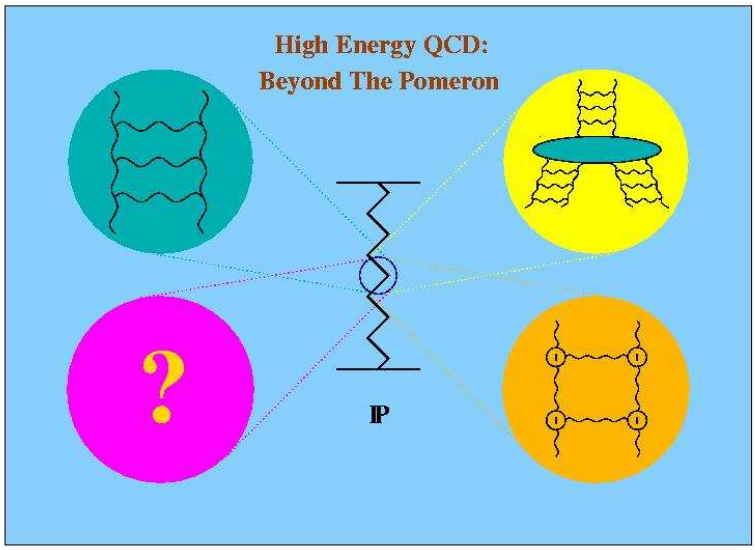
High Energy QCD Workshop *BNL*

23 May 2001 *Upton, New York*

Scaling Properties of High-Energy Diffractive Vector-Meson Production at High Momentum Transfer



- Selected Results from HERA
- Surprise in ρ^0 Photoproduction at High Momentum Transfer

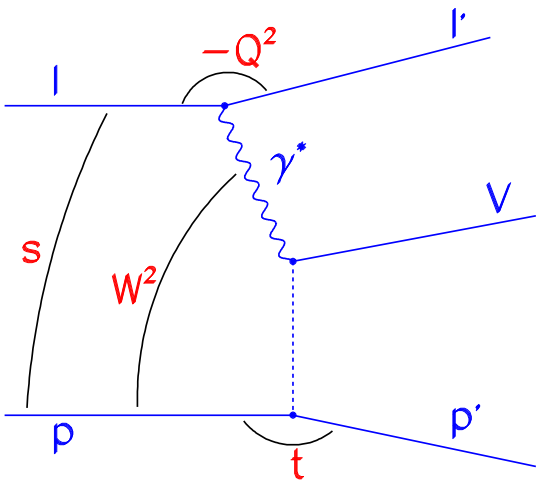
J. A. Crittenden

Deutsches Elektronen-Synchrotron

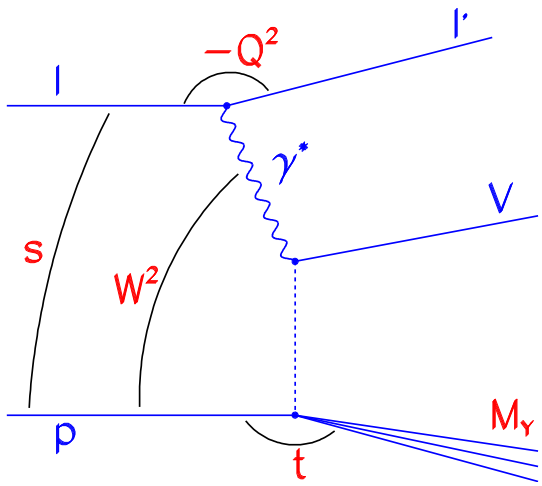
DESY

Production of Vector Mesons at HERA

Elastic



Proton-dissociative



$\sqrt{s}$: 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

$20 < W < 240$ 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 at high $|t|$

General Remarks on Exclusive VM Production at HERA

☞ **Investigation of vacuum-exchange processes**

Vacuum exchange has a complicated, poorly understood structure

☞ **Study properties of strong interaction**

⇒ Soft interactions

* Forward, total cross sections
* Exponential t-slopes, shrinkage
* Helicity rules

⇒ Hard interactions

* Short-distance vacuum exchange
* Scale definition
* Sensitive to $|xG(\mu, x)|^2$
* Helicity rules

The hard/soft transition can be studied in

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

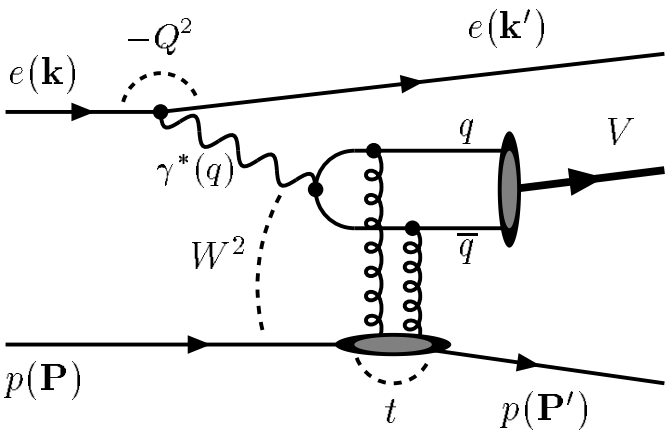
☞ **Exclusivity allows study of helicity structure**

⇒ The VM helicity state is directly related to the expected scaling behavior

⇒ The spin-density matrix elements are directly related to meson structure

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)

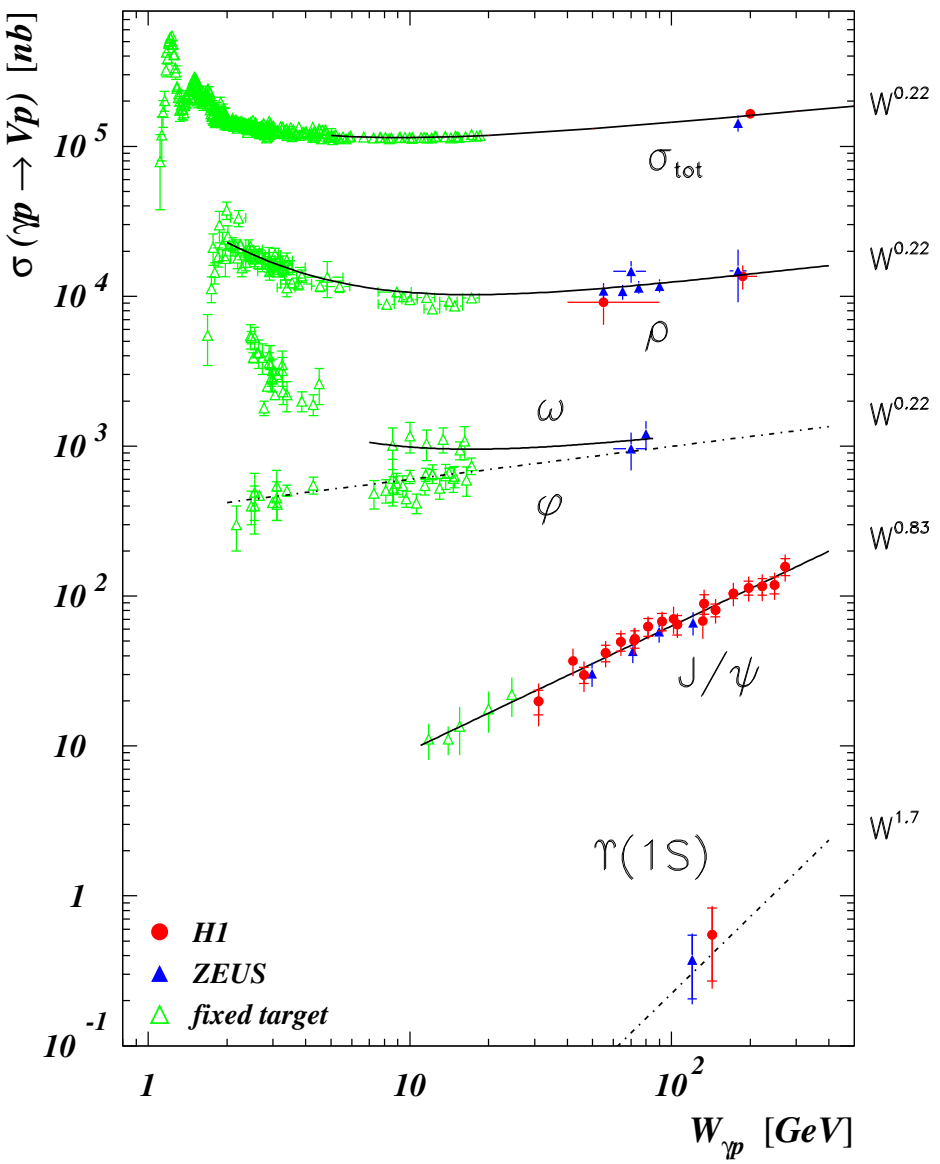
$$\bar{Q}^2 = \frac{Q^2+M_V^2-t}{4} \quad (?)$$

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 ?

Quick Review (I): Elastic J/ψ Photoproduction

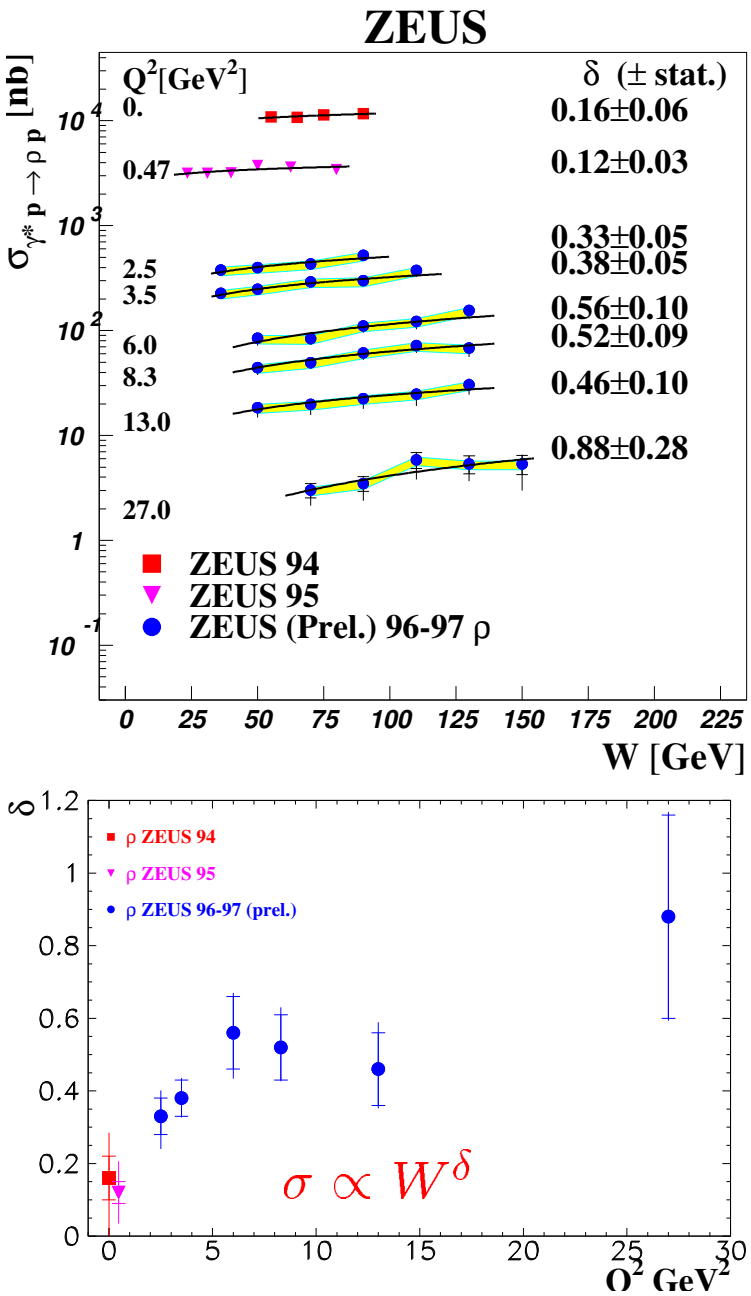
$$\gamma + p \to J/\psi + p$$



J/ψ energy dependence consistent with steep gluon density

Quick Review (II): Elastic ρ^0 Electroproduction

$$\gamma^* + p \to \rho^0 + p$$

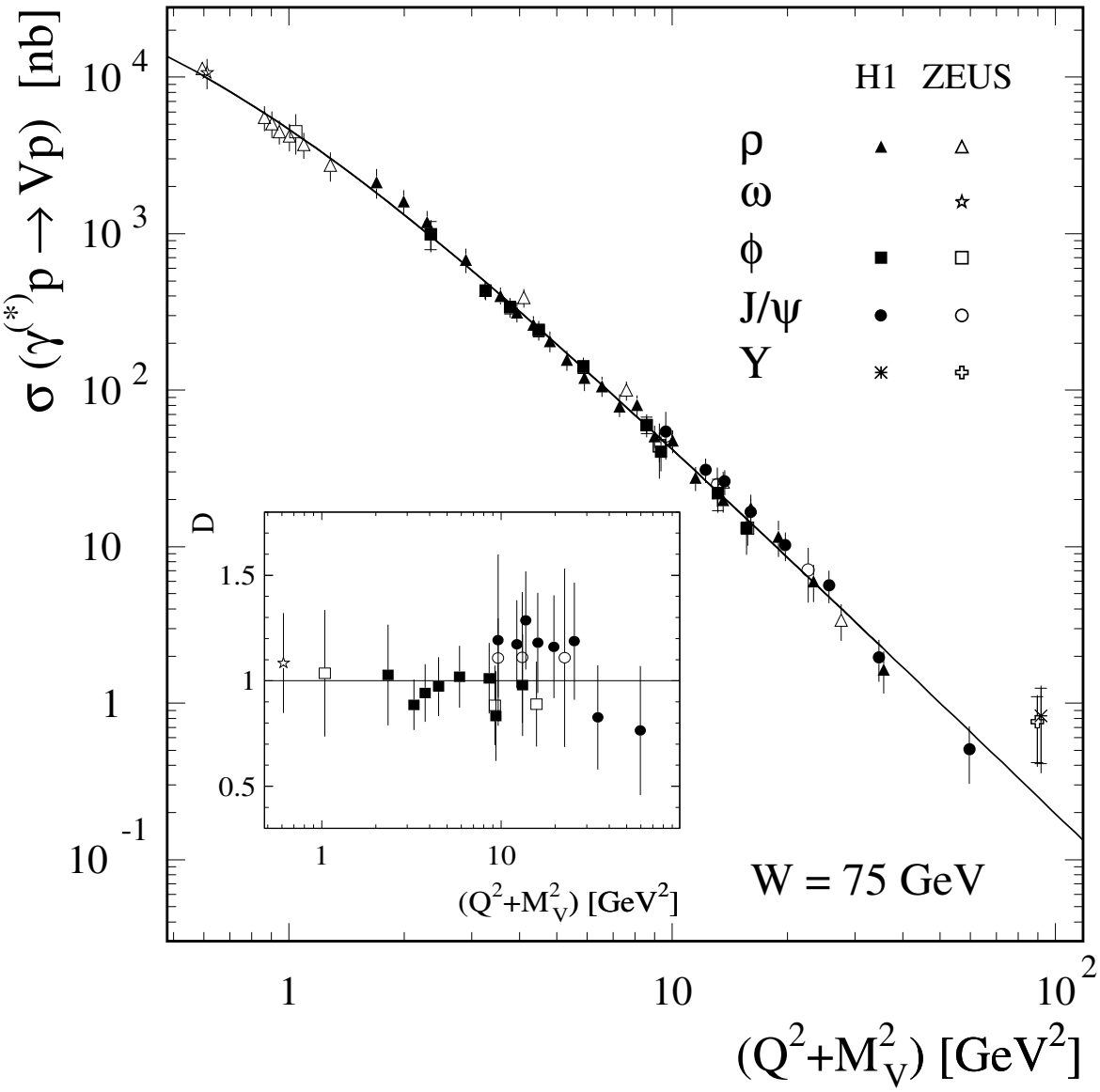


Energy dependence steepens with virtuality

(See talk by A.Kreisel/ZEUS at DIS2001)

Quick Review (III): Elastic VM Electroproduction

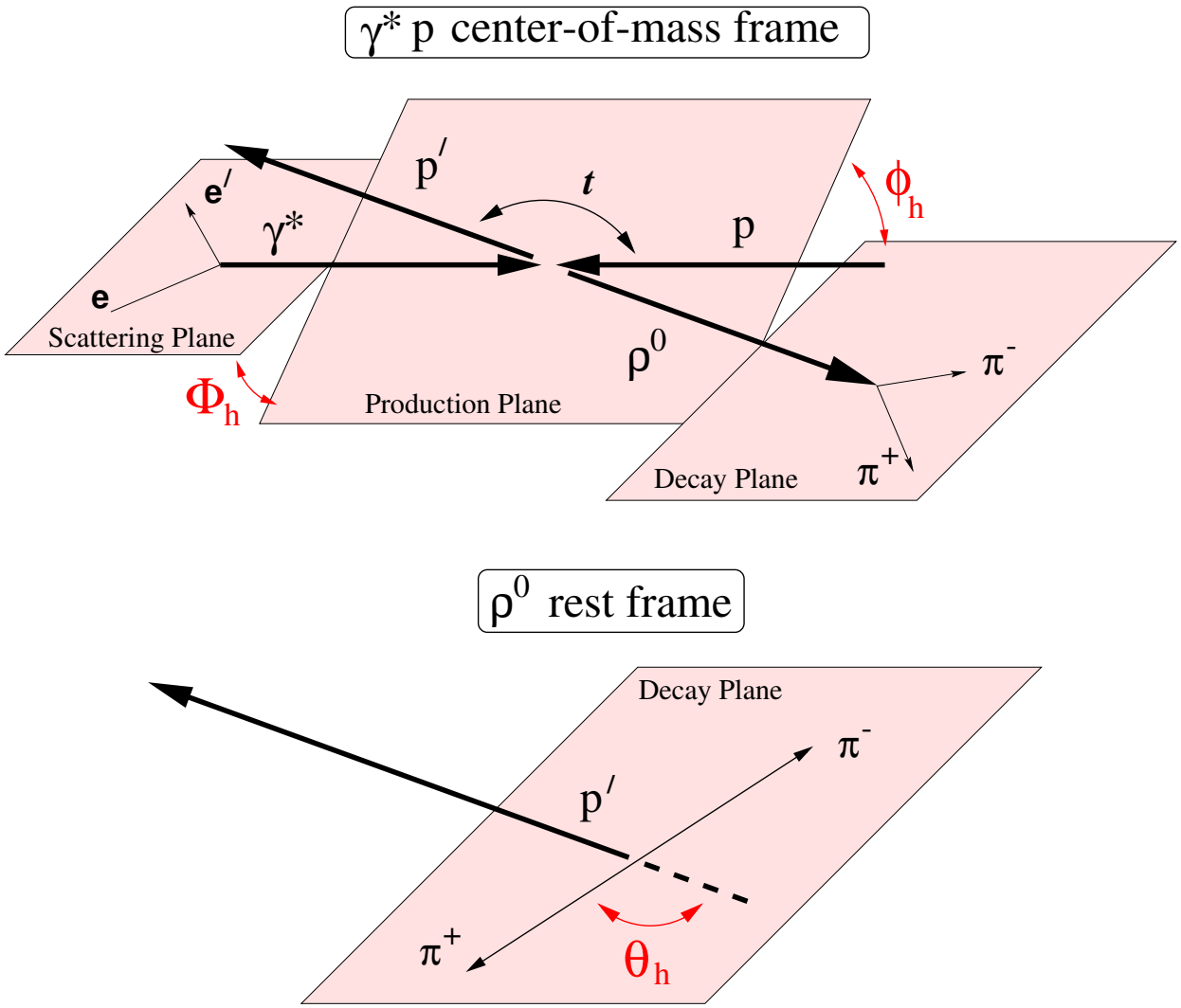
H1 Collaboration, Phys. Lett. B483 (2000) 360



Universal scaling (?)

(but this is $\sigma_L + \sigma_T$)

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^+

3-D Decay-Angle Distribution

(15 linearly independent parameters)

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

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

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

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

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

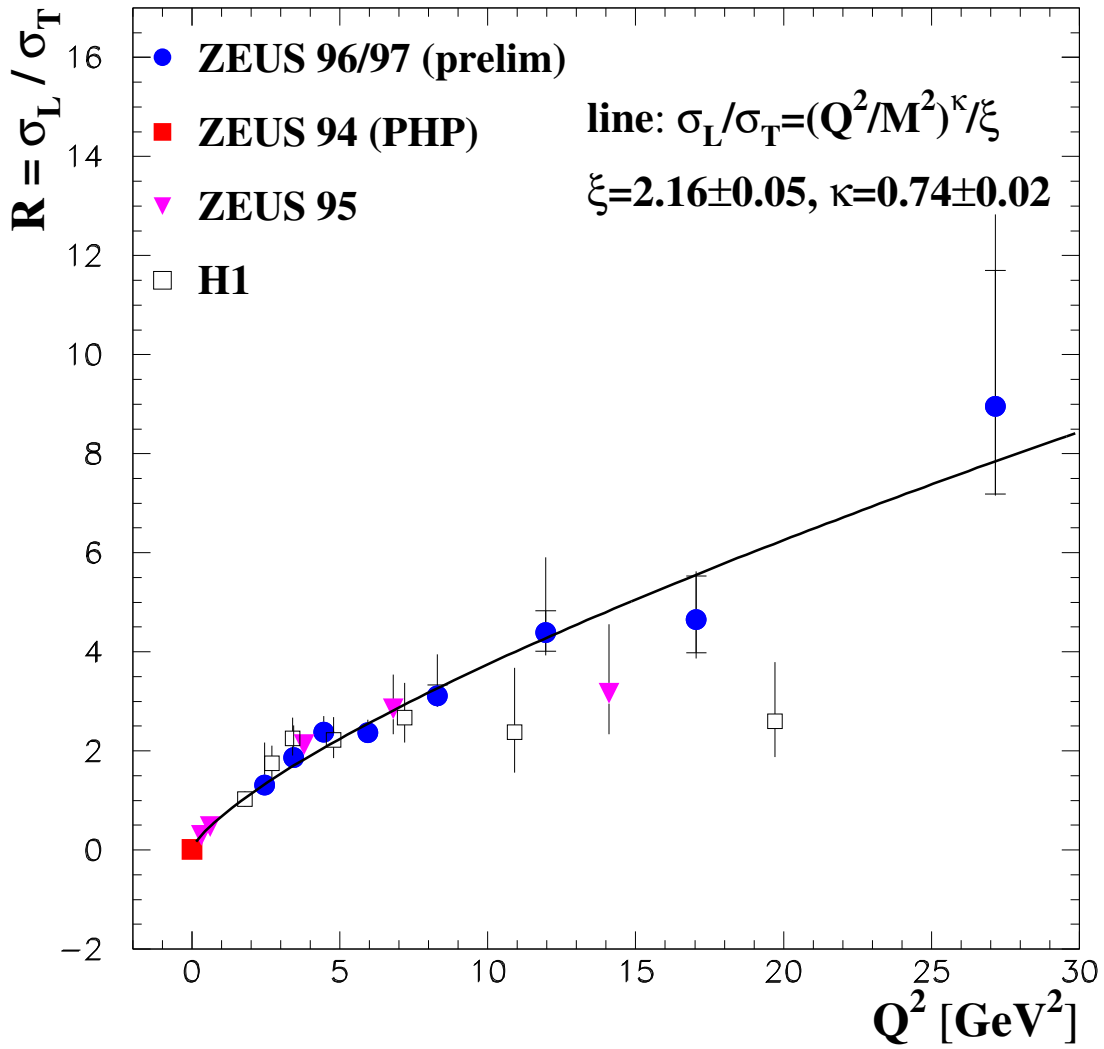
$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\Phi_h\big(\, \sqrt{2}\,\mathrm{Im}\, r^6_{10}\, \sin 2\theta_h \sin\phi_h + \mathrm{Im}\, r^6_{1-1}\sin^2\theta_h \sin 2\phi_h \big)\Big]$$

Quick Review (IV): σ_L/σ_T in Elastic ρ^0 Electroproduction

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

Δ now known to be small

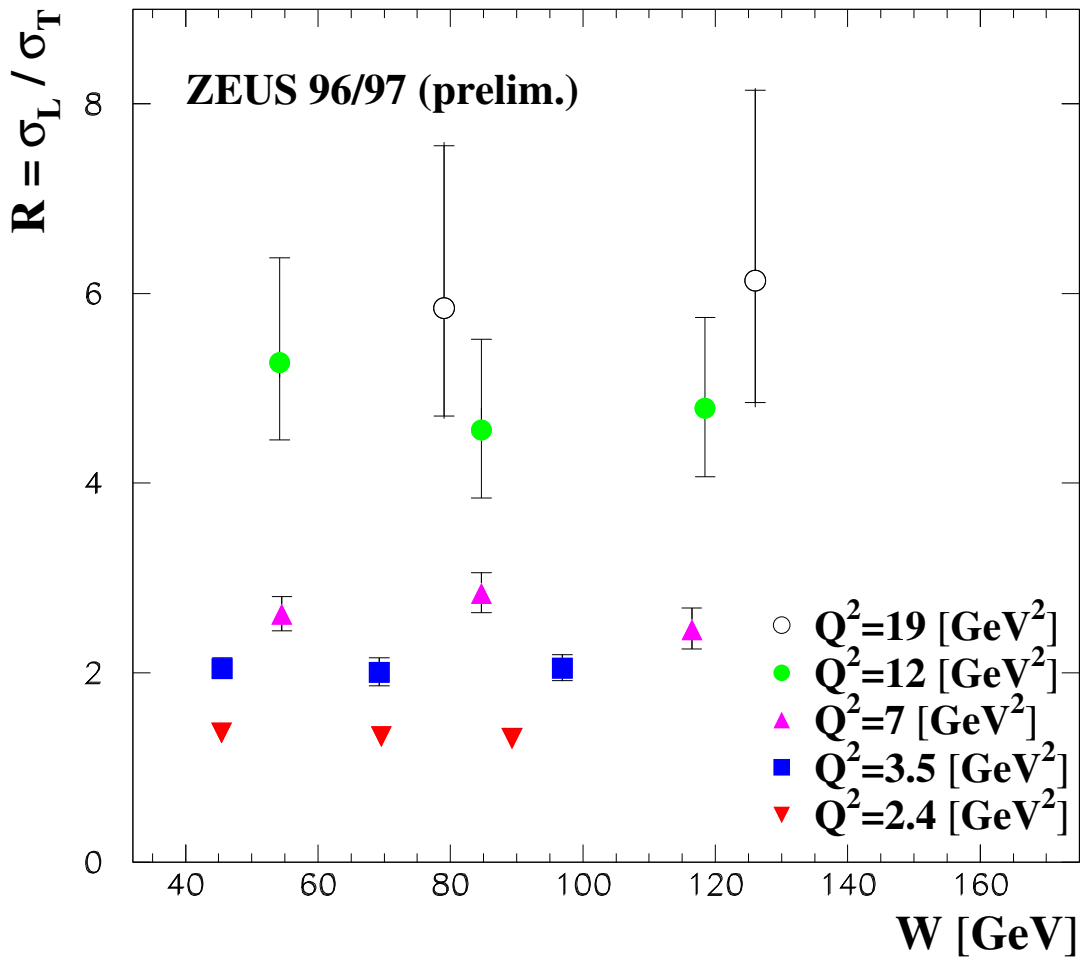
A. Kreisel/ZEUS at DIS2001



The dominance of σ_L was an early prediction of pQCD

Quick Review (V): σ_L/σ_T in Elastic ρ^0 Electroproduction

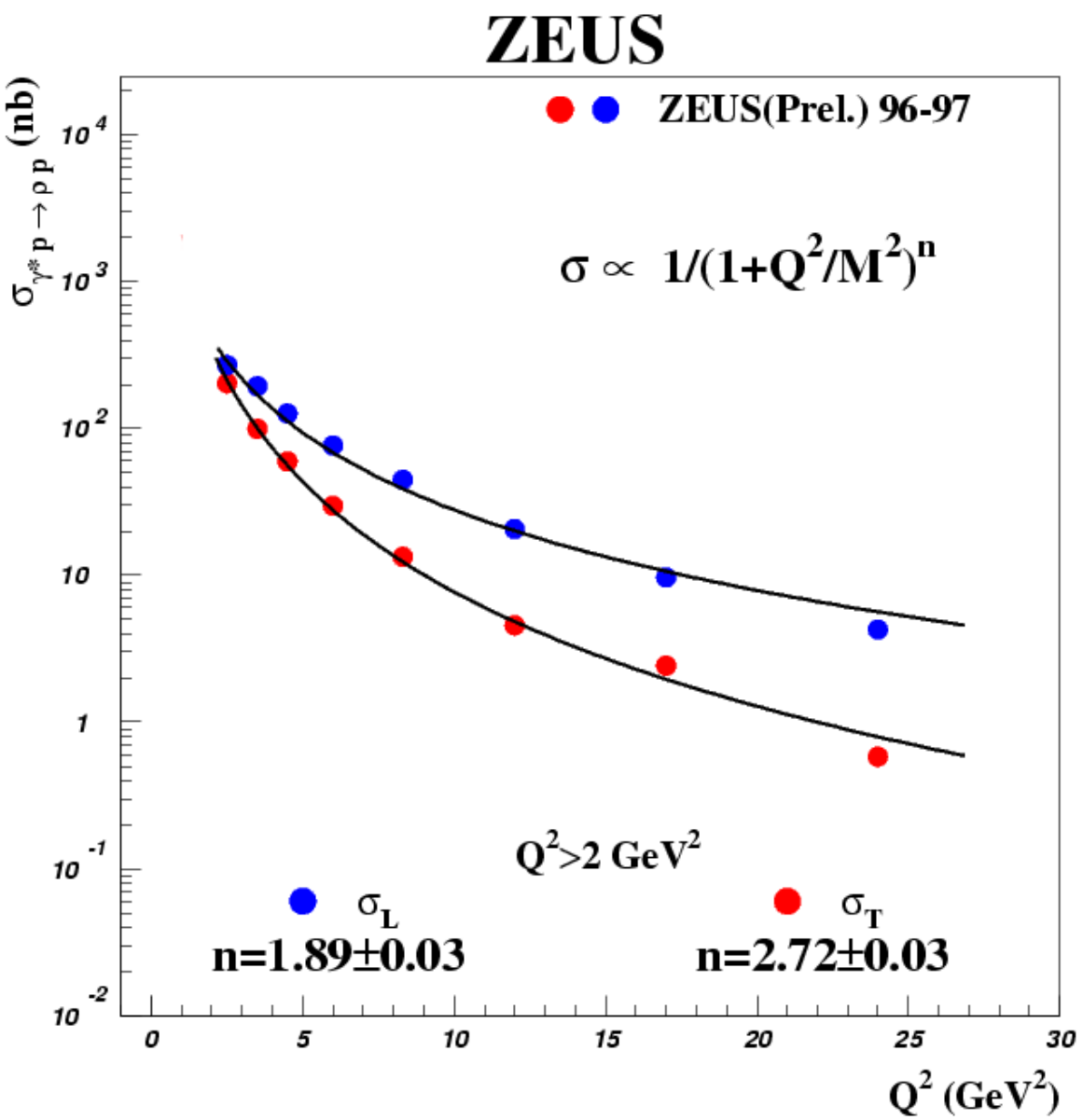
A. Kreisel/ZEUS at DIS2001



Why no energy dependence?

Quick Review (VI): σ_L/σ_T in Elastic ρ^0 Electroproduction

A. Kreisel at DIS2001

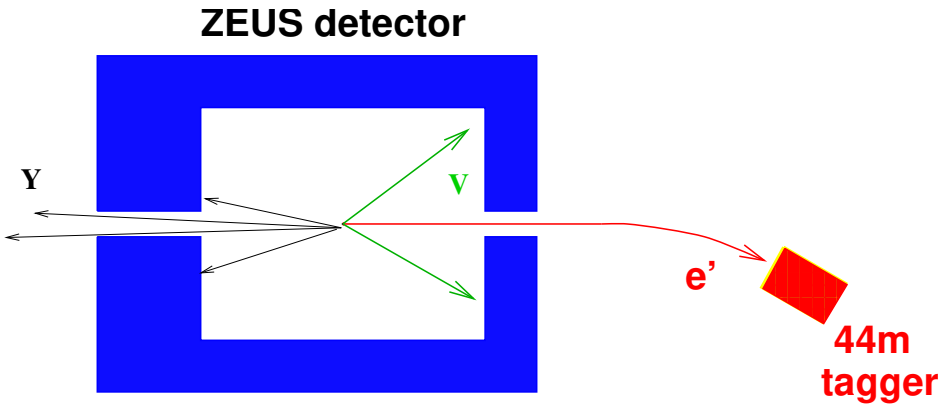


Remarkably hard scaling behavior for σ_T

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

Main Topic:
VM Photoproduction at High $|t|$

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

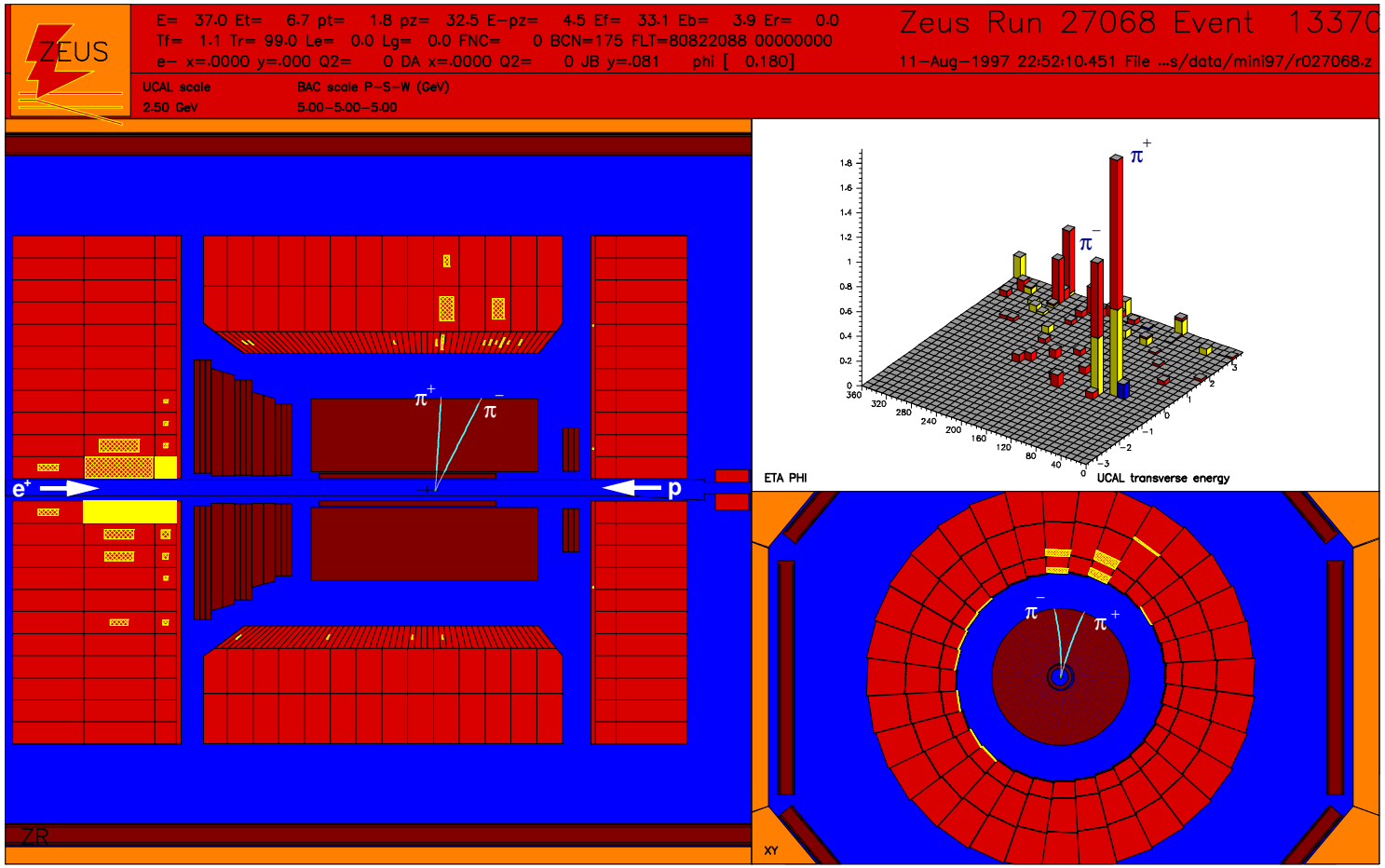
J/ψ: $\simeq$ 150

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 $0.01 < x < 1$

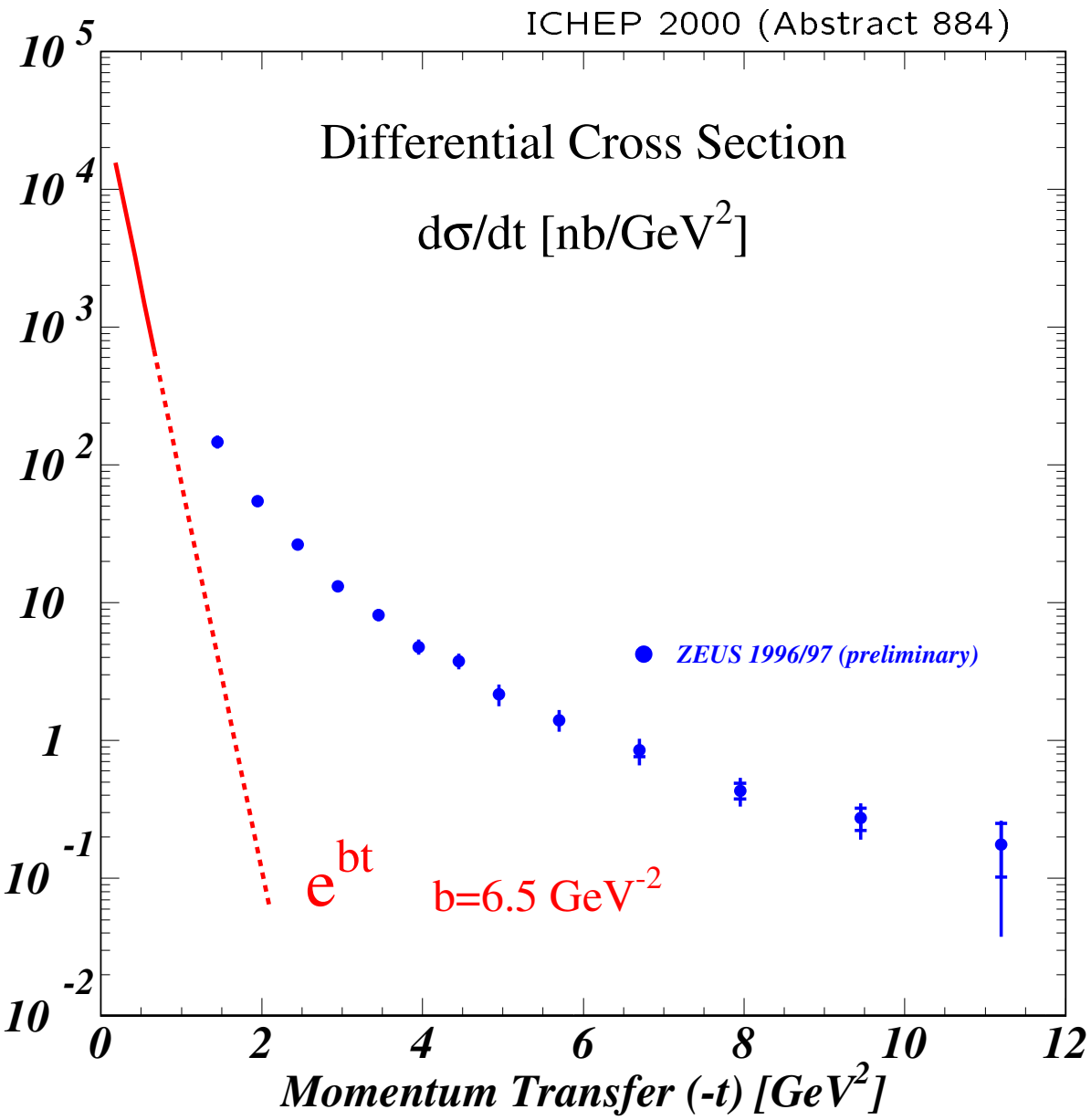
Candidate for ρ^0 Photoproduction at High $|t|$



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

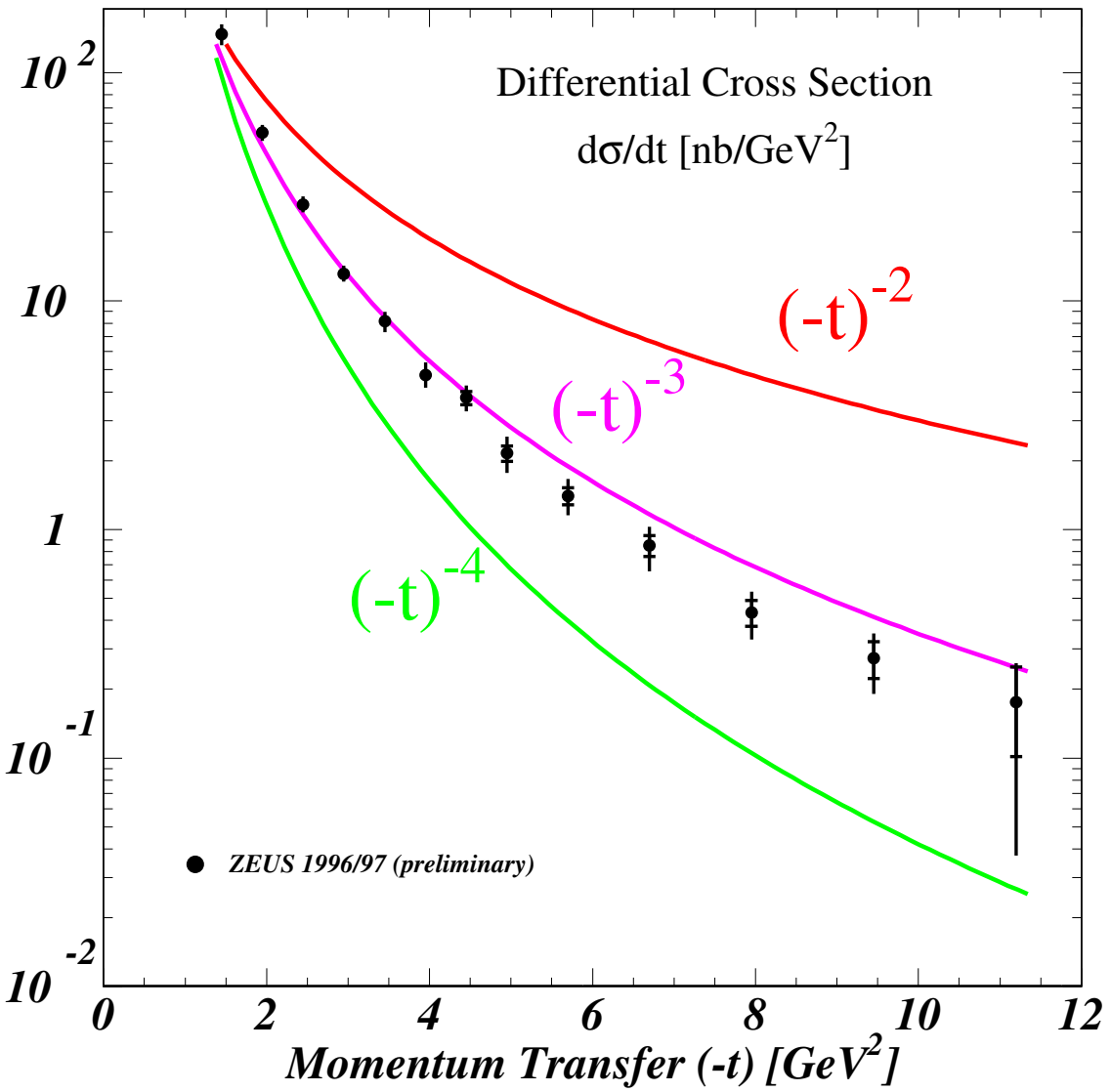
Diffractive ρ^0 Photoproduction (I)

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



Asymptotic region

Diffractive ρ^0 Photoproduction (II)



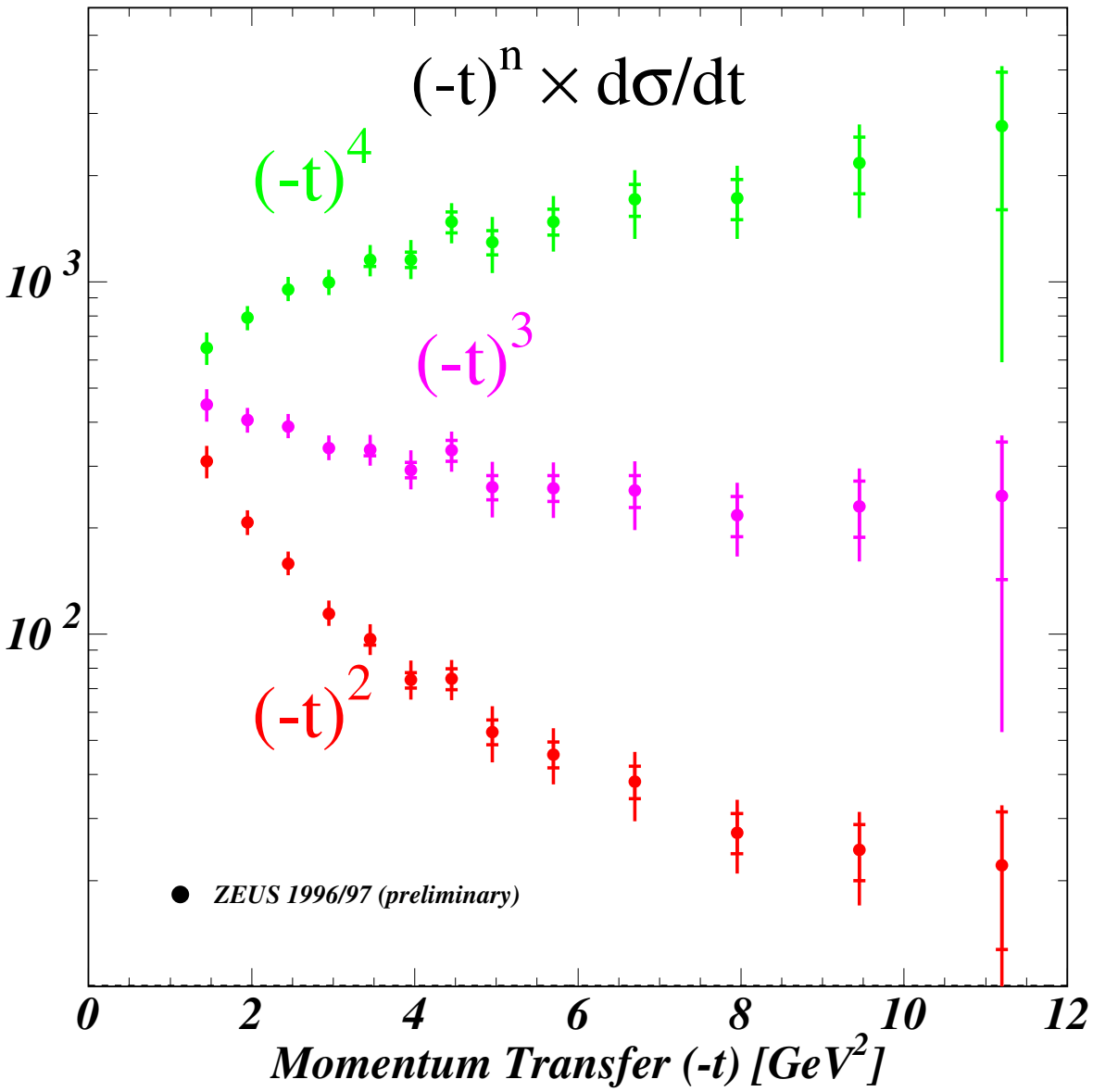
Scaling Property

Power dependence with

$n = 3$

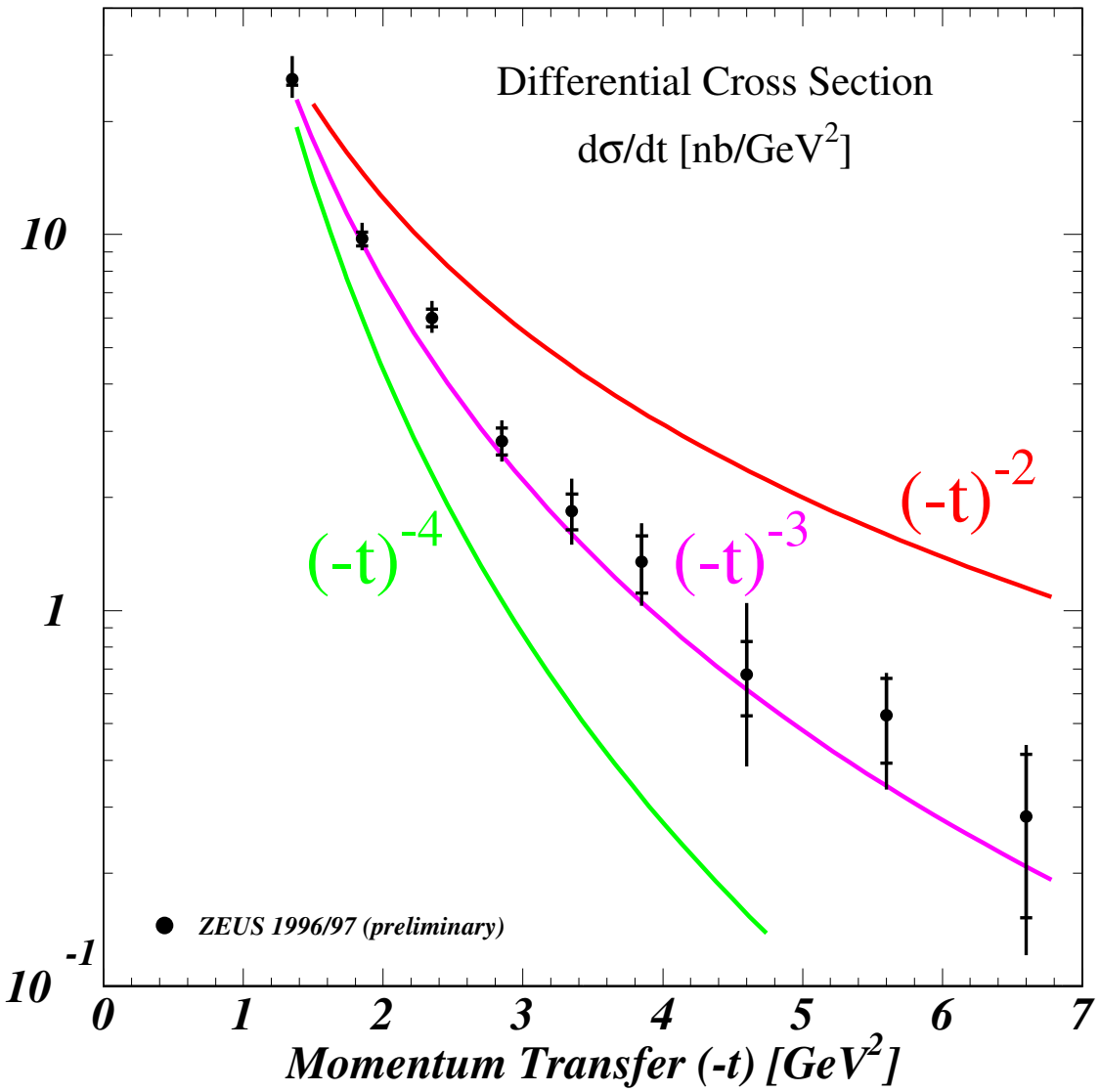
matches the data fairly well

Diffractive ρ^0 Photoproduction (III)



Multiplying with $(-t)^n$

Diffractive ϕ Photoproduction (I)



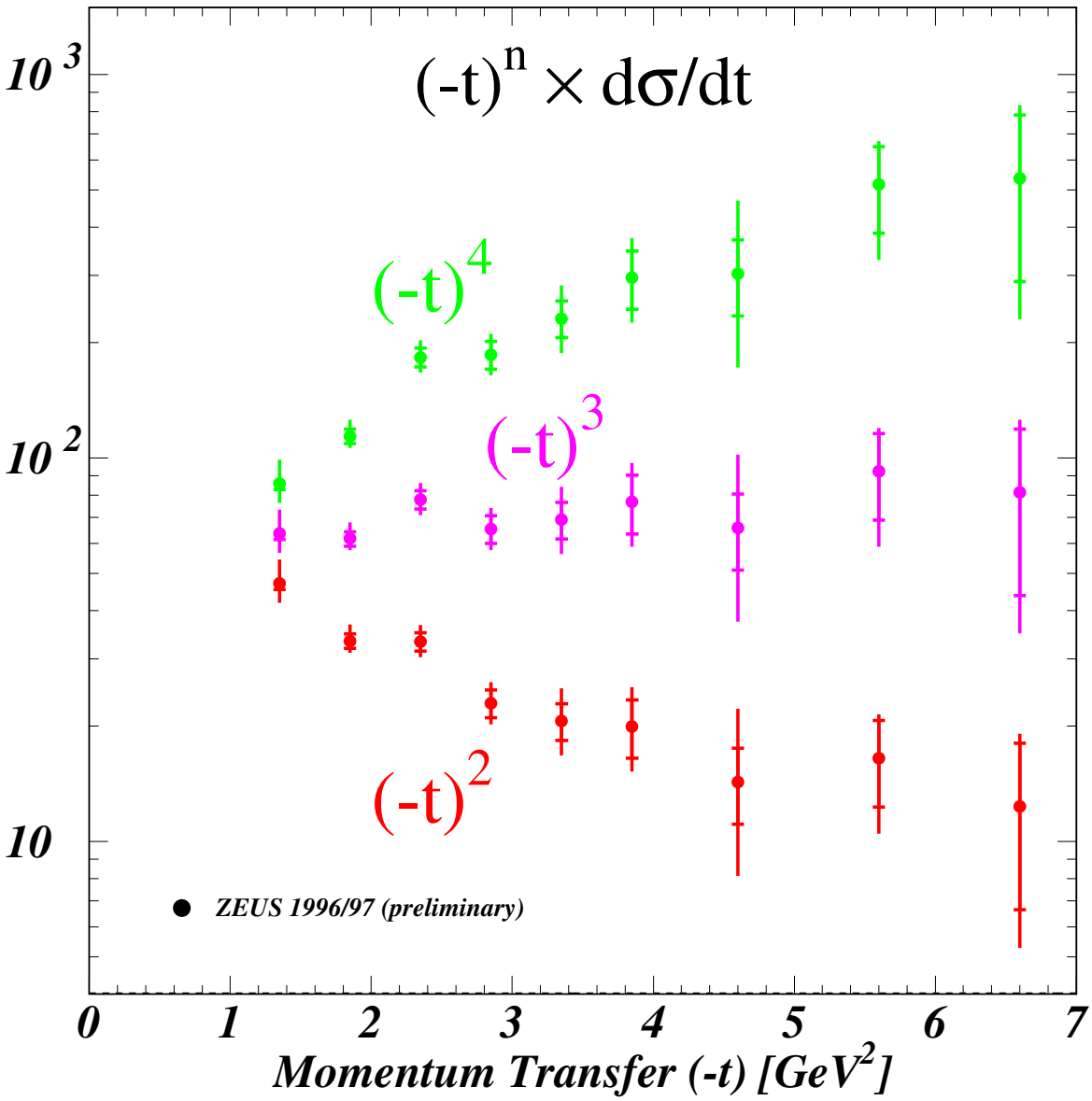
Scaling Property

Power dependence with

$n = 3$

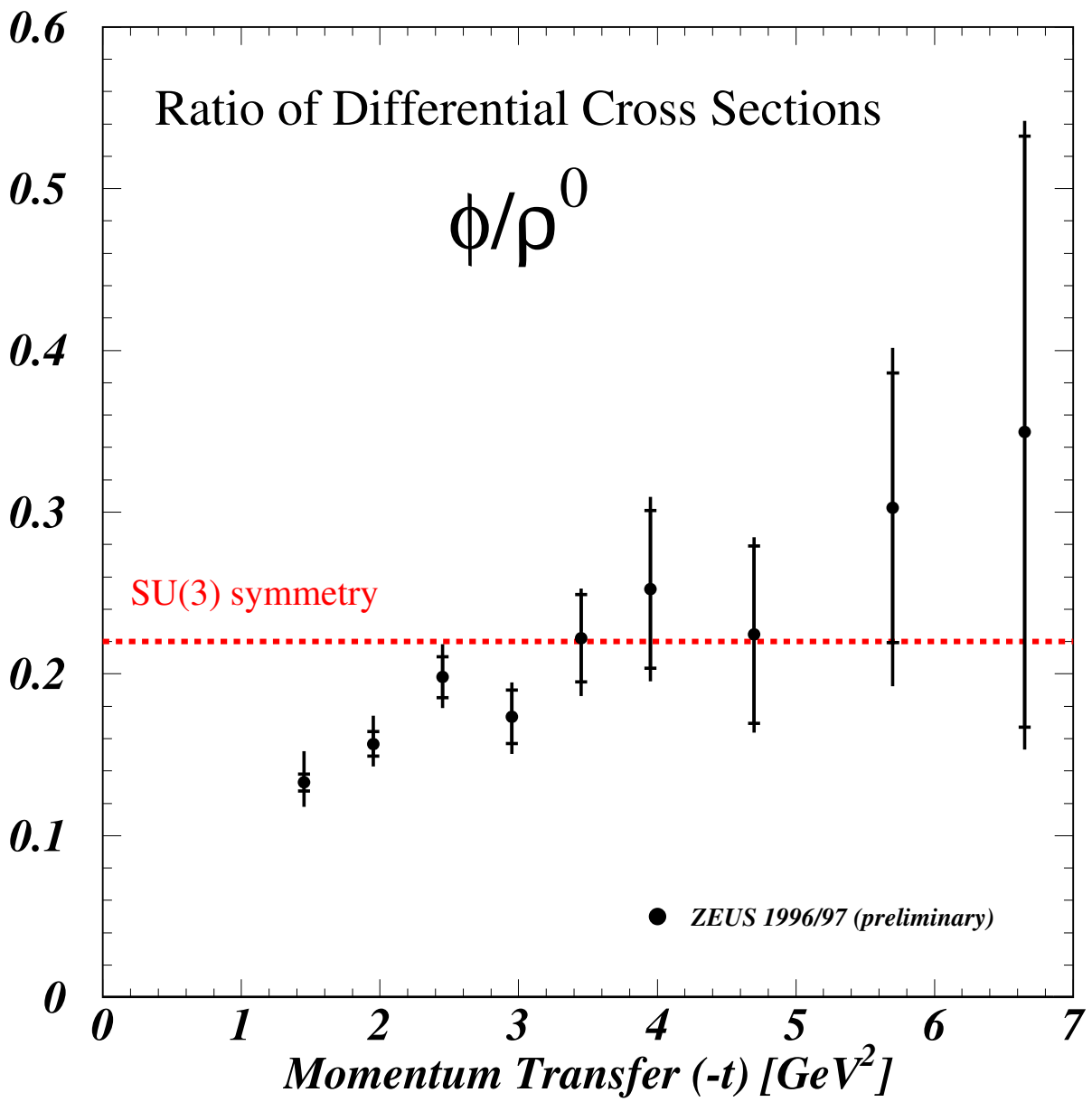
matches the data well

Diffractive ϕ Photoproduction (II)



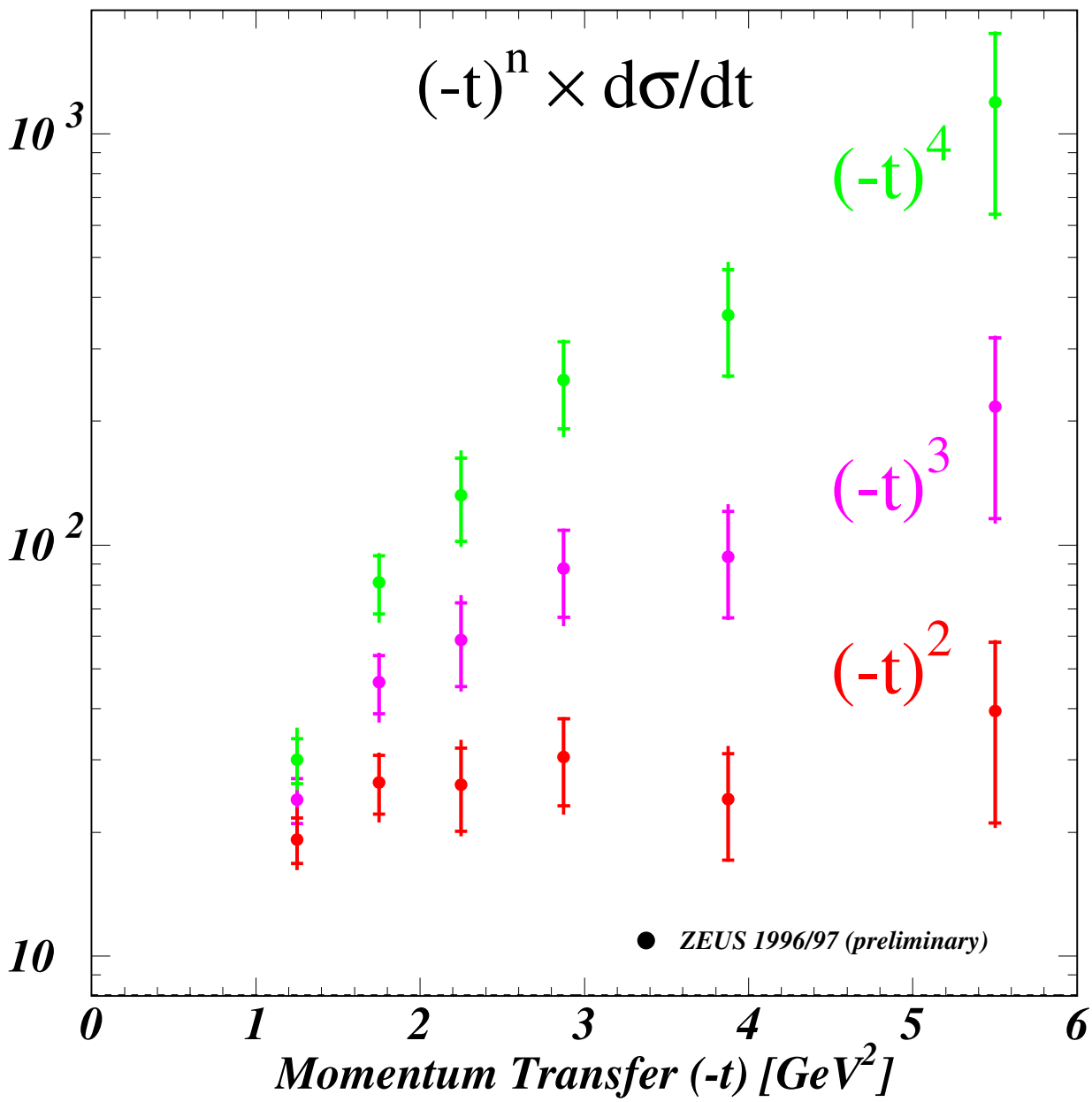
Multiplying with $(-t)^n$

Ratio of ϕ to ρ^0 Production



SU(3) symmetry observed at high $|t|$

Diffractive J/ψ Photoproduction (I)

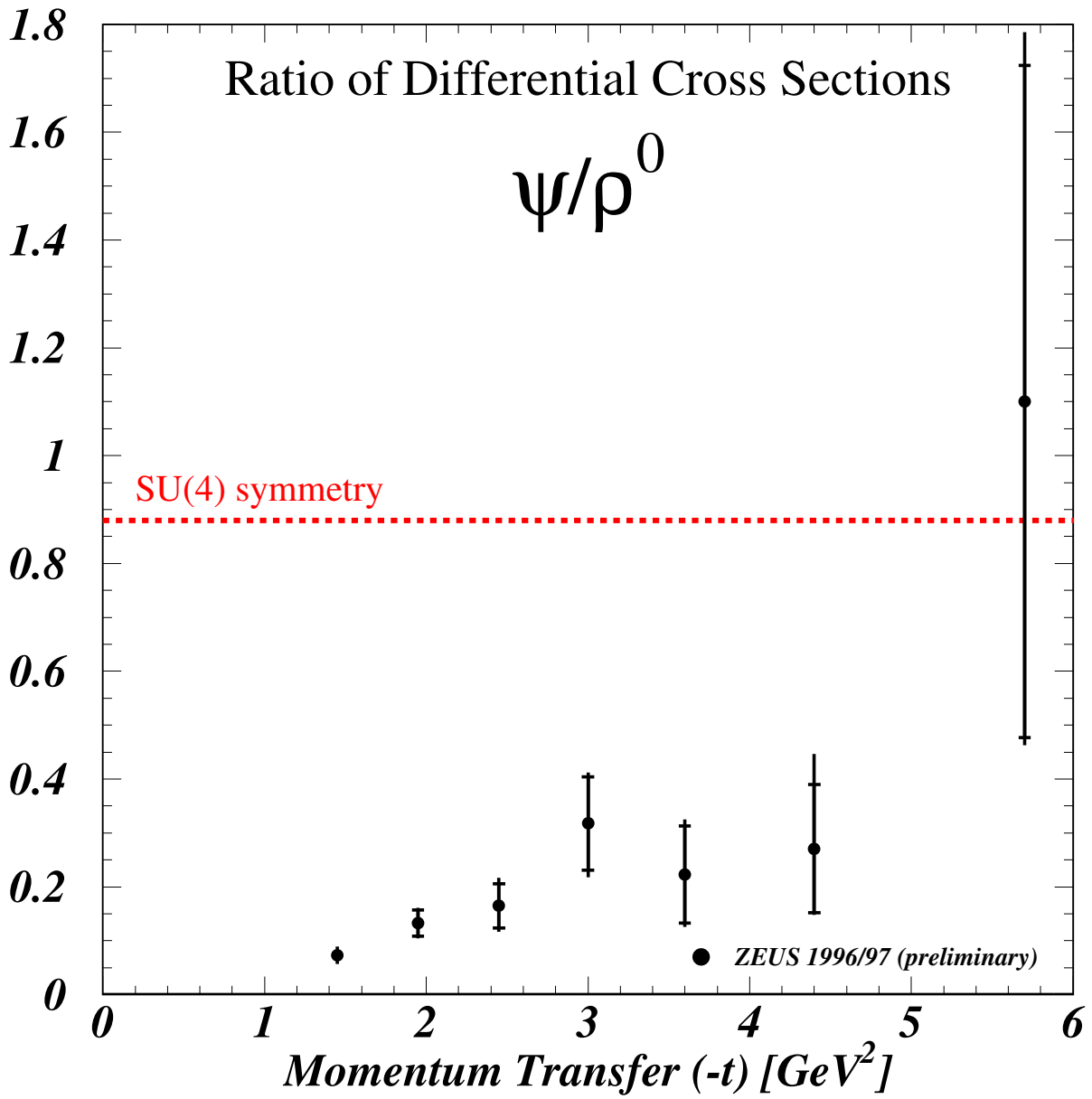


But here we have $|t| < M^2_{J/\psi}$

Meson structure effects may be important

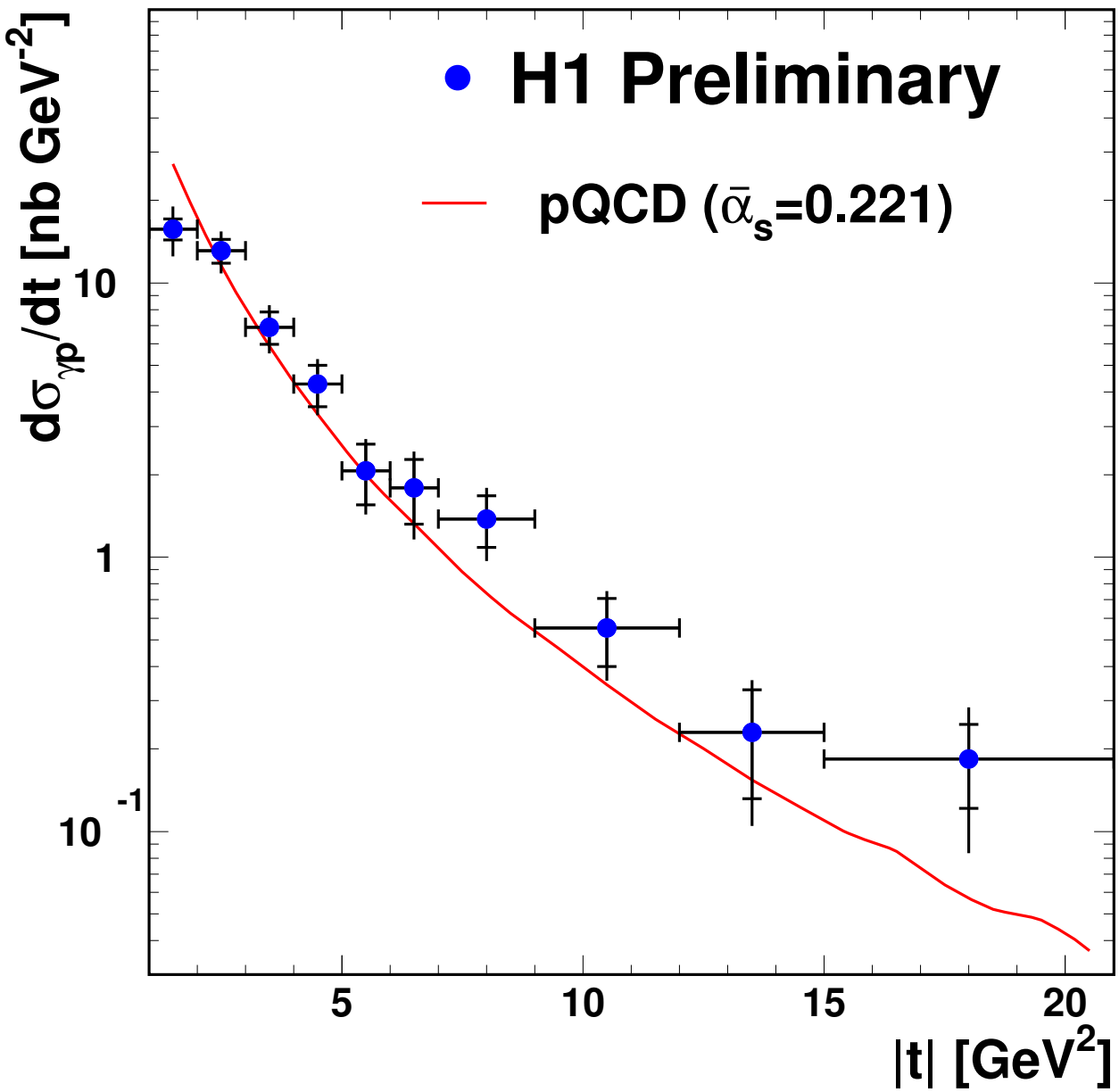
SU(4) symmetry broken (see next figure)

Ratio of J/ψ to ρ^0 Production



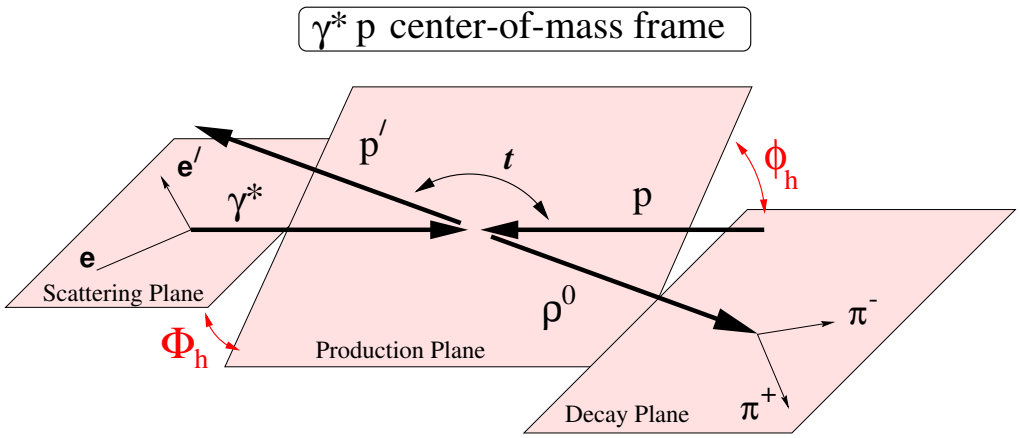
Diffractive J/ψ Photoproduction (II)

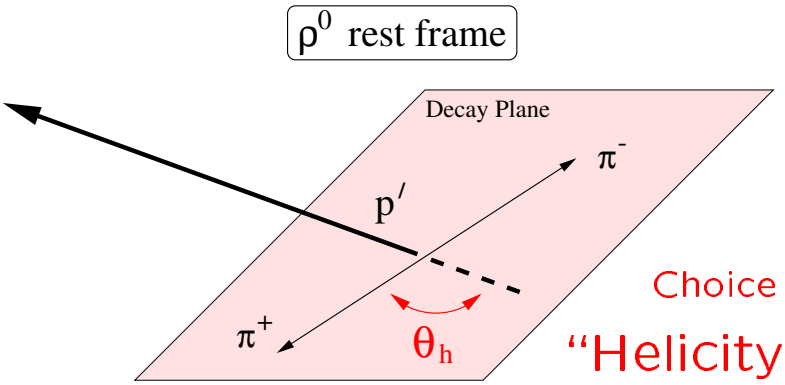
Talk by D. Brown/H1 at DIS2001



Preliminary H1 measurement also available

Decay-Angle Analysis (I)





Choice of Z-axis:

"Helicity 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

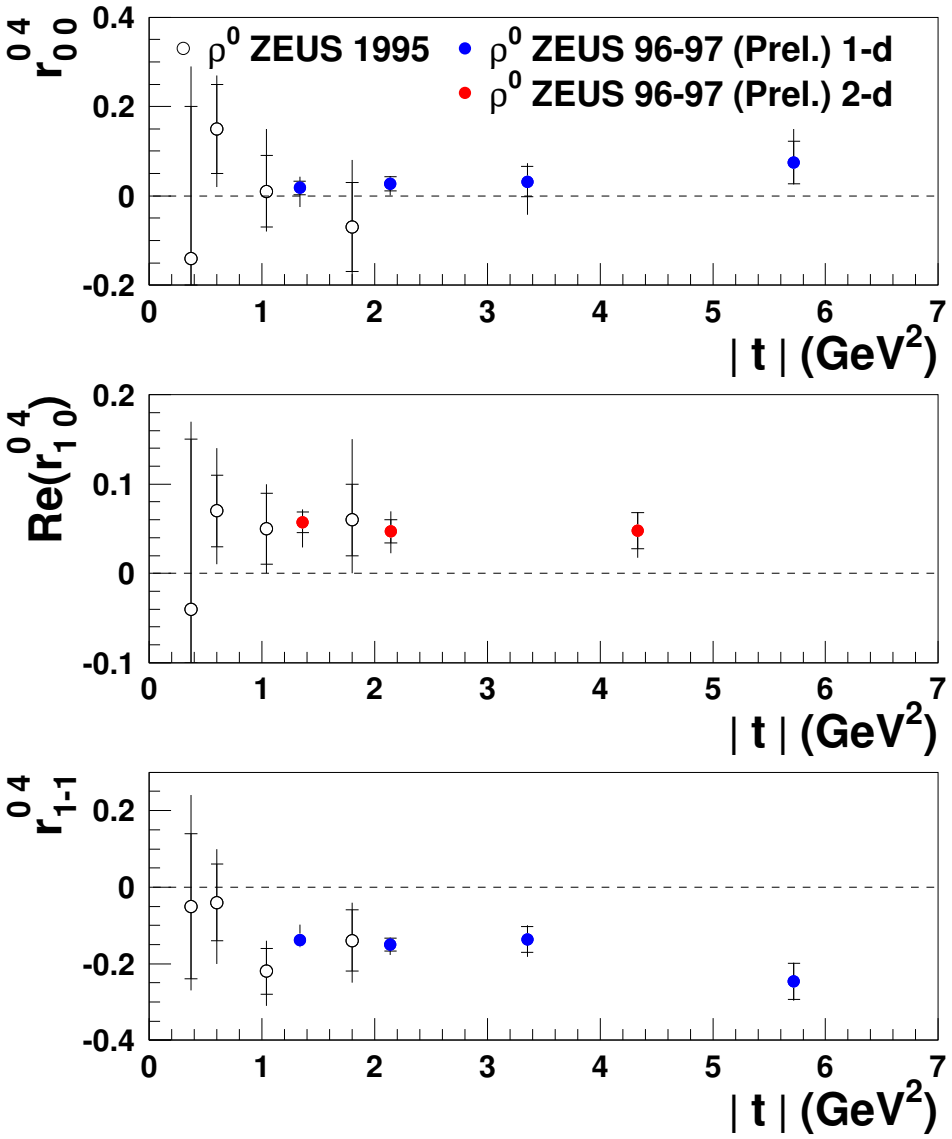
ϕ_h Azimuthal angle of π^+

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

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

Decay-Angle Analysis (II)

Talk by A. Kowal at DIS2001



Transverse polarization dominates

Helicity breaking 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

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

⇒ low-order process (*first* order ?)

⇒ 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 $\Lambda^2_{\rm QCD}$

⇒ 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?

Summary of Results on VM Photoproduction at High $|t|$

High-t vector-meson photoproduction presents an opportunity to study the dynamics of vacuum exchange

In the asymptotic region of momentum transfer

ρ^0/ϕ photoproduction exhibits a **very hard spectrum**

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} \propto (-t)^{-n} \quad n \simeq 3$$

The ρ^0/ϕ mesons are predominantly **transverse**

The ratio of ϕ to ρ^0 exhibits **SU(3) symmetry**

Attempted Synthesis

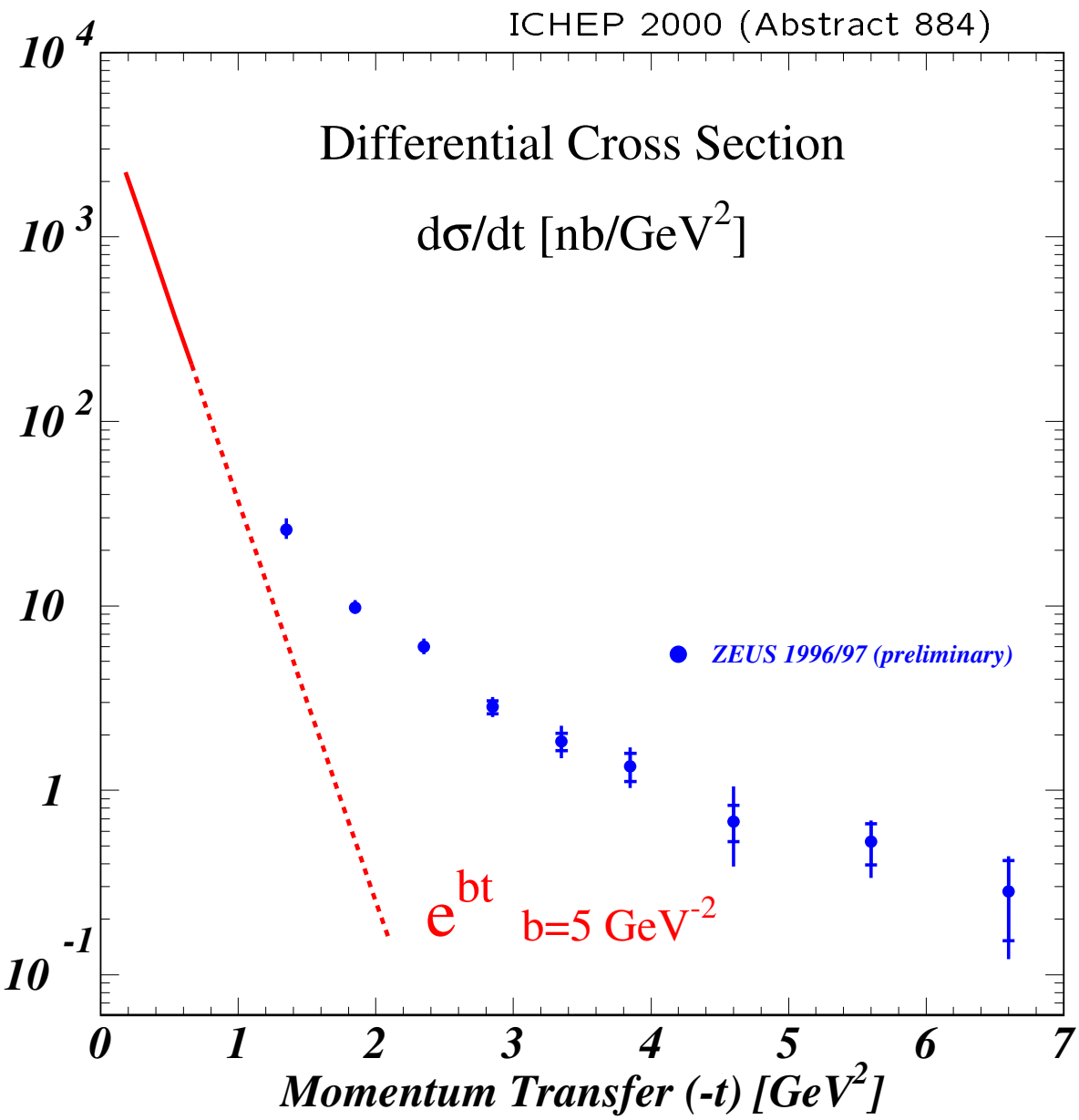
There appears to be increasing evidence for a point-like T→ T vacuum-exchange transition which is difficult to reconcile with QCD

- A QCD description requires chiral-symmetry breaking, for example, quark-mass effects.
- This requirement results in a t dependence stronger than observed.
- This T→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.

Diffractive ϕ Photoproduction

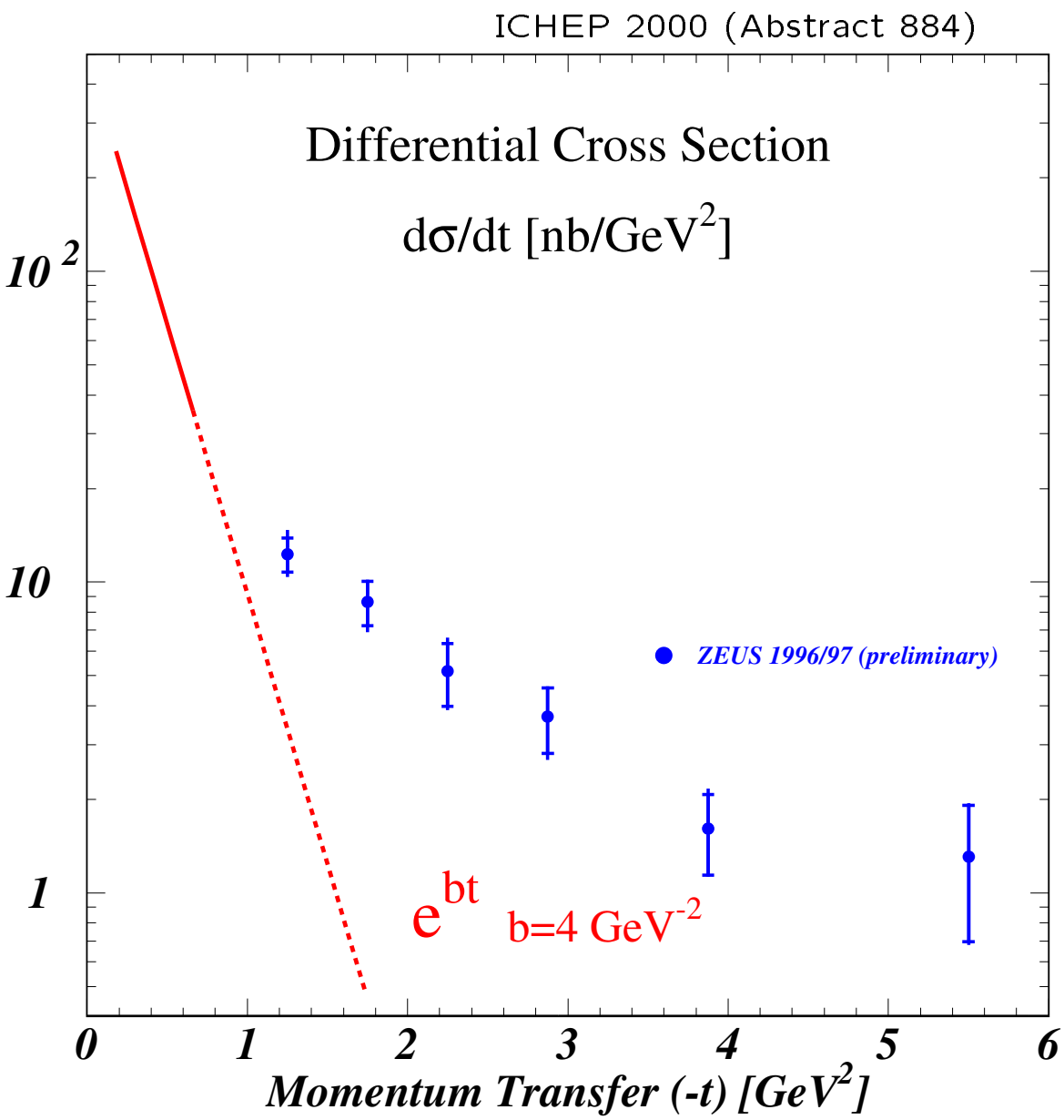
$$\gamma + p \rightarrow \phi + N$$



Asymptotic region

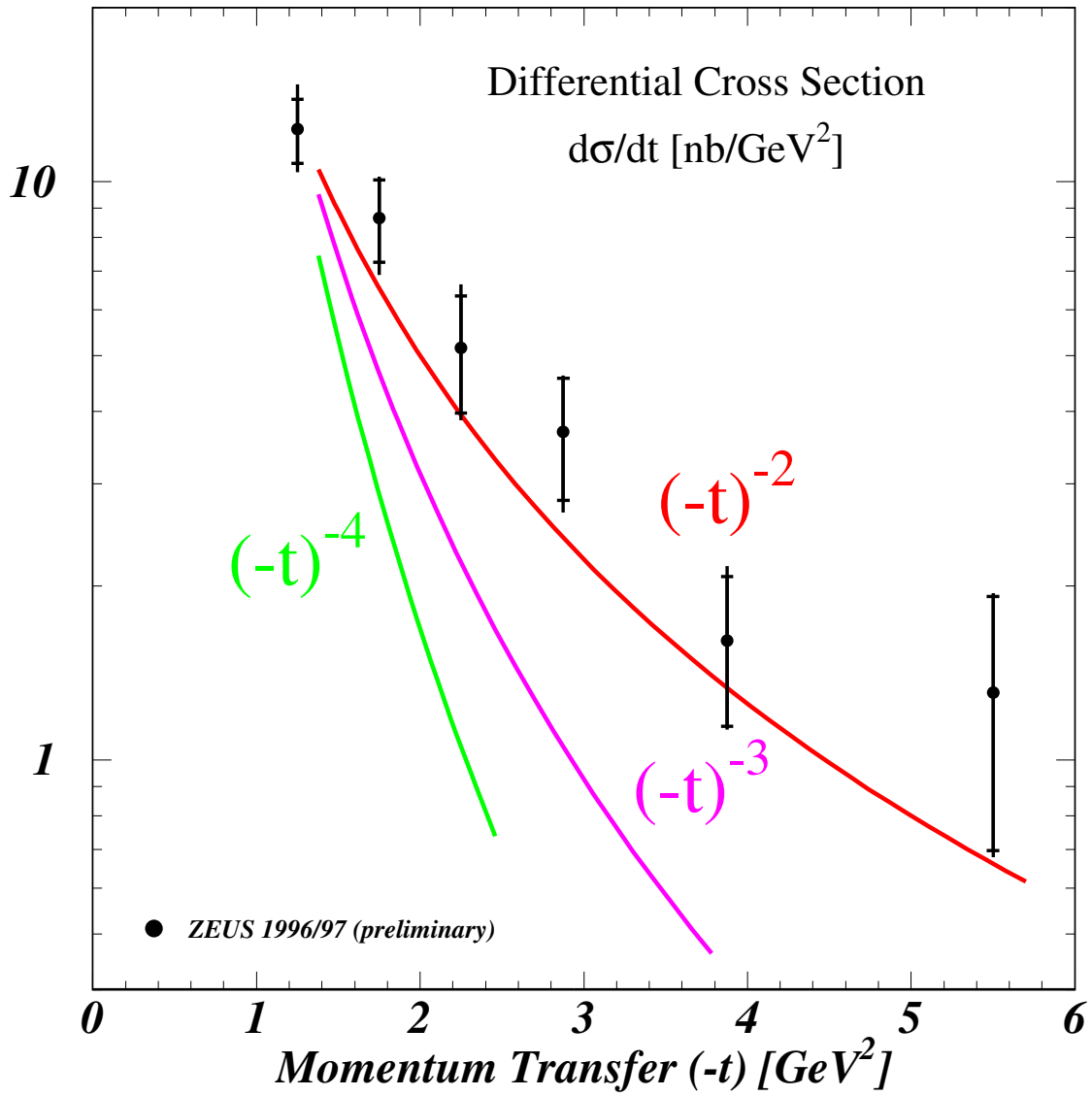
Diffractive J/ψ Photoproduction

$$\gamma + p \rightarrow J/\psi + N$$



NOT asymptotic region

Diffractive J/ψ Photoproduction



Scaling Property

Power dependence with

$n = 2$

matches the data fairly well