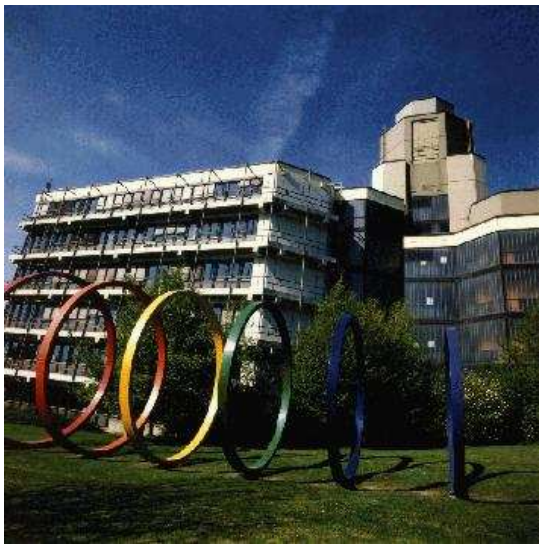
Particle Physics Seminar
Universität Dortmund

10 July 2001

Scaling Laws and Helicity Selection at HERA

Studies of the Exclusive Production of Photons and Vector Mesons at High Momentum Transfer in High-Energy Electron-Proton Interactions

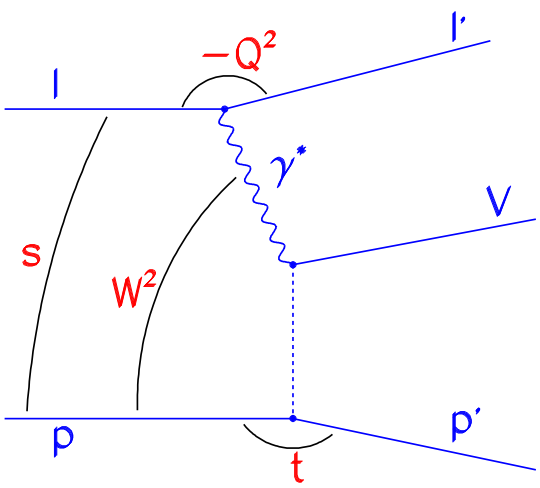


- ☞ **Helicity selection rules and scaling**
- ☞ **QCD description of diffractive processes**
- ☞ **Deeply virtual Compton scattering**
- ☞ **Scaling and helicity in VM electroproduction**
- ☞ **Surprise in high-$|t|$ VM photoproduction**

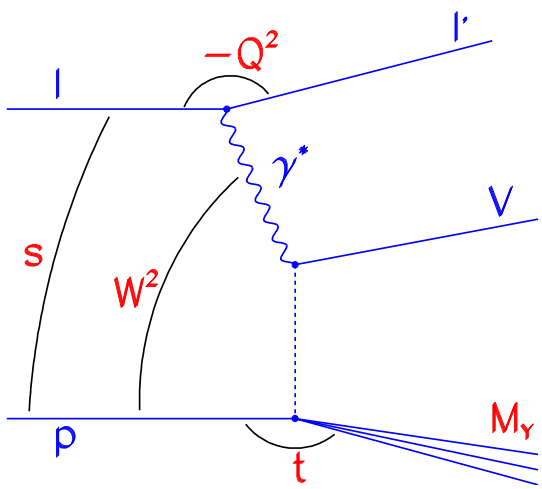
J. A. Crittenden/DESY
(On leave from Phys. Inst. Bonn)

Production of Vector Particles at HERA

Exclusive



Semi-Exclusive



$\sqrt{s}$: 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 ($Q^2 \ll |t| \Rightarrow t \simeq -P_T^2(V)$)

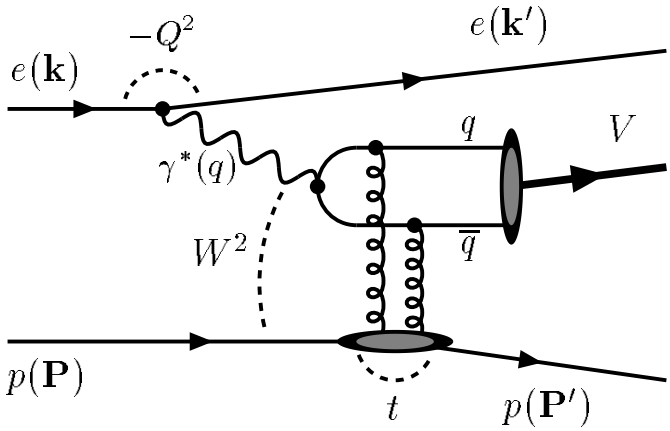
t: Square of Momentum Transfer at the Proton Vertex

$|t| < 13$ 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)

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

Can the hard scale necessary for perturbative QCD calculations be set by either Q^2, M_V^2, or $|t|$??

What experimental signatures for the region of pQCD validity ?

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 (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)

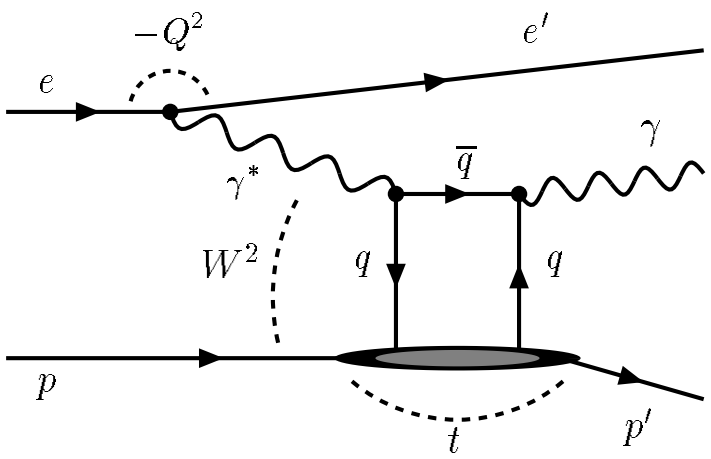
(Quark exchange diagrams for high $|t|$ photoproduction)

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

Deeply Virtual Compton Scattering

$$e + p \rightarrow e + p + \gamma$$

"Handbag" diagram



☞ "Leading order"
No α_S dependence (similar to $F_2(x, Q^2)$)

☞ Sensitive to *Skewed Parton Density Functions*

- Basic properties of the proton
- Non-local operators:
  "generalized", "off-diagonal", "unintegrated"
- Constrained to standard PDF's via sum rules
- Characteristic evolution properties

Frankfurt, Freund and Strikman

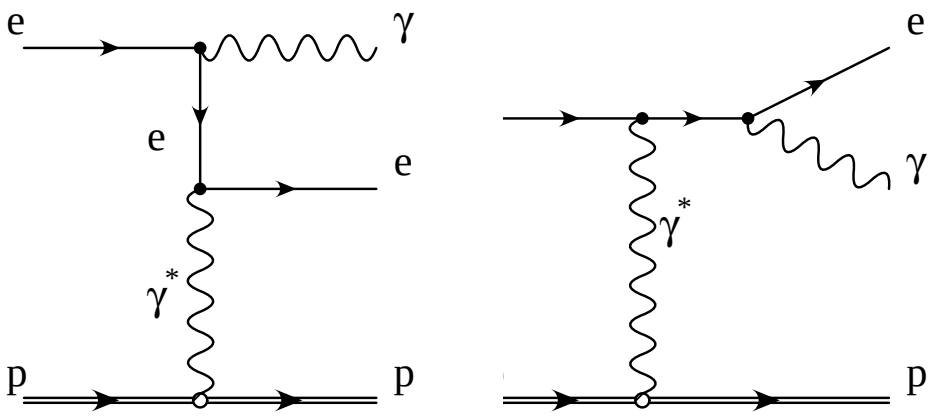
PRD 58, 114001 (1998), PRD 59 119901E (1999)

Calculation of LO process

based on relation to $F_2(x, Q^2)$

Coherent QED Background

Bethe-Heitler processes



Kinematically distinct from DVCS

☞ First-order QED: $\propto Q^4$

☞ DVCS: Q^2 dependence modified by SPD evolution

Interference can be exploited to observe azimuthal angular asymmetry in polarized ep interactions

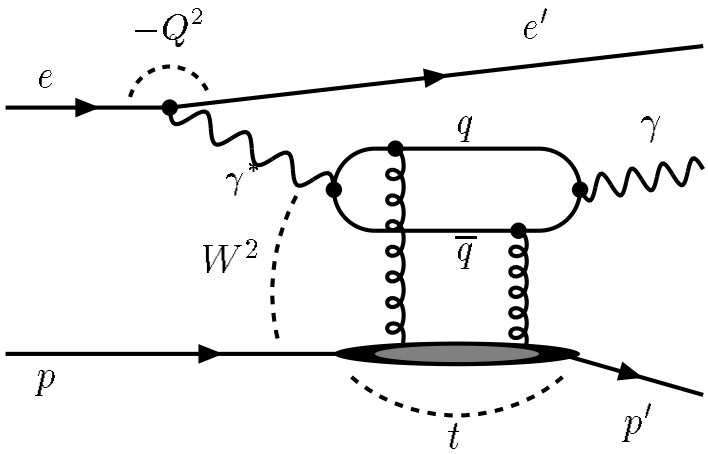
HERMES Collaboration, hep-ex/0106068

Very Recent NLO Calculation

A. Freund and M. McDermott
hep-ph/0106115
hep-ph/0106124
hep-ph/0106319

Includes radiative corrections to LO

AND



☞ Free of vector meson structure, but magnitude similar to LO

☞ Large quantitative uncertainties due to unknown SPD's

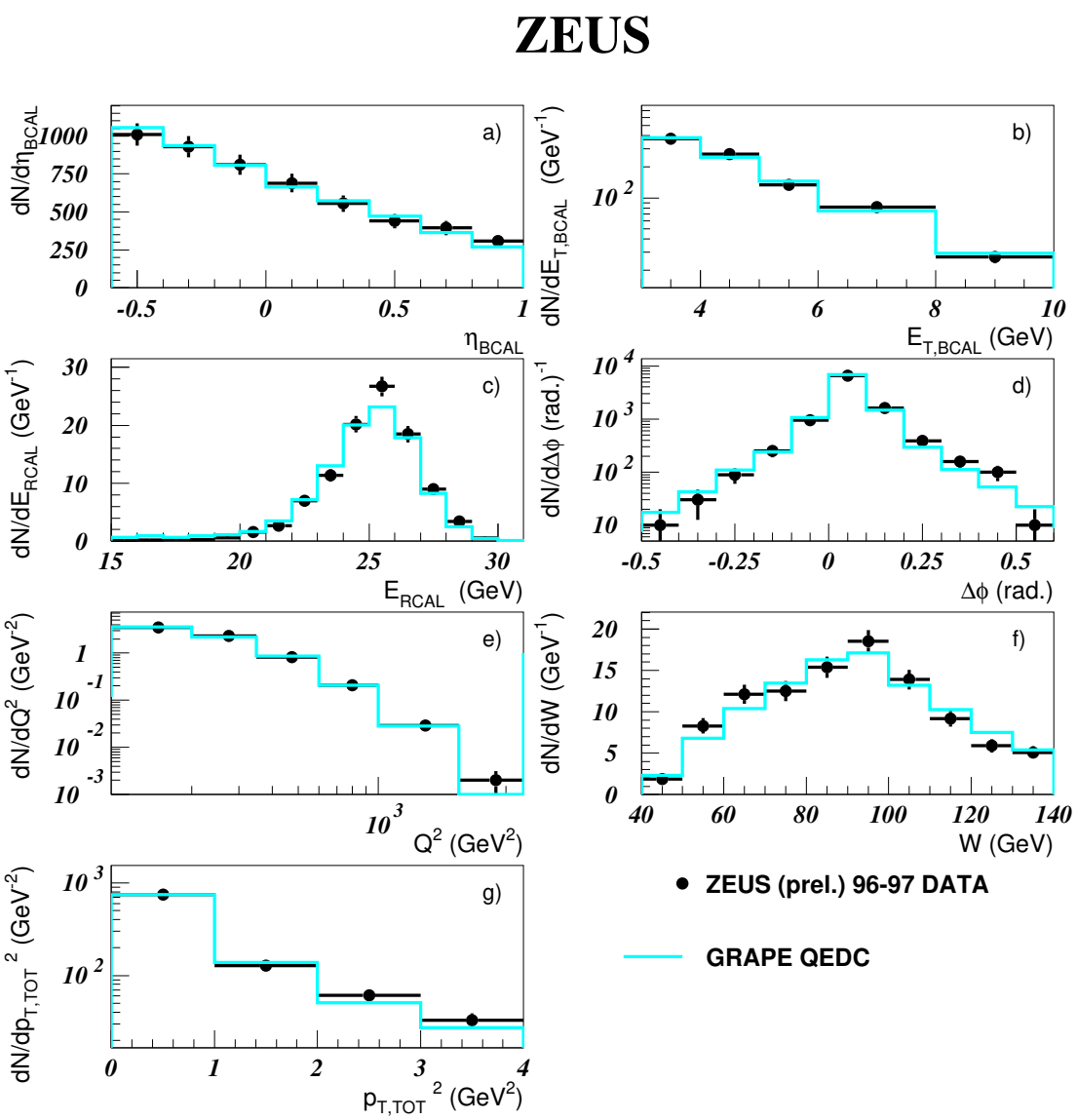
ZEUS DVCS Analysis

International Europhysics Conference on High Energy Physics
July 12-18, 2001 Budapest, Hungary

Abstract 564

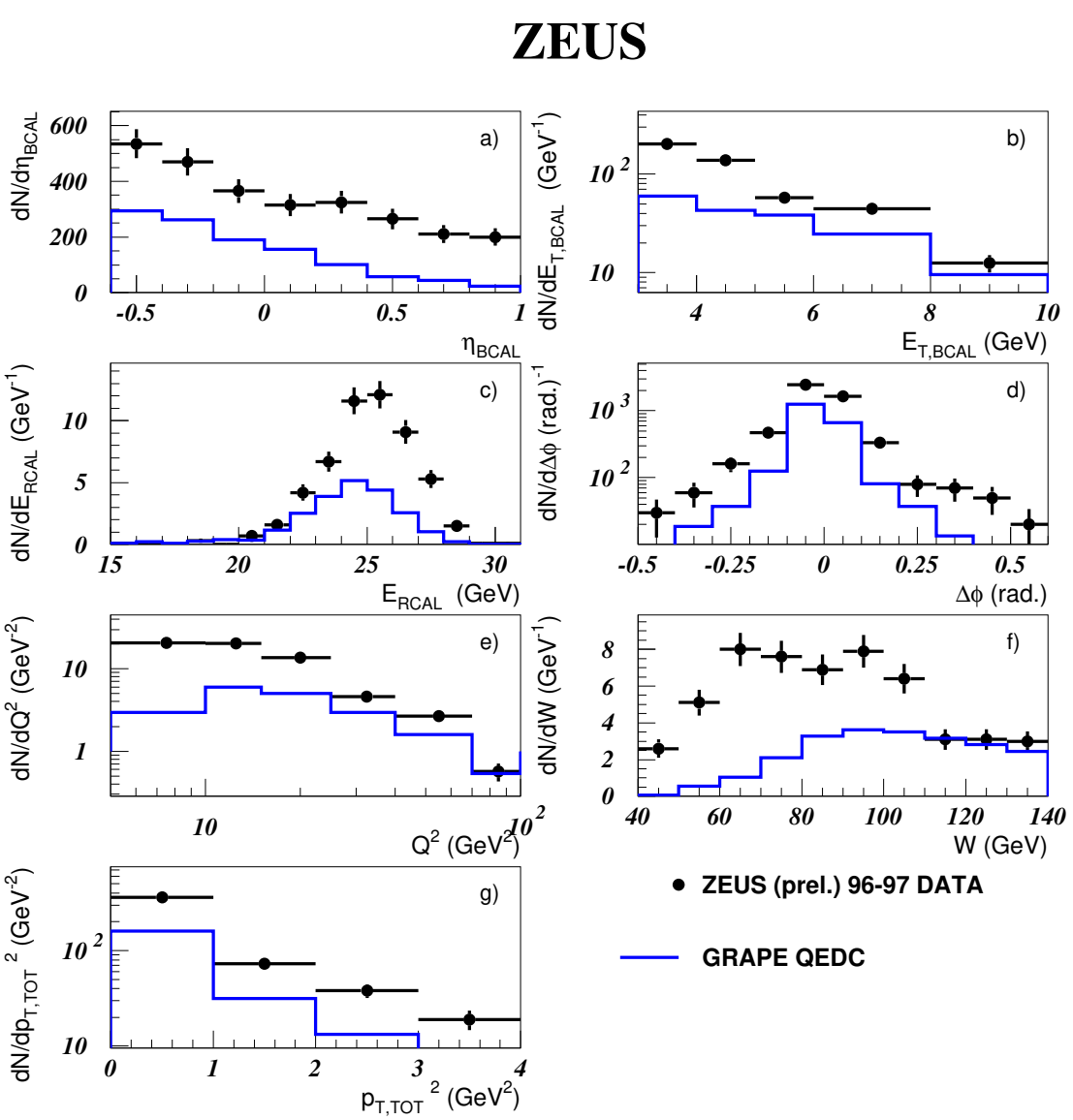
QED Compton Data Sample

(select on positron angle)



QED background well understood

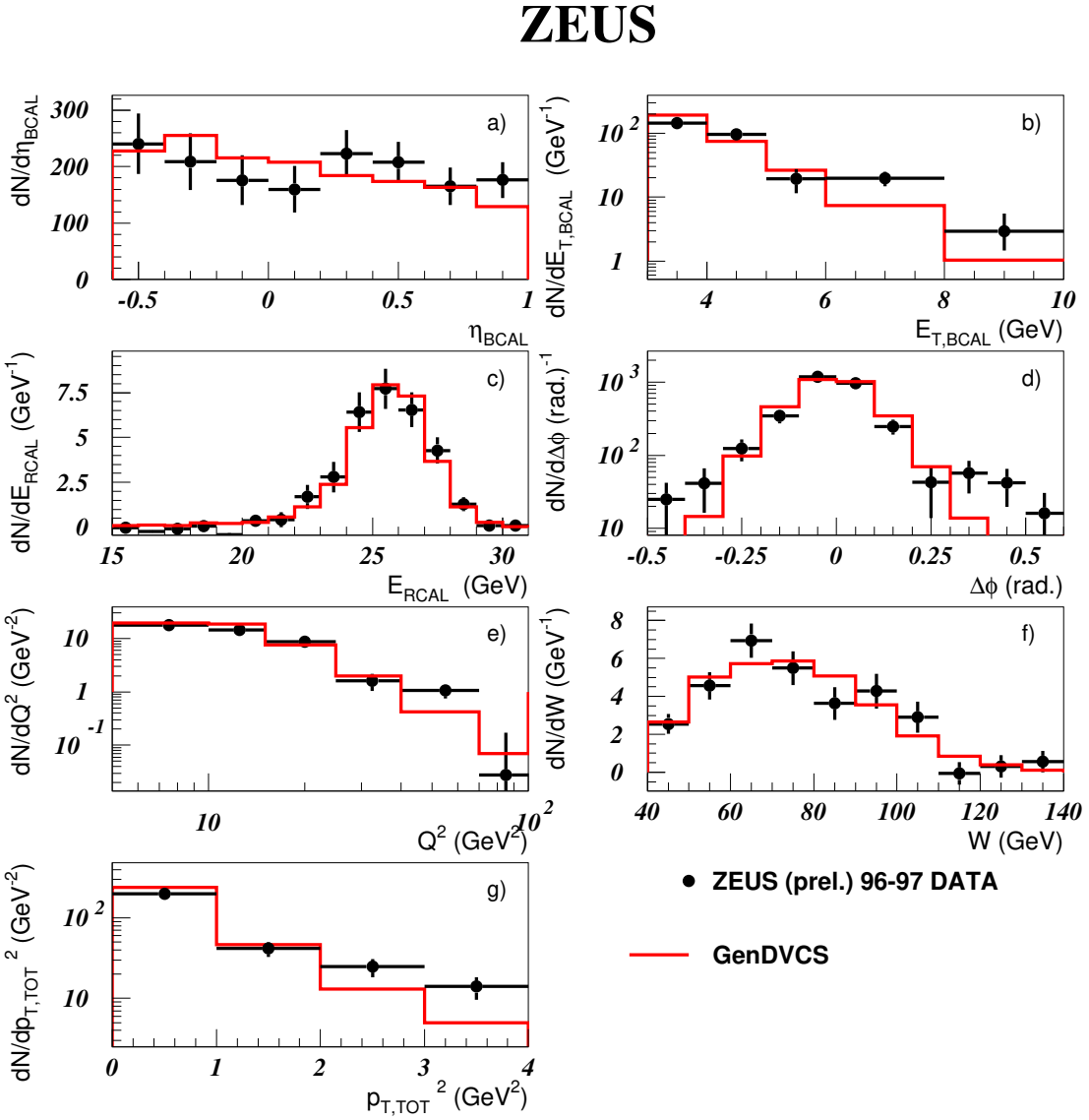
ZEUS DVCS-enriched Sample



Clear excess above QED observed

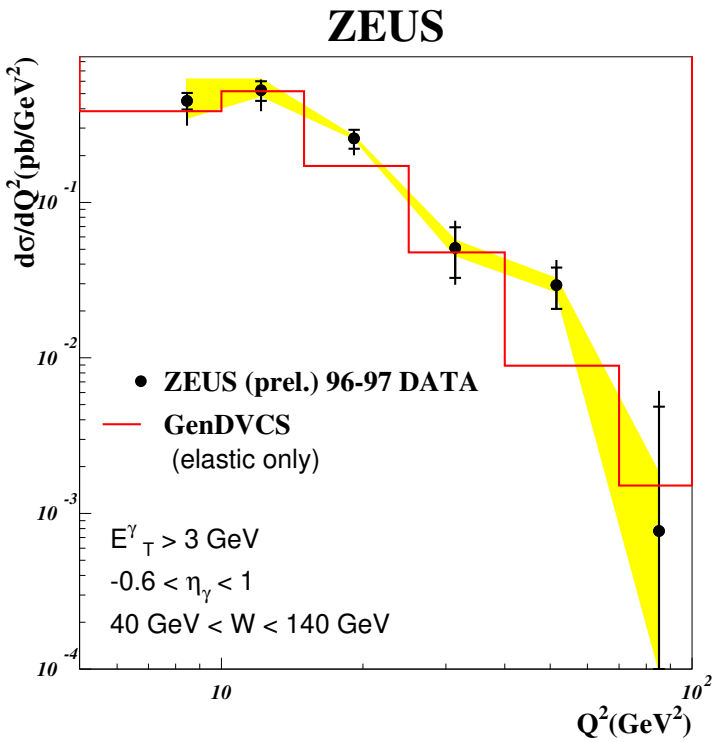
ZEUS Pure DVCS Sample

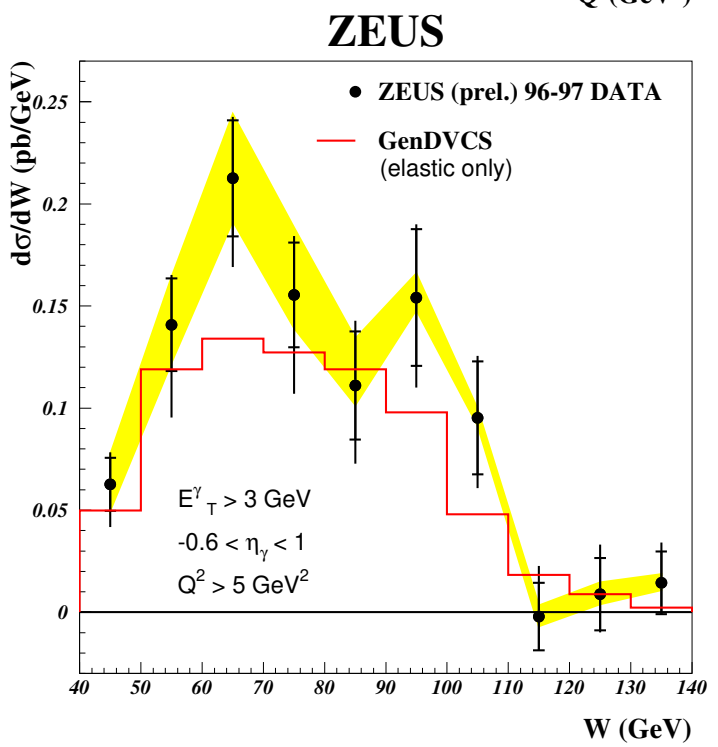
Comparison with DVCS LO Simulation



Data consistent with LO calculation (FFS)

ZEUS DVCS Cross Sections

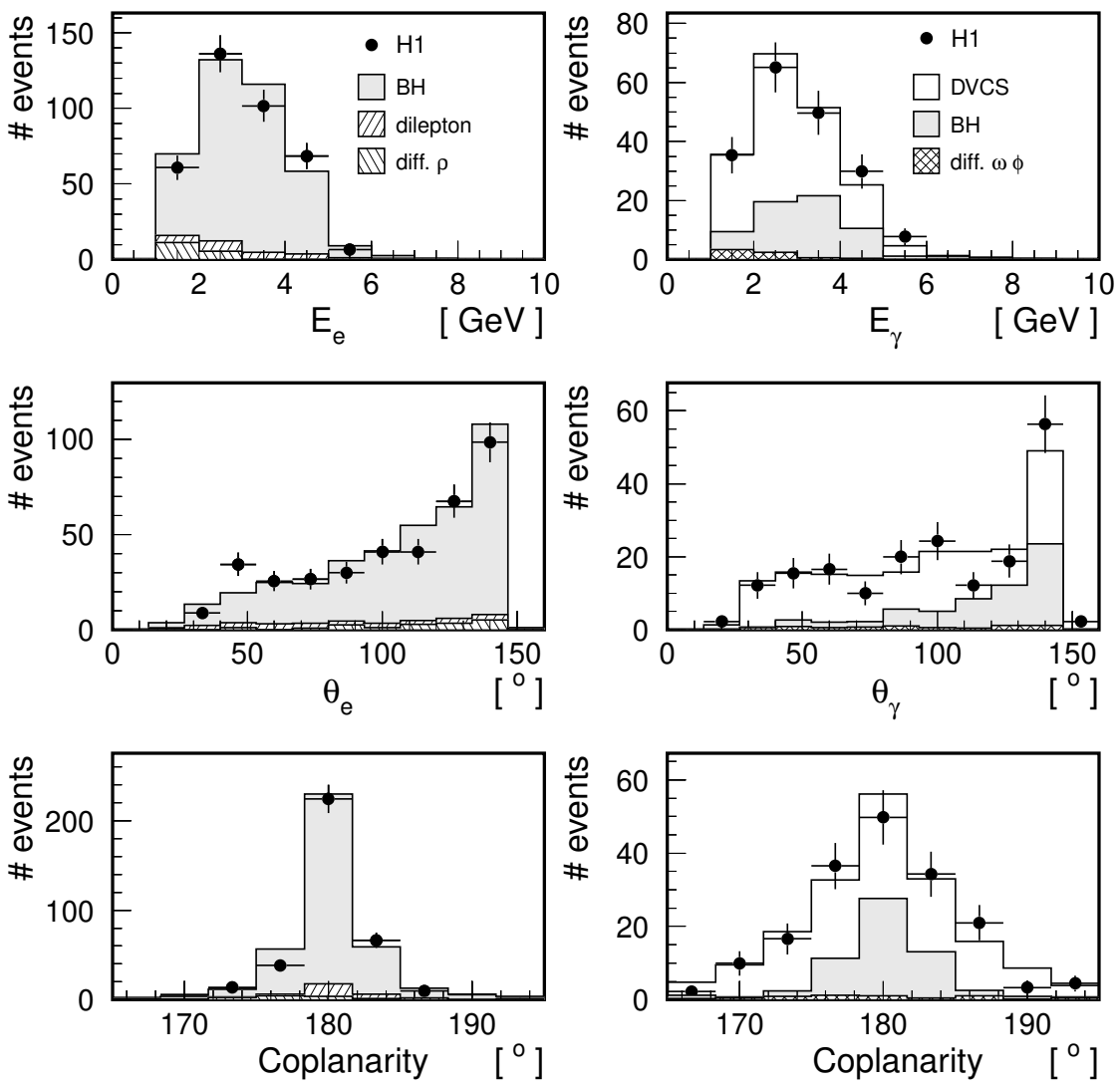




Present level of accuracy consistent with

LO DVCS calculation for elastic process

H1 DVCS Signal

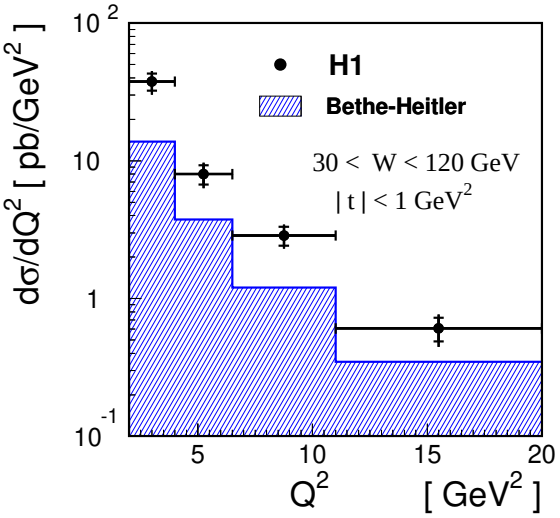


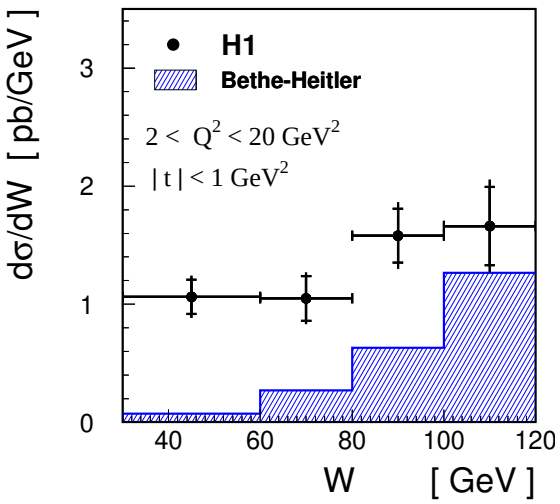
Clear excess above QED background observed

H1 DVCS Cross Sections

Differential Cross Sections

(QED contribution included)

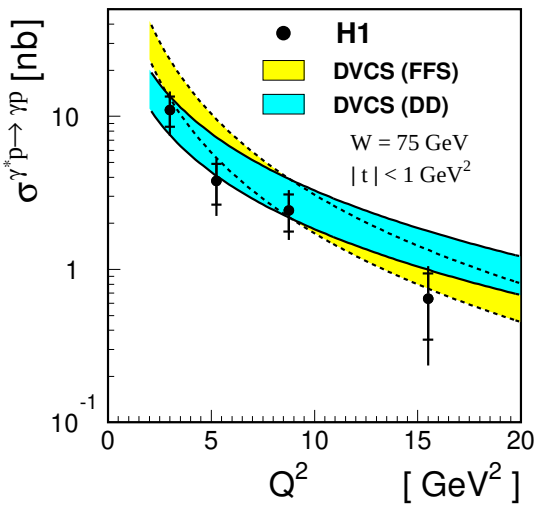


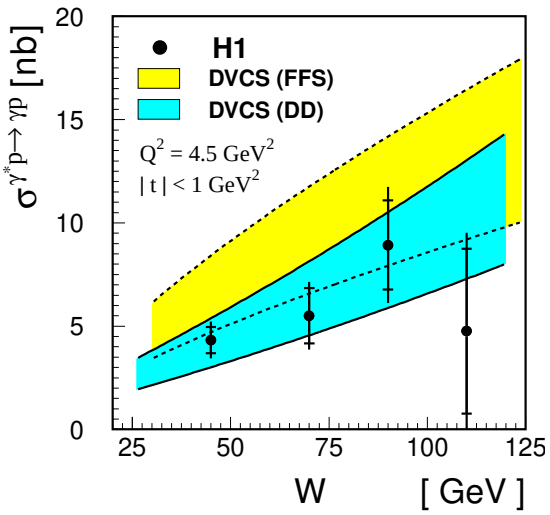


Q^2 dependence similar, DVCS dominates at low W

Total Cross Sections

(DVCS contribution alone)





Consistent with LO calculations

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

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

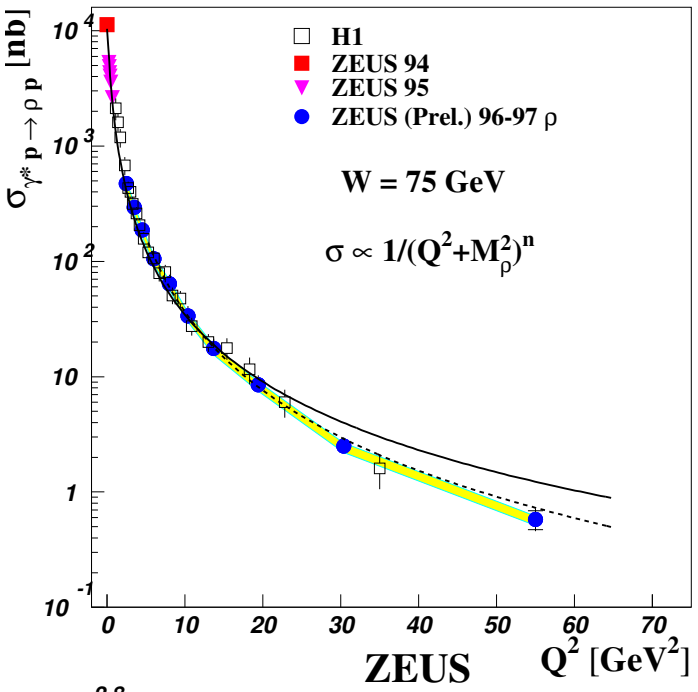
☞ **Exclusivity allows study of helicity structure via decay angles**

Helicity transfer $\Leftrightarrow$ { Scaling behavior ; Meson structure }

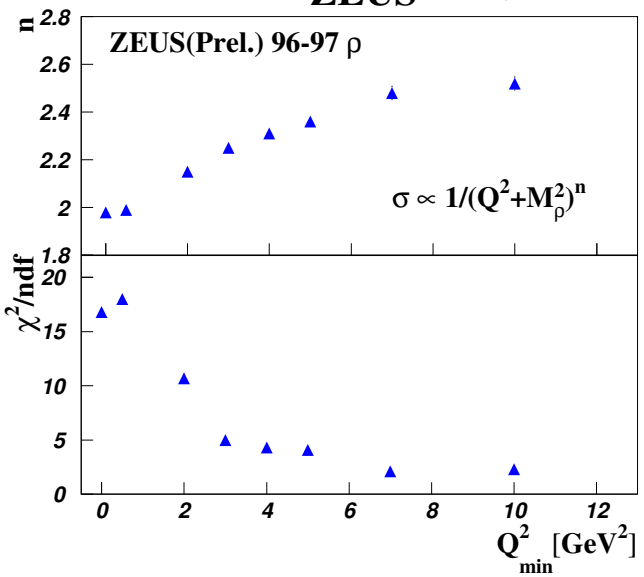
Elastic ρ^0 Electroproduction

A. Kreisel/ZEUS at DIS2001

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



n



χ^2/ndf

Power-law scaling?

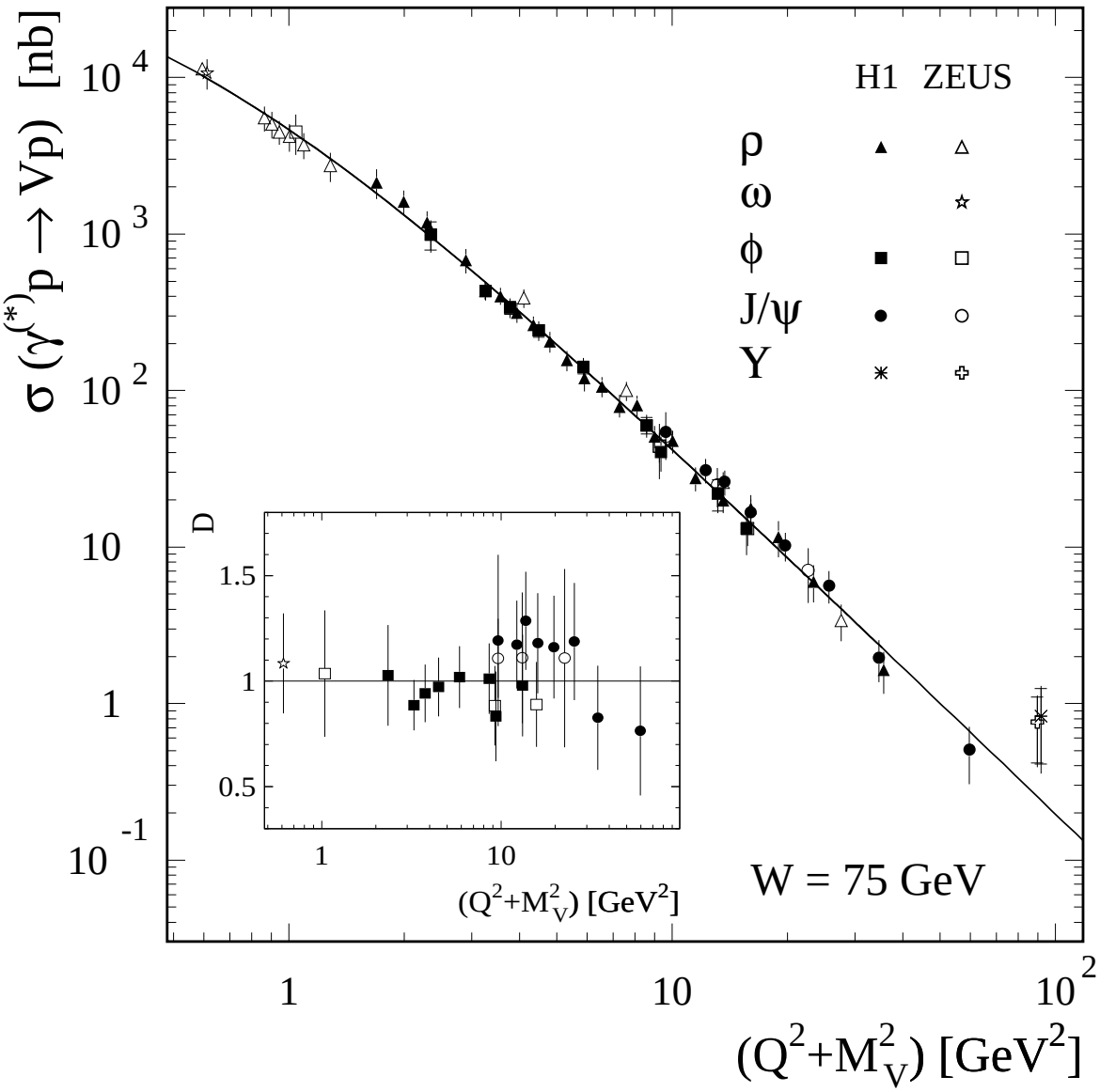
Yes, but power changing with Q^2

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

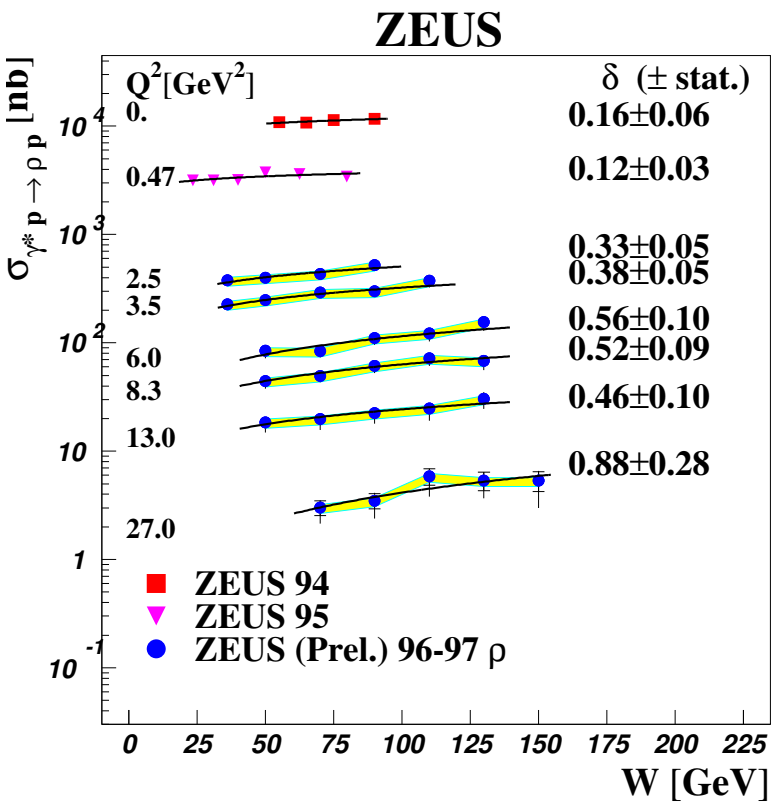
H1 Collaboration, Phys. Lett. B483 (2000) 360

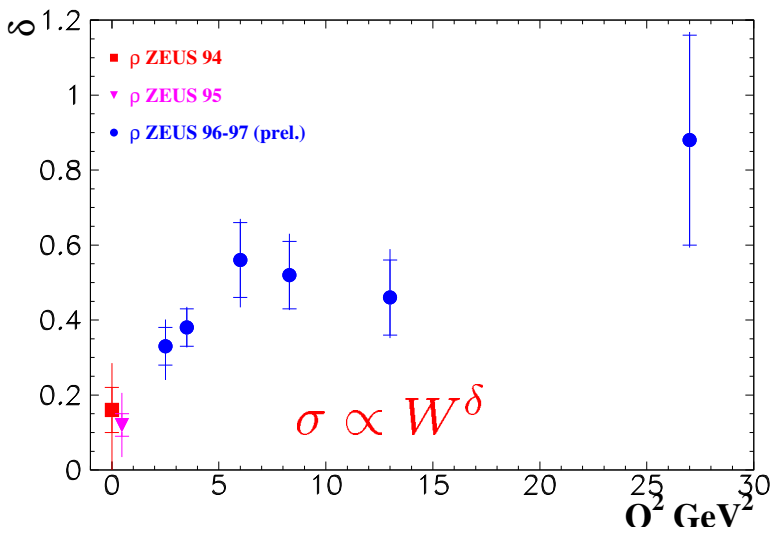


Universal scaling (?)

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

Does energy dependence vary with Q^2?

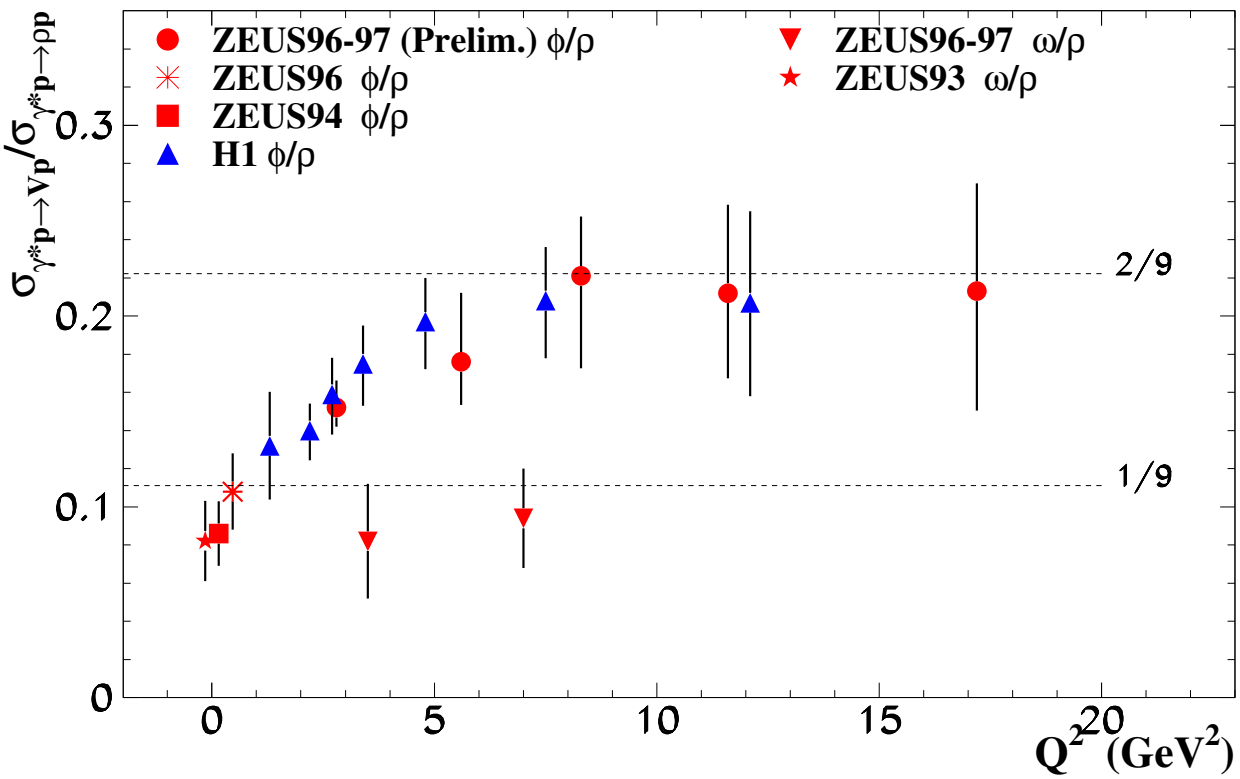




Energy dependence steepens with Q^2

Impressive support for pQCD description

What about flavor symmetry ?

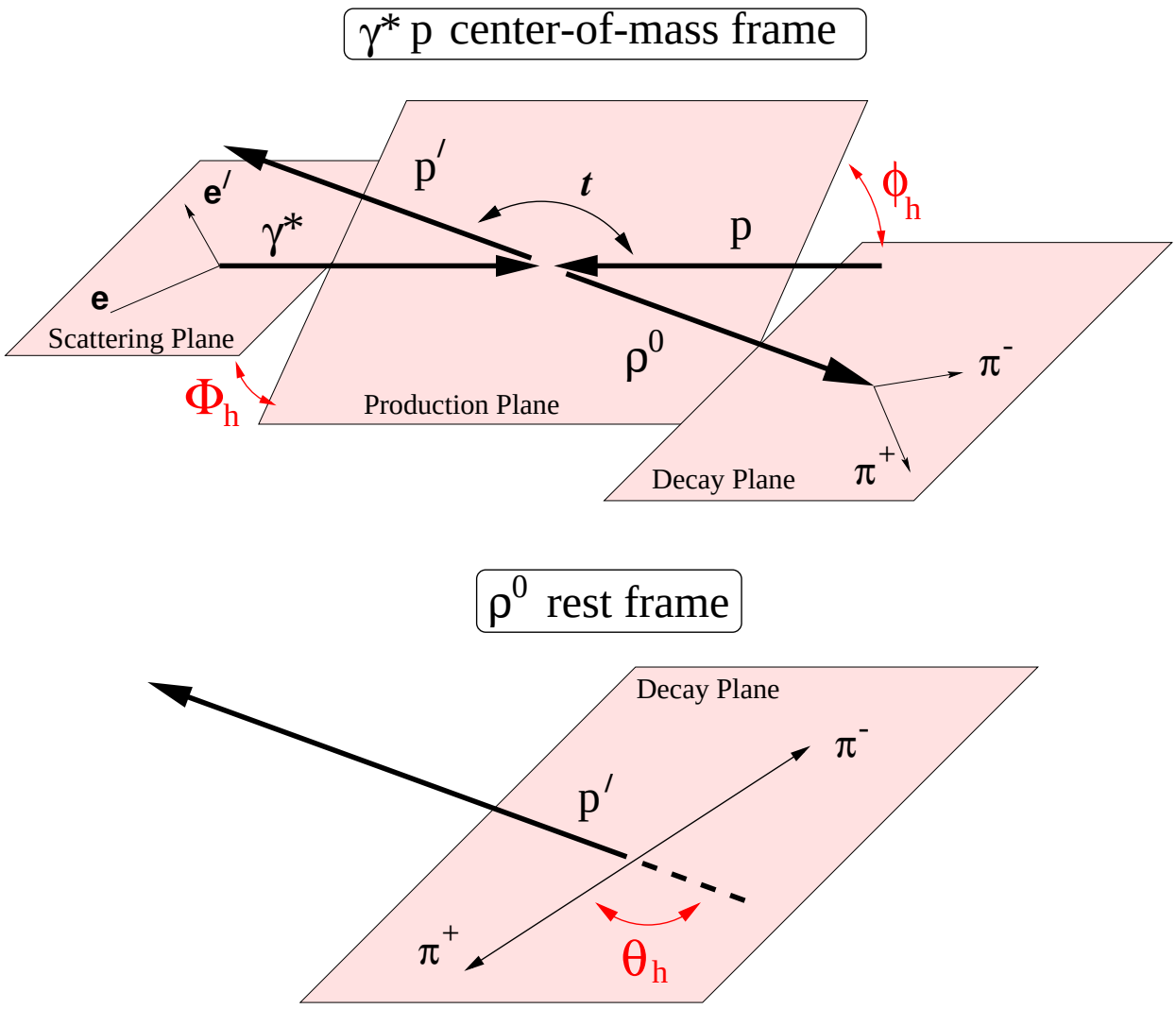


Magnitude of ϕ/ρ^0 ratio reaches the SU(3)-symmetry value in the same region where the scaling power equalizes

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

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

Helicity Analyses



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 $W(\theta,\phi)$

into four parts $W^i(\theta,\phi)$ (i=0,3) such that:

1. Unpolarized: $W(\theta,\phi) = W^0(\theta,\phi)$

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: $i, k = +1, 0, -1$)

$$r^{04}_{ik} = \frac{\rho^0_{ik} + \epsilon R \rho^4_{ik}}{1 + \epsilon R}$$

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

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

Constraints from hermiticity, parity conservation

3-D Decay-Angle Distribution

(15 linearly independent parameters)

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

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

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

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

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

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

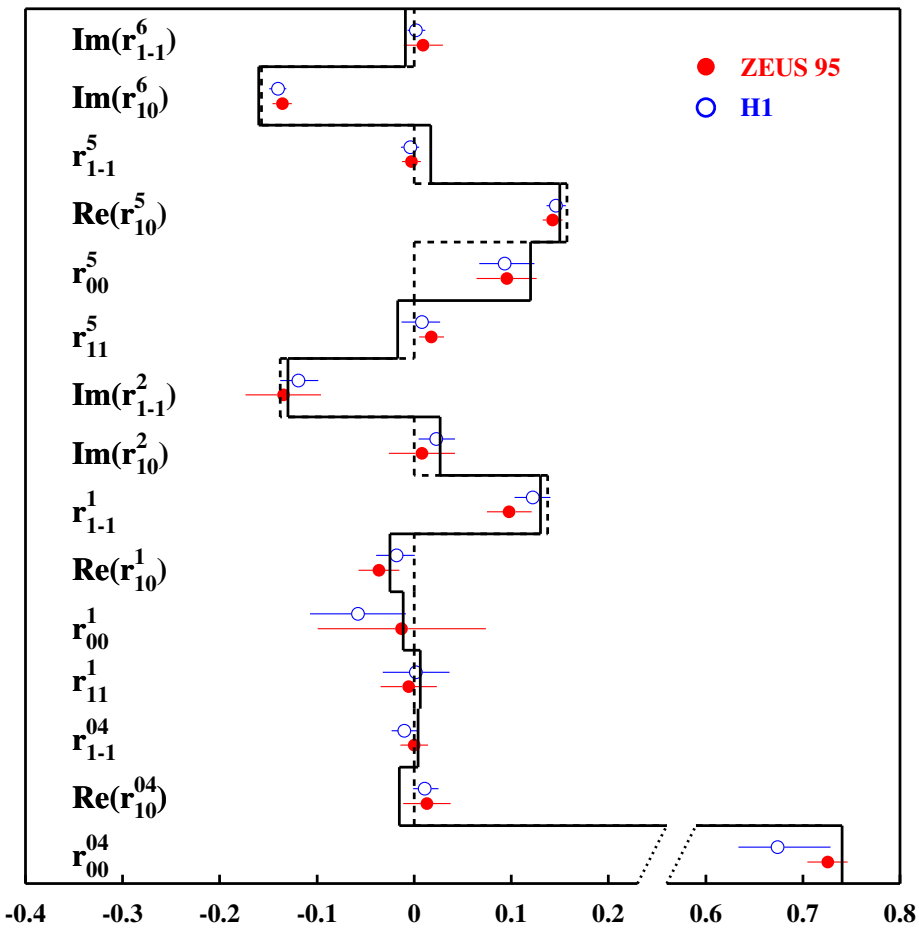
$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{T^2_{00} + 2\,T^2_{10}}{T^2_{01} + T^2_{11} + T^2_{1-1}}$$

(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

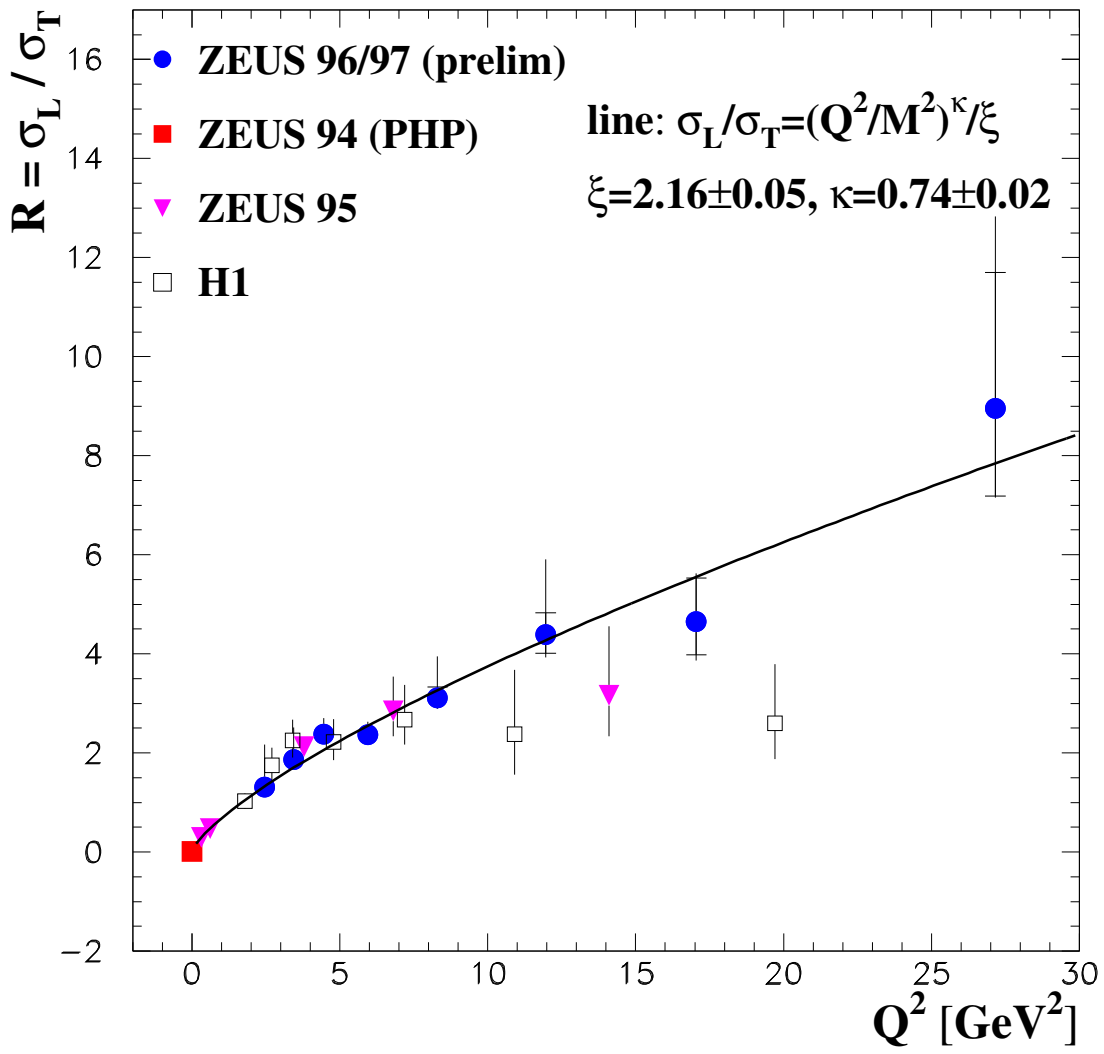
Predicted by Ivanov and Kirschner
Phys. Rev. D58 (1998) 114026

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

What about ratio of σ_L to σ_T?

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

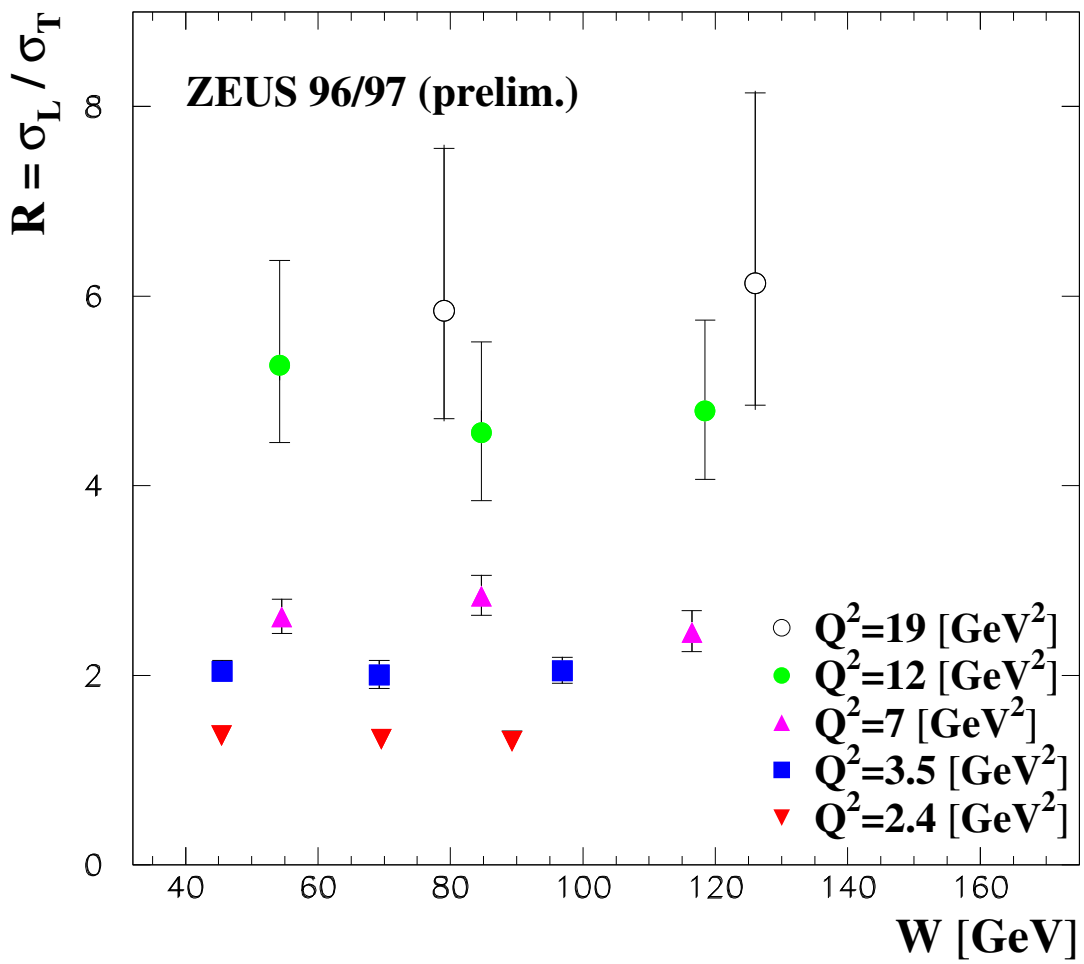
Δ now known to be small (helicity violation)



The dominance of σ_L
was an early prediction of pQCD

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

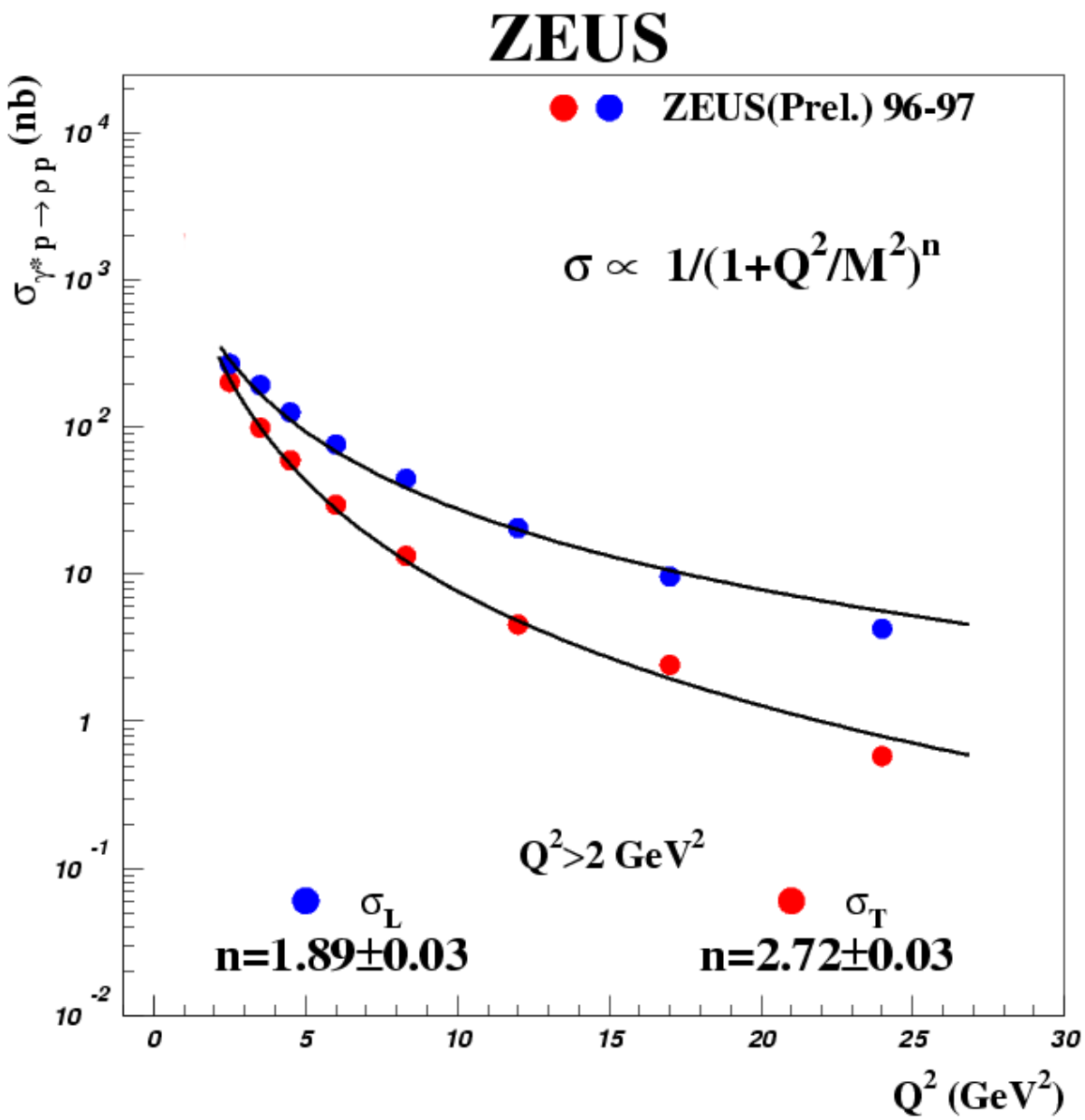
Energy dependence in σ_L/σ_T?



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

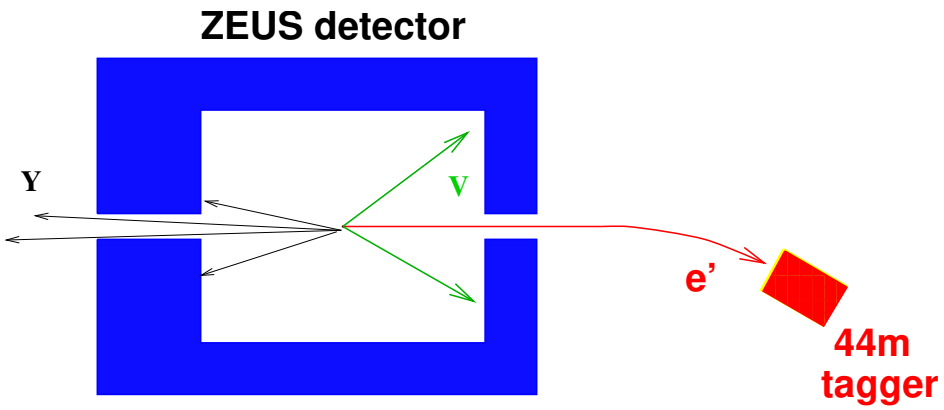
Remarkably hard scaling behavior for σ_T

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

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

A. Kowal/ZEUS at DIS2001

Photoproduction Tagging at $W \simeq 100$ GeV



$Q^2 < 0.02$ GeV^2

$23 < E_{e'} < 25$ GeV

$(\Rightarrow 80 < W < 120$ GeV$)$

ZEUS 1996/97 preliminary

Integrated luminosity: 24 pb^{-1}

ρ^0: $\simeq$ 18k

ϕ: $\simeq$ 2k

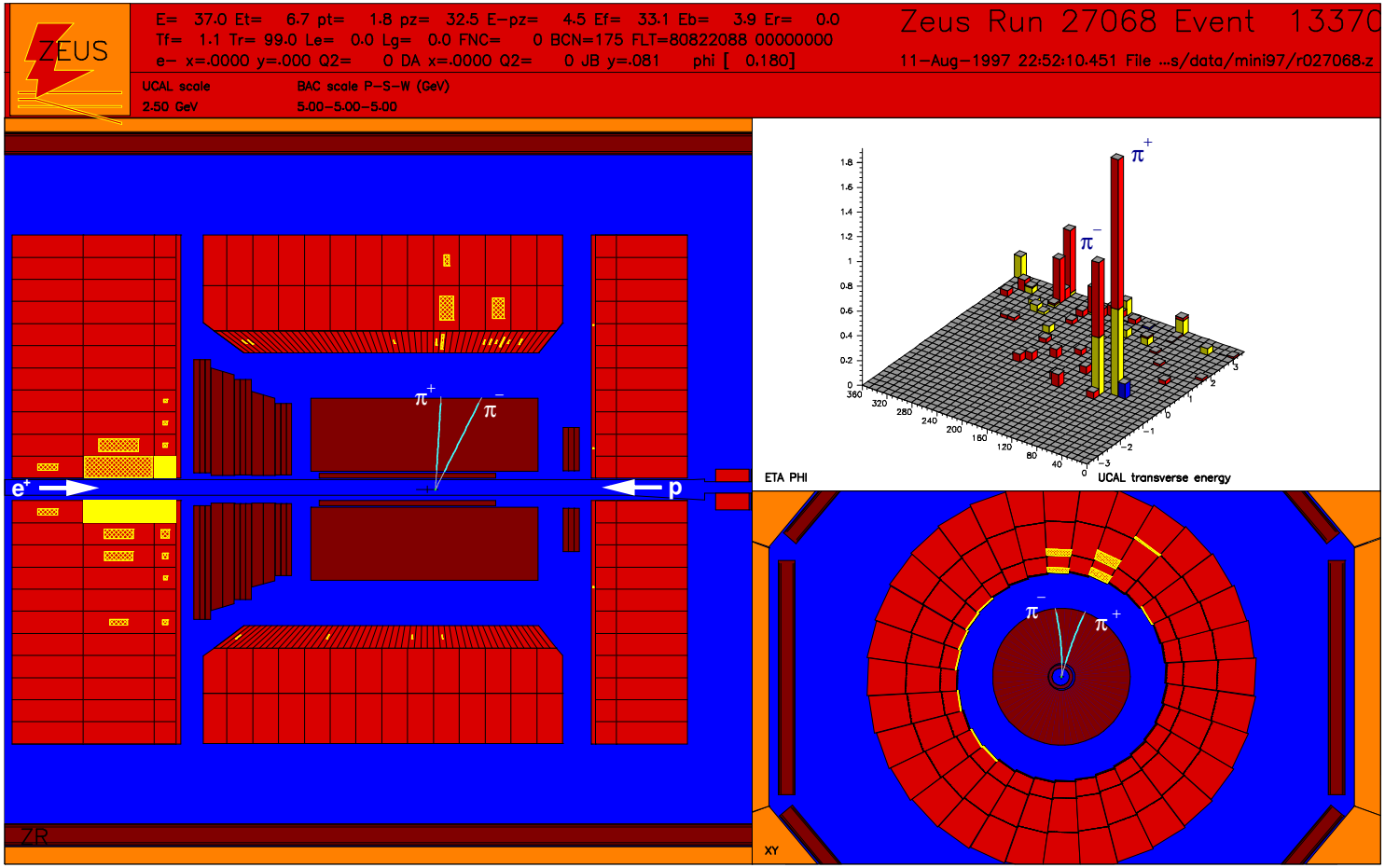
J/ψ: $\simeq$ 150

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 $0.01 < x < 1$

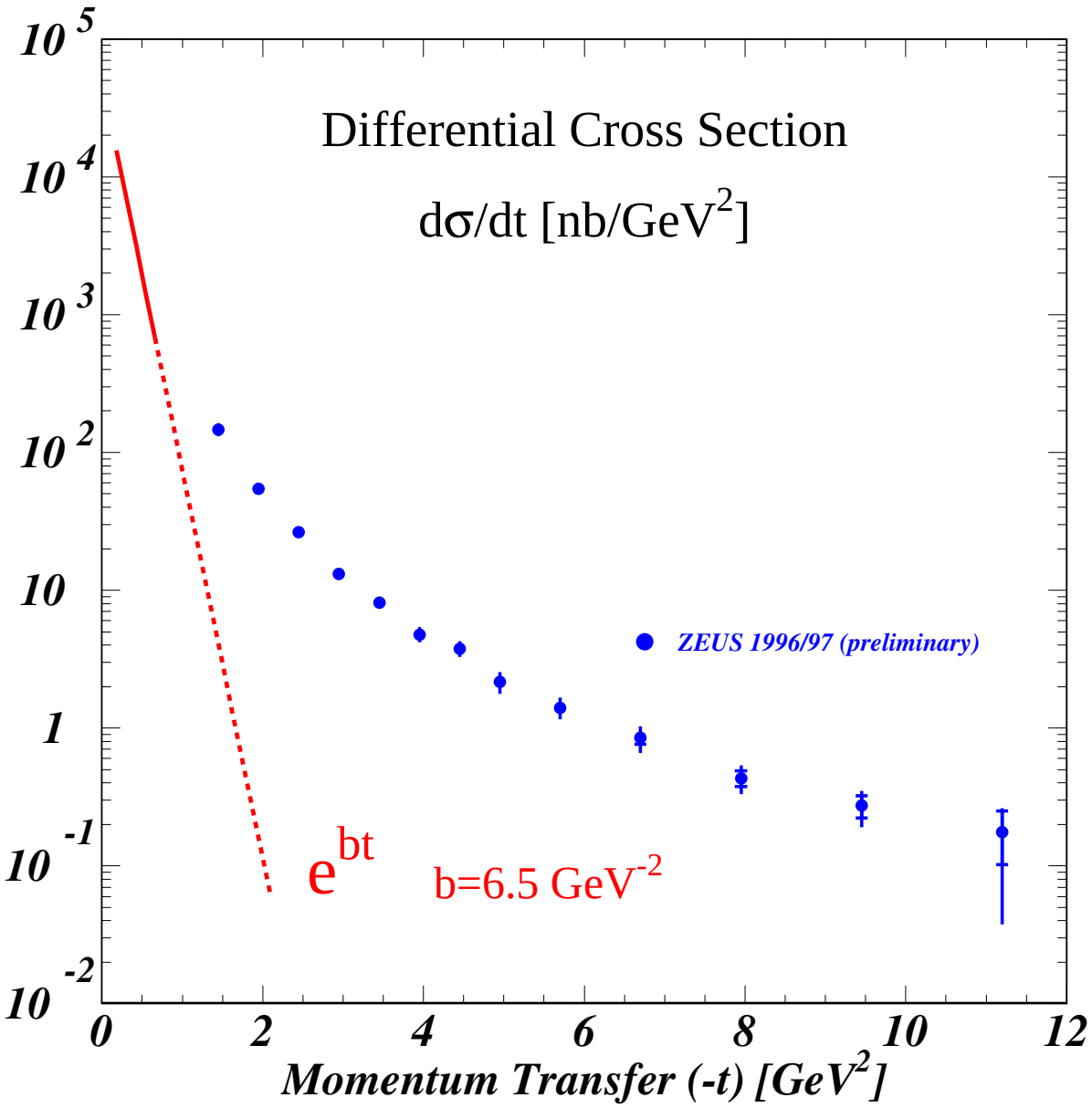
Candidate for ρ^0 Photoproduction at High $|t|$



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

Diffractive ρ^0 Photoproduction (I)

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

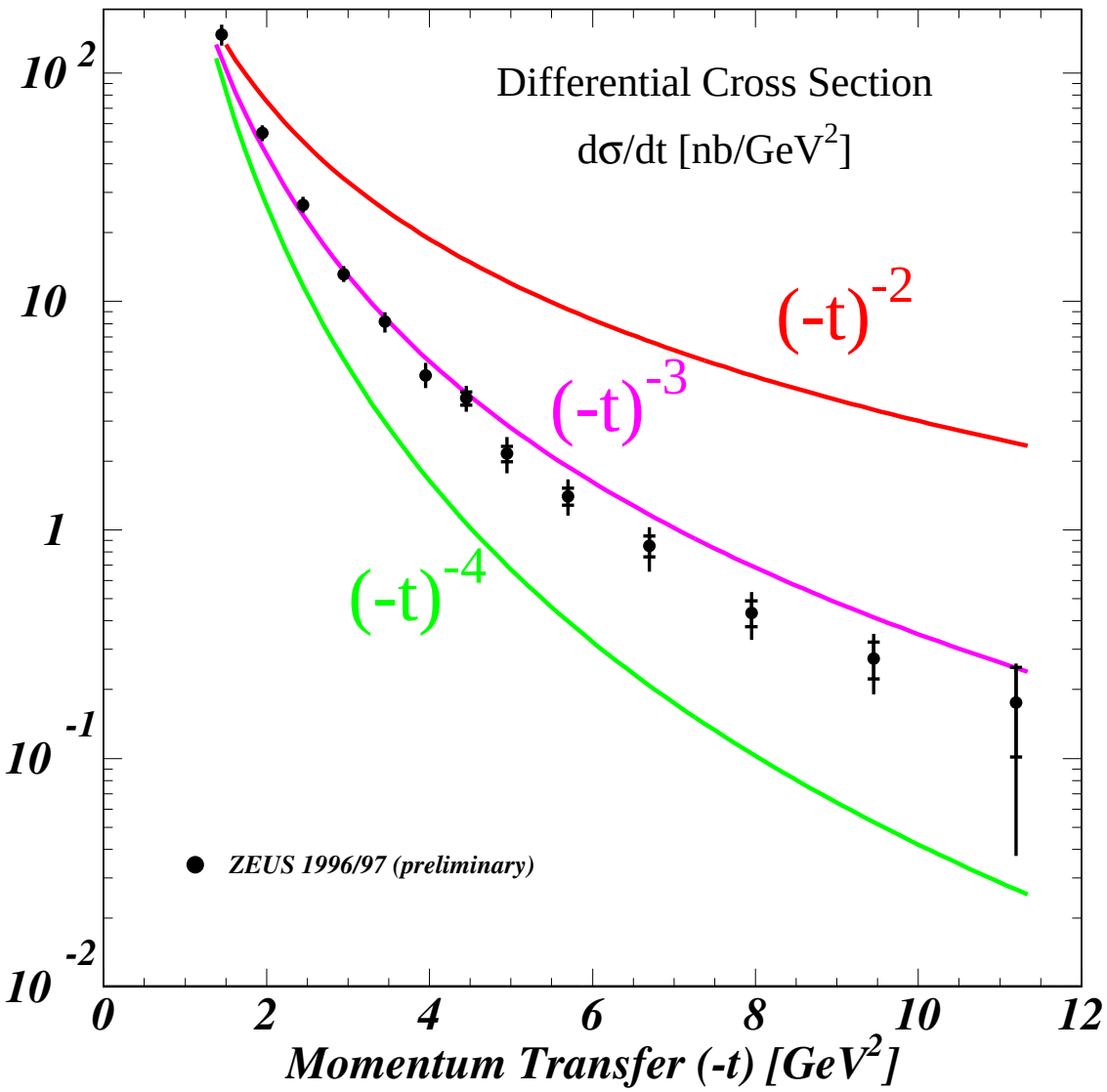


Asymptotic region $|t| \gg M_\rho^2$

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



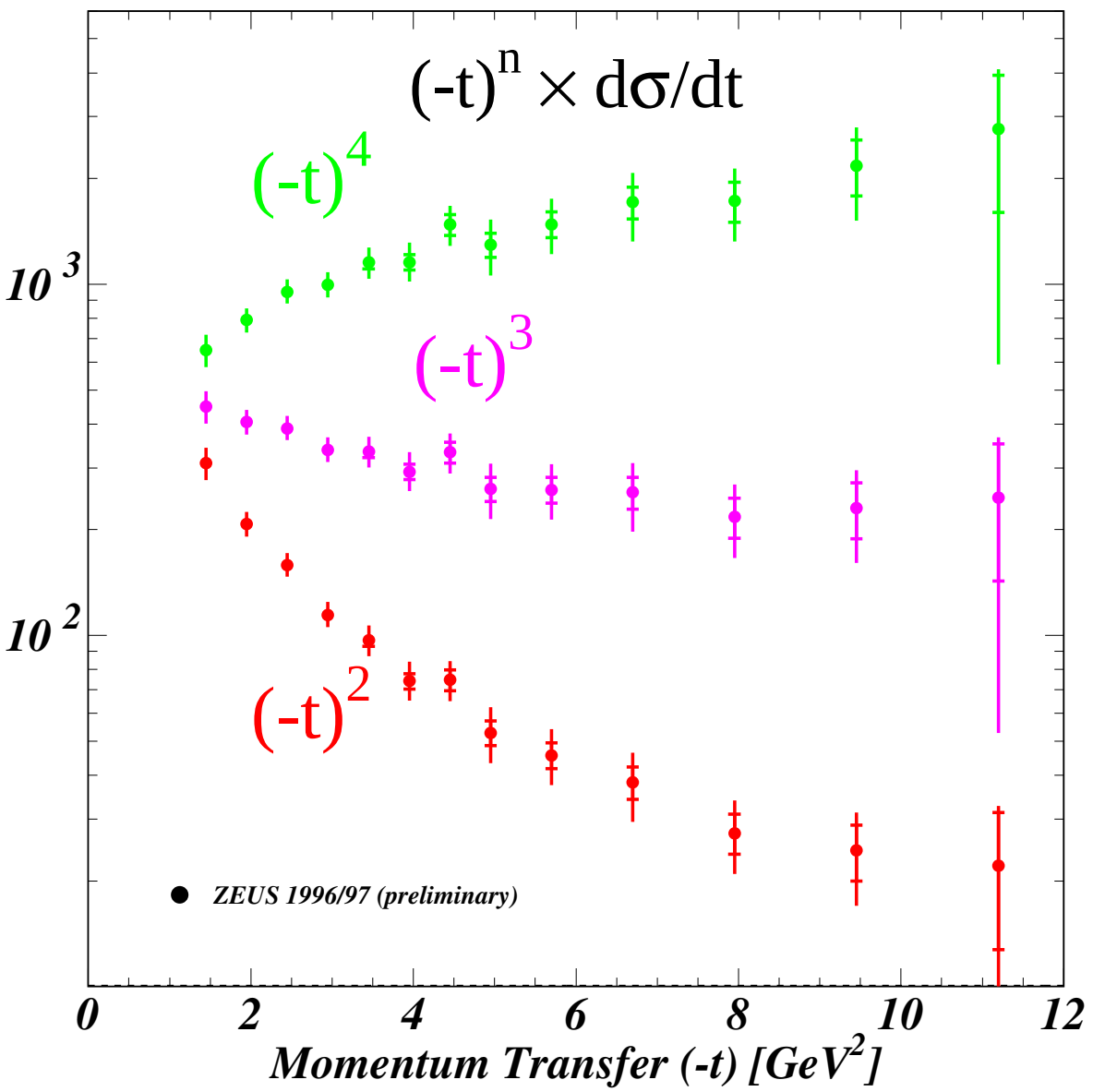
Scaling Property

Power dependence with

$n = 3$

matches the data fairly well

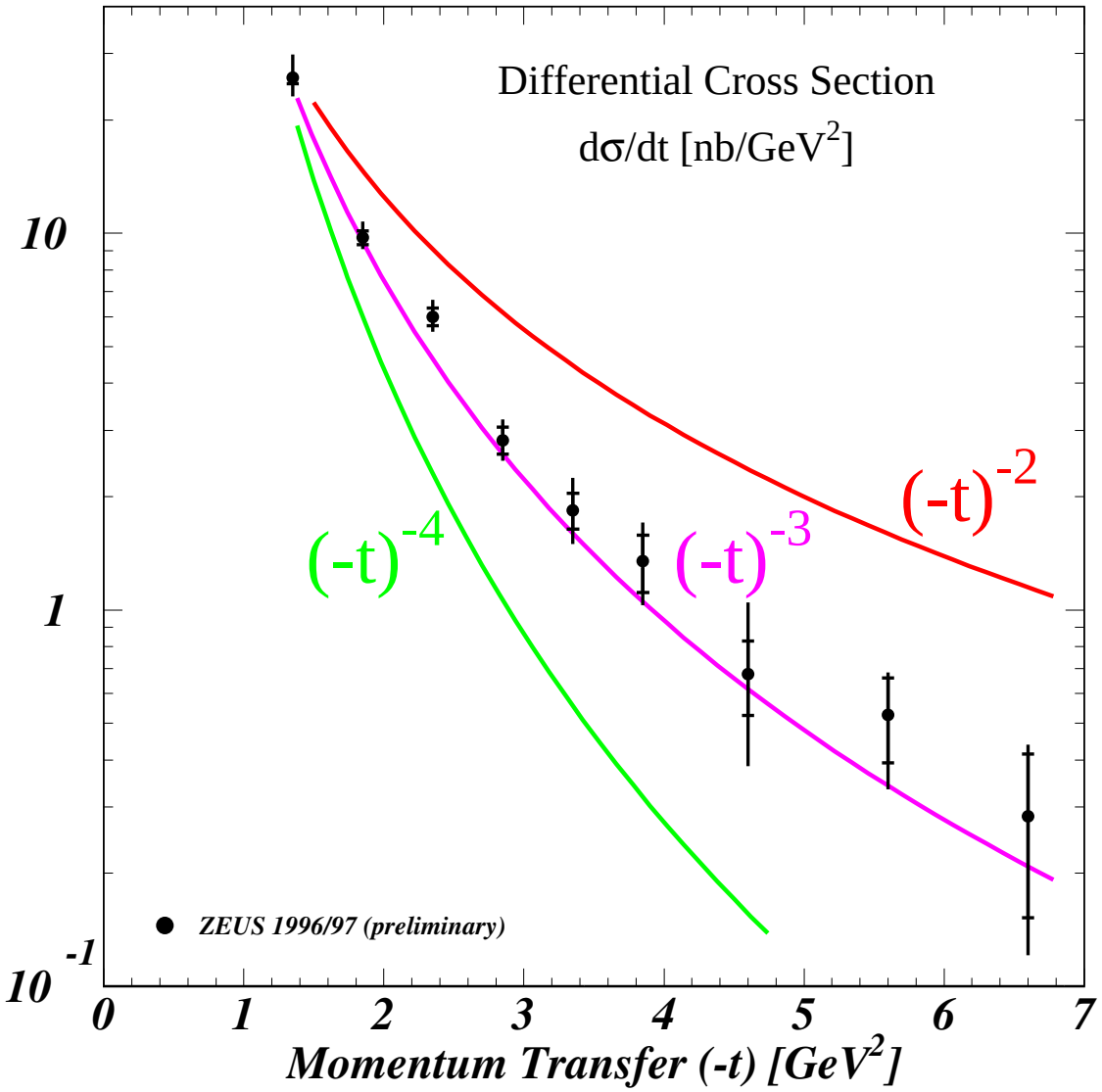
Diffractive ρ^0 Photoproduction (III)



Multiplying with $(-t)^n$

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

Diffractive ϕ Photoproduction (I)



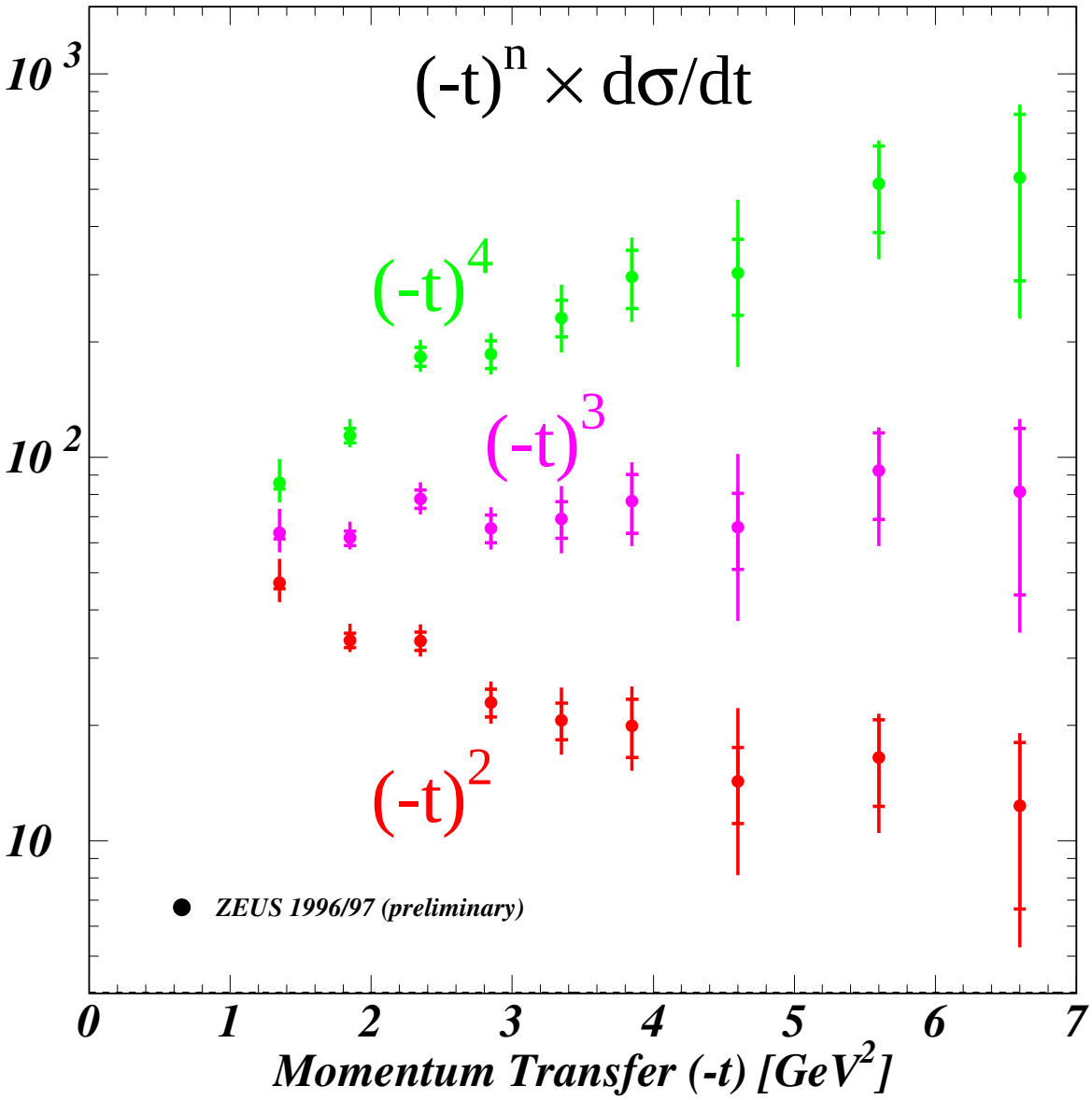
Scaling Property

Power dependence with

$n = 3$

matches the data well

Diffractive ϕ Photoproduction (II)

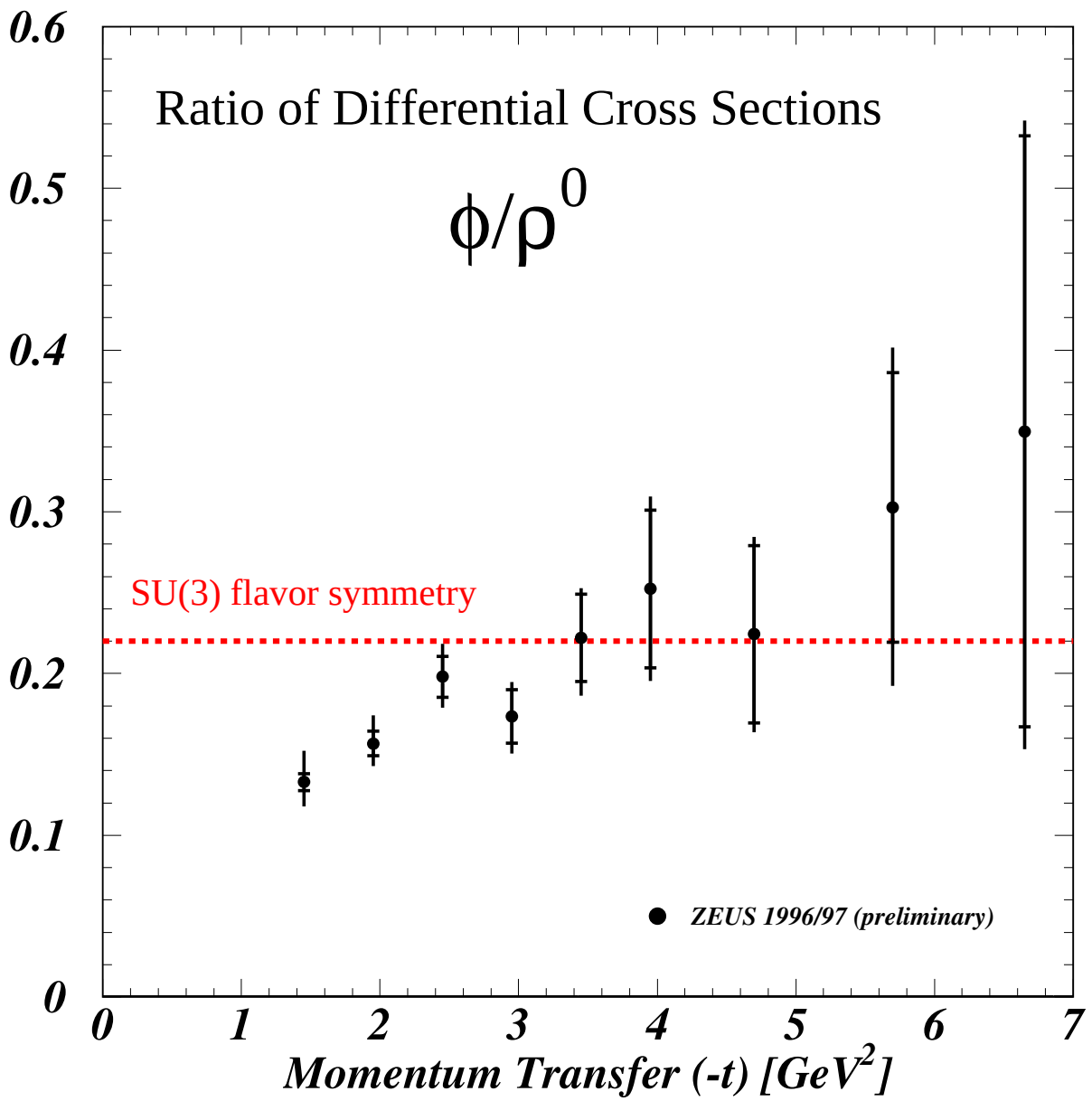


Multiplying with $(-t)^n$

Transition region observed for ρ^0 is absent for ϕ

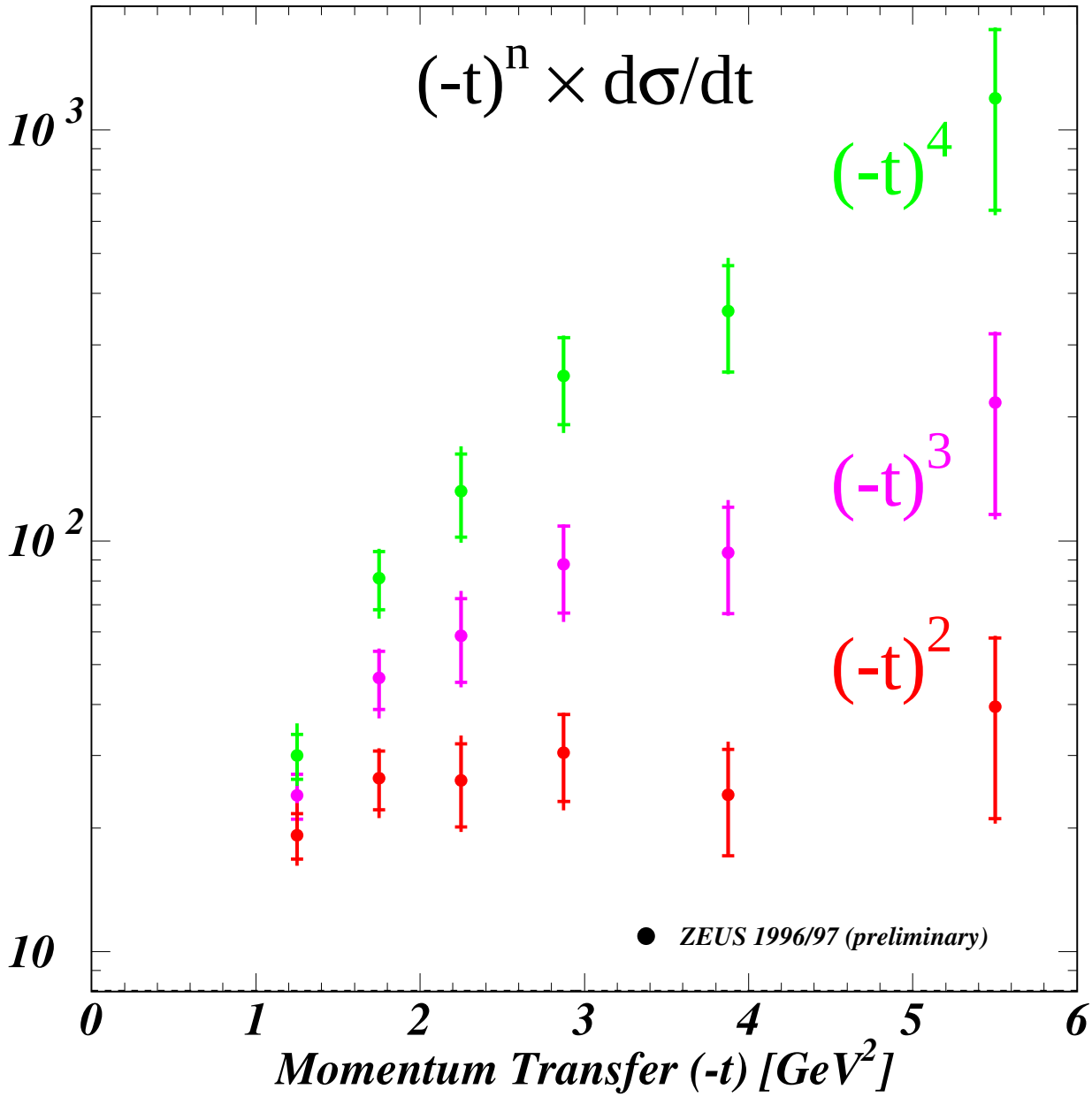
ϕ production free of non-vacuum-exchange backgrounds which contribute to ρ^0 and ω

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)

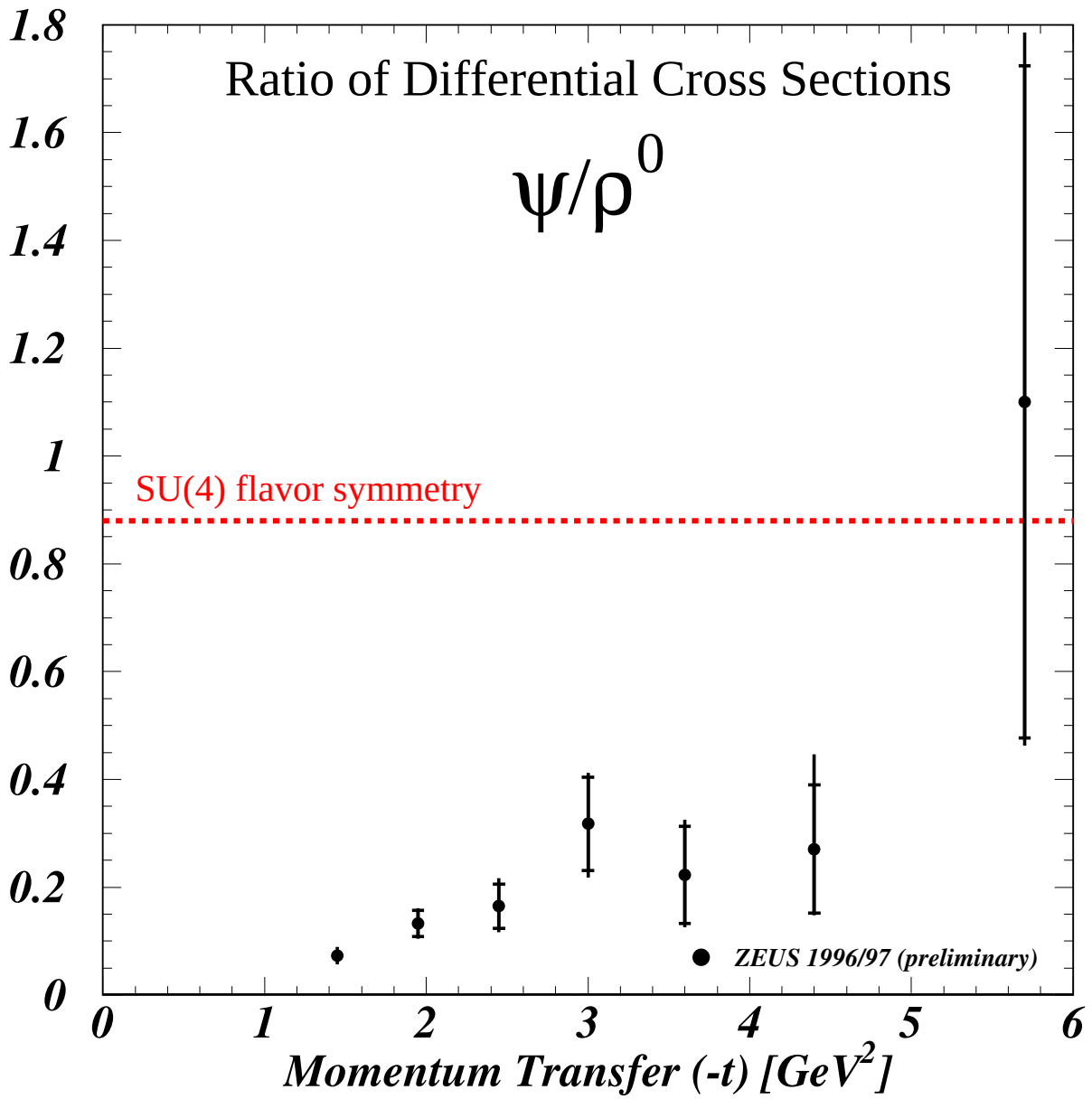


But here we have $|t| < M^2_{J/\psi}$

Meson structure effects may be important

SU(4) symmetry broken (see next figure)

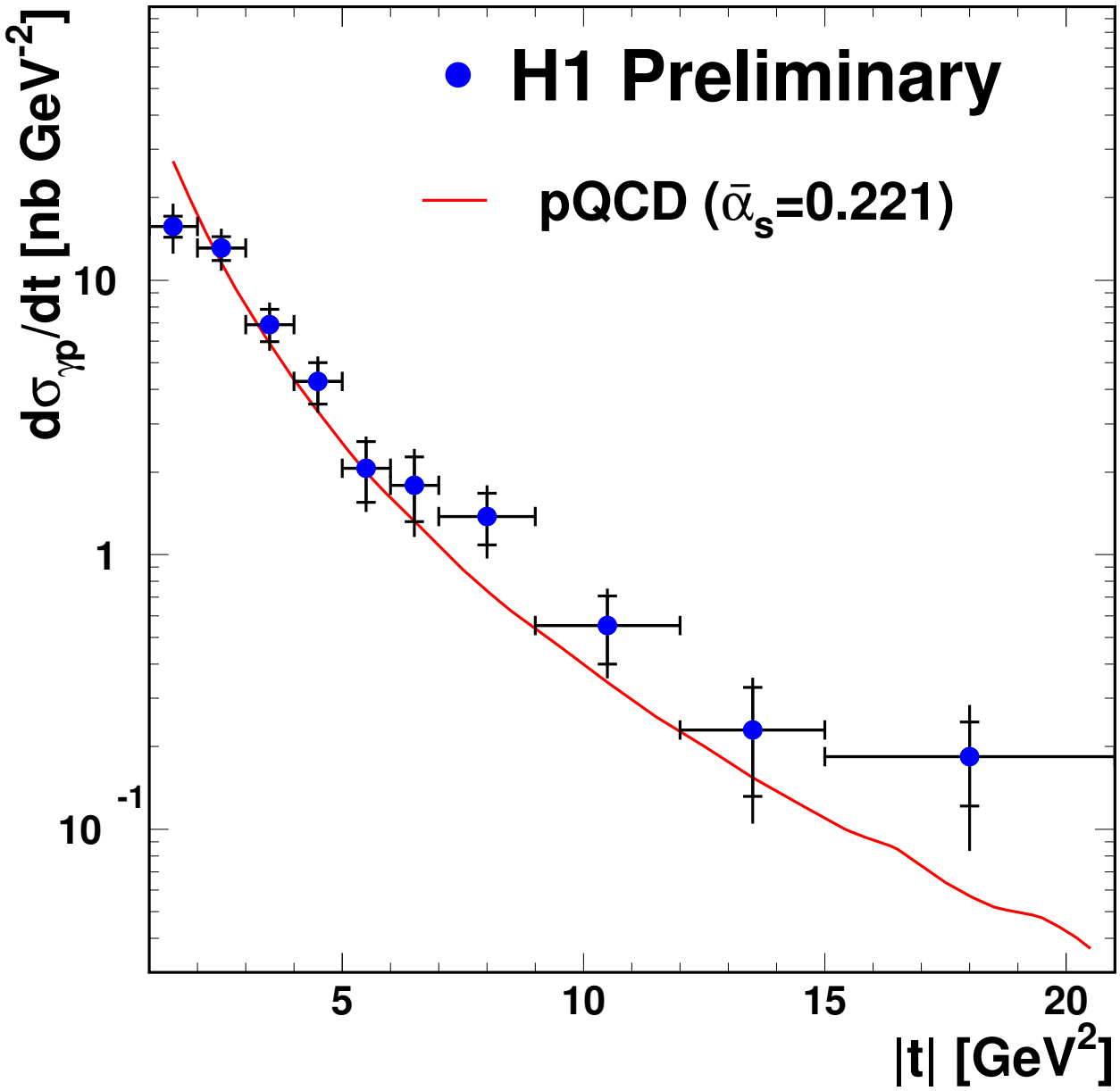
Ratio of J/ψ to ρ^0 Production



NOT asymptotic region ($|t| < M_V^2$)

Diffractive J/ψ Photoproduction (II)

Talk by D. Brown/H1 at DIS2001



Preliminary H1 measurement also available

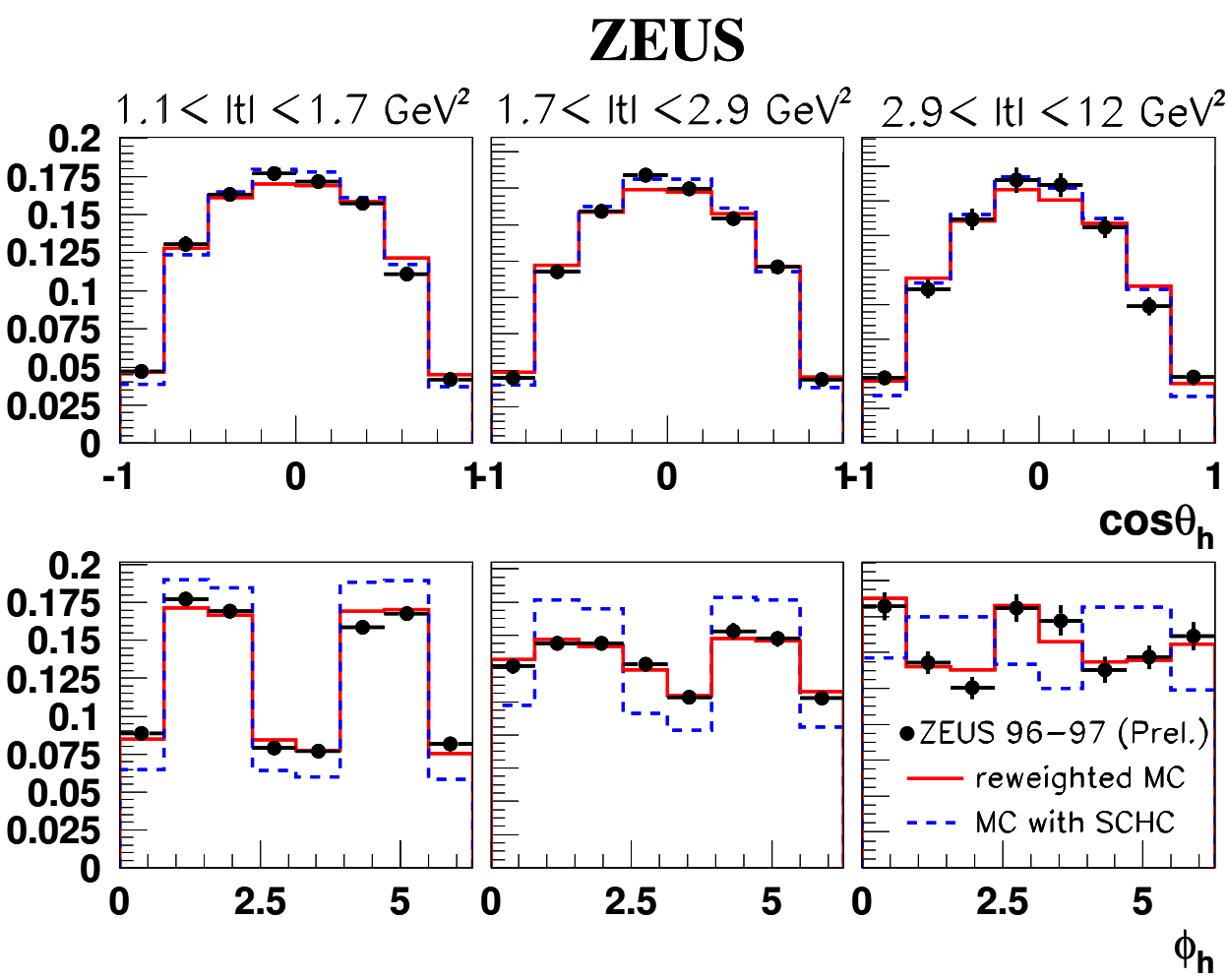
but should not be compared to ZEUS measurement because integrated over angle (M_Υ^2/W^2)

rather than over $x = -t/M_\Upsilon^2$

Helicity transfer in high-$|t|$ γp?

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

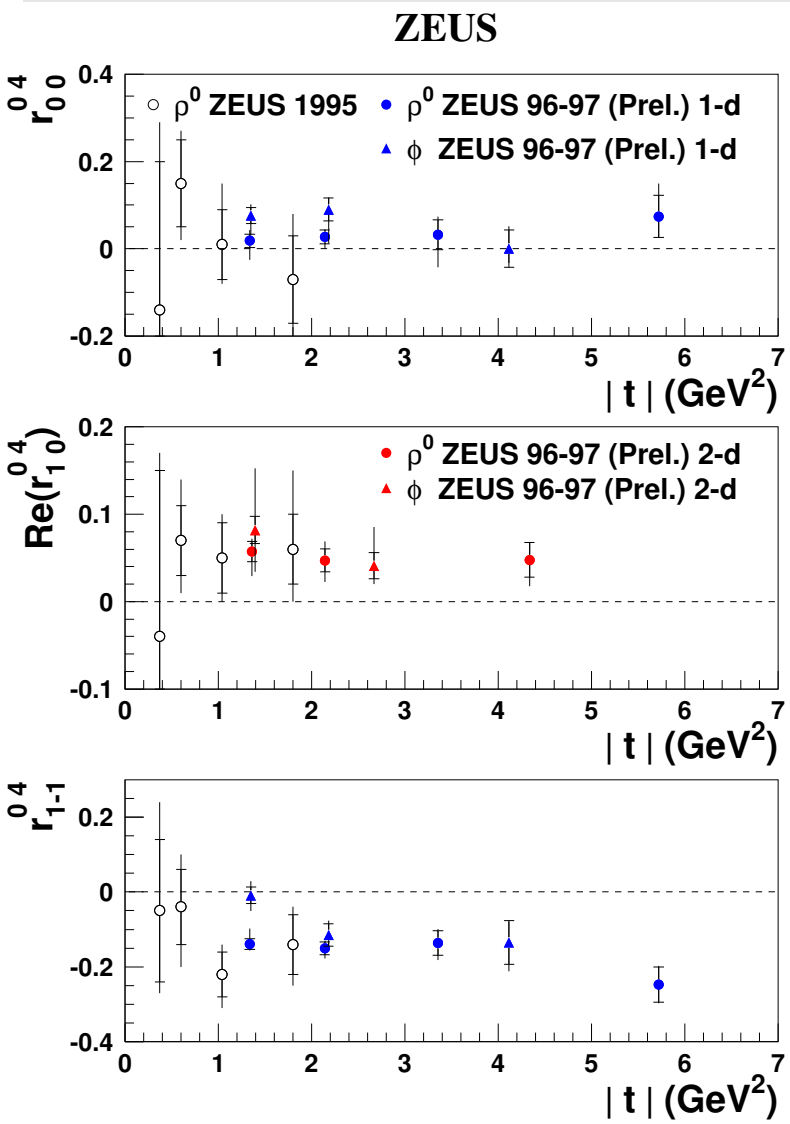
$$W(\cos\theta_h, \phi_h) = \frac{3}{4}\Big[\frac{1}{2}\left(1 - r^{04}_{00}\right) + \frac{1}{2}\left(3r^{04}_{00} - 1\right)\cos^2\theta_h - \sqrt{2}\,\mathrm{Re}(r^{04}_{10})\sin 2\theta_h \cos\phi_h - r^{04}_{1-1}\sin^2\theta_h \cos 2\phi_h \Big]$$



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 $|t|$

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

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 $\Lambda^2_{\rm QCD}$

$\Rightarrow$ 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 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.

Alternative Approaches

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

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

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

Anomalous f_1 trajectory exchange

Odd-signature partner of Pomeron arising from axial anomaly

Conclusions

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

Deeply Virtual Compton Scattering

- ☞ Clear signals observed at HERA
- ☞ New measurements of cross sections

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)
- ☞ 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