Diffraction 2014

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Recent HERA results with very Forward Neutrons and Photons

Sergey Levonian

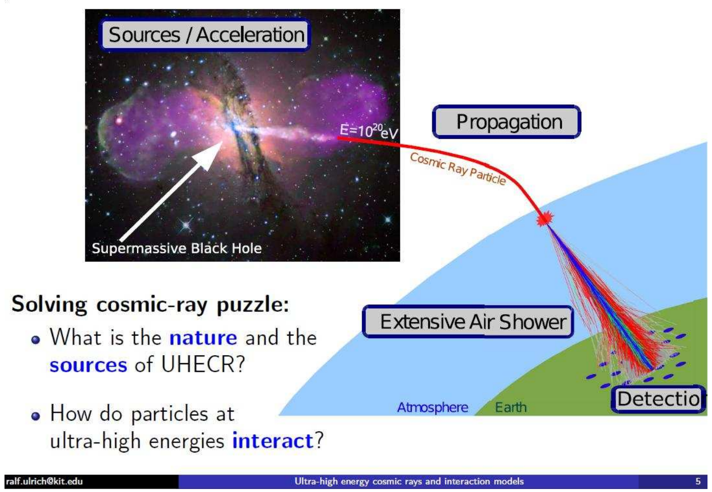
On behalf of H1 Collaboration

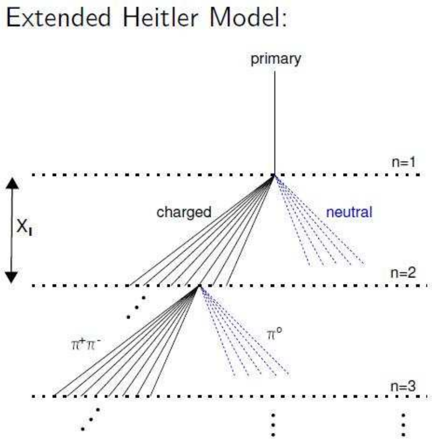
- Inclusive forward γ, n production in DIS and test of Feynman scaling
- Exclusive ρ^0 photoproduction with leading neutron ($\gamma p \to \rho^0 n \pi^+$)

Motivation and Challenges

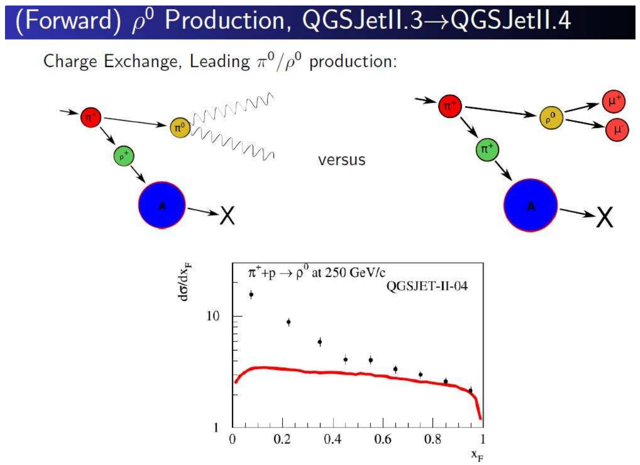
- Extreme forward region in particle collisions is still poorly understood
  - ▷ Theory: No (or few) firm predictions from first principles
  - ▷ Experiment: Difficult to measure due to detector acceptance limitations

- Important for correct analysis of (ultra-high energy) Cosmic Rays
  - ▷ Two pieces of the puzzle:
    – Sources/Propagation (prime interest)
    – Interaction/Detection (extensive air shower)
  - ▷ To understand the former one needs good MC models for the latter





(Ralf Ulrich, PANIC-2014)



S. Ostapchenko, ISVHECRI 2012

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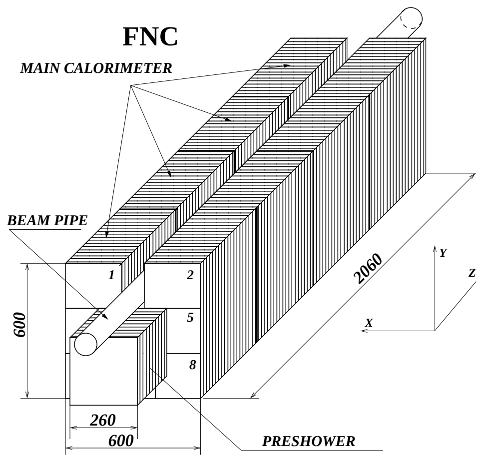
- Current situation (from PANIC summary):
  - ▷ Recent LHC data are very valuable for CR MC tuning but still no fully consistent picture yet
  - ▷ UHECR data becomes more precise and require also better precision of hadronic interaction modelling

- Specifics of HERA
  - ▷ Additional constraints for different kinematical regimes wrt hadron colliders (smaller collision energy can be "compensated" by studying scaling properties and transporting the measurements to higher energies)
  - ▷ Some observables are unique (e.g. possible extraction of $\gamma\pi$ cross sections)

Key Experimental Ingredients

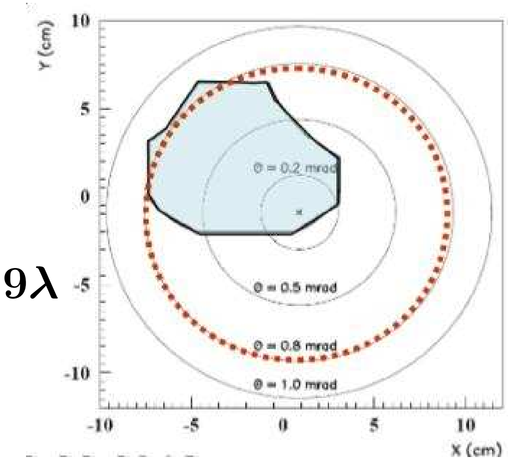
Improved H1 FNC (distinguish ($\langle P \rangle = 98\%$) and measure n and γ/π^0)



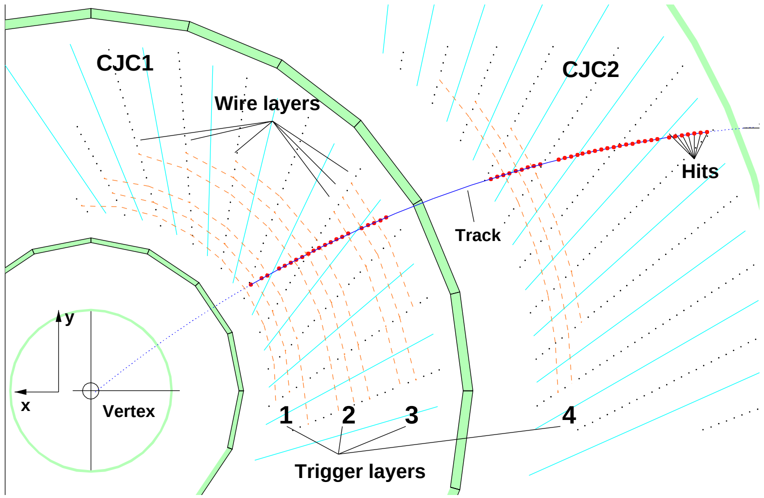
located at $z = 106$m from IP

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

Preshower: $60 X_0$, Main Calo: 8.9λ

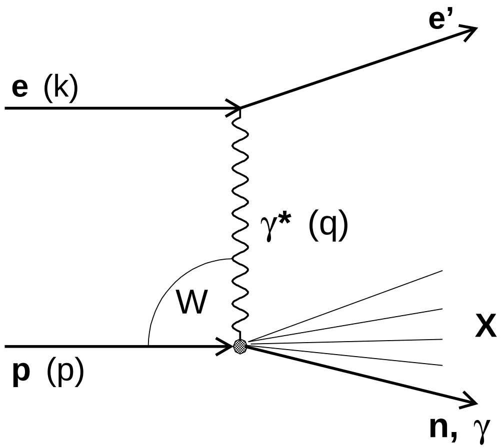


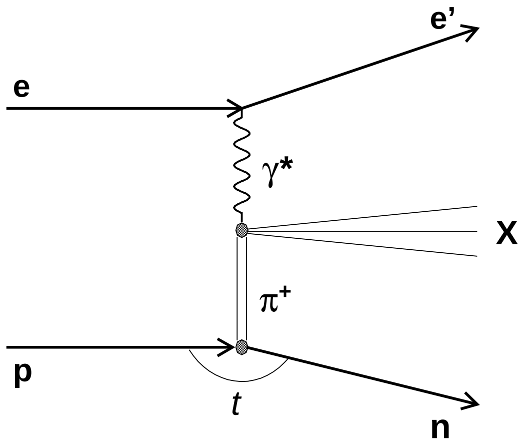
Powerful fast track trigger (allows untagged soft γp to be collected)



Inclusive forward γ, n production in DIS

$$e^{+} + p \longrightarrow e^{+} \binom{n}{\gamma} X$$





Data

$\mathcal{L} = 131$ pb^{-1}, $\sqrt{s} = 319$ GeV

$6 < Q^2 < 100$ GeV^2

$70 < W < 245$ GeV

$\eta_{\text{lab}} > 7.9, \quad x_F = 2p^*_{||}/W > 0.1$

$\gamma:$ 83000 ev. $\quad n:$ 230000 ev.

MC models

DIS: LEPTO/CDM (γ, n)

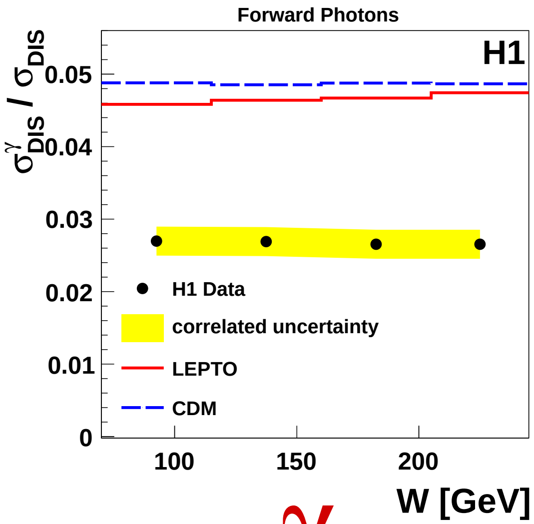
RAPGAP-π (n)

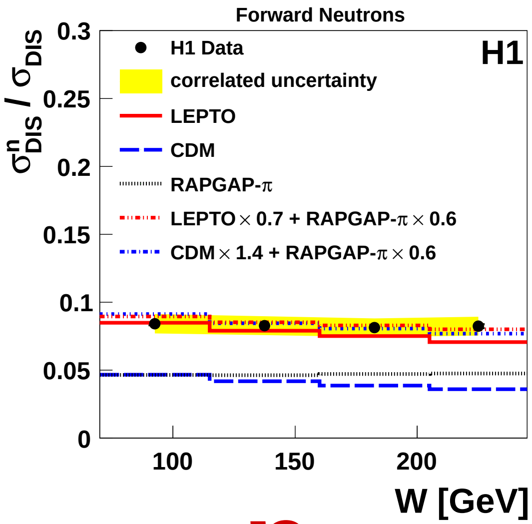
CR: EPOS LHC

SYBILL 2.1

QGSJET (3 versions)

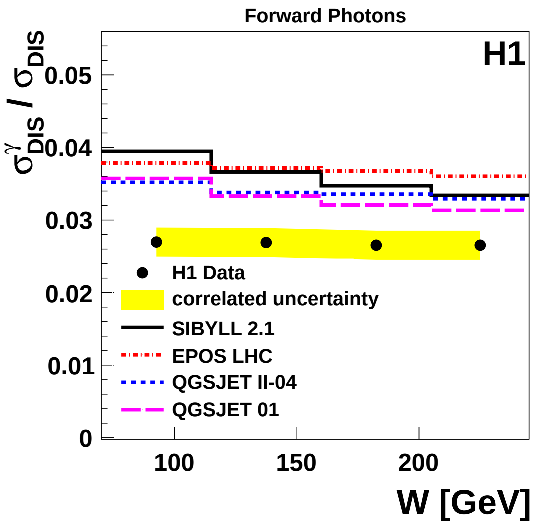
W dependence

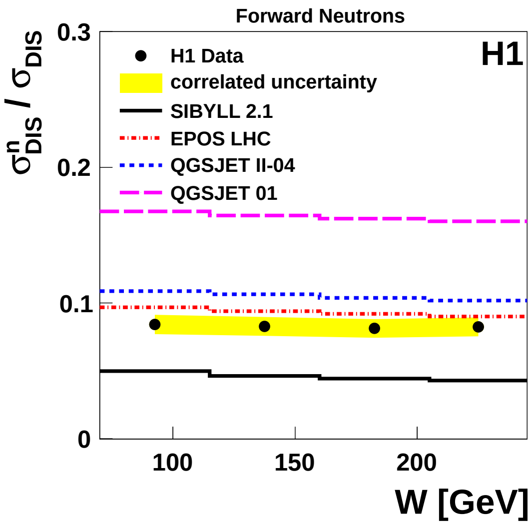




γ

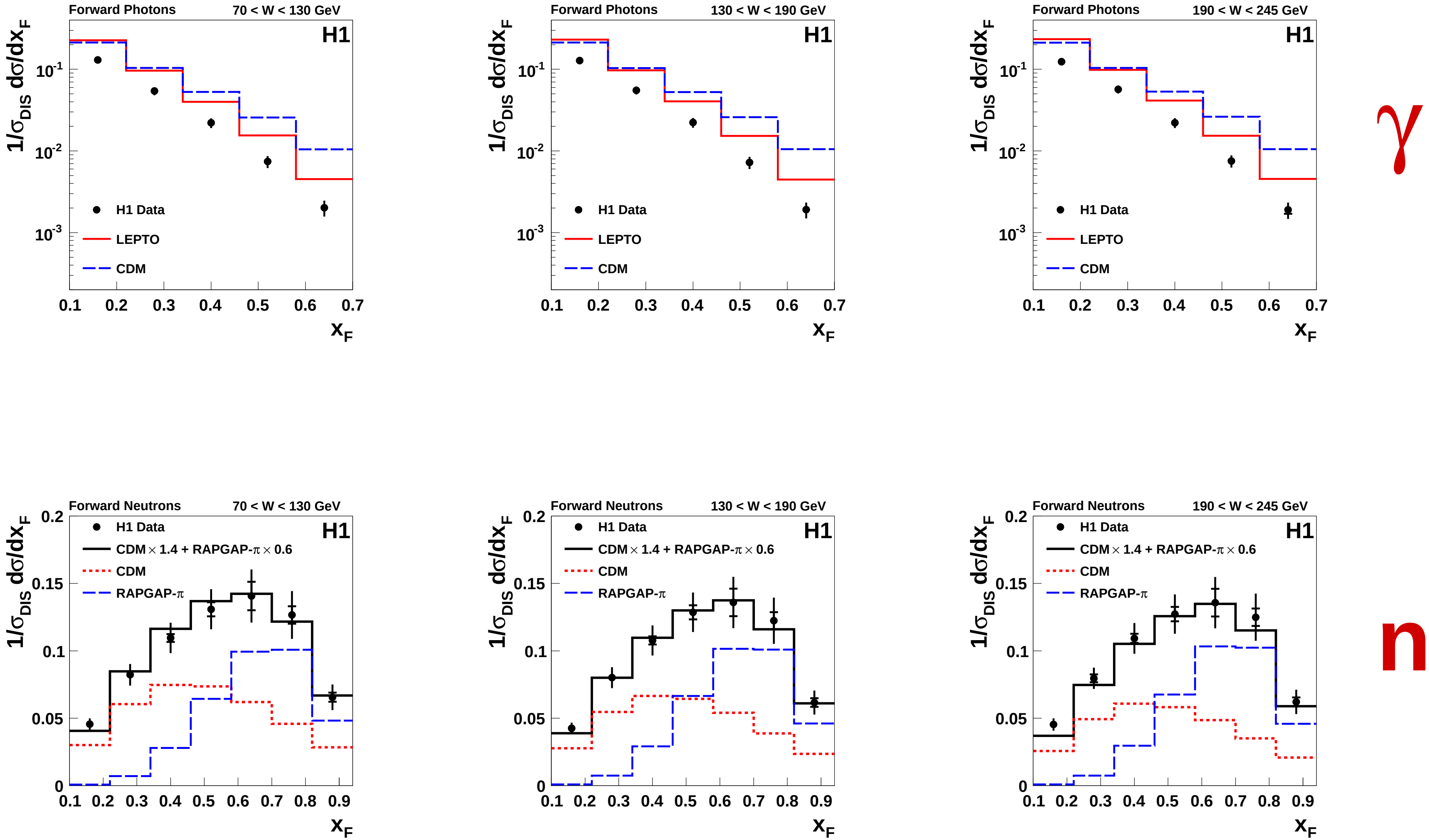
n



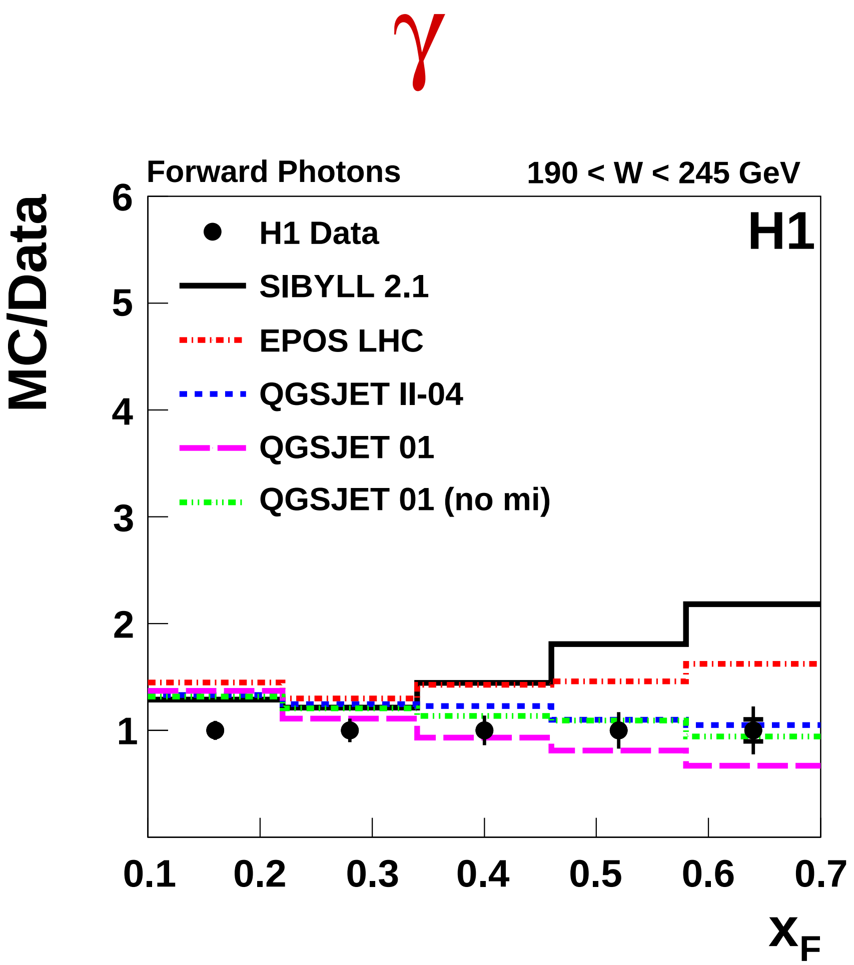


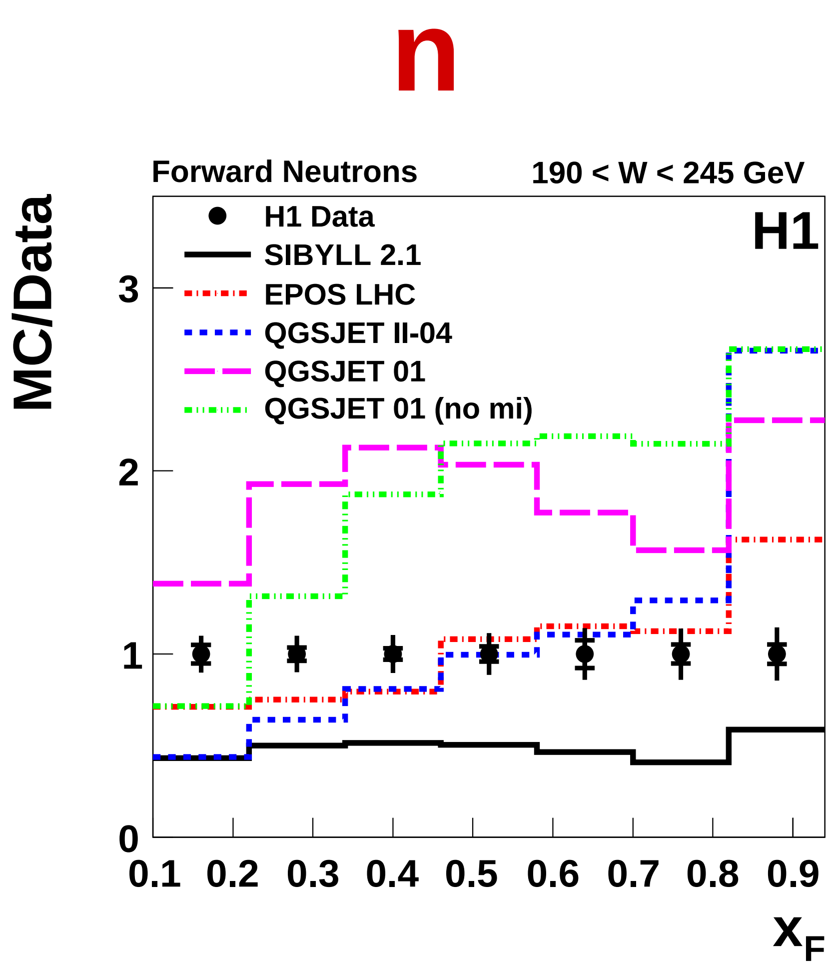
- (γ, n) yields are independent on W
- DIS MC overestimate photon rate by $\sim 70\%$ and describe neutrons
- CR MC overestimate photon rate by $30-40\%$ EPOS LHC is best for n

x_F spectra vs DIS MC models



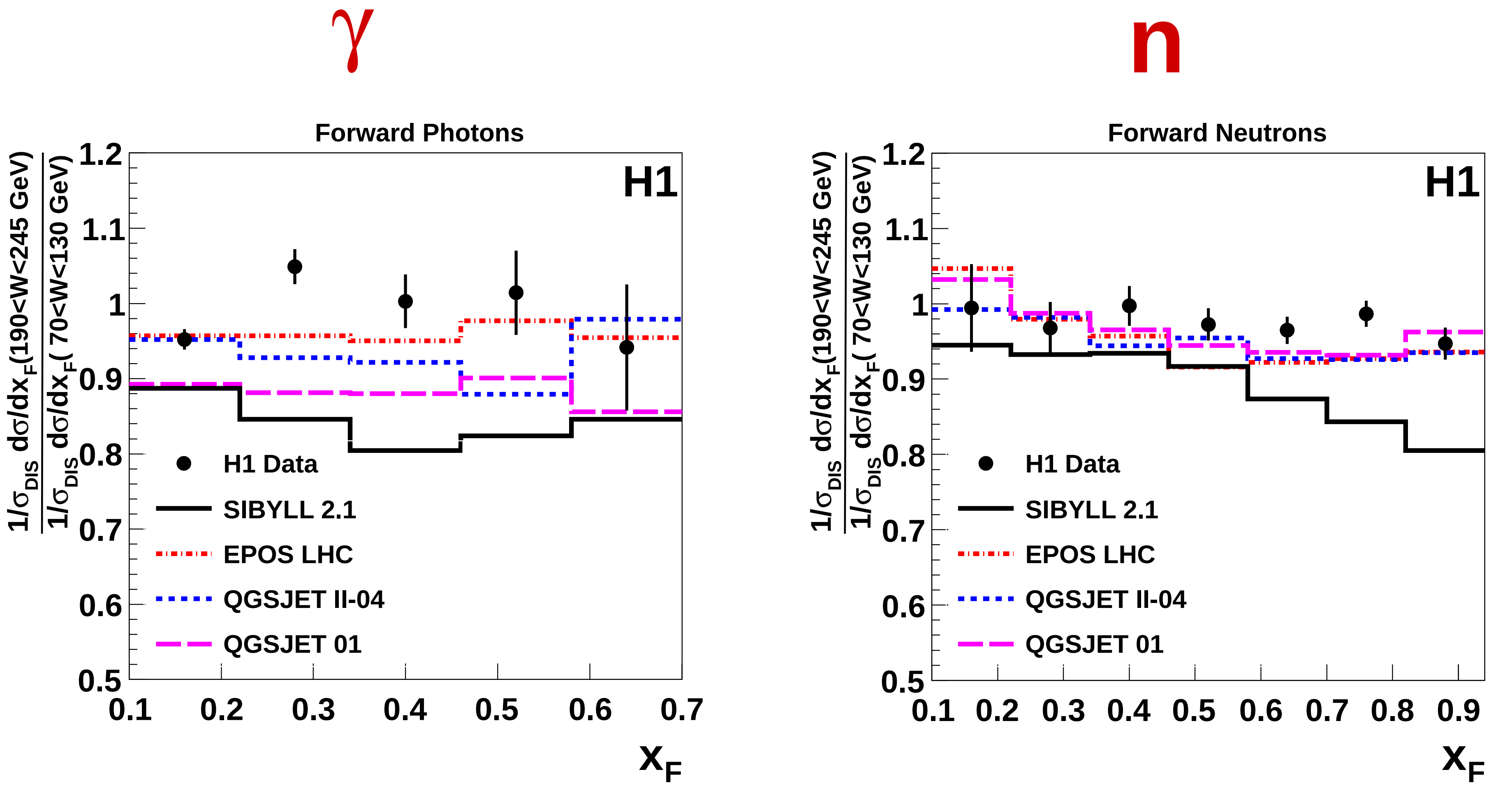
x_F spectra vs CR MC models





- None of the models describes simultaneously γ and n
- EPOS LHC gives best shape description for γ and resonable for n

Testing Feynman scaling hypothesis



- Data are consistent with Feynman scaling for both photons and neutrons
- CR models violate Feynman scaling for photons and (with exception of SYBILL) are consistent with Feynman scaling for neutrons

Summary (1)

- Inclusive production of very forward ($\eta_{lab} > 7.9$) photons and neutrons has been studied at HERA in DIS regime.

- The measured cross sections as a function of x_F confirm the validity of Feynman scaling in the energy range $70 < W < 245$ GeV.

- All MC models overestimate photon yield by $30 - 70\%$.
  The best description of x_F distributions gives EPOS LHC model.

- None of the existing models (both for DIS and CR) describes the photon and neutron data simultaneousely well.

Exclusive ρ^0 photoproduction with leading neutron

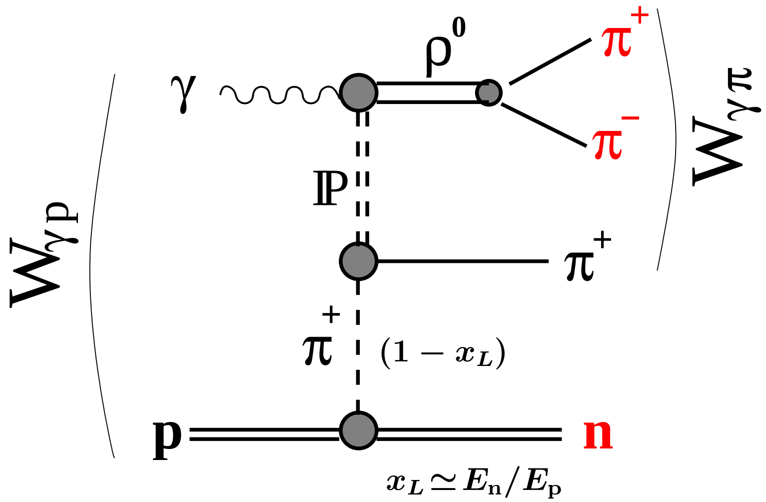
$$\gamma^* + \mathbf{p} \longrightarrow \rho^0 \, \pi^+ \, \mathbf{n}$$

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

Photoproduction:	$Q^2 < 2$ GeV^2	$(\langle Q^2 \rangle = 0.05$ 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	$(\langle W_{\gamma p} \rangle = 48$ GeV$)$
Leading n:	$E_n > 120$ GeV;	$\theta_n < 0.75$ mrad

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

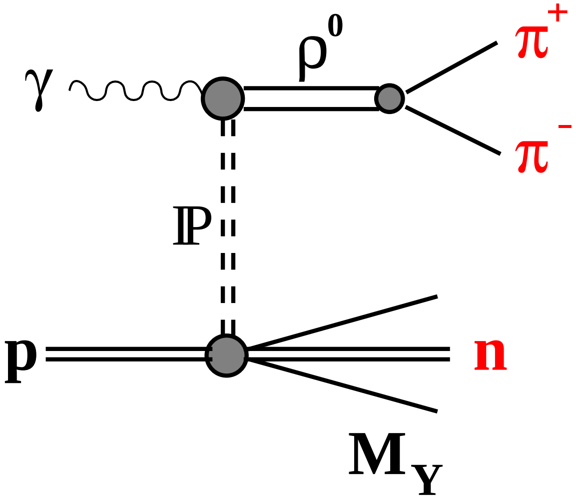
Contributing processes and their modelling



Pompyt × Pythia6

(π-flux) (elastic $\gamma\pi \rightarrow \rho^0\pi$)

Signal (DPP)



DiffVM

(elastic, p-diss, γ-diss, double diss)

Background

$$W_{\gamma p} \simeq \sqrt{2(E - p_z)_\rho E_p}$$

$$W_{\gamma\pi} \simeq W_{\gamma p}\sqrt{1 - x_L}$$

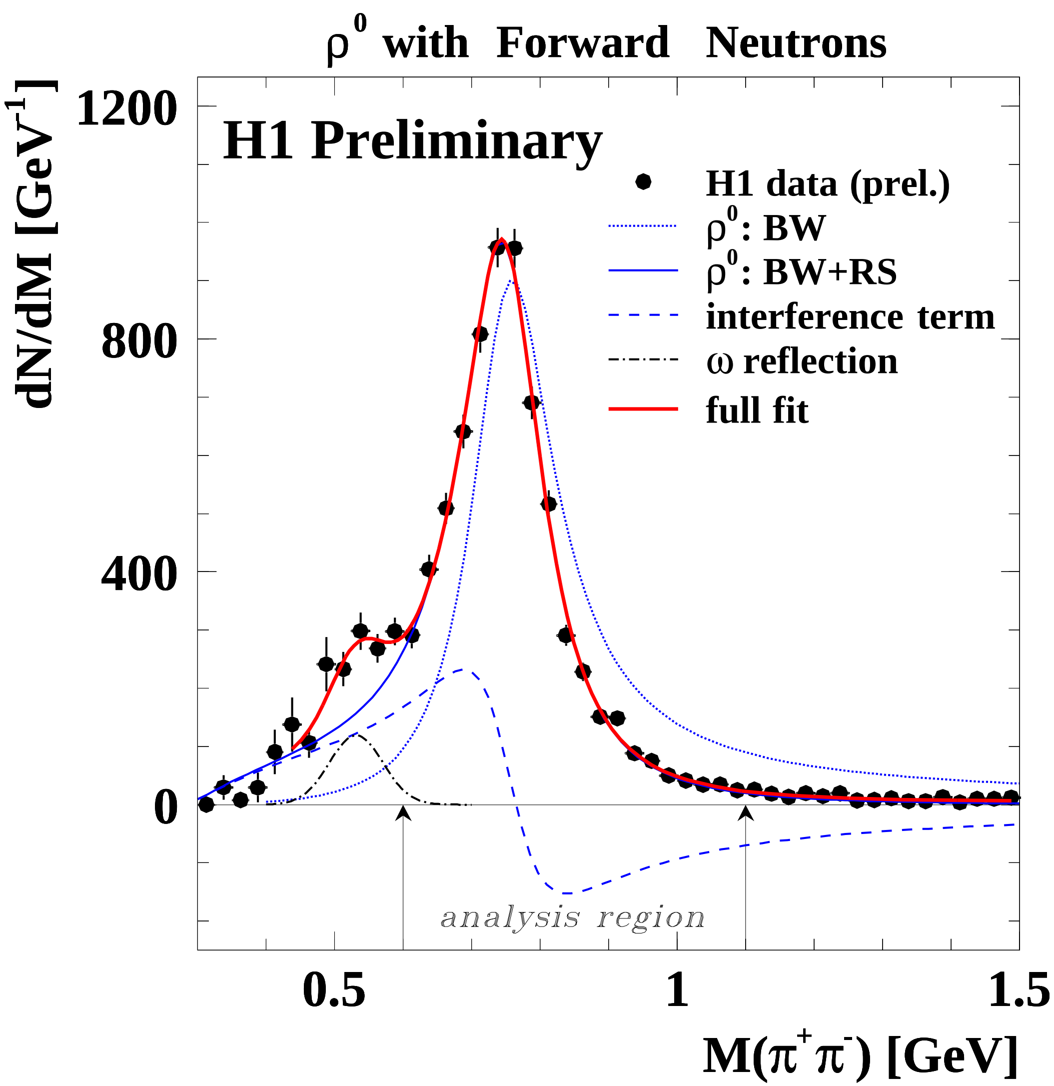
- DPP expectations: $f_{\pi/p}(x_L, t) \Rightarrow x_L$ shape, $p^2_{t,\rho}$ slope, $b = b_{\text{eff}}(M_{\pi N})$
- Diffractive bgr is well known (but has an irreducible part: $M_Y = N^\star \rightarrow n\pi^+$)

Analysis Summary

- Data sample
  - ▷ $2006-2007 e^{+}$ runs, $\sqrt{s}=319$ GeV, $\mathcal{L}=1.16$ pb^{-1} $\simeq$ 6600 events in final sample
  - ▷ Trigger: $\langle\epsilon_{L1}\rangle \simeq 0.8, \quad \langle\epsilon_{L2}\rangle \simeq 1.0$
- Tracking
  - ▷ 2 tracks with $p_t^{\rm tr} > 0.2$ GeV, $20^o < \theta^{\rm tr} < 160^o$ fitted to event vertex $|z_{vx}| < 30$ cm, net charge $= 0$
  - ▷ Effective mass range: $0.6 < M_{\pi\pi} < 1.1$ GeV (analysis); $\Rightarrow \sigma(\rho^0)$ for $0.28 < M_{\pi\pi} < 1.5$ GeV
- FNC
  - ▷ High energy neutron, $E_n > 120$ GeV, within good acceptance region: $\theta_n < 0.75$ mrad
  - ▷ Background fraction determined from x_L shape: $F_{\rm bg} = 0.36 \pm 0.06$ (subtracted from the data)
- Exclusivity
  - ▷ Nothing above noise level in the detector except two tracks from ρ^0 decay and the leading neutron
- Cross section measurement phase space and precision
  - ▷ Photoproduction: $Q^2 < 2$ GeV^2, $20 < W_{\gamma p} < 100$ GeV
  - ▷ Leading neutron: $0.35 < x_L < 0.95, \quad p_{t,n} < x_L \cdot 0.69$ GeV
  - ▷ ρ^0 meson: $0.28 < M_{\pi\pi} < 1.5$ GeV, $p_{t,\rho} < 1$ GeV

$$\delta_{\rm stat} = 2.1\% \oplus \delta_{\rm sys} = 15.5\% \oplus \delta_{\rm norm} = 5.9\% \quad \Rightarrow \quad \delta_{\rm tot} = 16.6\%$$

ρ-meson shape

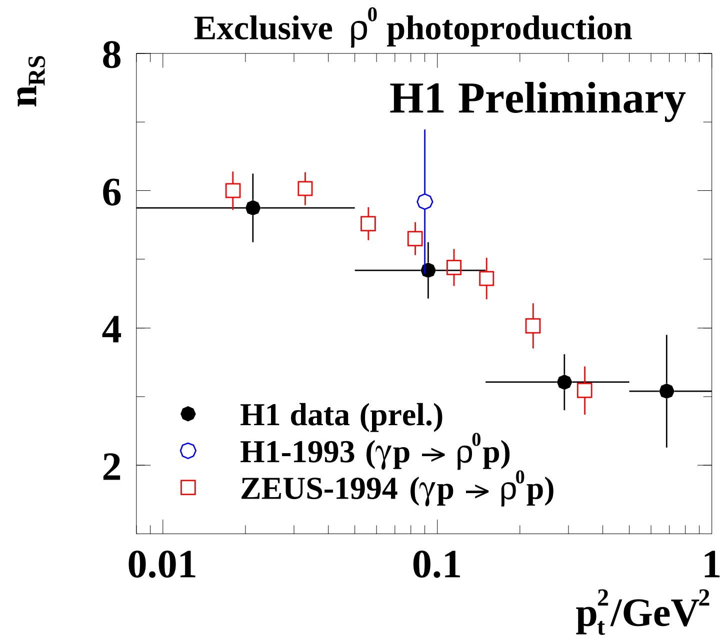


$$\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} \propto BW_\rho(M_{\pi\pi}) \left(\frac{M_\rho}{M_{\pi\pi}}\right)^{n_{RS}}$$

$M = 764 \pm 3$ MeV

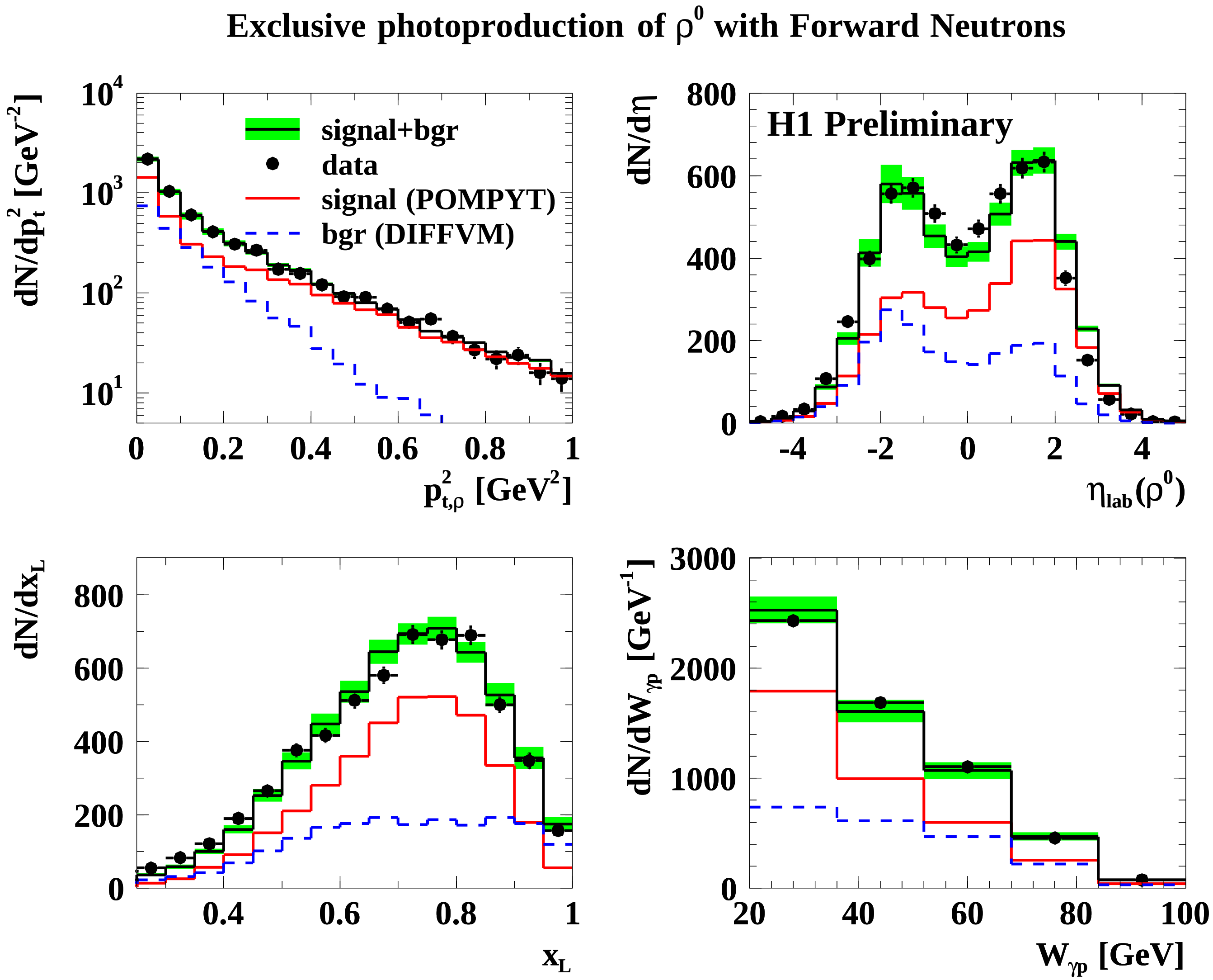
$\Gamma = 154 \pm 5$ MeV

$n_{RS} = 4.17 \pm 0.27$



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

Control Plots for basic kinematics



Data points are shown with stat. errors only; green band represents estimated bgr fraction uncertainty

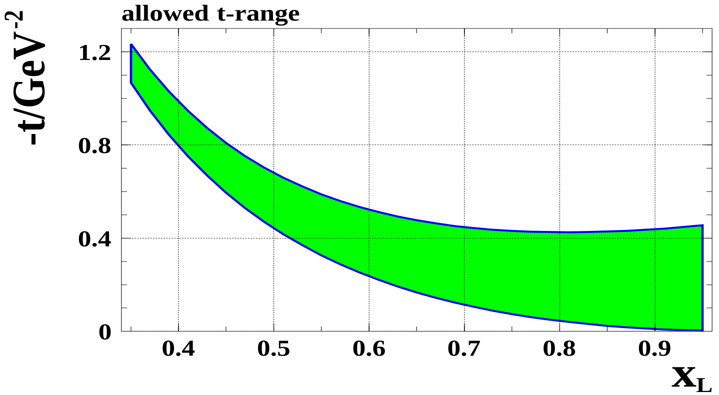
OPE and pion fluxes

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

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

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 $\overline{\sigma_{\gamma\pi}}(\langle W_{\gamma\pi}\rangle) = \frac{\sigma_{\gamma p}}{\int \Gamma_\pi}$



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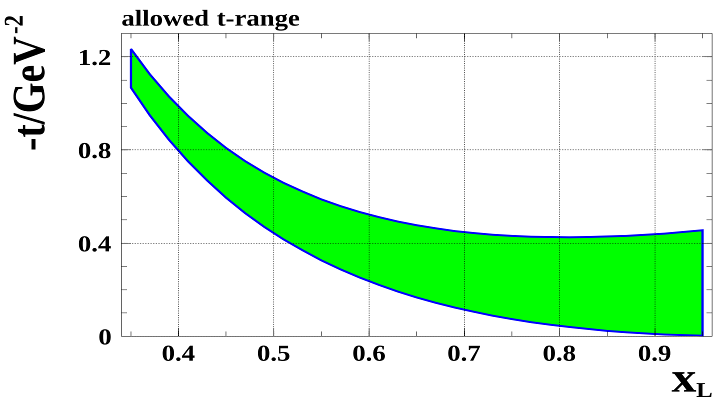
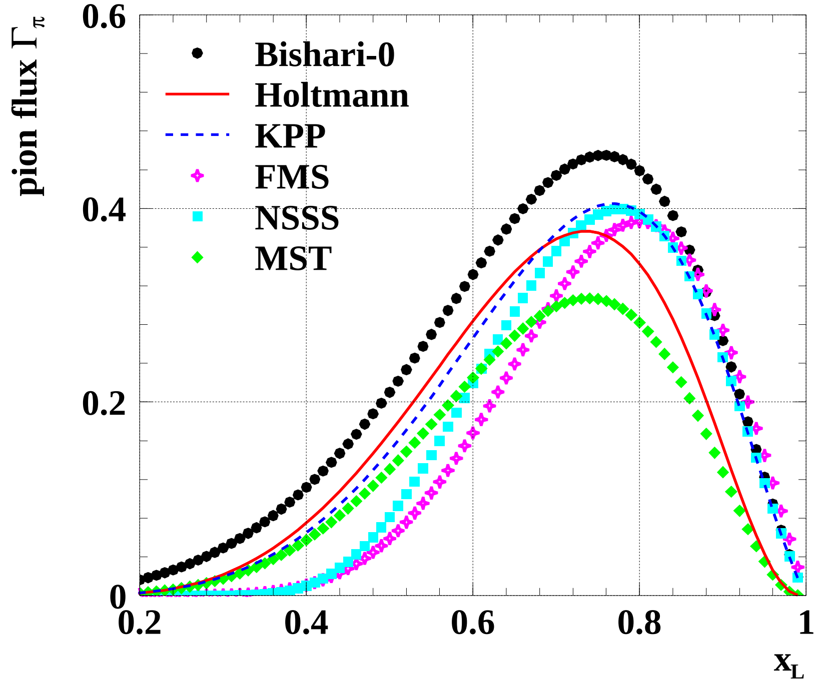


Problem: too many different fluxes on the market



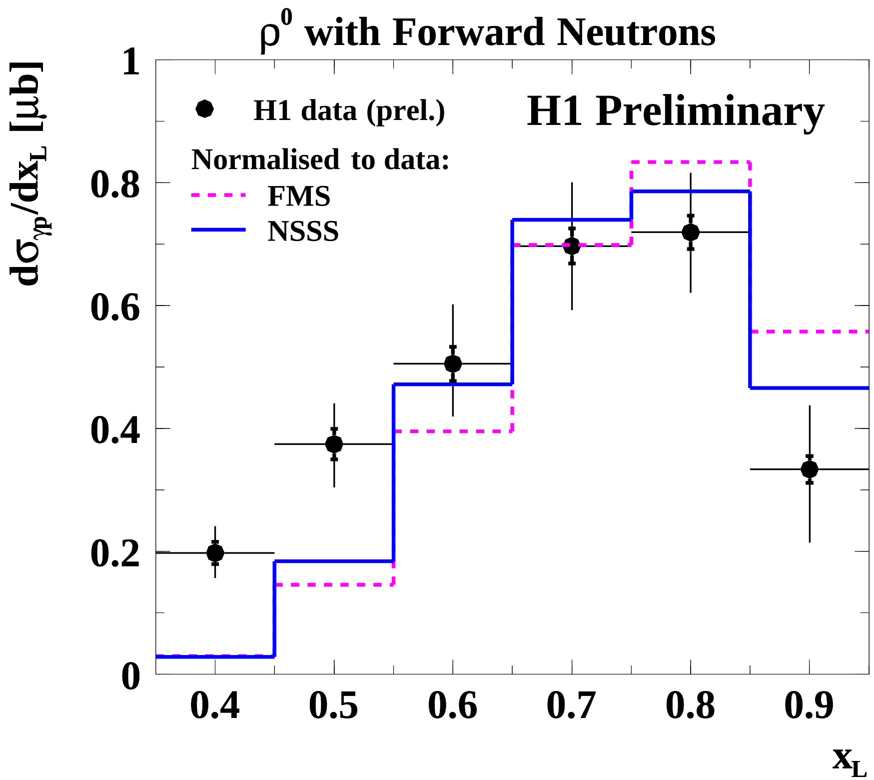
Typical examples:

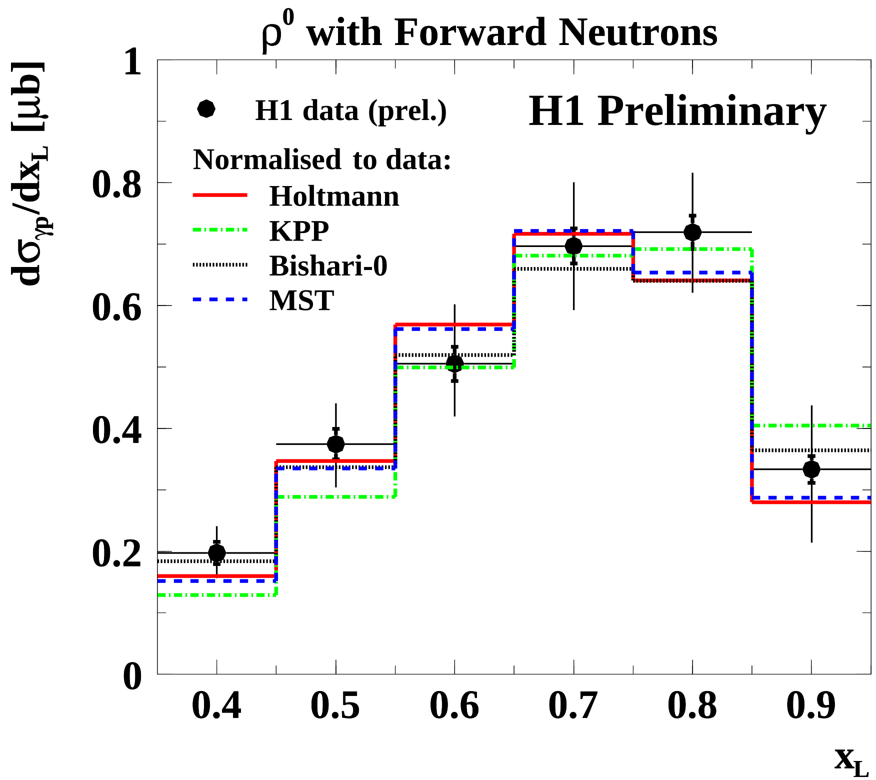
$f_{\pi^+/p}(x_L,t) = \frac{1}{2\pi}\frac{g_{p\pi N}^2}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\exp[-R_{\pi n}^2\frac{m_\pi^2-t}{1-x_L}]$ – H. Holtmann et al., *Nucl. Phys.* **A596** (1996) 631.

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

Pion fluxes confronted with H1 data

Make restricted selection of π-fluxes on the basis of shape comparison only





Example of fluxes excluded by the data

(too soft pions 'in the proton')

Fluxes compatible with H1 data

($\chi^2 = 2.1$ to 5.5 for 6 points)

Total cross sections

γp

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

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 OPE dominated range, $0.35 < x_L < 0.95$, and $20 < W_{\gamma\mathrm{p}} < 100$ GeV, $\theta_n < 0.75$ mrad

$$\boxed{\sigma(\gamma\mathrm{p} \to \rho^0\mathrm{n}(\pi^+)) = (280 \pm 6_{\mathrm{stat}} \pm 46_{\mathrm{sys}})\ \mathrm{nb}}$$

$\gamma\pi$

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

and for $\langle W_{\gamma\pi}\rangle = 22$ GeV

$$\boxed{\sigma_{\mathrm{el}}(\gamma\pi^+ \to \rho^0\pi^+) = (2.03 \pm 0.34_{\mathrm{exp}} \pm 0.51_{\mathrm{model}})\ \mu\mathrm{b}}$$

Taking interpolated value of $\sigma(\gamma p \to \rho^0 p) = 9.5 \pm 0.5\ \mu$b at corresponding energy, we obtain

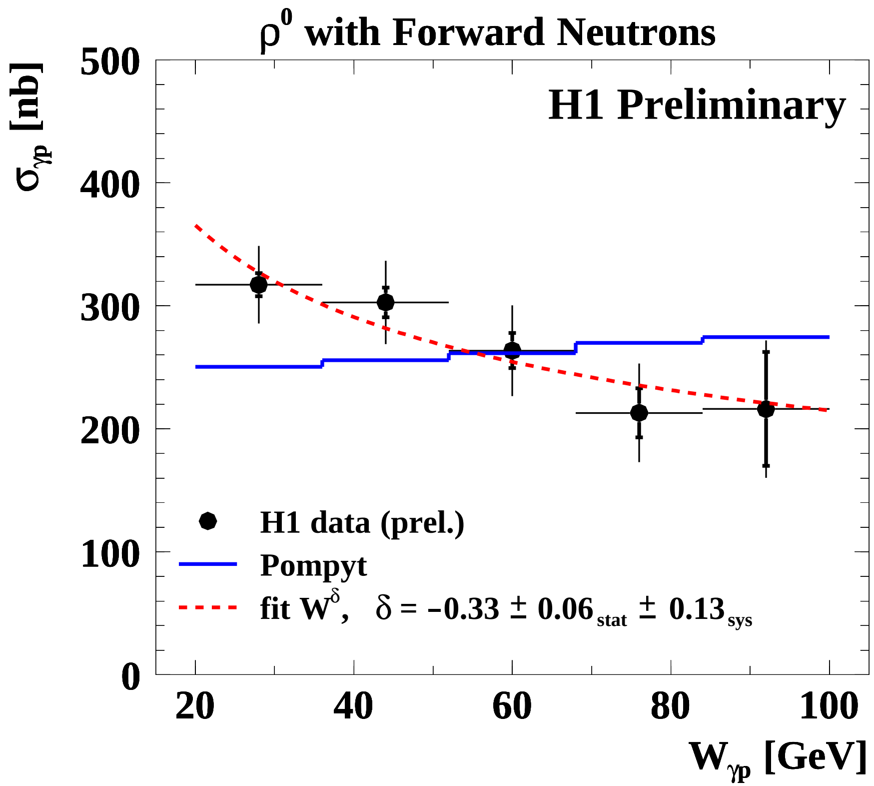
$$r_{\mathrm{el}} = \sigma^{\mathrm{el}}_{\gamma\pi}/\sigma^{\mathrm{el}}_{\gamma p} = 0.21 \pm 0.06$$

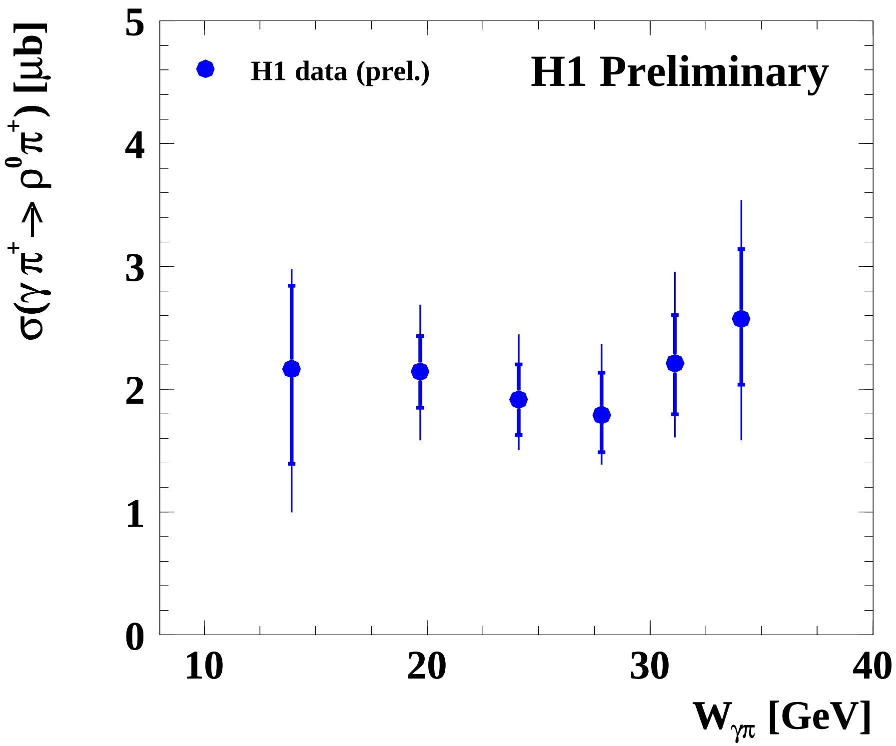
(cf. $r_{\mathrm{tot}} = \sigma^{\mathrm{tot}}_{\gamma\pi}/\sigma^{\mathrm{tot}}_{\gamma p} = 0.32 \pm 0.03$ [ZEUS, 2002])

Total γp and $\gamma\pi$ cross sections

Inner error bars – statistical uncertainty
outer error bars – $\sqrt{\text{stat}^2 + \text{sys}^2}$

Inner error bars – total experimental uncertainty
outer error bars – $\sqrt{\text{exp}^2 + \text{model}^2}$





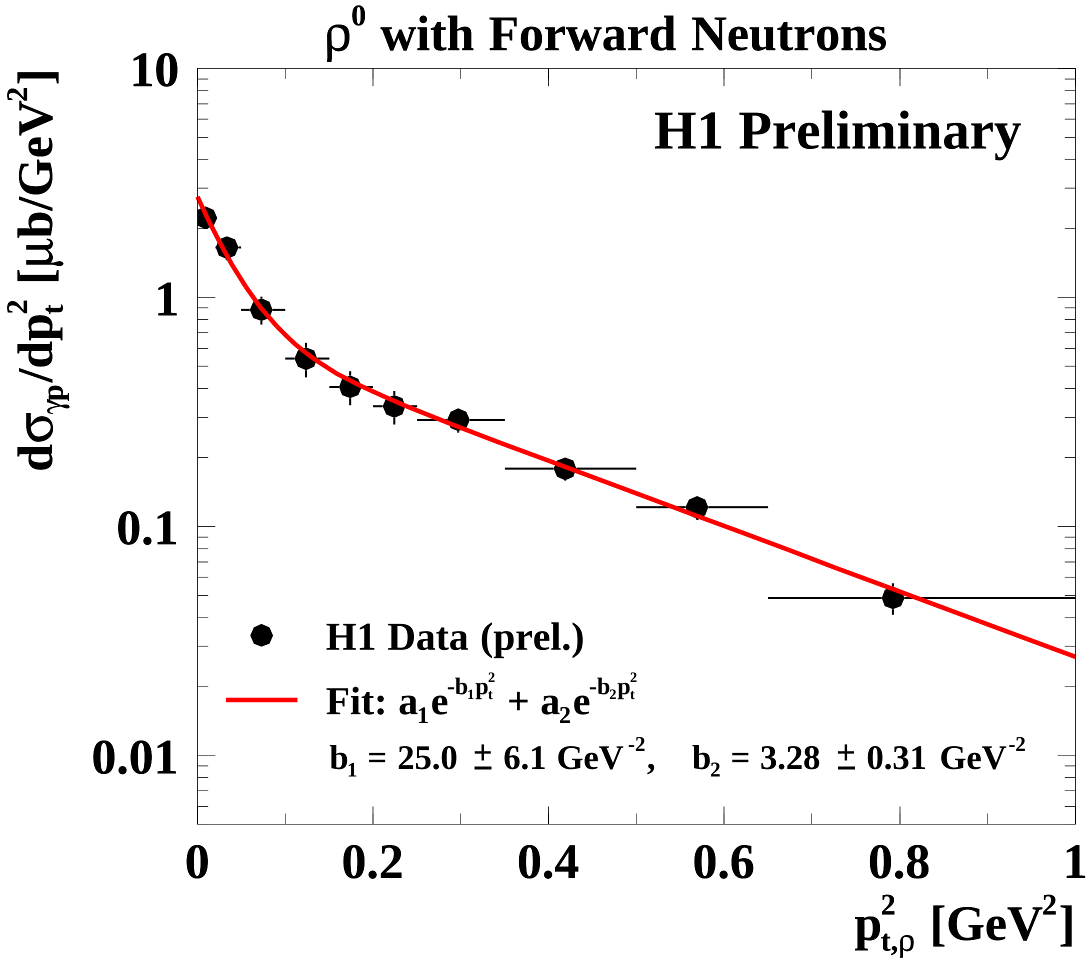
Regge motivated power low fit W^δ yields $\delta < 0$

(in qualitative agreement with DPP and in contrast to MC,
$\delta_{MC} = 0.08 \pm 0.02$*, which is expected from purely $I\!P$ exchange)*

Holtmann flux is used for the central values.

Conservative model uncertainty $\sim 25\%$

Differential cross section in p_t^2



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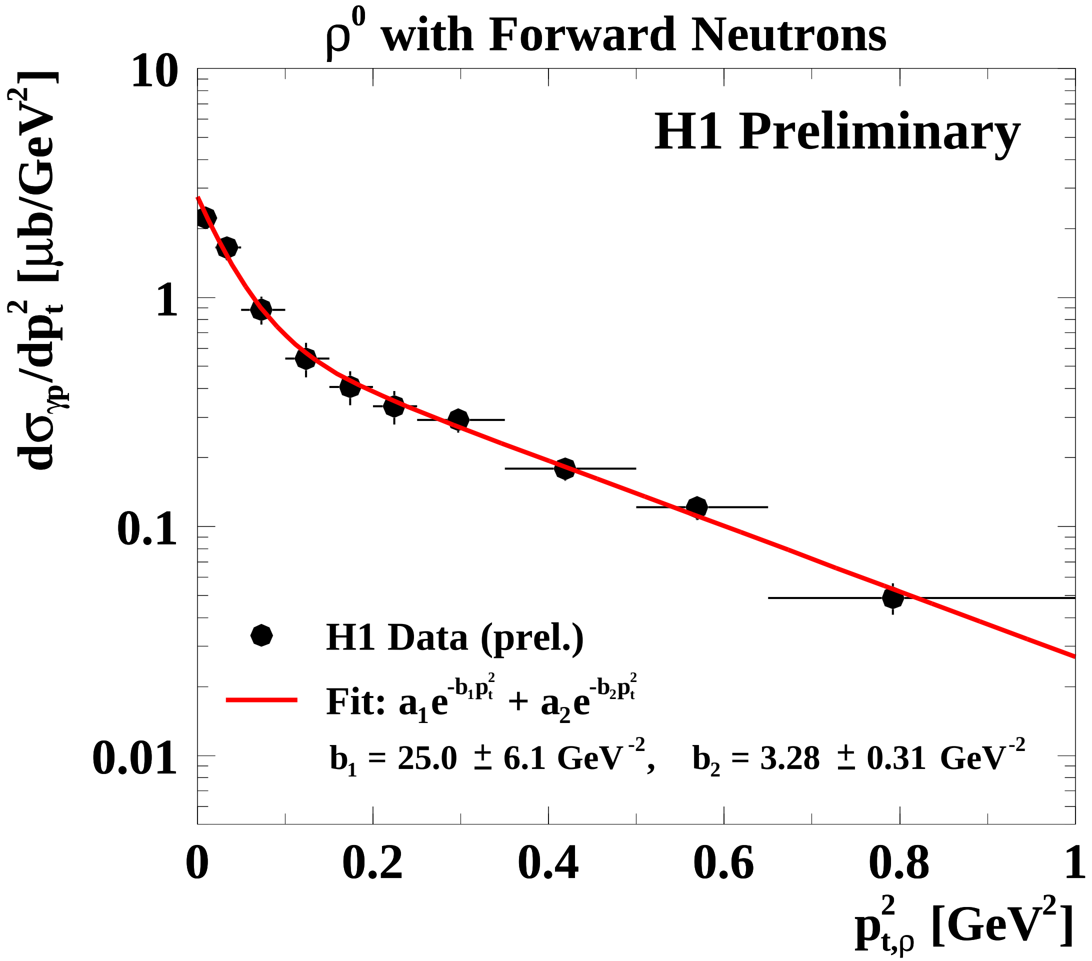
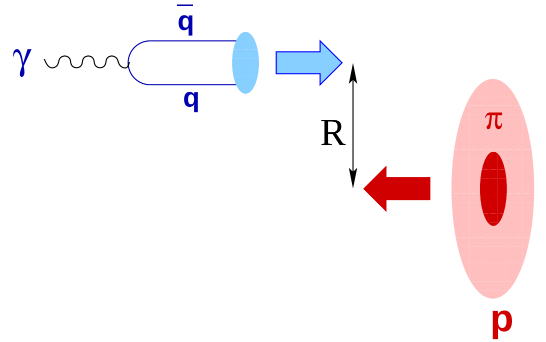
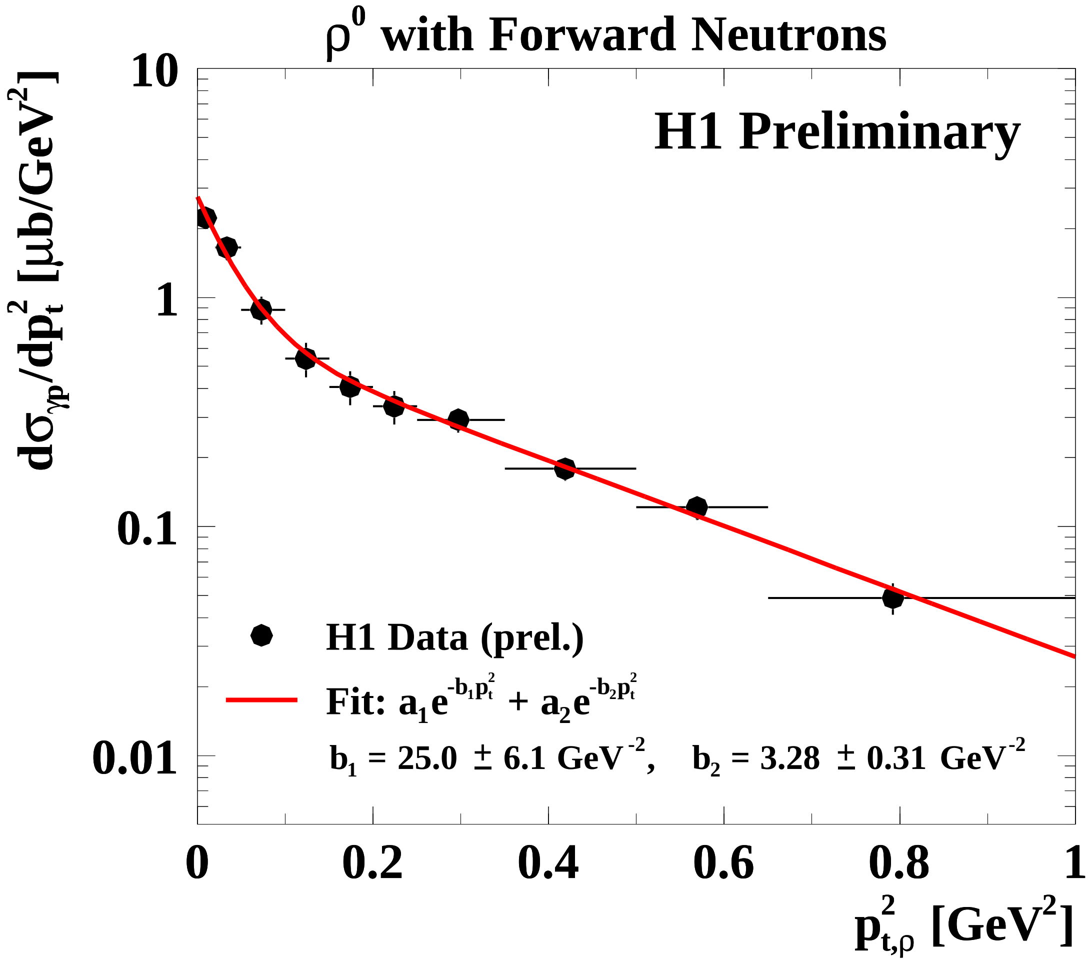
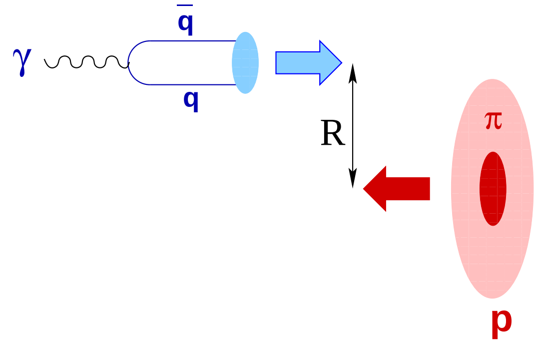


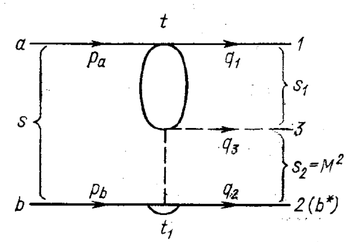


Geometric interpretation: $\langle r^2 \rangle = 2b_1 \cdot (\hbar c)^2 \simeq 2$ fm^2 $\Rightarrow (1.6 R_\mathrm{p})^2 \Rightarrow$ ultra-peripheral process

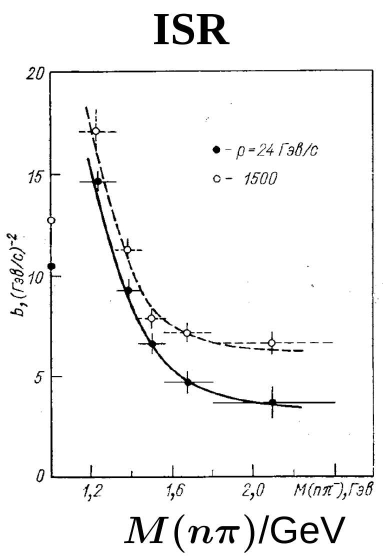
Differential cross section in p_t^2







DPP $2 \longrightarrow 3$



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

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

Summary (2)

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