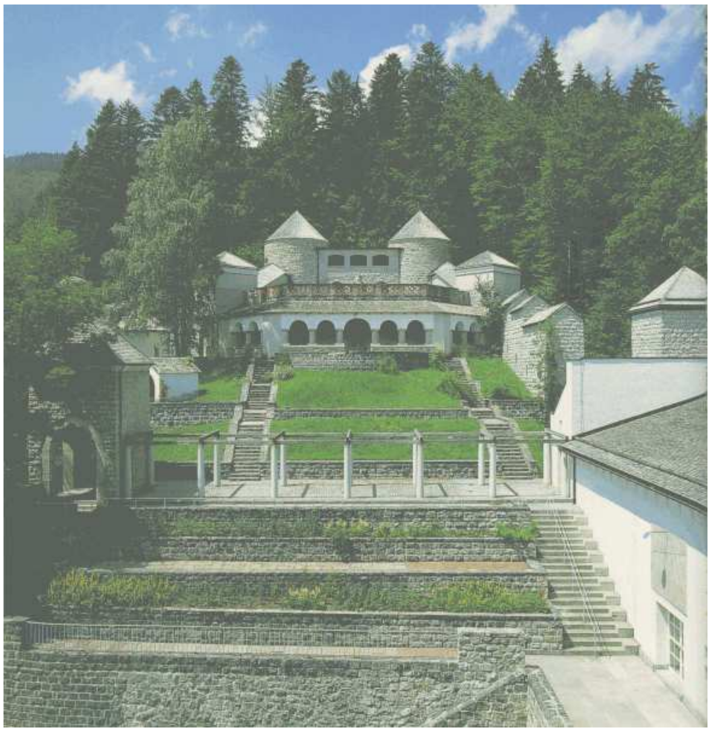
Ringberg Workshop — 21 June 2001

New Trends in HERA Physics 2001 — Ringberg Castle

Experimental Results on the Production of Light Vector Mesons



☞ **Helicity selection rules and scaling**

☞ **Regge analyses in ρ^0 production at high Q^2**

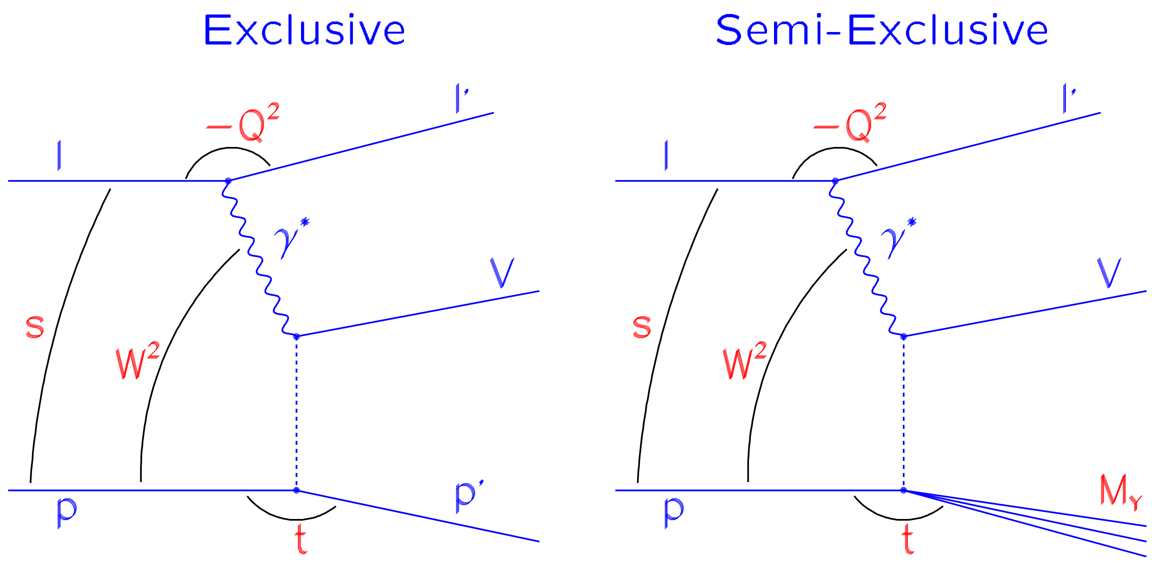
☞ **Studies of semi-exclusive processes at high $|t|$**

- **Electroproduction (H1)**
- **Photoproduction (ZEUS)**

J. A. Crittenden (DESY)

for the H1 and ZEUS collaborations

Production of Light Vector Mesons at HERA



$\sqrt{s}$: Center–of–mass energy of e–p system
1992-97: 300 GeV   1998-2000: 318 GeV

W: Center–of–mass energy of γ^*–p system
$40 < W < 150$ GeV

Q^2: Photon Virtuality
$10^{-10} < Q^2 < 60$ GeV^2 ($Q^2 \ll |t| \Rightarrow t \simeq -P_T^2(\mathrm{V})$)

t: Square of Momentum Transfer at the Proton Vertex
$|t| < 13$ GeV^2
Proton-dissociative process dominates for $|t| > 1$ GeV^2

General Remarks on VM Production at HERA

☞ **Investigation of vacuum-exchange processes**

Vacuum exchange has a complicated structure

☞ **Study properties of strong interaction**

A soft/hard transition is observed in

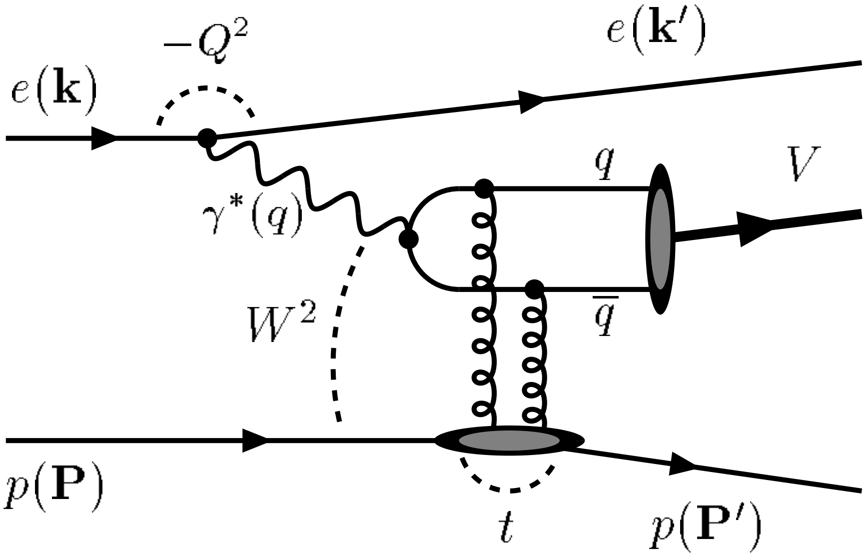
$$Q^2 \qquad M_V^2 \qquad |t|$$

☞ **Exclusivity allows study of helicity structure via decay angles**

$$\text{Helicity transfer} \Leftrightarrow \begin{cases} \text{Scaling behavior} \\ \text{Meson structure} \end{cases}$$

Perturbative QCD for Diffraction (?!)

Exchange of a color-neutral pair of gluons



Brodsky, Frankfurt, Gunion, Mueller, Strikman
PRD50 (1994) 3134

$$\left.\frac{\mathrm{d}\sigma^L_{\gamma^* \mathrm{p} \to \mathrm{Vp}}}{\mathrm{d}|t|}\right|_{t=0} \propto \frac{\alpha_s^2(Q^2)}{\alpha Q^6} \left| xG(x, Q^2) \right|^2$$

☞ Power-law scaling with momentum transfer

☞ Energy dependence determined by

$$\boxed{G(x, Q^2), \qquad x = Q^2/W^2}$$

☞ Flavor symmetry in the hard scatter

☞ Longitudinal cross section asymptotically dominant

Helicity selection and scaling behavior

Brodsky and Lepage (1979)

(Elastic electron scattering)

Ratio of ρ^0 long. form factor to transv. $\propto t$

Chernyak and Zhinitsky (1984)

ρ^0_{T} suppressed relative to ρ^0_{L} by factor t

If scalar gluons, form factor t dependence less by factor t

Brodsky, Frankfurt, Gunion, Mueller and Strikman (1994)

Leading amplitude couples long. photon to long. VM, $\propto Q^{-6}$

Predict transverse cross section (endpoint problems) $\propto Q^{-8}$

Ginzburg and Ivanov (1996)

(Photoproduction at high $|t|$)

Dominance of long. VM signifies perturbative region

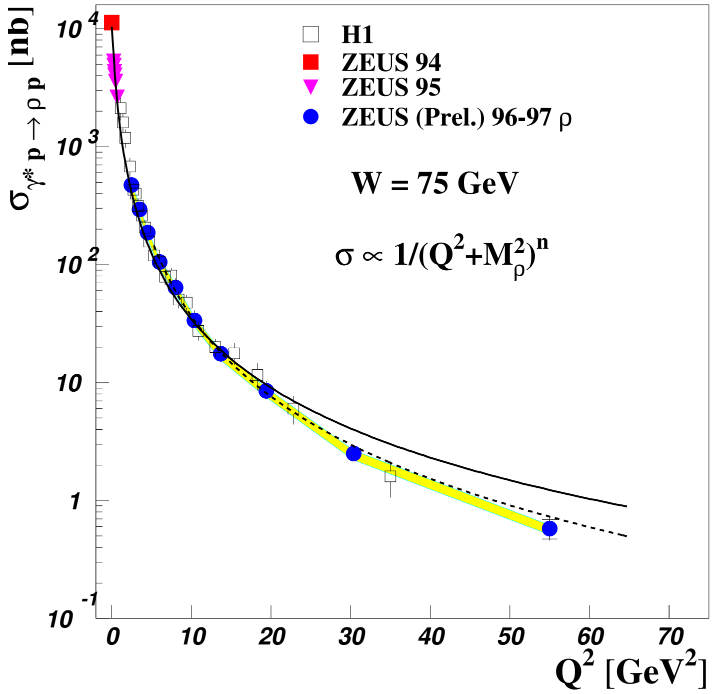
Brodsky, Diehl, Hoyer and Peigné (1999)

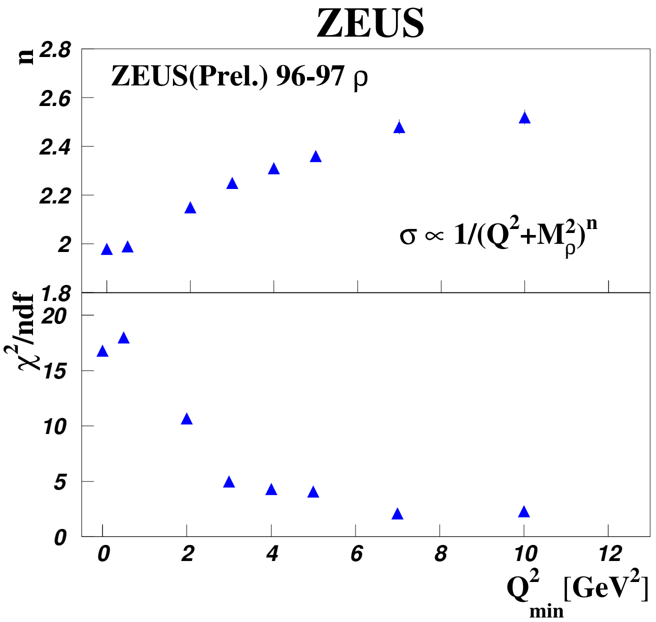
(Quark exchange diagrams for high $|t|$ photoproduction)

Transv. VM suppressed by $(-t)^2$ in γp and $(-t)$ in ep

Power-law scaling or not ?

A. Kreisel/ZEUS at DIS2001





Yes, but power changing with Q^2

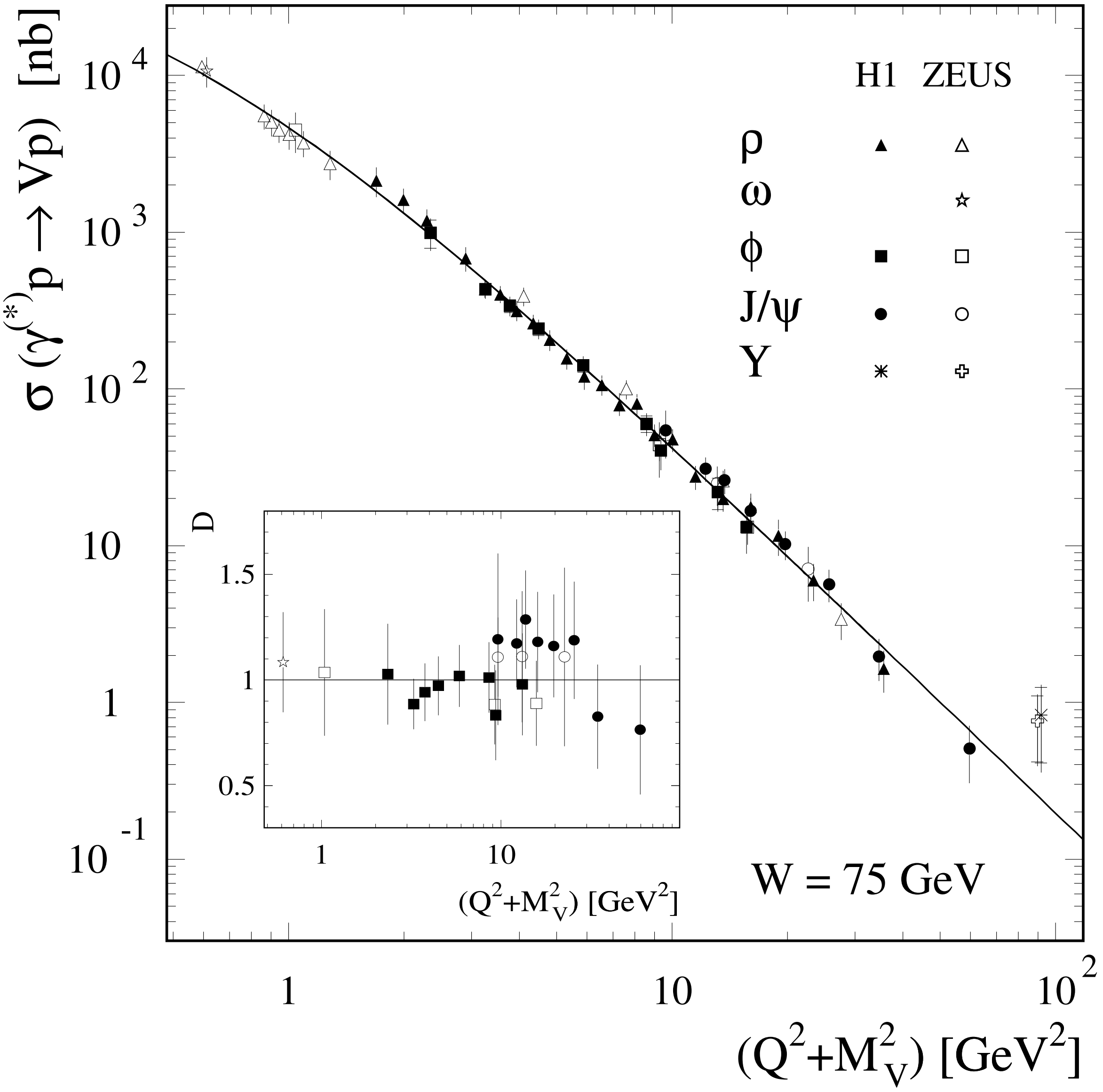
Approaching power of 6 at high Q^2

Note: QCD prediction for σ_L only

Applies only to $Q^2 \gg M_V^2$

Comparing the vector mesons

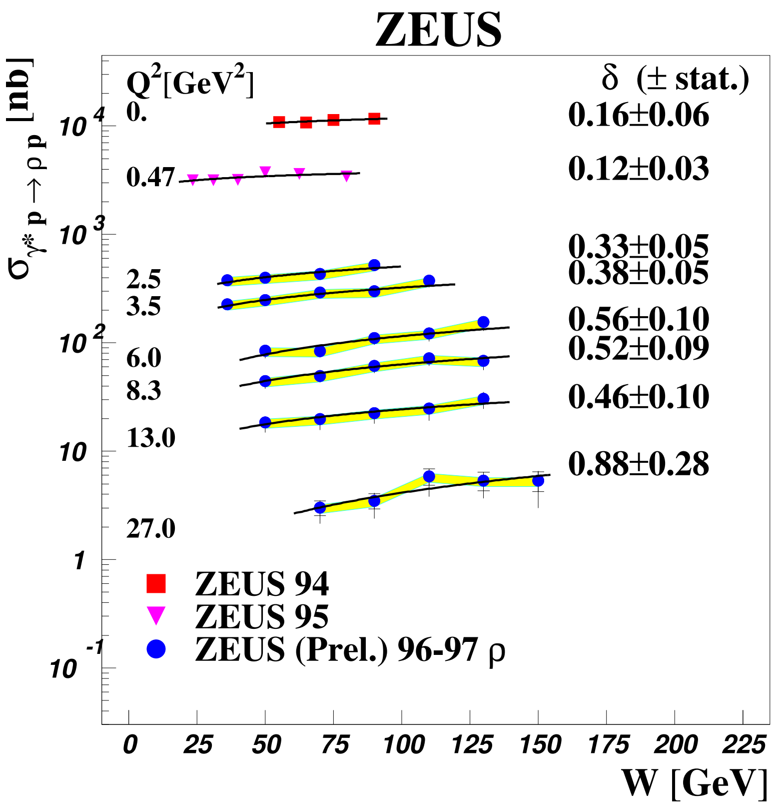
H1 Collaboration, Phys. Lett. B483 (2000) 360

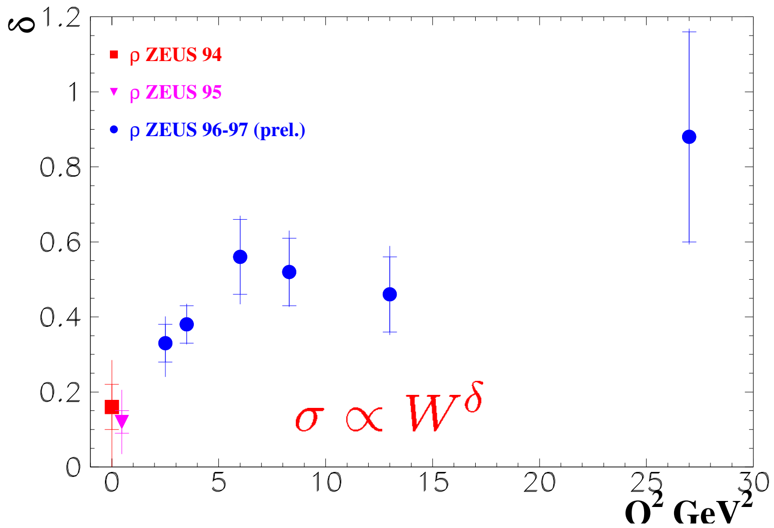


Universal scaling (?)

(Not expected for $\sigma_L + \sigma_T$!!)

Does energy dependence vary with Q^2?

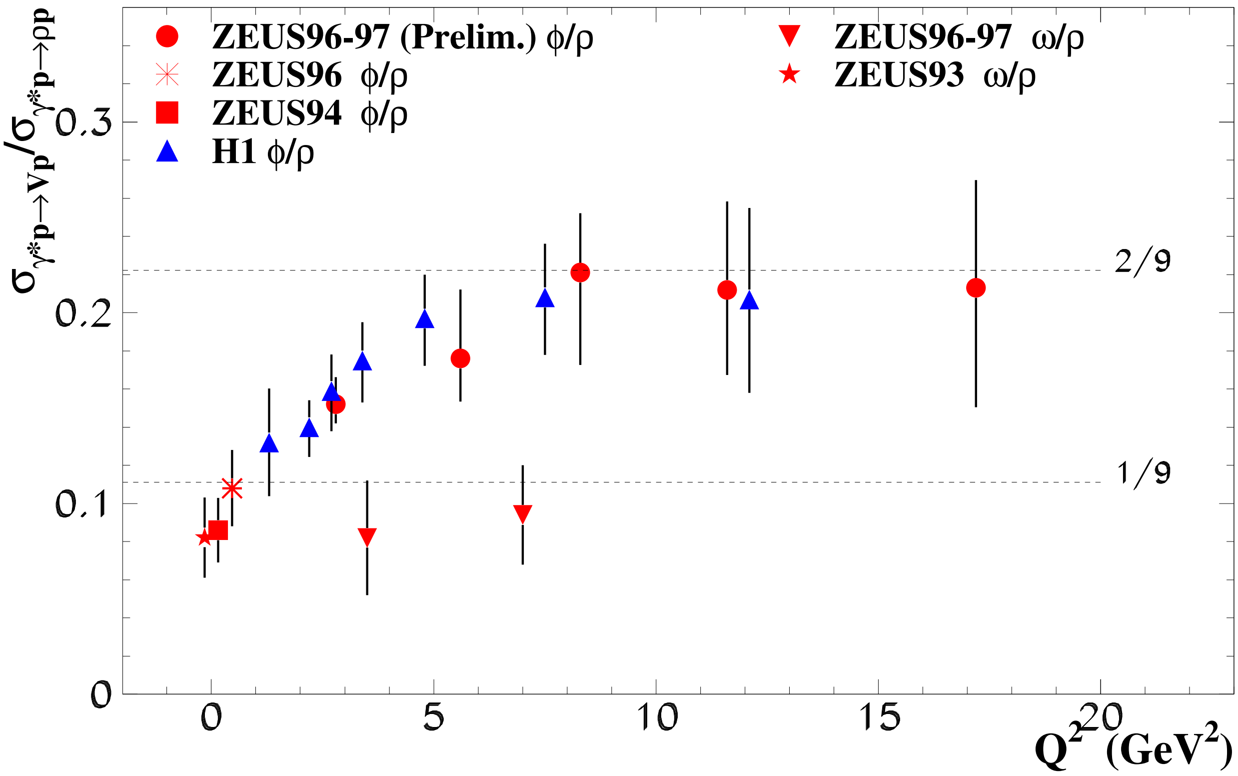




Energy dependence steepens with Q^2

Impressive support for pQCD description

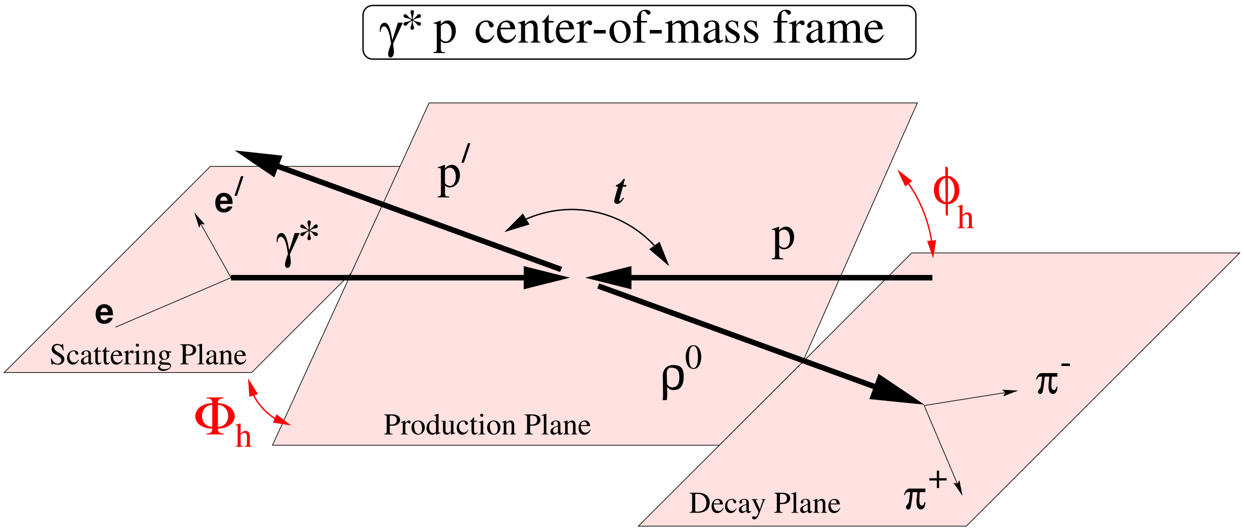
What about flavor symmetry ?

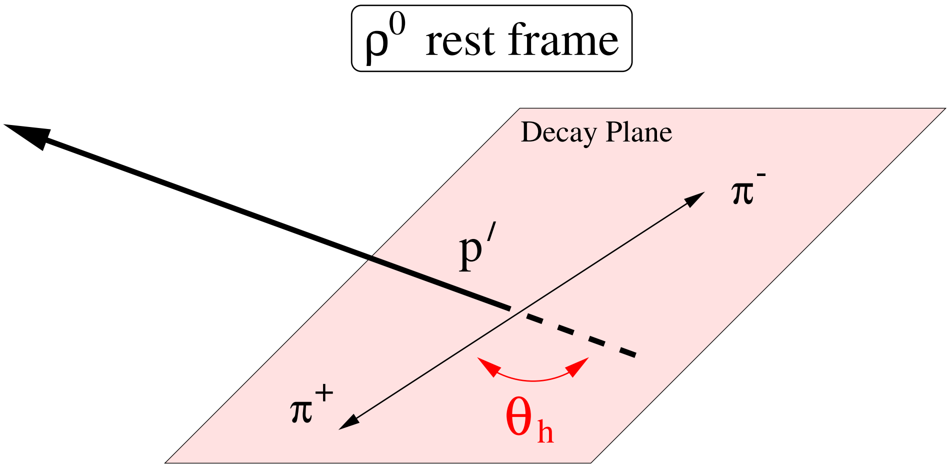


Magnitude of ϕ/ρ^0 ratio reaches the SU(3)-symmetry value in the same region where the scaling power equalizes

EITHER ϕ suppressed at low Q^2
OR ρ^0 and ω equally enhanced

Helicity Analyses





Φ_h Angle between the electron scattering plane and the ρ^0 production plane

θ_h Polar angle of π^+ in the ρ^0 rest frame

ϕ_h Azimuthal angle of π^+

Decomposing the Spin Density Matrix

How to couple real photons ($\lambda = \pm 1$)

to vector mesons ($\lambda = 0, \pm 1$) ??

Schilling, Seyboth, and Wolf, Nucl.Phys. B15, 397 (1970)

☞ Circular polarization: $\vec{\epsilon_\gamma} = \pm P_\gamma^c \,(0, 0, 1)$

☞ Linear polarization: $\vec{\epsilon_\gamma} = P_\gamma^l \,(-\cos\Phi, \sin\Phi, 0)$

Decompose ρ^0 decay angle distribution W(θ,ϕ)

into four parts W^i(θ,ϕ) (i=0,3) such that:

1. Unpolarized: W(θ,ϕ) = W^0(θ,ϕ)

2. Circularly polarized:

   $$W(\theta,\phi) = W^0(\theta,\phi) \pm P_\gamma^c \; W^3(\theta,\phi)$$

Need long. pol. initial-state lepton→E665(μ), HERMES(e)

H1, ZEUS wait for HERA II

3. Linearly polarized:

   $$W(\theta,\phi,\Phi) = W^0(\theta,\phi) - P_\gamma^l \cos 2\Phi \;\; W^1(\theta,\phi) - P_\gamma^l \sin 2\Phi \;\; W^2(\theta,\phi)$$

Generalizing to Virtual Photons

$$R = \frac{\sigma_L}{\sigma_T} > 0$$

Schilling and Wolf, Nucl.Phys. B61, 381 (1973)

Define linear combinations of the matrix elements:

(Helicity states of massive vector meson: $i, k = +1, 0, -1$)

$$r_{ik}^{04} = \frac{\rho_{ik}^{0} + \epsilon R \rho_{ik}^{4}}{1 + \epsilon R}$$

The angular distributions do not distinguish unpolarized transverse photons from longitudinally polarized photons!

$$r_{ik}^{\alpha} = \begin{cases} \dfrac{\rho_{ik}^{\alpha}}{1+\epsilon R} & \alpha = 1-3 \text{ (Trans.)} \\[2ex] \dfrac{\sqrt{R}\,\rho_{ik}^{\alpha}}{1+\epsilon R} & \alpha = 5-8 \text{ (L/T int.)} \end{cases}$$

Constraints from hermiticity, parity conservation

3-D Decay-Angle Distribution

(15 linearly independent parameters)

$$W(\cos\theta_h, \phi_h, \Phi_h) =$$

$$\frac{3}{4\pi}\Bigg[\left(\frac{1}{2}\left(1-r^{04}_{00}\right)+\frac{1}{2}\left(3r^{04}_{00}-1\right)\cos^2\theta_h -\sqrt{2}\,\mathrm{Re}\,r^{04}_{10}\,\sin 2\theta_h\cos\phi_h - r^{04}_{1-1}\sin^2\theta_h\cos 2\phi_h\right)$$

$$-\varepsilon\cos 2\Phi_h\left(r^{1}_{11}\sin^2\theta_h + r^{1}_{00}\cos^2\theta_h -\sqrt{2}\,\mathrm{Re}\,r^{1}_{10}\,\sin 2\theta_h\cos\phi_h - r^{1}_{1-1}\sin^2\theta_h\cos 2\phi_h\right)$$

$$-\varepsilon\sin 2\Phi_h\left(\sqrt{2}\,\mathrm{Im}\,r^{2}_{10}\,\sin 2\theta_h\sin\phi_h + \mathrm{Im}\,r^{2}_{1-1}\sin^2\theta_h\sin 2\phi_h\right)$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\cos\Phi_h\left(r^{5}_{11}\sin^2\theta_h + r^{5}_{00}\cos^2\theta_h -\sqrt{2}\,\mathrm{Re}\,r^{5}_{10}\,\sin 2\theta_h\cos\phi_h - r^{5}_{1-1}\sin^2\theta_h\cos 2\phi_h\right)$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\Phi_h\left(\sqrt{2}\,\mathrm{Im}\,r^{6}_{10}\,\sin 2\theta_h\sin\phi_h + \mathrm{Im}\,r^{6}_{1-1}\sin^2\theta_h\sin 2\phi_h\right)\Bigg]$$

The angular distributions are sensitive
to products of the helicity amplitudes:

$$T_{\lambda_{\rho^0}\lambda_\gamma}$$

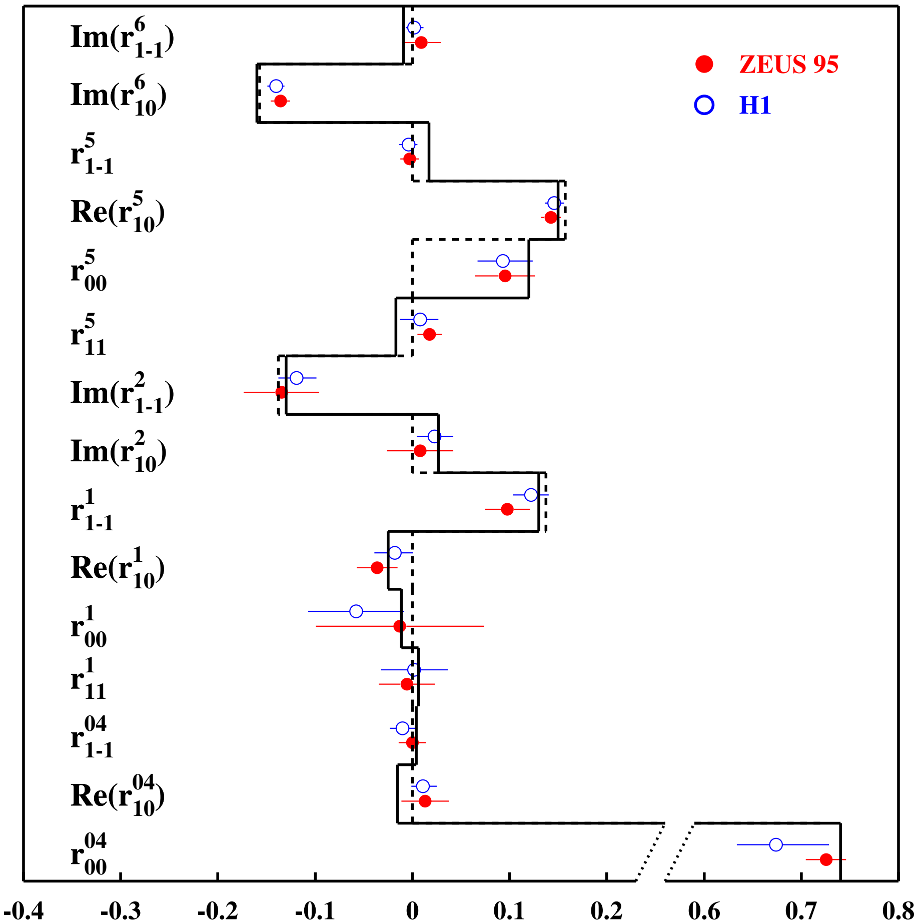
$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{T^2_{00}+2\,T^2_{10}}{T^2_{01}+T^2_{11}+T^2_{1-1}}$$

(Note both helicity-conserving and helicity-violating parts)

What have we learned so far?

ρ^0: ZEUS/EPJ C12 (2000) 393
H1/Phys. Lett. B483 (2000) 360

ϕ: H1/EPJ C13 (2000) 371



$$r^5_{00} \propto T_{00}T^*_{01} + T_{01}T^*_{00}$$

Longitudinal ρ^0 from transverse γ

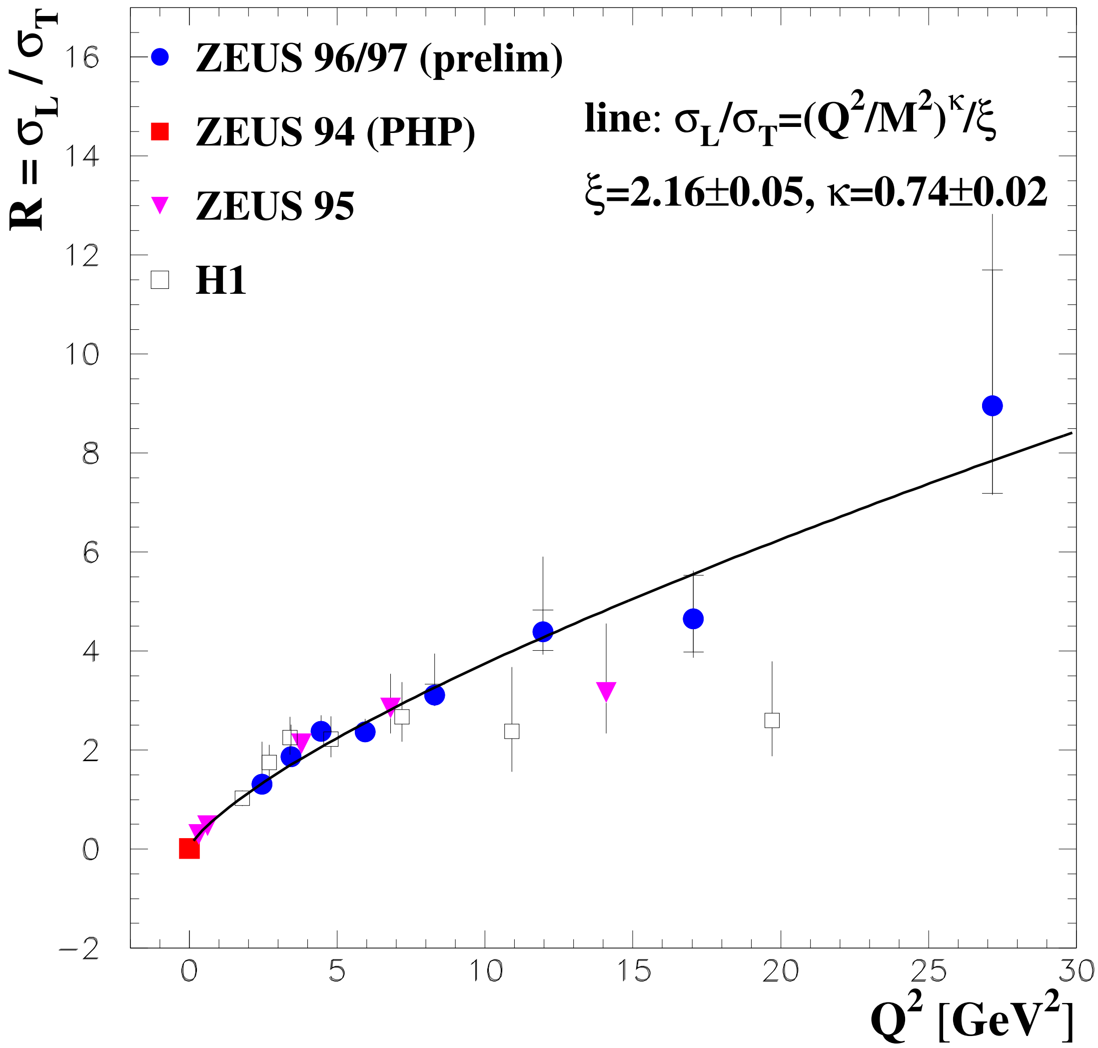
Predicted by Ivanov and Kirschner
Phys. Rev. D58 (1998) 114026

$r^5_{00} = 0$ if ρ^0 momentum equally shared by q and $\bar{q}$

What about ratio of σ_L to σ_T?

$$R = \frac{1}{\epsilon} \frac{r_{00}^{04} - \Delta^2}{1 - (r_{00}^{04} - \Delta^2)}$$

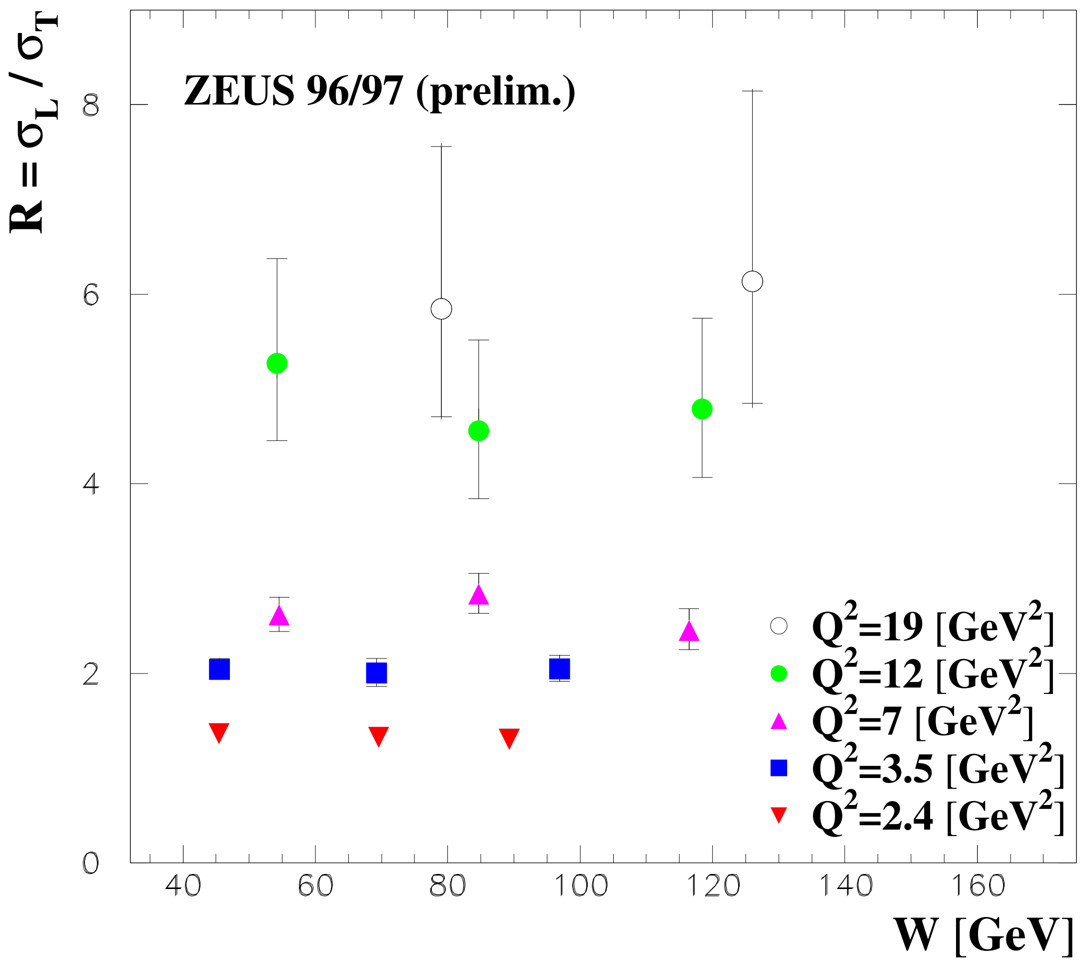
Δ now known to be small (helicity violation)



The dominance of σ_L
was an early prediction of pQCD

At high Q^2, σ_T also shows a hard scaling

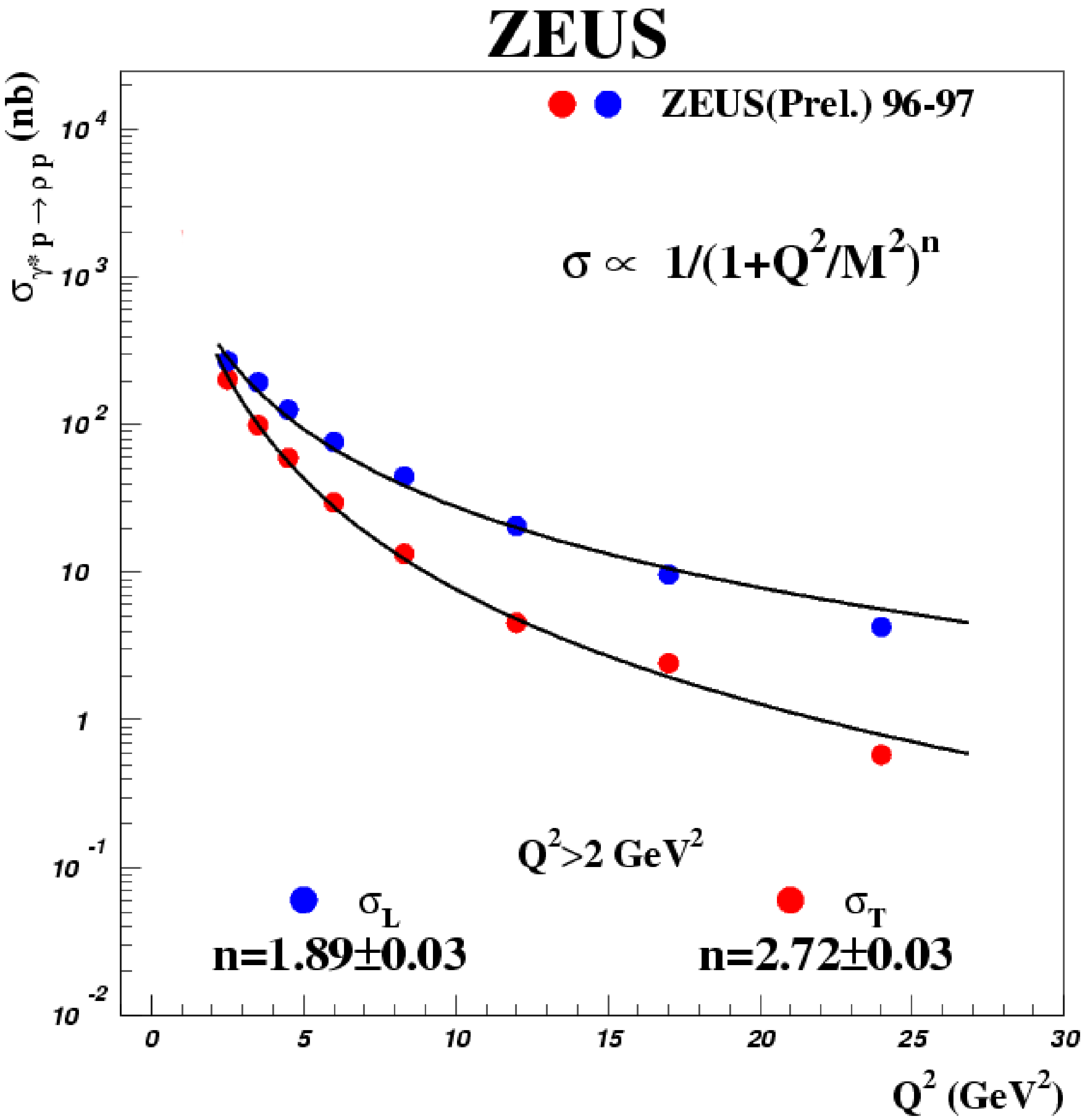
Energy dependence in σ_L/σ_T?



Energy dependence for σ_T and σ_L similar

σ_T driven by gluon as well?

What are the scaling powers in σ_L, σ_T?



Q^2 dependence for σ_L even weaker than for point cross section

Remarkably hard scaling behavior for σ_T

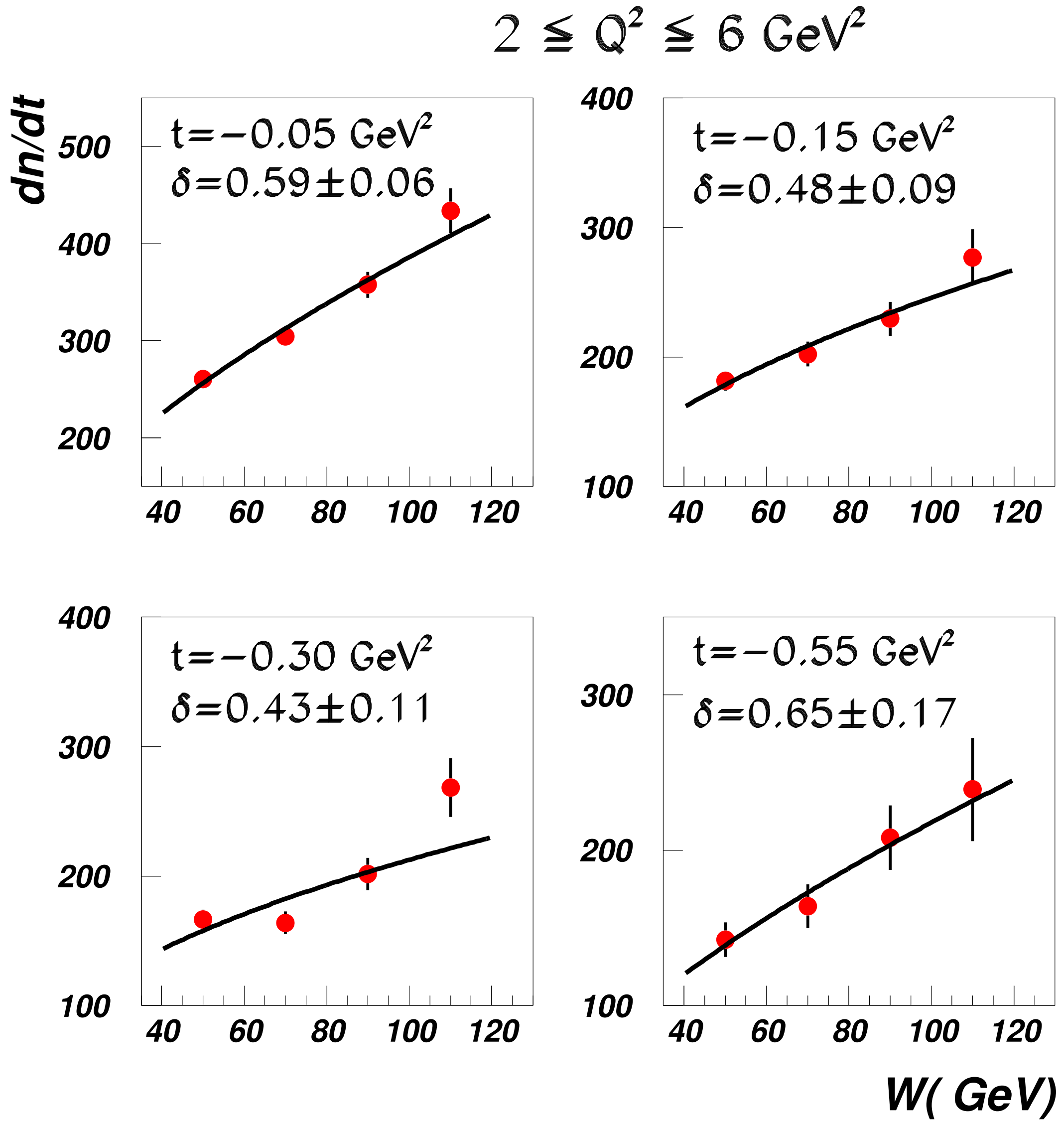
(The Q^2 dependence is even weaker than Q^{-6})

Does the "Pomeron trajectory" depend on Q^2 ??

$$\frac{d\sigma}{d|t|} \propto e^{b_0 t} \left(\frac{W}{W_0}\right)^{4(\alpha_{I\!P}(t)-1)}$$

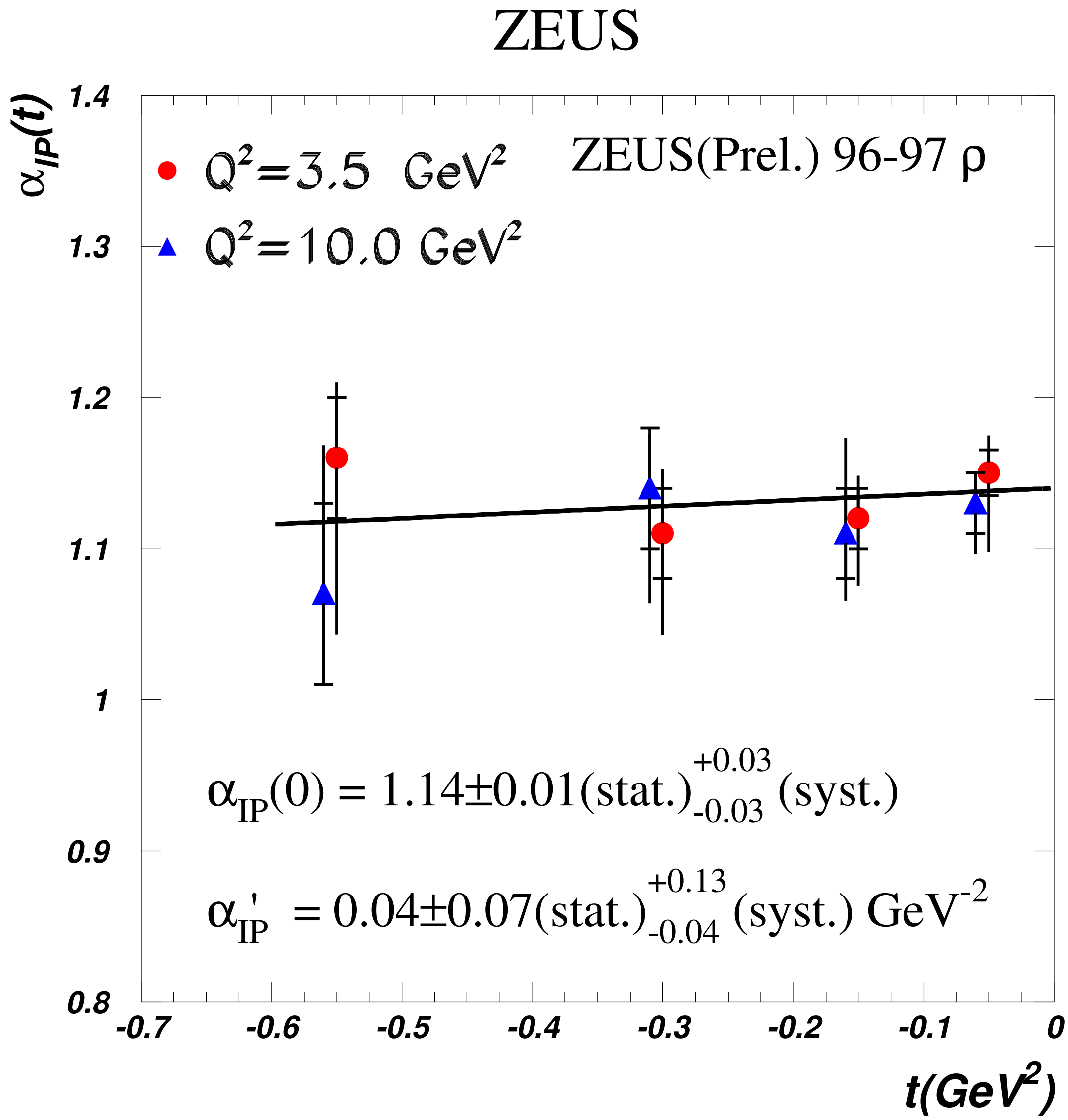
$$\boxed{\alpha_{I\!P}(t) = 1.08 + 0.25\,t}$$

Donnachie and Landshoff, Phys. Lett. B296, 227 (1992)



First measurement at high Q^2

What about shrinkage?

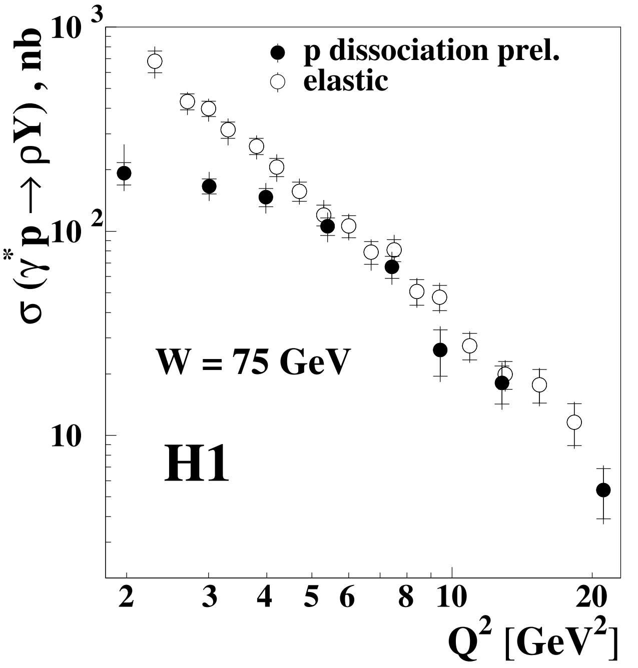


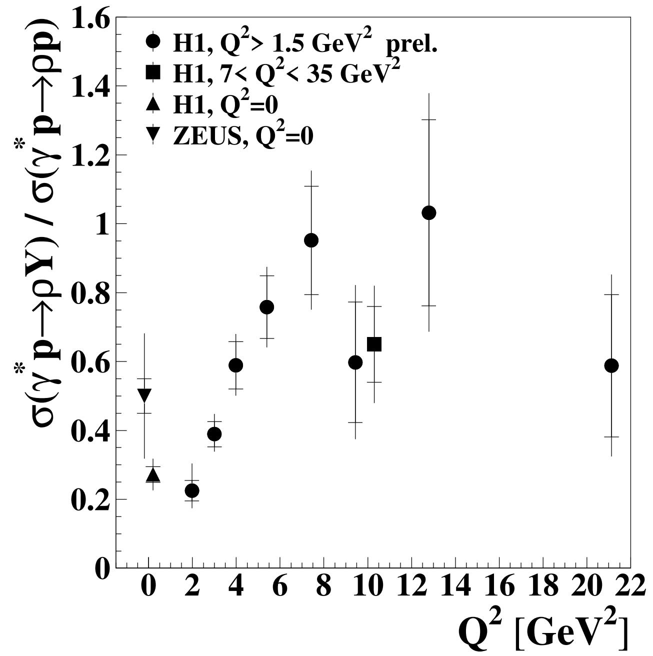
Soft Pomeron shrinkage unlikely

Dissociation and Regge factorization

J. Olsson/H1 at DIS2001

Does proton dissociation change our discussion of QCD?





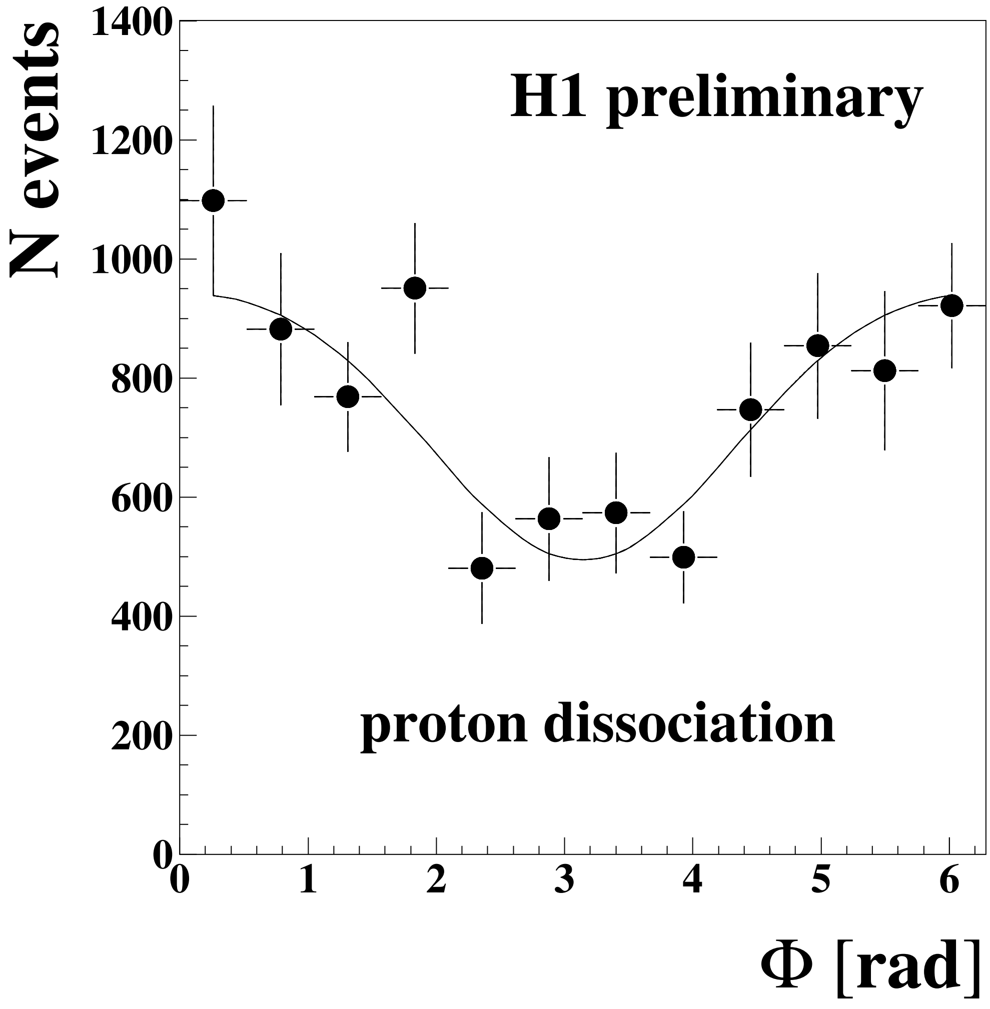
Ratio smaller than expected from pp scattering

Clear indication of breaking of Regge factorization

(Very surprising for low Q^2)

SCHC-breaking for dissociation?

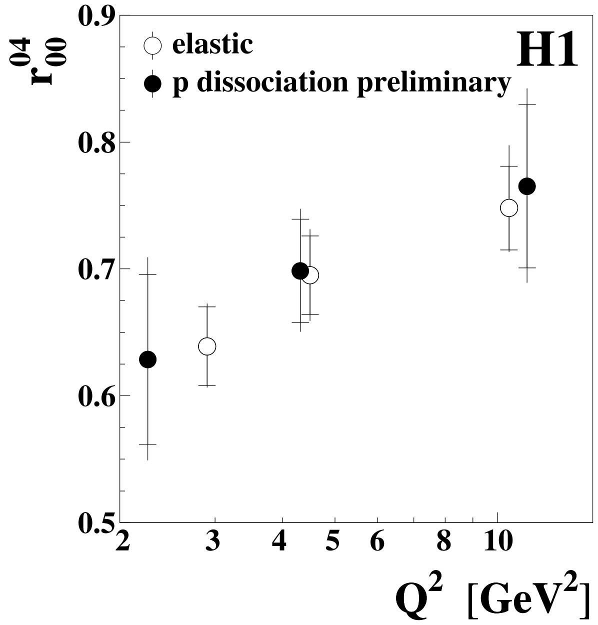
$$W(\Phi) \propto 1 - \epsilon \cos 2\Phi, (2r^1_{11} + r^1_{00}) + \sqrt{2\epsilon(1-\epsilon)} \cos\Phi \, (2r^5_{11} + r^5_{00})$$

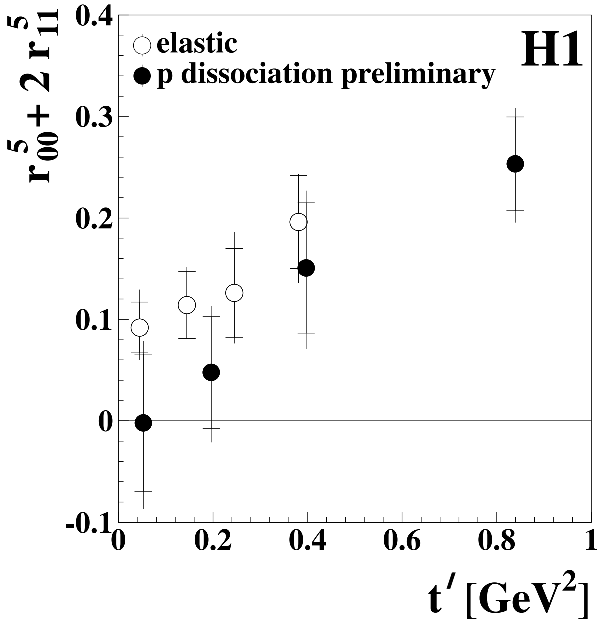


SCHC-breaking observed also for dissociative process

This method does not distinguish L→T from T→L

R, SCHC for the dissociative process

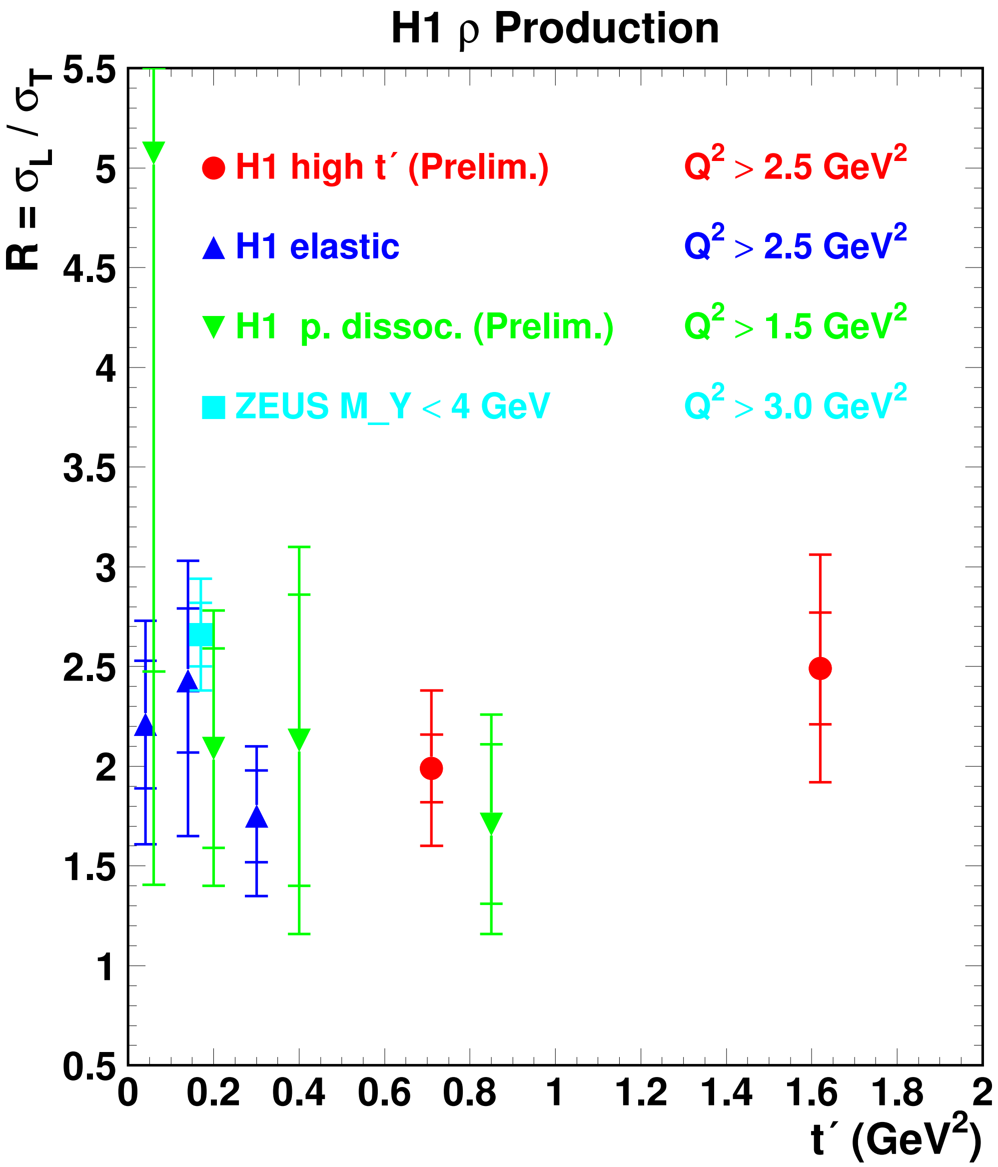




$\frac{\sigma_L}{\sigma_T}$ increases independently of proton dissociation

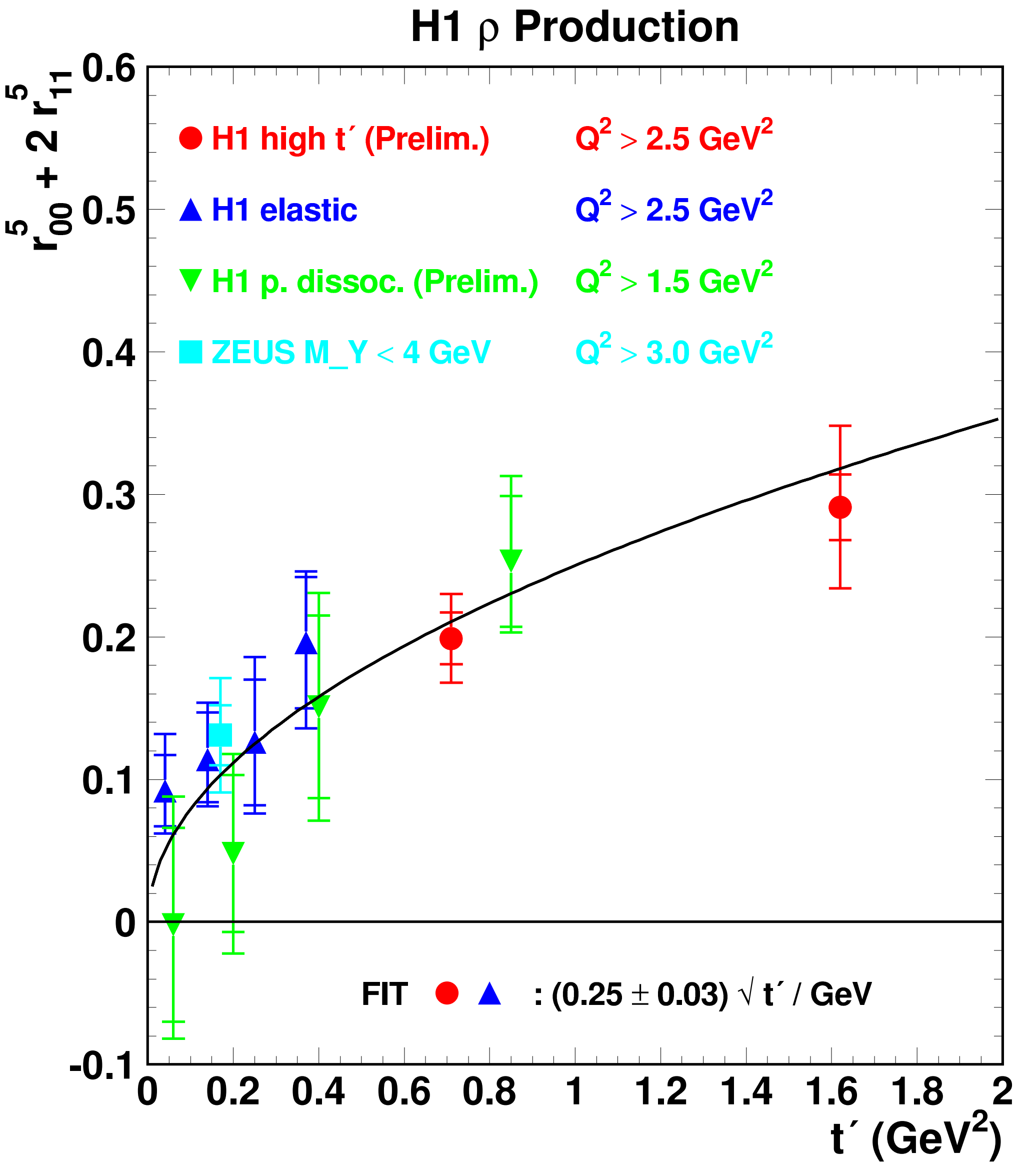
SCHC-breaking occurs independently of proton dissociation

Does R depend on $|t|$?



No strong t dependence in R

Does SCHC-breaking depend on $|t|$?

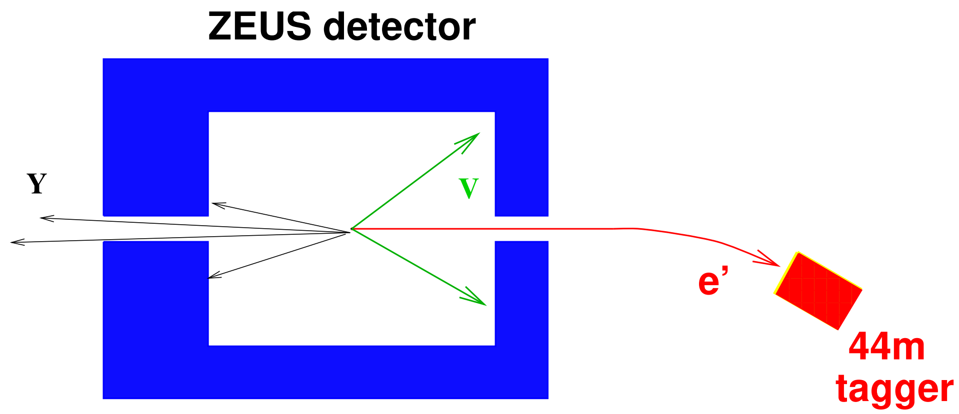


SCHC-breaking observed also for dissociative process

In Search of a Perturbative Description of VM Photoproduction at High $|t|$

A. Kowal/ZEUS at DIS2001

Photoproduction Tagging at $W \simeq$ 100 GeV



$$Q^2 < 0.02 \text{ GeV}^2$$
$$23 < E_{e'} < 25 \text{ GeV}$$
$$(\Rightarrow 80 < W < 120 \text{ GeV})$$

ZEUS 1996/97 preliminary

Integrated luminosity: 24 pb^{-1}

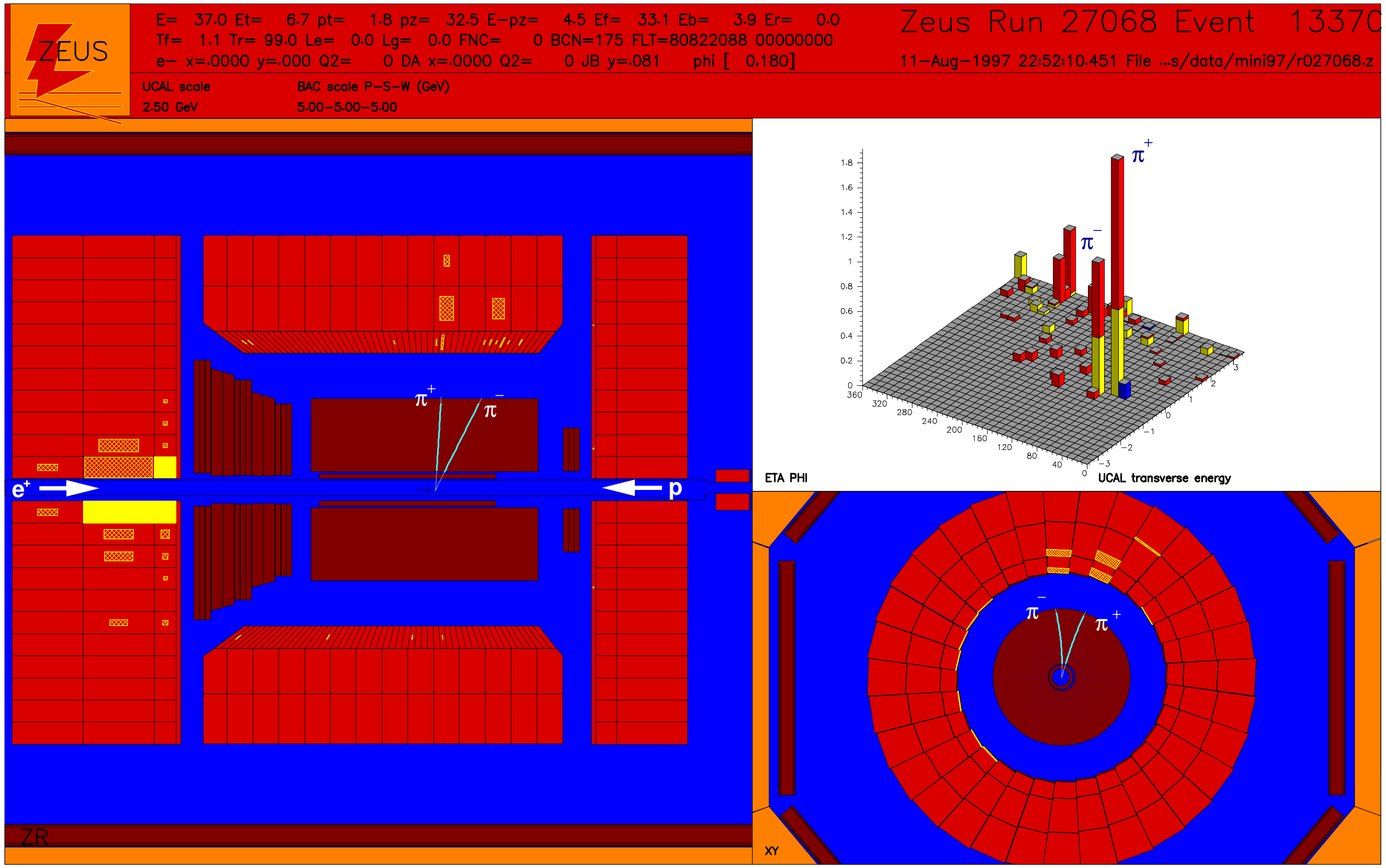
ρ^0: $\simeq$ 18k
ϕ: $\simeq$ 2k
J/ψ: $\simeq$ 150

Proton-dissociative process dominates at $|t| >$ 1 GeV^2

$$x = \frac{t}{t - M_Y^2}$$

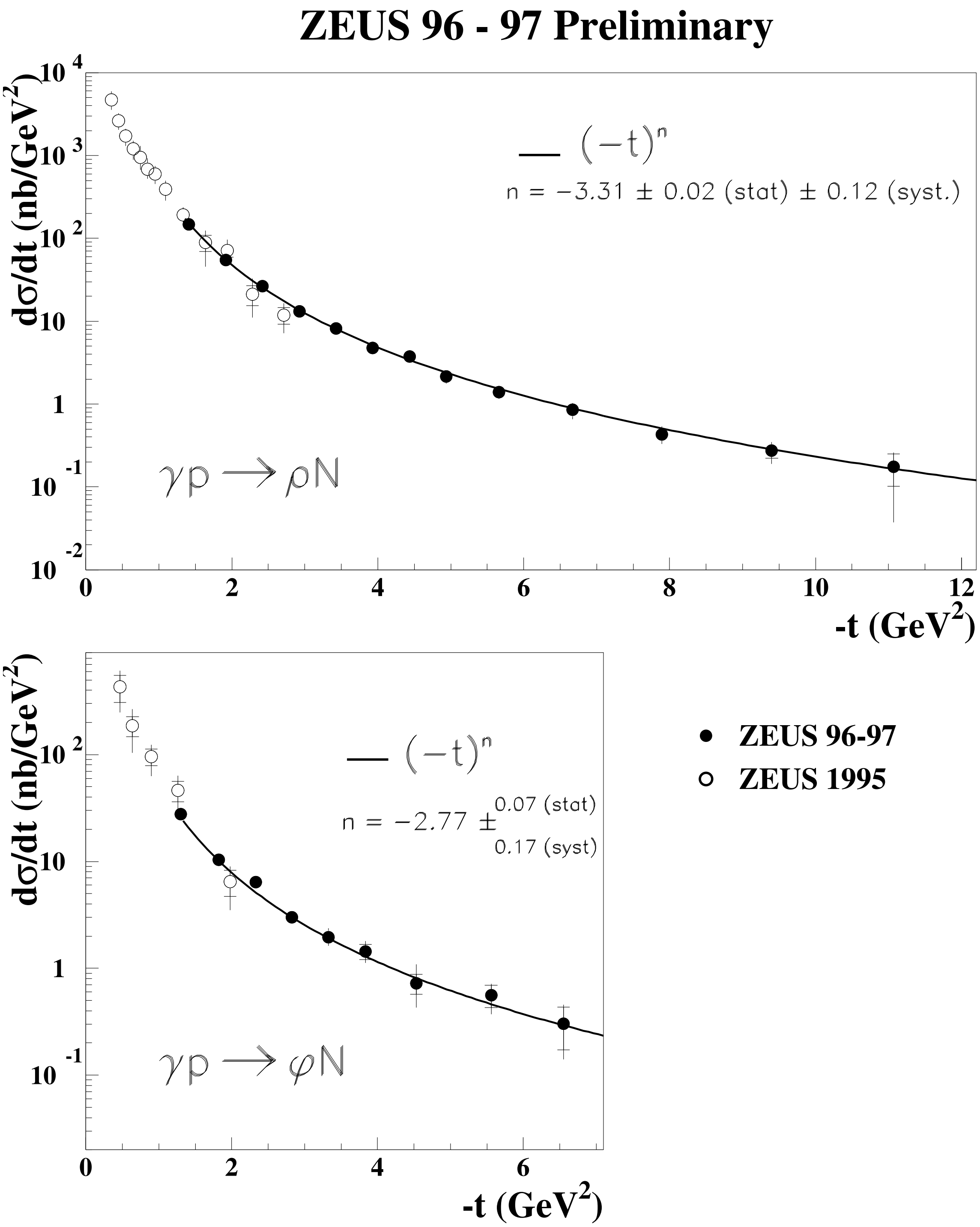
Cross sections $\frac{d\sigma}{dt}$ are integrated over $0.01 < x < 1$

Candidate for ρ^0 Photoproduction at High $|t|$



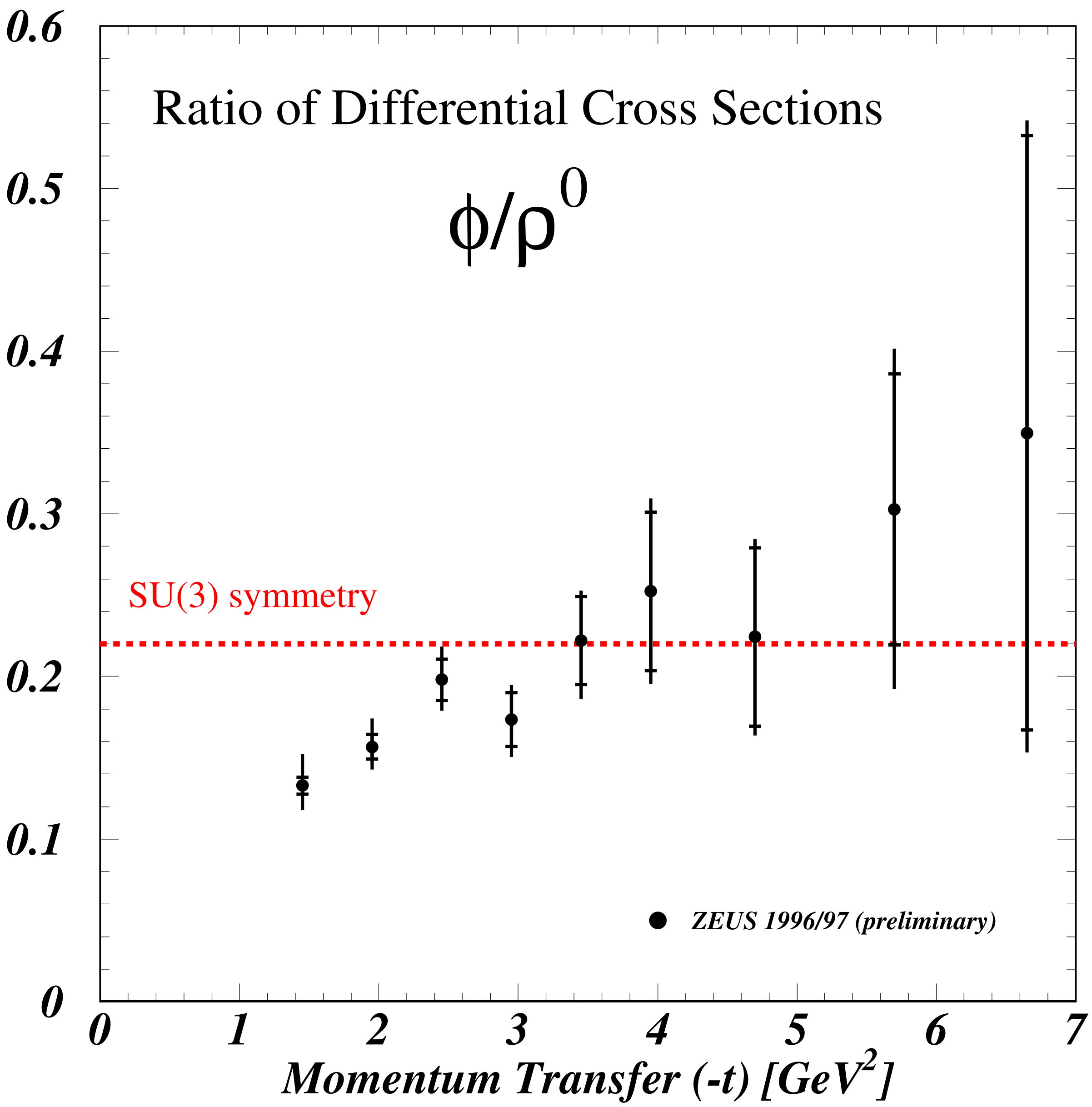
$$e^+p \to e^+N\,\rho^0 \to e^+ + \pi^+\pi^- + Y \qquad M_{\pi^+\pi^-} = 0.78\ \text{GeV},\ t = -10.0\ \text{GeV}^2,\ W = 81\ \text{GeV}$$

"Breakthrough" to power-law scaling!



Momentum-transfer spectrum impressively hard

Compare scaling for ρ^0 and ϕ

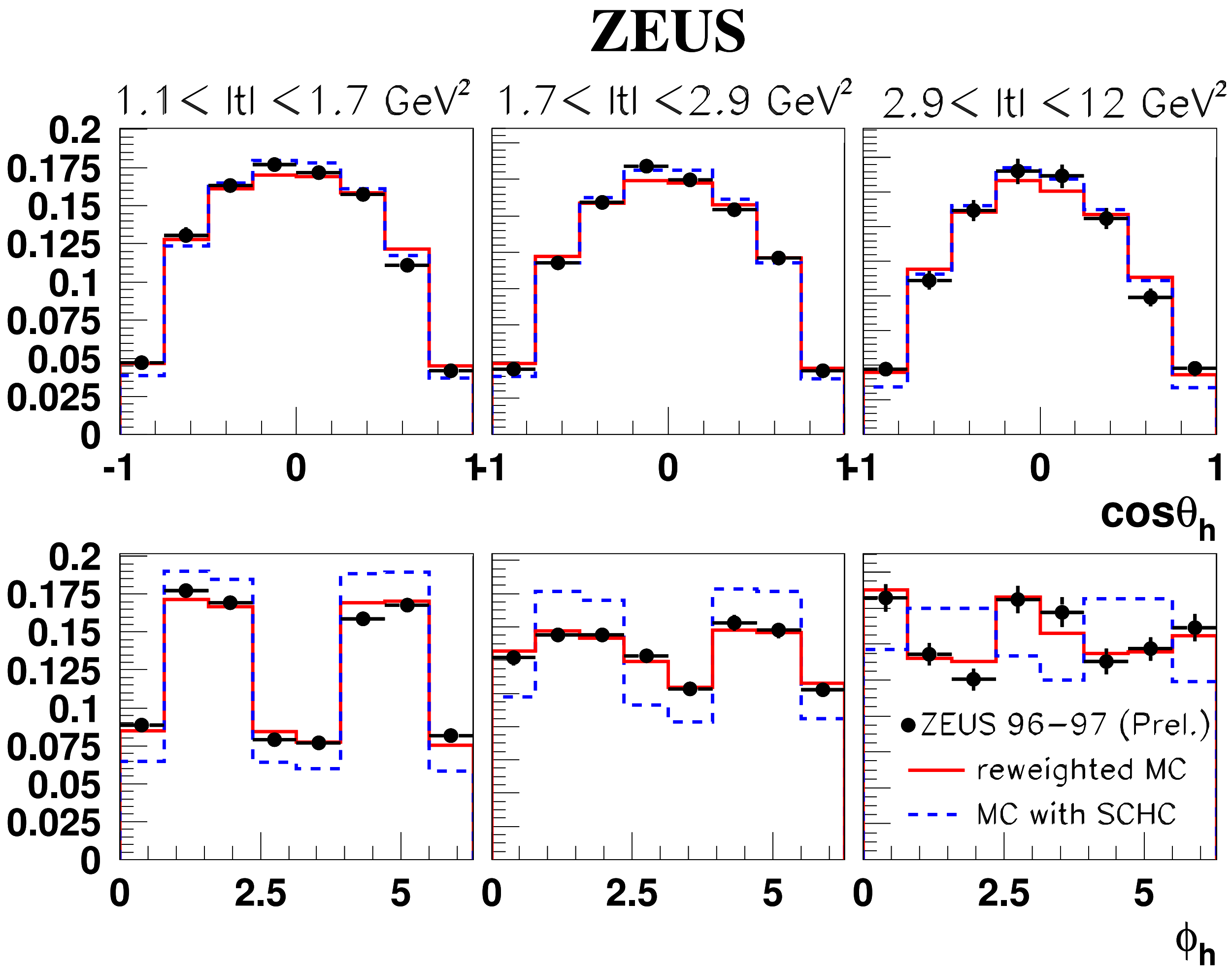


Again, magnitude of ϕ/ρ^0 ratio reaches the SU(3)-symmetry value in the same region where the scaling power equalizes (or not?)

Helicity transfer in high-$|t|$ γp?

At low Q^2, Φ_h poorly measured, so integrate over it:

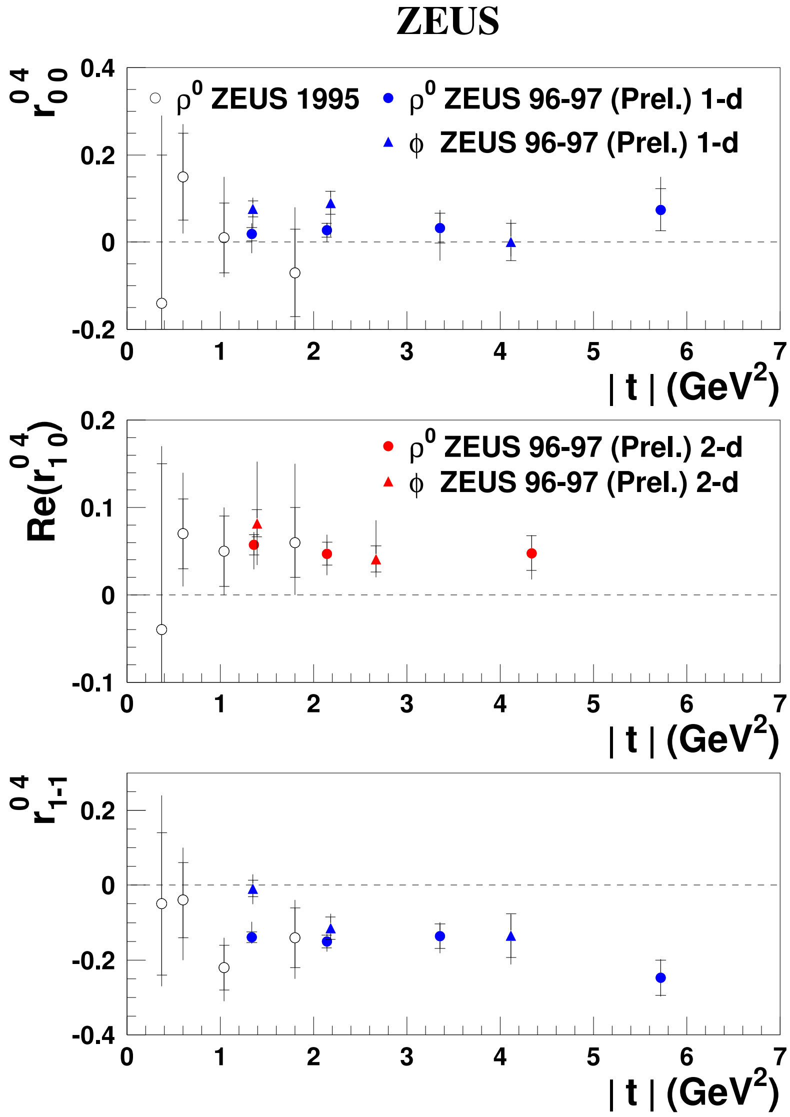
$$W(\cos\theta_h, \phi_h) = \frac{3}{4}\Big[\frac{1}{2}\left(1 - r^{04}_{00}\right) + \frac{1}{2}\left(3r^{04}_{00} - 1\right)\cos^2\theta_h - \sqrt{2}\mathrm{Re}(r^{04}_{10})\sin 2\theta_h \cos\phi_h - r^{04}_{1-1}\sin^2\theta_h\cos 2\phi_h \Big]$$



Clear violation of helicity conservation

New 2-dimensional analysis ...

T→L transition observed !



$r^{04}_{00} \propto T^2_{01}$

(Single-flip probability)

$Re(r^{04}_{10}) \propto Re\left(T_{11}T^*_{01}\right)$

(Single flip via interference)

$r^{04}_{1-1} \propto Re(T_{11}T^*_{1-1})$

(Double flip via interference)

Transverse polarization dominates

Single flip (T→L) clearly measured at level of few %

(But why no dependence on t?)

Also significant double-flip contribution

See Ivanov et al, Phys. Lett. B478 (2000) 101

Helicity violation via chiral-odd $q\bar{q}$ configurations in the photon

General remarks on scaling results for ρ^0,ϕ photoproduction at high $|t|$

☞ These are the first measurements of light-vector-meson photoproduction at values of t comparable to the Q^2 values in DIS which led to the discovery of charged proton constituents in 1967.

☞ *BUT* this is presumably a strong interaction, rather than electromagnetic.

☞ We observe an extremely hard t dependence
$\Rightarrow$ low-order process (*first* order ?)

☞ *The QCD helicity selection rules appear to be violated.*

☞ These values for t exceed the mass scales for ρ^0 and ϕ and exceed Λ^2_{QCD}
$\Rightarrow$ Asymptotic region

The t dependence characterizes the interaction.

Perturbative field theory

for vacuum exchange in the strong interaction (?)

What is the exchanged field?

What is the "charge"?
(Strength about 1/100 of confinement)

What is the reacting proton constituent?

Conclusions

Diffractive vector-meson production at HERA presents an opportunity to study the dynamics of vacuum-exchange processes

The light vector mesons ρ^0, ω and ϕ

- Study scaling with $\Delta p \gg$ M$_V$
  - Photon virtuality Q^2 (photon size)
  - Δp at proton vertex (resolve proton)
- Study flavor symmetry
- Study transition to pert. region in Q^2 and/or t
- Multivariable analysis of helicity structure

Many phenomenological successes for QCD so far, but recent results are raising serious questions

An amazing series of discoveries continues