Particle Physics Seminar 5 November 1999

Warsaw University

Recent Studies at HERA of the Helicity Structure of Diffractive Vector-Meson Production

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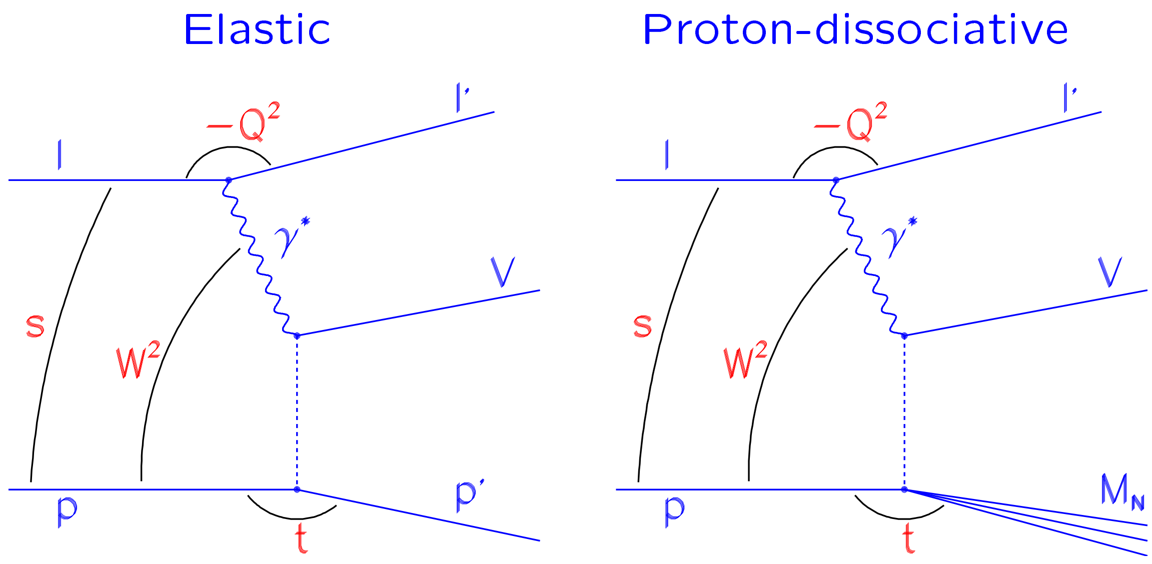
Diffractive Production of Vector Mesons



$\sqrt{s}$: Center–of–mass energy of e–p system
HERA (1992-97): 300 GeV

W: Center–of–mass energy of γ^*–p system
$20 < W < 240$ GeV

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

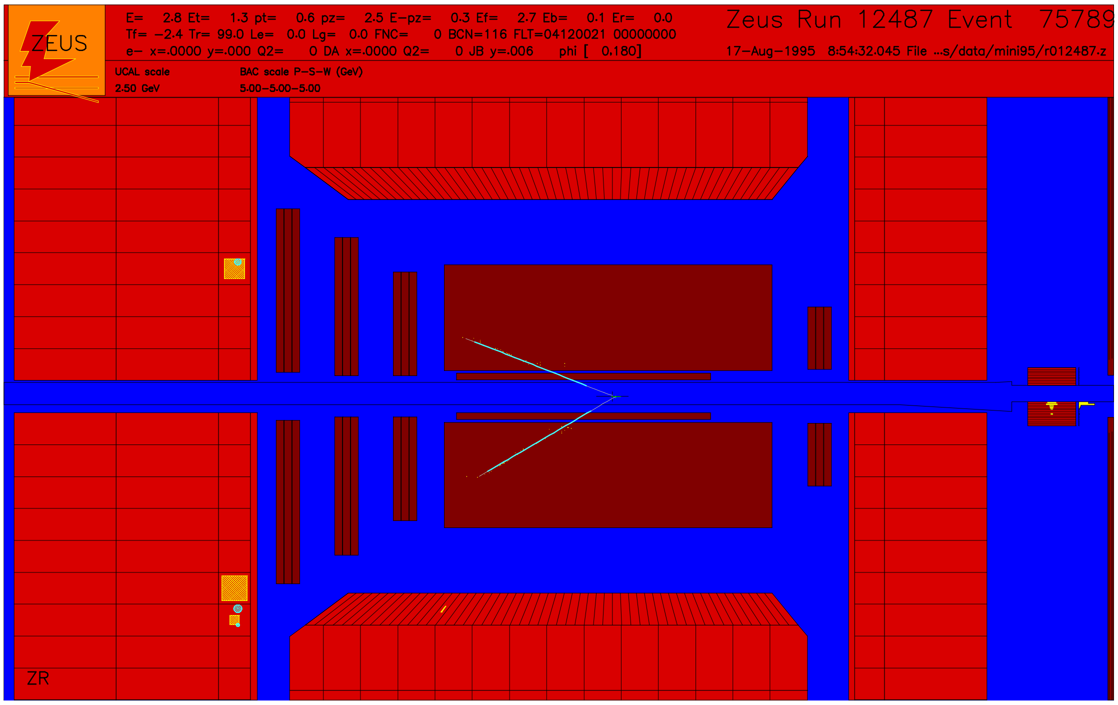
t: Square of Momentum Transfer at the Proton Vertex
$|t| < 13\ \mathrm{GeV}^2$
Proton-dissociative process dominates at high $|t|$

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

Diffractive Production of ρ^0 Mesons

ZEUS: Eur. J. Phys. C6 (1999) 603

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



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

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:

$$\boxed{x < 0.06}$$

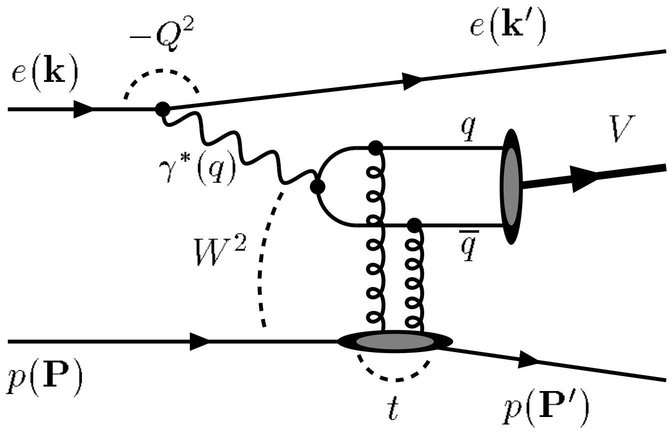
$$W^2 = Q^2\left[\frac{1}{x} - 1\right] + m_\mathrm{p}^2 \approx \frac{Q^2}{x}$$

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

Gilman, Hand conventions for virtual-photon flux definition

Perturbative QCD for Diffraction (?!)

☞ Exchange of a gluon "ladder"



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

Only longitudinal photons have point-like interactions !

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

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

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

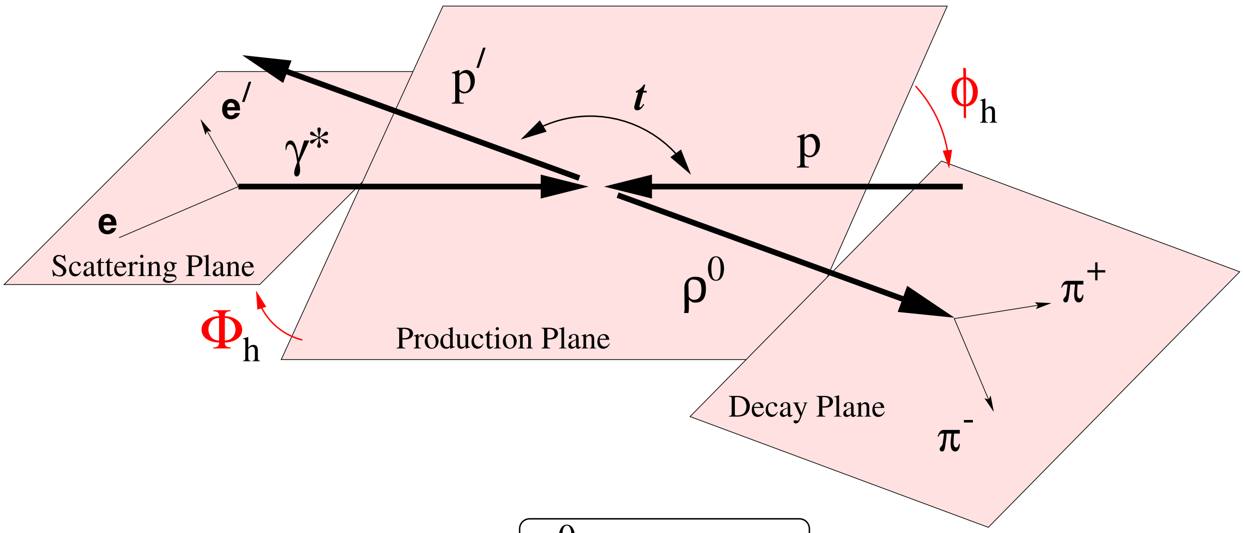
$$\bar{Q}^2 = \frac{Q^2 + M_V^2 - t}{4} \;\; (?)$$

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

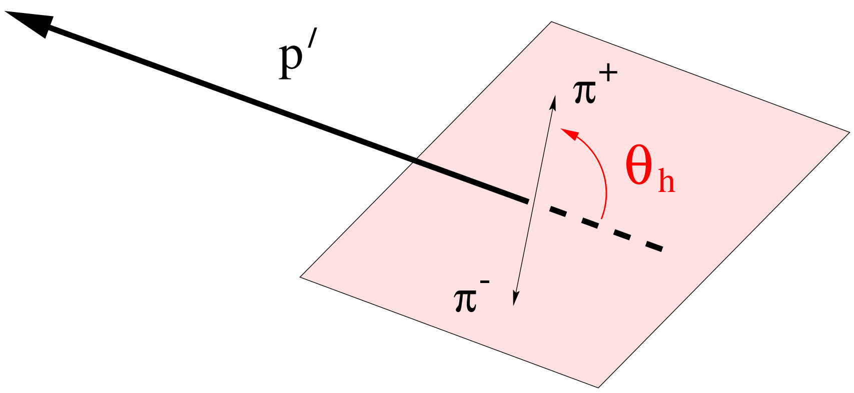
What experimental signatures for the region of pQCD validity ?

Helicity Analysis

$\gamma^* p$ center-of-mass frame



ρ^0 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 ($\lambda = 0, \pm 1$) ??

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) $\pm$ 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 $i, k = +1, 0, -1$)

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

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

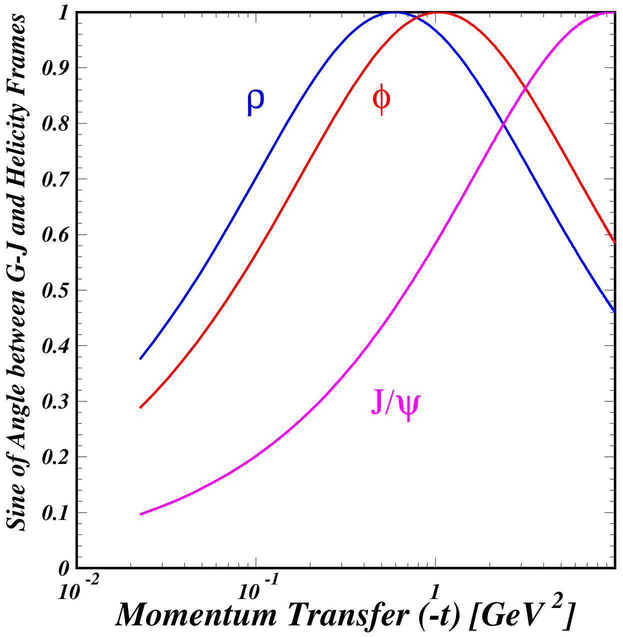
$$r_{ik}^{\alpha} = \begin{cases} \dfrac{\rho_{ik}^{\alpha}}{1+\epsilon R} & \alpha = 1-3 \text{ (Trans.)} \\ \dfrac{\sqrt{R}\,\rho_{ik}^{\alpha}}{1+\epsilon R} & \alpha = 5-8 \text{ (L/T int.)} \end{cases}$$

Constraints from hermiticity, parity conservation

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)

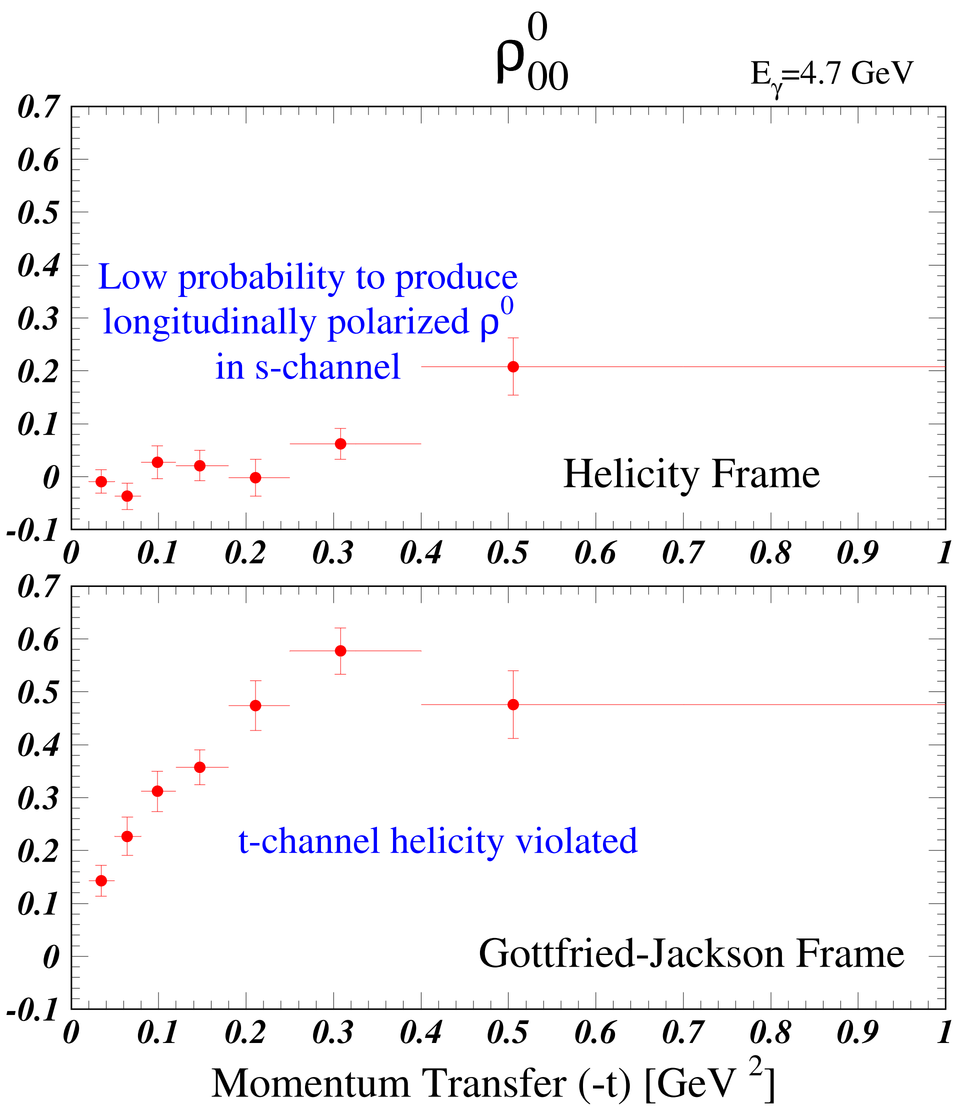
$$W(\cos\theta_h, \phi_h, \Phi_h) =$$

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

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 (9.3 GeV: PRD 7 (1973) 3150)
- 3k $\rho^0 \to \pi^+\pi^-$ reconstructed in bubble chamber



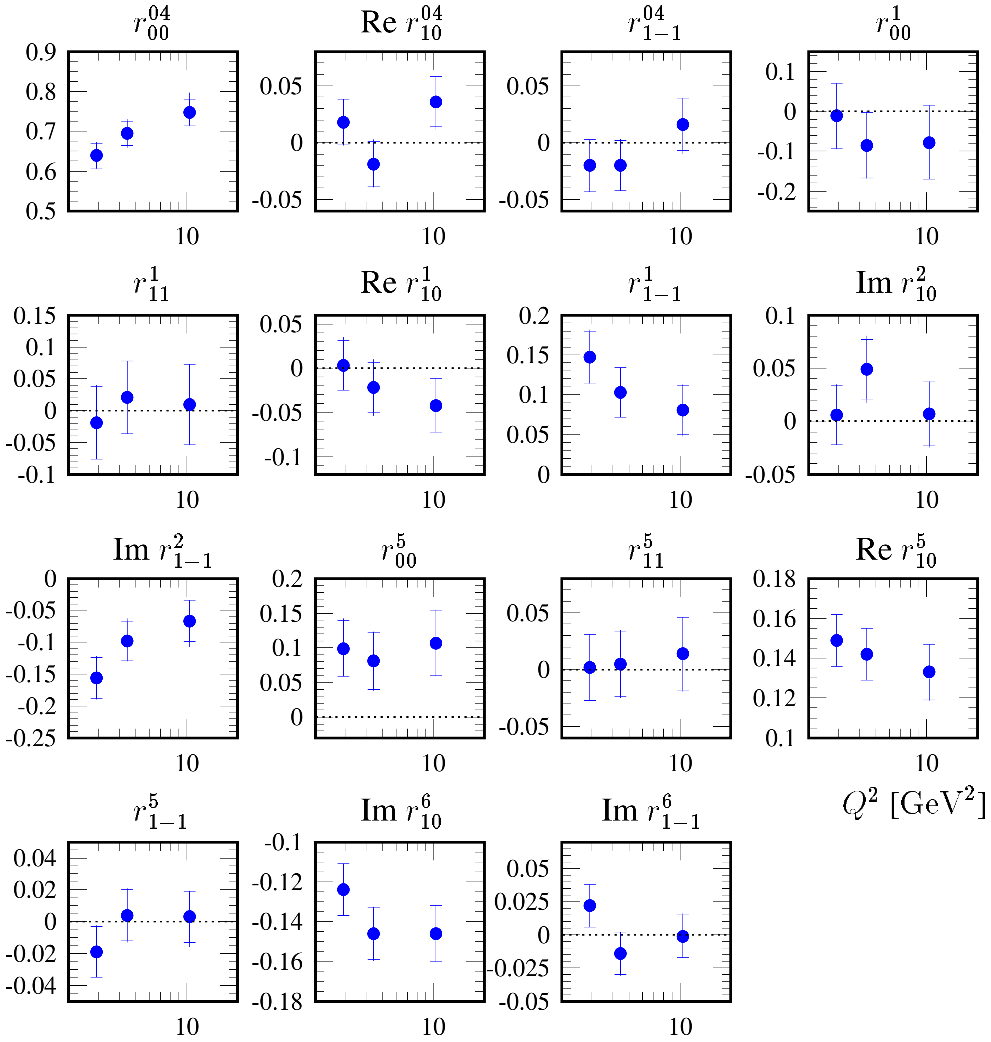
Inconsistent with t-channel exchange of spin 0 object

Gilman et al PL B31 (1970) 387

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

15-Parameter Helicity-Angle Fit in ρ^0 Electroproduction

H1 hep-ex/9902019

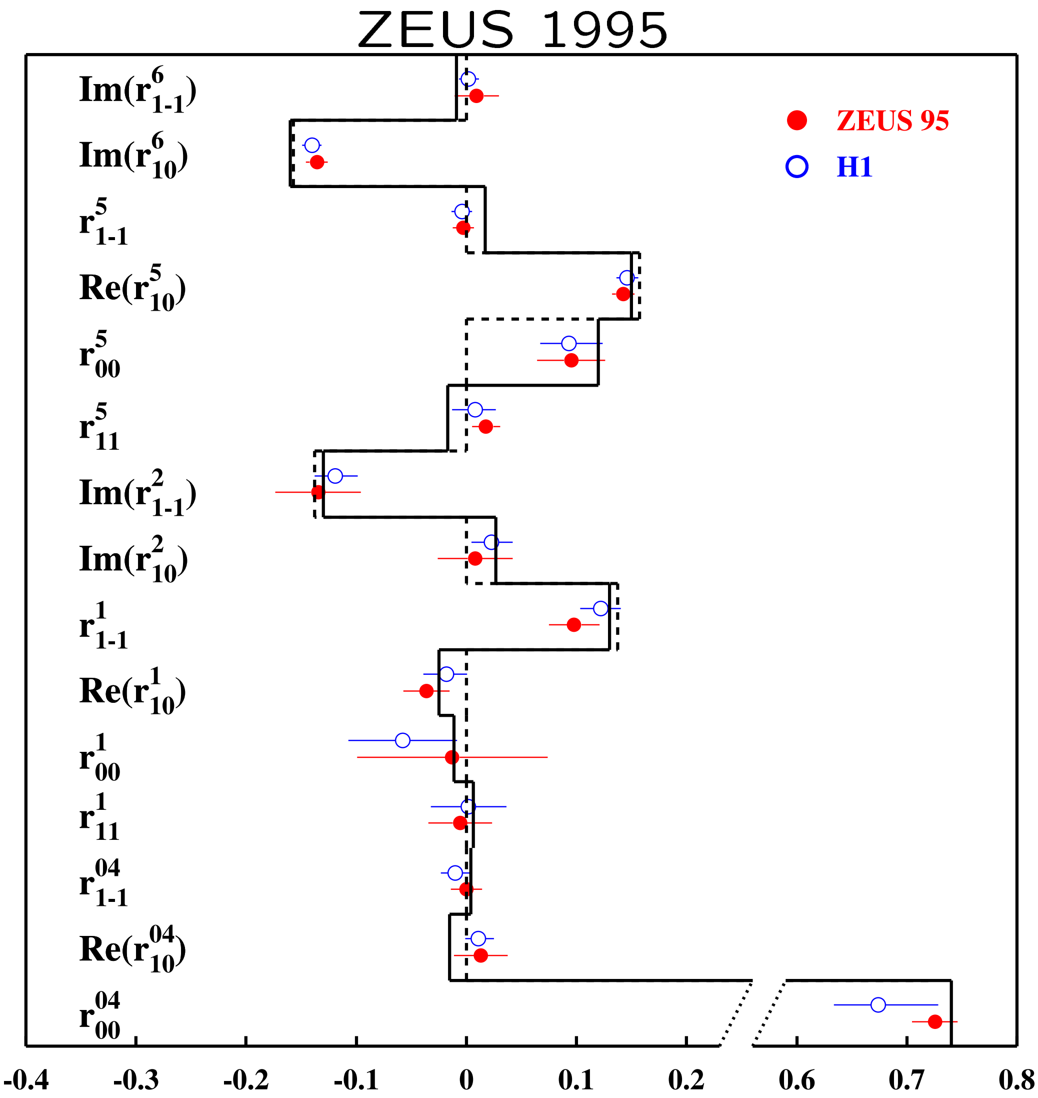


Dotted lines are SCHC values

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

15-Parameter Helicity-Angle Fit (II)

ZEUS ICHEP Abstract 792/792b



⟹ Agreement with Ivanov and Kirschner

(Phys. Rev. D58 (1998) 114026)

⟹ Results also obtained for low Q^2 and ϕ

Ivanov and Kirschner

Phys. Rev. D58 (1998) 114026

- Strong Q^2 dependence of $G(x, Q^2)$ at low x predicted by pQCD results in convergent integrals for transverse photons, overcoming endpoint divergences

  $\Longrightarrow$ A là Martin, Ryskin, Teubner

- Five helicity amplitudes: two helicity-conserving
  two single-flip
  one double-flip

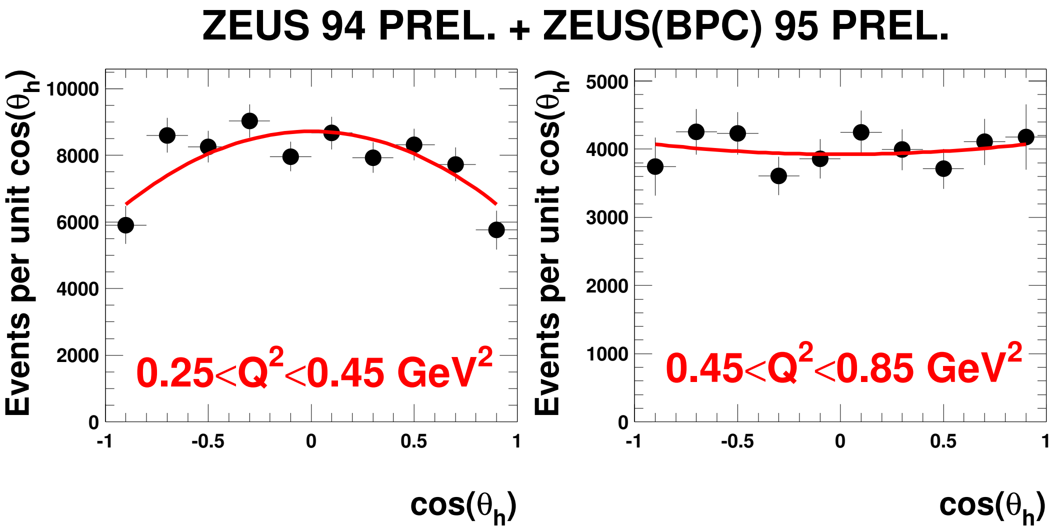
- Amplitude to produce longitudinal ρ's from transverse photons rendered experimentally accessible via its interference with the dominant helicity-conserving longitudinal amplitude

- This single-flip amplitude is higher twist and proportional to $\sqrt{t}$

- The single-flip amplitudes *vanish* if $z = 1/2$ i.e. they vanish in the nonrelativistic approximation for the ρ wave function

Measurement of $R = \frac{\sigma_L}{\sigma_T} > 0$ in ρ^0 Electroproduction

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

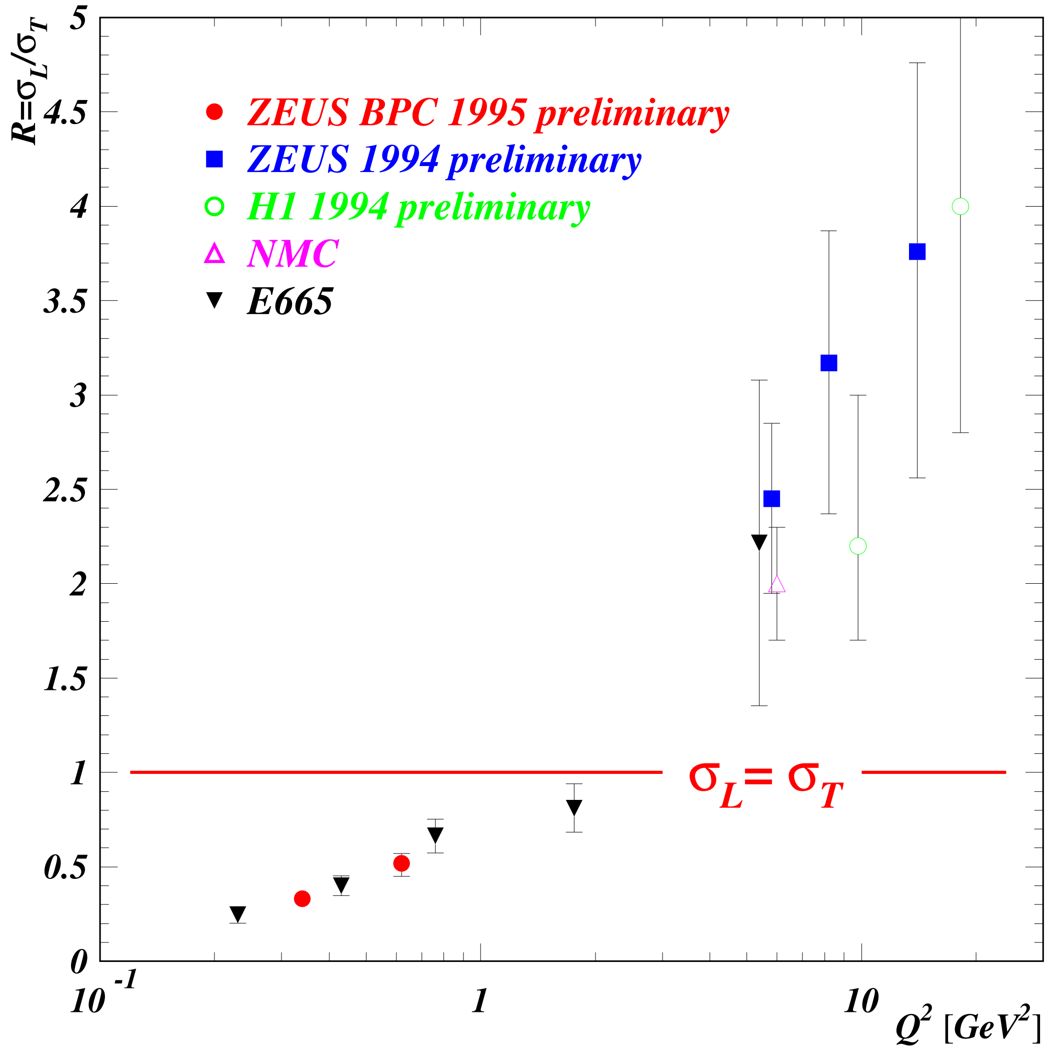


Q^2 (GeV^2)	r^{04}_{00}
0.34	0.24 ± 0.02(stat)
0.62	0.34 ± 0.03(stat)
5.8	$0.71^{+0.03}_{-0.04}$(stat)$^{+0.01}_{-0.01}$(sys)
8.2	$0.76^{+0.04}_{-0.04}$(stat)$^{+0.00}_{-0.02}$(sys)
14	$0.79^{+0.04}_{-0.05}$(stat)$^{+0.02}_{-0.01}$(sys)

$R = \frac{\sigma_L}{\sigma_T}$ vs Q^2 for ρ^0

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

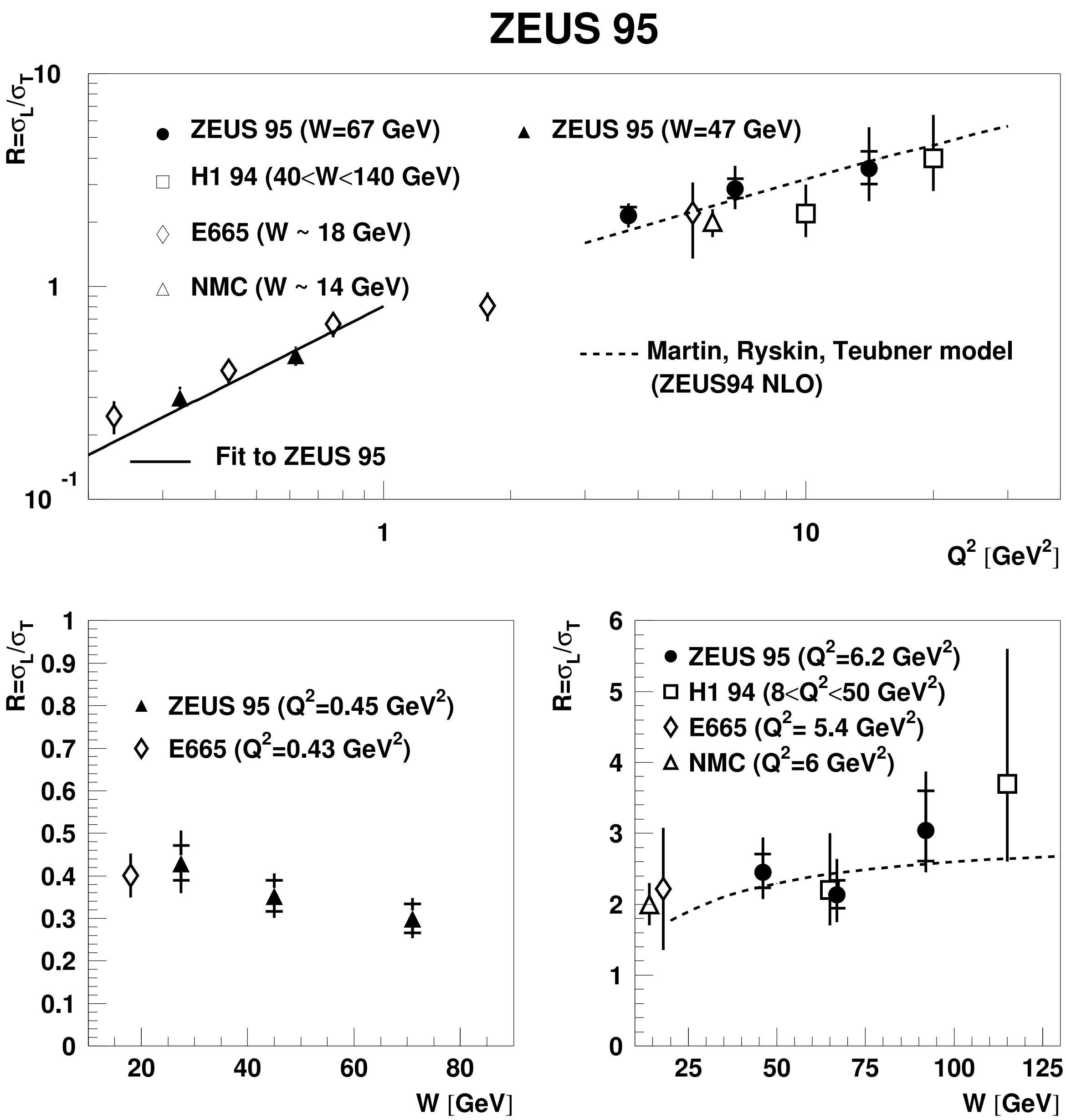
Δ now known to be small !



$\Rightarrow$ σ_L increases and becomes dominant

R vs Q^2 and W for ρ^0

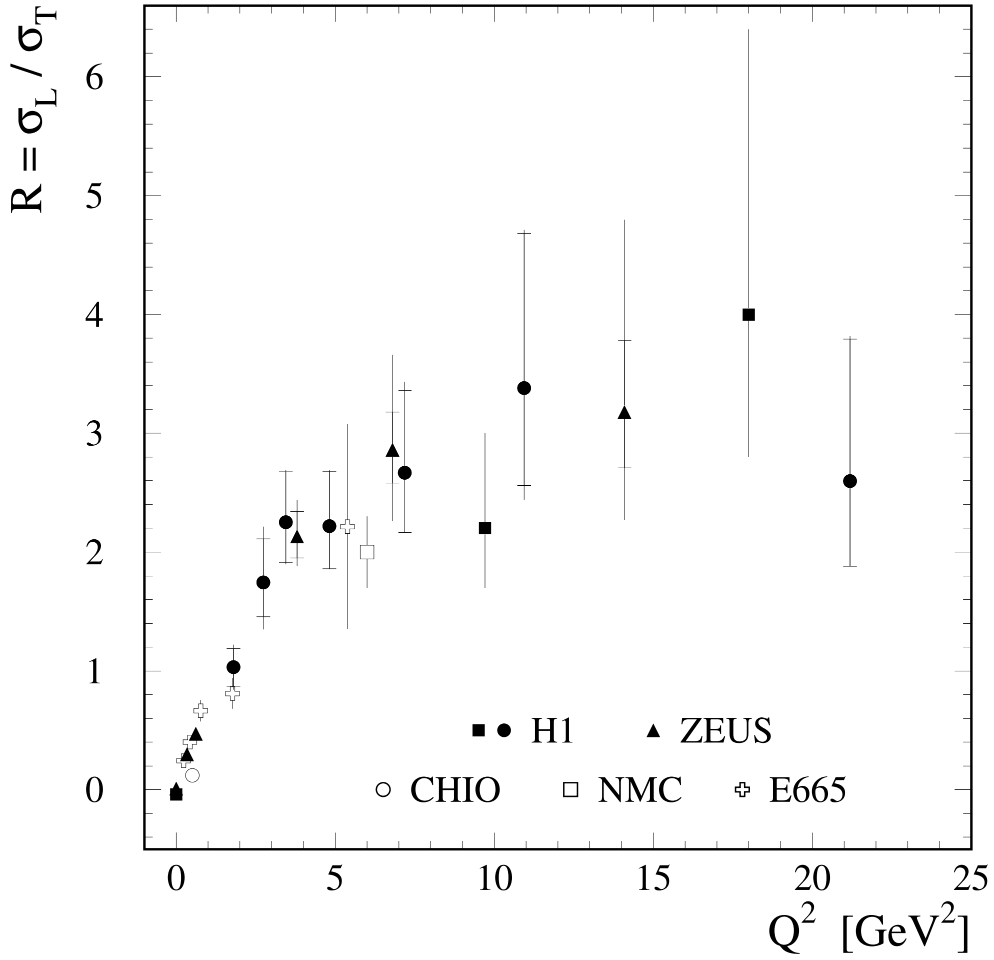
ZEUS: Eur. Phys. J. C6 (1999) 603



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

R vs Q^2 (H1 DIS ρ^0)

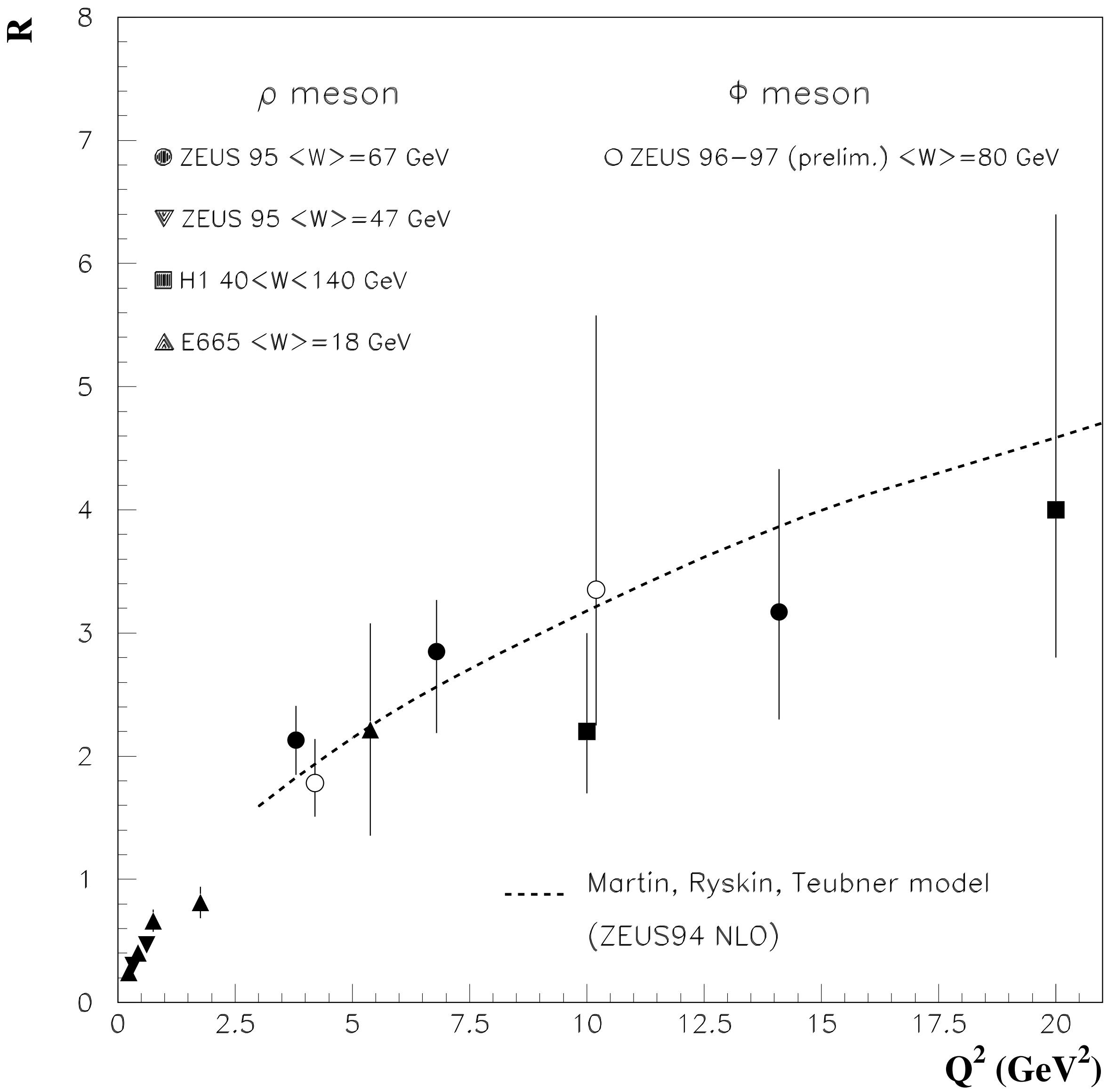
H1 hep-ex/9902019



$\Rightarrow$ σ_L/σ_T levelling off ??

R vs Q^2 (ZEUS DIS ϕ prel.)

ZEUS ICHEP Abstract 793

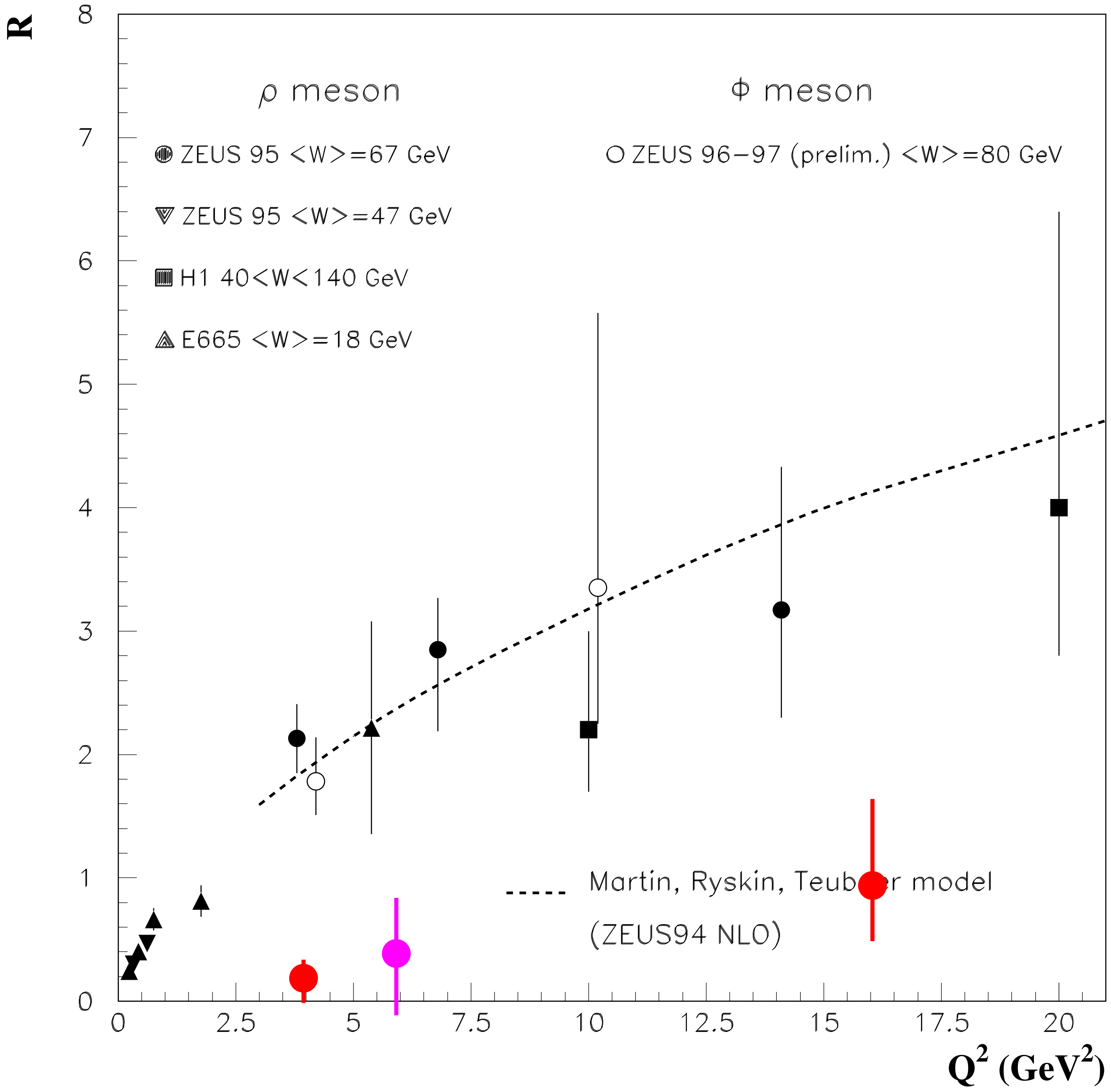


$\Rightarrow$ ϕ behaves like ρ^0 !!

R vs Q^2 for J/ψ

H1: Eur. Phys. J. C10 (1999) 373

ZEUS: Eur. Phys. J. C6 (1999) 603



$\Rightarrow$ R for J/ψ lower ! $\left[\propto \frac{Q^2}{M_V^2}\right]$

ρ^0 Photoproduction at High $|t|$

Can the momentum transfer $|t|$ serve as a perturbative scale?

Recent reatments in perturbative QCD:

D.Yu. Ivanov, Phys. Rev. **D53** (1996) 3564

S.J. Brodsky, M. Diehl, P. Hoyer, and S. Peigné, hep-ph/9812277

Semi-exclusive Processes: New Probes of Hadron Structure

$\Longrightarrow$ Predict longitudinal polarization of ρ^0 at high $|t|$

The final-state angular distributions are sensitive to products of the helicity amplitudes: $\mathrm{T}_{\lambda_{\pi\pi}\lambda_\gamma}$

In photoproduction, the contribution from longitudinal photons is small:

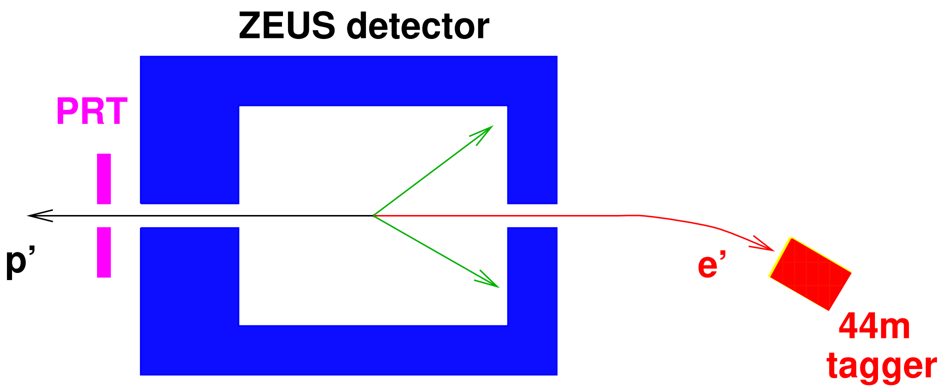
$$R \equiv \frac{\sigma_L}{\sigma_T} = \frac{T_{00}^2 + 2\,T_{10}^2}{T_{01}^2 + T_{11}^2 + T_{1-1}^2} \ll 1$$

Helicity Analysis

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

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

Photoproduction Tagging at High $|t|$ for $W \simeq$ 100 GeV



$$Q^2 < 0.01 \text{ GeV}^2$$
$$22 < E_{e'} < 25 \text{ GeV } (\Rightarrow W)$$

Proton Remnant Tagger used to separate elastic/dissociative

ZEUS 1995 preliminary

Int. luminosity: $\simeq 2$ pb^{-1}

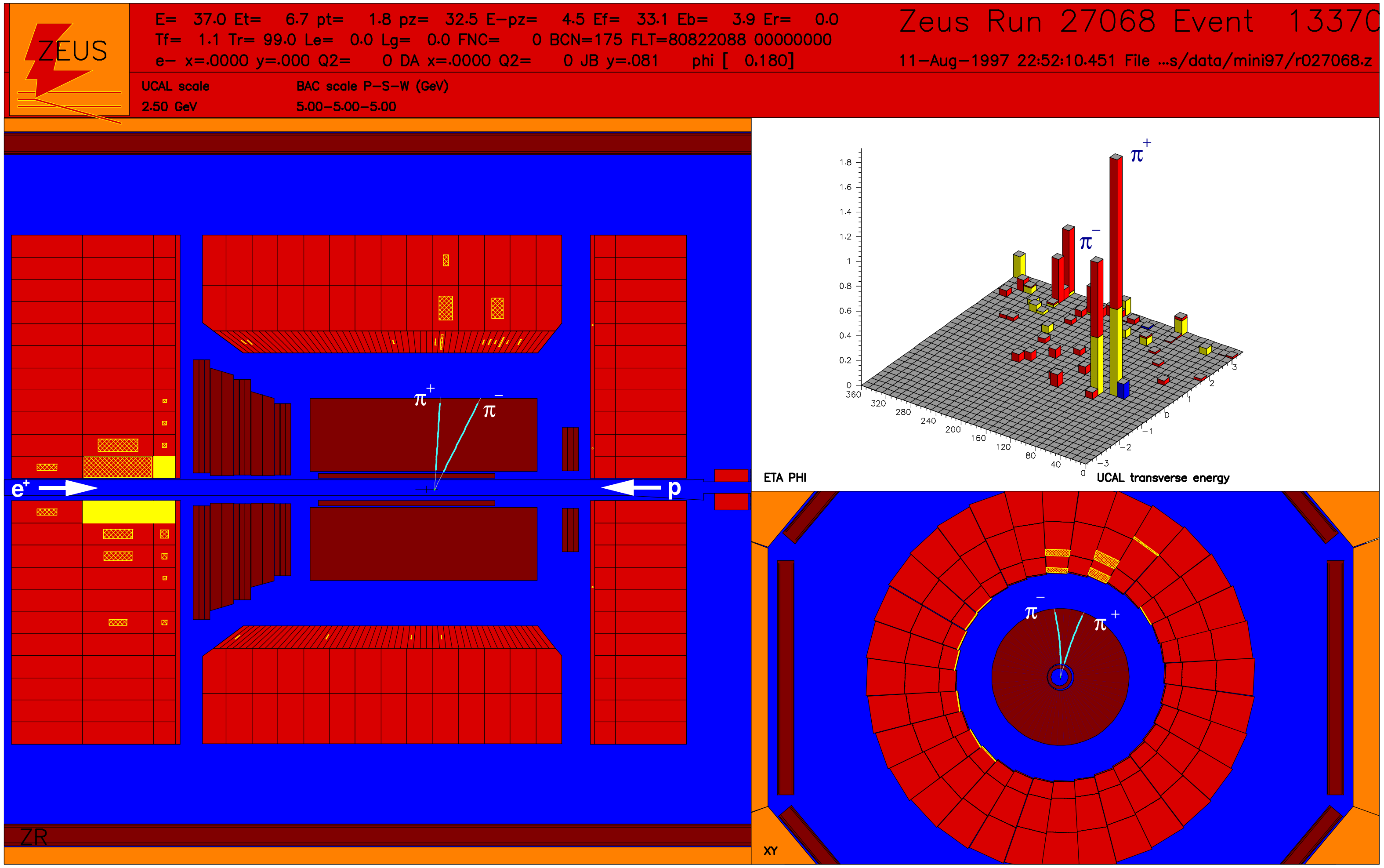
Elastic kinematic limit for ρ^0 $\longrightarrow$ $2 \cdot 10^{-8} < |t| < 2$ GeV^2

ZEUS 1996/97 preliminary

Int. luminosity: $\simeq 25$ pb^{-1}

$1 < |t| < 5$ GeV^2

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

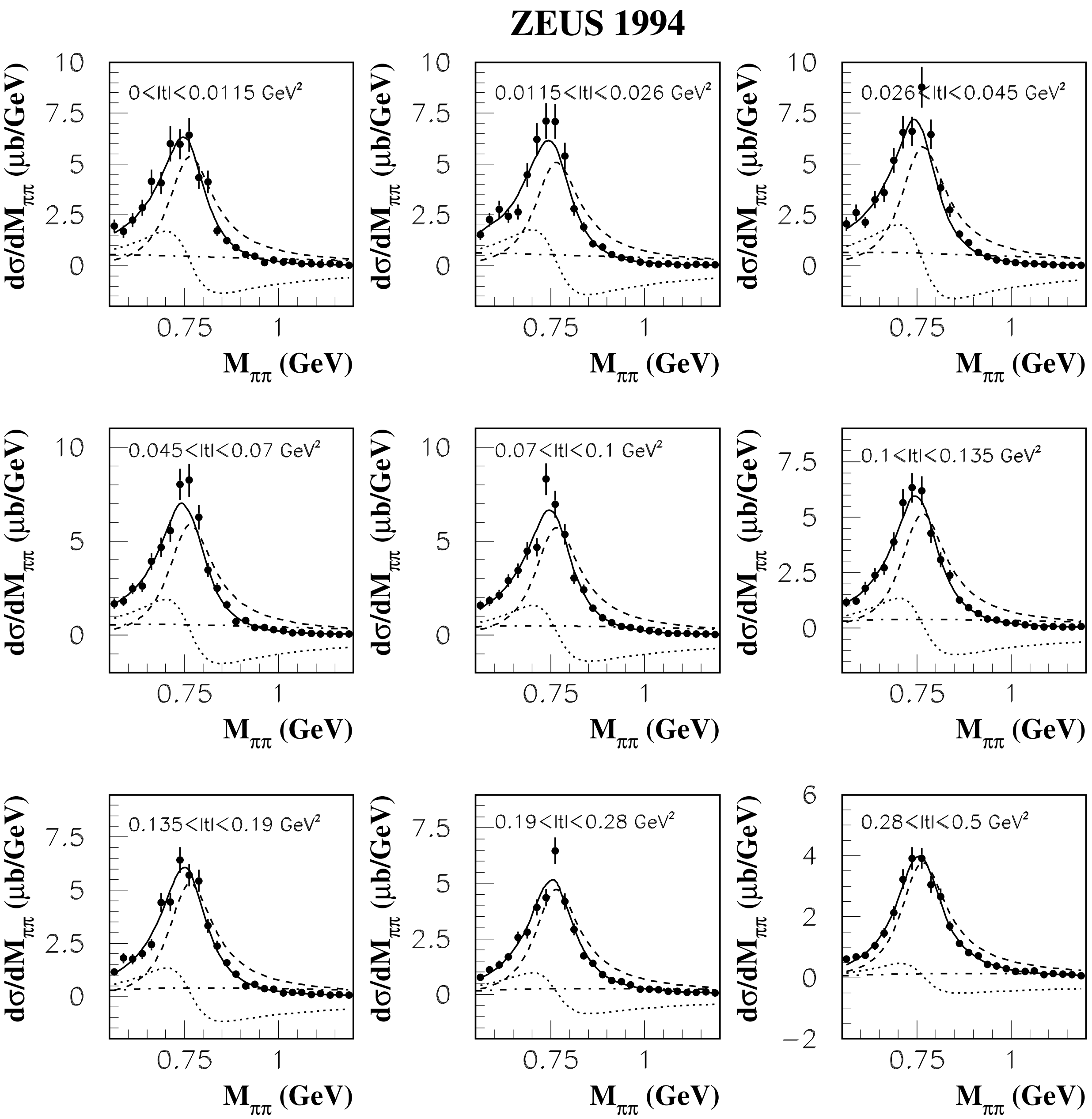


$e^+p \to e^+N\,\rho^0 \to e^+N\,\pi^+\pi^-$ $\quad M_{\pi^+\pi^-} = 0.78$ GeV, $t = -10.0$ GeV^2, $W = 81$ GeV

t Dependence of $\pi^+\pi^-$ Mass Shape (I)

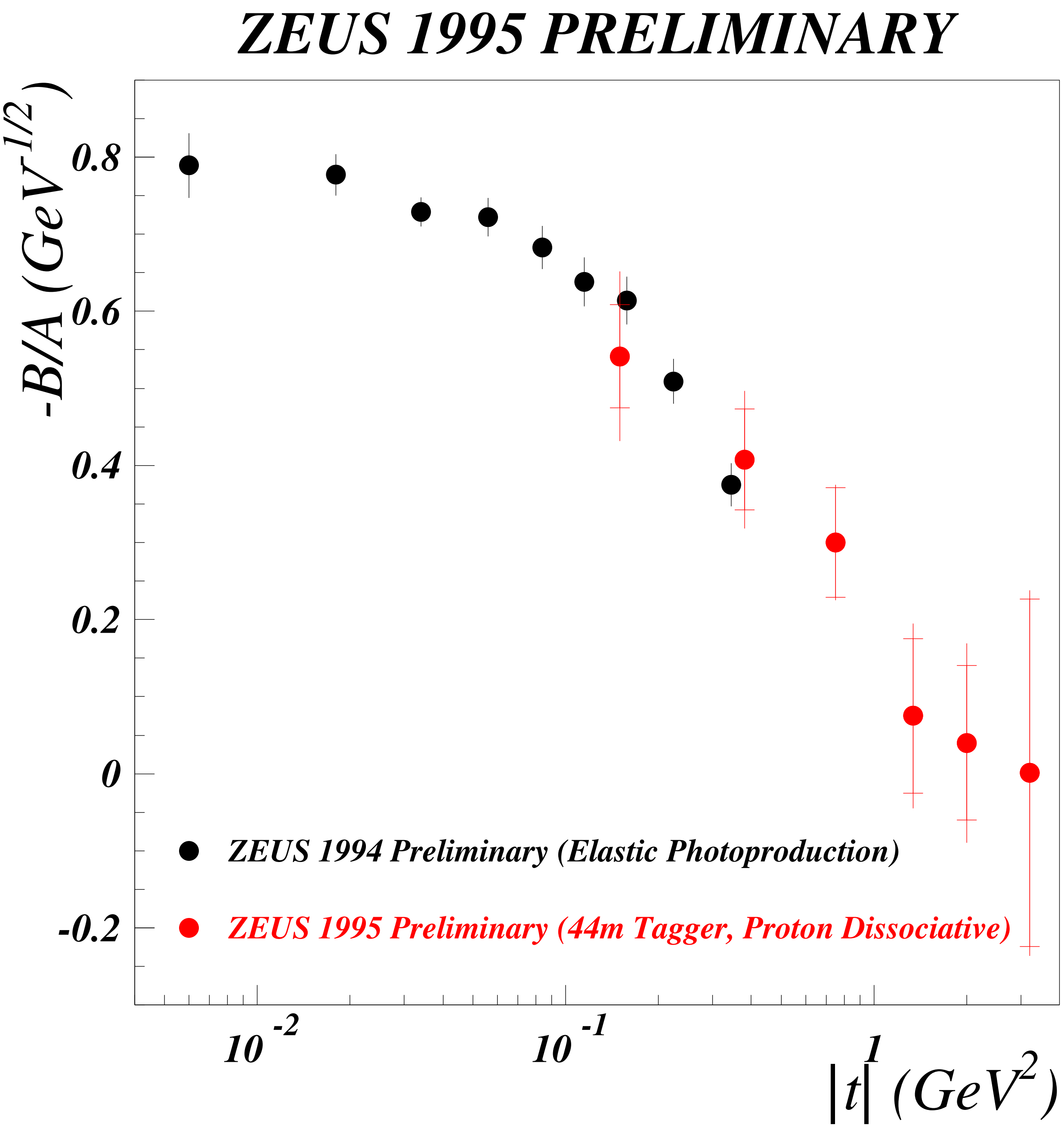
ZEUS: Eur. Phys. J. C2 (1998) 247

Elastic ρ^0 photoproduction (untagged)



$\Rightarrow$ Nonres. contribution decreases with $|t|$

t Dependence of $\pi^+\pi^-$ Mass Shape (II)

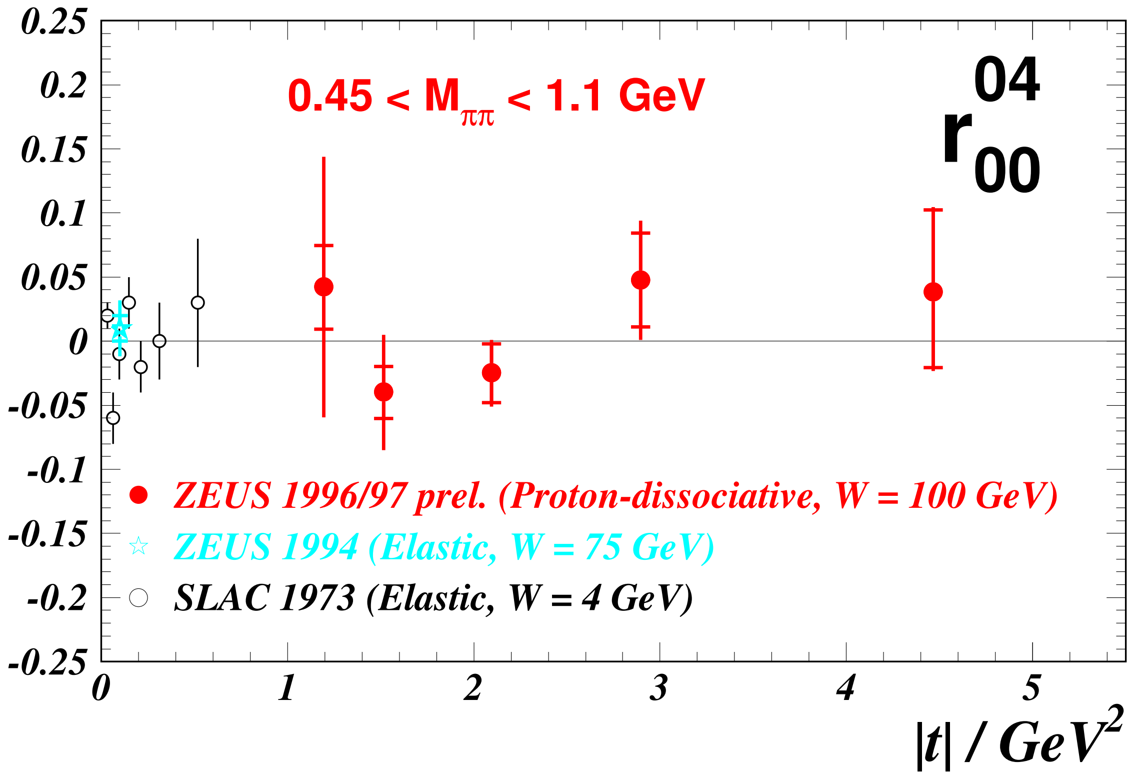


$\Rightarrow$ Compatible with BW for $|t| > 1$ GeV^2

High-$|t|$ Helicity Analysis (I)

$$r^{04}_{00} \simeq \frac{T^2_{01}}{T^2_{01}+T^2_{11}+T^2_{1-1}}$$

r^{04}_{00} measures the degree of longitudinal polarization

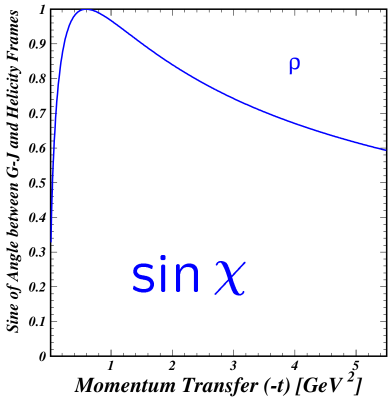


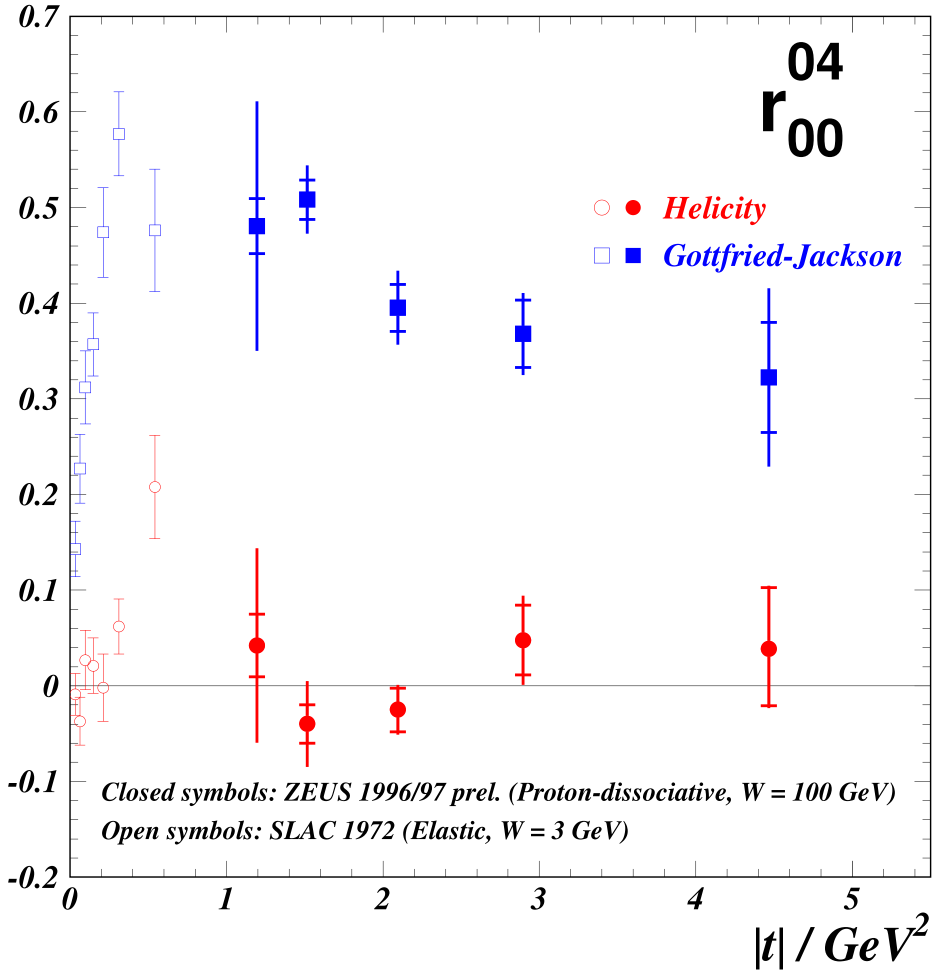
Long. pol. does *NOT* dominate at high $|t|$

Choice of Spin Axis

The angle χ between the Z-axes of the Gottfried-Jackson and Helicity systems

$$\cos\chi \;=\; \left(\frac{m_\rho^2+t}{m_\rho^2-t}\right)$$



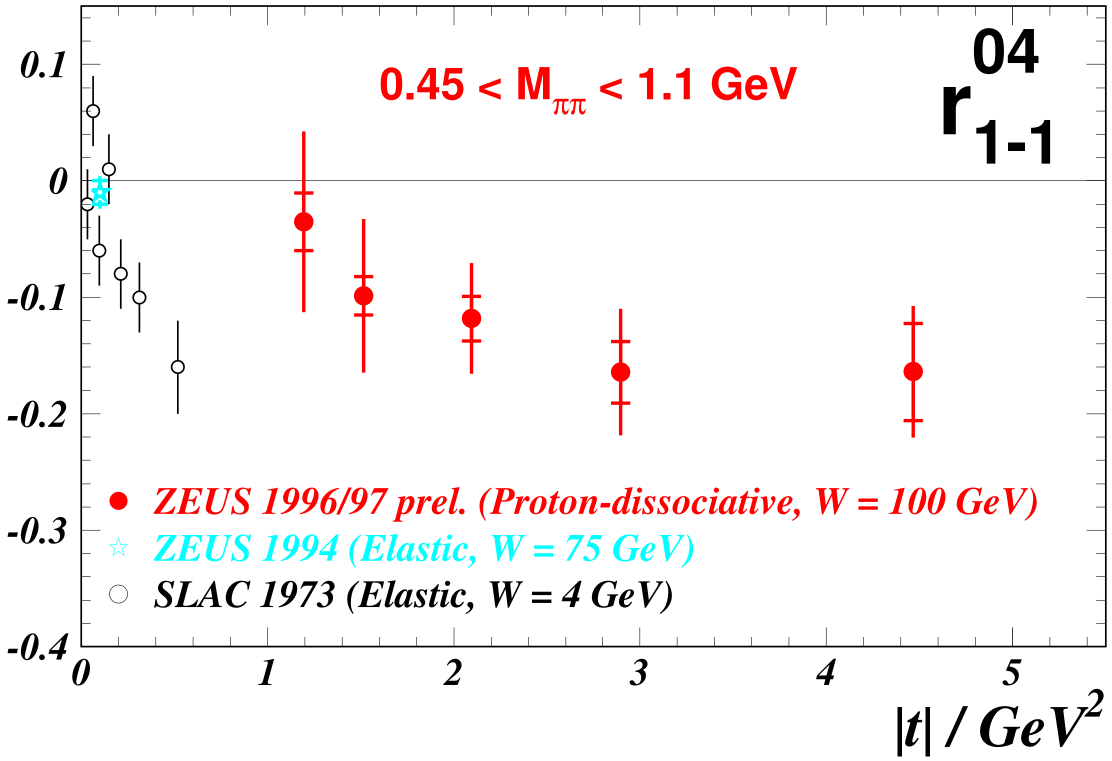


Extension of SLAC data to $|t| \gg m_\rho^2$

High-$|t|$ Helicity Analysis (II)

$$r^{04}_{1-1} \simeq \frac{Re(T_{11}T^*_{1-1})}{T^2_{01}+T^2_{11}+T^2_{1-1}}$$

r^{04}_{1-1} sensitive to helicity flip of trans. photon

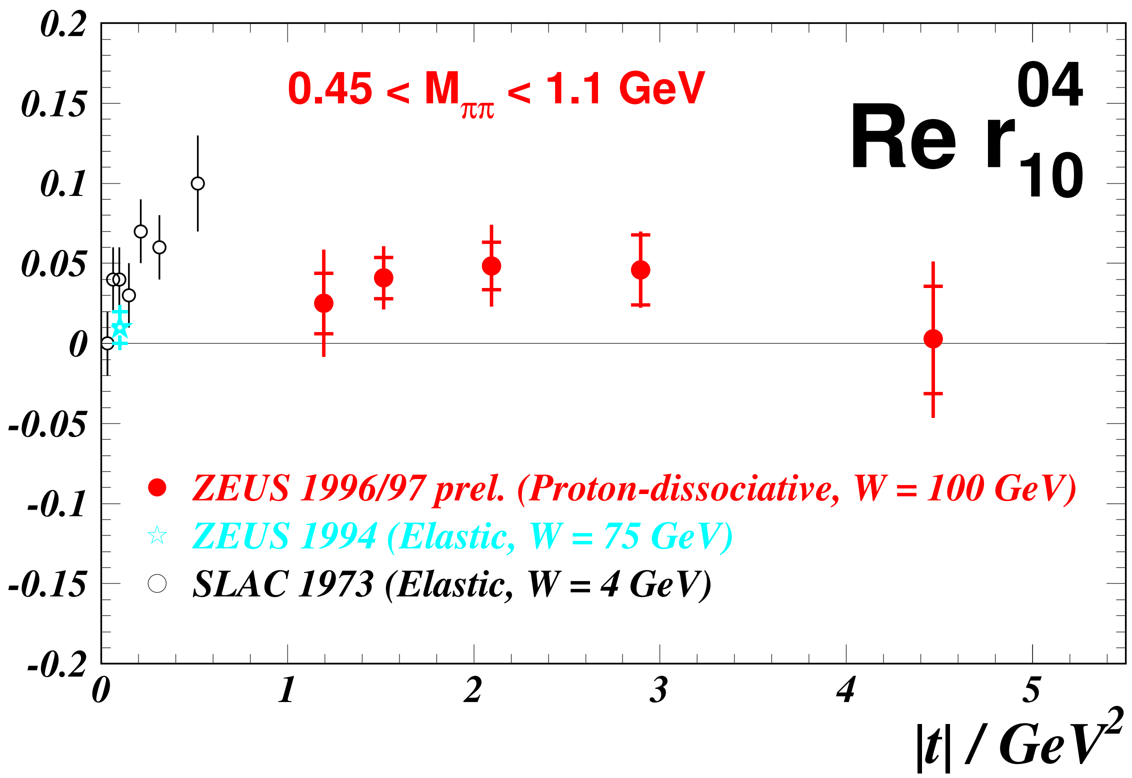


Clear double-flip contribution (But is it the ρ^0?)

High-$|t|$ Helicity Analysis (III)

$$Re(r^{04}_{10}) \simeq \frac{1}{2}\left[\frac{Re(T_{11}T^*_{01})+Re(T_{1-1}T^*_{0-1})}{T^2_{01}+T^2_{11}+T^2_{1-1}}\right]$$

$Re(r^{04}_{10})$ sensitive to single flip via interference

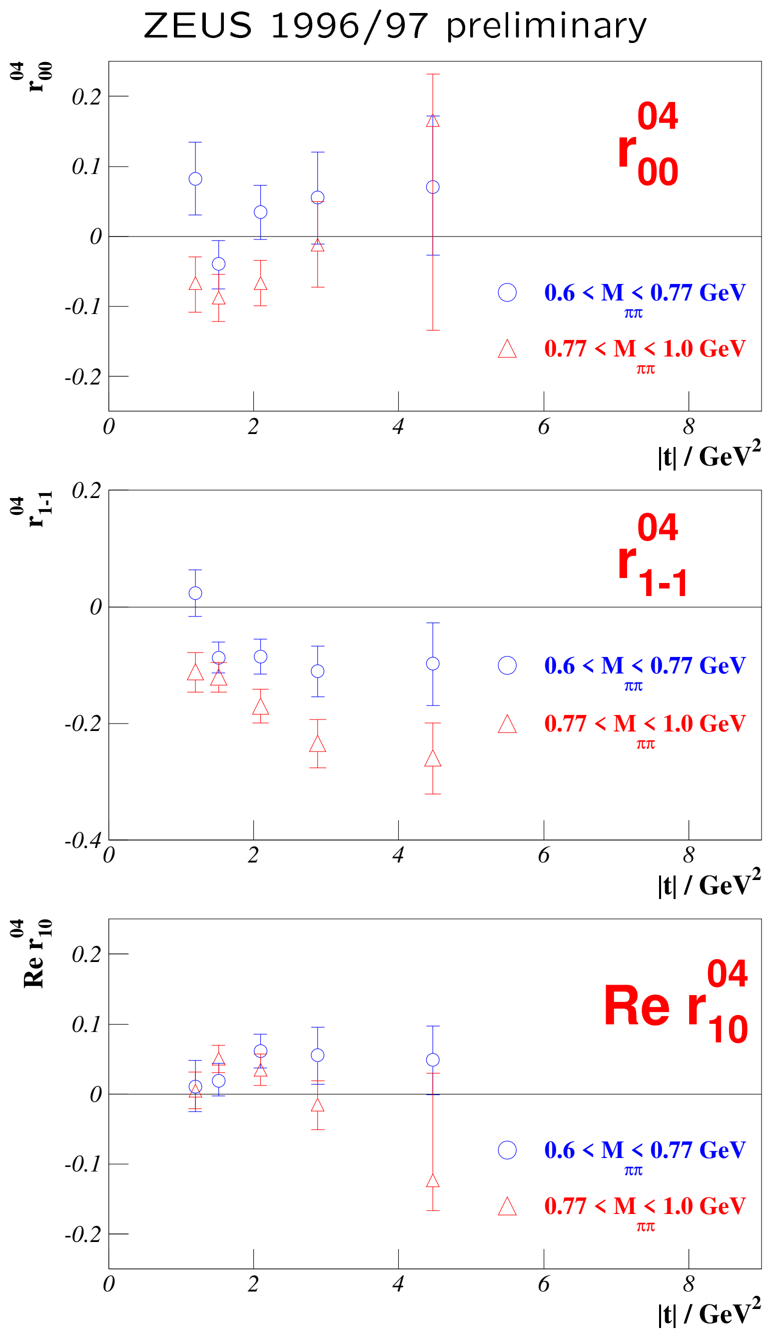


Indication of single-flip contribution (Is it the ρ^0?)

High-$|t|$ Helicity Analysis (IV)

Dipion-mass Dependence in r_{ij}^{04}

Are production and decay independent??



Single-flip contribution depends on mass region !

Conclusions

Decay-angle analyses at HERA of diffractive vector meson production have revealed a rich helicity structure

Impressive phenomenological successes have been obtained from QCD-based model calculations

Important mysteries remain to be solved

The field is very active both theoretically and experimentally