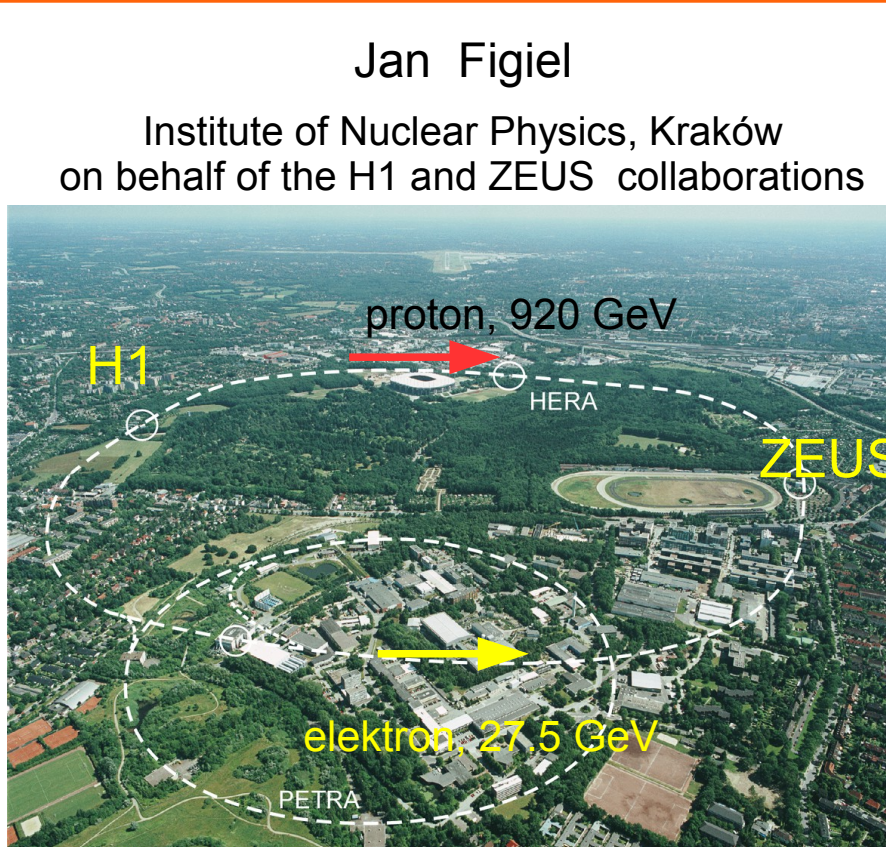




# Exclusive diffraction at HERA



... we investigate the **fundamental forces** and **particles** in  $e p$  collisions at highest energies – quark and gluon interactions, we verify the Standard Model and seek „new physics” ...  
... among the other - studying **diffractive** processes ...





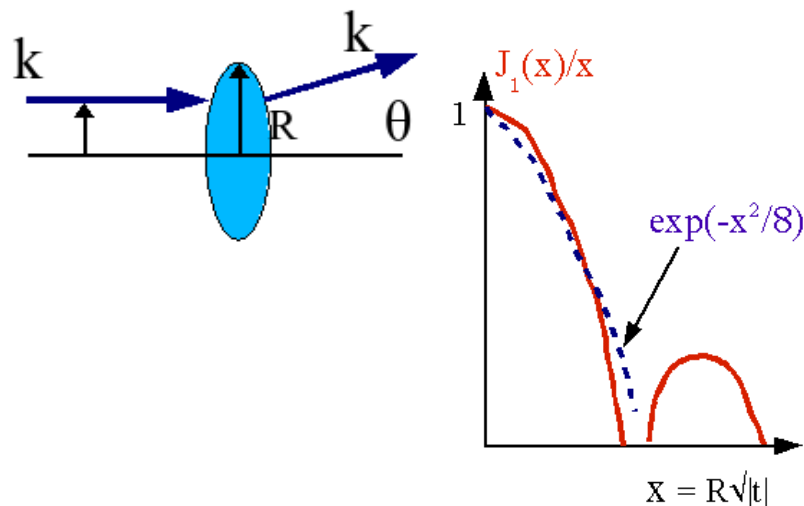
## Outline

- Introduction to diffraction in h-h and e-p interactions
- Exclusive diffraction at HERA – recent results:
  - Vector meson production,
  - Proton-dissociative VM production,
  - Exclusive dipion production,
- Summary



# Diffraction in hadron-hadron interactions (1)

Light scattering: Fraunhofer diffraction ( $1/k \ll R$ )

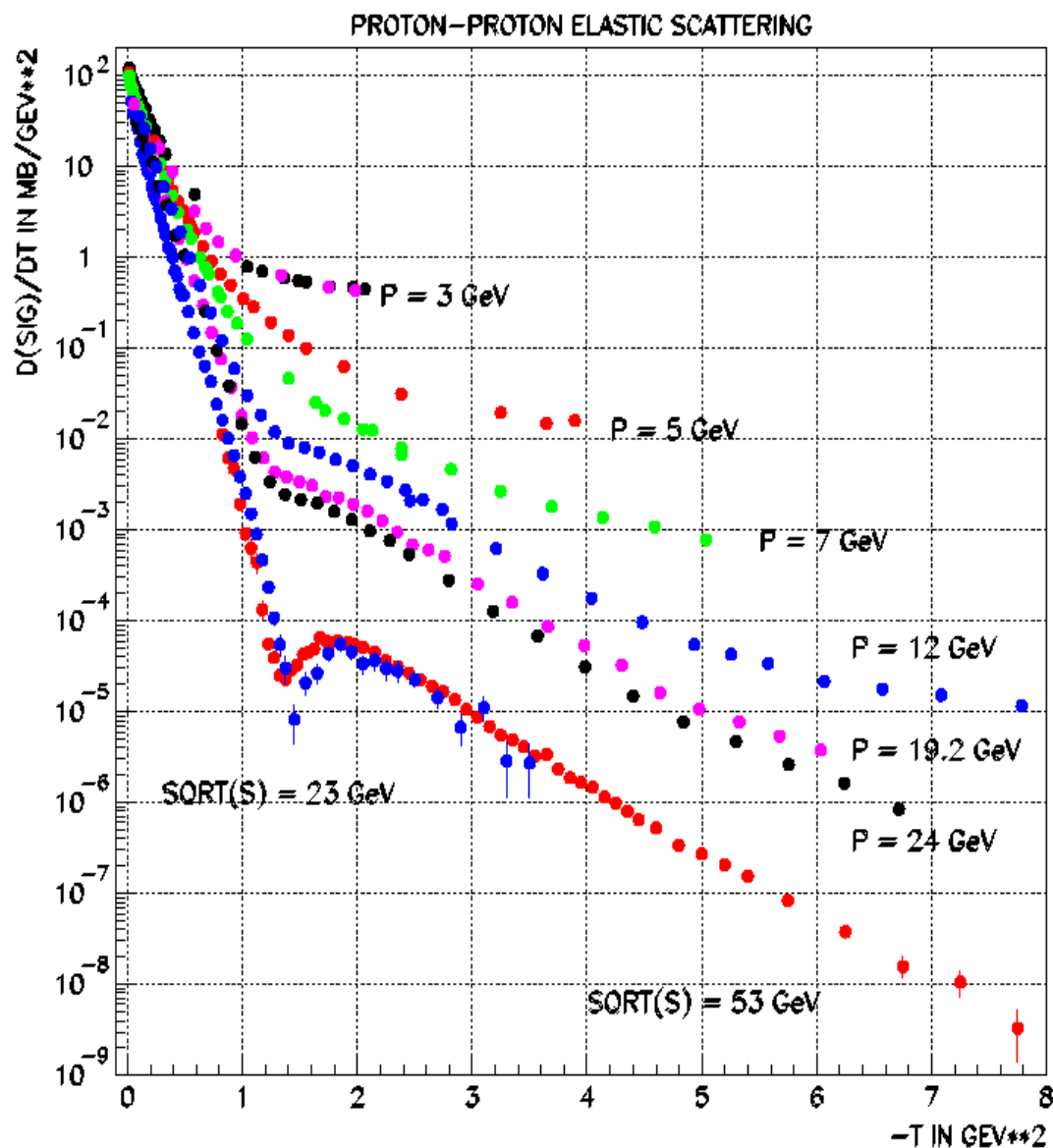


Elastic hadron-hadron scattering:

$$|t| = 4k^2 \sin^2(\theta/2),$$

$$d\sigma/dt \sim \exp(-b|t|),$$

$$b = (R/2)^2 \approx 8 - 10 \text{ GeV}^2$$

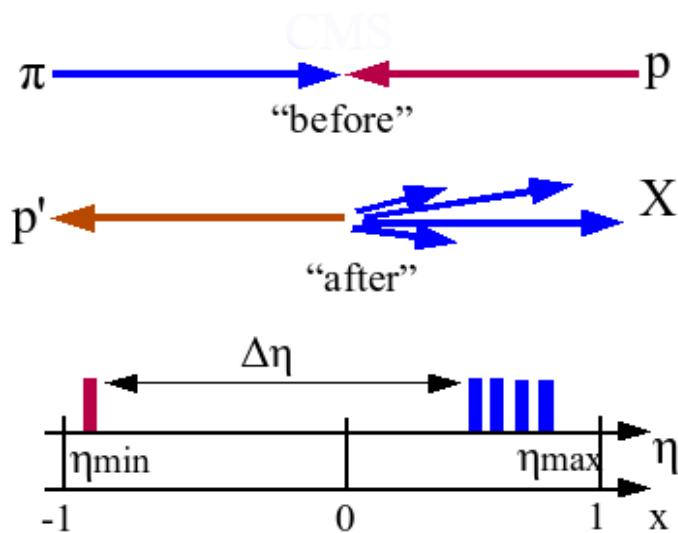




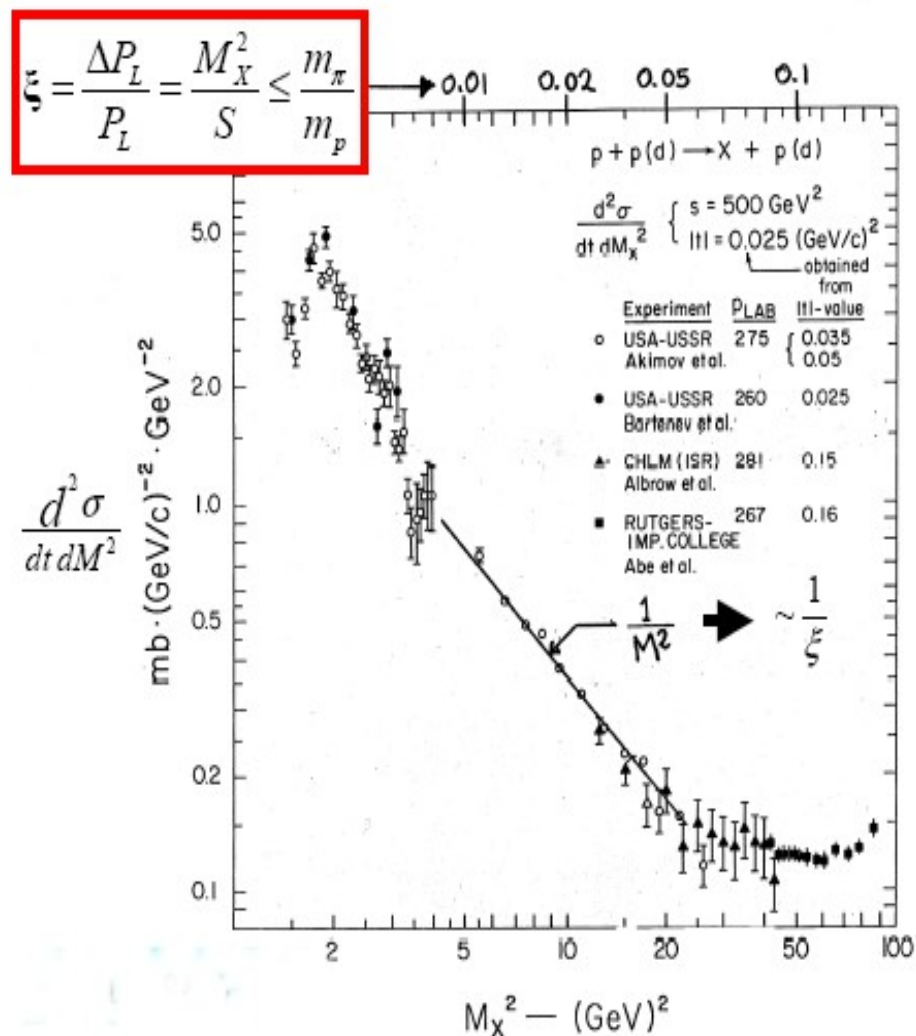
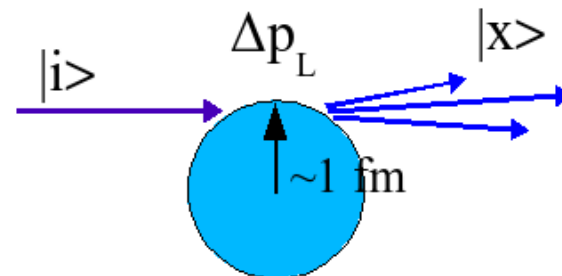
# Diffraction in hadron-hadron interactions (2)

Inelastic hadron diffractive dissociation  $\leftrightarrow$   
coherence condition:

- $\Delta I = \Delta Q = \Delta S = 0, \quad \Delta P = (-1)^J$
- $\xi = M_X^2/s = \Delta p_L/p_L = 1 - |x| < m_\pi/m_p = 0.15$
- $\Delta\eta = \ln(1/\xi) > 2$ , (“large rapidity gap, LRG”)



$s$  = squared CMS energy of hadrons  
 $\eta = -\ln(\tan(\theta/2))$ , (pseudo-)rapidity



# Diffraction in hadron-hadron interactions (3)

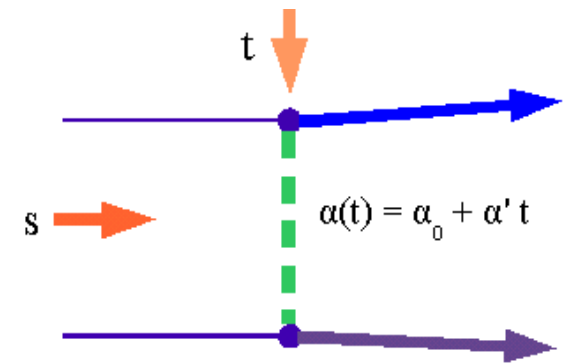
**Regge model** of hadronic interactions:

two-body reactions: “trajectory” exchange ( $s \rightarrow \infty$ )

$$\alpha(t) = \alpha_0 + \alpha' t$$

$$d\sigma/dt \sim F(t) s^{2\alpha(t)-2} = F(t) s^{2\alpha(0)-2} \exp(2\alpha' \log(s) t)$$

$$\sigma_{tot} \sim s^{\alpha(0)-1}$$



Elastic scattering ( $\rightarrow$  total cross-section):

exchange of Pomeron IP trajectory (vacuum quantum numbers)

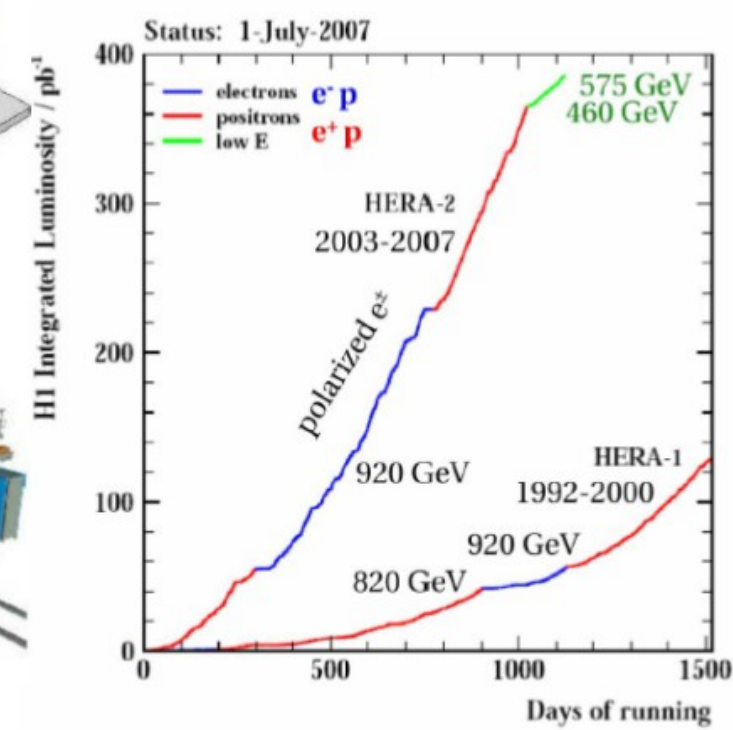
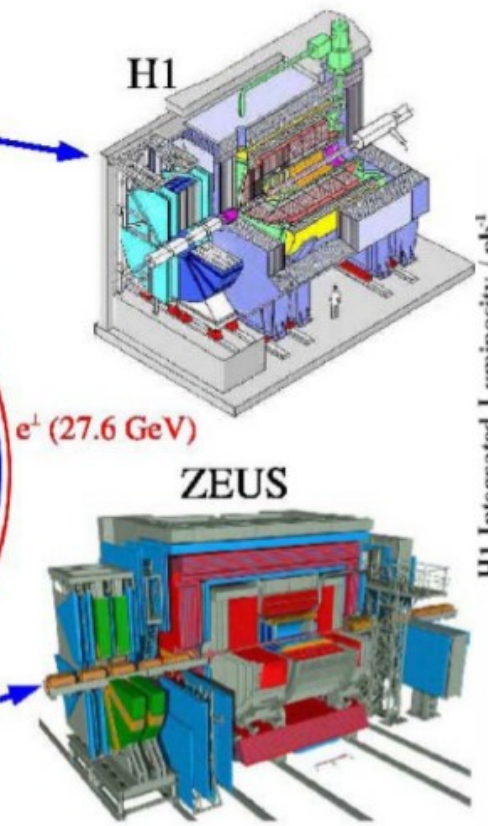
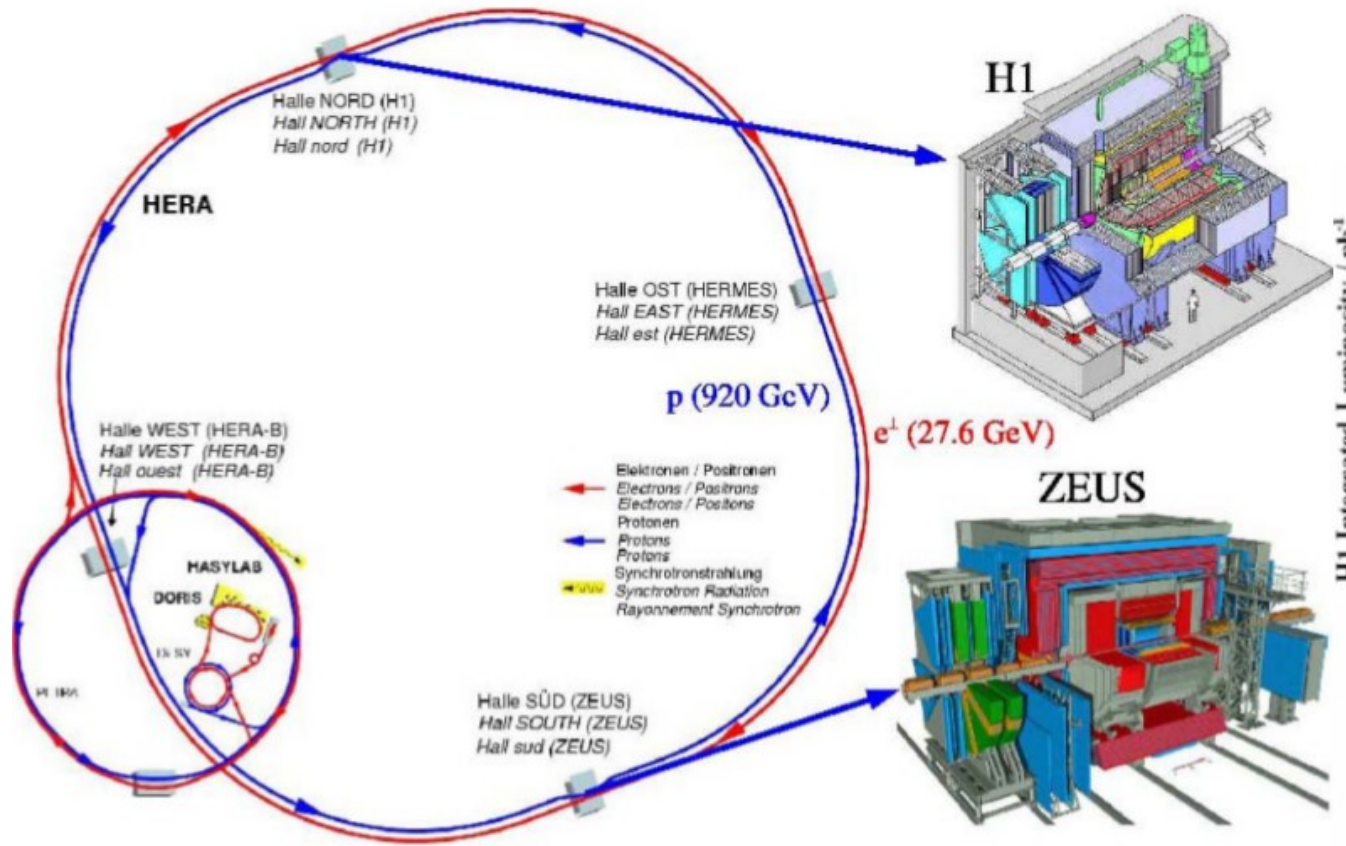
Universal parametrisation of Donnachie-Landshoff (“soft” Pomeron):

$$\alpha_{IP}(t) = 1.08 + 0.25 t$$

**PS: J. D. Bjorken: Regge model foundations are as solid as those of QCD, DIS1994**

# Diffraction in e-p interactions (1)

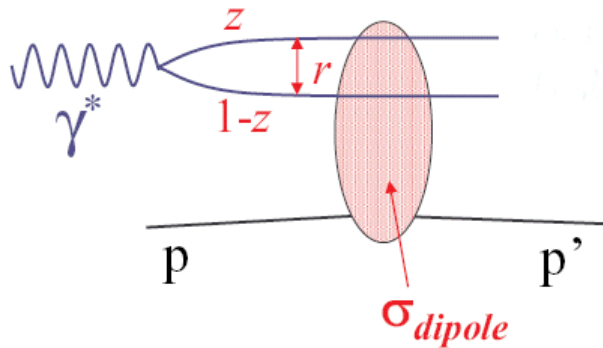
**HERA:**  $e^\pm$  (27.5 GeV) – p (820/920, 460, 575 GeV)  $\rightarrow$  c.m.s energy  $\leq$  320 GeV



HERA-1: 1992 – 2000, HERA-2: 2003 – 2007, total lumi  $0.5 \text{ fb}^{-1}$  per experiment

# Diffraction in e-p interactions (2)

HERA:  $e^\pm$  (27.5 GeV) – p (820/920 GeV)  $\rightarrow \gamma^* p \rightarrow$  hadrons



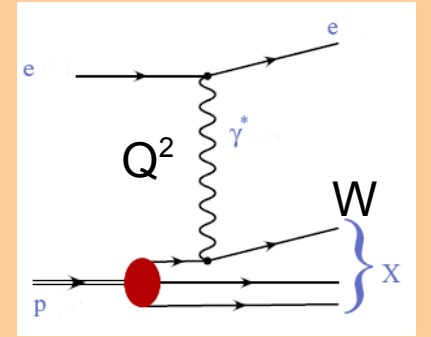
$Q^2$  –  $\gamma^*$  virtuality (0 –  $10^5$  GeV<sup>2</sup>)

$s \approx E_e E_p$ ,  $\sqrt{s} \approx 300$  GeV

$W$  –  $\gamma^* p$  CMS energy (20 -290 GeV)

$x \approx Q^2/W^2$  – Bjorken  $x$  = fractional parton momentum in proton Breit frame

$y \approx Q^2/(sx)$  – fractional energy transfer to  $p$

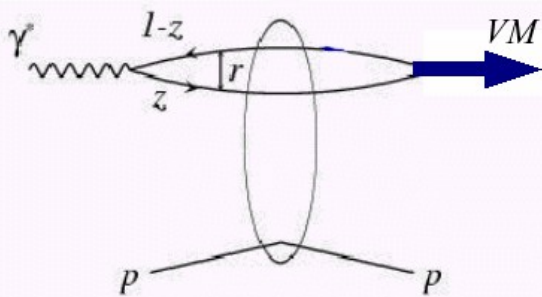


Coherence condition in proton rest frame:

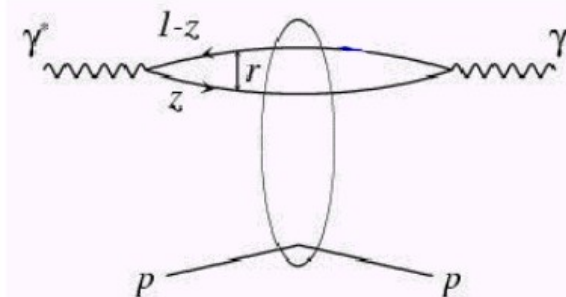
fluctuation length ( $\gamma^* \rightarrow$  dipol  $q\bar{q}$ ) =  $2E_\gamma / (m_{q\bar{q}}^2 + Q^2) > 1$  fm

$\rightarrow x < 0.01$

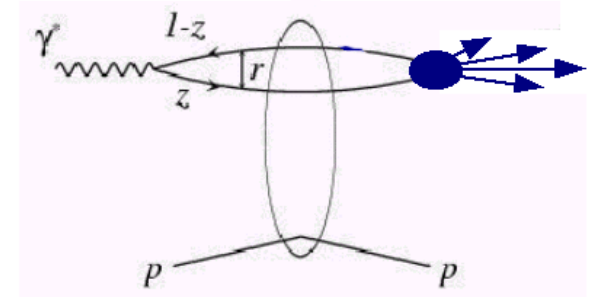
**At HERA diffraction is low Bjorken-x phenomenon!**



Vector meson production



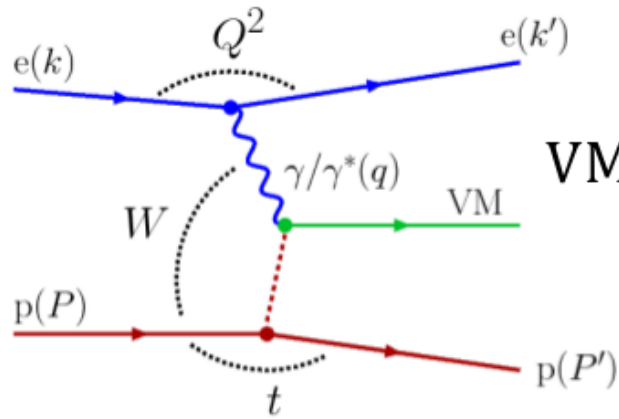
DVCS



inclusive diffraction

# Diffractive Vector Meson production (1)

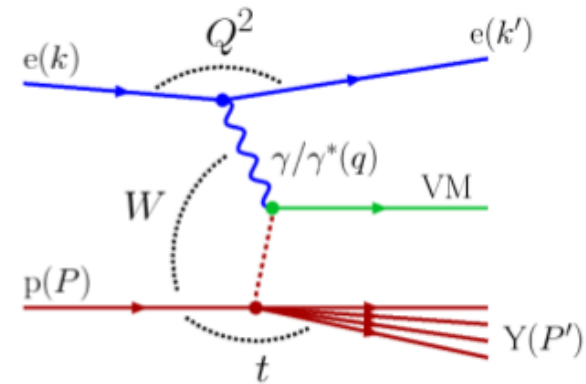
elastic (exclusive)



VM =  $\rho, \omega, \phi, J/\psi, \psi', \Upsilon$

$|t| < 1 \text{ GeV}^2$

proton dissociative



dominates at high  $|t|$

$Q^2$  photon virtuality

$$Q^2 = -q^2 = -(k - k')^2$$

$Q^2 \approx 0$  (PHP)

$W$  CMS energy of  $\gamma p$  system

$$W^2 = (q + P)^2$$

$Q^2 > 0$  (DIS)

$t$  (4-mom. transfer)<sup>2</sup> at p-vertex

$$t = (P - P')^2$$

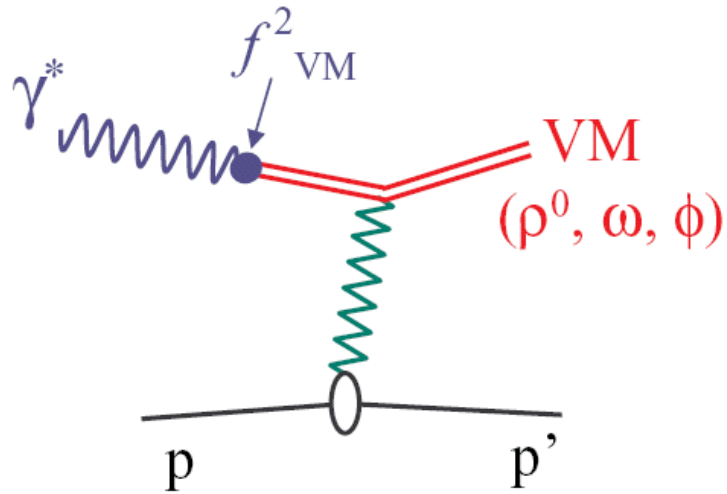
$x$  Bjorken  $x$  = fractional parton momentum in proton Breit frame

$$x \approx \frac{Q_2}{W_2}$$



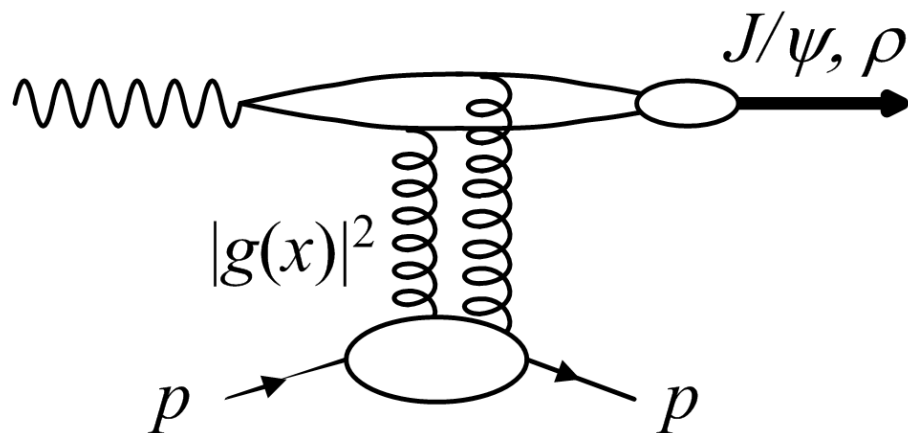
# Diffractive Vector Meson production (2)

## Vector Dominance Model + Regge



- $\gamma^* p \rightarrow VM p = (\gamma^* \rightarrow VM) \otimes (VM p \rightarrow VM p)$
- $VM p \rightarrow VM p \Rightarrow$  DL IPomeron exchange
  - $d\sigma/dt \sim \exp(-b(W)t)$ ,  $b \sim R_{int}^2 \approx 10 \text{ GeV}^{-2}$
  - $b(W) = (b_{VM} + b_p + \alpha' \ln(W^2))$  (“shrinkage”)
  - $\sigma_{VMp} \sim W^{4(\alpha_0-1)}/b(W) \sim W^\delta$ ,  $\delta \approx 0.22$

## Perturbative QCD

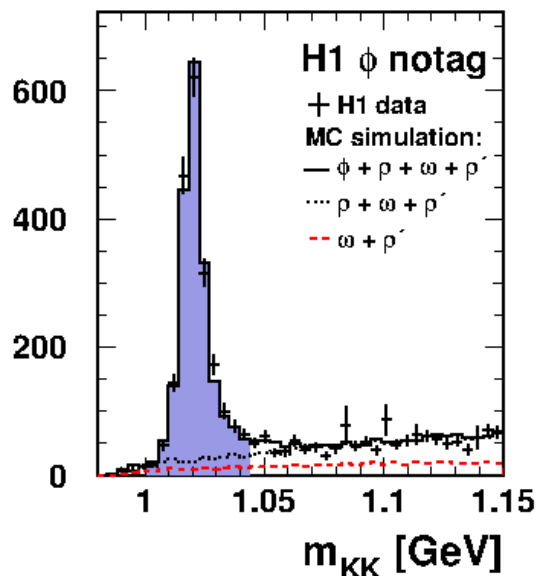
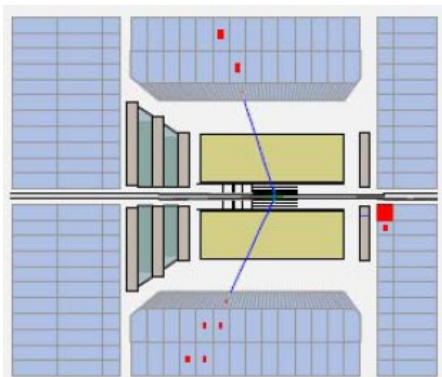


- Large  $Q^2$ ,  $M_{VM}$  or  $|t| \rightarrow$  small qq dipol
- QCD Pomeron exchange:  
 $\geq 2$  gluons (colour singlet)
  - $\sigma_{VMp} \sim (xg(x))^2 \sim W^{0.7}$  !!!
  - $b \ll 10 \text{ GeV}^{-2}$ , weak shrinkage

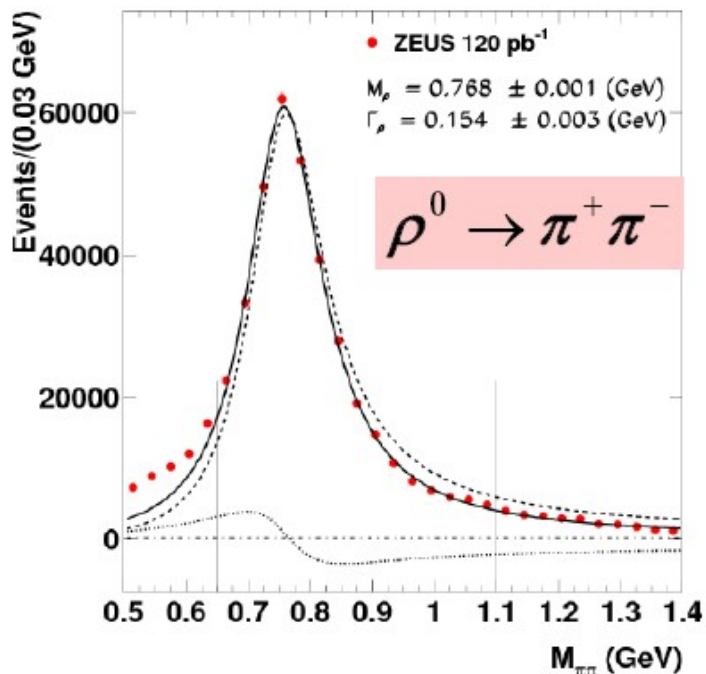
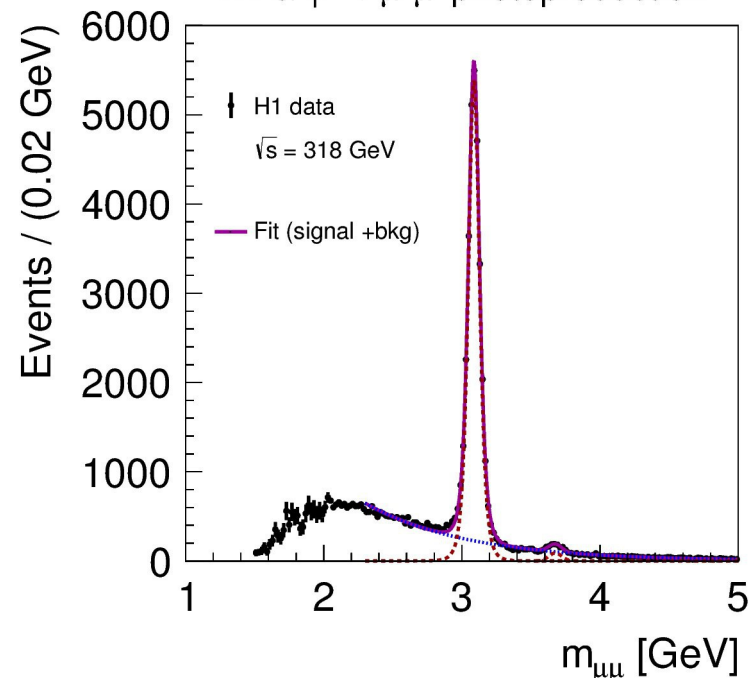
VM at HERA: transition between soft and hard regime; testbed of QCD scales

# Diffractive Vector Meson production (3)

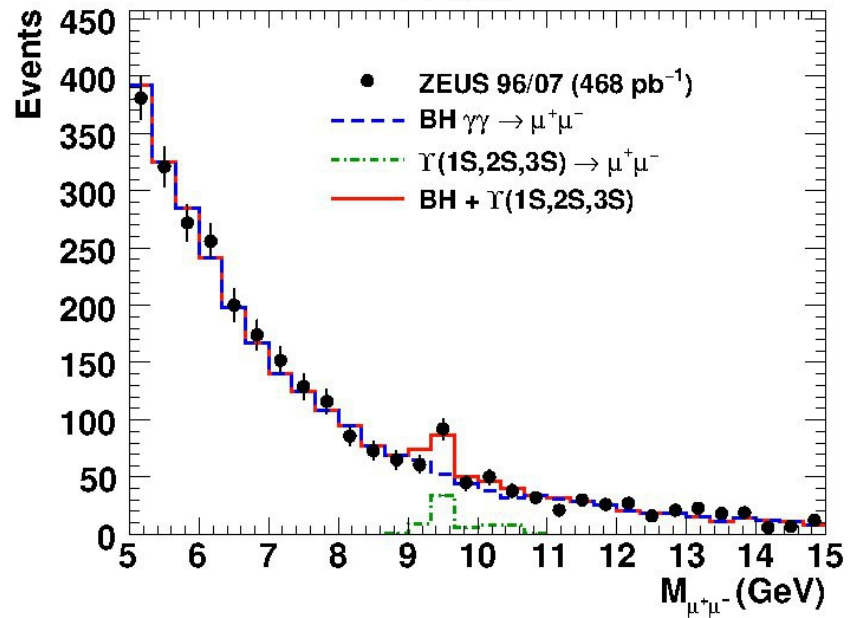
## H1, ZEUS



## H1 $J/\psi \rightarrow \mu^+\mu^-$ photoproduction

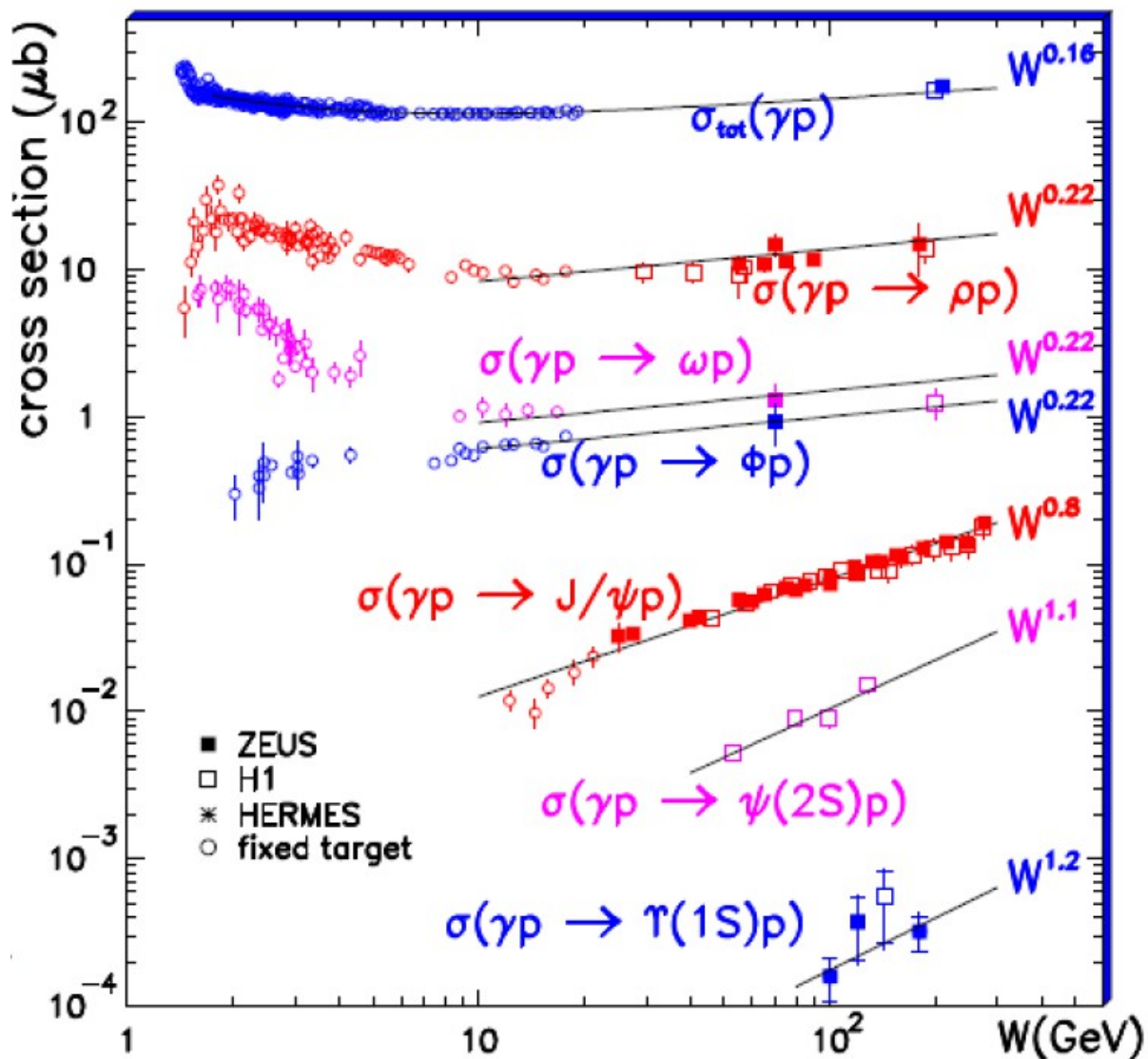


## ZEUS



# Vector mesons: energy dependence (1)

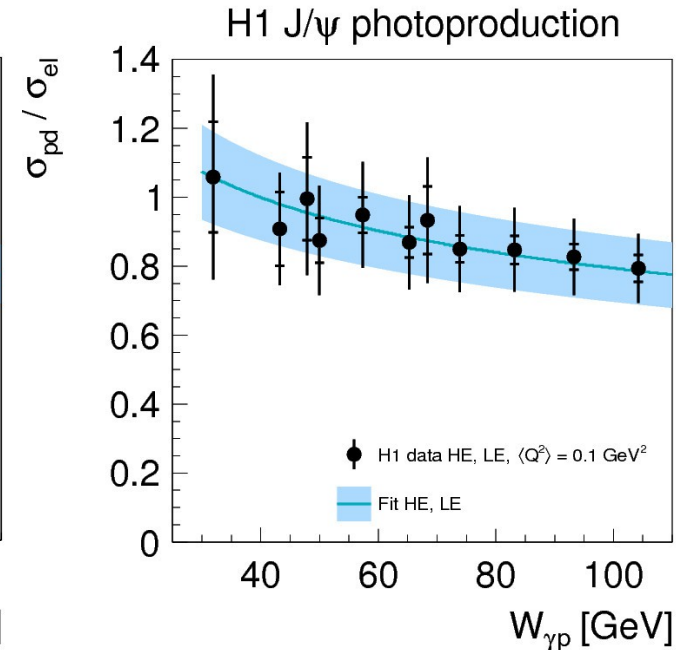
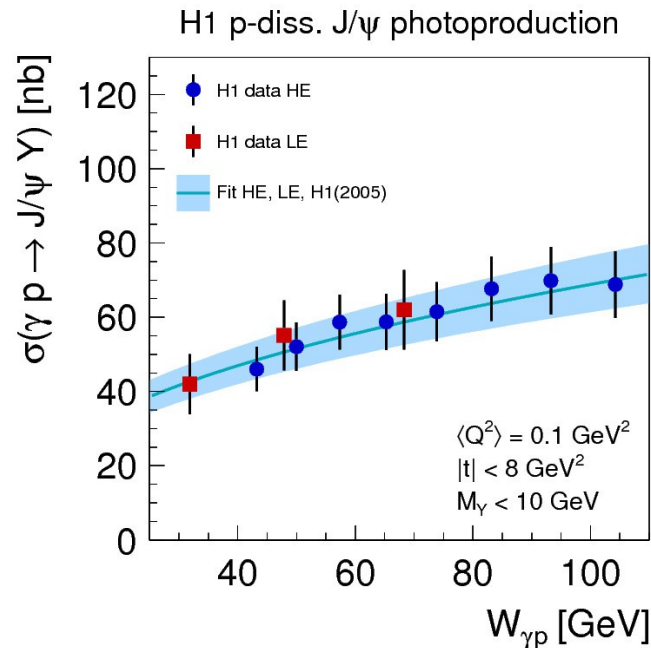
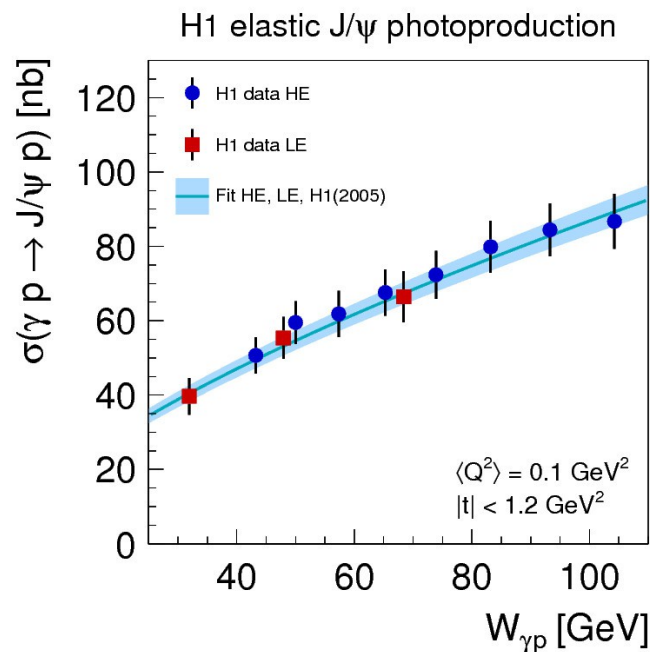
Photoproduction, energy dependence:  $\sigma \sim W^\delta$



The heavier vector meson –  
– the steeper  $W$ -dependence.  
VM mass sets QCD scale

# Vector mesons: energy dependence (2)

**H1 (DESY-13-058): Elastic and Proton-dissociative Photoproduction of  $J/\psi$  Mesons at HERA**  
 HE:  $\sqrt{s} \approx 318$  GeV, LE:  $\sqrt{s} \approx 225$  GeV, Eur. Phys. J. **C73** (2013) 2466



Simultaneous fit of elastic and p-diss. cross section:

$$\delta_{el} = 0.67 \pm 0.03, \quad \delta_{p\text{-diss}} = 0.42 \pm 0.05$$

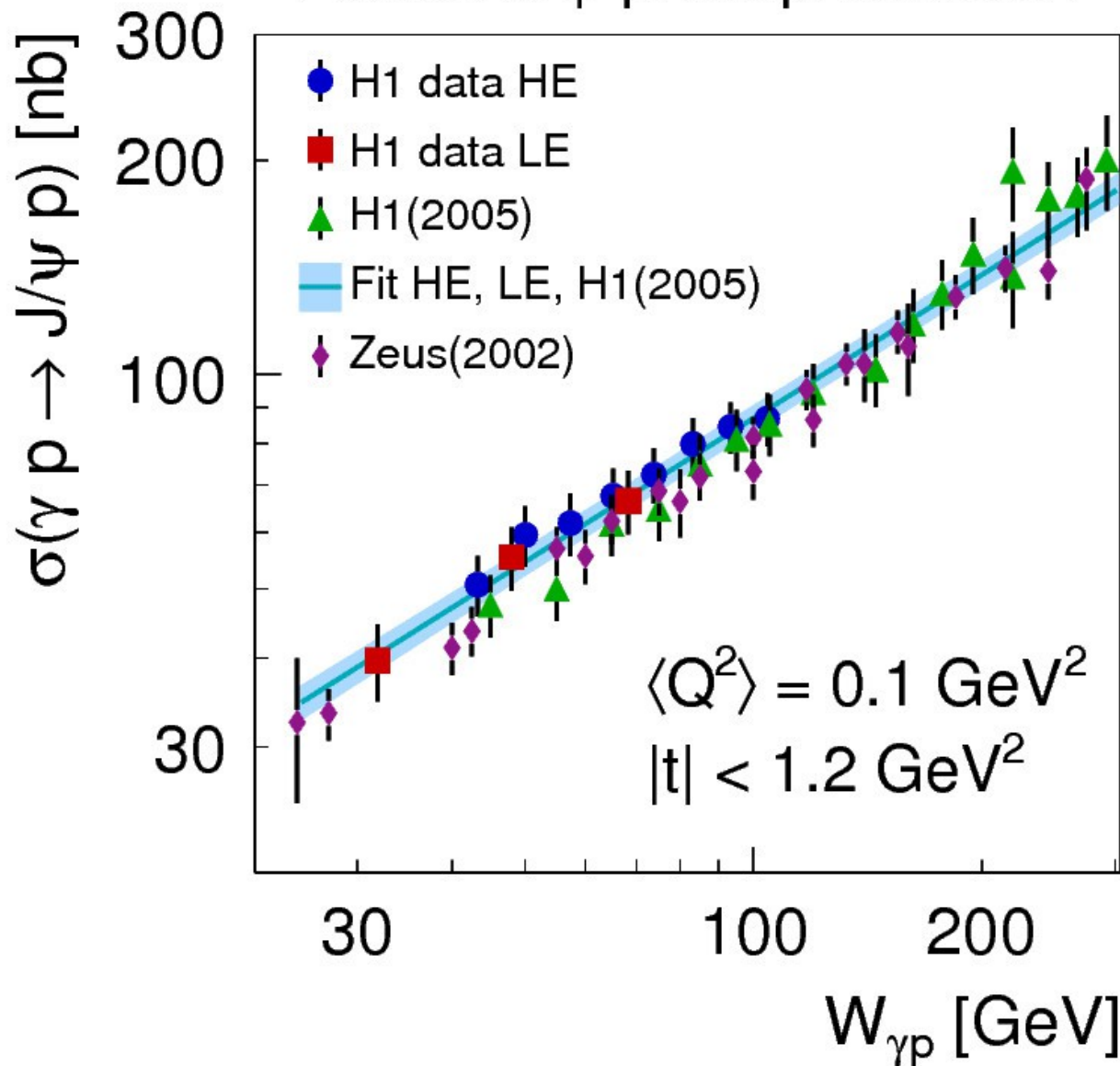


# Vector mesons: energy dependence (3)

H1 (DESY-13-058): Elastic and Proton-dissociative Photoproduction of  $J/\psi$  Mesons at HERA

EPJ **C73** (2013) 2466

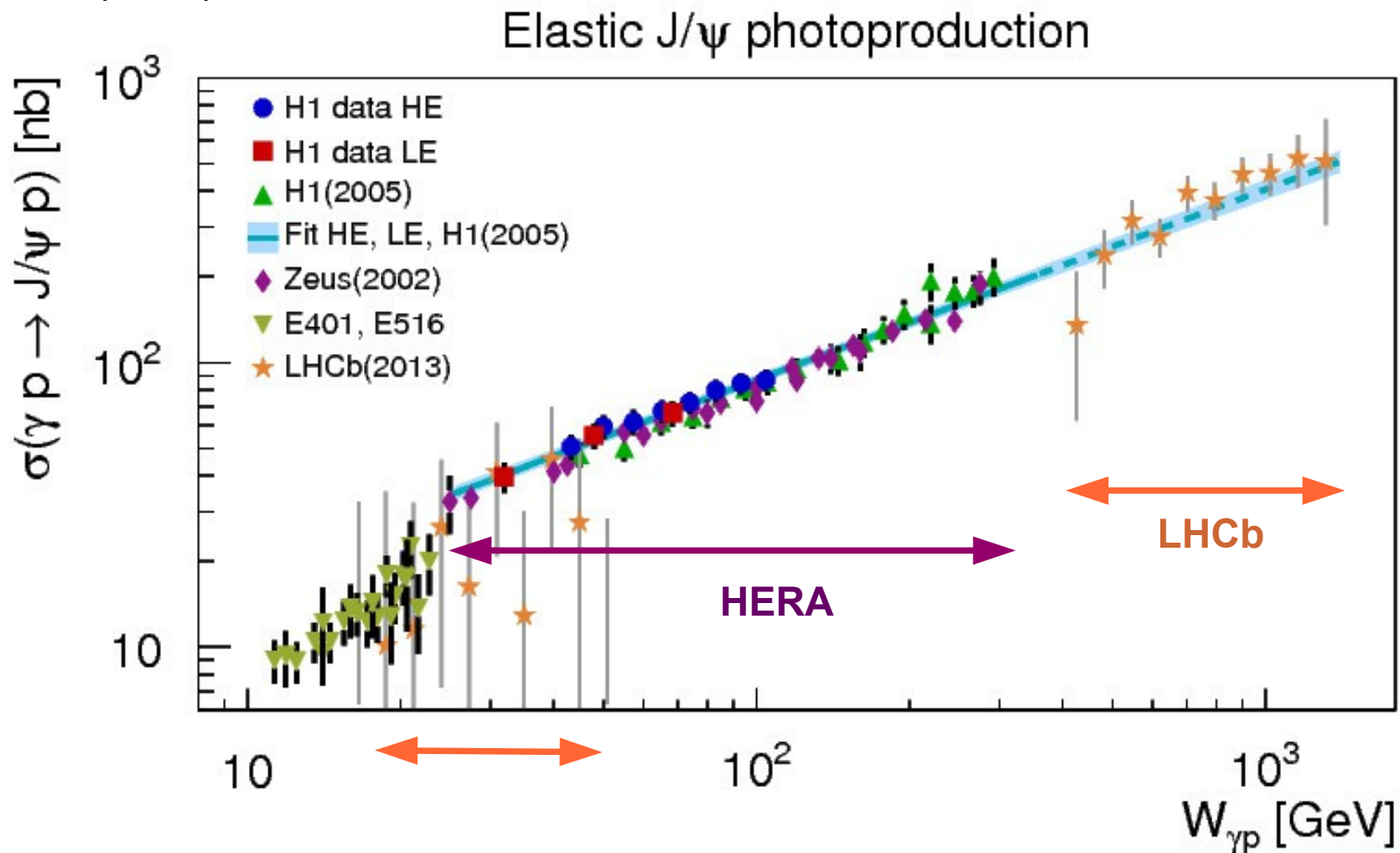
## Elastic $J/\psi$ photoproduction



Large overlap and good agreement  
Between H1 and ZEUS experiments

# Vector mesons: energy dependence (4)

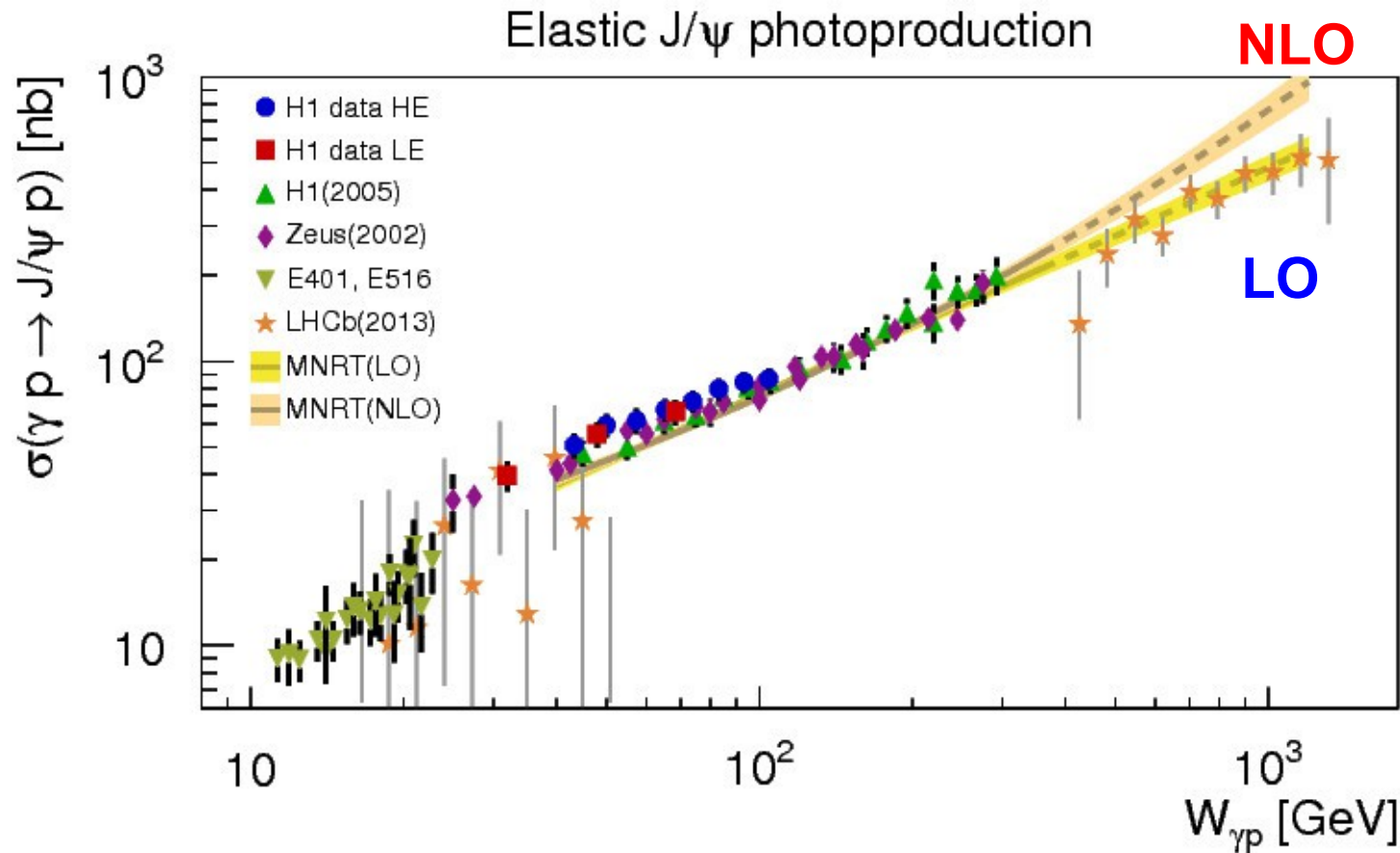
H1 (DESY-13-058): Elastic and Proton-dissociative Photoproduction of  $J/\psi$  Mesons at HERA  
EPJ **C73** (2013) 2466



H1 fit extrapolation to higher energy describes LHCb data as well!

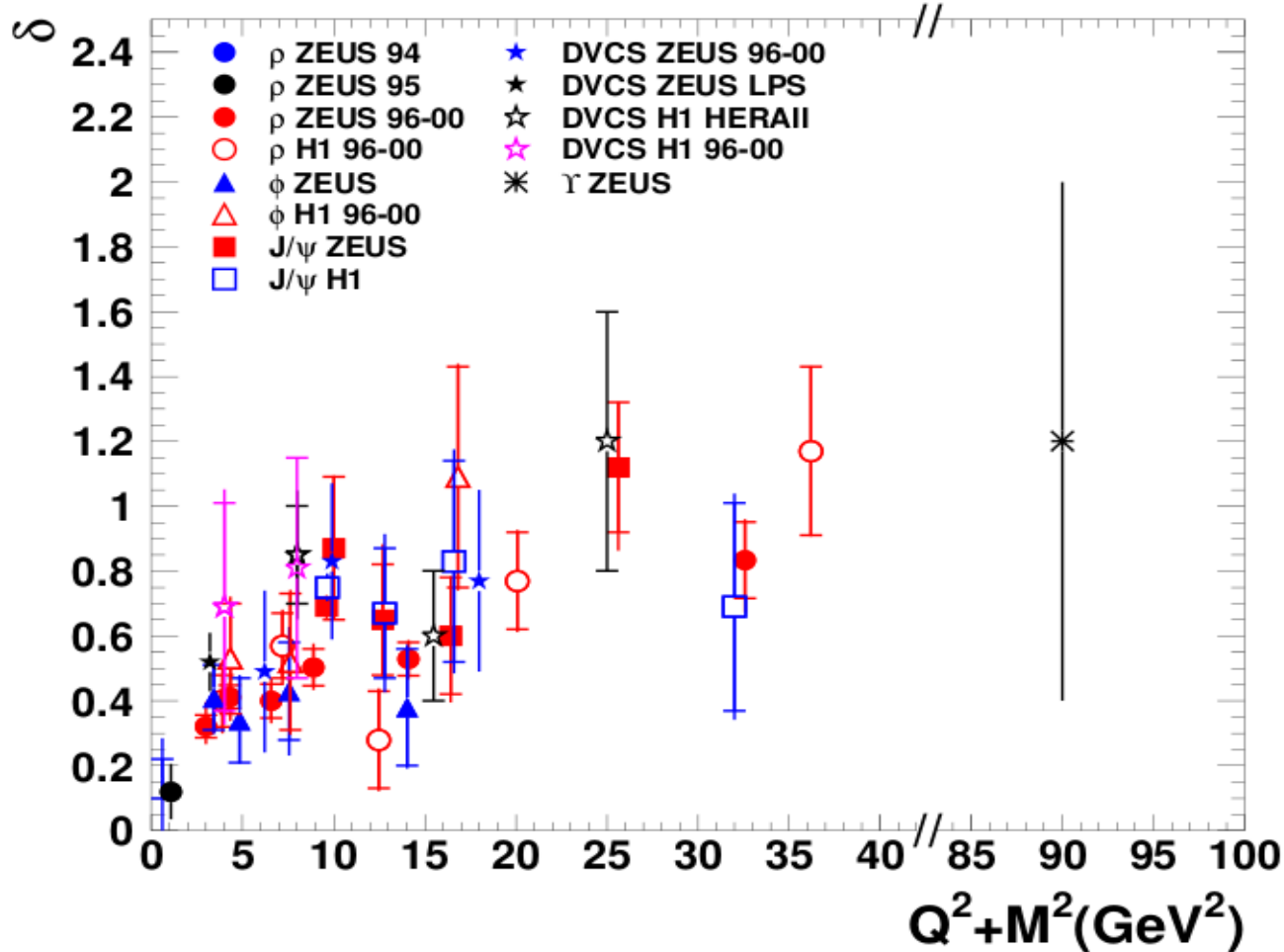
# Vector mesons: energy dependence (5)

pQCD calculations: A. Martin et al., arXiv: 0709.4406



- LO and NLO fits to previous  $J/\psi$  data from HERA (gluon densities!)
- Both fits extrapolated to higher energies...
- LO extrapolation describes LHCb data.

# VM and DVCS energy dependence compilation



$$\sigma \sim W^\delta$$

VMs: bigger “hard” scale  $Q^2+M^2$  – steeper rise with  $W$ ,  
 $Q^2+M^2$  scale governs “soft” – “hard” interaction transition

DVCS: always steep rise with  $W$  – “hard” interaction...

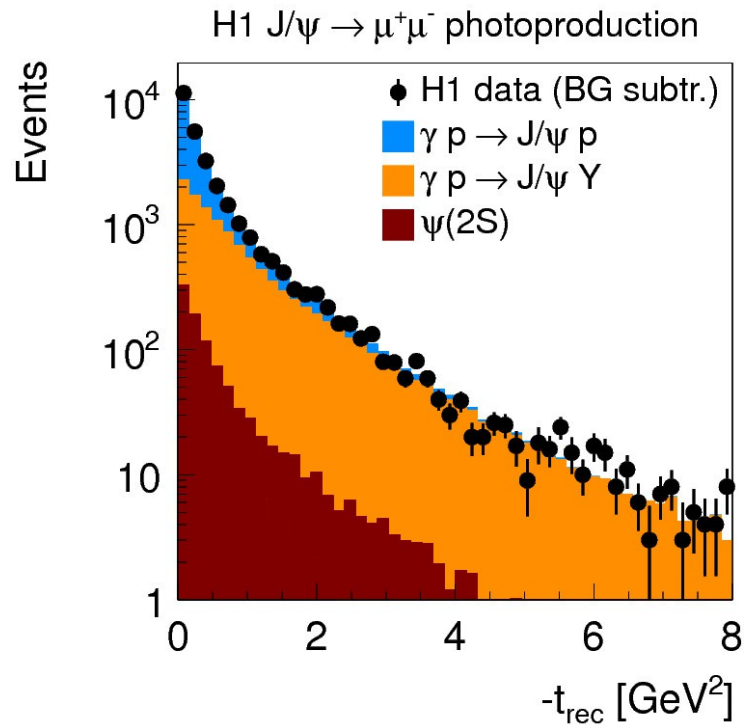


# Vector mesons: $t$ – dependence (1)

H1 (DESY-13-058): Elastic and Proton-dissociative Photoproduction of  $J/\psi$  Mesons at HERA  
EPJ **C73** (2013) 2466

“elastic”:  $d\sigma/dt \sim e^{-b|t|}$

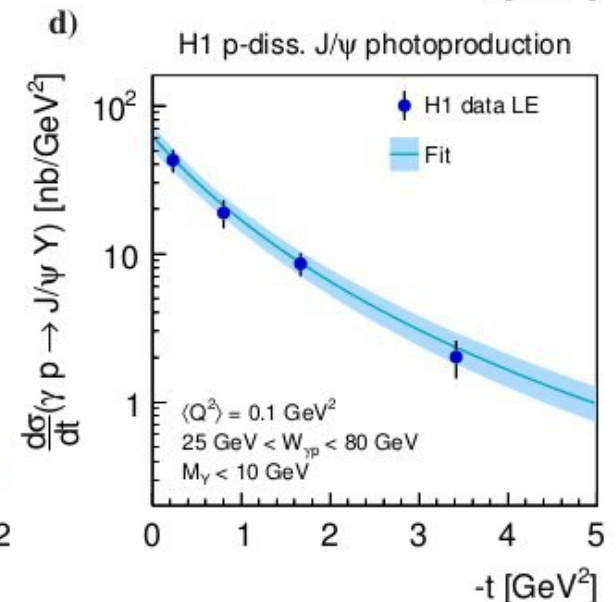
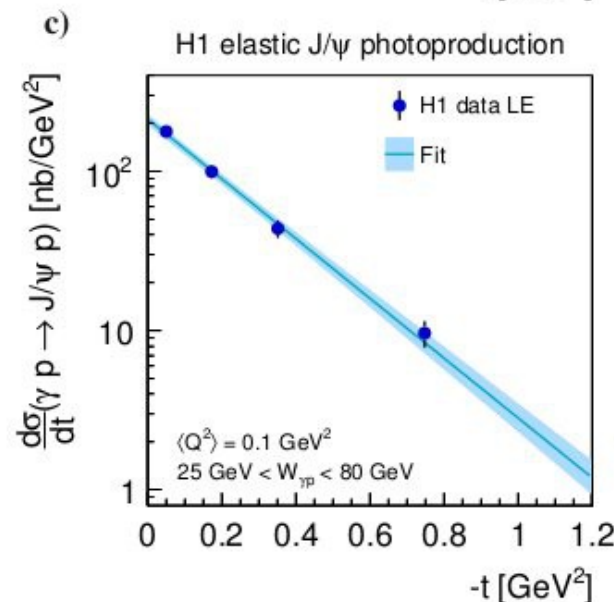
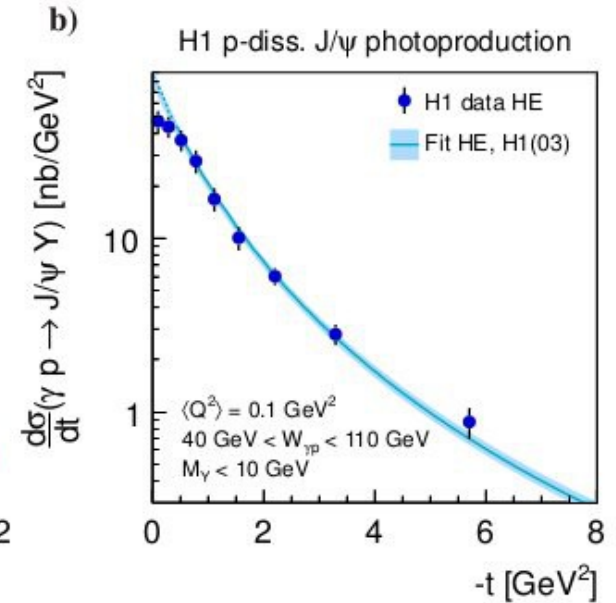
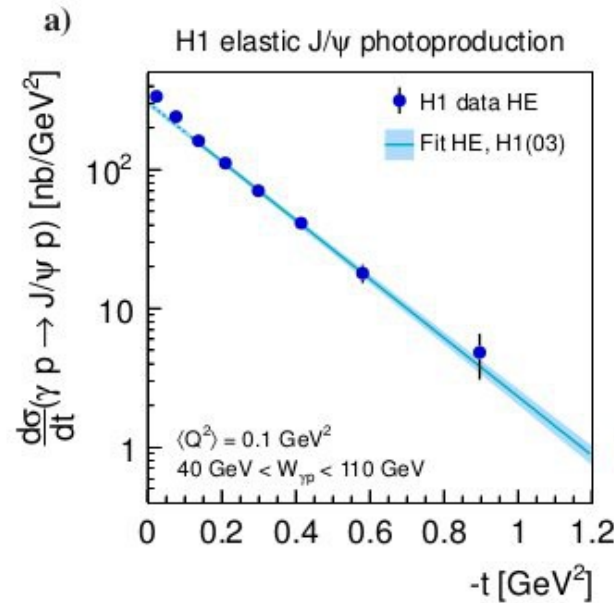
“p-diss.”:  $d\sigma/dt \sim (1+(b_{pd}/n)|t|)^{-n}$



$$b = 4.88 - 4.3 \pm 0.2 \text{ GeV}^2$$

$$b_{pd} = 1.79 - 1.6 \pm 0.2 \text{ GeV}^2$$

$$n = 3.58 \pm 0.15$$

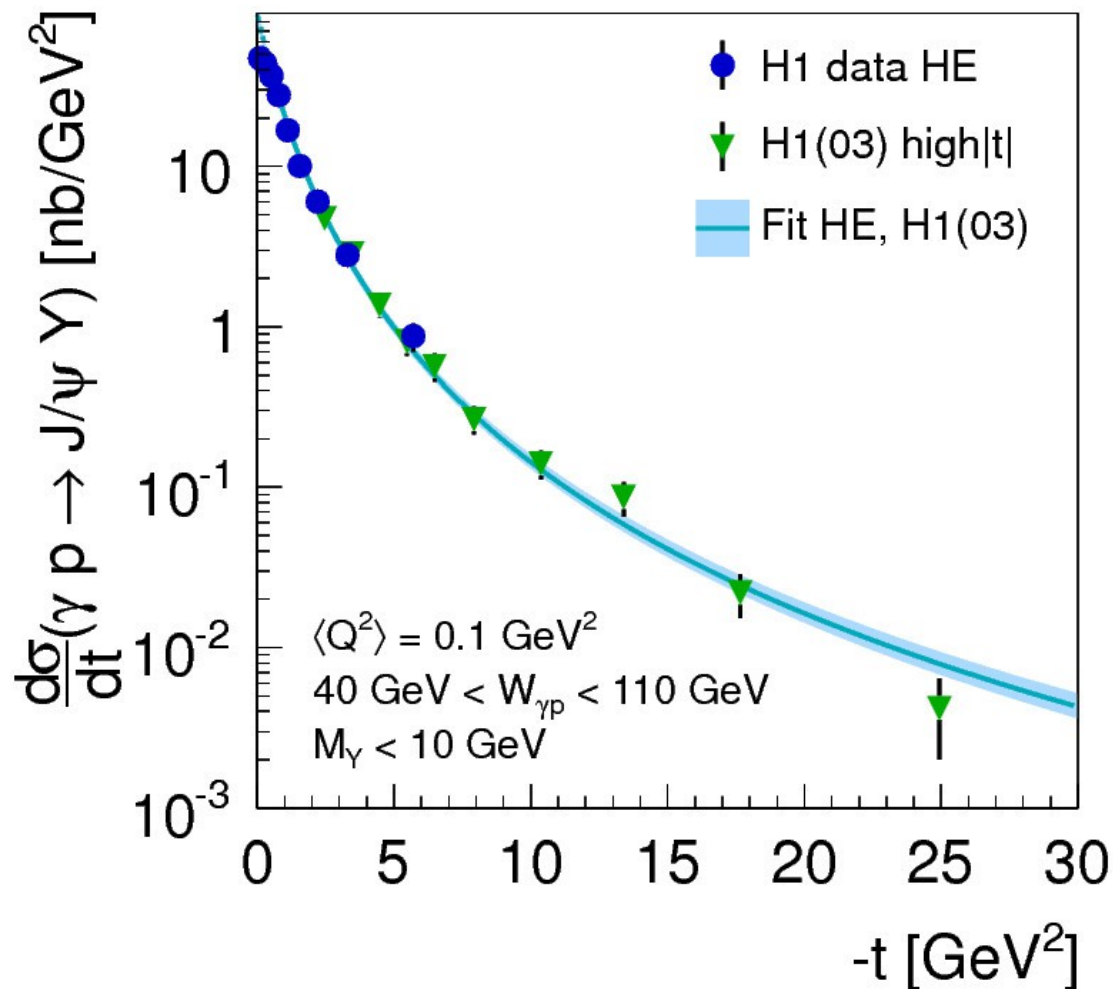


# Vector mesons: $t$ – dependence (2)

H1 (DESY-13-058): Elastic and Proton-dissociative Photoproduction of  $J/\psi$  Mesons at HERA

EPJ **C73** (2013) 2466

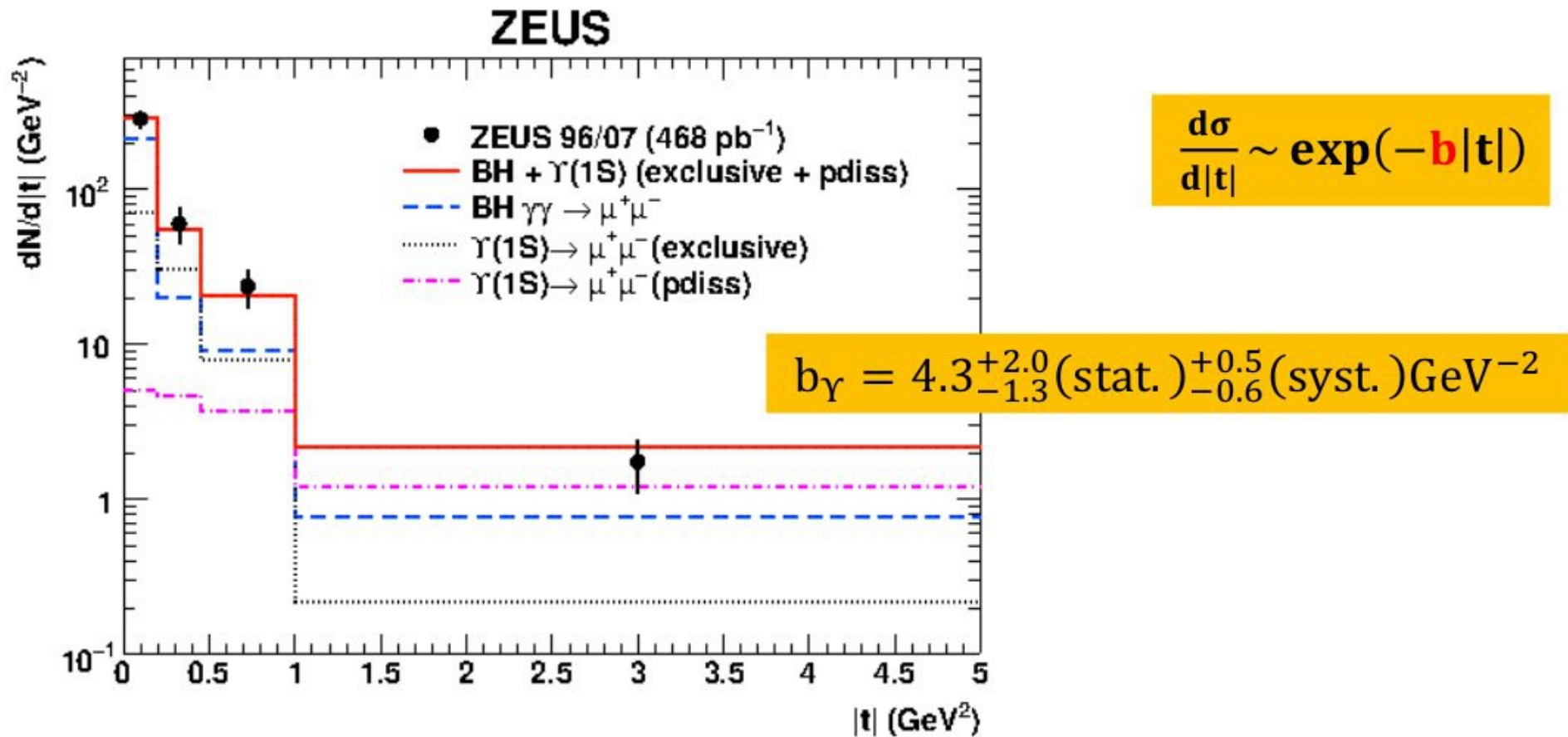
H1 p-diss.  $J/\psi$  photoproduction



- First measurement of p-diss. production at low  $|t|$ ,
- Previous H1(03) high  $|t|$  data extrapolated to present  $W$ ,  $Q^2$ ,  $M_Y$  range,
- Good agreement in the overlap region

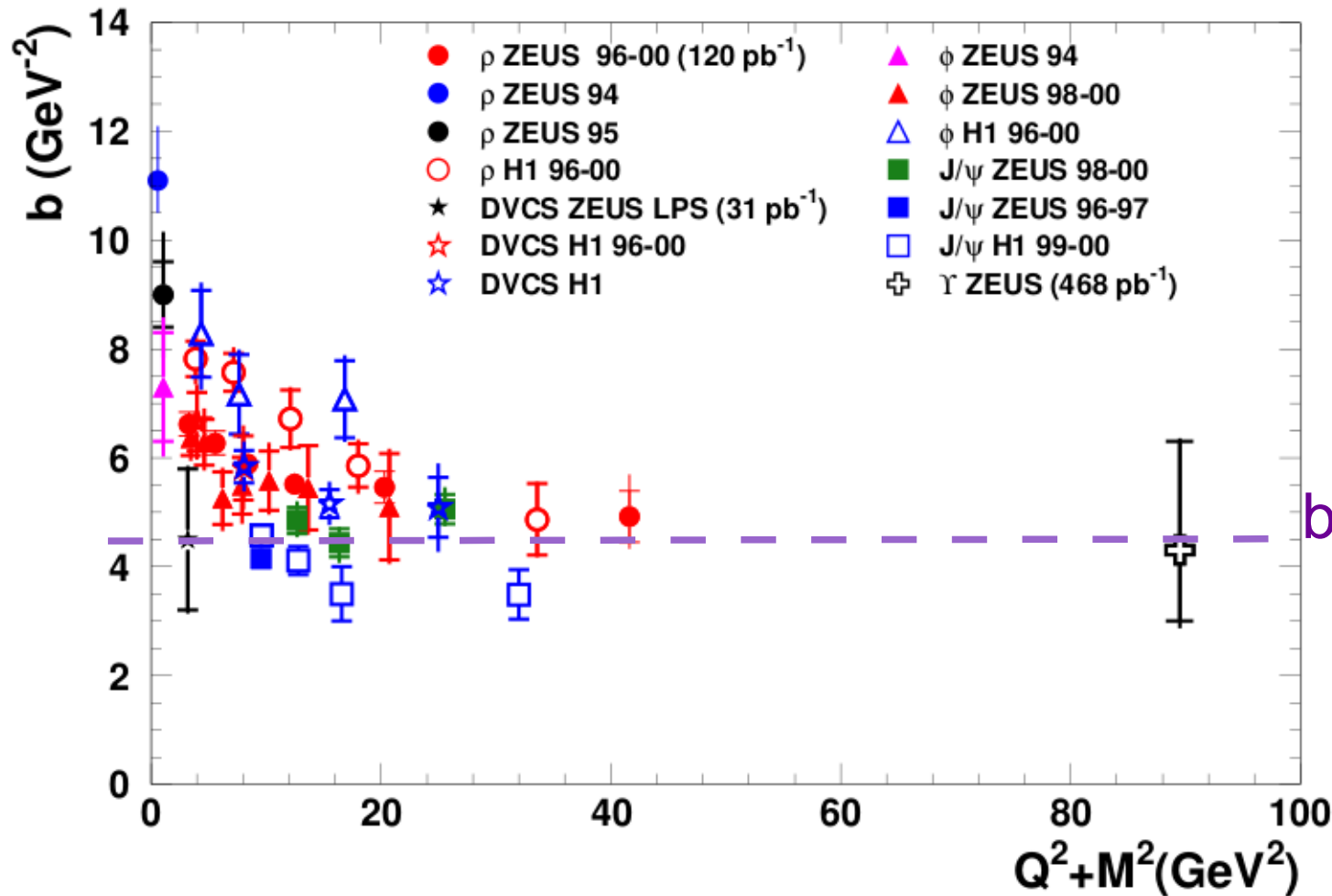
# Vector mesons: $t$ – dependence (3)

Measurement of the  $t$ -dependence in exclusive pph of  $\Upsilon(1S)$  mesons at HERA, **ZEUS** (Phys.Lett. **B708**(2012)14-20),  $Q^2 < 1 \text{ GeV}^2$ ,  $60 < W < 220 \text{ GeV}$



- Fit  $dN/dt$  with sum of elastic and p-diss.
- First measurement of slope  $b$  for  $\Upsilon$  photoproduction

# VM and DVCS: t-slope compilation



$$d\sigma/dt \sim e^{-b|t|}$$

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

$$\langle r^2 \rangle = b \cdot (hc)^2$$

Proton target:

$$b_p \approx 4.5 \text{ GeV}^{-2} \Rightarrow$$

$$\Rightarrow r_{\text{gluon}} \approx 0.6 \text{ fm}$$

$$\langle r_{\text{em}} \approx 0.8 \text{ fm}$$

Decreasing slope (and interaction size) with rising scale  $Q^2 + M^2$  -  
- transition between “soft” and “hard” interaction



# HERA vs Central Exclusive Production at LHC

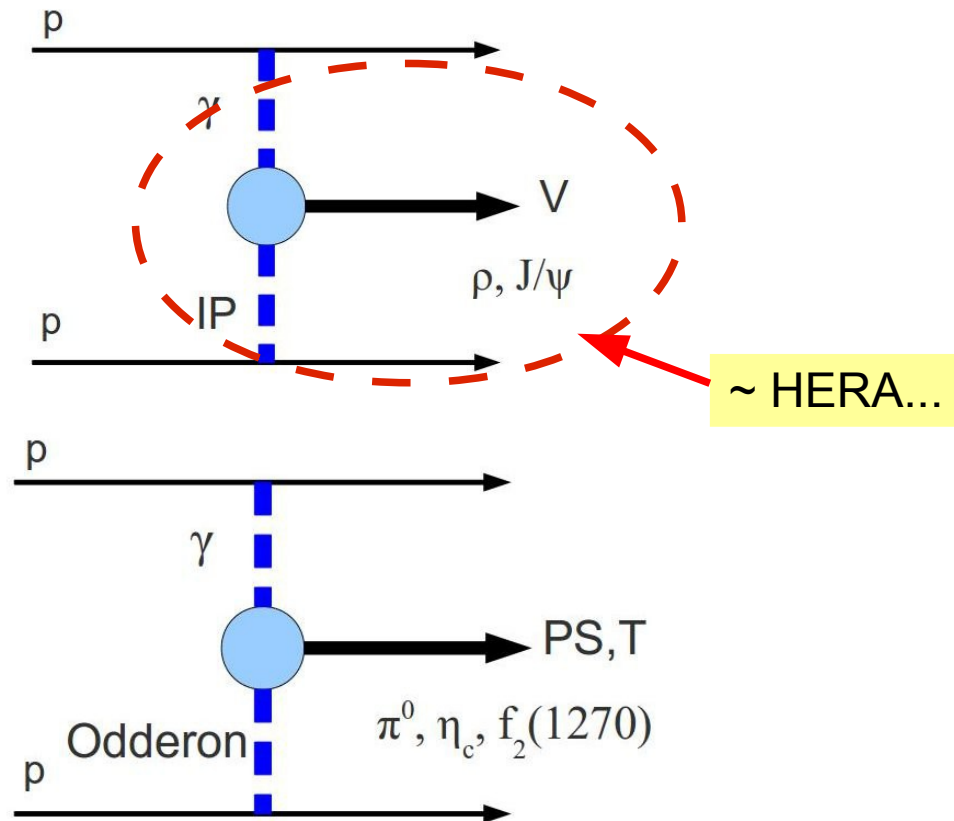
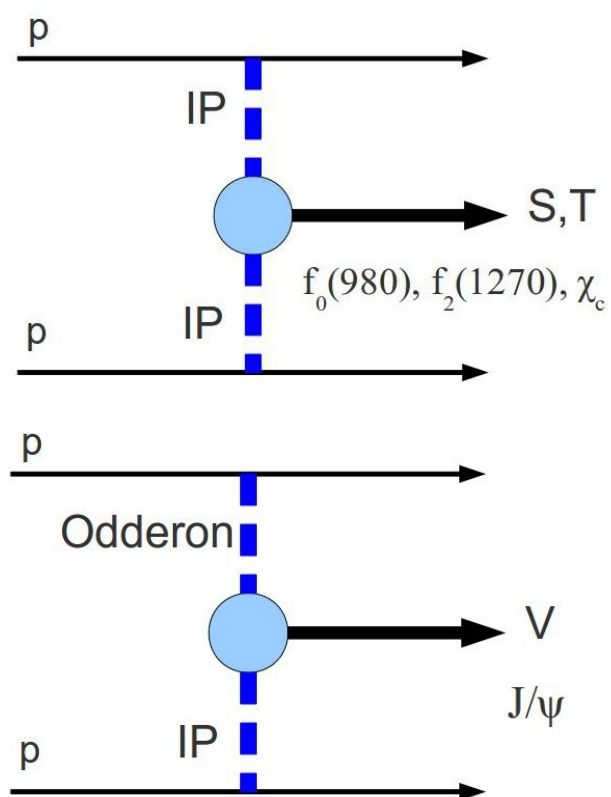
## Possible exchanges:

Pomeron ( $C=+1$ ), QCD: 2 gluons,

Odderon ( $C=-1$ ), QCD: 3 gluons

Photon  $\gamma$  ( $C=-1$ ),

Type	Meson	IG	JPC
S	$f_0/\sigma(600)$ , $f_0(980)$ , $f_0(1500)$ , $\chi_c$	$0^+$	$0^{++}$
PS	$\pi^0$ , $\eta_c$	$1^-/0^+$	$0^-+$
V	$\rho^0$ , $\omega(782)$ , $\phi$ , $J/\psi$	$1^+/0^-$	$1^{--}$
T	$f_2(1270)$ , $f_2'(1525)$	$0^+$	$2^{++}$



# Dipion electroproduction (1)

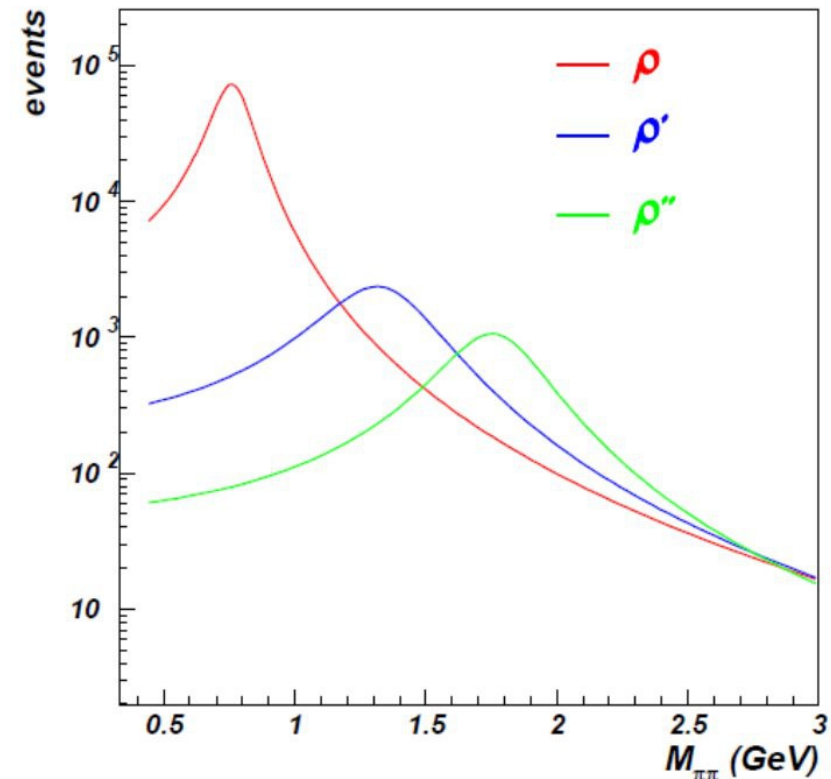
Exclusive electroproduction of two pions at HERA,  
**ZEUS** (Eur. Phys. J. C72 (2012) 1869),  $2 < Q^2 < 80 \text{ GeV}^2$ ,  $32 < W < 180 \text{ GeV}$ ,  $|t| < 0.6 \text{ GeV}^2$

$$\gamma^* p \rightarrow \pi^+ \pi^- p$$

- Two-pion mass spectrum (without non-resonant background) => pion EM form factor  $|F_\pi(M_{\pi\pi})|^2$
- Kuhn-Santamaria parametrisation including  $\rho(770)$ ,  $\rho'(1450)$  (radially excited 2S state) and  $\rho''(1700)$  (orbitally excited 2D state)

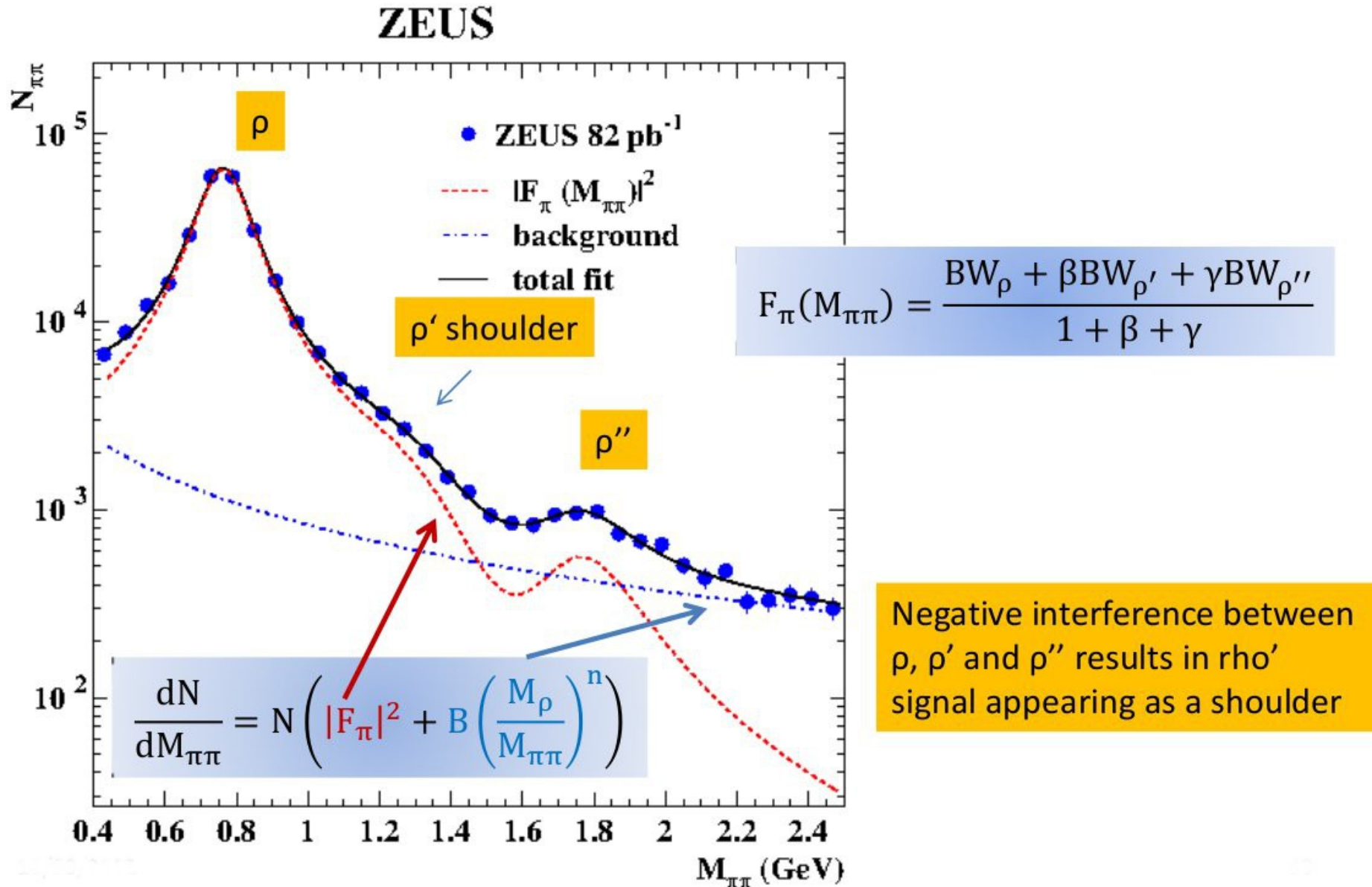
$$F_\pi(M_{\pi\pi}) = \frac{BW_\rho(M_{\pi\pi}) + \beta BW_{\rho'}(M_{\pi\pi}) + \gamma BW_{\rho''}(M_{\pi\pi})}{1 + \beta + \gamma}$$

$$BW_V(M_{\pi\pi}) = \frac{M_V^2}{M_V^2 - M_{\pi\pi}^2 - iM_V\Gamma_V(M_{\pi\pi})}$$



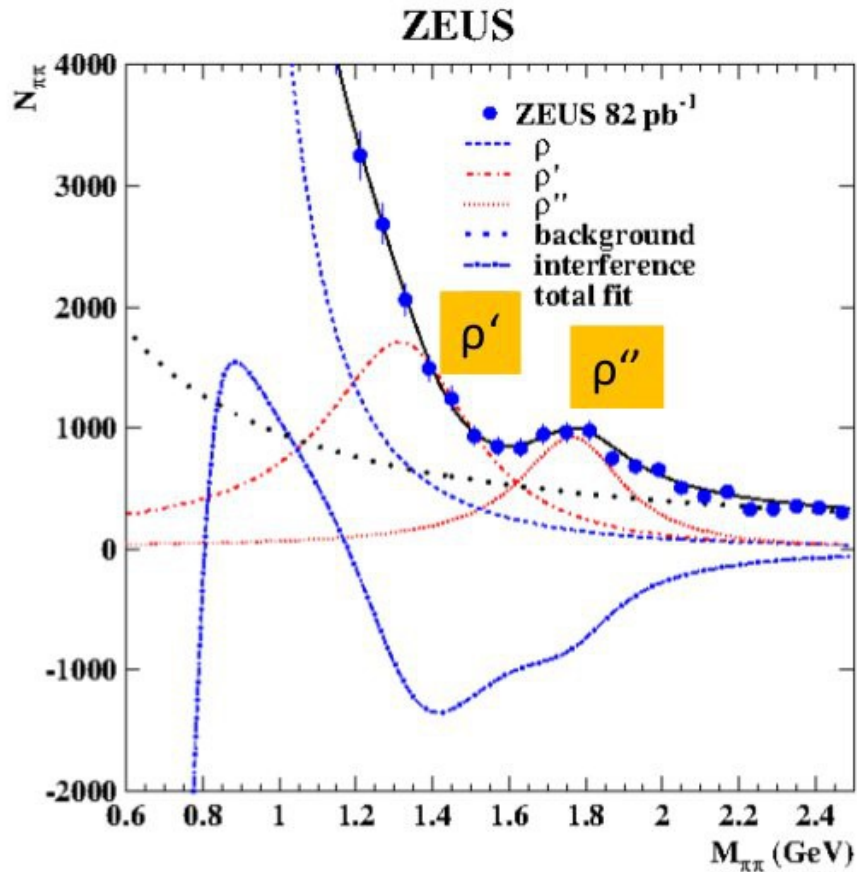
# Dipion electroproduction (2)

Fit three resonances...



# Dipion electroproduction (3)

Details of the fit...



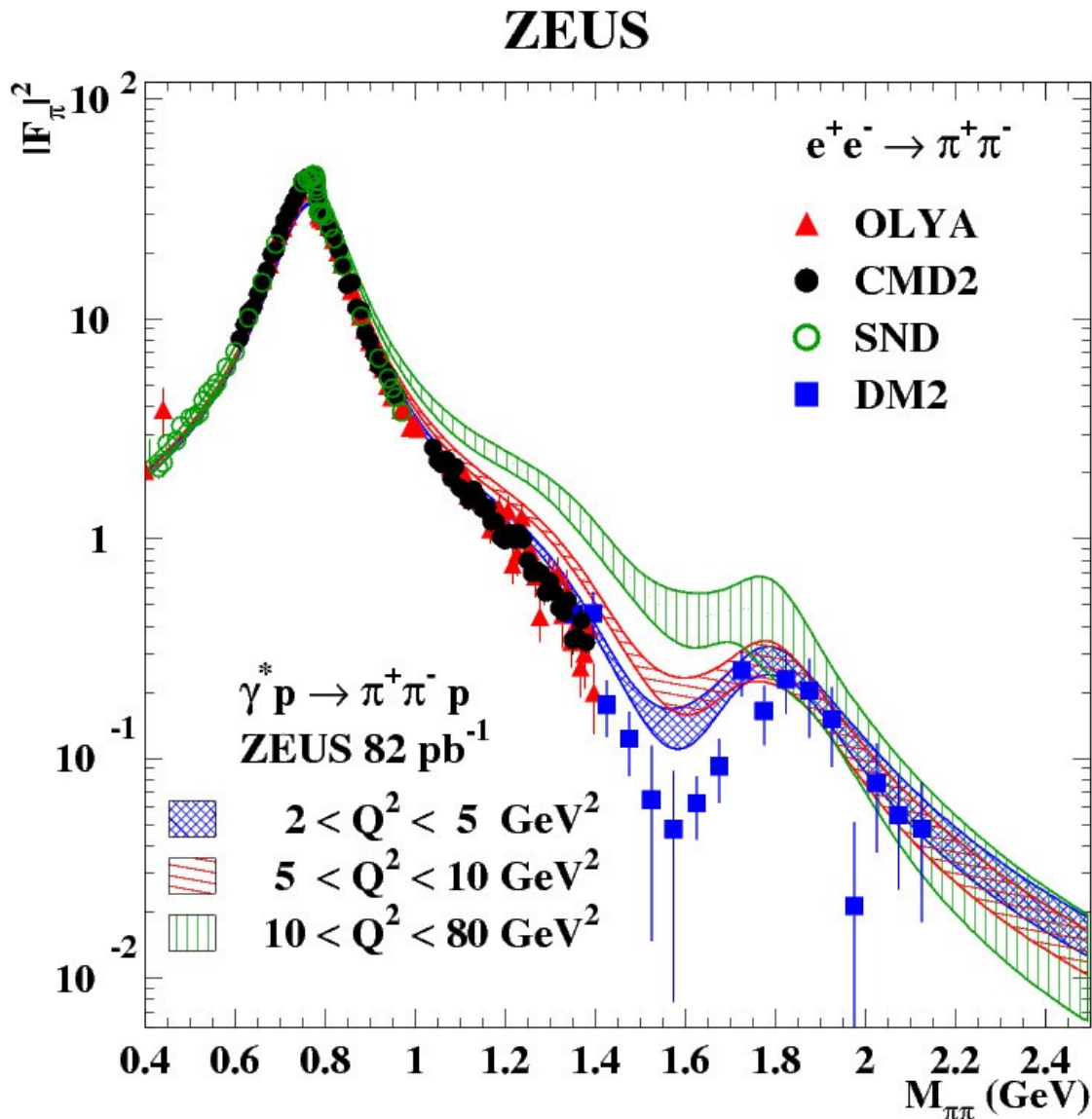
Parameter	ZEUS	PDG
$M_\rho$ (MeV)	$771 \pm 2^{+2}_{-1}$	$775.49 \pm 0.34$
$\Gamma_\rho$ (MeV)	$155 \pm 5 \pm 2$	$149.1 \pm 0.8$
$\beta$	$-0.27 \pm 0.02 \pm 0.02$	
$M_{\rho'}$ (MeV)	$1350 \pm 20^{+20}_{-30}$	$1465 \pm 25$
$\Gamma_{\rho'}$ (MeV)	$460 \pm 30^{+40}_{-45}$ !	$400 \pm 60$
$\gamma$	$0.10 \pm 0.02^{+0.02}_{-0.01}$	
$M_{\rho''}$ (MeV)	$1780 \pm 20^{+15}_{-20}$	$1720 \pm 20$
$\Gamma_{\rho''}$ (MeV)	$310 \pm 30^{+25}_{-35}$	$250 \pm 100$
$B$	$0.41 \pm 0.03 \pm 0.07$	
$n$	$1.30 \pm 0.06^{+0.18}_{-0.13}$	

Relative amplitudes measured real (!), interference important.



# Dipion electroproduction (4)

Compared to  $e^+e^- \rightarrow \pi^+\pi^- \dots$

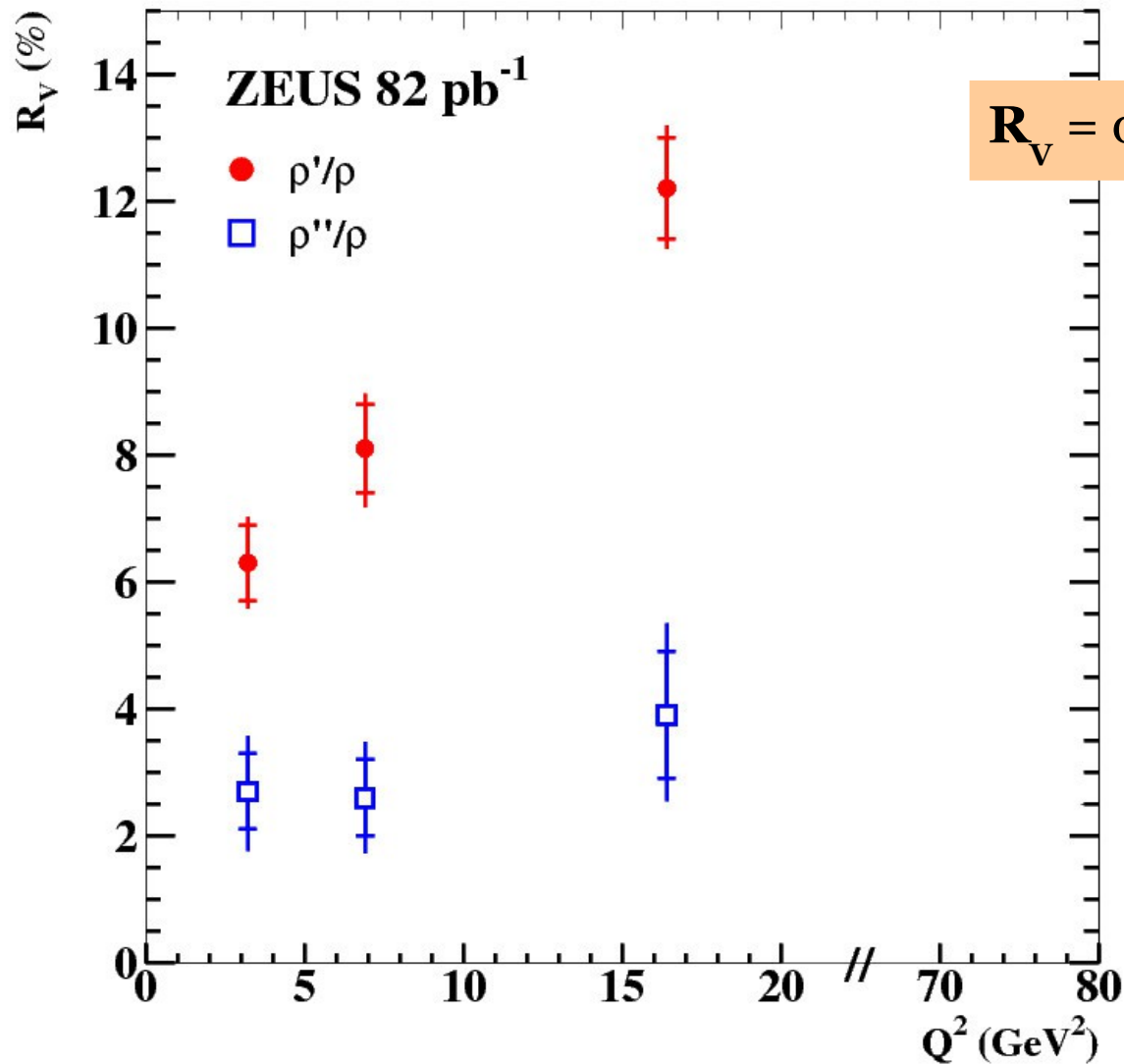


- Some differences between both reactions in the interference region
- $Q^2$  dependence of the form factor above  $\rho(770)$ ...

# Dipion electroproduction (5)

Ratio of excited  $\rho$  states in function of  $Q^2$

**ZEUS**



- $R_{\rho'}$  increases with  $Q^2$  -  
- expected in pQCD models:  
suppression at low  $Q^2$  due to  
a node in  $\rho'$  wave function...

# Summary

- New, “hard” face of diffraction in e-p collisions at HERA
- Interplay between soft and hard regime extensively studied
- Regge model + soft phenomenology vs perturbative QCD
- Vector Meson production and DVCS at HERA:
  - VM mass,  $Q^2$  and  $t$  provide control over “hardness” of the interaction,
  - energy dependence  $\leftrightarrow$  proton gluon density at low  $x$ ,
  - $t$ -distribution  $\leftrightarrow$  spatial structure of the interaction,
  - sensitivity to VM wave function,
  - testbed of pQCD which reproduces general behaviour of the data
- Diffractive analyses at HERA are still ongoing and new results arrive...
- Impact of HERA results on diffraction studies at LHC