QCD 16 19th HIGH-ENERGY PHYSICS INTERNATIONAL CONFERENCE IN QUANTUM CHROMODYNAMICS (QCD)

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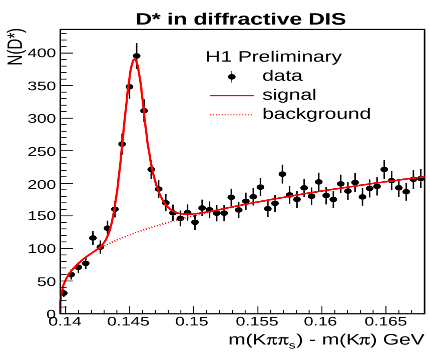
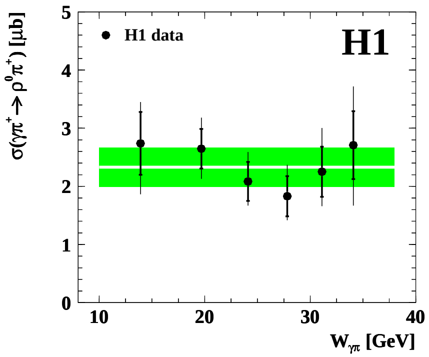
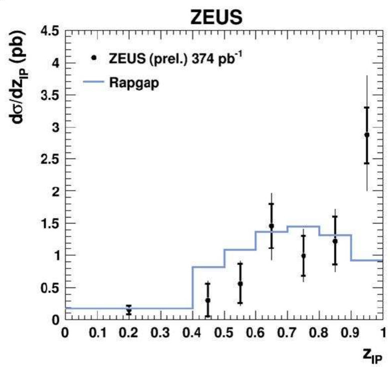
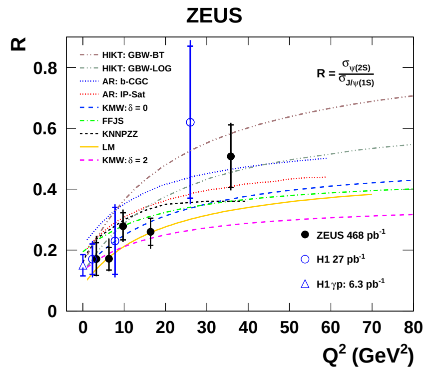
New Results on Diffraction at HERA

S. Levonian, DESY

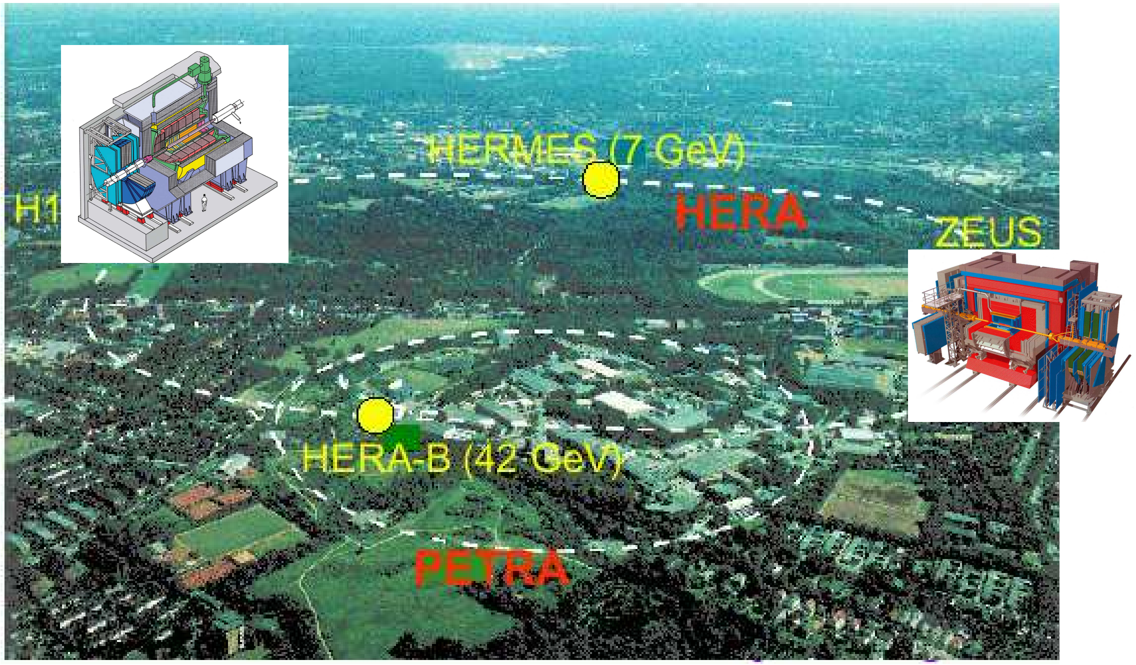








HERA: The World's Only ep Collider

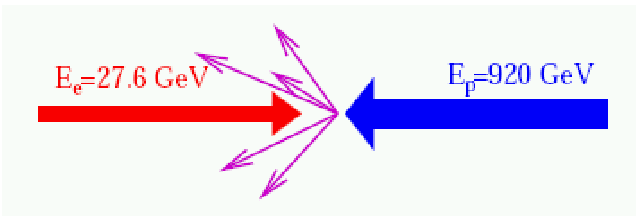


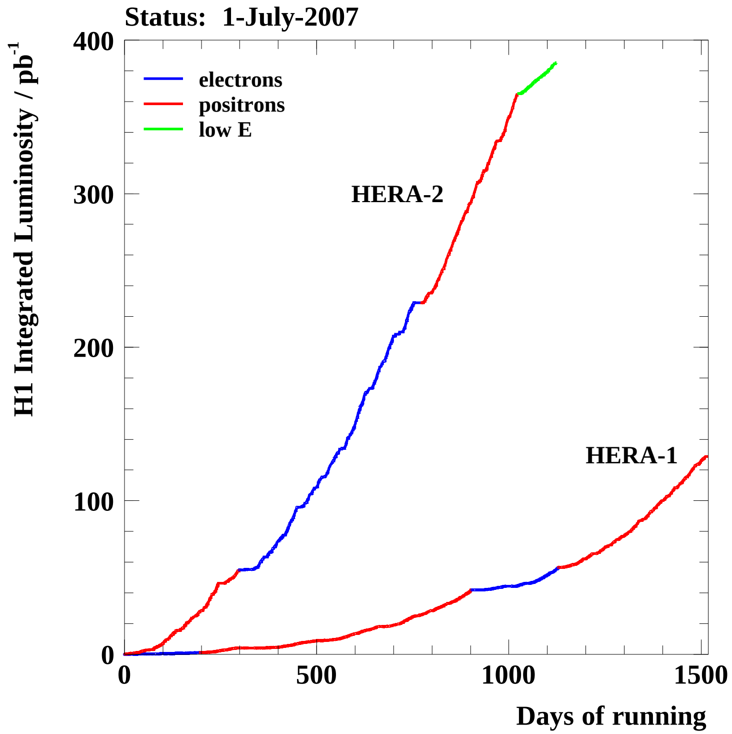
HERA-1 (1993-2000) $\simeq 120$ pb^{-1}

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

Final Data samples

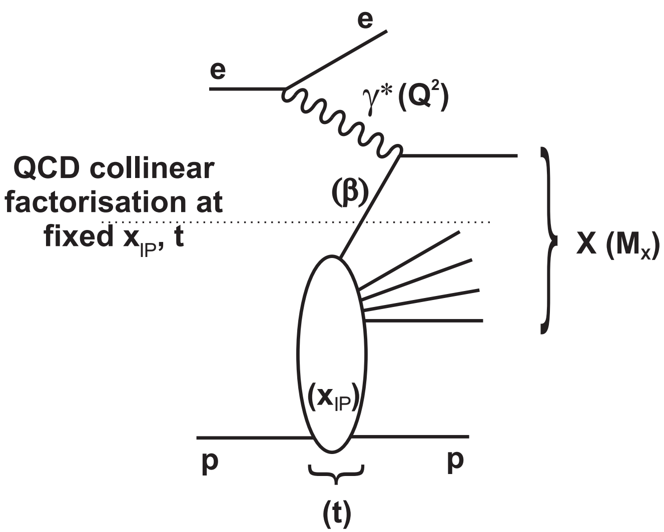
H1+ZEUS: 2×0.5 fb^{-1}

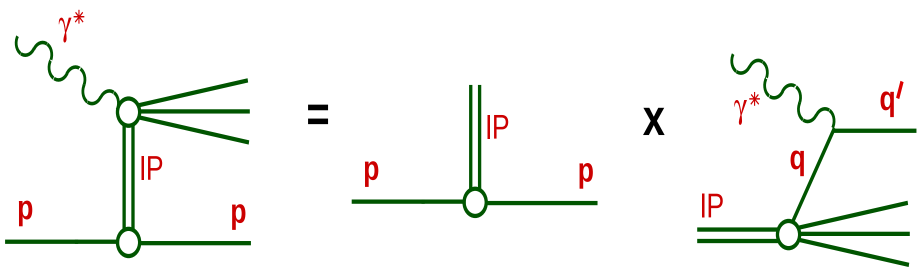




- 1998 E_p upgrade: $820 \Rightarrow 920$ GeV
  ($\sqrt{s}$: $301 \Rightarrow 319$ GeV)
- 2001 HERA-2 upgrade: $\mathcal{L} \times 3$, Polarised e^+/e^-
  ($\langle P \rangle = 40\%$)

Diffraction at HERA. Factorisation properties





QCD versus Regge factorisation

QCD factorisation

(rigorously proven for DDIS by Collins et al.):

$$\sigma_r^{D(4)} \propto \sum_i \hat{\sigma}^{\gamma^* i}(x, Q^2) \otimes f_i^D(x, Q^2; x_{I\!P}, t)$$

- $\hat{\sigma}^{\gamma^* i}$ – hard scattering part, same as in inclusive DIS
- f_i^D – diffractive PDF's, valid at fixed $x_{I\!P}, t$ which obey (NLO) DGLAP

Regge factorisation

(conjecture, e.g. RPM by Ingelman,Schlein):

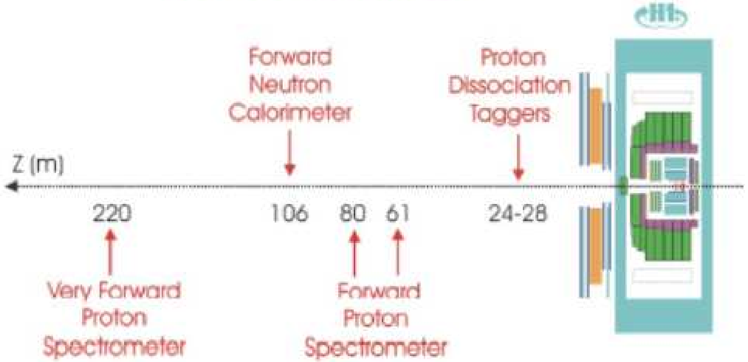
$$F_2^{D(4)}(x_{I\!P}, t, \beta, Q^2) = \Phi(x_{I\!P}, t) \cdot F_2^{I\!P}(\beta, Q^2)$$

- In this case shape of diffractive PDF's is independent of $x_{I\!P}, t$ while normalization is controlled by Regge flux $\Phi(x_{I\!P}, t)$

Selection of Diffractive Events

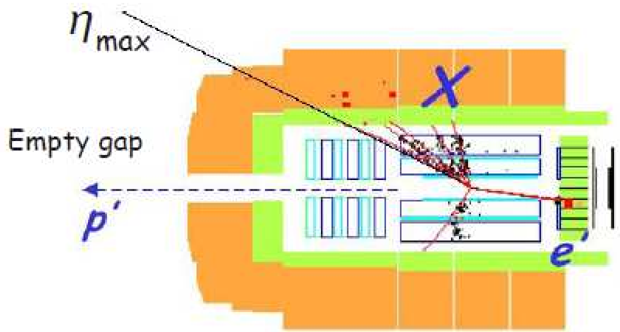
Measure the leading proton

→ Forward spectrometers (H1 FPS/VFPS)



- x_{IP} and t measurements
- Less statistics
- p-tagging systematics

Measure a Large Rapidity Gap



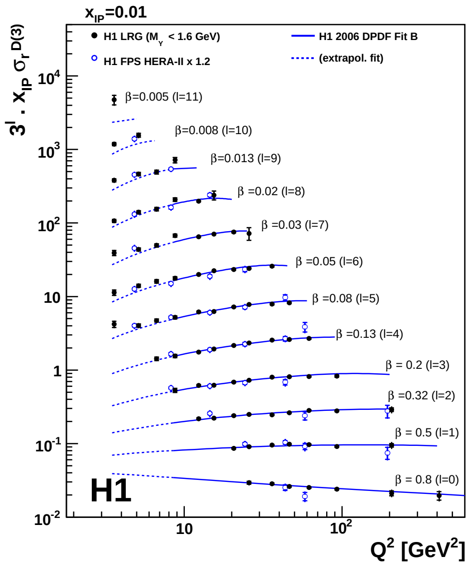
- Data integrated over $|t| < 1$ GeV^2
- High statistics
- Contamination from proton dissociation events

  → Needs to be controlled

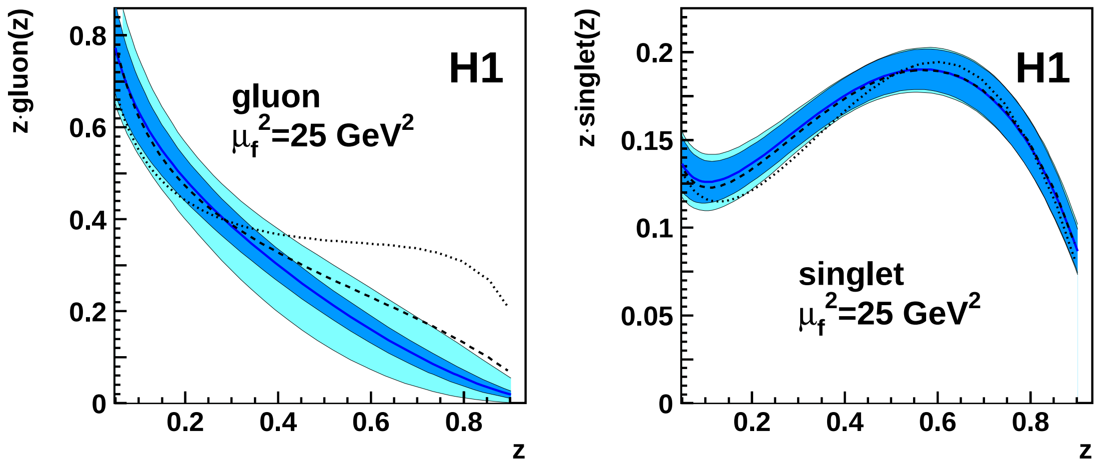
↘ Different systematics

↘ Different kinematic coverage

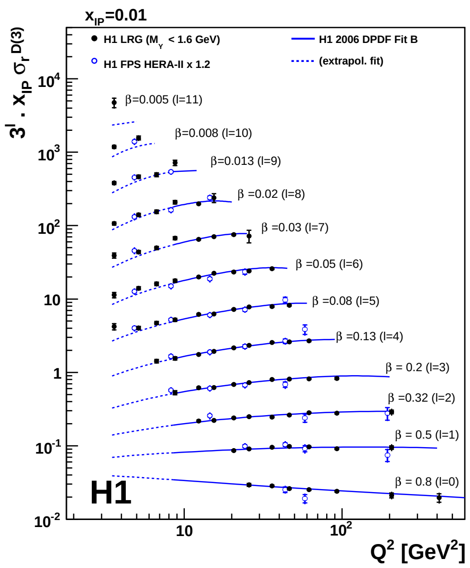
Diffraction at HERA: Some old Results



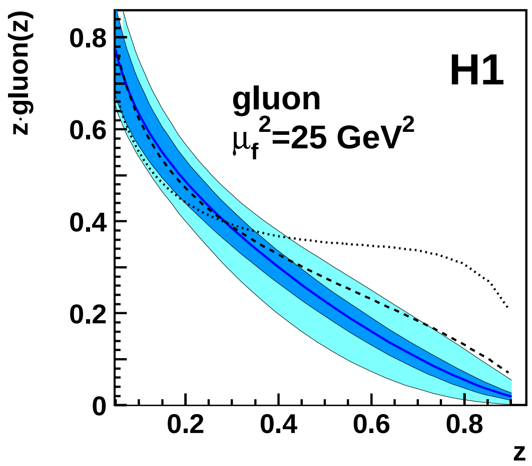
Inclusive Diffraction and DPDFs: gluon dominated $I\!P$

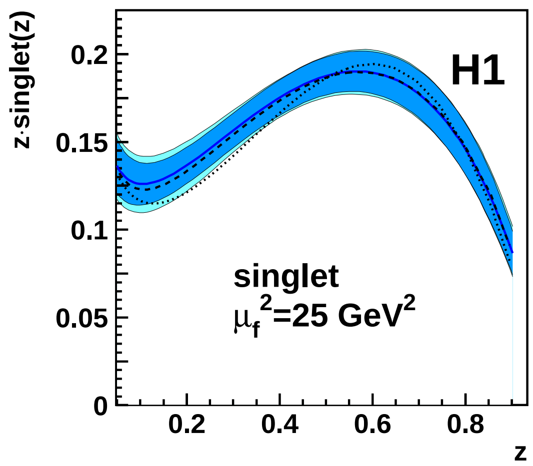


Diffraction at HERA: Some old Results



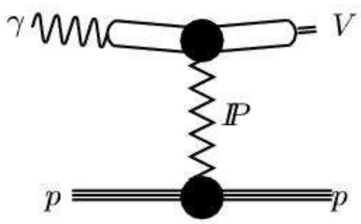
Inclusive Diffraction and DPDFs: gluon dominated $I\!\!P$



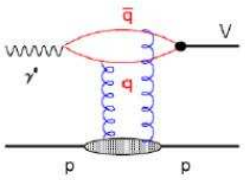


VM: soft vs hard $I\!\!P$

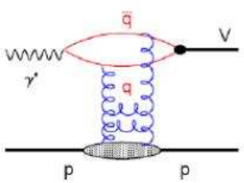
transition from soft to hard regime at $\mu^2 \simeq 4 \div 5$ GeV^2



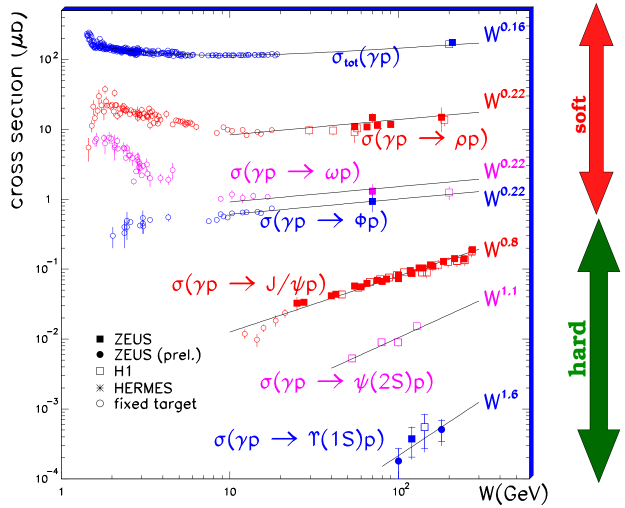
$\alpha_{I\!\!P}(t) = \alpha(0) + \alpha' t$

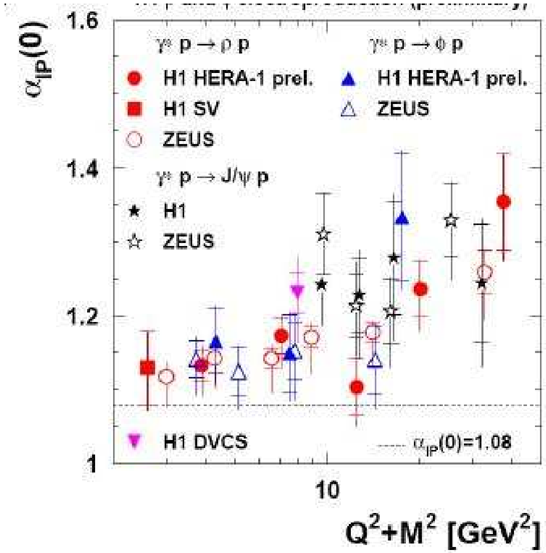


LO 2 gluons

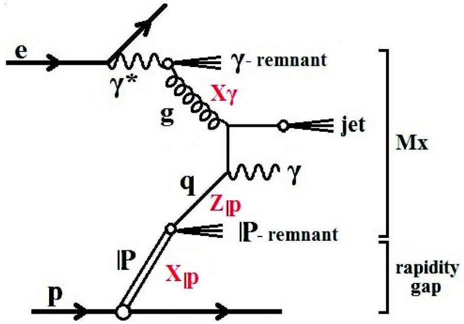


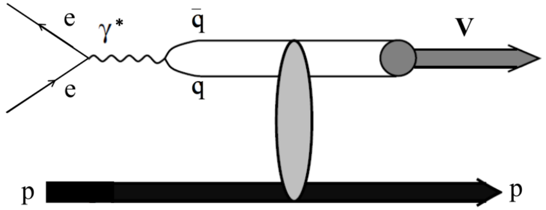
LL1/x ladder

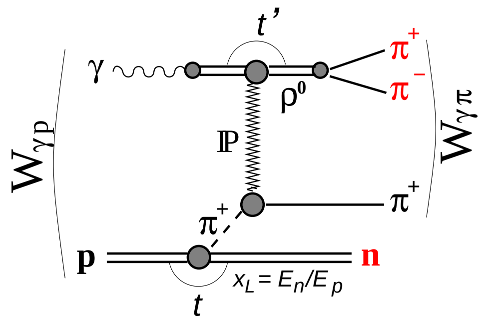




Selected new Results







■ Diffractive Photoproduction of Isolated Photons [ZEUS-prel-2015]

■ D^* Meson Production in Diffractive DIS at HERA [H1-prel-2016]

■ Cross-section Ratio $\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}}$ in Exclusive DIS [ZEUS-pub-2016]

■ Exclusive ρ^0 Meson Photoproduction with a Leading Neutron [H1-pub-2016]

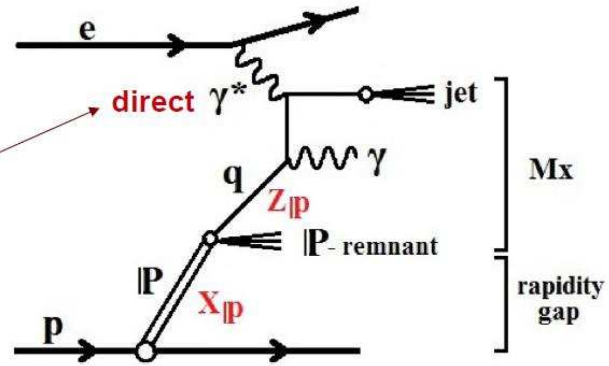
Isolated Photons in Diffractive Photoproduction

Isolated Photons in Diffractive PHP

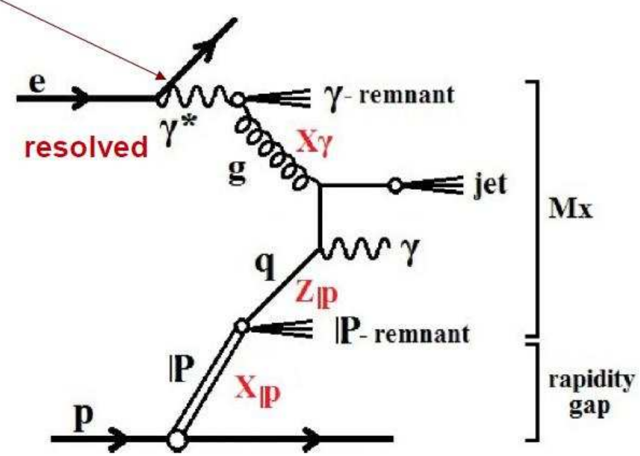
Examples of lowest-order diagrams
by which diffractive processes may generate a prompt photon

Direct incoming photon gives all its energy to the hard scatter ($x_\gamma = 1$).

Resolved incoming photon gives fraction x_γ of its energy.

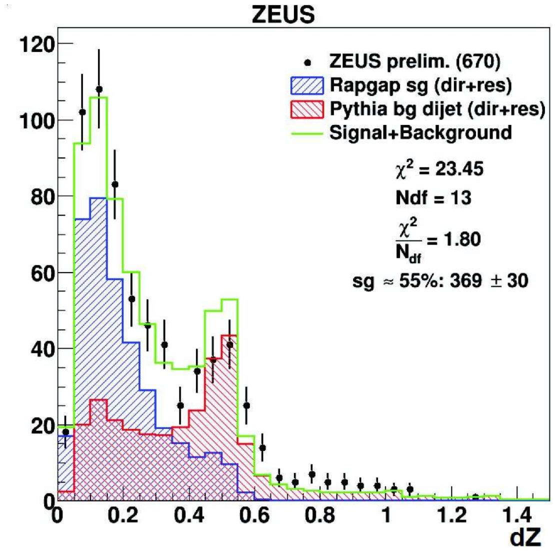


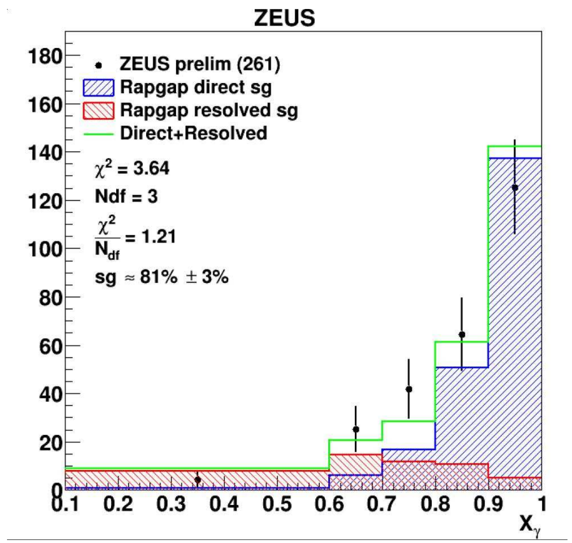
An outgoing photon must couple to a charged particle line and so the exchanged colourless object (“pomeron”) must be resolved in these lowest-order processes.



$4 < E_t^\gamma < 15$ GeV

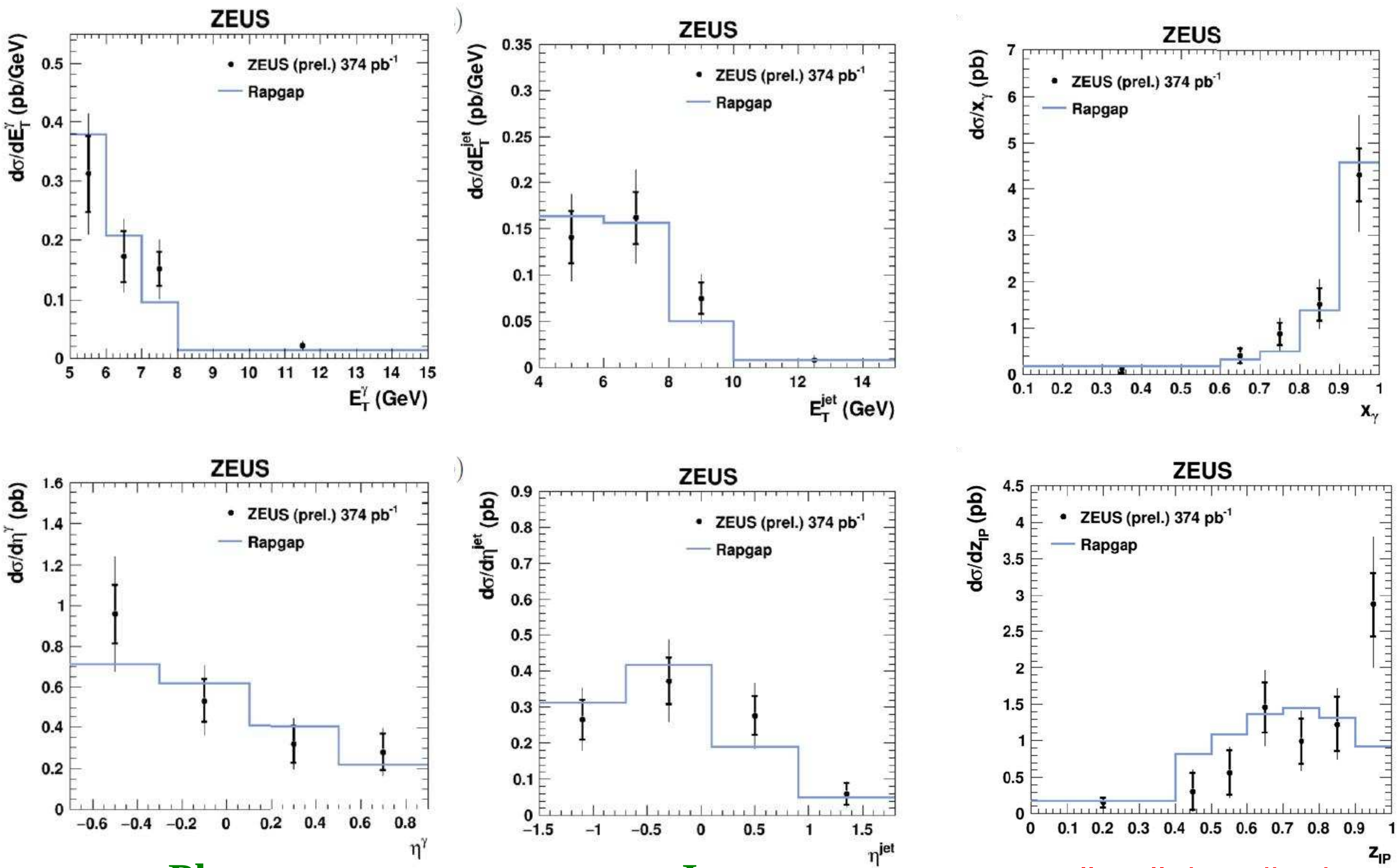
$-0.7 < \eta^\gamma < 0.9$





- Use energy-weighted e.m. cluster width $\langle \delta Z \rangle$ to distinguish γ from π^0, η background
- Diffraction: LRG signature, and $x_{I\!P} < 0.03$

Isolated Photon + Jet: Data vs MC model



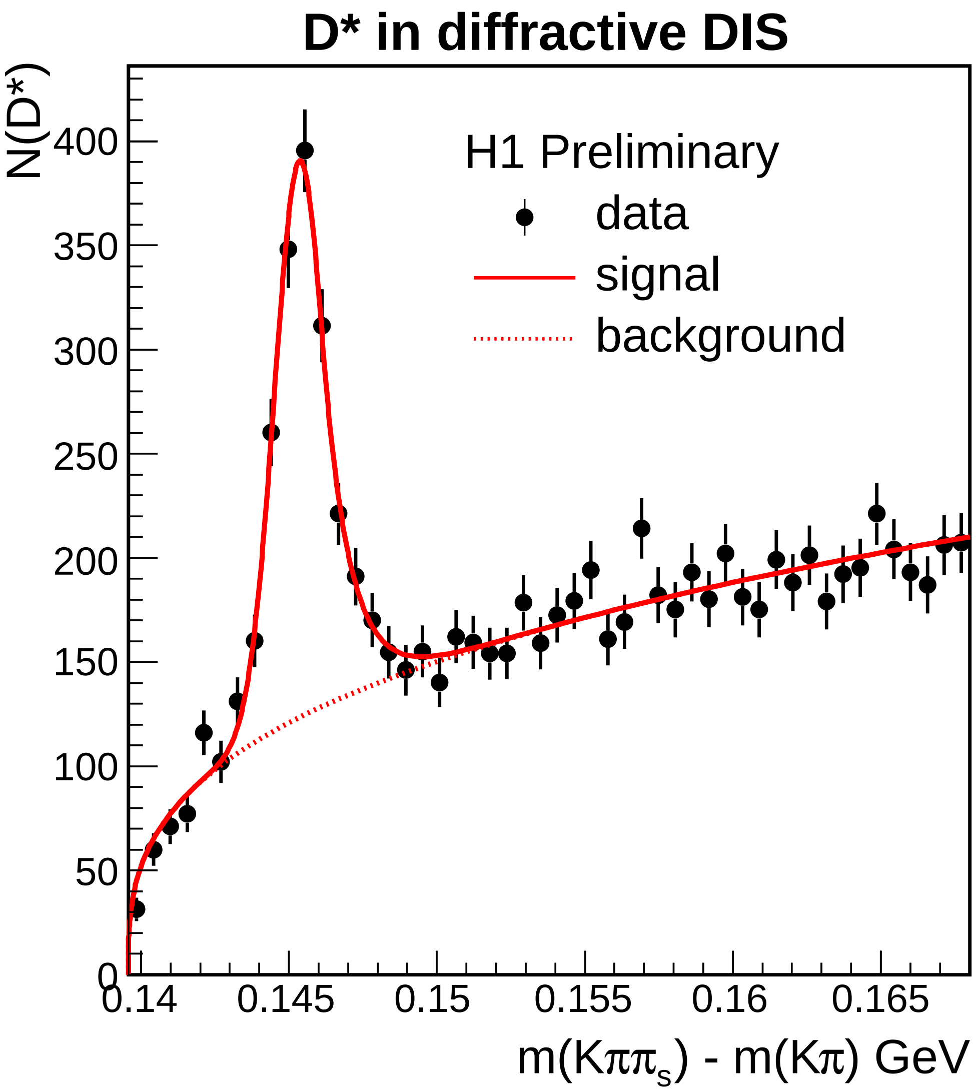
Photon **Jet**

All well described, except highest $z_{\mathbb{P}}$

Comparison with NLO QCD to follow

D^* in Diffractive DIS at HERA

D^* Production in Diffractive DIS: Data sample

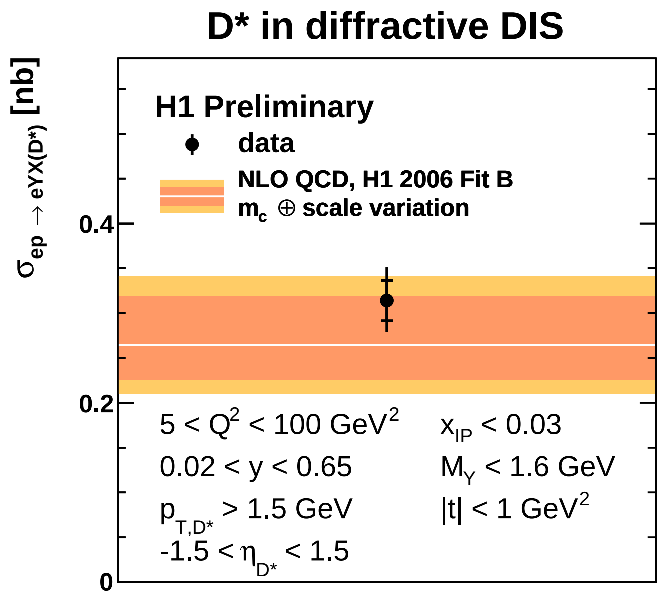


Based on $280\ \mathrm{pb}^{-1}$ HERA-2 data

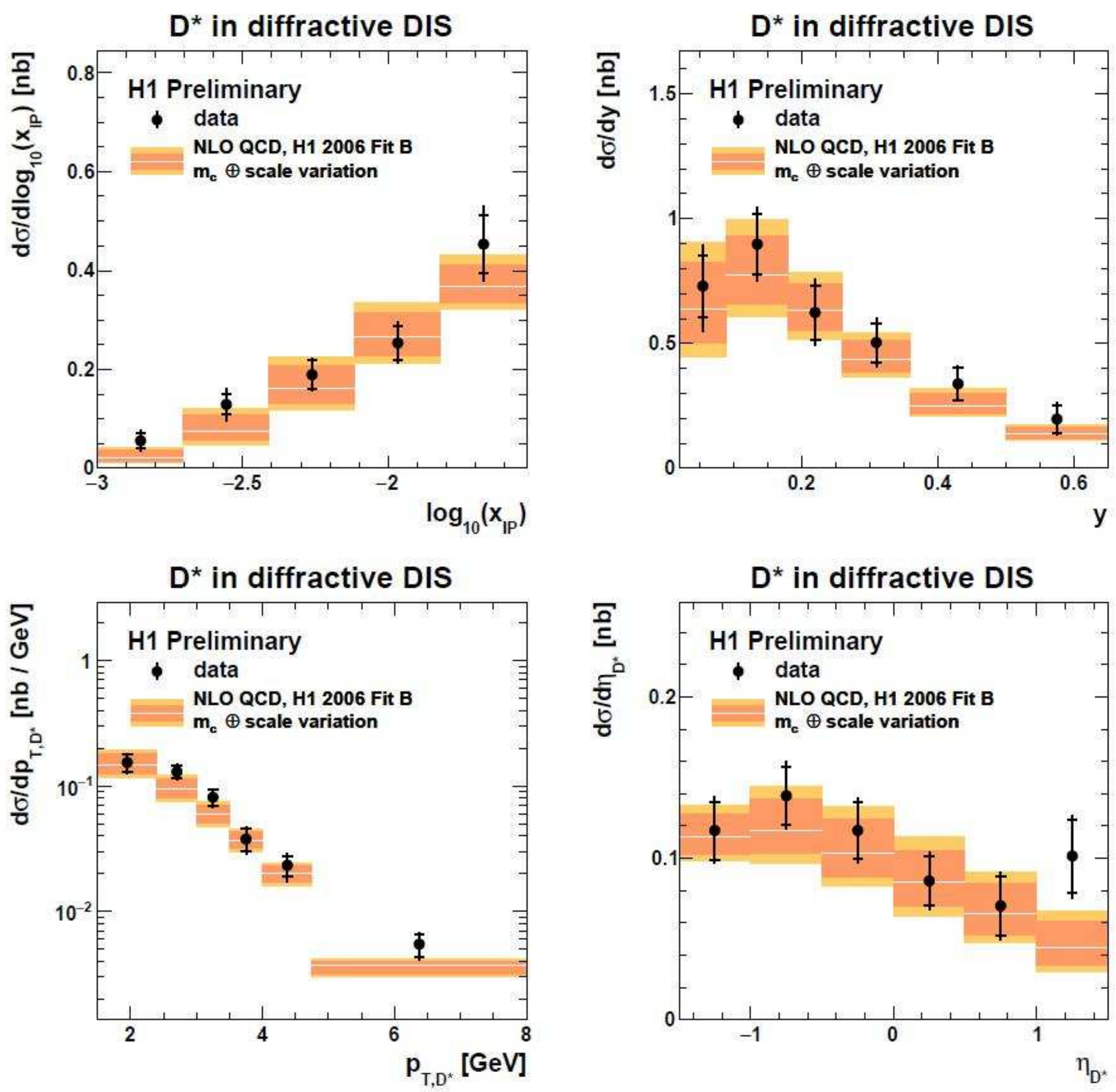
Open charm tagged with D^*

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

LRG selection of diffraction ($\sim 1100 D^*$)



D^* Production in Diffractive DIS: Data vs NLO

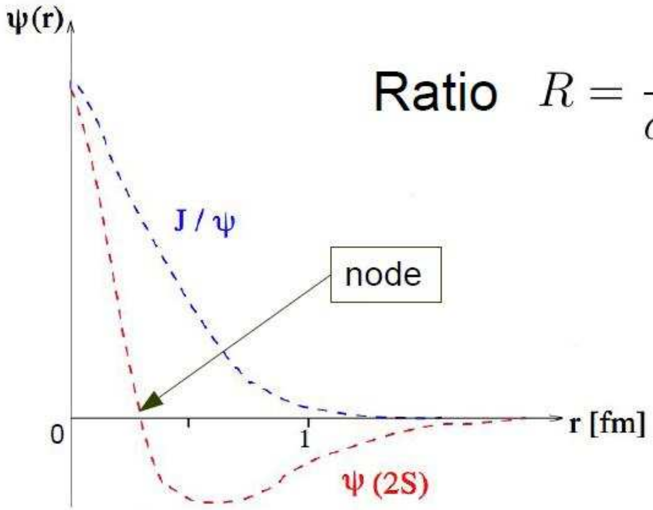


- NLO QCD by HQVDIS in FFNS (H1 DPDF-2006, $m_c = 1.5$GeV, $\mu_r^2 = \mu_f^2 = m_c^2 + 4Q^2$) in good agreement with data
- Charm fragm.func. as determined in H1 non-diffractive D^* analysis works here ⇒ supports universality of charm fragmentation
- Data could be used as additional input to the global DPDF fit

Cross–section Ratio $\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}}$ in DIS

Motivation

$\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in DIS

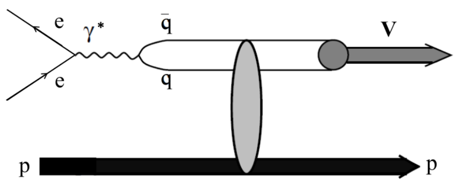


Ratio $R = \dfrac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi\, p}}$ gives information about the dynamics of hard process

sensitive to radial wave function of charmonium

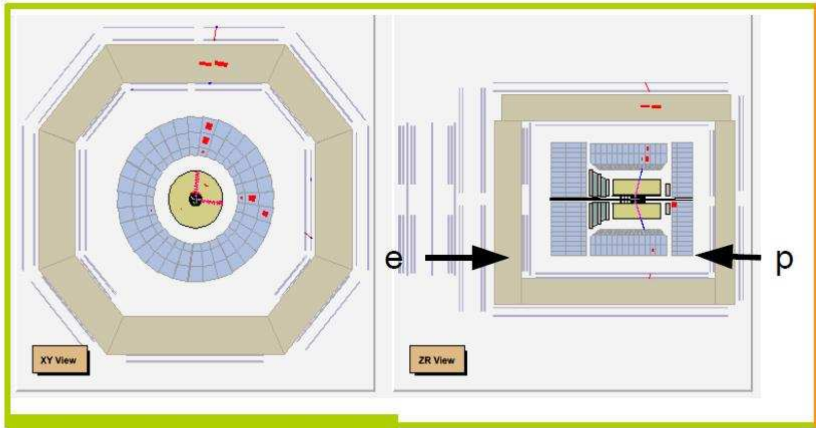
ψ(2S) wave function different from J/ψ wave function:

- Has a node at ≈ 0.35 fm
- $<r^2_{\psi(2S)}> \approx 2 <r^2_{J/\psi(1S)}>$

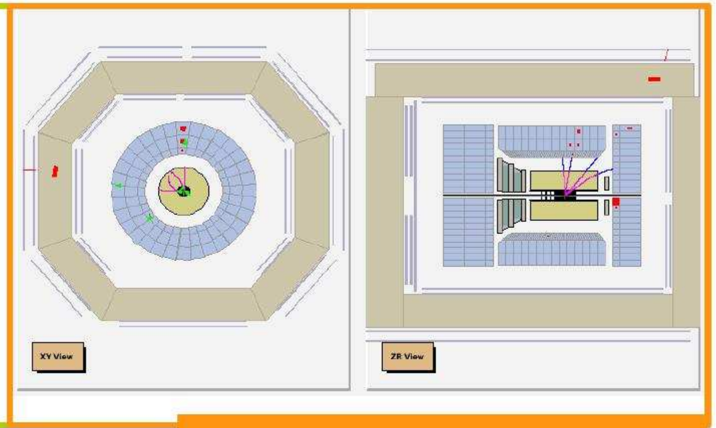


pQCD predictions: $R(Q^2 = 0) \simeq 0.17$ and rises with Q^2

Data samples and Decay channels



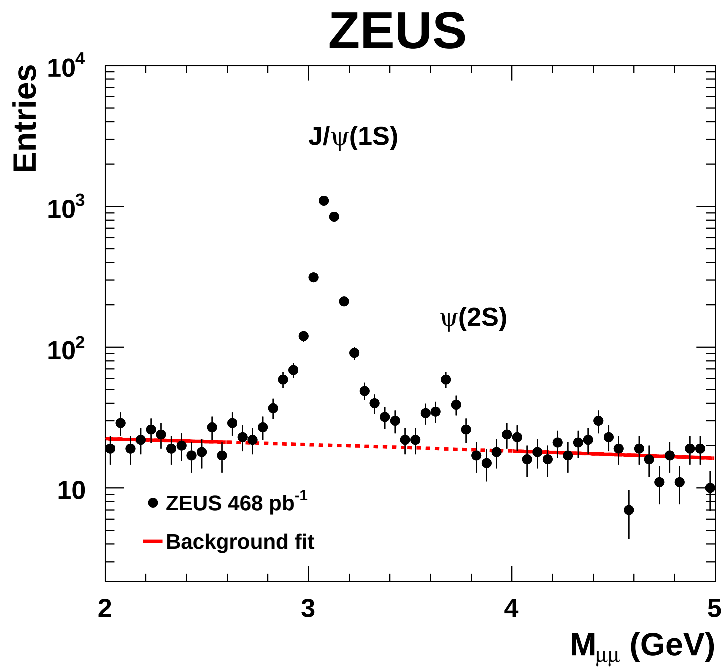
$J/\psi(1S) \to \mu^+\mu^-$



$\psi(2S) \to J/\psi(1S)\,\pi^+\pi^-$

$\psi(2S) \to J/\psi(1S)\,\pi^+\pi^-$; $J/\psi(1S) \to \mu^+\mu^-$
$\psi(2S) \to \mu^+\mu^-$
$J/\psi(1S) \to \mu^+\mu^-$

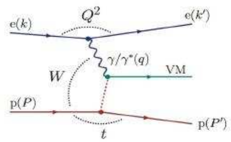
$5 < Q^2 < 80\,\mathrm{GeV}^2 \quad \mathcal{L} = 468\,\mathrm{pb}^{-1}$



Data samples

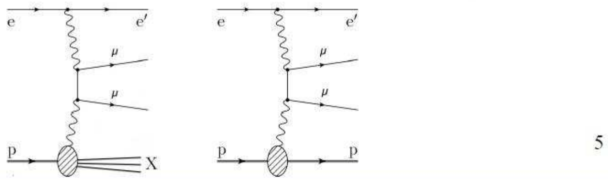
HERA I + HERA II data (1996 — 2007)
Integrated luminosity: 468 pb^{-1}

MC-data samples

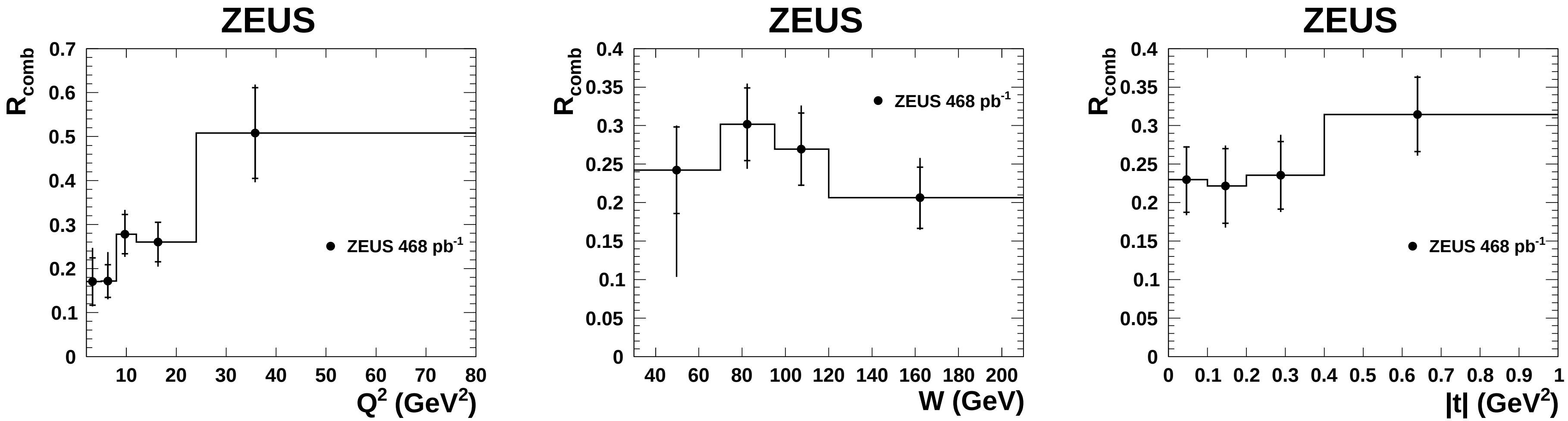


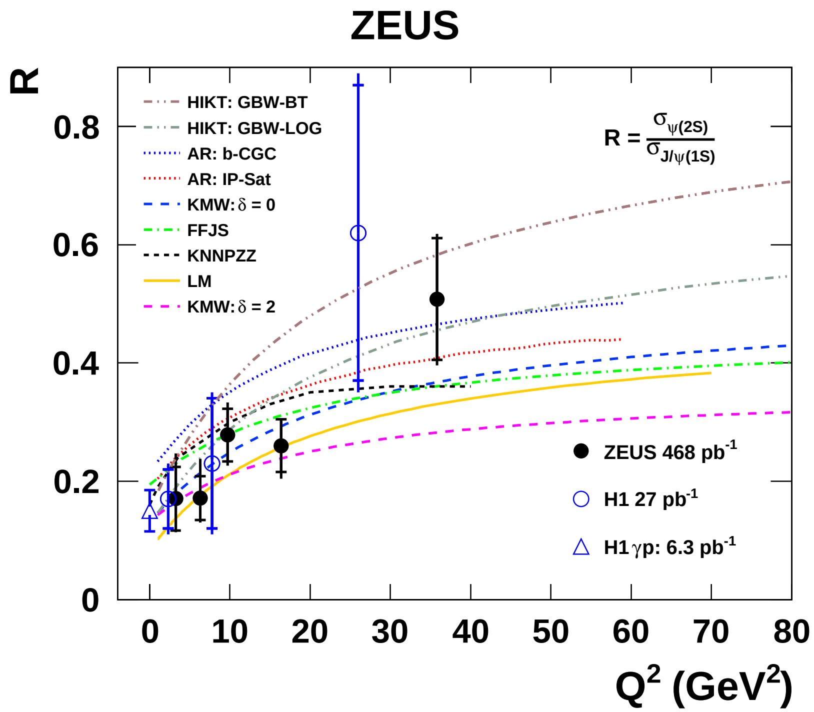
Signal MC: DIFFVM for exclusive VM production

Background MC: GRAPE for Bethe-Heitler mu-pair production



Results: $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ vs Q^2, W and $|t|$



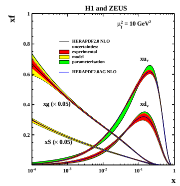


- Ratio rises with Q^2 and is constant in W and $|t|$
- HERA data in qualitative agreement with pQCD models
- Some discriminating power (albeit statistically limited)

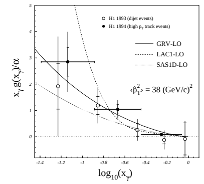
Rho–0 with a Leading Neutron at HERA

HERA as a ‘$4P$’ facility

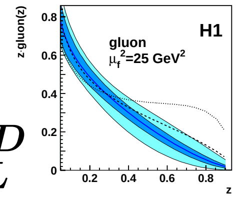
HERA enables to study structure of



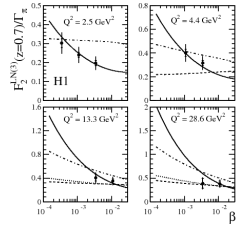
Proton – $F_2, F_L, \ldots$



Photon – g/γ



Pomeron – F_2^D, F_L^D

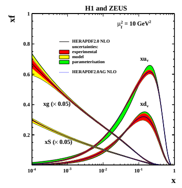


Pion – F_2^π

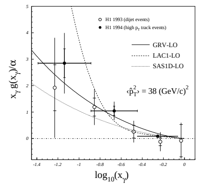
HERA as a '$4P$' facility

HERA enables to study structure of

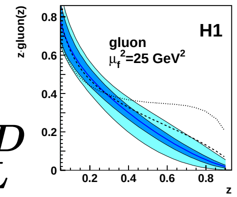
Proton – $F_2, F_L, \ldots$



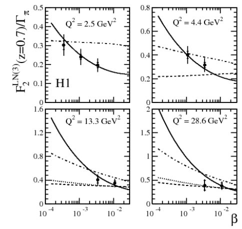
Photon – g/γ



Pomeron – F_2^D, F_L^D

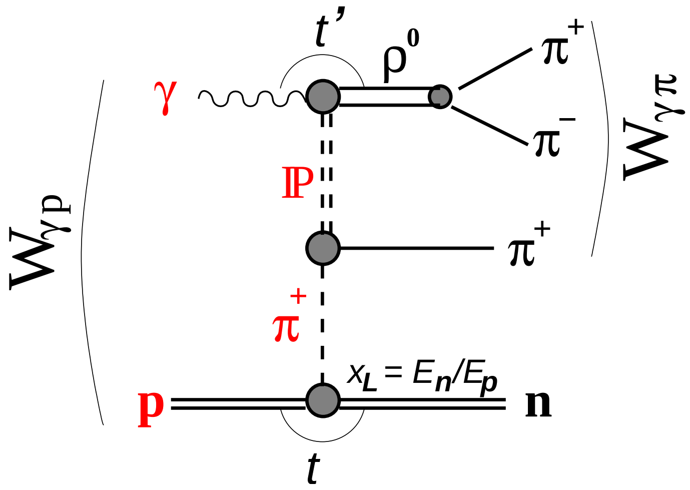


Pion – F_2^π



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

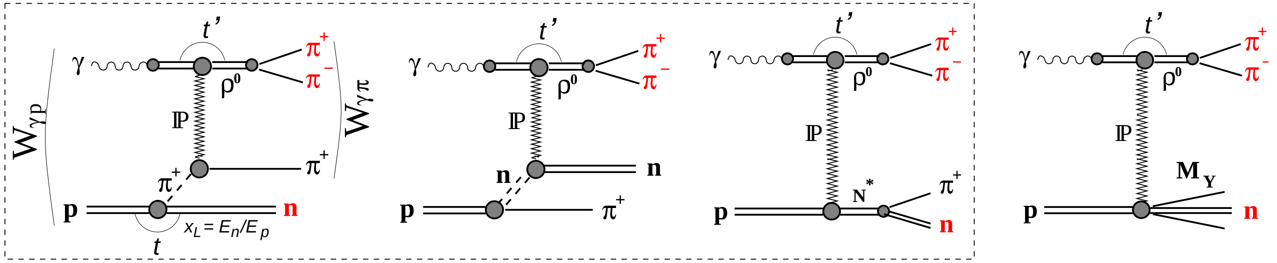
$$\gamma + p \longrightarrow \rho^0 \pi^+ n$$



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

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

ρ^0 with Leading Neutron: S/B decomposition



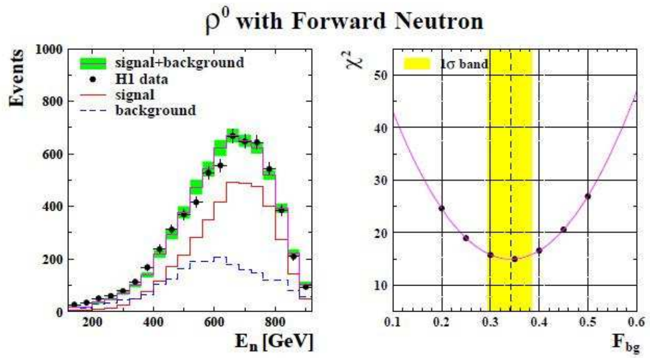
(a) (b) (c) (d)

Data sample: $\mathcal{L} = 1.16\ \text{pb}^{-1}$

~ 7000 events

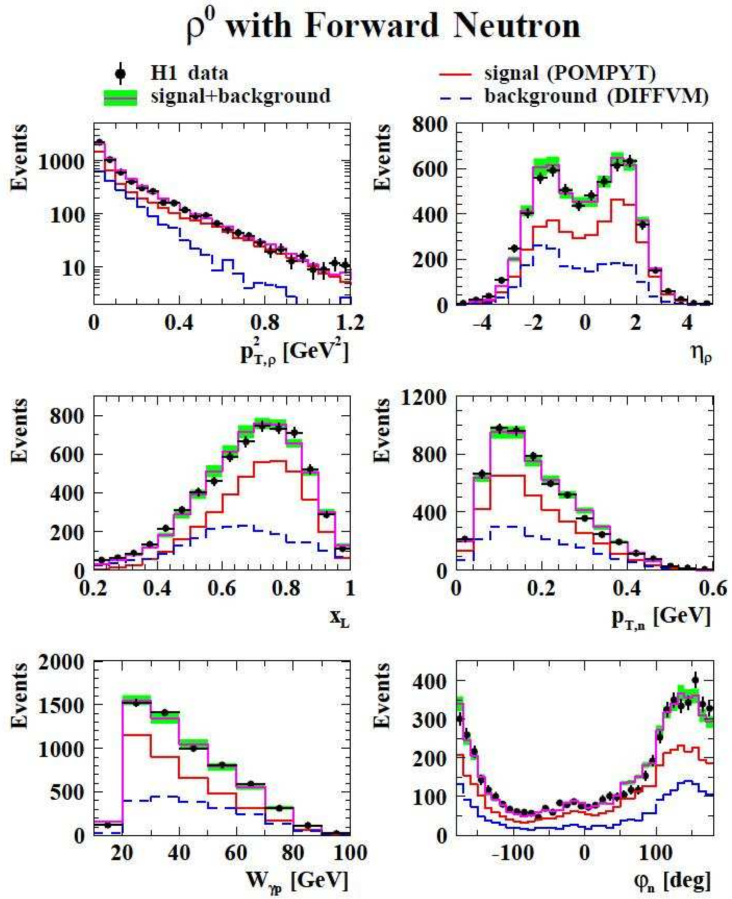
Precision: $\delta_{stat} = 2\%$

$\delta_{sys} = 14\%$



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

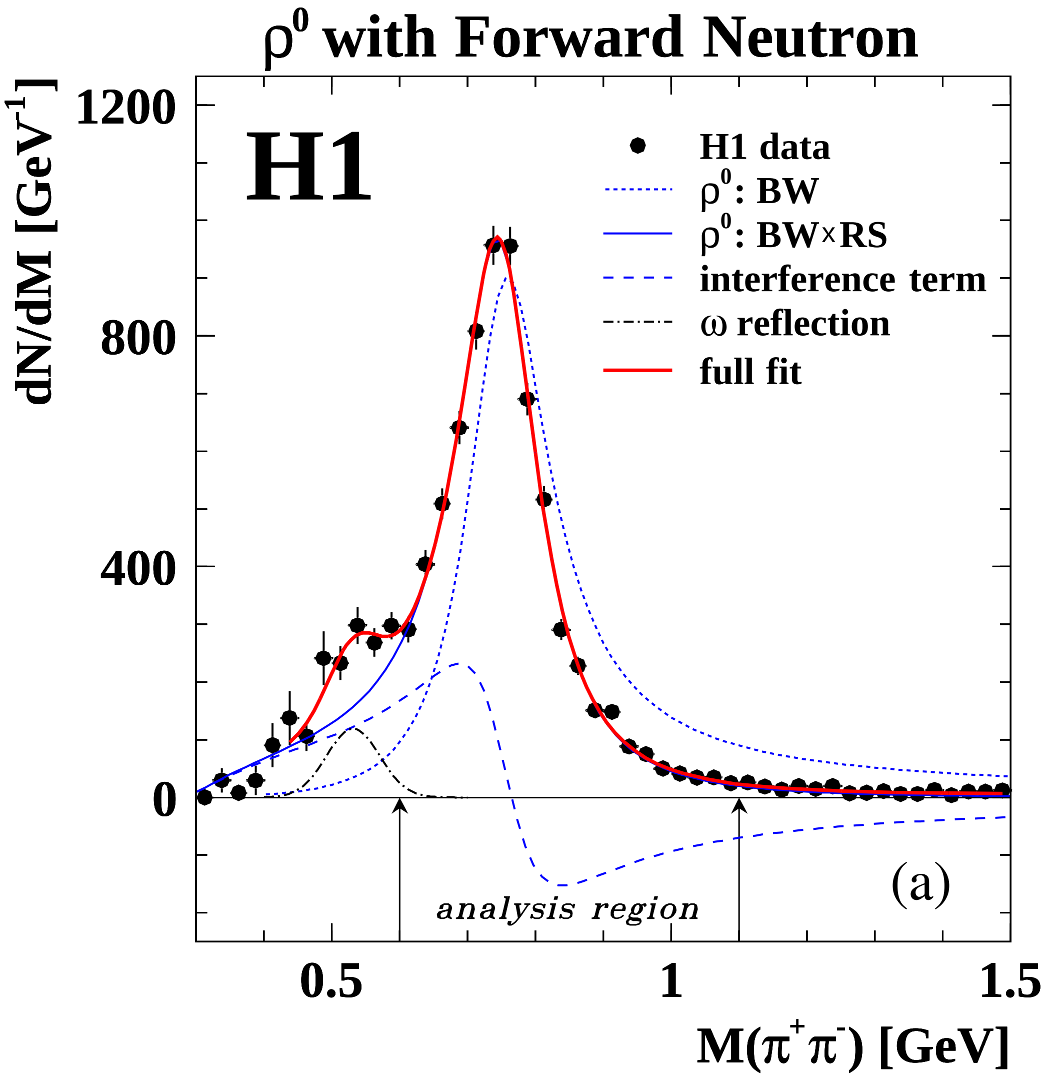
$F_{bg} = 0.34 \pm 0.05$



Data points are shown with statistical errors only;

green band represents estimated background fraction uncertainty

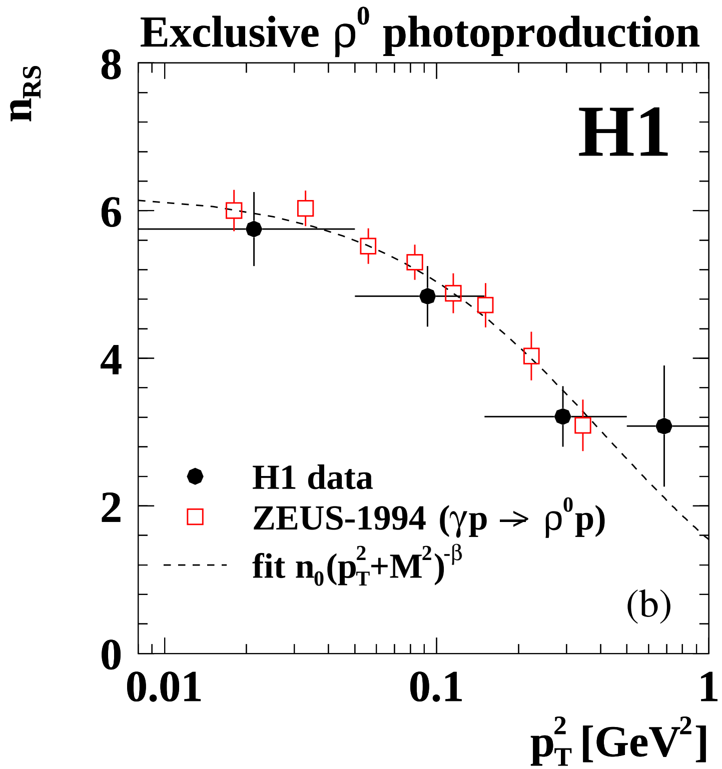
ρ-meson shape



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

$M = 764 \pm 3$ MeV

$\Gamma = 155 \pm 5$ MeV

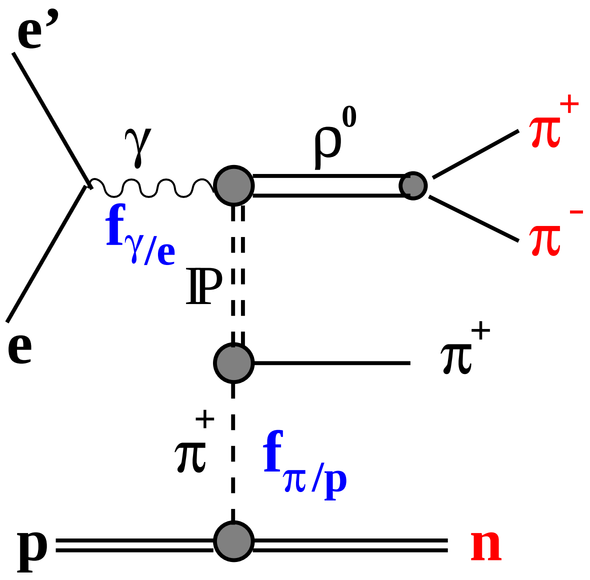


Analysis region: $0.6 < M_{\pi^+\pi^-} < 1.1$ GeV extrapolated using BW to the full range: $0.28 < M_{\rho^0} < 1.5$ GeV

Cross sections definitions

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

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



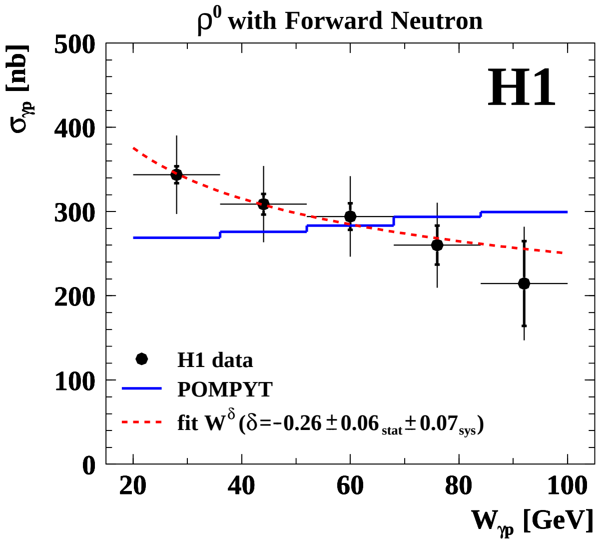
$$\sigma_{\gamma\pi} = \frac{\sigma_{\gamma p}}{\Gamma_\pi}$$

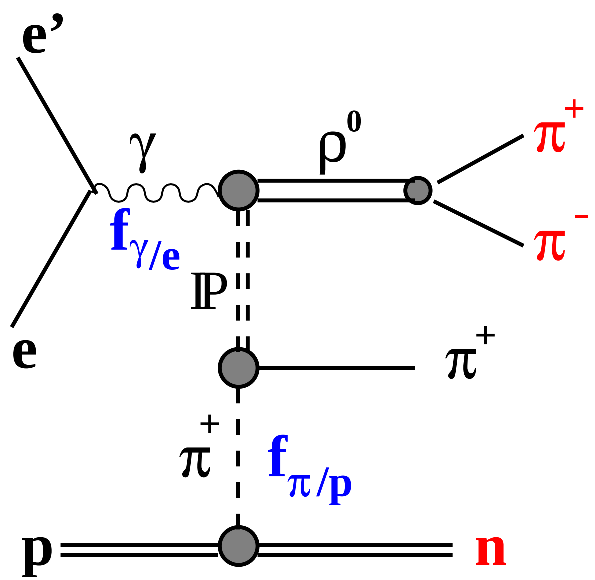
$$\Gamma_\pi = \int f_{\pi/p}(x_L, t)\mathrm{d}x_L\mathrm{d}t$$

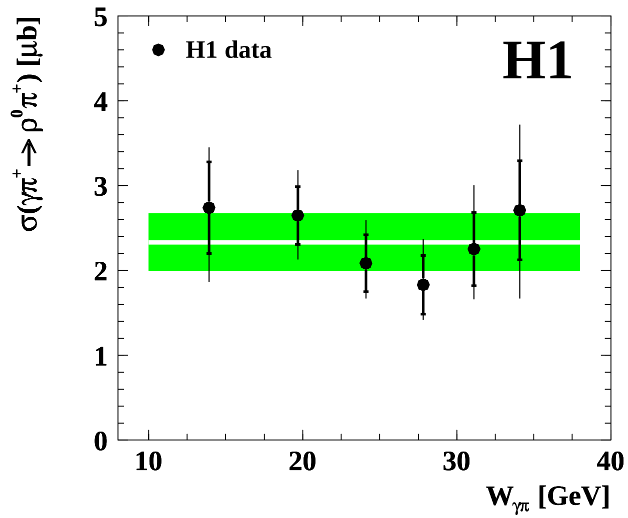
VMD: $$f_{\gamma/e}(y, Q^2) = \frac{\alpha}{2\pi Q^2 y}\left\{\left[1 + (1-y)^2 - 2(1-y)\left(\frac{Q^2_{\min}}{Q^2} - \frac{Q^2}{M_\rho^2}\right)\right]\frac{1}{\left(1+\frac{Q^2}{M_\rho^2}\right)^2}\right\}$$

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

Cross sections definitions



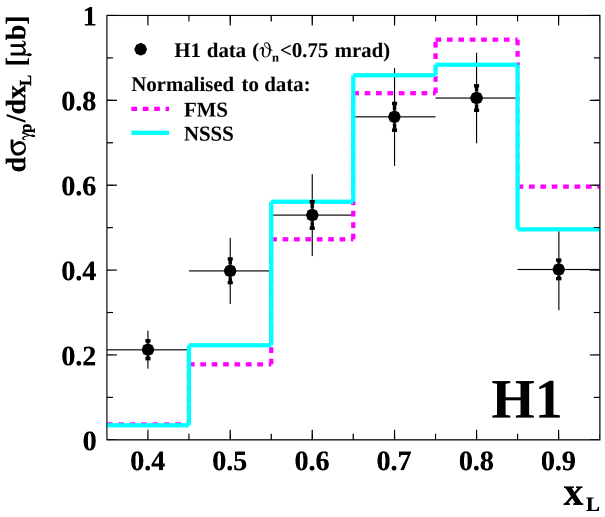


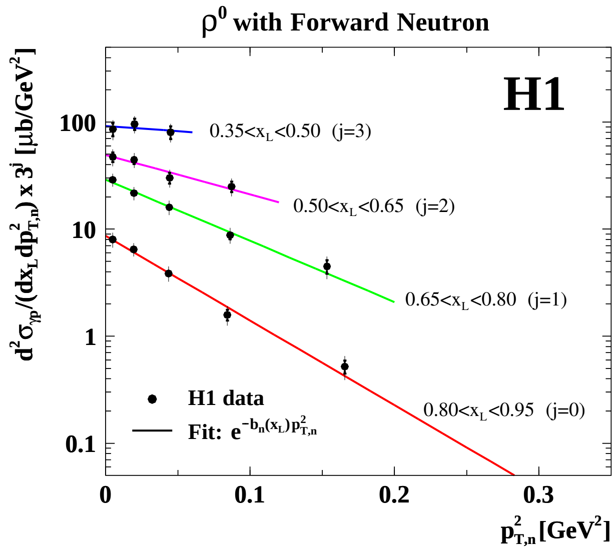


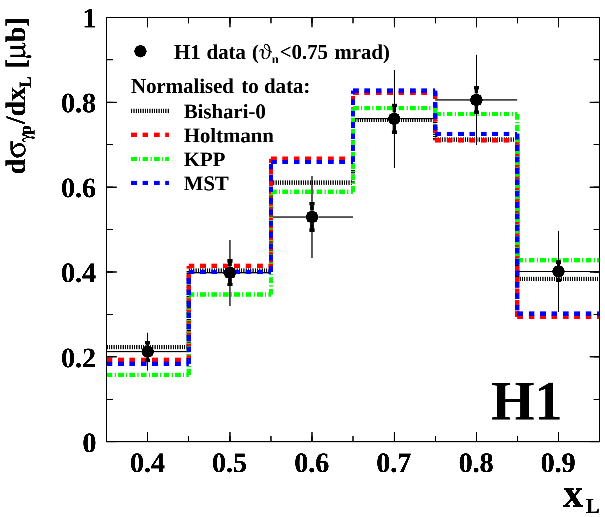
VMD:
$$f_{\gamma/e}(y,Q^2) = \frac{\alpha}{2\pi Q^2 y}\left\{\left[1+(1-y)^2 - 2(1-y)\left(\frac{Q^2_{\min}}{Q^2} - \frac{Q^2}{M_\rho^2}\right)\right]\frac{1}{\left(1+\frac{Q^2}{M_\rho^2}\right)^2}\right\}$$

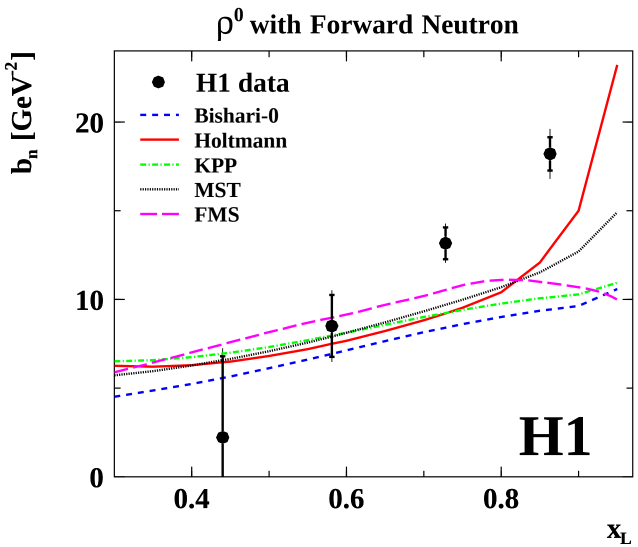
OPE:
$$f_{\pi/p}(x_L,t) = \frac{1}{2\pi}\frac{g^2_{p\pi N}}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\exp[-R^2_{\pi n}\frac{m_\pi^2-t}{1-x_L}]$$

Constraining pion flux







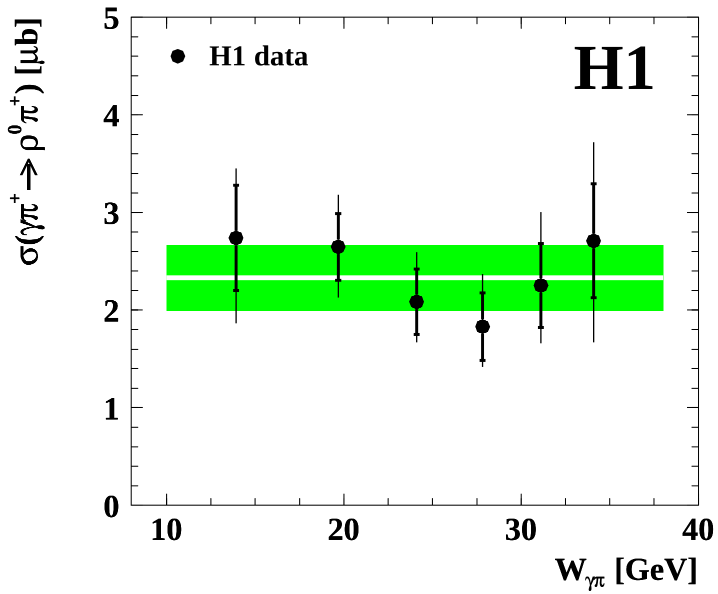


Failure to describe $b_n(x_L)$ suggests strong absorptive effects (n rescattering) $\Rightarrow$ try to quantify

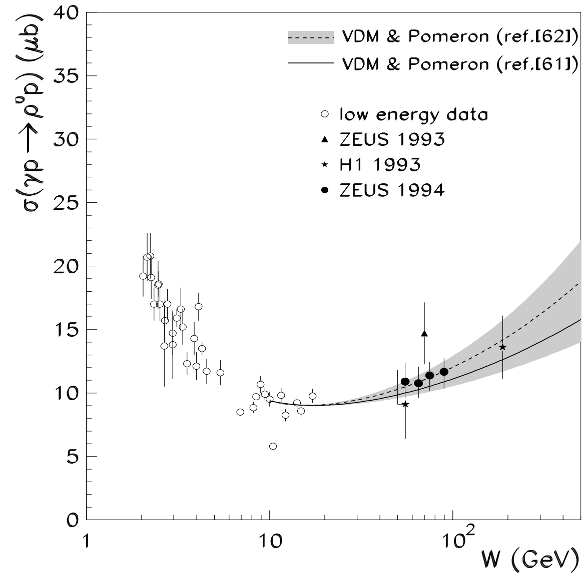
Estimate of absorption corrections

$(2.33 \pm 0.56)\mu$b

$\gamma\pi$



$(9.5 \pm 0.5)\mu$b



γp

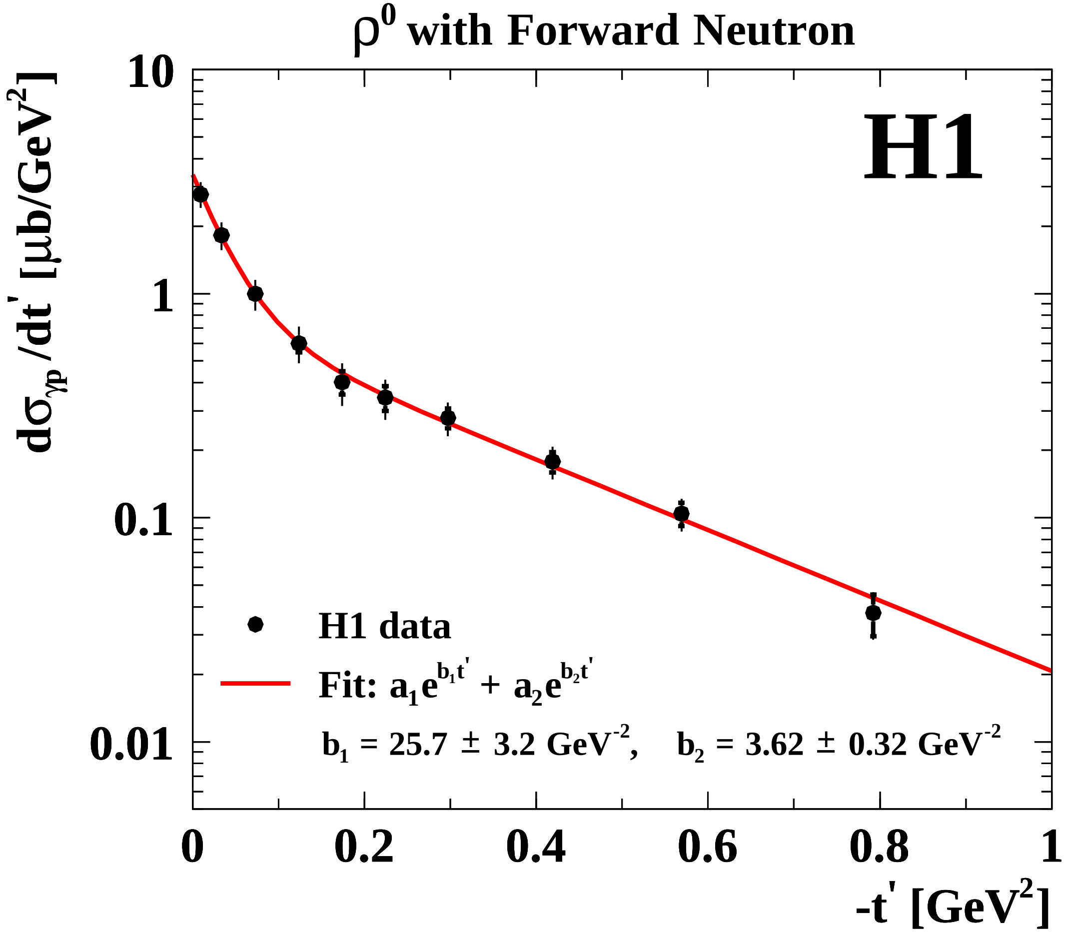
$$r_{\rm el} = \frac{\sigma^{\gamma\pi \to \rho^0\pi}}{\sigma^{\gamma p \to \rho^0 p}} = \begin{cases} 0.25 \pm 0.06 & \text{(exp.extracted)} \\ 0.57 \pm 0.03 & \text{(theo.expected)} \end{cases} \Rightarrow K_{\rm abs} = 0.44 \pm 0.11$$

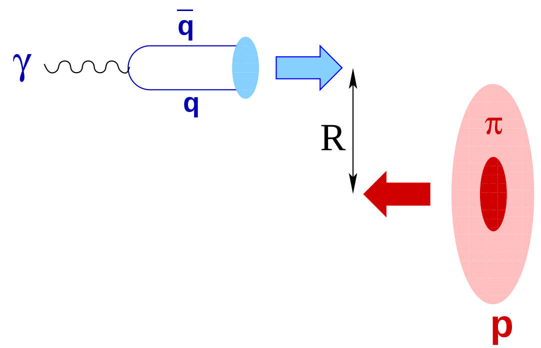
Optical Theorem: $\frac{d\sigma_{el}}{dt}\big|_{t=0} = b_{\rm el}\sigma_{\rm el} \propto \sigma_{\rm tot}^2 \Rightarrow r_{\rm el} = (\frac{b_{\gamma p}}{b_{\gamma\pi}}) \cdot (\sigma_{\rm tot}^{\gamma\pi}/\sigma_{\rm tot}^{\gamma p})^2$

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

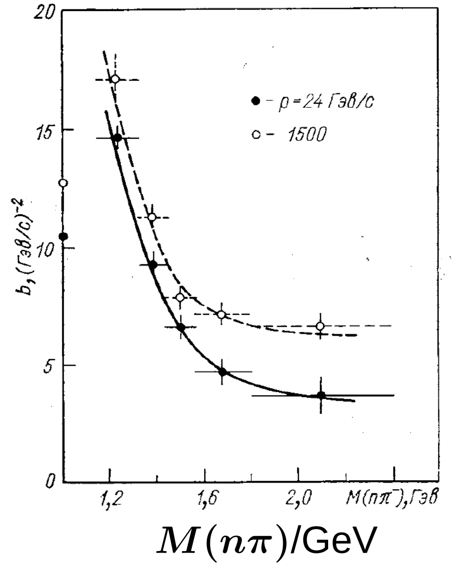
World data: $(b_{pp} \simeq 11.7, \ \ b_{\pi^+ p} \simeq 9.6, \ \ b_{\gamma p} \simeq 9.75)$ GeV^{-2}

Differential cross section in $p_{T,\rho}^2$





ISR



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

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

Summary

- Diffraction is an important part of HERA physics landscape. Despite overall consistent picture, the field is challenging, as it represents a complicated interplay of soft and hard phenomena.

- Statistically limited channels have been studied with full HERA data sample. Whenever a hard scale is present, pQCD calculations are successful.

- The data show sensitivity to some QCD models parameters. They can also be used to further constrain DPDF, especially at high $z_{I\!P}$.

- Photon-pion elastic cross section is extracted experimentally (in OPE approximation) for the first time.

- Strong absorptive effects are confirmed in Leading Neutron production. Since the nature of these is non-perturbative, exp. results are essential for tuning models of ‘Survival Gap Probability’.

Backup Slides

Open questions

- $F_2^{D(4)}$ from HERA-II VFPS data and final DPDF determination without assumption on Regge factorisation.

- Explain factorisation breaking mechanizm in PHP, in particular independence of Gap Survival Probability on x_γ.

- Multiscale problem: (Q^2, E_T, M_V, t).

- Where is an Odderon ?

- Can one observe Glueball in a double Pomeron reaction in PHP?
  $\gamma p \longrightarrow (\mathbb{P}\mathbb{P}) \longrightarrow M_X \quad (M_X = \sqrt{x_{\mathbb{P}1} x_{\mathbb{P}2}} W_{\gamma p} = 2 \div 4 \,\mathrm{GeV})$

HERA has finished, but not DIS physics.
What's next? **eRHIC ?** **LHeC ?**