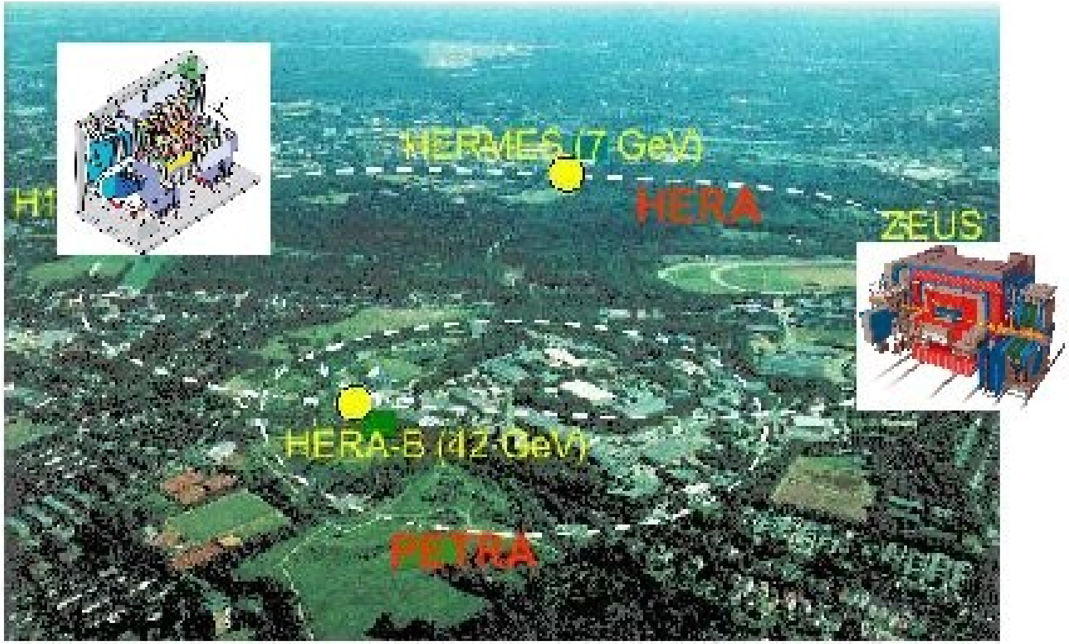
Diffraction - HERA – last

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.

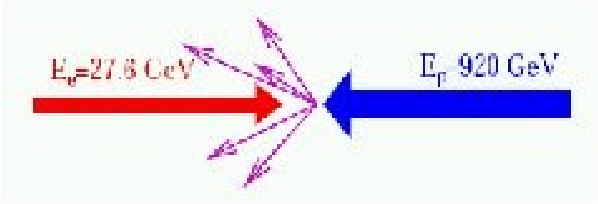
HERA: The World's Only ep Collider

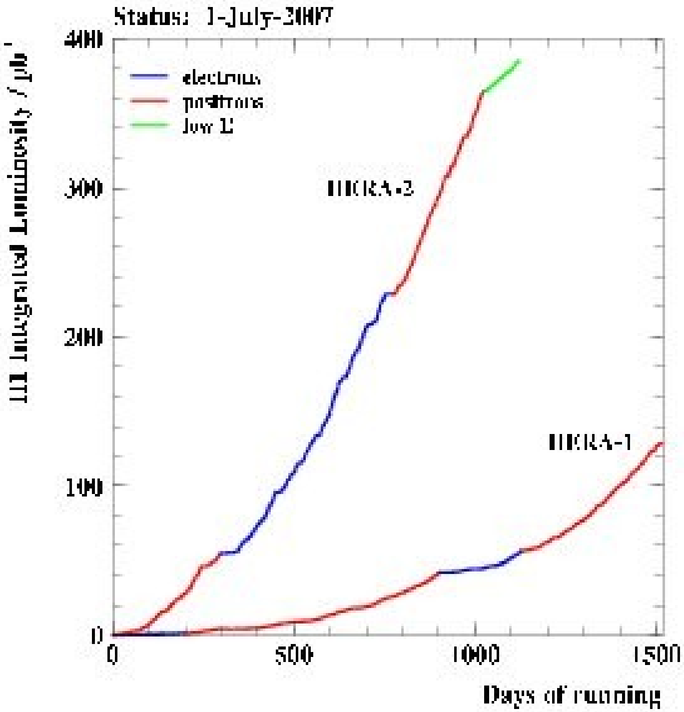


HERA-1 (1993-2000) $\simeq$ 120 pb^{-1}

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

Final Data samples
H1+ZEUS: 2×0.5 fb^{-1}

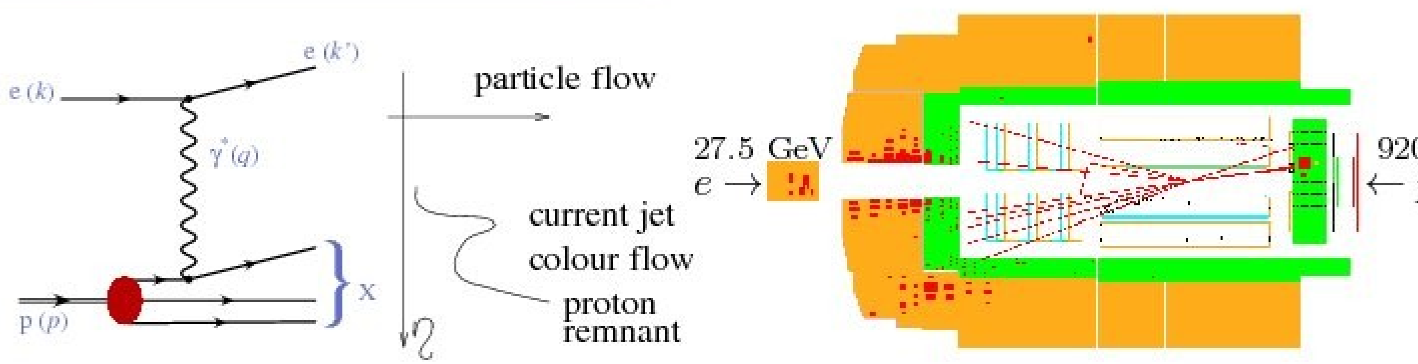




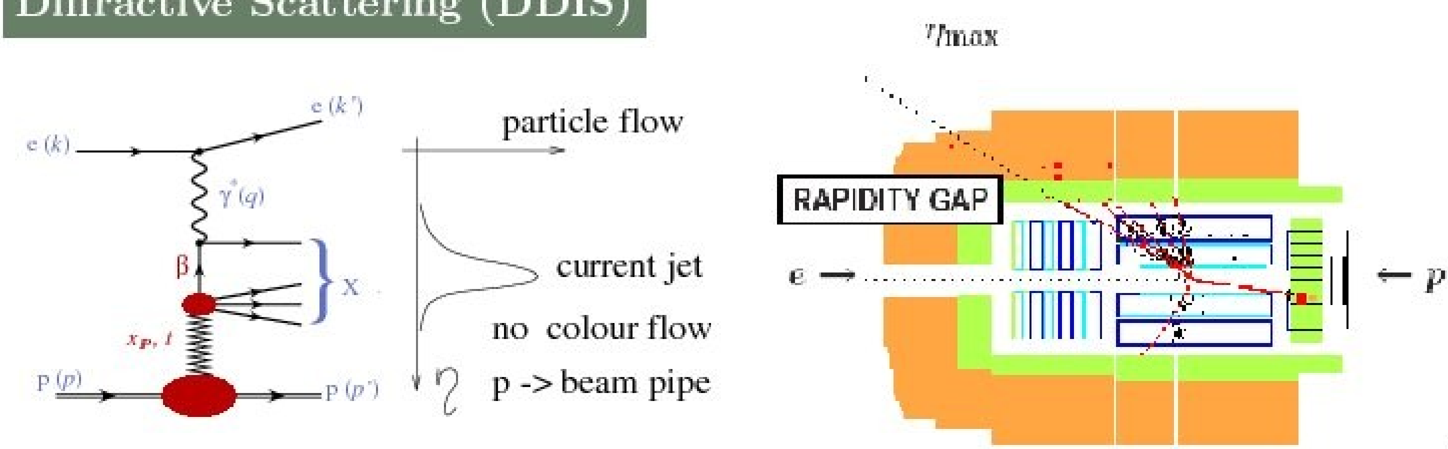
- 1998 E_p upgrade: $820 \Rightarrow 920$ GeV ($\sqrt{s}$: $301 \Rightarrow 319$ GeV)
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised e^-/e^+ ($\langle P \rangle = 40\%$)

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

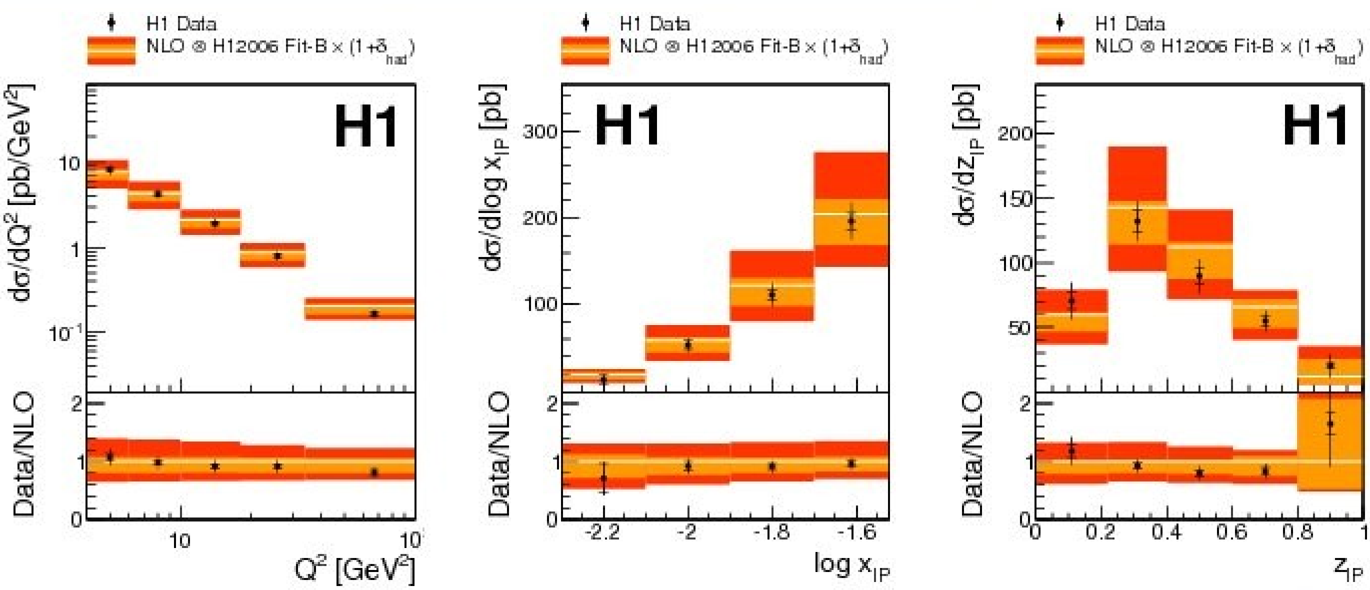
$$d\sigma^{ep\to eXY} = \sum_i f_i^D(x, Q^2, x_{IP}, t) \otimes d\hat{\sigma}^i(x, Q^2)$$

optionaly, also proton vertex factorization

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

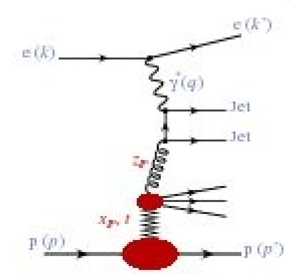
Test of QCD factorisation: H1 Dijet in DIS

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



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

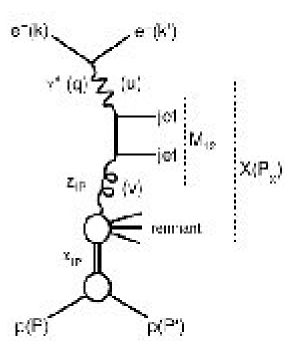
→ QCD factorisation OK (in DIS)



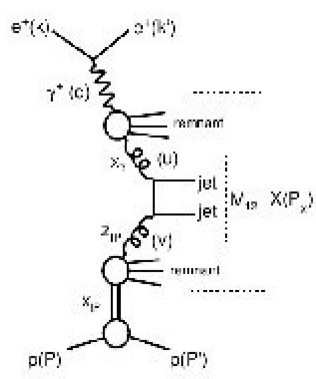
Tests of collinear factorization in diffraction in H1

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



DIS
DIS-like in γp



γ-PDF in γp

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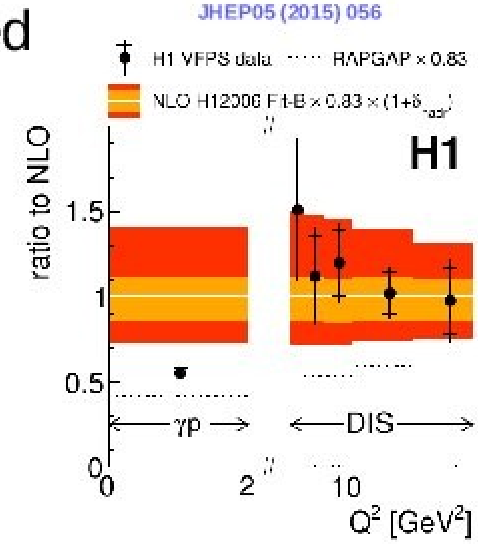
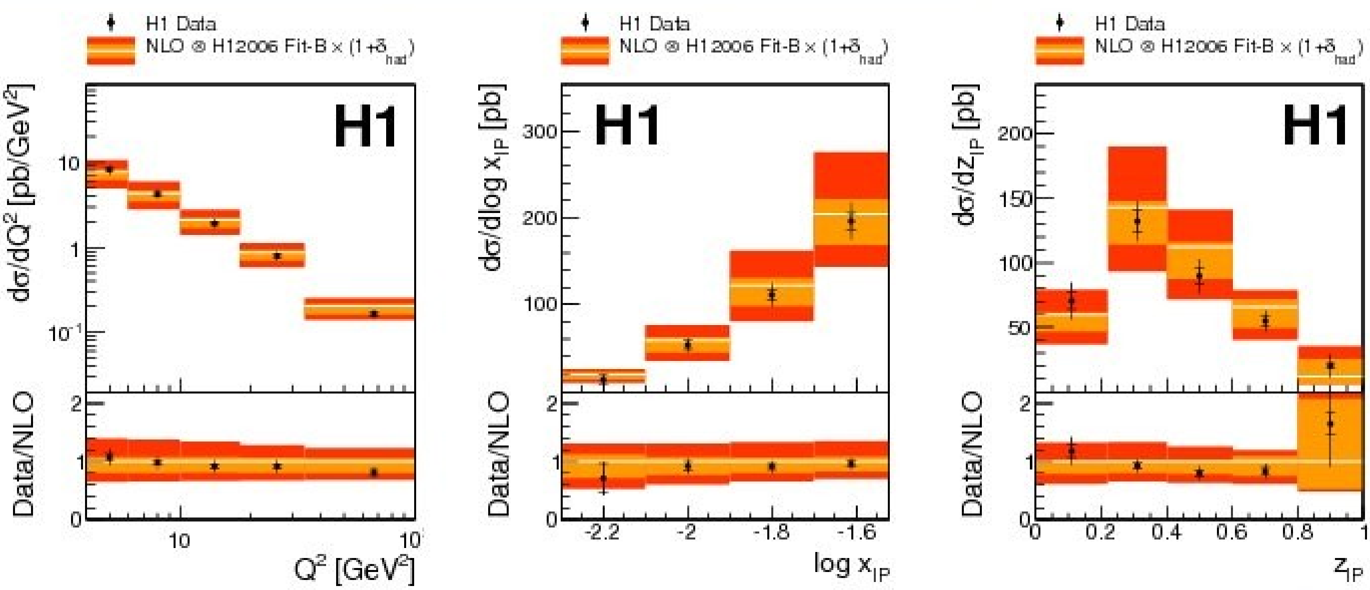
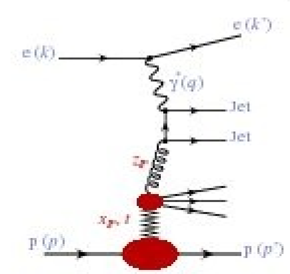


Test of QCD factorisation: H1 Dijet in DIS

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



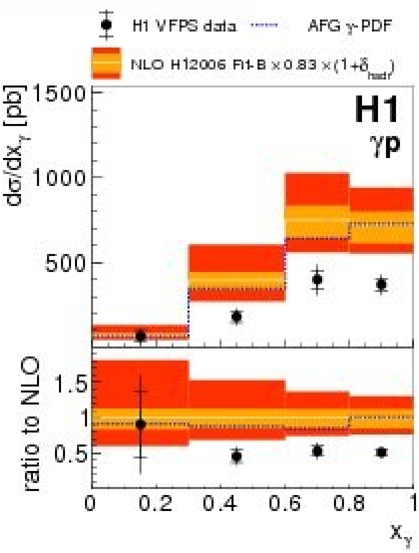
- from F_2^D measurements DPDFs are extracted and used to predict dijet production in DIS regime

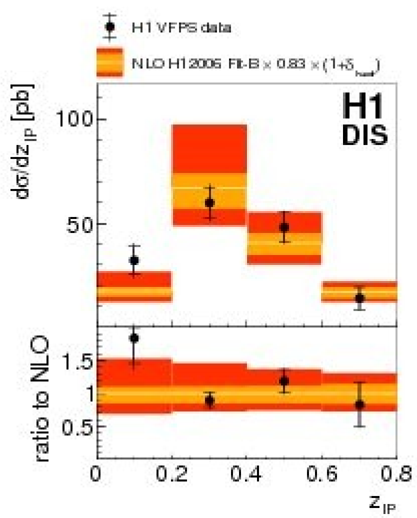


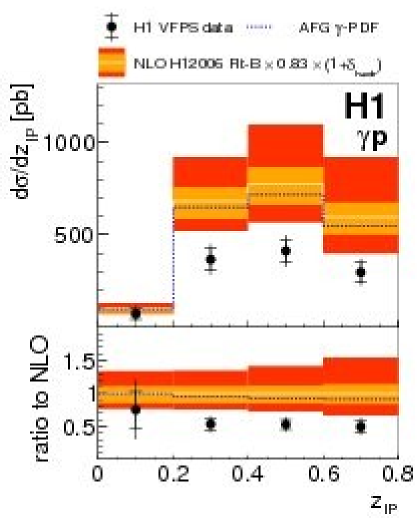
→ QCD factorisation OK (in DIS)

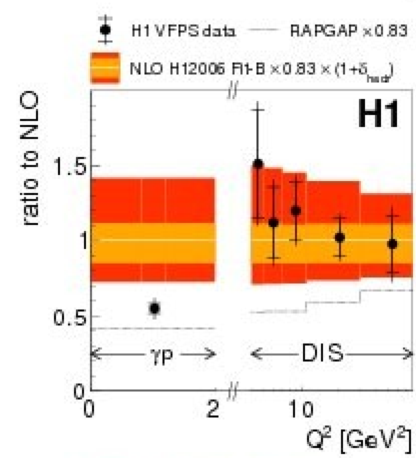
VFPS: Dijet in DIS and in Photoproduction

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



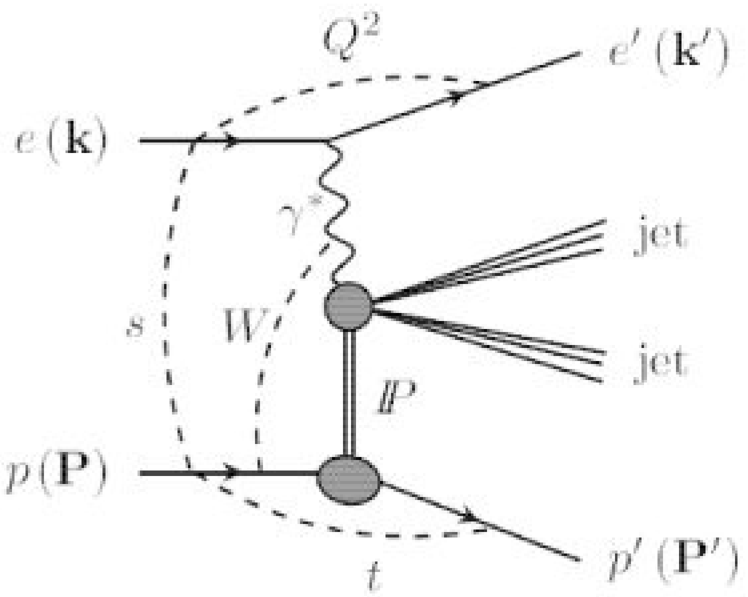






Exclusive dijet production in diffractive DIS

$e + p \rightarrow e + jet1 + jet2 + p$



Data 2003 – 2007 372 pb^{-1}

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

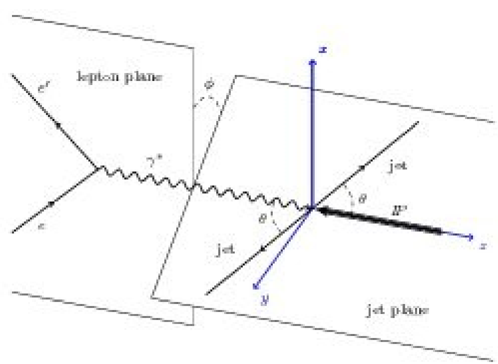
Select two hard jets may to allow comparison pQCD models

Models predict different shape for dijet azimuthal angular distribution

Exclusive Dijets in DIS

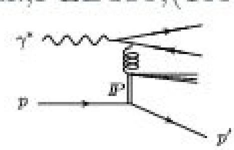
LRG: $Q^2 > 25$ GeV^2, $x_{I\!P} < 0.01$, $N_{\rm jet} = 2$, $P_T^{\rm jets} > 2$ GeV

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

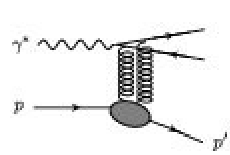


→ $d\sigma/d\phi \sim 1 + A(P_T^{\rm jet}) \cos 2\phi$ [J.Bartels et al.,PLB386,(1996)389]

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

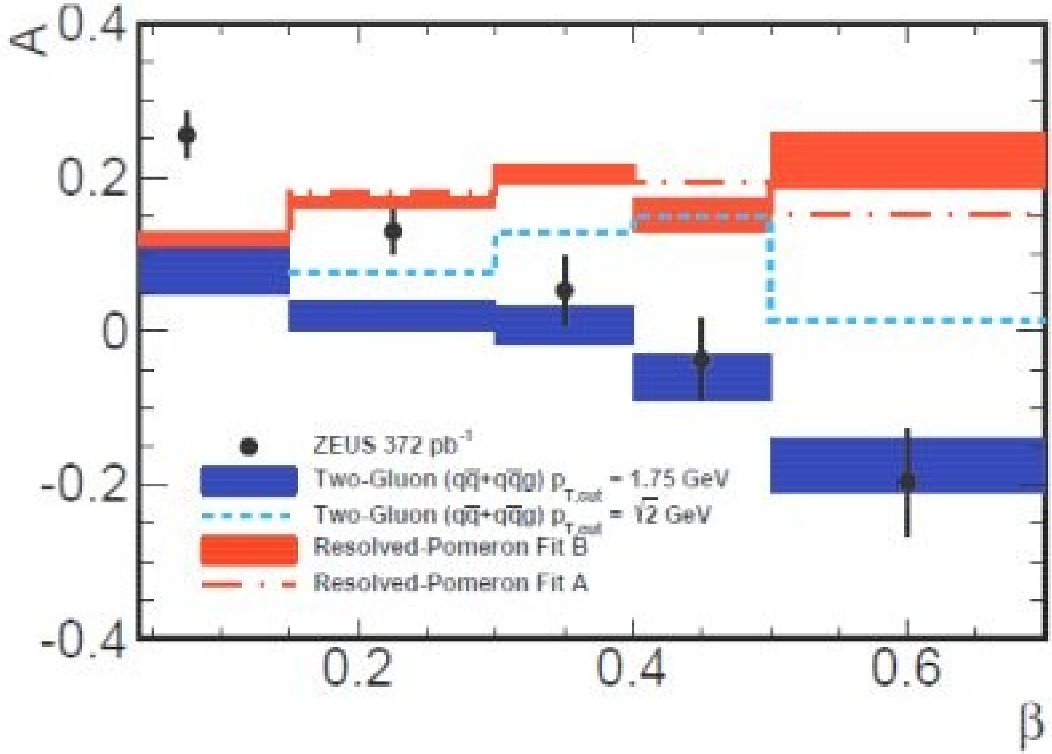


$A < 0$ two gluons exchange.



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

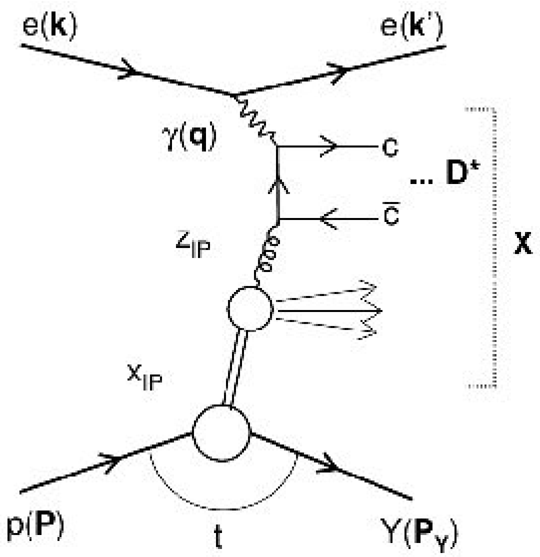
Two-Gluon-Exchange model
Value of A varies from positive to negative
Model agrees quantitatively with the data in the range $0.3 < \beta < 0.7$

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)



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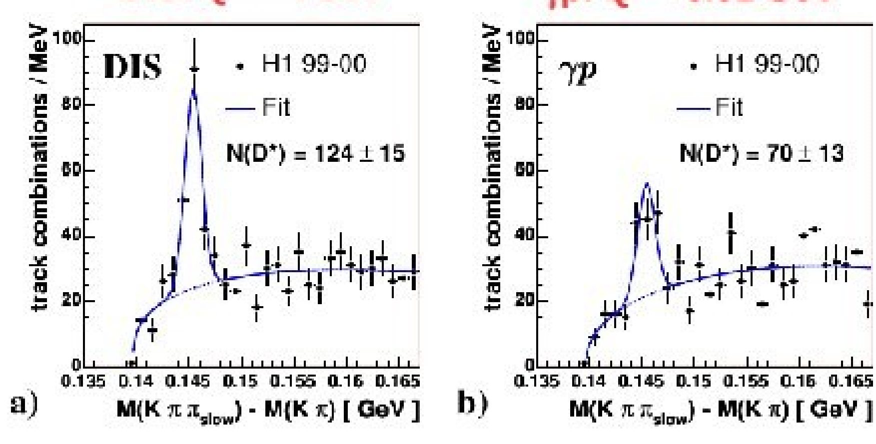
DIS: $Q^2 > 4$ GeV^2

γp: $Q^2 < 0.01$ GeV^2



L ~ 50 pb^{-1}

D* production in diffractive DIS

new H1 measurement - preliminary

$ep \rightarrow e\,Y\,X(D^*)$

- H1-HERA 2 data

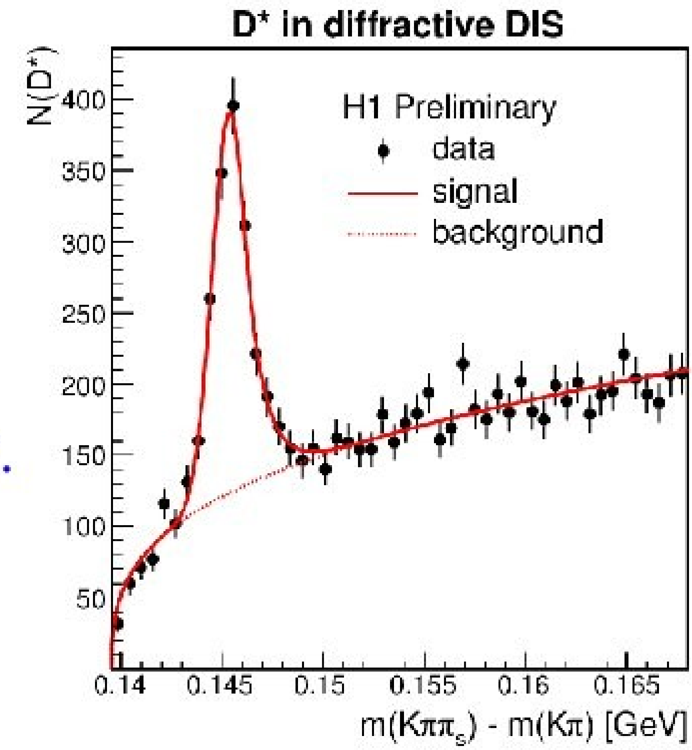
  $L_{int} \sim 280\ pb^{-1}$

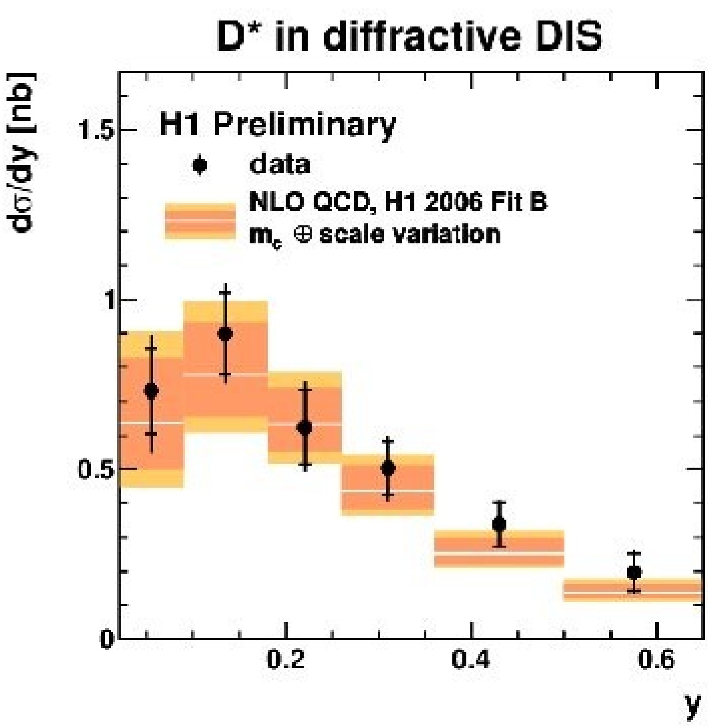
- D* reconstructed fully in:

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

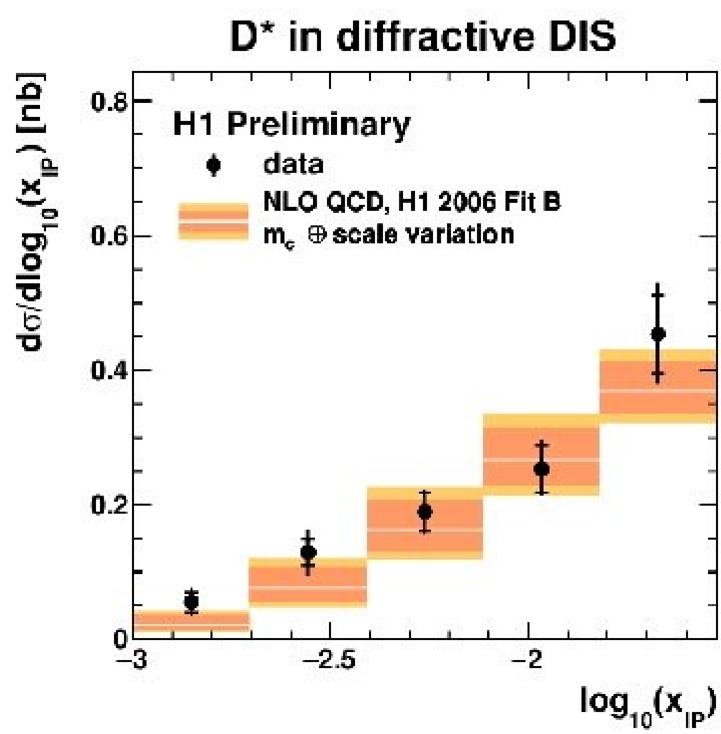
(BR ~ 2.6 %)

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





D* in diffractive DIS
dσ/dy [nb]
H1 Preliminary
data
NLO QCD, H1 2006 Fit B
m_c ⊕ scale variation
1.5
1
0.5
0
0.2
0.4
0.6
y



D* in diffractive DIS
dσ/dlog10(x_IP) [nb]
H1 Preliminary
data
NLO QCD, H1 2006 Fit B
m_c ⊕ scale variation
0.8
0.6
0.4
0.2
0
−3
−2.5
−2
log10(x_IP)

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 --> pi + pi + N

Example - JETF v45, p913, 1963
Cross-section pi+ pi- --> pi+ pi- = 34 +- 9 mb
(energy in cms = 4-7 Mpi)

FIAN – 1988, v 186 p 106
Gamma + p --> gamma' + pi+ neutron
Cross-section gamma-pi+ = (5.4+-1.) 10**(-32) cm**2/st
Egm=650 mev, s1=6.5mpi
alfa(pi+) = -beta(pi+) = (20 =-12) 10**(-43) cm**3

UNSTABLE PARTICLES AS TARGETS IN SCATTERING EXPERIMENTS

G. F. Chew

Radiation Laboratory
University of California
Berkeley, California

and

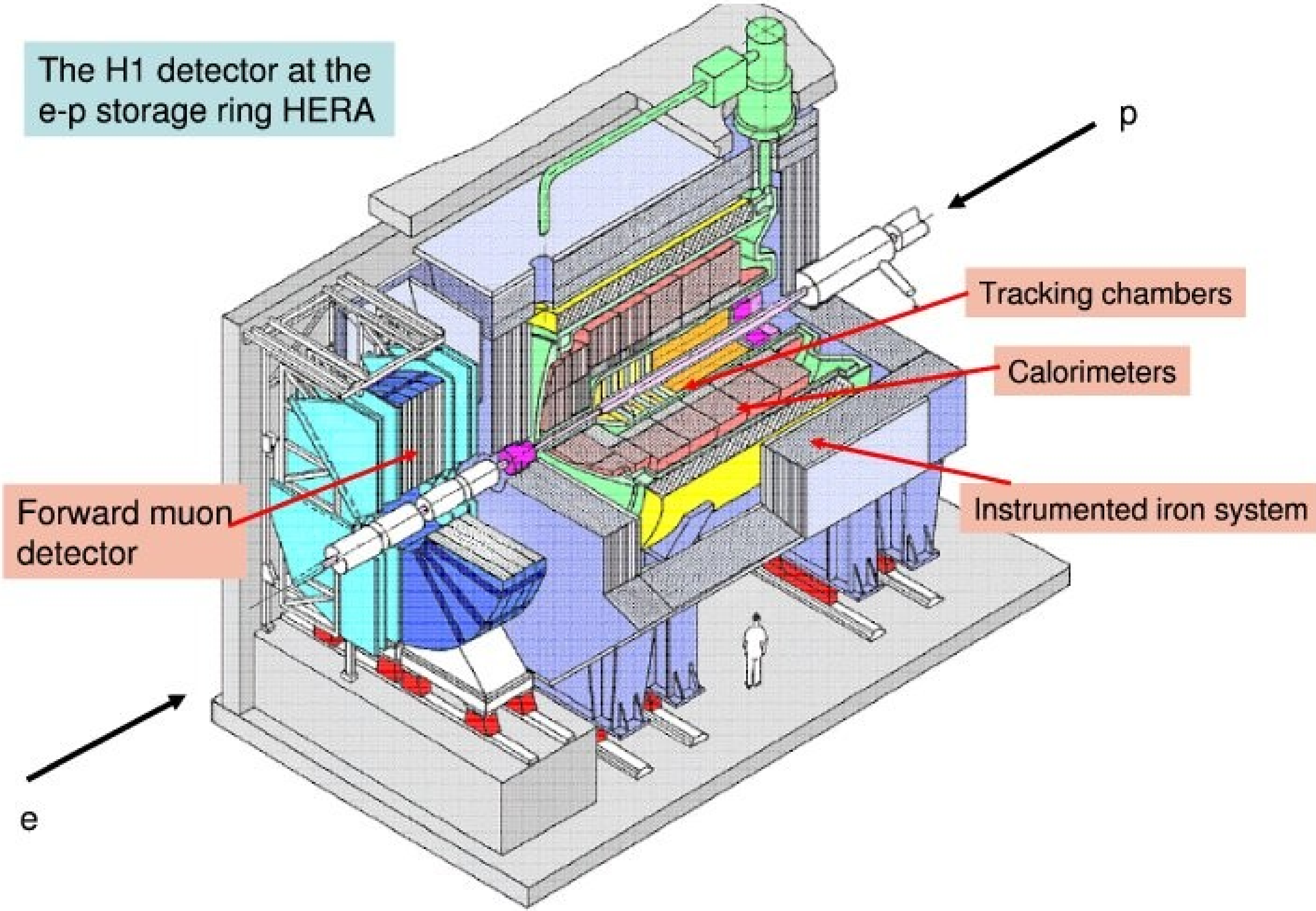
F. E. Low

Radiation Laboratory, University of California
Berkeley, California
and
Department of Physics and Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, Massachusetts

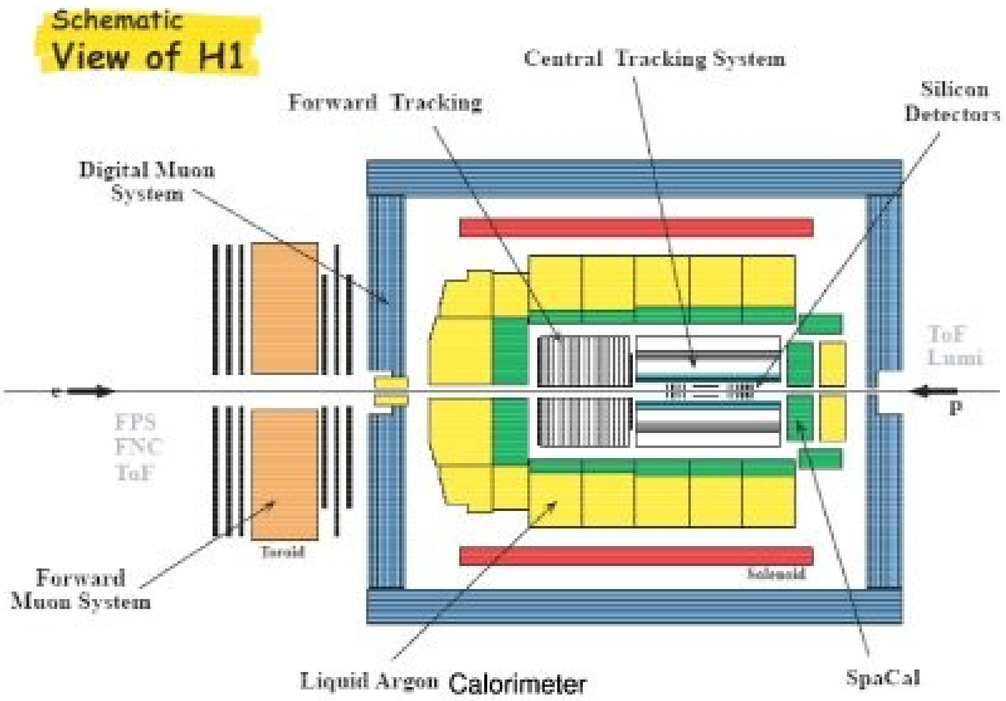
August 21, 1958

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.


The H1 detector at the
e-p storage ring HERA
p
Tracking chambers
Calorimeters
Instrumented iron system
Forward muon
detector
e

Side view


Schematic
View of H1
Central Tracking System
Forward Tracking
Silicon
Detectors
Digital Muon
System
ToF
Lumi
e
p
FPS
FNC
ToF
Toroid
Solenoid
Forward
Muon System
Liquid Argon Calorimeter
SpaCal

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Reaction of interest and the analysis phase space

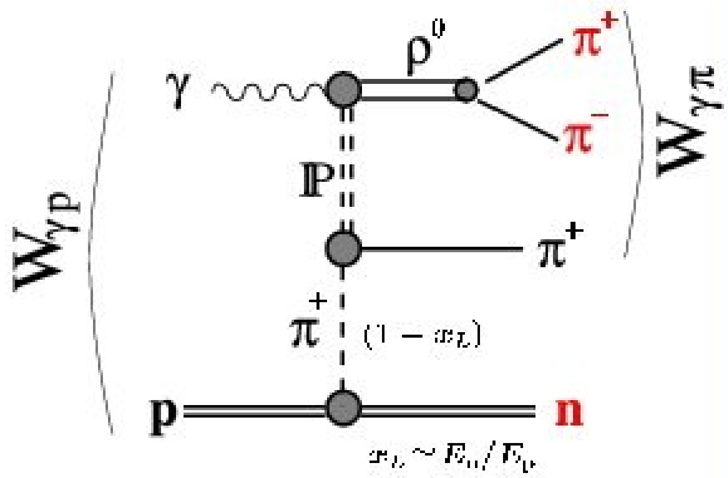
$$\gamma^* + \mathbf{p} \longrightarrow \rho^0 \, \pi^+ \, \mathbf{n}$$

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

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

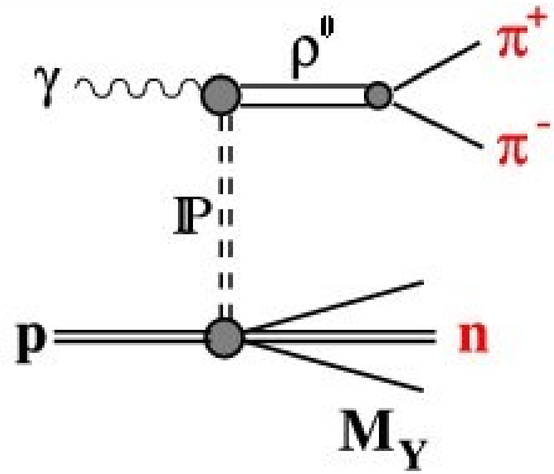
Contributing processes and their modelling



Pompyt × Pythia6

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

Signal (DPP)



DiffVM

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

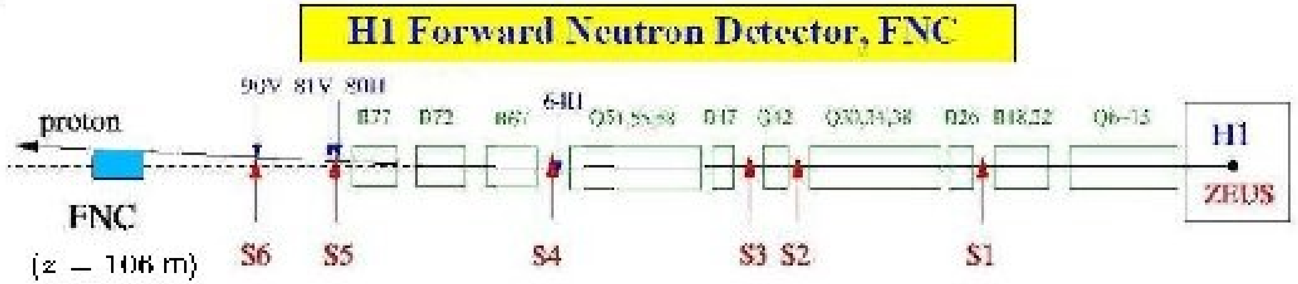
Background

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

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

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

Typical Event



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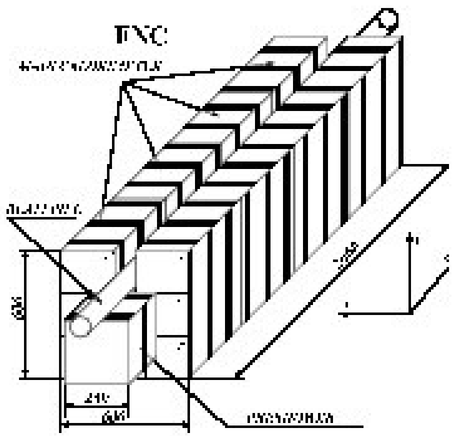
Key Experimental Ingredients

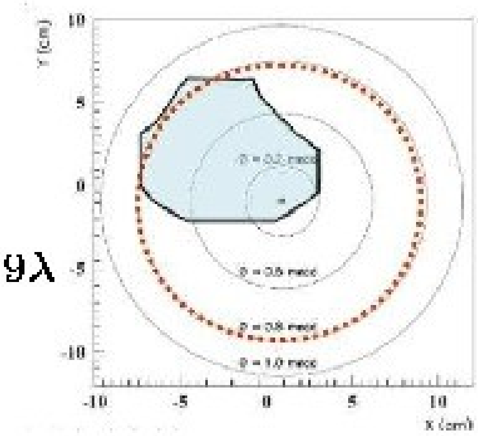
Improved H1 FNC (distinguish ($\langle P \rangle = 98\%$) and measure n and γ/π^0)



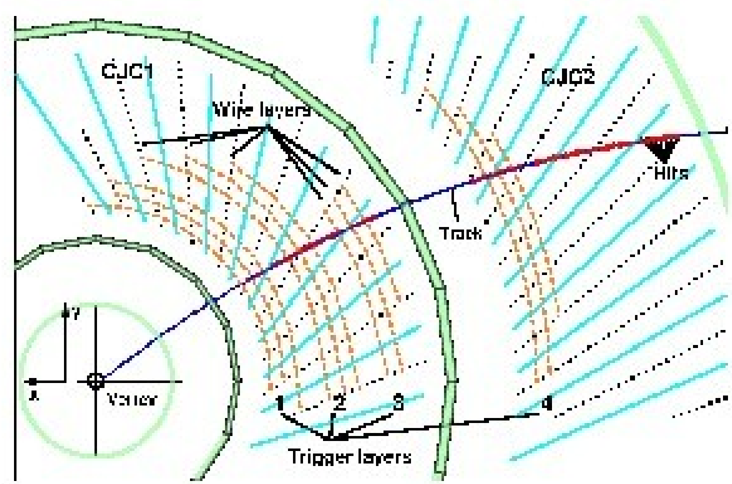
located at $z = 106$m from IP

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

Preshower: $60X_0$, Main Calo: 8.9λ



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



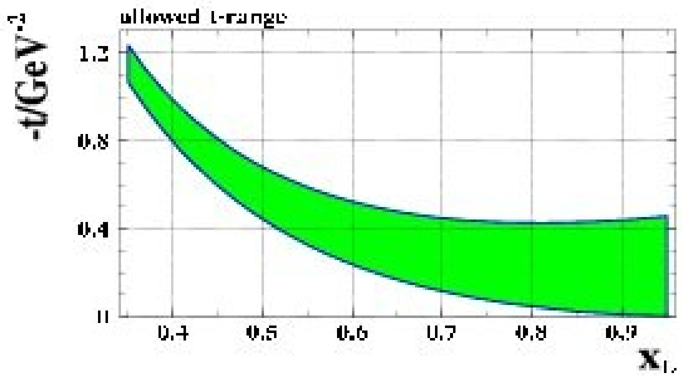
OPE and pion fluxes

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

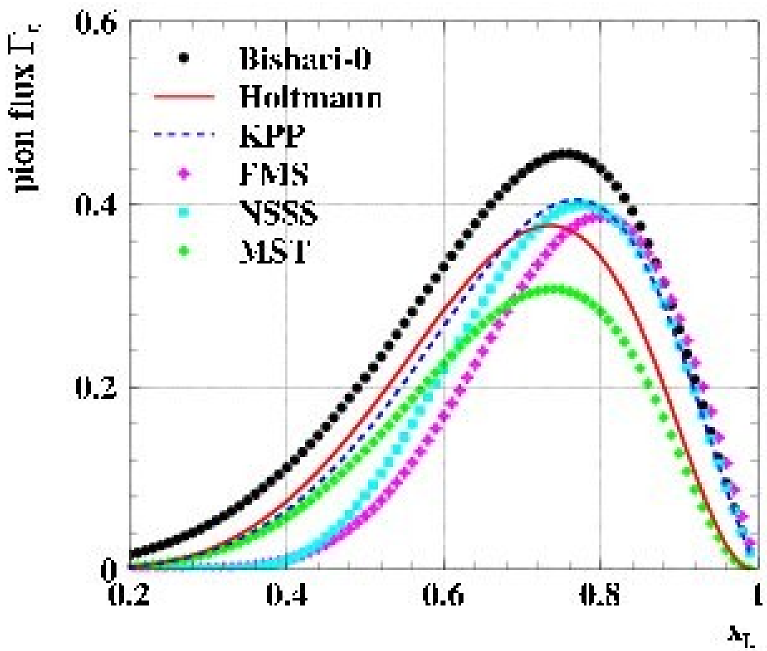
$$\frac{d\sigma_{\gamma p}}{dx_L} = \int_{t_0(x_L)}^{t_{min}(x_L)} f_{\pi/p}(x_L,t)\,dt \cdot \sigma_{\gamma\pi}(W_{\gamma\pi})$$

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

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



<u>Problem:</u> too many different fluxes on the market



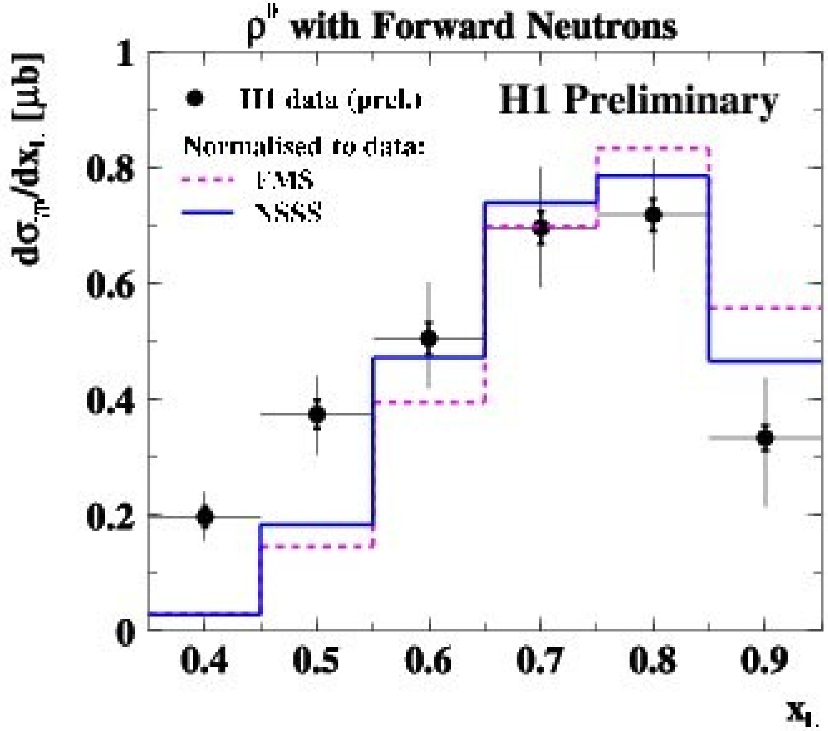
Typical examples:

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

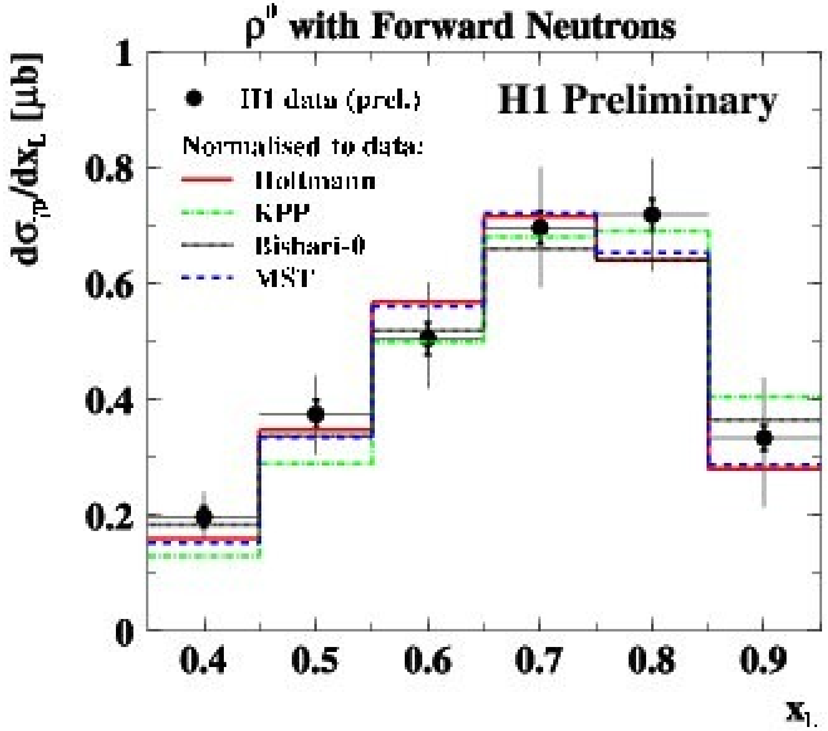
Pion fluxes confronted with H1 data

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

Total cross sections

γp

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

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 $20 < W_{\gamma p} < 100$ GeV, $\theta_n < 0.75$ mrad

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

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

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

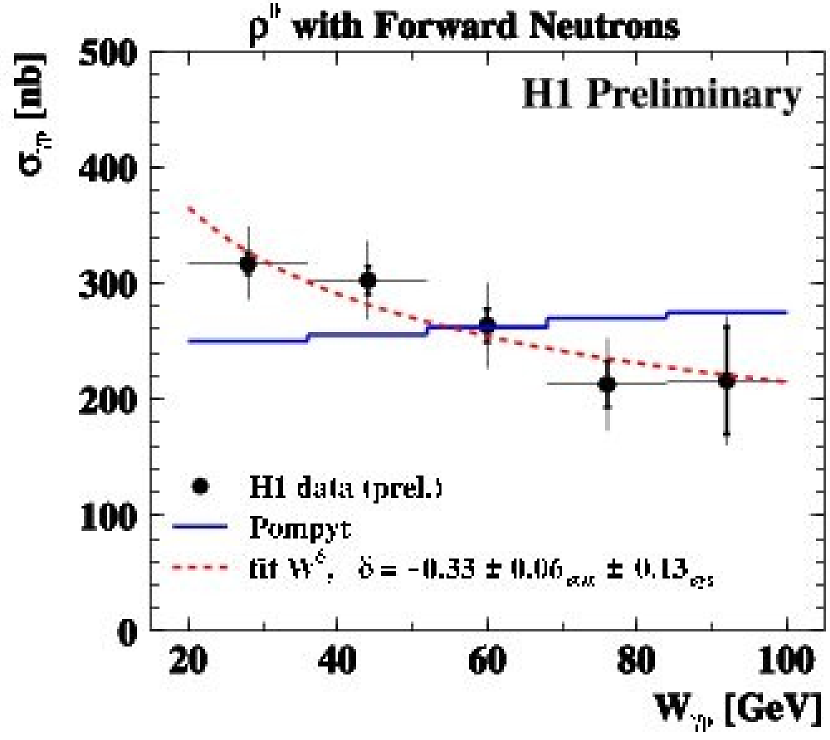
Taking interpolated value of $\sigma(\gamma p \to \rho^0 p) = 9.5 = 0.5\ \mu b$ at corresponding energy, we obtain

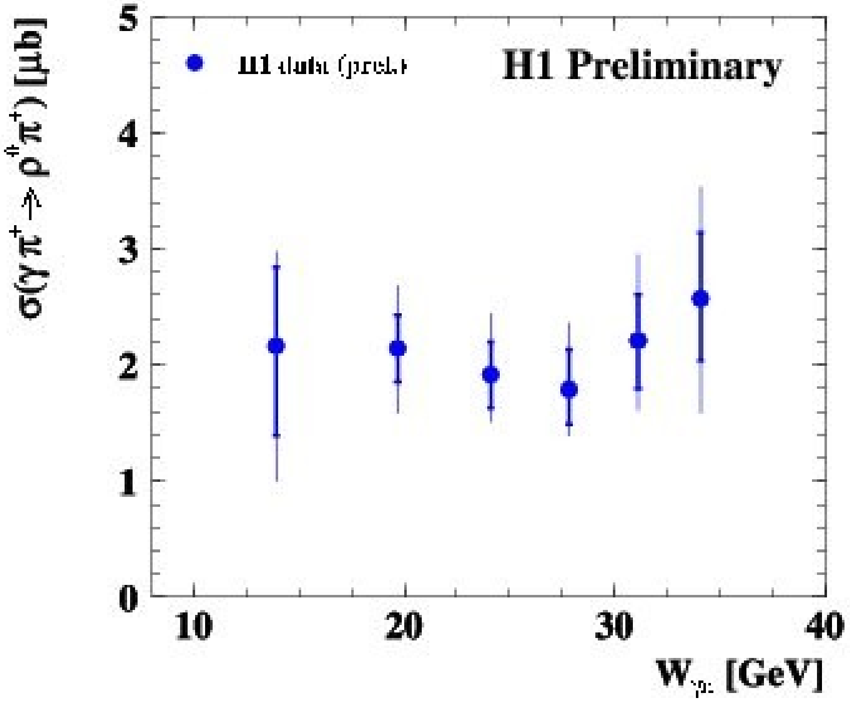
$r_{el} = \sigma^{el}_{\gamma\pi}/\sigma^{el}_{\gamma p} = 0.21 \pm 0.06$ (cf. r_{tot} $\sigma^{tot}_{\gamma\pi}/\sigma^{tot}_{\gamma p}$ 0.32 ± 0.03 [ZEUS, 2002])

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



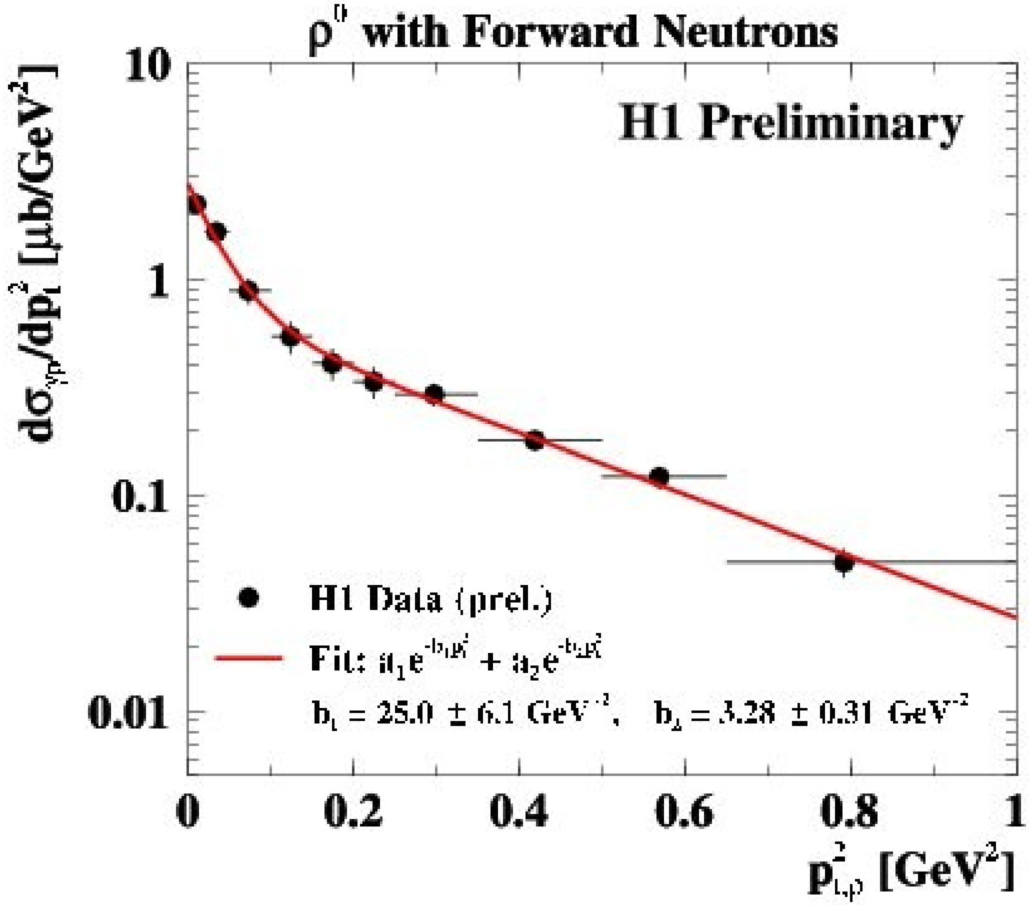


Regge motivated power low fit W^δ yields $\delta < 0$

Holtmann flux is used for the central values.

Model uncertainty $\sim 25\%$

Differential cross section in p_t^2



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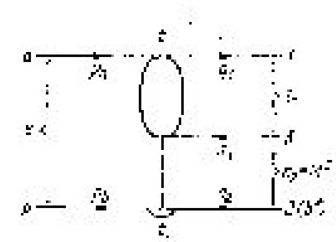
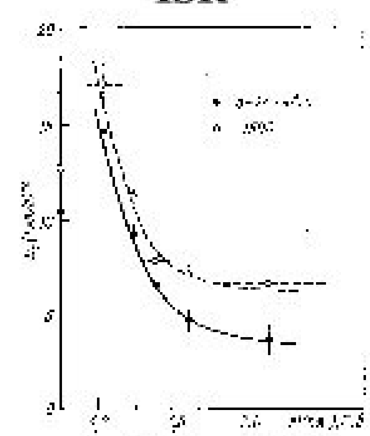


DPP $2 \rightarrow 3$



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

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

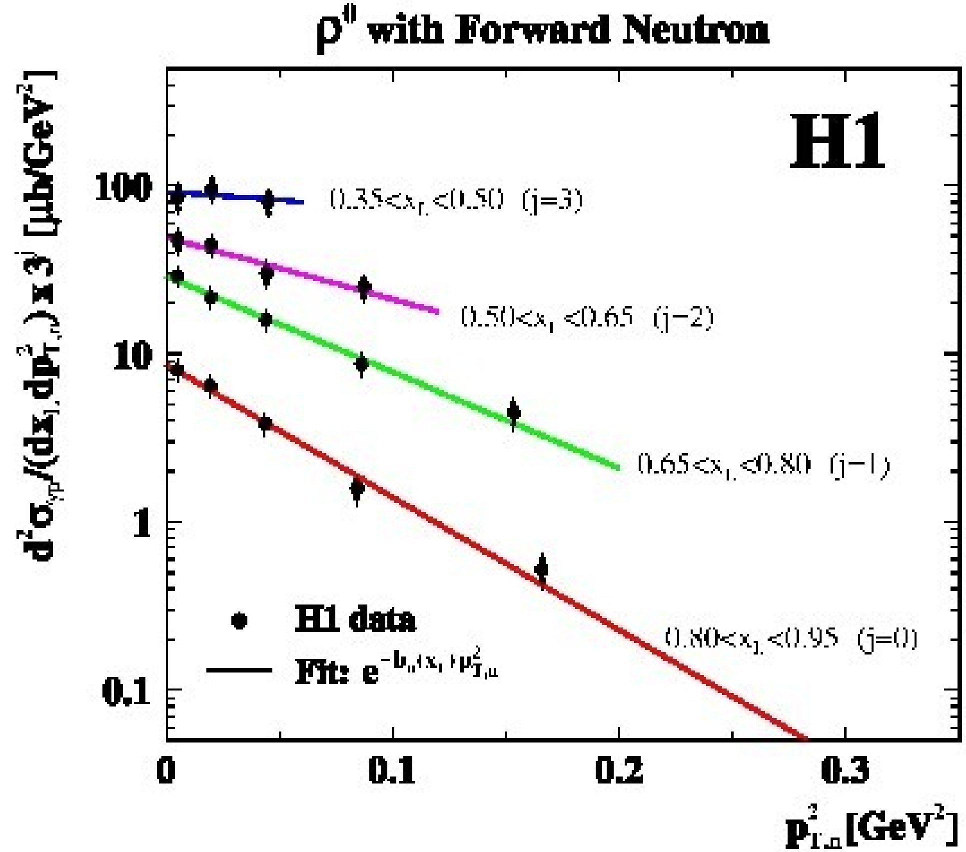


Figure 7: Double differential cross section $d^2\sigma_{\gamma p}/dx_L dp^2_{T,n}$ of neutrons in the range $20 < W_{\gamma p} < 100$ GeV fitted with single exponential functions. The cross sections in different x_L bins j are scaled by the factor 3^j for better visibility. The binning scheme is shown 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%.

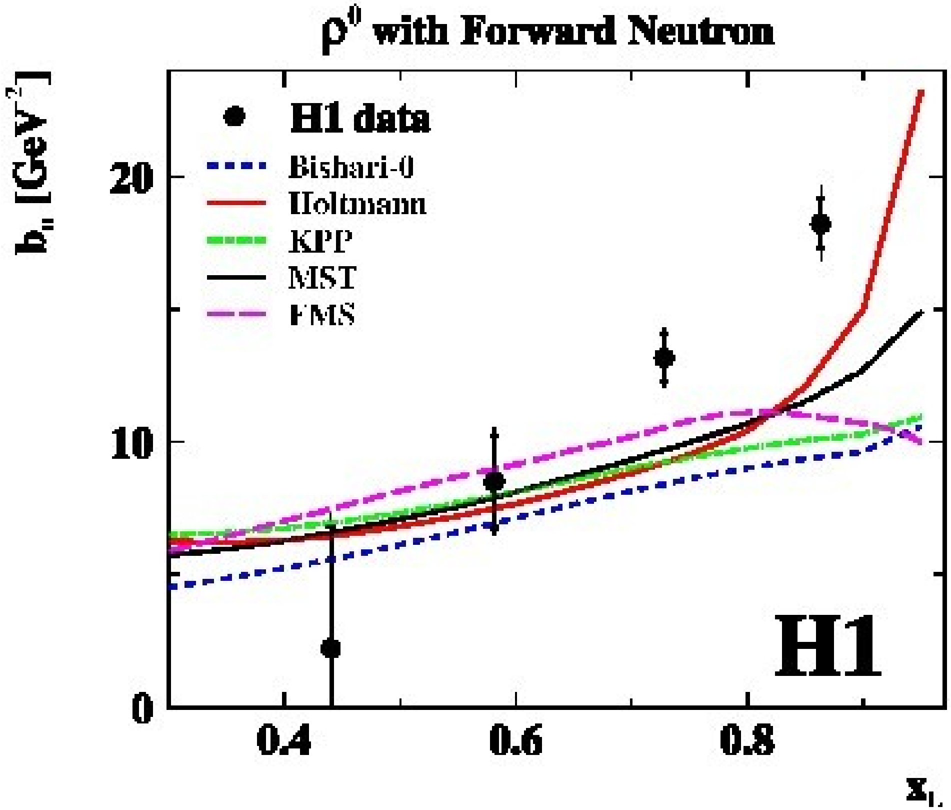


Figure 8: The exponential slopes fitted through the p_T^2 dependence of the leading neutrons as a function of x_L. The inner error bars represent statistical errors and the outer error bars are statistical and systematic errors added in quadrature. The data points are compared to the expectations of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

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Exclusive processes with a leading neutron in ep collisions

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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 ρ, ϕ and J/Ψ production as well as the Deeply Virtual Compton Scattering are analysed assuming a diffractive interaction between the color dipole and the pion emitted by the incident proton. We compare our predictions with the HERA data on ρ production and estimate the magnitude of the absorption corrections. We show that the color dipole formalism is able to describe the current data. Finally, we present our estimate for the exclusive cross sections which can be studied at HERA and in future electron-proton colliders.

PACS numbers: 12.38.-t, 24.85.+p, 25.30.-c
Keywords: Quantum Chromodynamics, Leading Particle Production, Saturation effects.

I. 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 interactions at high energies (For a review see, e.g. 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) in exclusive processes ($\gamma^* p \rightarrow E p$ with $E = \rho, \phi, J/\Psi, \gamma$) 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 these 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 (parton 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 quark - antiquark dipole and that the interaction of the dipole with the target can be described by the color dipole cross section $\sigma_{dp}(x, \boldsymbol{r})$, with the transverse size of the dipole $\boldsymbol{r}$ fixed during the interaction process. In this approach all information about the target and strong interaction physics is encoded in $\sigma_{dp}(x, \boldsymbol{r})$, which is determined by the imaginary part of the forward amplitude of the scattering between a small dipole (a colorless quark-antiquark pair) and a dense hadron target, denoted by $\mathcal{N}(x, \boldsymbol{r}, \boldsymbol{b})$, where the dipole has transverse size given by the vector $\boldsymbol{r} = \boldsymbol{x} - \boldsymbol{y}$, with $\boldsymbol{x}$ and $\boldsymbol{y}$ being the transverse vectors of the quark and antiquark, respectively, and $\boldsymbol{b} = (\boldsymbol{x}+\boldsymbol{y})/2$ is the impact parameter. In the Color Glass Condensate (CGC) formalism [4, 5], $\mathcal{N}$ 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 [5, 6]. 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 known in the low and high density 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 for the reduced inclusive cross section as well as the data for the exclusive processes in a large range of photon - proton center - of - mass energies W, photon virtualities Q^2 and t - values.

HERA has also provided high precision experimental data on semi - inclusive $ep \rightarrow enX$ processes, where the incident proton is converted into a neutron via a charge exchange [8]. Very recently the first measurements of

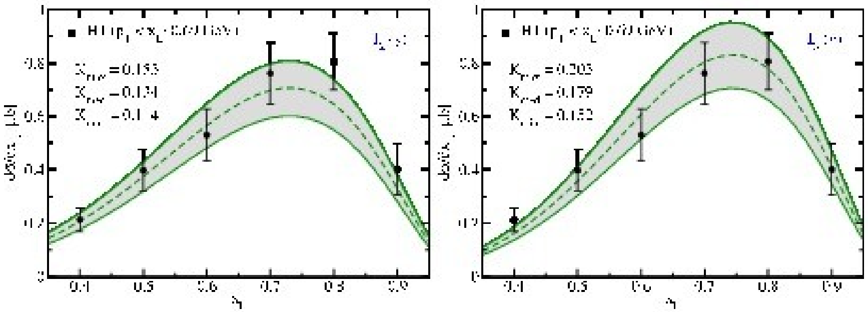

FIG. 6: (Color online) Leading neutron spectra in exclusive ρ photoproduction obtained considering the possible range of values of the K factor fixed using the other set of experimental data and two models for the pion flux. H1 data [6] obtained assuming that $p_T < 0.69 \cdot x_L$ GeV.

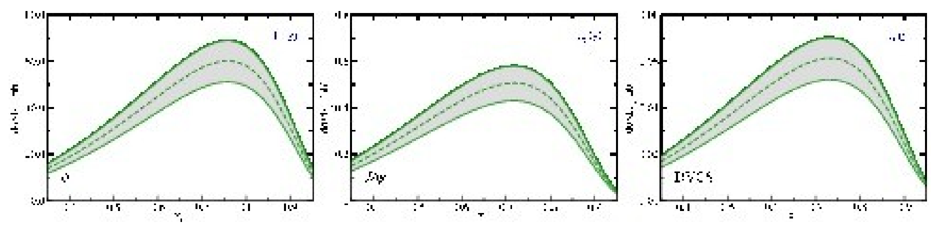

FIG. 7: (Color online) Predictions for the leading neutron spectra in exclusive ϕ, J/Ψ and DVCS production in the HERA kinematical range: $W = 90$ GeV and $p_T < 0.2$ GeV.

sections, the experimental analysis of these exclusive 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 useful to constrain leading neutron spectra, which are of crucial 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 future at 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 momentum ($x_L > 0.3$) 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 [20], we proposed to describe the semi - inclusive leading neutron process using using the color dipole 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 Feynman scaling is expected at large energies. In this paper we have extended our analysis to exclusive 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 vector meson wave function, of the dipole model and and of the pion flux. We demonstrated that the HERA data on the exclusive ρ photoproduction associated with a leading neutron can be quite well described