

Diffraction - HERA – last

- 1 – diff. DIS – 2 jets - H1
- 2 - diff. DIS + Phot. -roman pot - H1
- 3 - Exclusiv 2-jets – ZEUS
- 4 - Dstar – new – H1
- 5 - Leading neutron + rho – 'elastic' - H1

On behalf of H1 + ZEUS Collaboration
Vazdik I.A.

HERA: The World's Only ep Collider

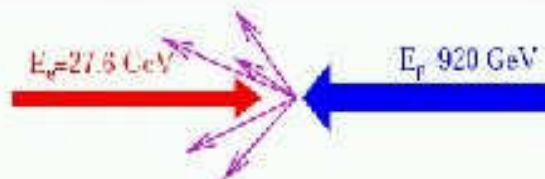


HERA-1 (1993-2000) $\simeq 120 \text{ pb}^{-1}$

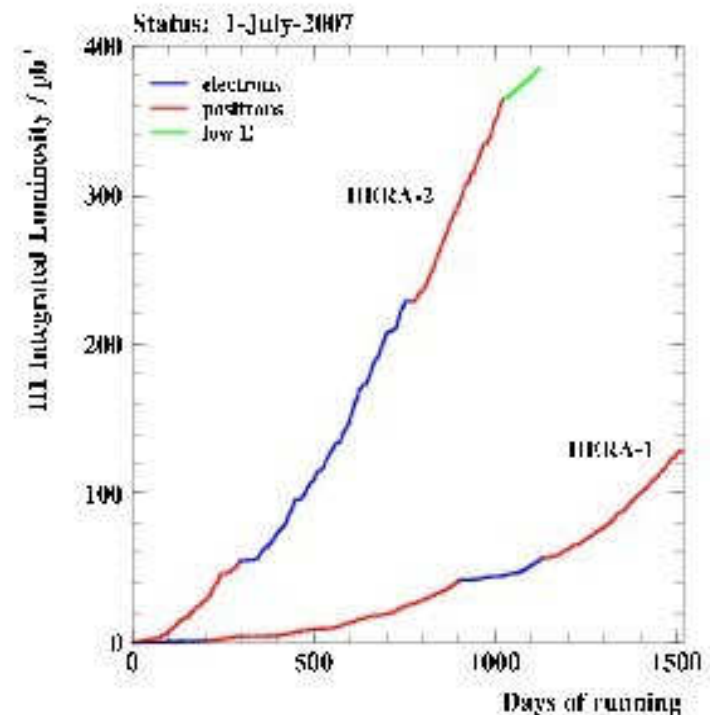
HERA-2 (2003-2007) $\simeq 380 \text{ pb}^{-1}$

Final Data samples

H1+ZEUS: $2 \times 0.5 \text{ fb}^{-1}$

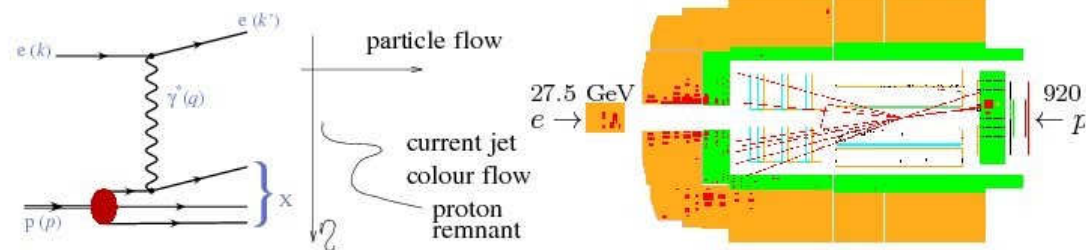


- 1998 E_p upgrade: $820 \Rightarrow 920 \text{ GeV}$
($\sqrt{s}$: $301 \Rightarrow 319 \text{ GeV}$)
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised e^-/e^+
($\langle P \rangle = 40\%$)

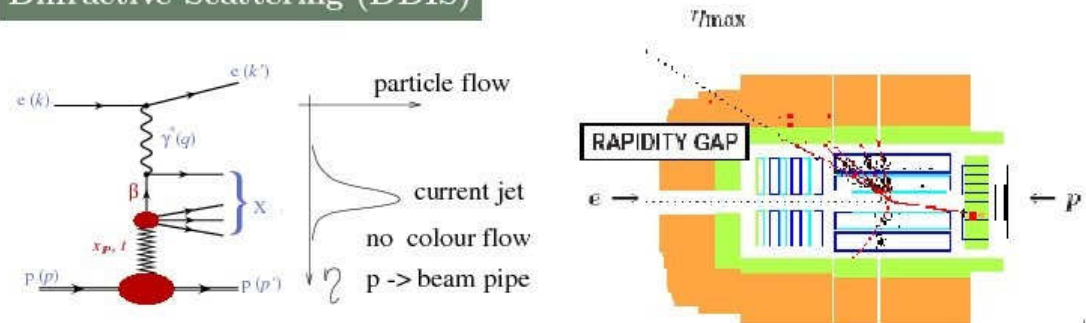


Diffractive Scattering

Deep Inelastic Scattering (DIS)



Diffractive Scattering (DDIS)



Diffractive deep inelastic scattering

- large data samples collected on inclusive diffractive DIS by H1
- diffractive parton distribution functions (DPDF) extracted from inclusive DDIS under assumption of:

collinear factorization

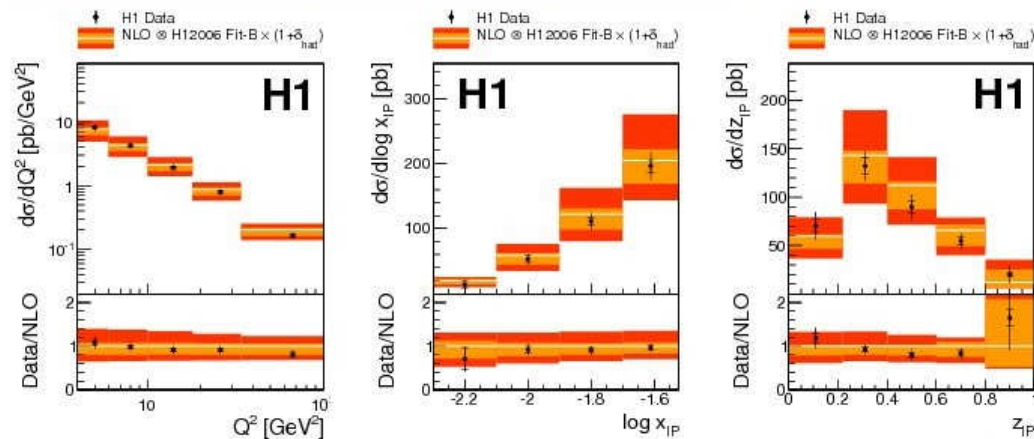
$$d\sigma^{ep \rightarrow eXY} = \sum_i f_i^D(x, Q^2, x_{IP}, t) \otimes d\hat{\sigma}^i(x, Q^2)$$

optionally, also proton vertex factorization

$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_{i/IP}(\beta = x/x_{IP}, Q^2)$$

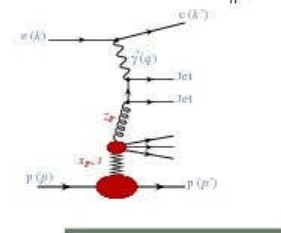
Test of QCD factorisation: H1 Dijet in DIS

LRG: $Q^2 > 4 \text{ GeV}^2$, $P_T^{jet1} > 5.5 \text{ GeV}$, $P_T^{jet2} > 4 \text{ GeV}$



- from F_2^D measurements DPDFs are extracted and used to predict dijet production in DIS regime

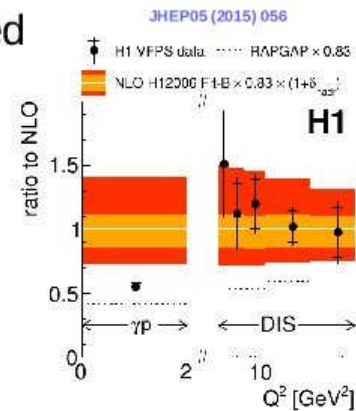
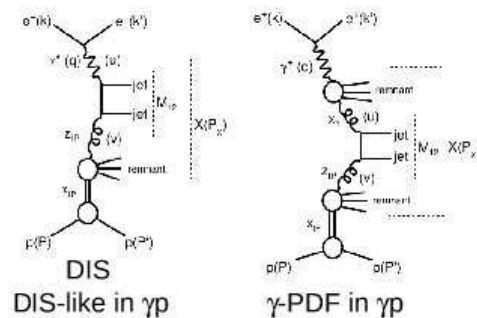
➔ QCD factorisation OK (in DIS)



Tests of collinear factorization in diffraction in H1

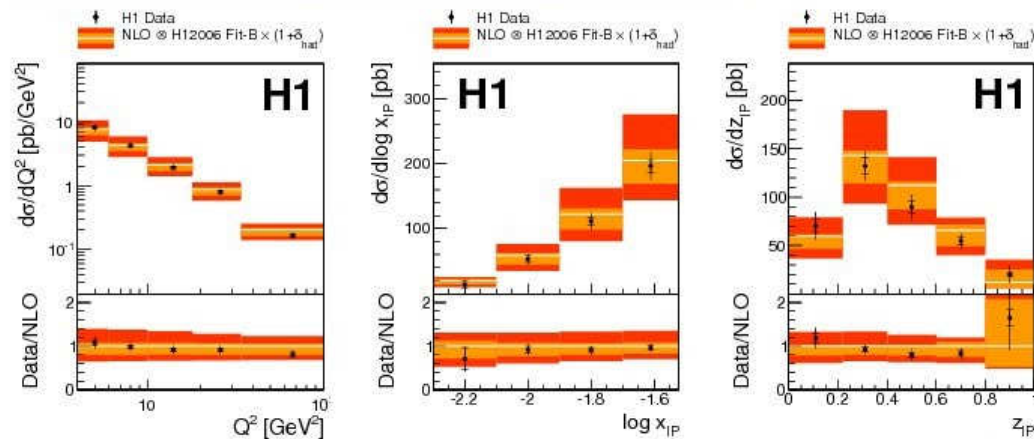
Dijets in diffractive photoproduction

- predictions based on H1 DPDFs overestimate diffractive hadron-hadron data - gap survival ($S^2 < 1$)
- similarly expected in photoproduction regime of ep ($Q^2 \sim 0$)
- mechanism still not fully explained



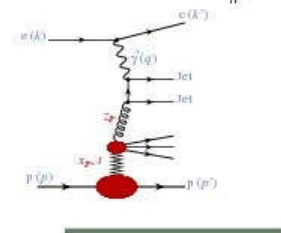
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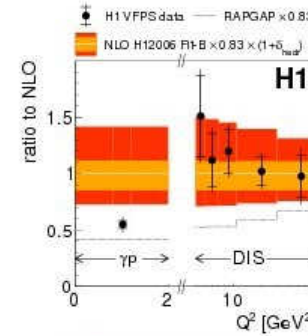
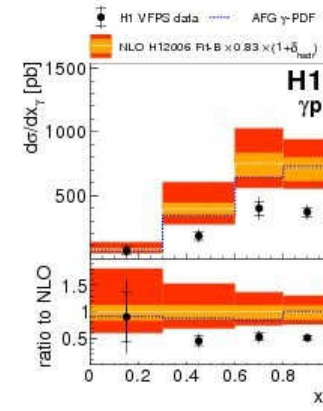
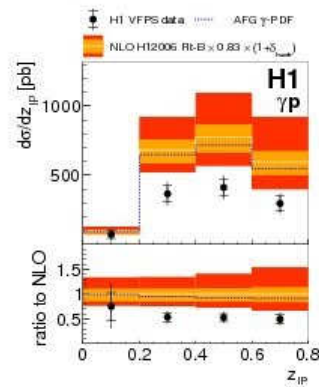
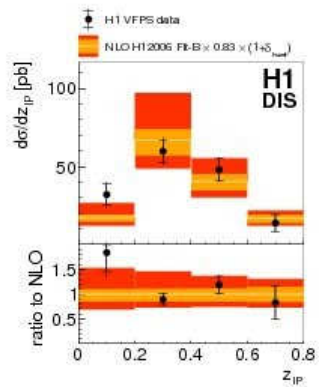
- from F_2^D measurements DPDFs are extracted and used to predict dijet production in DIS regime

➔ QCD factorisation OK (in DIS)



VFPS: Dijet in DIS and in Photoproduction

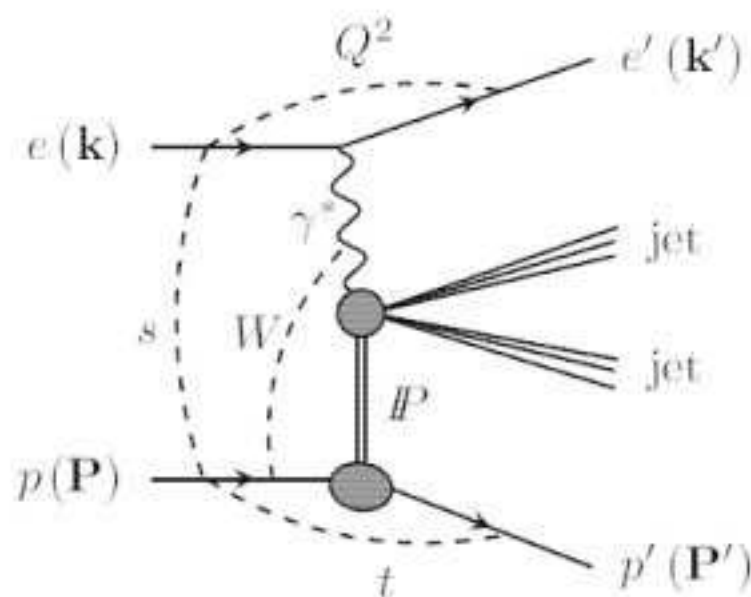
DIS	$\gamma - p$
$4 < Q^2 < 80 \text{ GeV}^2$	$Q^2 < 2 \text{ GeV}^2$
$0.2 < y < 0.8$	
$E_T^{jet1(2)} > 5.5(4) \text{ GeV}$	
$-1 < \eta_{jet1,2} < 2.5$	
$0.010 < x_P < 0.024$	
$ t < 0.6 \text{ GeV}^2$	
$M_Y = M_p$	





Exclusive dijet production in diffractive DIS

$$e + p \rightarrow e + \text{jet1} + \text{jet2} + p$$



Data 2003 – 2007 372 pb⁻¹

- $Q^2 = -q^2 > 25 \text{ GeV}^2$ - virtuality of the photon
- $90 < W < 250 \text{ GeV}$ - photon-proton center-of-energy
- x – Bjorken x – fraction of proton's momentum carried by struck quark
- $x_{\text{IP}} < 0.01$ – fraction of proton's momentum carried by exchanged color singlet
- $t = (p - p')^2$ – four momentum transfer squared at proton vertex
- $0.5 < \beta < 0.7$, $\beta = x / x_{\text{IP}}$ – fraction of Pomeron momentum 'seen' by photon
- only dijet, scattered electron and proton in the final state

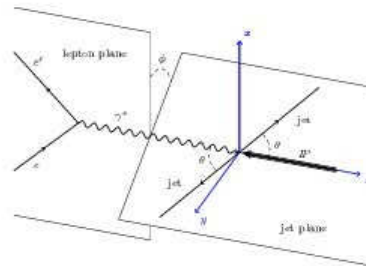
Select two hard jets may to allow comparison pQCD models

Models predict different shape for dijet azimuthal angular distribution

Exclusive Dijets in DIS

LRG: $Q^2 > 25 \text{ GeV}^2$, $x_{\mathbb{P}} < 0.01$, $N_{\text{jet}} = 2$, $P_T^{\text{jets}} > 2 \text{ GeV}$

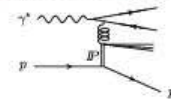
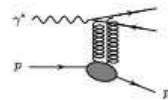
- using Durham jet algorithm in $\gamma^* - \mathbb{P}$ rest frame in exclusive mode (all objects are in jets), $y_{\text{cut}} = 0.15$.
- test the **nature of the exchanged object** in diffractive interactions
- reconstruct **ϕ angle** between lepton and jet planes



→ $d\sigma/d\phi \sim 1 + A(P_T^{\text{jet}}) \cos 2\phi$ [J.Bartels et al., PLB386, (1996)389]

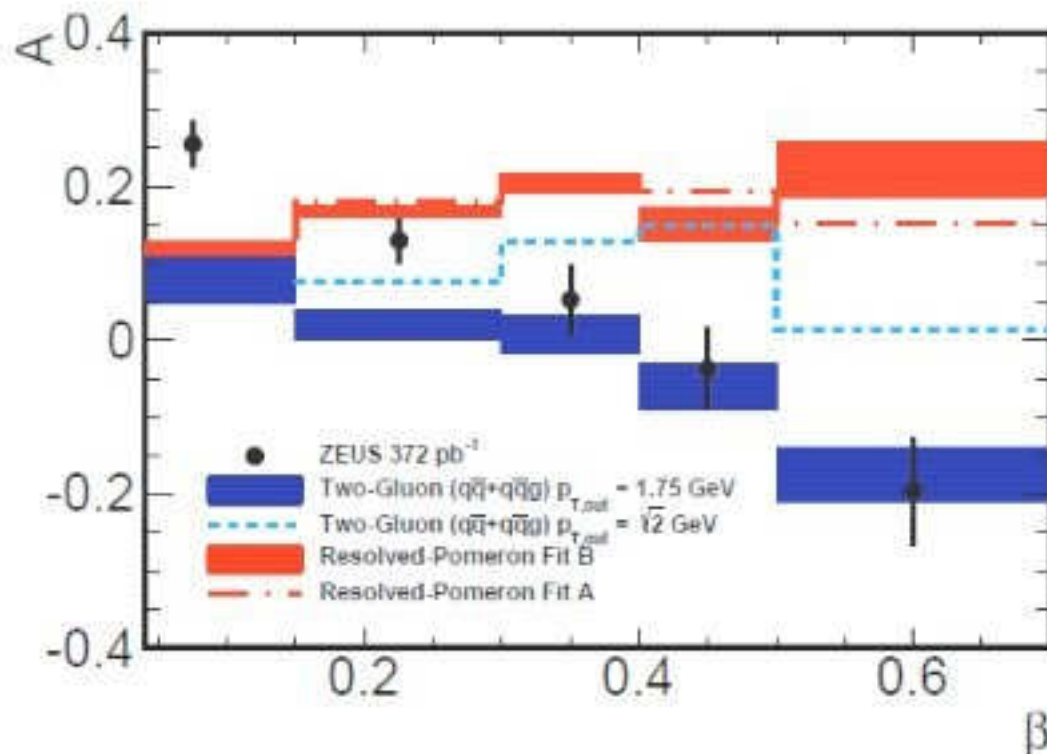
$A > 0$ for $q\bar{q}$ produced from single gluon

$A < 0$ two gluons exchange.



Exclusive dijet production in diffractive DIS

$1 + A \cos(2\Phi)$: comparison with model predictions



Resolved Pomeron model

Almost constant,
Positive value of A in the
whole β range

Two-Gluon-Exchange model

Value of A varies from positive to negative

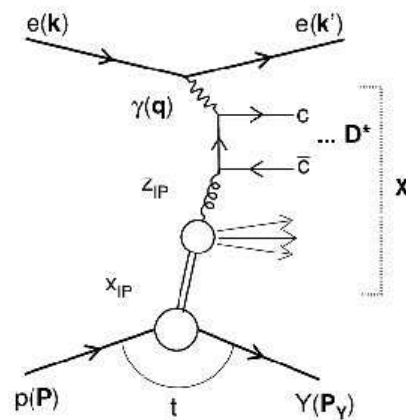
Model agrees quantitatively with the data in the range $0.3 < \beta < 0.7$

Data favour the Two-Gluon-Exchange model prediction

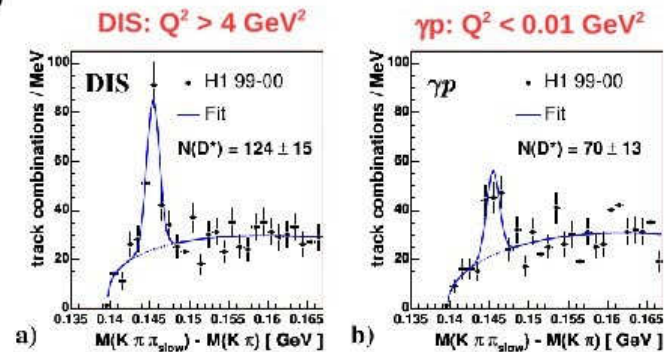
Tests of collinear factorization in diffraction in H1

Open charm in diffraction

- tagged with presence of D^* in the final state
- gluon initiated
- low statistics (w.r.t. dijets)



Eur.Phys.J.C50 (2007) 1



$L \sim 50 \text{ pb}^{-1}$

D* production in diffractive DIS

new H1 measurement - preliminary

$$ep \rightarrow eYX(D^*)$$

- H1-HERA 2 data

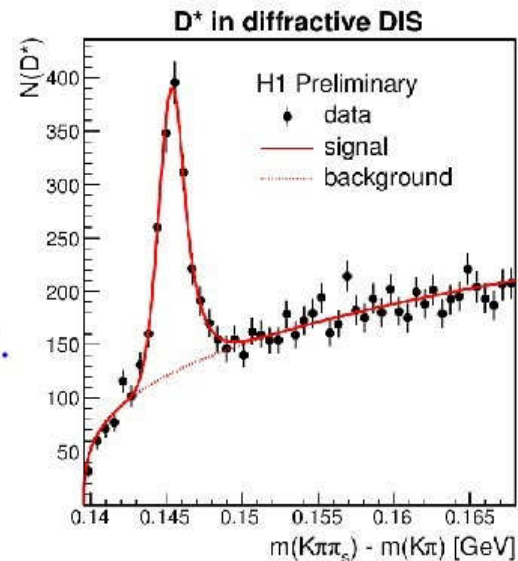
$$L_{\text{int}} \sim 280 \text{ pb}^{-1}$$

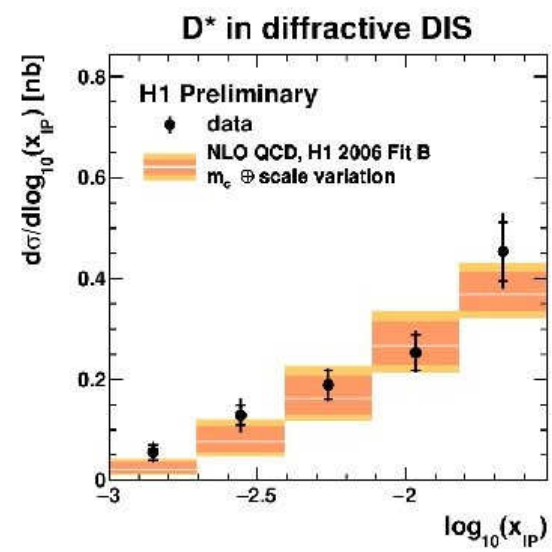
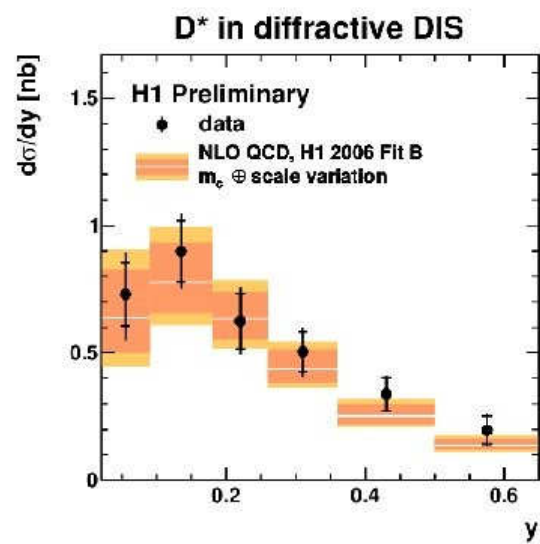
- D* reconstructed fully in:

$$D^{*+} \rightarrow D^0 \pi_{\text{slow}}^+ \rightarrow (K^- \pi^+) \pi_{\text{slow}}^+ + C.C.$$

(BR ~ 2.6 %)

- fits of $\Delta m = m(D_{\text{cand}}^*) - m(D_{\text{cand}}^0)$
- large rapidity gap selection
- $5 < Q^2 < 100 \text{ GeV}^2$ $0.02 < y < 0.65$
 $p_{T,D^*} > 1.5 \text{ GeV}$ $|\eta_{D^*}| < 1.5$... both in laboratory frame
 $x_{\text{IP}} < 0.03$





History -

G.F. Chew and F.E.Low Phys.Rev. 113,1640, 1959

C.Goebel Phys.Rev.Lett vol 1 p337 1958

Mainly reaction – $\pi + N \rightarrow \pi + \pi + N$

Example - JETF v45, p913, 1963

Cross-section $\pi^+ \pi^- \rightarrow \pi^+ \pi^- = 34 \pm 9 \text{ mb}$
(energy in cms = 4-7 Mpi)

FIAN – 1988, v 186 p 106

$\gamma + p \rightarrow \gamma' + \pi^+ \text{ neutron}$

Cross-section $\gamma\text{-}\pi^+ = (5.4 \pm 1.) 10^{(-32)} \text{ cm}^{**2}/\text{st}$

$E_{\gamma} = 650 \text{ mev}$, $s_1 = 6.5 \text{ mpi}$

$\alpha(\pi^+) = -\beta(\pi^+) = (20 \pm 12) 10^{(-43)} \text{ cm}^{**3}$

UNSTABLE PARTICLES AS TARGETS IN SCATTERING EXPERIMENTS

G. F. Chew

Radiation Laboratory
University of California
Berkeley, California

and

F. E. Low

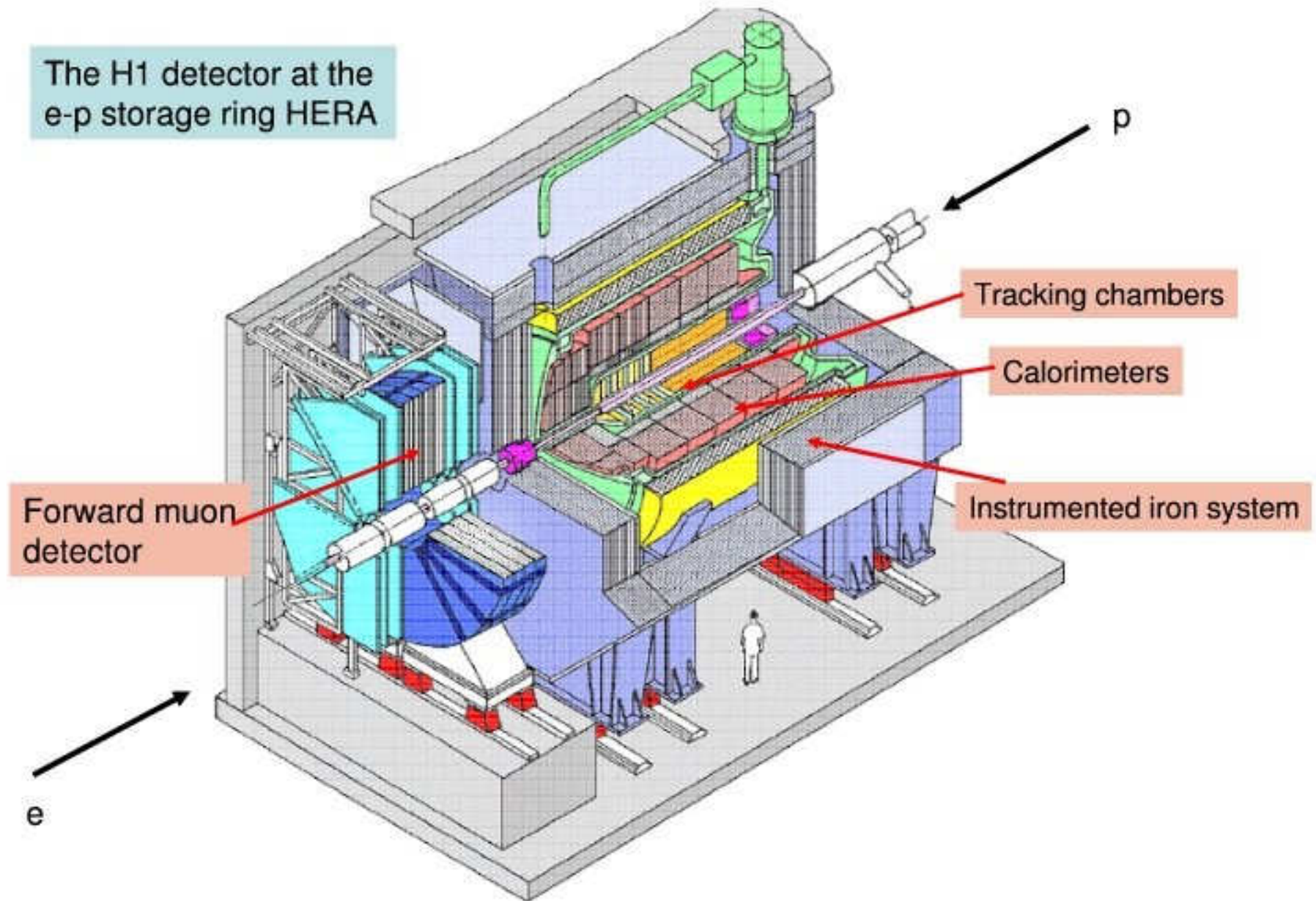
Radiation Laboratory, University of California
Berkeley, California
and

Department of Physics and Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, Massachusetts

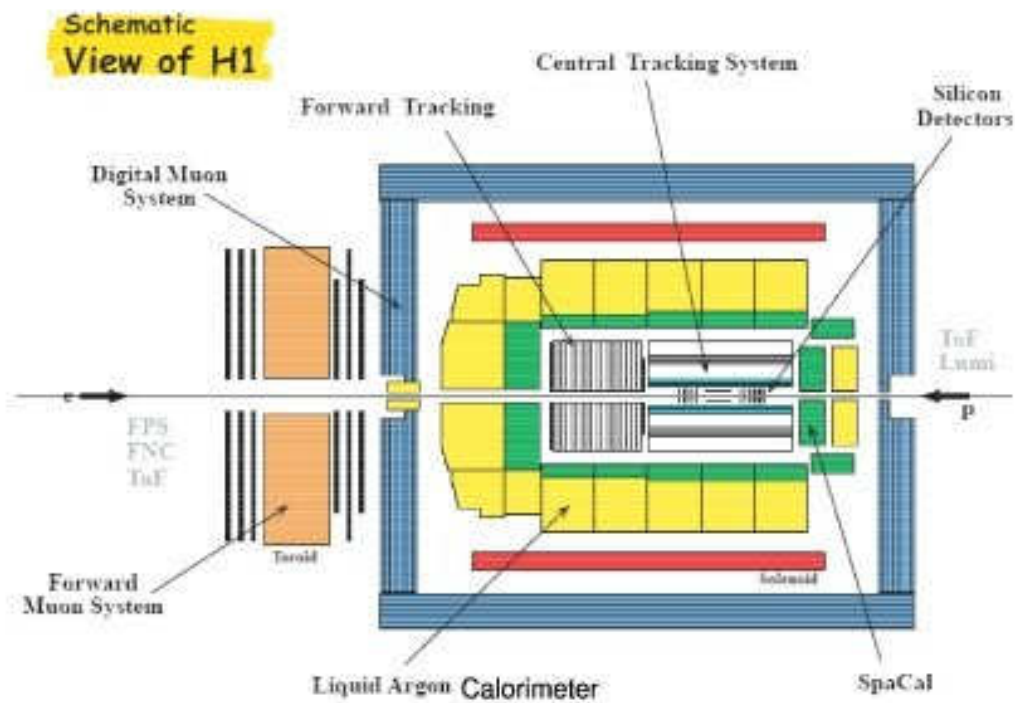
August 21, 1958

ABSTRACT

A general method is suggested for analyzing the scattering of particle A by particle B, leading to three or more final particles, in order to obtain the cross section for the interaction of A with a particle which is virtually contained in B. Binding complications are absent if a plausible assumption about the location and residues of poles in the S-matrix is accepted. The method is useful for unstable particles from which free targets cannot be made; the special examples of pion and neutron targets are discussed in detail.



Side view



Reaction of interest and the analysis phase space

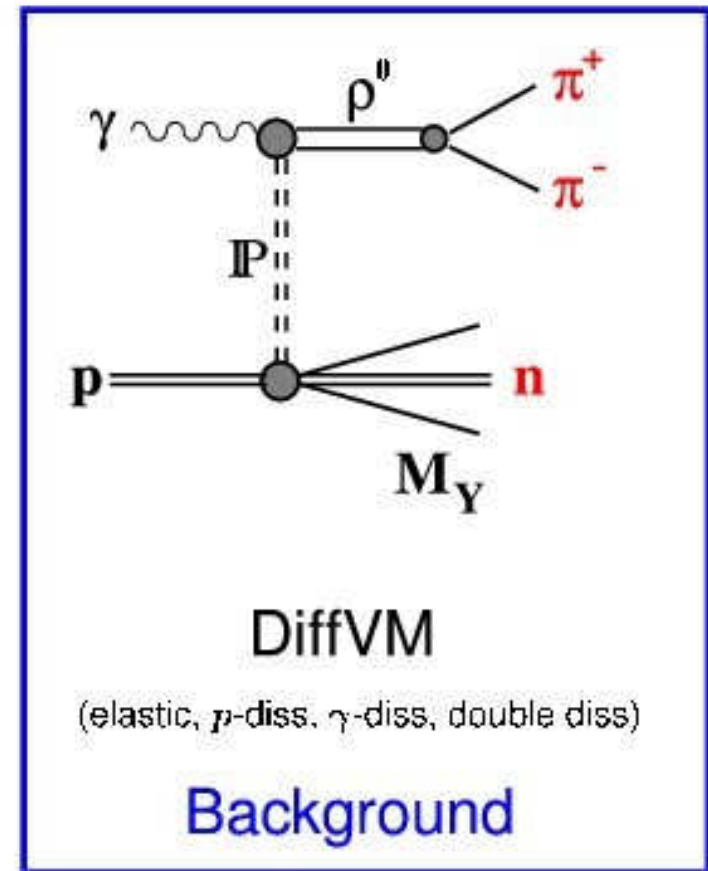
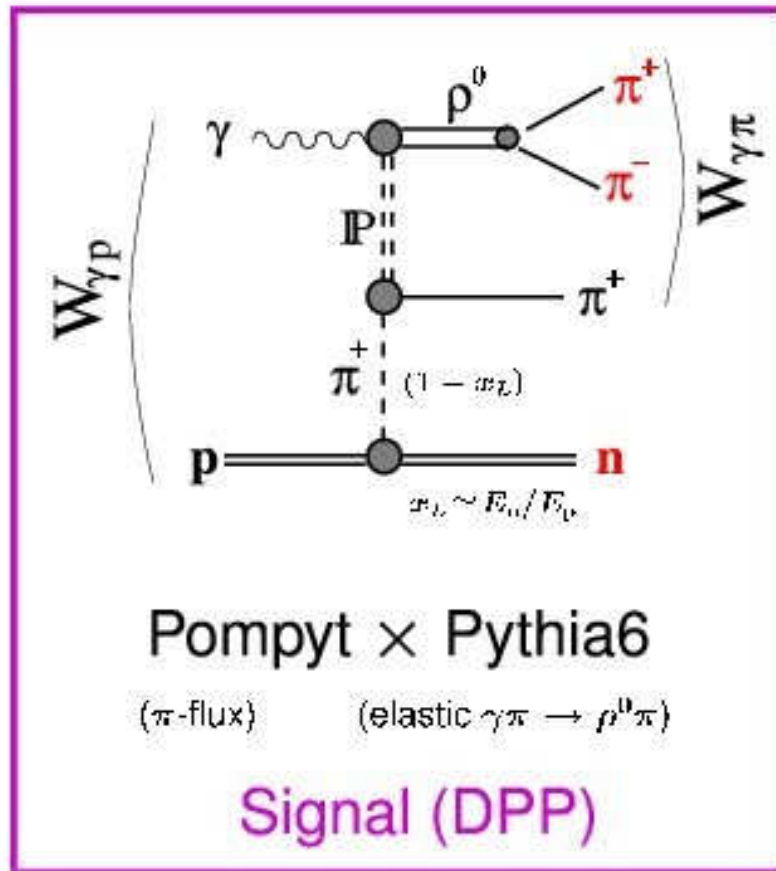


Photoproduction:	$Q^2 < 2 \text{ GeV}^2$	$(\langle Q^2 \rangle = 0.05 \text{ GeV}^2)$
Low p_t :	$ t < 1 \text{ GeV}^2$	$(\langle t \rangle = 0.20 \text{ GeV}^2)$
Small mass:	$0.3 < m_{\pi\pi} < 1.5 \text{ GeV}$	(m_{ρ^0})
π^+, π^- in CT:	$20 < W_{\gamma p} < 100 \text{ GeV}$	$(\langle W_{\gamma p} \rangle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



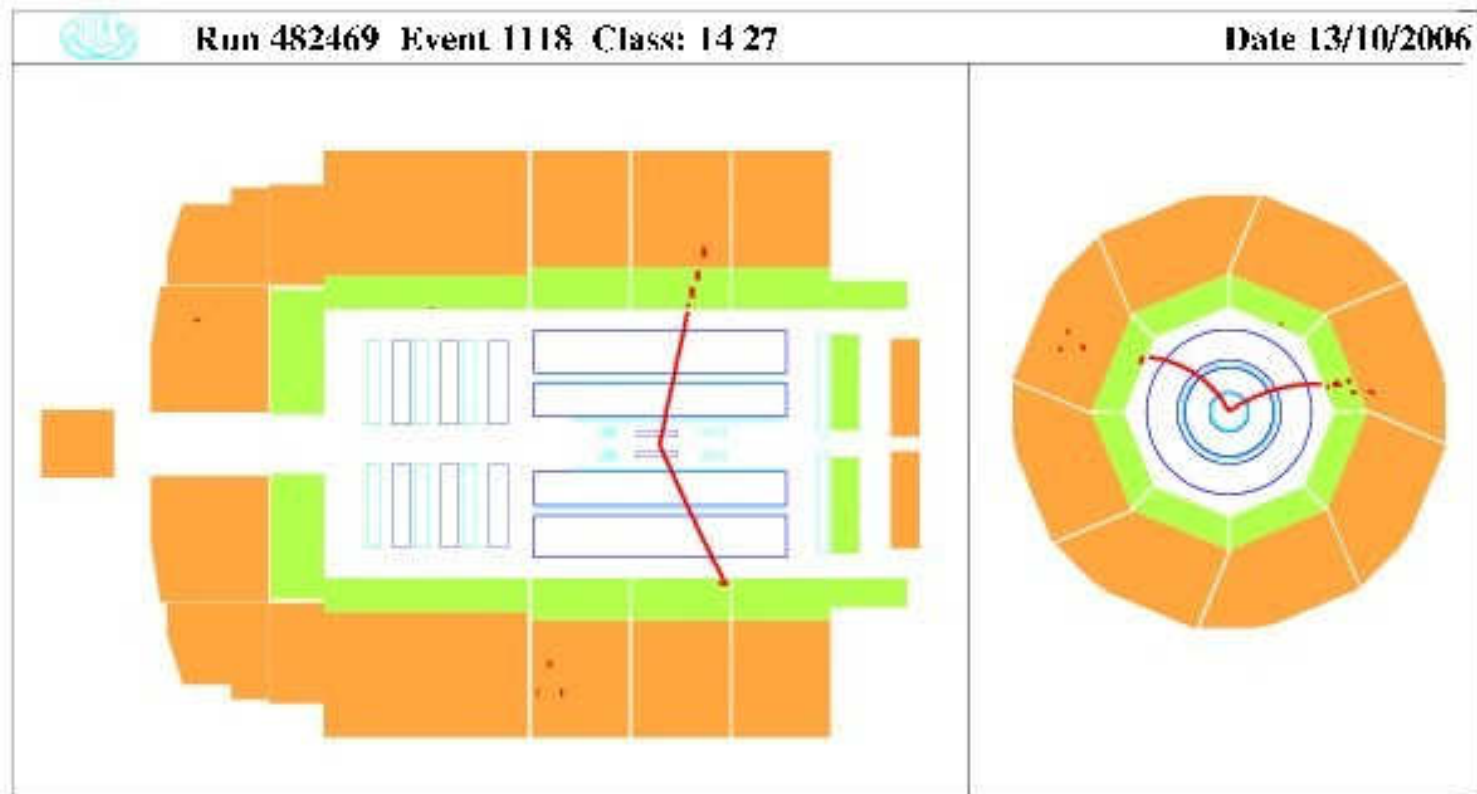
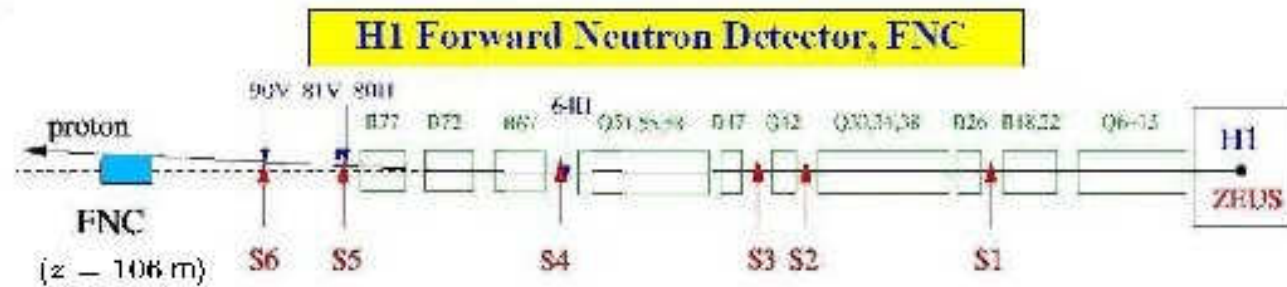
$$W_{\gamma p} \simeq \sqrt{2(E - p_z)_p E_p}$$

• DPP expectations: $f_{\pi/\rho}(x_L, t) \rightarrow x_L$ shape, $p_{t,\rho}^2$ slope, $b - b_{diff}(M_{\pi N})$

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

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

Typical Event



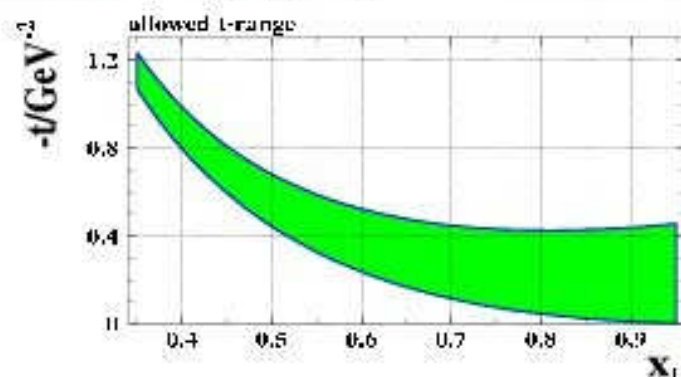
OPE and pion fluxes

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

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

$$\text{where } t = -\frac{p_{\pi, \perp}^2}{x_L} = \frac{(1-x_L)(m_\pi^2 - m_p^2 x_L)}{x_L}$$

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



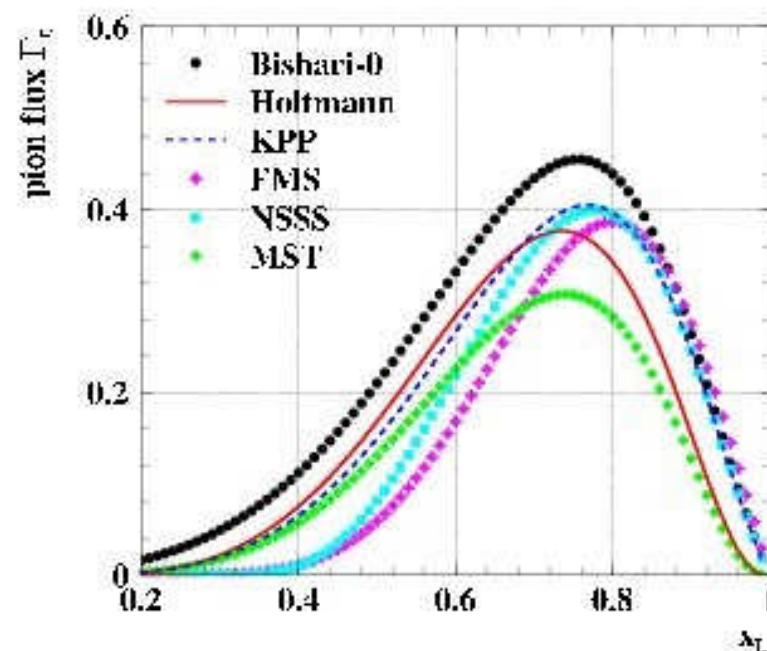
Typical examples:

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

— H. Holtmann et al., *Nucl. Phys. A* 596 (1996) 631.

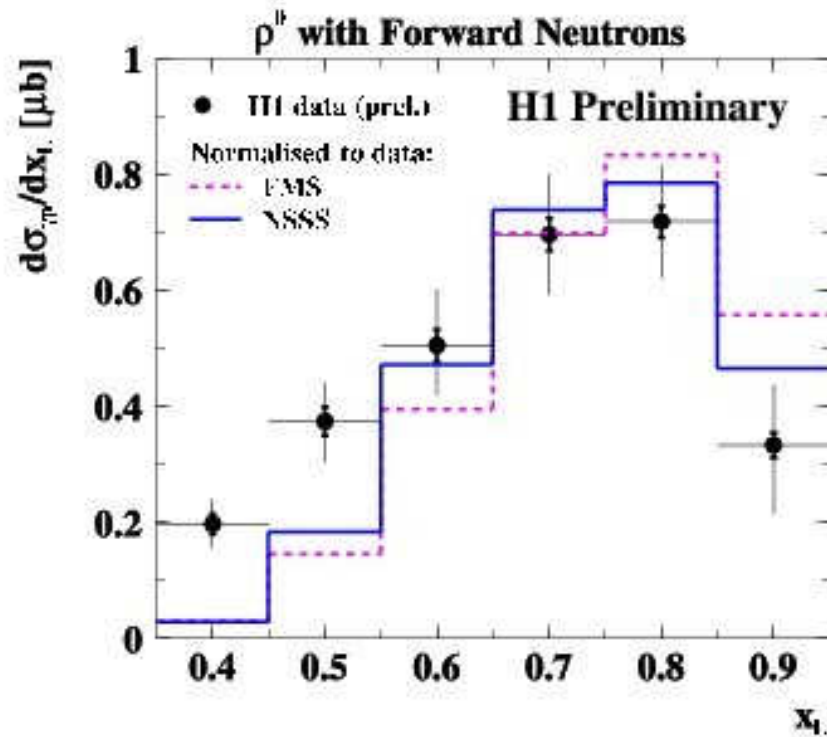
$$f_{\pi^+/p}(x_L, t) = \frac{1}{2\pi} \frac{g_{\pi^+ p}^2}{4\pi} (1-x_L)^{1-2\alpha'_\pi t} \frac{-t}{(m_\pi^2 - t)^2} \exp\left[-R_\pi^2 (m_\pi^2 - t)\right] \quad \text{— B. Kopeliovich et al., } Z. Phys. C73 (1996) 125.$$

Problem: too many different fluxes on the market

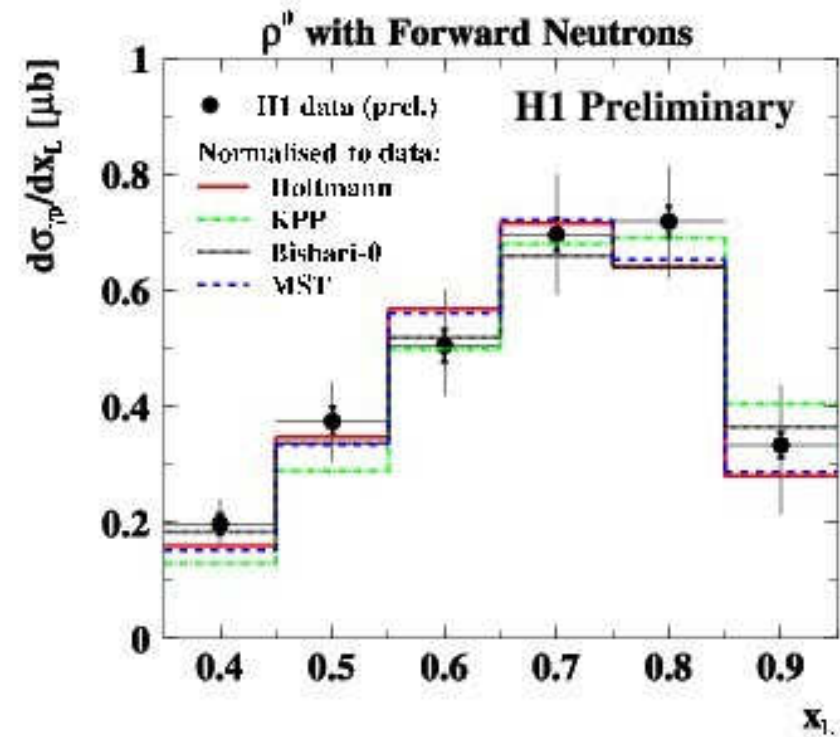


Pion fluxes confronted with H1 data

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**

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 $20 < W < 100 \text{ GeV}$, $Q^2 < 2 \text{ GeV}^2$
- C_ρ – numerical factor accounting for extrapolation to full ρ^0 mass range

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

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



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

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

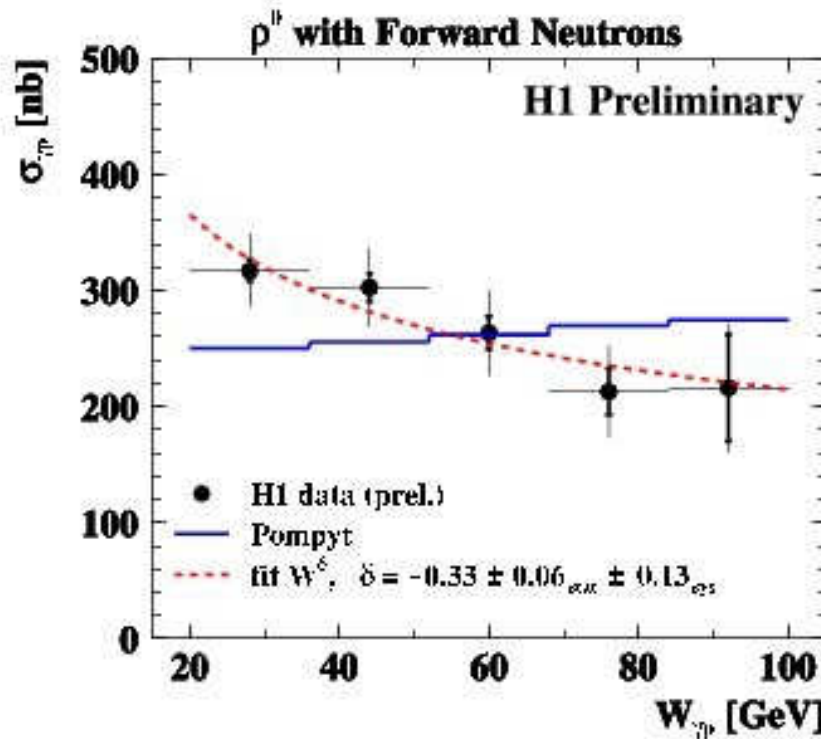
$$\sigma_{\text{el}}(\gamma\pi^+ \rightarrow \rho^0\pi^+) = (2.03 \pm 0.34_{\text{exp}} \pm 0.51_{\text{model}}) \mu\text{b}$$

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

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

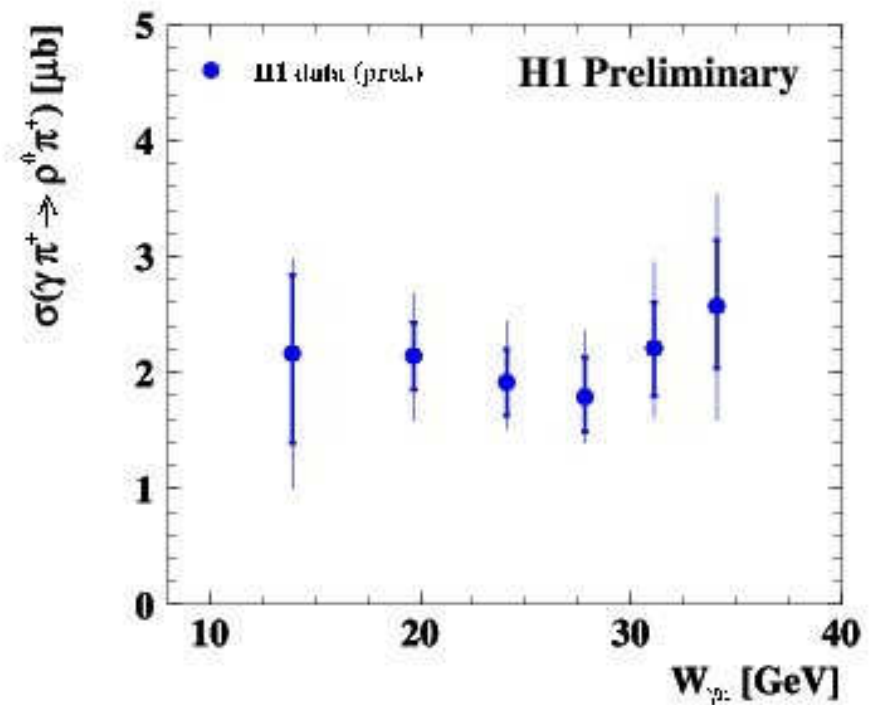
Total γp and $\gamma\pi$ cross sections

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



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

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

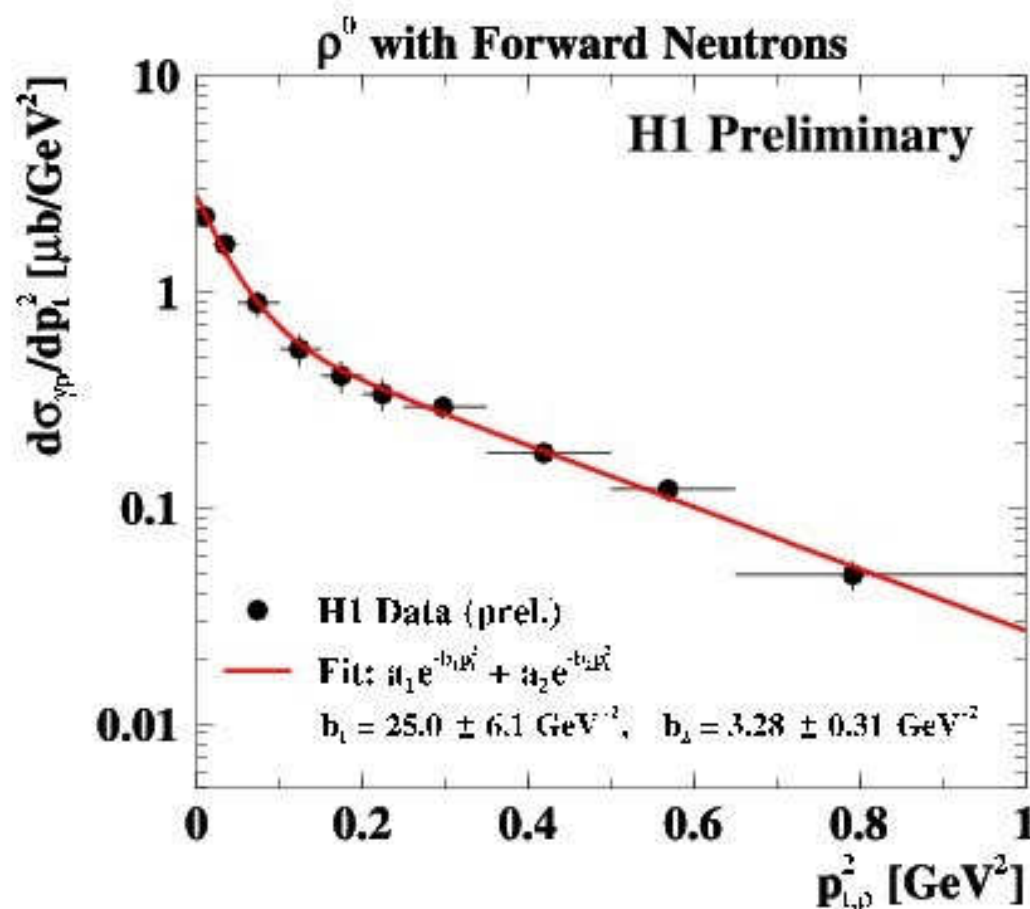


Holtmann flux is used for the central values.

Model uncertainty $\sim 25\%$

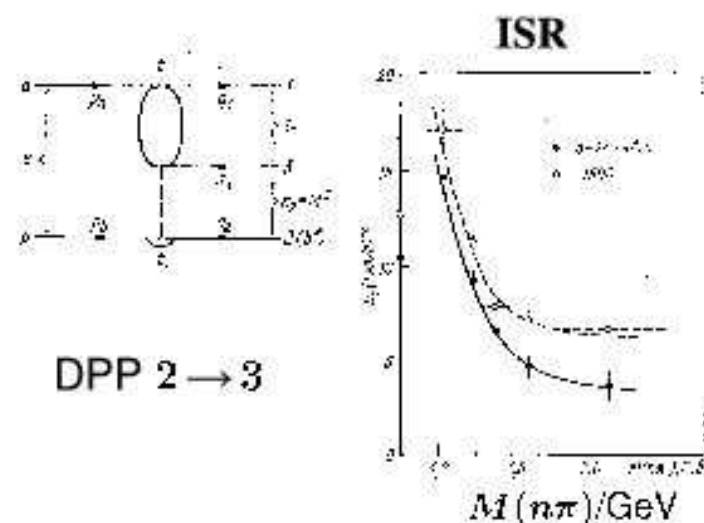
Differential cross section in p_t^2

16



N.P.Zotov, V.A.Tsarev - 1978

Soviet Journal of Particles and Nuclei 9(3)266-290



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

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

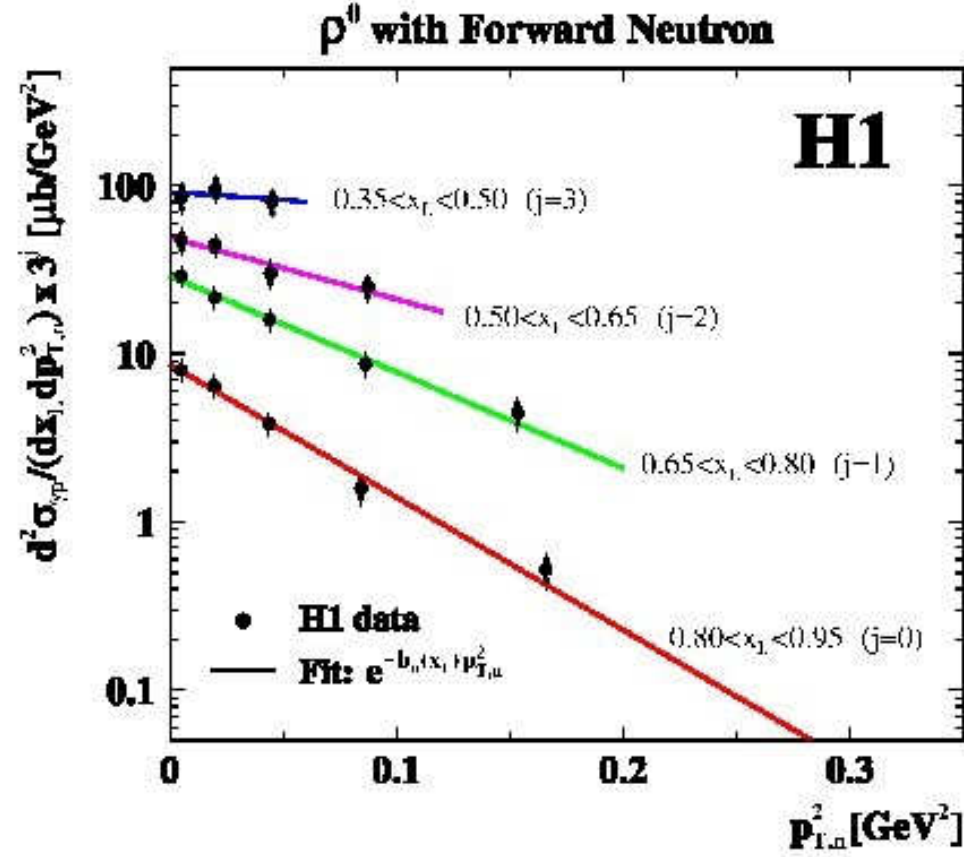


Figure 7: Double differential cross section $d^2\sigma_{\rho^0}/(dx_j dp_{T,j}^2)$ of neutrinos in the range $20 < W_{\rho^0} < 100$ GeV fitted with single exponential functions. The cross sections in different x_1 bins j are scaled by the factor 3 for better visibility. The binning scheme is shown in figure 2c. The data points are shown with statistical (inner error bars) and total (outer error bars) uncertainties excluding an overall normalisation error of 4.4%.

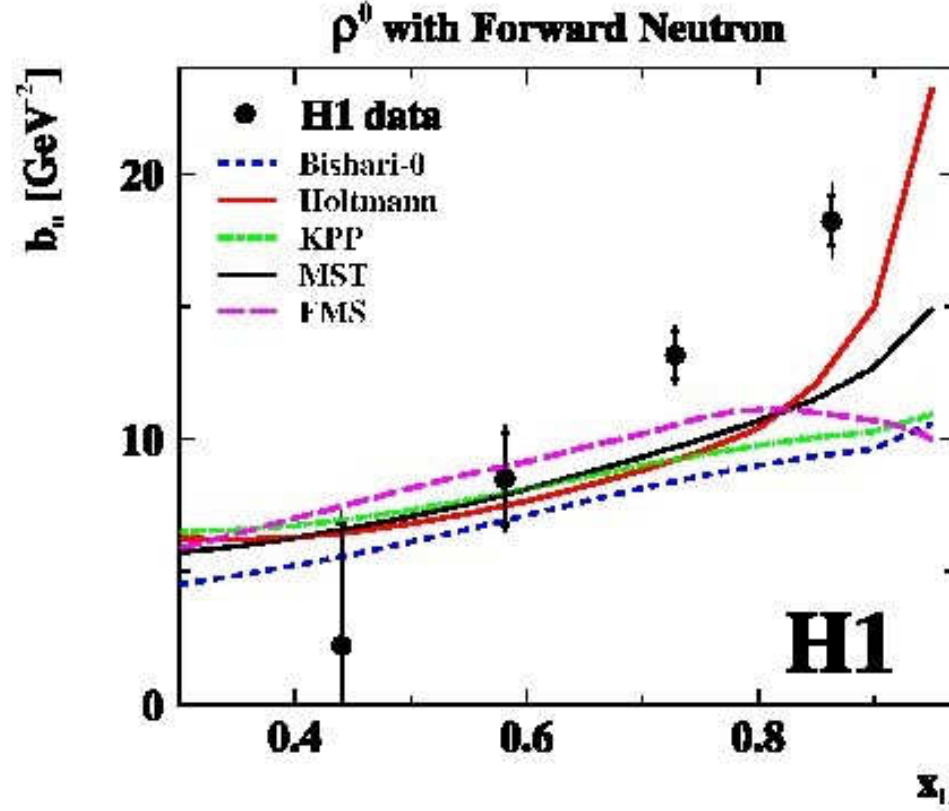


Figure 8: The exponential slopes fitted through the x_L^2 dependence of the leading neutrons as a function of x_L . The inner error bars represent statistical errors and the outer error bars are statistical and systematic errors added in quadrature. The data points are compared to the expectations of several parametrisations of the pion flux within the OPT model.

Exclusive processes with a leading neutron in ep collisionsV.P. Gonçalves^{1,2}, F.S. Navarra³ and D. Spigolon⁴

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In this paper we extend the color dipole formalism to the study of exclusive processes associated with a leading neutron in ep collisions at high energies. The exclusive $\gamma_e p \rightarrow \gamma_e p$ and J/ψ production as well as the Deeply Virtual Compton Scattering, are analyzed assuming a diffraction interaction between the color dipole and the p (or) controlled by two hard protons. We compare our predictions with the HERA data on p production and estimate the magnitude of the non-perturbative effects. We show that the color dipole formalism is able to describe the current data. Finally, we present our estimate for the exclusive cross section, which can be studied at HERA and in future electron-proton colliders.

PACS numbers: 13.85.Bz, 24.85.+g, 23.60.+e

Keywords: QCD, Diffraction, Leading Proton, Dipole, Soft and Hard Effects

1. INTRODUCTION

The study of electron-proton (ep) collisions at HERA has improved our understanding of the structure of the proton as well as about the dynamics of the strong interaction at high energies (For a review, see Ref. [1]). In particular, the study of diffractive processes has been one of the most successful areas at HERA, with vector meson production and Deeply Virtual Compton Scattering (DVCS) as exclusive processes ($ep \rightarrow E_p$ with $E_p = p, \gamma, J/\psi, \dots$) being important probes of the transition between the soft and hard regimes of QCD. These processes have been the subject of intense theoretical and experimental investigations, with one of the main motivations for their studies being the possibility to probe the QCD dynamics at high energies, driven by the gluon content of the proton which is strongly subject to non-linear effects (proton saturation) [2]. An important lesson from the analysis of the HERA data at small values of the Bjorken- x variable is that the inclusive and diffractive processes can be satisfactorily described using a unified framework – the color dipole formalism. This approach was proposed many years ago in Ref. [3] and considers that the high-energy photon can be described by a color anti-triplet and a triplet dipole and that the interaction of the dipole with the target can be described by the color dipole cross section $\sigma_{\text{CD}}(r, x)$, with the transverse size of the dipole r being the transverse separation between the quark and antiquark. In this approach, the interaction of the target and the scattering physics is encoded in $\sigma_{\text{CD}}(r, x)$, which is determined by the imaginary part of the forward amplitude of the scattering between a small dipole (colorless quark-antiquark pair) and a dense hadron target, denoted by $N(x, r, b)$, where the dipole has transverse size given by the vector $r = x - y$, with x and y being the transverse vectors of the quark and antiquark, respectively, and $b = (x+y)/2$ is the impact parameter. In the Color-Glass Condensate (CGC) formalism [4, 5], N contains all the information about non-linear and quantum effects in the hadron wave function. It can be obtained by solving an appropriate evolution equation in the rapidity $Y \equiv \ln(1/x)$, which in its simplest form is the Balitsky-Kovchegov (BK) equation [6, 7]. Alternatively, the scattering amplitude can be obtained using phenomenological models based on saturation physics constructed taking into account the analytical solutions of the BK equation, which are more reliable in the low and high energy regimes. As demonstrated in [7], the combination between the color dipole formalism and saturation physics are quite successful to describe the recent and very precise HERA data on the reduced inclusive cross section as well as the data on the exclusive processes in a large range of photon-proton center-of-mass energies $\sqrt{s}$, photon virtualities Q^2 and x values.

HERA has also provided high precision experimental data on semi-inclusive $ep \rightarrow e p \gamma$ processes, where the hadronic proton is converted into a neutron via a charge exchange $\gamma^* p \rightarrow n$. Very recently the first measurements of

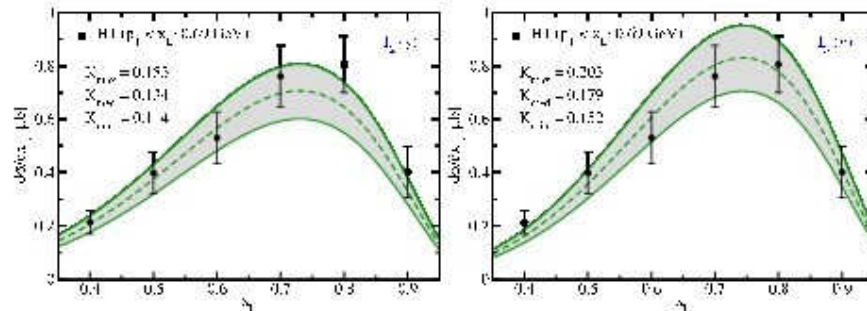


FIG. 6: (Color online) Leading neutron spectra for data and p - p photoproduction obtained using the possible range of values of the K factor fixed using the other set of experimental data and ray models for the other fixed $\Gamma_{\gamma^*}^{\text{tot}}/\sigma_{\text{tot}}$ obtained assuming that $p_{\perp} < 0.05$ GeV.

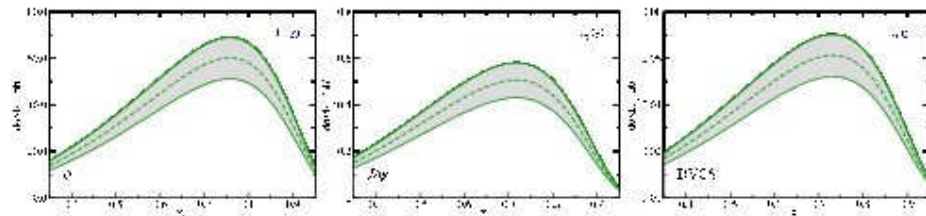


FIG. 7: (Color online) Predictions for the leading neutron spectra in exclusive, d , t/p and DVCS production in the HERA kinematic range ($\sqrt{s} = 27$ GeV and $p_{\perp} < 0.2$ GeV).

set, thus, the experimental analysis of the rare using processes associated with a leading neutron is feasible in future ep colliders. In particular, as the cross sections strongly increase when $Q^2 \rightarrow 0$, the analysis of the vector meson photoproduction in ep collisions can be made to understand leading neutron spectra, which are of great importance in particle production in cosmic ray physics. Another possibility is the study of this process in ultraperipheral hadronic collisions, with the leading neutron being a tag for exclusive production. In principle, these processes can be studied in the frame of the LHC. Such proposition will be discussed in detail in a forthcoming publication.

IV. SUMMARY

One of the important goals in particle physics is to understand the production of leading particles, i.e., the production of baryons which have large fractional longitudinal momenta ($x_1 > 0.5$) and the same valence quarks (or at least one of them) as the incoming particles. Recent measurements of the leading neutron spectra in ep collisions at HERA have shed a new light on this subject. However, the description of the semi-inclusive and exclusive leading neutron processes remains without a satisfactory theoretical description. In a previous work [23], we proposed a description of the semi-inclusive leading neutron process using the two-couple formalism, which successfully describes the inclusive and diffractive HERA data taking into account the QCD dynamics and the non-linear effects which are expected to be present at large energies. Making use of very simple assumptions about the relation between the dipole-pion and the dipole-proton scattering amplitudes and about the absorptive corrections, we demonstrated that the semi-inclusive data can be described by the formalism and that Reggeon scaling is expected at large energies. In this paper we have extended our analysis to the rare processes associated with a leading neutron. Considering the same assumptions used for the semi-inclusive case, we have analysed in detail the dependence of our predictions on the choice of the non-linear scattering function of the dipole model and on the parameters. We demonstrated that the HERA exclusive and inclusive p - p photoproduction associated with a leading neutron can be quite well described