



Diffraction 2014

International Workshop on Diffraction in High-Energy Physics



Recent HERA results with very Forward Neutrons and Photons



Sergey Levonian

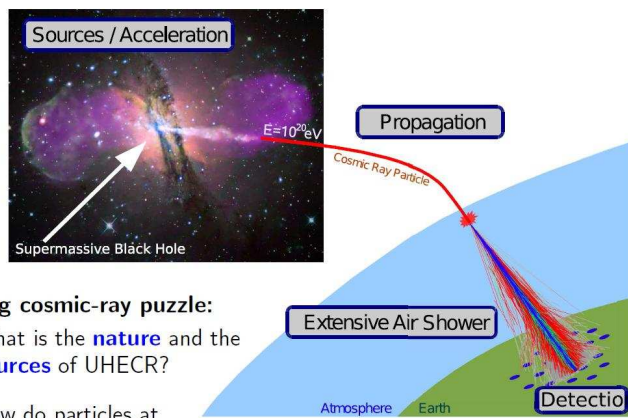
On behalf of H1 Collaboration



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

Motivation and Challenges

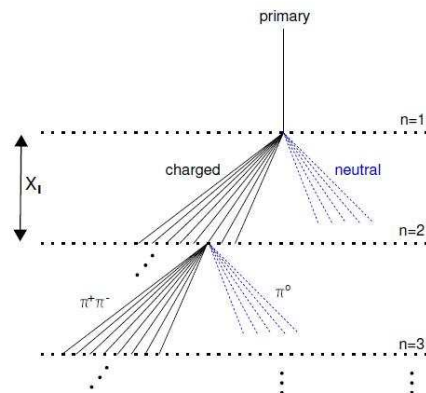
- Extreme forward region in particle collisions is still poorly understood
 - ▷ Theory: No (or few) firm predictions from first principles
 - ▷ Experiment: Difficult to measure due to detector acceptance limitations
- Important for correct analysis of (ultra-high energy) Cosmic Rays
 - ▷ Two pieces of the puzzle:
 - Sources/Propagation (prime interest)
 - Interaction/Detection (extensive air shower)
 - ▷ To understand the former one needs good MC models for the latter



Solving cosmic-ray puzzle:

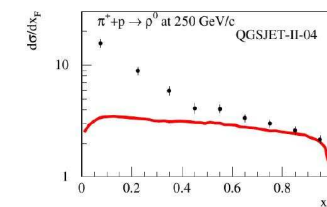
- What is the **nature** and the **sources** of UHECR?
- How do particles at ultra-high energies **interact**?

Extended Heitler Model:



(Forward) ρ^0 Production, QGSJetII.3 \rightarrow QGSJetII.4

Charge Exchange, Leading π^0/ρ^0 production:



S. Ostapchenko, ISVHECRI 2012

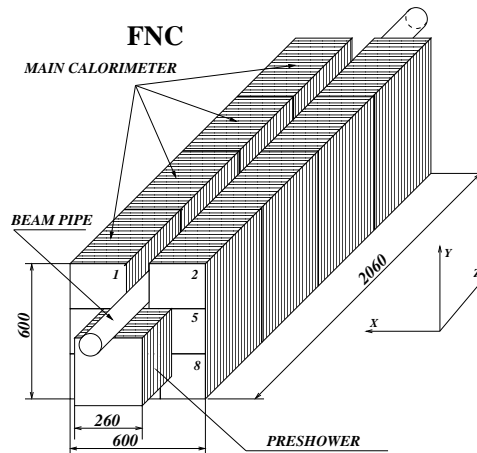
(Ralf Ulrich, PANIC-2014)

Motivation and Challenges

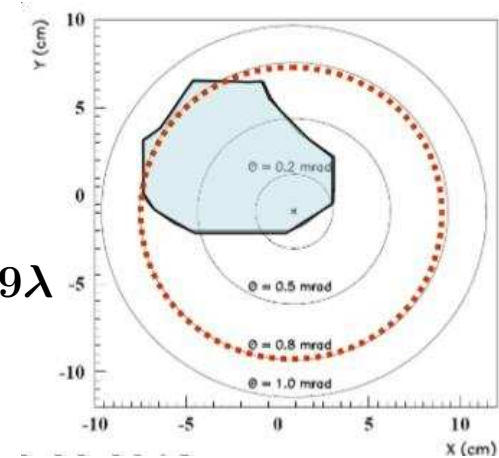
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 - ▷ To understand the former one needs good MC models for the latter
- Current situation (from PANIC summary):
 - ▷ Recent LHC data are very valuable for CR MC tuning but still no fully consistent picture yet
 - ▷ UHECR data becomes more precise and 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

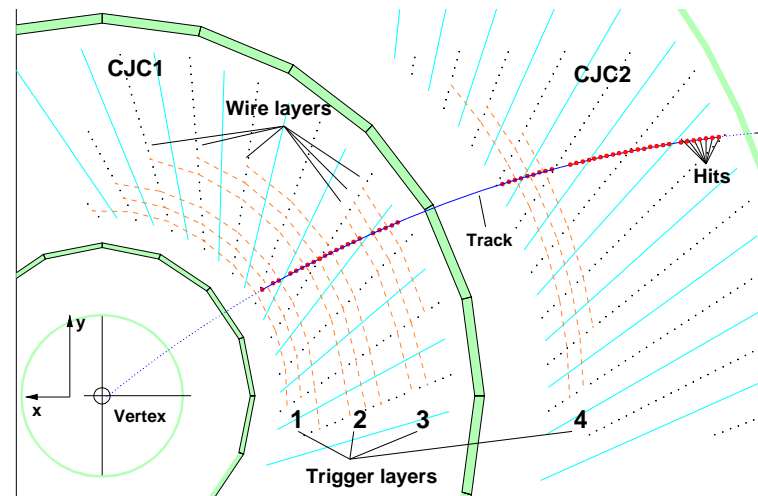
Improved H1 FNC (distinguish ($\langle P \rangle = 98\%$) and measure n and γ/π^0)



located at $z = 106\text{m}$ from IP
 $\langle A \rangle \simeq 30\%$ for $\theta < 0.8 \text{ mrad}$
 Preshower: $60X_0$, Main Calo: 8.9λ

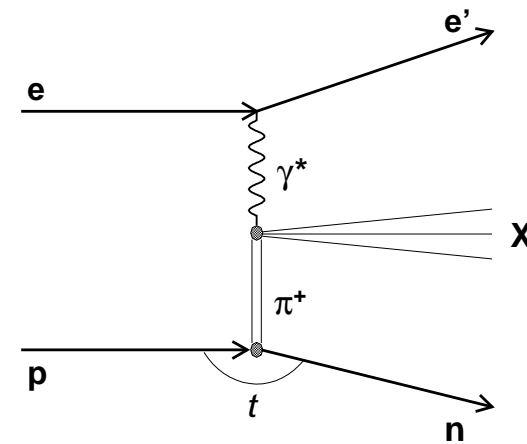
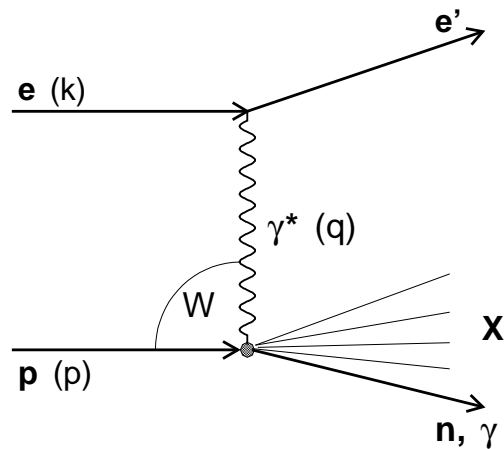


Powerful fast track trigger (allows untagged soft γp to be collected)



Inclusive forward γ, n production in DIS

$$e^+ + p \longrightarrow e^+ \begin{pmatrix} n \\ \gamma \end{pmatrix} X$$



Data

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

$$6 < Q^2 < 100 \text{ GeV}^2$$

$$70 < W < 245 \text{ GeV}$$

$$\eta_{\text{lab}} > 7.9, \quad x_F = 2p_{\parallel}^*/W > 0.1$$

$$\gamma : 83000 \text{ ev.} \quad n : 230000 \text{ ev.}$$

MC models

DIS: LEPTO/CDM (γ, n)

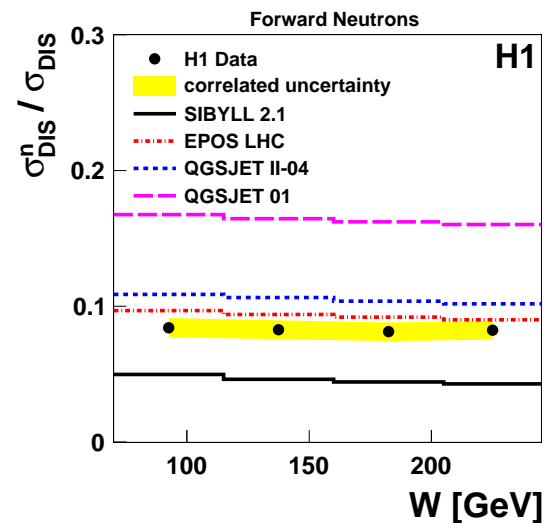
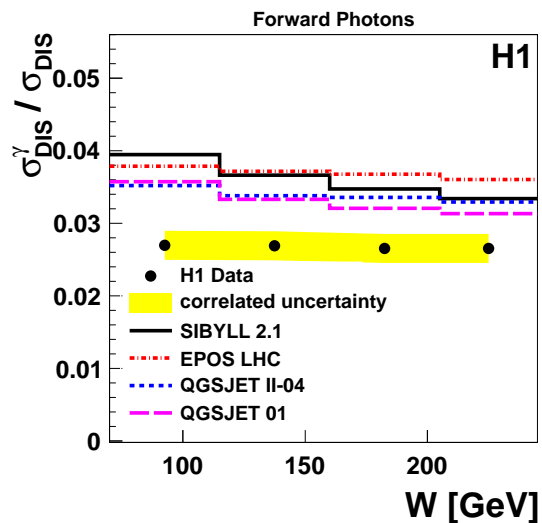
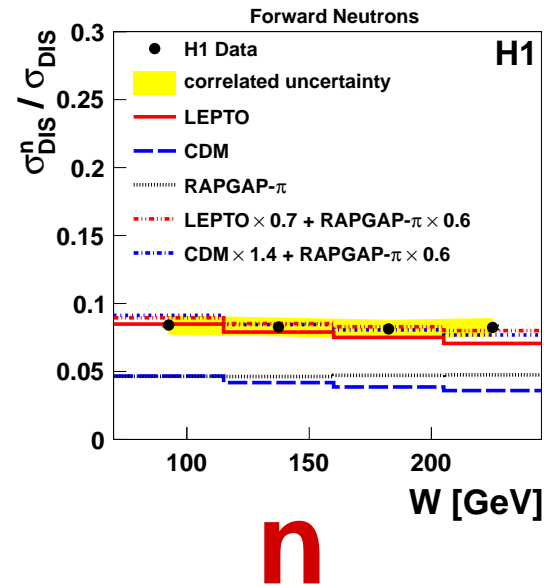
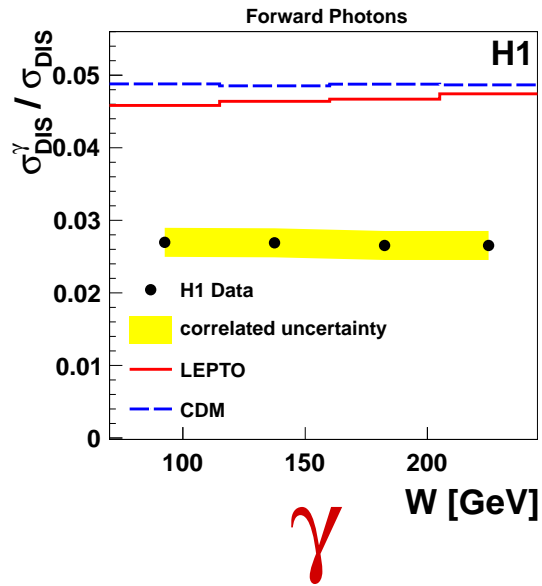
RAPGAP- π (n)

CR: EPOS LHC

SYBILL 2.1

QGSJET (3 versions)

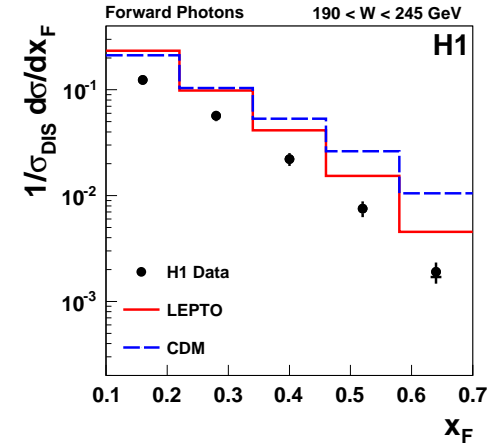
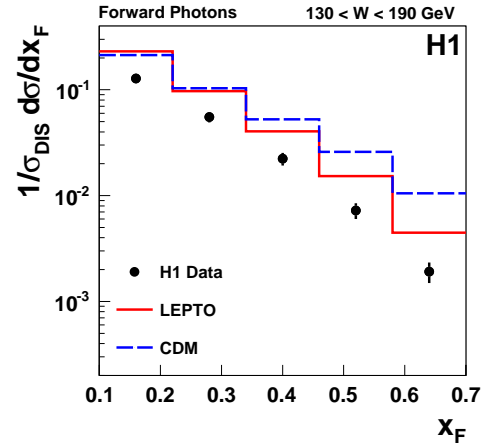
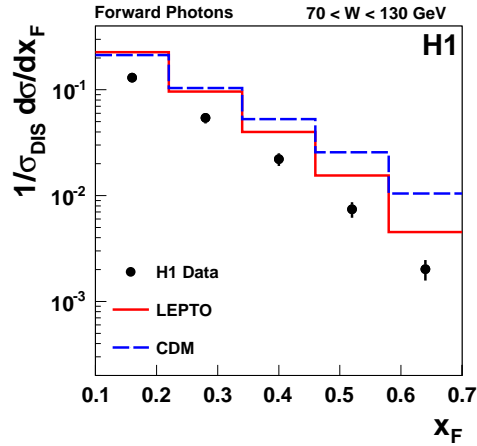
W dependence



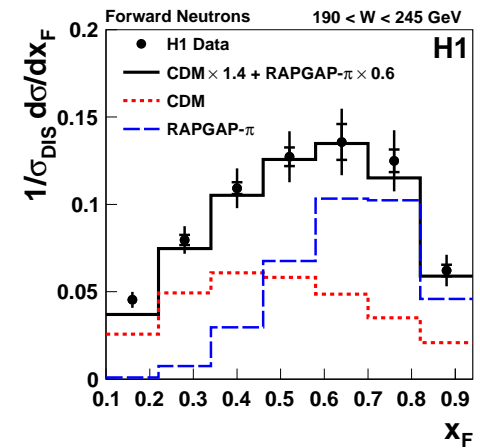
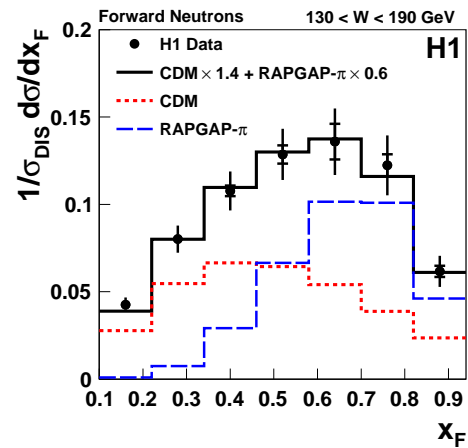
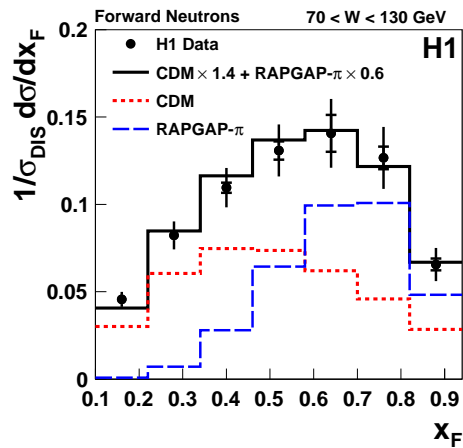
- (γ, n) yields are independent on W
- DIS MC overestimate photon rate by $\sim 70\%$ and describe neutrons

- CR MC overestimate photon rate by 30–40% EPOS LHC is best for n

x_F spectra vs DIS MC models



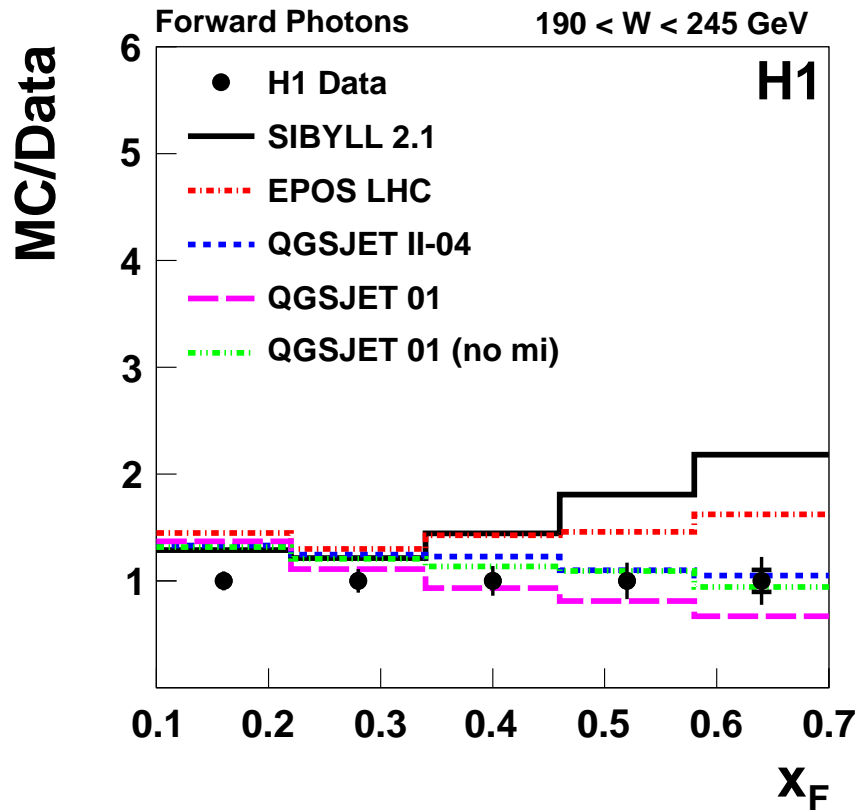
γ



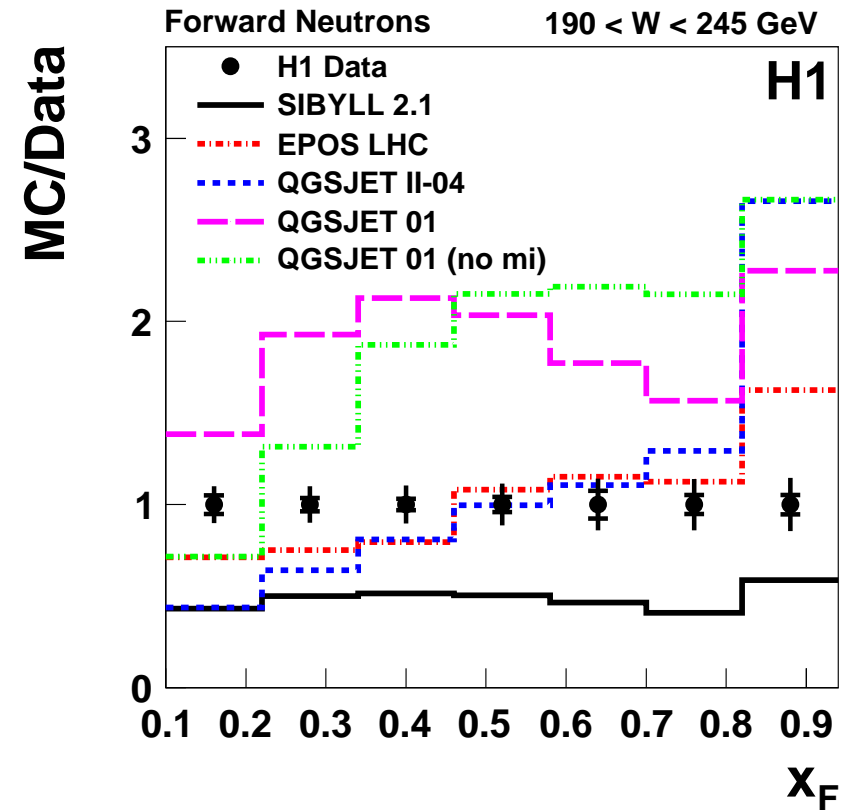
n

x_F spectra vs CR MC models

γ



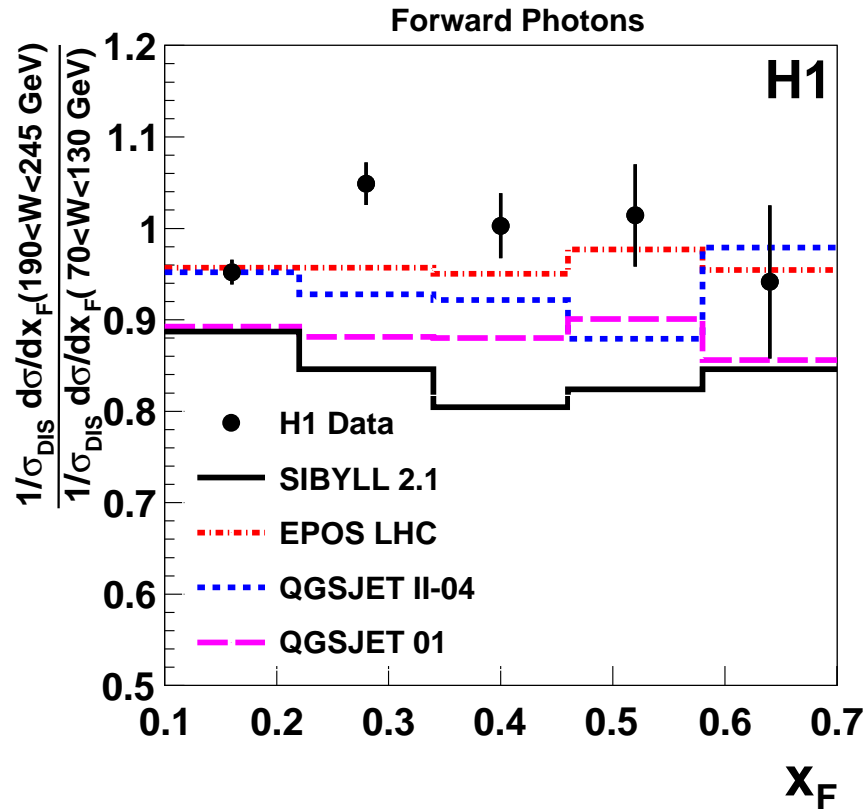
n



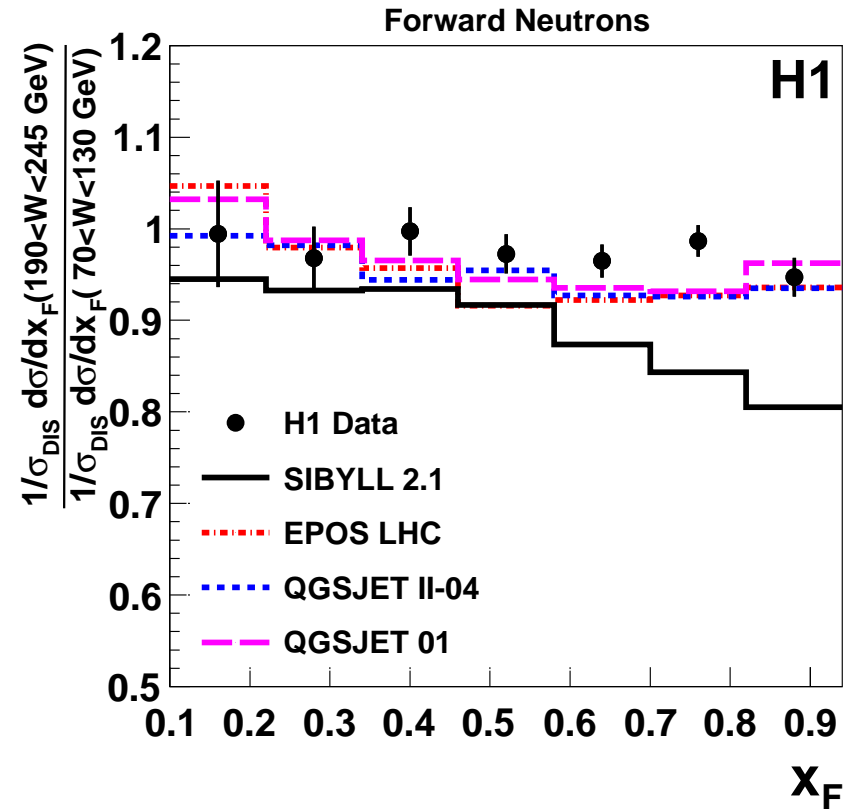
- None of the models describes simultaneously γ and n
- EPOS LHC gives best shape description for γ and reasonable for n

Testing Feynman scaling hypothesis

γ



n

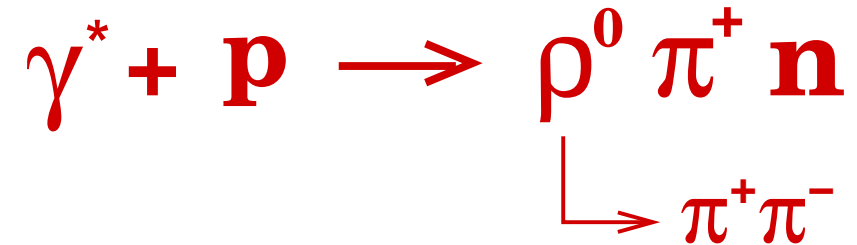


- Data are consistent with Feynman scaling for both photons and neutrons
- CR models violate Feynman scaling for photons and (with exception of SYBILL) are consistent with Feynman scaling for neutrons

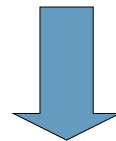
Summary (1)

- 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 simultaneously well.

Exclusive ρ^0 photoproduction with leading neutron

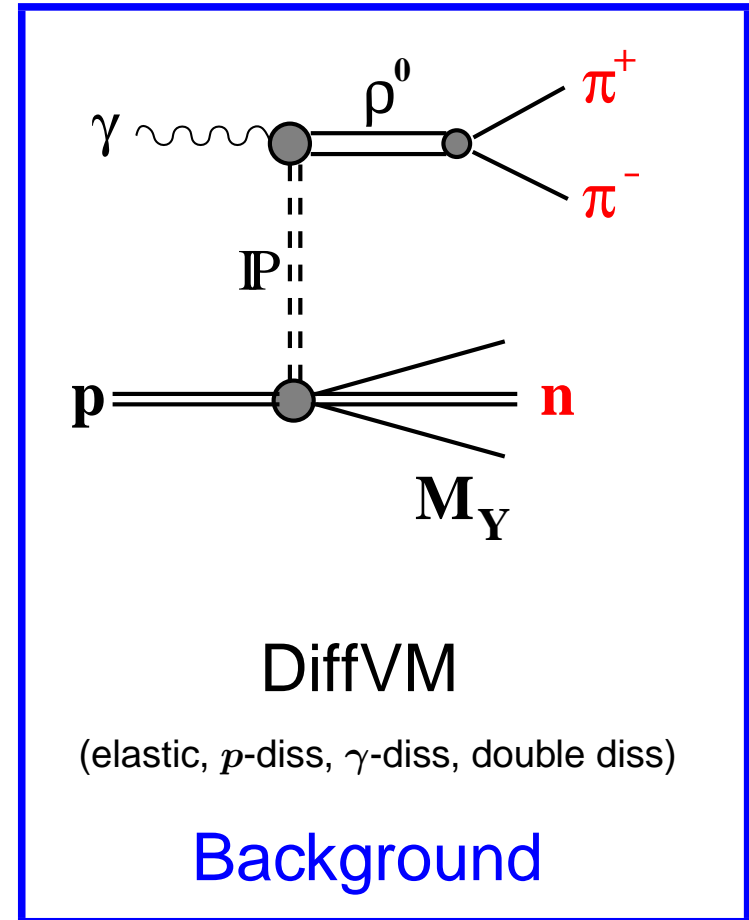
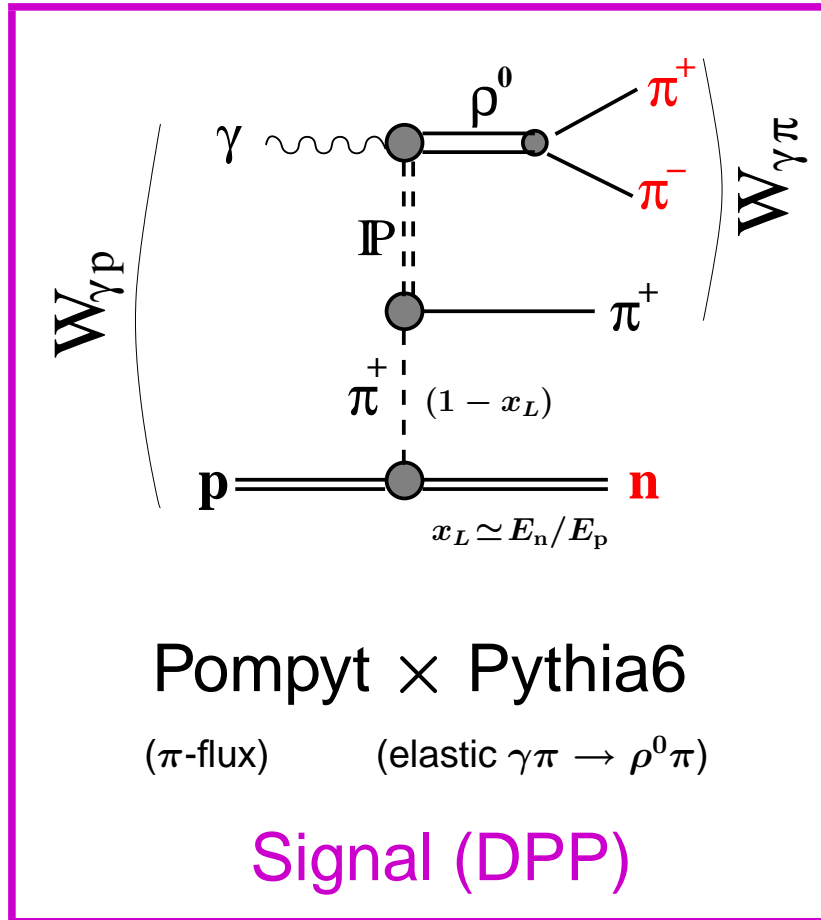


Photoproduction:	$Q^2 < 2 \text{ GeV}^2$	$(\langle Q^2 \rangle = 0.05 \text{ GeV}^2)$
Low p_t :	$ t < 1 \text{ GeV}^2$	$(\langle t \rangle = 0.20 \text{ GeV}^2)$
Small mass:	$0.3 < m_{\pi\pi} < 1.5 \text{ GeV}$	(m_{ρ^0})
π^+, π^- in CT:	$20 < W_{\gamma p} < 100 \text{ GeV}$	$(\langle W_{\gamma p} \rangle = 48 \text{ GeV})$
Leading n :	$E_n > 120 \text{ GeV};$	$\theta_n < 0.75 \text{ mrad}$



No hard scale present \Rightarrow Regge framework is most appropriate

Contributing processes and their modelling



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

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

- DPP expectations: $f_{\pi/p}(x_L, t) \Rightarrow x_L$ shape, $p_{t,\rho}^2$ slope, $b = b_{\text{eff}}(M_{\pi N})$

- Diffractive bgr is well known (but has an irreducible part: $M_Y = N^* \rightarrow n\pi^+$)

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: $\langle \epsilon_{L1} \rangle \simeq 0.8$, $\langle \epsilon_{L2} \rangle \simeq 1.0$

- Tracking

- ▷ 2 tracks with $p_t^{\text{tr}} > 0.2$ GeV, $20^\circ < \theta^{\text{tr}} < 160^\circ$ 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: $F_{\text{bg}} = 0.36 \pm 0.06$ (subtracted from the data)

- Exclusivity

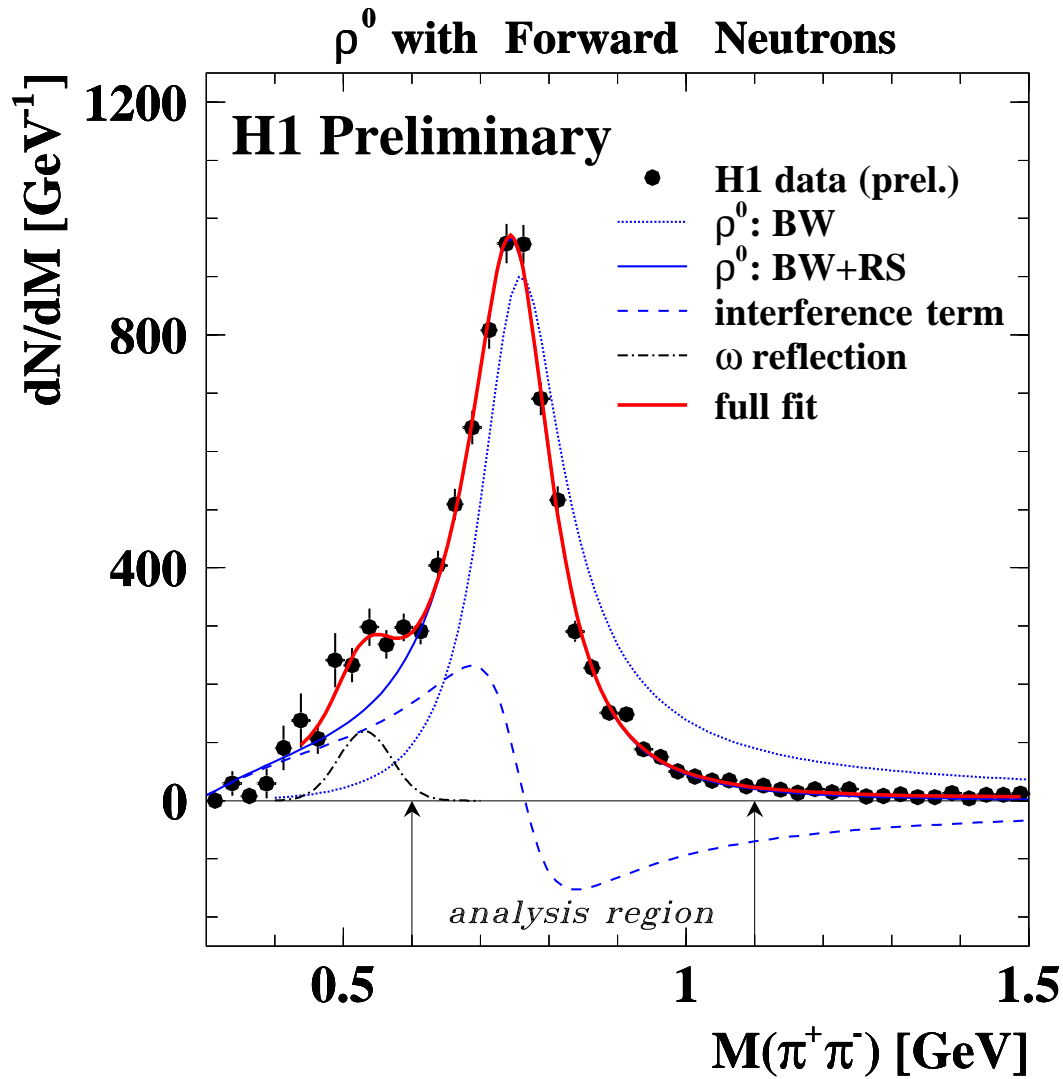
- ▷ Nothing above noise level in the detector except two tracks from ρ^0 decay and the leading neutron

- Cross section measurement phase space and precision

- ▷ Photoproduction: $Q^2 < 2$ GeV 2 , $20 < W_{\gamma p} < 100$ GeV
- ▷ Leading neutron: $0.35 < x_L < 0.95$, $p_{t,n} < x_L \cdot 0.69$ GeV
- ▷ ρ^0 meson: $0.28 < M_{\pi\pi} < 1.5$ GeV, $p_{t,\rho} < 1$ GeV

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

ρ -meson shape

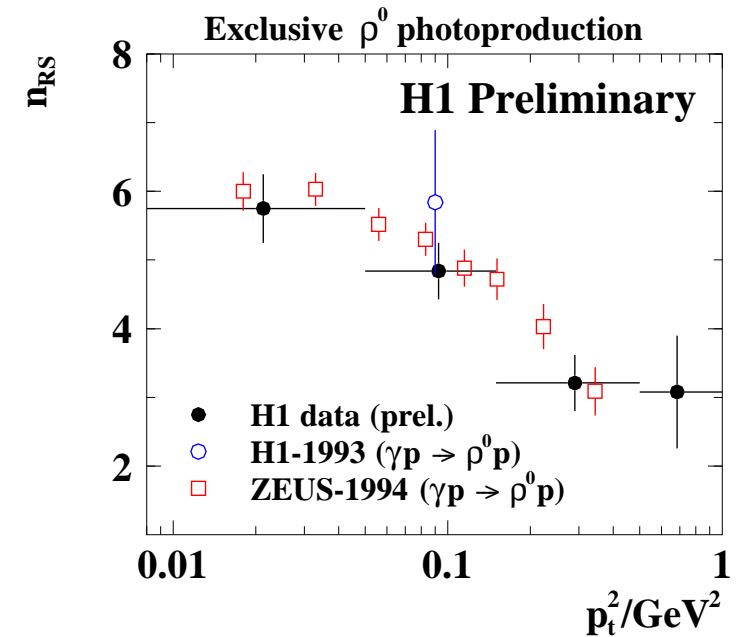


$$\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} \propto BW_{\rho}(M_{\pi\pi}) \left(\frac{M_{\rho}}{M_{\pi\pi}}\right)^{n_{RS}}$$

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

$$\Gamma = 154 \pm 5 \text{ MeV}$$

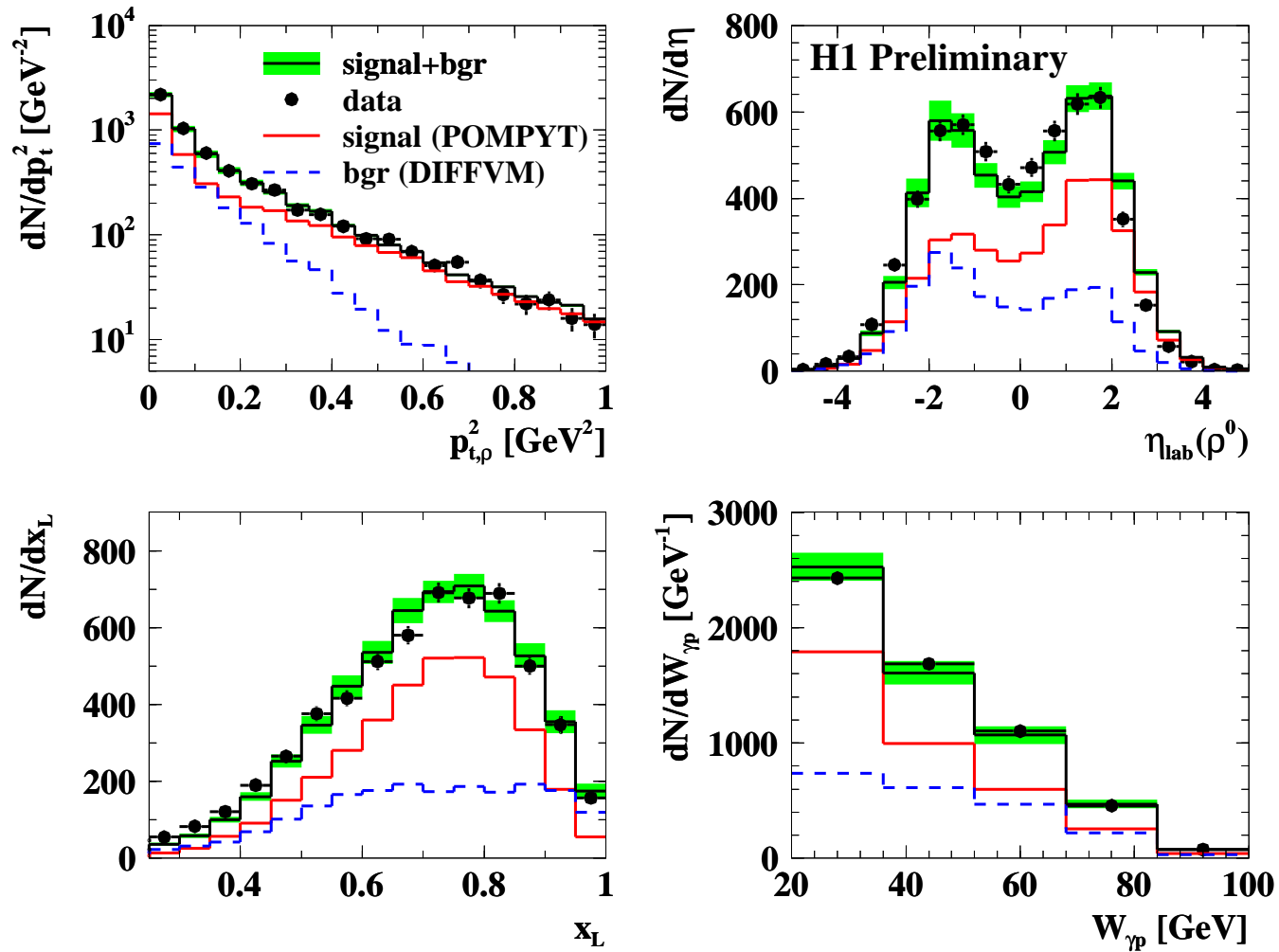
$$n_{RS} = 4.17 \pm 0.27$$



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

Exclusive photoproduction of ρ^0 with Forward Neutrons



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

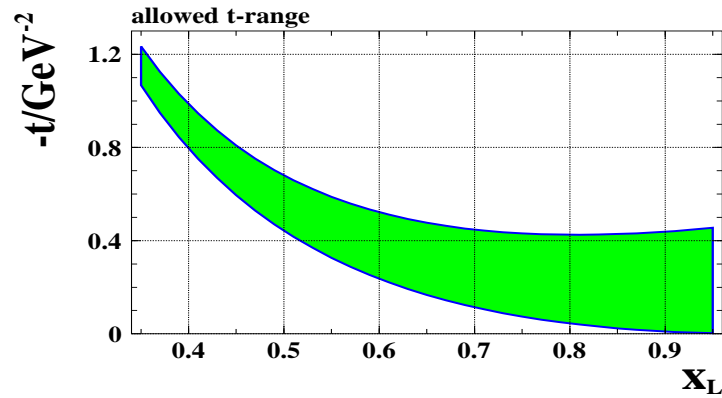
OPE and pion fluxes

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

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

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

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



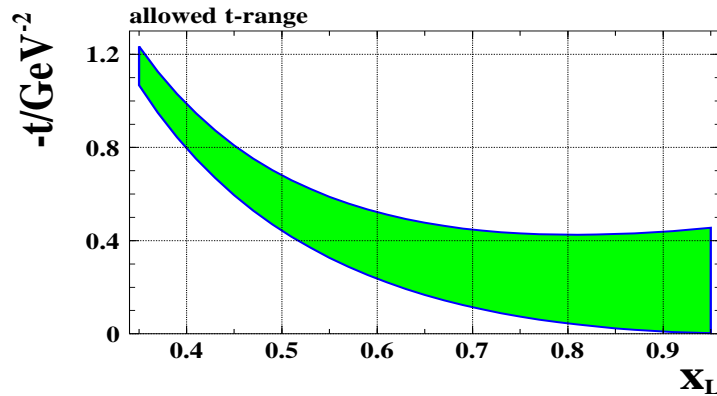
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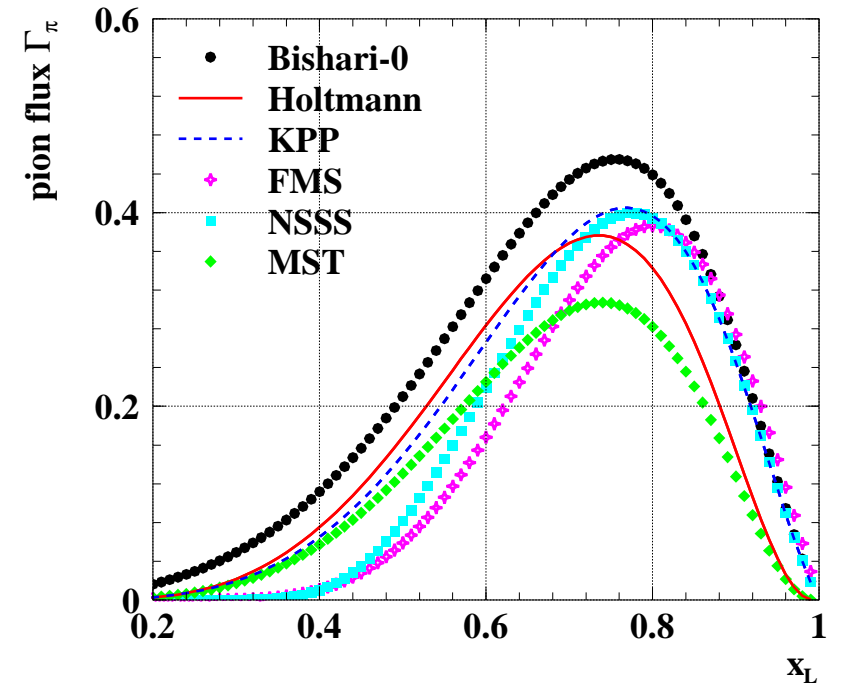
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Problem: too many different fluxes on the market



Typical examples:

$$f_{\pi^+/p}(x_L, t) = \frac{1}{2\pi} \frac{g_{p\pi N}^2}{4\pi} (1-x_L) \frac{-t}{(m_\pi^2 - t)^2} \exp\left[-R_{\pi n}^2 \frac{m_\pi^2 - t}{1-x_L}\right]$$

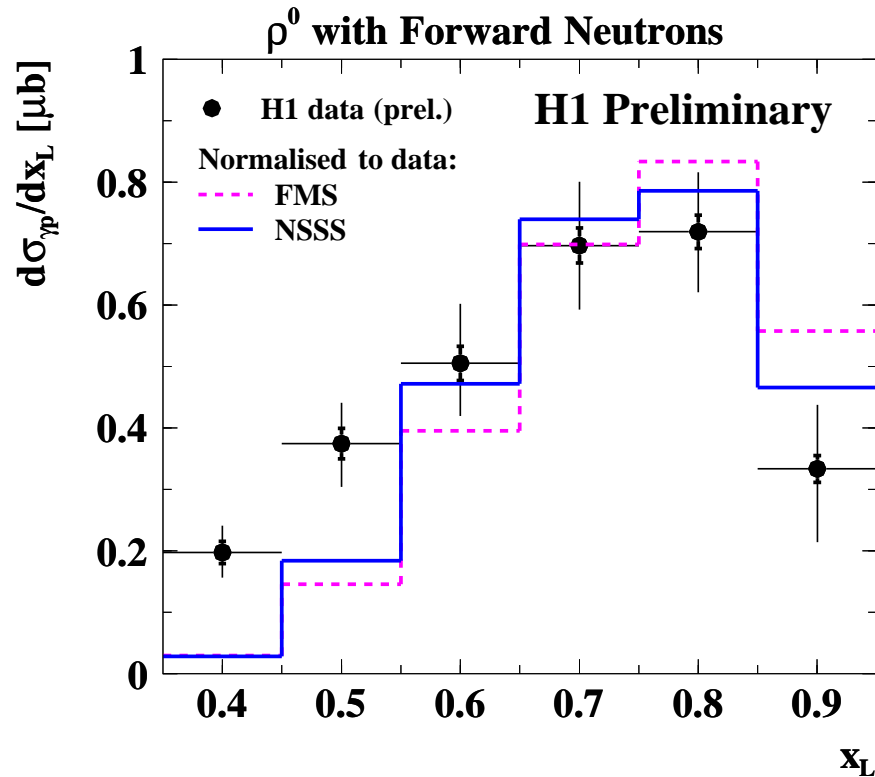
— H. Holtmann et al., *Nucl. Phys.* **A596** (1996) 631.

$$f_{\pi^+/p}(x_L, t) = \frac{1}{2\pi} \frac{g_{p\pi N}^2}{4\pi} (1-x_L)^{1-2\alpha'_\pi t} \frac{-t}{(m_\pi^2 - t)^2} \exp\left[-R_\pi^2 (m_\pi^2 - t)\right]$$

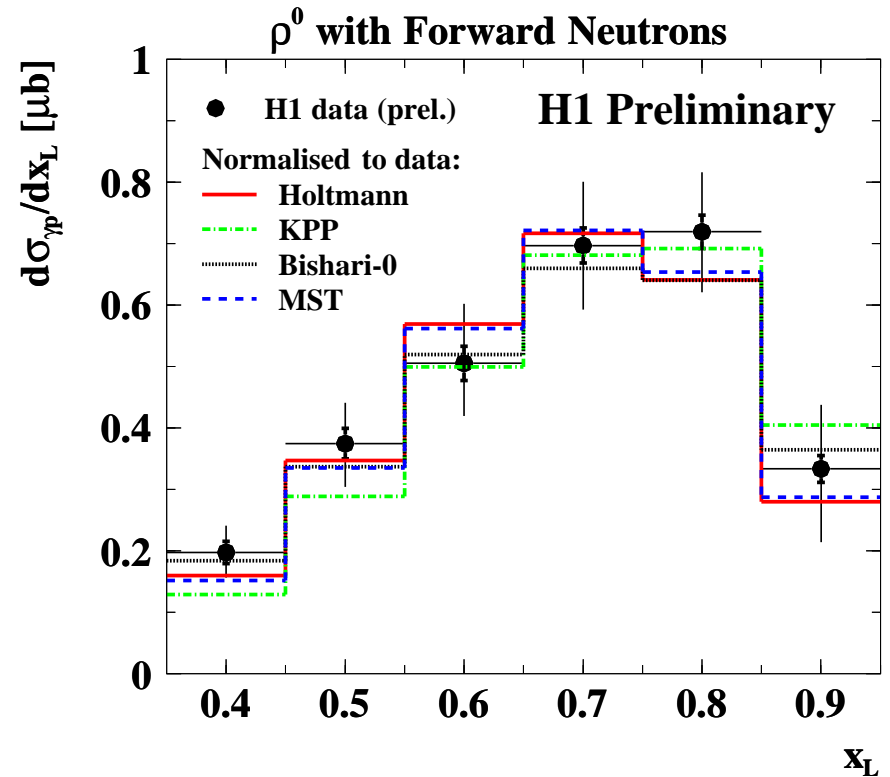
— B. Kopeliovich et al., *Z. Phys.* **C73** (1996) 125.

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



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

Where

N_{bgr} – diffractive dissociation bgr from MC

\mathcal{L} – integrated luminosity

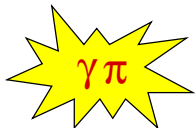
$A \cdot \epsilon$ – correction for detector acceptance and efficiency

\mathcal{F} – photon flux integrated over kinematic domain $20 < W < 100$ GeV, $Q^2 < 2$ GeV²

C_{ρ} – numerical factor accounting for extrapolation to full ρ^0 mass range

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

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



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

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

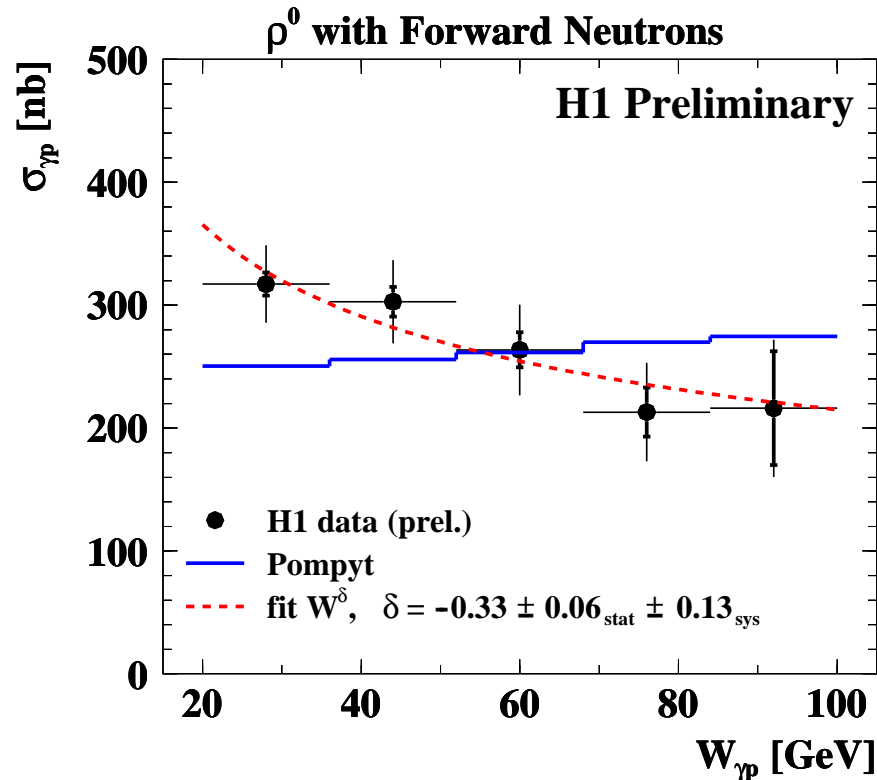
$$\sigma_{\text{el}}(\gamma\pi^+ \rightarrow \rho^0\pi^+) = (2.03 \pm 0.34_{\text{exp}} \pm 0.51_{\text{model}}) \mu\text{b}$$

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

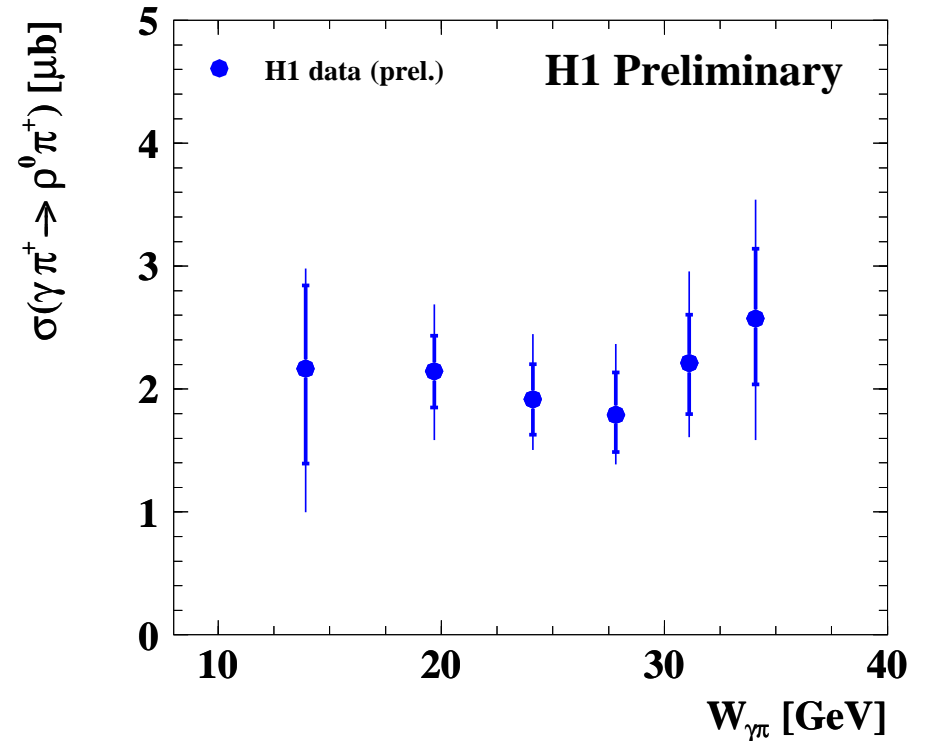
$$r_{\text{el}} = \sigma_{\gamma\pi}^{\text{el}} / \sigma_{\gamma p}^{\text{el}} = 0.21 \pm 0.06 \quad (\text{cf. } r_{\text{tot}} = \sigma_{\gamma\pi}^{\text{tot}} / \sigma_{\gamma p}^{\text{tot}} = 0.32 \pm 0.03 \text{ [ZEUS, 2002]})$$

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 – $\sqrt{\text{exp}^2 + \text{model}^2}$



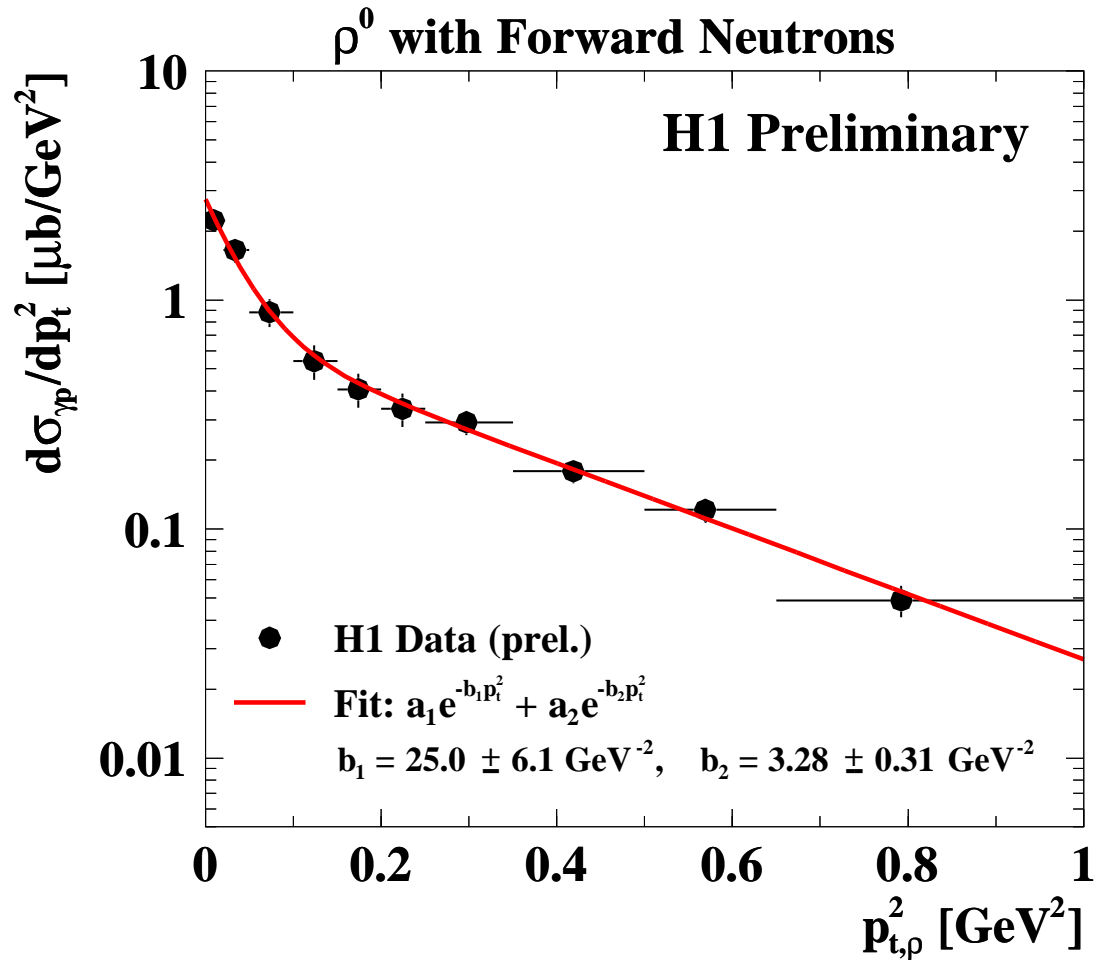
Regge motivated power law fit W^δ yields $\delta < 0$

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

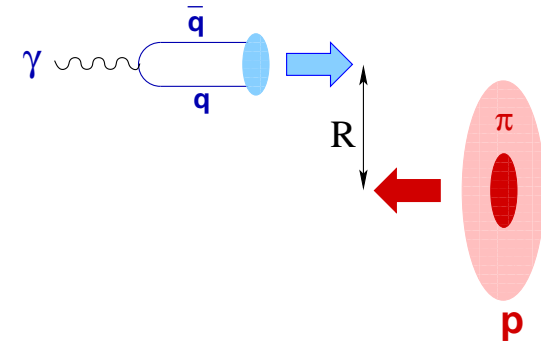
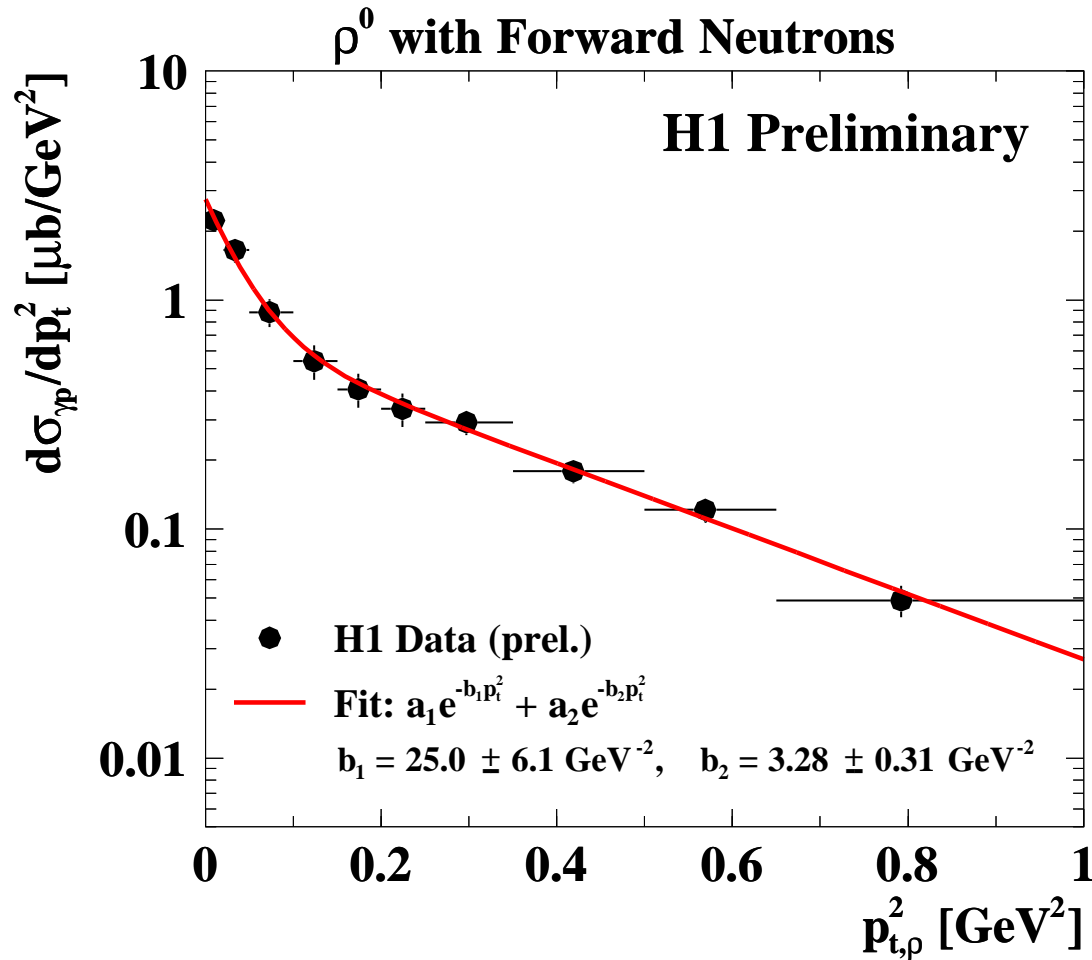
Holtmann flux is used for the central values.

Conservative model uncertainty $\sim 25\%$

Differential cross section in p_t^2

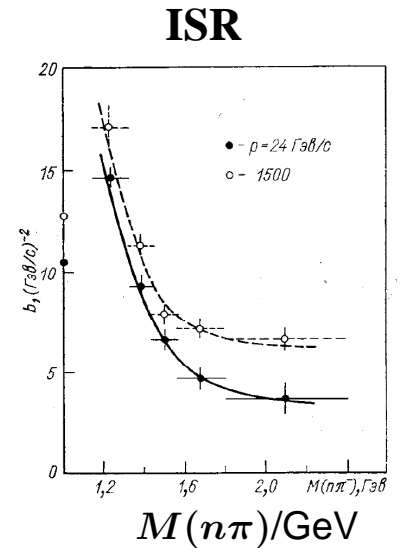
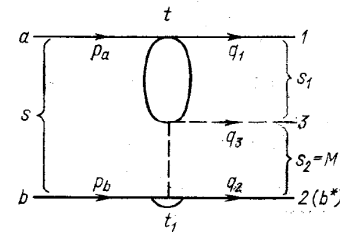
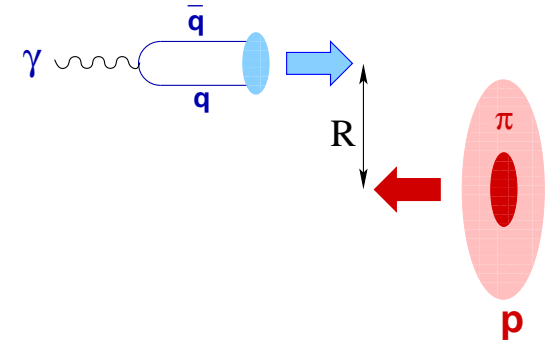
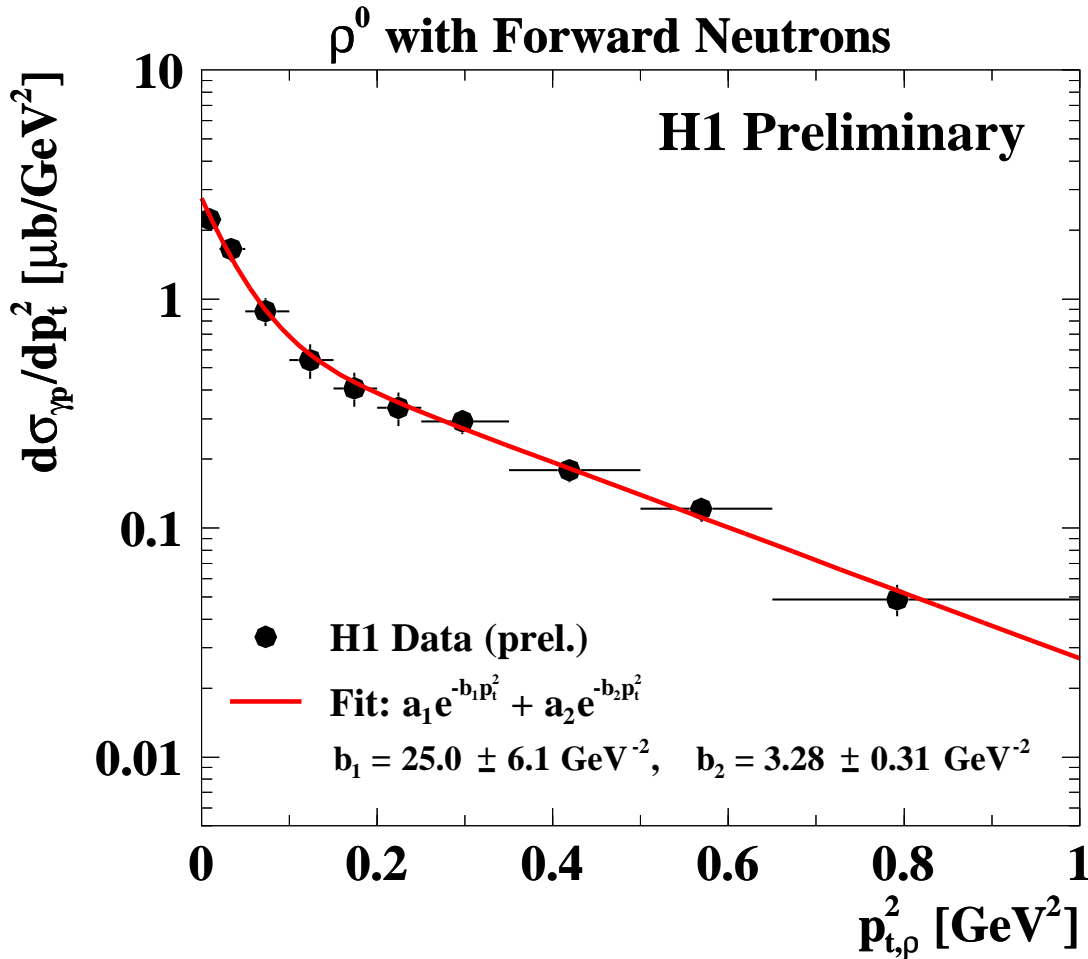


Differential cross section in p_t^2



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

Differential cross section in p_t^2



Geometric interpretation: $\langle r^2 \rangle = 2b_1 \cdot (\hbar c)^2 \simeq 2 \text{ fm}^2 \Rightarrow (1.6 R_p)^2 \Rightarrow$ 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.