What we can learn from vector meson production at HERA?

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on behalf of the ZEUS and H1 Collaborations

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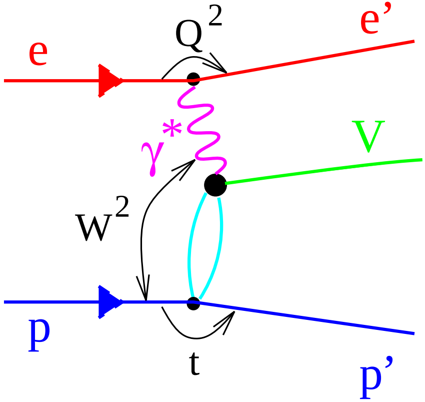
Outline

- **Introduction**
- **Elastic Photo and Electroproduction of Vector Mesons and Deeply Virtual Compton Scattering (DVCS)**
  - W**-dependence**
  - Q^2**-dependence**
  - **t-dependence**
  - **Helicity studies**
  - **Effective Pomeron trajectory**
- **Summary**

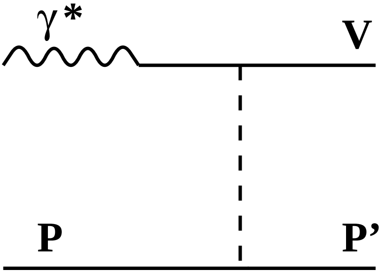
Vector meson production



$V = (\gamma, \rho^o, \omega, \phi, J/\psi, \Upsilon)$

- $Q^2 = -(e - e')^2$ 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)

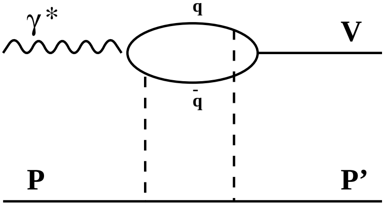
Predictions :

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

Experimental observations :

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

pQCD models (hard physics)

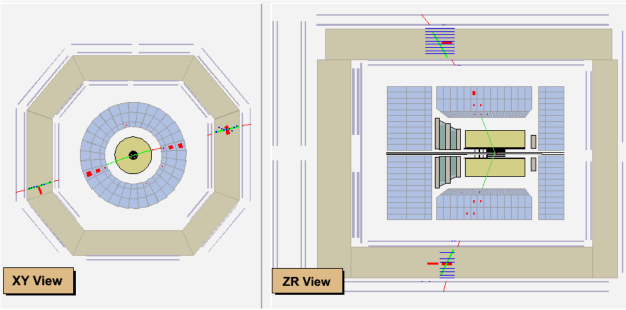


- the photon fluctuates into a $q\bar{q}$ state
- the $q\bar{q}$ pair scatters off the proton target
- the scattered $q\bar{q}$ pair turns into a vector meson.

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, $b \sim 4 - 5\,\mathrm{GeV}^{-2} \quad \Longrightarrow \quad \alpha' \to 0\,?$

VM production $\gamma p \rightarrow Vp$

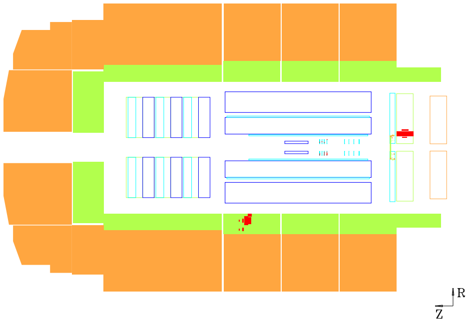


Kinematic range

$$Q^2 \rightarrow 0 \div 100\,\mathrm{GeV}^2$$
$$W \rightarrow 20 \div 300\,\mathrm{GeV}$$
$$|t| \rightarrow 0 \div 1\,\mathrm{GeV}^2$$

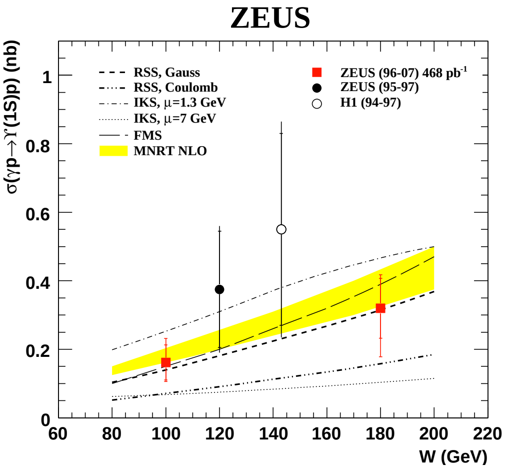
- Photoproduction: $Q^2 \approx 0$ (do not observe the scattered e)
- tracks reconstructed by tracking detector
- no energy deposits not associated with tracks or the positron

DVCS: $\gamma^* p \rightarrow \gamma p$



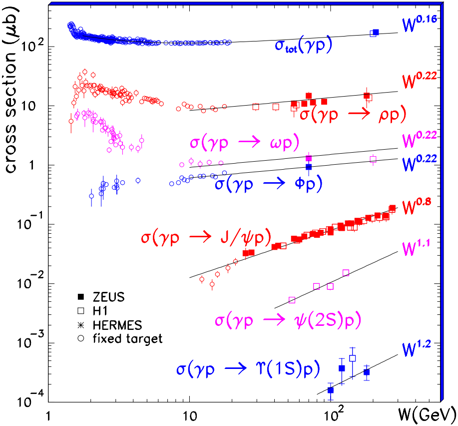
- **DVCS event display**
- **Electroproduction:** $Q^2 > 0$
  (observe the scattered e **in the main detector)**

Elastic Photoproduction $\gamma p \rightarrow \Upsilon p$



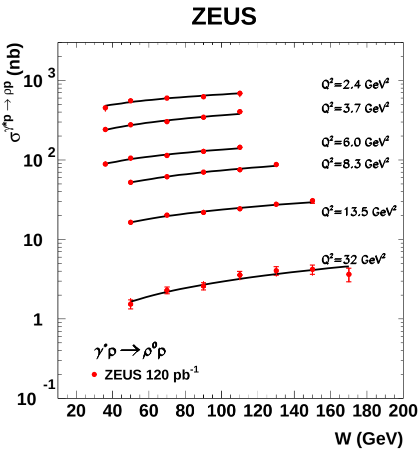
- **cross section W dependence, $\sigma \sim W^{\delta}$:**
- **two measured points δ= 1.2±0.8**
- **consistent with theoretical prediction, $\delta \sim 1.7$**

Elastic Photoproduction



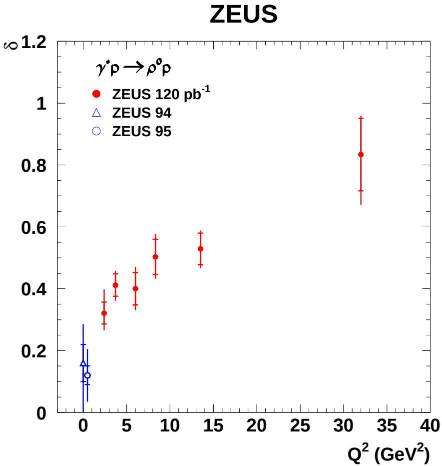
- **fit:** $\sigma \sim W^{\delta}$
- **process becomes hard as scale (mass) becomes larger,** $(M_{J/\Psi}/M_{\Phi})^2 \sim 10$ **!**

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



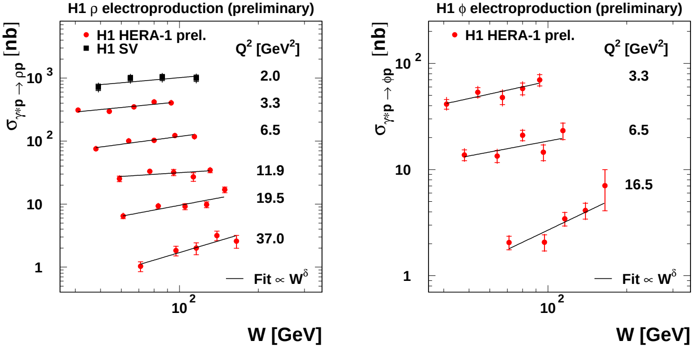
- **fit:** $\sigma \sim W^{\delta}$
- **Cross section W dependence becomes steeper at high Q^2**

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



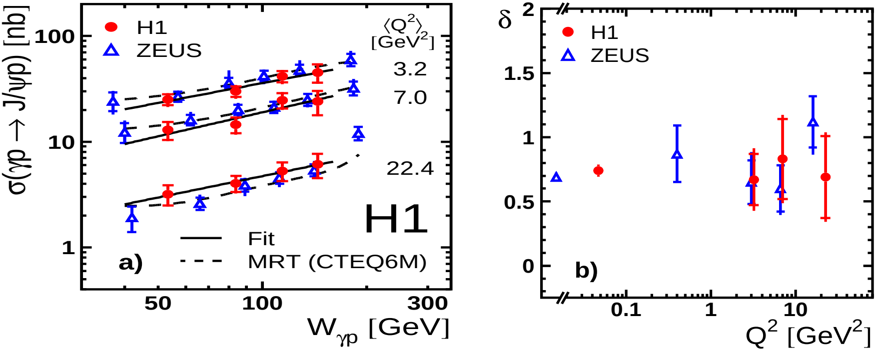
- $\sigma \sim W^{\delta}$
- **Soft physics predicts for energy dependence $\delta \sim$ 0.2**

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



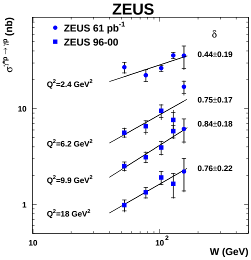
- **similar behavior, cross section W dependence becomes steeper at high Q^2, measured by H1 for ρ and Φ mesons**

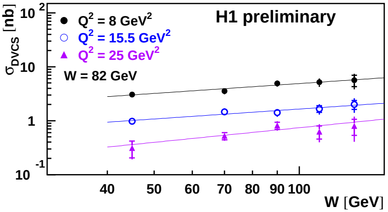
Elastic Electroproduction $\gamma^* p \to J/\Psi p$

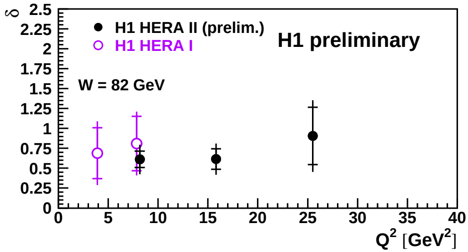


- **cross section for J/Ψ production as a function of** $W, \sigma \sim W^{\delta}$
- $\delta(Q^2 = 0, M^2_{J/\Psi} \simeq 10 GeV^2) \sim 0.7$

DVCS

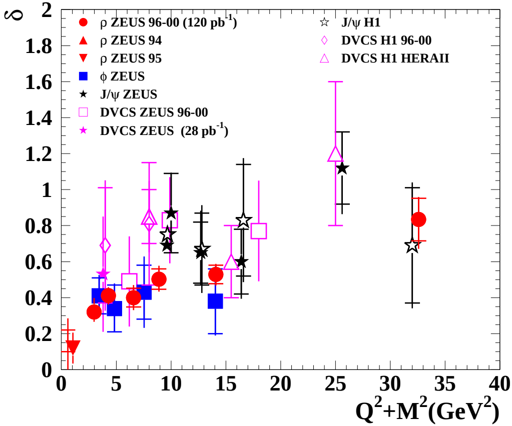






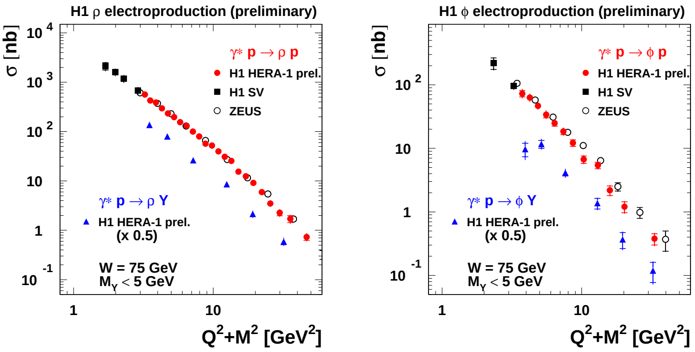
- **H1: δ = 0.63±0.08±0.14**
- **ZEUS: δ = 0.52±0.09**

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



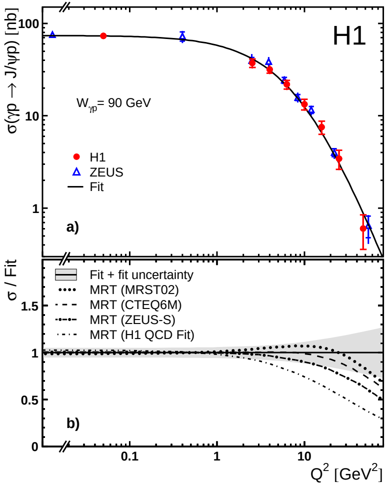
- **process becomes hard as scale** $(Q^2 + M^2)$ **becomes larger**

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



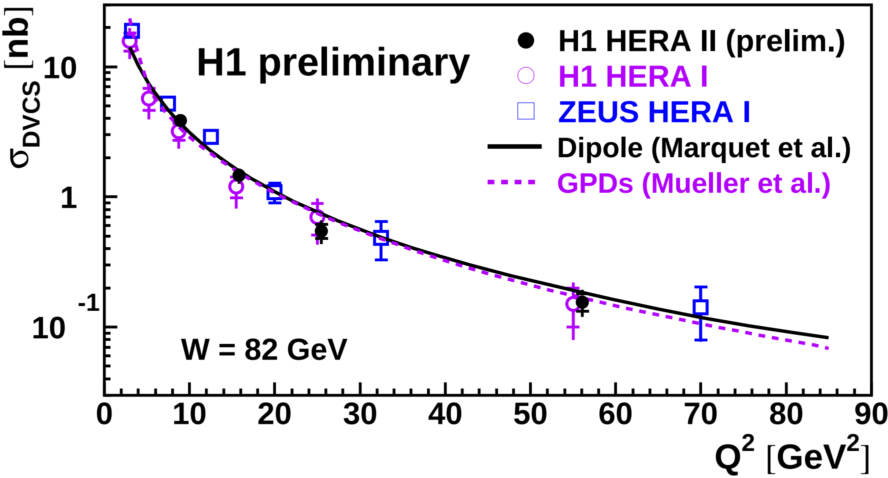
- **H1/ZEUS: perfect agreement**
- **fit:** $\sigma \propto (Q^2 + M^2)^{-n} \Longrightarrow \sigma_L \propto \frac{\alpha_S^2(Q)}{Q^6}|xG(x, Q^2)|^2$
- $Q^2 \geq$**0 GeV**^{2}**, n** $\simeq$ **2.00** $\pm$ **0.01,** χ^2**/ndf** $\sim$ **10**
- $Q^2 \geq$**10 GeV**^{2}**, n** $\simeq$ **2.5**$\pm$**0.02,**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

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



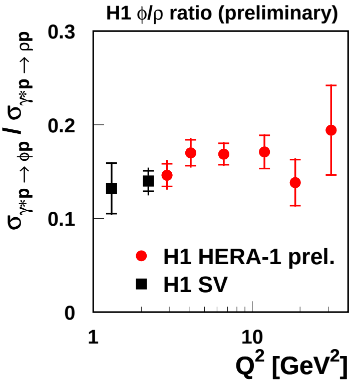
- **H1/ZEUS: perfect agreement**
- $\sigma \propto (Q^2 + M^2)^{-n}$
- $Q^2 \geq$**0 GeV**^{2}**, n=2.486±0.08±0.068**

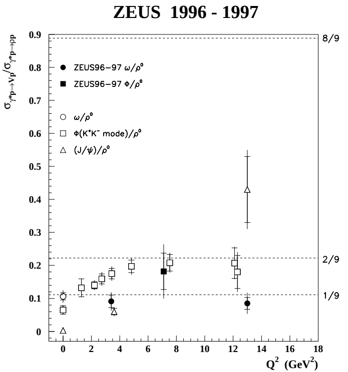
Q^2 *dependence: DVCS*



- **H1/ZEUS: perfect agreement**
- $\sigma \propto Q^{-2n}$
- $Q^2 \geq$**1.5 GeV^2, n=1.54$\pm$0.05**

Q^2 dependence: Vector Mesons production ratio

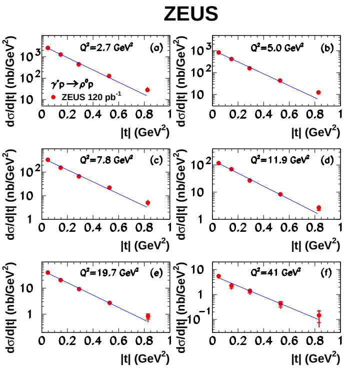


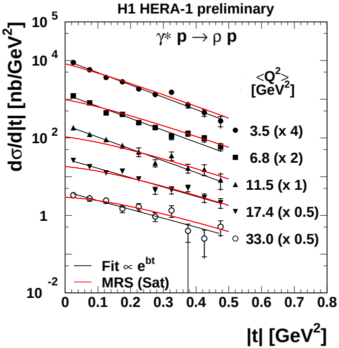


- **flavour independence:**

$$\rho : \omega : \phi : J/\psi = 9 : 1 : 2 : 8$$

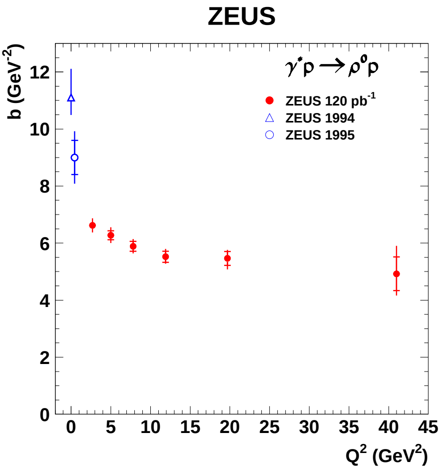
t dependence





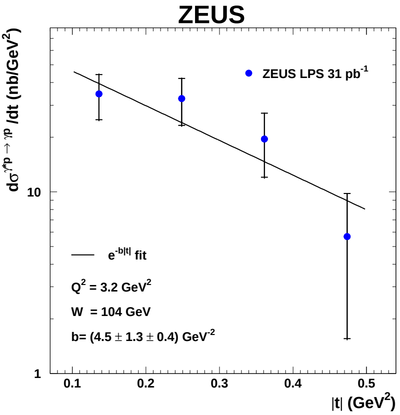
- $d\sigma/d|t| \sim exp(-b|t|)$ **for different bins of** Q^2

t dependence: ρ-meson



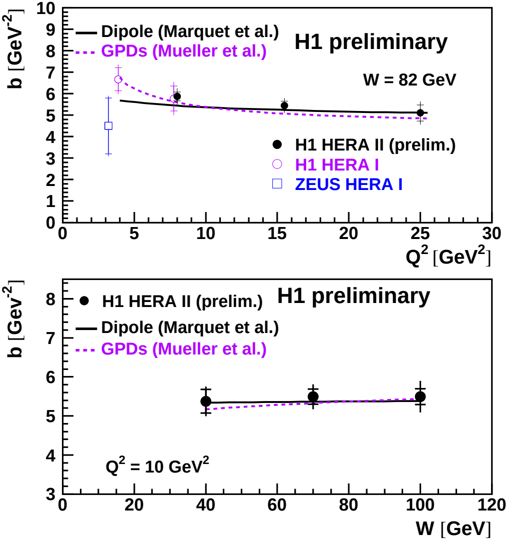
- b **slope as a function of** Q^2

t dependence: DVCS



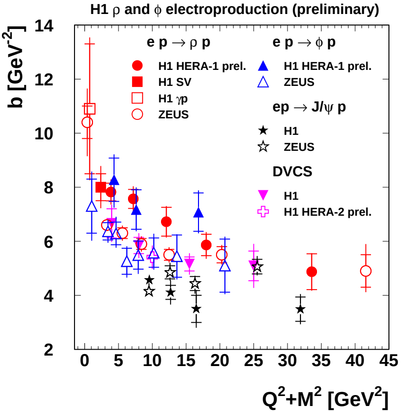
- Q^2 = 3.2 GeV^2, W = 104 GeV
- b=4.5±1.3±0.4 GeV^{-2}

t dependence: DVCS



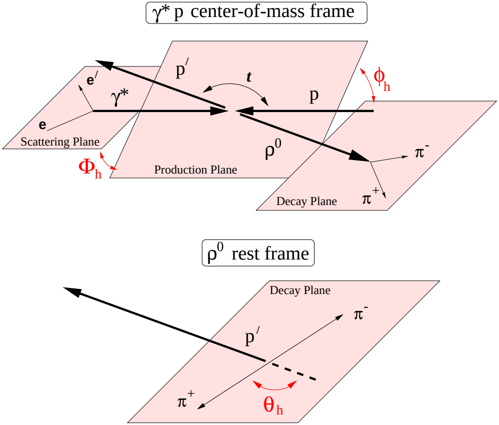
- b **slope as a function of** $W \Longrightarrow$ **no** W **dependence**
- b**=5.41±0.14±0.31 GeV**$^{-2}$

$b(Q^2 + M^2)$



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

Helicity Studies

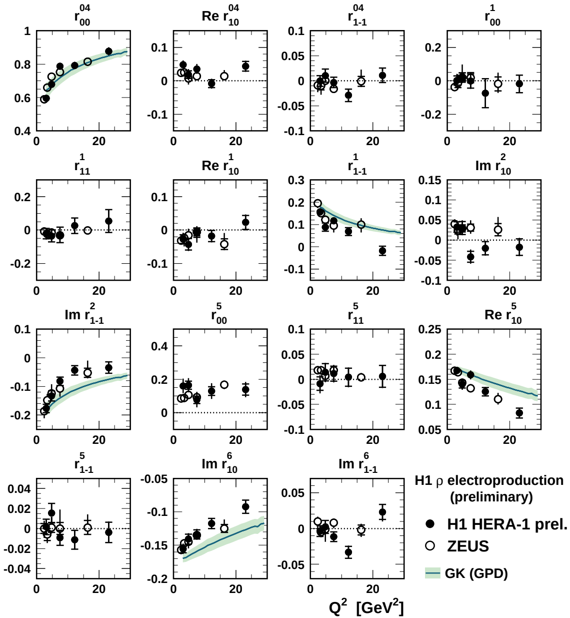


Angular distribution $\Longrightarrow$ 3 angles (θ_h, ϕ_h and Φ_h) and 15 combinations of spin-density matrix elements r_{ij}^{kl} $\Longrightarrow$ helicity amplitudes $T_{\lambda_V \lambda_\gamma}$

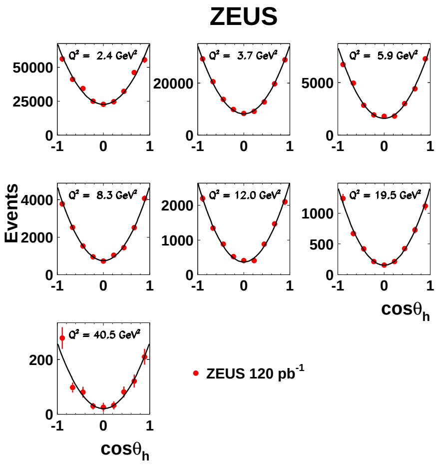
Helicity Studies

- **s-channel helicity conservation (SCHC)**
  - $\gamma_T^* \rightarrow \rho_T$
  - $\gamma_L^* \rightarrow \rho_L$
  - **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**
- $r_{00}^5 \sim$ **single-flip amplitude,** $\gamma_T^* \rightarrow \rho_L$
- r_{00}^5 **deviates from zero !**
- $r_{00}^5 = 0.095 \pm 0.019 \pm 0.024$ **(ZEUS) and**
  $r_{00}^5 = 0.093 \pm 0.024^{+0.19}_{-0.10}$ **(H1)**
- **if SCHC holds** $\rightarrow R = \sigma_L/\sigma_T = r_{00}^{04}/\epsilon(1 - r_{00}^{04})$
- **if not:** $r_{00}^{04} \rightarrow r_{00}^{04} - \Delta^2$, $\Delta \propto r_{00}^5/\sqrt{2r_{00}^{04}}$
- **R(SCHC) - R(SCHNC) $\sim$ 3 %**

Helicity Studies: Q^2-dependence



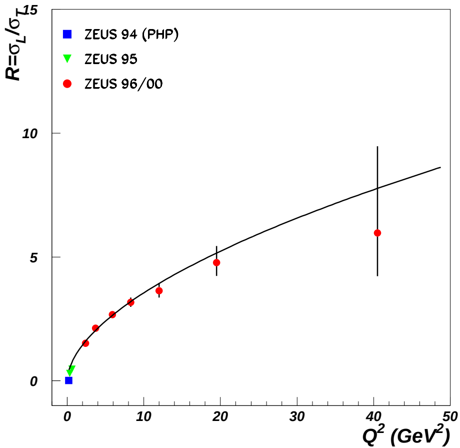
Helicity Studies



fit to $cos\theta_h$**:**

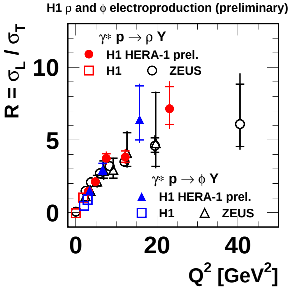
$$d\sigma/dcos\theta_h \propto 1 - r_{00}^{04} + (3r_{00}^{04} - 1)cos^2\theta_h$$

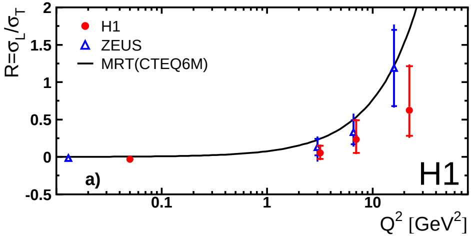
Helicity Studies



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

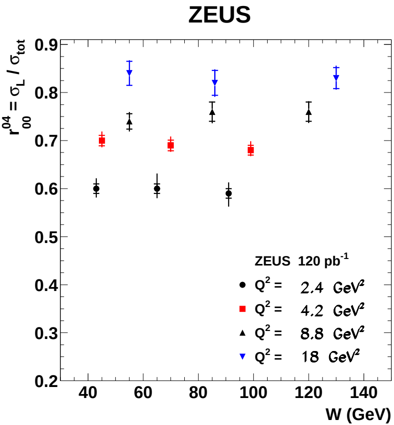
Helicity Studies





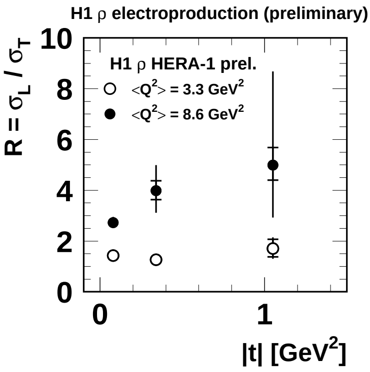
- σ_L/σ_T **for** ρ, ϕ **and** J/Ψ **mesons**
- R **increases with** Q^2

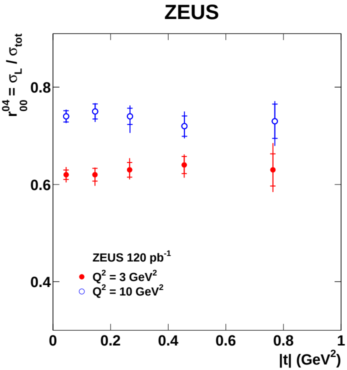
Helicity Studies



- $r^{04}_{00} = \sigma_L/\sigma_{tot} \qquad R = \sigma_L/\sigma_T = r^{04}_{00}/\epsilon(1 - r^{04}_{00}), \qquad \epsilon \simeq 1$
- **σ_L and σ_T have the same W dependence**
- **the typical dipole size contributing to ρ production - independent of the photon polarization**

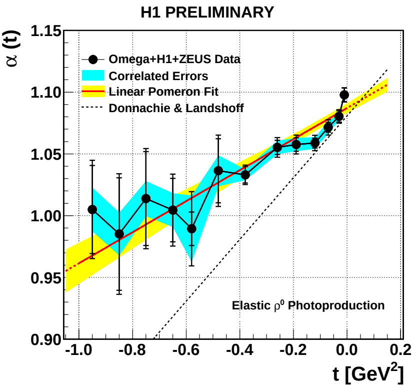
Helicity Studies





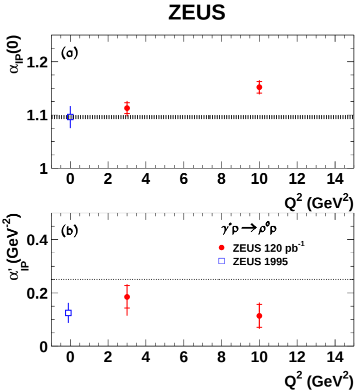
- $R = \sigma_L/\sigma_T \sim \exp(-(b_L - b_T)|t|)$
- **H1:** $b_L < b_T$
- **ZEUS:** $b_L \approx b_T$

Effective Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' \cdot t$



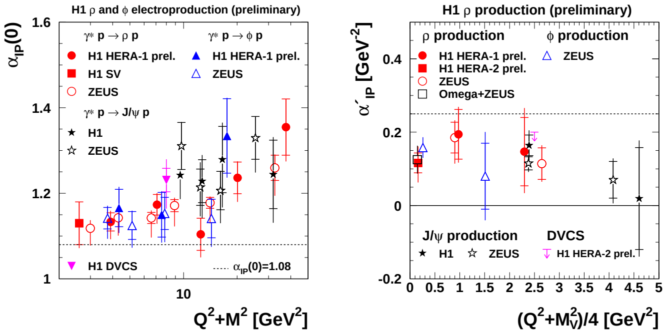
- **Global fit:** ρ^o **Photoproduction, (Omega, H1, ZEUS)**
  $(1.0871 \pm 0.0026 \pm 0.003) + (0.126 \pm 0.013 \pm 0.012)\ GeV^{-2} \cdot t$
- **H1:** $(1.093 \pm 0.003^{+0.008}_{-0.007}) + (0.116 \pm 0.027^{+0.038}_{-0.046})\ GeV^{2} \cdot t$
- **ZEUS:** $(1.096 \pm 0.021) + (0.125 \pm 0.038)\ GeV^{-2} \cdot t$

Effective Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' \cdot t$



- **ZEUS, ρ^o electroproduction:**
- $\alpha(0)$ **increases with** Q^2
- α'**, within errors, is** Q^2 **independent**
- **lines** $\longrightarrow$ **DL parameterization**

Effective Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' \cdot t$



- $\alpha(0)$: **energy behavior of the total cross section,** $\sigma_{tot} \sim W^{2(\alpha(0)-1)}$
- α': **shrinkage of the diffractive peak,** $b(W) = b_0 + 4\alpha' \ln(W/W_0)$
- **effective Pomeron trajectory: a larger intercept and smaller slope than expected from soft physics**

Summary

What we have learnt from VM production? H1, ZEUS based on HERA data show:

- **Vector Meson production and DVCS 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 $b \sim 5$ GeV^{-2}**
- **The ratio, σ_L/σ_T, increases with Q^2, but is independent of W**
- **The effective Pomeron trajectory has a larger intercept and smaller slope than those extracted from soft interactions**

All these features are compatible with expectations of hard diffraction $\rightarrow$ pQCD