Recent Results on Exclusive Production of Vector Mesons at HERA

Heiko Beier, DESY

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2. Measurement of VMs at HERA
3. Photoproduction of ρ and J/Ψ
4. ρ^0 Production at low and high Q^2
5. Other VMs at high Q^2
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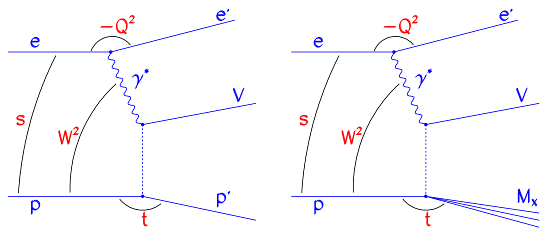
Introduction

Production of Vector Mesons in ep reaction:



$$V = \rho, \phi, \omega, \rho', J/\Psi, \Psi', \ldots$$

Motivation: Study nature of diffractive process

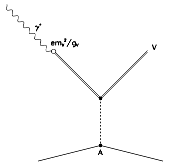
- Interplay of soft and hard physics
- Test pQCD calculations
- Sensitivity to parton distributions in proton

HERA is a unique tool $\leftrightarrow$ large coverage of Q^2 and W region

$Q^2 = 10^{-10} - 30\ \text{GeV}^2$ (virtuality of photon)
$W = 20 - 200\ \text{GeV}$ ($\gamma^* p$ c.m.s energy)
$|t| = 0 - 5\ \text{GeV}^2$ (squared mom. transfer at p vertex)

Theoretical Status

Regge theory (exchange of soft $\mathbb{P}$ trajectory
$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} \cdot t = 1.0808 + 0.25t$;
DL parameterization)

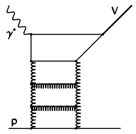


and Vector Meson Dominance

give good description of hadronic interactions and low energy γp measurements (...but remain phenomenologic)

Aim: Understand diffraction in language of QCD

$\Rightarrow$ perturbative QCD; need hard scale $(Q^2, m_V, t, \ldots ?)$



Different models
Common feature:
Pomeron $\leftrightarrow$
system of gluons

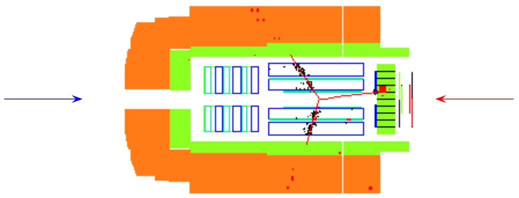
Predictions:

- strong W-dependence; $\sigma(W) \propto \left[xg(x,Q^2)\right]^2$
- Q^2 and W dependence of $R = \sigma_L/\sigma_T$

General Event Selection

- Reconstruction of charged particles by tracking
- No energy in calorimeter (not due to tracks or e')
- Scattered e in different parts of detector (Q^2 dependent)

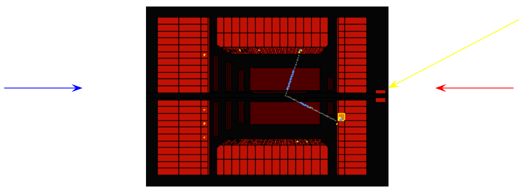
Large Q^2: e in main detector



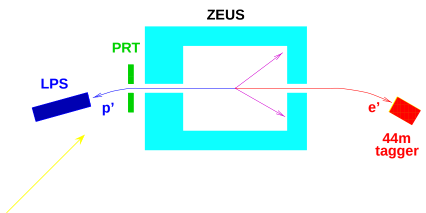
intermediate Q^2: e in special detectors

(e.g.: ZEUS-BPC, measuring at small e' scattering angles)

$Q^2 \approx 0$ (photoproduction): e untagged



or tagged downstream



Additional components in forward direction for detection of outgoing proton

- FPS/LPS (H1/ZEUS) for measurement of proton momentum
- Taggers for detection of dissociated proton system (PRT, forward muon chambers)

Diffractive VM production in γp

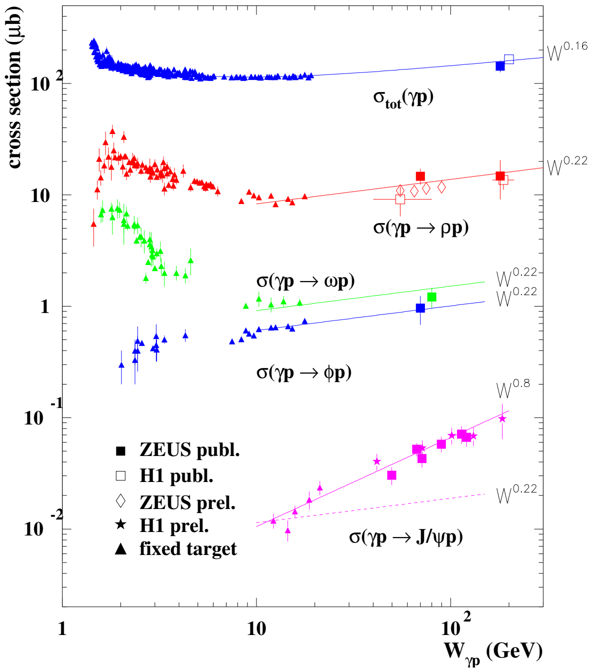
What do we expect ?

1. Weak energy dependence of cross section $\sigma \simeq W^{0.22}$ at HERA
2. Shrinkage of the forward peak $\frac{d\sigma}{dt} \propto \exp -b|t|$ with $b = b_0 + 2\alpha'_{\mathrm{IP}} \ln W^2$
3. s-channel helicity conservation (SCHC)

What do we measure ?

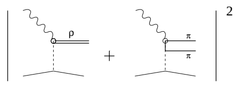
1. .... $\longrightarrow$
2. .... $\longrightarrow$
3. broad evidence for SCHC at low t in all experiments $\surd$

1. Cross Section in γp

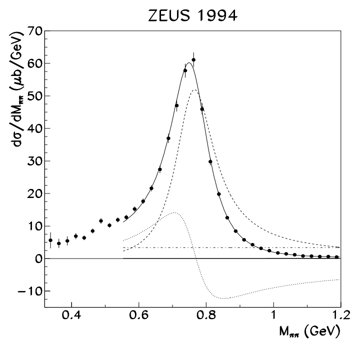


ρ^0: high statistics sample (ZEUS 94 Preliminary)

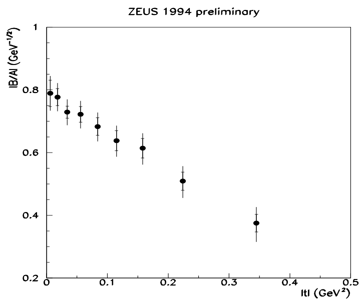
Determination of cross section complicated by contribution from non-resonant $\pi\pi$ amplitude
Estimated from Söding model $\rightarrow$ interference pattern



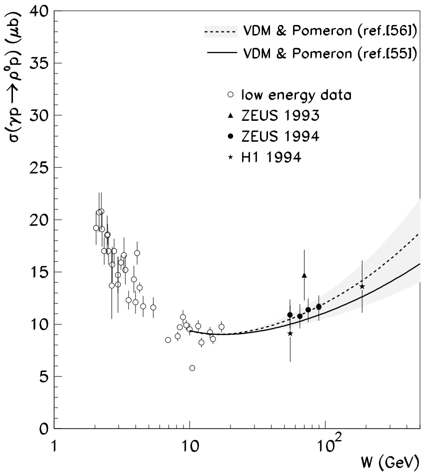
$$d\sigma/dM_{\pi\pi} = \left| A \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + iM_\rho\Gamma_\rho} + B \right|^2$$



$M_\rho = 770 \pm\ 0.2$ MeV
$\Gamma_\rho = 146 \pm\ 0.3$ MeV
contribution from non-res. amplitude $|B/A|$ depends on $|t|$ expected by Söding model



Cross Section



Weak energy dependence, compatible with soft $\mathbb{P}$ exchange

Extraction of $\alpha_{\mathbb{P}}(0)$ limited by lever arm in W

Fit to ZEUS 94 prel.: rise of cross section $\sigma \propto W^{\epsilon}$ gives

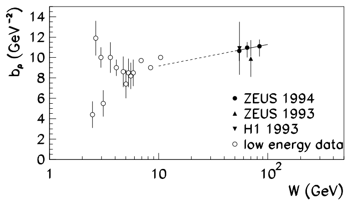
$$\epsilon = 0.16 \pm 0.06^{+0.11}_{-0.14}$$

(for soft $\mathbb{P}$ $\epsilon \simeq 0.22$)

2. t dependence of cross section

ZEUS 94 prel.: W dependence of slope of $d\sigma/dt$ at small t

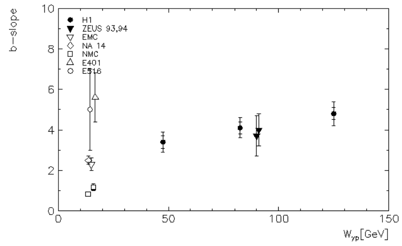
$$b = b_0 + 2\alpha'_{\mathbb{P}} \ln W^2$$



$$\alpha' = 0.23 \pm 0.15^{+0.10}_{-0.07} \text{ (ZEUS94 prel. only)}$$

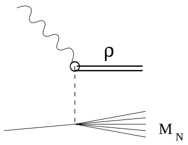
Large error, hard to measure shrinkage within one experiment

Compatible numbers for ϕ, ω (fitted to fixed target data)



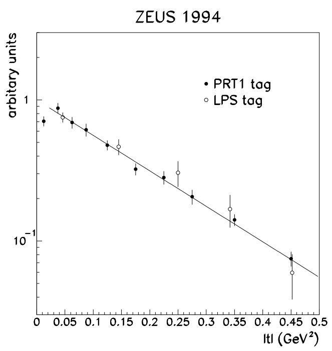
J/Ψ: fit H1 only $\rightarrow \alpha' = 0.36 \pm 0.21$ (94+95 prel.)

ρ with proton dissociation



Tag by either

LPS: $x_L = p_z^{out}/p^{in} < 0.98$ or
PRT: require coincident MIP signal
} good agreement



$b_{PRT} = 5.8 \pm 0.3 \pm 0.5$

$b_{LPS} = 5.7 \pm 0.6 \pm 0.9$

(b in GeV^{-2})

$50 < W < 100$ GeV

ZEUS 94 prel.

$|t| < 0.5$ GeV^2

$M_N^2 < 0.1 W^2$

$$b(\gamma p \rightarrow \rho p) - b(\gamma p \rightarrow \rho N) \simeq 5$$

Cross section ratio:

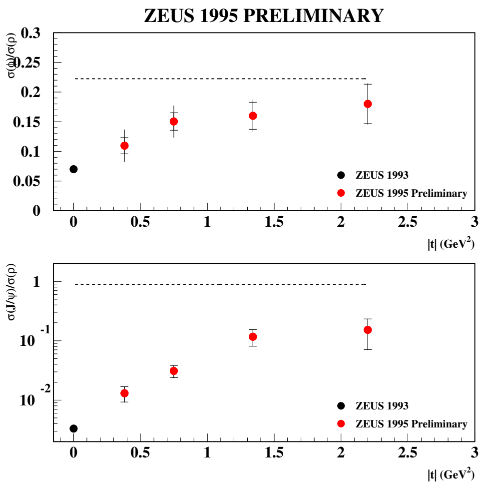
$$\sigma(\gamma p \rightarrow \rho p)/\sigma(\gamma p \rightarrow \rho N) = 2.0 \pm 0.2 \pm 0.7$$

(ZEUS 94 preliminary)

Photoproduction at large $|t|$

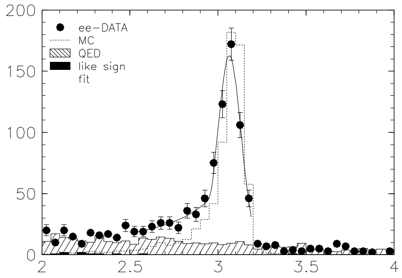
ZEUS: tag photons 44m behind IP
($70 < W < 120$ GeV, $Q^2 < 0.01$ GeV^2)

Measurement of cross section for ρ, ϕ and J/Ψ production at different values of $|t|$



Evidence for $|t|$ entering as a hard scale in the process

Heavier VM in php

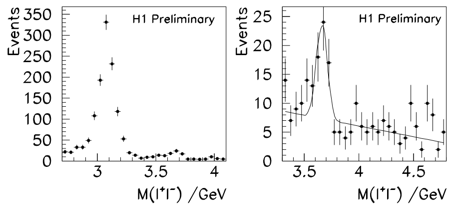


J/Ψ production in decay modes e^+e^- and $\mu^+\mu^-$ measured by ZEUS and H1

shown: H1 (ee)

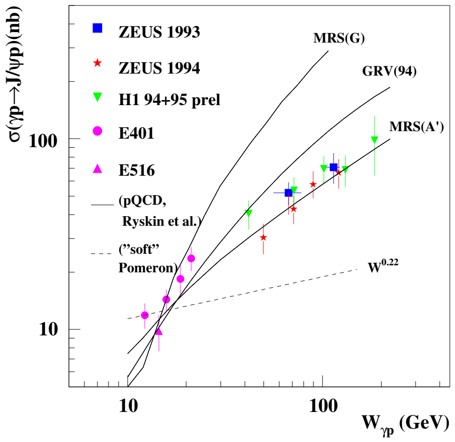
H1: first measurement of $\Psi'(\Psi(2S))$ production at HERA energies

2 prong modes: $\Psi' \to \mu^+\mu^-/e^+e^-(0.8\%)$



(also 4 prong decay $\Psi' \to J/\Psi\,\pi^+\pi^-$ measured)

pQCD description of elastic J/Ψ production



Energy dependence of $\sigma(\gamma p \to J/\Psi p)$ described by Ryskin model:

$$\sigma_{\gamma p} \propto (\bar{x}g(\bar{x},\bar{q}^2))^2 \text{ (LLA)}$$

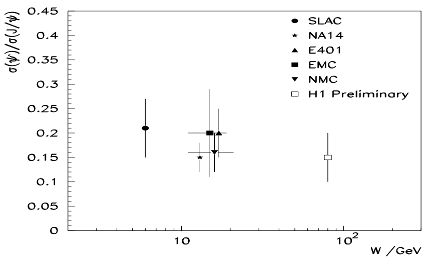
$\bar{x}$ = fraction of of proton's momentum carried by the gluon $\propto 1/W^2$

$\bar{q}^2 = (Q^2 + |t| + M^2_{J/\Psi})/4 \simeq M^2_{J/\Psi}/4 \simeq 2.5\,\mathrm{GeV}^2$

(scale of interaction)

Normalization uncertainty in model, but shape can help to discriminate between parameterizations of $xg(x)$

Cross Section for Ψ' production



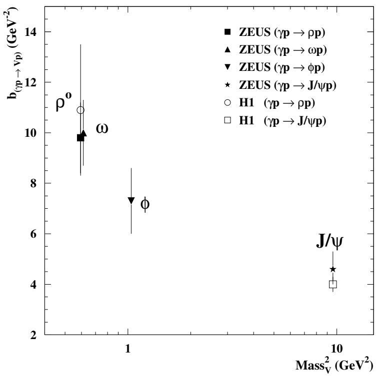
H1 Preliminary:

$\frac{\sigma(\Psi')}{\sigma(J/\Psi)} = 0.15 \pm 0.05$ (at $W = 80\,\mathrm{GeV}$)

(compatible with fixed target measurements)

$\sigma(\gamma p \to \Psi' X) = 18 \pm 4 \pm 4\,\mathrm{nb}$ (at $W = 80\,\mathrm{GeV}$)

(much larger than at low W)



t slope for J/Ψ production significantly smaller than for ρ

Slope decreases with M_V !

Summary: photoproduction of VM

- Production of light VM (ρ, ϕ, ω) well described by Regge theory (soft $\mathbb{P}$)
  - weak energy dependence of cross section
  - shrinkage of the forward peak (α' consistent with DL parameterization)
- For ρ significant contribution from non-resonant amplitude (Söding model)
- Evidence for $|t|$ providing a hard scale
- J/Ψ photoproduction exhibits a steep W dependence in the cross section
- First indication for similar energy dependence of even heavier VM (Ψ')

Vector Mesons at $Q^2 > 0$

1. ρ^0 at intermediate and high Q^2

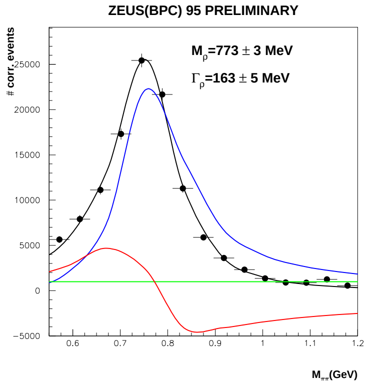
2. ϕ

3. J/Ψ

ρ^0 Mass Signals

With increasing Q^2 contribution

of non-resonant $\pi\pi$ amplitude decreases

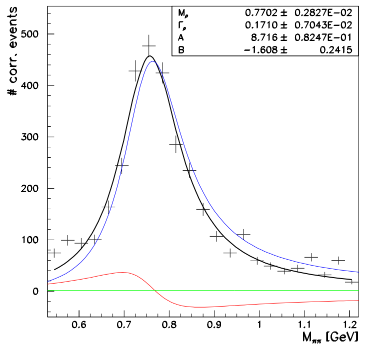


ZEUS BPC

(beam pipe calorimeter)

$0.25 < Q^2 < 0.85\ \mathrm{GeV}^2$

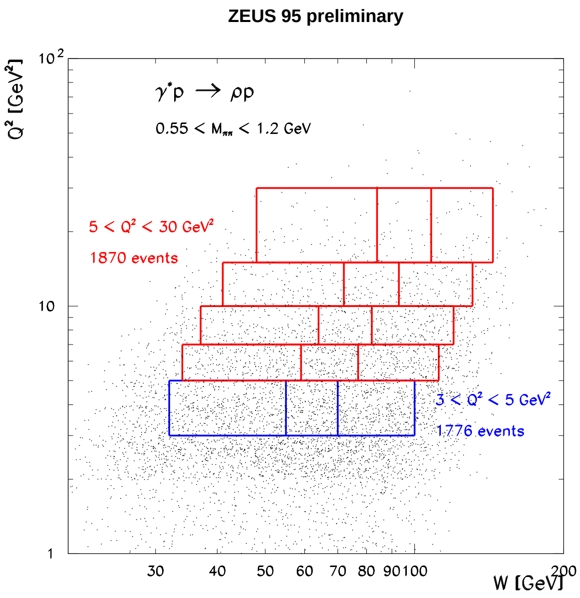
$\sim$ 6000 events



ZEUS 95 prel.

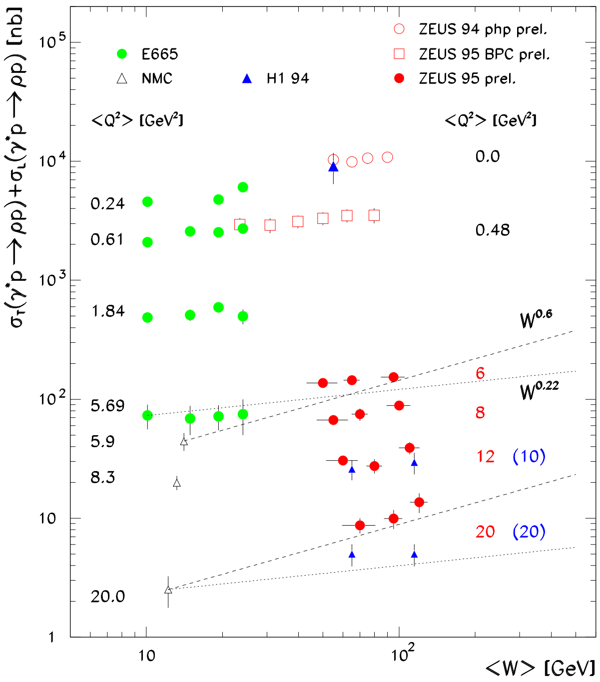
$5 < Q^2 < 30\ \mathrm{GeV}^2$

$\sim$ 1900 events



Factor 3 in statistics due to luminosity 94→95 and optimization of rear detector

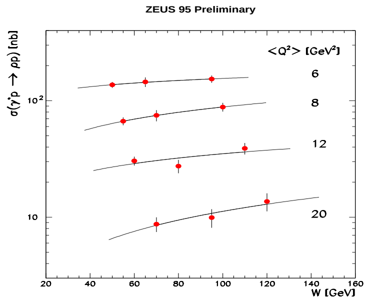
Overview: $\sigma(\gamma^* p \to \rho p)$



latest ZEUS high Q^2 still with 20% normalization uncertainty

W dependence of cross section

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



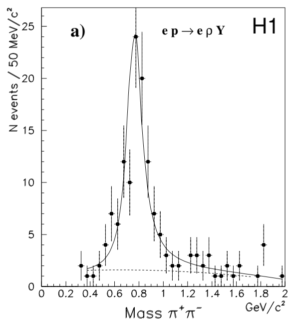
Fit: $\sigma(\gamma^* p \to \rho p) \propto W^{\epsilon}$

$< Q^2 >$ GeV^2	95 prel.
0.5 (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 ϵ
- explained in pQCD by increase of gluon density with Q^2 at fixed x

Proton Dissociation at high Q^2

Publication by H1: tag dissociated system with forward detectors ($2.5 < \eta < 7.5$)



$M_N^2 < 0.05 W^2$
$|t| < 0.8$ GeV^2

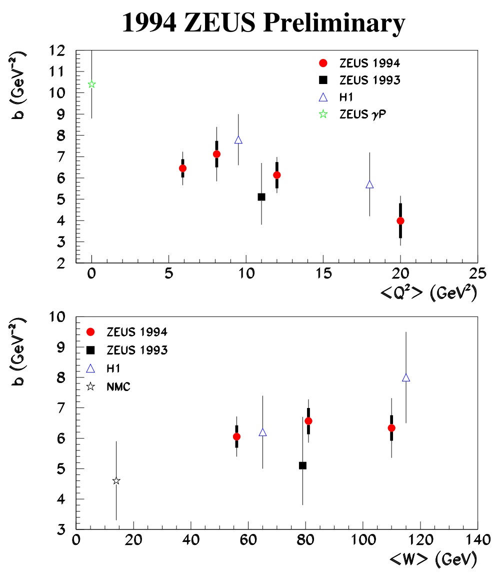
$$\frac{\sigma(ep \to e\rho Y)}{\sigma(ep \to e\rho p)} = 0.65 \pm 0.11(\text{stat.}) \pm 0.13(\text{syst.})$$

for $7 < Q^2 < 35$ GeV^2 and $60 < W < 180$ GeV
(compatible with ratio in photoproduction: $0.5 \pm 0.05 \pm 0.18$)
[at different M_N, $|t|$, W]

- Ratio indepent of W and Q^2
- Decay angular distributions compatible with elastic case

$\Rightarrow$ Indication for factorization of proton dissocation process

t dependence of cross section

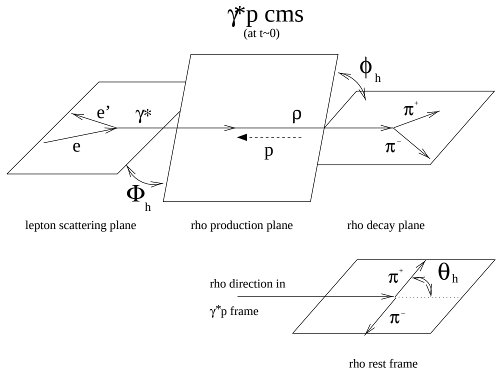


- b decreases with Q^2
- Shrinkage ? (large errors)

p dissociation: $b_{pdiss} = 2.1 \pm 0.5 \pm 0.5\text{GeV}^{-2}$
elastic: $b_{el} = 7.0 \pm 0.8 \pm 0.6\text{GeV}^{-2}$
} H1 94

(remember for php: $b_{pdiss} - b_{el} \simeq 5$)

Analysis of Angular Distributions



In DIS full angular distribution
($\cos\theta_h, \phi_h, \Phi_h$ or $\Psi_h \equiv \phi_h - \Phi_h$)
measurable.

Analyze distributions in terms of ρ spin density matrix.
Most simple assumption: s-channel helicity conservation and natural parity exchange in t-channel

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

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

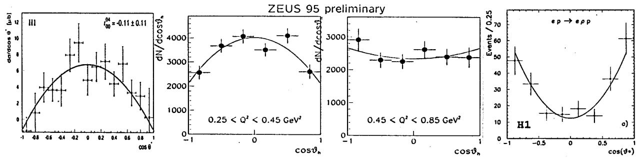
δ: phase between two helicity amplitudes:

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

r_{00}^{04}: probability for ρ being in helicity 0 state

Distributions in $\cos\theta_h$:

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



ZEUS 94 / 95-BPC prel.

$< W >$ [GeV]	$< Q^2 >$ [GeV^2]	r_{00}^{04}	$\cos\delta$
52	0.34	$0.24^{+0.02}_{-0.02}$	
52	0.62	$0.33^{+0.03}_{-0.03}$	
100	5.8	$0.71^{+0.03}_{-0.04}$	$0.92^{+0.06}_{-0.09}$
100	8.2	$0.76^{+0.04}_{-0.04}$	$0.99^{+0.05}_{-0.07}$
100	14.0	$0.79^{+0.04}_{-0.05}$	$0.81^{+0.10}_{-0.14}$

Other matrix elements, e.g.: r_{1-1}^{1}

if SCHC & nat. P exch.: $r_{1-1}^{1} = 1/2(1 - r_{00}^{04})$

$< W >$ [GeV]	$< Q^2 >$ [GeV^2]	measured r_{1-1}^{1}	r_{1-1}^{1} from r_{00}^{04}
52	0.34	0.36 ± 0.02	0.38 ± 0.01
52	0.62	0.32 ± 0.02	0.34 ± 0.01
100	5.8	0.13 ± 0.04	0.14 ± 0.02
100	8.2	0.11 ± 0.04	0.12 ± 0.02
100	14.0	0.11 ± 0.04	0.10 ± 0.02

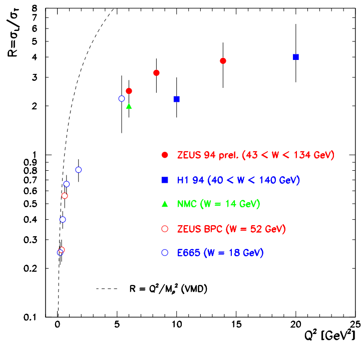
In general angular distributions consistent with SCHC & nat. P exchange.

(for $|t| < 0.6$ GeV^2)

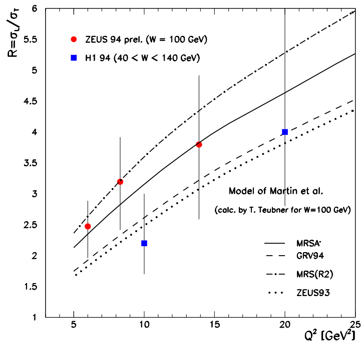
$R = \sigma_L/\sigma_T$

Given evidence for SCHC: calculate R from r_{00}^{04}

$$R = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

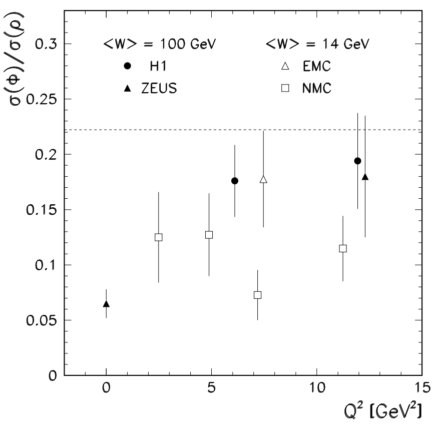


Q^2 dependence not described by VMD type parameterizations



but by pQCD model of Martin, Ryskin, Teubner

ϕ production at large Q^2

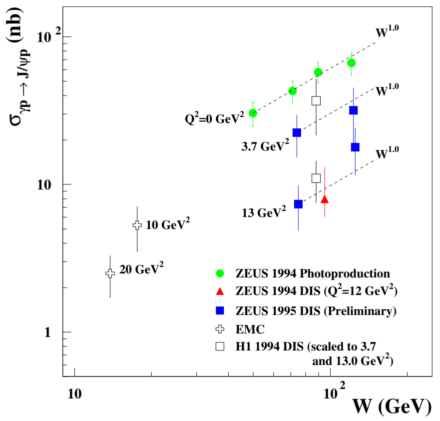


At large Q^2 the ratio $\sigma(\phi)/\sigma(\rho)$ approaches the value 2 : 9

Expected for SU(3) symmetry and flavor independent production mechanism

(compare: $\sigma(\phi)/\sigma(\rho)$ vs. $|t|$ in photoproduction)

J/Ψ production at large Q^2



- J/Ψ seems to show similar steepness in rise of cross section vs. W as in php
- Caution in comparing HERA results with other experiments.
  $\sigma_{\gamma^* p}$ might have been measured in different conditions (see ρ)

Conclusions

- numerous measurements of VM production at HERA (too many to cover everything)
- photoproduction of light VMs is in agreement with expectations from soft $\mathbb{P}$ exchange
- but HERA offers more variables: evidence for $|t|$ and M_V to quantitatively change the cross section behavior (hard scale)
- With gain in luminosity we begin to pin down W dependence at larger Q^2 for ρ production
- VM production is consistent with SCHC over a wide range in W and Q^2 and small $|t|$
- The process of proton dissociation is better understood with improvements in forward direction of detectors