Exclusive ρ^0 Meson Photoproduction with a Leading Neutron at HERA

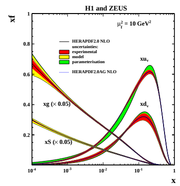
Sergey Levonian

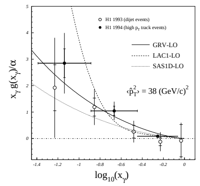
On behalf of H1 Collaboration

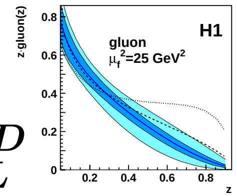
Results presented in this talk: [arXiv:1508.03176] (submitted to EPJC)

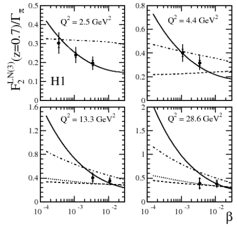
HERA as a '4P' facility

HERA enables to study structure of

Proton – $F_2, F_L, \ldots$ 

Photon – g/γ 

Pomeron – F_2^D, F_L^D 

Pion – F_2^π 

HERA as a ‘4P’ facility

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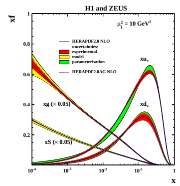
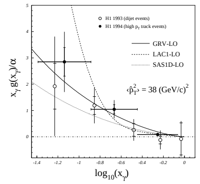


Proton – $F_2, F_L, \ldots$



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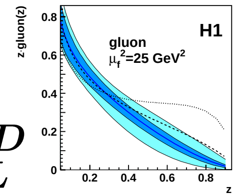

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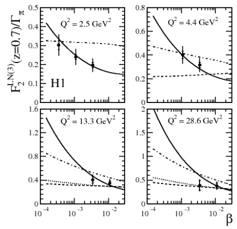
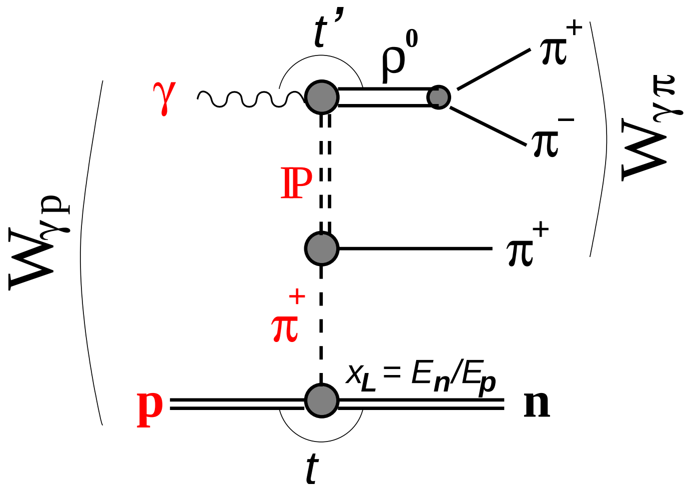


Pion – F_2^π

Here for the first time we investigate the reaction involving all these objects simultaneously:

$$\gamma + \mathbf{p} \longrightarrow \rho^0\, \pi^+\, \mathbf{n}$$

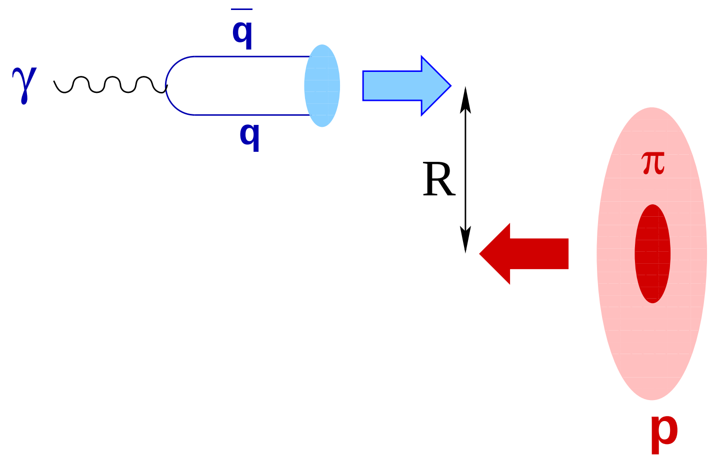


Introduction

- First observation of exclusive photoproduction on (virtual) pion
  - ▷ Unique for HERA (before that γ, π beams did exist, but no target)
  - ▷ Extends further (very powerful) VM field at HERA
  - ▷ Additional constraints to pion flux models
  - ▷ Information about absorption effects in leading baryon production at HERA

- Key observables:
  - ▷ $x_L = E_n/E_p$ (or $x_\pi = 1 - x_L$) distribution: $\sim f_{\pi/p}(x_L)$
  - ▷ W dependence: $\sim W^\delta$ – nature of exchange object(s)
  - ▷ t-slope of ρ^0 ($b \propto R^2$ in geometric picture)

- Main experimental difficulty:
  - ▷ Trigger (tagged γp – too large W to observe VM;
    untagged γp – too high rates/prescales)
  - ▷ Limited acceptance for forward π and N ($\eta_{\text{lab}} \geq 6$)



Reaction of interest and the analysis phase space

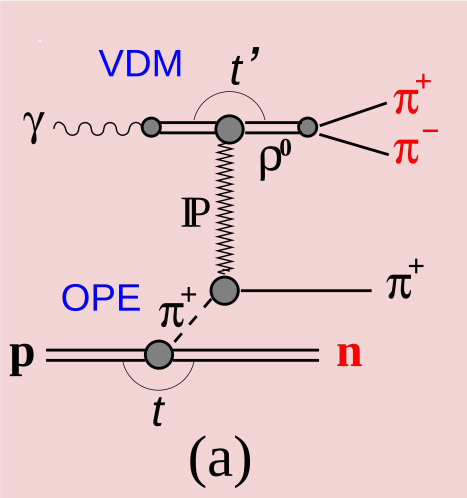
$$\gamma^* + \mathbf{p} \longrightarrow \rho^0 \, \pi^+ \, \mathbf{n}$$

$$\rho^0 \to \pi^+ \pi^-$$

Photoproduction:	$Q^2 < 2$ GeV^2	$(\langle Q^2 \rangle = 0.04$ GeV$^2)$
Low p_t:	$\lvert t \rvert < 1$ GeV^2	$(\langle \lvert t \rvert \rangle = 0.20$ GeV$^2)$
Small mass:	$0.3 < m_{\pi\pi} < 1.5$ GeV	(m_{ρ^0})
π^+, π^- in CT:	$20 < W_{\gamma p} < 100$ GeV	$(\langle W_{\gamma p} \rangle = 45$ GeV$)$
Leading n:	$E_n > 120$ GeV;	$\theta_n < 0.75$ mrad

No hard scale present $\Rightarrow$ Regge framework is most appropriate

Drell-Hiida-Deck diagrams and diffractive background



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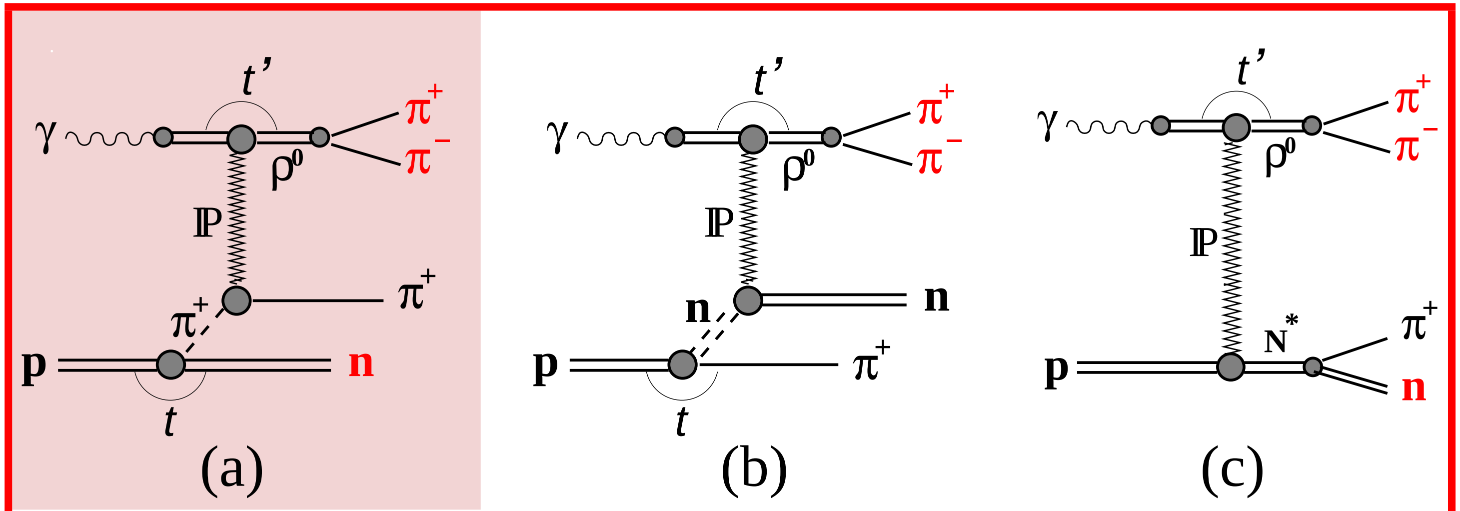
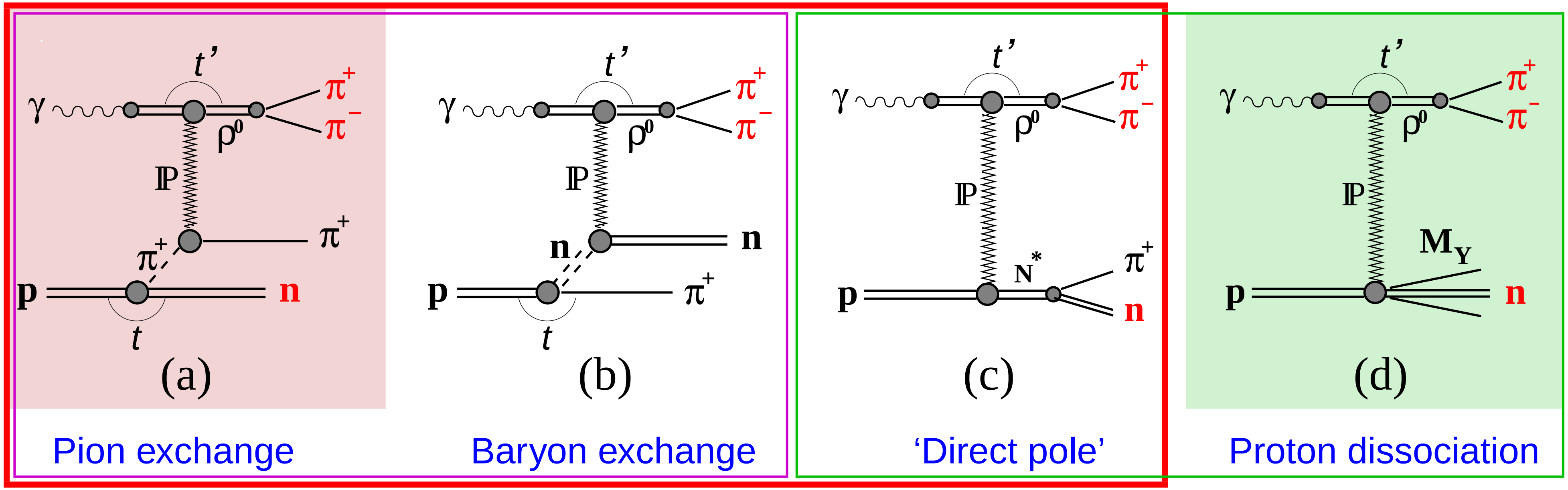


Pion exchange

Baryon exchange

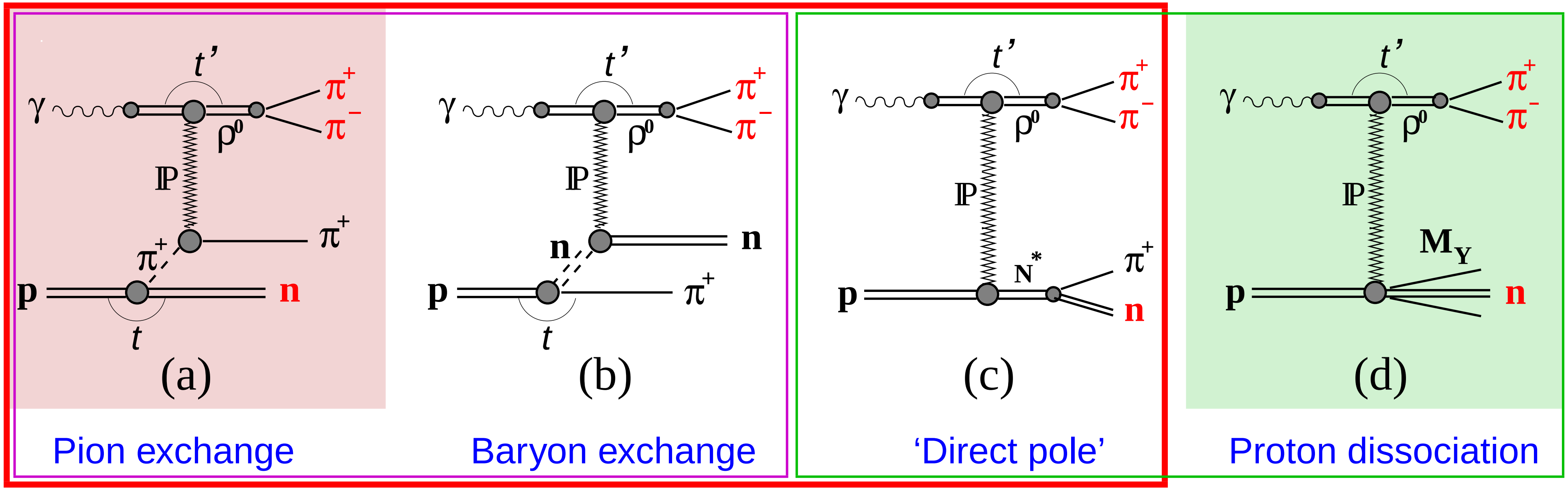
'Direct pole'

Drell-Hiida-Deck diagrams and diffractive background



(P o m p y t   M C)   (D i f f V M   M C)

Drell-Hiida-Deck diagrams and diffractive background

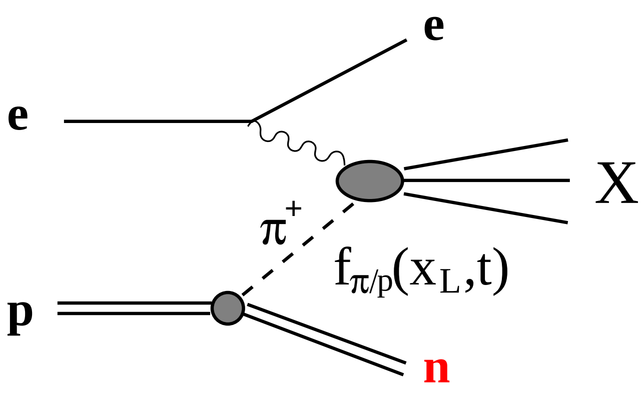


(Pompyt MC)　　(DiffVM MC)

Properties *(S. Drell and K. Hiida (1961); R. Deck (1964); F. Hayot et al. (1977); A. Kaidalov (1979))*

- At large s and $t' \to 0$ $\quad A_b \simeq -A_c$ and π-exchange dominates
- $\sigma(\gamma p \to \rho^0 n \pi^+) = |A_a + A_b + A_c|^2$ ⇒ Interference!
- At small $M_{n\pi^+}$ – prominent peak in t' (kinematics $+$ interference)

$p \to n\pi^+$ vertex, pion flux and OPE validity

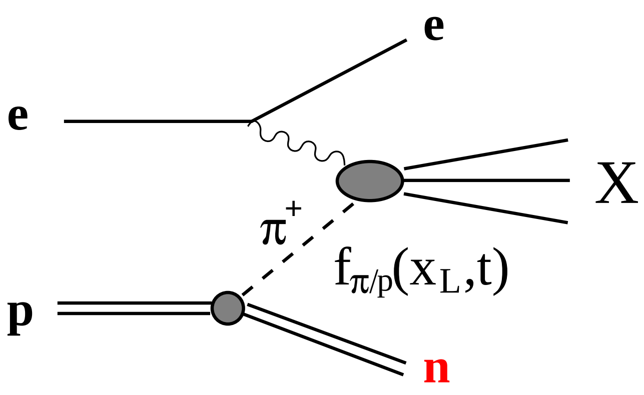


LN in DIS: F_2^π, access to the g/π

But:
- other exchanges (ρ, a_2) - ? ($\Rightarrow$ low t)
- factorisation (rescattering/abs.corr.) - ?
- pion flux models (too many on the market)

$$f_{\pi/p}(x_L, t) \propto (1 - x_L)\frac{-t}{(m_\pi^2 - t)^2} F^2(t, x_L)$$

$p \to n\pi^+$ vertex, pion flux and OPE validity



$$\frac{f_{\rho/p}}{f_{\pi/p}} \simeq (m_\pi^2 + |t|)^2/(M_\rho^2 + |t|)^2 \simeq 1/(\frac{M_\rho^2}{|t|} + 1)^2$$

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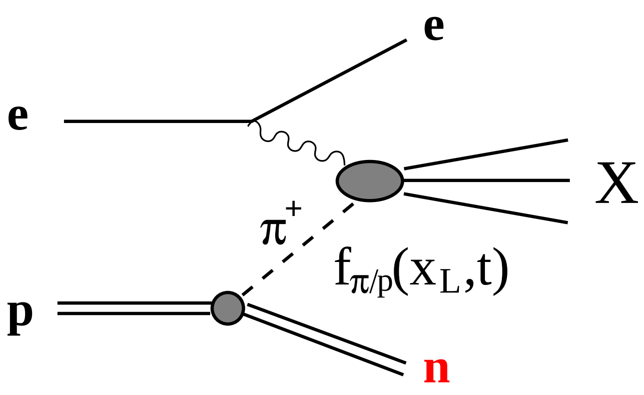

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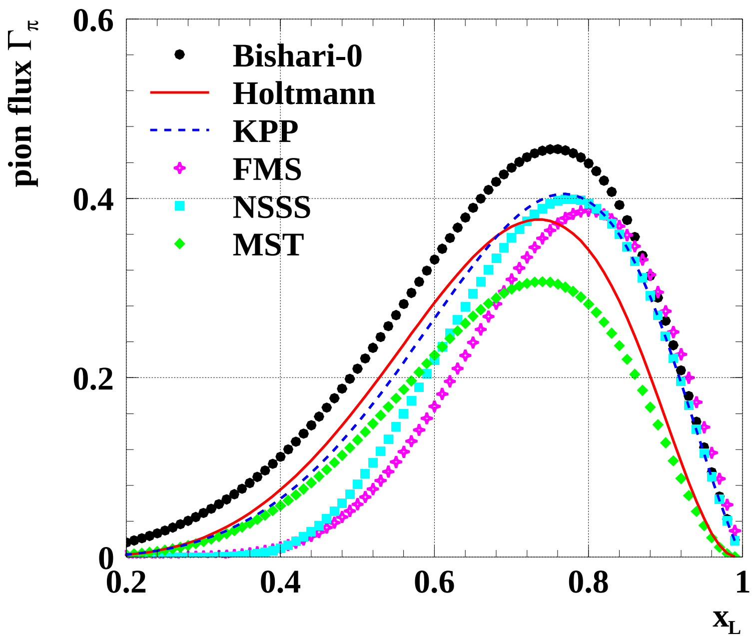
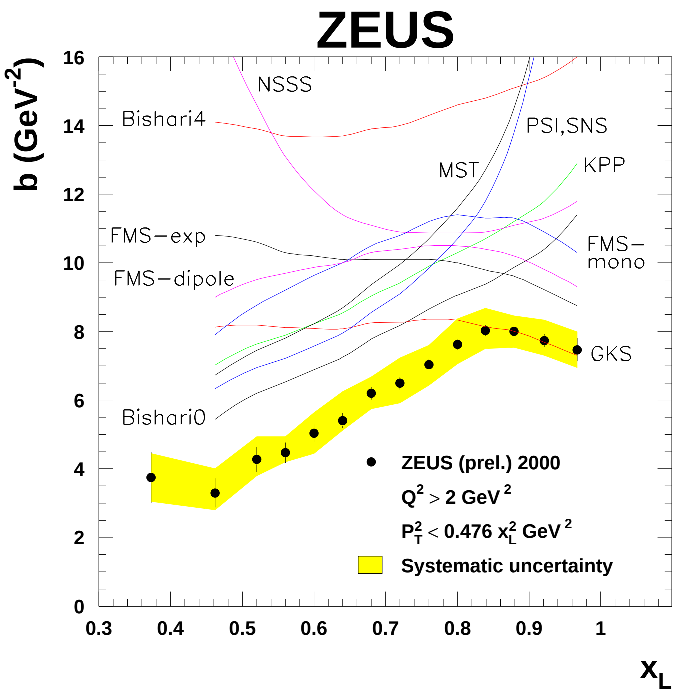
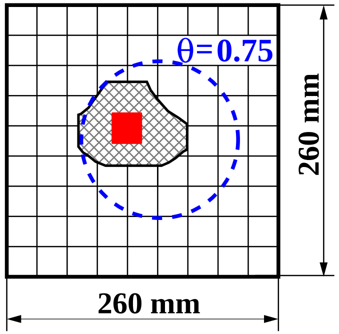
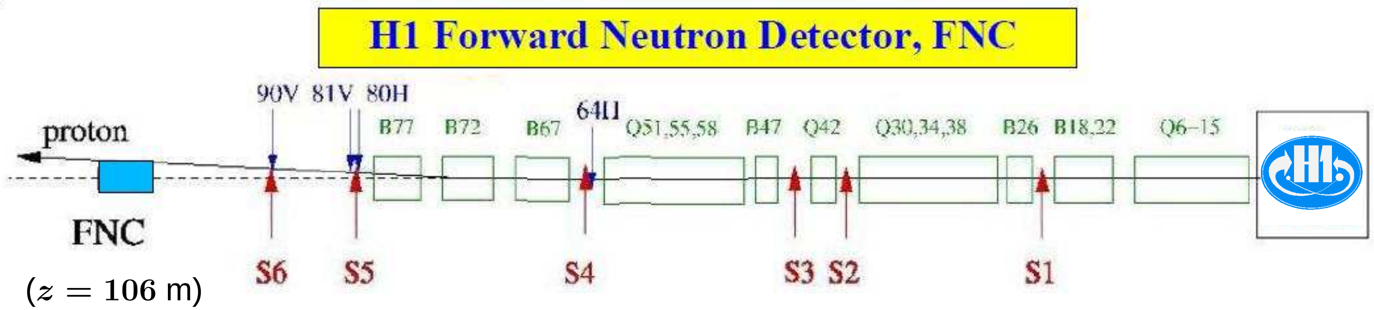


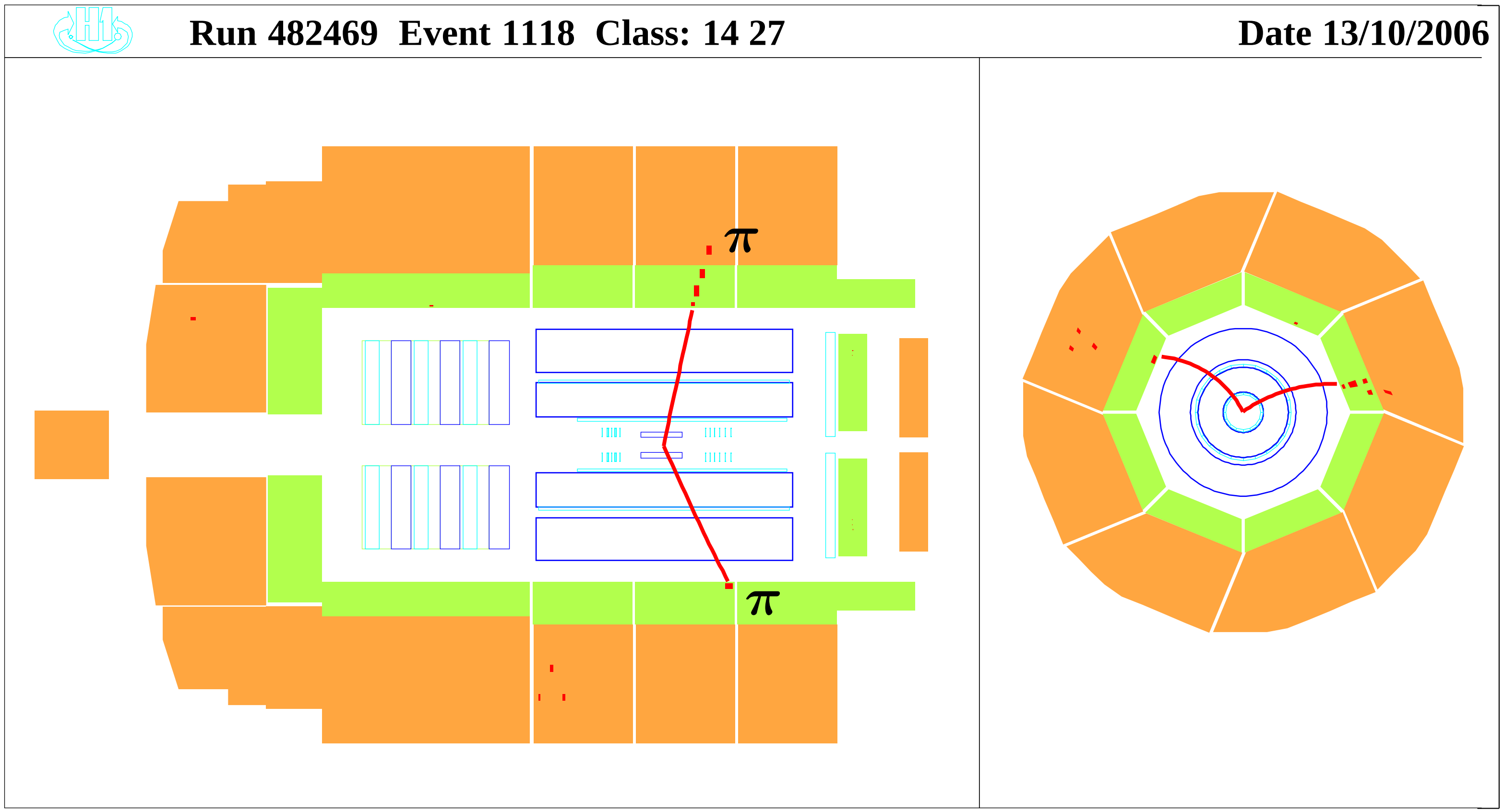


Any new experimental information on the pion flux is important!

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

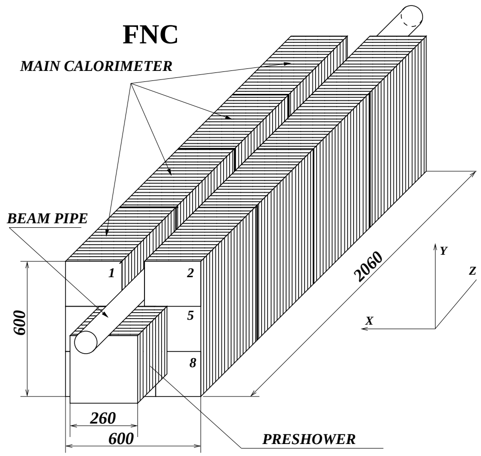






Key Experimental Ingredients

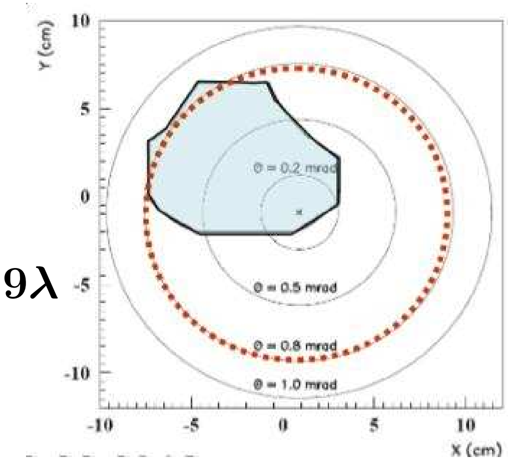
Improved H1 FNC (distinguish ($\langle P \rangle = 98\%$) and measure n and γ/π^0)



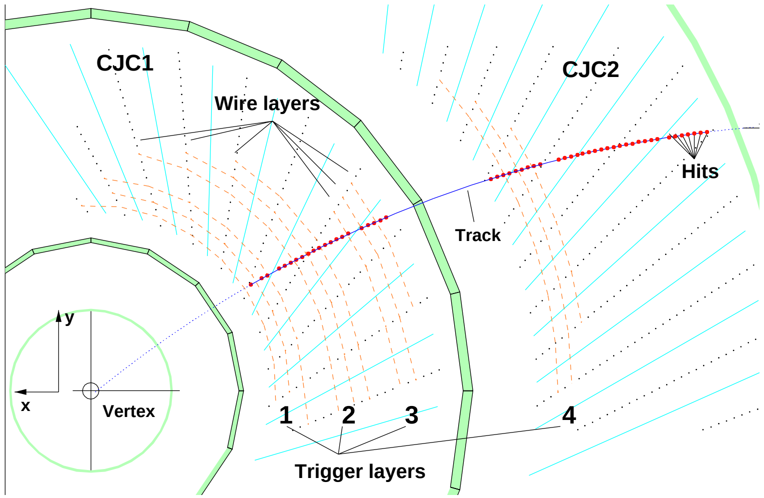
located at $z = 106$m from IP

$\langle A \rangle \simeq 30\%$ for $\theta < 0.8$ mrad

Preshower: $60X_0$, Main Calo: 8.9λ



Powerful fast track trigger (allows untagged soft γp to be collected)



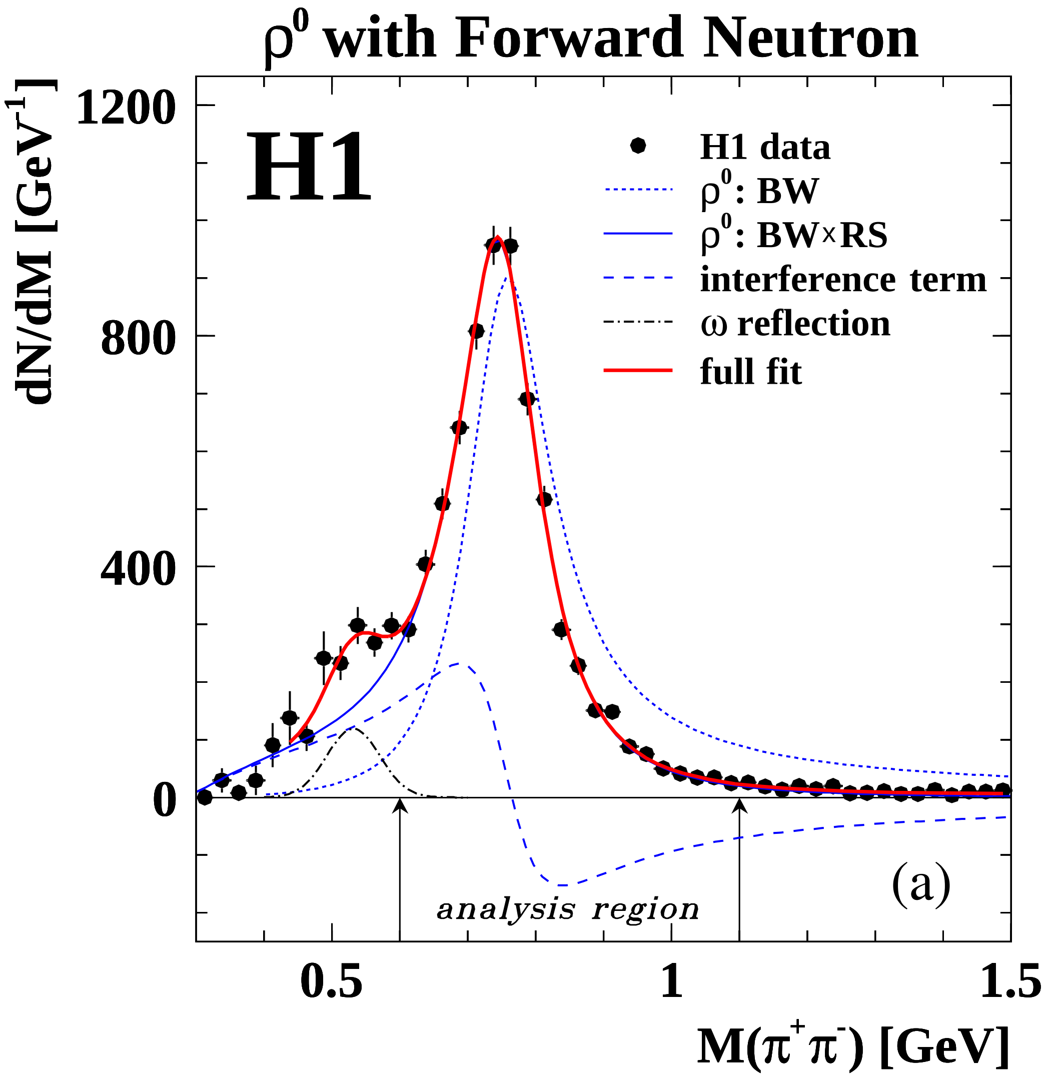
Event selection and the Analysis phase space

Event selection $(2006-2007e^+p)$	Analysis PS	Measurement PS
Triger s14 **PHP** No e' in the detector	$Q^2 < 2$ GeV^2	(VDM flux: $\sigma_{ep} \to \sigma_{\gamma p}$) $Q^2 = 0$ GeV^2
ρ^0 2 tracks, net charge $= 0$ $p_t > 0.2$ GeV, $20^o < \theta < 160^o$ from $\|z_{\rm vx}\| < 30$ cm $0.3 < M_{\pi\pi} < 1.5$ GeV	$20 < W_{\gamma p} < 100$ GeV $p_{t,\rho} < 1.0$ GeV $0.6 < M_{\pi\pi} < 1.1$ GeV	$20 < W_{\gamma p} < 100$ GeV $p_{t,\rho} < 1.0$ GeV $2m_\pi < M_\rho < M_\rho + 5\Gamma_\rho$
n $E_n > 120$ GeV $\theta_n < 0.75$ mrad $x_{FNC} < 2.5$cm, $y_{FNC} < 7.5$cm	$x_L > 0.2$ $\theta_n < 0.75$ mrad	$0.35 < x_L < 0.95$ $p_{t,n} < 0.69 \cdot x_L$ GeV
$\sim$ 7000 events	$\sim$ 6100 events	$\sim$ 5770 events
$\sigma_{\gamma\pi}$ (OPE dominated range) OPE1 OPE2	$p_{t,n} < 0.2$ GeV ($\sim$ 3500 events) $p_{t,n} < 0.2$ GeV, $0.65 < x_L < 0.95$ ($\sim$ 2200 events)	

$\mathcal{L} = 1.16$ pb^{-1}

$$\delta_{\rm stat} = 2.0\% \oplus \delta_{\rm sys} = 13.9\% \oplus \delta_{\rm norm} = 4.4\% \Rightarrow \delta_{\rm tot} = 14.7\%$$

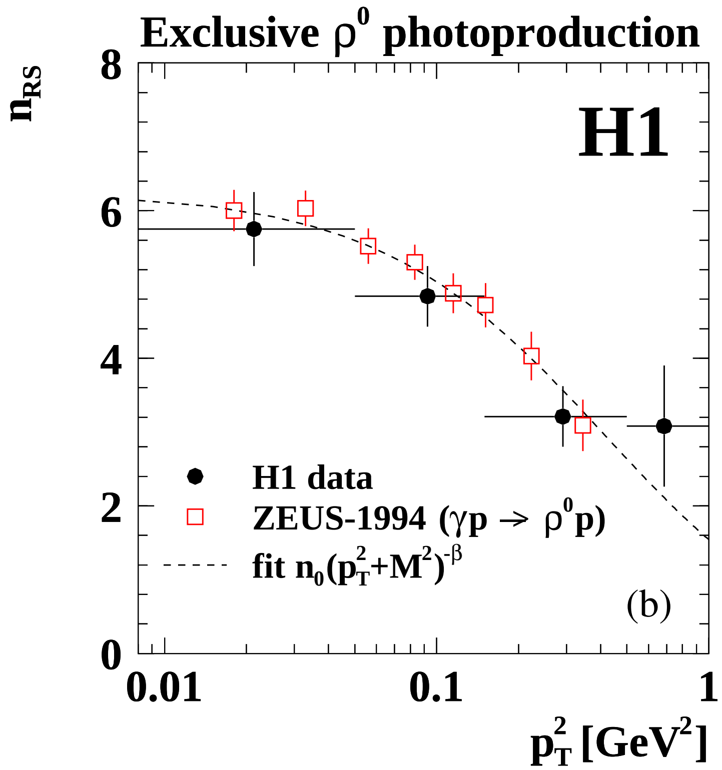
ρ-meson shape



$$\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} \propto BW_\rho(M_{\pi\pi}) \left(\frac{M_\rho}{M_{\pi\pi}}\right)^{n_{RS}}$$

$$M = 764 \pm 3 \text{ MeV}$$

$$\Gamma = 155 \pm 5 \text{ MeV}$$



Analysis region: $0.6 < M_{\pi^+\pi^-} < 1.1$ GeV extrapolated using BW to the full range: $0.28 < M_{\rho^0} < 1.5$ GeV

ρ-meson decay angle

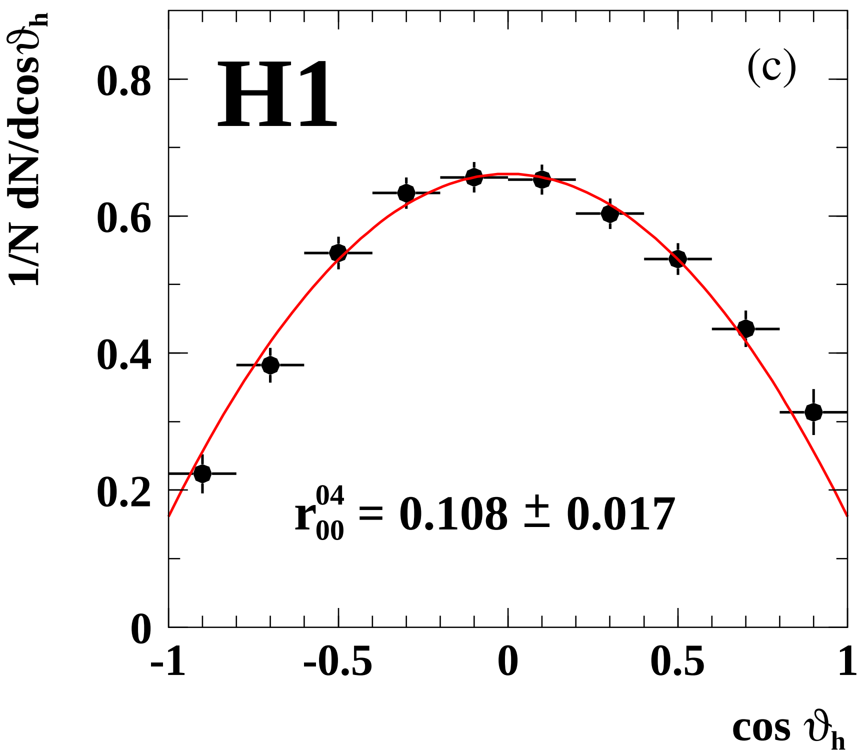
$$\int W(\theta_h, \phi_h, \Phi)\mathrm{d}\phi_h \mathrm{d}\Phi \propto$$

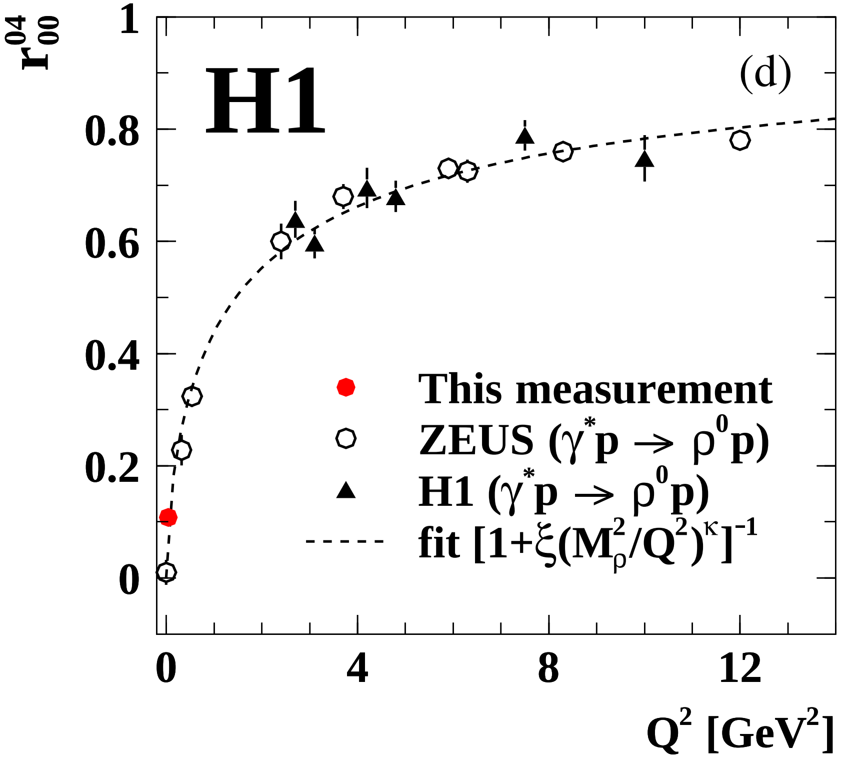
$$1 - r_{00}^{04} + (3r_{00}^{04} - 1)\cos^2\theta_h$$

Empirical fit: $r_{00}^{04} = \frac{1}{1+\xi(M_\rho^2/Q^2)^\kappa}$

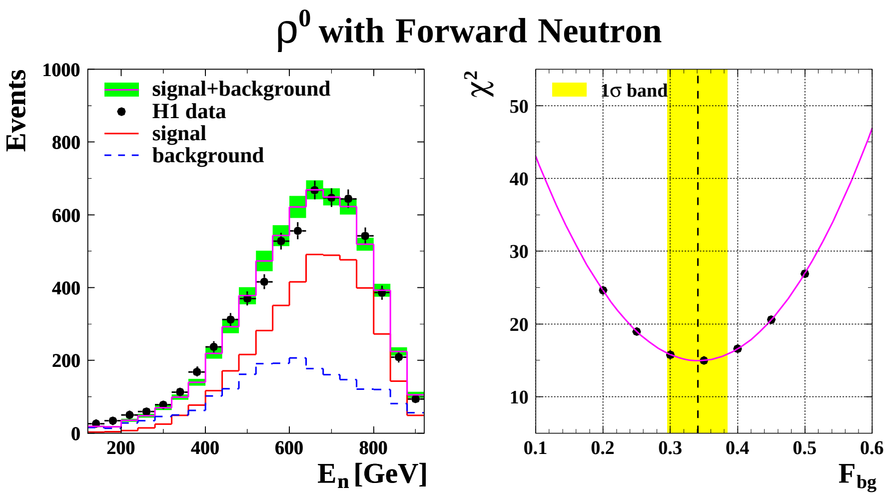
$$\xi = 1.85 \pm 0.10 \quad \kappa = 0.67 \pm 0.03$$

$(P(\chi^2) = 0.41)$





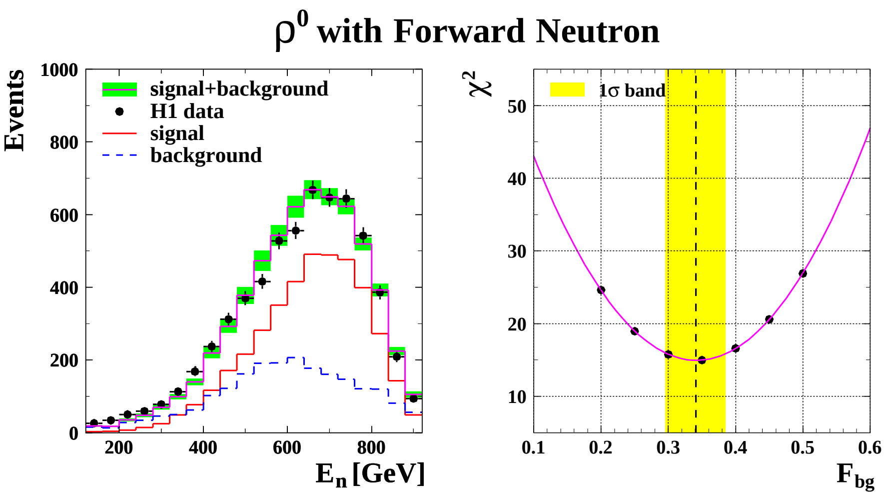
S/B decomposition and Control plots



E_n $\quad\quad$ $B/(S+B)$

$$F_{bg} = 0.34 \pm 0.05$$

S/B decomposition and Control plots



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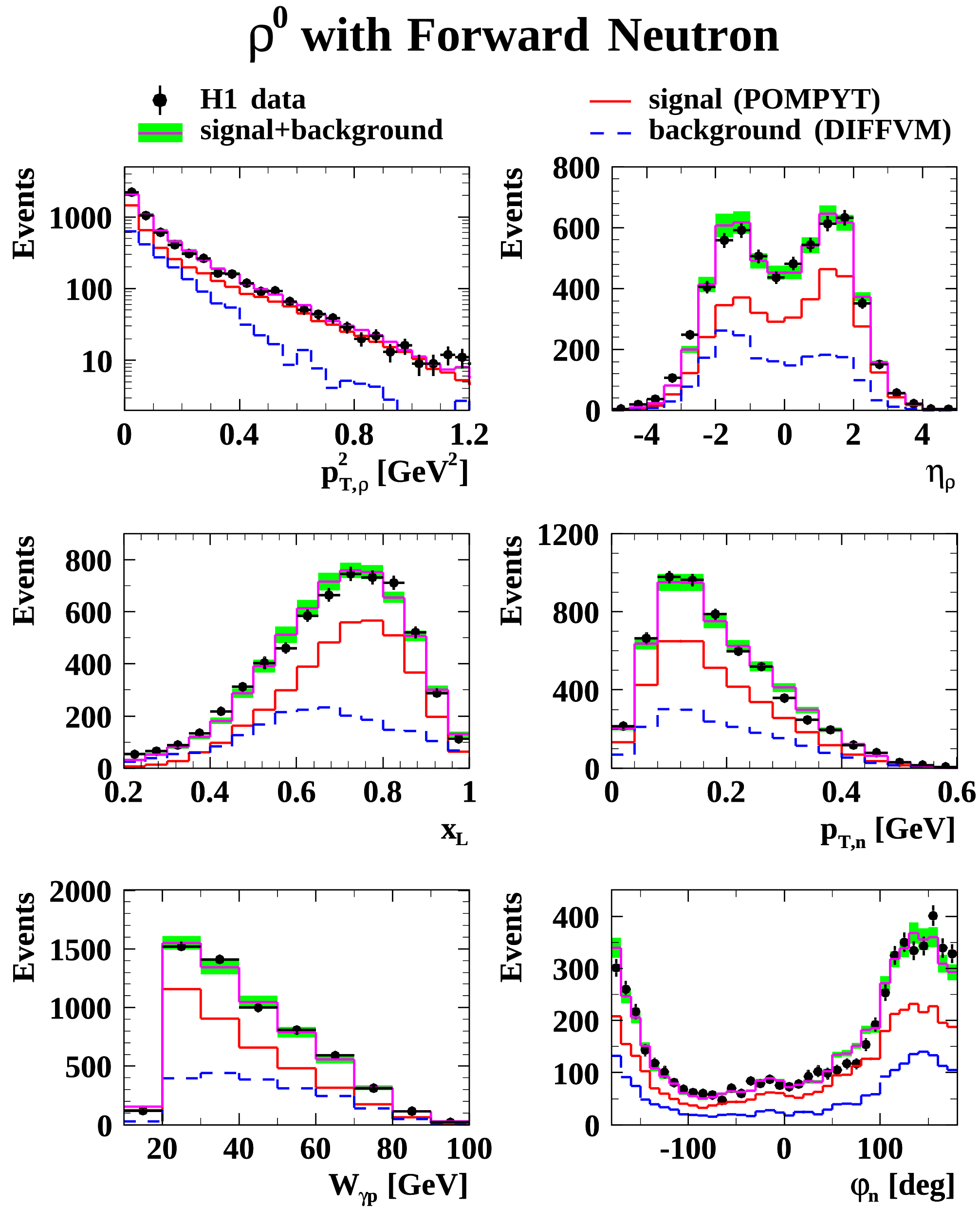


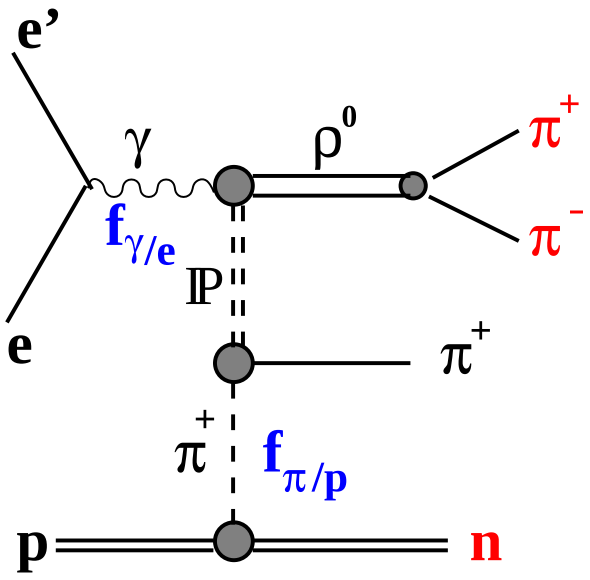
Data points are shown with statistical errors only;

green band represents estimated background fraction uncertainty

Cross sections definitions

$$\sigma_{\gamma p} = \frac{\sigma_{ep}}{\Phi_\gamma}$$

$$\Phi_\gamma = \int f_{\gamma/e}(y,Q^2)\mathrm{d}y\mathrm{d}Q^2$$



$$\sigma_{\gamma\pi} = \frac{\sigma_{\gamma p}}{\Gamma_\pi}$$

$$\Gamma_\pi = \int f_{\pi/p}(x_L,t)\mathrm{d}x_L\mathrm{d}t$$

VMD: $$f_{\gamma/e}(y,Q^2) = \frac{\alpha}{2\pi Q^2 y}\left\{\left[1+(1-y)^2-2(1-y)\left(\frac{Q^2_{\min}}{Q^2}-\frac{Q^2}{M_\rho^2}\right)\right]\frac{1}{\left(1+\frac{Q^2}{M_\rho^2}\right)^2}\right\}$$

OPE: $$f_{\pi/p}(x_L,t) = \frac{1}{2\pi}\frac{g^2_{p\pi N}}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\exp[-R^2_{\pi n}\frac{m_\pi^2-t}{1-x_L}]$$

Total cross sections

γp

$$\sigma_{\gamma p} = \frac{\sigma_{ep}}{\int f_{\gamma/e}(y,Q^2)\mathrm{d}y\mathrm{d}Q^2} = \frac{N_{\mathrm{data}} - N_{\mathrm{bgr}}}{\mathcal{L}(A\cdot\epsilon)\mathcal{F}} \cdot C_\rho$$

Where

- N_{bgr} – diffractive dissociation bgr from MC
- $\mathcal{L}$ – integrated luminosity
- $A\cdot\epsilon$ – correction for detector acceptance and efficiency
- $\mathcal{F}$ – photon flux integrated over kinematic domain $20 < W < 100$ GeV, $Q^2 < 2$ GeV^2
- C_ρ – numerical factor accounting for extrapolation to full ρ^0 mass range

For the range $0.35 < x_L < 0.95$ and averaged over $20 < W_{\gamma p} < 100$ GeV

$$\sigma(\gamma p \to \rho^0 n(\pi^+)) = (310 \pm 6_{\mathrm{stat}} \pm 45_{\mathrm{sys}})\ \mathrm{nb}$$ for $\theta_n < 0.75$ mrad

$$\sigma(\gamma p \to \rho^0 n(\pi^+)) = (130 \pm 3_{\mathrm{stat}} \pm 19_{\mathrm{sys}})\ \mathrm{nb}$$ for $p_{T,n} < 0.2$ GeV

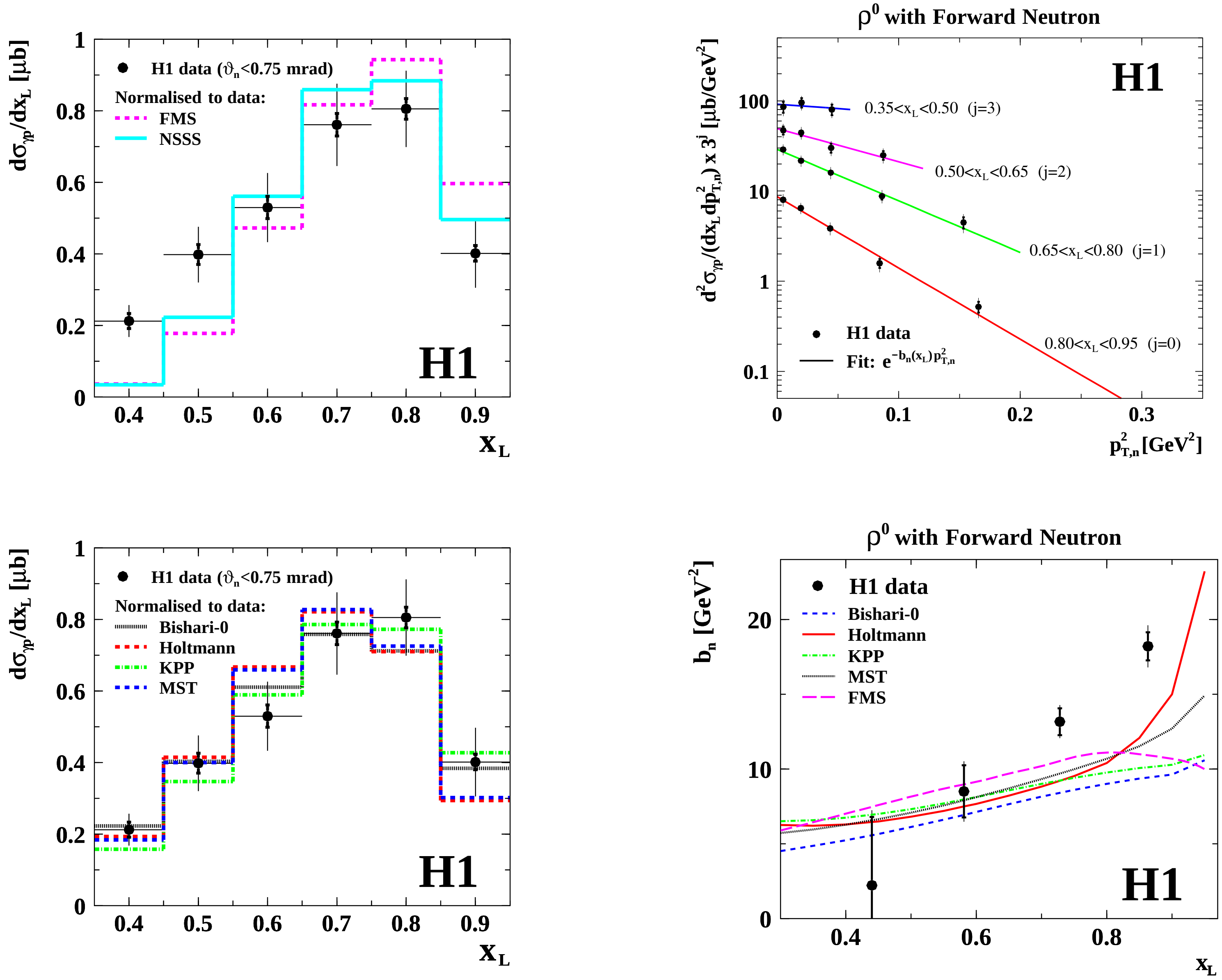
γπ

$$\sigma_{\gamma\pi}(\langle W_{\gamma\pi}\rangle) = \frac{\sigma_{\gamma p}}{\int f_{\pi^+/p}(x_L,t)dx_L dt},$$

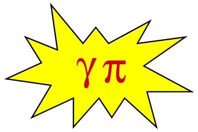
and for $\langle W_{\gamma\pi}\rangle = 24$ GeV

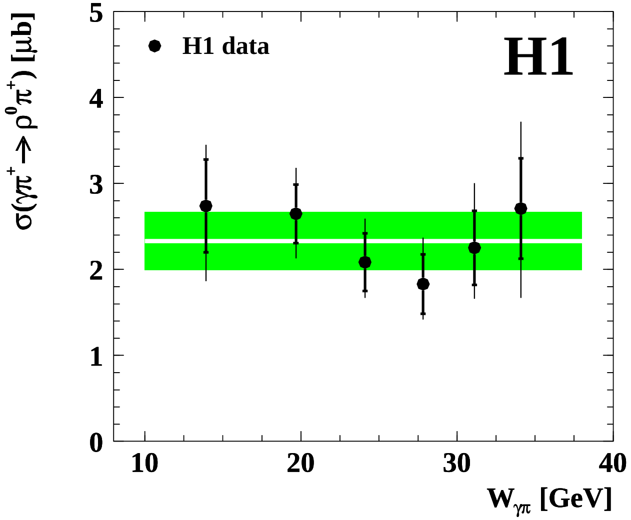
$$\sigma_{\mathrm{el}}(\gamma\pi^+ \to \rho^0\pi^+) = (2.33 \pm 0.34(\mathrm{exp})^{+0.47}_{-0.40}(\mathrm{model}))\ \mu\mathrm{b}$$

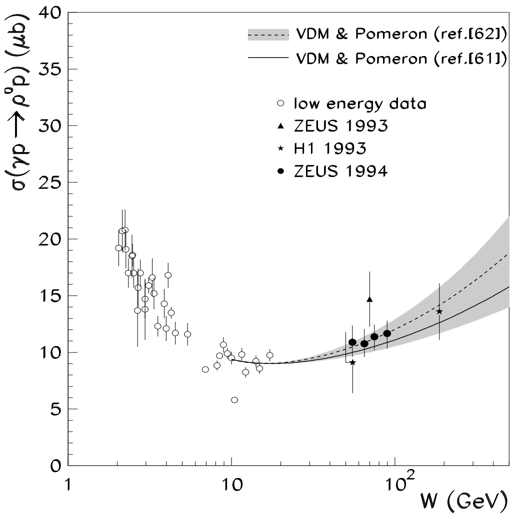
Constraining pion flux



Estimate of absorption corrections





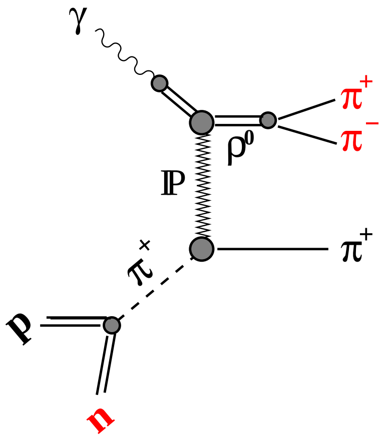


$$r_{\rm el} = \frac{\sigma_{\gamma\pi\to\rho^0\pi}}{\sigma^{\gamma p\to\rho^0 p}} = \begin{cases} 0.25 \pm 0.06 & \text{(exp.extracted)} \\ 0.57 \pm 0.03 & \text{(theo.expected)} \end{cases} \quad \Rightarrow \quad K_{\rm abs} = 0.44 \pm 0.11$$

Look into other processes. What do we see there?

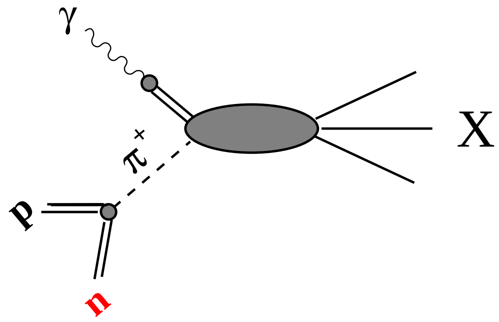
Cross sections ratio

H1 (2015)



$\sigma_{el}^{\gamma\pi}$ (W=24 GeV)

ZEUS (2002)



$\sigma_{tot}^{\gamma\pi}$ (W=107 GeV)

$\sigma_{\rm el}^{\gamma\pi}/\sigma_{\rm el}^{\gamma p} = 0.25 \pm 0.06$	Exp.result	$\sigma_{\rm tot}^{\gamma\pi}/\sigma_{\rm tot}^{\gamma p} = 0.32 \pm 0.03$
OT+eikonal approach+data: $r_{\rm el} \simeq 0.57$	Theory	AQM: $r_{\rm tot} \simeq 2/3$

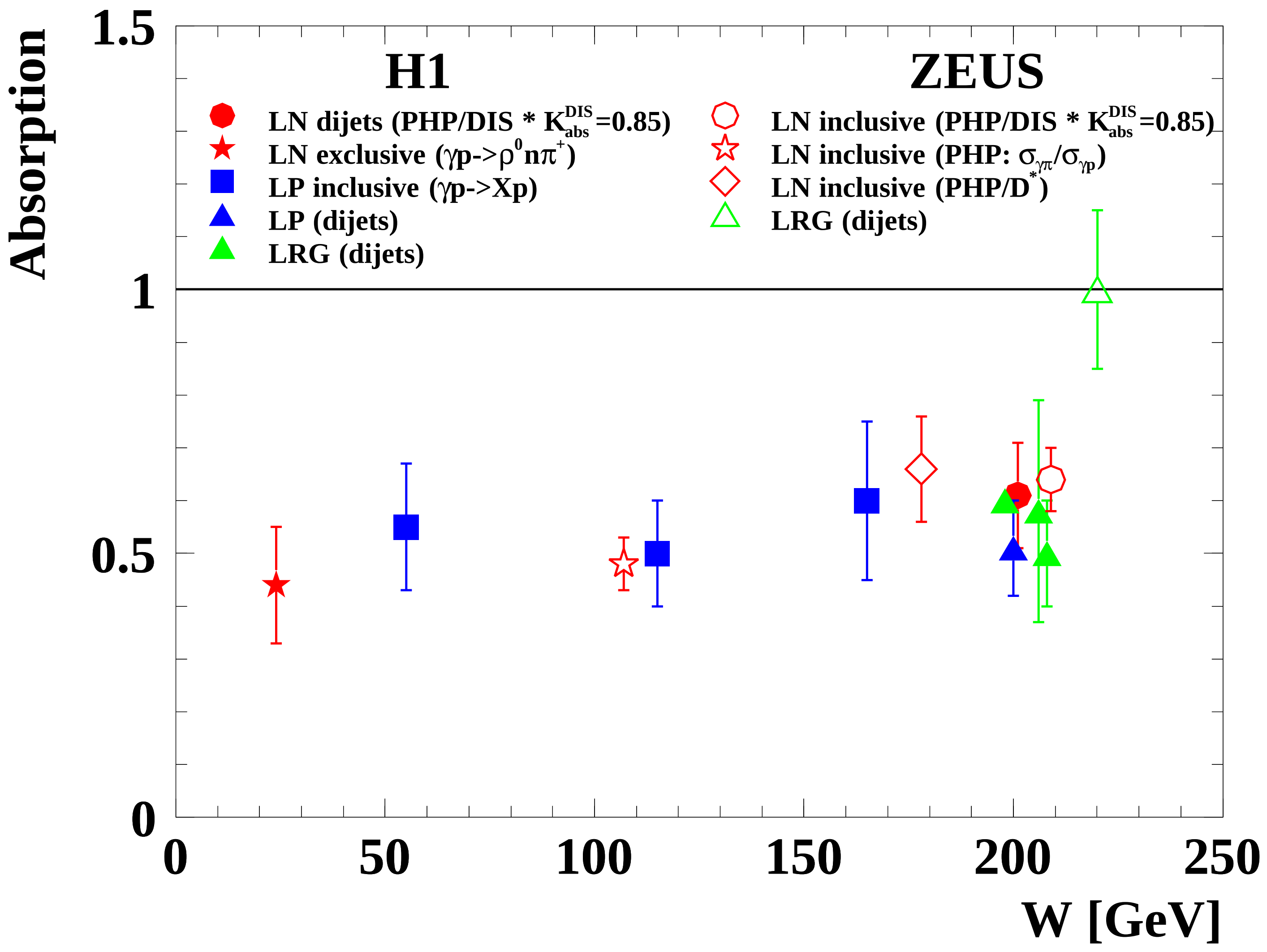
Large absorption effects!

Optical Theorem: $\frac{d\sigma_{el}}{dt}\big|_{t=0} = b_{\rm el}\sigma_{\rm el} \propto \sigma_{\rm tot}^2$ ⇨ $r_{\rm el} = (\frac{b_{\gamma p}}{b_{\gamma\pi}}) \cdot (\sigma_{\rm tot}^{\gamma\pi}/\sigma_{\rm tot}^{\gamma p})^2$

Eikonal approach: $b = \langle R^2 \rangle; \quad b_{12} = b_1 + b_2$

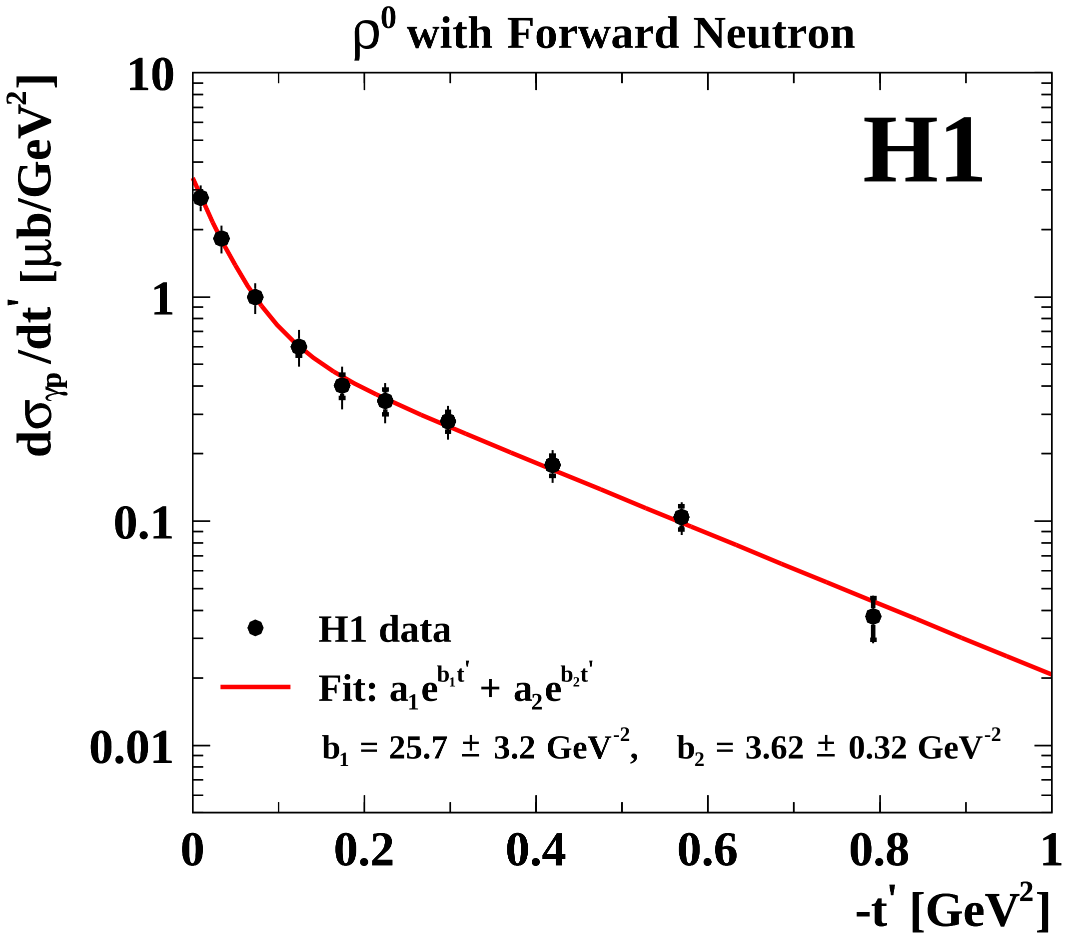
World data: $(b_{pp} \simeq 11.7, \;\; b_{\pi^+ p} \simeq 9.6, \;\; b_{\gamma p} \simeq 9.75)$ GeV^{-2}

Absorptive factors, K_{abs}, in different PHP reactions

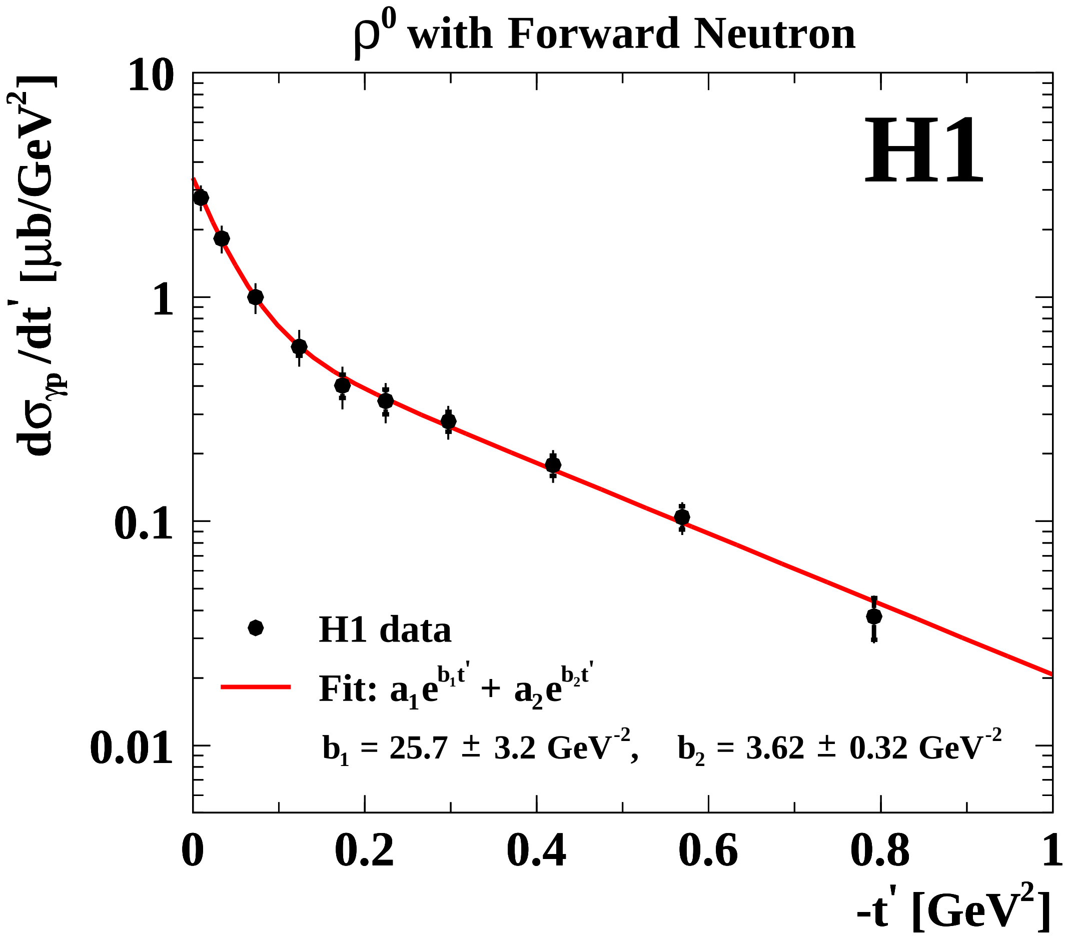


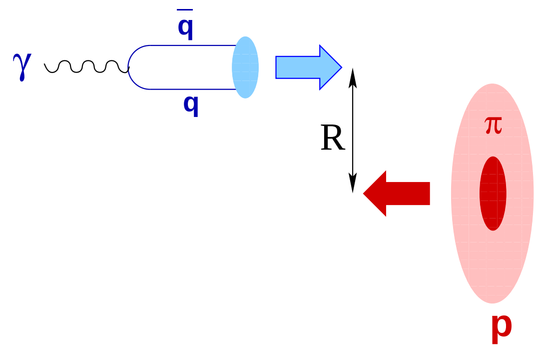
Unofficial private summary!

Differential cross section in p_t^2



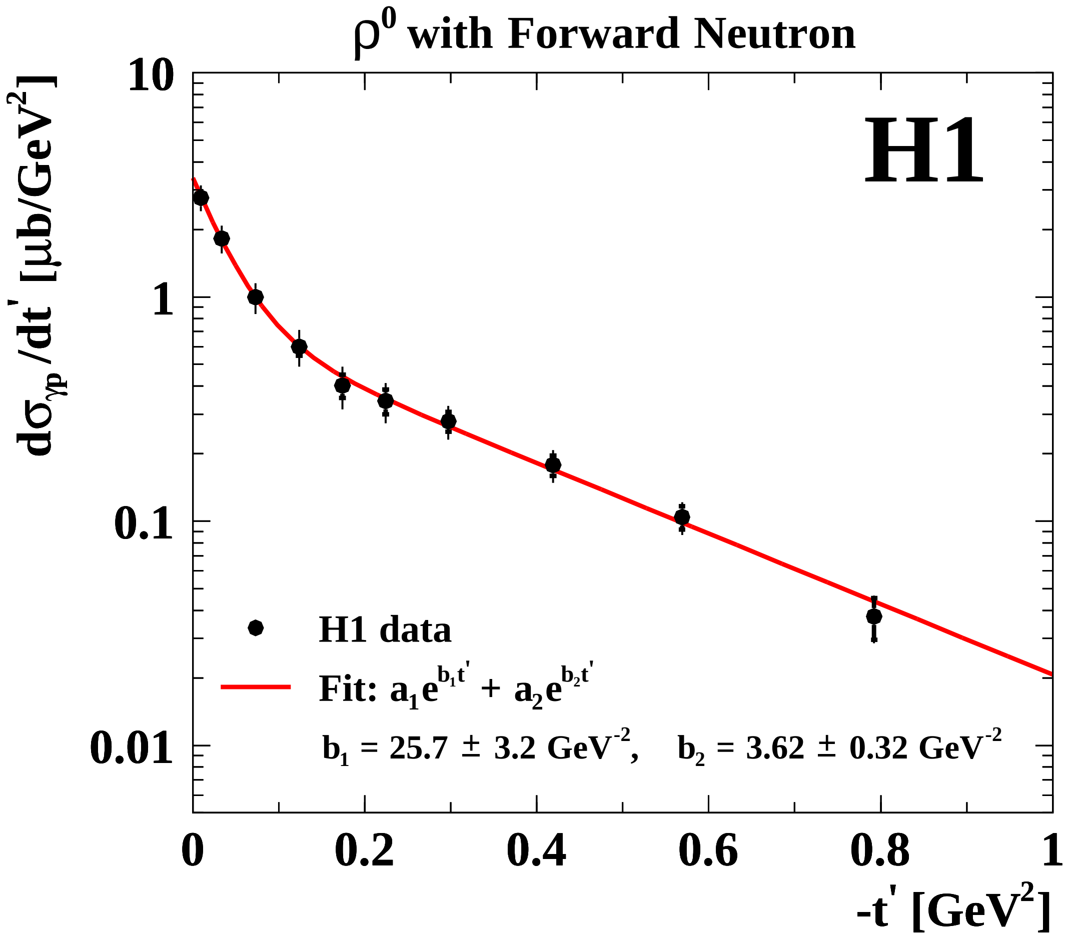
Differential cross section in p_t^2

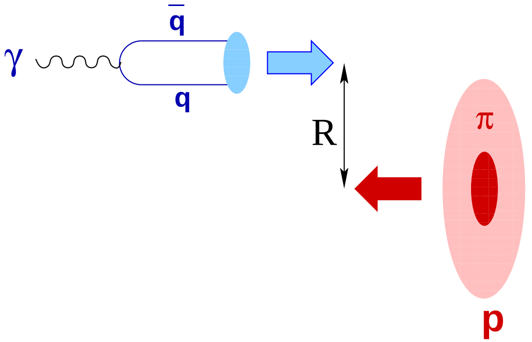


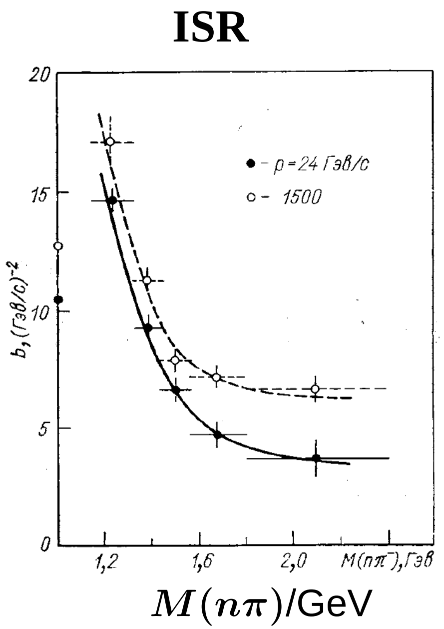


Geometric interpretation: $\langle r^2 \rangle = 2b_1 \cdot (\hbar c)^2 \simeq 2$ fm^2 $\Rightarrow (1.6 R_p)^2 \Rightarrow$ ultra-peripheral process

Differential cross section in p_t^2







Geometric interpretation: $\langle r^2 \rangle = 2b_1 \cdot (\hbar c)^2 \simeq 2$ fm^2 $\Rightarrow (1.6 R_p)^2 \Rightarrow$ ultra-peripheral process

DPP explanation: low mass $\pi^+ n$ state $\to$ large slope, high masses $\to$ less steep slope

Summary

- Photoproduction cross section for exclusive ρ^0 production associated with leading neutron is measured for the first time at HERA.
- Differential cross sections for the reaction $\gamma \mathrm{p} \rightarrow \rho^0 \mathrm{n} \pi^+$ exhibit features typical for exclusive double peripheral process.
- The elastic photon-pion cross section, $\sigma(\gamma\pi^+ \rightarrow \rho^0\pi^+)$, is extracted in the OPE approximation.
- The estimated cross section ratio $r_{\mathrm{el}} = \sigma_{\mathrm{el}}^{\gamma\pi}/\sigma_{\mathrm{el}}^{\gamma p} = 0.25 \pm 0.06$, suggests large absorption corrections, of $\sim 60\%$, suppressing the rate of the studied reaction $\gamma p \rightarrow \rho^0 n \pi^+$.

Backup Slides

Model calculation for $pn \to p(\pi^- n)$ at $\sqrt{s} = 14$ GeV

V.A. Tsarev and N.P. Zotov, Sov. J. Part. and Nuclei (1978)

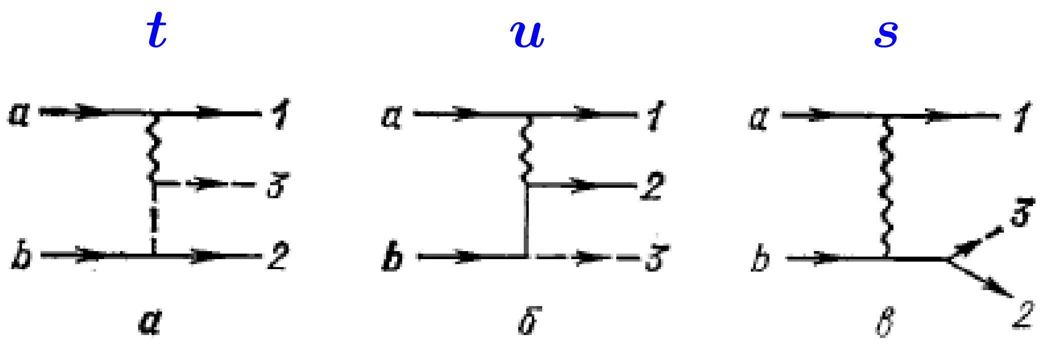


Рис. 17. Диаграммы ДХД для процесса $b + a \to 2 + 3 + 1$: a — t (π)-диаграмма; $б$ — u-диаграмма; $в$ — s-диаграмма

Если в амплитудах A_u и A_s пренебречь спиновыми факторами, то из (17) и (19) получим

$$A_u \approx (u - m^2)^{-1} \exp [(b_N/2)(u - m^2)];$$
$$A_s \approx -(m^2 - s_2)^{-1} \exp [(b_N/2)(m^2 - s_2)].$$

Поскольку из (13)

$$u - m^2 = m^2 - s_2 - (t_1 - \mu^2) + t,$$

то при малых t_1 и t $A_u + A_s \approx 0$ [5—7, 30, 31]. При учете спина

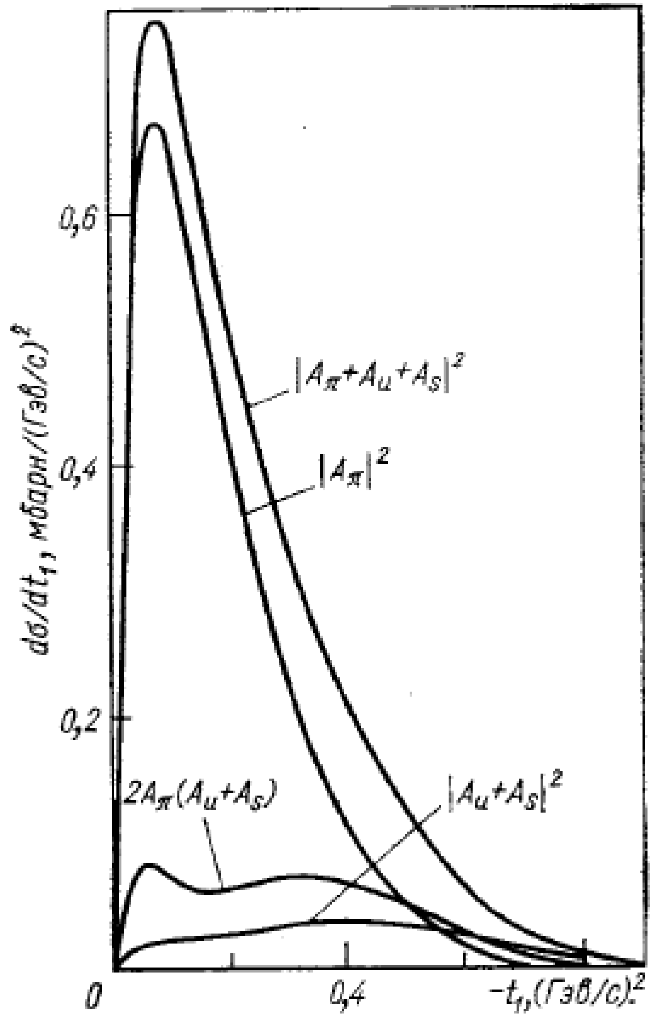


Рис. 21. Вклады π-, u- и s-диаграмм ДХД в $d\sigma/dt_1$ [37]

OPE and pion fluxes

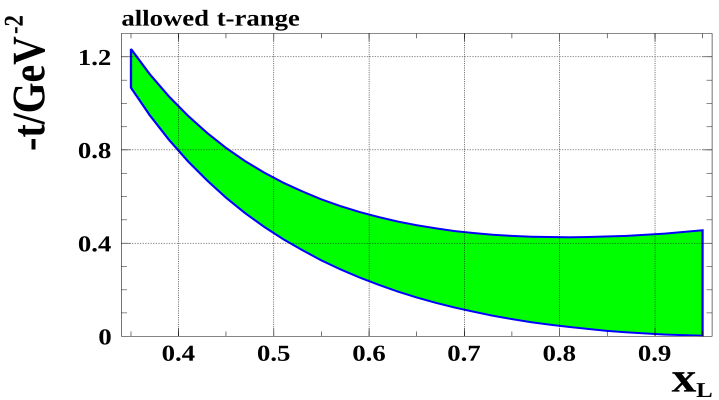
$$\frac{d^2\sigma_{\gamma p}(W^2,x_L,t)}{dx_L dt} = f_{\pi/p}(x_L,t)\sigma_{\gamma\pi}((1-x_L)W^2)$$

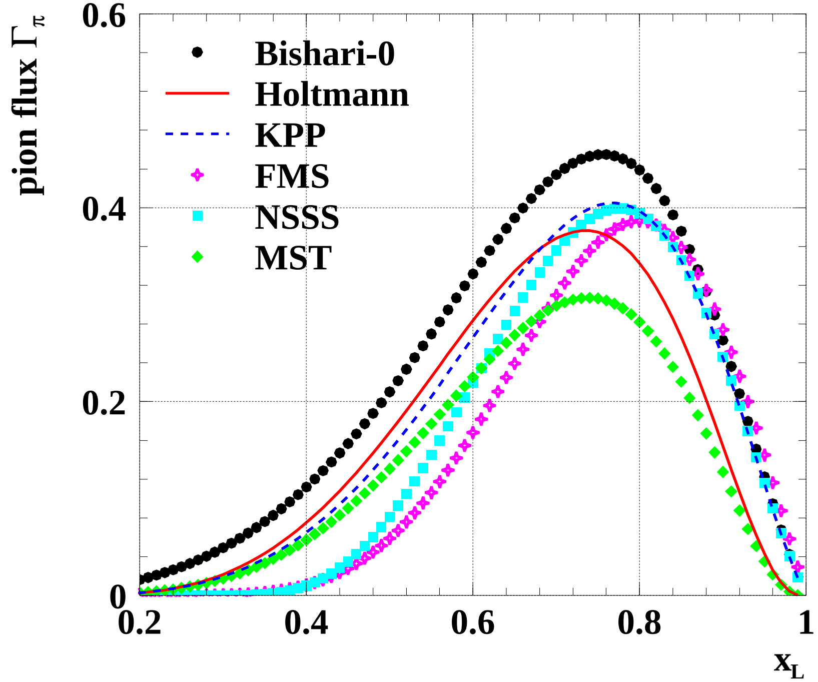
$$\boxed{\frac{d\sigma_{\gamma p}}{dx_L} = \int_{t_0(x_L)}^{t_{min}(x_L)} f_{\pi/p}(x_L,t)dt \cdot \sigma_{\gamma\pi}(W_{\gamma\pi})}$$

where $t = -\frac{p_{t,n}^2}{x_L} - \frac{(1-x_L)(m_n^2 - m_p^2 x_L)}{x_L}$

$\sigma_{\gamma\pi}(W_{\gamma\pi}) = \frac{1}{\Gamma_\pi(x_L)}\frac{d\sigma_{\gamma p}}{dx_L}$ and $\overline{\sigma_{\gamma\pi}}(\langle W_{\gamma\pi}\rangle) = \frac{\sigma_{\gamma p}}{\int \Gamma_\pi}$

Problem: too many different fluxes on the market



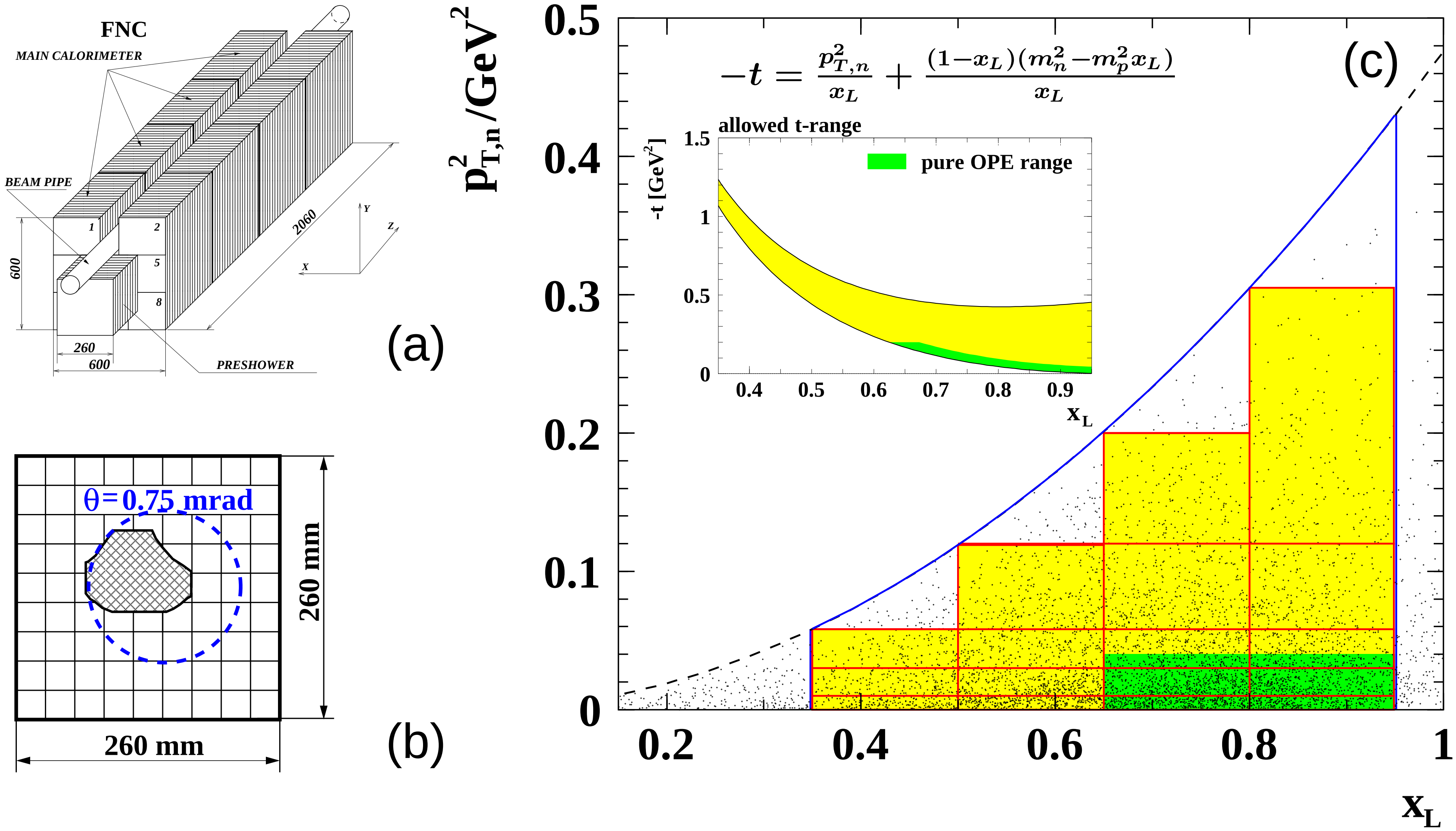


Typical examples:

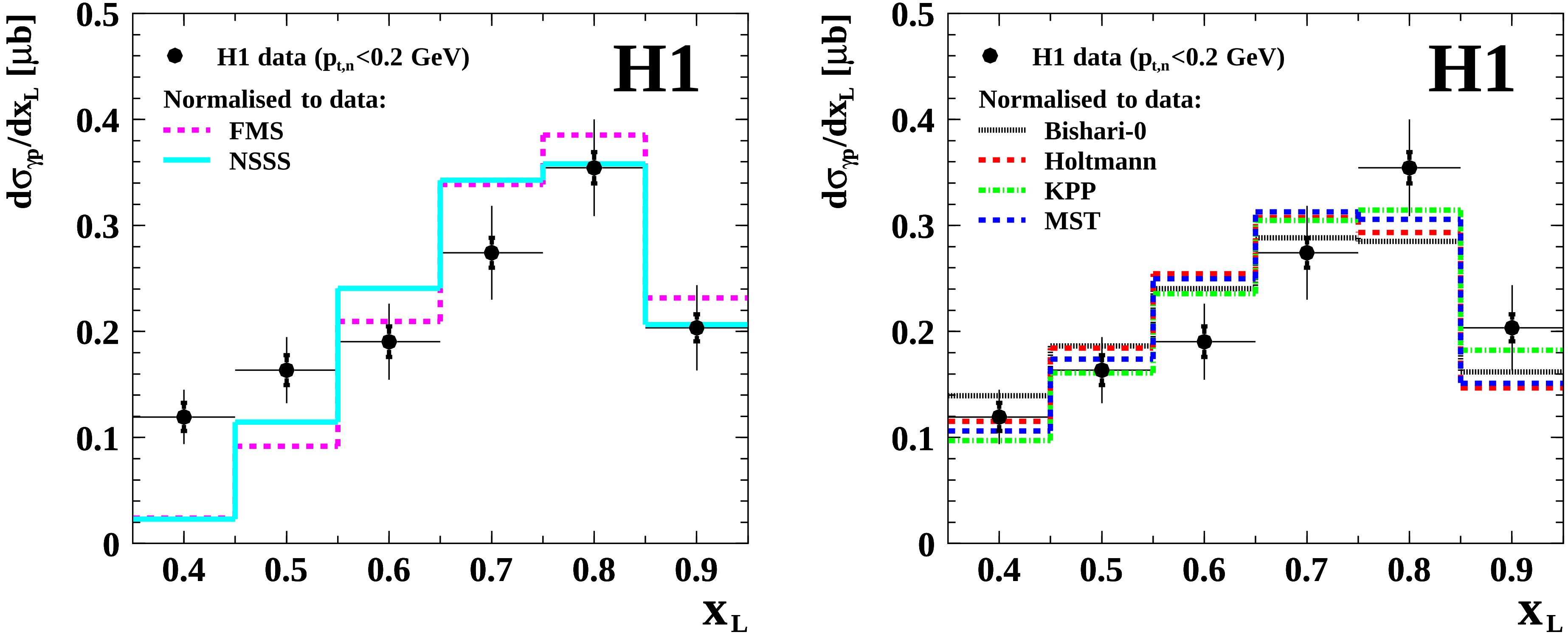
$$f_{\pi^+/p}(x_L,t) = \frac{1}{2\pi}\frac{g_{p\pi N}^2}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\exp[-R_{\pi n}^2\frac{m_\pi^2-t}{1-x_L}]$$ – H. Holtmann et al., *Nucl. Phys.* **A596** (1996) 631.

$$f_{\pi^+/p}(x_L,t) = \frac{1}{2\pi}\frac{g_{p\pi N}^2}{4\pi}(1-x_L)^{1-2\alpha'_\pi t}\frac{-t}{(m_\pi^2-t)^2}\exp[-R_\pi^2(m_\pi^2-t)]$$ – B. Kopeliovich et al., *Z. Phys.* **C73** (1996) 125.

FNC Acceptance sketch

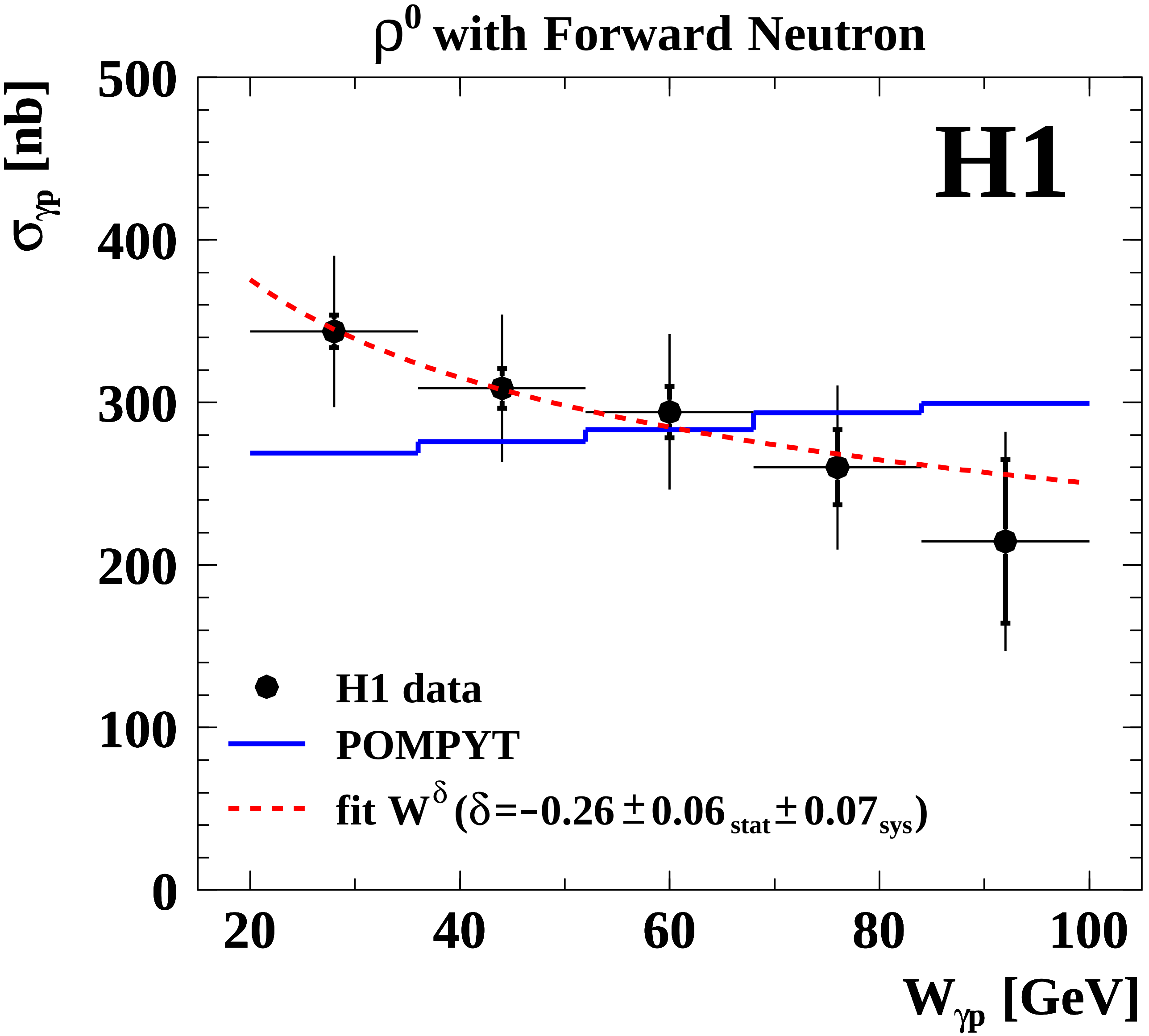


Differential cross section $d\sigma_{\gamma p}/dx_L$



For OPE safe range $p_{T,n} < 0.2$ GeV

Energy dependence of the cross section $\sigma_{\gamma p \rightarrow \rho^0 n \pi^+}$



Estimating the value of K_{abs}

- Optical Theorem (plus exponential t dependence):

$$d\sigma_{el}/dt\ |_{t=0} = b_{\rm el}\sigma_{\rm el} \propto \sigma^2_{\rm tot}; \ \Rightarrow\ \sigma_{\rm el} \propto \sigma^2_{\rm tot}/b_{\rm el}$$

- Relations between elastic slopes ($b \propto \langle R^2 \rangle$; $b_{ij} = b_i + b_j$):

$$r_b \equiv \frac{b_{12}}{b_{13}} = \frac{b_1 + b_2}{b_1 + b_3} = \frac{b_1 + b_2}{(b_1 + b_2) + (b_2 + b_3) - 2b_2} = \frac{b_{12}}{b_{12} + b_{23} - b_{22}} = \frac{1}{1 - \frac{b_{22} - b_{23}}{b_{12}}}$$

- Data at $\sqrt{s} \simeq 24$ GeV (for $\gamma p \to \rho^0 p$ an interpolated value of $b_{\gamma p}$ is given):

$$b_{pp} = (11.7 \pm 0.2)\ \mathrm{GeV}^{-2}; \ \ b_{\pi^+ p} = (9.6 \pm 0.25)\ \mathrm{GeV}^{-2}; \ \ b_{\gamma p} = (9.75 \pm 0.50)\ \mathrm{GeV}^{-2}$$

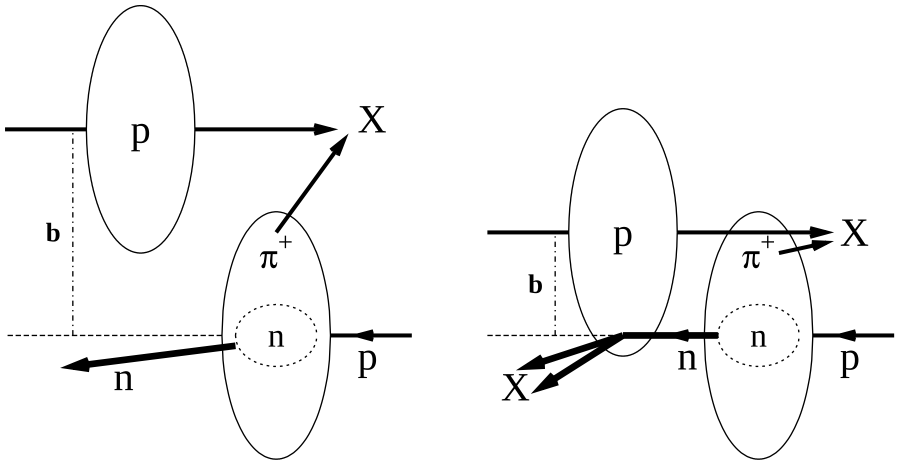
- Ratio r_{el} ($1 = \gamma,\ 2 = p,\ 3 = \pi^+$):

$$r_{el} = \left(\frac{b_{\gamma p}}{b_{\gamma \pi}}\right) \cdot \left(\frac{\sigma^{\gamma\pi}_{\rm tot}}{\sigma^{\gamma p}_{\rm tot}}\right)^2 = \left(\frac{1}{1 - (2.1/9.75)}\right) \cdot \left(\frac{2}{3}\right)^2 = (0.57 \pm 0.03)$$

- Absorption factor:

$$K_{abs} = \frac{r_{el}(\mathrm{measured})}{r_{el}(\mathrm{estimated})} = \frac{0.25 \pm 0.06}{0.57 \pm 0.03} = 0.44 \pm 0.11$$

Absorptive effects calculations [1,2] for $\gamma^* p \to nX$

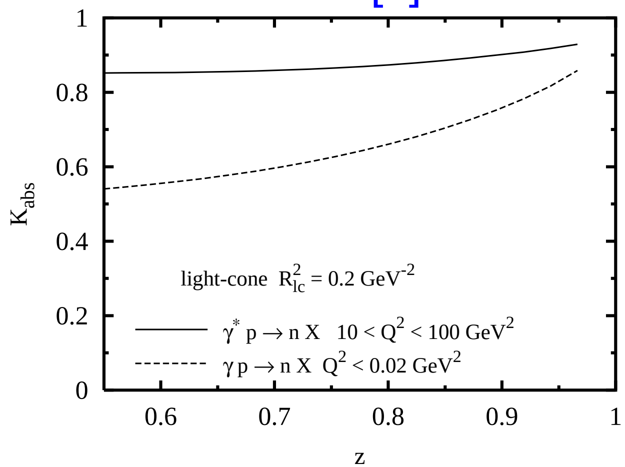


Collision at two different impact parameters in the Glauber picture

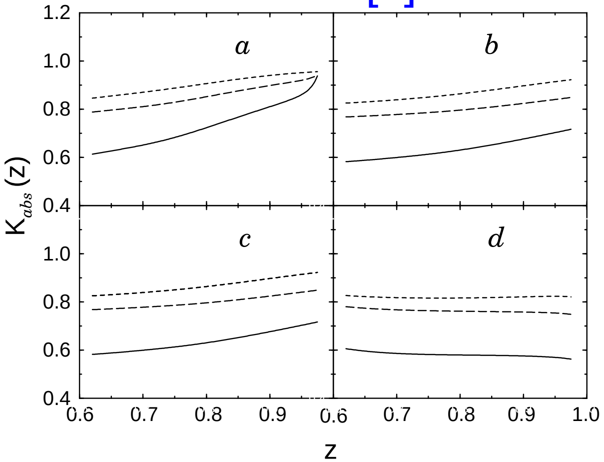
Left: peripheral collision, leaving the neutron as a spectastor.

Right: more central collision, destroying the neutron through rescattering.

AP [2]



NSZ [1]



a) $p^2_{T,n} = 0.0$ GeV^2

b) $p^2_{T,n} = 0.1$ GeV^2

c) $p^2_{T,n} = 0.2$ GeV^2

d) $p^2_{T,n} = 0.3$ GeV^2

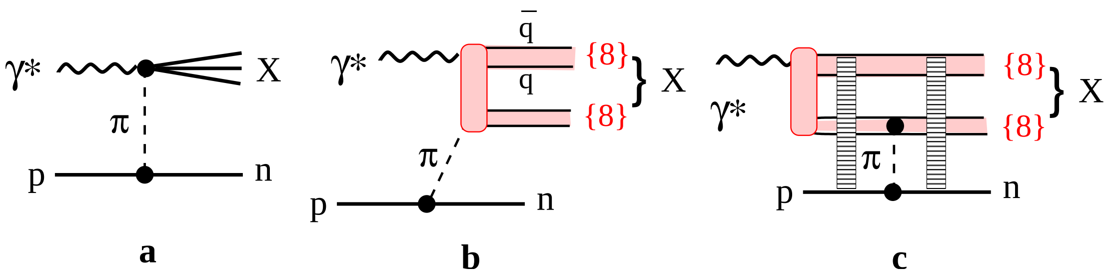
solid line: $pp \to Xn$

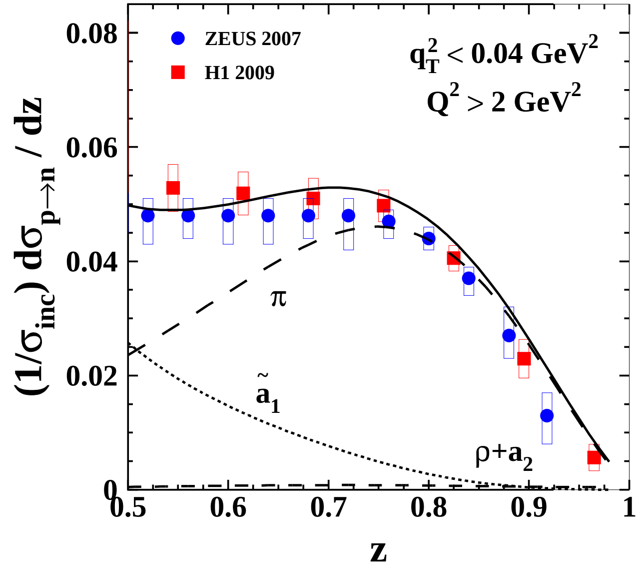
dashed lines: $\gamma^* p \to Xn$

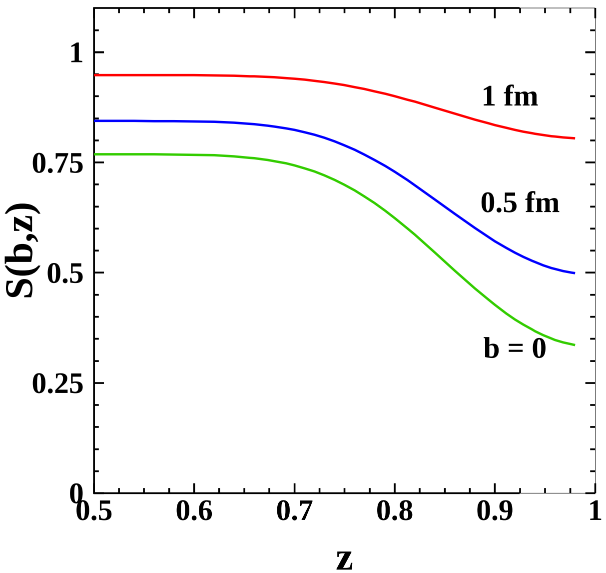
$\Rightarrow \; K_{abs}(DIS) = 0.85 \pm 0.05$

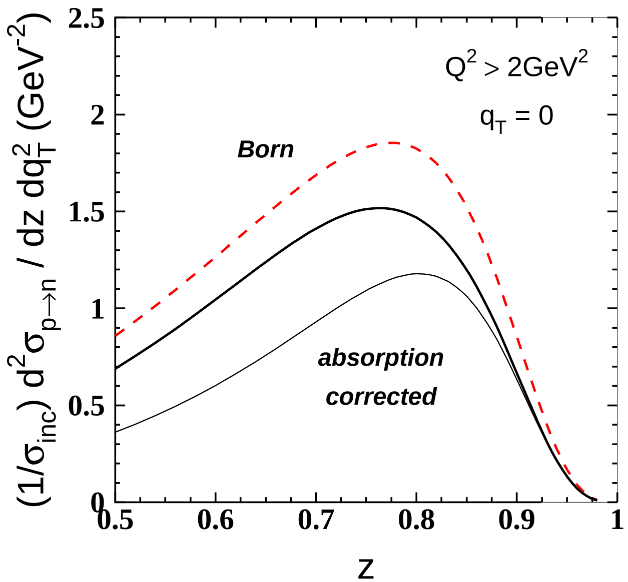
Absorptive effects calculations for $\gamma^* p \to nX$

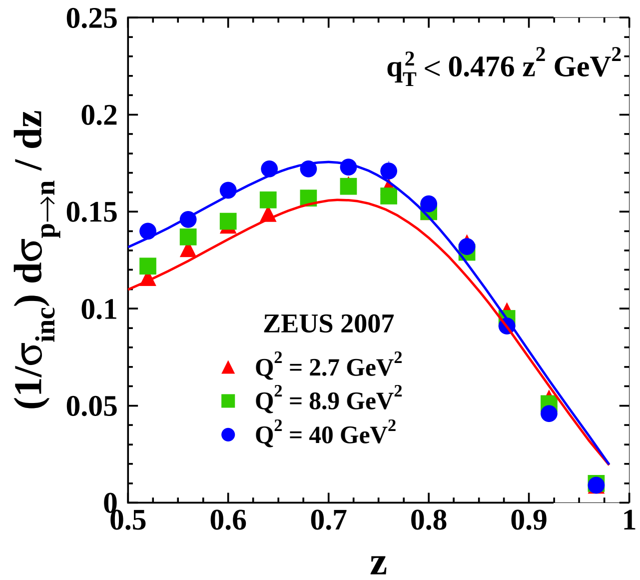
$$K_{abs}(DIS) = 0.70 \pm 0.05$$





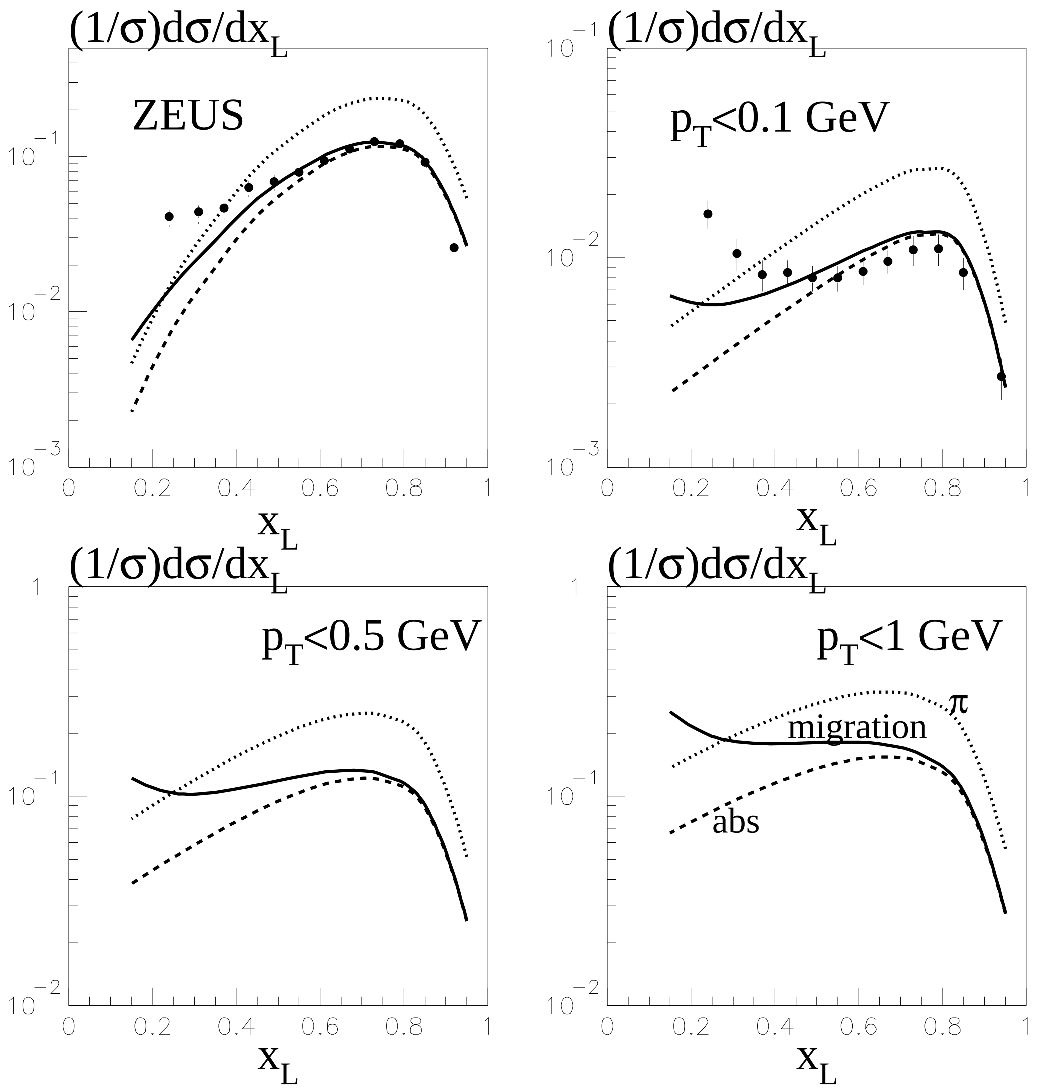






B.Z. Kopeliovich *et al.*, Phys. Rev. **D85** (2012) 114025 [arXiv:1205.0067]

KKMR model vs ZEUS LN PHP data



The model is able to explain a factor of 2 in cross section reduction due to absorption and migration