ZEUS Weekly Meeting
DESY

24 September 2001

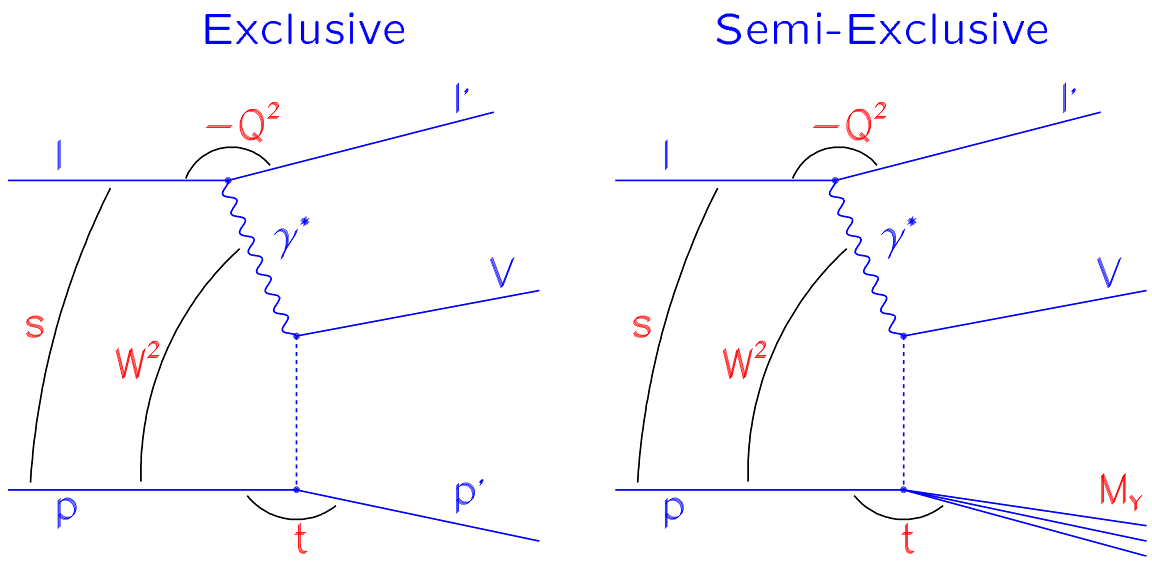
The Vector-Meson Puzzle

Scaling Laws and Helicity Selection

- ☞ **Helicity selection rules and scaling**
- ☞ **QCD description of diffractive processes**
- ☞ **Scaling and helicity in VM electroproduction**
- ☞ **Surprise in high-$|t|$ VM photoproduction**

J. A. Crittenden/DESY
(On leave from Phys. Inst. Bonn)

Production of 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 ($Q^2 \ll |t| \Rightarrow t \simeq -P_{\mathrm{T}}^2(\mathrm{V})$)

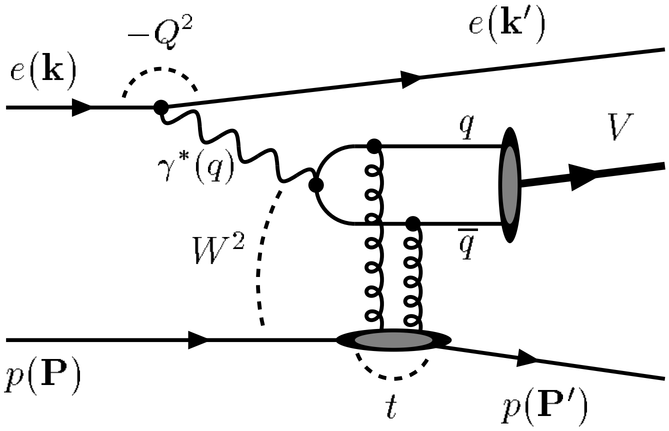
t: Square of Momentum Transfer at the Proton Vertex

$|t| < 13$ GeV^2

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

Perturbative QCD for Diffraction (?!)

☞ Exchange of a color-neutral pair of gluons



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

Only longitudinal photons have point-like interactions !

$$\left.\frac{d\sigma^L_{\gamma^* p \to Vp}}{d|t|}\right|_{t=0} = A_V \frac{\alpha_s^2(\bar{Q}^2)}{\alpha \bar{Q}^6} \left| \left[1 + \frac{i\pi}{2} \frac{d}{d(\ln x)} \right] xG(x, \bar{Q}^2) \right|^2$$

Energy dependence determined by $G(x, \bar{Q}^2)$, $x \approx Q^2/W^2$

Ryskin, Z.Phys. C57 (1993) 89 (J/ψ photoproduction)

$$\bar{Q}^2 = \frac{Q^2 + M_V^2 - t}{4} \ (?)$$

What experimental signatures for the region of pQCD validity ?

☞ ZEUS has concentrated on energy (x_{Bj}) dependence.
(E.g. Sascha Savin at XXXI Symp. on Mult. Dynamics)

☞ In this talk I consider the dependence on momentum transfer as requiring an explanation involving point-like reaction.
(E.g. scaling arguments for DIS at SLAC in 1967)

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 Zhitnitsky (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 $\propto Q^{-8}$
(but endpoint problems!)

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

General Remarks on Vector-Meson 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

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

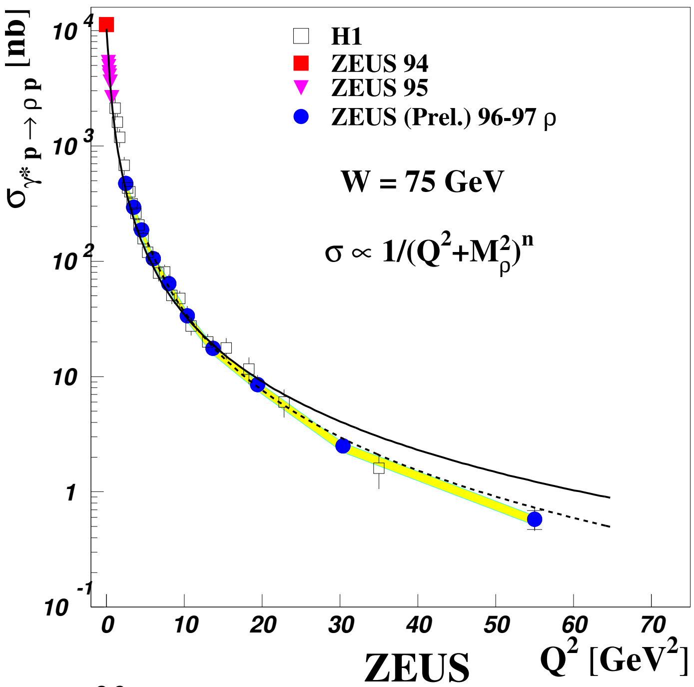
☞ **Exclusivity allows study of helicity structure via decay angles**

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

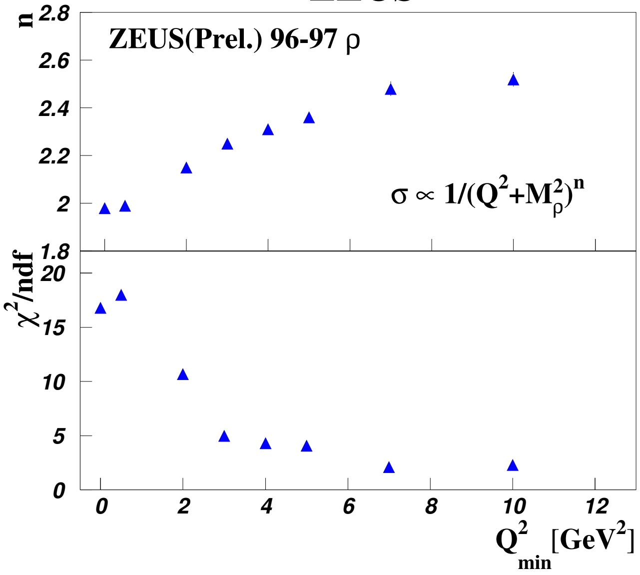
Elastic ρ^0 Electroproduction

A. Kreisel/ZEUS at DIS2001

$$\sigma \propto (Q^2 + M_V)^{-n}$$



n



χ^2/ndf

Power-law scaling?

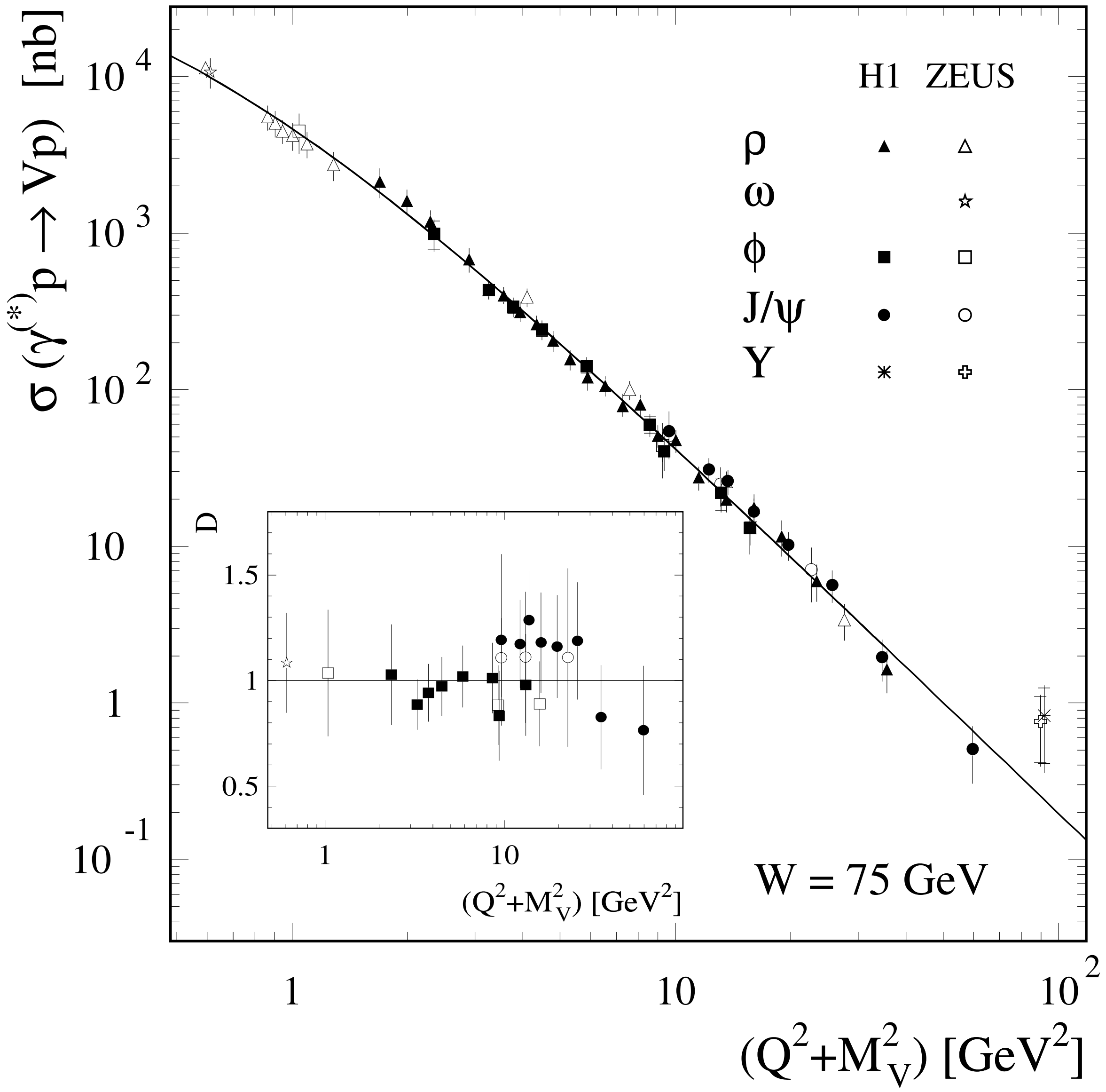
Yes, but power changing with Q^2

Approaching power of 6 at high Q^2

Note: Brodsky et al. prediction for σ_L and $Q^2 \gg M_V^2$ only

Comparing the vector mesons

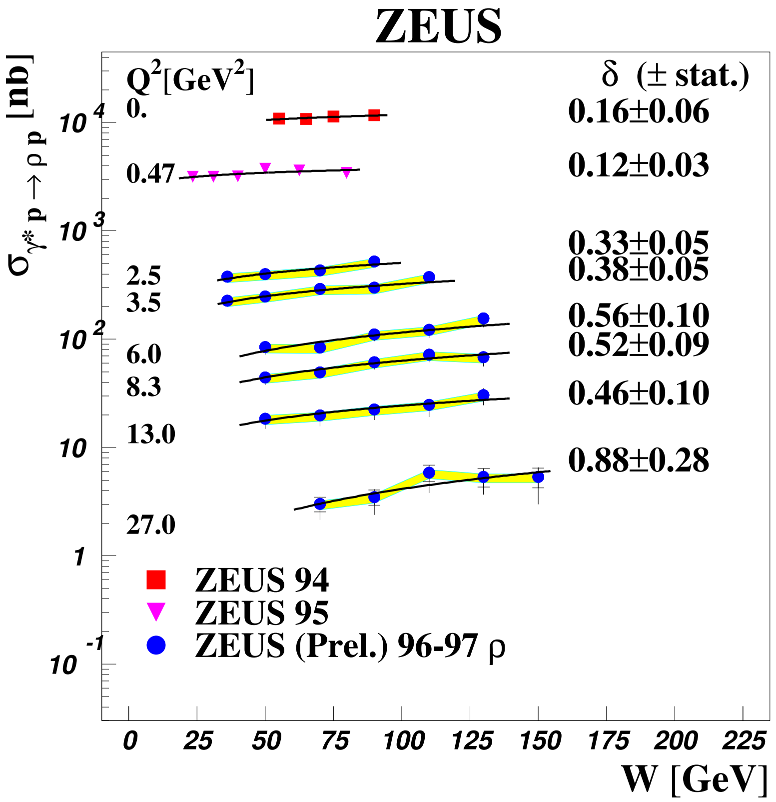
H1 Collaboration, Phys. Lett. B483 (2000) 360

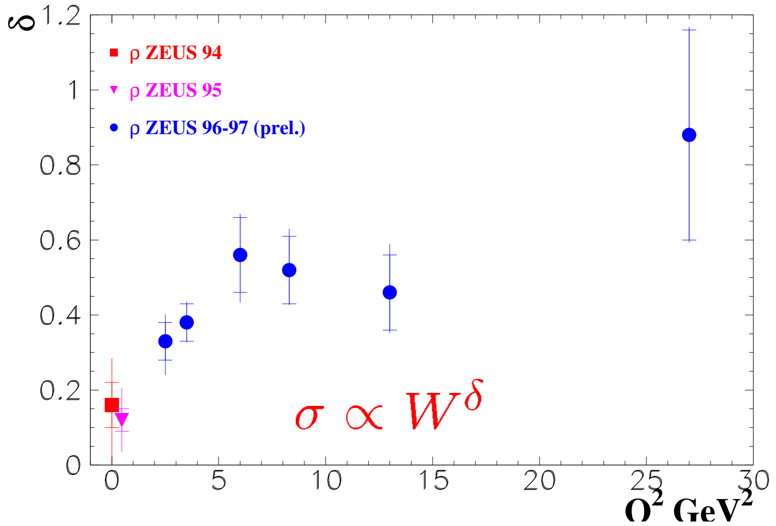


Universal scaling (?)

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

Does energy dependence vary with Q^2?

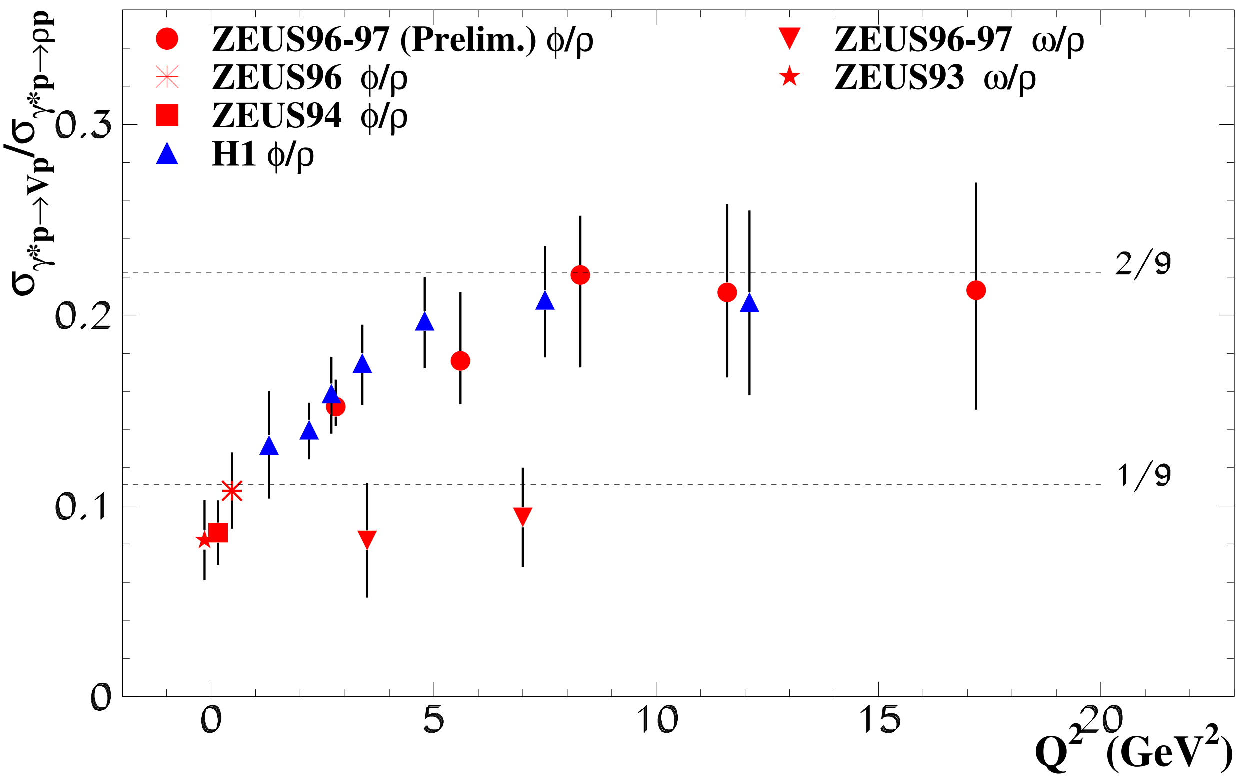




Energy dependence steepens with Q^2

Impressive support for pQCD description

What about flavor symmetry ?



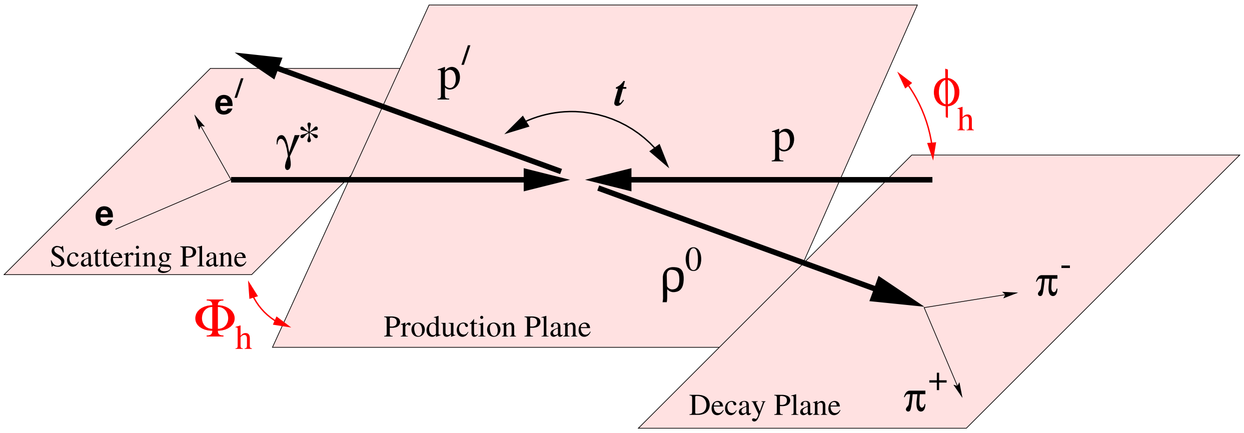
Magnitude of ϕ/ρ^0 ratio reaches the SU(3)-symmetry value in the same region where the scaling power equalizes

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

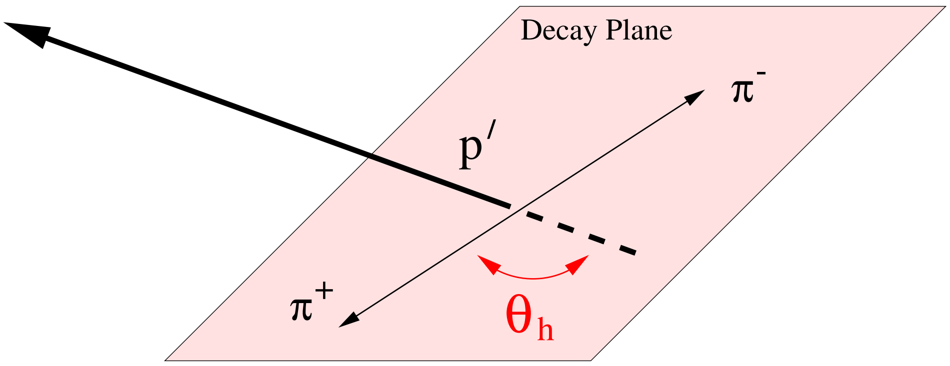
(see high-$|t|$ photoproduction results below)

Helicity Analyses

$\boxed{\gamma^* \text{ p center-of-mass frame}}$



$\boxed{\rho^0 \text{ rest frame}}$



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: $\vec{\epsilon_\gamma} = \pm P^c_\gamma\,(0,0,1)$

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

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(θ,ϕ) = W^0(θ,ϕ) $\pm$ P$^c_\gamma$ W^3(θ,ϕ)

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

H1, ZEUS wait for HERA II

3. Linearly polarized:

   W(θ,ϕ,Φ) = W^0(θ,ϕ) - P^l_γ $\cos 2\Phi$ W^1(θ,ϕ)
   - P^l_γ $\sin 2\Phi$ W^2(θ,ϕ)

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!

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

Constraints from hermiticity, parity conservation

3-D Decay-Angle Distribution

(15 linearly independent parameters)

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

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

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

$$+\sqrt{2\varepsilon(1+\varepsilon)}\cos\Phi_h\big(\,r^5_{11}\sin^2\theta_h + r^5_{00}\cos^2\theta_h$$
$$-\sqrt{2}\,\mathrm{Re}\,r^5_{10}\,\sin 2\theta_h\cos\phi_h$$
$$-r^5_{1-1}\sin^2\theta_h\cos 2\phi_h\,\big)$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\Phi_h\big(\,\sqrt{2}\,\mathrm{Im}\,r^6_{10}\,\sin 2\theta_h\sin\phi_h$$
$$+\mathrm{Im}\,r^6_{1-1}\sin^2\theta_h\sin 2\phi_h\big)\Big]$$

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

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

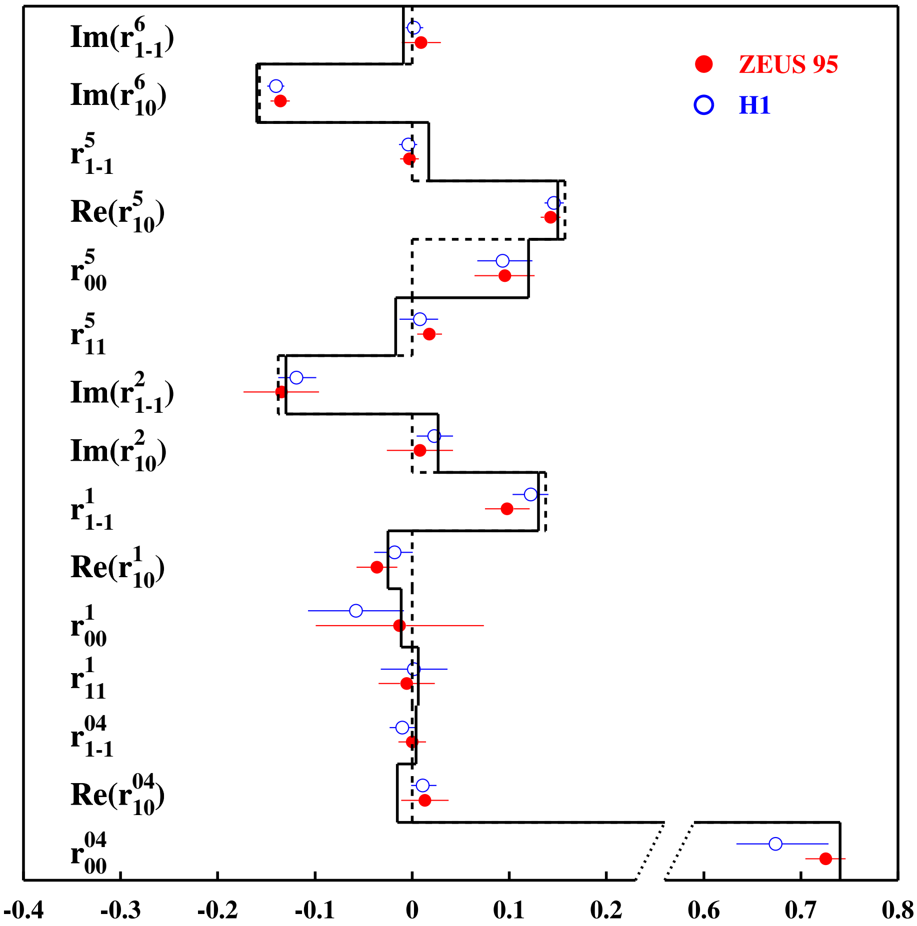
$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{T^2_{00}+2\,T^2_{10}}{T^2_{01}+T^2_{11}+T^2_{1-1}}$$

(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

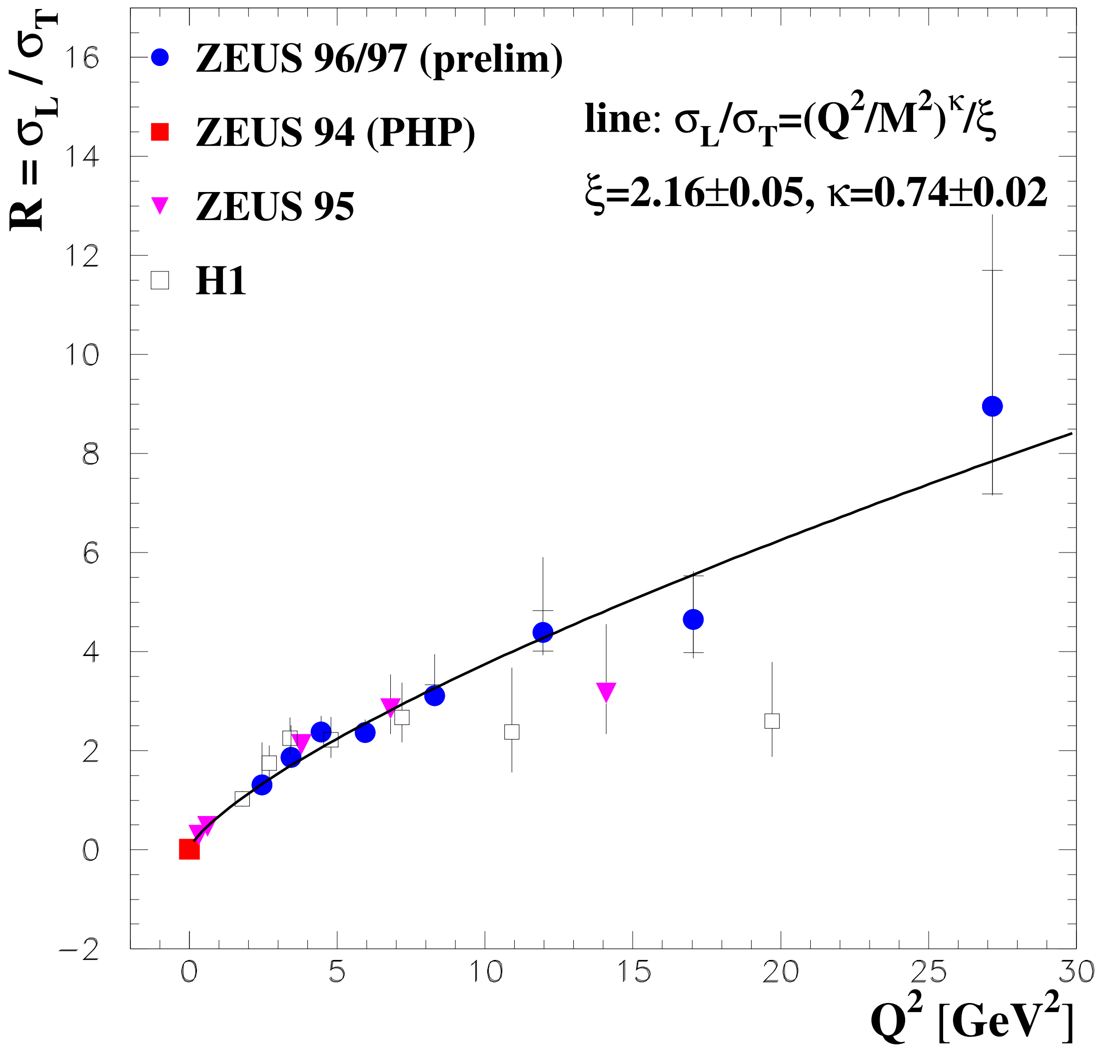
Predicted by Ivanov and Kirschner
Phys. Rev. D58 (1998) 114026

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

What about ratio of σ_L to σ_T?

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

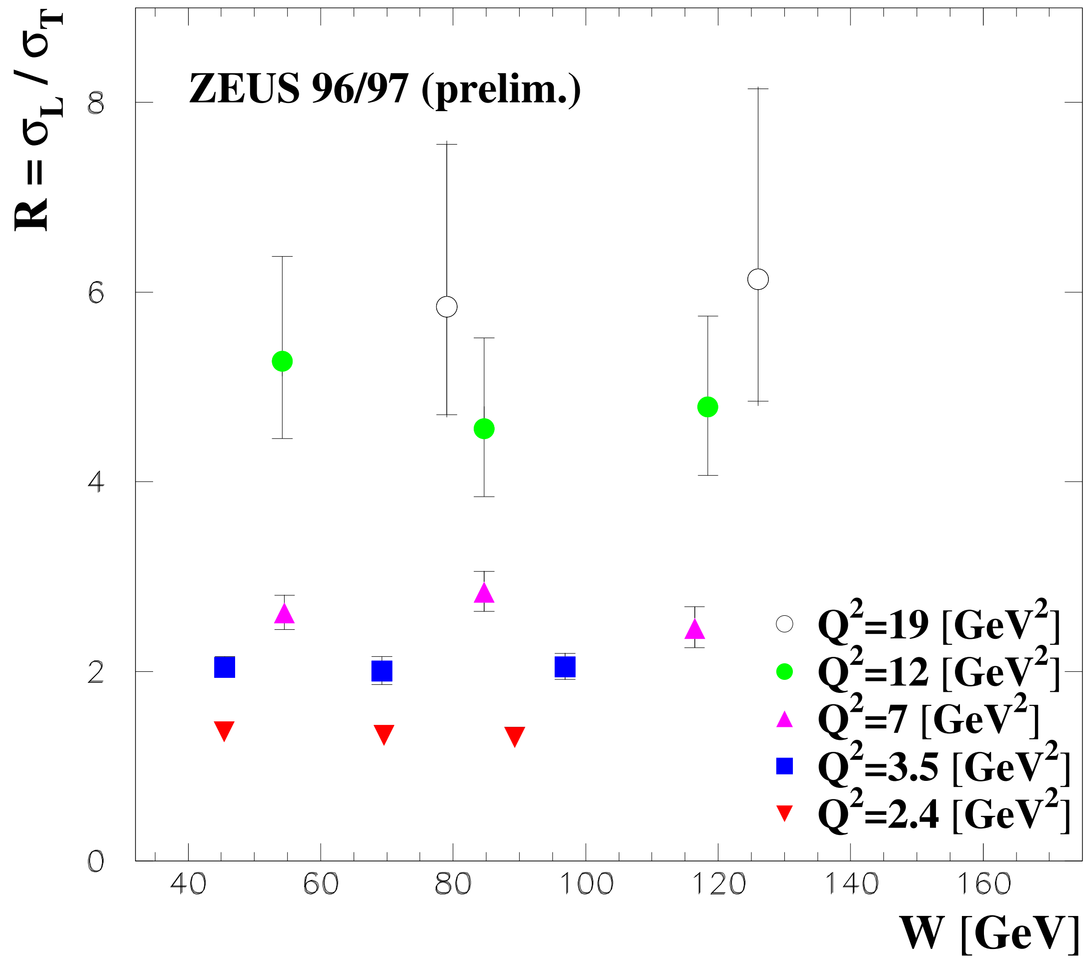
Δ now known to be small (helicity violation)



The dominance of σ_L was an early prediction of pQCD ($\lesssim$ 1994)

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

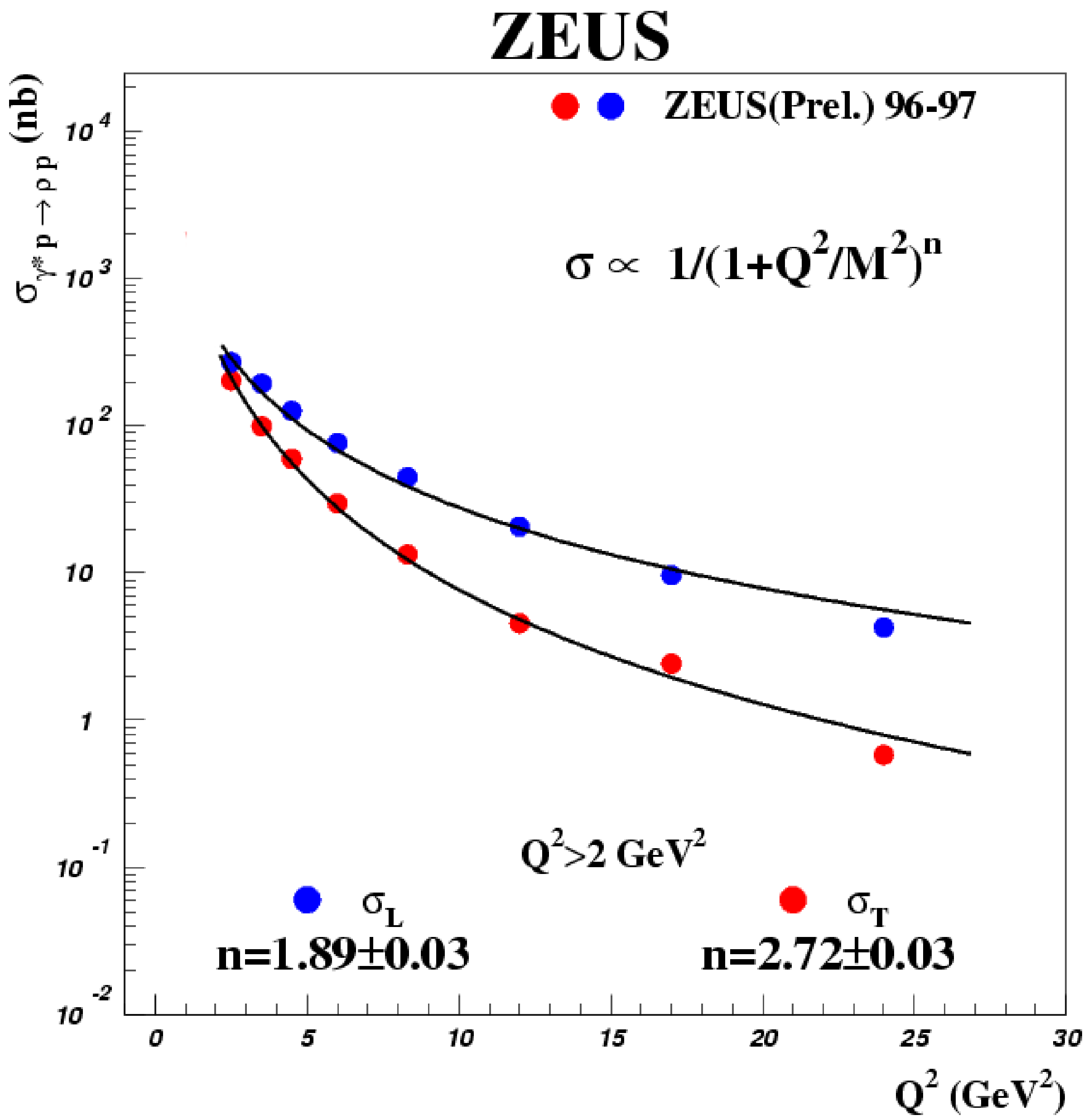
Energy dependence in $\sigma_\mathrm{L}/\sigma_\mathrm{T}$?



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

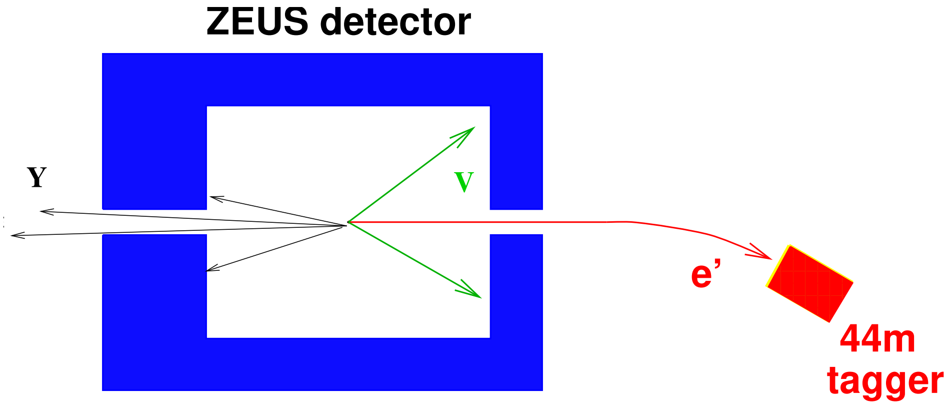
Remarkably hard scaling behavior for σ_T

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

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

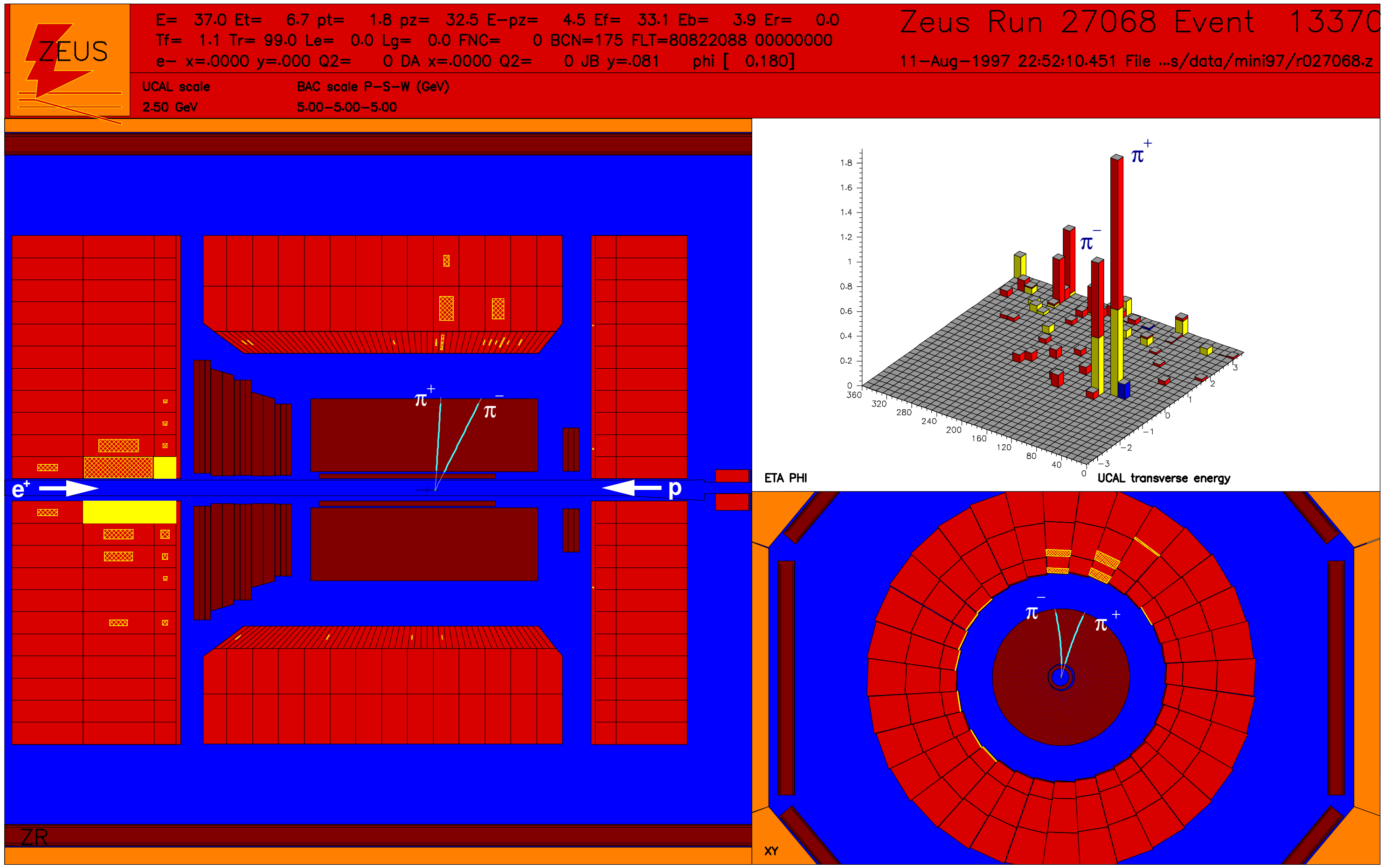
J/ψ: $\simeq$ 150

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 $0.01 < x < 1$

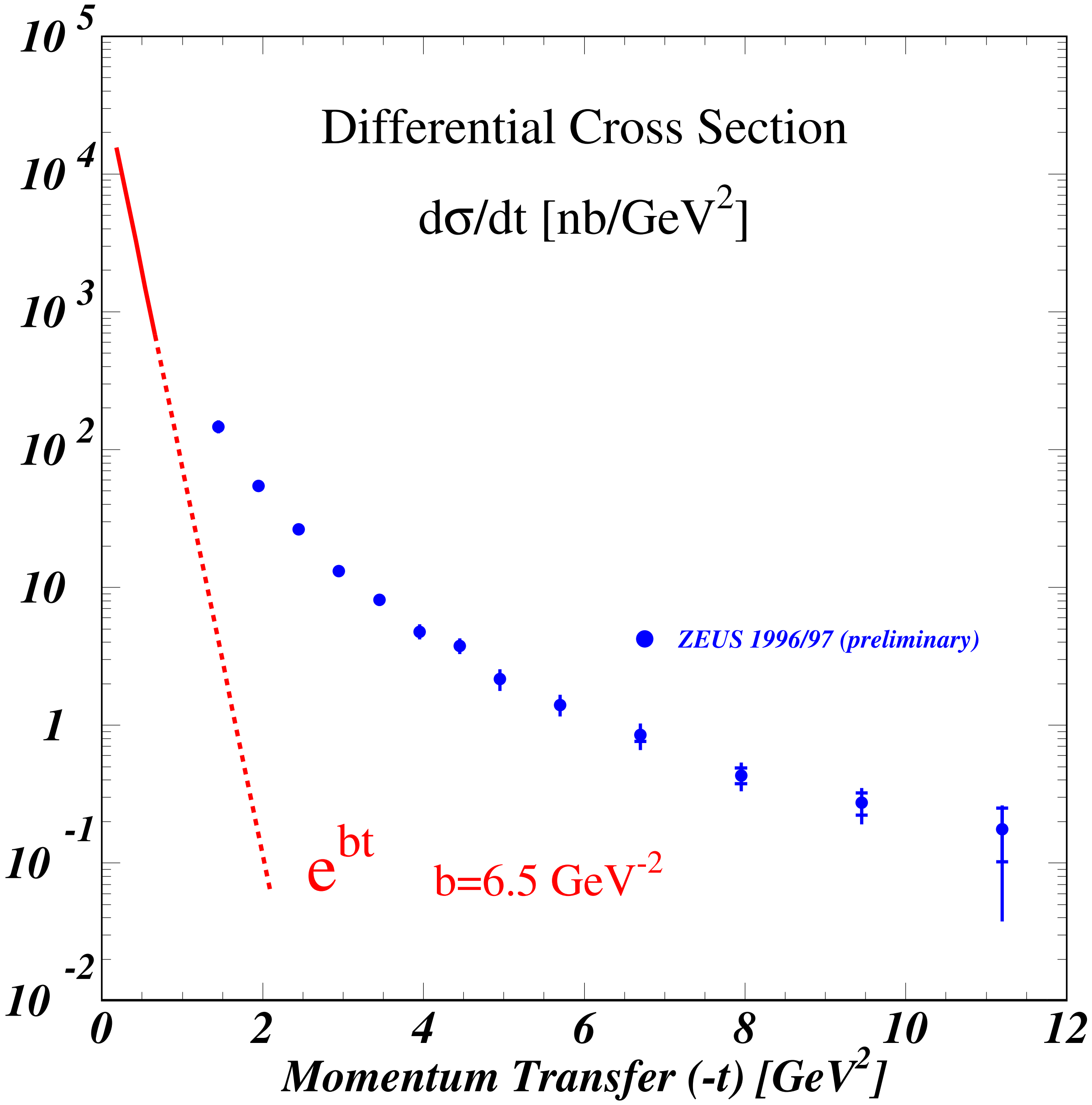
Candidate for ρ^0 Photoproduction at High $|t|$



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

Diffractive ρ^0 Photoproduction (I)

$$\gamma + p \rightarrow \rho^0 + Y$$

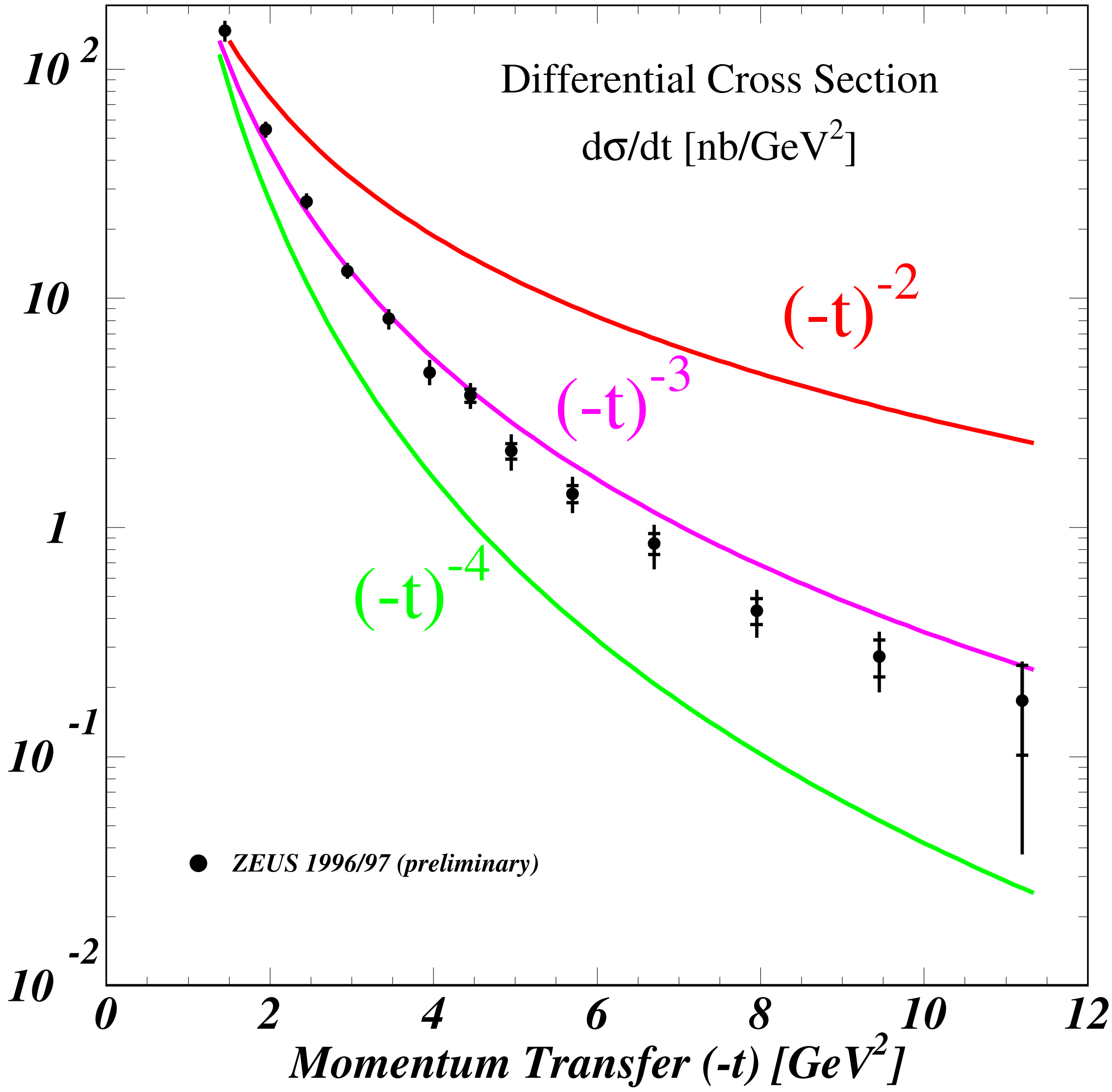


Asymptotic region $|t| \gg M_\rho^2$

Strength of high-$|t|$ process $\simeq 1/100$ of forward mechanism

Diffractive ρ^0 Photoproduction (II)

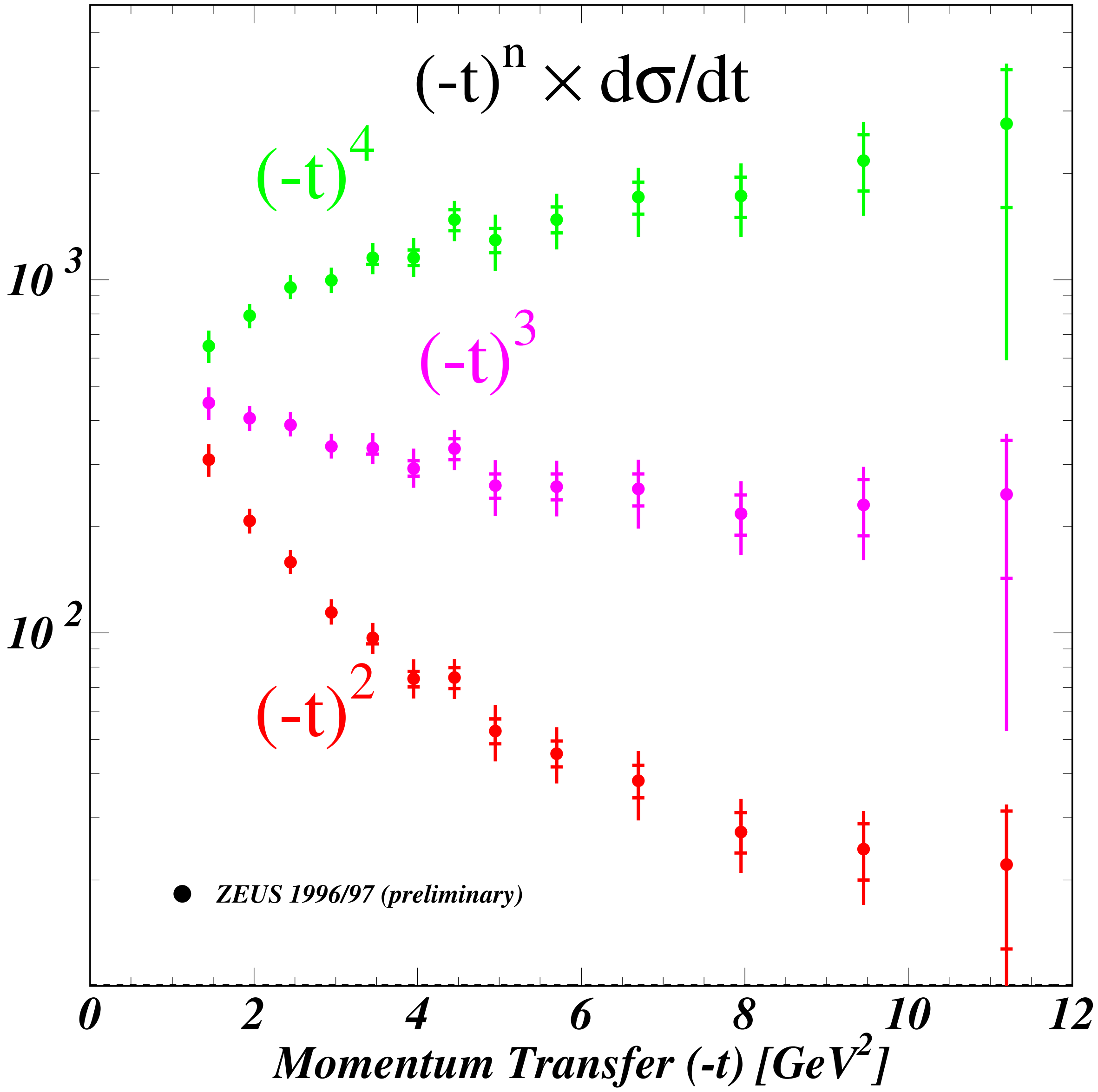
JAC, APS Meeting, 9 Aug 2000, hep-ex/0010079



<u>Scaling Property</u>

Power dependence with
$n = 3$
matches the data fairly well

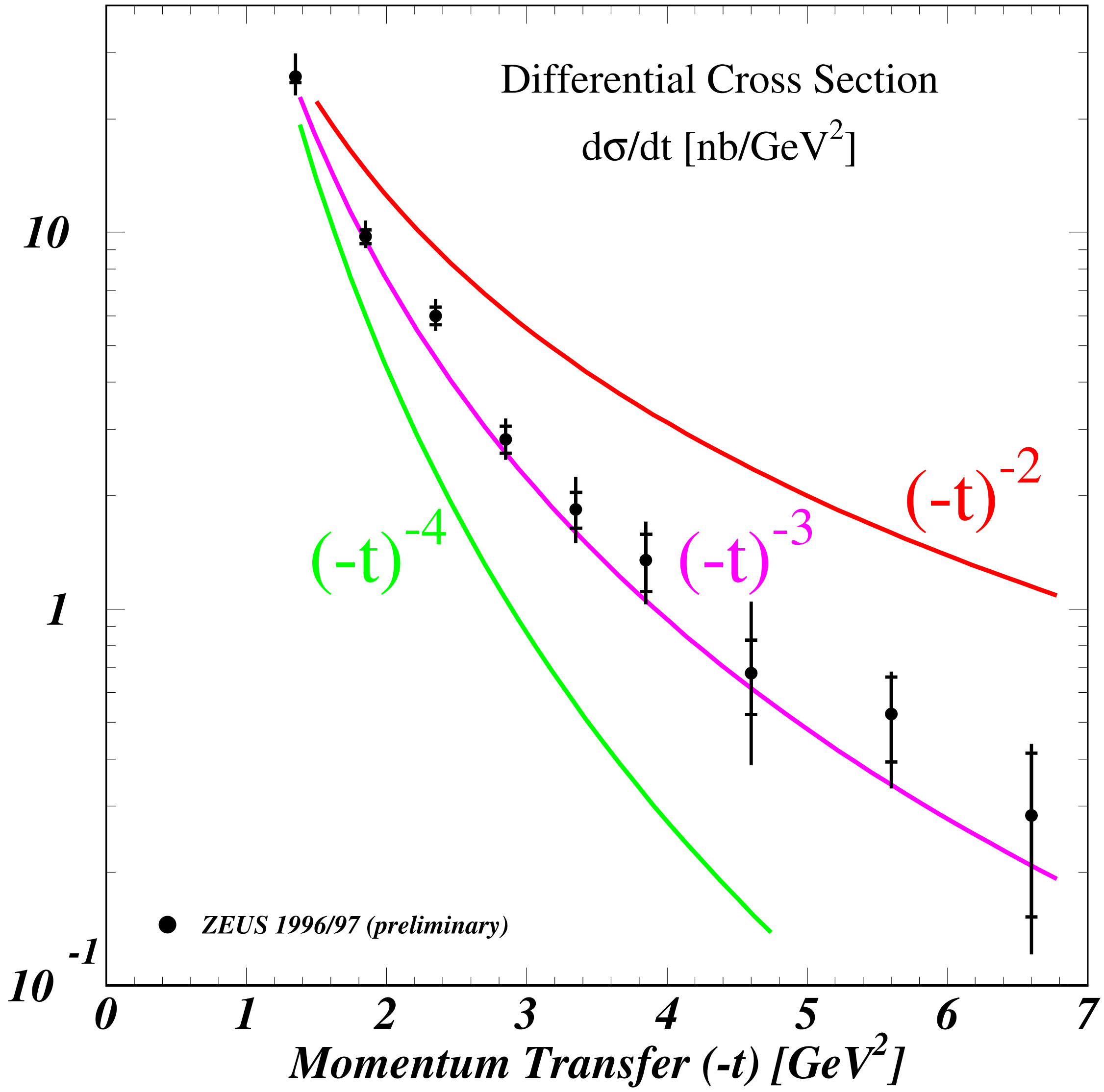
Diffractive ρ^0 Photoproduction (III)



Multiplying with $(-t)^n$

$2 \leq |t| \leq 4$ GeV^2 transition region to $(-t)^3$

Diffractive ϕ Photoproduction (I)



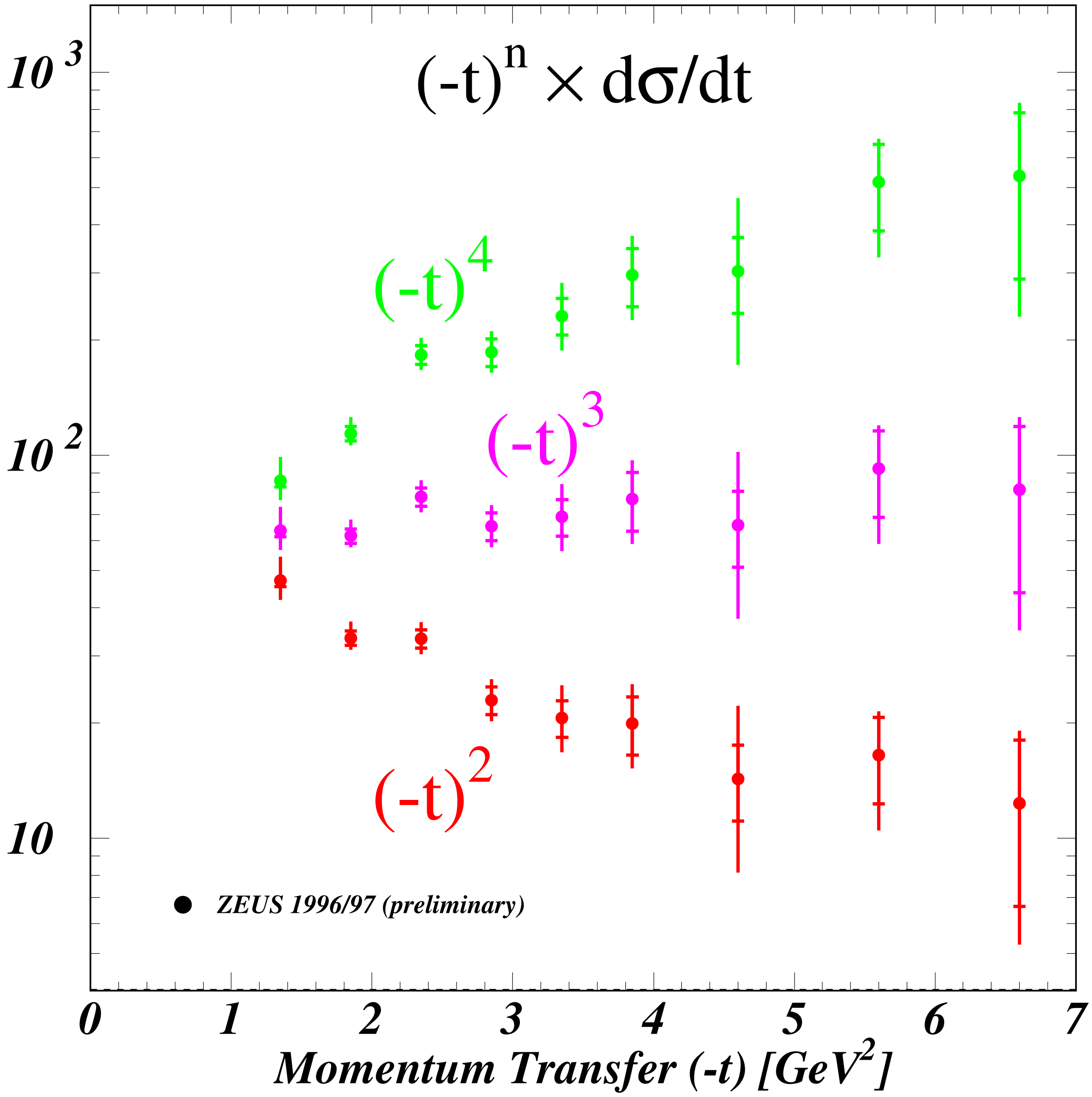
<u>Scaling Property</u>

Power dependence with

$n = 3$

matches the data well

Diffractive ϕ Photoproduction (II)

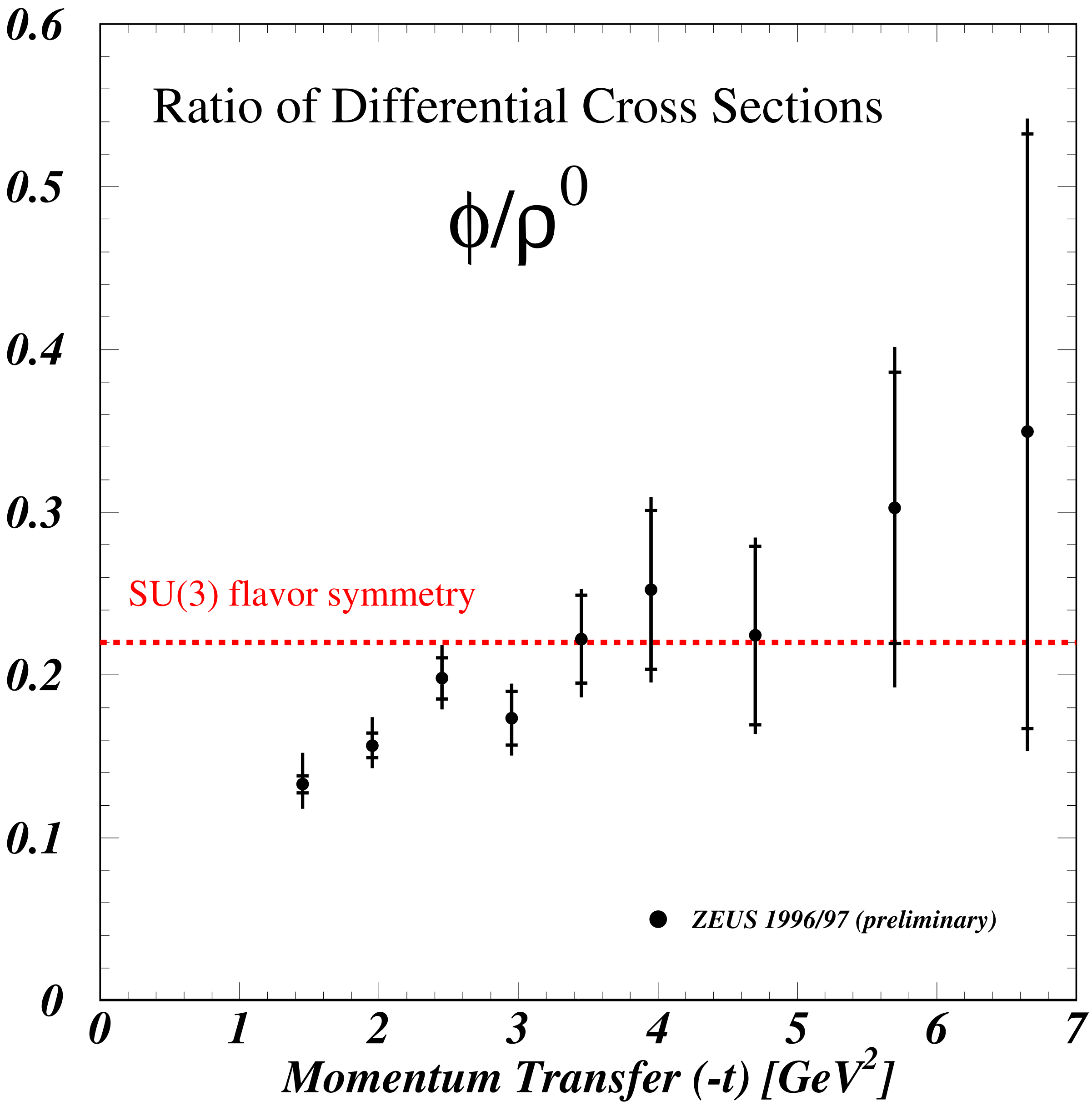


Multiplying with $(-t)^n$

Transition region observed for ρ^0 is absent for ϕ

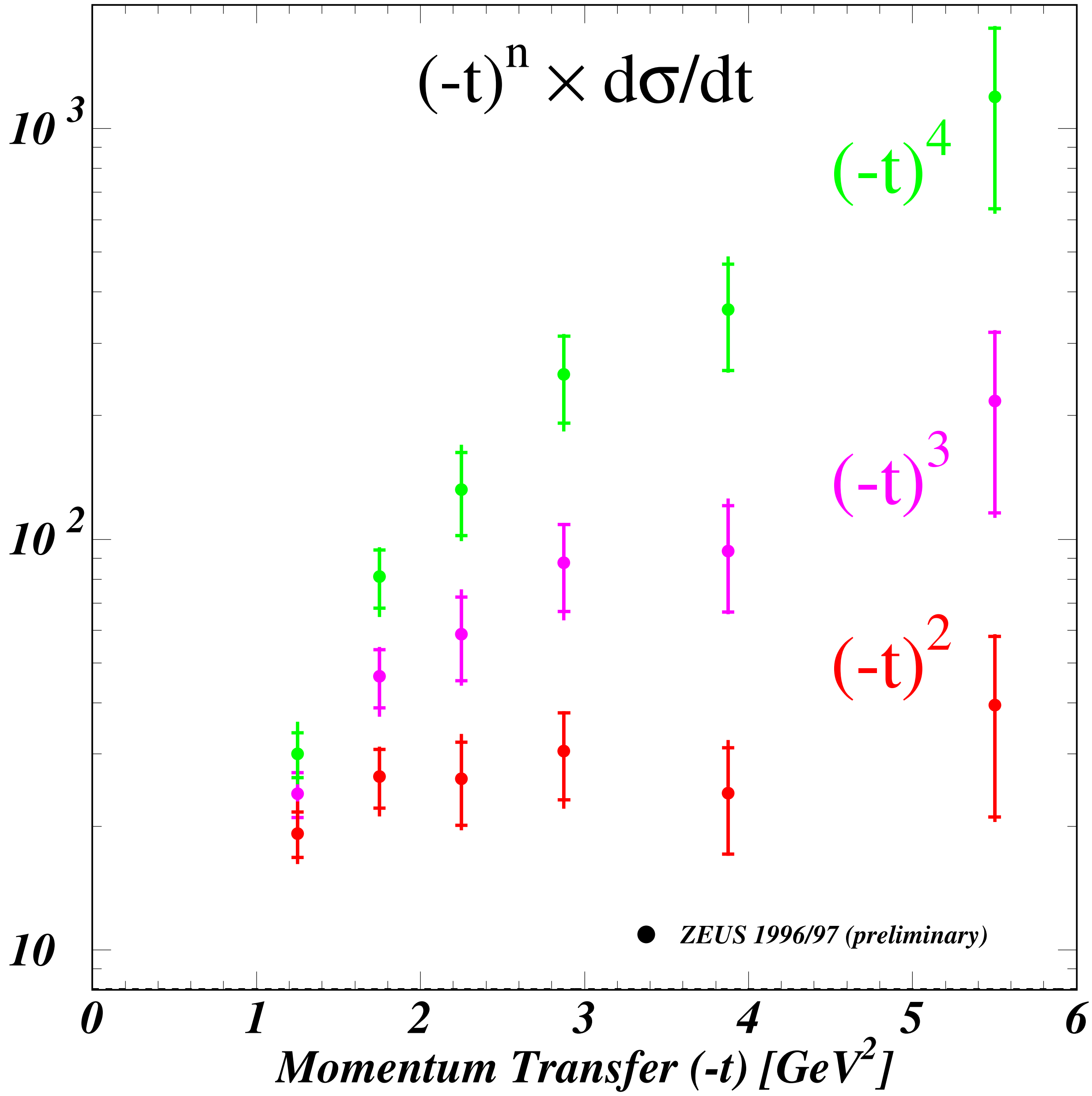
ϕ production free of non-vacuum-exchange backgrounds which contribute to ρ^0 and ω

Compare scaling for ρ^0 and ϕ



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

Diffractive J/ψ Photoproduction (I)

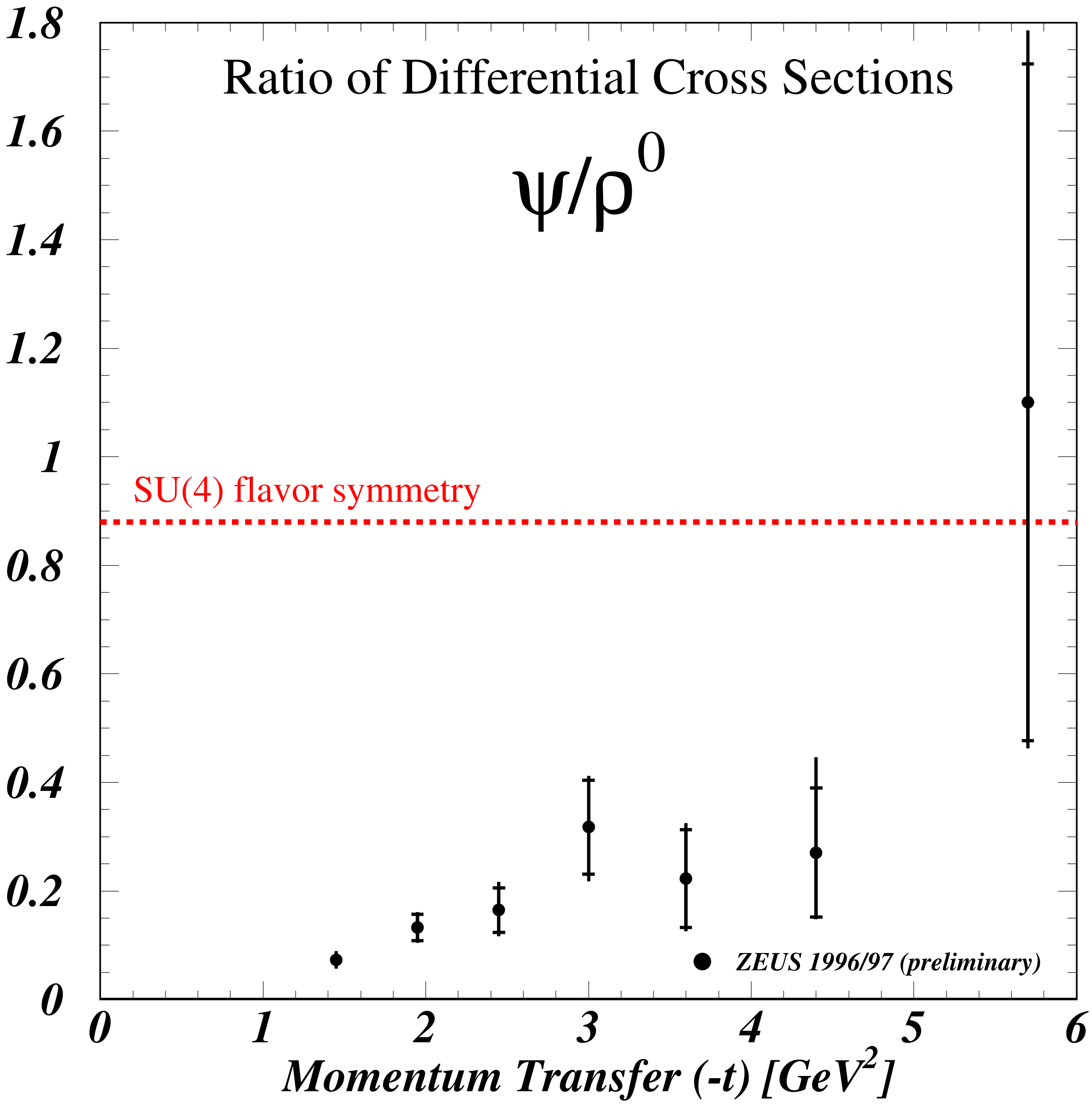


But here we have $|t| < M^2_{J/\psi}$

Meson structure effects may be important

SU(4) symmetry broken (see next figure)

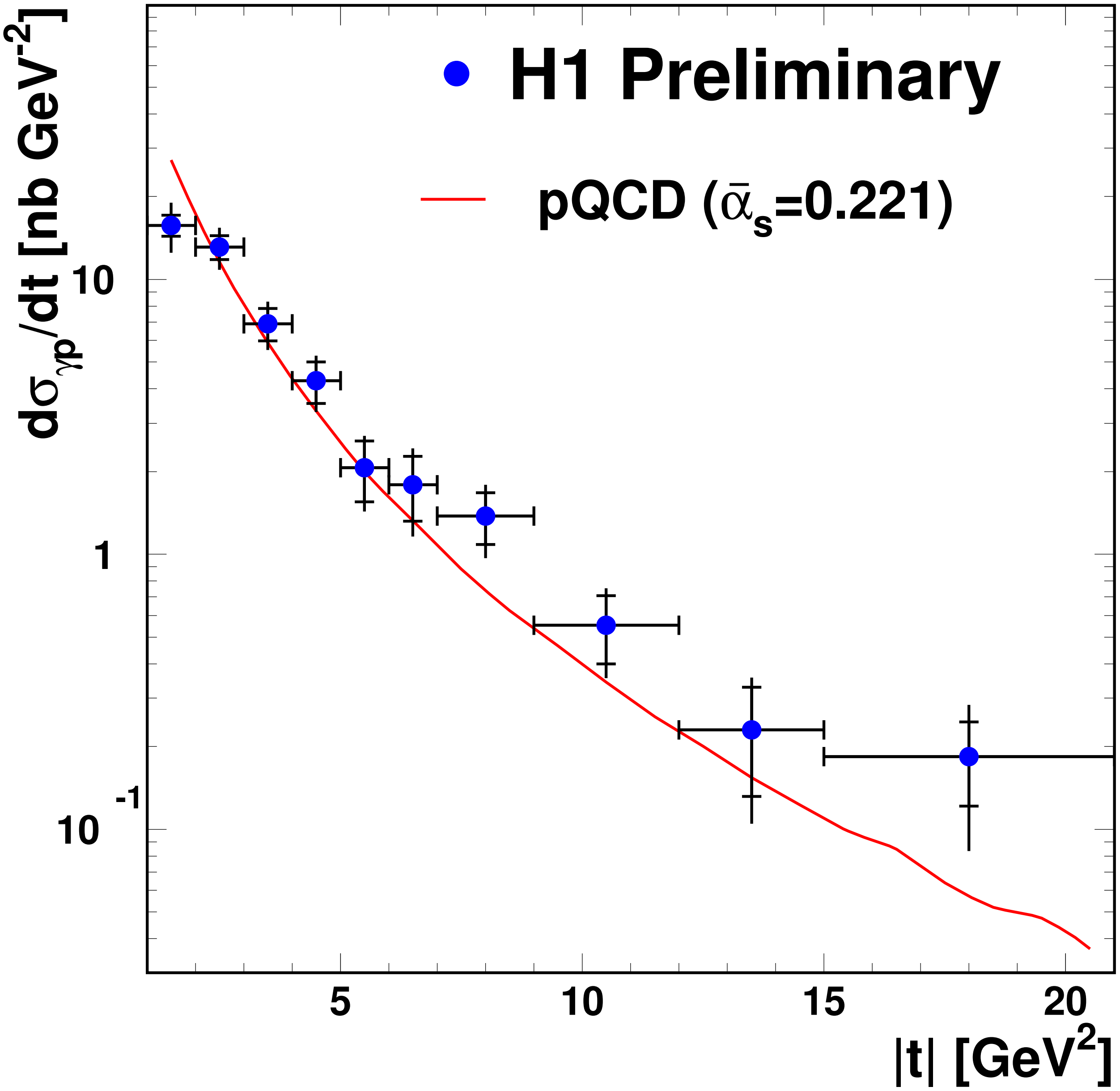
Ratio of J/ψ to ρ^0 Production



NOT asymptotic region ($|t| < \mathrm{M_V^2}$)

Diffractive J/ψ Photoproduction (II)

Talk by D. Brown/H1 at DIS2001



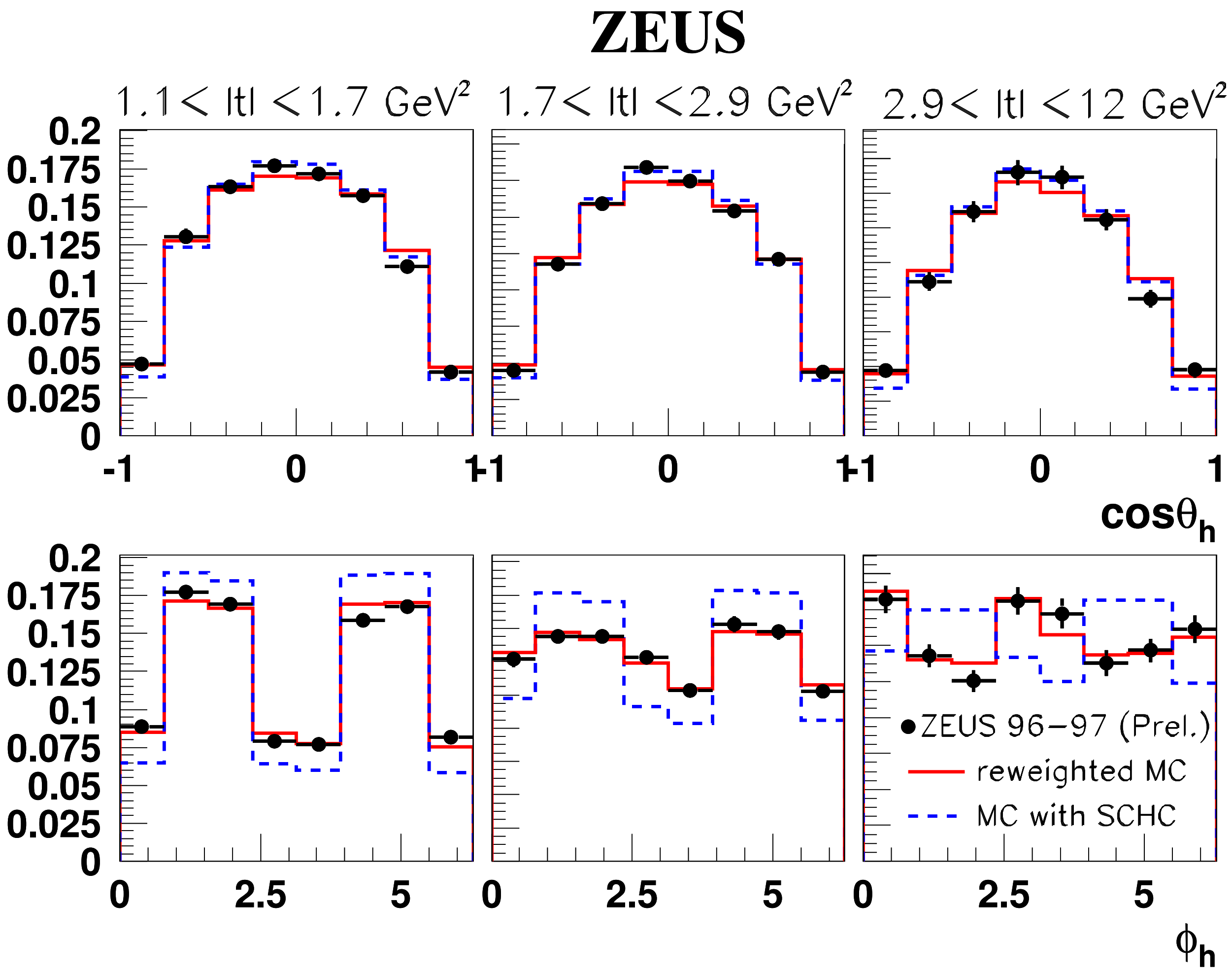
Preliminary H1 measurement also available

but should not be compared to ZEUS measurement
because integrated over angle (M_Y^2/W^2)
rather than over $x = -t/M_Y^2$

Helicity transfer in high-$|t|$ γp?

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

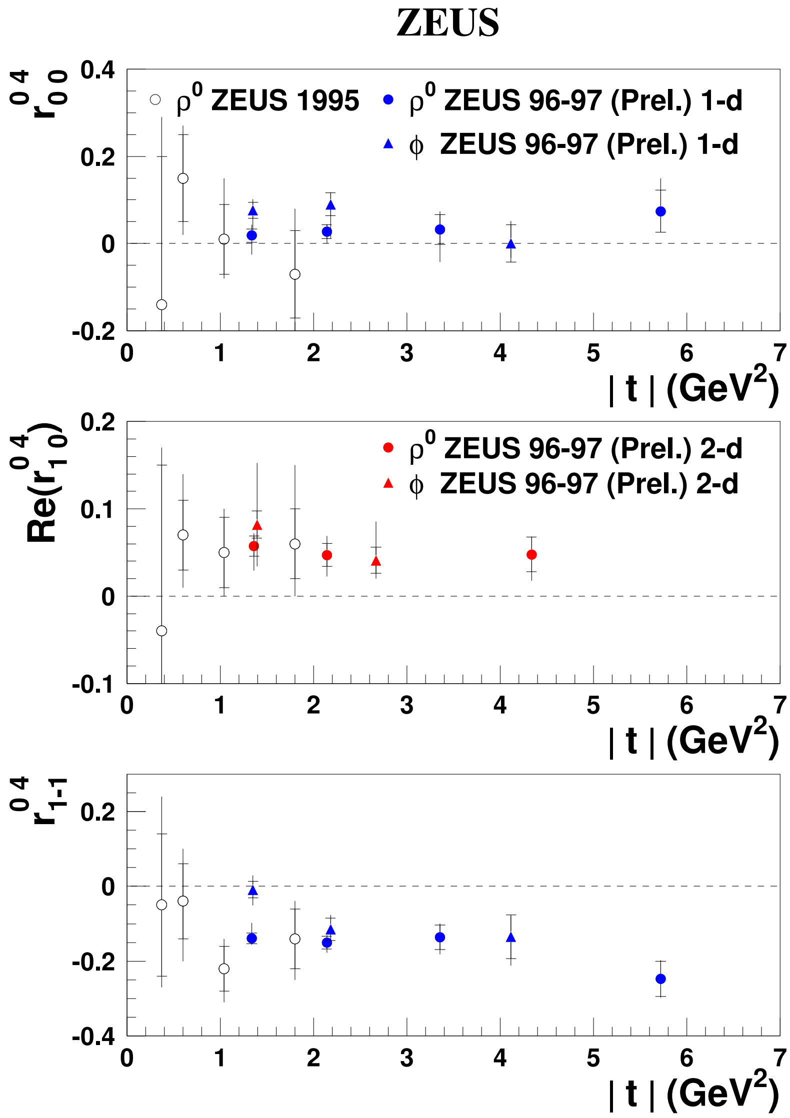
$$W(\cos\theta_h,\phi_h) = \frac{3}{4}\Big[\ \frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\theta_h - \sqrt{2}\mathrm{Re}(r^{04}_{10})\sin 2\theta_h\cos\phi_h - r^{04}_{1-1}\sin^2\theta_h\cos 2\phi_h\ \Big]$$



Very accurate measurement of helicity transfer properties

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)

... but transverse VM polarization dominates

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

(But why no dependence on t?)

Also significant double-flip contribution

What exactly is the "surprise" ?

QCD Descriptions of High-$|t|$ Photoproduction

Humpert and Wright (1977)
(and others ...)

High $|t|$ encourages expansion in α_S

Ginzburg and Ivanov (1996)
(and others ...)

Helicity conservation in QCD

implies asymptotic dominance of longitudinal vector mesons

Ivanov, Kirschner, Schaefer, Szymanowski (2000)

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

yields dominance of transverse VMs at intermediate $|t|$

$$\frac{d\sigma_{\gamma p \to VY}}{d|t|} \propto \frac{\alpha_S^4(-t)}{(-t)^4} |G(x, -t)|$$

Mystery #1

How to get $(-t)^{-3}$ for transverse VMs ?

Chernyak and Zhitnitsky (1984):
"These rules hold for any vector or axial-vector coupling ..."

Mystery #2

Why doesn't the coupling run ?

Some general remarks
(and some questions)

☞ 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 ?)

$\Rightarrow$ What about the meson form factor ?

☞ *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?

Are there point-like interactions of hadronic bound states?

Attempted Synthesis

There appears to be increasing evidence for a point-like T$\rightarrow$ T vacuum-exchange transition which is difficult to reconcile with the present formulation of QCD

- A QCD description requires chiral-symmetry breaking, for example, quark-mass effects.
- This requirement results in a t dependence stronger than observed.
- This T$\rightarrow$T transition contributes to VM electroproduction well into the Q^2 region where pQCD successfully describes the production of longitudinal vector mesons.
- It is the dominant VM-photoproduction process at high momentum transfer.

The successful field theoretical description of this process will be a prime candidate for a theory which can be used in higher orders to describe diffractive processes at low momentum transfer, elastic and total hadronic cross sections.

Approaches other than Two-Gluon Exchange

J.R. Forshaw and G. Poludniowski (hep-ph/0107068)

Apply solution of the non-forward BFKL equation

Assume non-relativistic, δ-function wave function even for the light vector mesons
$\Leftrightarrow$ dominance of transverse vector mesons

Also assume that the strong coupling does not run

N.I. Kochelev et al. (hep-ph/0011042)

Anomalous f_1 trajectory exchange

Odd-signature partner of Pomeron arising from axial anomaly

$\Leftrightarrow$ Amazingly good match to entire t range

A Scalar Field in QCD ??

Seems ridiculous.
Surely there would have to be other
(major!) phenomenological consequences.

Christof Wetterich

(Phys.Rev. D64 (2001) 036003, hep-ph/0107068)

Color symmetry broken by scalar $q\bar{q}$-condensate

Yields massive spin-1 fields with spectrum of vector mesons.
Massive spin-1/2 fields exhibit spectrum of baryons.
Confinement is a direct consequence.
Electromagnetic U(1) symmetry also broken.
$\Rightarrow$ "Weinberg" mixing between photons and gluons

DESY Seminar 9 July 2001

QCD Ground State with Spontaneously Broken Color

"We know there is no scalar in QCD. However, in this talk I intend to convince you that real-life QCD behaves exactly as though it is spontaneously broken by a scalar field."

"Scalar Vervollständigung"

Johan Bijnens (Remarks at LP2001, Rome)

"Most of us believe that when we understand how
QCD chiral symmetry is broken,
the answer will look similar to this approach."

Gluon/photon-mixing is a *necessary* consequence.

Spontaneously Broken Color

C. Wetterich, Phys. Rev. D64 (2001) 036003

Spontaneously broken color

Christof Wetterich[1]

Institut für Theoretische Physik
Universität Heidelberg
Philosophenweg 16, D-69120 Heidelberg

Abstract

The vacuum of QCD is characterized by the Higgs mechanism. Color is "spontaneously broken" by a quark-antiquark condensate in the octet representation. The massive gluons carry integer electric charges and are identified with the vector mesons. The fermionic excitations consist of the low mass baryon octet and a singlet. The interactions between these particles and the light pseudoscalar octet are largely determined by chiral symmetry and a nonlinear local symmetry. A consistent phenomenological picture of strong interactions at long distances arises from a simple effective action.

Conclusions

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

The light vector mesons ρ^0, ω and ϕ

- ☞ Study scaling with $\Delta p \gg \mathrm{M_V}$
  - Photon virtuality Q^2 (photon size)
  - Δp at proton vertex (resolve proton)
- ☞ Flavor symmetry $\rightarrow$ Asymptotic region
- ☞ Study transition to pert. region in Q^2 and/or t
- ☞ Multivariable analysis of helicity structure

Many phenomenological successes for QCD,

but recent results are raising serious questions