Parallel Session P3
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Light Vector Meson Production at HERA

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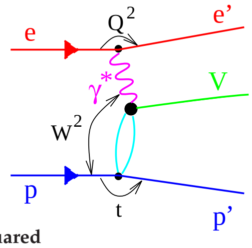
(For the ZEUS and H1 Collaborations)

Outline:

1. Introduction and Motivation
2. Photoproduction ($Q^2 \sim 0$) of ρ and ϕ
3. Tagged Electroproduction at Small Q^2
4. Deep Inelastic Electroproduction at Large Q^2
5. Conclusions

Vector Meson Production

Processes and Variables



- $V^0 = (\rho^0, \omega, \phi, \rho', J/\psi, \psi', ...)$
- $q^2 = -Q^2$ is the γ^* 4-momentum transfer squared
- $W = \gamma^* p$ center of mass (CM) energy: $W^2 = (q+P)^2$
- $-t \approx p_T^2 = (px_{elec} + px_V)^2 + (py_{elec} + py_V)^2$ at the proton vertex, unless measured directly with a proton spectrometer

Data with e^+ at 27.5 GeV and p at 820 GeV (in pb^{-1}):

Year:	1994	1995	1995 (SV)	1995 (44 m)	1996-7 (44 m)
H1:	2.8	3.9	0.125		
ZEUS:	2.7	6	——	2.7	18

Measurements

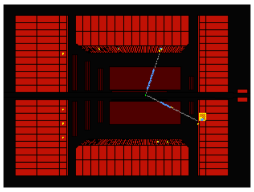
- Reconstruction of charged particles is performed using central tracking detectors
- No extra energy in the main detector (other than 2 tracks or e′)
- Scattered e′ (not) observed in different detectors (Q^2 dependent)

Reactions

- 'Elastic' production $\gamma^* p \to V^0 p$ and proton dissociation $\gamma^* p \to V^0 N$
- where γ^* is a photon with virtuality Q^2

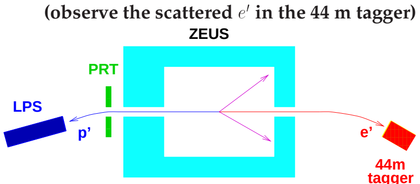
(i) Untagged photoproduction: $Q^2 \approx 0$ (median $Q^2 \sim 10^{-4}$ GeV^2)

(do not observe the scattered e' $10^{-10} < Q^2 < 4$ GeV^2)



(ii) Tagged photoproduction: $Q^2 \sim 10^{-2}$ GeV^2 at large $|t|$

(observe the scattered e' in the 44 m tagger)

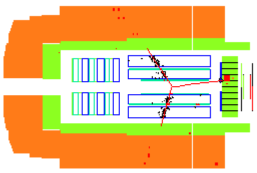


(iii) Tagged electroproduction: $0.25 < Q^2 < 0.85$ GeV^2

(observe the scattered e' in the BPC)

(iv) Deep inelastic electroproduction: $1 < Q^2 < 40$ GeV^2

(observe the scattered e' in the main detector)



Vector Meson Production

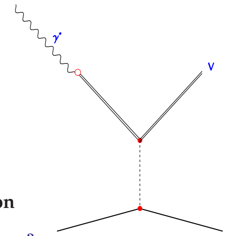
Scales

- Three possible variables: $Q^2,\ M^2,\ t \quad (W^2?)$
- SOFT ie small $|t| < 0.6$ GeV^2, small $Q^2 \sim 0$, small mass:
  1. $\gamma p \to (\rho,\ \omega,\ \phi)p$
- HARD ie small $Q^2 \sim 0$, small (or large) mass, large t:
  2. $\gamma p \to (\rho,\ \phi,\ J/\psi)p$
- HARD ie small $Q^2 \sim 0$, small t, high $M^2_{J/\psi}$ scale:
  3. $\gamma p \to (J/\psi,\ \psi', ..)p \quad (\rho' p??)$
- HARD ie small t, small (or large) mass, high Q^2, ($3 < Q^2 < 40$ GeV^2):
  4. $\gamma^* p \to (\rho,\ \phi,\ J/\psi)p$

Why study exclusive vector meson production at HERA?

- It is a diffractive process at high W, and high scales, and involves the 'elastic' dissociation of a highly virtual particle (the photon);
- It could provide information on the nature of the (soft/hard?) $\mathbb{P}$;
- In the absence of a measurement of $F_L^{diffraction}$, the longitudinal diffractive structure function, it can yield information on $R = \sigma_L/\sigma_T$ for diffractive processes;
- One of the few calculable exclusive processes for pQCD;
- Can study the transition between nonperturbative and pQCD.

Theoretical Overview



Vector Dominance Model

- Photon fluctuates into VM
- Predicts $1/Q^4$ dependence of cross section

$$\sigma(Q^2) = \sigma(0)\left(\frac{m_\rho^2}{m_\rho^2 + Q^2}\right)^2 \left(1 + \epsilon\xi^2 \frac{Q^2}{m_\rho^2}\right)$$

- Describes Q^2 dependence at low Q^2

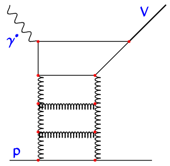
Donnachie and Landshoff

- Regge theory - Soft $\mathbb{P}$omeron intercept $\alpha_{\mathbb{P}}(0) = 1 + \epsilon$, ϵ = 0.0808

$$\sigma_{\mathrm{elastic}}(W) \propto \frac{\sigma^2_{\mathrm{TOT}}(W)}{b(W)} \propto \frac{W^{4\epsilon}}{b(W)} \approx \frac{W^{0.32}}{b(W)} \sim W^{0.2}$$

$$b(W) = b(W_0) + 4\alpha' \ln(\frac{W}{W_0})$$

- $1/Q^6$ dependence



Other Recent QCD inspired models

Nemchik et al., Brodsky et al., Ryskin, Martin et al.,....

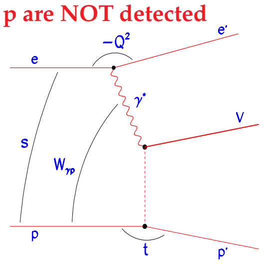
- Describe $\mathbb{P}$omeron in terms of 2-gluon exchange
- VM produced dominantly by longitudinally polarised γ
- $\sigma_L \propto [xg(x,Q^2)]^2 \sim W^{\approx 1}$
- $1/Q^6$ dependence of σ_L, but modified by $\alpha_s(Q^2) \cdot xg(x,Q^2)$

Untagged photoproduction - elastic ρ at $Q^2 \approx 0$

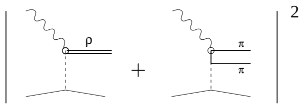
The scattered e^+ and p are NOT detected

Kinematic range:

- $Q^2 \sim 10^{-4}$ GeV^2
- $|t| < 0.5$ GeV^2
- $50 < W_{\gamma p} < 100$ GeV



The skewed mass distribution can be understood in terms of an interference between resonant ρ and non-resonant $\pi\pi$ production:

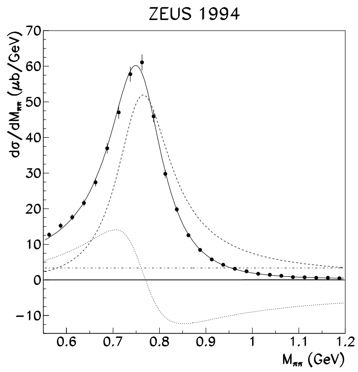


Söding parameterization:

$$\frac{d\sigma}{dM_{\pi\pi}} = \left|A\frac{\sqrt{M_{\pi\pi}M_\rho\Gamma_\rho}}{M^2_{\pi\pi} - M^2_\rho + iM_\rho\Gamma_\rho} + B\right|^2$$

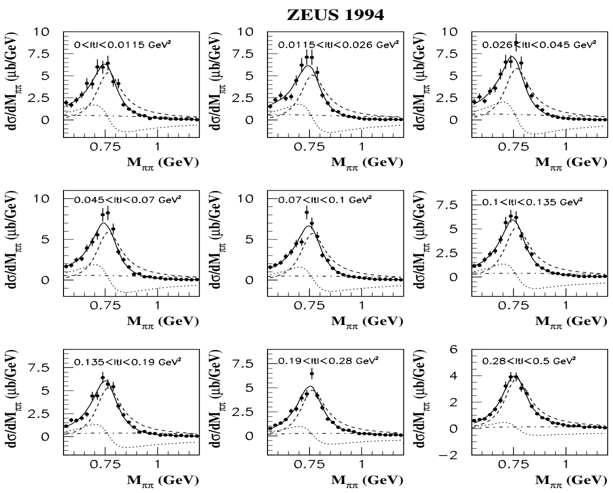
B = non-resonant amplitude

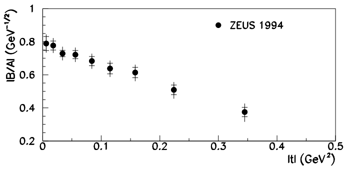
= constant

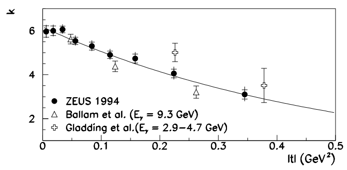


M_ρ = 770 $\pm$ 2 MeV
Γ_ρ = 146 $\pm$ 3 MeV
contribution from non-res. amplitude $|B/A|$ depends on $|t|$ expected by Söding model

Untagged photoproduction - elastic ρ at $Q^2 \approx 0$







Söding parameterization:

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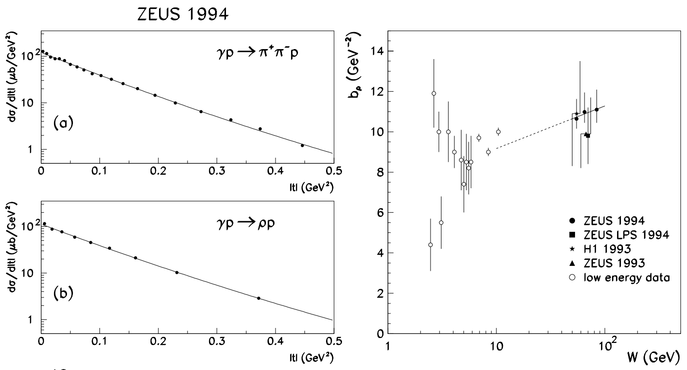
B = non-resonant amplitude

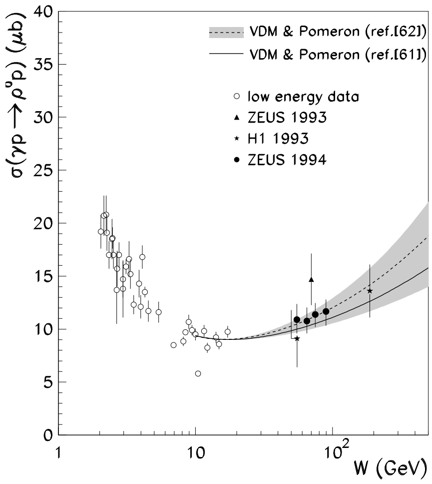
= constant

Ross-Stodolsky parametrization:

$$\frac{d\sigma}{dM_{\pi\pi}} = f_\rho BW_\rho(M_{\pi\pi})\left(\frac{M_\rho}{M_{\pi\pi}}\right)^k$$

Untagged photoproduction - elastic ρ at $Q^2 \approx 0$





Fit to $e^{(bt+ct^2)}$:

$b = 10.9 \pm 0.3^{+1.0}_{-0.5}$ GeV^{-2}
$c = 2.7 \pm 0.9^{+1.9}_{-1.7}$ GeV^{-4}

Fit to ZEUS data only:

$$b = b_0 + 2\alpha'_{\mathbb{P}} \ln W^2$$

$$\alpha'_{\mathbb{P}} = 0.23 \pm 0.15^{+0.10}_{-0.07}\ \mathrm{GeV}^{-2}$$

$$\sigma \sim W^\kappa$$

$$\kappa = 0.16 \pm 0.06^{+0.11}_{-0.15}$$

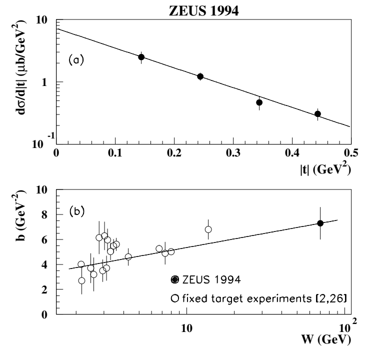
Consistent with soft pomeron

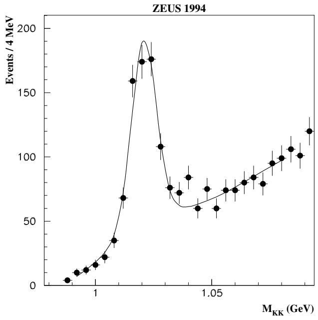
Untagged photoproduction - elastic ϕ at $Q^2 \approx 0$

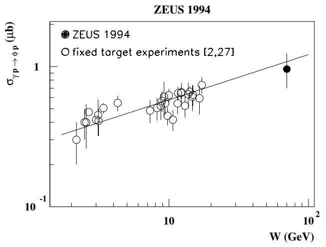
The scattered e^+ and p are NOT detected

Kinematic range:

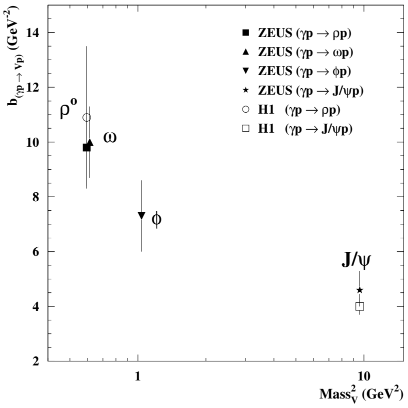
- $Q^2 \sim 10^{-4}$ GeV^2
- $|t| < 0.5$ GeV^2
- $40 < W < 100$ GeV







$b_\phi = 7.3 \pm 1.0 \pm 0.8$ **GeV**$^{-2}$



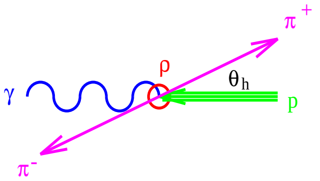
Untagged photoproduction - elastic ρ, ω, ϕ at $Q^2 \approx 0$

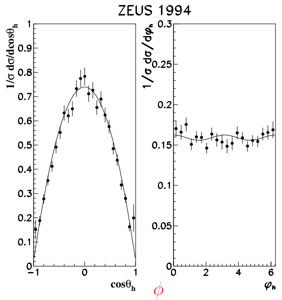
Helicity Decay Distributions

- Measure VM spin state from s-channel helicity distribution $\mathrm{H}(\cos\theta_{\mathrm{h}}, \phi_{\mathrm{h}}) =$

$$\frac{3}{8\pi}[(1 - \mathrm{r}^{04}_{00} + (3\mathrm{r}^{04}_{00} - 1)\cos^2\theta_{\mathrm{h}}) - 2\sqrt{2}\mathrm{Re}[\mathrm{r}^{04}_{10}]\sin 2\theta_{\mathrm{h}}\cos\phi_{\mathrm{h}} - 2\mathrm{r}^{04}_{1-1}\sin^2\theta_{\mathrm{h}}\cos 2\phi_{\mathrm{h}}]$$

- r^{04}_{00} represents the probability that the produced ρ^o has helicity 0; if SCHC holds: r^{04}_{1-1} = 0, Re r^{04}_{10} = 0 and r^{04}_{00} should be small (transverse photons).





ρ ω ϕ

$\mathrm{r}^{04}_{00} = 0.01 \pm 0.01 \pm 0.02 \quad 0.11 \pm 0.08 \pm 0.26 \quad -0.01 \pm 0.04$ (ZEUS)

$\mathrm{r}^{04}_{00} = -0.11 \pm 0.11 \pm 0.04$ (H1)

$\mathrm{r}^{04}_{1-1} = -0.01 \pm 0.01 \pm 0.01 \quad -0.04 \pm 0.08 \pm 0.12 \quad 0.03 \pm 0.05$ (ZEUS)

$\mathrm{Re}[\mathrm{r}^{04}_{10}] = 0.01 \pm 0.01 \pm 0.01$ (ZEUS)

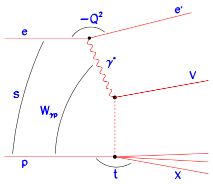
- indicating that the VM mesons are mostly transversely polarized with helicity $\pm$ 1 and that SCHC holds.

Tagged photoproduction at large $|t|$

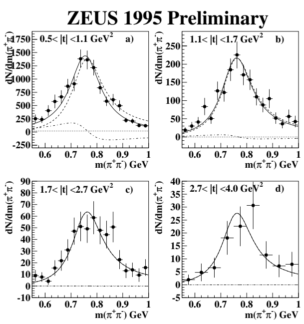
The scattered e^+ is detected in the ZEUS 44 m tagger

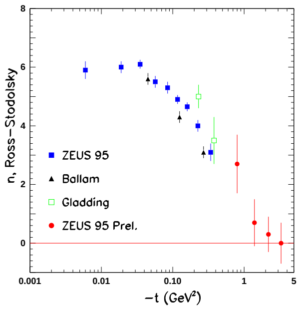
Kinematic range (1995):

- $Q^2 < 10^{-2}$ GeV^2
- $85 < W < 105$ GeV



Cross sections include elastic and proton dissociation:





Conclusions:

- values of $|B/A| \to 0$ and $n \to 0$ as $|t|$ increases
- non-resonant term and skewing are disappearing at large $|t|$

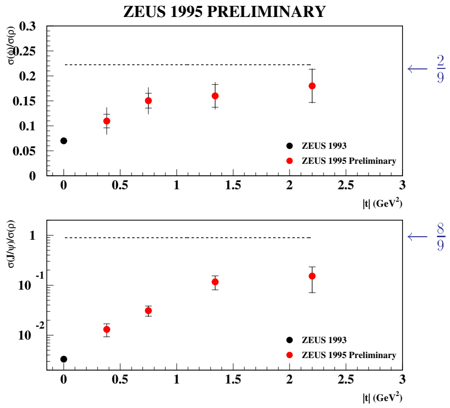
Tagged photoproduction at large $|t|$

The scattered e^+ is detected in the ZEUS 44 m tagger

Kinematic range (1995):

- $Q^2 < 10^{-2}$ GeV^2
- $85 < W < 105$ GeV

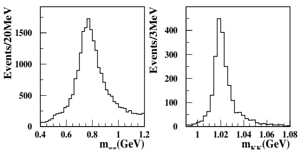
Measurement of the cross section for ρ, ϕ (and J/Ψ) production at different $|t|$. At high $|t|$, it is mostly $\gamma p \to VX$, rather than Vp.



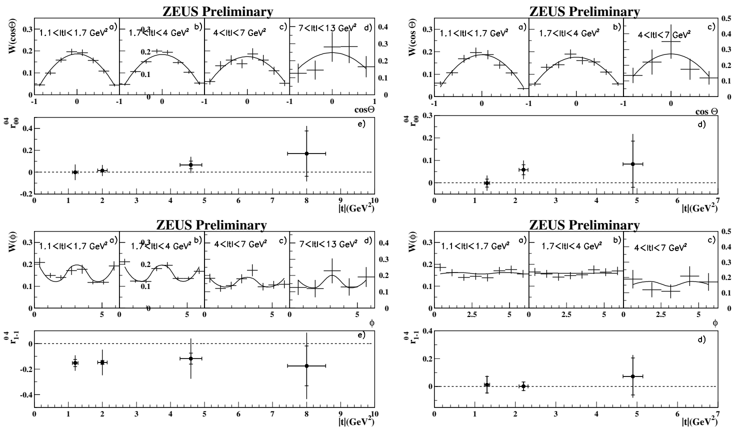
- Restoration of SU(3) symmetry (?)
- Evidence for $|t|$ entering as a hard scale in the process

Tagged photoproduction at large $|t|$

Kinematic range (1996-7):



- $\mathrm{Q^2} < 10^{-2}$ GeV^2
- $80 < \mathrm{W} < 120$ GeV



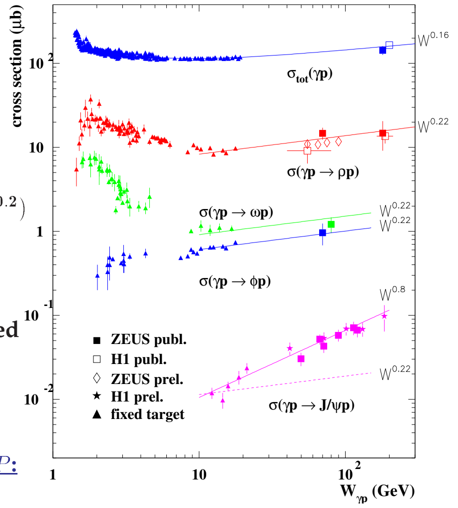
$\mathrm{W(\cos\theta_h)} = \frac{3}{4}[1 - \mathrm{r^{04}_{00}} + (3\mathrm{r^{04}_{00}} - 1)\cos^2\theta_h]$, $\mathrm{W(\phi_h)} = \frac{1}{2\pi}[1 - 2\mathrm{r^{04}_{1-1}}\cos 2\phi_h]$

Conclusions:

- dominant $\sin^2\theta_h$ behavior indicates that VMs have helicity ± 1
- at large $|t|$, there is a deviation from $r^{04}_{1-1} = 0$ expected by SCHC
- suggesting an interference between helicity non-flip and double-flip amplitudes in ρ production

Untagged photoproduction - elastic $\rho, \omega, \phi, J/\psi$ at $Q^2 \approx 0$

Summary: For



- $\gamma p \to \rho p$
- $\gamma p \to \omega p$
- $\gamma p \to \phi p$

Consistent with soft $I\!P$:

- σ rises slowly ($\sim$ W$^{0.2}$)
- b large ($\sim$ 10 GeV^{-2})
- b shrinks with W (?)
- transversely polarized

But for:

- $\gamma p \to J/\psi p$

INconsistent with soft $I\!P$:

- σ rises fast ($\sim$ W$^{0.8}$)
- b small ($\sim$ 4 GeV^{-2}) and no shrinkage (??)
- polarization consistent with SCHC

And for: $\gamma p \to$ VN at large $|t|$:

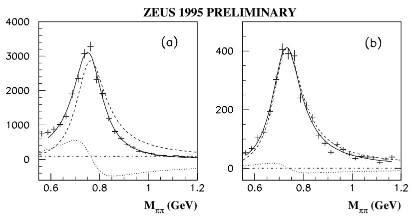
- SU(4) restored in $R(\phi/\rho)$?
- non-resonant contribution $\to 0$ with increasing $|t|$
- large $|t|$ provides a hard pQCD scale?

Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

Mass Shape

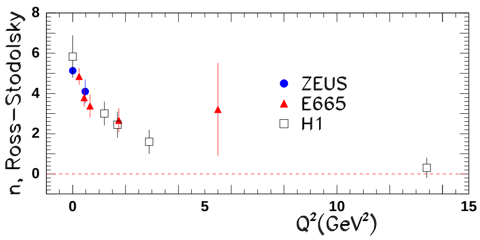
Kinematic range (BPC):

- $0.25 < \mathrm{Q^2} < 0.85$ GeV^2
- $|\mathrm{t}| < 0.5$ GeV^2
- $20 < \mathrm{W} < 90$ GeV



Kinematic range (ZEUS):

- $5 < \mathrm{Q^2} < 30$ GeV^2
- $|\mathrm{t}| < 0.5$ GeV^2
- $34 < \mathrm{W} < 144$ GeV



- As Q^2 increases, the non-resonant term and mass skewing are disappearing, as is seen for large $|t|$

Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

Mass Shape

Kinematic range (H1):

- $1 < \mathrm{Q^2} < 5$ GeV^2
- $|\mathrm{t}| < 0.5$ GeV^2
- $40 < \mathrm{W} < 140$ GeV

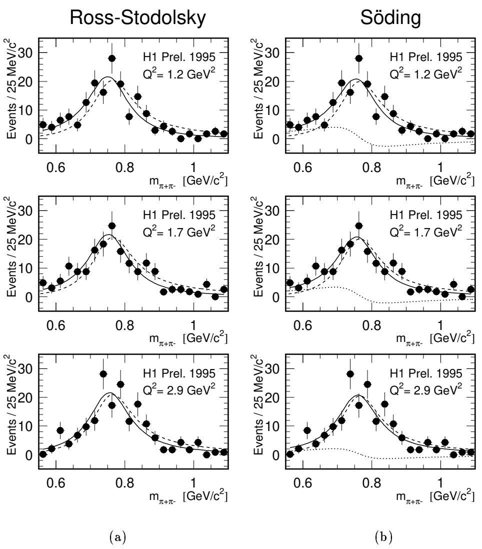
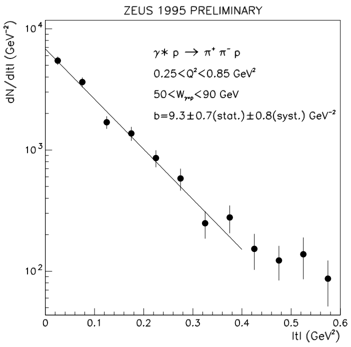
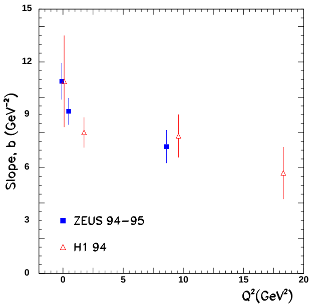


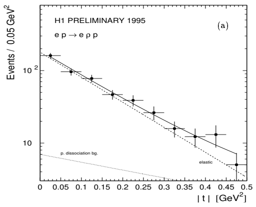
Figure 4: Acceptance corrected $m_{\pi^+\pi^-}$ mass distribution for the final event sample in three Q^2 bins (low Q^2 at the top, high Q^2 at the bottom) using a) the Ross-Stodolsky parameterisation of eq. (3); b) the Söding parameterisation of eq. (7). The solid line is the result of the fit, the dashed line corresponds to a non-skewed Breit-Wigner contribution. For the Söding parameterisation, the dotted line corresponds to the interference between the resonant and the non-resonant amplitude.

Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

t dependence







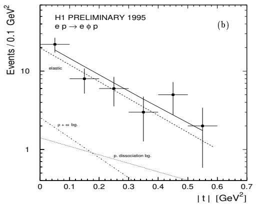
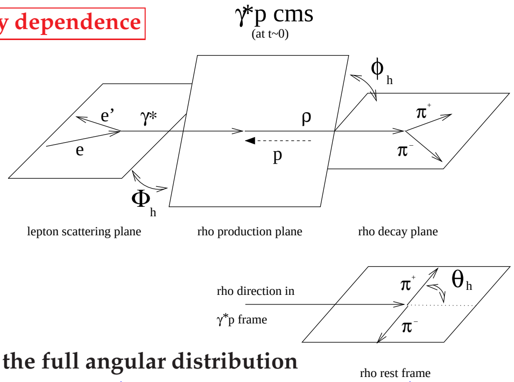


Figure 7: Acceptance corrected t distribution a) for ρ; b) for ϕ meson production. The full line corresponds to the global fit as a sum of three exponentials, corresponding to the elastic resonant signal, the proton dissociation background and the non-resonant background. The dashed line corresponds to the elastic signal alone, the dotted line to the proton dissociation background, and, in the ϕ case, the dashed dotted line corresponds to the non-ϕ background under the ϕ signal.

b decreases with Q^2
Shrinkage ?
Need data at fixed Q^2 as a function of W

Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

Helicity dependence



In DIS, the full angular distribution

($\cos\theta_h, \phi_h, \Phi_h$ or $\Psi_h \equiv \phi_h - \Phi_h$)

is measurable.

Analyze the distributions in terms of the ρ spin density matrix.

The simplest assumption: s-channel helicity conservation and natural parity exchange in the t-channel

$$W(\cos\theta_h, \Psi) = \frac{1}{1+\epsilon R}\frac{3}{8\pi}\{\sin^2\theta_h(1+\epsilon R\cos 2\Psi) + 2\epsilon R\cos\theta_h - \sqrt{2\epsilon(1+\epsilon)R}\cos\delta\sin 2\theta_h\cos\Psi$$

$$\textbf{with } R = \frac{1}{\epsilon}\cdot\frac{r^{04}_{00}}{1-r^{04}_{00}} = \frac{\sigma_L}{\sigma_T}$$

δ: phase between two helicity amplitudes:

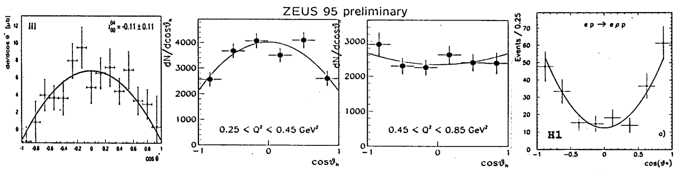
$$T_{1\frac{1}{2}1\frac{1}{2}}T^*_{0\frac{1}{2}0\frac{1}{2}} = |T_{1\frac{1}{2}1\frac{1}{2}}|\cdot|T_{0\frac{1}{2}0\frac{1}{2}}|e^{-i\delta}.$$

Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

Helicity dependence

Distributions in $\cos\theta_h$:

$Q^2 = 0$ $\quad$ $0.25 < Q^2 < 0.85$ **GeV^2** $\quad$ $Q^2 > 8$ **GeV^2**



$< W >$ [GeV]	$< Q^2 >$ [GeV^2]	r^{04}_{00}	$\cos\delta$	Expt.
50	0.33	0.23 ± 0.03		ZEUS
50	0.58	0.32 ± 0.03		ZEUS
100	1.75	0.51 ± 0.04	0.88 ± 0.07	H1
80	5.9	0.76 ± 0.02	$0.92^{+0.06}_{-0.09}$	ZEUS
80	8.3	0.73 ± 0.04	$0.99^{+0.05}_{-0.07}$	ZEUS
81	13.4	0.73 ± 0.05		H1
80	14.1	$0.80^{+0.05}_{-0.03}$	$0.81^{+0.10}_{-0.14}$	ZEUS

Other matrix elements, e.g.: r^1_{1-1} from $W(\psi) = \frac{1}{2\pi}(1 + 2\epsilon r^1_{1-1}cos2\psi)$
if SCHC and natural parity exchange: $r^1_{1-1} = 1/2(1 - r^{04}_{00})$

$< W >$ [GeV]	$< Q^2 >$ [GeV^2]	measured r^1_{1-1}	r^1_{1-1} from r^{04}_{00}
50	0.33	0.36 ± 0.02	0.38 ± 0.01
50	0.58	0.33 ± 0.04	0.34 ± 0.01
80	5.9	0.09 ± 0.04	0.12 ± 0.02
80	8.3	0.13 ± 0.04	0.13 ± 0.02
80	14.1	0.08 ± 0.05	0.10 ± 0.02

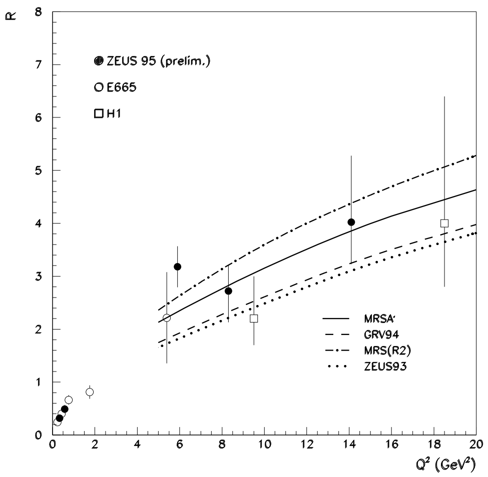
In general, the angular distributions are consistent with SCHC and natural parity exchange **(for $|t| < 0.6$ GeV^2).**

Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

Q^2 dependence of R

- **For SCHC:**

$$\mathrm{R} = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon}\cdot\frac{r^{04}_{00}}{1-r^{04}_{00}}$$

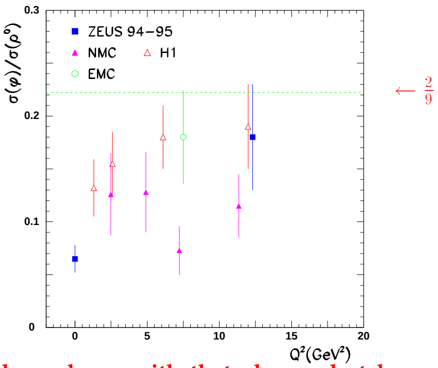


- **Curves are from Martin et al.**

Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

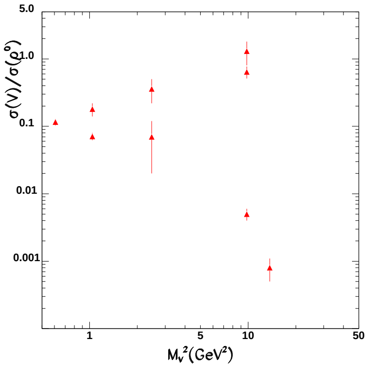
Ratio of $\sigma(\phi)/\sigma(\rho)$

- **versus Q^2**



- **Compare this dependence with that observed at large $|t|$ in photoproduction.**

- **versus M_V^2**



Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

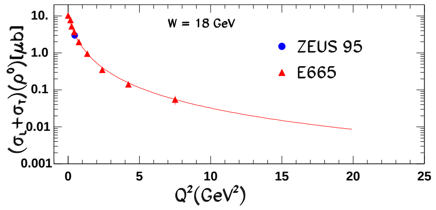
Q^2 dependence

$$\frac{d^2\sigma^{ep}}{dydQ^2} = \Gamma_T(y, Q^2)(\sigma_T^{\gamma p} + \epsilon\sigma_L^{\gamma p})$$

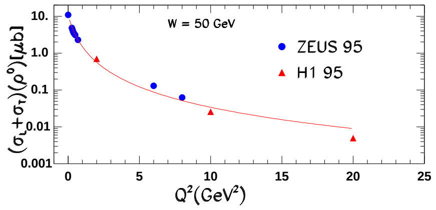
where the flux of transverse photons is $\Gamma_T = \frac{\alpha}{2\pi}\cdot\frac{1+(1-y)^2}{yQ^2}$, and $\epsilon = \frac{\Gamma_L}{\Gamma_T} = \frac{2(1-y)}{(1+(1-y)^2}$ is the ratio of longitudinal to transverse photon fluxes. Usually $\sigma(\gamma^* p \to \rho p) = \sigma_T^{\gamma p} + \epsilon\sigma_L^{\gamma p}$ is measured by experiments. But we will consider the quantity

$$\sigma = \sigma_T + \sigma_L = \frac{1+R}{1+\epsilon R}\cdot\sigma(\gamma^* p \to \rho p) = (1 - r_{00}^{04} + \frac{r_{00}^{04}}{\epsilon})\sigma(\gamma^* p \to \rho p)$$

where SCHC is assumed.

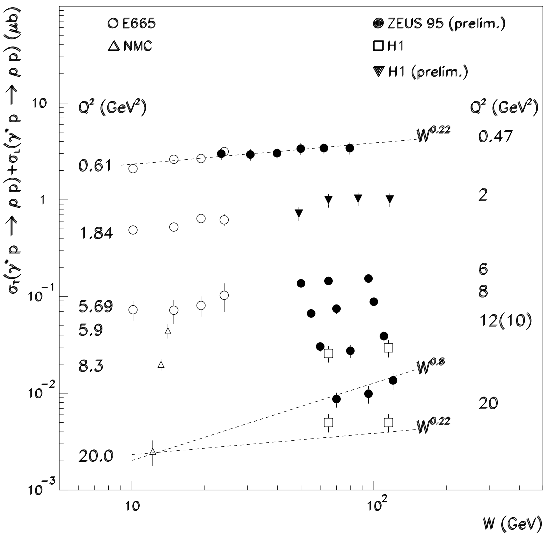


- **The Q^2 dependence is well described by $\sigma(Q^2) = \sigma(0)\cdot(1+\frac{Q^2}{m_\rho^2})^{-n}$ (with n=2).**



Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

W and Q^2 dependence



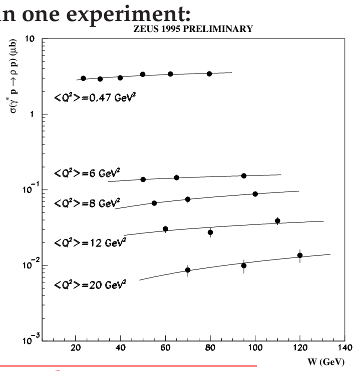
- ***W* dependence depends upon a comparison with different experiments**

Tagged and Deep Inelastic Electroproduction - ρ at high Q^2

W dependence

Considerable normalisation uncertainties in fixed target measurements $\Rightarrow$ need to fit within one experiment:

Fit: $\sigma(\gamma^* p \to \rho p) \propto W^\kappa$:

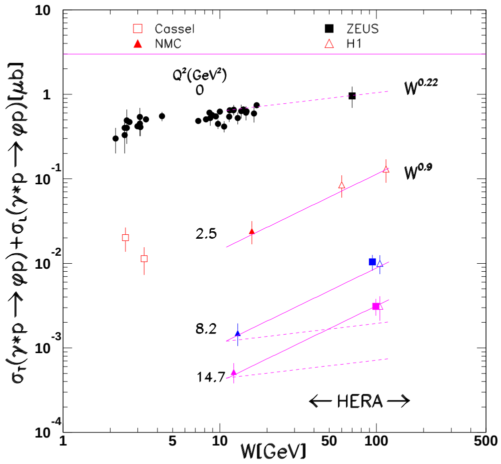


$< Q^2 >, GeV^2$	κ
0	$0.16 \pm 0.06^{+0.11}_{-0.15}$
0.47 (BPC)	$0.18 \pm 0.05 \pm 0.13$
6	$0.18 \pm 0.16 \pm 0.05$
8	$0.47 \pm 0.16 \pm 0.09$
12	$0.38 \pm 0.21 \pm 0.13$
20	$0.77 \pm 0.19 \pm 0.19$

- **indication for Q^2 dependence of κ**
- **explained in pQCD by the increase of the gluon density with Q^2 at fixed x**

Tagged and Deep Inelastic Electroproduction - ϕ at high Q^2

W and Q^2 dependence



- W **dependence seems to be stronger for** $Q^2 > 2$ **GeV**^{2} **(?)**
- **But depends upon a comparison with different experiments**

Results

- **Clear** $\rho, \phi, \omega, J/\Psi$ **signals observed in photoproduction at HERA**
- **Clear** $\rho, \phi, J/\psi$ **signals observed in electroproduction at HERA**
- **The weak rise of the cross section with** $W_{\gamma p}$ **for** $\gamma p \to \rho p, \omega, \phi p$ **is consistent with the soft $\mathbb{P}$omeron prediction**
- **The strong rise of** σ **with** $W_{\gamma p}$ **for** $\gamma p \to (J/\psi)p$ **and** $\gamma^* p \to \rho p, \phi p, J/\psi p$ **is inconsistent with the soft $\mathbb{P}$omeron prediction but is consistent with 2-gluon exchange calculations**
- **The ratios of the** V^0 **to** ρ **cross sections have been measured at HERA for** $Q^2 = 0$ **and at** $< Q^2 > \sim 12$ **GeV**^{2} **and increase with** Q^2

Conclusions for Exclusive Vector Meson Production

- **When there is only a SOFT scale (**$Q^2 \sim 0$**, small** M^2**, small** t**), we observe a weak rise in the cross section with** $W_{\gamma p}$**, consistent with the soft $\mathbb{P}$omeron.**
- **When there is at least one HARD scale (**Q^2 **or** M^2**), we observe a strong rise with** $W_{\gamma p}$**, inconsistent with the soft $\mathbb{P}$omeron**

Open questions

- **What about when** t **is the HARD scale and small** Q^2, M^2**?**
- **How small is small and how large is large scale?**
  ie. $\gamma^* p \to \rho p$ **for** $0.25 < Q^2 < 0.85$ **GeV**^{2} **is still soft?**
- **Still more to do to study the transition between soft and hard VM production**