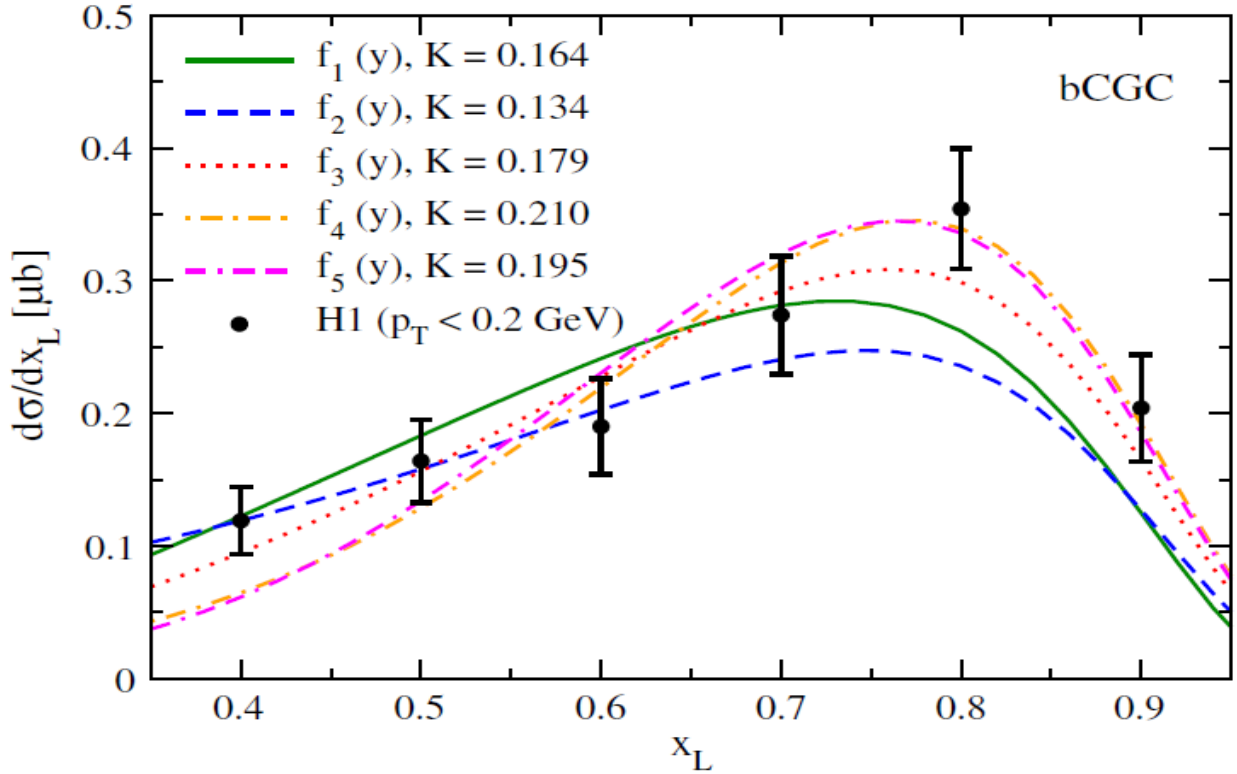
Our strategy to constrain the K-factor: For a given model of the pion flux, Rq and dipole scattering amplitude, we estimate the total cross section. The value of K will be the value necessary to make our predictions consistent with the HERA data.

Important to remember that: $\sigma(\gamma^* \pi \to E\pi) \propto \mathcal{K}_{exc} \cdot {R_q}^2$

Results for Exclusive Processes

$$\gamma p \to \rho^0 \pi^+ n$$

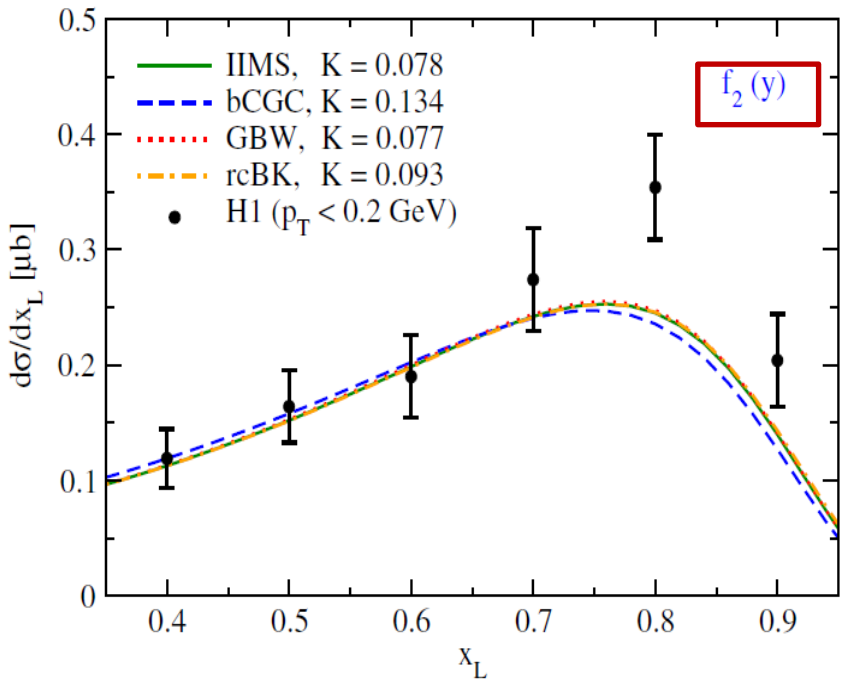
Dependence on the pion flux:

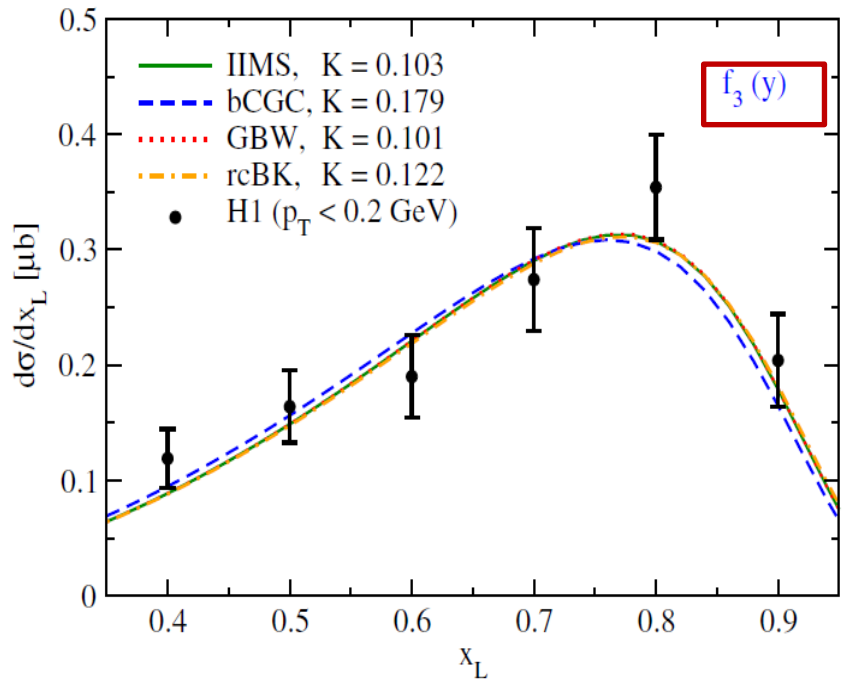


Results for Exclusive Processes

$$\gamma p \to \rho^0 \pi^+ n$$

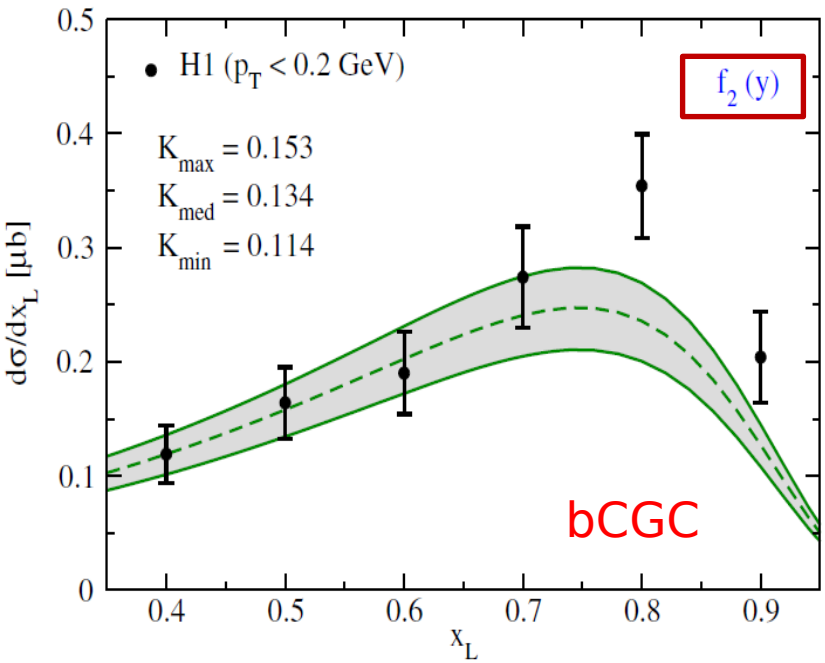
Dependence on the dipole - target amplitude:

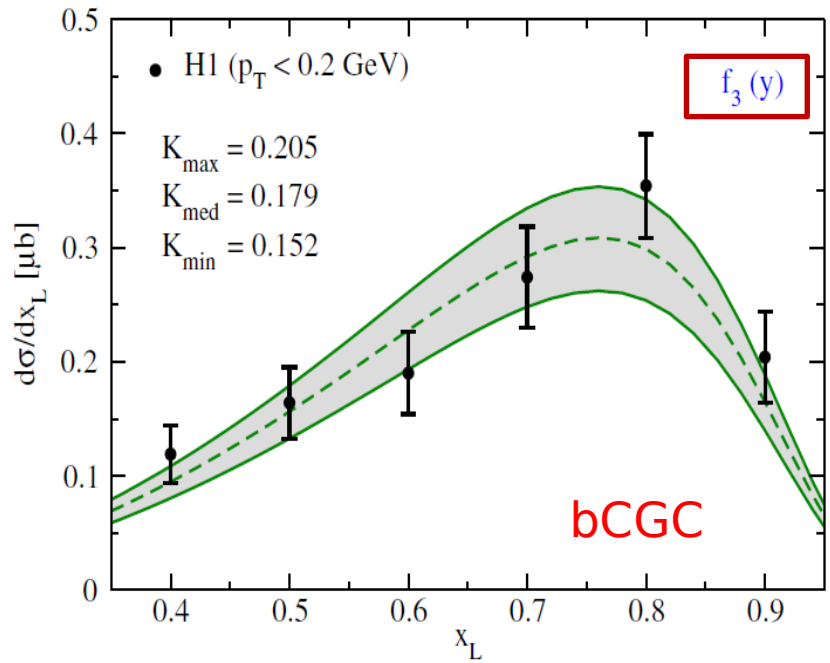




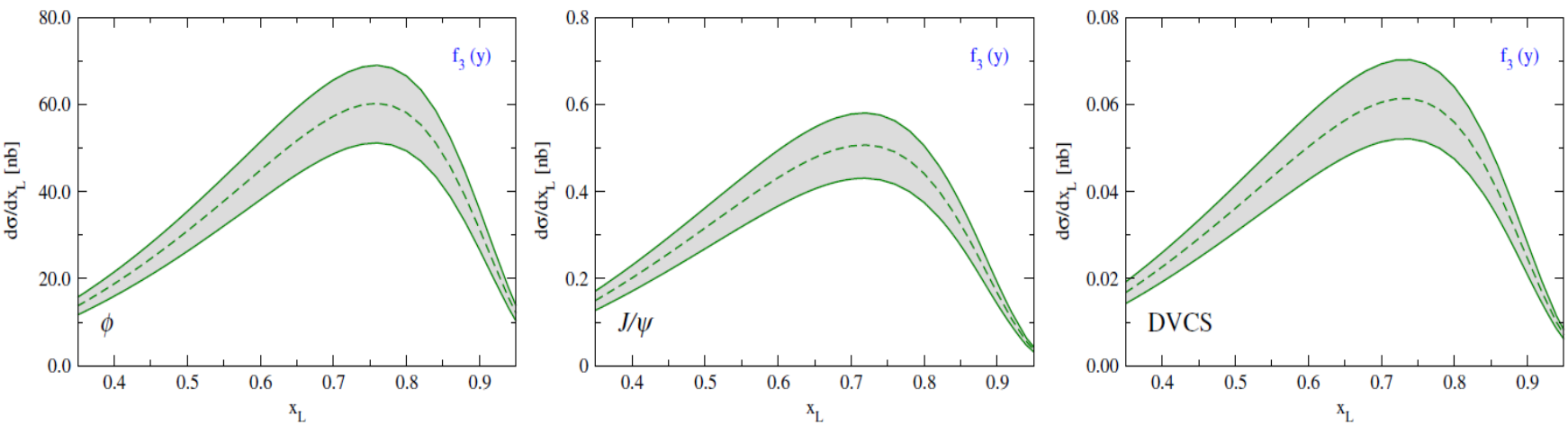
Results for Exclusive Processes

$$\gamma p \to \rho^0 \pi^+ n$$





Predictions for Exclusive Processes with a leading neutron at HERA



$$Q^2 = 0.04 \text{ GeV}^2$$

$$\sigma(\gamma p \to \phi \pi n) = 25.47 \pm 3.70 \text{ nb}$$

$$\sigma(\gamma p \to J/\Psi \pi n) = 0.22 \pm 0.03 \text{ nb}$$

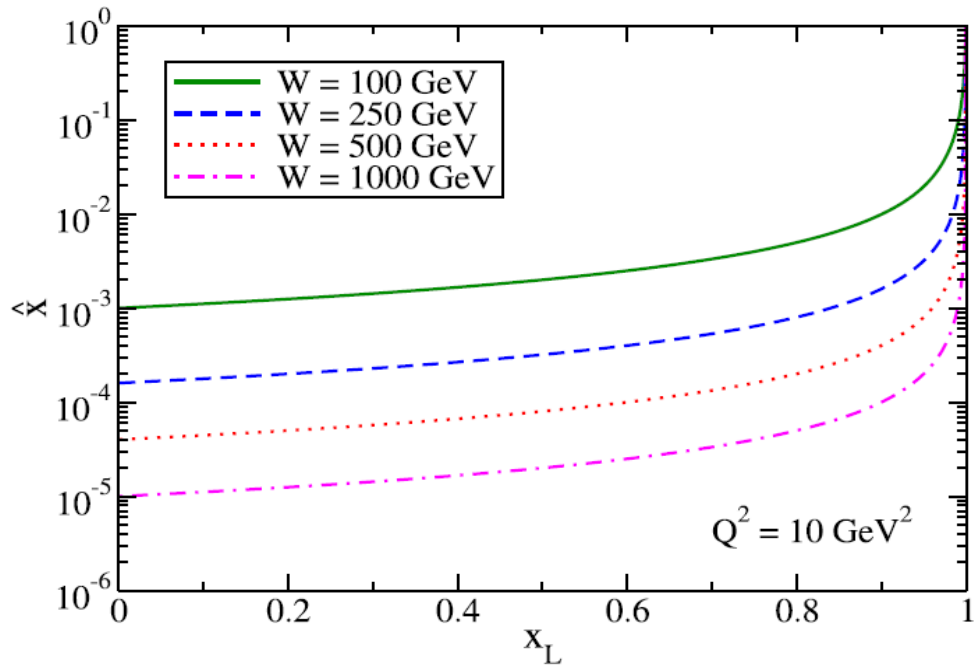
$$Q^2 = 10 \text{ GeV}^2$$

$$\sigma(\gamma^* p \to \gamma \pi n) = 0.008 \pm 0.001 \text{ nb}$$

Future ep colliders

Typical values of Bjorken-x probed in future ep colliders:

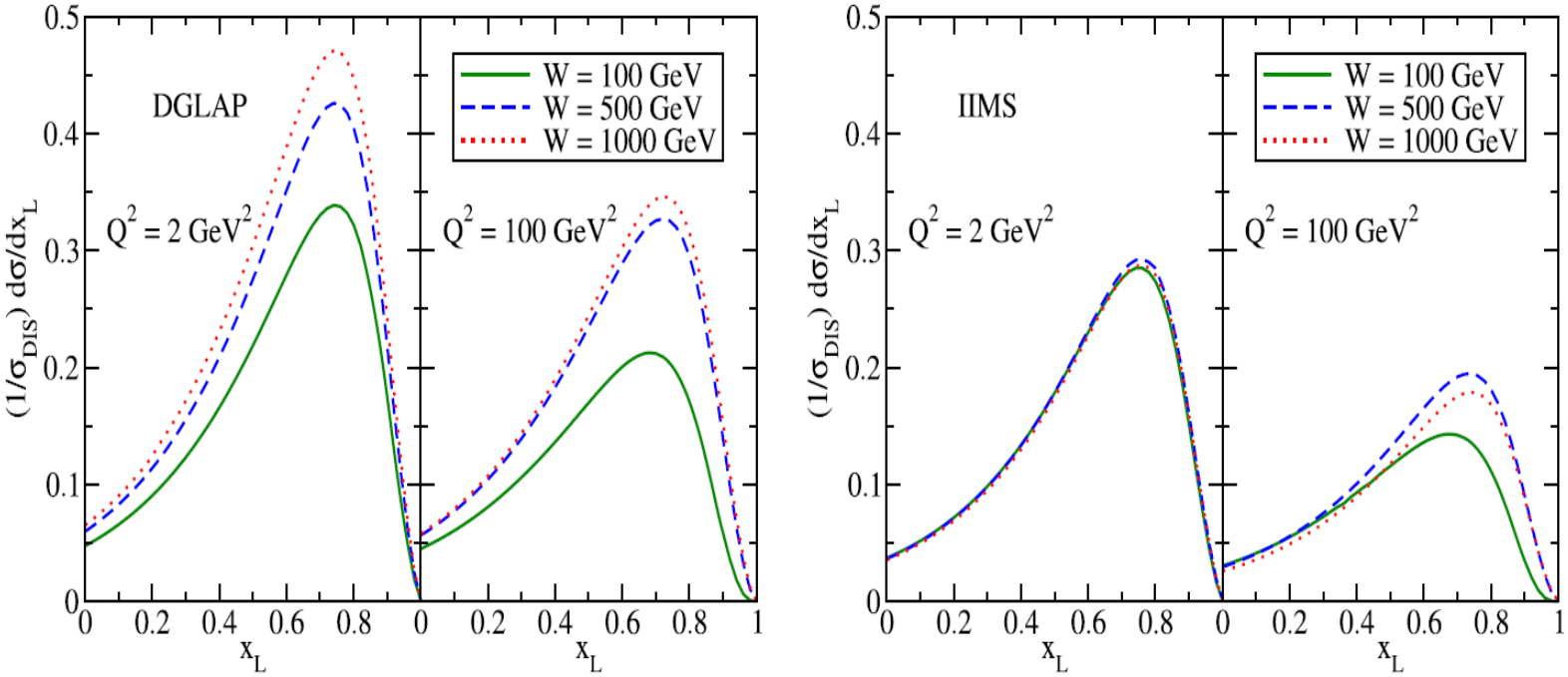
$$\hat{x} = \frac{Q^2 + m_f^2}{\hat{W}^2 + Q^2} = \frac{Q^2 + m_f^2}{(1 - x_L)W^2 + Q^2}$$



Future ep colliders

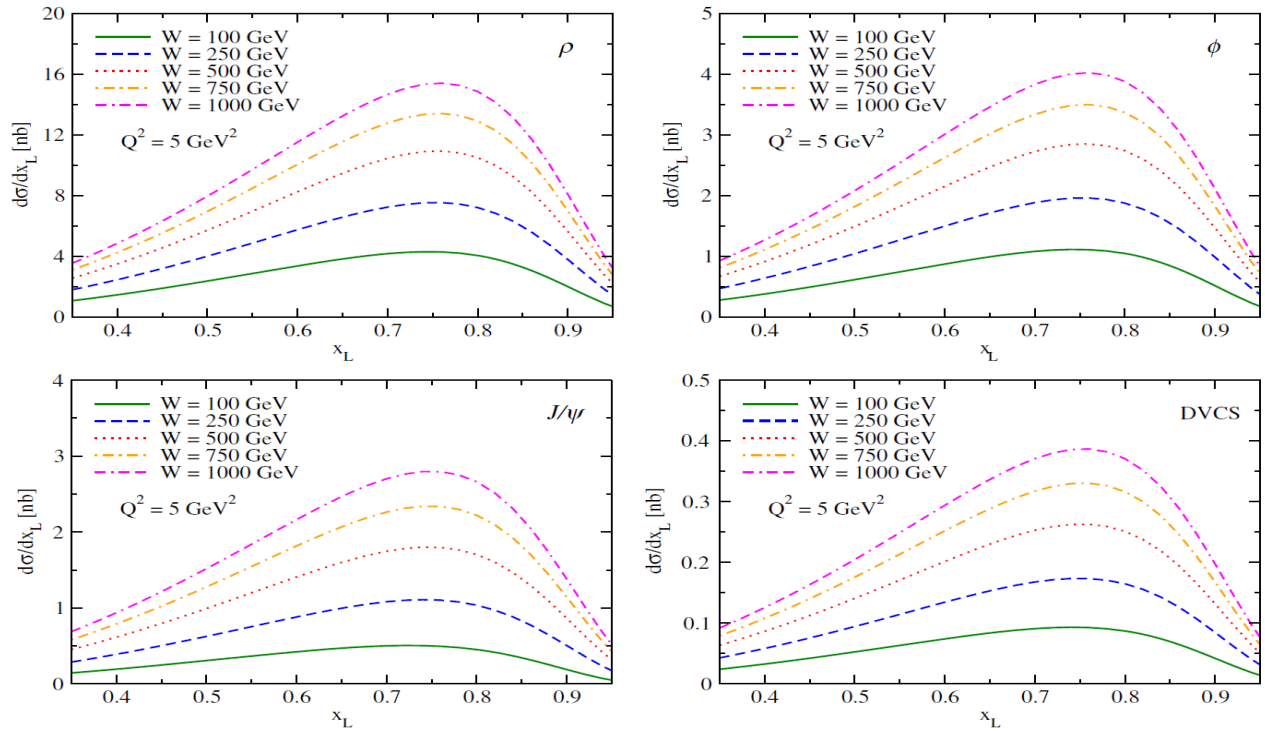
Feynman scaling in inclusive processes:

Linear X Nonlinear



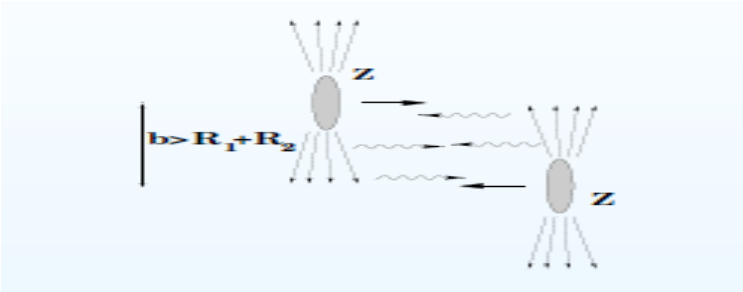
Future ep colliders

Dependence on the energy for exclusive processes:



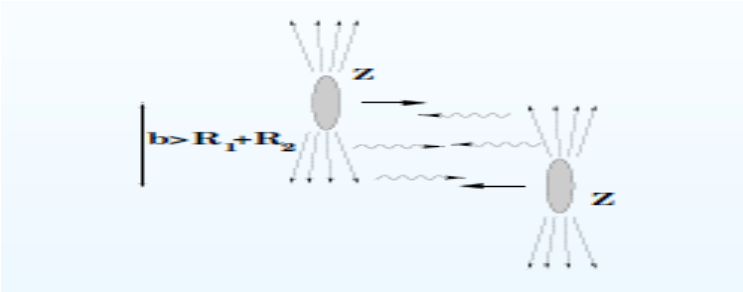
$$\left.\begin{array}{l} W = 1 \text{ TeV} \\ Q^2 = 5 \text{ GeV}^2 \end{array}\right\} \begin{array}{l} \sigma(\gamma^* p \to \rho\pi n) = 6.55 \pm 0.95 \text{ nb} \\ \sigma(\gamma^* p \to \phi\pi n) = 1.71 \pm 0.25 \text{ nb} \\ \sigma(\gamma^* p \to J/\Psi\pi n) = 1.20 \pm 0.17 \text{ nb} \end{array}$$

Photon - induced interactions at the LHC



1. γh Processes: $\sigma(h_1 h_2 \to X) = n_h(\omega) \otimes \sigma^{\gamma h \to X}(W_{\gamma h})$
2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \to X}(W_{\gamma\gamma})$

Photon - induced interactions at the LHC

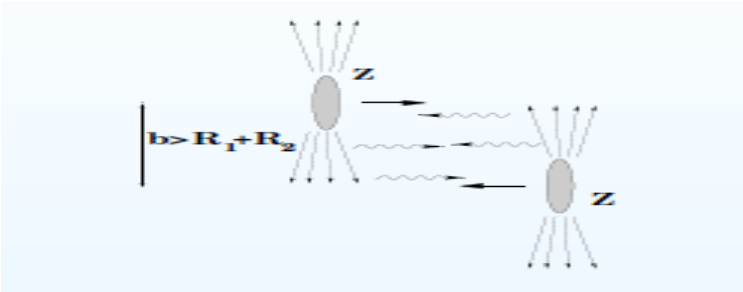


1. γh Processes: $\sigma(h_1 h_2 \to X) = n_h(\omega) \otimes \sigma^{\gamma h \to X}(W_{\gamma h})$
2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \to X}(W_{\gamma\gamma})$

Center of mass energies

LHC	pp	$W_{\gamma p} \lesssim 8390$ GeV	$W_{\gamma\gamma} \lesssim 4504$ GeV
LHC	$pPb(Ar)$	$W_{\gamma A} \lesssim 1500\,(2130)$ GeV	$W_{\gamma\gamma} \lesssim 260\,(480)$ GeV
LHC	$PbPb$	$W_{\gamma A} \lesssim 950$ GeV	$W_{\gamma\gamma} \lesssim 160$ GeV
HERA	ep	$W_{\gamma p} \lesssim 200$ GeV	–

Photon - induced interactions at the LHC



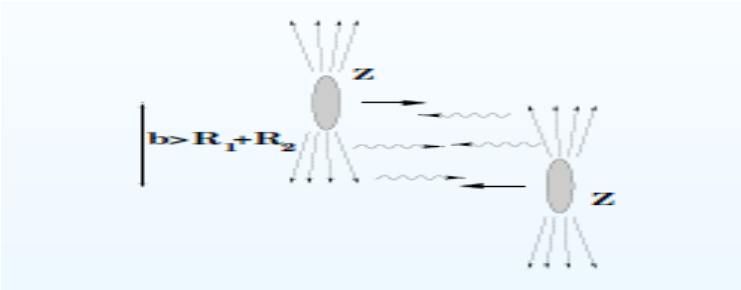
1. γh Processes: $\sigma(h_1 h_2 \to X) = n_h(\omega) \otimes \sigma^{\gamma h \to X}(W_{\gamma h})$
2. $\gamma\gamma$ Processes: $\sigma(h_1 h_2 \to X) = n_1(\omega) \otimes n_2(\omega) \otimes \sigma^{\gamma\gamma \to X}(W_{\gamma\gamma})$

Center of mass energies

LHC	pp	$W_{\gamma p} \lesssim 8390$ GeV	$W_{\gamma\gamma} \lesssim 4504$ GeV
LHC	$pPb(Ar)$	$W_{\gamma A} \lesssim 1500\,(2130)$ GeV	$W_{\gamma\gamma} \lesssim 260\,(480)$ GeV
LHC	$PbPb$	$W_{\gamma A} \lesssim 950$ GeV	$W_{\gamma\gamma} \lesssim 160$ GeV
HERA	ep	$W_{\gamma p} \lesssim 200$ GeV	–

- Photoproduction in pp collisions at LHC probes energies one order of magnitude larger than HERA.

Photon - induced interactions at the LHC

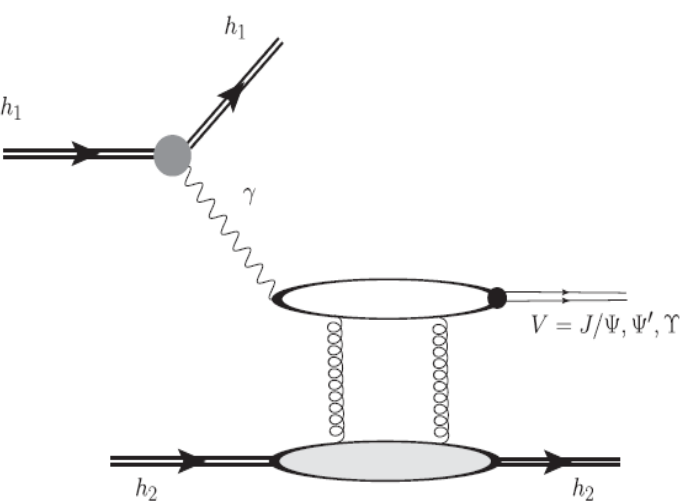


γh Processes: $\sigma(h_1 h_2 \to X) = n_h(\omega) \otimes \sigma^{\gamma h \to X}(W_{\gamma h})$

- Exclusive processes: $\gamma p \to X p$

  $\Rightarrow$ Heavy vector meson photoproduction ($X = J/\Psi,\ \Upsilon$)

  The final state is characterized by two rapidity gaps ($pp \to p \otimes X \otimes p$).

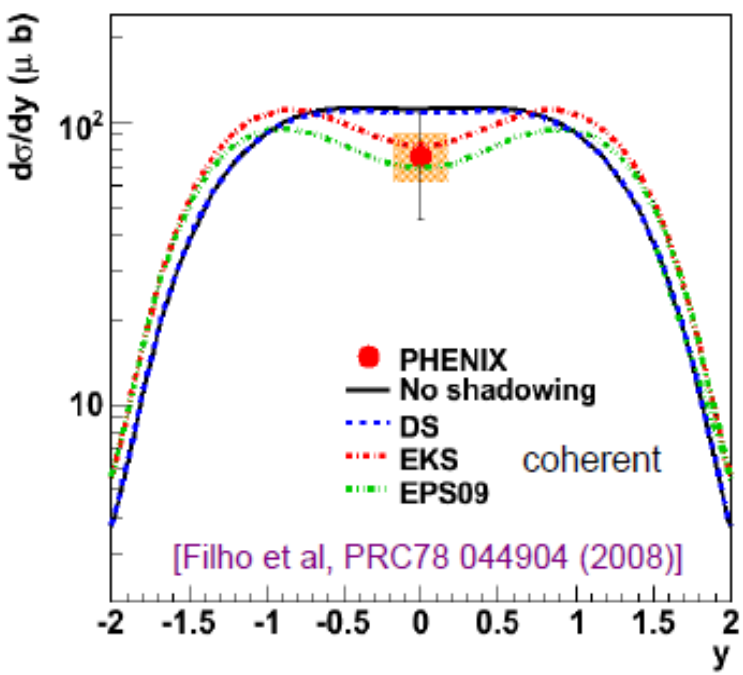


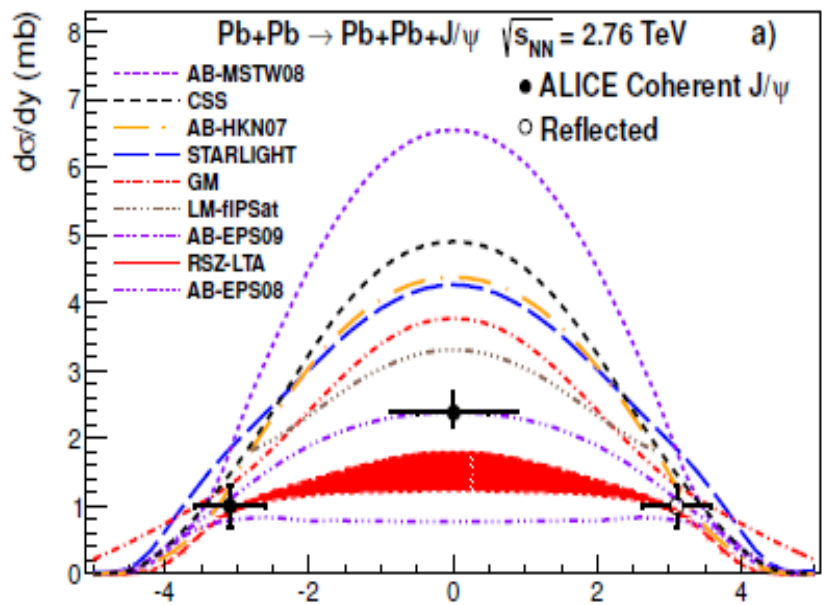
- Cross section is proportional to the square of the proton/nuclear gluon distribution.
- Diffractive vector meson photoproduction in UPHIC is a probe of the gluon distribution [a]

[a] VPG, Bertulani, PRC65, 054905 (2002)

Diffractive vector meson photoproduction in UPHIC

Probing the nuclear gluon distribution





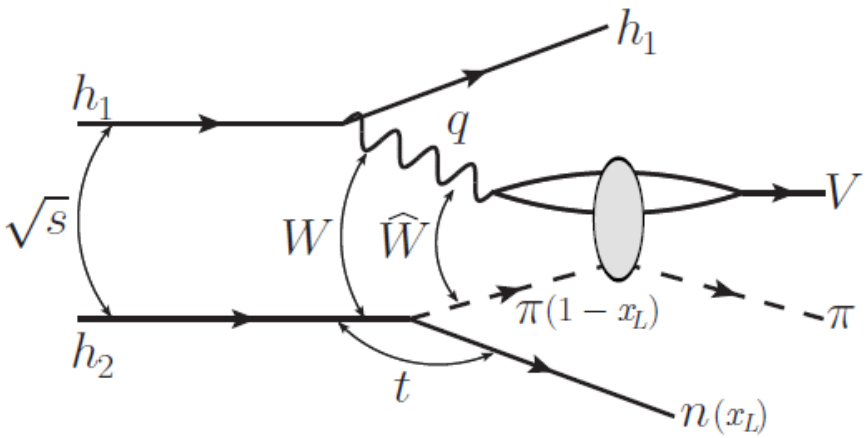
- Since $x = M_{J/\Psi}/\sqrt{s}\exp(-y)$ we have:

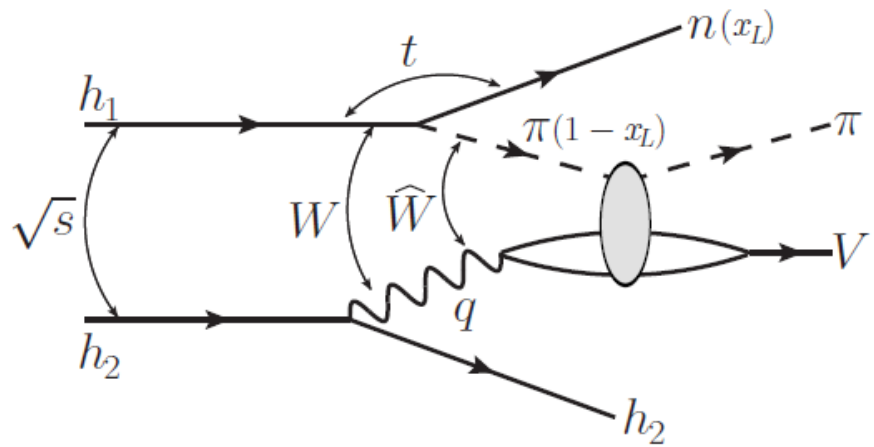
  $y = -3 \Rightarrow x = 0.02$

  $y = 0 \Rightarrow x = 0.001$ in $xg_A(x, Q^2)$.

Predictions for the LHC

- Vector Meson photoproduction with a leading neutron in UPHIC

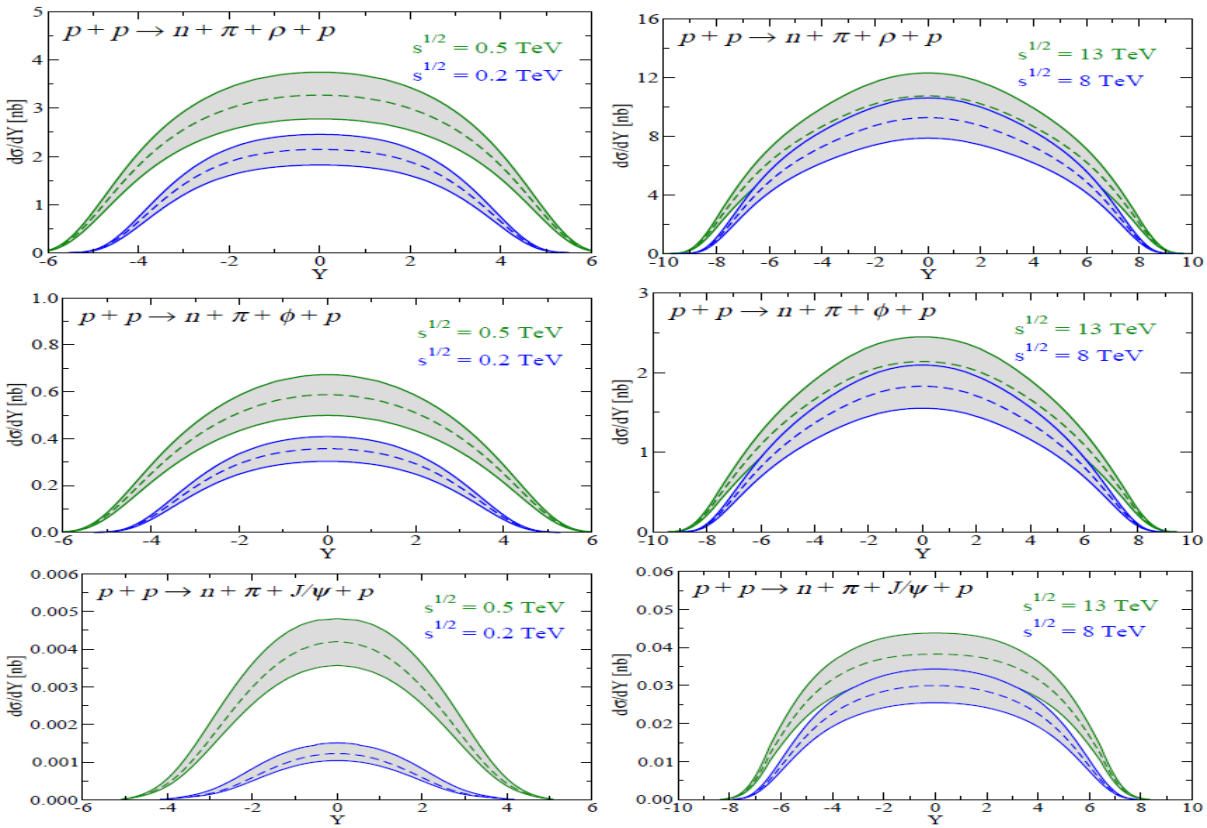




$$\frac{d\sigma\ [h_1 + h_2 \to h_3 \otimes V \otimes \pi + n]}{dY} = \left[\omega \frac{dN}{d\omega}|_{h_1}\, \sigma_{\gamma h_2 \to V \otimes \pi + n}\,(\omega)\right]_{\omega_L} + \left[\omega \frac{dN}{d\omega}|_{h_2}\, \sigma_{\gamma h_1 \to V \otimes \pi + n}\,(\omega)\right]_{\omega_R}$$

Predictions for the LHC

- Vector Meson photoproduction with a leading neutron in UPHIC



Predictions for the LHC

- Vector Meson photoproduction with a leading neutron in UPHIC

$\sigma(V)$ [nb]		$\sqrt{s} = 0.2$ TeV	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 8.0$ TeV	$\sqrt{s} = 13.0$ TeV
ρ	K_{min}	12.17	22.06	90.12	110.51
	K_{med}	14.34	25.98	106.12	130.14
	K_{max}	16.42	29.75	121.54	149.04
ϕ	K_{min}	1.83	3.58	16.67	20.73
	K_{med}	2.15	4.21	19.63	24.42
	K_{max}	2.46	4.83	22.48	27.96
J/ψ	K_{min}	0.0042	0.019	0.25	0.35
	K_{med}	0.0049	0.022	0.30	0.42
	K_{max}	0.0064	0.026	0.34	0.48

Summary

- ✓ The color dipole formalism can be used to describe the inclusive and exclusive processes with a leading neutron at HERA.

Summary

- ✓ The color dipole formalism can be used to describe the inclusive and exclusive processes with a leading neutron at HERA.
- ✓ The nonlinear effects in the QCD dynamics imply Feynman scaling at large energies.

Summary

- ✓ The color dipole formalism can be used to describe the inclusive and exclusive processes with a leading neutron at HERA.
- ✓ The nonlinear effects in the QCD dynamics imply Feynman scaling at large energies.
- ✓ Large cross sections for inclusive and exclusive processes with a leading neutron in future ep colliders and at the LHC.

Summary

- ✓ The color dipole formalism can be used to describe the inclusive and exclusive processes with a leading neutron at HERA.
- ✓ The nonlinear effects in the QCD dynamics imply Feynman scaling at large energies.
- ✓ Large cross sections for inclusive and exclusive processes with a leading neutron in future ep colliders and at the LHC.
- ✓ Next steps: D-meson production, dijet production, …

Summary

- ✓ The color dipole formalism can be used to describe the inclusive and exclusive processes with a leading neutron at HERA.
- ✓ The nonlinear effects in the QCD dynamics imply Feynman scaling at large energies.
- ✓ Large cross sections for inclusive and exclusive processes with a leading neutron in future ep colliders and at the LHC.
- ✓ Next steps: D-meson production, dijet production, …

Thank you for your attention !

Extras

Chiral perturbation theory

$$f_{\pi/p}(y, k_T^2) = \frac{g_A^2 m_p^2}{4\pi f_\pi^2} \int_0^{p_{T\,max}^2} dk_t^2 \frac{y(k_t^2 + y^2 m_p^2)}{[k_T^2 + y m_p^2 + (1-y) m_\pi^2]^2}$$

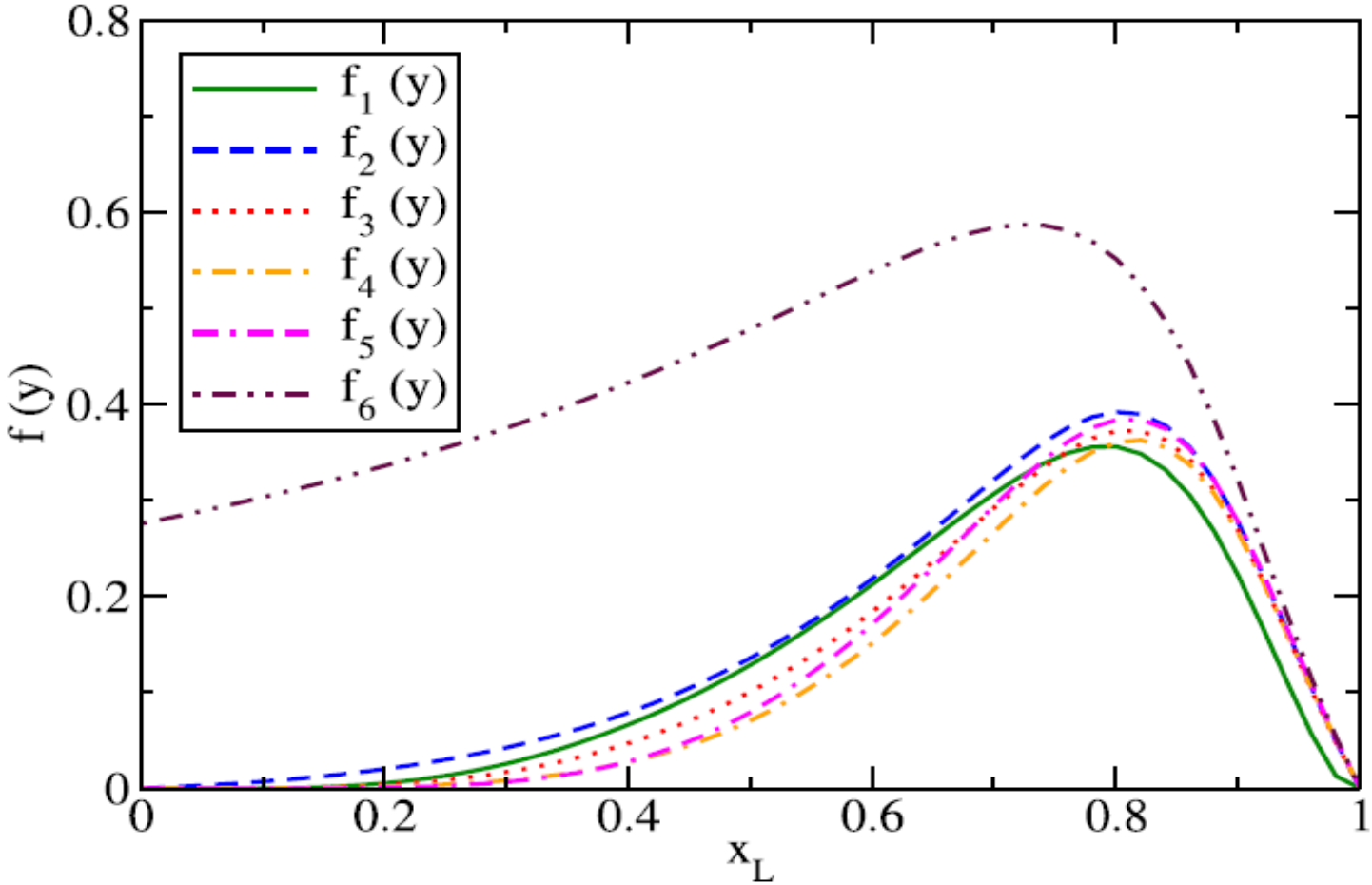
Salamu, Ji, Melnitchouk, Wang, PRL (2015)

Burkardt et al., PRD (2013)

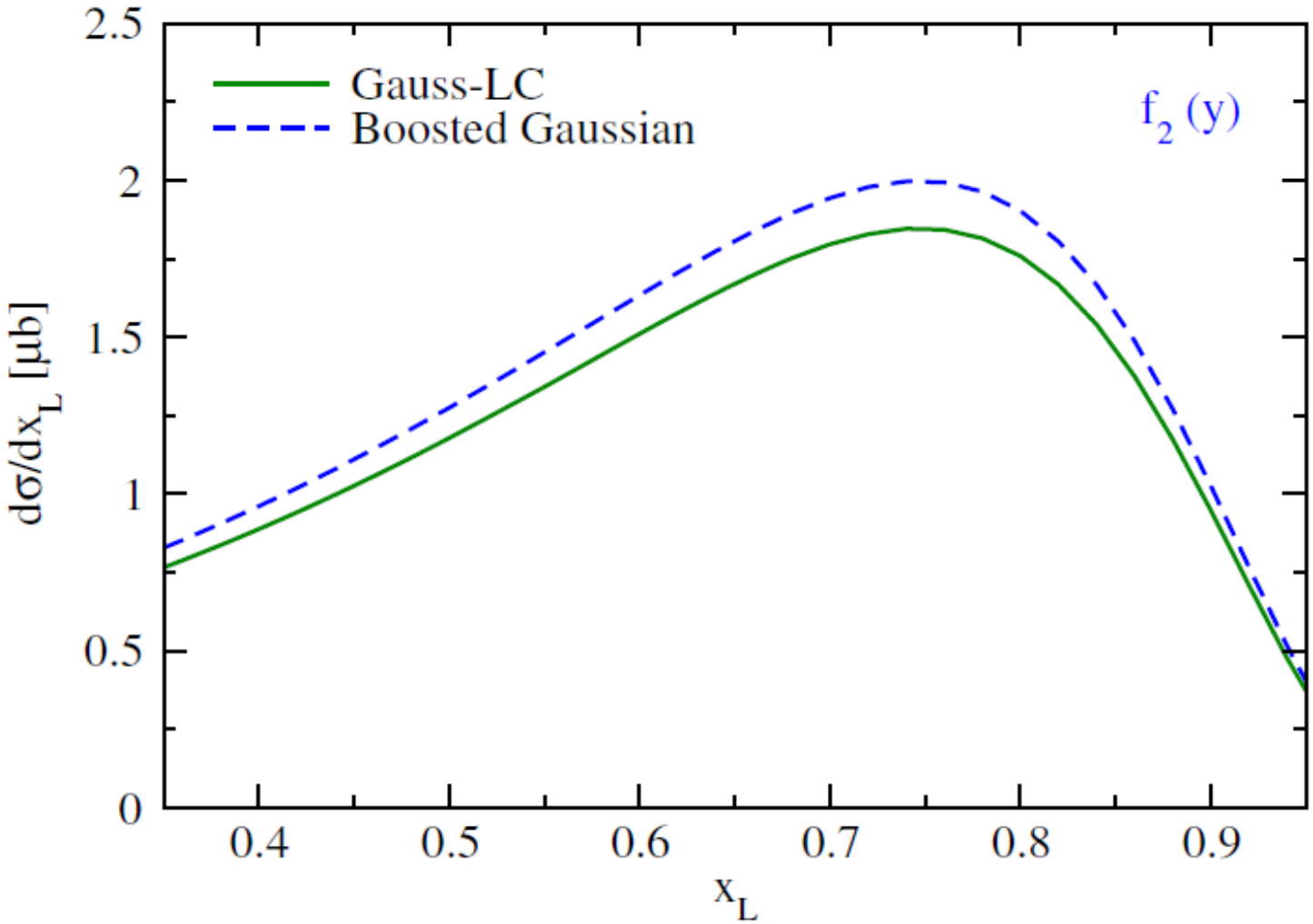
$$\mathcal{L}_{\pi N}^{\mathrm{PS}} = -g_{\pi NN} \bar{\psi}_N i \gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} \psi_N, \longrightarrow \mathcal{L}_{\pi N} = \frac{g_A}{2 f_\pi} \bar{\psi}_N \gamma^\mu \gamma_5 \boldsymbol{\tau} \cdot \partial_\mu \boldsymbol{\pi} \psi_N - \frac{1}{(2 f_\pi)^2} \bar{\psi}_N \gamma^\mu \boldsymbol{\tau} \cdot (\boldsymbol{\pi} \times \partial_\mu \boldsymbol{\pi}) \psi_N,$$

Leading Neutron Processes at HERA

Pion flux / Pion splitting functio $y = 1 - x_L$



Dependence on the vector meson wave function



Parameter free prediction

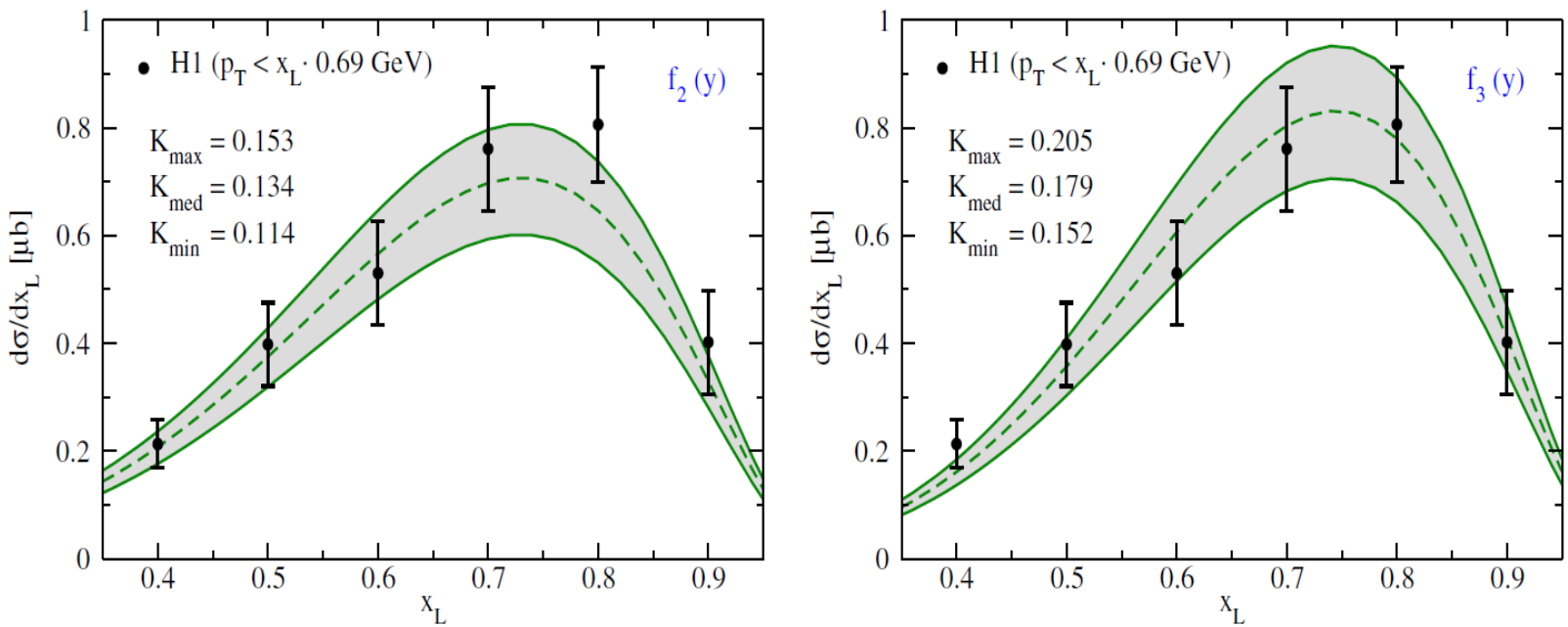


FIG. 6. Leading neutron spectra in exclusive ρ photoproduction obtained by considering the possible range of values of the K factor fixed using the other set of experimental data and two models for the pion flux. H1 data [9] are obtained by assuming that $p_T < 0.69 \cdot x_L$ GeV.

Future ep colliders

ependence on the photon virtuality for exclusive processes: