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Inclusive and Exclusive Processes with a Leading Neutron in ep collisions

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

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

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- 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.

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- 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.

Leading Neutron Processes at HERA

Inclusive process:

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

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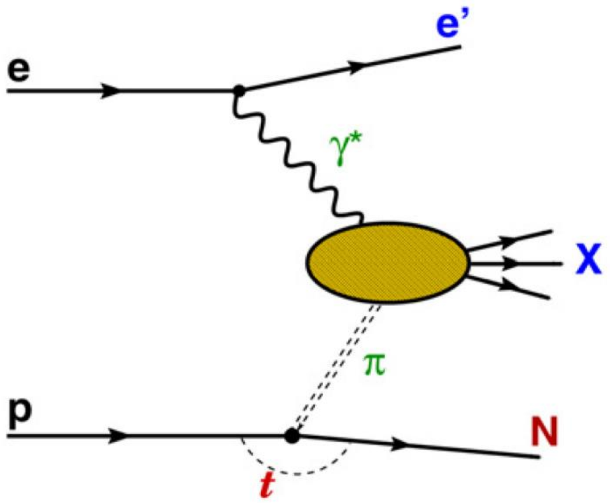

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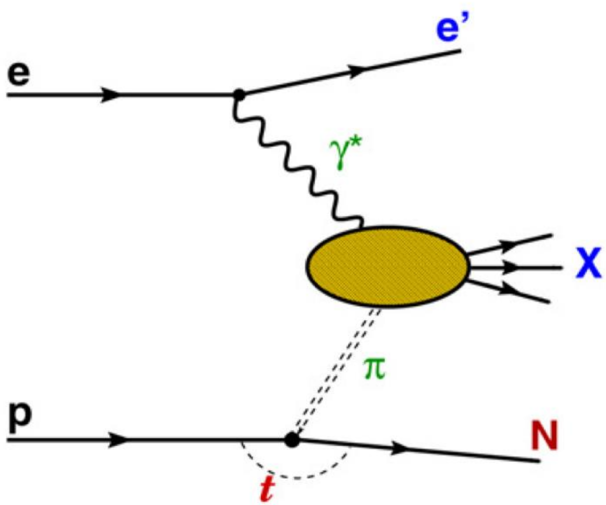

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$\eta > 7.9$
$0.1 < x_F < 0.94$
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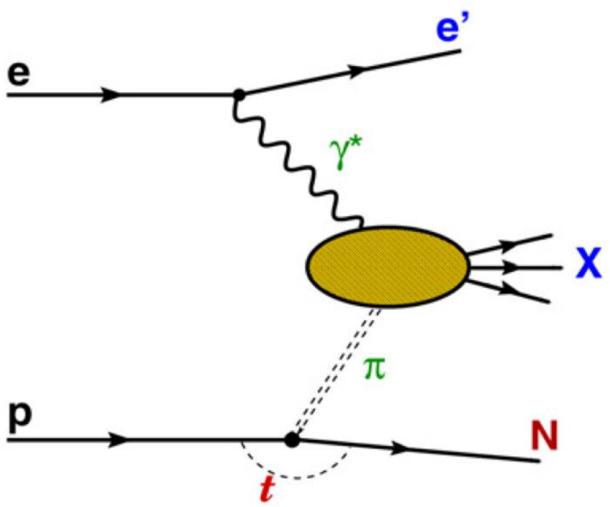

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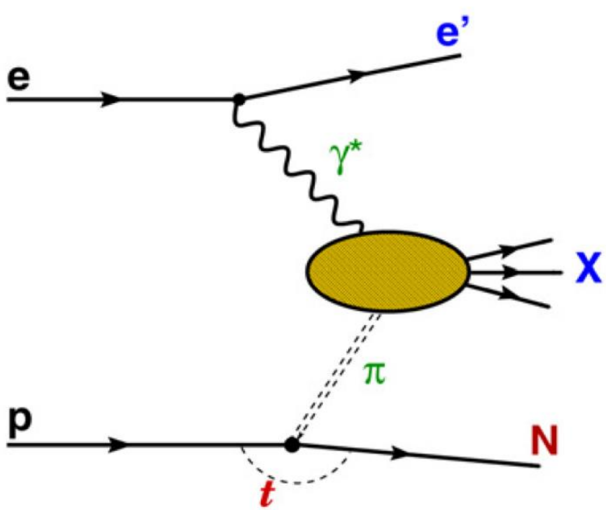

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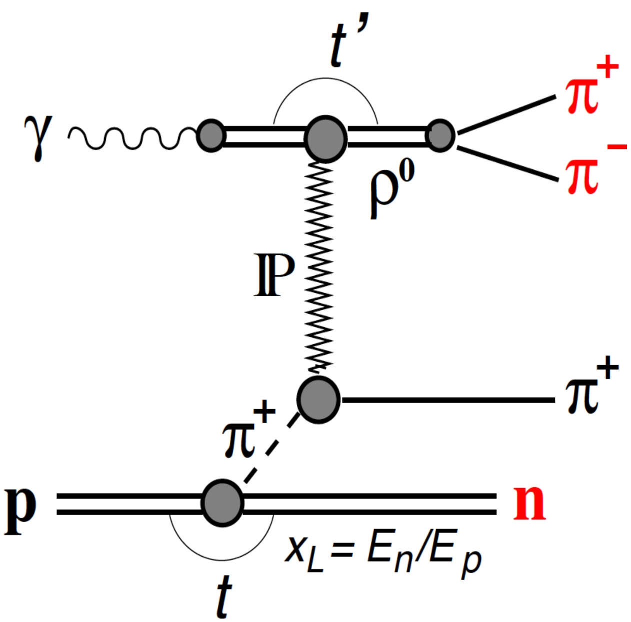

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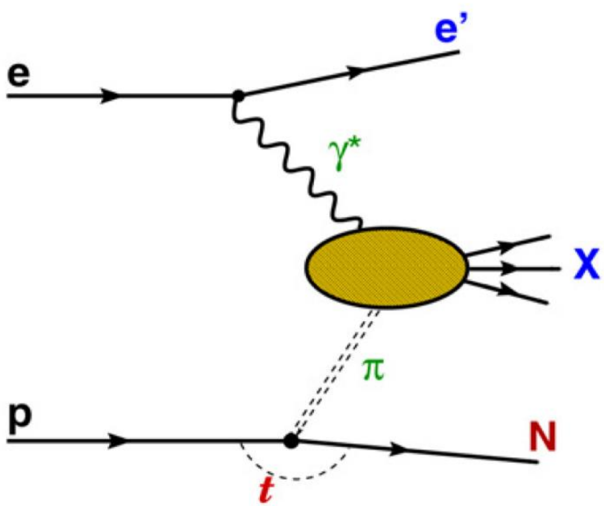

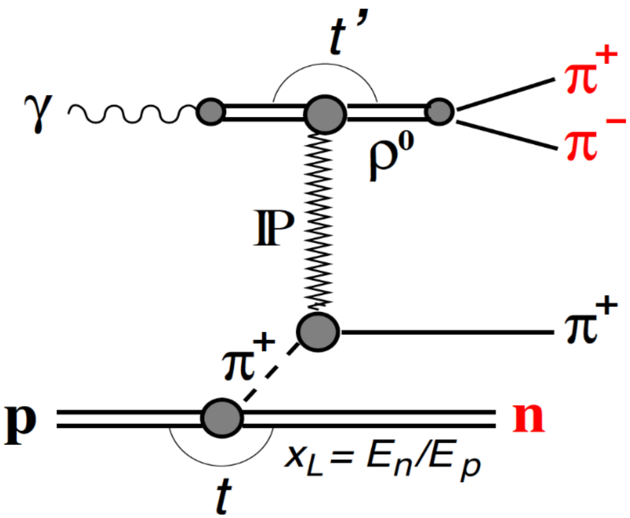

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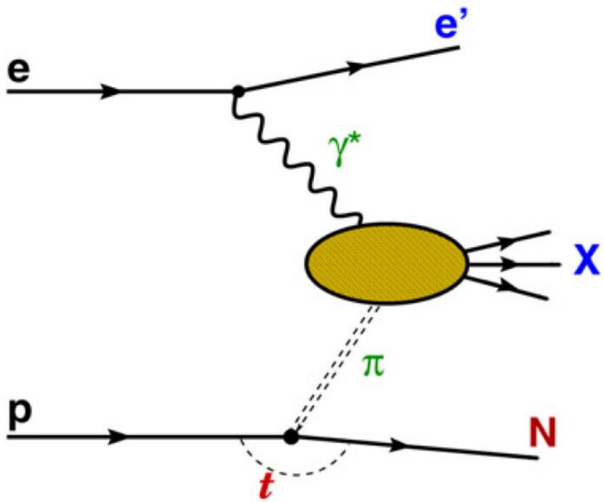
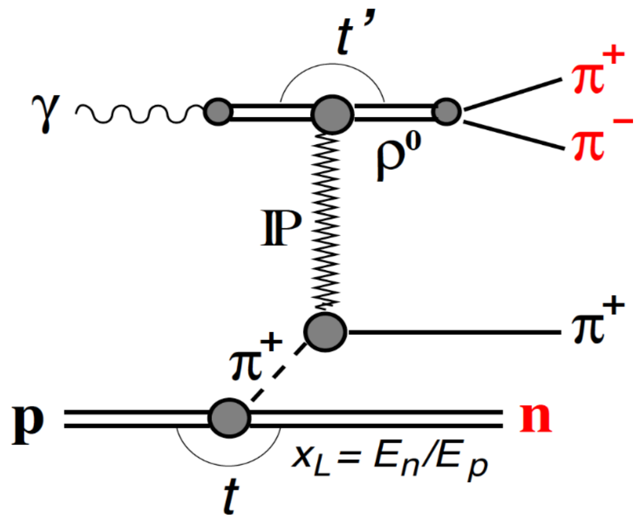
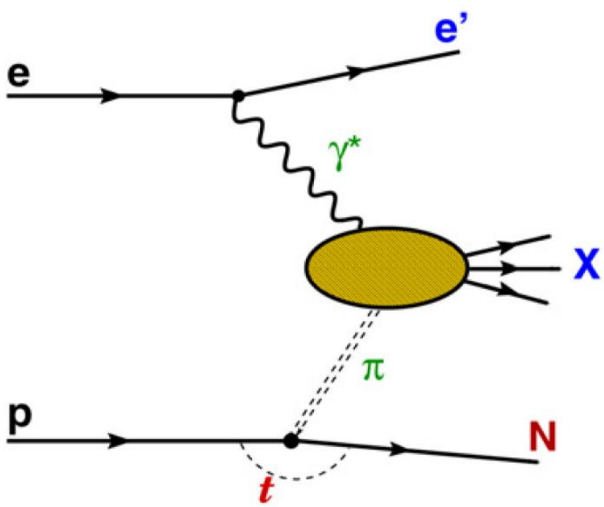


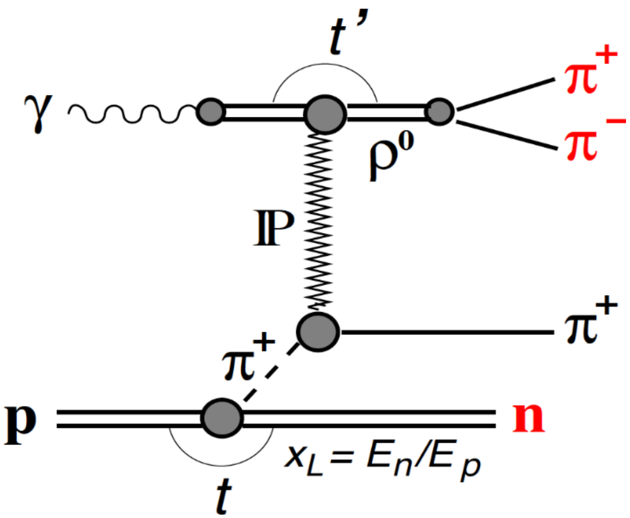


$$\frac{d^2\sigma(W, Q^2, x_L, t)}{dx_L dt} = f_{\pi/p}(x_L, t)\sigma_{\gamma^*\pi}(\hat{W}^2, Q^2)$$

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

Leading Neutron Processes at HERA





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Pion flux / Pion splitting function

Leading Neutron Processes at HERA

Pion flux / Pion splitting function:

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

Form factors:

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

light cone

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

reggeized pion

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

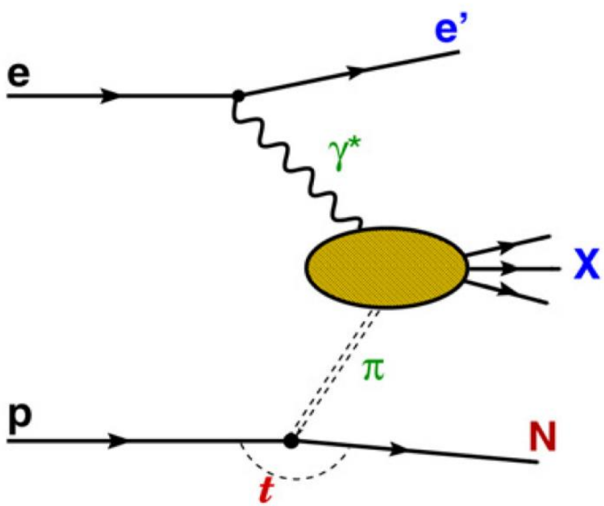
$$F_4(x_L,t) = \frac{(\Lambda^2-m_\pi^2)}{(\Lambda^2-t^2)} \quad , \quad \alpha(t) = 0$$

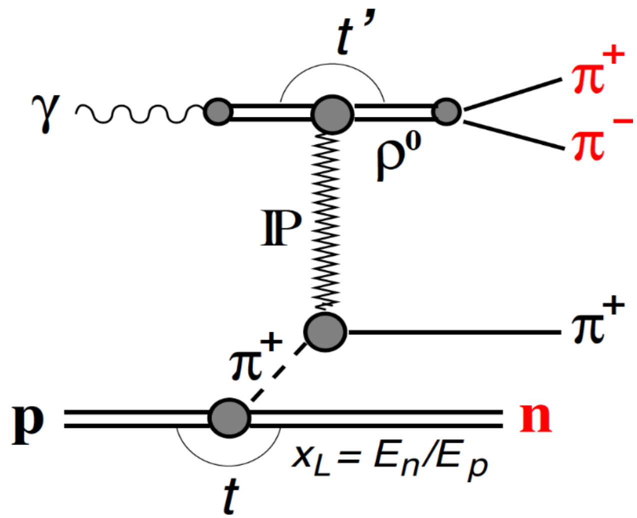
monopole

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

dipole

Leading Neutron Processes at HERA



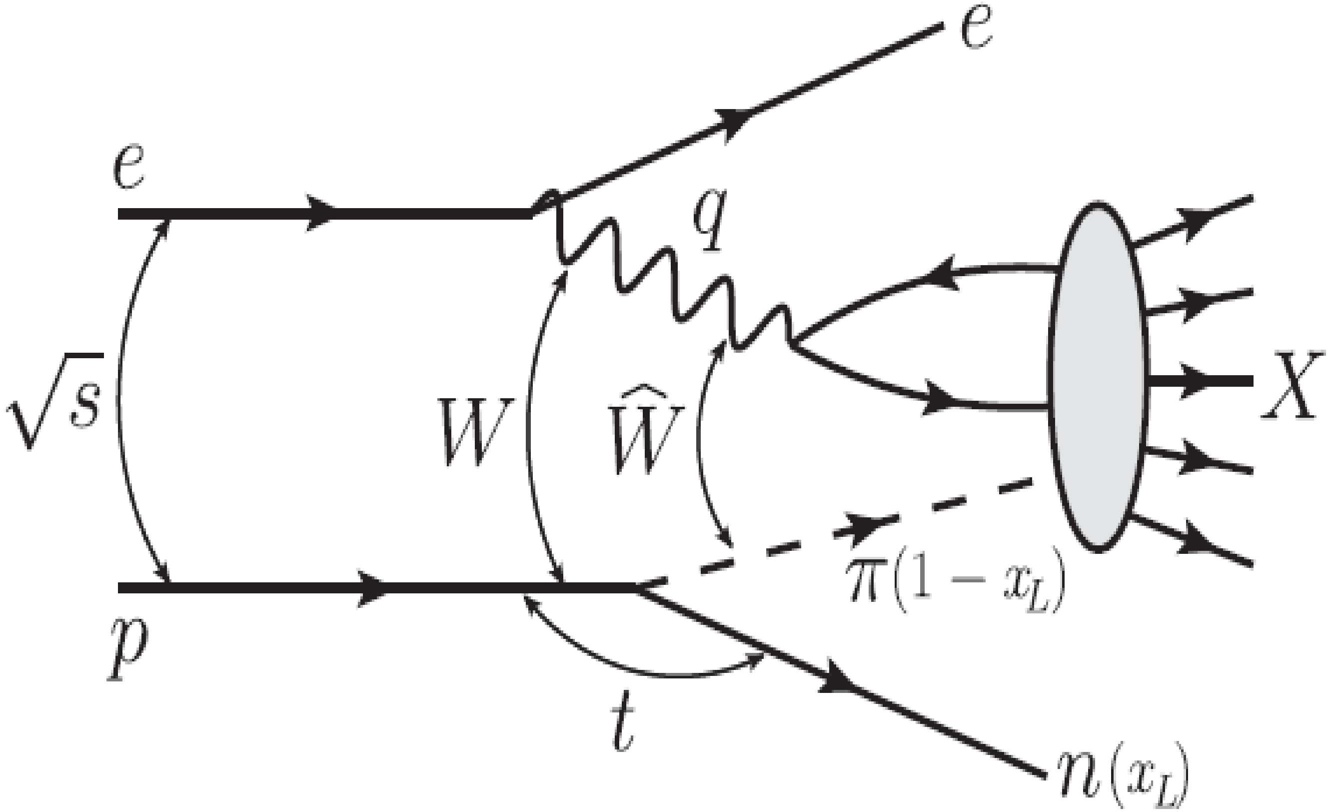


$$\frac{d^2\sigma(W,Q^2,x_L,t)}{dx_L dt} = f_{\pi/p}(x_L,t)\sigma_{\gamma^*\pi}(\hat{W}^2,Q^2)$$

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:



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

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:

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

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

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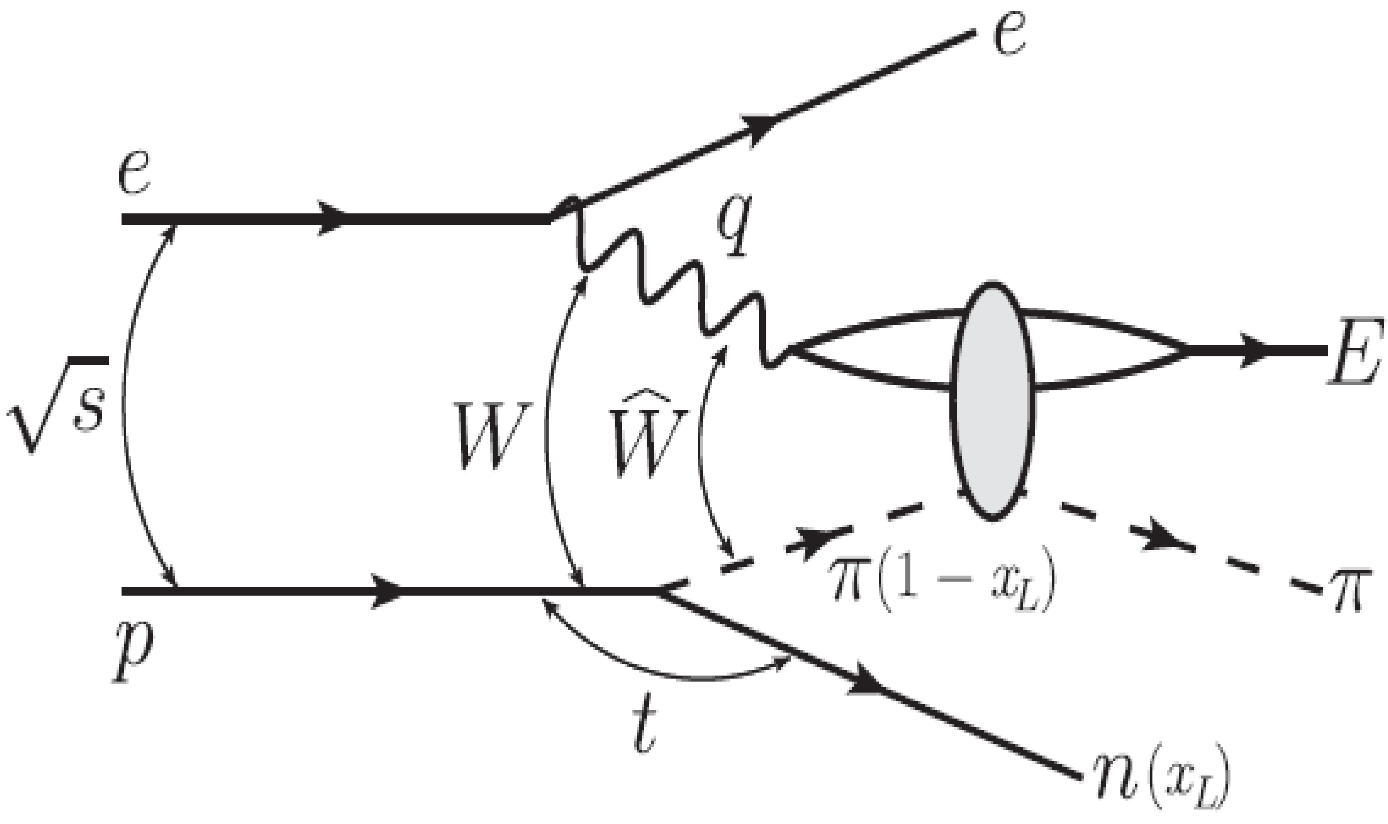
Exclusive processes: $E = \rho,\ \phi,\ J/\Psi,\ \gamma$



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

Scattering amplitude:

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

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Overlap functions for Vector Mesons:

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

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

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Overlap functions for Deeply Virtual Compton Scattering (DVCS):

$$(\Psi_\gamma^*\Psi)_T^f = \frac{N_c\alpha_{\rm em}e_f^2}{2\pi^2}\{[z^2+\bar{z}^2]\varepsilon_1K_1(\varepsilon_1r)\varepsilon_2K_1(\varepsilon_2r)+m_f^2K_0(\varepsilon_1r)K_0(\varepsilon_2r)\}$$

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Leading Neutron Processes in the Color Dipole Formalism

Main assumption:

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

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With :

- R_q = cte $\qquad 1/3 \leq R_q \leq 2/3$

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

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

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

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):

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

- Running coupling Balitsky- Kovchegov equation (rcBK)

Leading Neutron Processes in the Color Dipole Formalism

Absorption effects:

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

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Open questions:

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

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

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:

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Consequently :

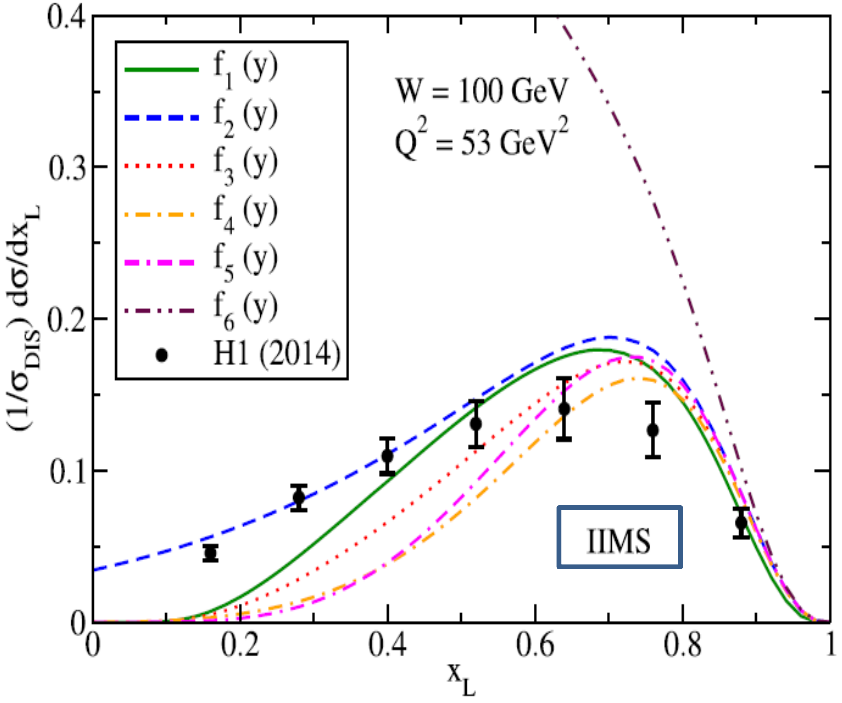
$$\sigma_{\gamma^*\pi}(\hat{x},Q^2) \propto \mathcal{K}_{inc} \cdot R_q$$

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

Results for Inclusive Processes

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

$\boxed{R_q = 2/3 \text{ ; K = 1}}$



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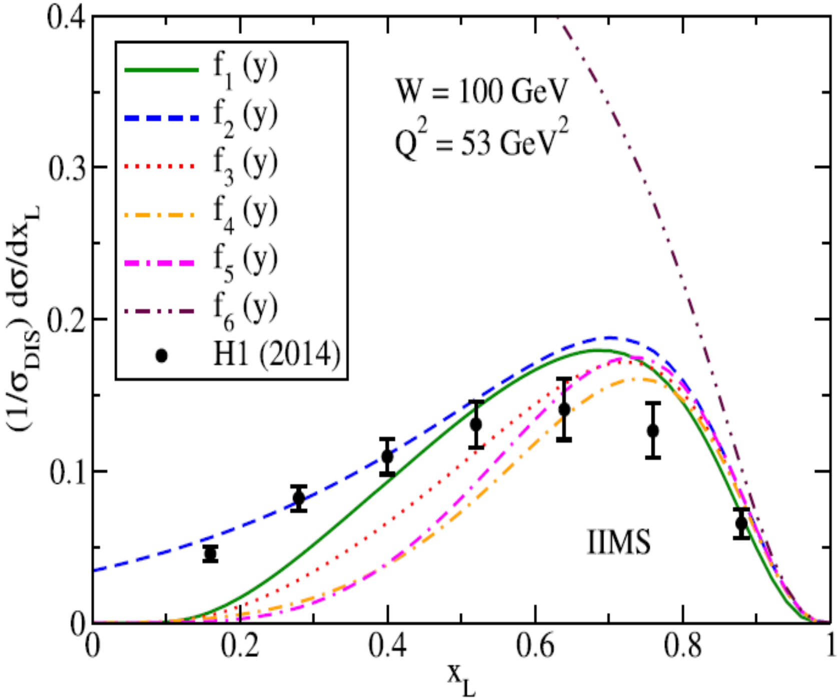

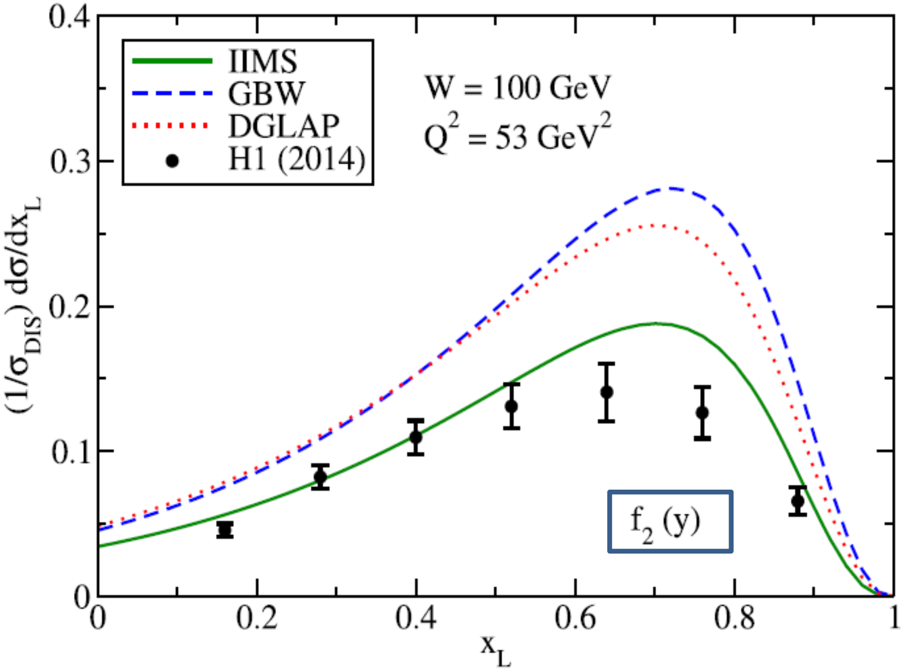

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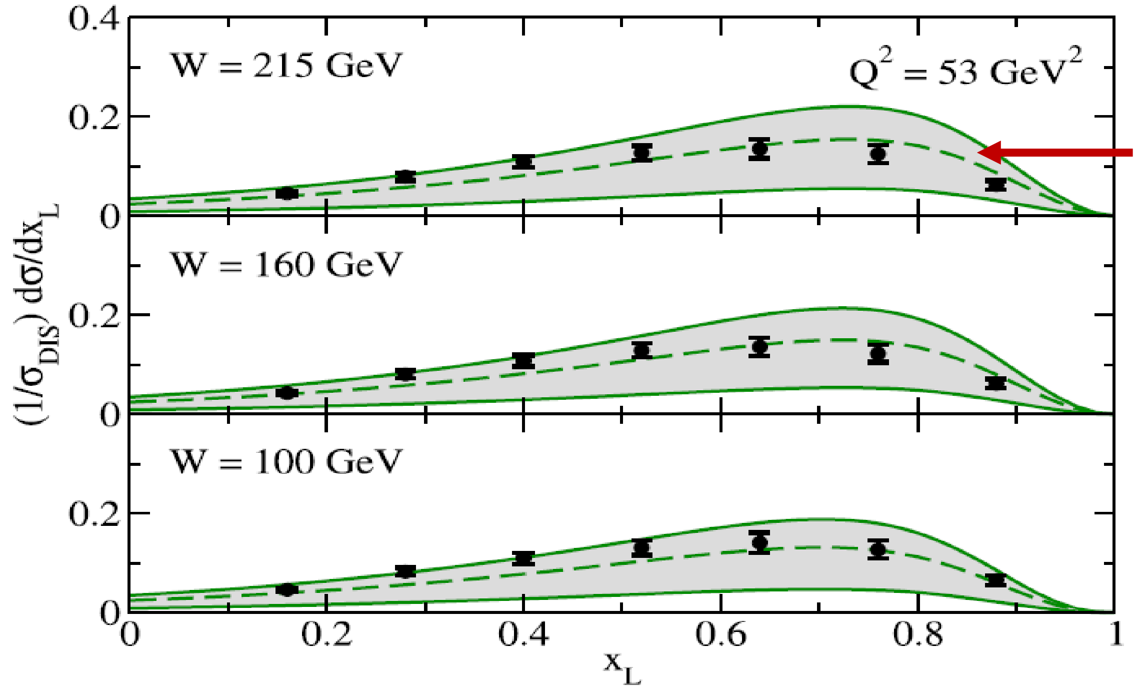

Rq . K = 0.5

Results for Inclusive Processes

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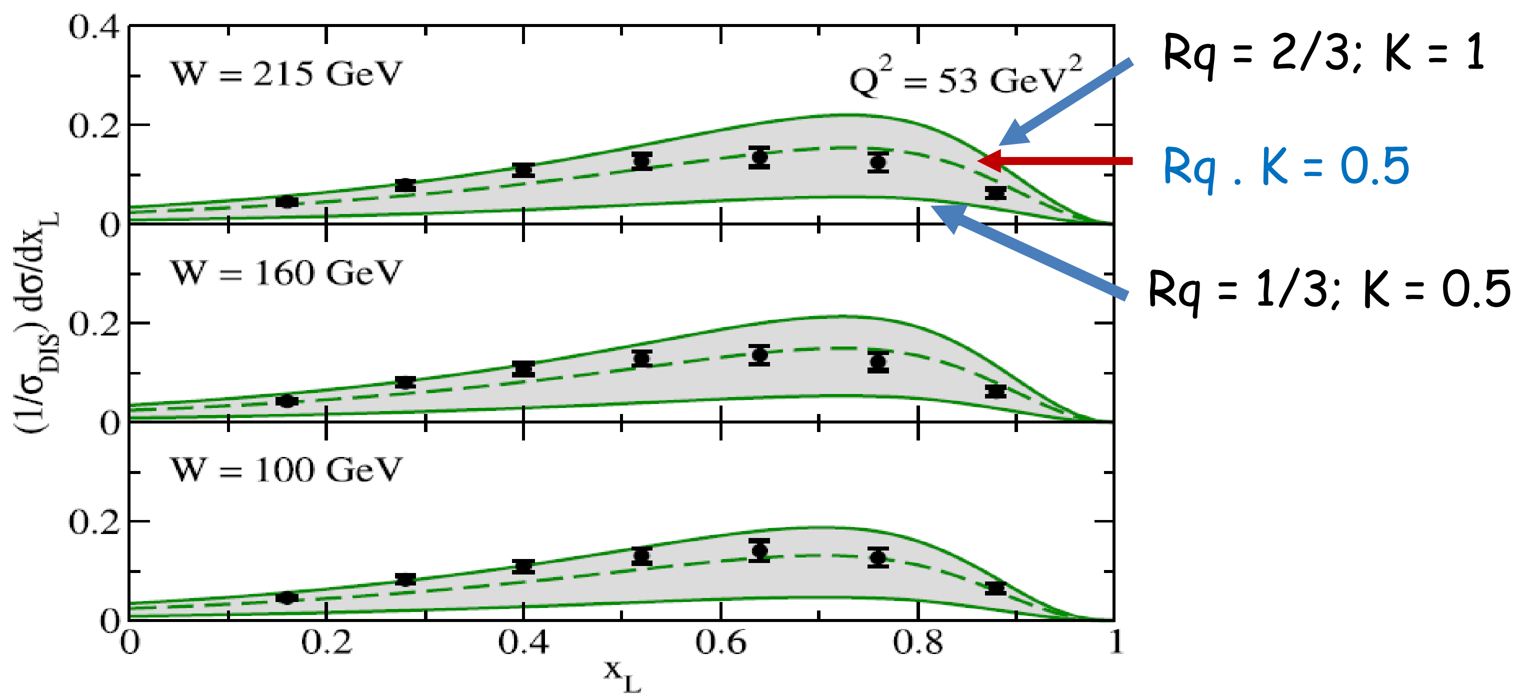

Results for Exclusive Processes

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

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

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

Results for Exclusive Processes

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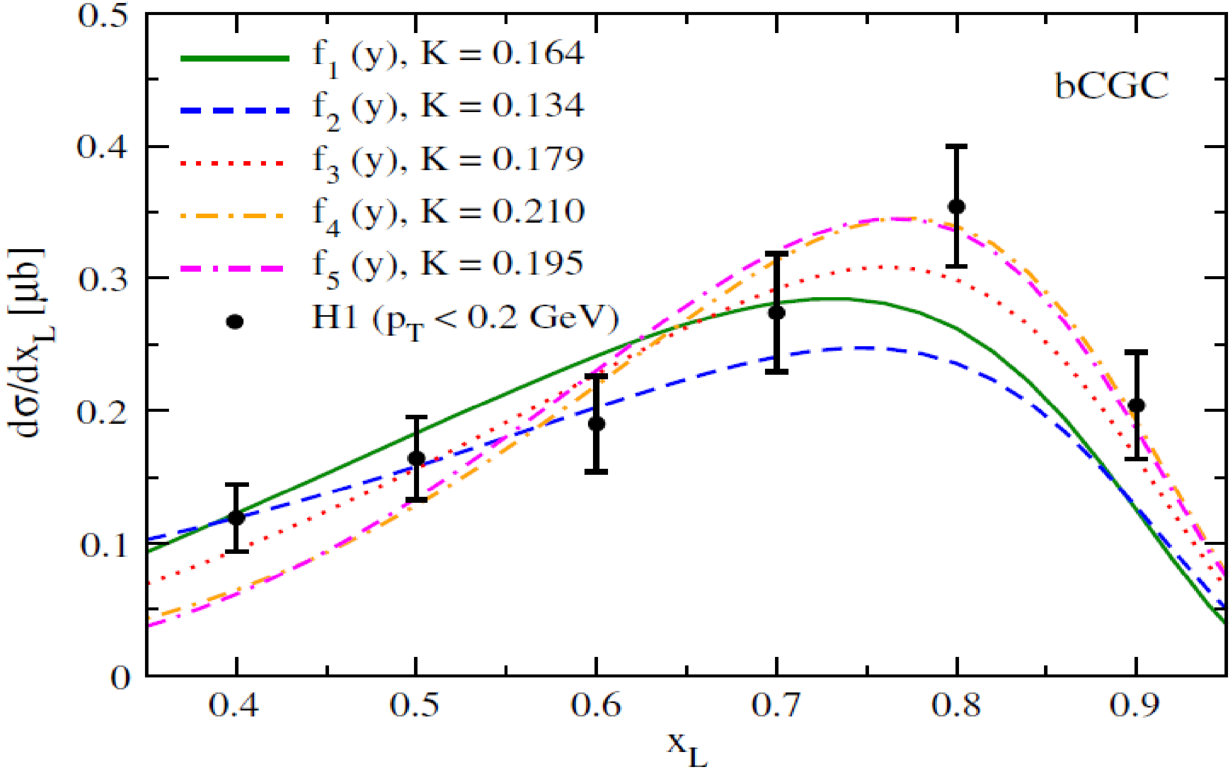
Dependence on the pion flux:



Results for Exclusive Processes

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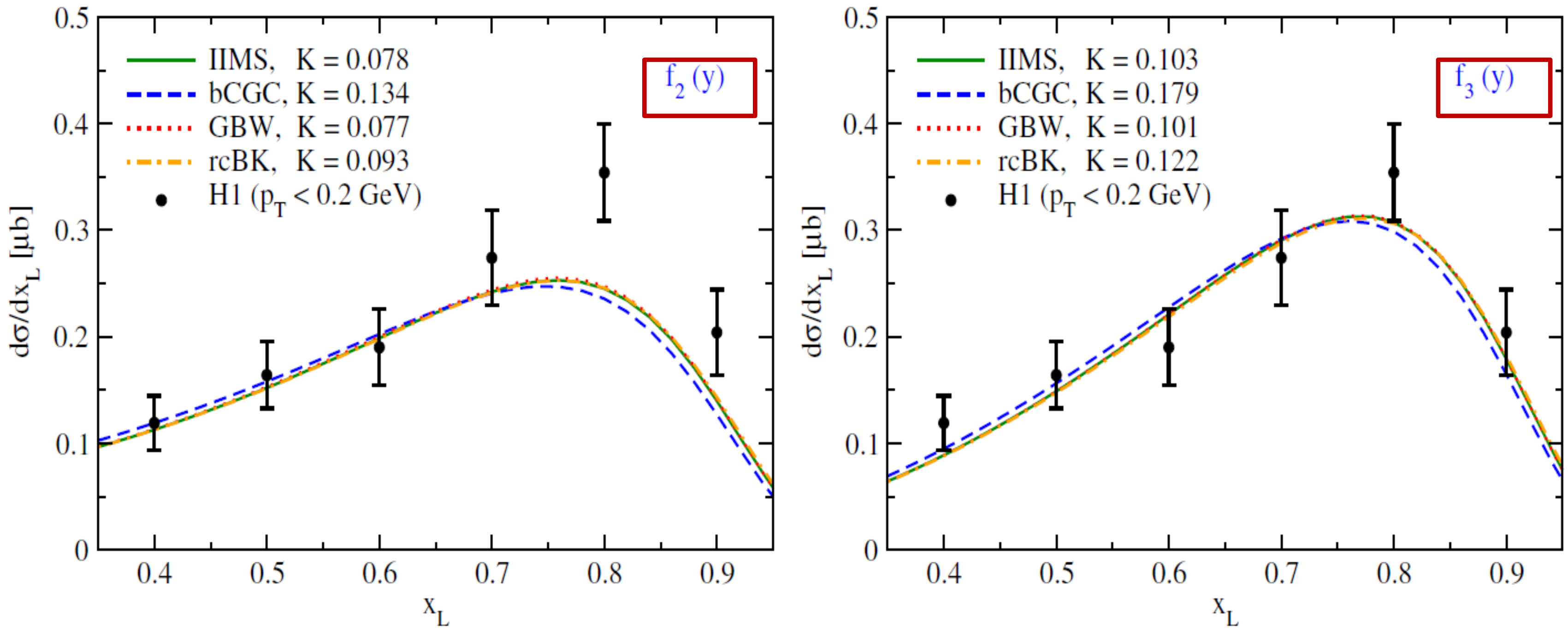
Dependence on the dipole – target amplitude:



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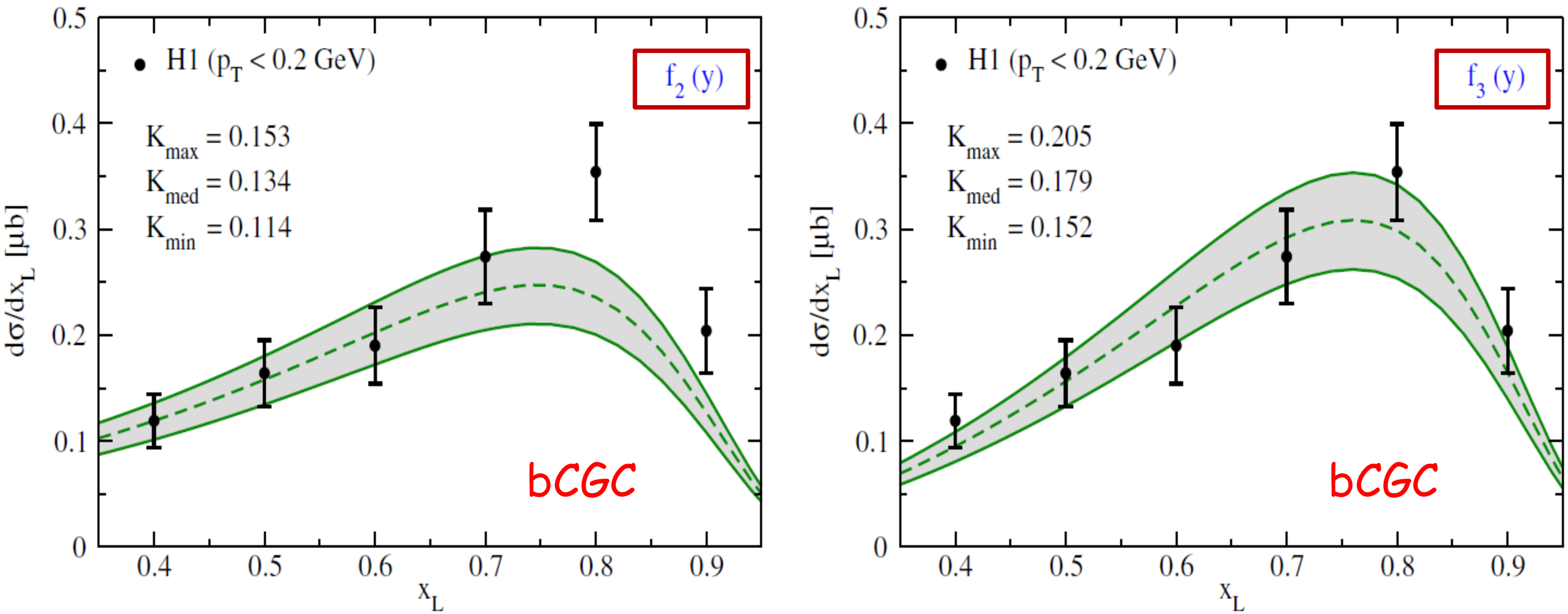
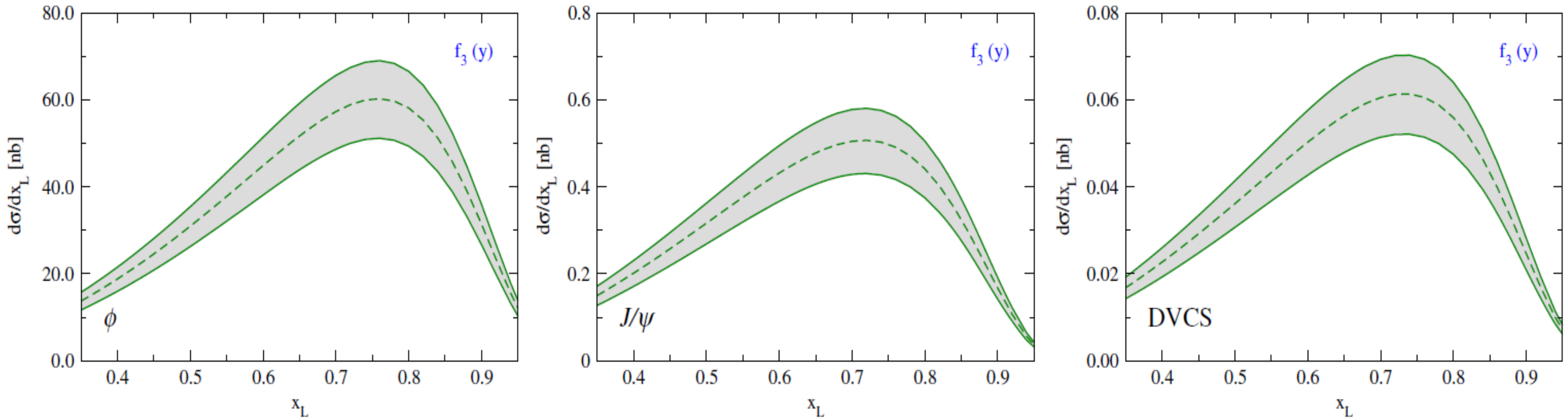


Predictions for Exclusive Processes with a leading neutron at HERA



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

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

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

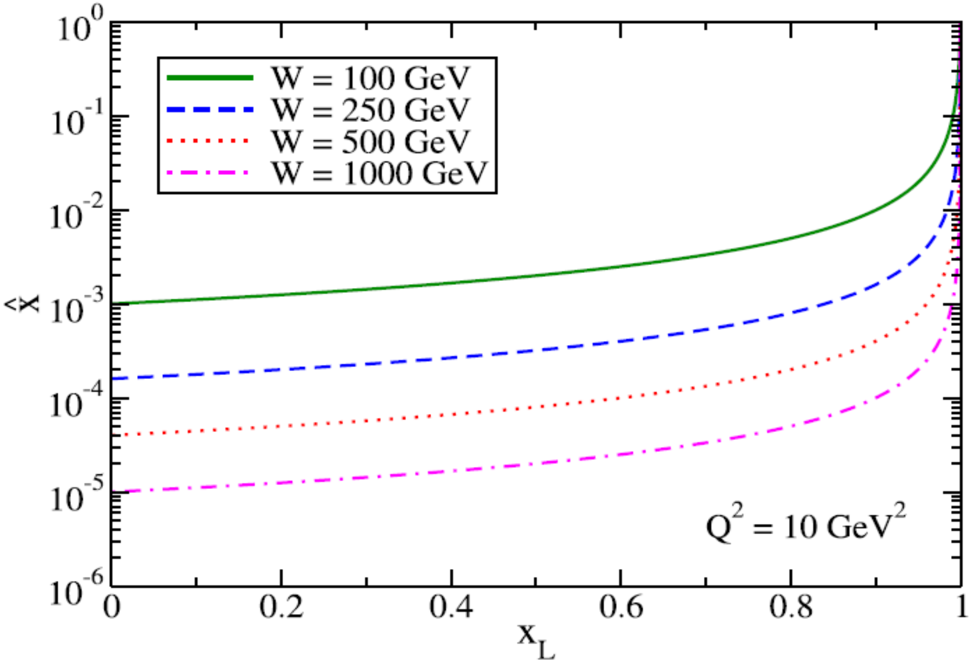
$$Q^2 = 10 \ \mathrm{GeV}^2$$

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

Future ep colliders

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

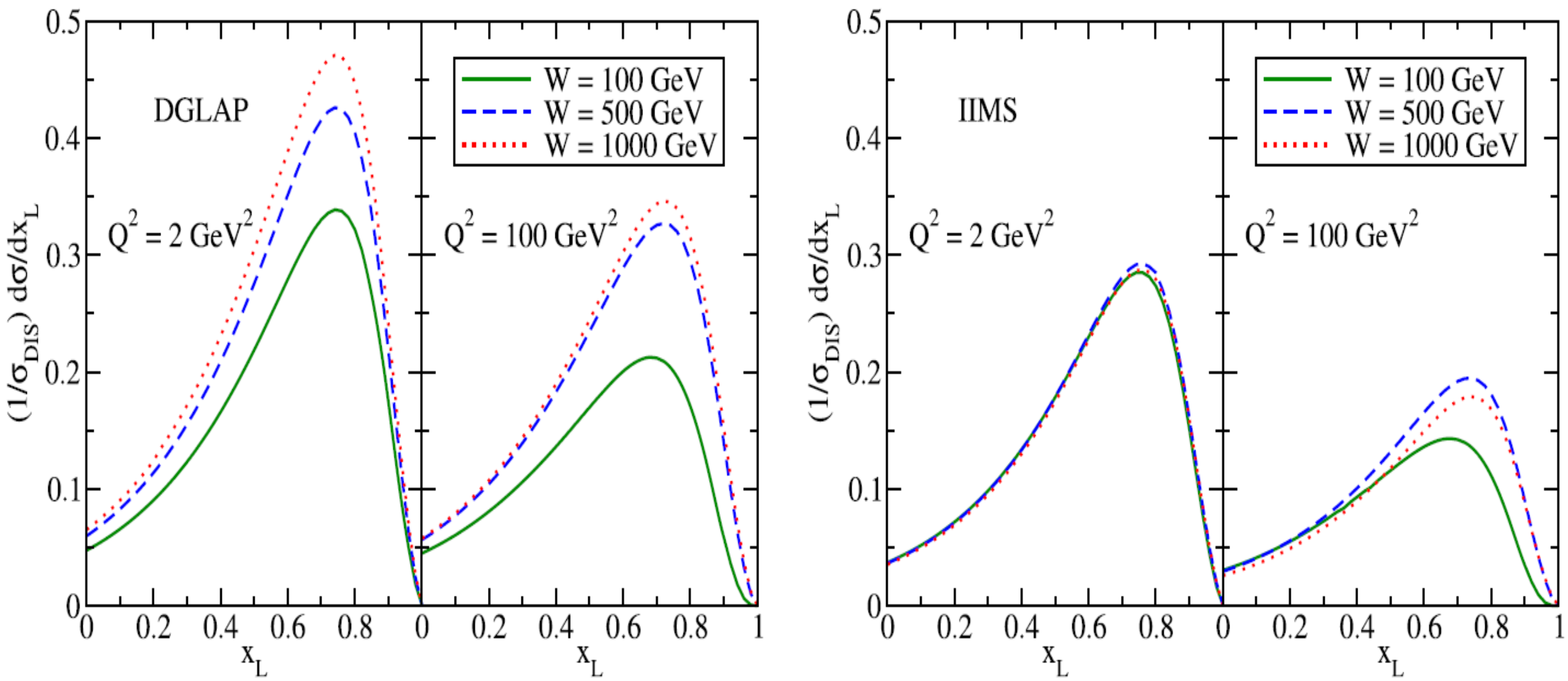
$$\hat{x} = \frac{Q^2 + m_f^2}{\hat{W}^2 + Q^2} = \frac{Q^2 + m_f^2}{(1 - x_L)W^2 + Q^2}$$



Future ep colliders

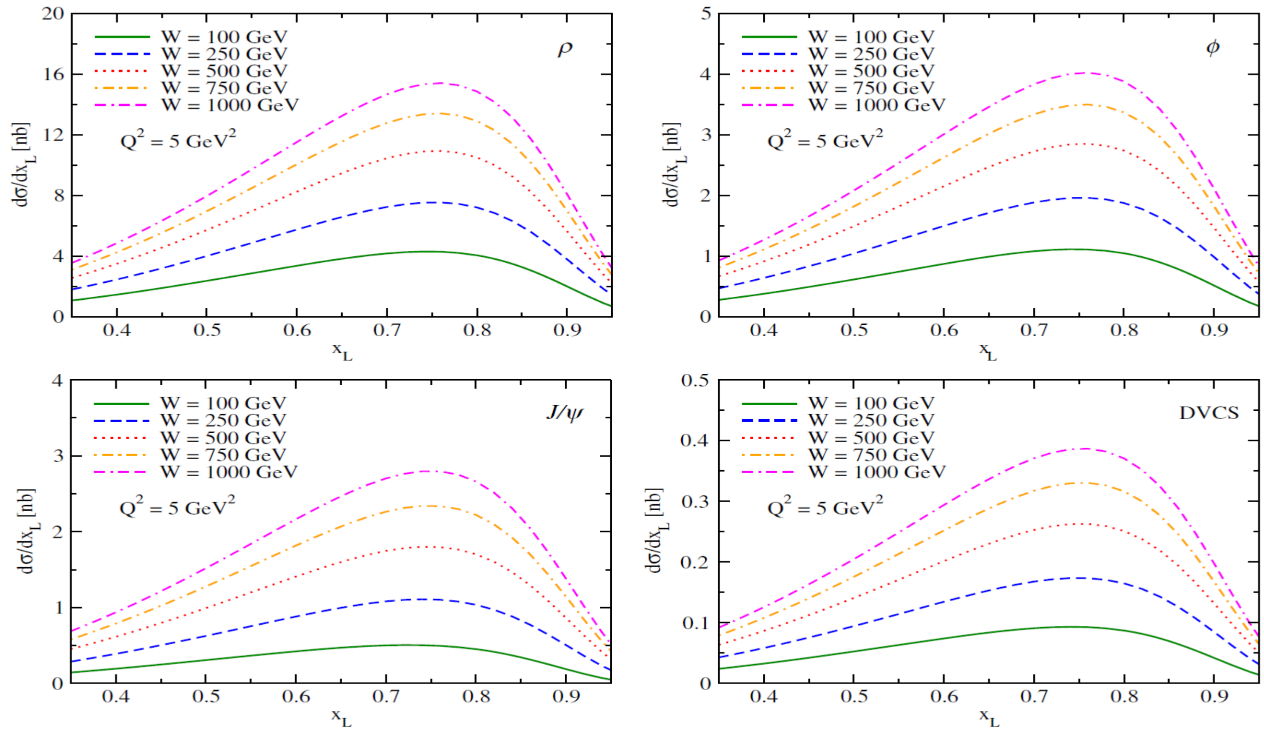
Feynman scaling in inclusive processes:

Linear X Nonlinear



Future ep colliders

Dependence on the energy for exclusive processes:



$$W = 1\ \text{TeV}$$
$$Q^2 = 5\ \text{GeV}^2$$

$$\sigma(\gamma^* p \to \rho \pi n) = 6.55 \pm 0.95\ \text{nb}$$
$$\sigma(\gamma^* p \to \phi \pi n) = 1.71 \pm 0.25\ \text{nb}$$
$$\sigma(\gamma^* p \to J/\Psi \pi n) = 1.20 \pm 0.17\ \text{nb}$$

Summary

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Thank you for your attention !

Extras

Chiral perturbation theory

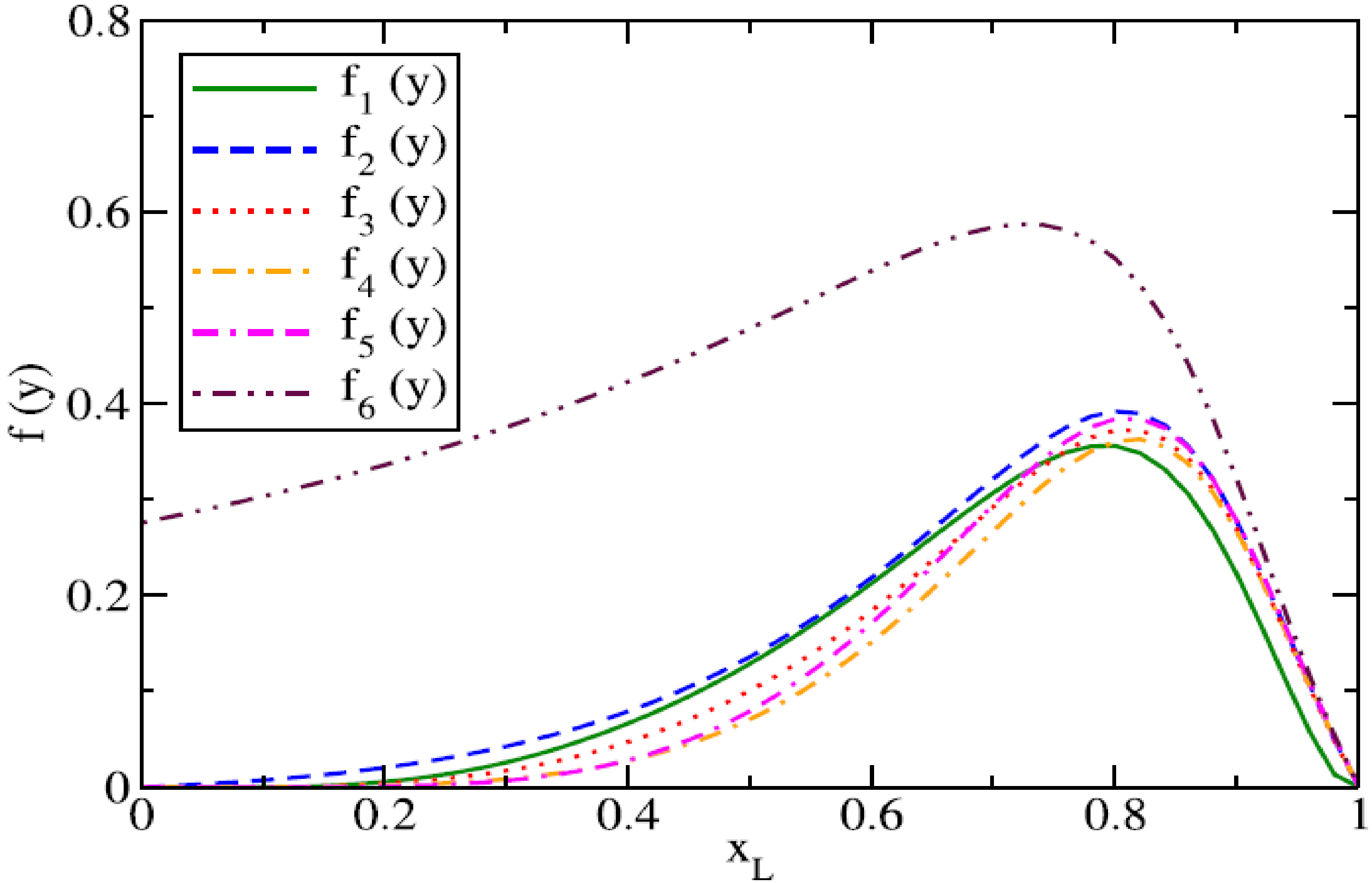
$$f_{\pi/p}(y, k_T^2) = \frac{g_A^2 m_p^2}{4\pi f_\pi^2} \int_0^{p_{T\,max}^2} dk_t^2 \frac{y(k_t^2 + y^2 m_p^2)}{[k_T^2 + y m_p^2 + (1-y) m_\pi^2]^2}$$

Salamu, Ji, Melnitchouk, Wang, PRL (2015)
Burkardt et al., PRD (2013)

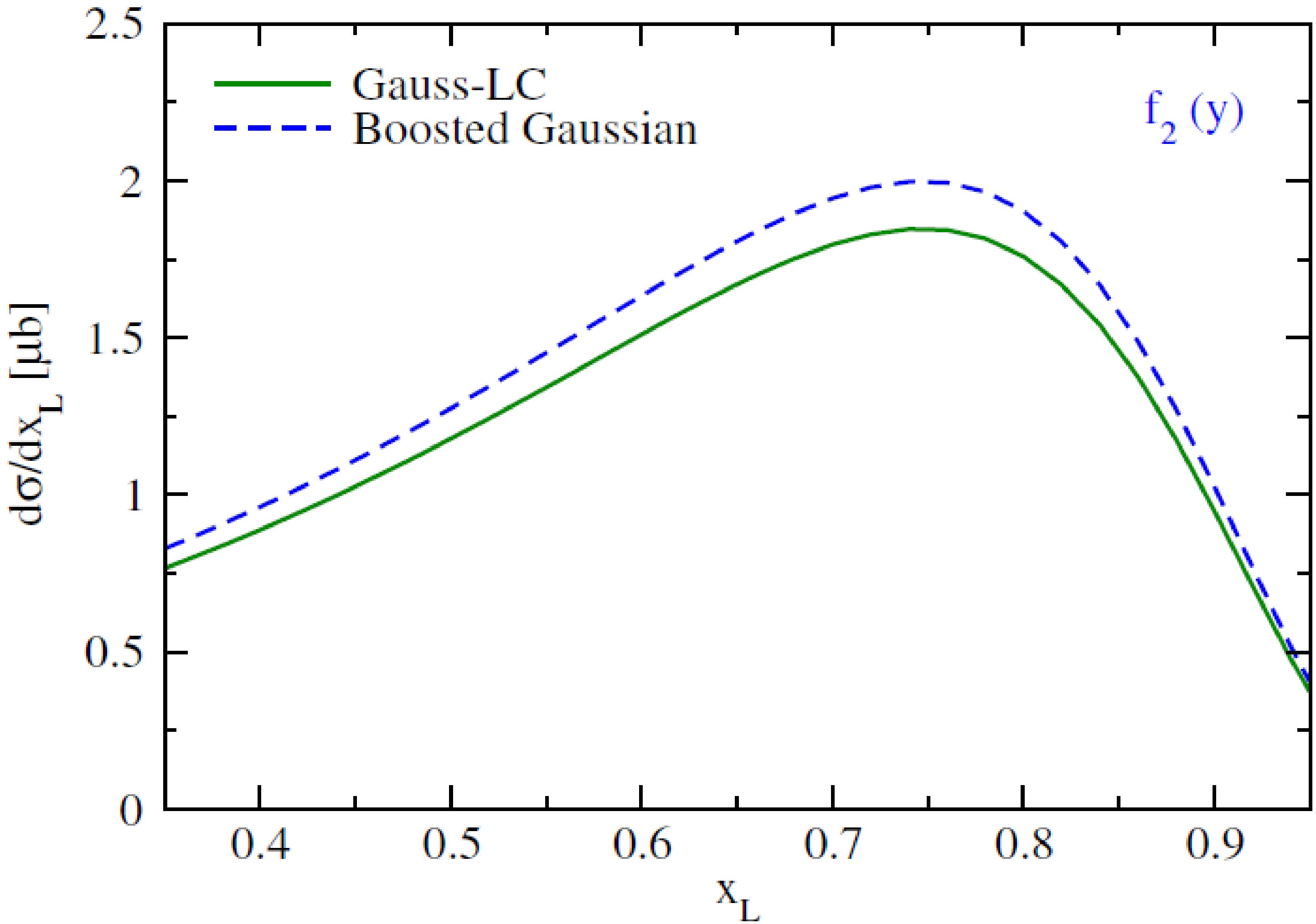
$$\mathcal{L}_{\pi N}^{\mathrm{PS}} = -g_{\pi NN} \bar{\psi}_N i \gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} \psi_N, \longrightarrow \mathcal{L}_{\pi N} = \frac{g_A}{2 f_\pi} \bar{\psi}_N \gamma^\mu \gamma_5 \boldsymbol{\tau} \cdot \partial_\mu \boldsymbol{\pi} \psi_N - \frac{1}{(2 f_\pi)^2} \bar{\psi}_N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

Leading Neutron Processes at HERA

Pion flux / Pion splitting function: $y = 1 - x_L$



Dependence on the vector meson wave function



Parameter free prediction

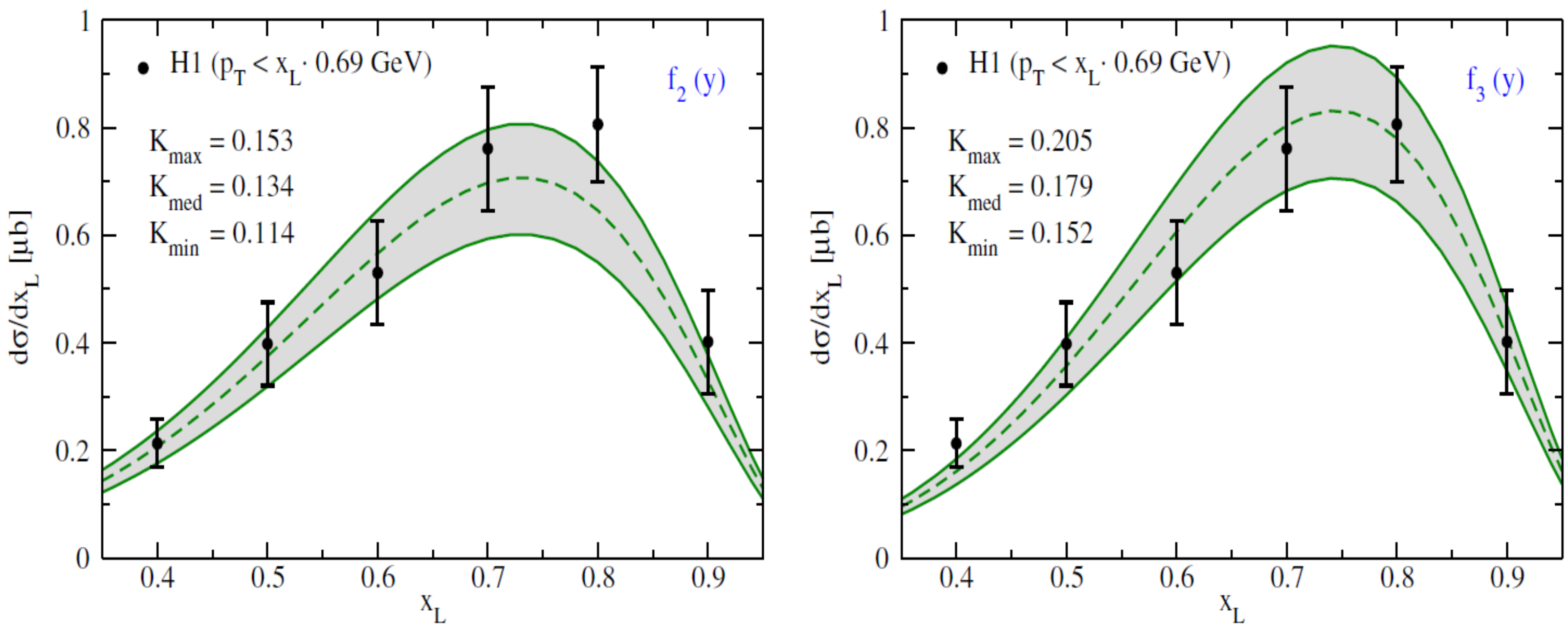


FIG. 6. Leading neutron spectra in exclusive ρ photoproduction obtained by considering the possible range of values of the K factor fixed using the other set of experimental data and two models for the pion flux. H1 data [9] are obtained by assuming that $p_T < 0.69 \cdot x_L$ GeV.

Future ep colliders

Dependence on the photon virtuality for exclusive processes: