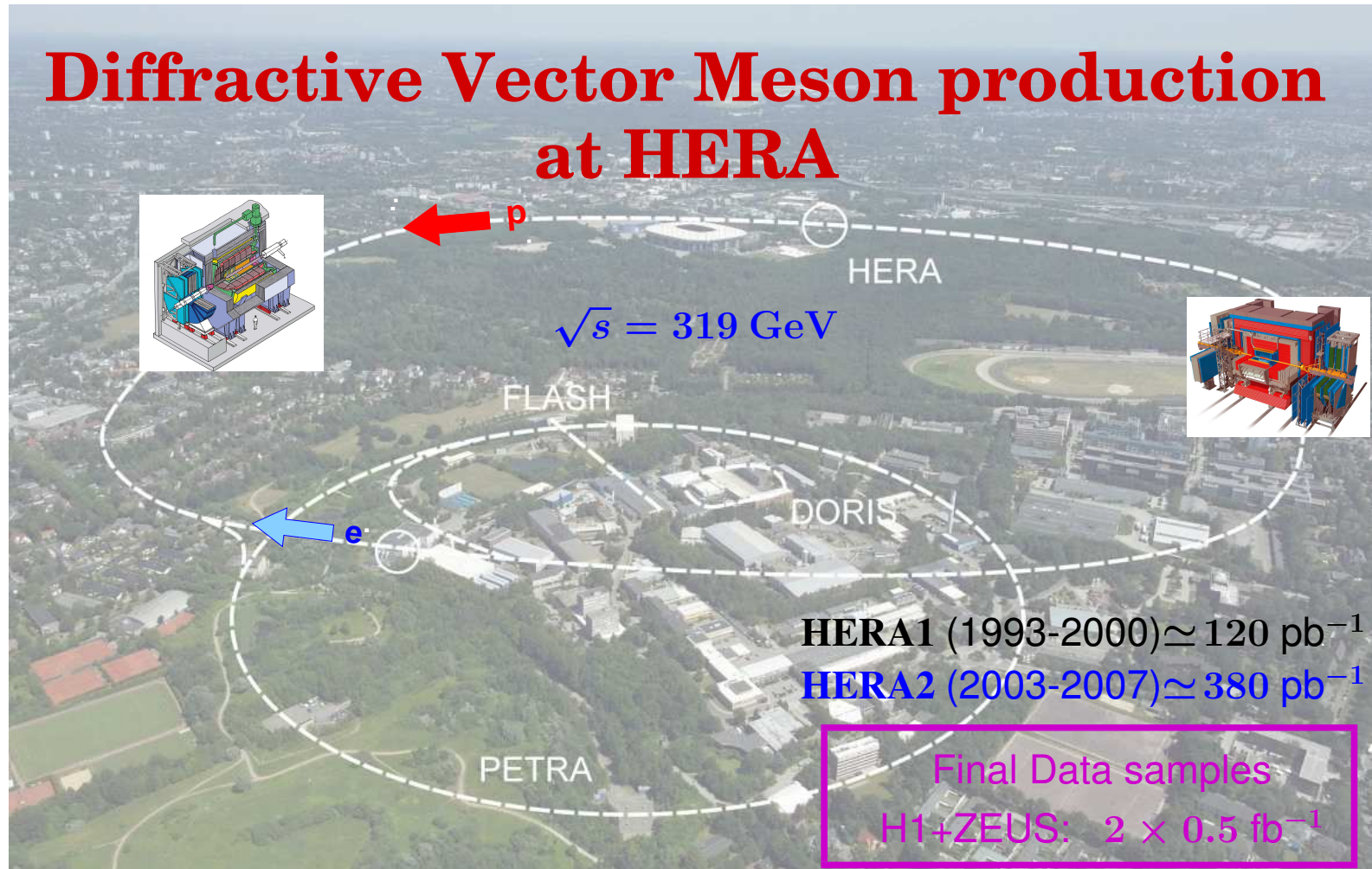




Sergey Levonian
DESY, Hamburg

Diffractive Vector Meson production at HERA



H1 and ZEUS publications about VM at HERA

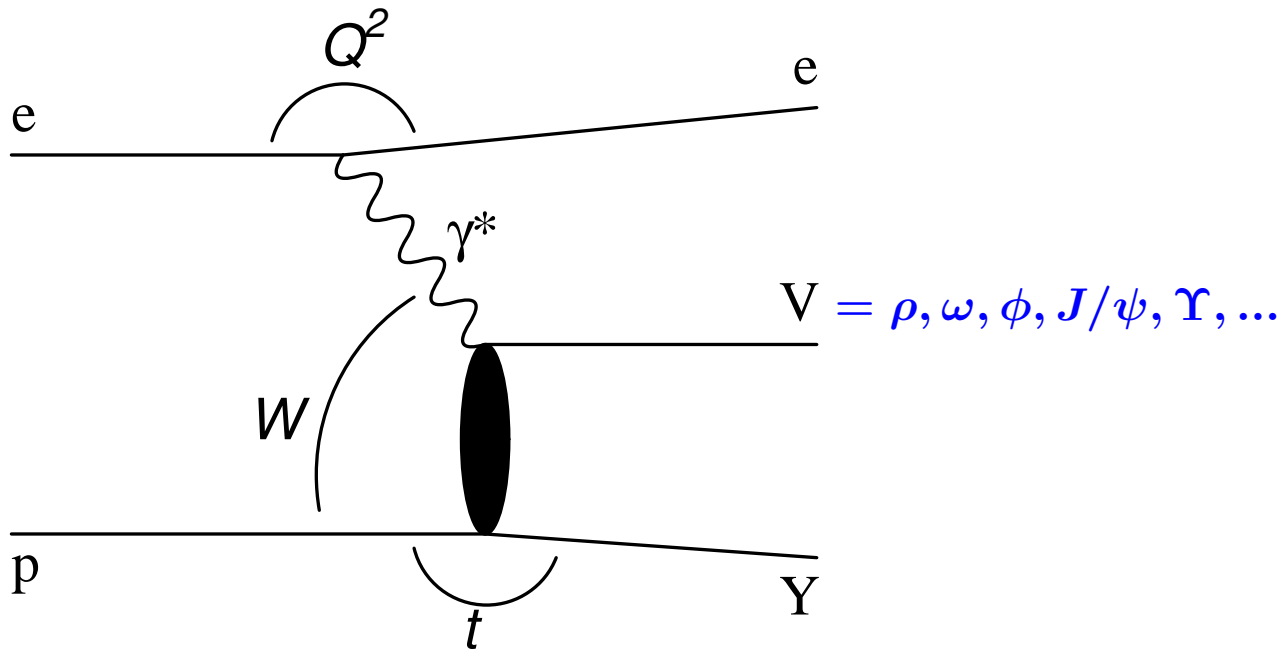
H1 Topic	Journal	ZEUS Topic	Journal
Exclusive $\pi^+\pi^-$ and ρ^0 in PHP Exclusive ρ^0 with Leading n in PHP Elastic and p-diss J/ψ in PHP Diffractive ρ^0 and ϕ in DIS Diffractive PHP of ρ^0 with large t Elastic J/ψ in PHP and DIS Diffractive PHP of J/ψ with large t Diffractive PHP of $\psi(2S)$ Helicity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

Measured are: $\rho, \rho', \omega, \phi, J/\psi, \psi(2S), \Upsilon$ in EL and PD channels and for $0 < Q^2 < 100\text{GeV}^2$
 More than 5000 references; a couple of new "preliminary" results and ongoing analyses. \Rightarrow

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



Covered PS at HERA

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

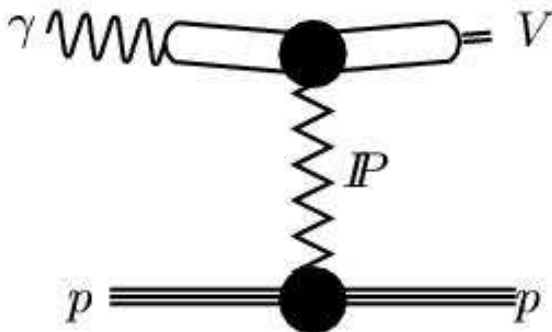
$$25 < W < 305 \text{ GeV}$$

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

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

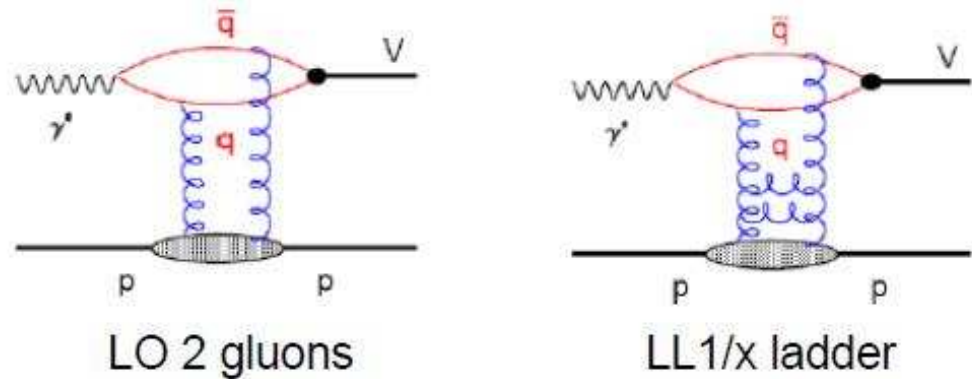
No hard scale present



VDM \oplus Regge

soft \mathbb{P} omeron exchange
 $\alpha_{\mathbb{P}}(0)=1.08; \alpha'_{\mathbb{P}}=0.25$
 $\sigma \propto W^{4(\alpha_{\mathbb{P}}-1)}$

Hard scale(s) present



CD picture ($\sigma \propto \Psi_{\gamma^* \rightarrow q\bar{q}} \cdot \sigma_{(q\bar{q})p} \cdot \Psi_{q\bar{q} \rightarrow V}$)

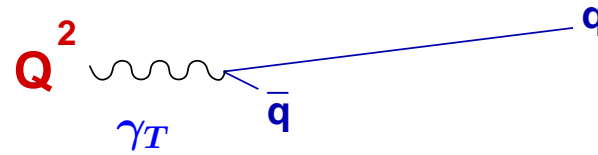
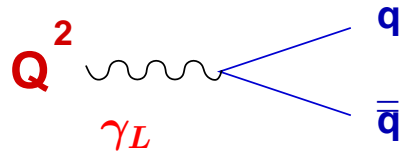
hard \mathbb{P} omeron diagrams
 $\alpha_{\mathbb{P}}(0) \simeq 1.20; \alpha'_{\mathbb{P}} \simeq 0$
 $\sigma \propto [xg(x, Q^2)]^2$

Questions of interest

- γp vs hh - is \mathbb{P} trajectory universal?
- Is \mathbb{P} trajectory indeed linear?
- Transition to hard regime: when and how?
- Direct access to (low x) gluons
- DGLAP vs BFKL evolution
- Confront $\sigma_{(q\bar{q})p}$ models with data

Baseline for γ^*A physics

Interplay between soft and hard processes in DIS

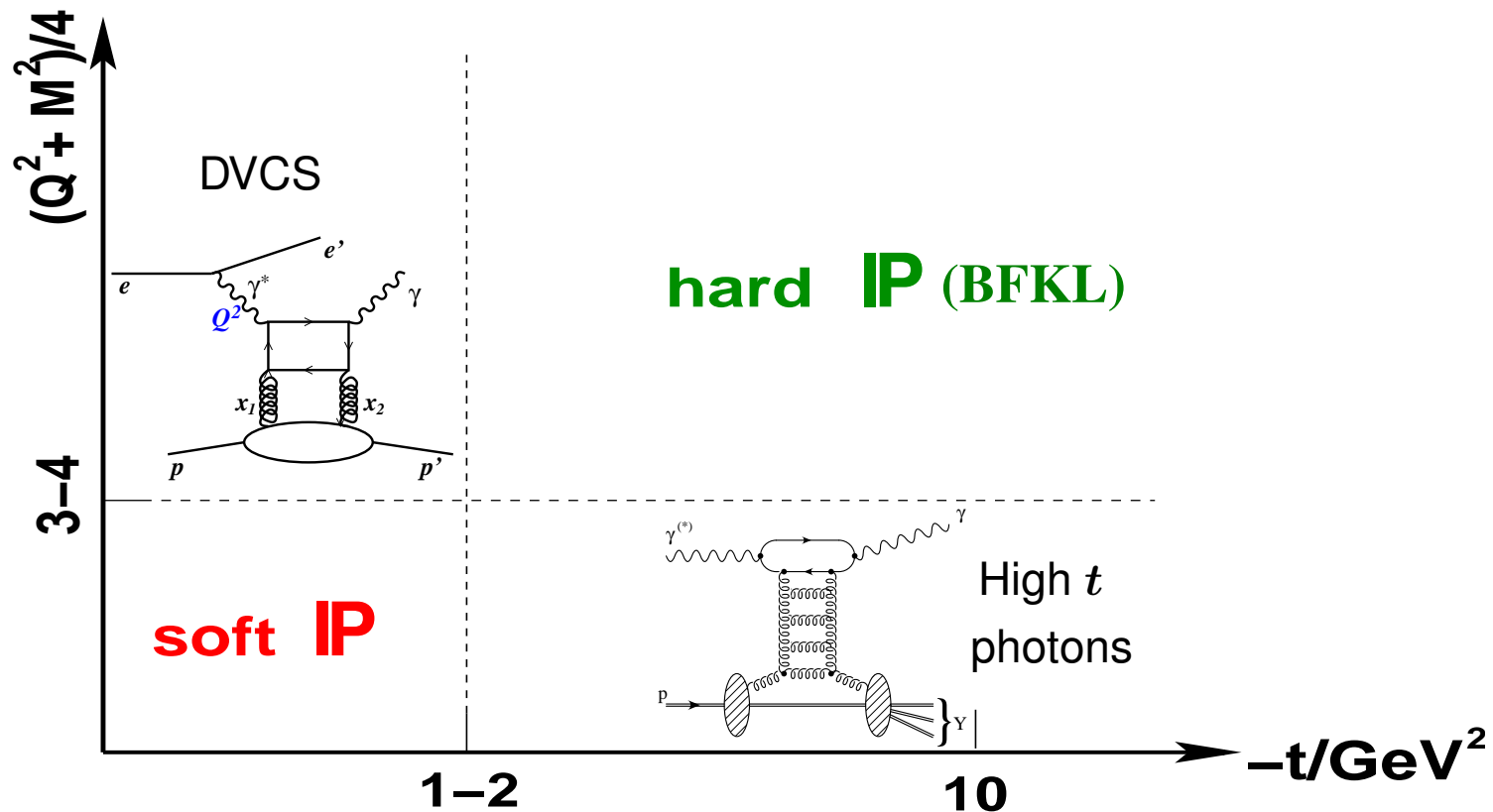


$$\gamma_L (z \simeq 0.5): \langle r_t^2 \rangle \simeq (z(1-z)Q^2 + m_q^2)^{-1} \simeq 1/[(Q/2)^2 + m_q^2] \quad (P \sim 1)$$

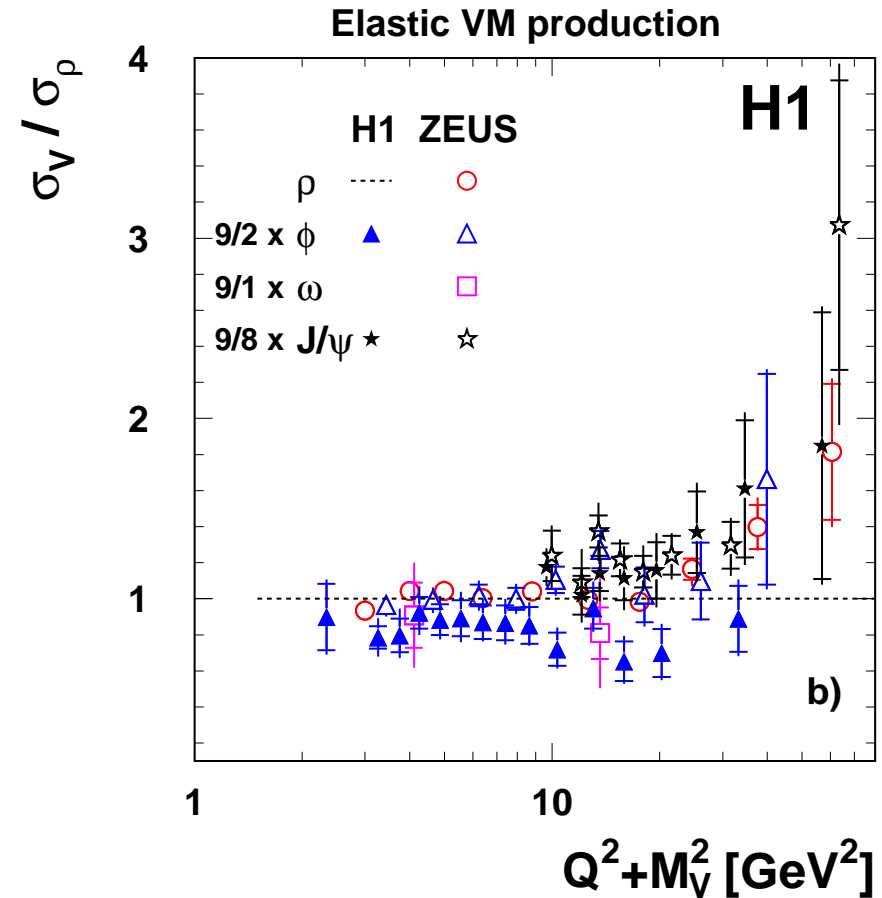
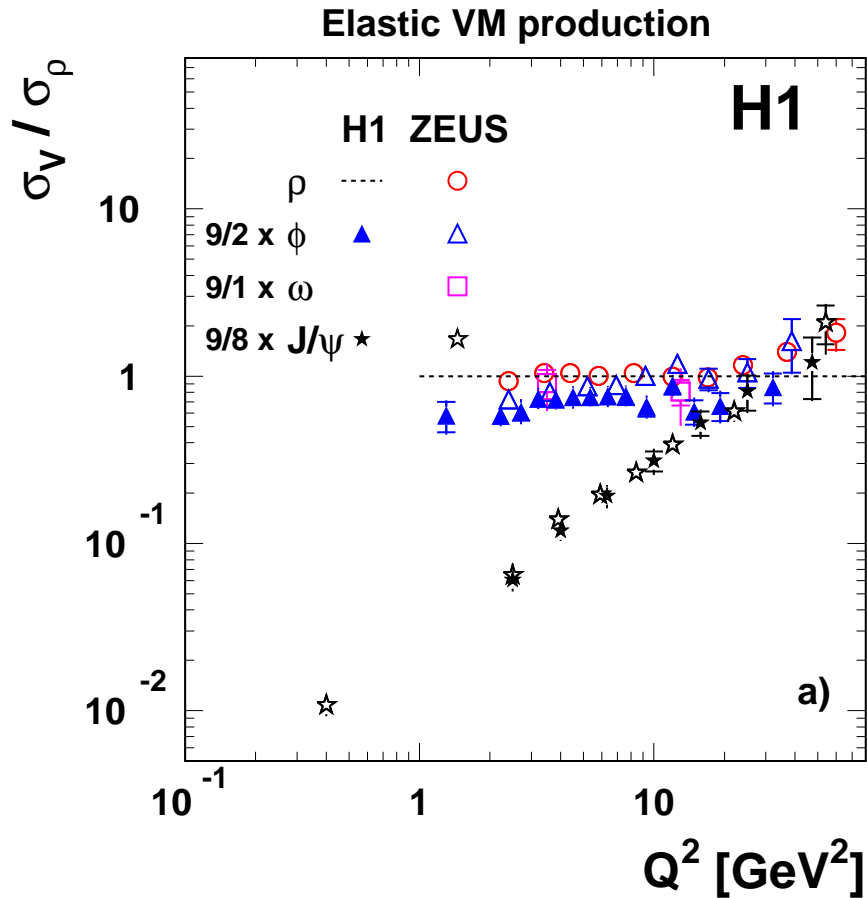
$$\gamma_T (z \simeq 0; 1): \langle r_t^2 \rangle \simeq (z(1-z)Q^2 + m_q^2)^{-1} \simeq 1/m_q^2 \quad (P \sim m_q^2/Q^2)$$

Small dipole ('hard')

Large dipole ('soft')



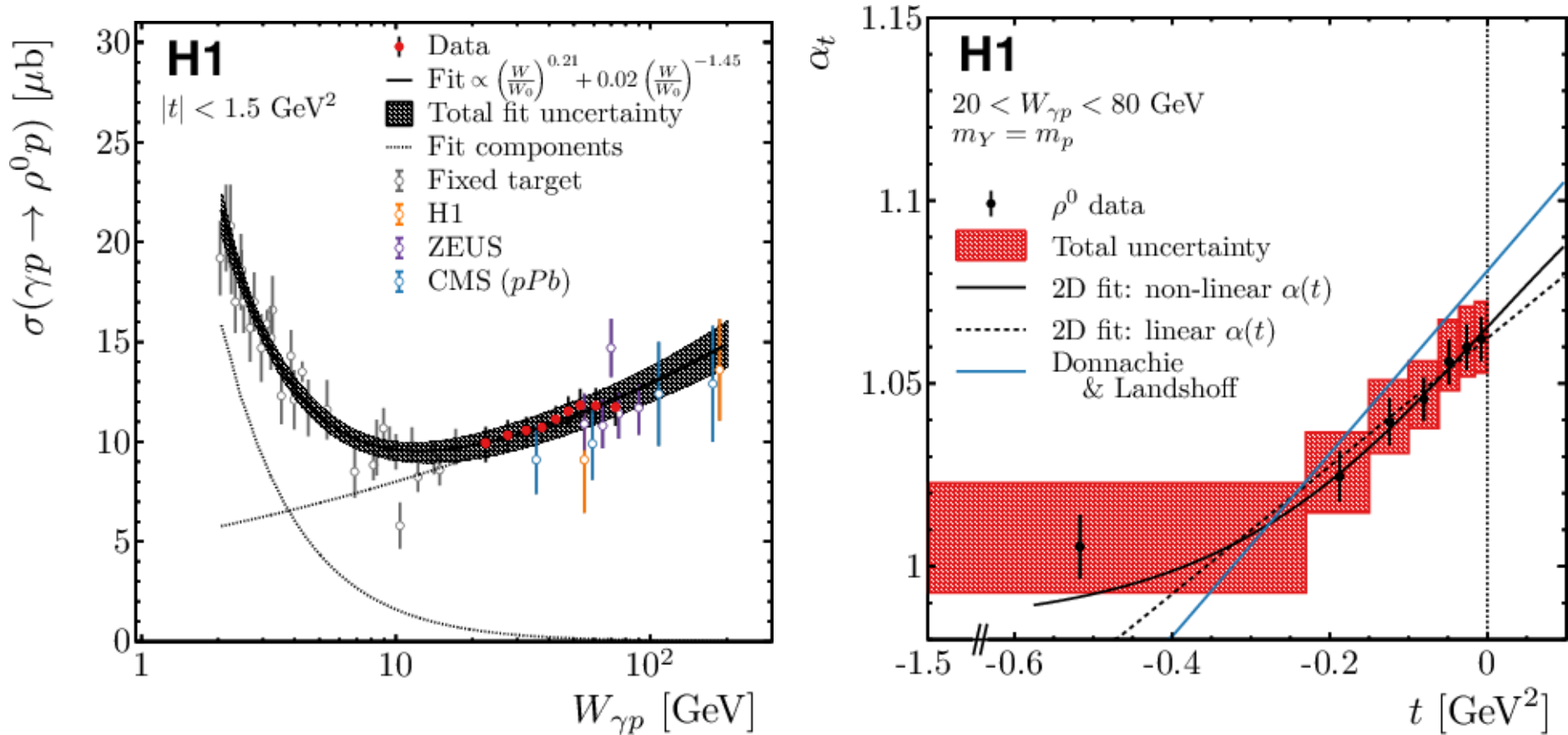
Flavour dependence. Universality



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 $Q^2 + M_V^2$

⇒ Cross sections are essentially determined by the dipole size

Soft regime. Regge in full glory

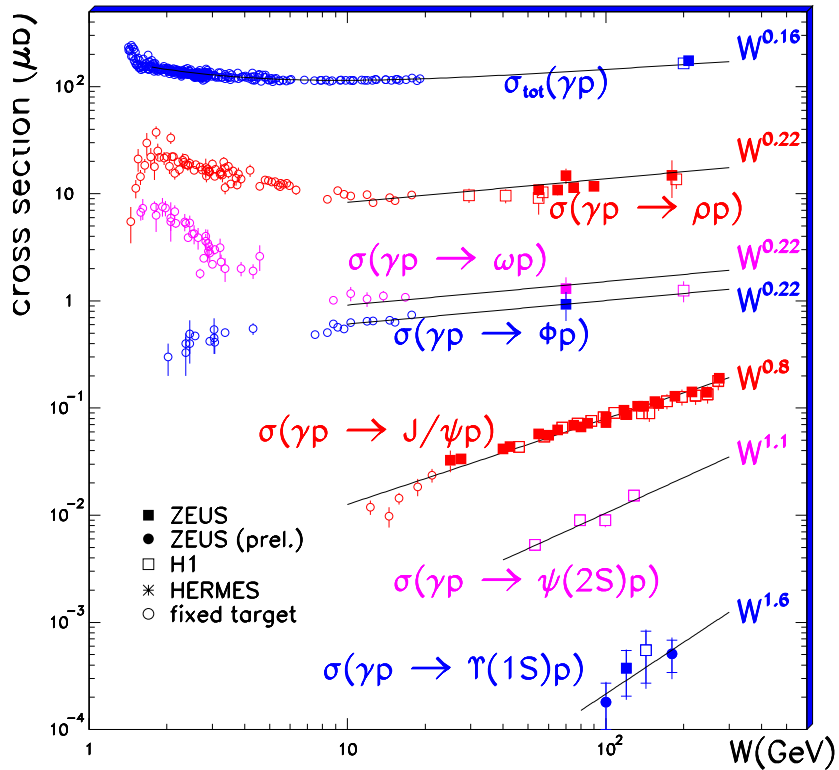


Most recent and precise measurement of elastic ρ^0 in PHP [*H1 Collab., EPJC 80 (2020), 1189*]

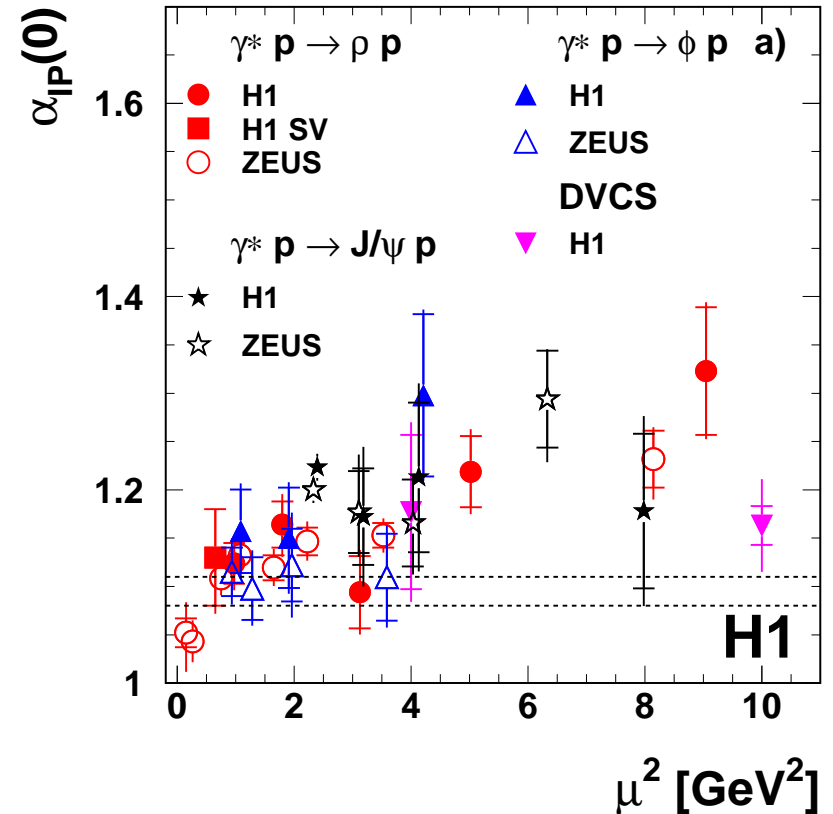
Typical soft behaviour with $\alpha_{\mathbb{P}}(0) = 1.065 \pm 0.004 \pm 0.007$

\mathbb{P} trajectory is linear at small $|t|$ with possible non-linearity at $|t| > 0.2 \text{ GeV}^2$

W dependence. Transition from soft to hard regime



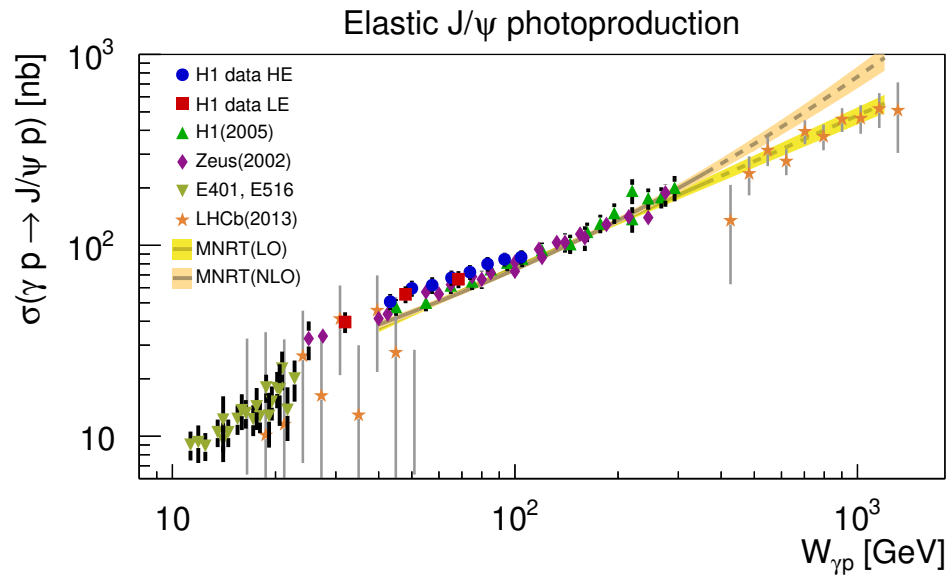
Elastic Photoproduction of VM



Elastic VM in PHP and DIS; DVCS

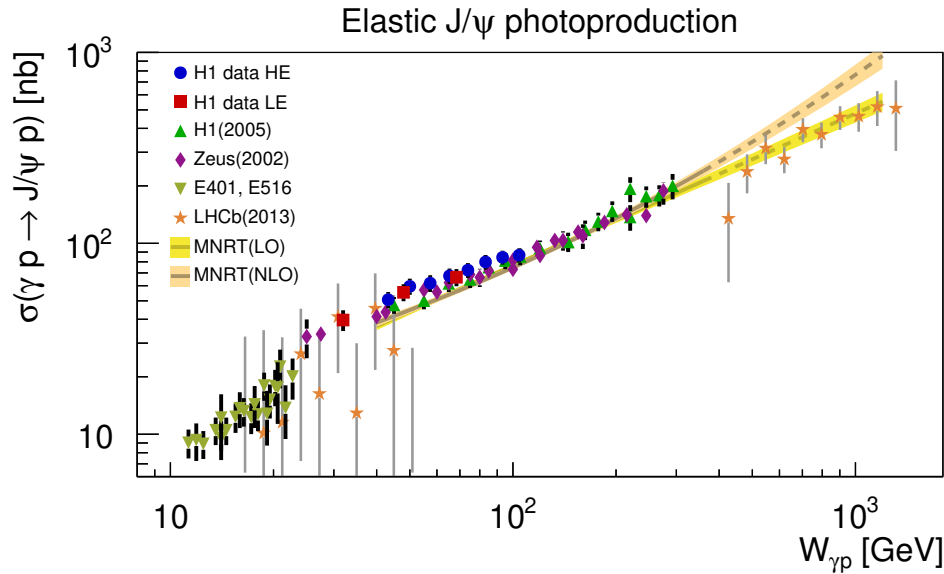
Transition from soft to hard regime occurs at 'universal' scale $\mu^2 = (Q^2 + M_V^2)/4 \simeq 3 \div 4 \text{ GeV}^2$

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

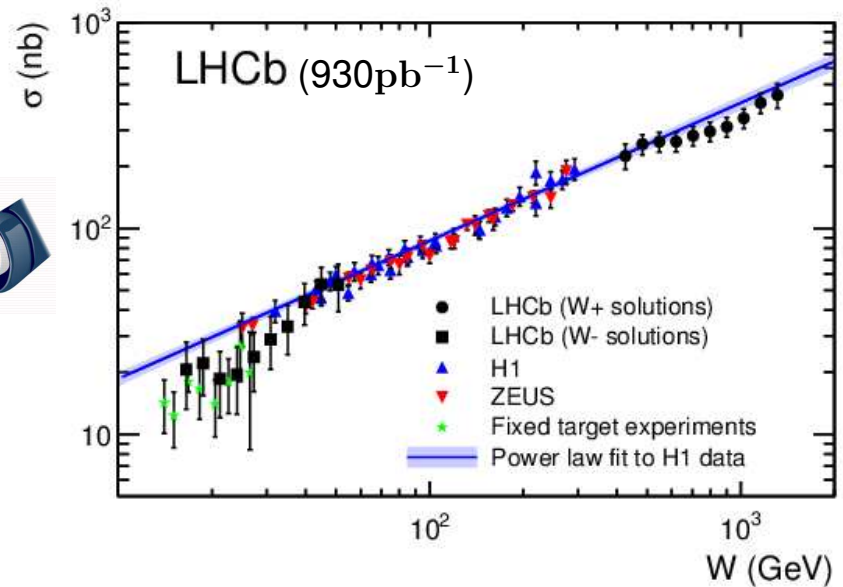
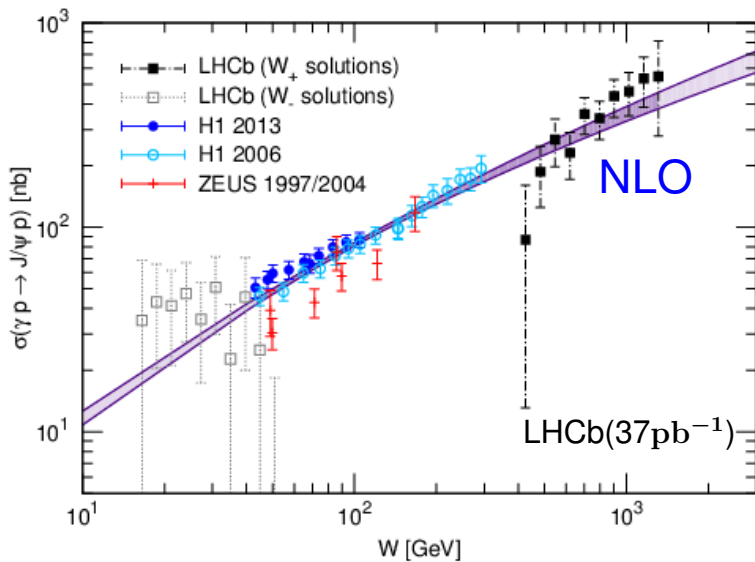


- Extrapolating HERA fit describes LHCb
- Low x gluon, based on old HERA data (A. Martin et al, 2008). NLO too steep

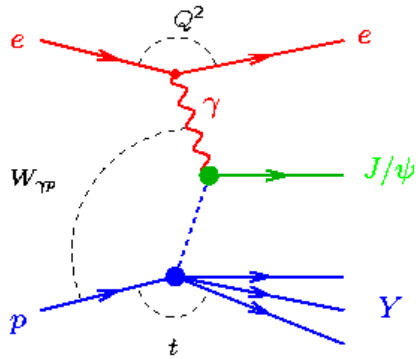
8 Elastic Photoproduction of J/ψ mesons - Sensitivity to the g/p



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



9 Photoproduction of J/ψ mesons with large t - BFKL \mathcal{P} at work



Hard scale at both vertices

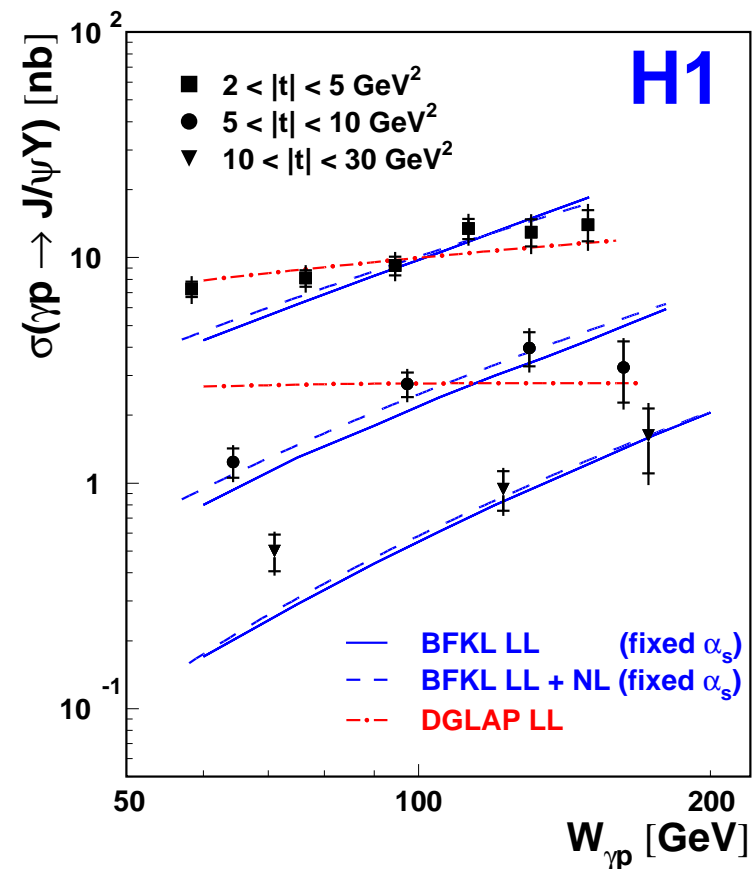
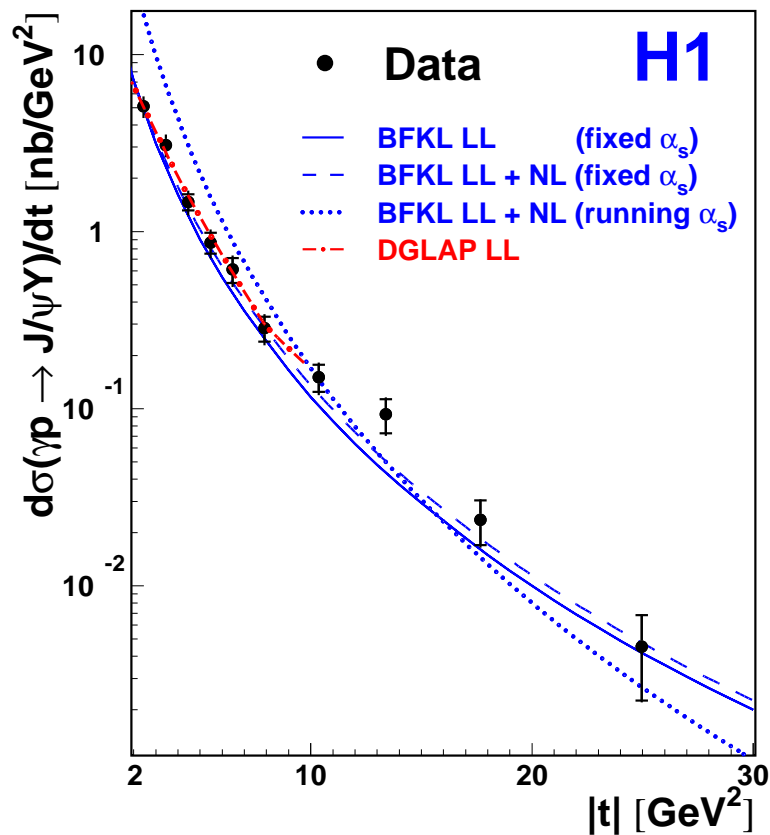
Data sample: $\mathcal{L} = 78 \text{ pb}^{-1}$

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

Final statistics: 846 ± 30 events

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

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



t –dependence. Shrinkage of diffractive peak

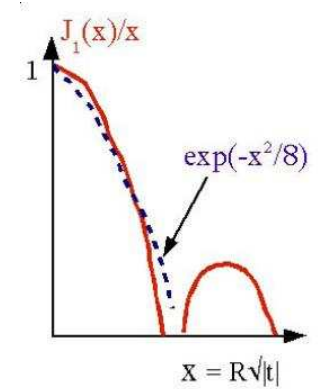
$d\sigma/dt \sim e^{-b|t|} \rightarrow$ diffractive peak (approximated from Bessel function)

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

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

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

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



t -dependence. Shrinkage of diffractive peak

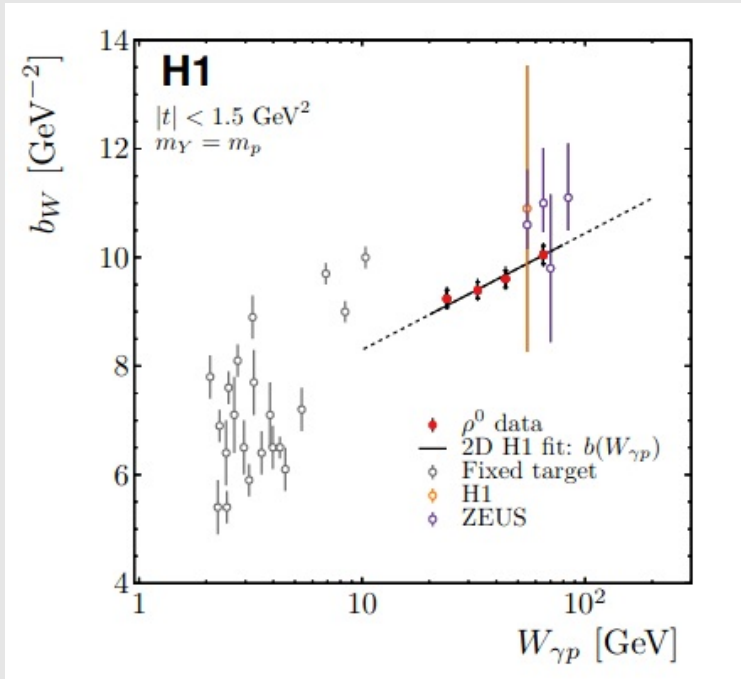
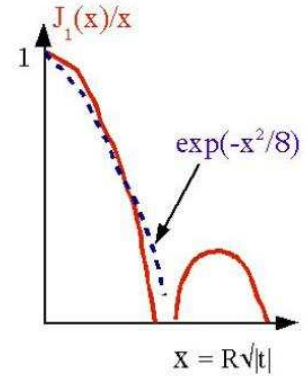
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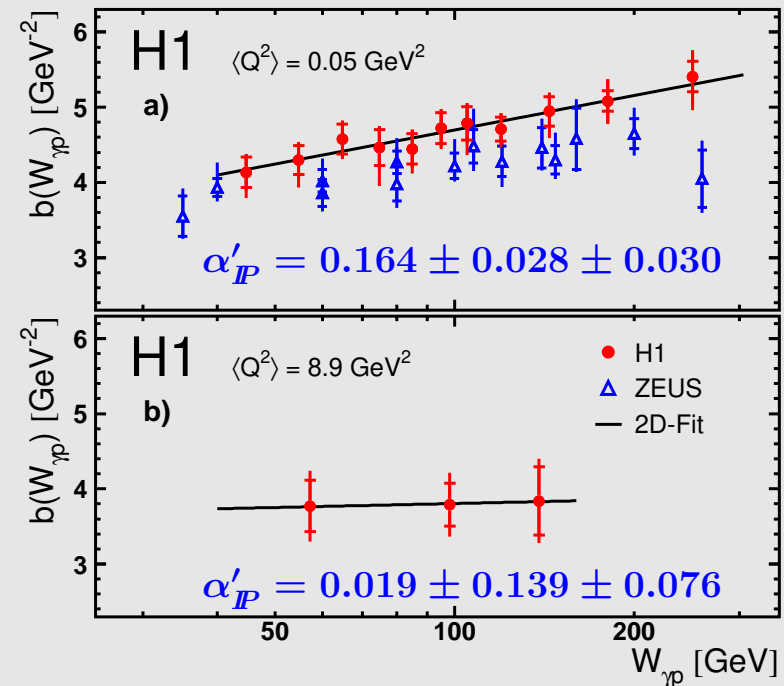
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$\gamma p \rightarrow \rho^0 p$ (PHP): $\alpha'_{\mathbb{P}} = 0.233 \pm 0.064 \pm 0.029$



$\gamma^* p \rightarrow J/\psi p$ (PHP, DIS)

t -dependence. Elastic slope vs Universal scale

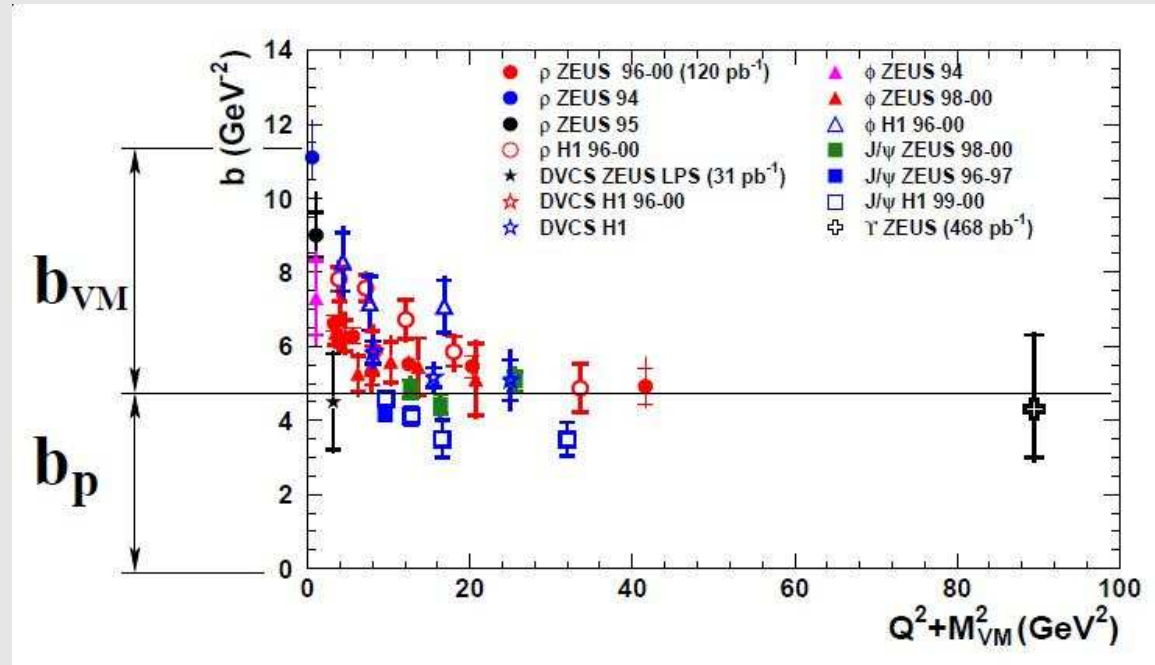
Dipole picture interpretation:

$$b = b_{VM} + b_p$$

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

$b_p \rightarrow$ size of the gluons area:

$$\langle r^2 \rangle = 2b_p \cdot (\hbar c)^2 \simeq 0.6 \text{ fm}$$



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

t -dependence. Elastic slope vs Universal scale

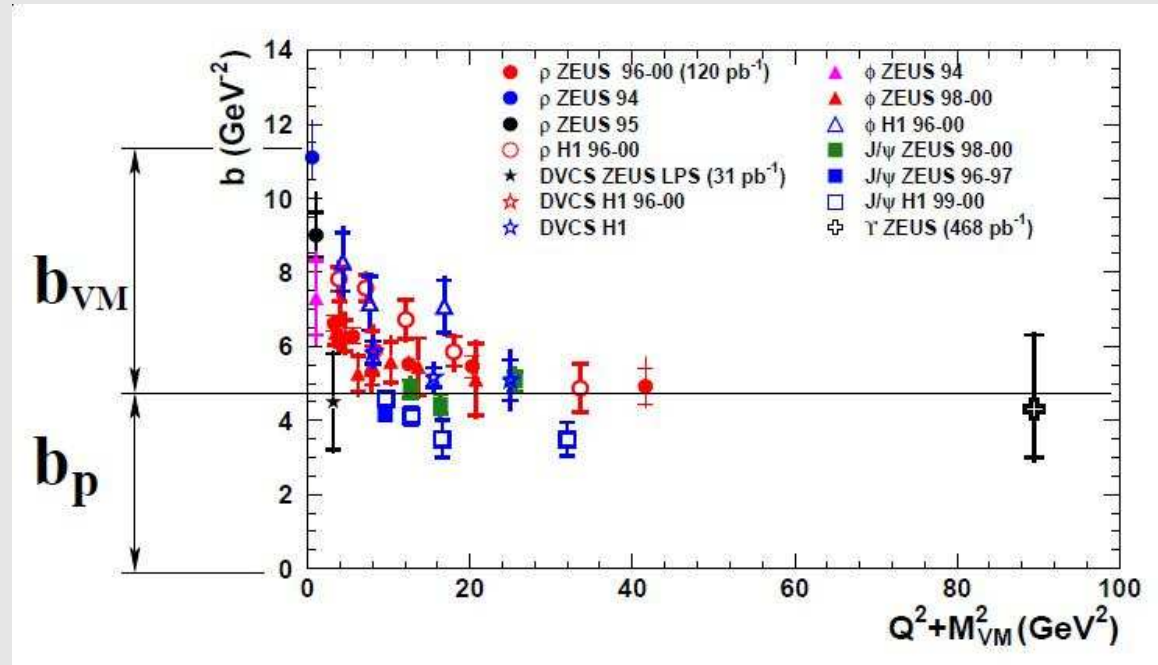
Dipole picture interpretation:

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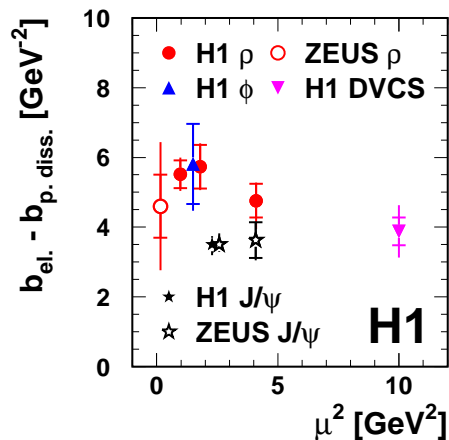
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$b_{el} - b_{pd}$ data suggests
even 20% smaller size

Lattice QCD: $\sim 0.35 \text{ fm}$

t -dependence. Elastic slope vs Universal scale

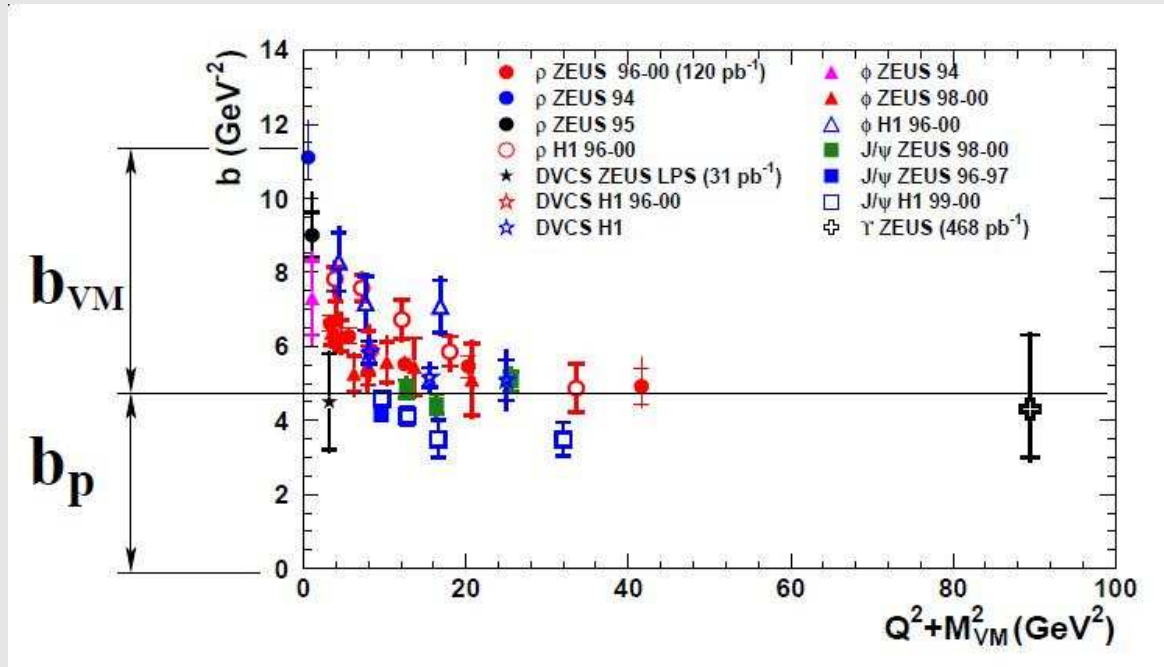
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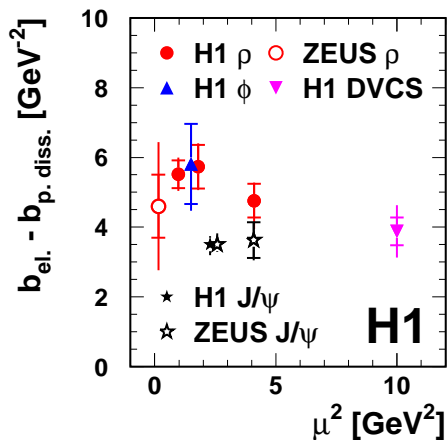
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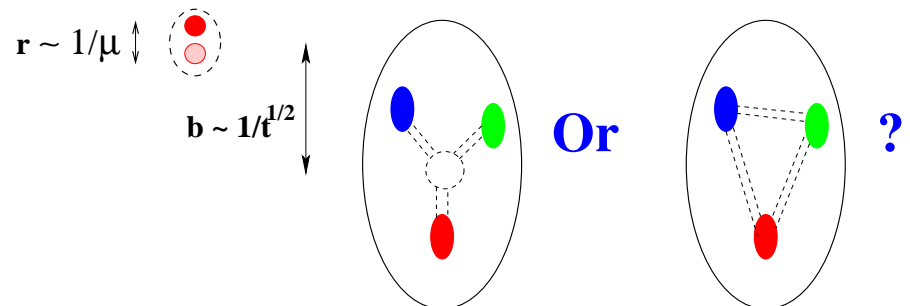
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$b_{el} - b_{pd}$ data suggests even 20% smaller size

Lattice QCD: $\sim 0.35 \text{ fm}$

What is proton topology?



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

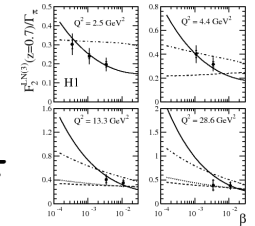
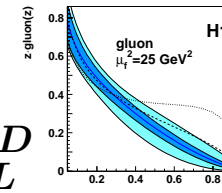
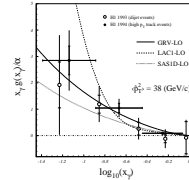
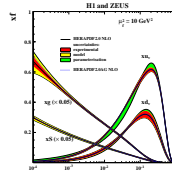
HERA enables to study structure of

Proton – F_2, F_L, \dots

Photon – g/γ

Pomeron – F_2^D, F_L^D

Pion – F_2^π



HERA as a '4P' facility

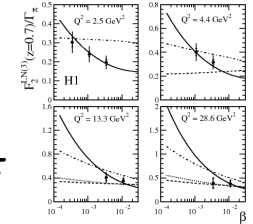
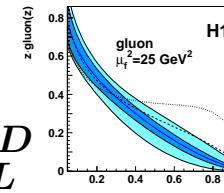
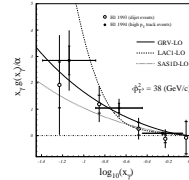
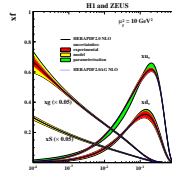
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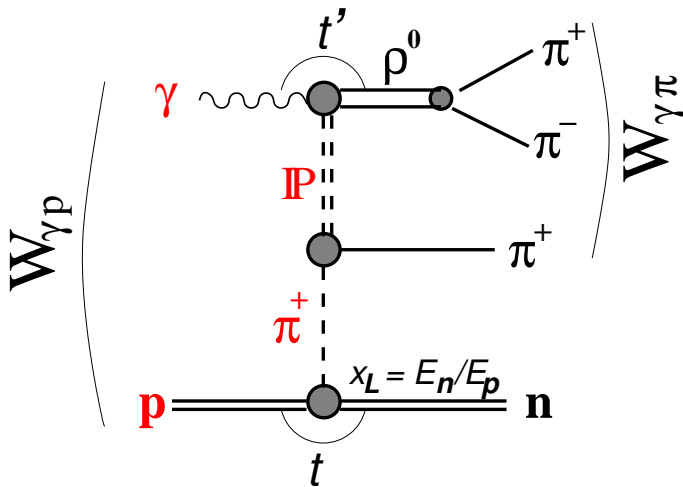
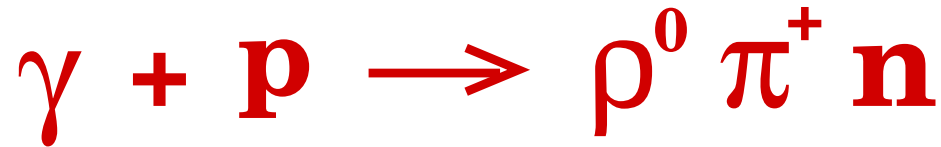
Photon – g/γ

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:

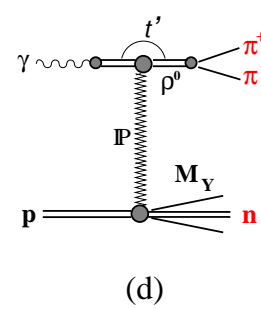
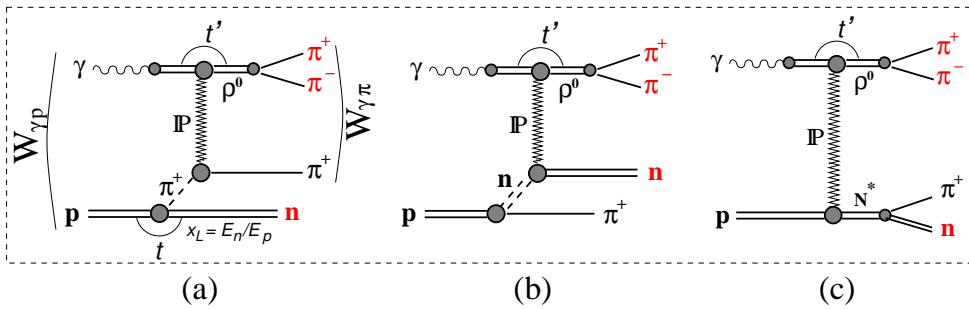


Photoproduction:	$Q^2 < 2 \text{ GeV}^2$	$\langle Q^2 \rangle = 0.04 \text{ GeV}^2$
Low p_t :	$ t < 1 \text{ GeV}^2$	$\langle t \rangle = 0.20 \text{ GeV}^2$
Small mass:	$0.3 < m_{\pi\pi} < 1.5 \text{ GeV}$	(m_{ρ^0})
π^+, π^- in CT:	$20 < W_{\gamma p} < 100 \text{ GeV}$	$\langle W_{\gamma p} \rangle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

No hard scale present \Rightarrow Regge framework is most appropriate

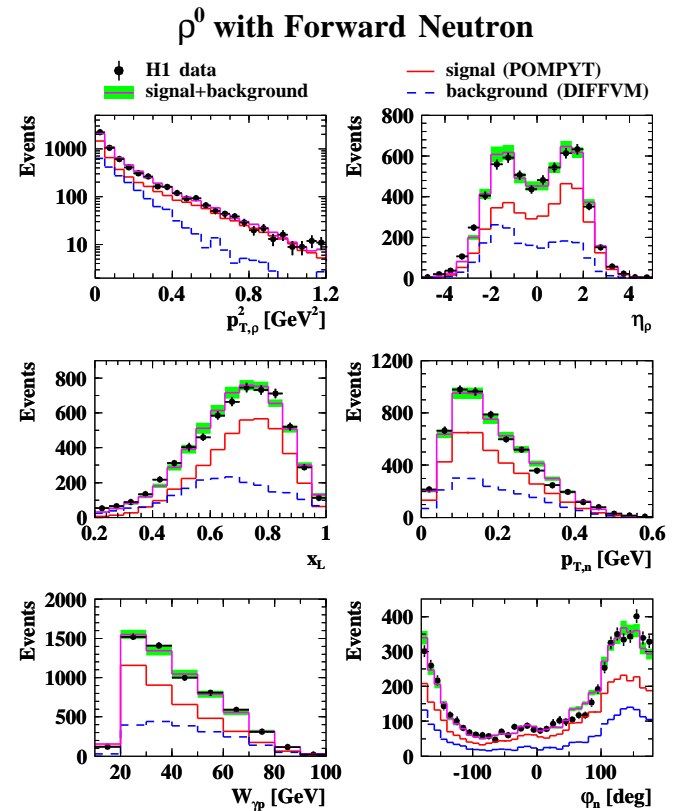
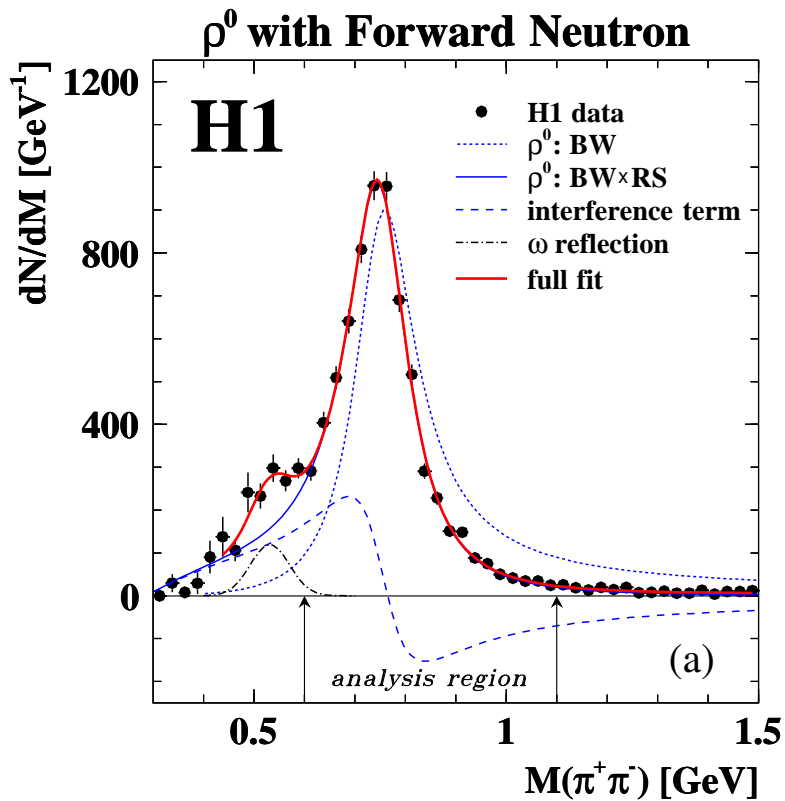


ρ^0 with Leading Neutron: Control plots

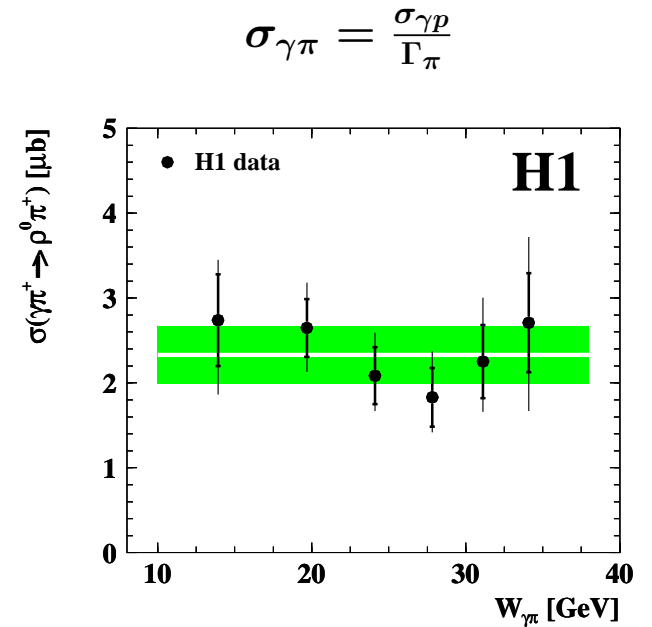
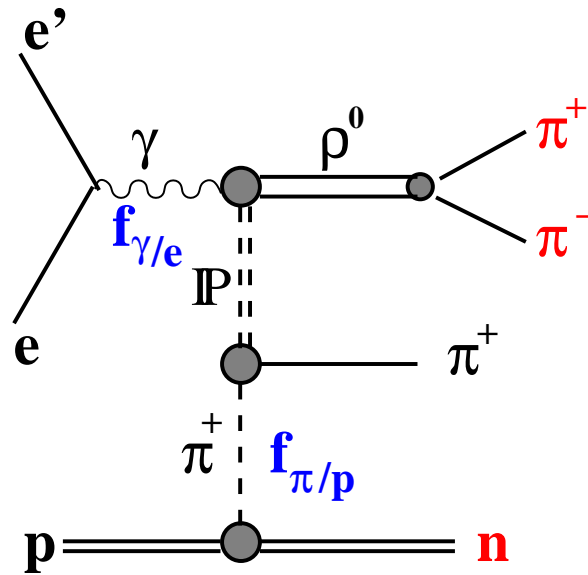
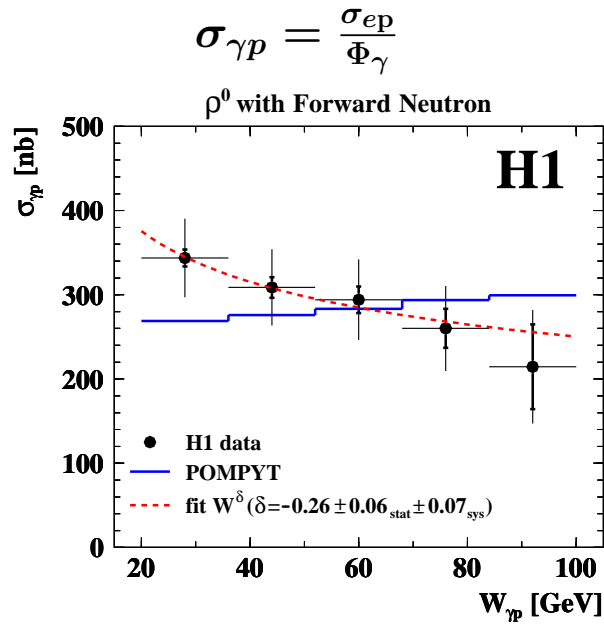


Data sample: $\mathcal{L} = 1.16 \text{ pb}^{-1}$
 ~ 7000 events

Precision: $\delta_{\text{stat}} = 2\%$
 $\delta_{\text{sys}} = 14\%$



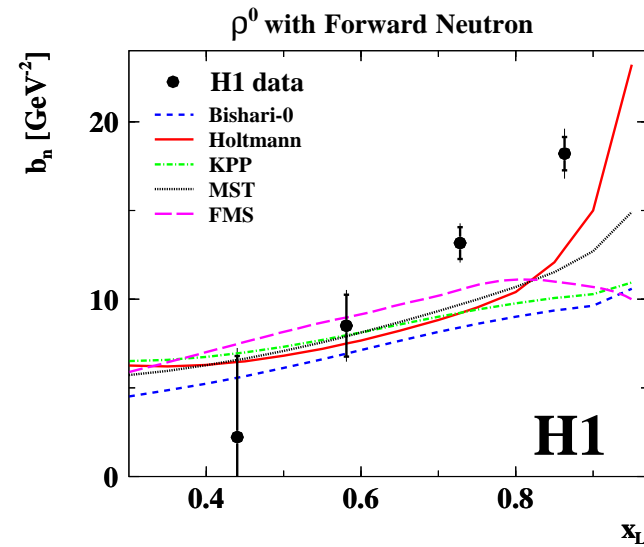
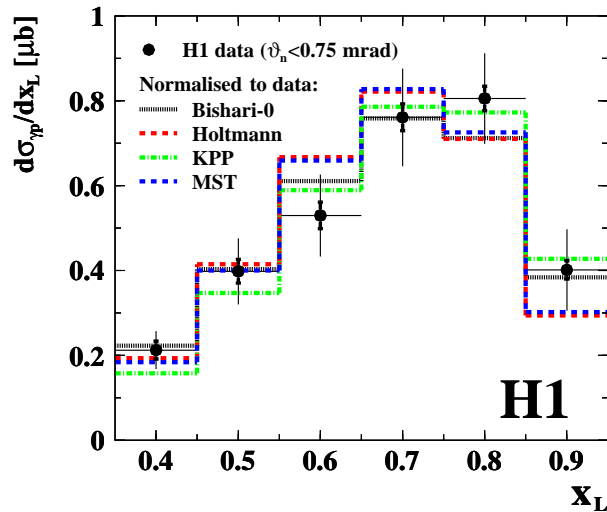
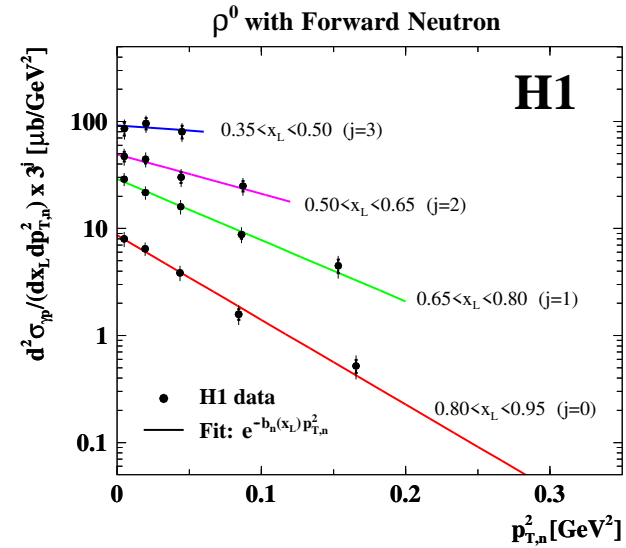
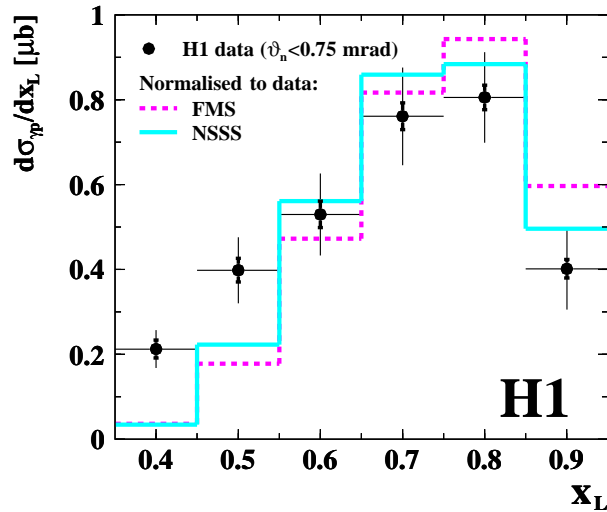
Cross sections definitions



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

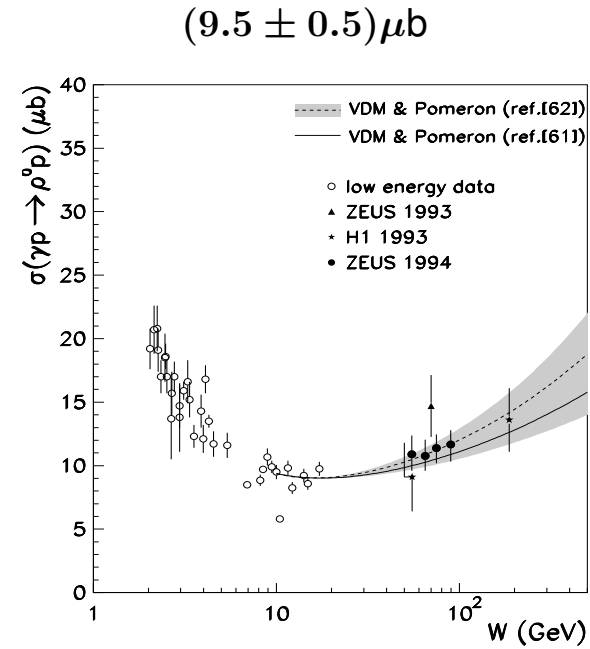
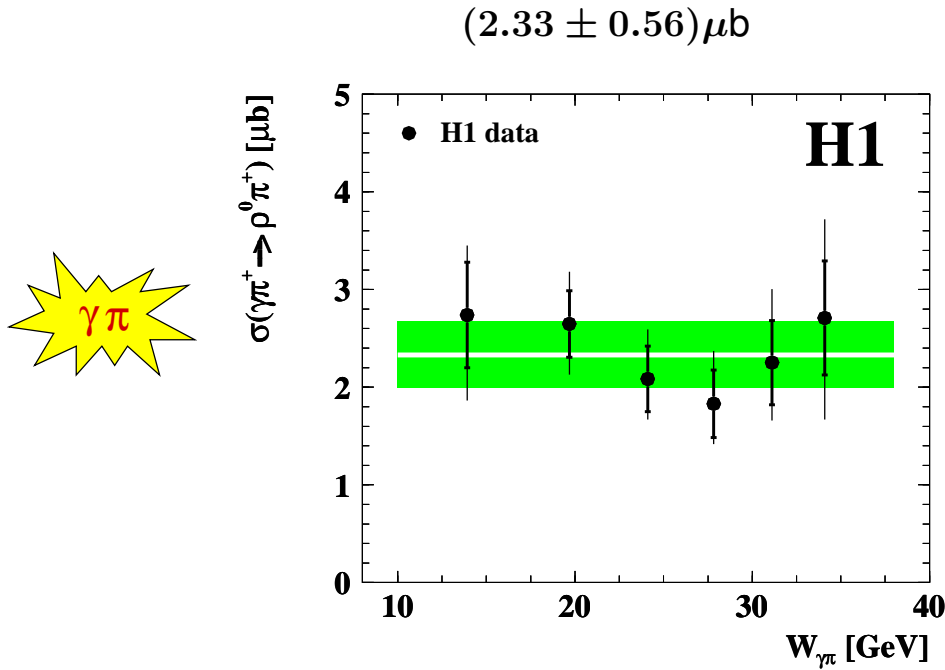
OPE:
$$f_{\pi/p}(x_L, t) = \frac{1}{2\pi} \frac{g_{p\pi N}^2}{4\pi} (1-x_L) \frac{-t}{(m_{\pi}^2 - t)^2} \exp\left[-R_{\pi n}^2 \frac{m_{\pi}^2 - t}{1-x_L}\right]$$

Constraining pion flux



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

Estimate of absorption corrections



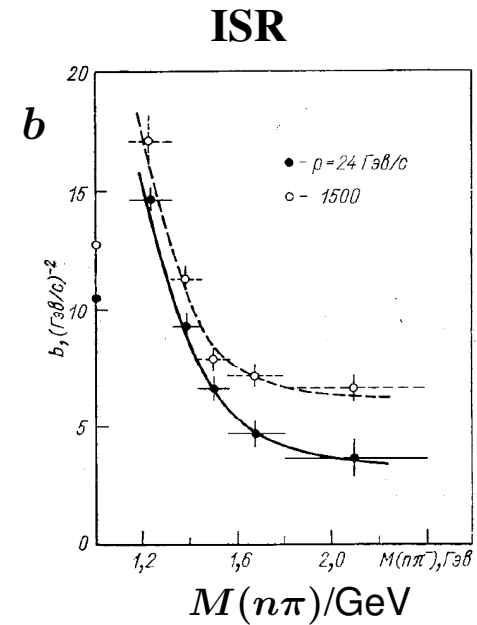
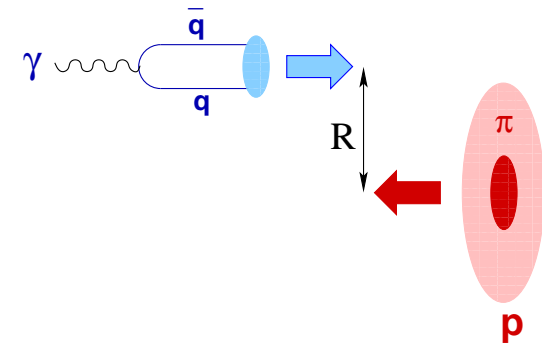
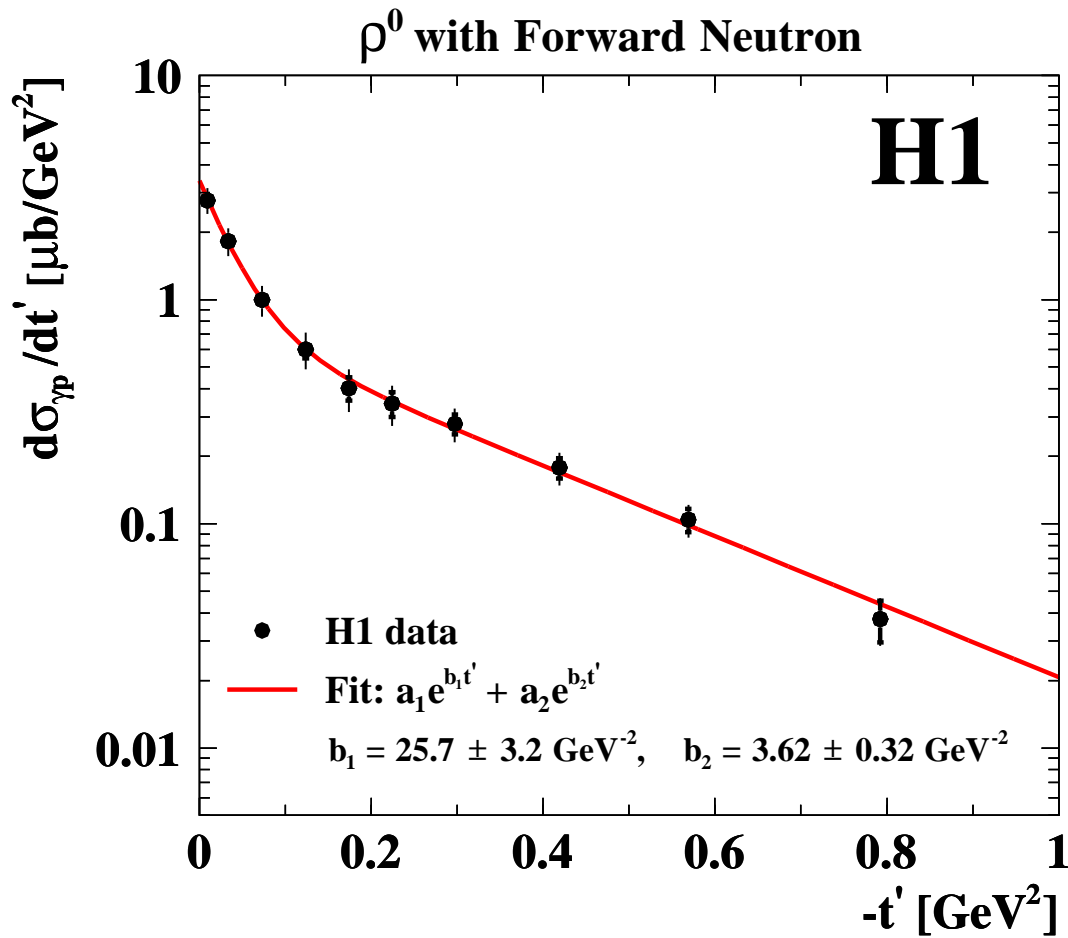
$$r_{\text{el}} = \frac{\sigma_{\gamma\pi \rightarrow \rho^0 \pi}}{\sigma_{\gamma p \rightarrow \rho^0 p}} = \begin{cases} 0.25 \pm 0.06 & (\text{exp.extracted}) \\ 0.57 \pm 0.03 & (\text{theo.expected}) \end{cases} \Rightarrow K_{\text{abs}} = 0.44 \pm 0.11$$

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

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

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

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



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

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

Open questions

- HERA **limitations**: missing nuclear targets; target polarisation \Rightarrow
Big program for EIC (gluon saturation, colour transp., spin physics, ...)
- Where is an **Odderon**?
Direct searches [1] were negative. Try via \mathbb{P} - \mathcal{O} interference [2,3].
- Can one observe **Glueball** in a double Pomeron reaction in PHP?
 $p - \text{gap} - M_X - \text{gap} - V$ ($M_X = \sqrt{x_{\mathbb{P}1}x_{\mathbb{P}2}}W_{\gamma p} = 2 \div 6 \text{ GeV}$)
- What is nucleon topology? Gluonic form factor of the proton?

[1] H1 Collaboration, *Phys. Lett. B* 544 (2002) 35.

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

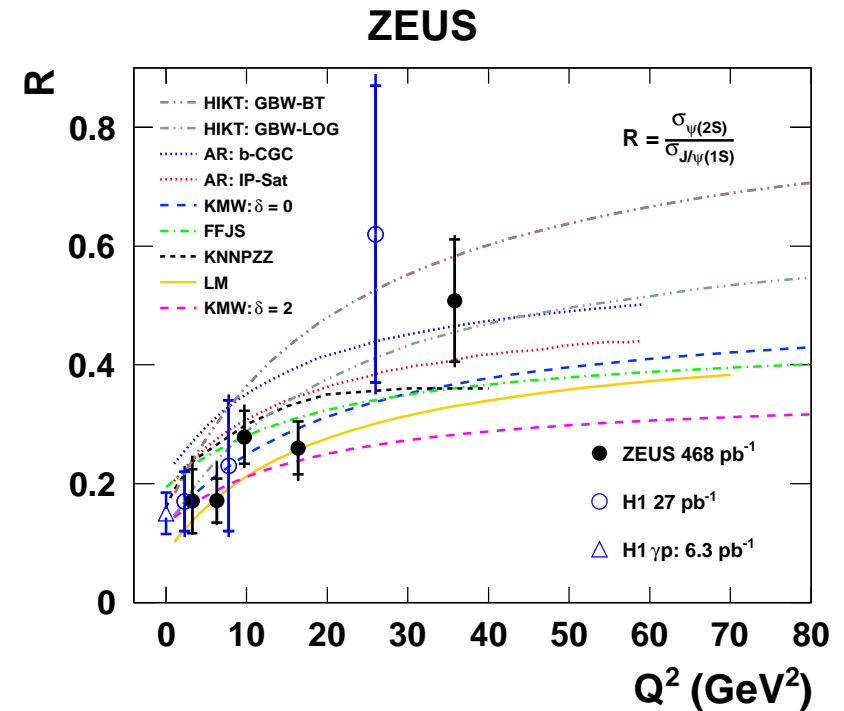
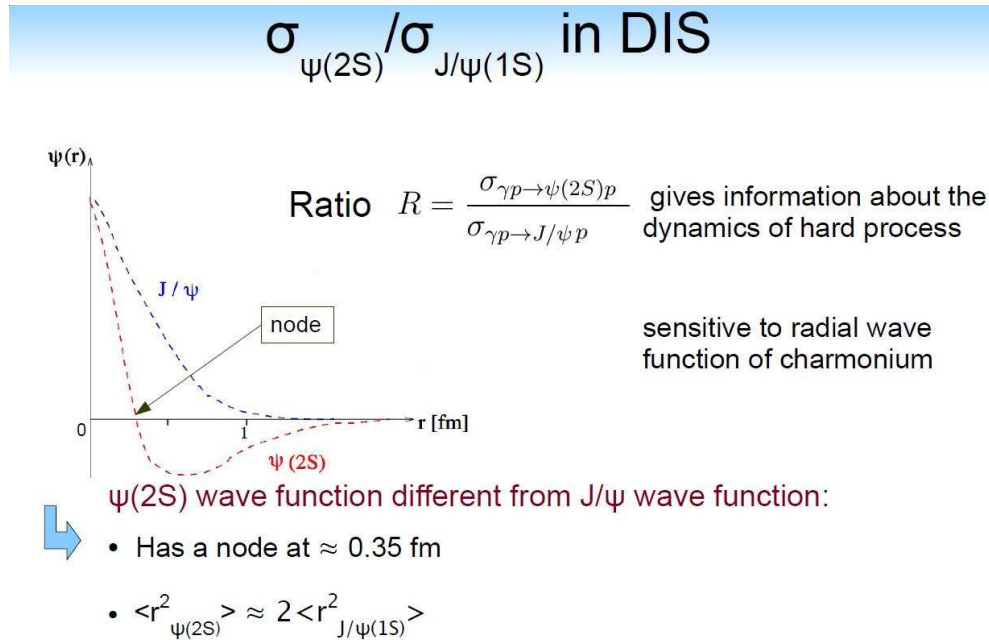
[3] C. Ewerz *et al.*, *Annals Phys.* 342 (2014) 31; A. Bolz *et al.*, *JHEP* 1501, (2015) 215.

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

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



- 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)

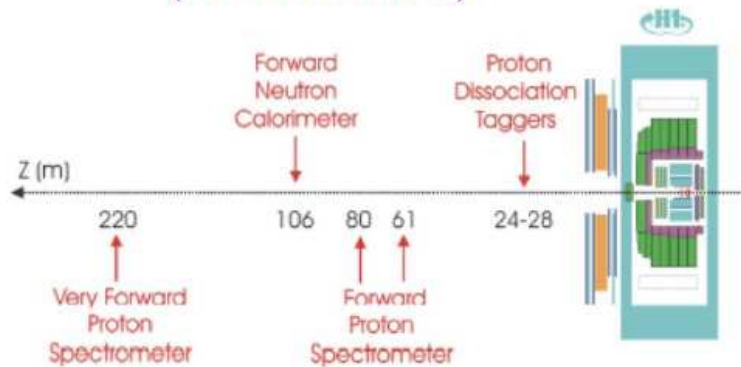
pQCD predictions:

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

Selection of Diffractive Events in H1

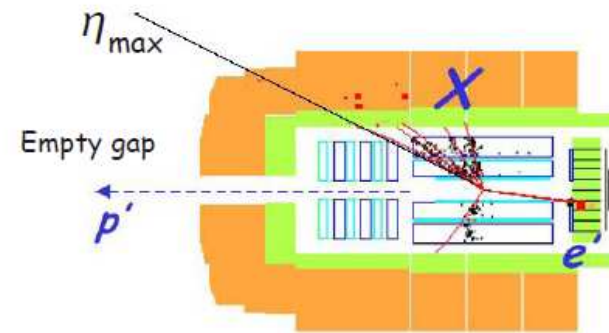
Measure the leading proton

→ Forward spectrometers
(H1 FPS/VFPS)



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

Measure a Large Rapidity Gap

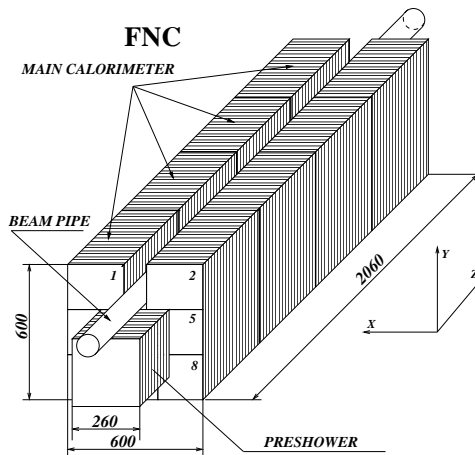


- Data integrated over $|t| < 1 \text{ GeV}^2$
- High statistics
- Contamination from proton dissociation events
→ Needs to be controlled

- ↘ Different systematics
- ↘ Different kinematic coverage

VM+n: Key Experimental Ingredients

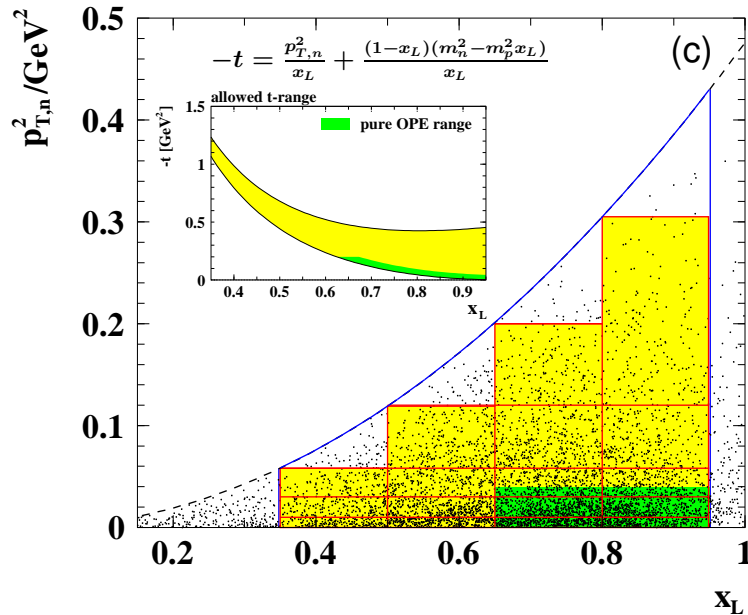
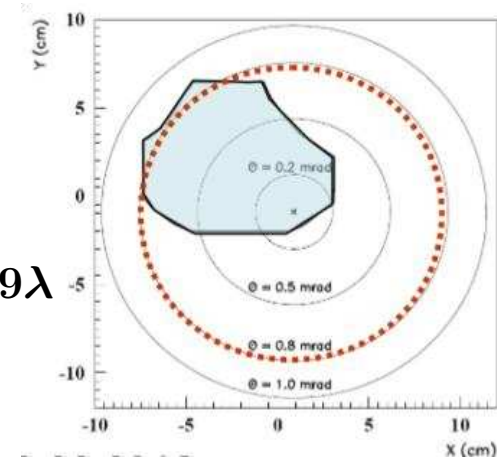
Improved H1 FNC (distinguish ($\langle P \rangle = 98\%$) and measure n and γ/π^0)



located at $z = 106\text{m}$ from IP

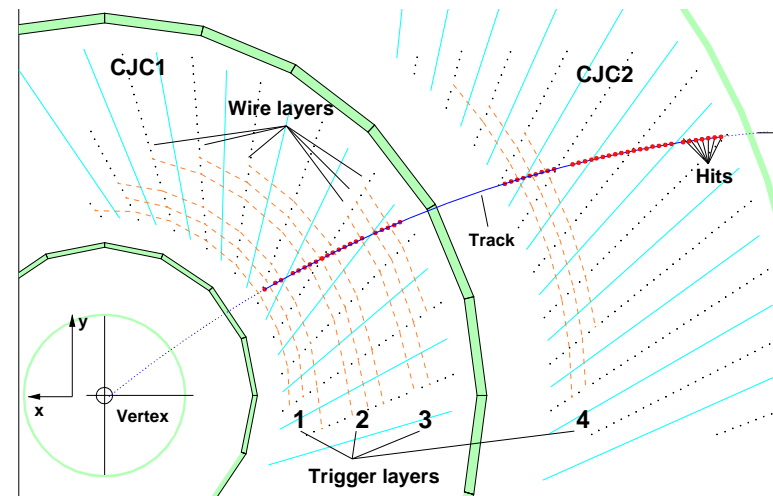
$\langle A \rangle \simeq 30\%$ for $\theta < 0.8$ mrad

Preshower: $60X_0$, Main Calo: 8.9λ



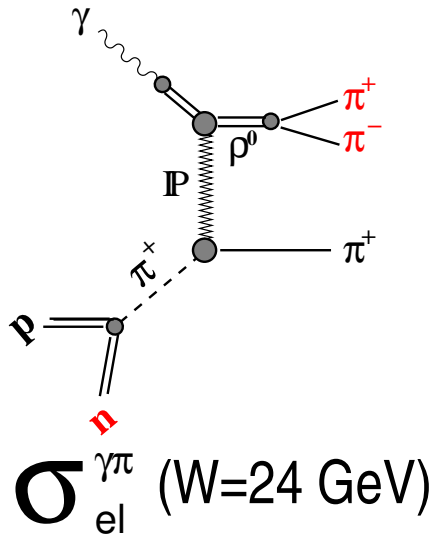
Powerful fast track trigger

(allows untagged soft γp to be collected)

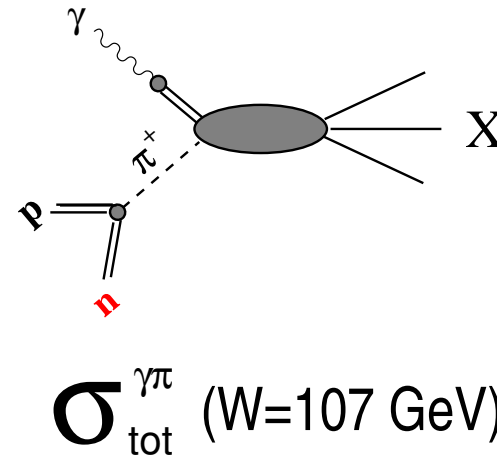


Large absorption in LN reactions

H1 (2015)



ZEUS (2002)



$$\sigma_{\text{el}}^{\gamma\pi} / \sigma_{\text{el}}^{\gamma p} = 0.25 \pm 0.06$$

OT+eikonal approach+data: $r_{\text{el}} \simeq 0.57$

Exp.result

Theory

$$\sigma_{\text{tot}}^{\gamma\pi} / \sigma_{\text{tot}}^{\gamma p} = 0.32 \pm 0.03$$

AQM: $r_{\text{tot}} \simeq 2/3$

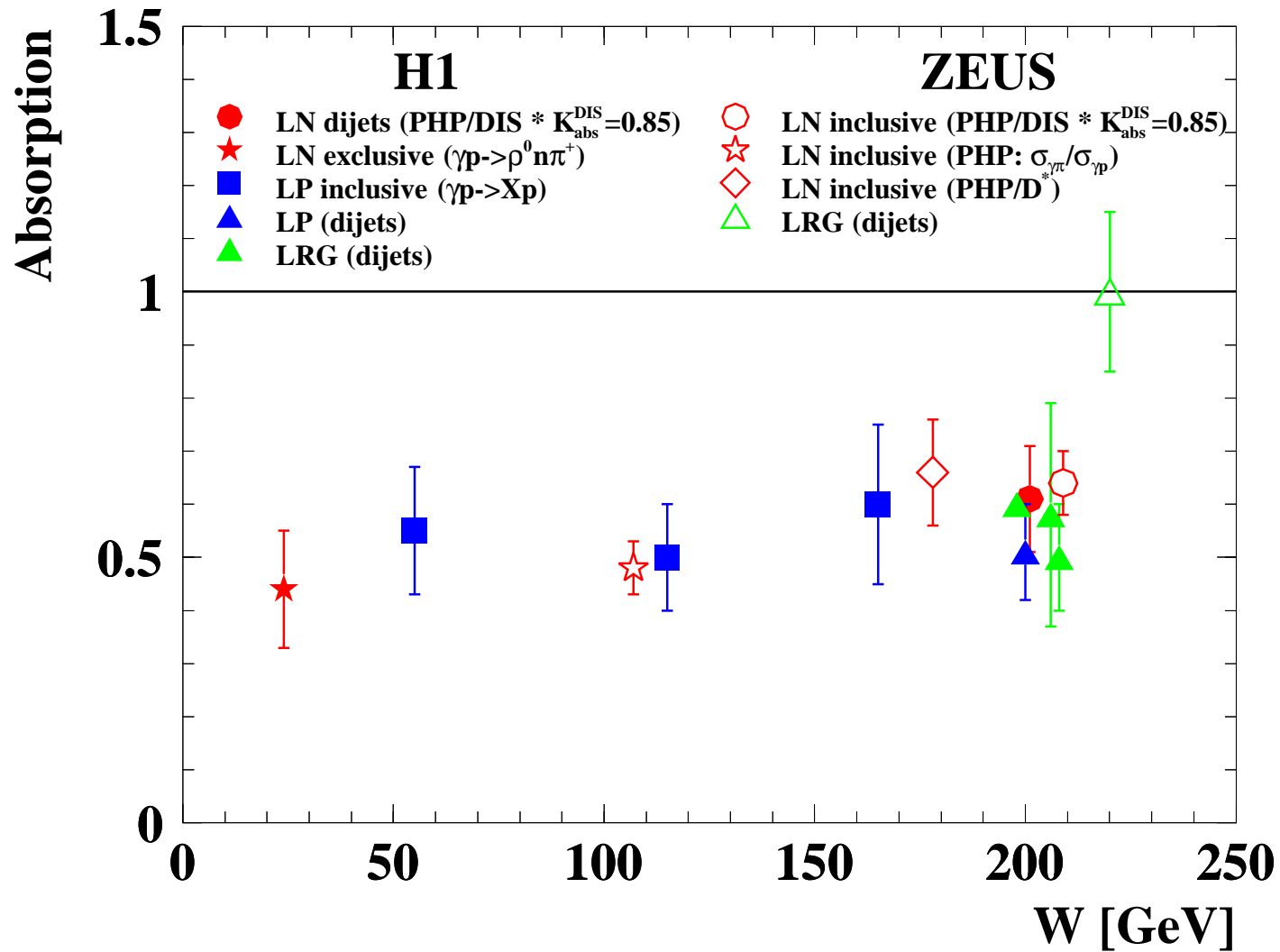
Large absorption effects!

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

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



Unofficial private summary!