High-Energy Seminar *Carnegie Mellon University*

4 November 1998

New Perspectives
on
Exclusive Diffractive Processes
in
High-Energy Photon-Proton Interactions

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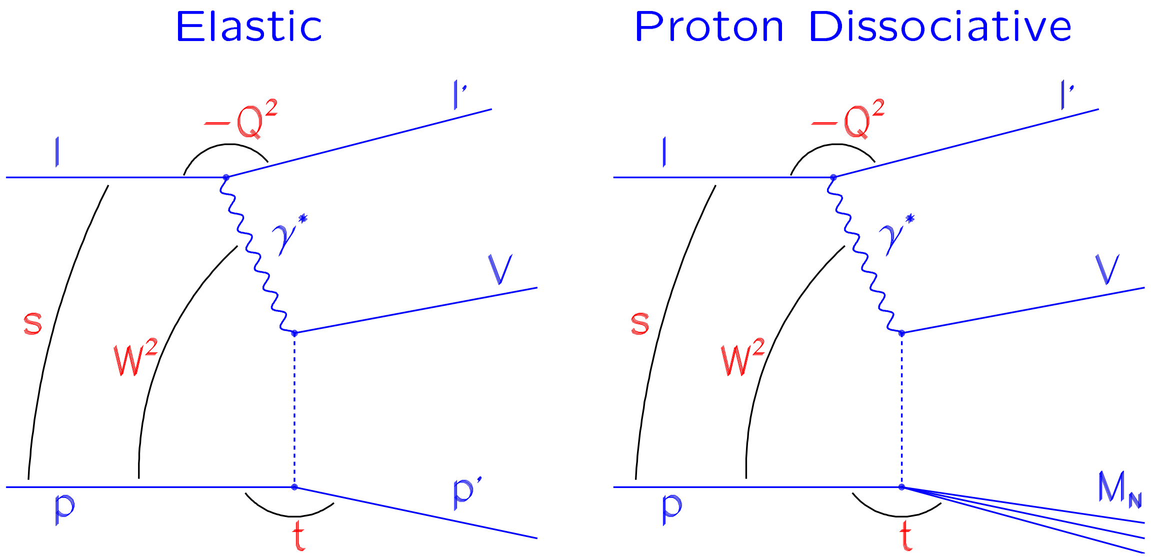
Diffractive Leptoproduction of Vector Mesons


Elastic

Proton Dissociative

$\sqrt{s}$: Center–of–mass energy of e–p system

HERA (ep, H1/ZEUS): 300 GeV

FNAL (μp, E665): $\simeq$30 GeV

W: Center–of–mass energy of γ^*–p system

(HERA: 20 – 240 GeV FNAL: 6 – 27 GeV)

Q^2: Photon Virtuality

(HERA: 10^{-10} – 60 GeV^2 FNAL: 0.15 – 20 GeV^2)

t: Square of Momentum Transfer at the Proton Vertex

(HERA: $|t| < 13$ GeV^2 FNAL:$|t| < 1$ GeV^2)

$$|t|_{\mathrm{min}} = m_{\mathrm{p}}^2 \frac{(M_{\mathrm{V}}^2+Q^2)^2}{W^4}$$

Virtual-Photon Lifetime

Heisenberg uncertainy relation: $\Delta t \geq \frac{1}{2\Delta E}$

Photon virtuality: $\Delta E = k_{\gamma^*} - \sqrt{k_{\gamma^*}^2 - Q^2}$

HERA energies: $200 < k_{\gamma^*} < 32\,000$ GeV

$$\Rightarrow \Delta E \approx \frac{1}{2}\frac{Q^2}{k_{\gamma *}} = m_{\mathrm{p}}\, x$$

Condition to define γ^*p cross section: $\frac{1}{2m_{\mathrm{p}}x} > 2R_{\mathrm{p}}$
For $R_{\mathrm{p}} = 0.8$ fm:

$$\boxed{x < 0.06}$$

$$W^2 = Q^2\left[\frac{1}{x} - 1\right] + m_{\mathrm{p}}^2 \approx \frac{Q^2}{x}$$

Low-x physics
is
high-energy physics
with
virtual-photon beams

Gilman, Hand conventions for virtual-photon flux definition

Regge Phenomenology

☞ Energy Dependence of Elastic Cross Sections

⇒ Exchange of the phenomenological Pomeron

$$\frac{d\sigma}{d|t|} \propto e^{b_0 t} \left(\frac{s}{s_0}\right)^{2(\alpha_{I\!P}(t)-1)}$$

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

$$\left.\frac{d\sigma}{dt}\right|_{t=0} \propto \left(\frac{s}{s_0}\right)^{2(\alpha_{I\!P}(0)-1)}$$

$$\propto W^{4\epsilon} = W^{0.32}$$

☞ "Shrinkage"

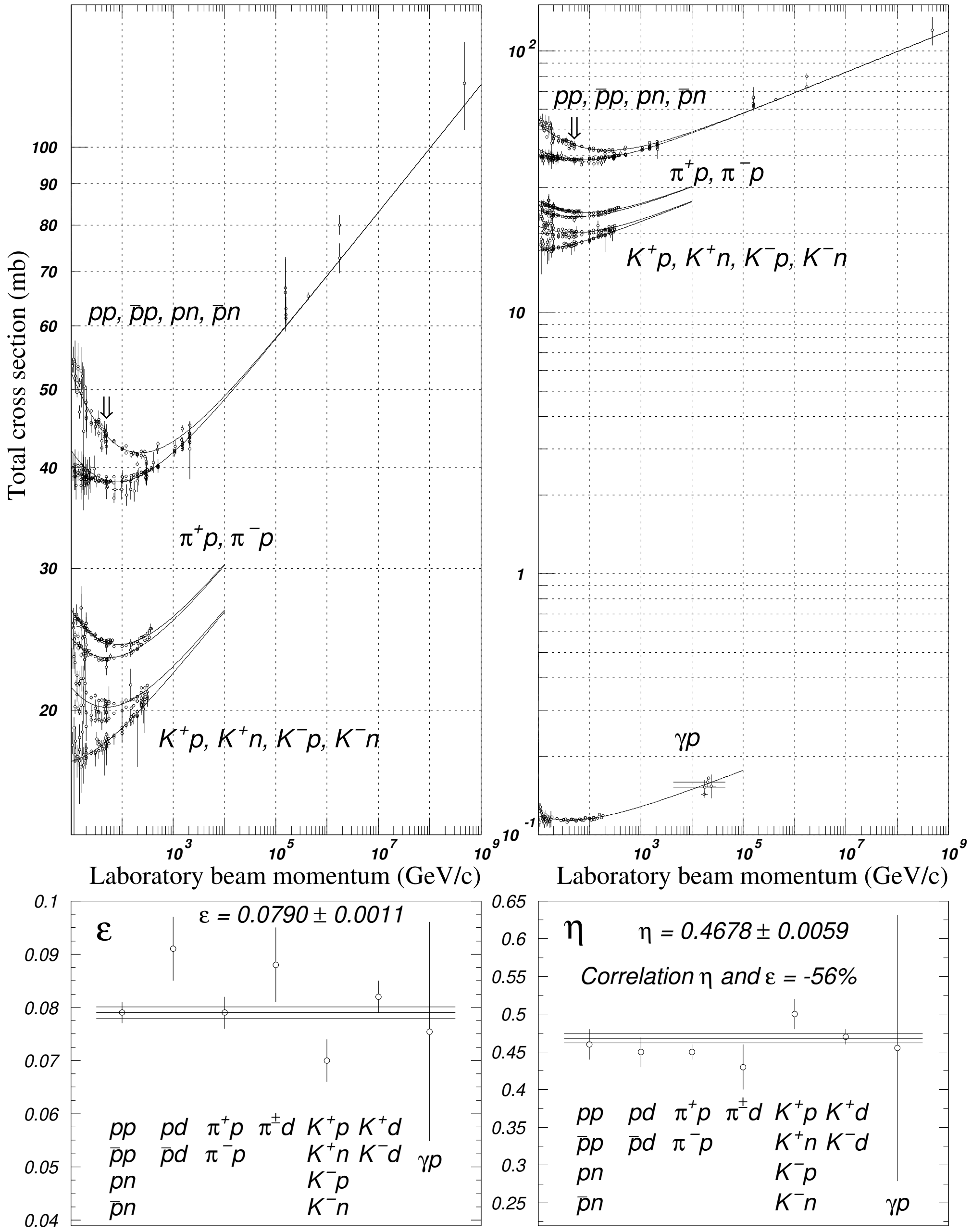
$\frac{d\sigma}{dt} \propto e^{b\,t}$ with $b = b_0 + 2\,\alpha'_{I\!P} \ln \frac{s}{s_0}$

b is a measure of interaction size: $b \propto R_{\mathrm{p}}^2 + R_{\mathrm{VM}}^2$

Total Cross Sections

Donnachie + Landshoff, PL B296 (1992) 227

$$\sigma^{tot} = X\, s^{\epsilon} + Y\, s^{-\eta}$$

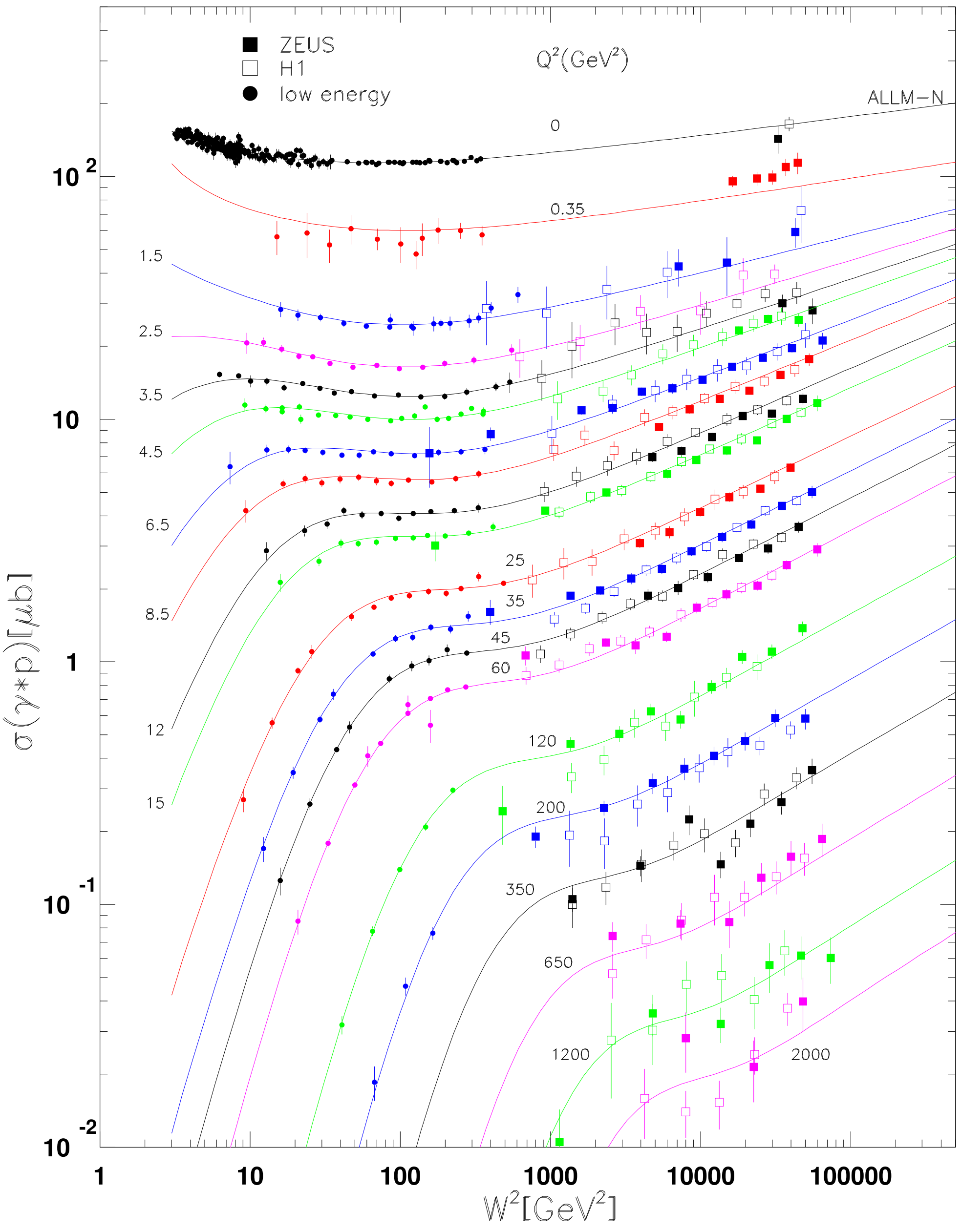


PDG
1996

$$\epsilon = 0.0790 \pm 0.0011 \qquad \eta = 0.4678 \pm 0.0059$$

Total Photon-Proton Cross Sections

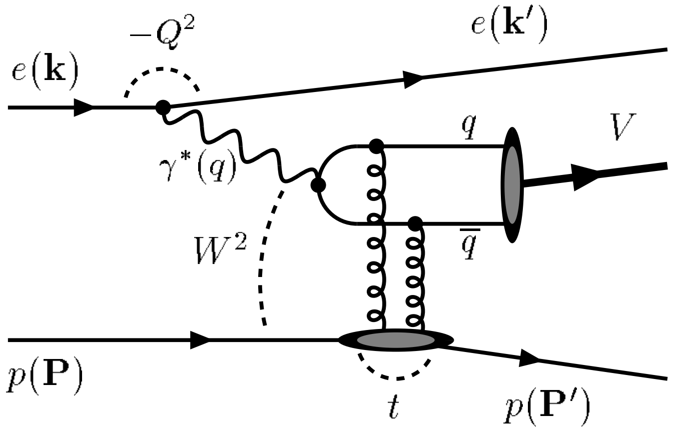
$$\sigma^{tot}_{\gamma^* p} \approx \frac{4\pi^2\alpha}{Q^2(1-x)} F_2(x, Q^2)$$



⇒ Steeply rising cross sections at high energy!

Perturbative QCD for Diffraction (?!)

☞ Exchange of a gluon "ladder"



Brodsky, Frankfurt, Gunion, Mueller, Strikman, PRD50 (1994) 3134
Only longitudinal photons have point-like interactions !

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

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

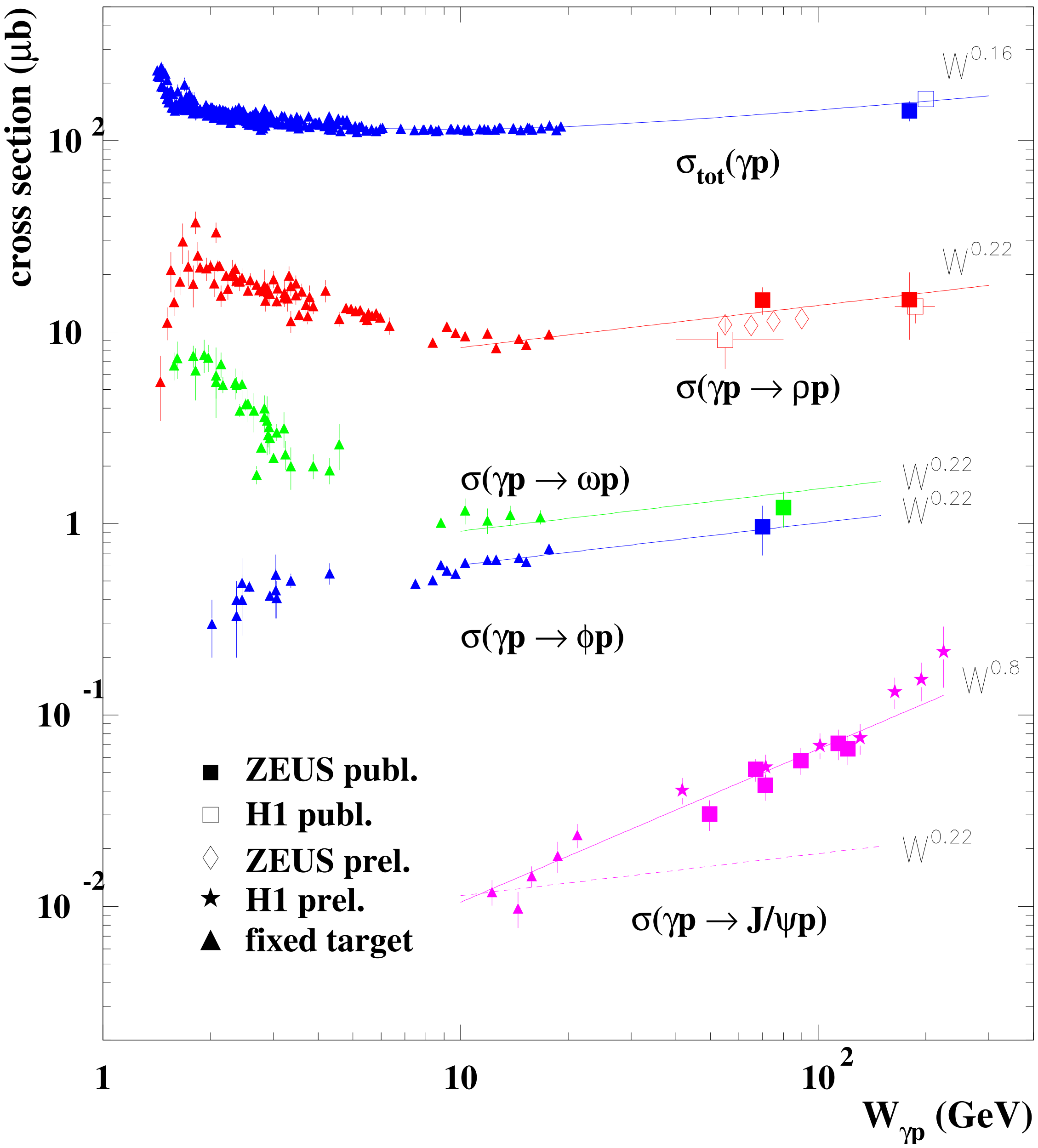
Ryskin, Z.Phys. C57 (1993) 89 (J/ψ Photoproduction)

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

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

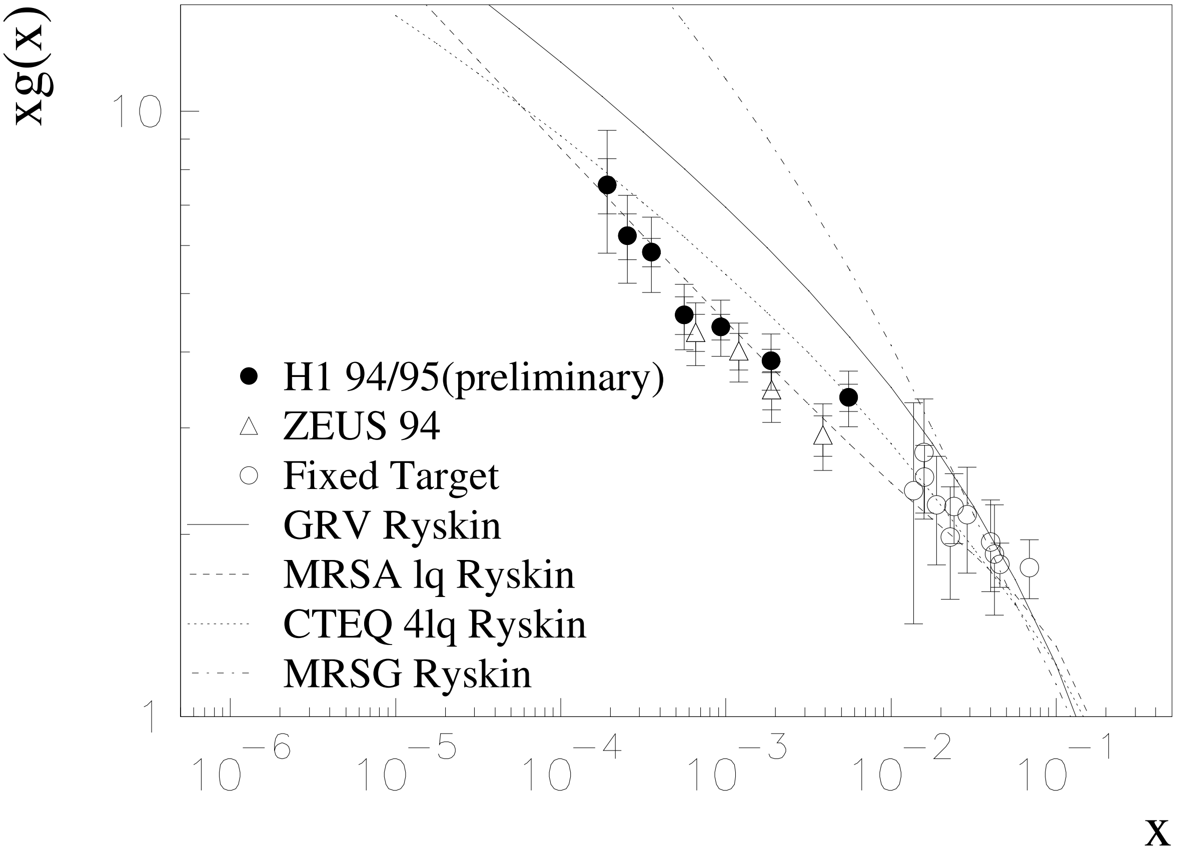
What experimental signatures for the region of pQCD validity ?

Elastic Vector-Meson Photoproduction Cross Sections



$\Longrightarrow$ Energy dependence for the J/ψ much steeper !

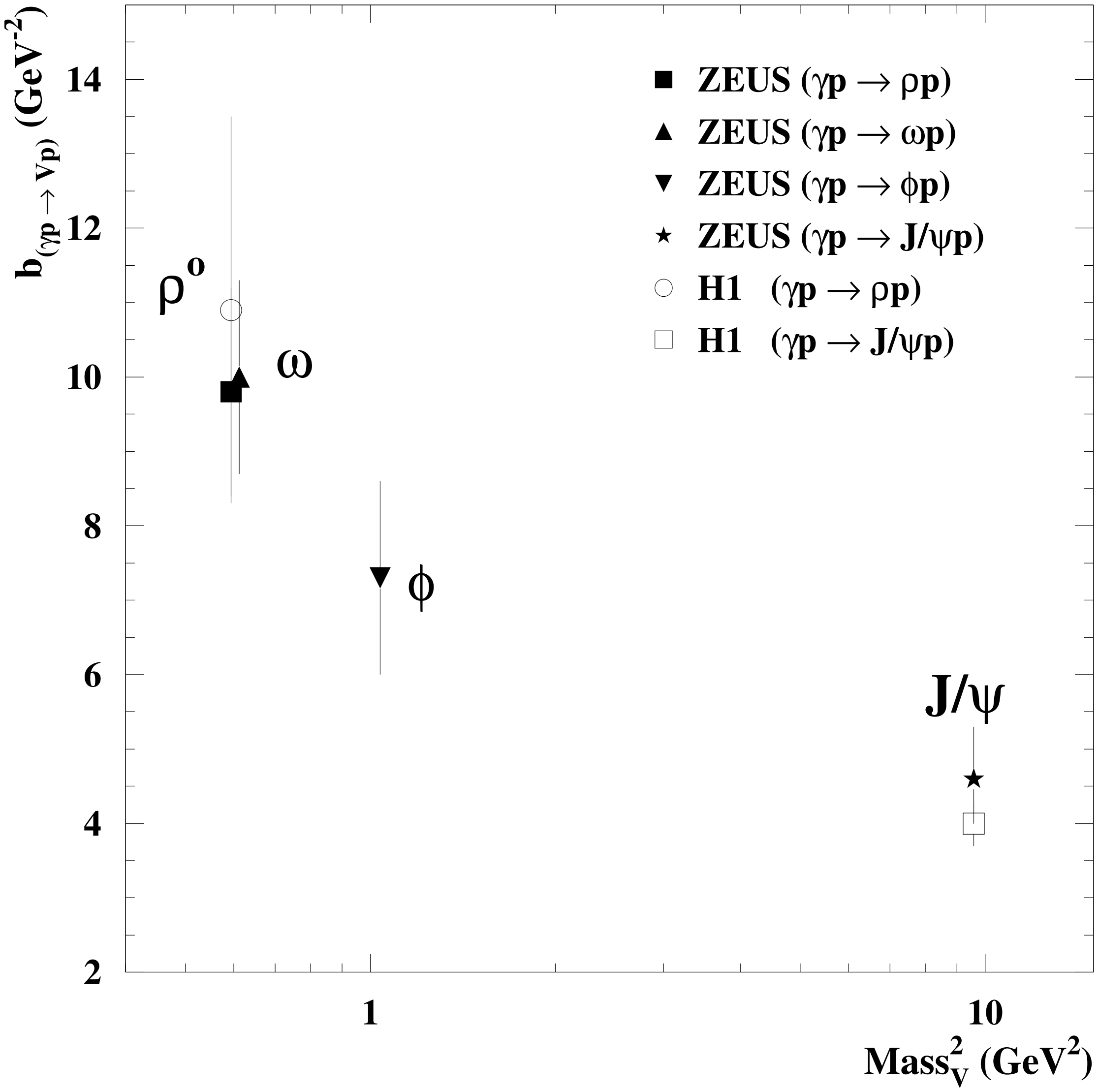
Elastic J/ψ Cross Sections



Ryskin et al, Z. Phys. C76 (1997) 231

$\Longrightarrow$ Can derive shape of gluon distribution !!

Photoproduction t-Slope vs $\mathrm{M}^2_{\mathrm{VM}}$

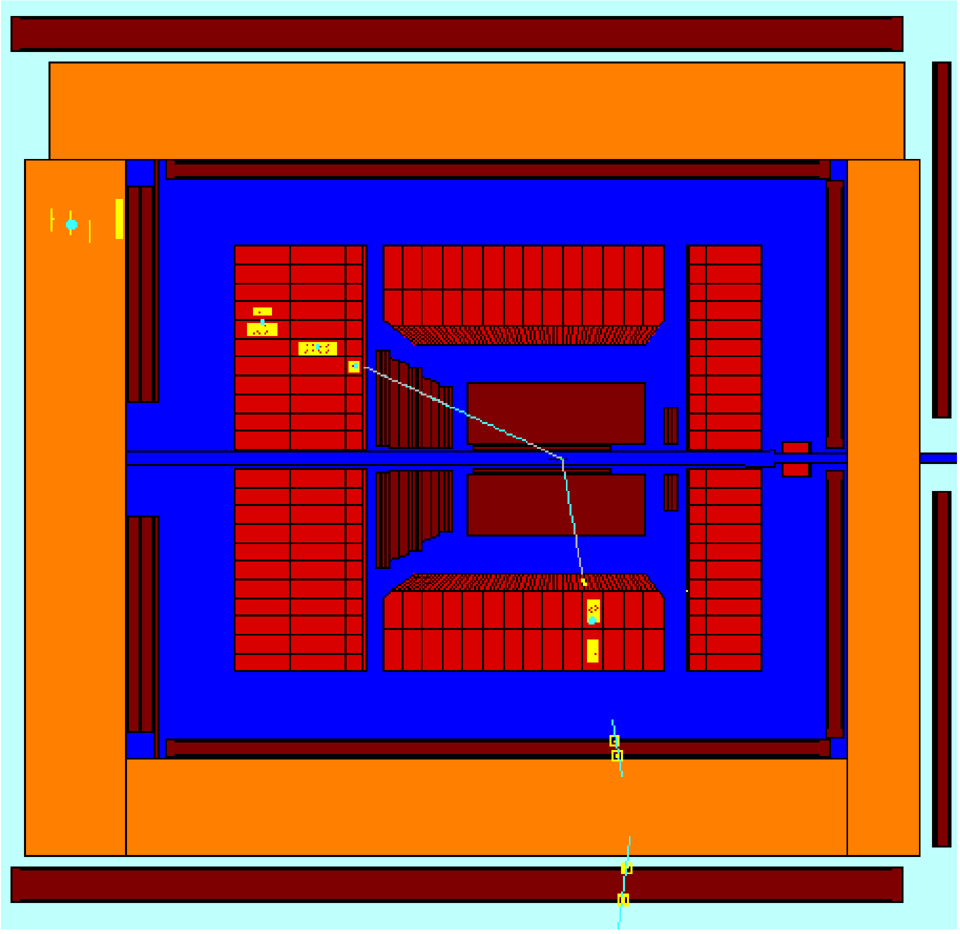


$$b = b_{\mathrm{p}} + b_{J/\psi} : \quad b_{J/\psi} < 1\,\mathrm{GeV}^2$$

ZEUS Υ Signal

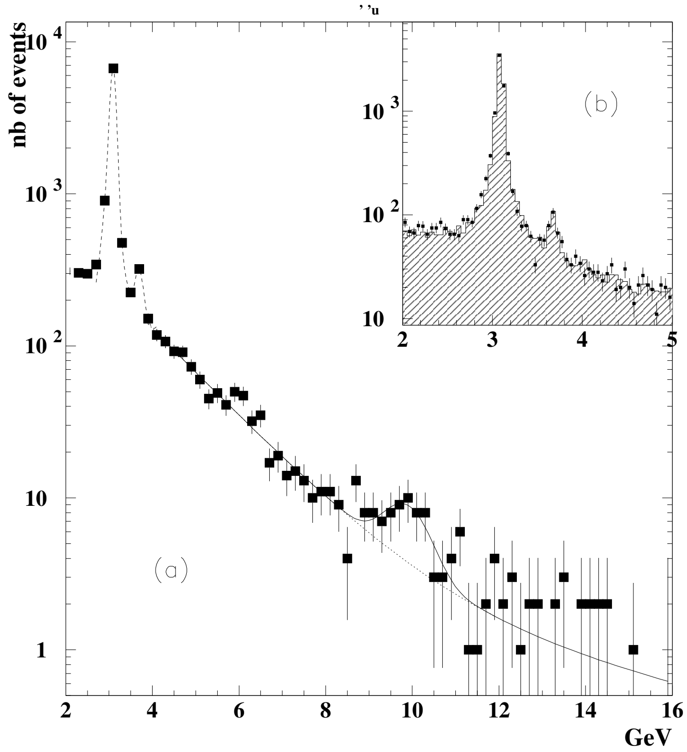
ZEUS: hep-ex/9807020

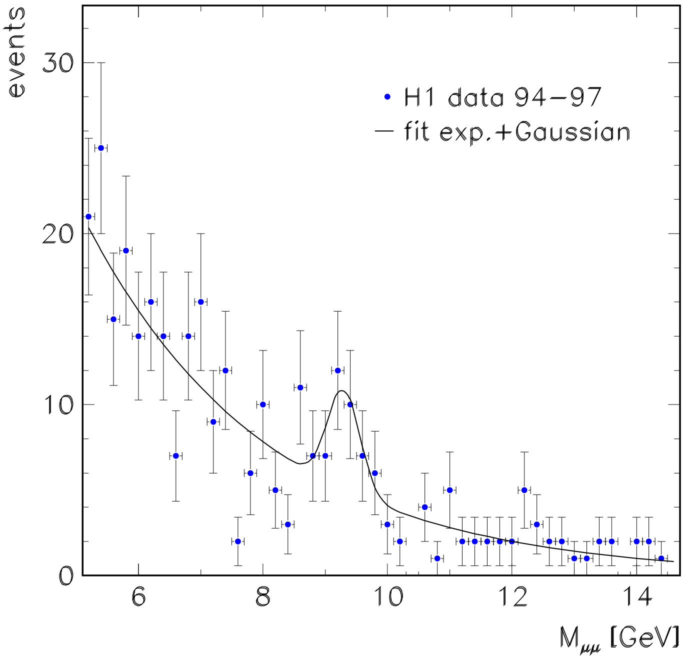
Measurement of Elastic Υ photoproduction at HERA



Example of elastic $\mu^+\mu^-$ photoproduction

Elastic $\mu^+\mu^-$ Mass Spectra

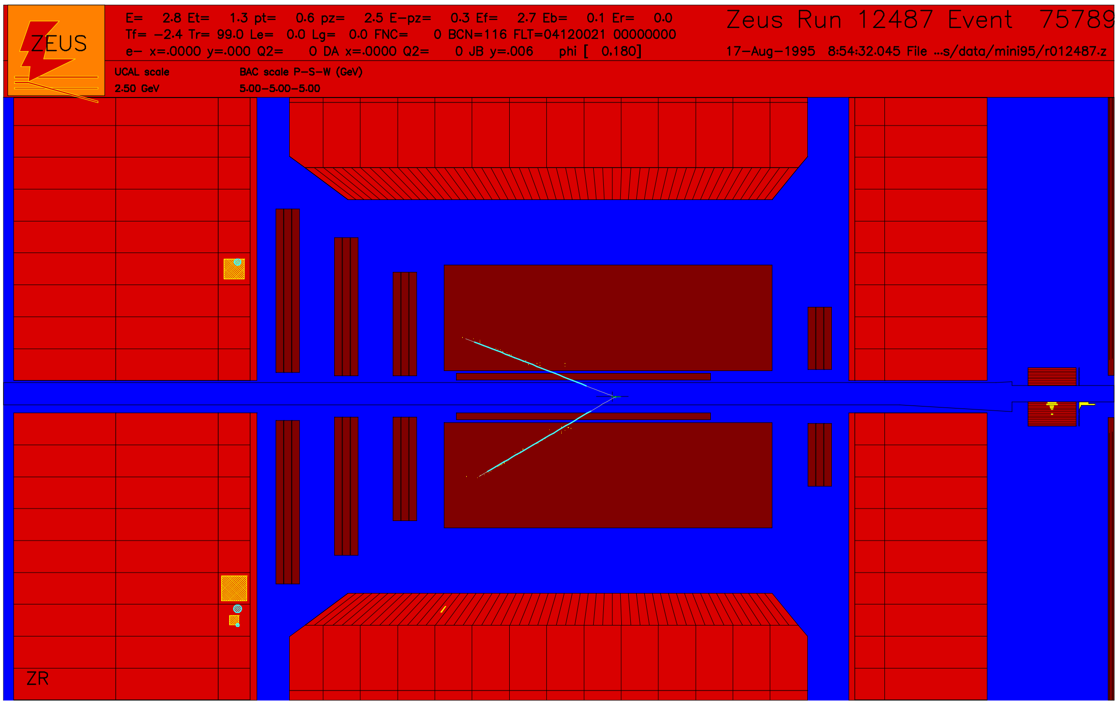




Diffractive Production of ρ^0 Mesons

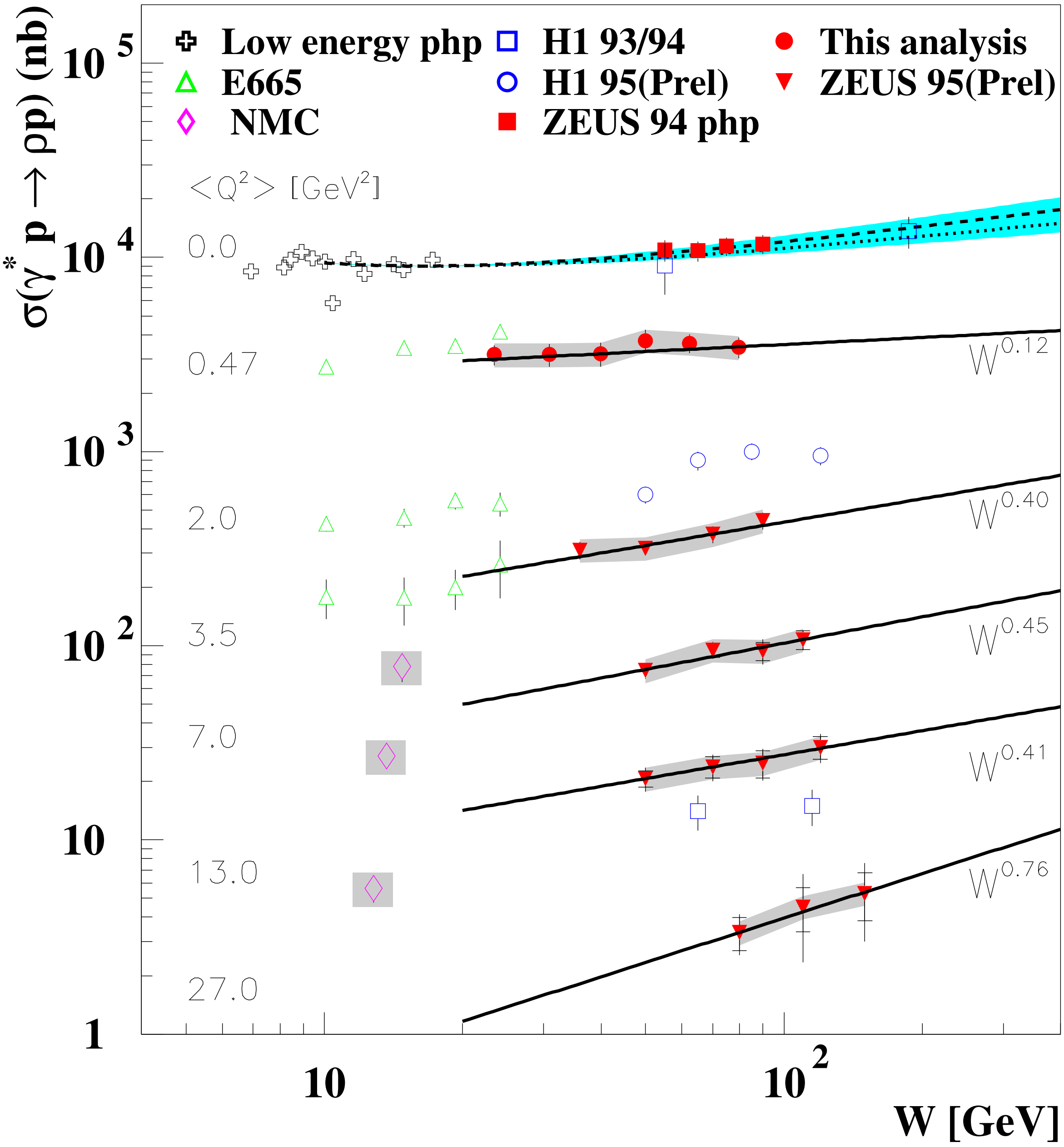
ZEUS: hep-ex/9808020

(Exclusive Electroproduction of ρ^0 and J/ψ)


ZEUS
E= 2.8 Et= 1.3 pt= 0.6 pz= 2.5 E−pz= 0.3 Ef= 2.7 Eb= 0.1 Er= 0.0
Tf= −2.4 Tr= 99.0 Le= 0.0 Lg= 0.0 FNC= 0 BCN=116 FLT=04120021 00000000
e− x=.0000 y=.000 Q2= 0 DA x=.0000 Q2= 0 JB y=.006 phi [0.180]
Zeus Run 12487 Event 75789
17−Aug−1995 8:54:32.045 File ...s/data/mini95/r012487.z
UCAL scale
2.50 GeV
BAC scale P−S−W (GeV)
5.00−5.00−5.00
ZR

e^+ in BPC	e^+ in UCAL
3.8 pb^{-1}	6.0 pb^{-1}
$0.25 < Q^2 < 0.85$ GeV^2	$3 < Q^2 < 50$ GeV^2
$20 < W_{\gamma^* p} < 90$ GeV	$32 < W_{\gamma^* p} < 167$ GeV
5462 events	3039 events

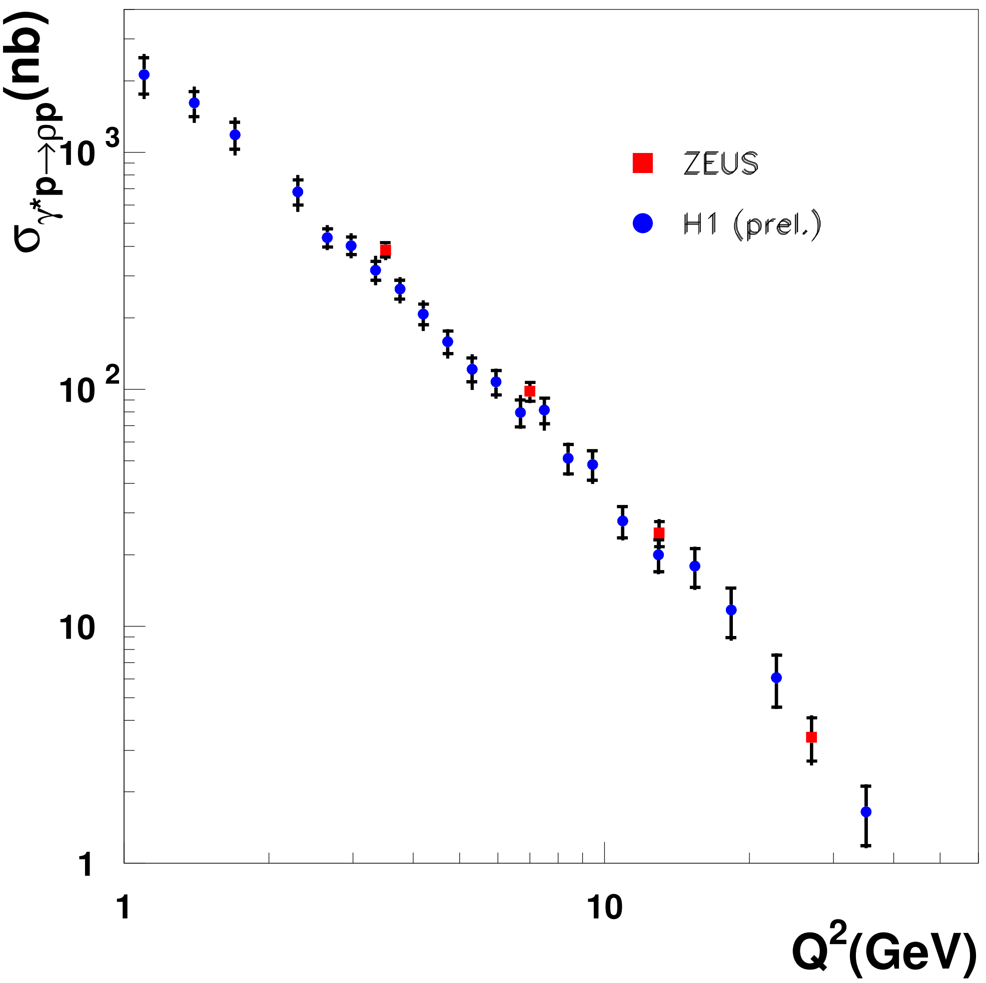
Elastic ρ^0 Cross Sections (I)



⇒ Disagreement ZEUS/H1? E665/NMC?

Elastic ρ^0 Cross Sections (II)

H1 ICHEP Abstract 564

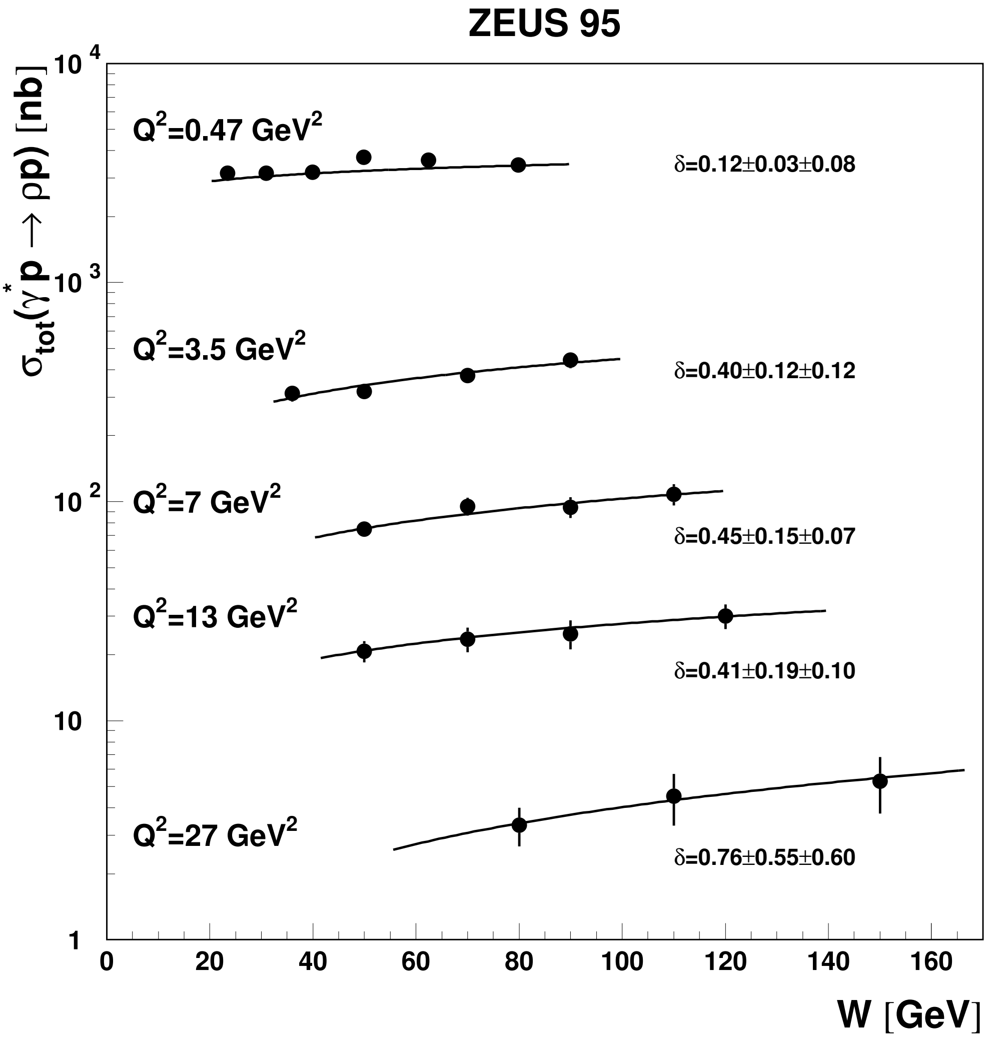


⇒ Beautiful measurement of Q^2 dependence by H1 !!

⇒ ZEUS/H1 inconsistency gone !!

Elastic ρ^0 Cross Sections (III)

ZEUS: hep-ex/9808020



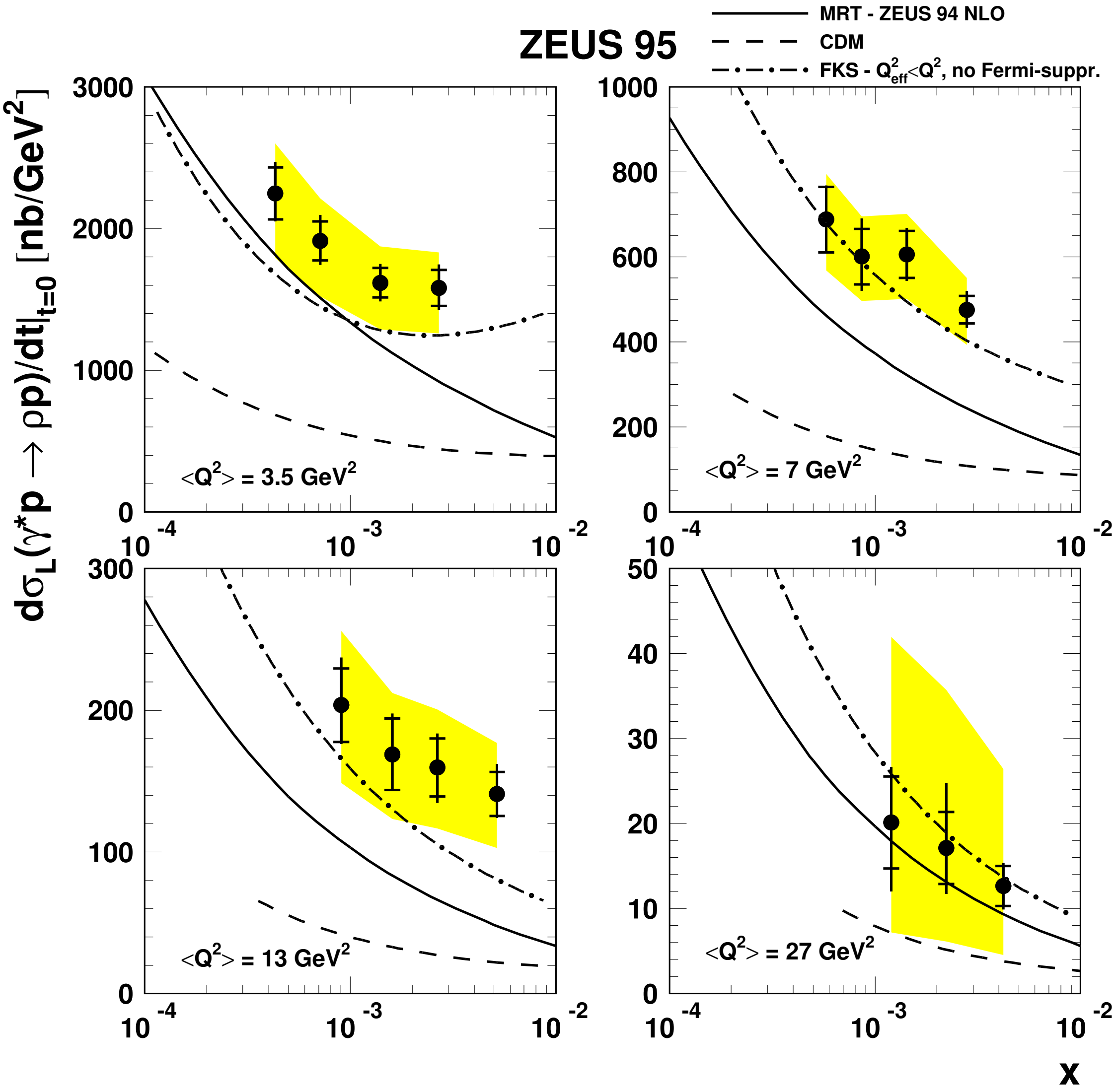
$\Rightarrow$ Steepening with Q^2 expected in pQCD

$\Rightarrow$ $\approx 2\sigma$ effect

Elastic ρ^0 Cross Sections (V)

ZEUS longitudinal cross sections
compared to models

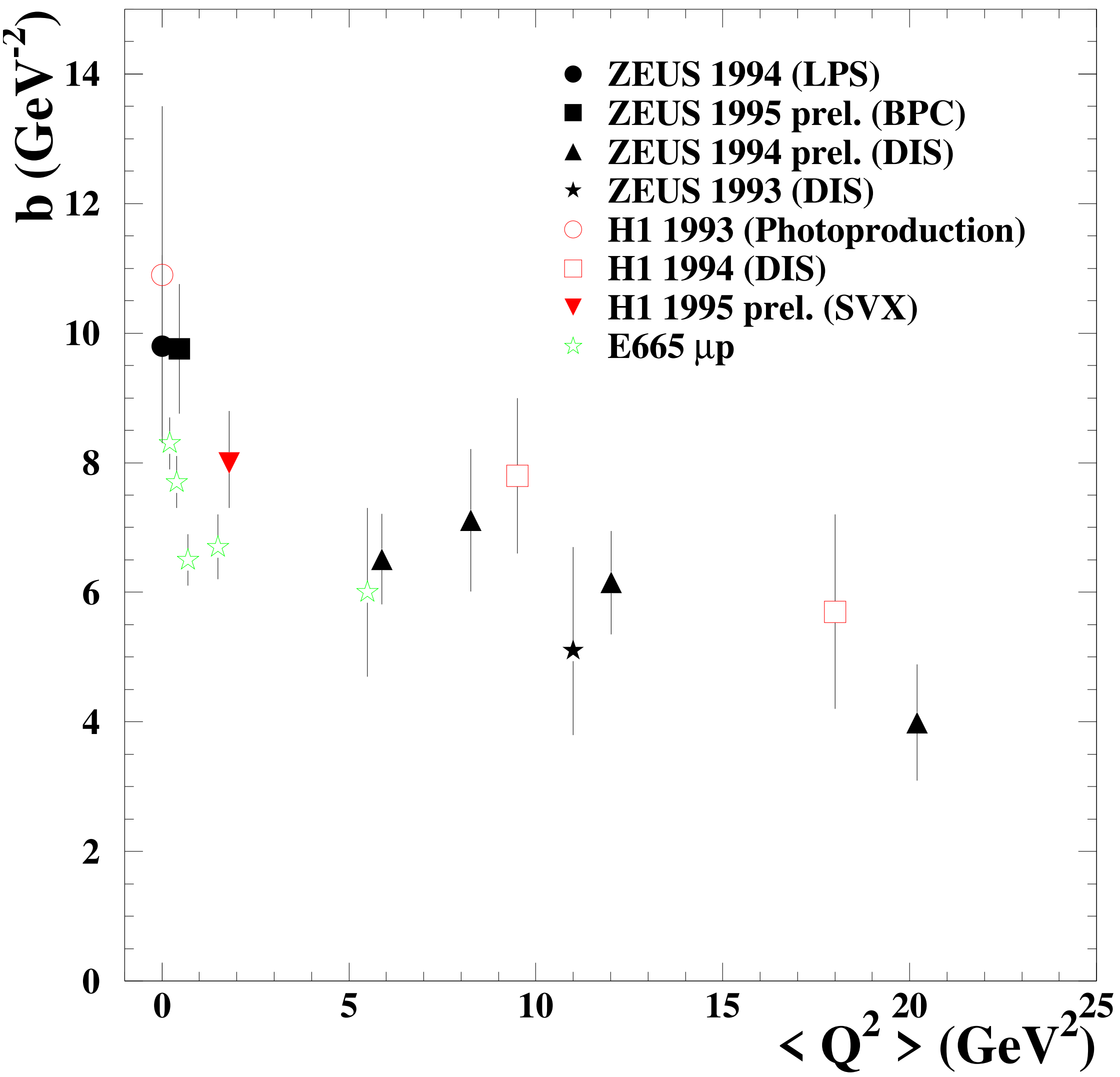
(hep-ex/9808020)



⇒ Comparisons inconclusive

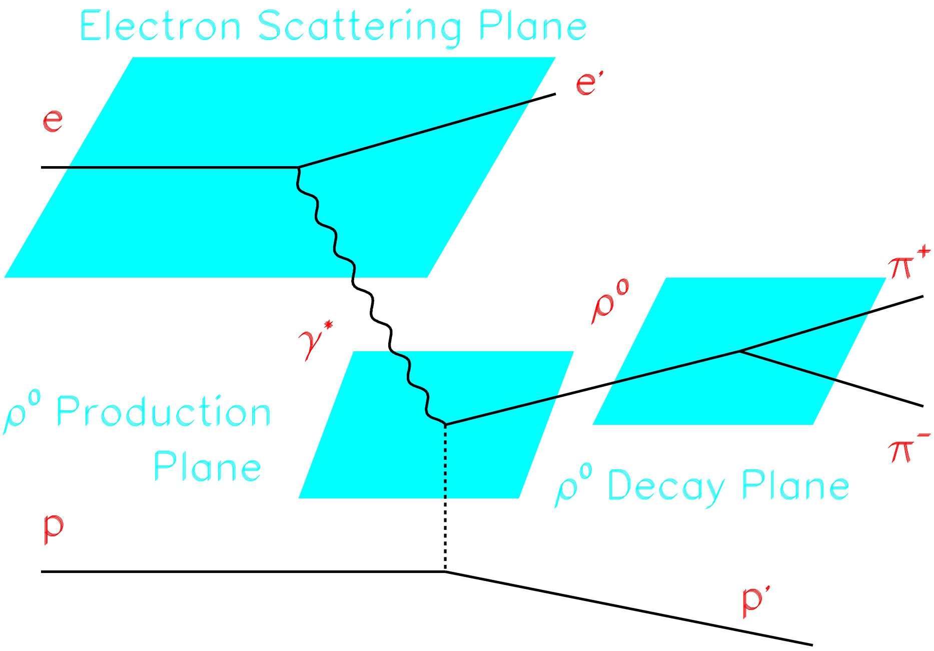
(May need NLO calculation)

t-Slope for ρ^0 Mesons vs Q^2



⇒ The shrinking photon !!

Helicity Analyses


Electron Scattering Plane
e
e′
γ^*
ρ^0
π^+
π^-
ρ^0 Production Plane
ρ^0 Decay Plane
p
p′

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^+

If helicity is conserved in the γ/ρ^0 transition, then the decay angular distributions depend only on the difference $\psi_h = \phi_h - \Phi_h$.

Decomposing the Spin Density Matrix

How to couple real photons ($\lambda = \pm 1$)
to vector mesons ($\lambda = 0, \pm 1$) ??

Helicity conserved in strong interactions
(but in what frame??)

Schilling, Seyboth, and Wolf, Nucl.Phys. B15, 397 (1970)
Formalism developed generally for arbitrary
real photon polarization (2x2 matrices!)

- 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) ± P$^c_\gamma$ W^3(θ,ϕ)
   Need long. pol. initial-state lepton→E665(μ),HERMES(e)
3. Linearly polarized:
   W(θ,ϕ,Φ) = W^0(θ,ϕ) - P^l_γ $\cos 2\Phi$ W^1(θ,ϕ)
   - P$^l_\gamma$ $\sin 2\Phi$ W^2(θ,ϕ)

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

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

Define linear combinations of the matrix elements:

(Helicity states $i, k = +1, 0, -1$)

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

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

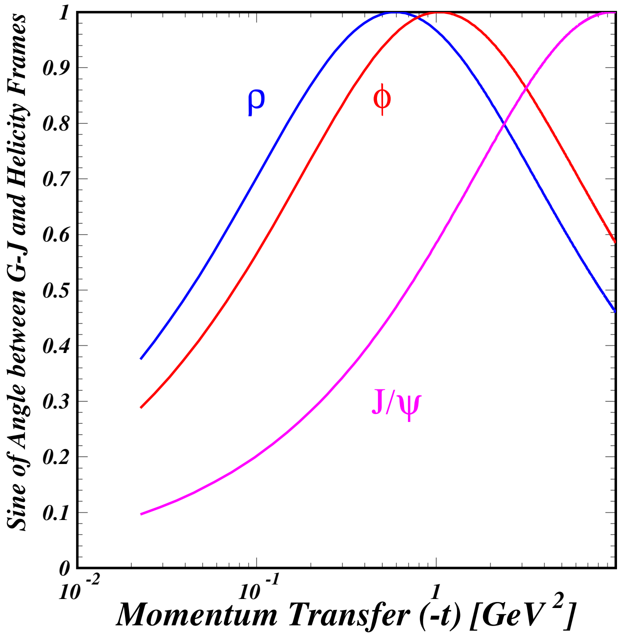
$$r^{\alpha}_{ik} = \begin{cases} \dfrac{\rho^{\alpha}_{ik}}{1+\epsilon R} & \alpha = 1-3 \text{ (Trans.)} \\ \dfrac{\sqrt{R}\,\rho^{\alpha}_{ik}}{1+\epsilon R} & \alpha = 5-8 \text{ (L/T int.)} \end{cases}$$

Constraints from hermiticity, parity conservation

The Choice of Frame

- Gottfried-Jackson frame
  Spin quantized along photon direction (t-channel)
- Helicity frame
  Spin quantized along meson direction (s-channel)

The angle χ between the two frames: $\cos\chi = \left(\frac{m_\rho^2 + t}{m_\rho^2 - t}\right)$



$\Longrightarrow$ ρ^0 most sensitive to a violation of helicity conservation in the s-channel amplitudes (SCHC)

Gilman et al., Phys. Lett. B31 (1970) 387

3-D Decay-Angle Distribution

(15 linearly independent parameters)

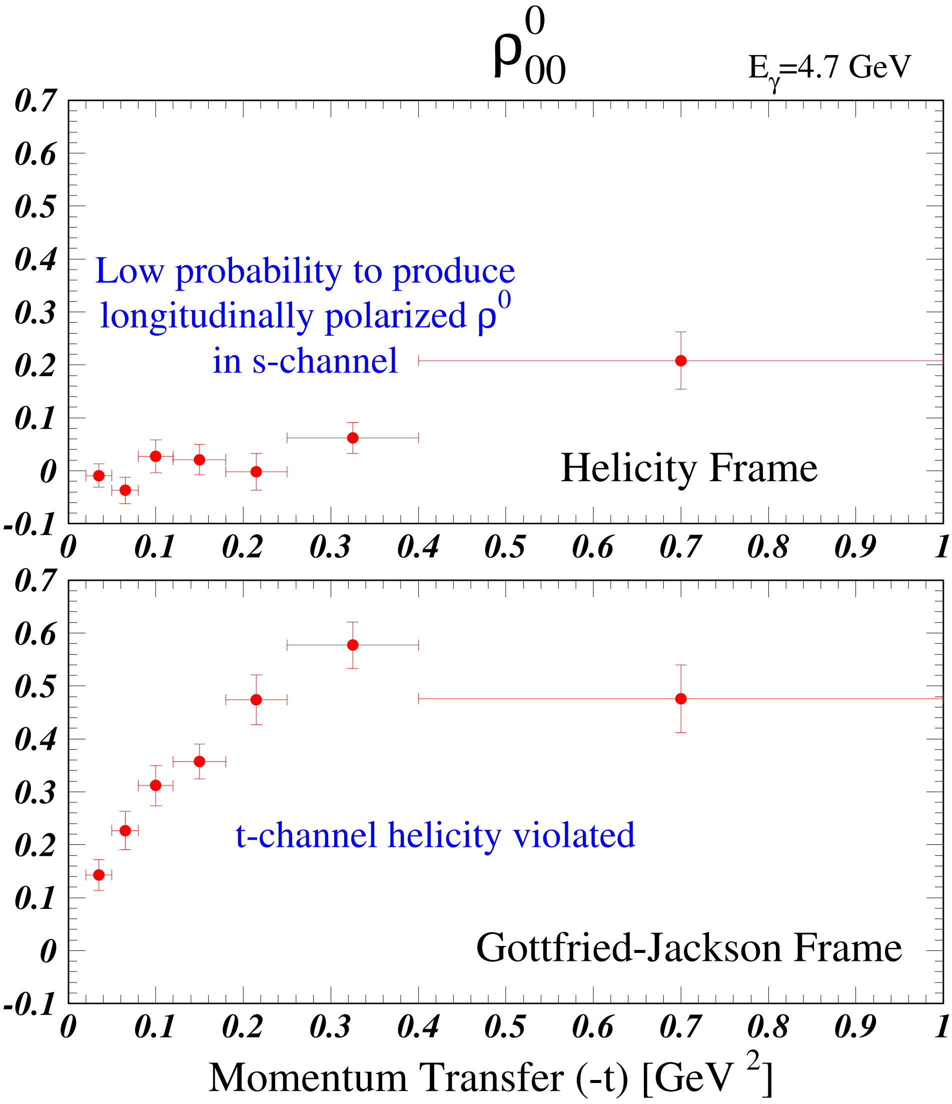
$$W(\cos\theta_h, \phi_h, \Phi_h) =$$

$$
\begin{aligned}
\frac{3}{4\pi}\Big[\ &\Big(\frac{1}{2}\big(1 - r^{04}_{00}\big) + \frac{1}{2}\big(3r^{04}_{00} - 1\big)\cos^2\theta_h \\
&\quad -\sqrt{2}\,\mathrm{Re}\,r^{04}_{10}\ \sin 2\theta_h \cos\phi_h - r^{04}_{1-1}\sin^2\theta_h \cos 2\phi_h\Big) \\
&-\varepsilon\cos 2\Phi_h\big(\ r^{1}_{11}\sin^2\theta_h + r^{1}_{00}\cos^2\theta_h \\
&\qquad -\sqrt{2}\,\mathrm{Re}\,r^{1}_{10}\ \sin 2\theta_h \cos\phi_h \\
&\qquad -r^{1}_{1-1}\sin^2\theta_h\cos 2\phi_h\ \big) \\
&-\varepsilon\sin 2\Phi_h\big(\ \sqrt{2}\,\mathrm{Im}\,r^{2}_{10}\ \sin 2\theta_h \sin\phi_h \\
&\qquad +\mathrm{Im}\,r^{2}_{1-1}\sin^2\theta_h \sin 2\phi_h\ \big) \\
&+\sqrt{2\varepsilon(1+\varepsilon)}\cos\Phi_h\big(\ r^{5}_{11}\sin^2\theta_h + r^{5}_{00}\cos^2\theta_h \\
&\qquad -\sqrt{2}\,\mathrm{Re}\,r^{5}_{10}\ \sin 2\theta_h \cos\phi_h \\
&\qquad -r^{5}_{1-1}\sin^2\theta_h\cos 2\phi_h\ \big) \\
&+\sqrt{2\varepsilon(1+\varepsilon)}\sin\Phi_h\big(\ \sqrt{2}\,\mathrm{Im}\,r^{6}_{10}\ \sin 2\theta_h \sin\phi_h \\
&\qquad +\mathrm{Im}\,r^{6}_{1-1}\sin^2\theta_h \sin 2\phi_h\big)\Big]
\end{aligned}
$$

SCHC in ρ^0 Photoproduction

Ballam et al., Phys. Rev. D5, 545 (1972)

- Backscattered laser beam at SLAC
- Linear polarization measured to be greater than 90%
- 2.8 and 4.7 GeV photons
- 3k $\rho^0 \to \pi^+\pi^-$ reconstructed in bubble chamber



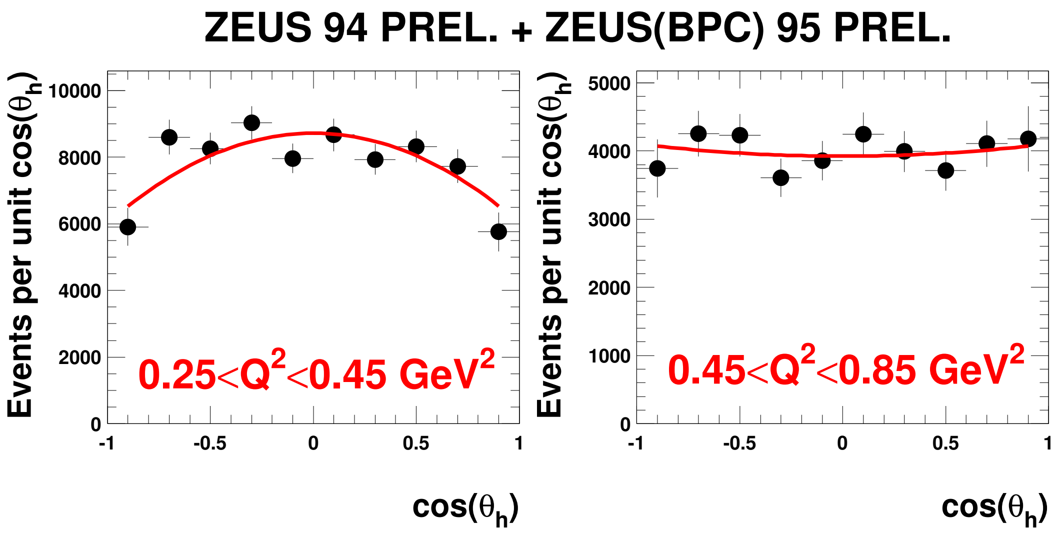
Inconsistent with t-channel exchange of spin 0 object

Gilman et al PL B31 (1970) 387

$\Longrightarrow$ Conclude SCHC holds for $|t| < 0.4$ GeV^2

ρ^0 Electroproduction at HERA

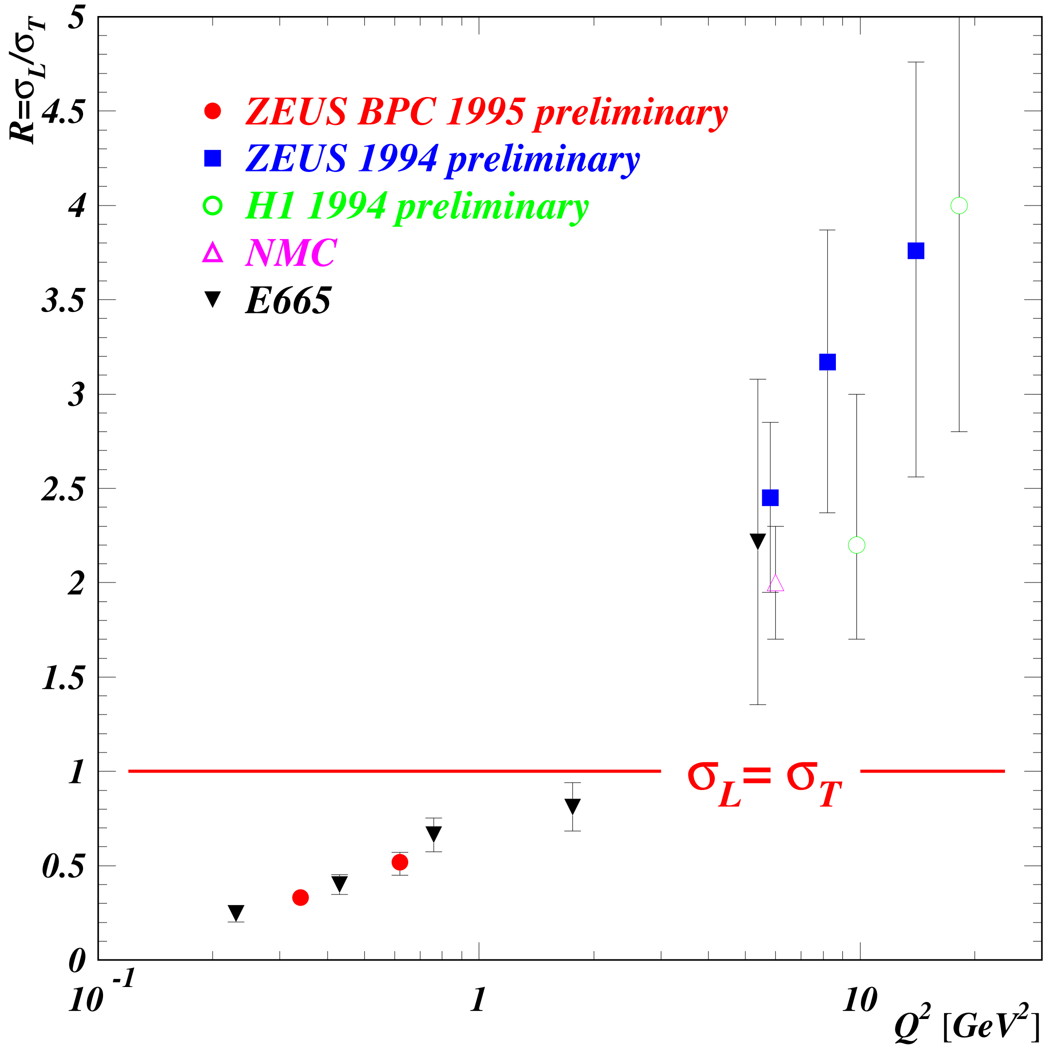
$$\frac{dN}{d\cos\theta_h} \propto 1 - r_{00}^{04} + (3r_{00}^{04} - 1)\cos^2\theta_h$$



Q^2 (GeV^2)	r_{00}^{04}
0.34	0.24 ±0.02(stat)
0.62	0.34 ±0.03(stat)
5.8	$0.71^{+0.03}_{-0.04}$(stat)$^{+0.01}_{-0.01}$(sys)
8.2	$0.76^{+0.04}_{-0.04}$(stat)$^{+0.00}_{-0.02}$(sys)
14	$0.79^{+0.04}_{-0.05}$(stat)$^{+0.02}_{-0.01}$(sys)

$R = \frac{\sigma_L}{\sigma_T}$ vs Q^2

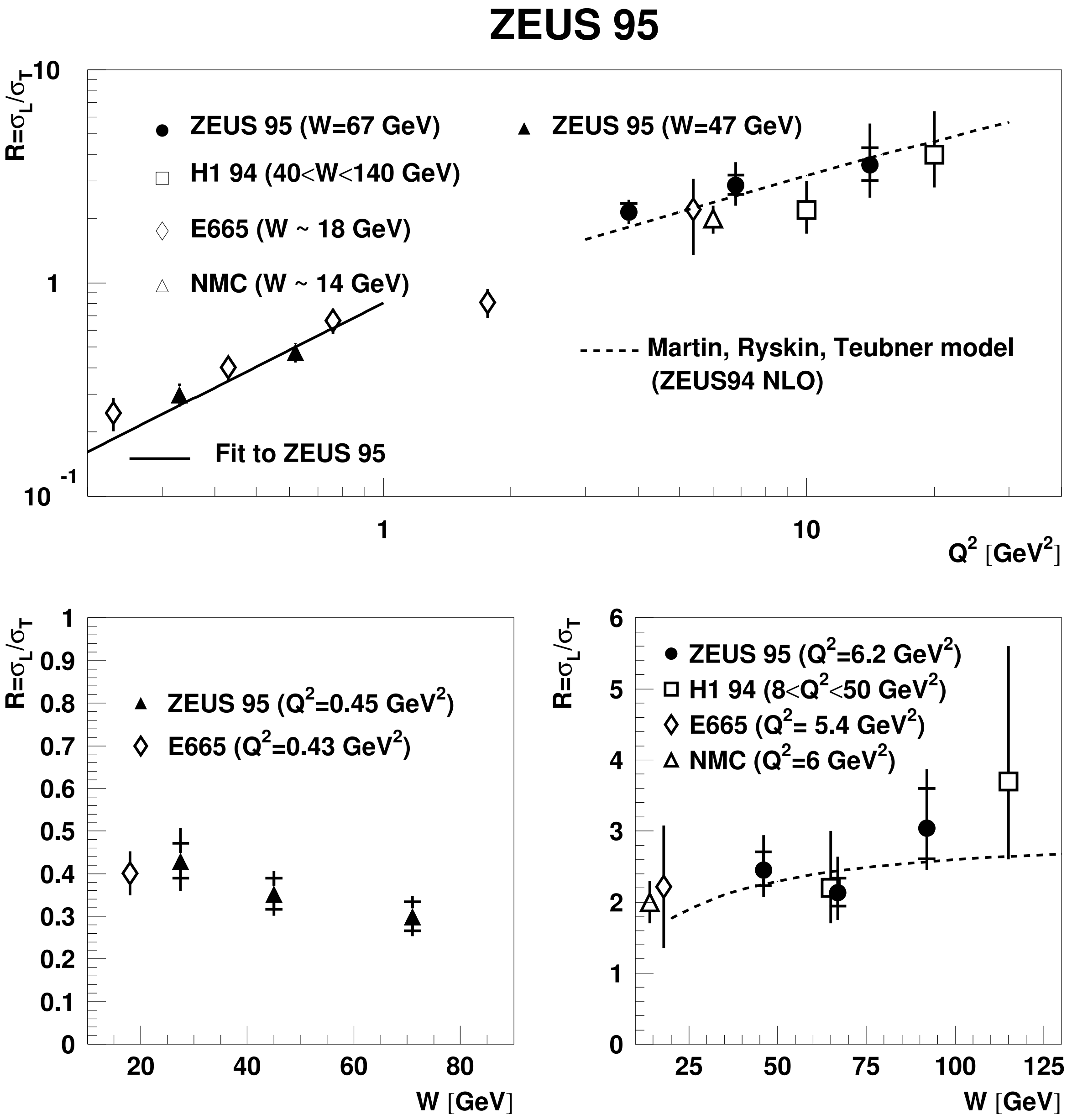
Assuming SCHC: $R = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}$



$\Rightarrow$ σ_L increases and becomes dominant

R vs Q^2 and W for ρ^0

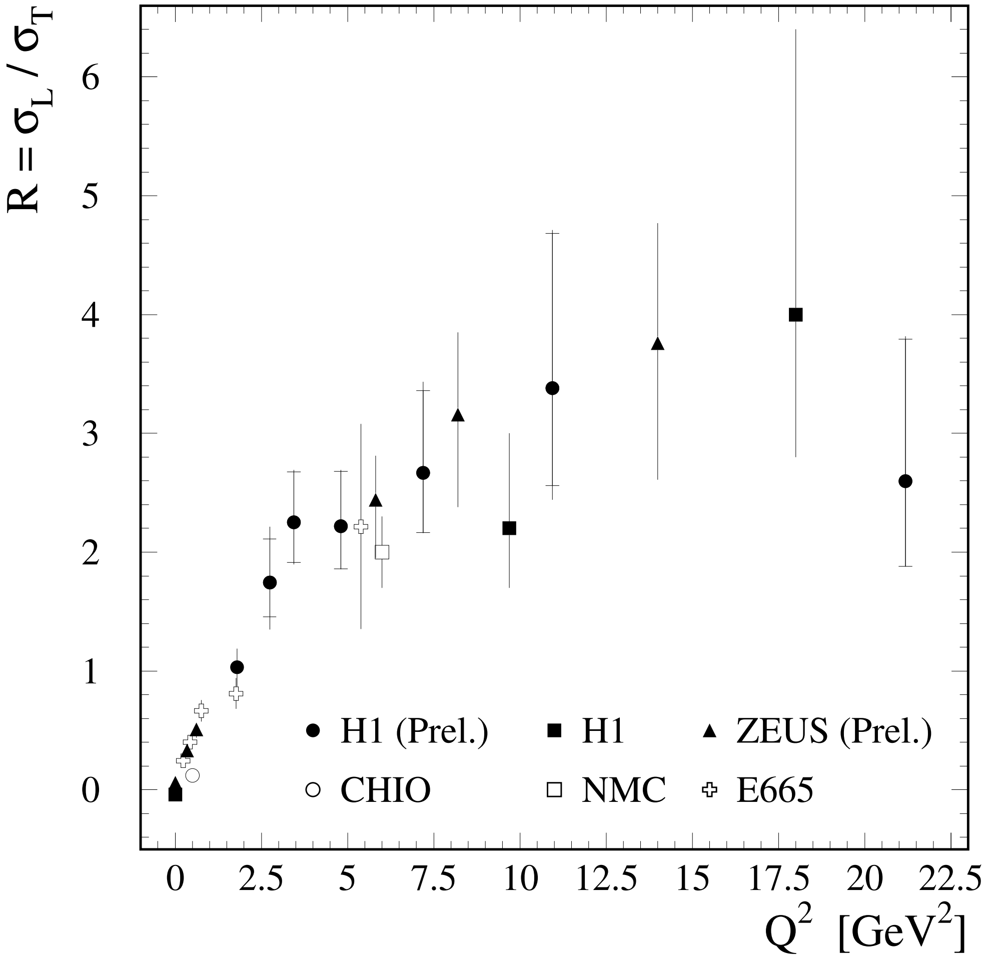
ZEUS: hep-ex/9808020



$\Rightarrow$ Do σ_T and σ_L have similar W dependence ?

R vs Q^2 (H1 DIS ρ^0 prel.)

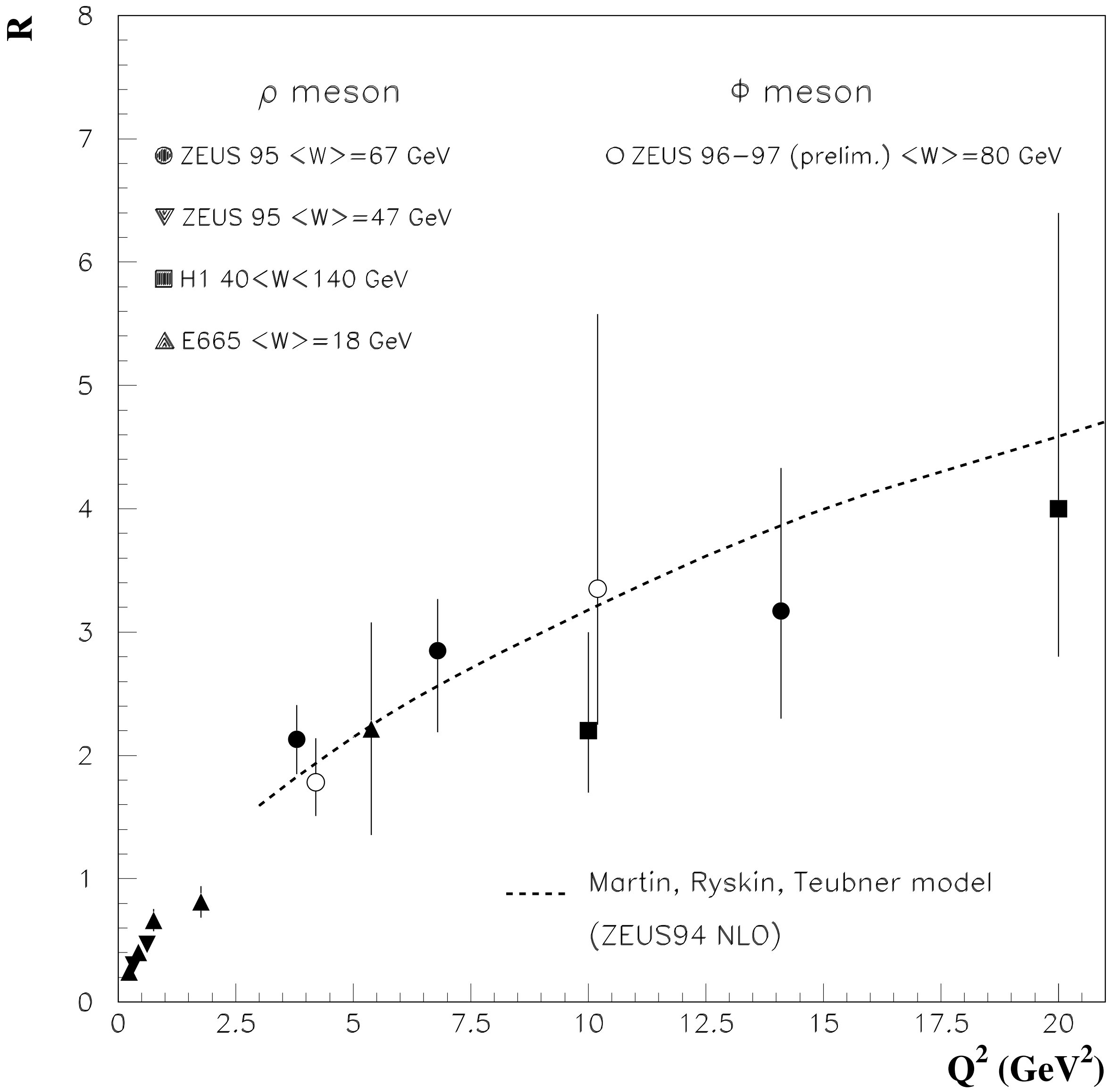
H1 ICHEP Abstract 564



$\Rightarrow$ σ_L/σ_T levelling off ??

R vs Q^2 (ZEUS DIS ϕ prel.)

ZEUS ICHEP Abstract 793

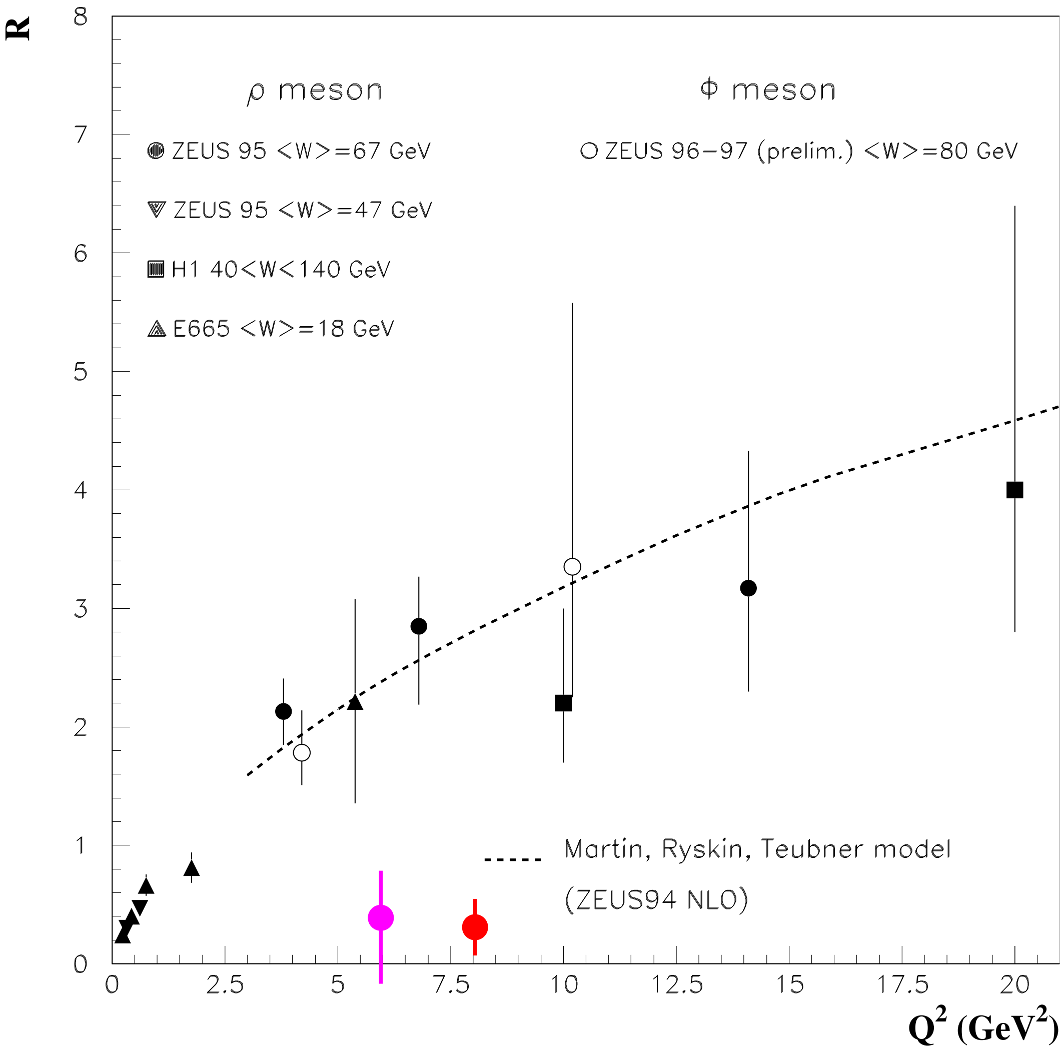


$\Rightarrow$ ϕ behaves like ρ^0 !!

R vs Q^2 for J/ψ

H1 ICHEP Abstract 572

ZEUS hep-ex/9808020

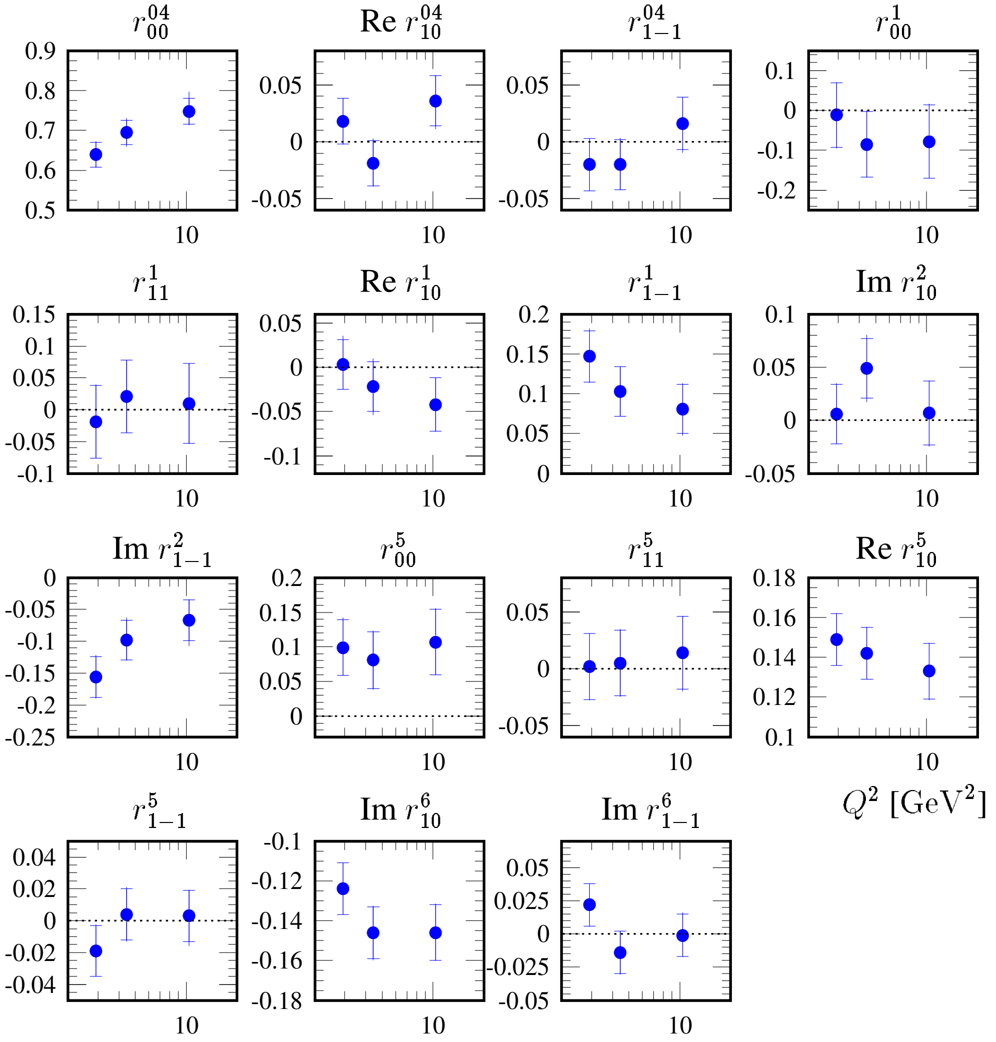


$\Rightarrow$ R for J/ψ lower !!

15-Parameter Helicity-Angle Fit (I)

H1 ICHEP Abstract 564

H1 PRELIMINARY

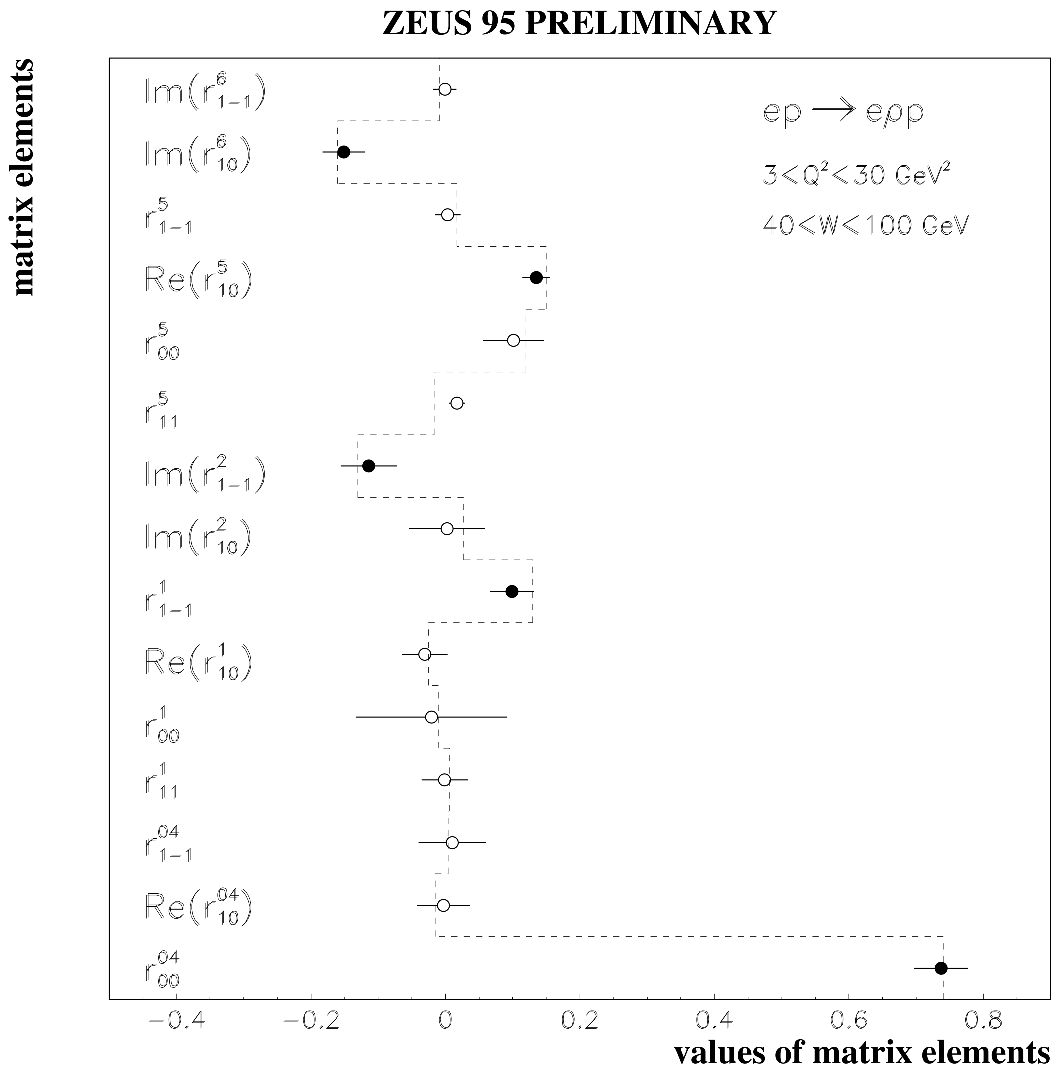


Dotted lines are SCHC values

$\Rightarrow$ SCHC violated ($r^5_{00} > 0$)

15-Parameter Helicity-Angle Fit (II)

ZEUS ICHEP Abstract 792/792b



⇒ Agreement with Ivanov and Kirschner (hep-ph/9807324)

⇒ Results also obtained for low Q^2 and ϕ

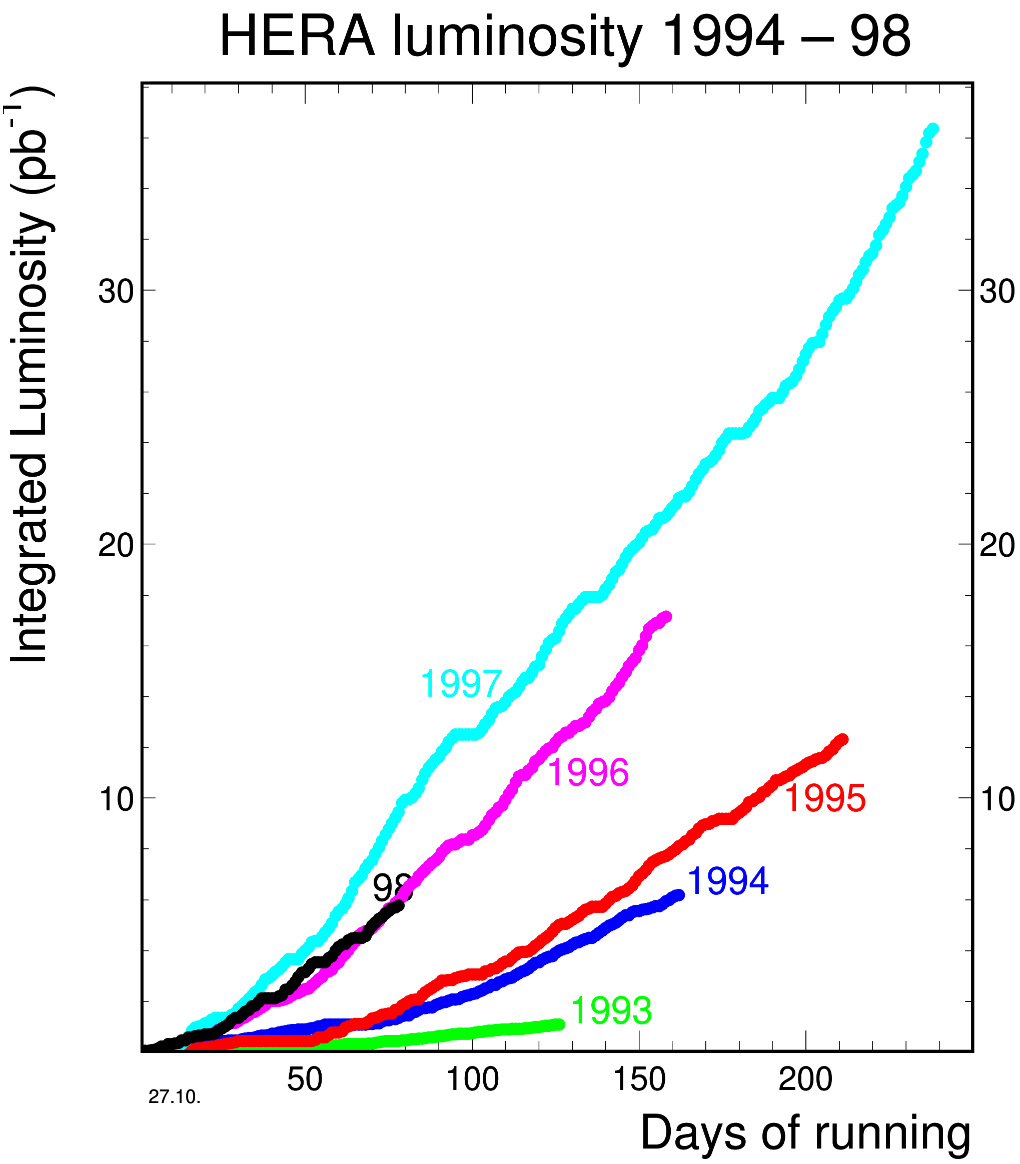
Conclusions

Early investigations at HERA of
vector meson leptoproduction
encourage descriptions of
hard diffractive processes
based on perturbative QCD

The results show preliminary evidence
for the hard scale to be given by
either Q^2, M_V^2, or $|t|$

The H1 and ZEUS experiments are
sensitive to the transition region in
EACH of these variables

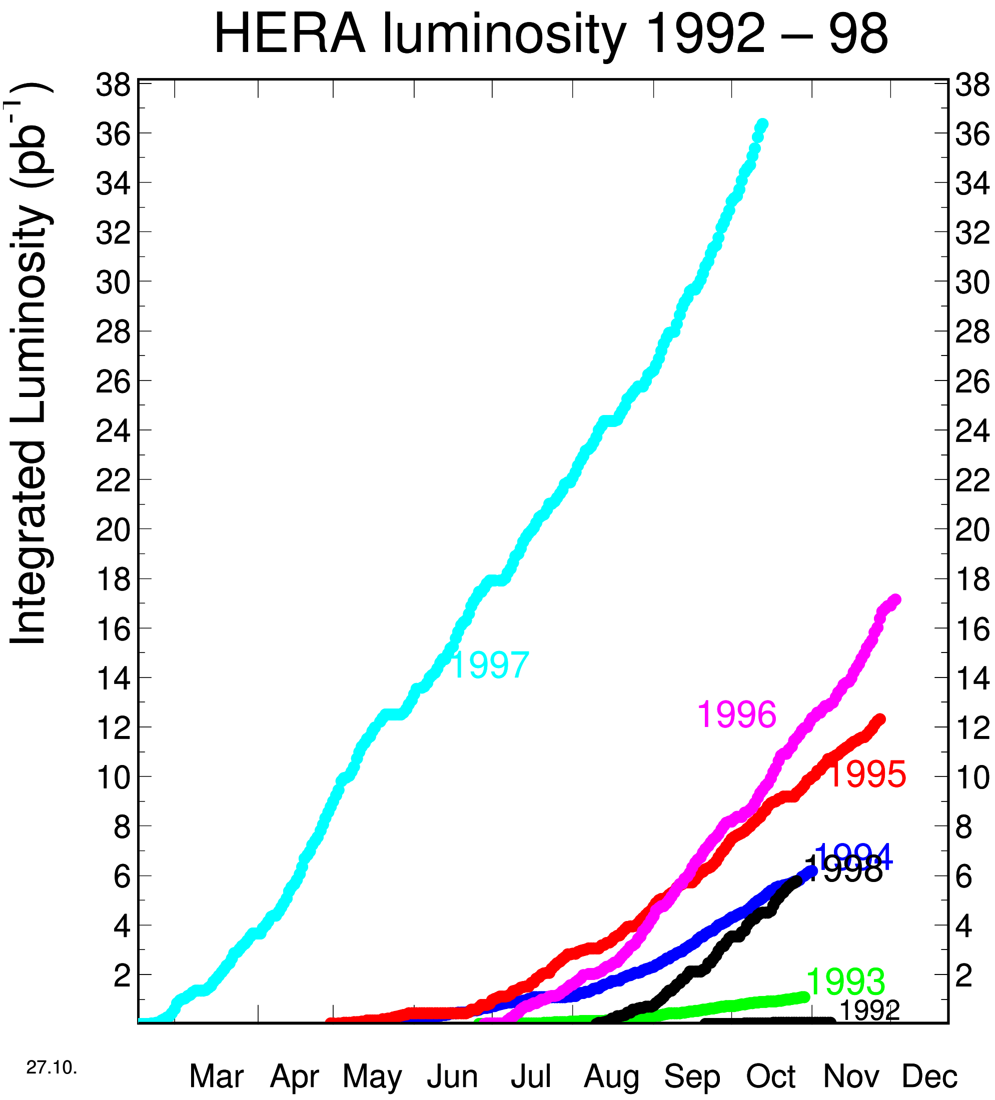
HERA Luminosity History (I)



Switched back to electrons in 1998
after improvements to vacuum system

Proton energy raised from 820 GeV to 920 GeV

HERA Luminosity History (II)



Luminosity upgrade in 2000

with a goal of 1 fb^{-1} by 2005

We expect an increase of a factor 20

over the present integrated luminosity