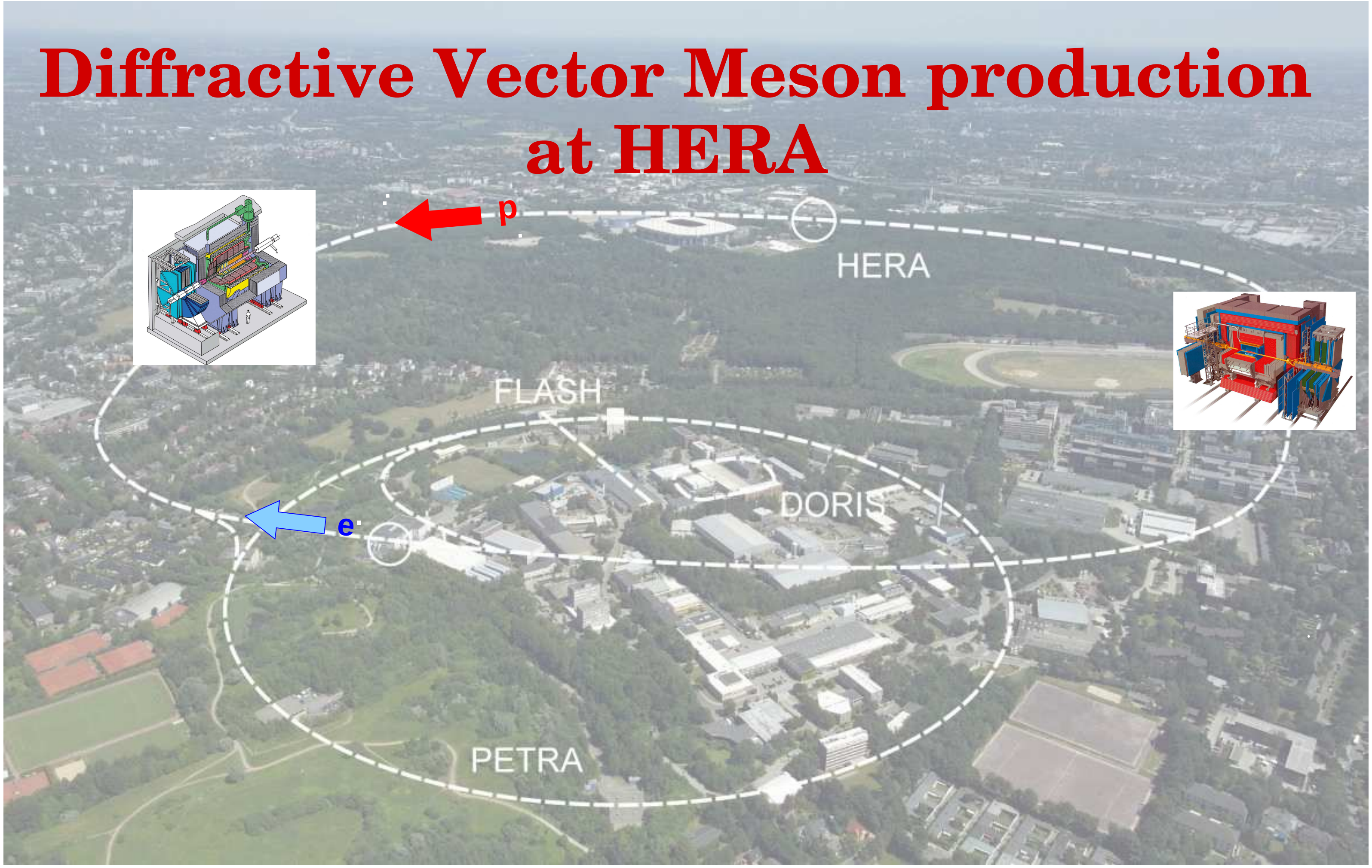
Sergey Levonian
DESY, Hamburg

Diffractive Vector Meson production at HERA



CFNS workshop: Open Questions in Photon-Induced Interactions

Online, 27-Apr-2021

H1 and ZEUS publications about VM at HERA

H1 Topic	Journal	ZEUS Topic	Journal
Exclusive $\pi^+\pi^-$ and ρ^0 in PHP	Eur.Phys.J.C80 (2020), 1189	$R(\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)})$ in DIS	Nucl. Phys. B 909 (2016) 934
Exclusive ρ^0 with Leading n in PHP	Eur.Phys.J.C76 (2016) 1, 41	Exclusive Electroproduction of 2π	Eur.Phys.J. C 72 (2012) 1869
Elastic and p-diss J/ψ in PHP	Eur.Phys.J.C73 (2013) 2466	$\Upsilon(1S)$ in PHP (t-dependence)	Phys.Lett. B 708 (2012) 14
Diffractive ρ^0 and ϕ in DIS	JHEP05 (2010) 032	P-dissociative J/ψ in PHP at large t	JHEP 05 (2010) 085
Diffractive PHP of ρ^0 with large t	Phys.Lett.B 638 (2006) 422	Exclusive PHP of Υ Mesons	Phys. Lett. B 680 (2009) 4
Elastic J/ψ in PHP and DIS	Eur.Phys.J.C46 (2006) 585	Exclusive ρ^0 in DIS	PMC Physics A 1, 6
Diffractive PHP of J/ψ with large t	Phys Lett B568 (2003) 205	Exclusive ϕ in DIS	Nucl. Phys. B 718 (2005) 3
Diffractive PHP of $\psi(2S)$	Phys.Lett.B541 (2002) 251	Exclusive J/ψ in DIS	Nucl. Phys. B 695 (2004) 3
Helicity structure of ρ^0 in DIS	Phys.Lett.B539 (2002) 25	P-dissociative VM in PHP at large t	Eur. Phys. J. C 26 (2003) 389
Elastic ϕ in DIS	Phys.Lett.B483 (2000) 360	Exclusive PHP of J/ψ mesons	Eur. Phys. J. C 24 (2002) 345
Elastic J/ψ and Υ in PHP	Phys.Lett.B483 (2000) 23	Exclusive ω in DIS	Phys. Lett. B 487 (2000) 273
Elastic ρ^0 in DIS	Eur.Phys.J.C13 (2000) 371	Diffractive PHP of VM at large t	Eur. Phys. J. C 14 (2000) 213
Quasi-elastic ($z > 0.95$) $\psi(2S)$ in PHP	Phys.Lett.B421 (1998) 385	Spin-Density ME of Exclusive ρ^0 in DIS	Eur. Phys. J. C 12 (2000) 393
P-diss. ρ^0 and Elastic ϕ in DIS	Z.Phys.C75 (1997) 607	Exclusive ρ^0 and J/ψ in DIS	Eur. Phys. J. C 6 (1999) 603
Elastic and Inelastic J/ψ in PHP	Nucl.Phys.B472 (1996) 3	Elastic Υ Photoproduction	Phys. Lett. B 437 (1998) 432
Elastic ρ^0 and J/ψ at large Q^2	Nucl.Phys.B468 (1996) 3	Elastic and p-Dissociative ρ^0 in PHP	Eur. Phys. J. C 2 (1998) 247
Elastic Rho0 in PHP	Nucl.Phys.B463 (1996) 3	Elastic J/ψ in PHP	Z. Phys. C 75 (1997) 215
		Elastic ω in PHP	Z. Phys. C 73 (1996) 73
		$\gamma^\star p \to \phi p$ in DIS	Phys. Lett. B 380 (1996) 220
		Elastic ϕ in PHP	Phys. Lett. B 377 (1996) 259
		Elastic ρ^0 in PHP	Z. Phys. C 69 (1995) 39
		Exclusive ρ^0 in DIS	Phys. Lett. B 356 (1995) 601

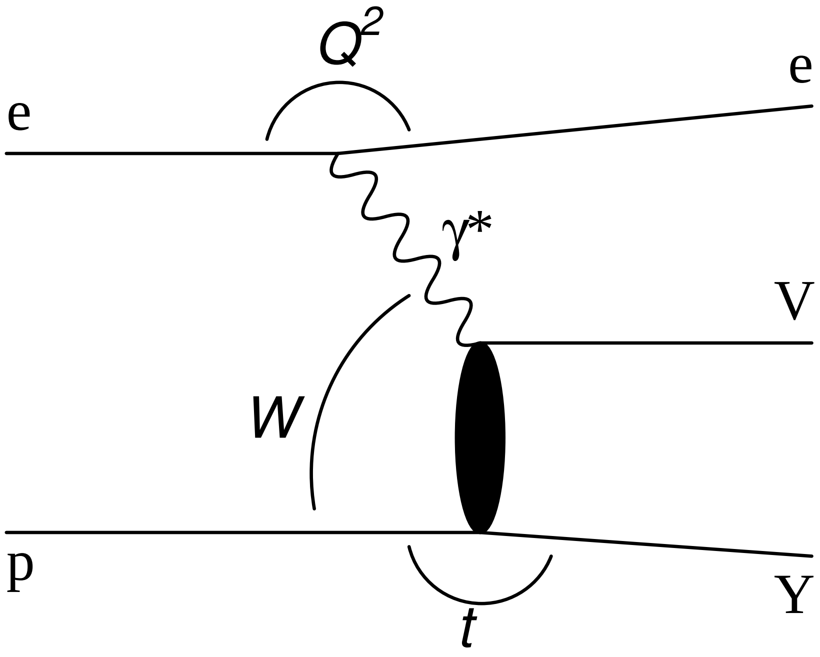
Measured are: $\rho, \rho', \omega, \phi, J/\psi, \psi(2S), \Upsilon$ in EL and PD channels and for $0 < Q^2 < 100\mathrm{GeV}^2$

More that 5000 references; a couple of new ”preliminary” results and ongoing analyses. ⇒

Too much to cover in one talk.

Plan of the talk

- Overall picture and General properties
- An example of one interesting analysis
- Some lessons and suggestions for future experiments



$V = \rho, \omega, \phi, J/\psi, \Upsilon, \ldots$

Covered PS at HERA

$$0 < Q^2 < 100 \text{ GeV}^2$$

$$25 < W < 305 \text{ GeV}$$

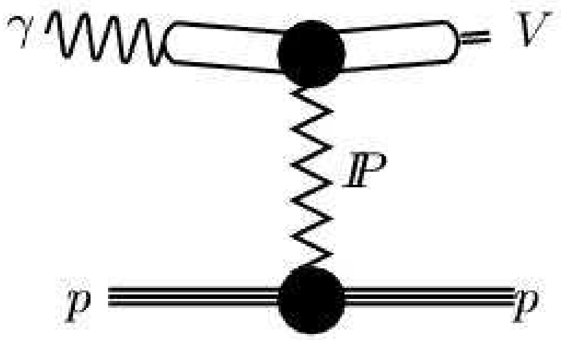
$$0 < |t| < 30 \text{ GeV}^2$$

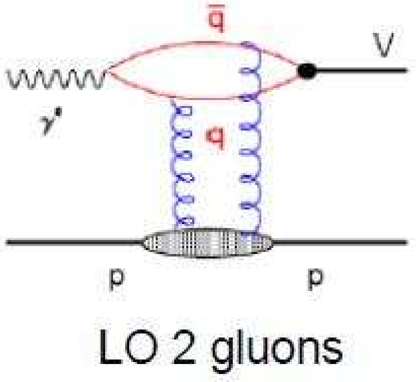
Hard scale can be provided by Q^2 and M_V^2 (at γ^* vertex) or/and by $|t|$ (at p vertex)

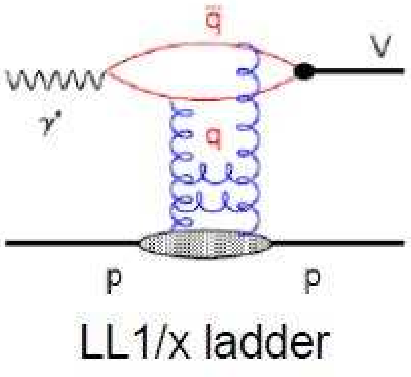
Modelling VM Production at HERA

No hard scale present: VDM⊕Regge

Hard scale(s) present: CD picture ($\sigma \propto \Psi_{\gamma^*\to q\bar{q}} \cdot \sigma_{(q\bar{q})p} \cdot \Psi_{q\bar{q}\to V}$)







soft $I\!P$omeron exchange

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

$\alpha_{I\!P}(0)$=1.08; $\alpha'_{I\!P}$=0.25

$\sigma \propto W^{4(\alpha_{I\!P}-1)}$

hard $I\!P$omeron diagrams

$\alpha_{I\!P}(0) \simeq 1.20$; $\alpha'_{I\!P} \simeq 0$

$\sigma \propto [xg(x, Q^2)]^2$

Modelling VM Production at HERA

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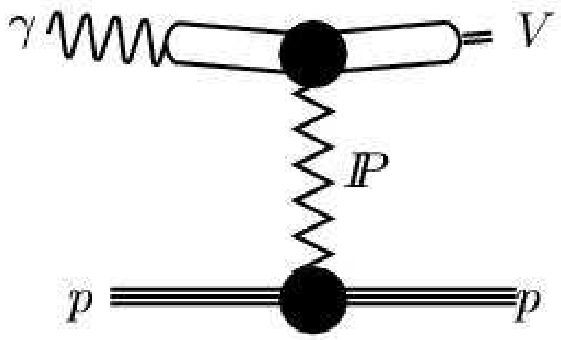
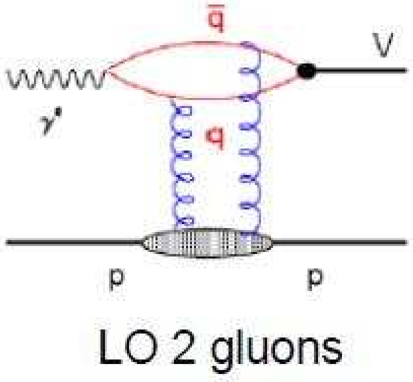
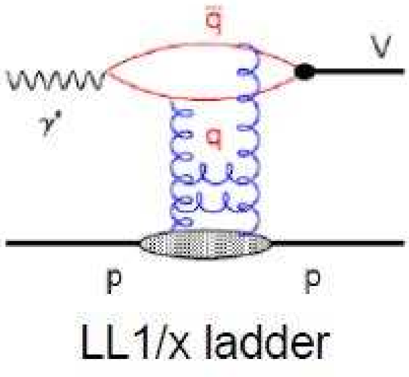




LO 2 gluons



LL1/x ladder

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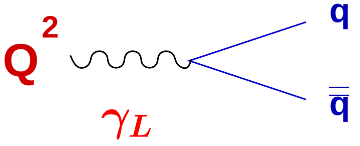
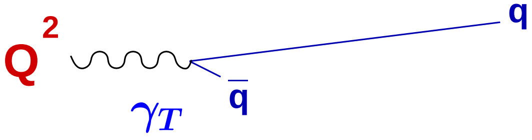
Interplay between soft and hard processes in DIS





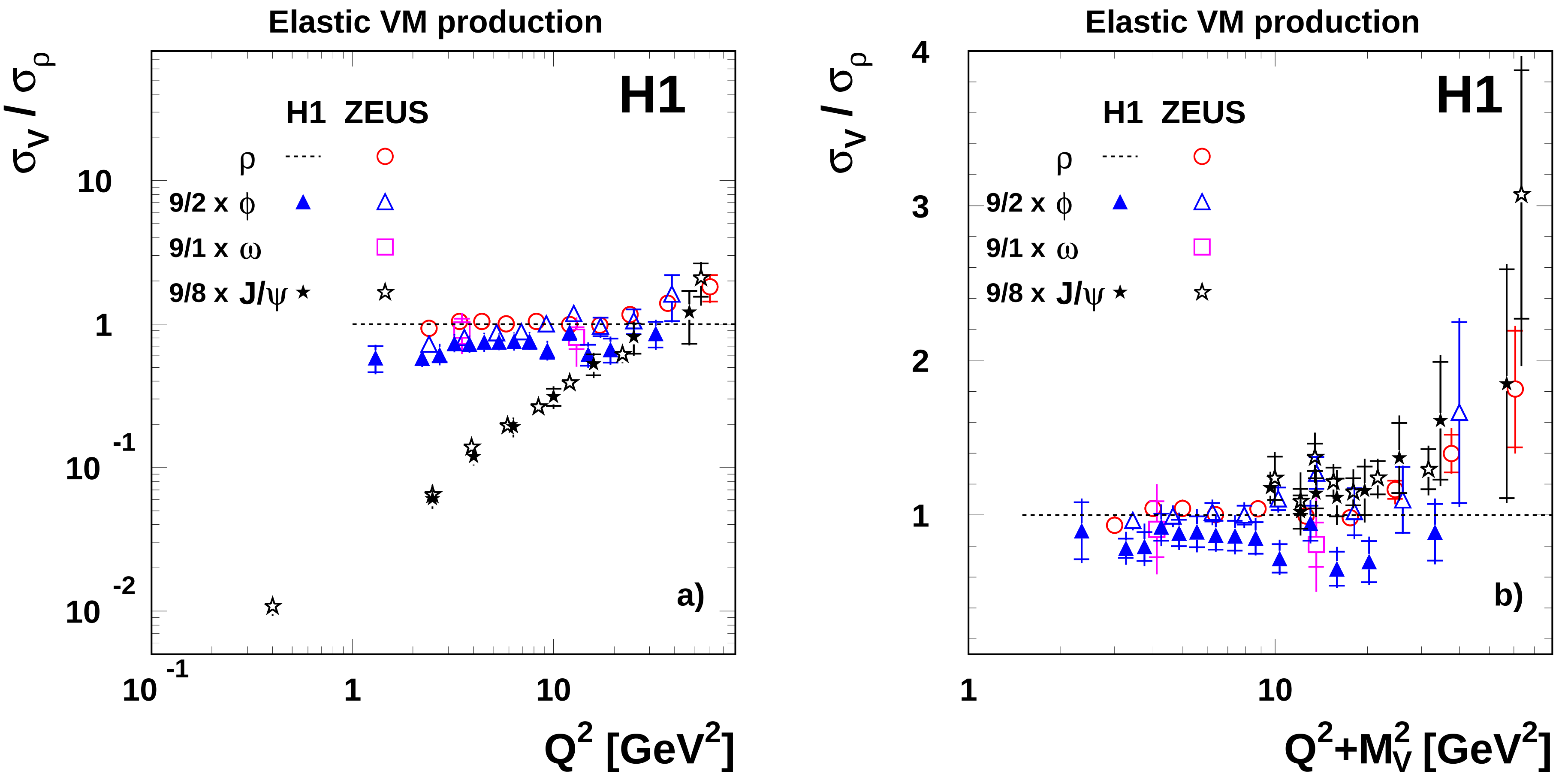
γ_L ($z \simeq 0.5$): $\langle r_t^2 \rangle \simeq (z(1-z)Q^2 + m_q^2)^{-1} \simeq 1/[(Q/2)^2 + m_q^2]$ $(P \sim 1)$

γ_T ($z \simeq 0; 1$): $\langle r_t^2 \rangle \simeq (z(1-z)Q^2 + m_q^2)^{-1} \simeq 1/m_q^2$ $(P \sim m_q^2/Q^2)$

Small dipole (‘hard’)

Large dipole (’soft’)

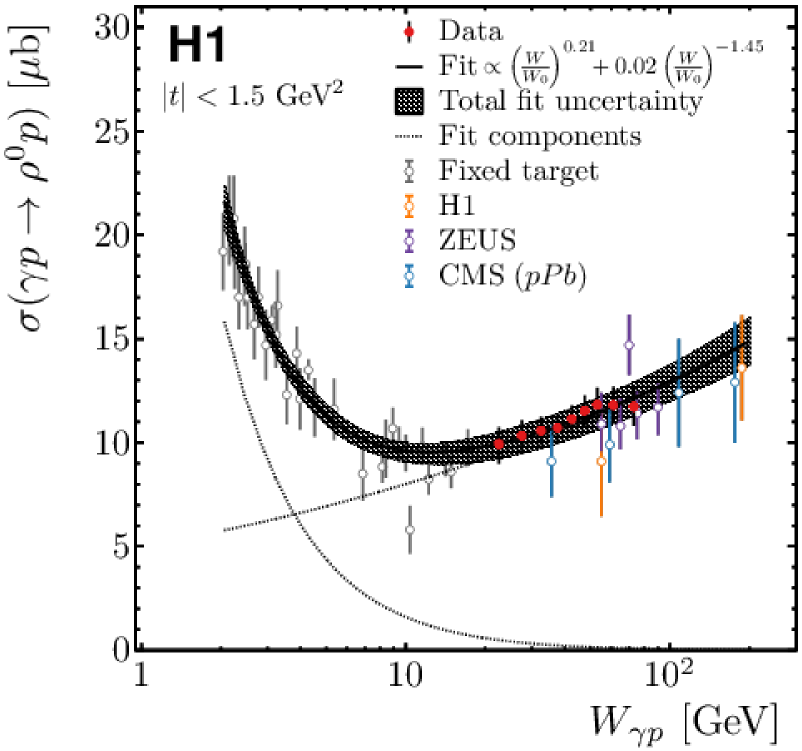
Flavour dependence. Universality



Ratios (scaled according to quark charge content) show large difference as a function of Q^2, but they become close to 1 (up to WF effects) once plotted vs scaling variable $Q^2 + M_V^2$

$\Rightarrow$ Cross sections are essentially determined by the dipole size

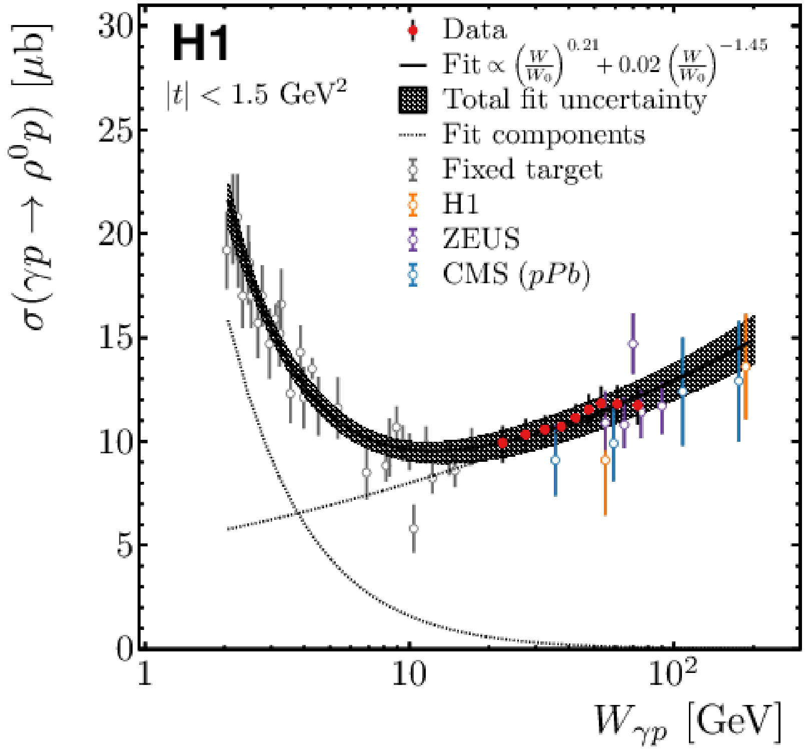
W dependence. Transition from soft to hard regime

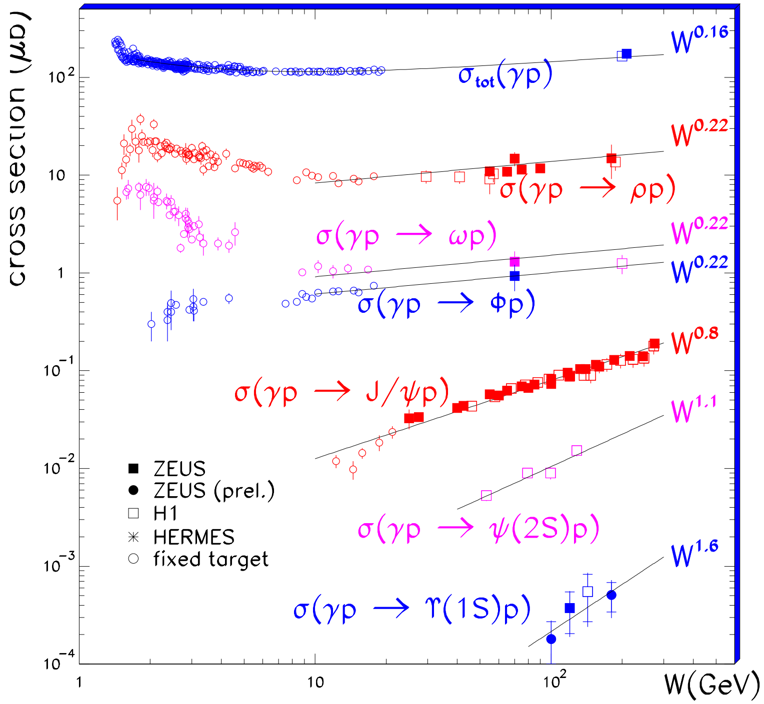


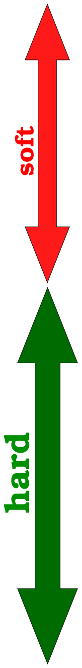
Most recent measurement of elastic ρ^0 in PHP

Typical soft behaviour with $\alpha_{I\!P}(0) = 1.065 \pm 0.008$

W dependence. Transition from soft to hard regime







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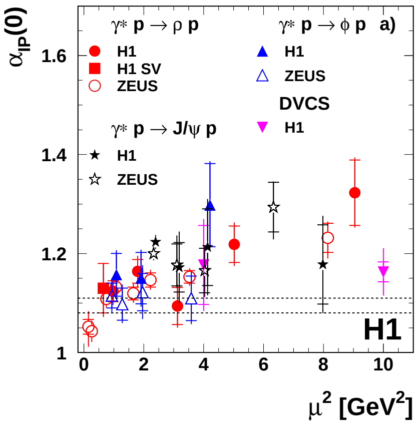
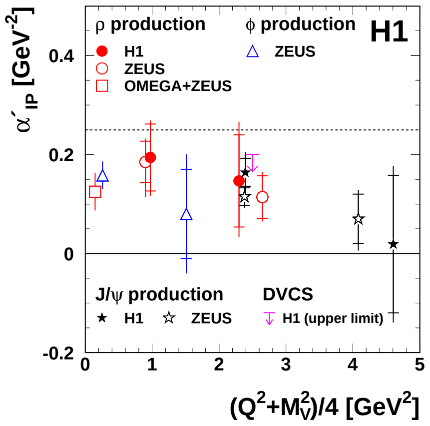
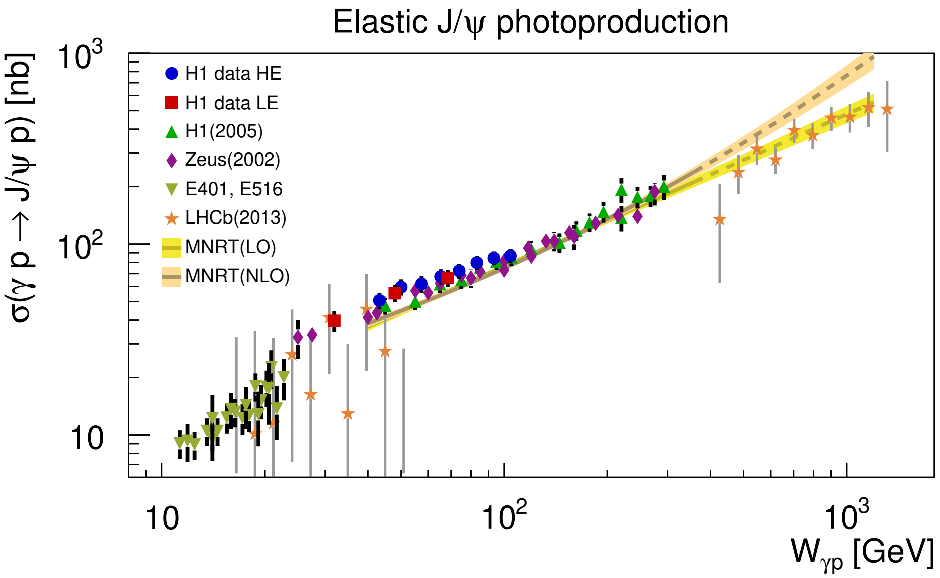




Transition from soft to hard regime occurs at 'universal' scale $\mu^2 = (Q^2+M_V^2)/4 \simeq 3 \div 5$ GeV^2

Elastic Photoproduction of J/ψ mesons - Sensitivity to the g/p



- Extrapolating HERA fit describes LHCb
- Low x gluon, based on old HERA data (A. Martin et al, 2008). NLO too steep

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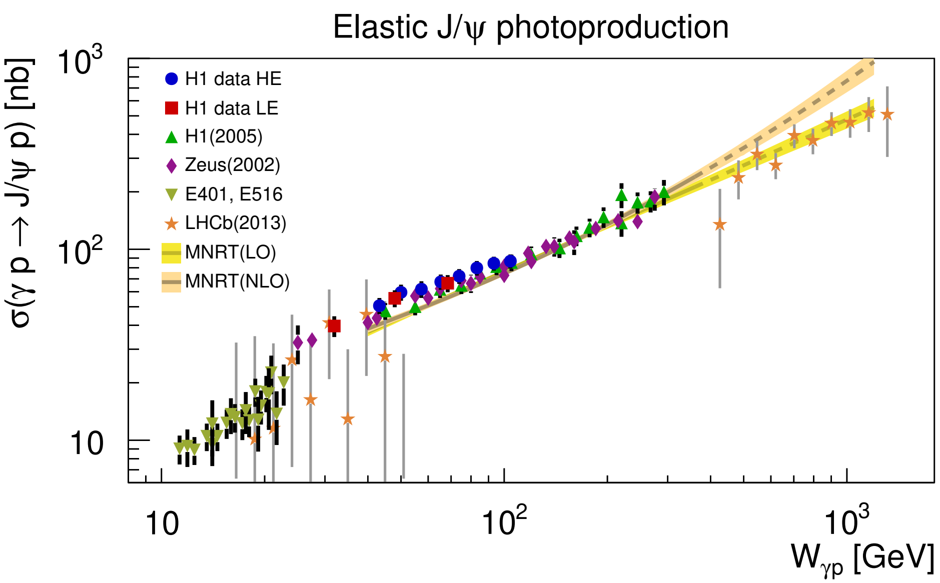
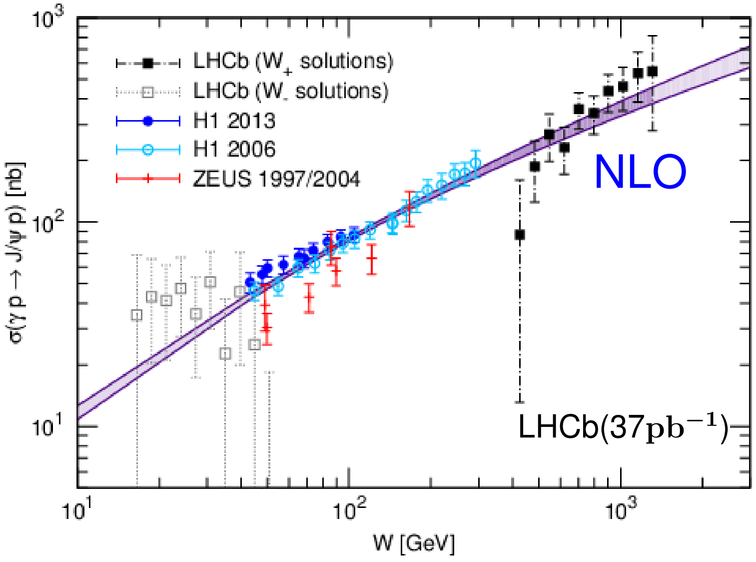
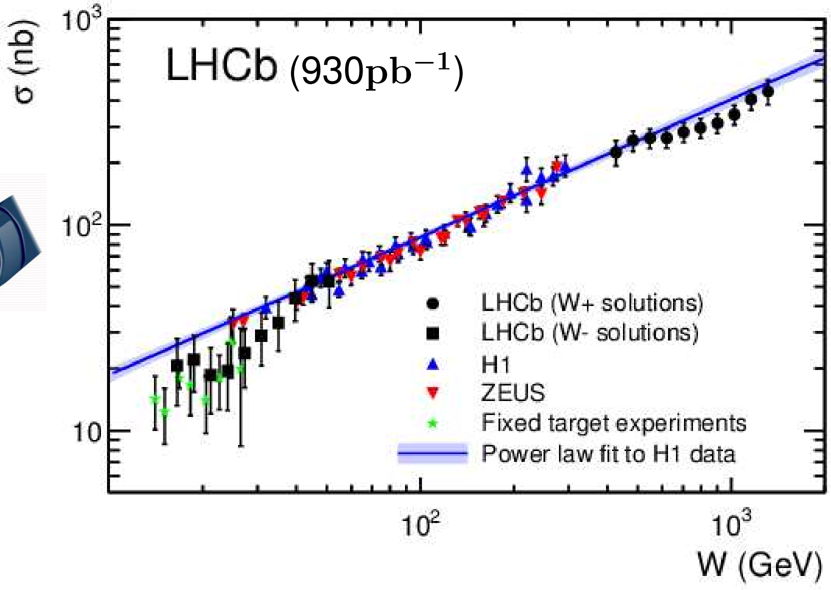
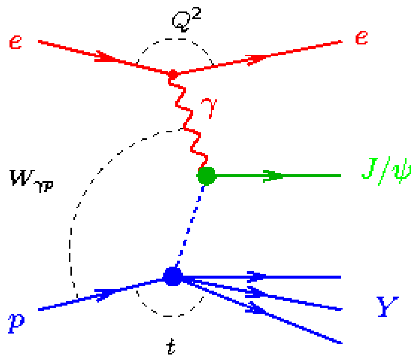


- Extrapolating HERA fit describes LHCb
- Low x gluon, based on old HERA data (A. Martin et al, 2008). NLO too steep
- New QCD analysis (A.Martin et al, 2013) skewed $g(x, x', k_T)$, abs.corr. for LHC
- New LHCb data (930pb^{-1}) [arXiv:1401.3288]





Photoproduction of J/ψ mesons with large t - BFKL $I\!P$ at work



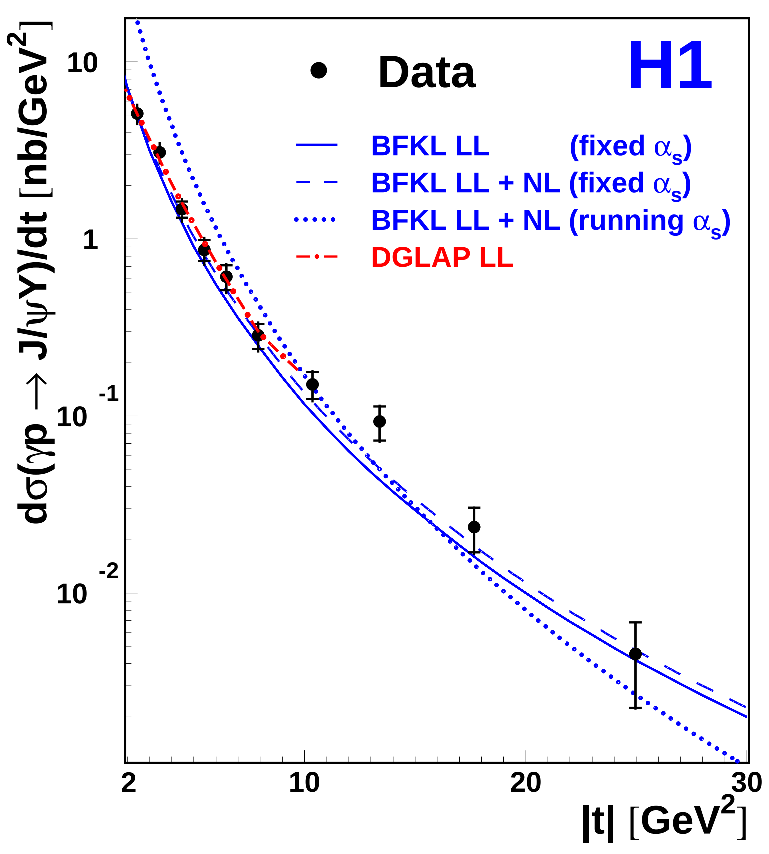
Data sample: $\mathcal{L} = 78\ \mathrm{pb}^{-1}$

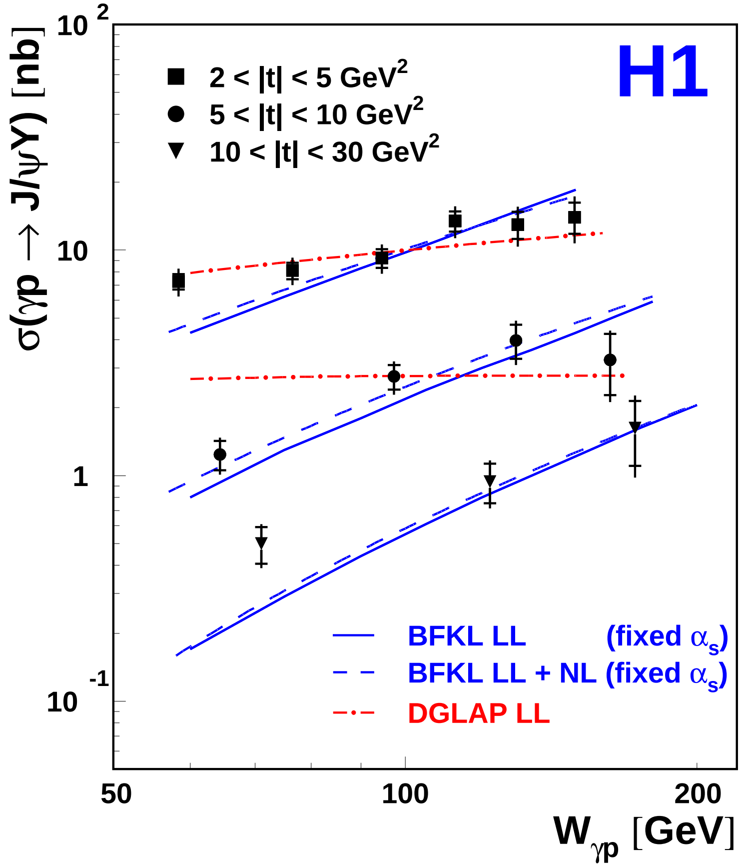
$|t| > 2,\ 50 < W < 150,\ z > 0.95$

Final statistics: 846 ± 30 events

$$\alpha_{I\!P}(0) = 1.17 \pm 0.05$$

$$\alpha'_{I\!P} = -0.014 \pm 0.009$$





$t-$dependence. Shrinkage of diffractive peak

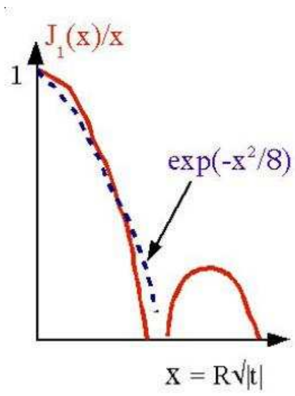
$d\sigma/dt \sim e^{-b|t|}$ → diffractive peak (approximated from Bessel function)

$b = (R/2)^2$ → transverse size of the target (geometric picture)

Predictions: $b = b_0 + 4\alpha'_{I\!P} \ln(W/W_0)$;

soft $I\!P$: shrinkage of diffractive peak ($\alpha'_{I\!P} = 0.25$); large $b_0 \approx 10$ GeV^{-2}

hard $I\!P$: no (or small) shrinkage ($\alpha'_{I\!P} < 0.1$); small $b_0 \approx 5$ GeV^{-2}



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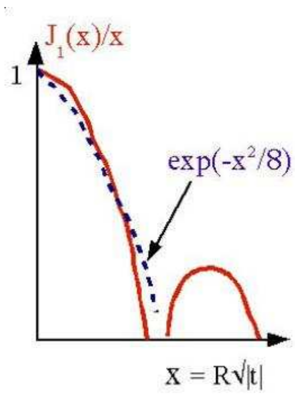

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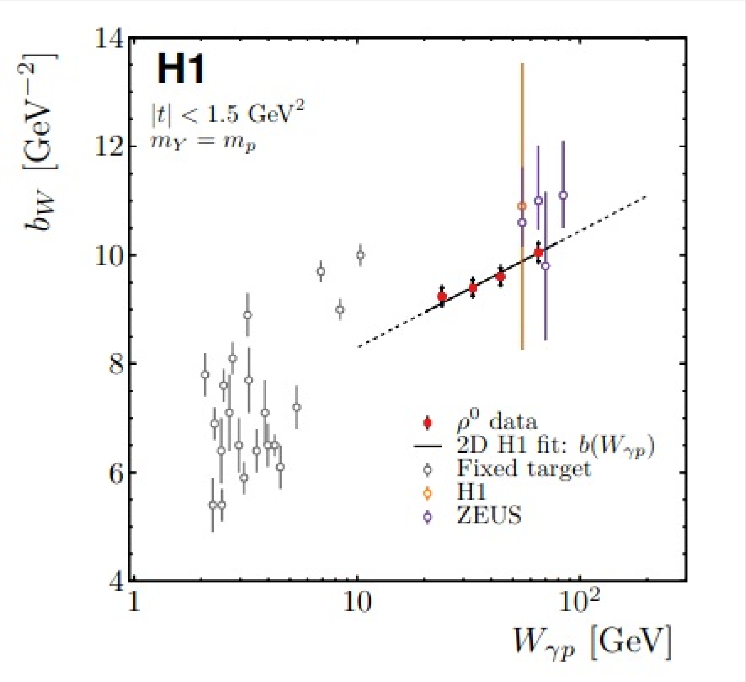
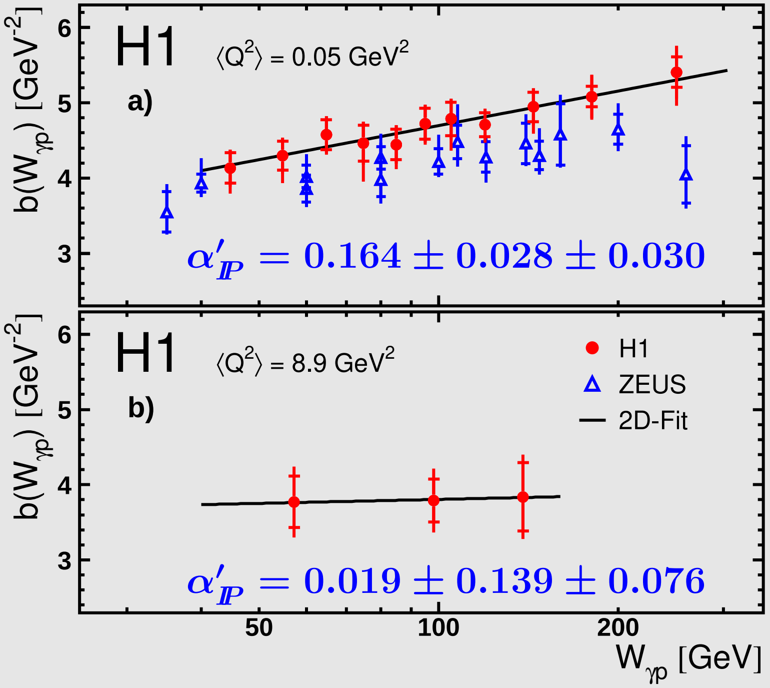


$\gamma p \to \rho^0 p$ (PHP): $\alpha'_{I\!P} = 0.233 \pm 0.064 \pm 0.029$



$\gamma^\star p \to J/\psi p$ (PHP,DIS)

$t-$dependence. Elastic slope vs Universal scale

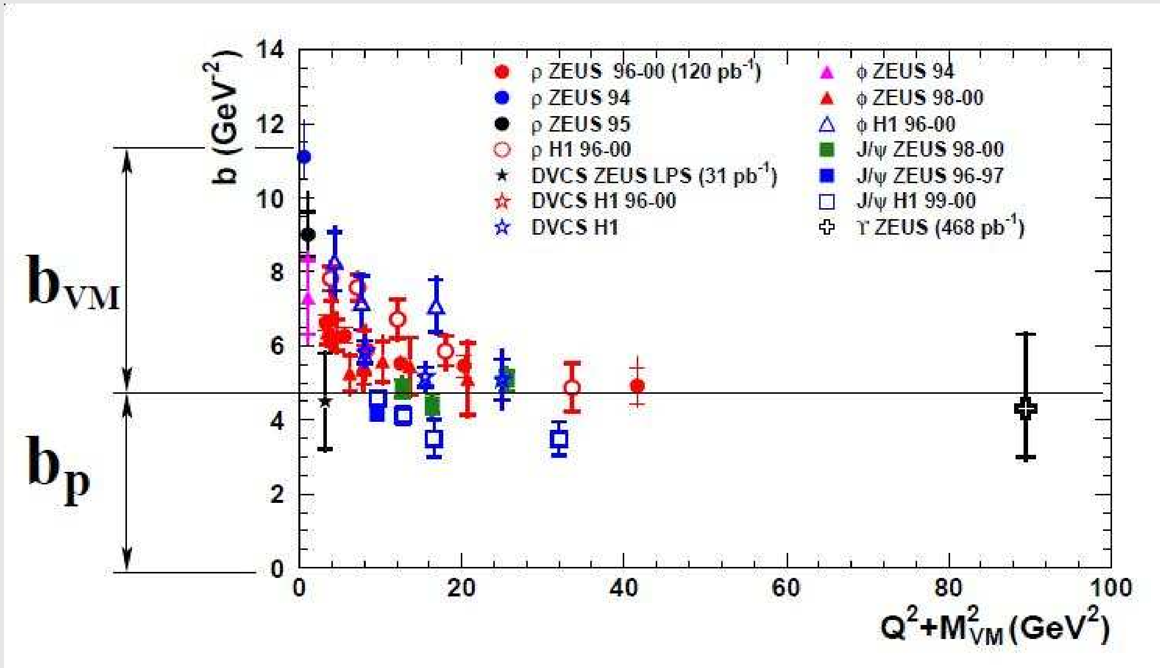
Dipole picture interpretation:

$$b = b_{VM} + b_{\rm p}$$

$$b_{VM} \sim 1/(Q^2 + M^2_{VM})$$

$b_{\rm p} \longrightarrow$ size of the gluons area:

$\langle r^2 \rangle = 2b_{\rm p} \cdot (\hbar c)^2 \simeq 0.6$ fm



➡ Gluons confinement area (0.6 fm) is smaller than the proton size (0.8 fm)

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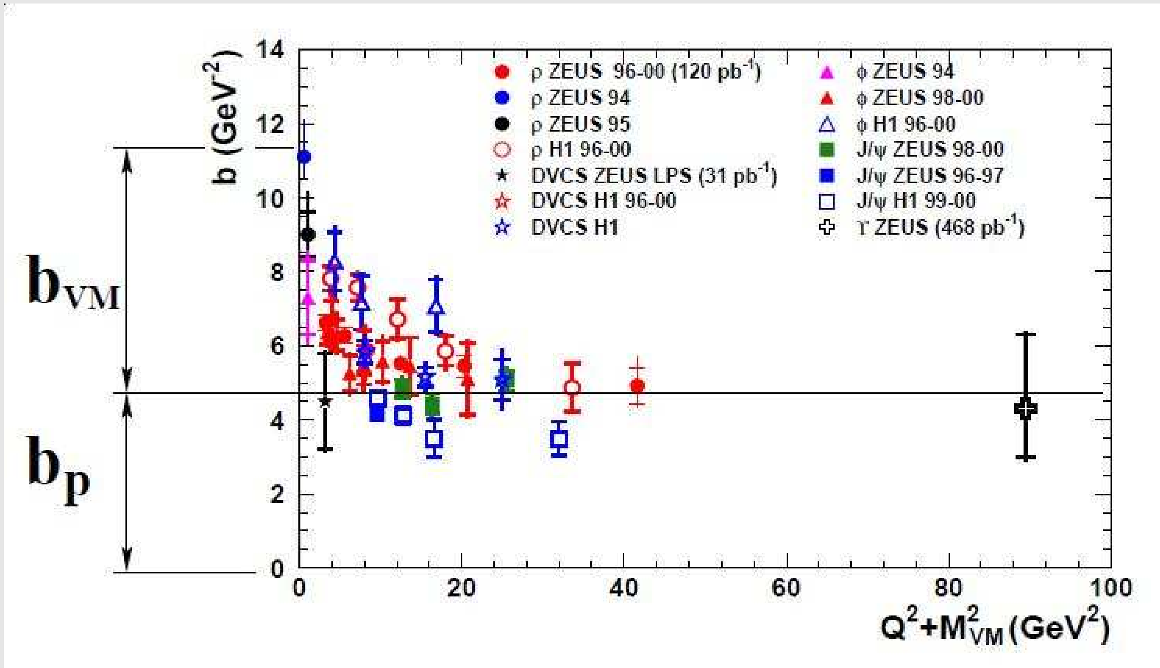

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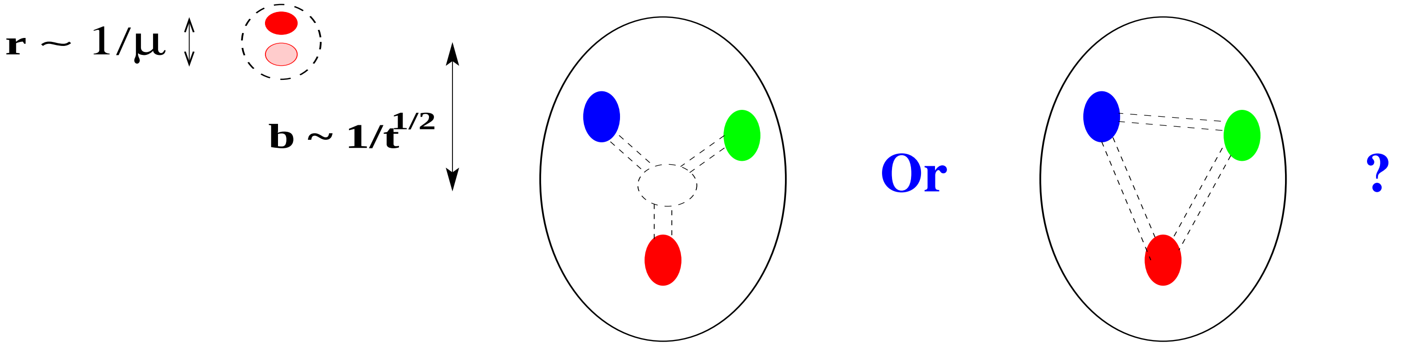


Intermediate summary

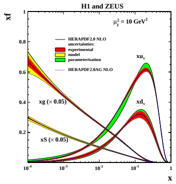
- Exclusive VM production at HERA provides a rich field for the QCD understanding of diffraction over a large kinematic domain.
- Many aspects are not covered in this talk, like helicity studies, spin density ME, WF effects, comparison of elastic to proton dissociative channels etc.
- Full list of published analyses in the field can be found in page 1.
- Several new analyses are ongoing, but we lack a manpower.
  You are welcome to join!

Now for illustration I try to describe just one specific analysis, showing typical experimental challenges in such seemingly simple reactions.

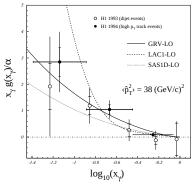
HERA as a ‘4P’ facility

HERA enables to study structure of

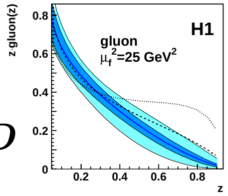
Proton $- F_2, F_L, \ldots$



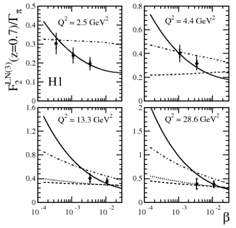
Photon $- g/\gamma$



Pomeron $- F_2^D, F_L^D$



Pion $- F_2^\pi$



HERA as a ‘$4P$’ facility

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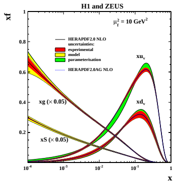
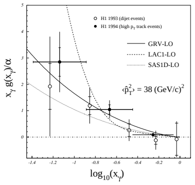
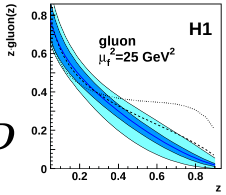


Proton – $F_2, F_L, \ldots$

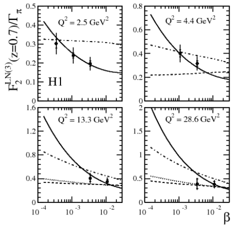
Photon – g/γ



Pomeron – F_2^D, F_L^D

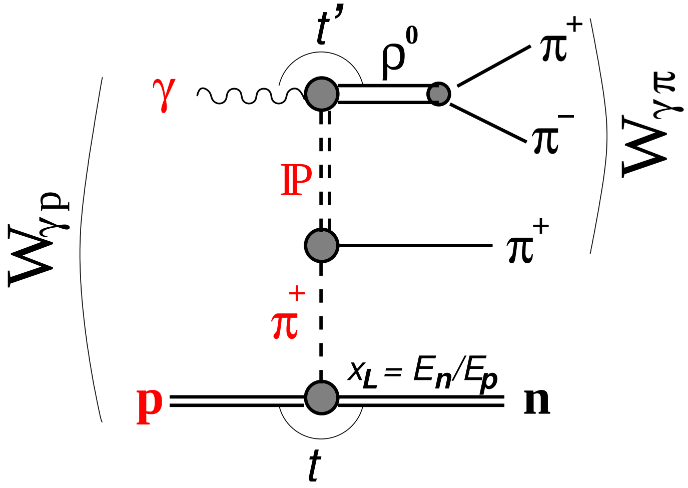


Pion – F_2^π



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

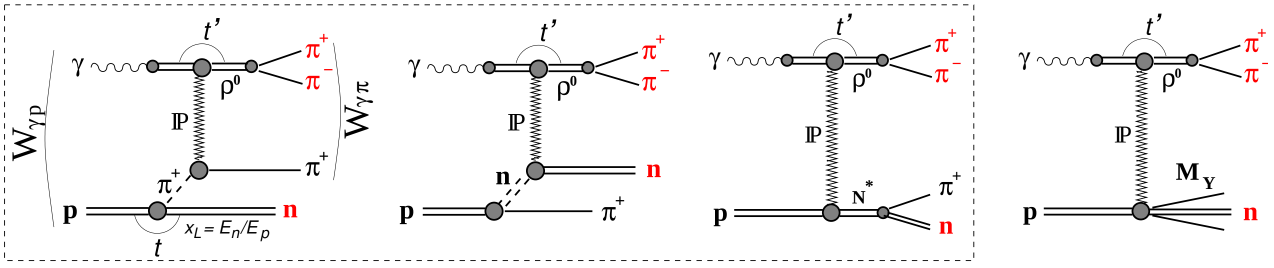
$$\gamma + \mathbf{p} \longrightarrow \rho^0\, \pi^+\, \mathbf{n}$$



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 ⇒ Regge framework is most appropriate

ρ^0 with Leading Neutron: Control plots



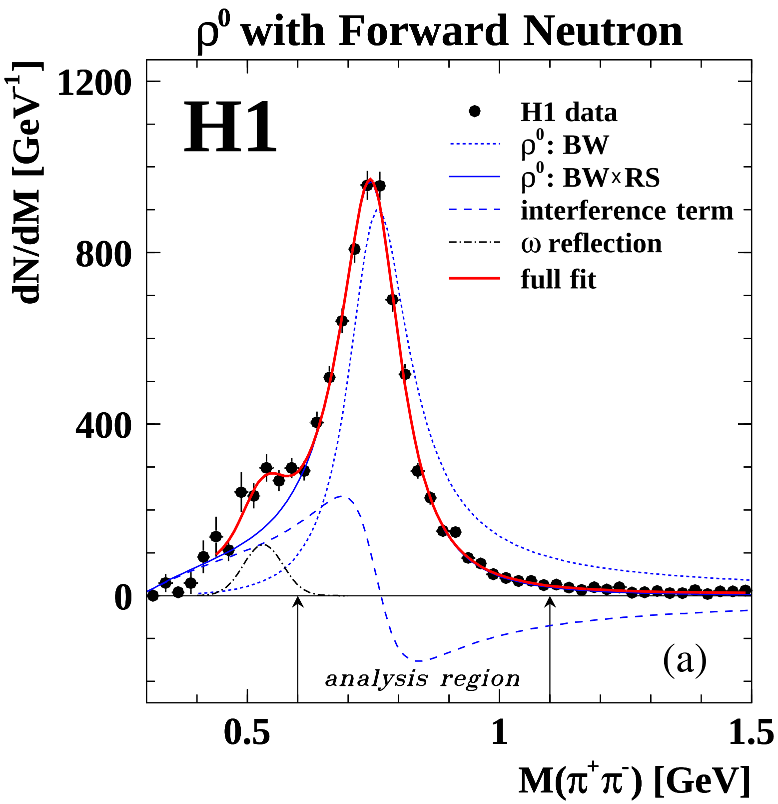
(a) (b) (c) (d)

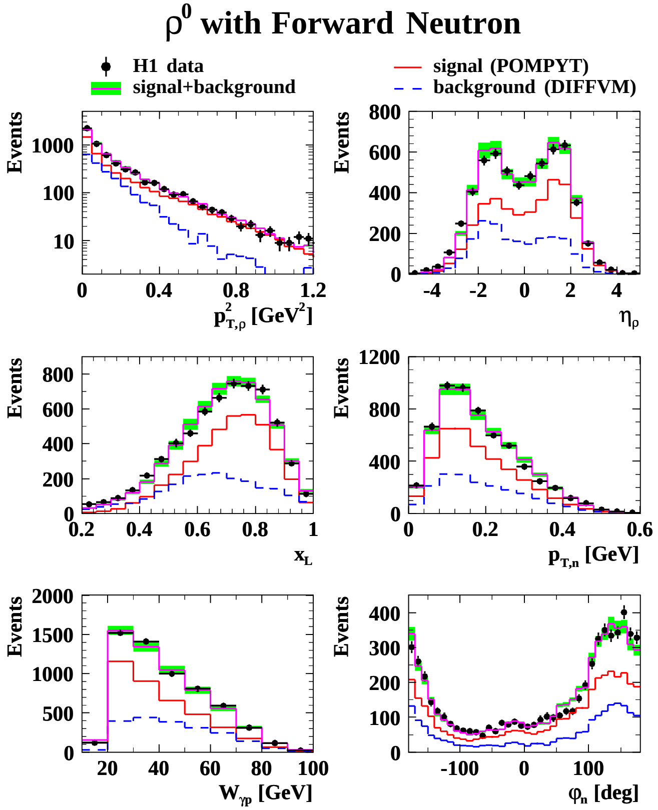
Data sample: $\mathcal{L} = 1.16$ pb^{-1}

$\sim$ 7000 events

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

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

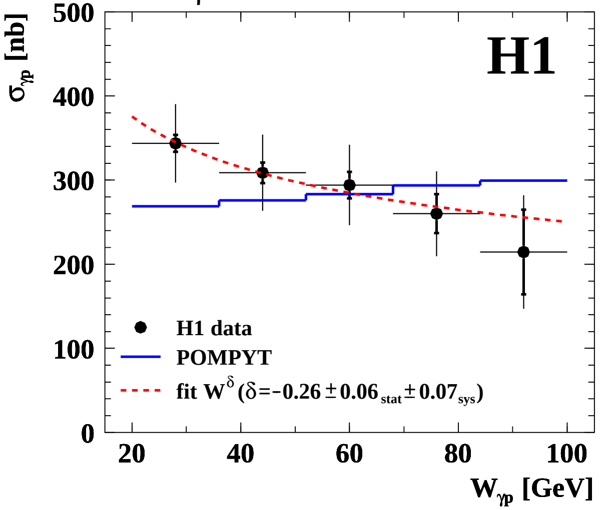


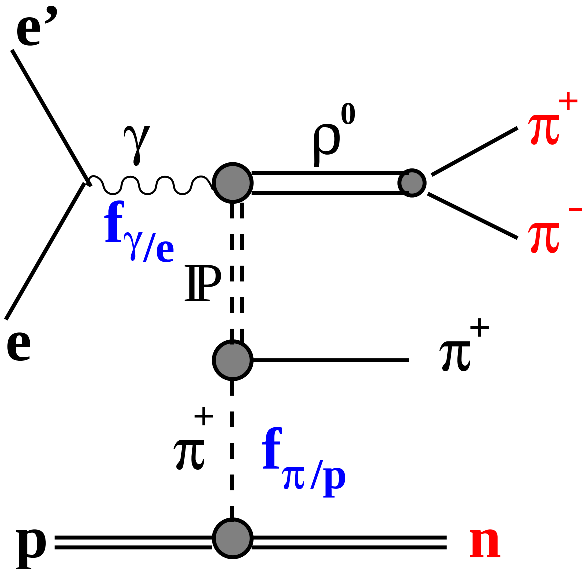


Cross sections definitions

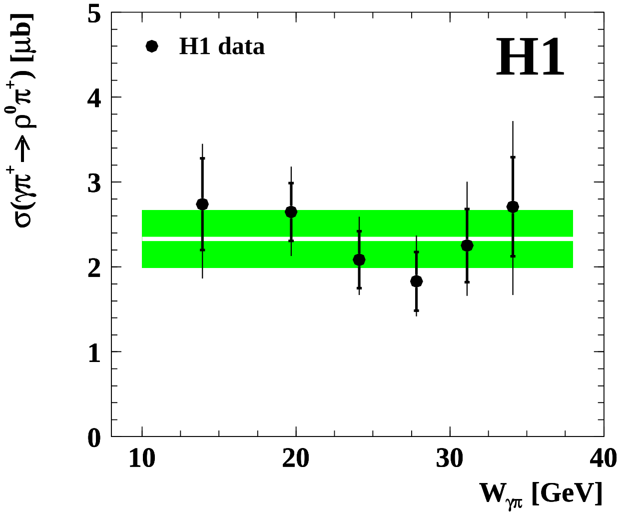
$$\sigma_{\gamma p} = \frac{\sigma_{ep}}{\Phi_\gamma}$$

ρ^0 with Forward Neutron





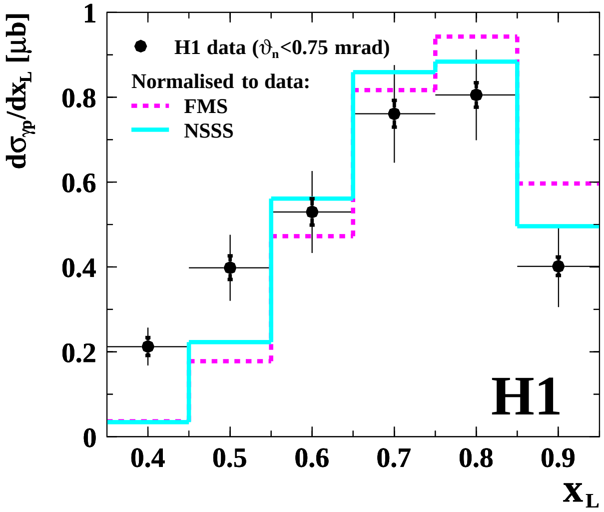
$$\sigma_{\gamma\pi} = \frac{\sigma_{\gamma p}}{\Gamma_\pi}$$

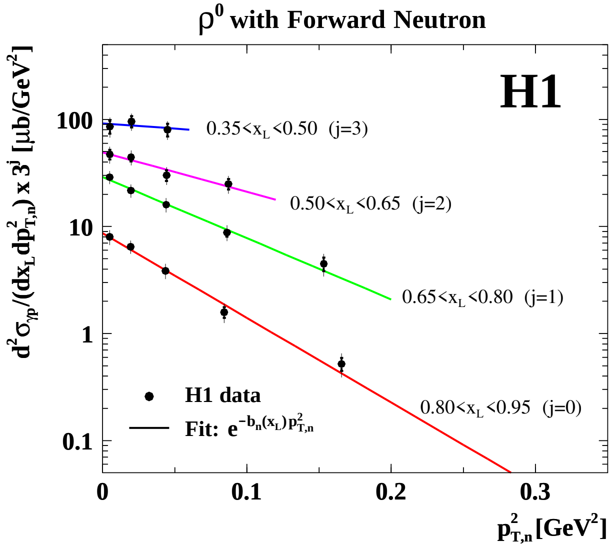


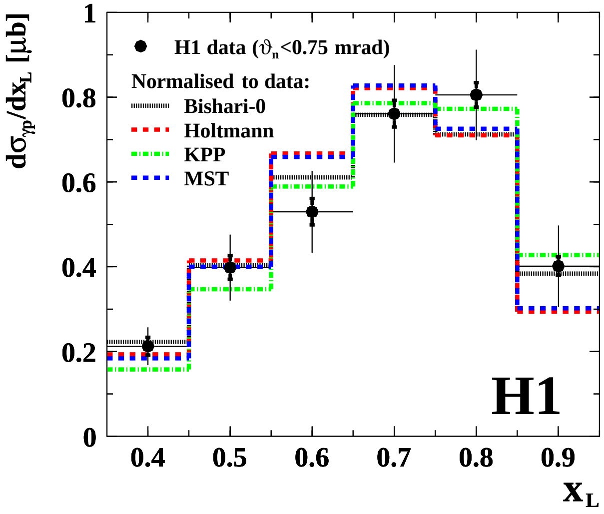
VMD: $$f_{\gamma/e}(y,Q^2) = \frac{\alpha}{2\pi Q^2 y}\left\{\left[1+(1-y)^2 - 2(1-y)\left(\frac{Q^2_{\min}}{Q^2} - \frac{Q^2}{M^2_\rho}\right)\right]\frac{1}{\left(1+\frac{Q^2}{M^2_\rho}\right)^2}\right\}$$

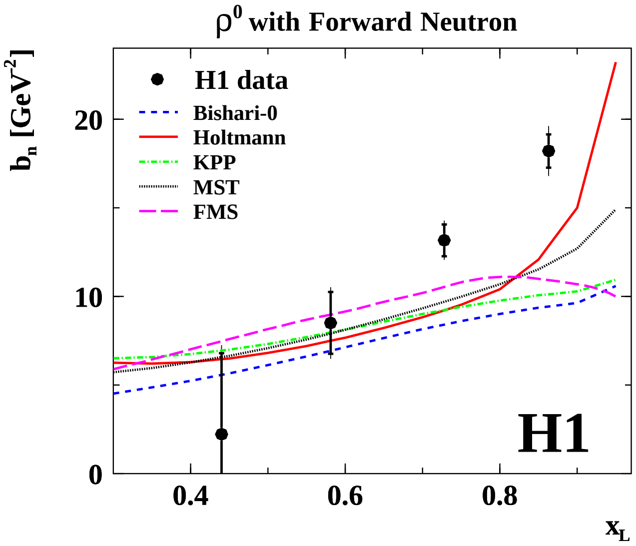
OPE: $$f_{\pi/p}(x_L,t) = \frac{1}{2\pi}\frac{g^2_{p\pi N}}{4\pi}(1-x_L)\frac{-t}{(m^2_\pi - t)^2}\exp[-R^2_{\pi n}\frac{m^2_\pi - t}{1-x_L}]$$

Constraining pion flux







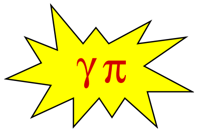


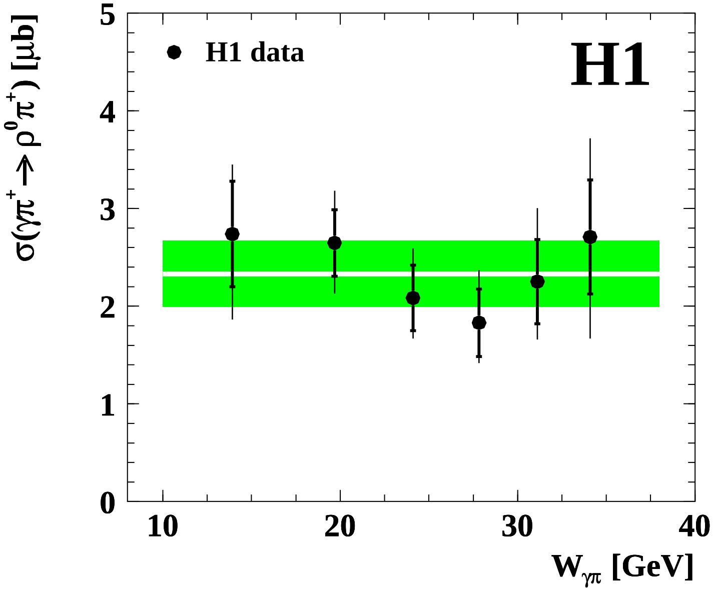
Failure to describe $b_n(x_L)$ suggests strong absorptive effects (n rescattering) $\Rightarrow$ try to quantify

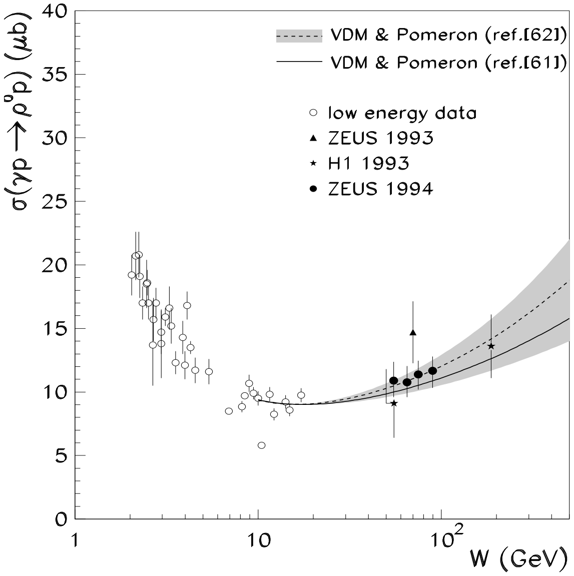
Estimate of absorption corrections

$(2.33 \pm 0.56)\mu$b

$(9.5 \pm 0.5)\mu$b







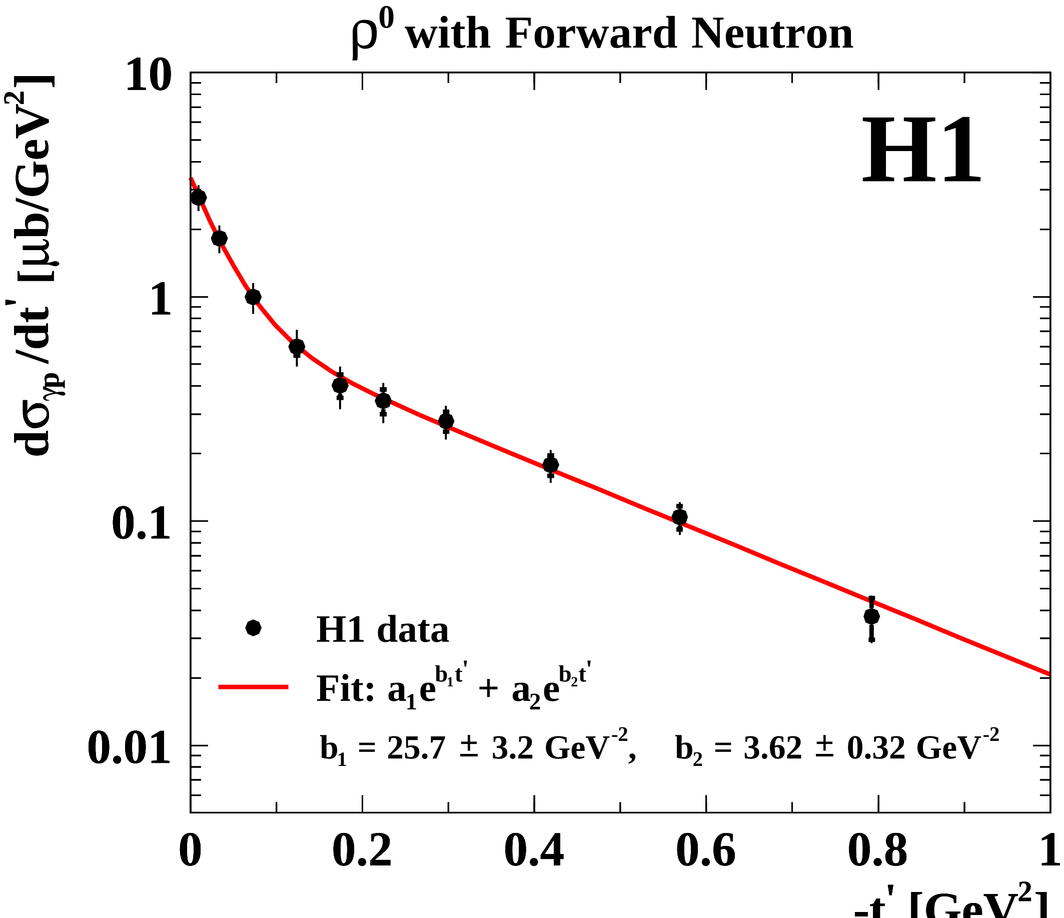
$$r_{\rm el} = \frac{\sigma_{\gamma\pi\to\rho^0\pi}}{\sigma^{\gamma p\to\rho^0 p}} = \begin{cases} 0.25 \pm 0.06 & (\text{exp.extracted}) \\ 0.57 \pm 0.03 & (\text{theo.expected}) \end{cases} \Longrightarrow K_{\rm abs} = 0.44 \pm 0.11$$

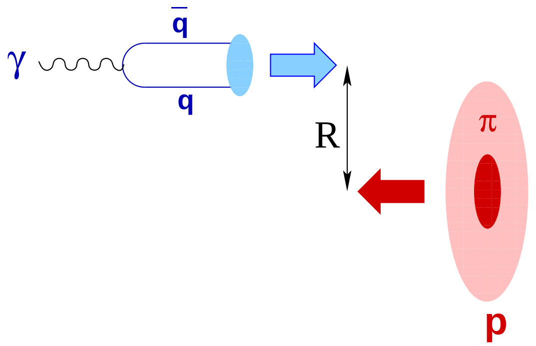
Optical Theorem: $\frac{d\sigma_{el}}{dt}\,|_{t=0} = b_{\rm el}\sigma_{\rm el} \propto \sigma^2_{\rm tot}$ $\Longrightarrow$ $r_{\rm el} = (\frac{b_{\gamma p}}{b_{\gamma\pi}}) \cdot (\sigma^{\gamma\pi}_{\rm tot}/\sigma^{\gamma p}_{\rm tot})^2$

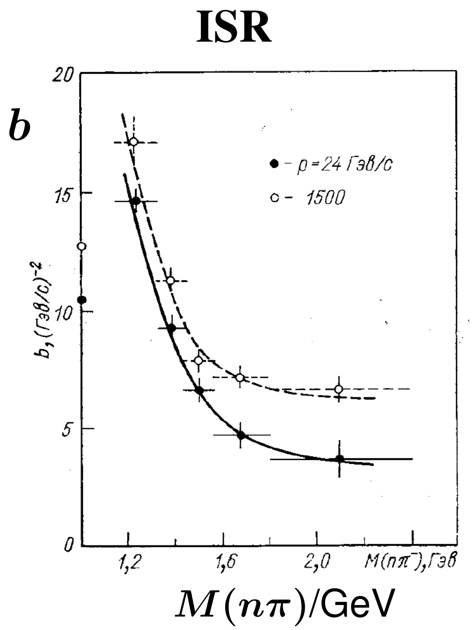
Eikonal approach: $b = \langle R^2 \rangle; \quad b_{12} = b_1 + b_2$

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

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







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

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

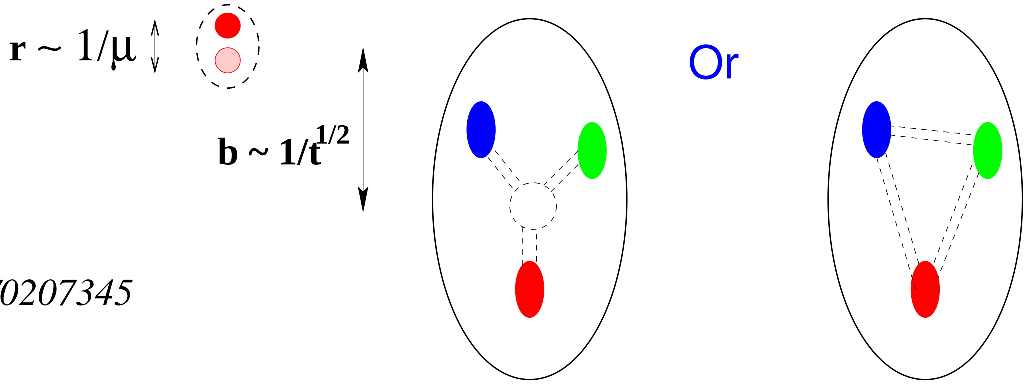
Open questions

- HERA limitations: missing nuclear targets; target polarisation ⇒
  Big program for EIC (gluon saturation, colour transp., spin physics, ...)

- Where is an Odderon?
  Direct searches [1] were negative. Try via $I\!P$-$\mathcal{O}$ interference [2,3].

- Can one observe Glueball in a double Pomeron reaction in PHP?
  $p - \mathrm{gap} - M_X - \mathrm{gap} - V \quad (M_X = \sqrt{x_{I\!P1} x_{I\!P2}}\, W_{\gamma p} = 2 \div 4\ \mathrm{GeV})$

- Is $g_p(x)$ t independent?
  What is nucleon topology?



[1] H1 Collab., Phys. Lett. B544 (2002) 35.

[2] I.Ginzburg, I.Ivanov, N.Nikolaev, arXiv:hep-ph/0207345

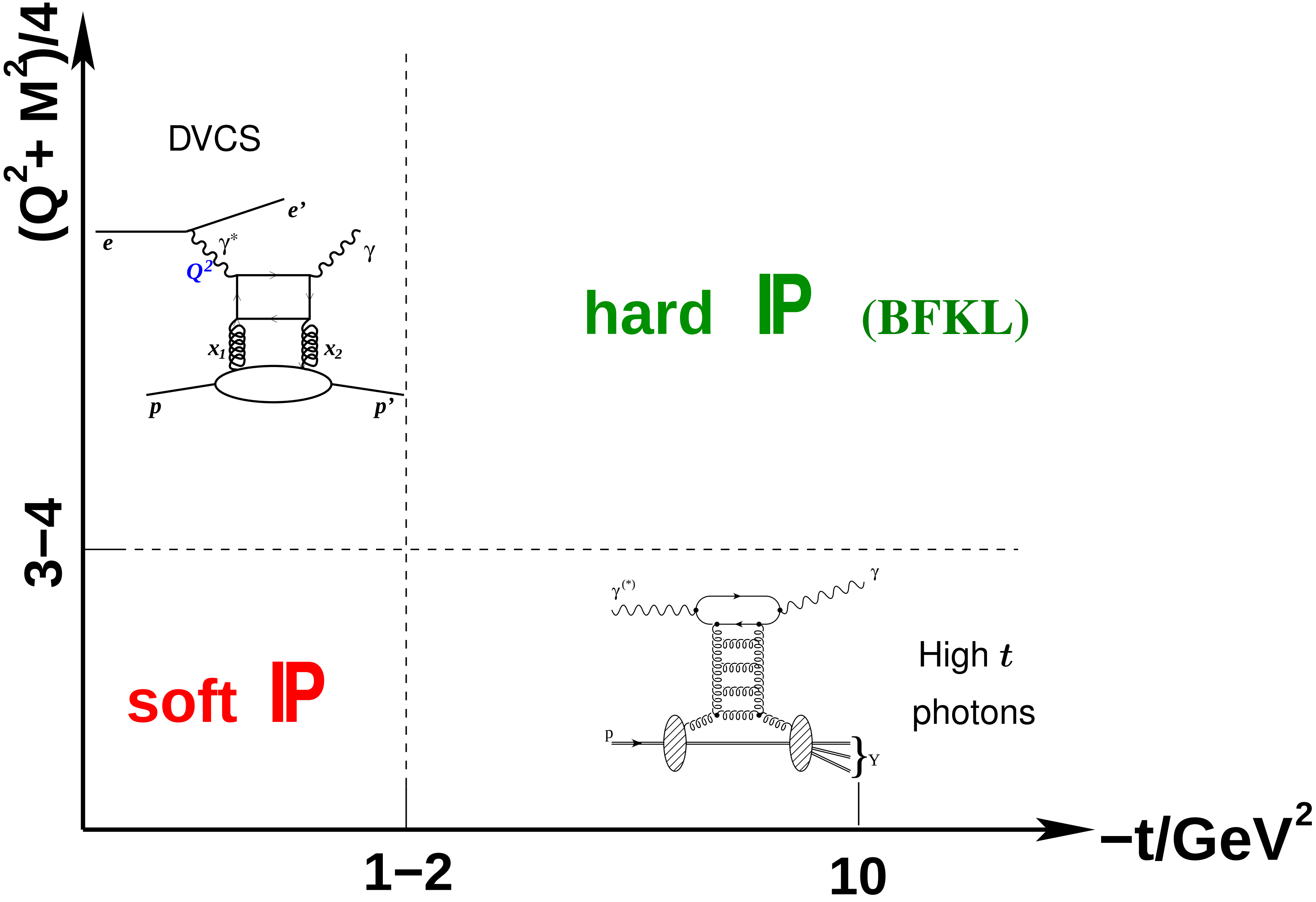
[3] C. Ewerz et al., Annals Phys. 342 (2014) 31;
A. Bolz et al., JHEP 1501, (2015) 215.

Some Lessons

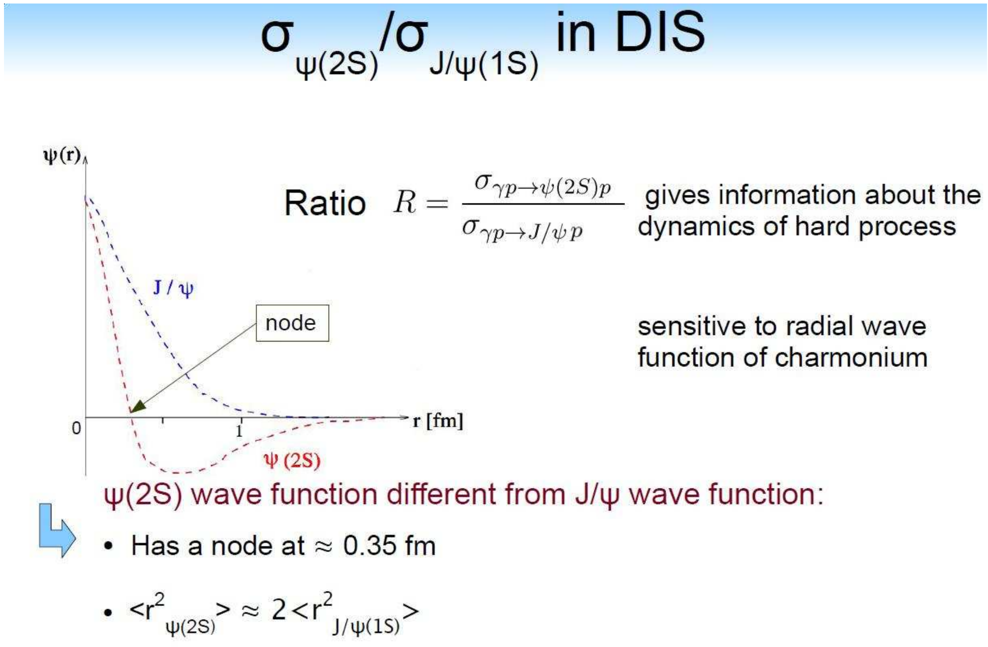
- Well equipped forward region, up to very large η is essential.
  Also, extend forward tracking as much as possible.
- Zero degree neutron/γ(?) detector (especially in view of nuclear targets).
- LRG selection and p-tagging in Roman Pots are complementary.
  Try to exploit both methods.
- Good e/γ separation in the backward region (High-t γ, DVCS)
- Efficient (track based) trigger for soft events!
  (Low/medium W e-tagger helps in case of light VM's)
- Unfolding technique is vital (e.g. for fwd-tag/untag to EL/PD classes)

Extra slides

Relevant scales?



Studies of WF effects in $c\bar{c}$ system



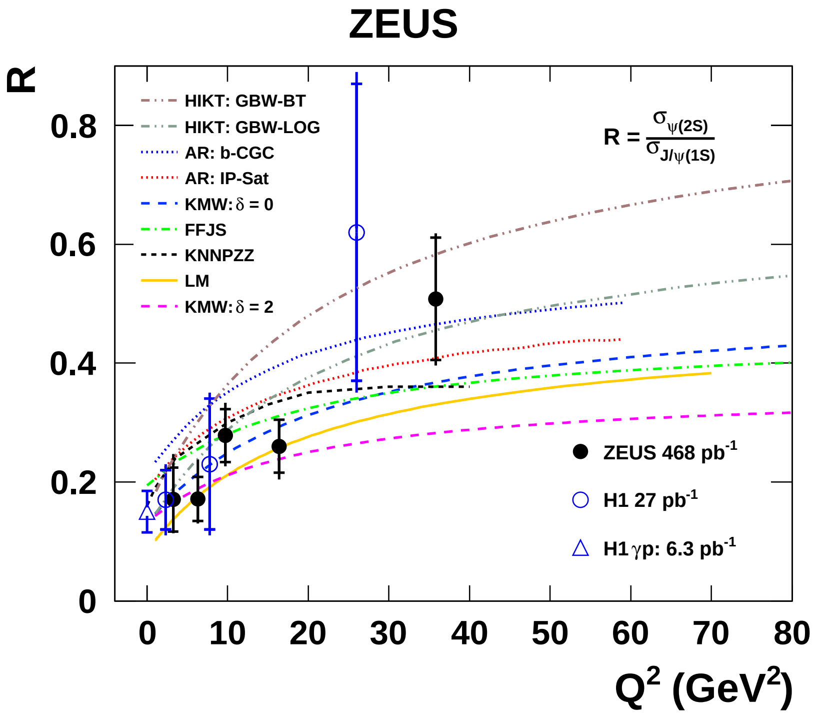
$\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in DIS

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:

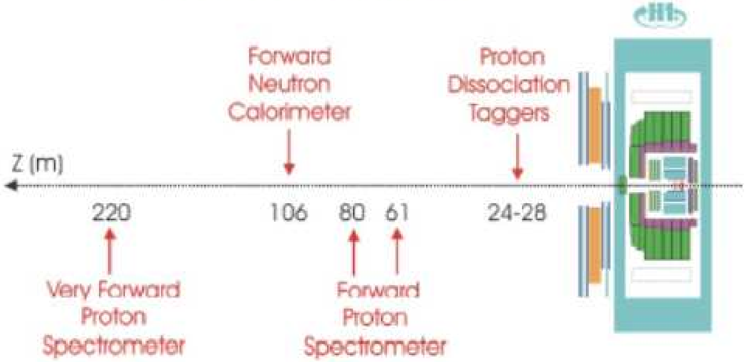
$R(Q^2 = 0) \simeq 0.17$ and rises with Q^2

- 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)

Selection of Diffractive Events in H1

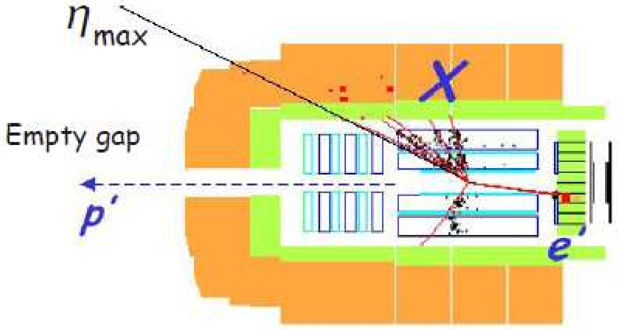
Measure the leading proton

→ 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

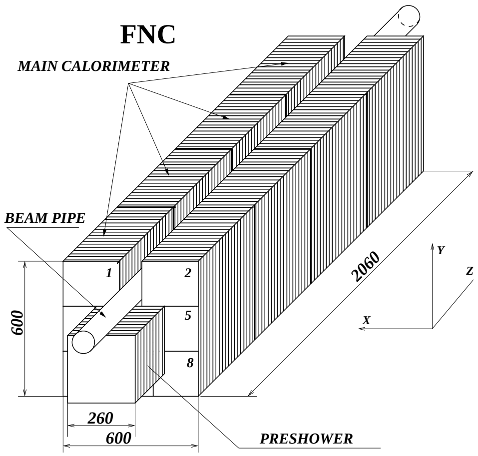
→ Needs to be controlled

↘ Different systematics

↘ Different kinematic coverage

VM+n: Key Experimental Ingredients

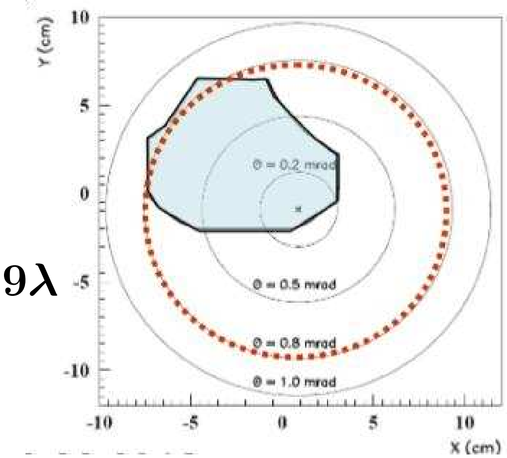
Improved H1 FNC (distinguish ($\langle P \rangle = 98\%$) and measure n and γ/π^0)

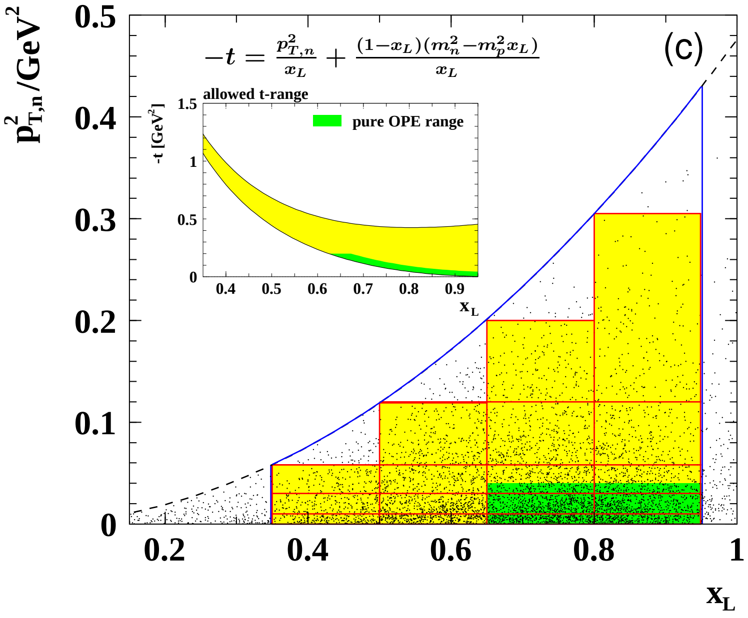


located at $z = 106$m from IP

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

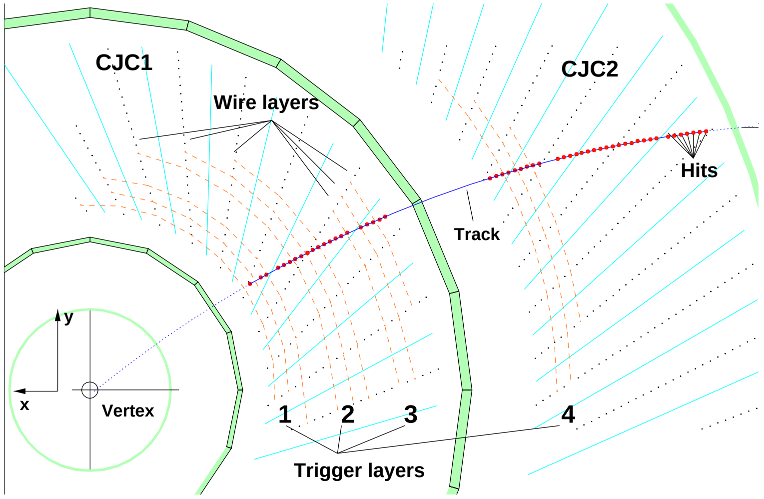
Preshower: $60X_0$, Main Calo: 8.9λ





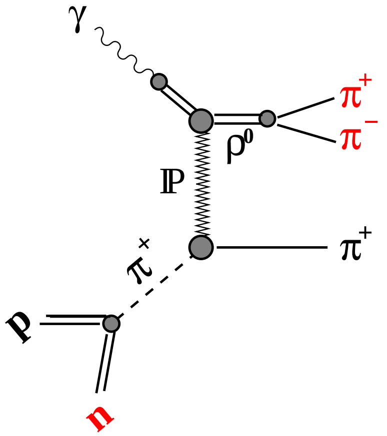
Powerful fast track trigger

(allows untagged soft γp to be collected)



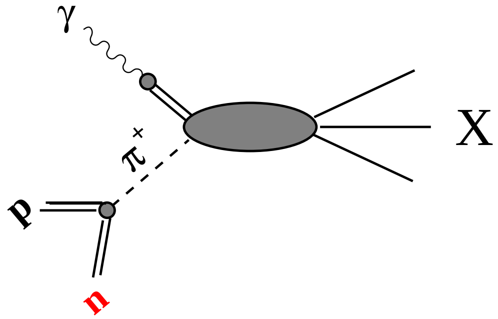
Large absorption in LN reactions

H1 (2015)



$\sigma_{\text{el}}^{\gamma\pi}$ (W=24 GeV)

ZEUS (2002)



$\sigma_{\text{tot}}^{\gamma\pi}$ (W=107 GeV)

$\sigma_{\text{el}}^{\gamma\pi}/\sigma_{\text{el}}^{\gamma p} = 0.25 \pm 0.06$	Exp.result	$\sigma_{\text{tot}}^{\gamma\pi}/\sigma_{\text{tot}}^{\gamma p} = 0.32 \pm 0.03$
OT+eikonal approach+data: $r_{\text{el}} \simeq 0.57$	Theory	AQM: $r_{\text{tot}} \simeq 2/3$

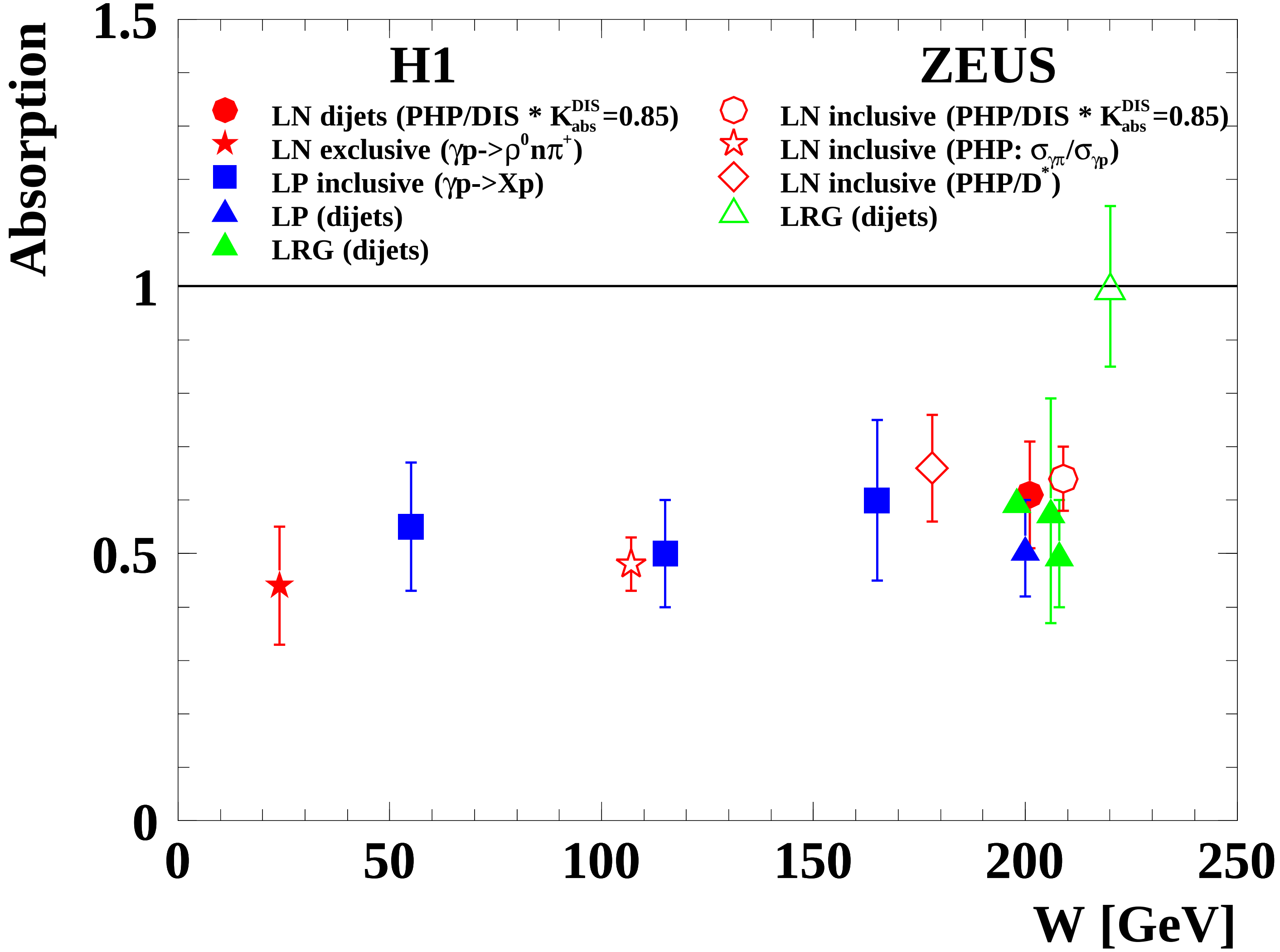
Large absorption effects!

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

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}

Absorptive factors, K_{abs}, in different PHP reactions



Unofficial private summary!