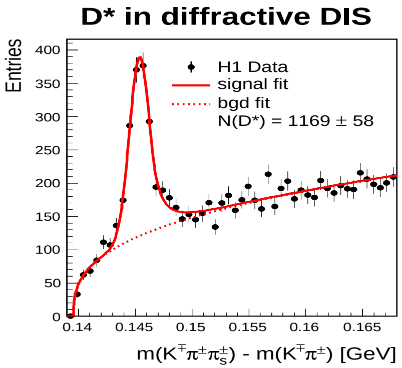
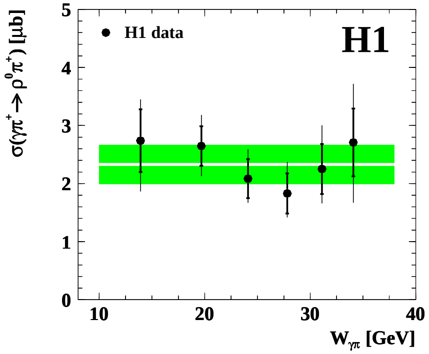
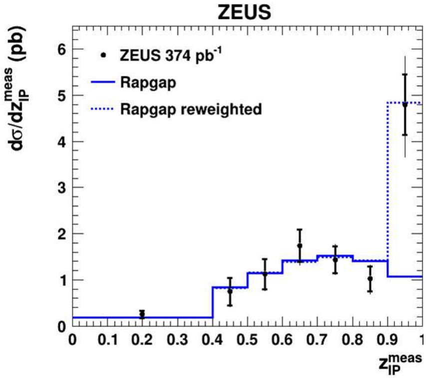
18-th Lomonosov Conference
on Elementary Particle Physics
August 24-30, 2017 Moscow, Russia

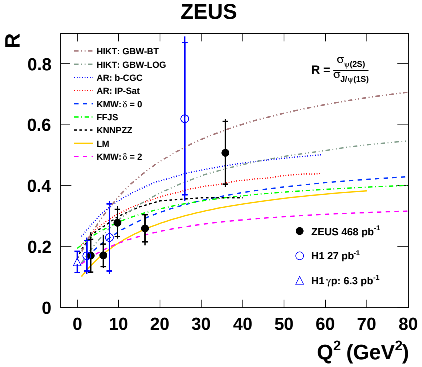
New Results on Diffraction at HERA

S. Levonian, DESY

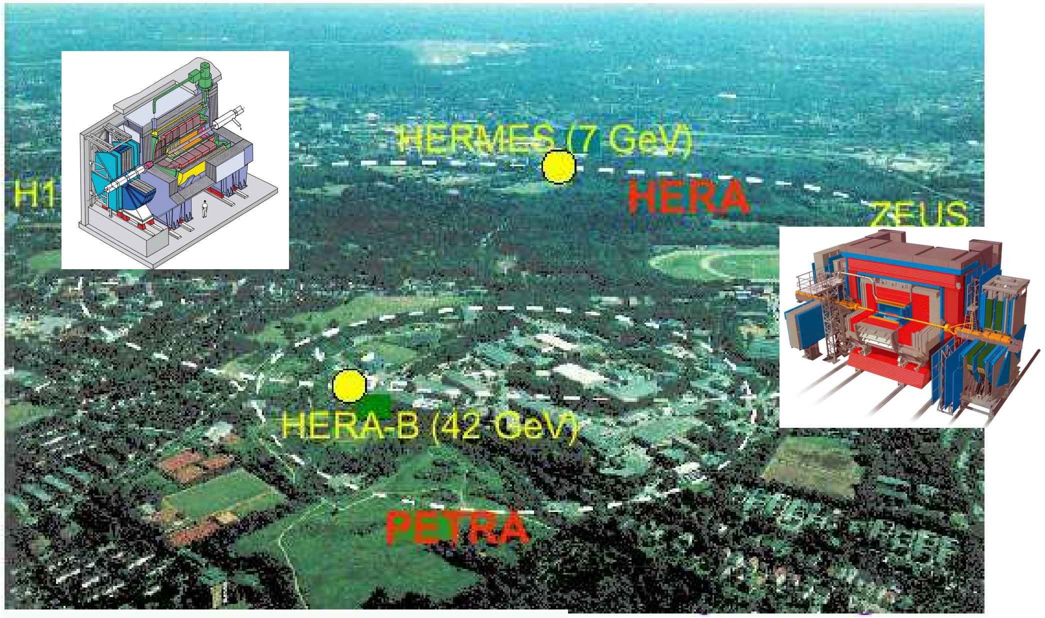








HERA: The World's Only ep Collider

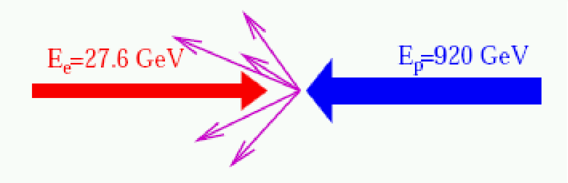


HERA-1 (1993-2000) $\simeq 120$ pb^{-1}

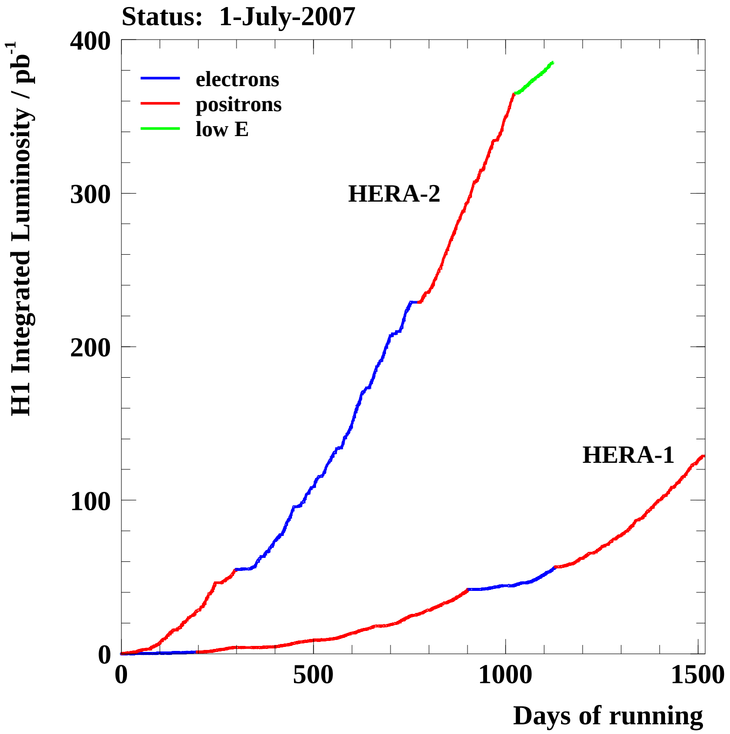
HERA-2 (2003-2007) $\simeq 380$ pb^{-1}

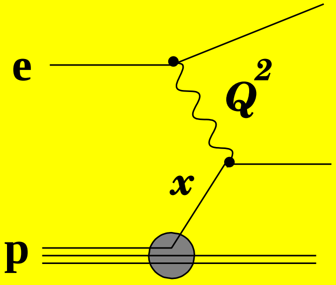
Final Data samples

H1+ZEUS: 2×0.5 fb^{-1}



$(\sqrt{s} = 319$ GeV$)$





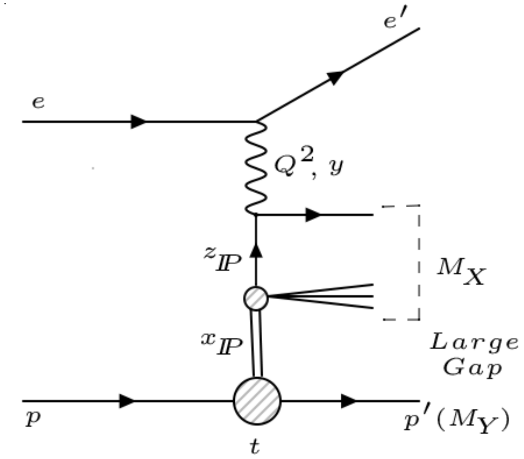
$Q^2 > 1$ **GeV^2**

Deep Inelastic Scattering (DIS)

$Q^2 \approx 0$ **GeV^2**

Photoproduction (PHP)

Diffraction at HERA

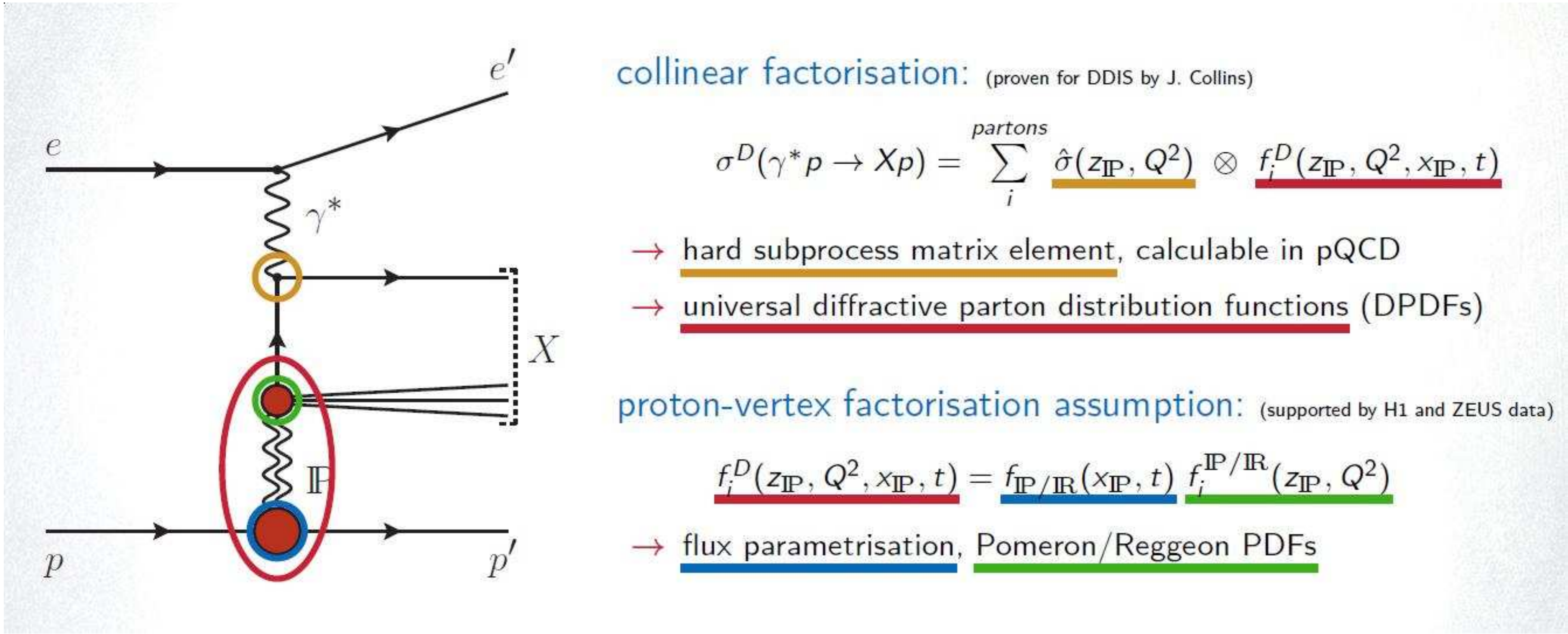


Q^2, y – standard DIS variables

$t = (p - p')^2$ – 4-momentum transfer squared at the proton vertex

$x_{I\!P}$ – proton momentum fraction carried by the colour singlet exchange (Pomeron)

$z_{I\!P} = x/x_{I\!P}$ – fractional long.mom. of the Pomeron transferred to hard subpr.



collinear factorisation: (proven for DDIS by J. Collins)

$$\sigma^D(\gamma^* p \to Xp) = \sum_i^{\text{partons}} \underline{\hat{\sigma}(z_{\mathbb{P}}, Q^2)} \otimes \underline{f_i^D(z_{\mathbb{P}}, Q^2, x_{\mathbb{P}}, t)}$$

→ hard subprocess matrix element, calculable in pQCD

→ universal diffractive parton distribution functions (DPDFs)

proton-vertex factorisation assumption: (supported by H1 and ZEUS data)

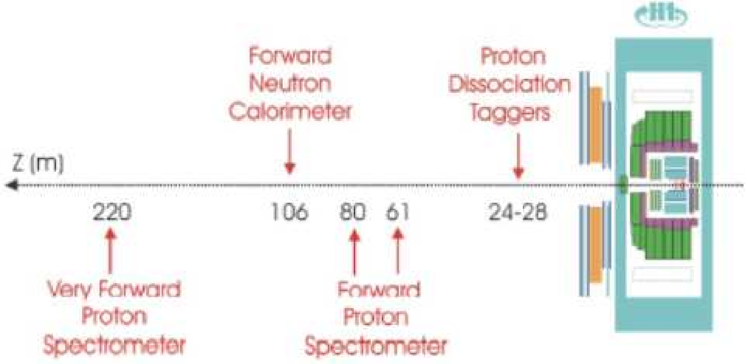
$$\underline{f_i^D(z_{\mathbb{P}}, Q^2, x_{\mathbb{P}}, t)} = \underline{f_{\mathbb{P}/\mathbb{R}}(x_{\mathbb{P}}, t)}\ \underline{f_i^{\mathbb{P}/\mathbb{R}}(z_{\mathbb{P}}, Q^2)}$$

→ flux parametrisation, Pomeron/Reggeon PDFs

Selection of Diffractive Events

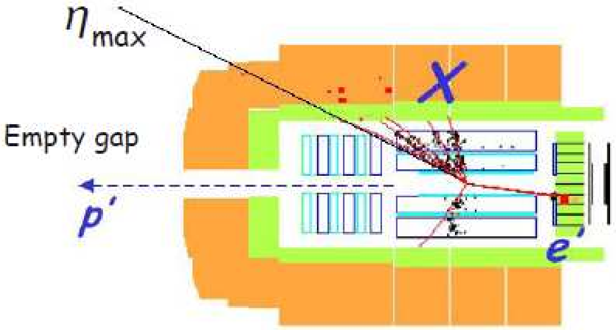
Measure the leading proton

➔ Forward spectrometers (H1 FPS/VFPS)



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

Measure a Large Rapidity Gap



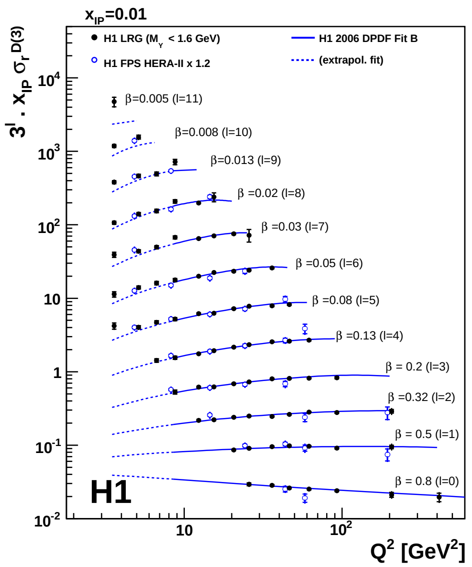
- Data integrated over |t| < 1 GeV^2
- High statistics
- Contamination from proton dissociation events

➔ Needs to be controlled

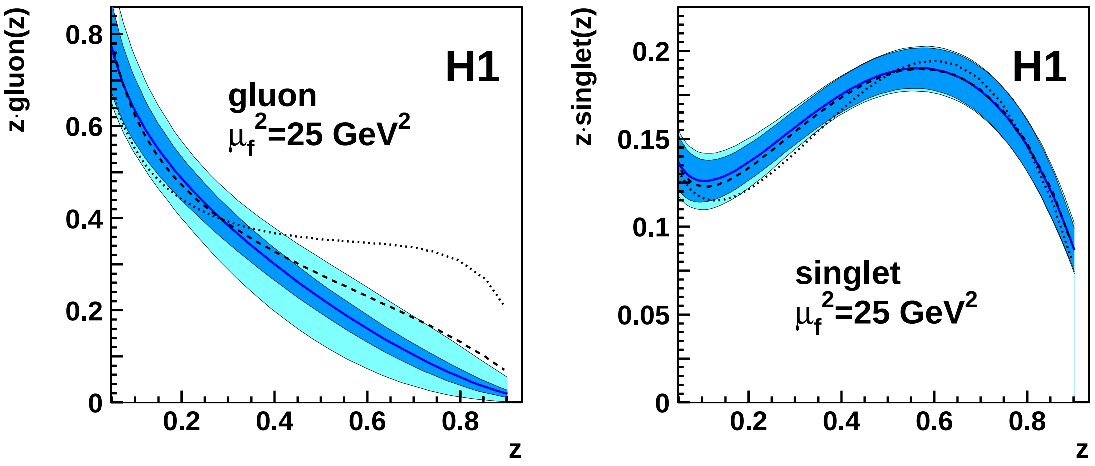
➘ Different systematics

➘ Different kinematic coverage

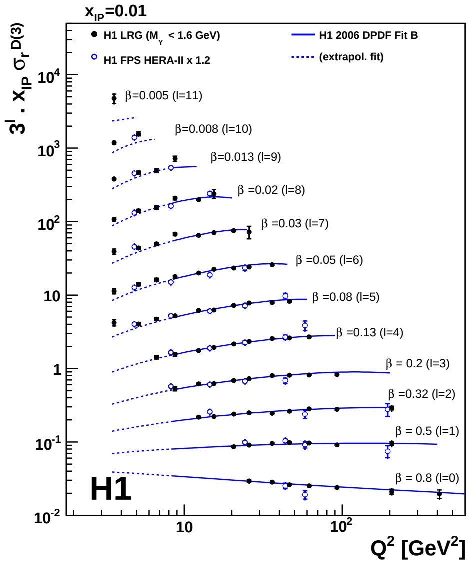
Inclusive and Exclusive Diffraction at HERA



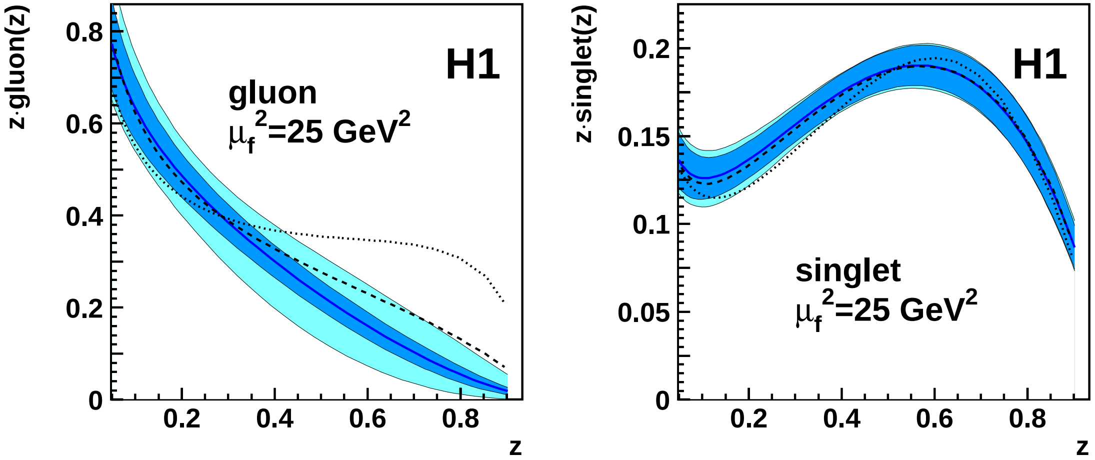
Inclusive Diffraction and DPDFs: gluon dominated $I\!P$



Inclusive and Exclusive Diffraction at HERA

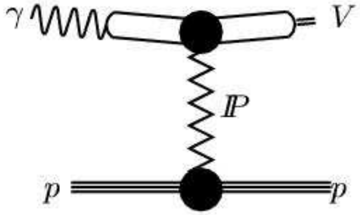


Inclusive Diffraction and DPDFs: gluon dominated $I\!P$

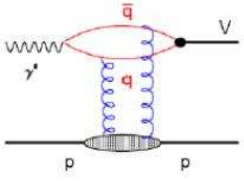


VM: soft vs hard $I\!P$

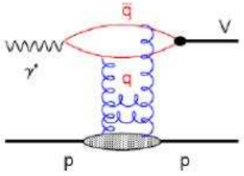
transition from soft to hard regime at $\mu^2 \simeq 4 \div 5$ GeV^2



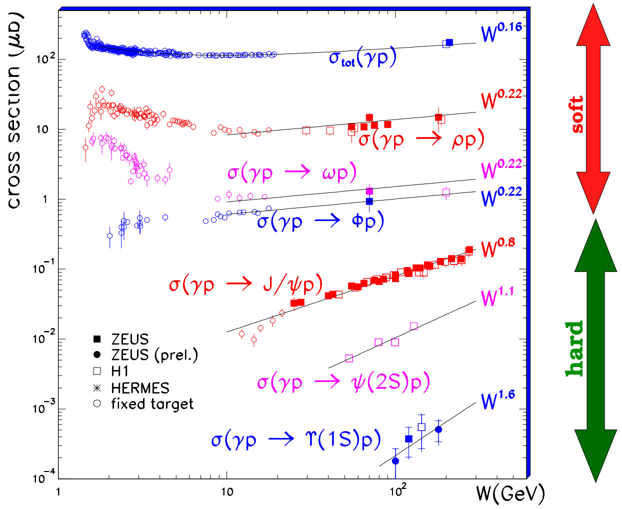
$\alpha_{I\!P}(t) = \alpha(0) + \alpha' t$

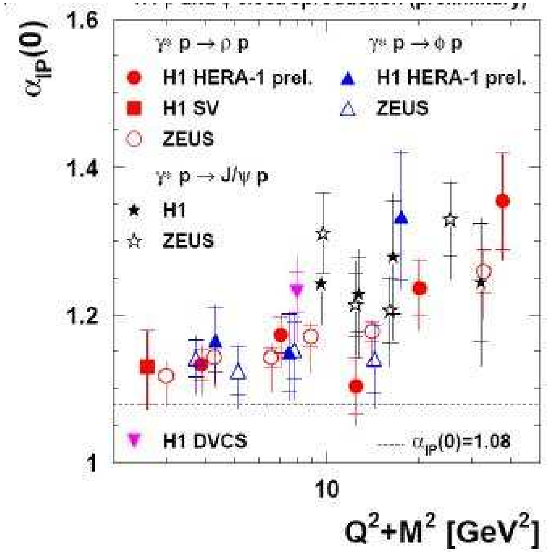


LO 2 gluons

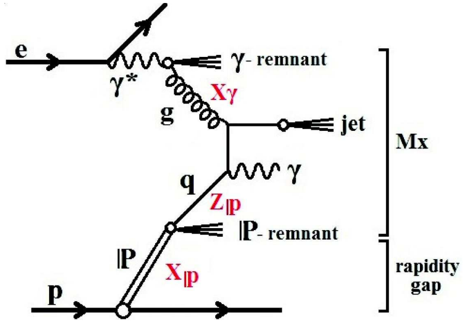


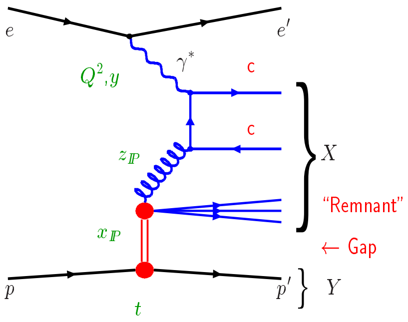
LL1/x ladder

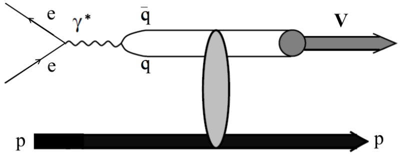


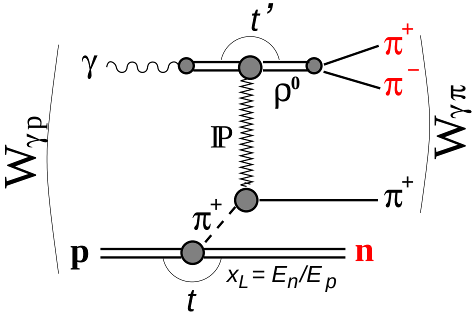


Selected new Results









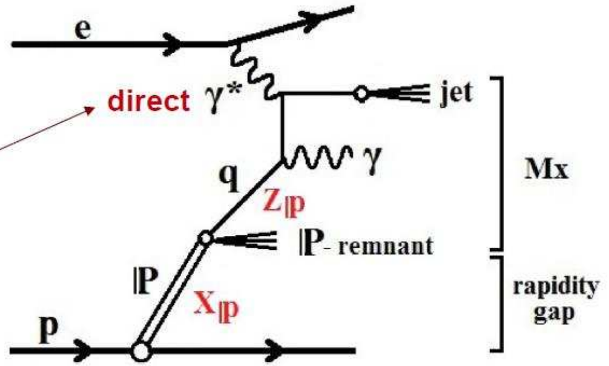
- ■ Diffractive Photoproduction of Isolated Photons [ZEUS-2017]
- ■ D^* Meson Production in Diffractive DIS at HERA [H1-2017]
- ■ Cross-section Ratio $\dfrac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}}$ in Exclusive DIS [ZEUS-2016]
- ■ Exclusive ρ^0 Meson Photoproduction with a Leading Neutron [H1-2016]

Isolated Photons in Diffractive Photoproduction

Isolated Photons in Diffractive PHP

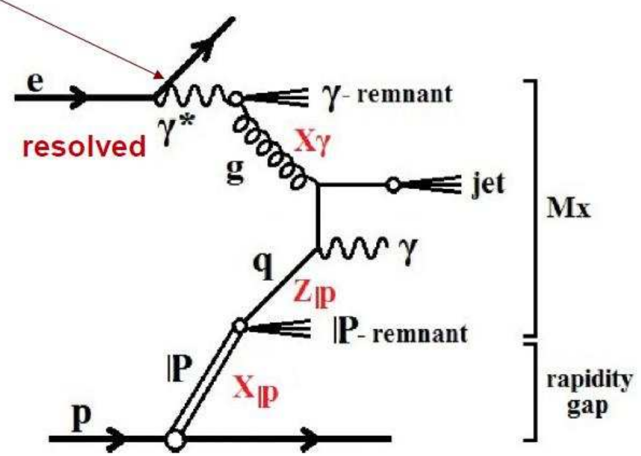
Examples of lowest-order diagrams
by which diffractive processes may generate a prompt photon

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.

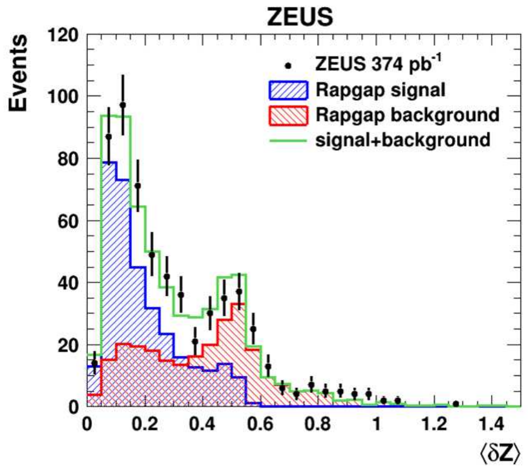


$5 < E_t^\gamma < 15$ GeV

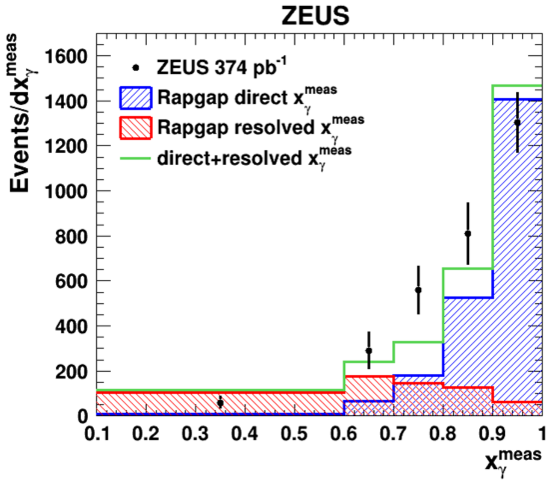
$-0.7 < \eta^\gamma < 0.9$

- Data: HERA-I – 82 pb^{-1}
  HERA-II – 374 pb^{-1}
- Diffraction: LRG signature, and $x_{I\!P} < 0.03$

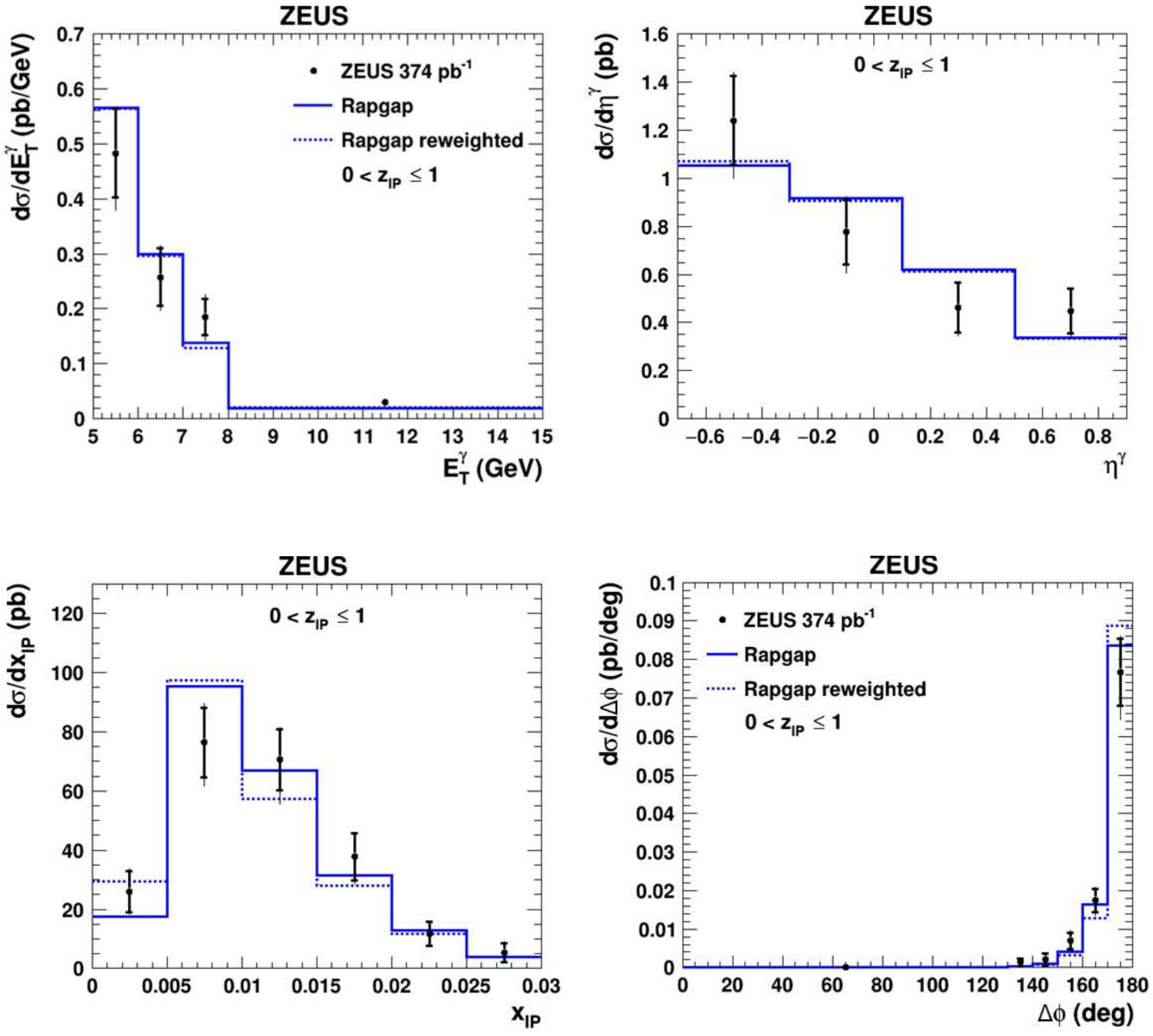
Use E-weighted e.m. cluster width $\langle \delta Z \rangle$ to distinguish γ from π^0, η background



A $70:30$ mixture of direct to resolved photons is found and used throughout



Isolated Photon + Jet: Data vs MC model



Measurement phase space:

$Q^2 < 1$ GeV^2, $0.2 < y < 0.7$

$5 < E_t^\gamma < 15$ GeV; $-0.7 < \eta^\gamma < 0.9$

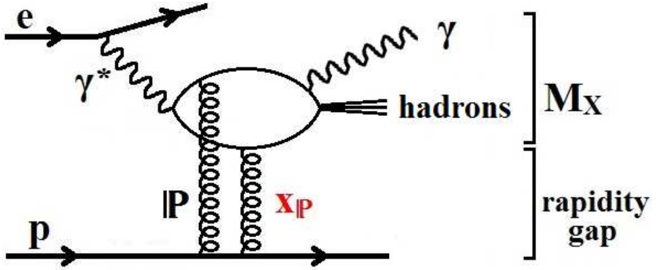
$4 < E_t^{\rm jet} < 35$ GeV; $-1.5 < \eta^{\rm jet} < 1.8$

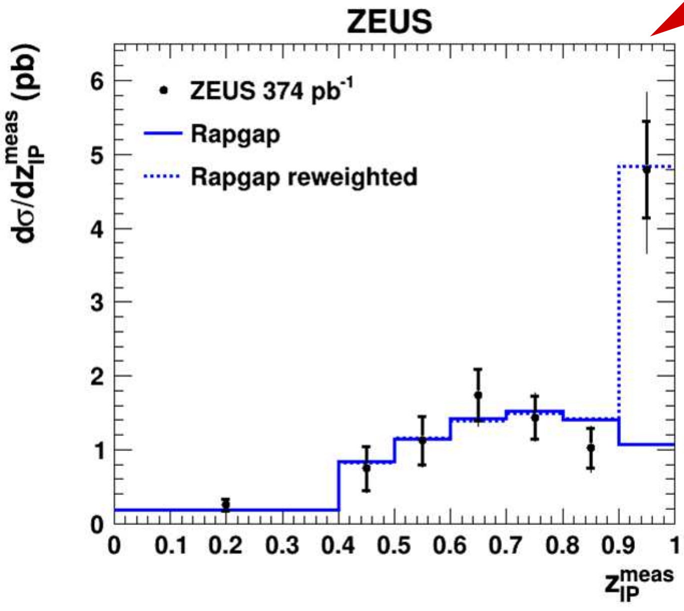
$\eta_{\max} < 2.5$; $x_{I\!P} < 0.03$

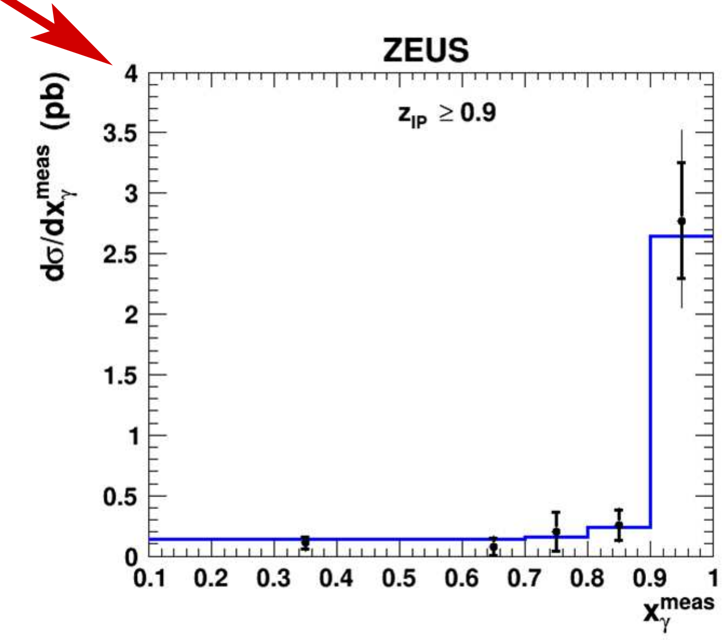
Compare data to Rapgap MC using H1-2006 DPDF Fit B (determined for $z_{I\!P} < 0.8$; above this value extrapolation is used)

All differential x-sections are well described by MC, except highest $z_{I\!P}$ $\Rightarrow$

Isolated Photons in Diffractive PHP



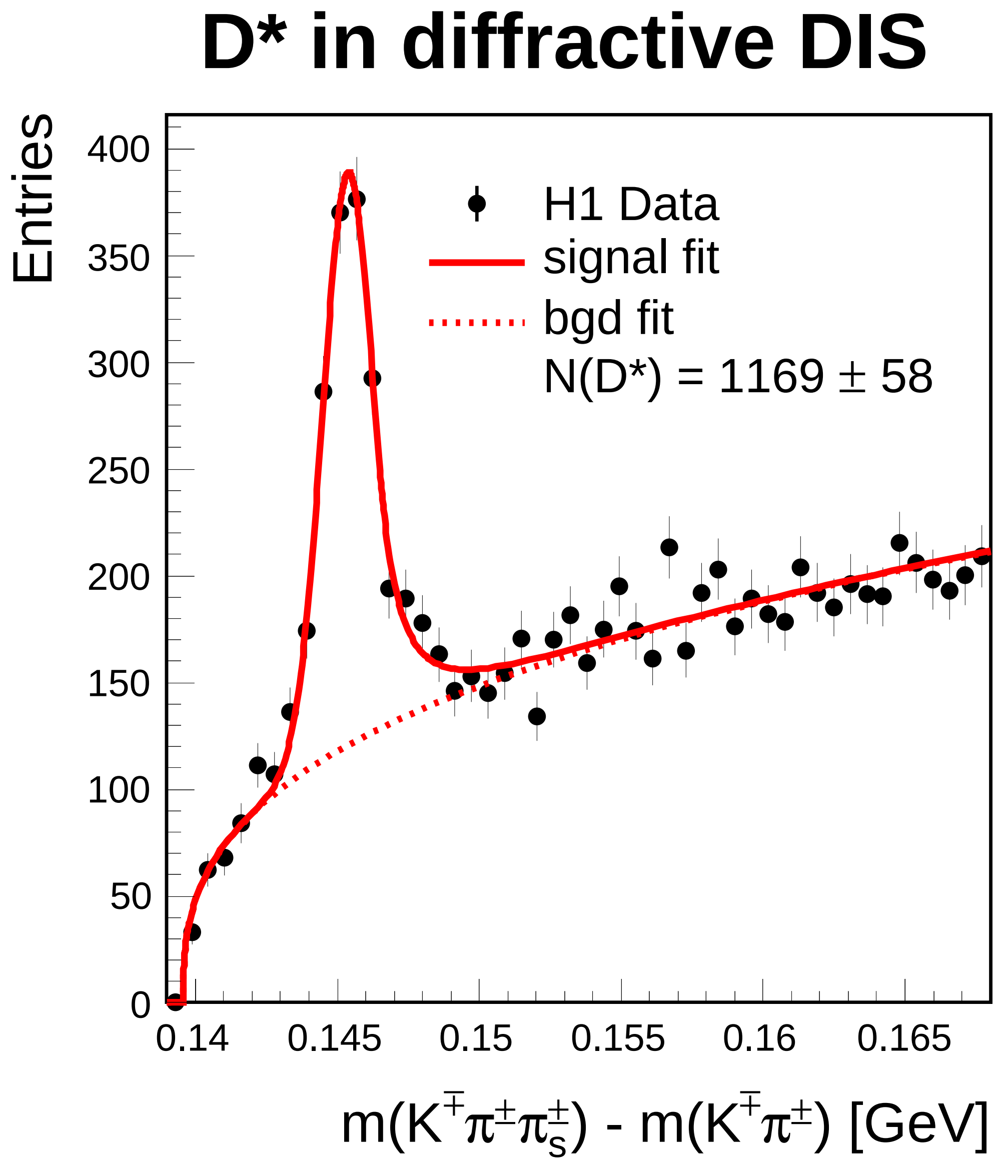




$\sim 40\%$ of cross section is due to ‘direct Pomeron’ contribution

D^* in Diffractive DIS at HERA

D^* Production in Diffractive DIS: Data sample



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

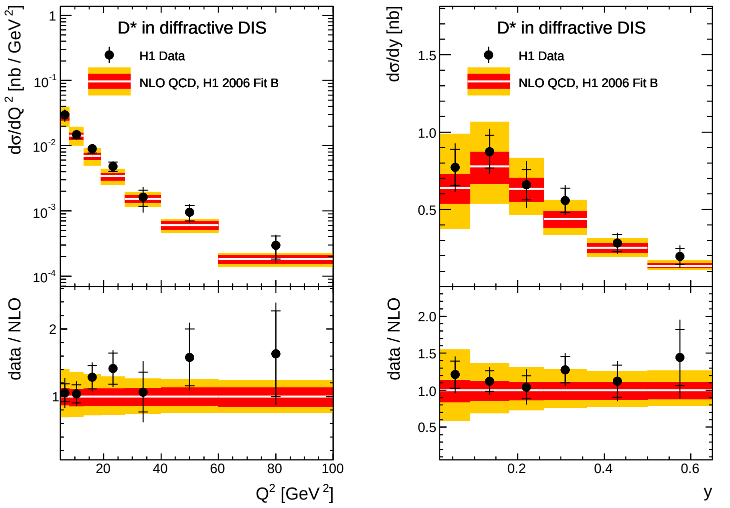
Open charm tagged with D^*

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

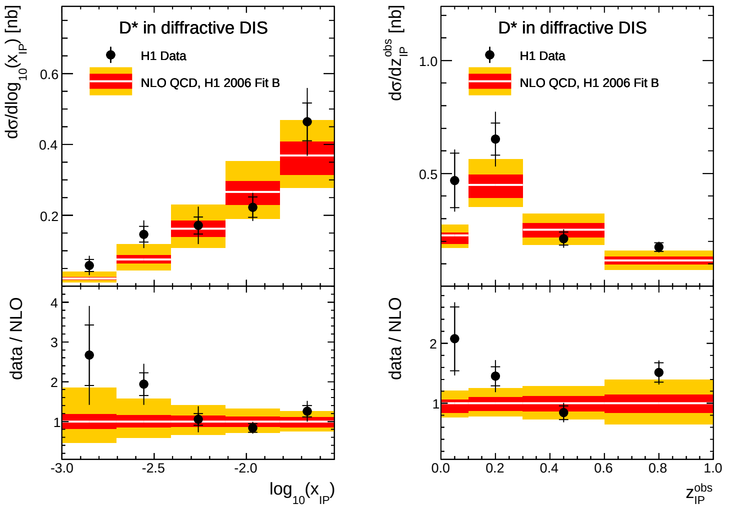
LRG selection of diffraction ($\sim 1100 D^*$)

DIS phase space
$5 < Q^2 < 100$ GeV^2 $0.02 < y < 0.65$
D^* kinematics
$p_{t,D^*} > 1.5$ GeV $-1.5 < \eta_{D^*} < 1.5$
Diffractive phase space
$x_{I\!P} < 0.03$ $M_Y < 1.6$ GeV $\|t\| < 1$ GeV^2

D^* Production in Diffractive DIS: Data vs NLO



Electron variables (Q^2, y)



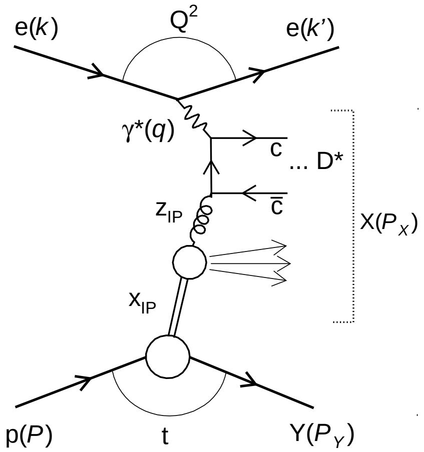
Diffractive variables (log$x_{I\!P}$, $z_{I\!P}$)

- NLO QCD given 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 ⇒ test of

  diffractive QCD factorisation and DPDF



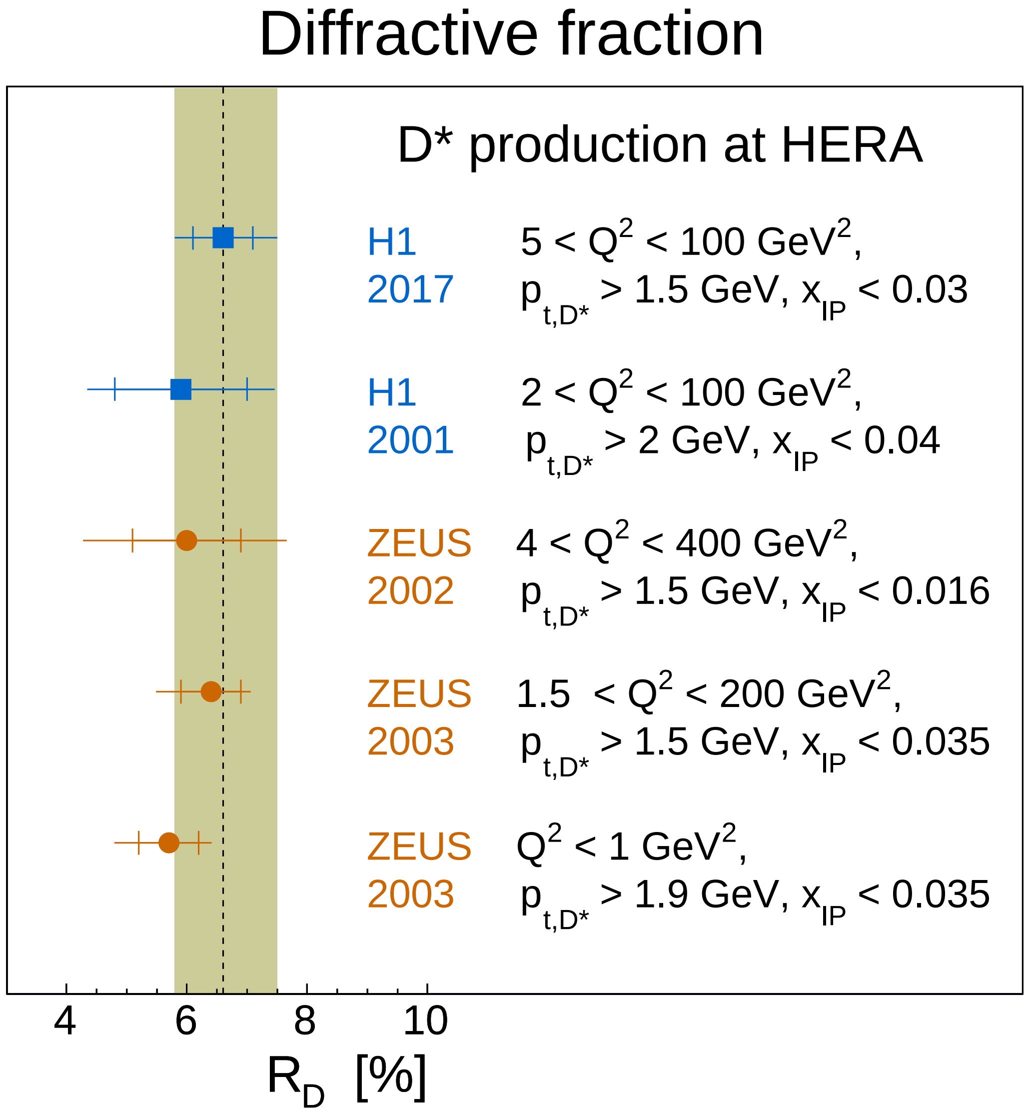
- Charm fragm.functions as determined in H1 non-diffractive D^* analysis works here ⇒ supporting universality of charm fragmentation

- Theory scale unc. dominates (yellow band)

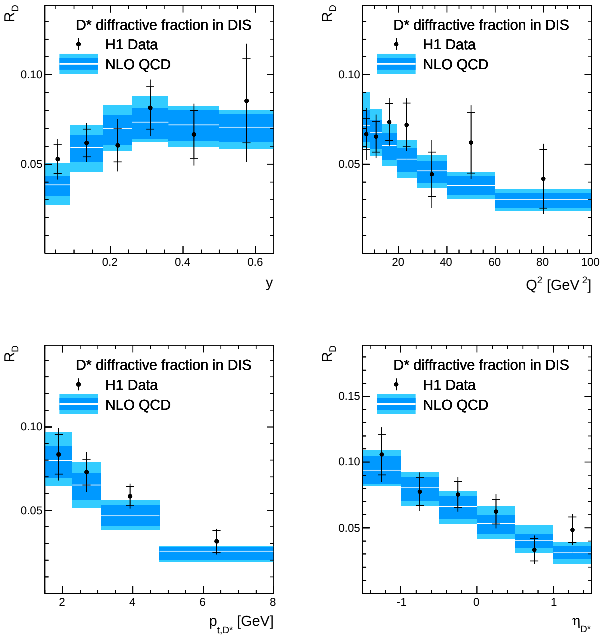
  DPDF uncertainty (red) similar to data precision

  Data could be used as additional input to the global DPDF fit

*D** in DIS: Diffractive Fraction



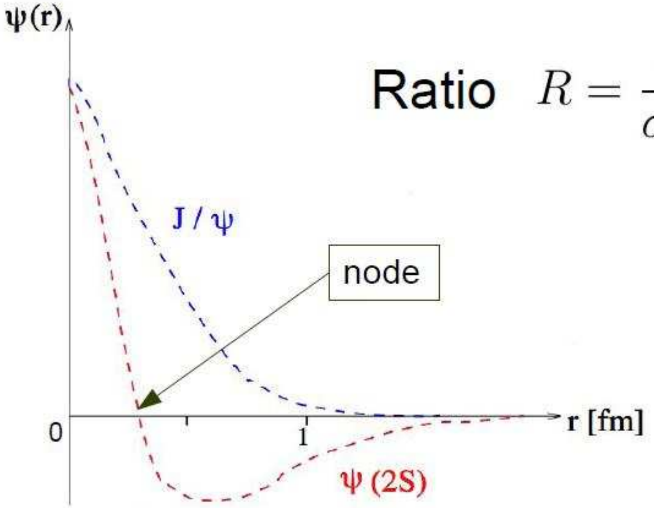
- NLO QCD also describes diffractive fractions, which found to be largely independent on kinematic PS



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

Motivation

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

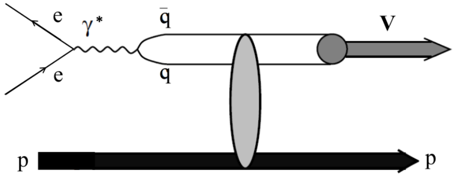


Ratio $R = \frac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi\, p}}$ gives information about the dynamics of hard process

sensitive to radial wave function of charmonium

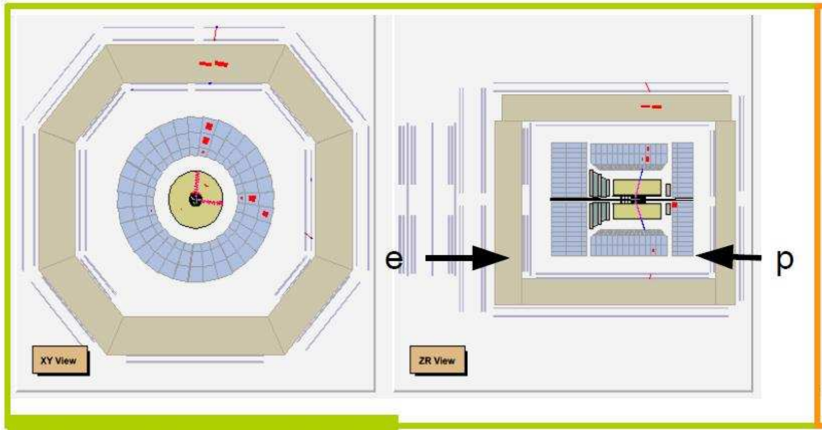
ψ(2S) wave function different from J/ψ wave function:

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

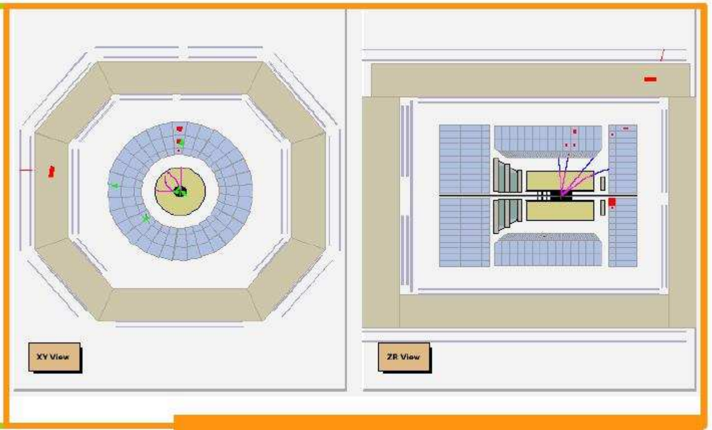


pQCD predictions: $R(Q^2 = 0) \simeq 0.17$ and rises with Q^2

Data samples and Decay channels



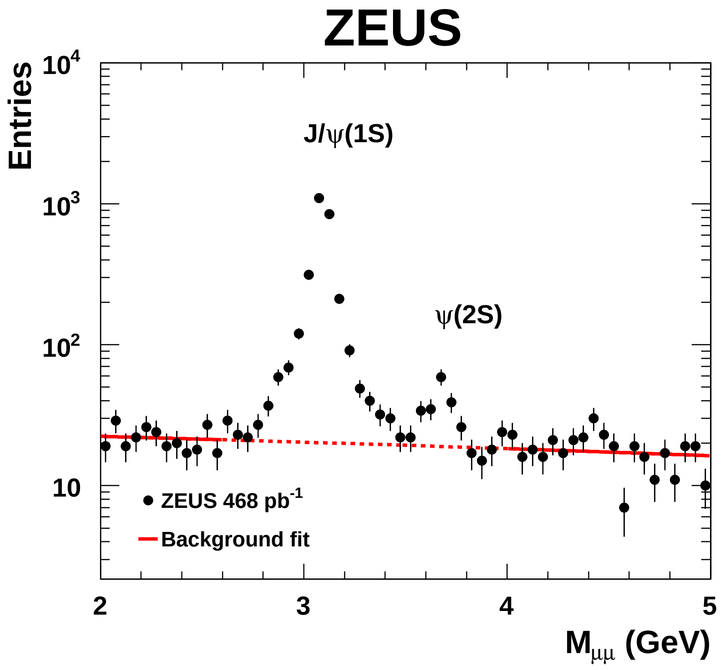
J/ψ(1S) → $\mu^+\mu^-$



ψ(2S) → J/ψ(1S) $\pi^+\pi^-$

ψ(2S) → J/ψ(1S) $\pi^+\pi^-$; J/ψ(1S) → $\mu^+\mu^-$
ψ(2S) → $\mu^+\mu^-$
J/ψ(1S) → $\mu^+\mu^-$

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

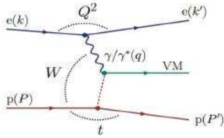


Data samples

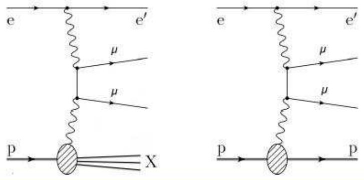
HERA I + HERA II data (1996 — 2007)
Integrated luminosity: 468 pb^{-1}

MC-data samples

Signal MC: DIFFVM for exclusive VM production



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



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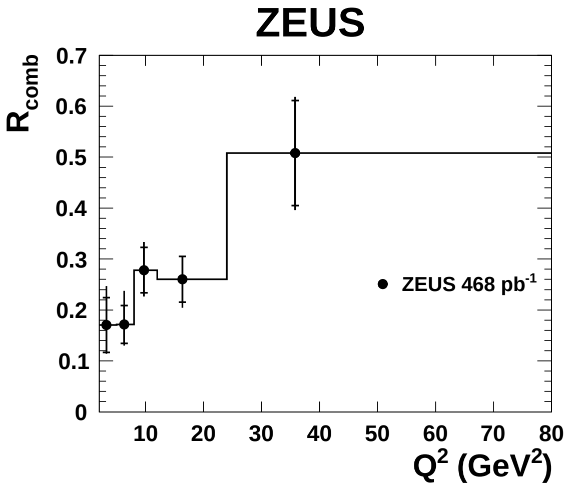
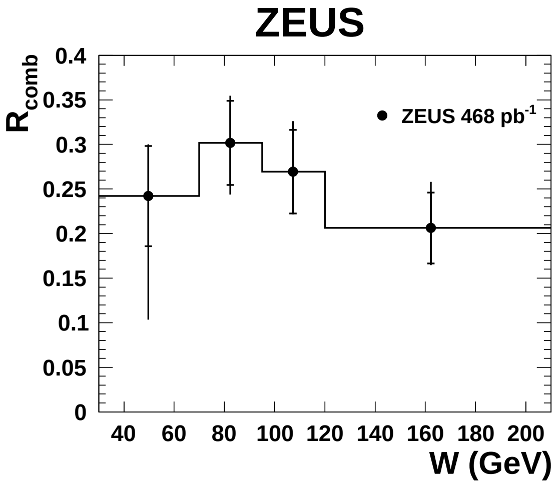
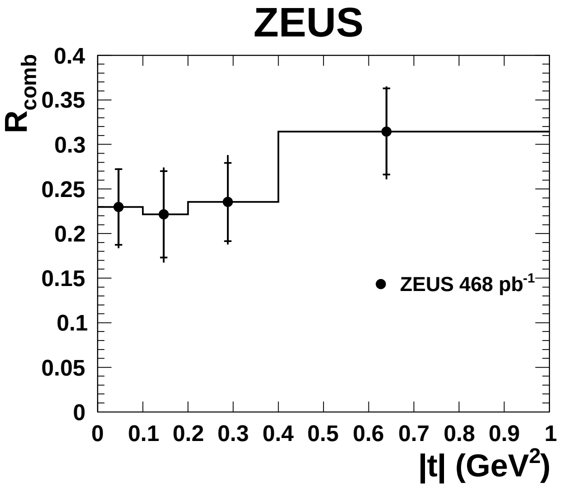
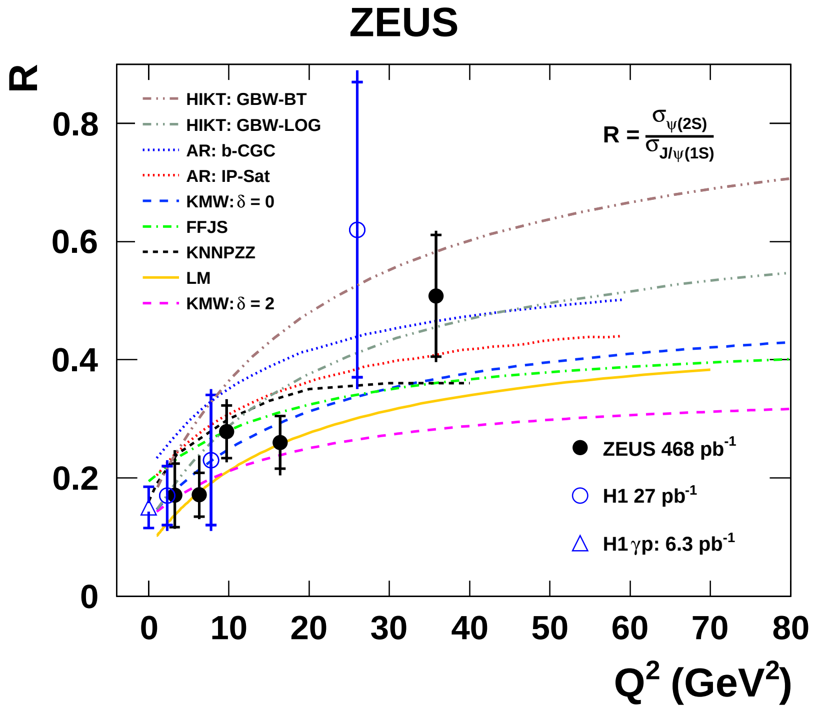
Results: $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ vs Q^2, W and $|t|$







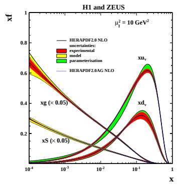


- Ratio rises with Q^2 and is constant in W and $|t|$
- HERA data in qualitative agreement with pQCD models
- Some discriminating power (albeit statistically limited)

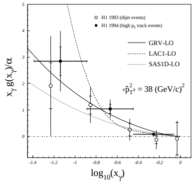
Rho–0 with a Leading Neutron at HERA

HERA as a ‘4P’ facility

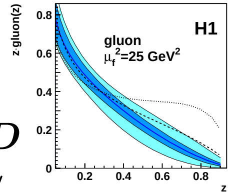
HERA enables to study structure of



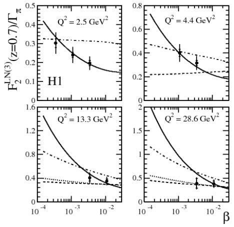
Proton – F_2, F_L, ...



Photon – g/γ



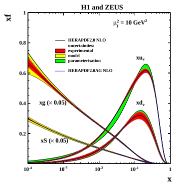
Pomeron – F_2^D, F_L^D



Pion – F_2^π

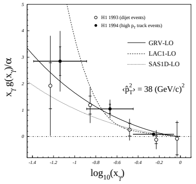
HERA as a ‘4P’ facility

HERA enables to study structure of

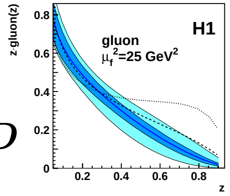


Proton – $F_2, F_L, \ldots$

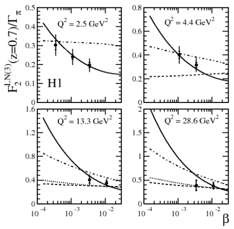
Photon – g/γ



Pomeron – F_2^D, F_L^D

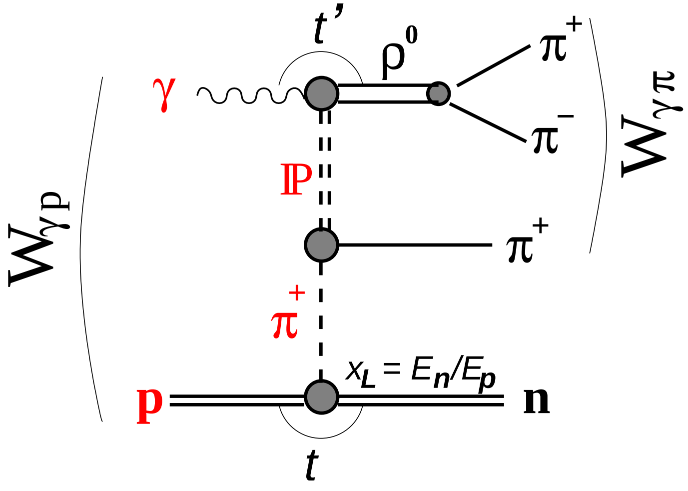


Pion – F_2^π



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

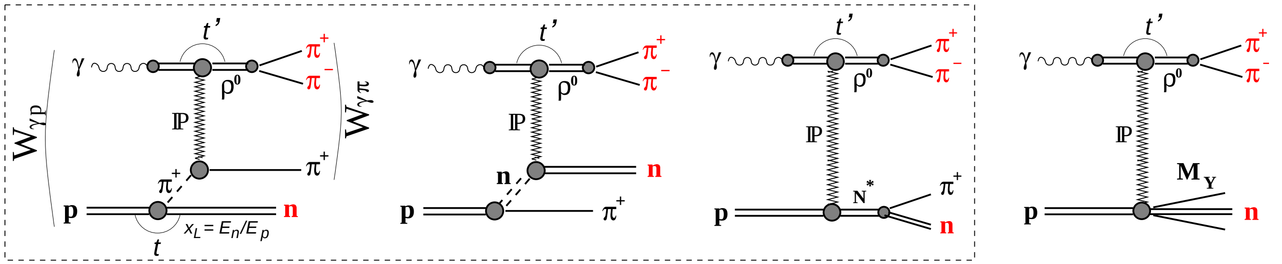
$$\gamma + \mathbf{p} \longrightarrow \rho^0 \pi^+ \mathbf{n}$$



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: Control plots



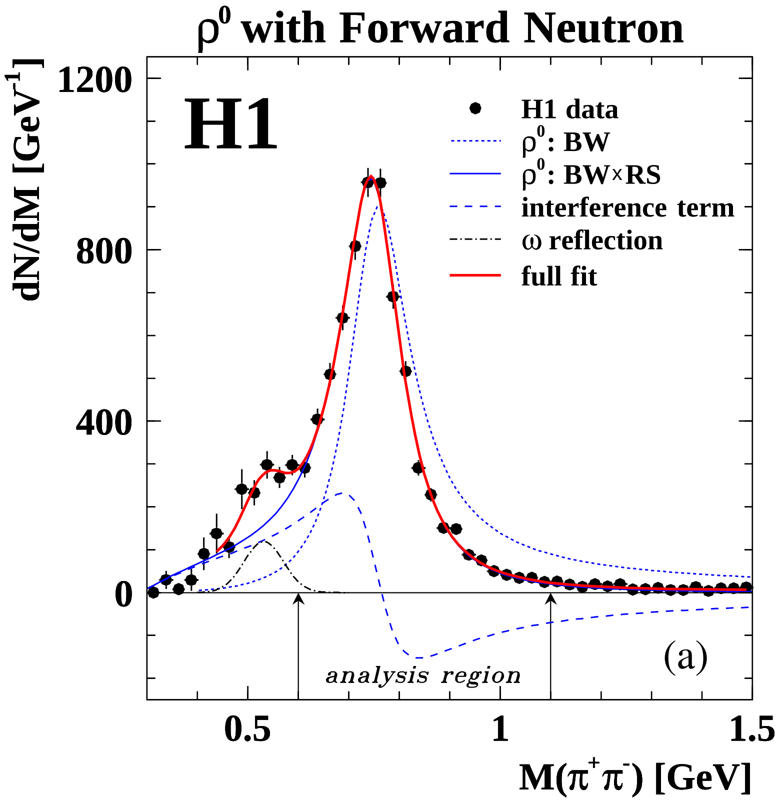
(a) (b) (c) (d)

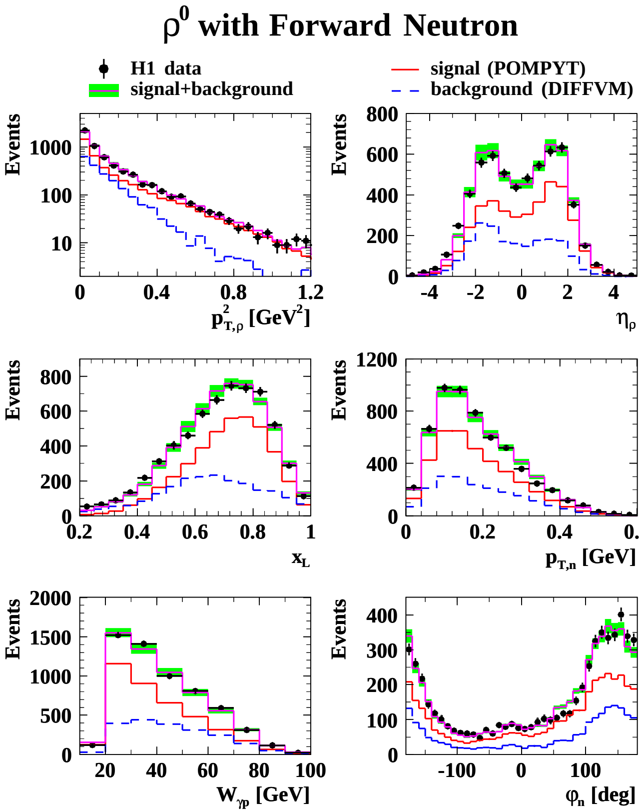
Data sample: $\mathcal{L} = 1.16\ \mathrm{pb}^{-1}$

~ 7000 events

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

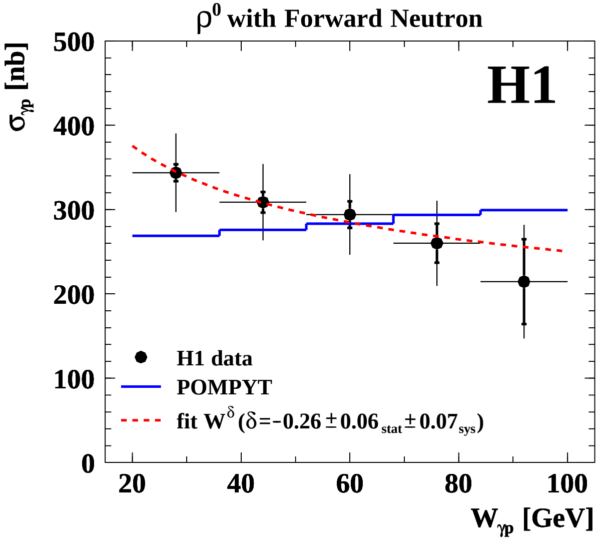
$\delta_{\mathrm{sys}} = 14\%$

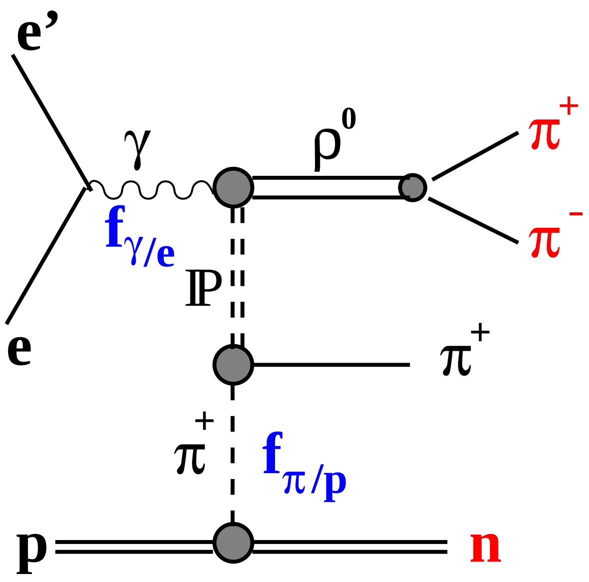




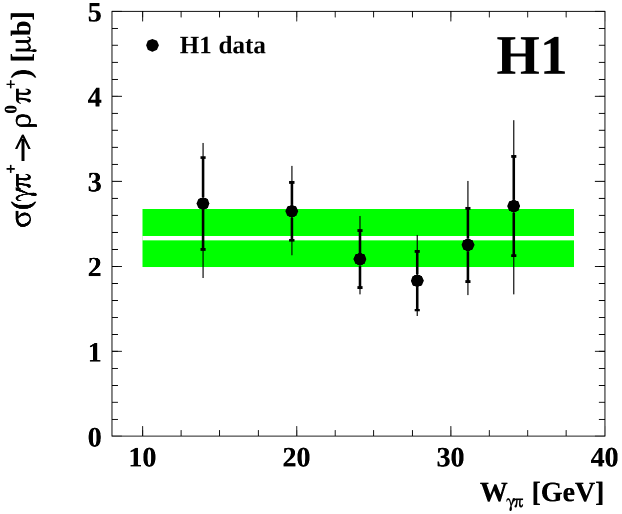
Cross sections definitions

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





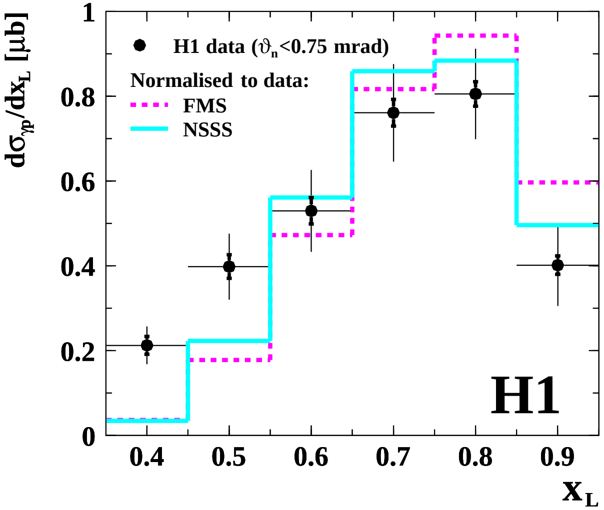
$$\sigma_{\gamma\pi} = \frac{\sigma_{\gamma p}}{\Gamma_\pi}$$

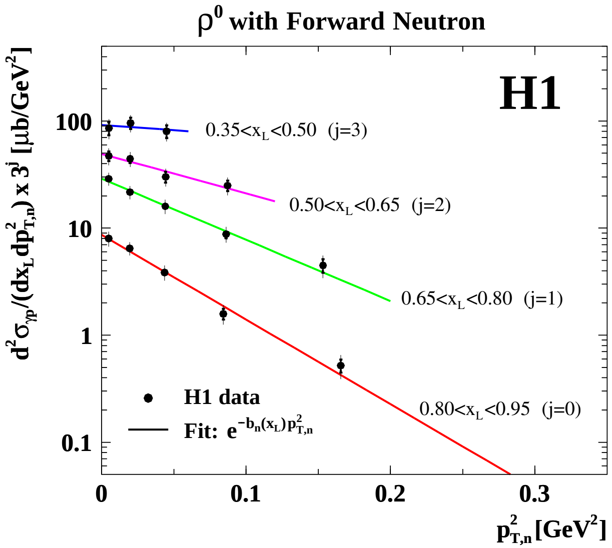


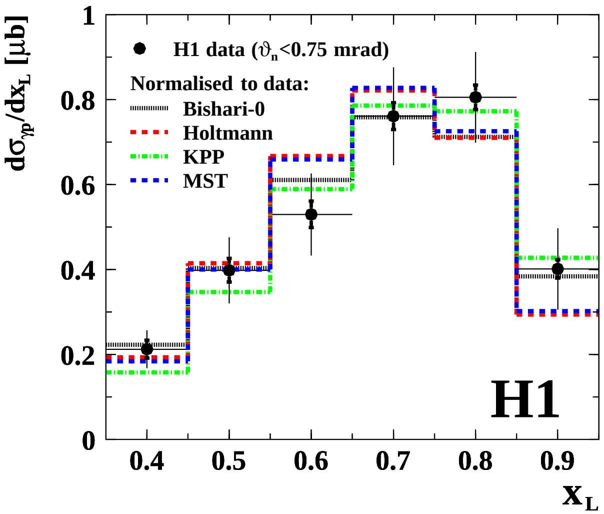
VMD: $$f_{\gamma/e}(y,Q^2) = \frac{\alpha}{2\pi Q^2 y}\left\{\left[1+(1-y)^2-2(1-y)\left(\frac{Q^2_{\min}}{Q^2}-\frac{Q^2}{M_\rho^2}\right)\right]\frac{1}{\left(1+\frac{Q^2}{M_\rho^2}\right)^2}\right\}$$

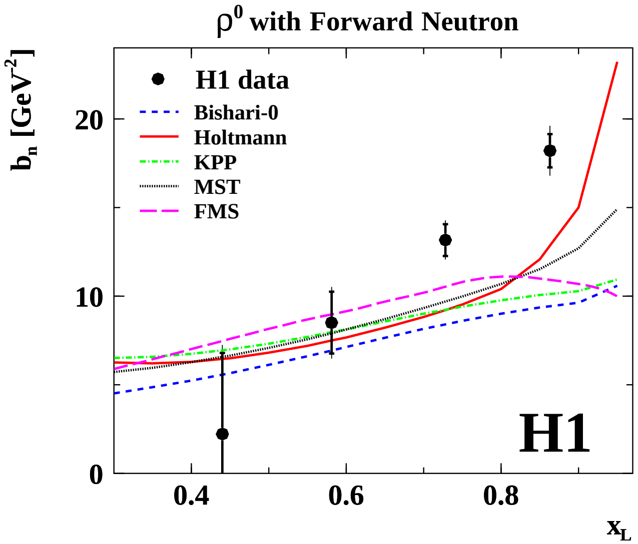
OPE: $$f_{\pi/p}(x_L,t) = \frac{1}{2\pi}\frac{g^2_{p\pi N}}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\exp[-R^2_{\pi n}\frac{m_\pi^2-t}{1-x_L}]$$

Constraining pion flux







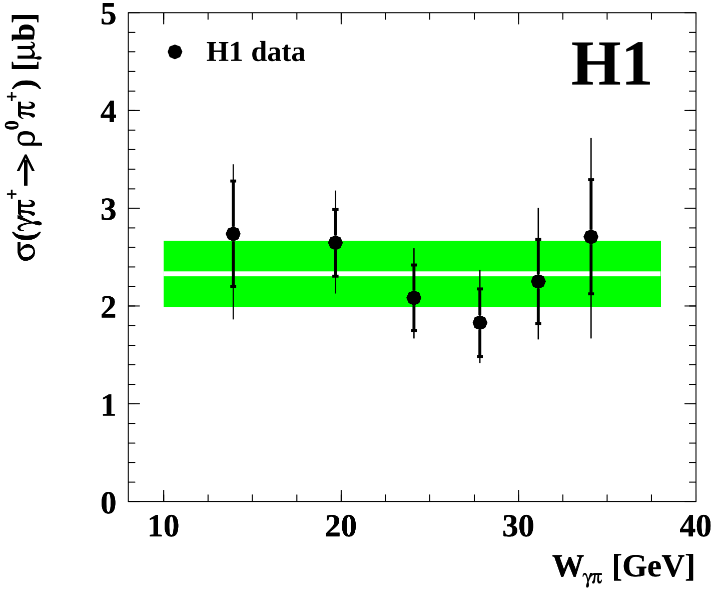


Failure to describe $b_n(x_L)$ suggests strong absorptive effects (n rescattering) ⇒ try to quantify

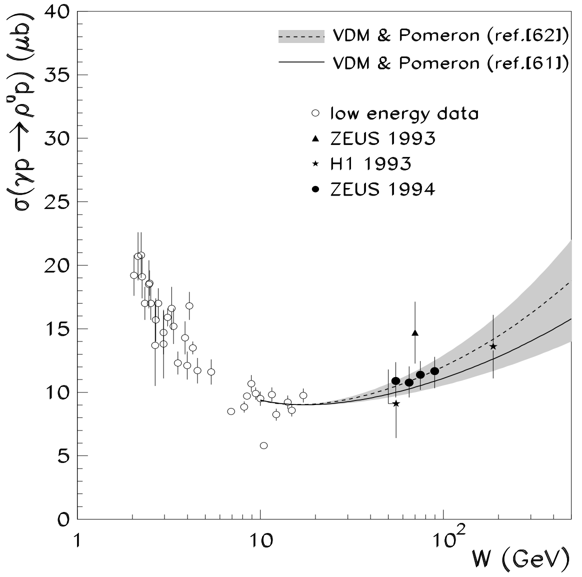
Estimate of absorption corrections

γπ

$(2.33 \pm 0.56)\mu\text{b}$



$(9.5 \pm 0.5)\mu\text{b}$



γp

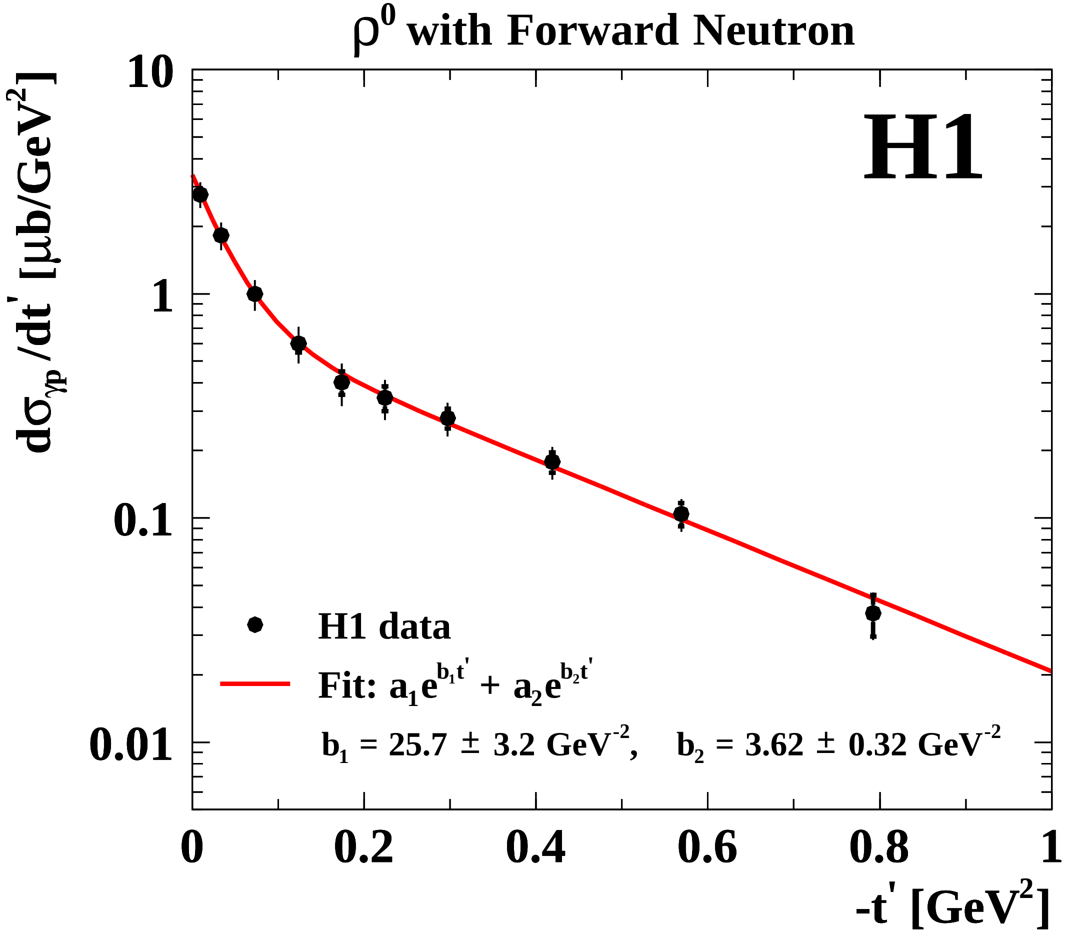
$$r_{\text{el}} = \frac{\sigma^{\gamma\pi\to\rho^0\pi}}{\sigma^{\gamma p\to\rho^0 p}} = \begin{cases} 0.25 \pm 0.06 & (\text{exp.extracted}) \\ 0.57 \pm 0.03 & (\text{theo.expected}) \end{cases} \Longrightarrow K_{\text{abs}} = 0.44 \pm 0.11$$

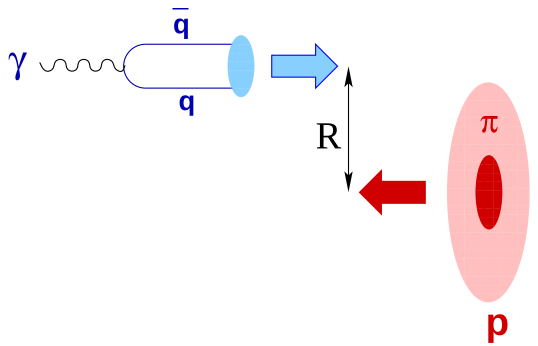
Optical Theorem: $\frac{d\sigma_{el}}{dt}\,|_{t=0} = b_{\text{el}}\sigma_{\text{el}} \propto \sigma^2_{\text{tot}} \Longrightarrow r_{\text{el}} = (\frac{b_{\gamma p}}{b_{\gamma\pi}}) \cdot (\sigma^{\gamma\pi}_{\text{tot}}/\sigma^{\gamma p}_{\text{tot}})^2$

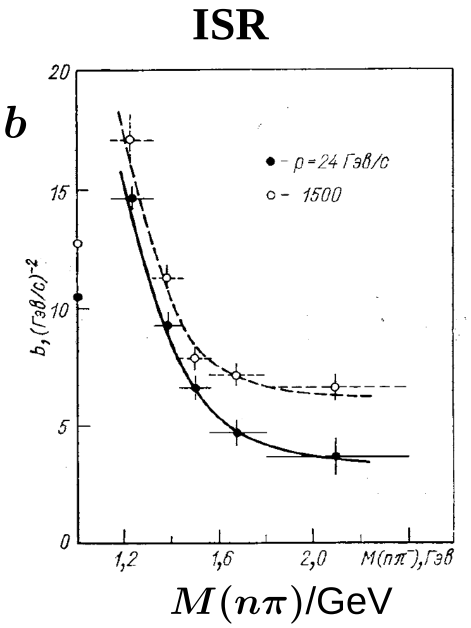
Eikonal approach: $b = \langle R^2 \rangle; \quad b_{12} = b_1 + b_2$

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 $p^2_{T,\rho}$







Geometric interpretation: $\langle r^2 \rangle = 2b_1 \cdot (\hbar c)^2 \simeq 2\ \text{fm}^2 \Rightarrow (1.6R_\text{p})^2 \Rightarrow$ 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 mechanism in PHP, in particular apparent independence of Gap Survival Probability on x_γ.

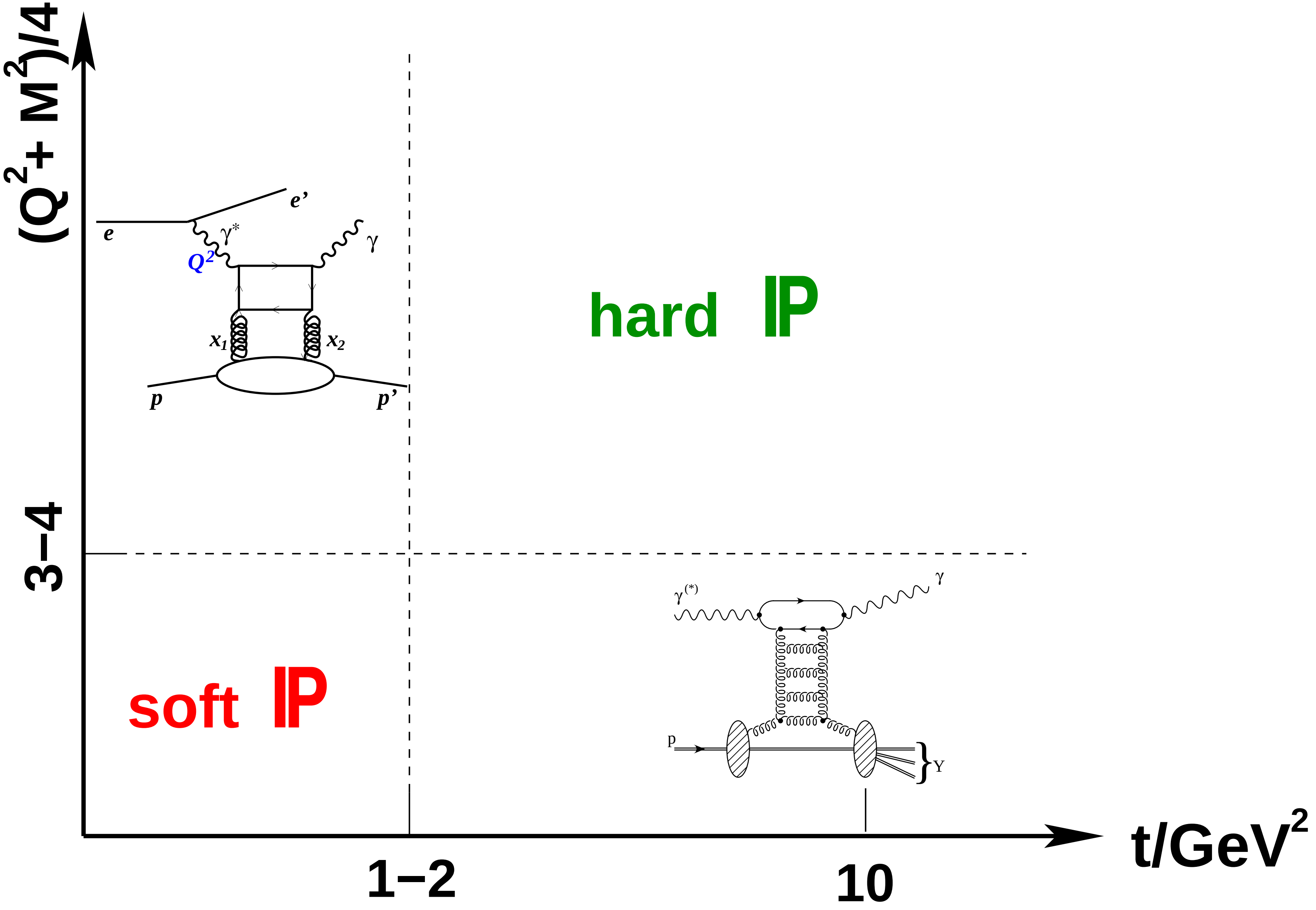
- Multiscale problem: (Q^2, E_T, M_V, t).

- Where is an Odderon ?

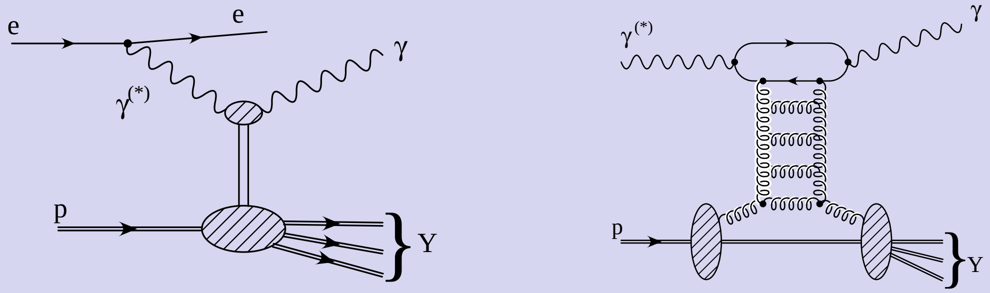
- Can one observe Glueball in a double Pomeron reaction in PHP?
  $\gamma p \longrightarrow (I\!\!P I\!\!P) \longrightarrow M_X \quad (M_X = \sqrt{x_{I\!\!P 1} x_{I\!\!P 2}} W_{\gamma p} = 2 \div 4 \, \mathrm{GeV})$

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

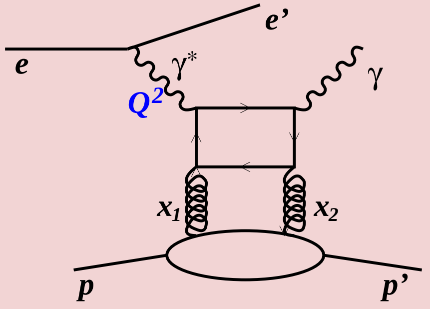
VM (or γ) and DVCS: Relevant scales?



Diffractive scattering of γ at large $|t|$ and DVCS

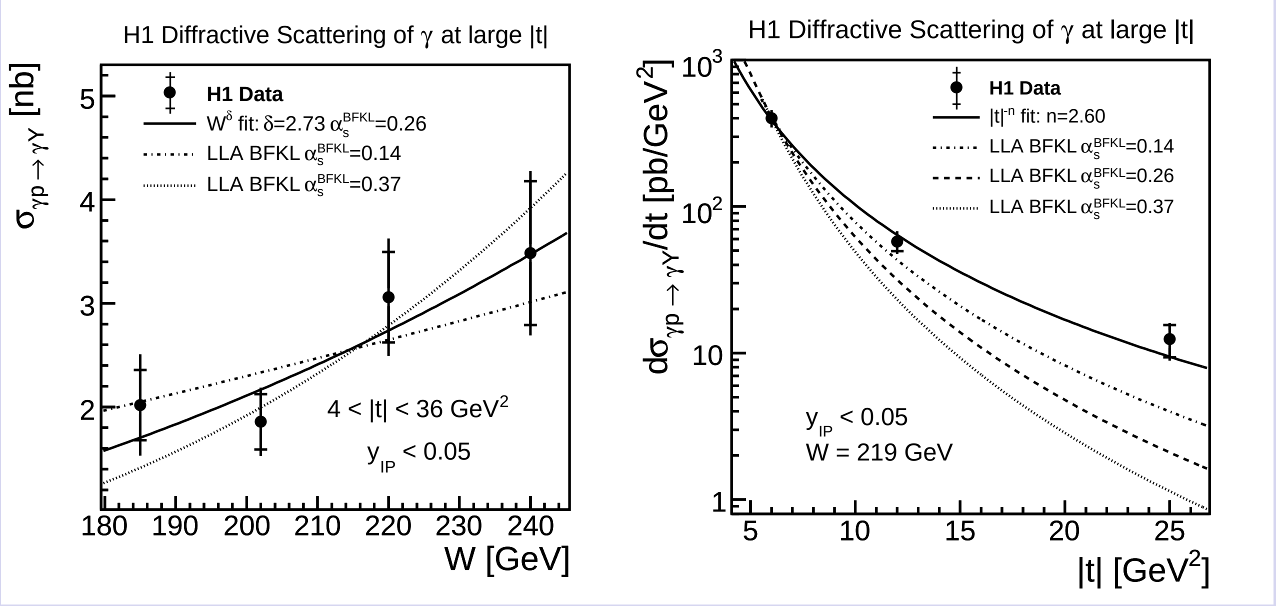


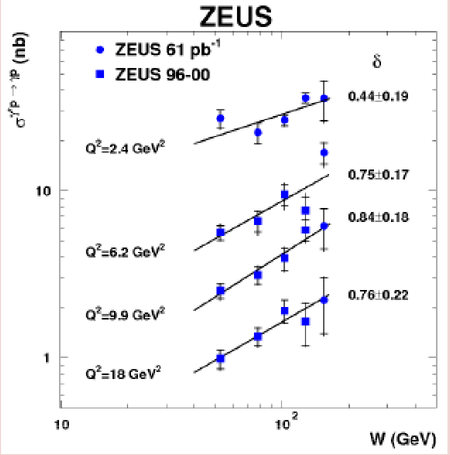
PHP ($Q^2 < 0.01$ GeV^2)

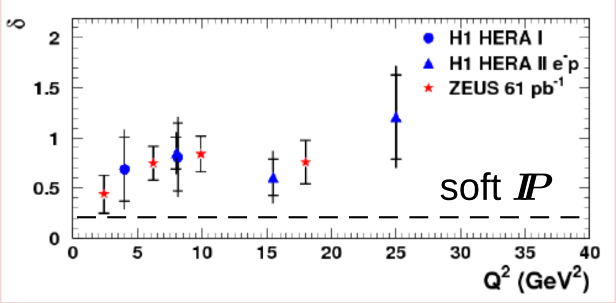


DIS ($Q^2 > 2$ GeV^2)

$$\sigma(W) \propto W^{4\omega_0} \qquad \omega_0 = 4N_c\frac{\alpha_s^{BFKL}}{\pi}\ln 2 \qquad \frac{d\sigma}{dt} \propto |t|^{-n}$$







Hard Pomeron at work