Vector meson production at HERA

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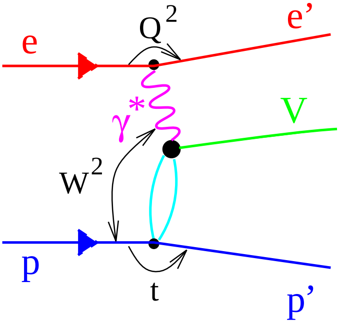
Outline

- **Introduction**
- **Elastic Photo and Electroproduction of Vector Mesons**
  - W**-dependence**
  - Q^2**-dependence**
  - **t-dependence**
  - **Helicity studies**
- **Two pion electroproduction**
- **Summary**

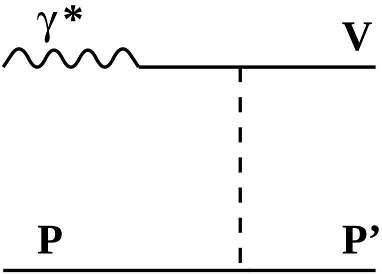
Vector meson production



$V = (\rho, \omega, \phi, J/\psi, \Upsilon +$ **excited states)**

- $Q^2 = -(e - e')^2$ photon virtuality
- W is $\gamma^* p$ center of mass (CM) energy
- $t = (p - p')^2$ momentum transfer squared at the proton vertex

VDM and Regge theory (soft physics)



- The photon fluctuates into a vector meson, V, which carries the same quantum numbers as the photon ($\gamma p \rightarrow \mathrm{Vp}$)
- The vector meson scatters elastically off the incoming proton ($\mathrm{Vp} \rightarrow \mathrm{Vp}$)

VDM and Regge theory (soft physics)

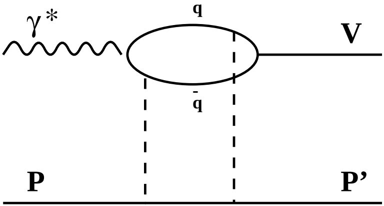
Predictions :

- $\frac{d\sigma(\gamma p \to Vp)}{dt} \propto e^{-bt}(W^2/W_0^2)^{2(\alpha(0)-1)}$

Experimental observations :

- $\alpha(t) = \alpha(0) + \alpha' t$
- $\alpha(0)$= 1.096$\pm$0.003 α'= 0.25
  (DL – Donnachie, Landshoff parameterisation)
- Shrinkage of the diffractive peak
  $b(W) = b_0 + 4\alpha' \ln(W/W_0)$ $b_0 \sim 10$ GeV^{-2}
- Weak energy dependence of cross section
  $\sigma \propto W^{\delta}$, $\delta \simeq 0.2$

pQCD models (hard physics)

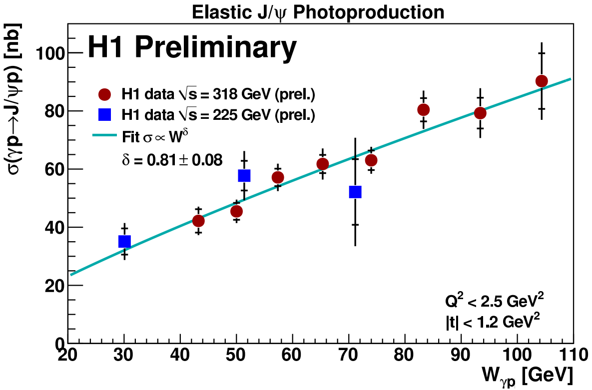


- the photon fluctuates into a $q\bar{q}$ state
- the $q\bar{q}$ pair scatters off the proton target
- the scattered $q\bar{q}$ pair turns into a vector meson.

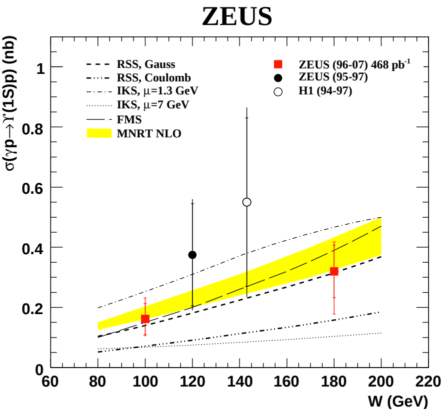
Predictions :

- $\sigma_L \propto \frac{\alpha_S^2(Q)}{Q^6}|xG(x,Q^2)|^2$
- fast increase of the $\gamma^* p \to Vp$ cross section with energy W
- universal exponential t dependence, $b \sim 4-5\,\mathrm{GeV}^{-2} \quad \Longrightarrow \quad \alpha' \to 0\,?$

Elastic Photoproduction $\gamma p \to J/\Psi p$

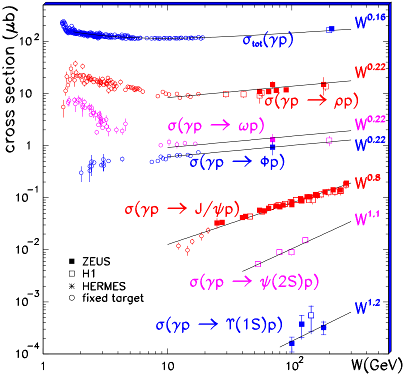


- **cross section W dependence, $\sigma \sim W^{\delta}$:**
  δ= 0.81$\pm$0.08, (ZEUS: $\delta = 0.69 \pm 0.02 \pm 0.03$)



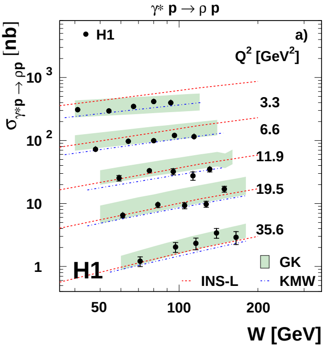
- **cross section W dependence, $\sigma \sim W^{\delta}$:**
- **two measured points δ= 1.2$\pm$0.8**
- **consistent with theoretical prediction, $\delta \sim 1.7$**

Elastic Photoproduction

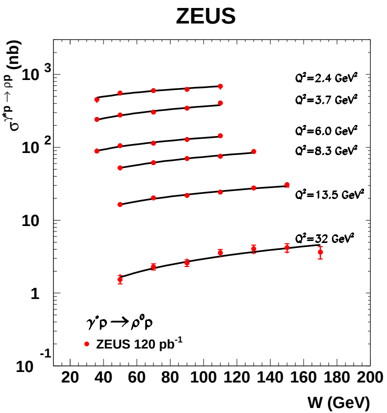


- **fit:** $\sigma \sim W^{\delta}$
- **process becomes hard as scale (mass) becomes larger,** $(M_{J/\Psi}/M_{\Phi})^2 \sim 10$ **!**

Elastic Electroproduction $\gamma^* p \to \rho(\phi) p$

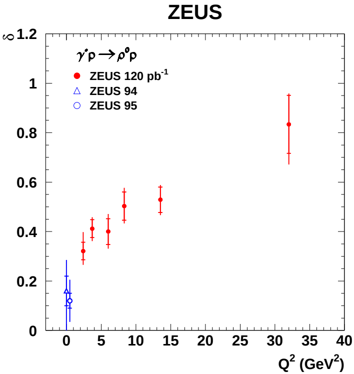


- **cross section W dependence becomes steeper at high Q^2, measured by H1 for ρ and Φ mesons**



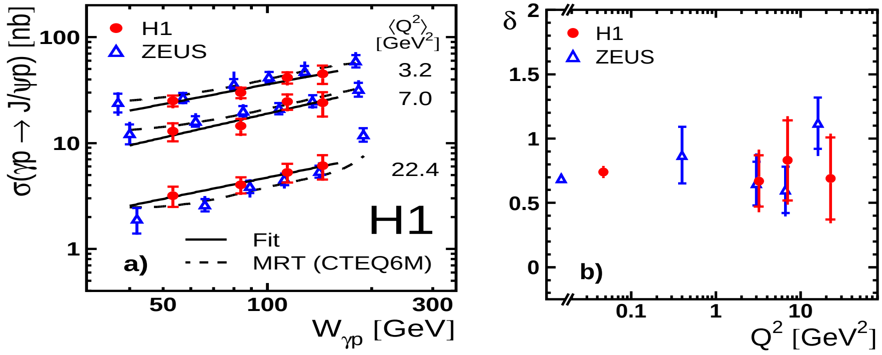
- **fit: $\sigma \sim W^\delta$**
- **Cross section W dependence becomes steeper at high Q^2**

Elastic Electroproduction $\gamma^* p \to \rho p$



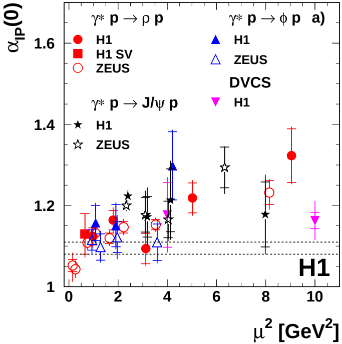
- $\sigma \sim W^{\delta}$
- **Soft physics predicts for energy dependence $\delta \sim$ 0.2**

Elastic Electroproduction $\gamma^* p \rightarrow J/\Psi p$



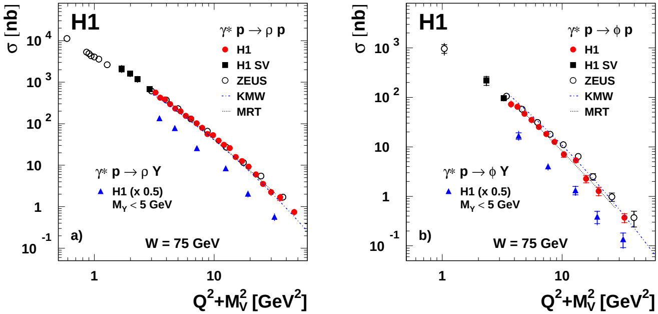
- **cross section for J/Ψ production as a function of** $W, \sigma \sim W^{\delta}$
- $\delta(Q^2 = 0, M^2_{J/\Psi} \simeq 10GeV^2) \sim 0.8$

Elastic Electroproduction: $\sigma \sim W^{\delta(Q^2)}$



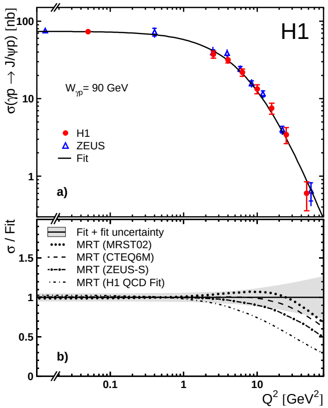
- **process becomes hard as scale ($\mu^2 = (Q^2 + M^2)/4$) becomes larger**

Q^2 dependence: $\gamma^* p \to \rho(\phi) p$



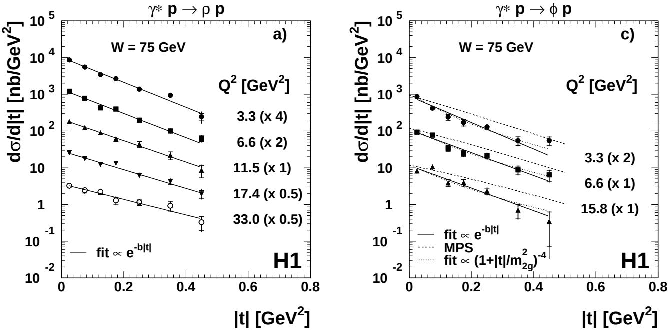
- **H1/ZEUS: perfect agreement**
- **fit:** $\sigma \propto (Q^2 + M^2)^{-n} \Longrightarrow \sigma_L \propto \frac{\alpha_S^2(Q)}{Q^6} |xG(x, Q^2)|^2$
- $Q^2 \geq$**0 GeV^2, n $\simeq$ 2.00 $\pm$ 0.01, χ^2/ndf $\sim$ 10**
- $Q^2 \geq$**10 GeV^2, n $\simeq$ 2.5$\pm$0.02, χ^2/ndf $\sim$ 1.5**

Q^2 dependence: $\gamma^* p \to J/\Psi p$



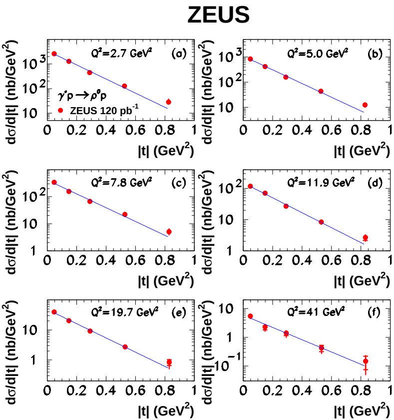
- **H1/ZEUS: perfect agreement**
- $\sigma \propto (Q^2 + M^2)^{-n}$
- $Q^2 \geq$**0 GeV^2, n=2.486$\pm$0.08$\pm$0.068**

t dependence



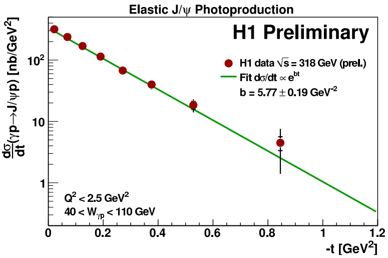
- $d\sigma/d|t| \sim exp(-b|t|)$ **for different bins of** Q^2

t dependence



- $d\sigma/d|t| \sim exp(-b|t|)$ **for different bins of** Q^2

Elastic J/Ψ photoproduction



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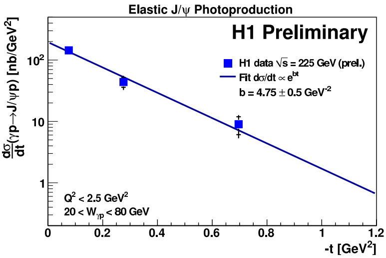
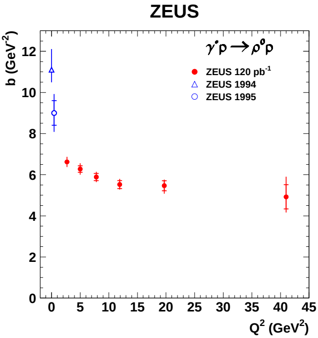
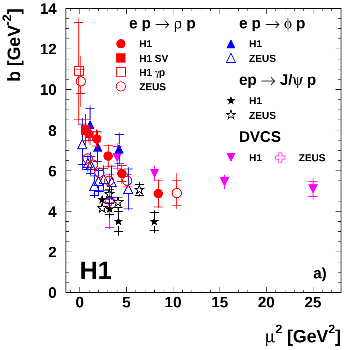


- H1 data:
- $\sqrt{s} = 318$ GeV $\longrightarrow b = 5.77 \pm 0.19$ Gev^2
- $\sqrt{s} = 225$ GeV $\longrightarrow b = 4.75 \pm 0.50$ Gev^2

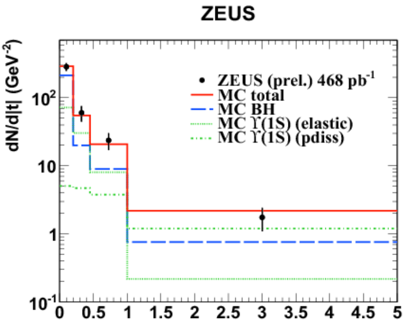
b slope





- **Value of *b* decreases from soft ($\sim$ 10 GeV^{-2}) to hard ($\sim$ 4-5 GeV^{-2})**

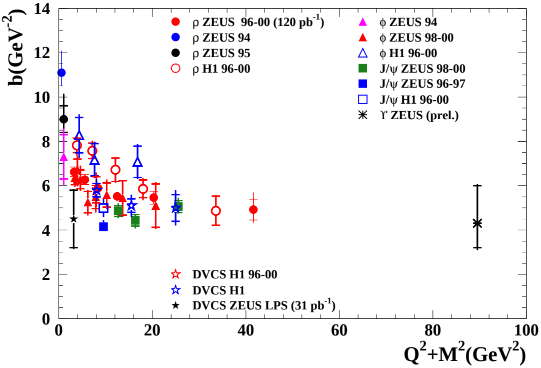
Υ meson - t dependence



$dN/d|t|$ distribution
for events in the mass range (9.33-9.66) GeV:

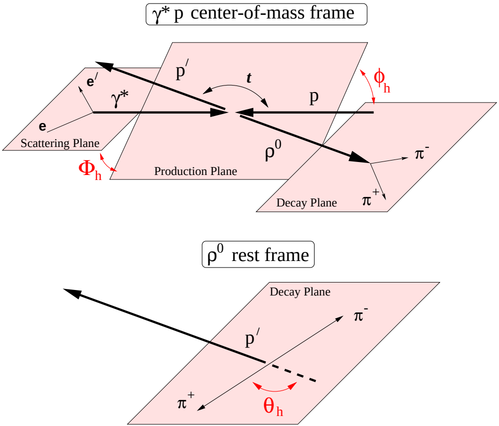
- $\Upsilon(1S)$ signal and BH background normalisation fixed from mass fit
- $\Upsilon(1S)$ signal splited between elastic and pdiss (75:25) (syst.)
- $\Upsilon(1S)$ slope b_{pdiss} = 0.65 GeV^{-2} (syst.)
- BH shape is treated as well known (syst.)
- binned maximum log-likelihood fit to extract the elastic b slope parameter

ϒ meson - t dependence



- measurement of the t-slope b for $\Upsilon(1S)$ meson doubles the scale $Q^2 + M^2$ explored by previous studies
- $\Upsilon(1S)$ elastic PHP: $b = 4.3^{+1.7}_{-1.1} \pm 0.5\ \text{GeV}^{-2}$

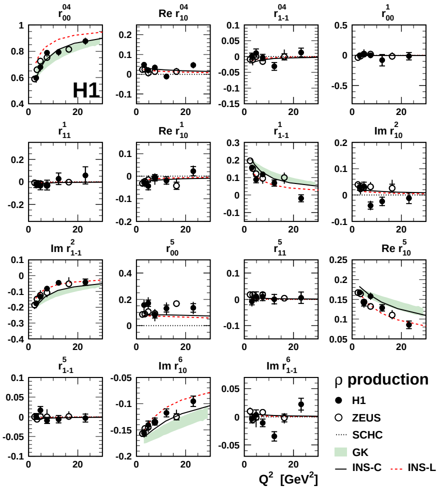
Helicity Studies



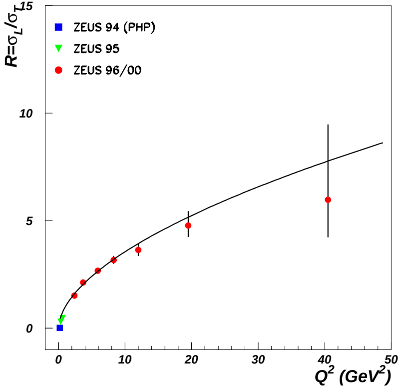
Angular distribution $\Longrightarrow$ 3 angles (θ_h, ϕ_h and Φ_h) and 15 combinations of spin-density matrix elements r_{ij}^{kl} $\Longrightarrow$ helicity amplitudes $T_{\lambda_V \lambda_\gamma}$

- **s-channel helicity conservation (SCHC)**
  - $\gamma^*_T \to \rho_T$
  - $\gamma^*_L \to \rho_L$
  - **single flip, double flip amplitudes equal zero**
- **natural parity exchange $(P = (-1)^J)$ in the t-channel (NPE)**
- **5 non-zero spin-density matrix elements**
- **15 parameters fit to total angular distribution**
- $r^5_{00} \sim$ **single-flip amplitude,** $\gamma^*_T \to \rho_L$
- r^5_{00} **deviates from zero !**
- $r^5_{00} = 0.095 \pm 0.019 \pm 0.024$ **(ZEUS) and**
  $r^5_{00} = 0.093 \pm 0.024^{+0.19}_{-0.10}$ **(H1)**
- **if SCHC holds** $\to R = \sigma_L/\sigma_T = r^{04}_{00}/\epsilon(1 - r^{04}_{00})$
- **if not:** $r^{04}_{00} \to r^{04}_{00} - \Delta^2$, $\Delta \propto r^5_{00}/\sqrt{2r^{04}_{00}}$
- **R(SCHC) - R(SCHNC) $\sim$ 3 %**

Helicity Studies: Q^2-dependence

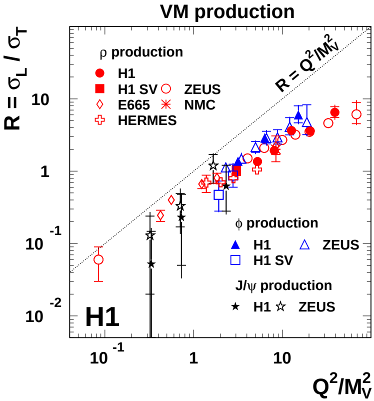


Helicity Studies: σ_L/σ_T



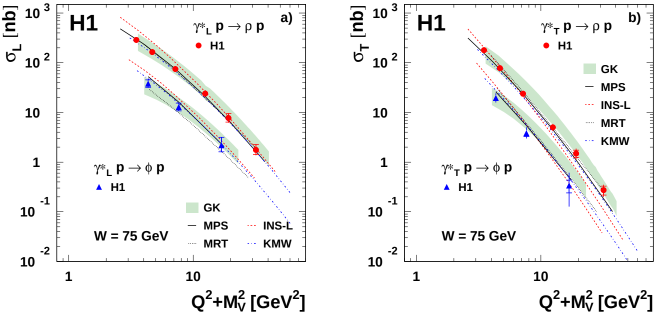
- $R = \sigma_L/\sigma_T = r^{04}_{00}/\epsilon(1 - r^{04}_{00}), \quad \epsilon \simeq 1$
- **Q^2=40 GeV^2** $\Longrightarrow \quad \sigma_L/\sigma_{tot} \sim$ **85%**
- **fit to ZEUS only :** $R = \sigma_L/\sigma_T = \xi(Q^2/M^2)^\kappa$
- $\xi = 0.74 \pm 0.04$ **and** $\kappa = 0.56 \pm 0.03$

Helicity Studies: σ_L/σ_T



- σ_L/σ_T **for** ρ, ϕ **and** J/Ψ **mesons**
- R **as a function of the scaling variable** Q^2/M^2

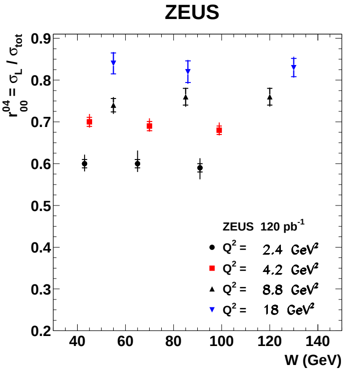
Helicity Studies: σ_L and σ_T

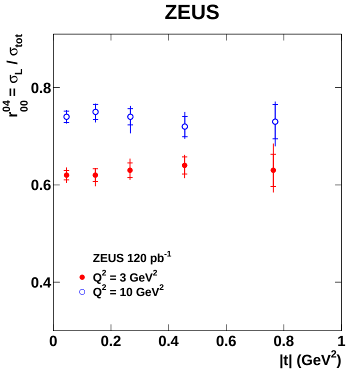


$$(Q^2 + M^2)^{-n}$$

- $\rho \Longrightarrow n_L = 2.17 \pm 0.09 \pm 0.07 \; n_T = 2.86 \pm 0.07^{+0.11}_{-0.12}$
- $\Phi \Longrightarrow n_L = 2.06 \pm 0.49 \pm 0.09 \; n_T = 2.97 \pm 0.52^{+0.14}_{-0.16}$

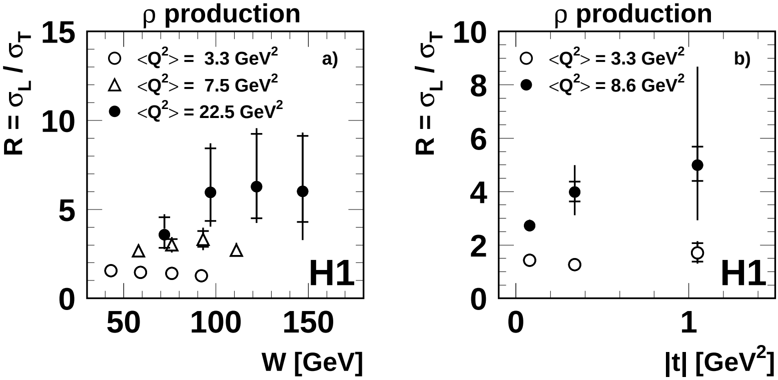
Helicity Studies: W dependence





- $r^{04}_{00} = \sigma_L / \sigma_{tot} \quad R = \sigma_L / \sigma_T = r^{04}_{00} / \epsilon (1 - r^{04}_{00}), \quad \epsilon \simeq 1$
- **σ_L and σ_T have the same W and $|t|$ dependencies**

Helicity Studies:

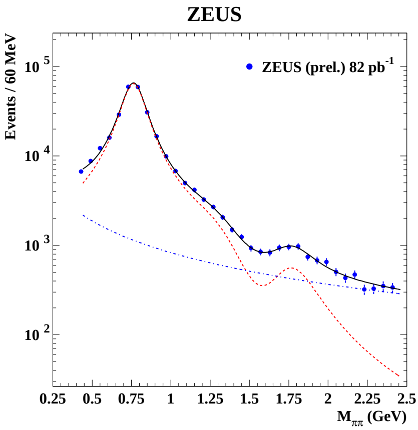


- $R = \sigma_L/\sigma_T \sim \exp(-(b_L - b_T)|t|)$
- **H1:** $b_L < b_T$

pion form factor

- $\gamma^* + p \to 2\pi + p \Longrightarrow 0.4 < M_{\pi\pi} < 2.5$ GeV
- $dN/dM_{\pi\pi} = A[|F_\pi(M_{\pi\pi})|^2 + B(M_\rho/M_{\pi\pi})^n]$
- $F_\pi(M_{\pi\pi})$ is the pion electro-magnetic form factor
- $F_\pi(M_{\pi\pi}) = \frac{BW(\rho)+\beta BW(\rho')+\gamma BW(\rho'')}{1+\beta+\gamma}$
- known as Kuhn-Santamaria parametrization
- $BW \longrightarrow$ Breit Wigner amplitude
- $BW(M_V) = \frac{M_V^2}{M_{\pi\pi}^2 - M_V^2 - \imath M_V \Gamma_V}$
- β and γ are relative amplitudes

Main fit: 3 vector resonances - ρ, ρ' and ρ''



- red line $\longrightarrow$ $|F_\pi(M_{\pi\pi})|^2$, squared pion form factor
- blue line $\longrightarrow$ background
- black line $\longrightarrow$ total fit

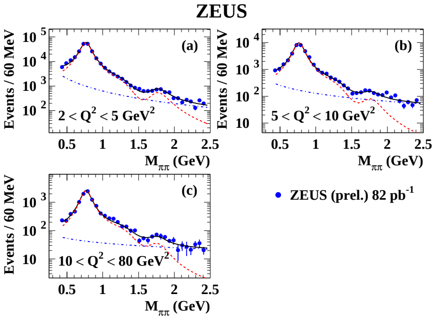
ZEUS (prel) vs PDG

Par.	ZEUS(prel)	PDG
M_ρ	$771 \pm 2^{+2}_{-1}$	775.49±0.34
Γ_ρ	$155 \pm 5 \pm 2$	149.4±1
$M_{\rho'}$	$1360 \pm 20^{+20}_{-30}$	1465±25
$\Gamma_{\rho'}$	$460 \pm 30^{+40}_{-45}$	400±60
β	$-0.27 \pm 0.02 \pm 0.02$	
$M_{\rho''}$	$1770 \pm 20^{+15}_{-20}$	1720±20
$\Gamma_{\rho''}$	$310 \pm 30^{+25}_{-35}$	250±100
γ	$0.10 \pm 0.02^{+0.02}_{-0.01}$	

Table 1: Fit parameters obtained using $F_\pi(M_{\pi\pi})$ parametrization. Masses and widths are in MeV.

- sign of amplitudes $\longrightarrow (+ - +)$ like $e^+e^- \to \pi^+\pi^-$
- a destructive interference in range $\sim$ 1.6 GeV

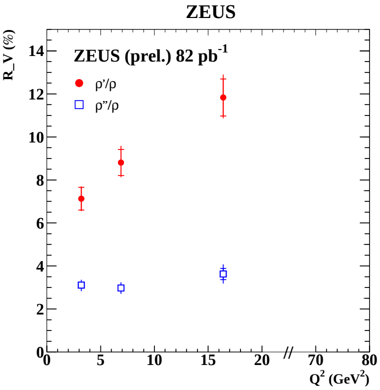
The Q^2 dependence



Results of the mass fit for different ranges of Q^2:
$a) \, 2 \div 5; b) \, 5 \div 10$ and c) $10 \div 80$ GeV^2.
Masses and widths are fixed to values given in Table 1.

- $|\beta|$ increases with Q^2 while $\gamma \to Q^2$ independent

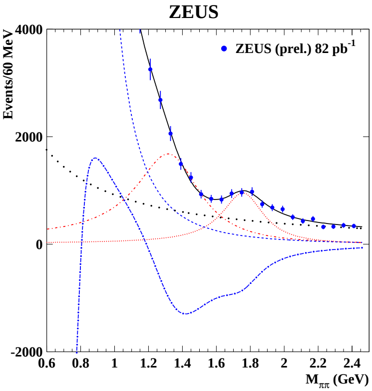
$\rho'/\rho \quad \rho''/\rho$ as function of Q^2



- Q^2 bins: $2 \div 5$; $5 \div 10$; $10 \div 80$ GeV^2
- the ratio ρ'/ρ means $\sigma(\rho') \cdot Br(\rho' \to \pi\pi)/\sigma(\rho)$
- ρ'/ρ increases with Q^2 while ρ''/ρ - constant

H1, ZEUS based on HERA data show:

- **Vector Meson production cross sections rise with energy if a hard scale, Q^2 or M^2, is present.**
- **The exponential slope of the t distribution decreases with $Q^2 + M^2$ and levels off at $b \sim$ 4-5 GeV^{-2}**
- **The ratio, σ_L/σ_T, increases with Q^2, but is independent of W**
- **Two pion mass distribution, $0.4 < M_{\pi\pi} < 2.5$ GeV, is well described by the pion electromagnetic form factor which includes three resonances, ρ, ρ' and ρ''**
- **$\rho'/\rho \rightarrow$ increases with Q^2 while $\rho''/\rho \rightarrow Q^2$ independent**


ZEUS
ZEUS (prel.) 82 pb^{-1}
Events/60 MeV
4000
2000
0
-2000
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
$M_{\pi\pi}$ (GeV)