INT/JLab Workshop *Jefferson Lab*

20 May 1999 *Newport News*

Topical Results on Vector-Meson Production from ZEUS and H1

Joint INT/JLab Workshop on
Exclusive and Semi-exclusive Processes
at High Momentum Transfer

- Upsilon Photoproduction
- $R \equiv \frac{\sigma_L}{\sigma_T}$ for ρ^0, ϕ, and J/ψ Electroproduction
- VM Photoproduction at High $|t|$

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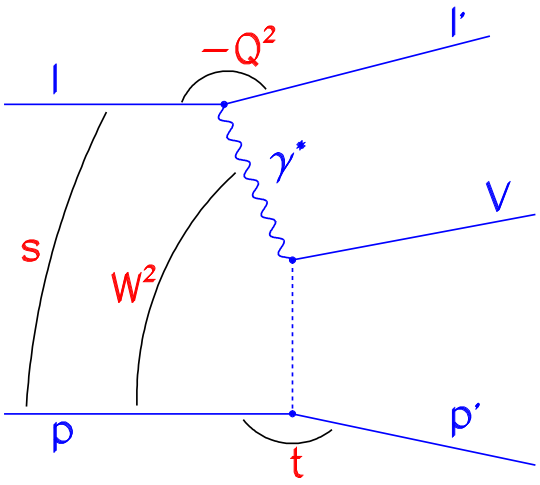
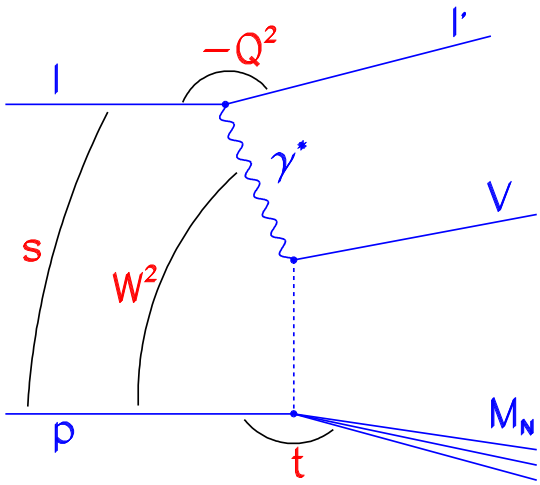
Production of Vector Mesons at HERA

Elastic



Proton-dissociative



$\sqrt{s}$: 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

$10^{-10} < Q^2 < 60$ GeV^2 ($Q^2 \ll |t| \Rightarrow t \simeq -P_T^2(V)$)

t: Square of Momentum Transfer at the Proton Vertex

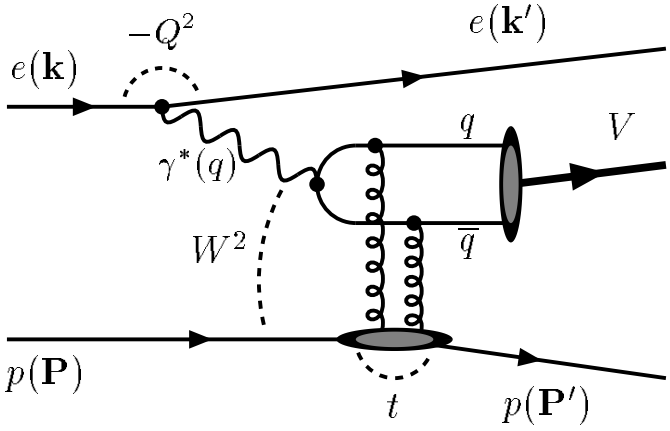
$|t| < 13$ GeV^2

Proton-dissociative process dominates at high $|t|$

$$|t|_{\text{min}} = m_p^2 \frac{(M_V^2+Q^2)^2}{W^4}$$

Perturbative QCD for Diffraction (?!)

Exchange of a gluon "ladder"



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

Only longitudinal photons have point-like interactions !

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

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

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

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

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

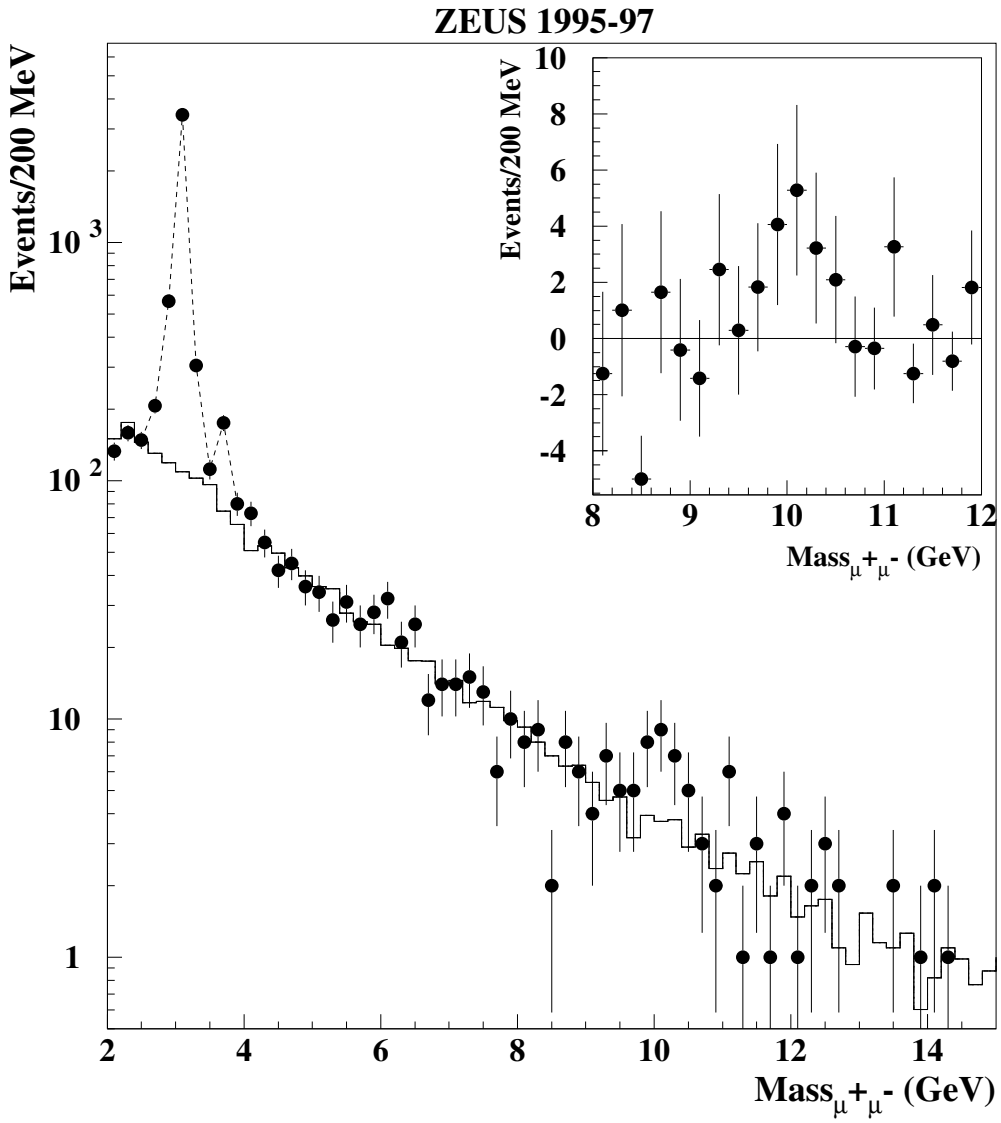
What experimental signatures for the region of pQCD validity ?

Observation of Υ Photoproduction

ZEUS: PL B437 (1998) 432 H1 prel: ICHEP 1998 Abstract 574

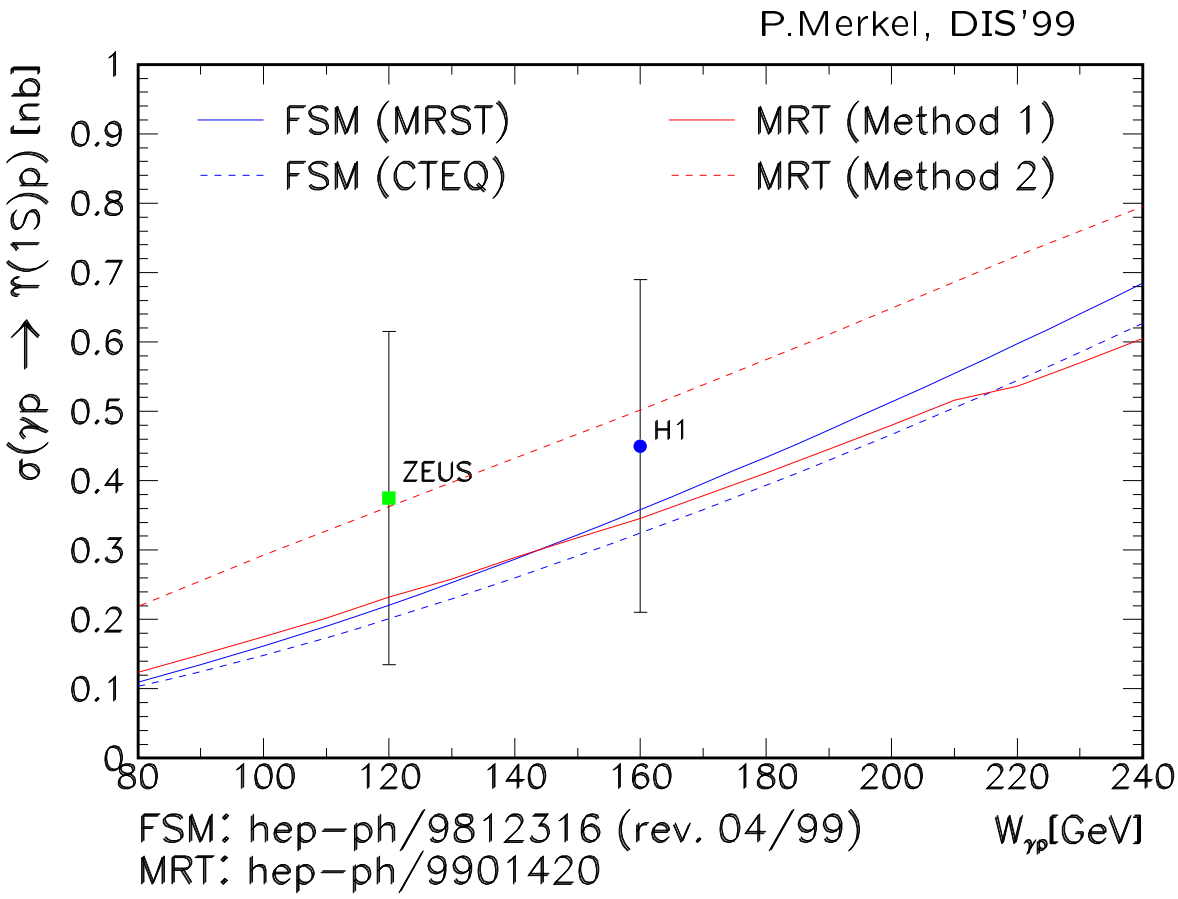
$$\gamma p \rightarrow \mu^+\mu^- p$$

$80 < W < 280\,\text{GeV}, Q^2 < 1\,\text{GeV}^2$



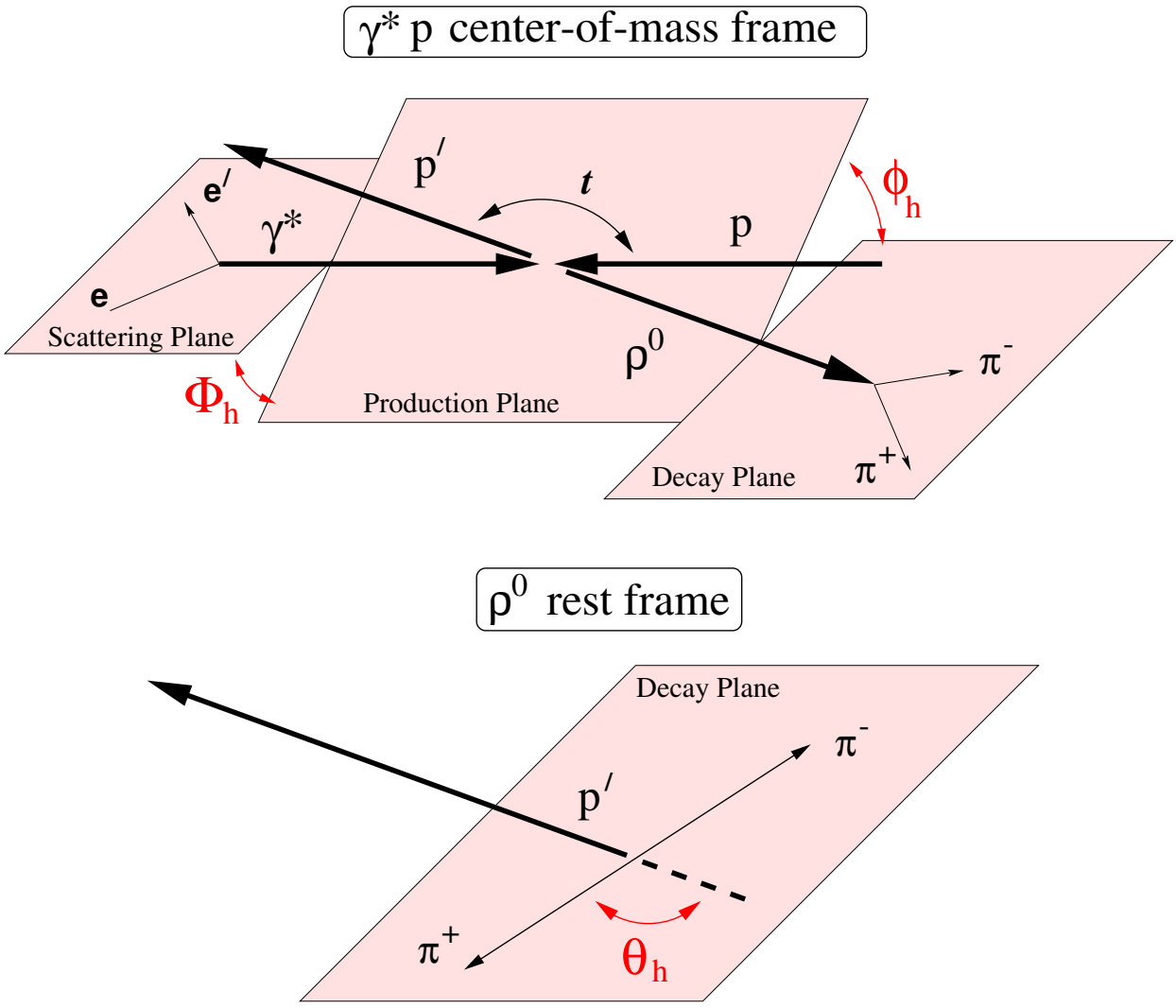
The Υ resonances are not resolved !

Υ Cross Section Calculations



$\Rightarrow$ Sensitive to off-diagonal parton distributions !

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 ($\lambda = 0, \pm 1$) ??

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

- 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$\rightarrow$E665(μ),HERMES(e)

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

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

3-D Decay-Angle Distribution

(15 linearly independent parameters)

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

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

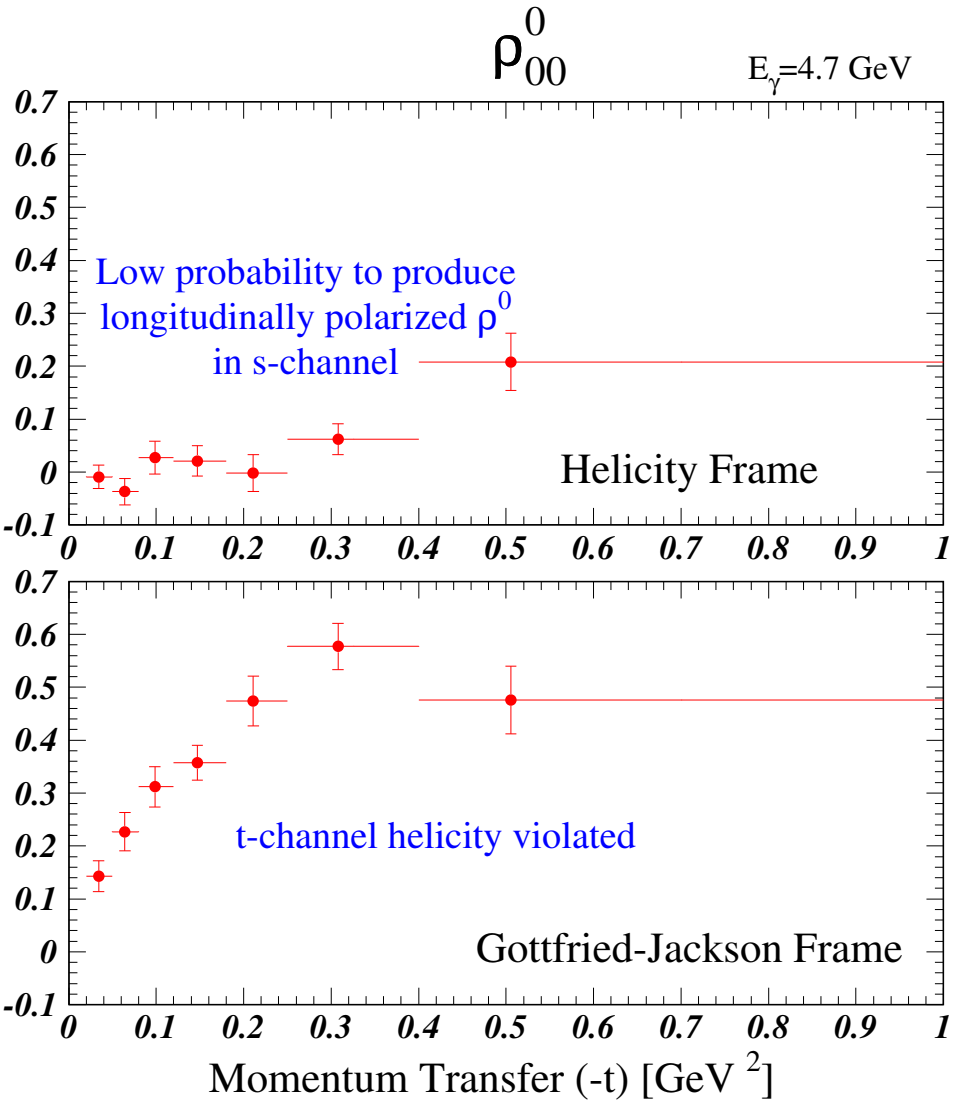
$$-\varepsilon\cos 2\Phi_h(\ r^1_{11}\sin^2\theta_h + r^1_{00}\cos^2\theta_h$$
$$-\sqrt{2}\,\mathrm{Re}\, r^1_{10}\ \sin 2\theta_h\cos\phi_h$$
$$-r^1_{1-1}\sin^2\theta_h\cos 2\phi_h\ )$$
$$-\varepsilon\sin 2\Phi_h(\ \sqrt{2}\,\mathrm{Im}\, r^2_{10}\ \sin 2\theta_h\sin\phi_h$$
$$+\mathrm{Im}\, r^2_{1-1}\sin^2\theta_h\sin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

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

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

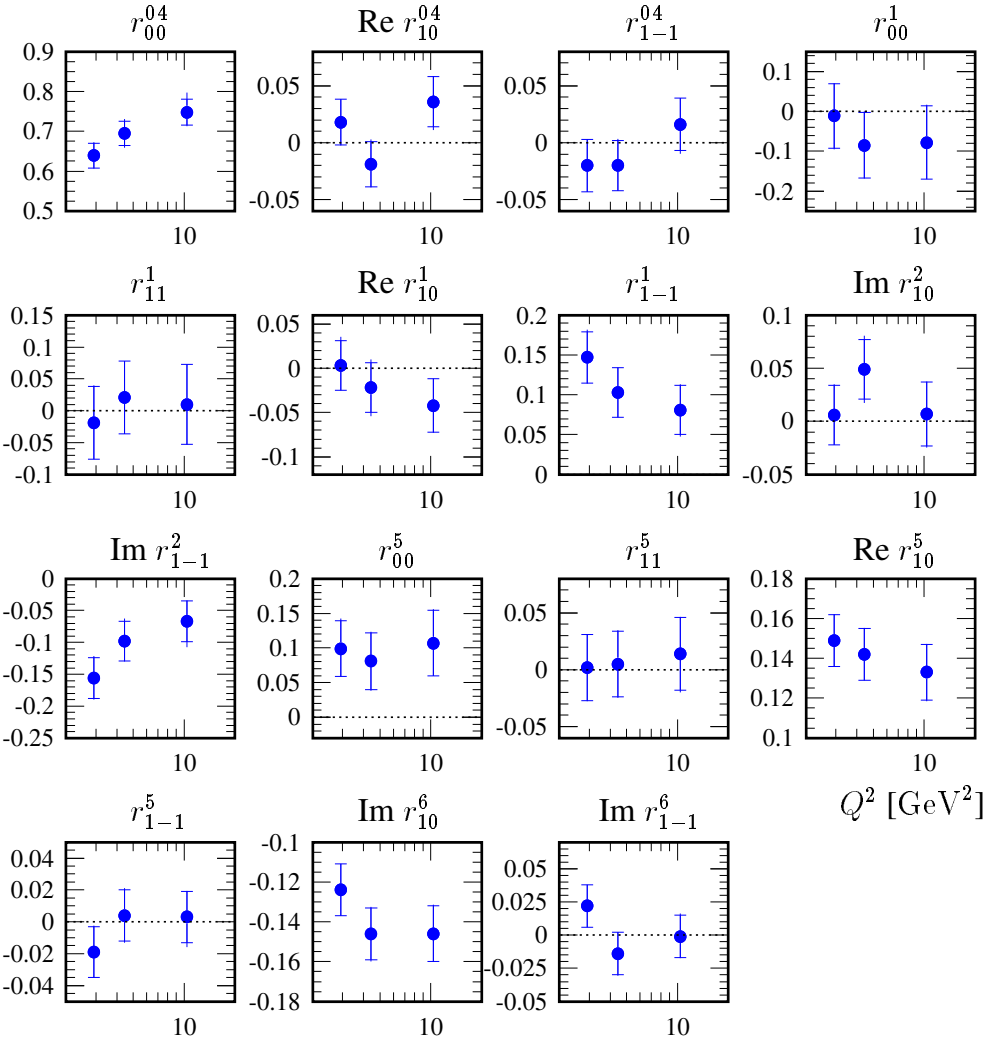
Gilman et al PL B31 (1970) 387

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

15-Parameter Helicity-Angle Fit (I)

H1 hep-ex/9902019

submitted to Eur.Phys. C

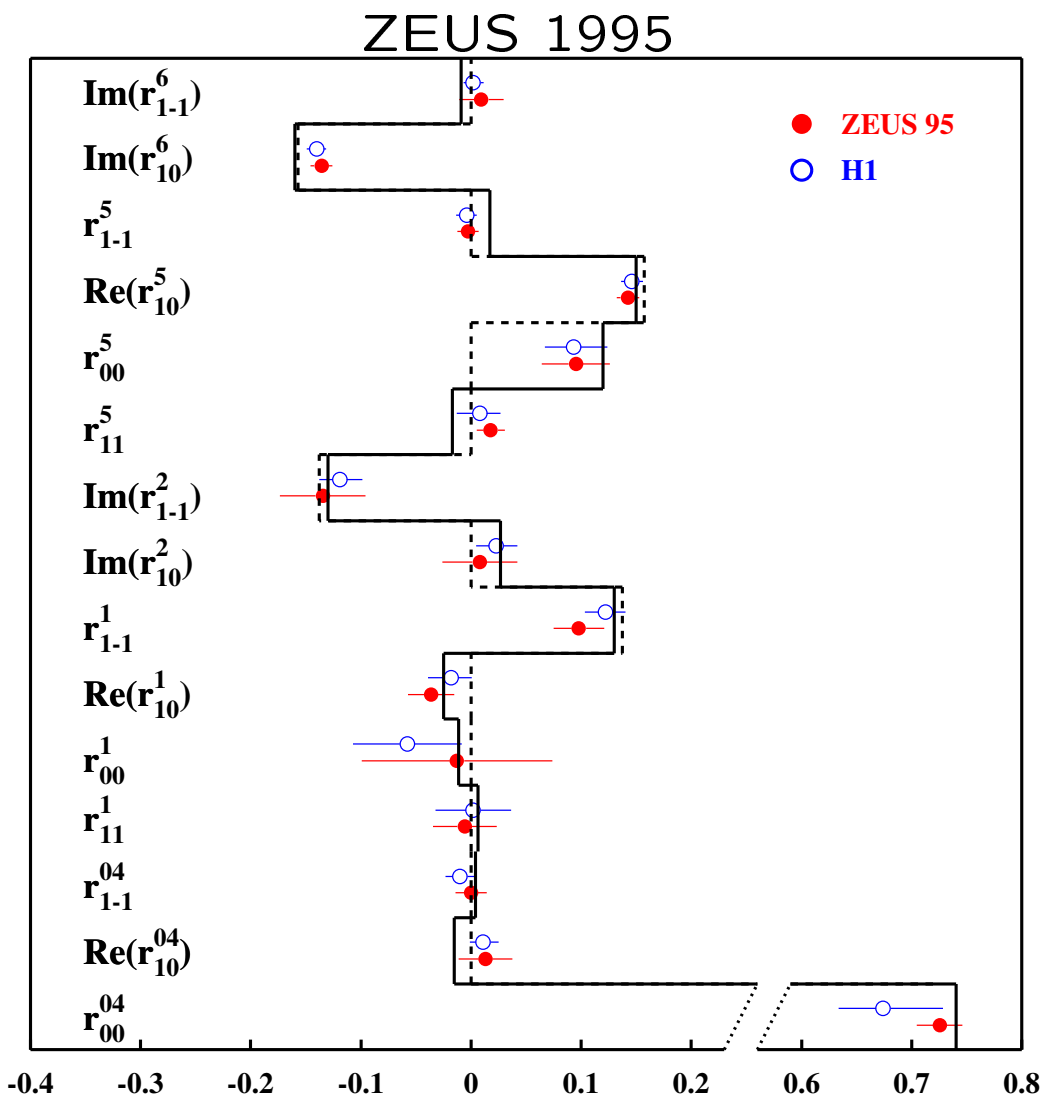


Dotted lines are SCHC values

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

15-Parameter Helicity-Angle Fit (II)

ZEUS ICHEP Abstract 792/792b

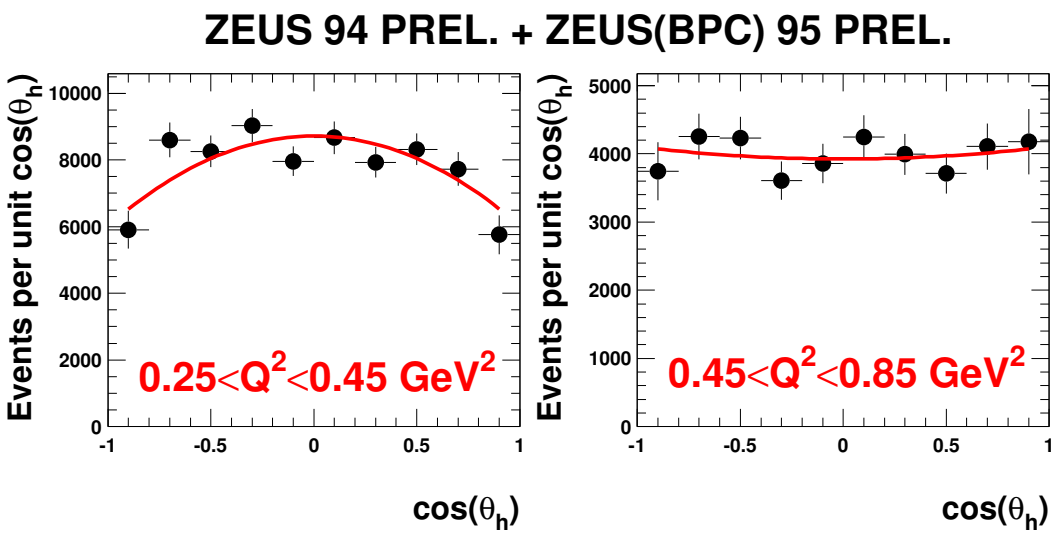


$\Rightarrow$ Agreement with Ivanov and Kirschner (Phys. Rev. D58 (1998) 114026)

$\Rightarrow$ Results also obtained for low Q^2 and ϕ

ρ^0 Electroproduction at HERA

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

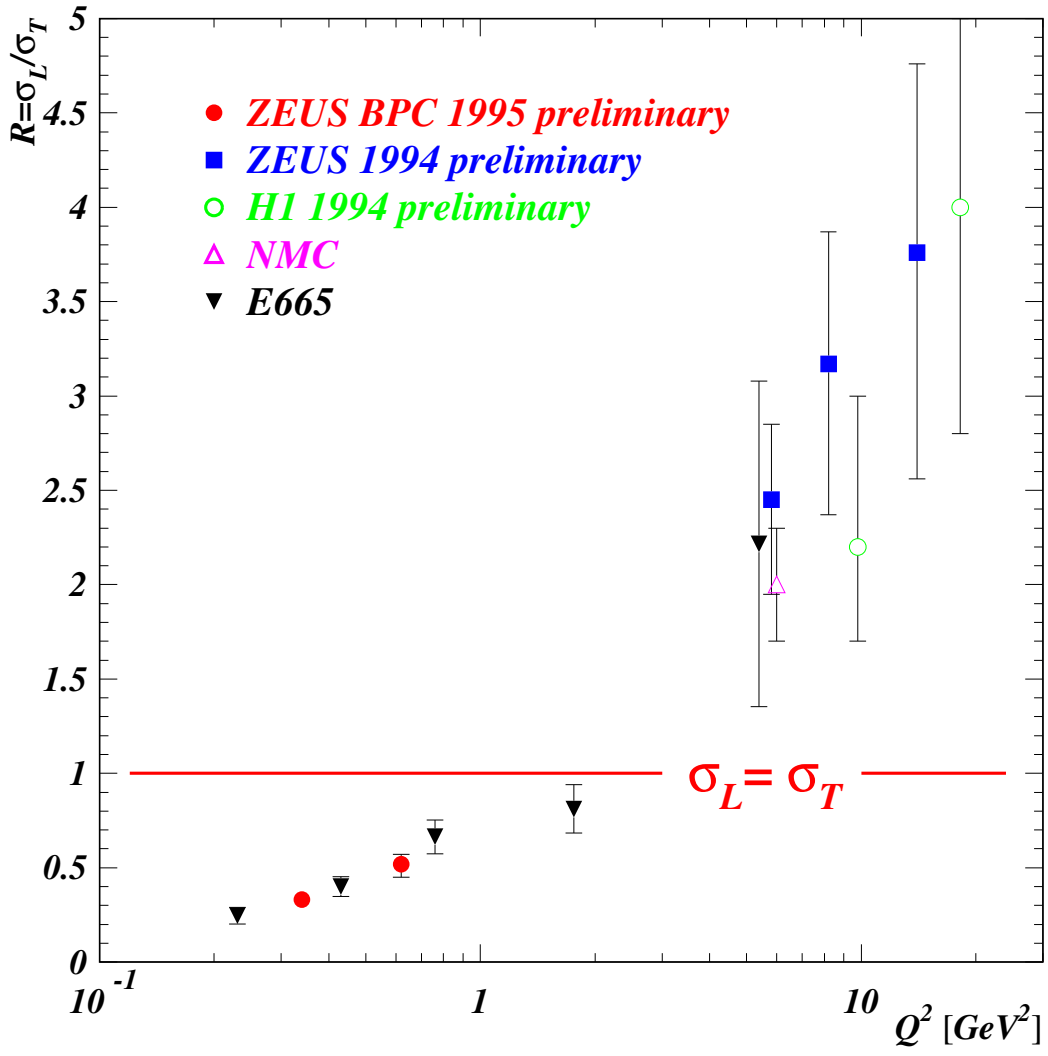


Q^2 (GeV^2)	r_{00}^{04}
0.34	0.24 ±0.02(stat)
0.62	0.34 ±0.03(stat)
5.8	$0.71^{+0.03}_{-0.04}$(stat)$^{+0.01}_{-0.01}$(sys)
8.2	$0.76^{+0.04}_{-0.04}$(stat)$^{+0.00}_{-0.02}$(sys)
14	$0.79^{+0.04}_{-0.05}$(stat)$^{+0.02}_{-0.01}$(sys)

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

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

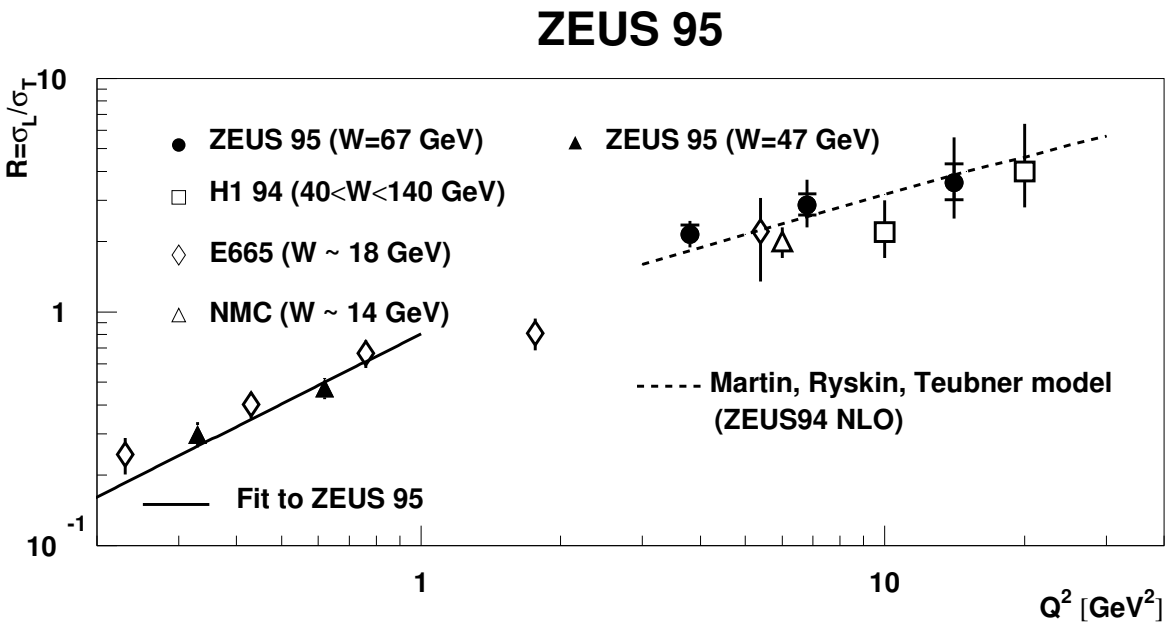
Δ now known to be small !

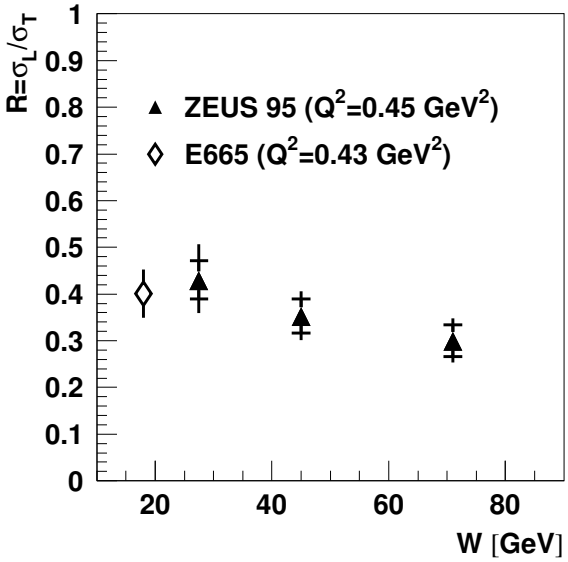


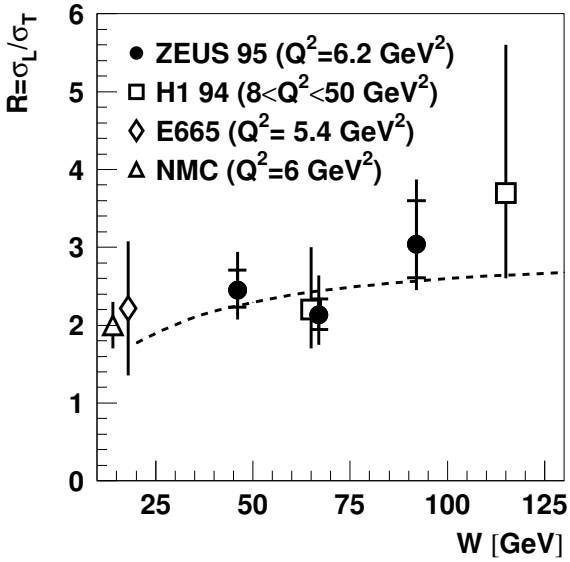
$\Rightarrow$ σ_L increases and becomes dominant

R vs Q^2 and W for ρ^0

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



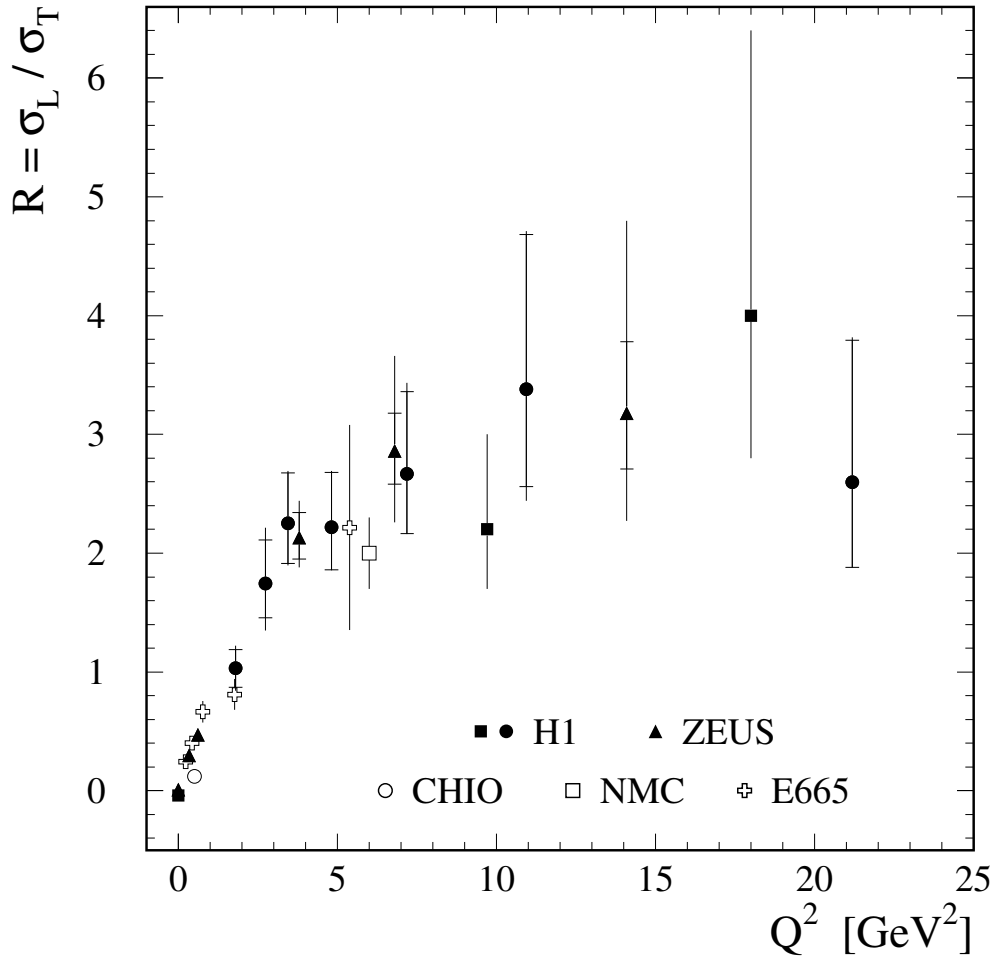




$\Rightarrow$ Do σ_T and σ_L have similar W dependence ?

R vs Q^2 (H1 DIS ρ^0)

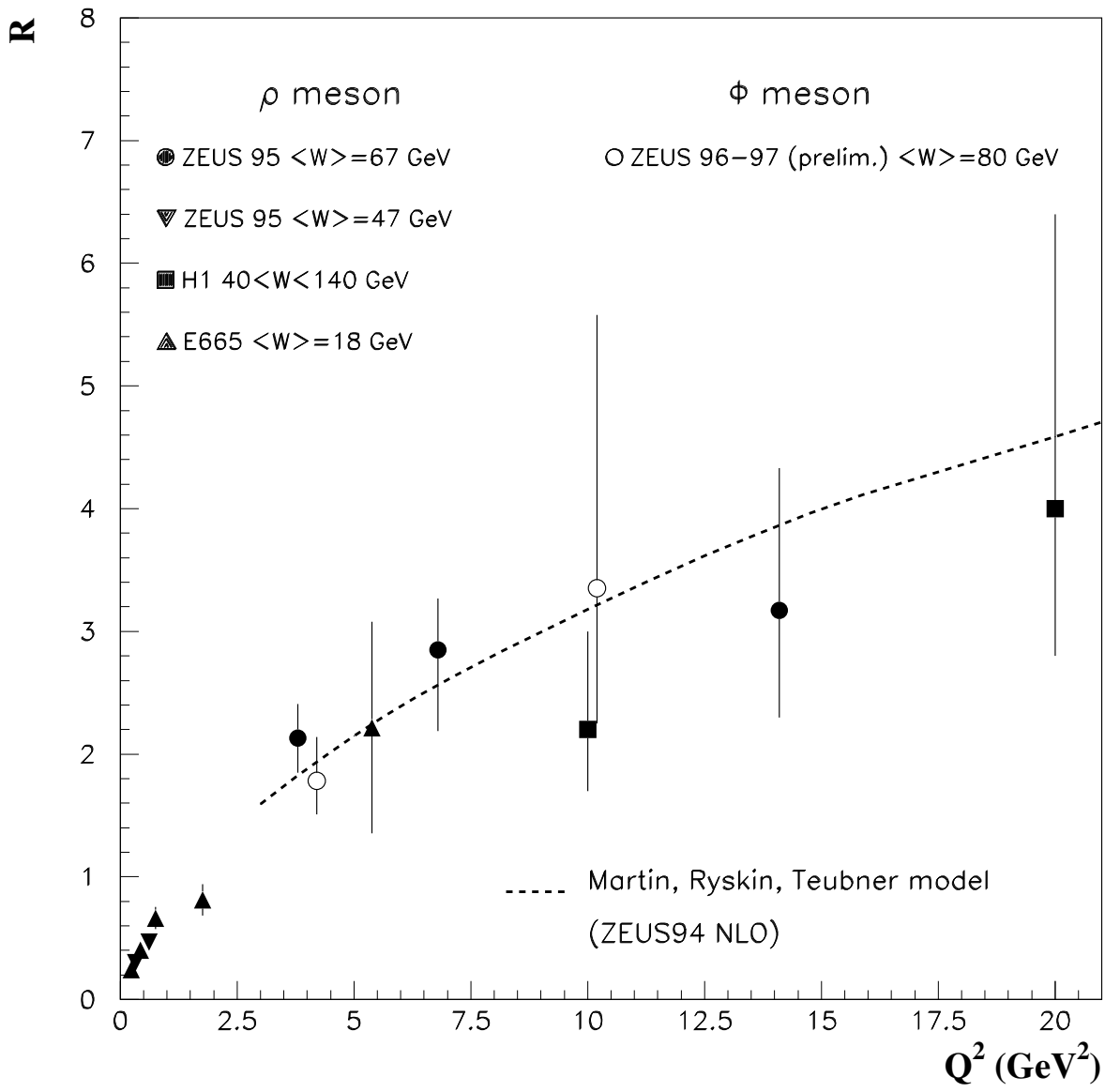
H1 hep-ex/9902019



$\Rightarrow$ σ_L/σ_T levelling off ??

R vs Q^2 (ZEUS DIS ϕ prel.)

ZEUS ICHEP Abstract 793

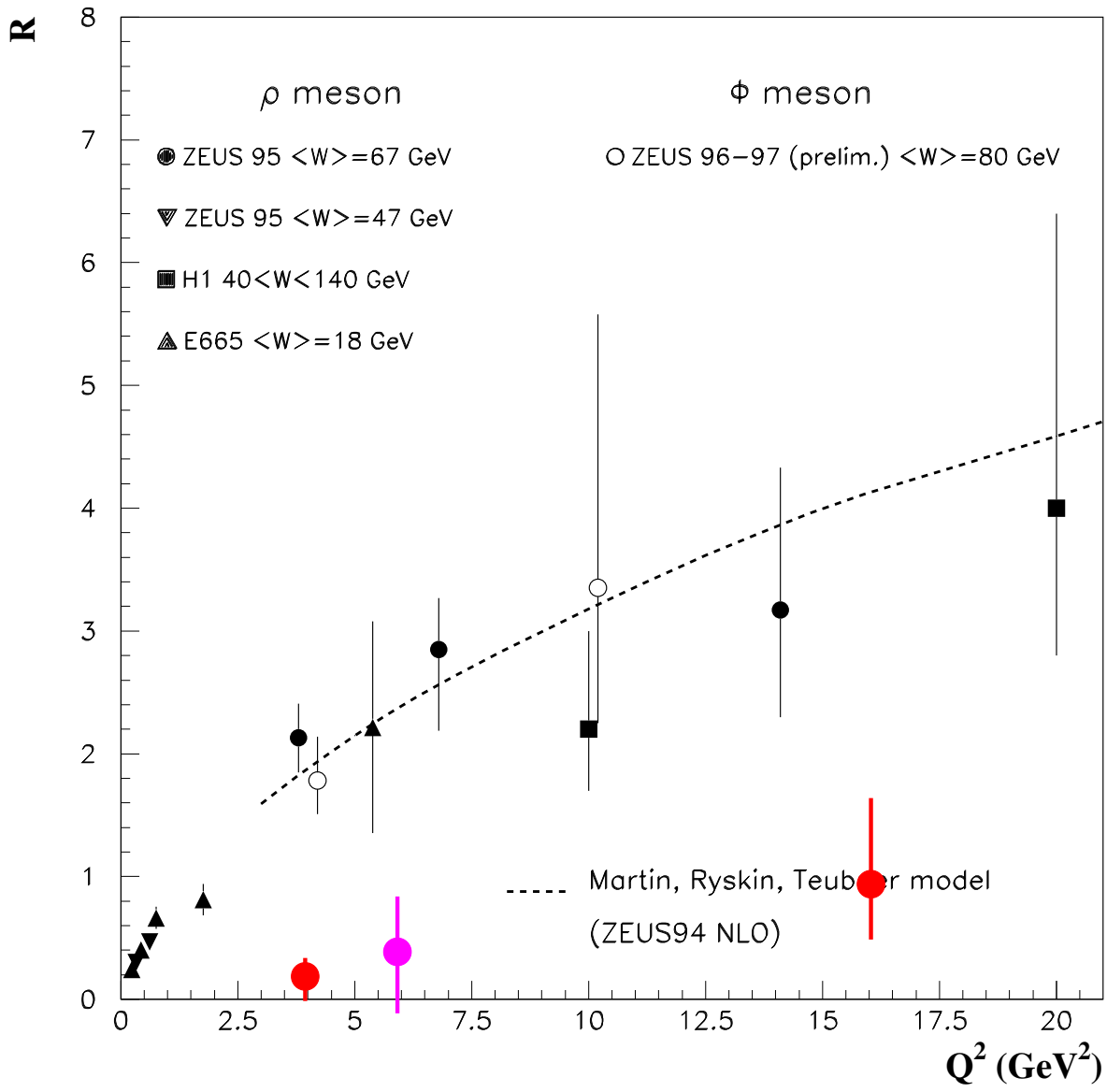


$\Rightarrow$ ϕ behaves like ρ^0 !!

R vs Q^2 for J/ψ

H1 hep-ex/9903008

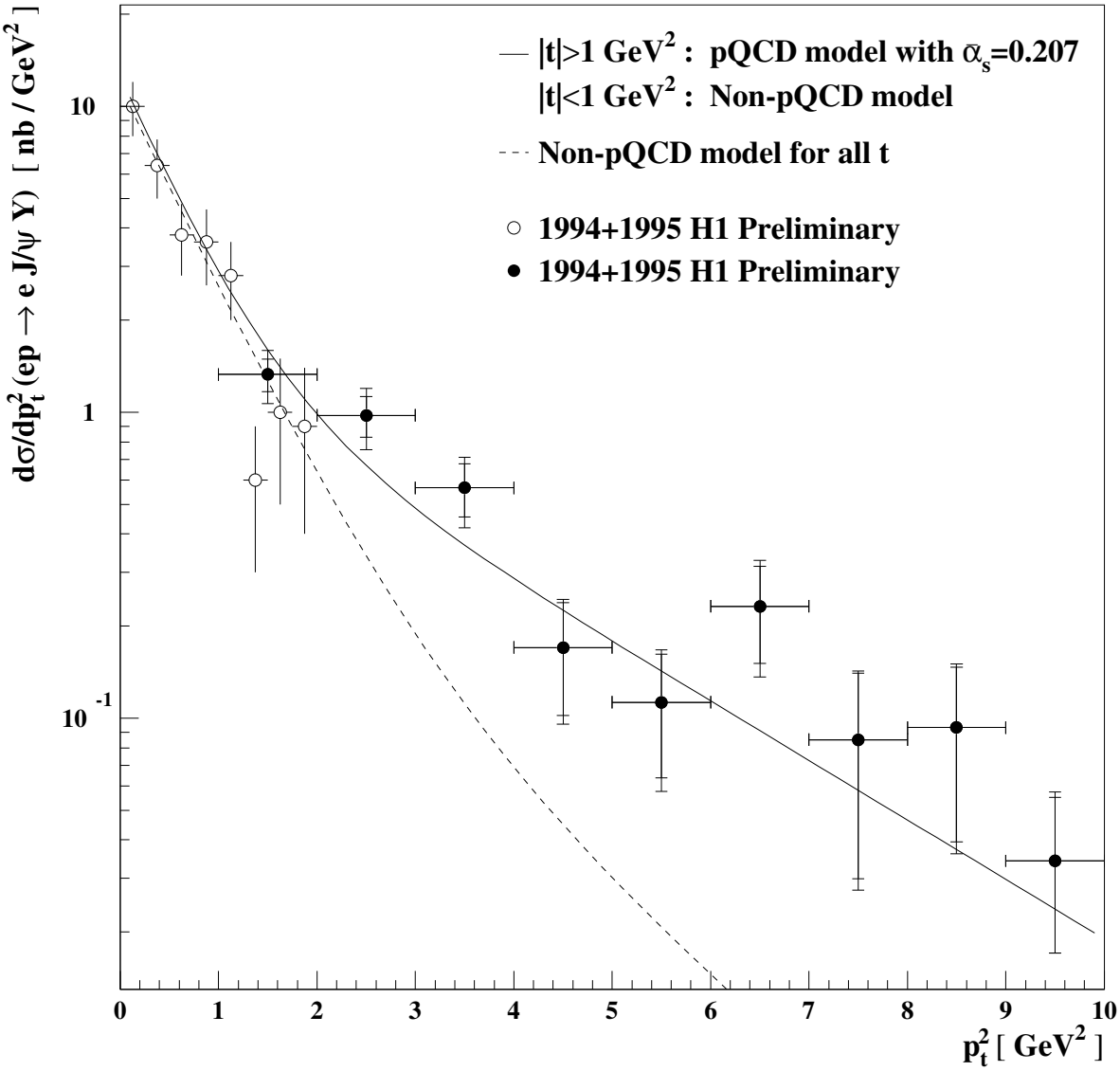
ZEUS Eur. Phys. J. C6 (1999) 603



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

J/ψ Photoproduction at High $|t|$

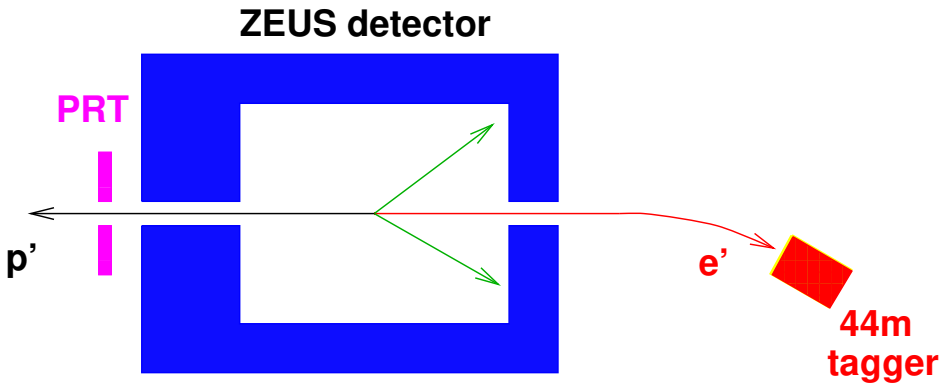
L.West, LISHEP'98



$\Rightarrow$ pQCD may work at high $|t|$!!

Bartels et al, PL B375 (1996) 301 (BFKL approach)

ρ^0 Photoproduction Tagging at $W \simeq$ 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}

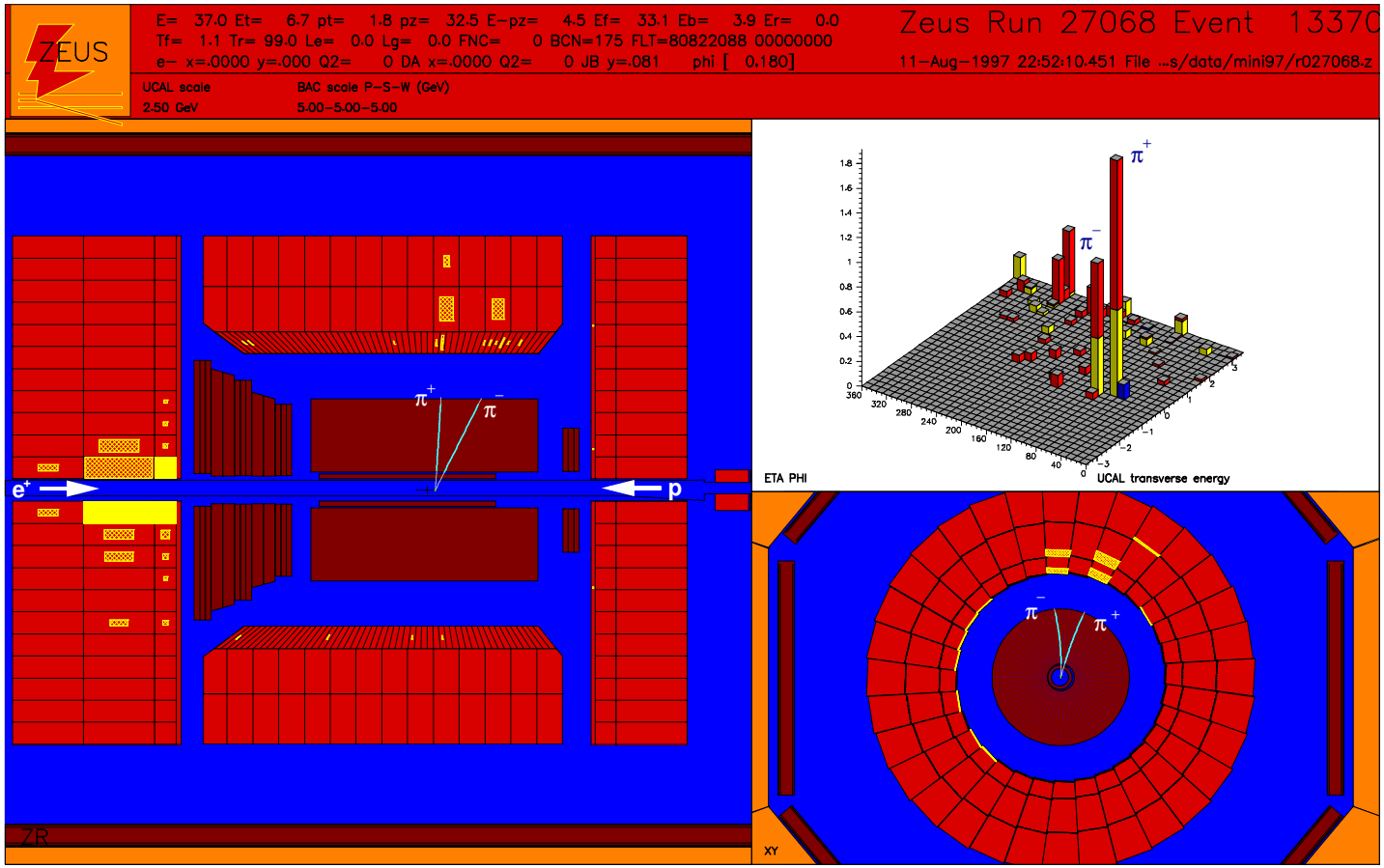
Elastic kinematic limit $\longrightarrow$ $2 \cdot 10^{-8} < |t| < 3$ GeV^2

ZEUS 1996/97 preliminary

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

$1 < |t| < 9$ GeV^2 (bin limits)

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

Phenomenology

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

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

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

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

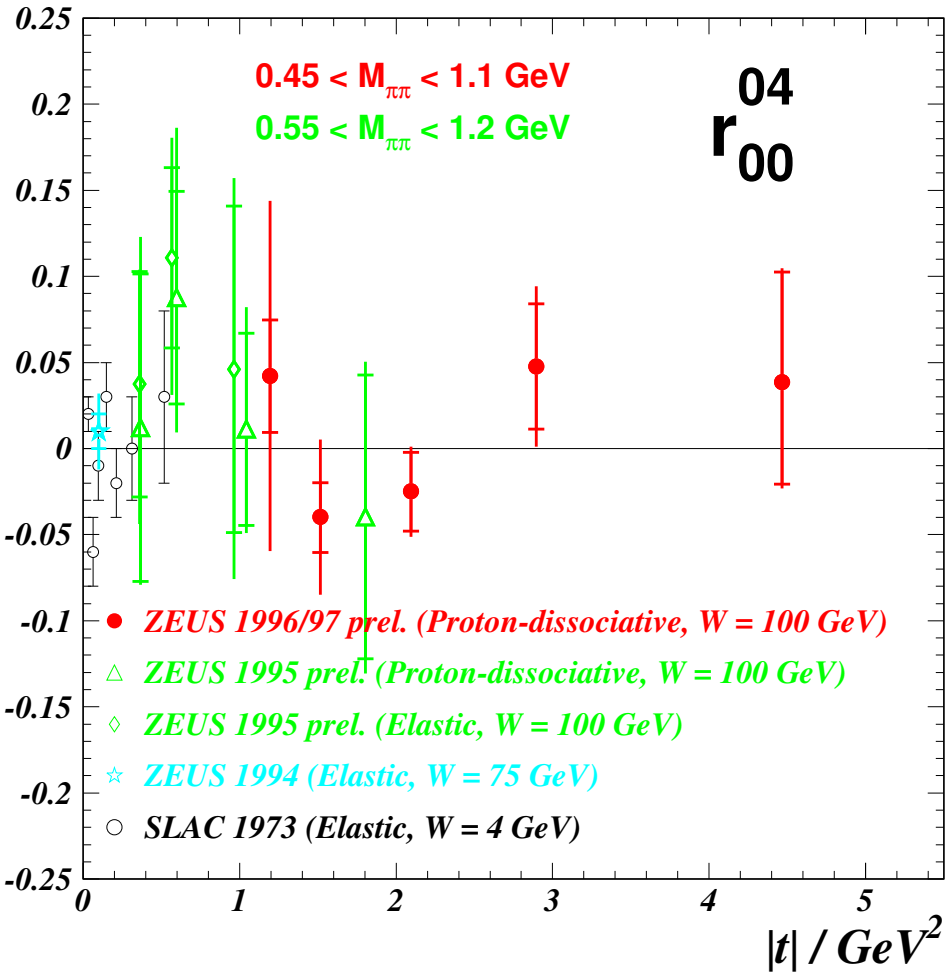
At low Q^2, Φ_h poorly measured, so integrate over it:

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

Helicity Analysis (I)

$$r_{00}^{04} \simeq \frac{T_{01}^2}{T_{01}^2 + T_{11}^2 + T_{1-1}^2}$$

r_{00}^{04} *measures the degree of longitudinal polarization*

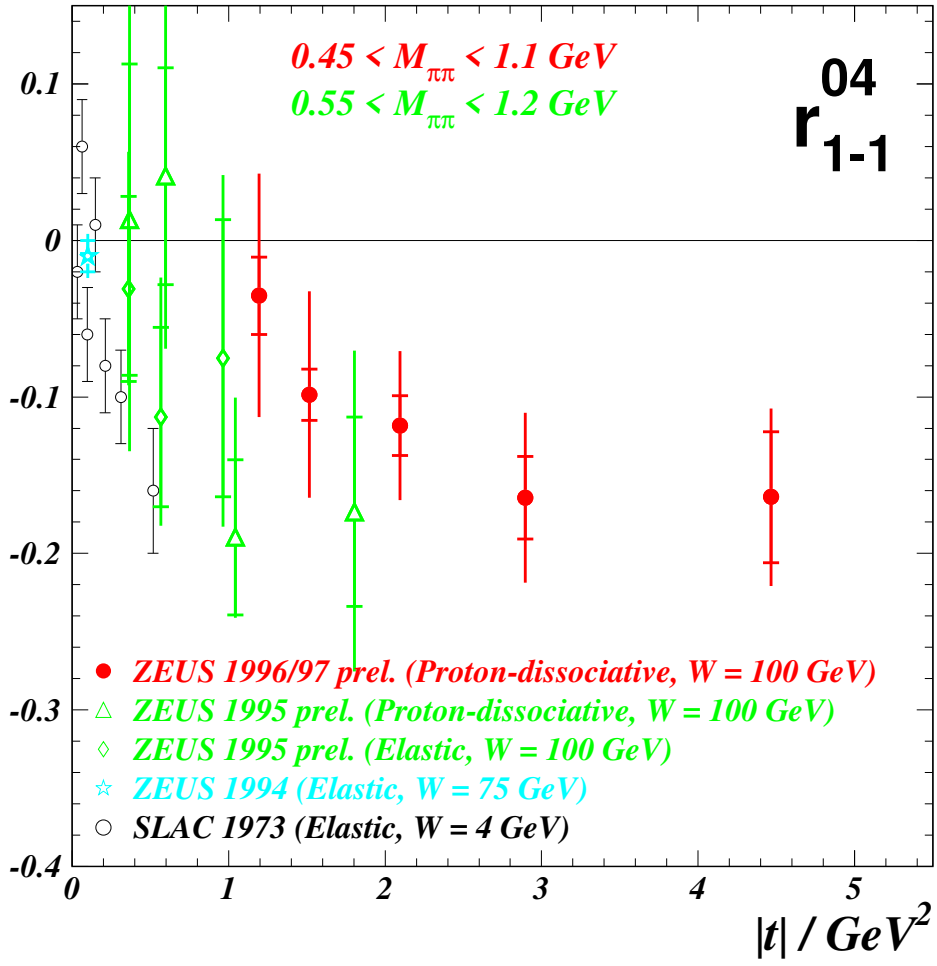


Long. pol. does *NOT* dominate at high $|t|$

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*

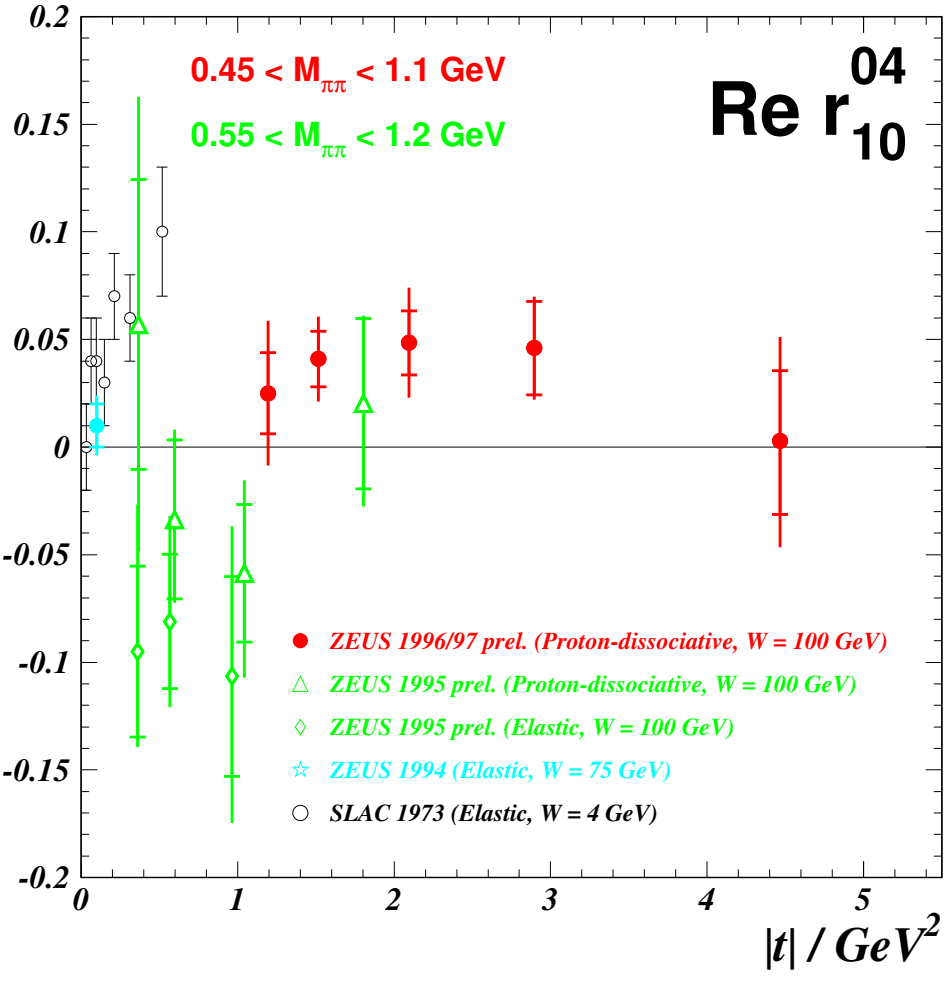


Clear double-flip contribution (But is it the ρ^0?)

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

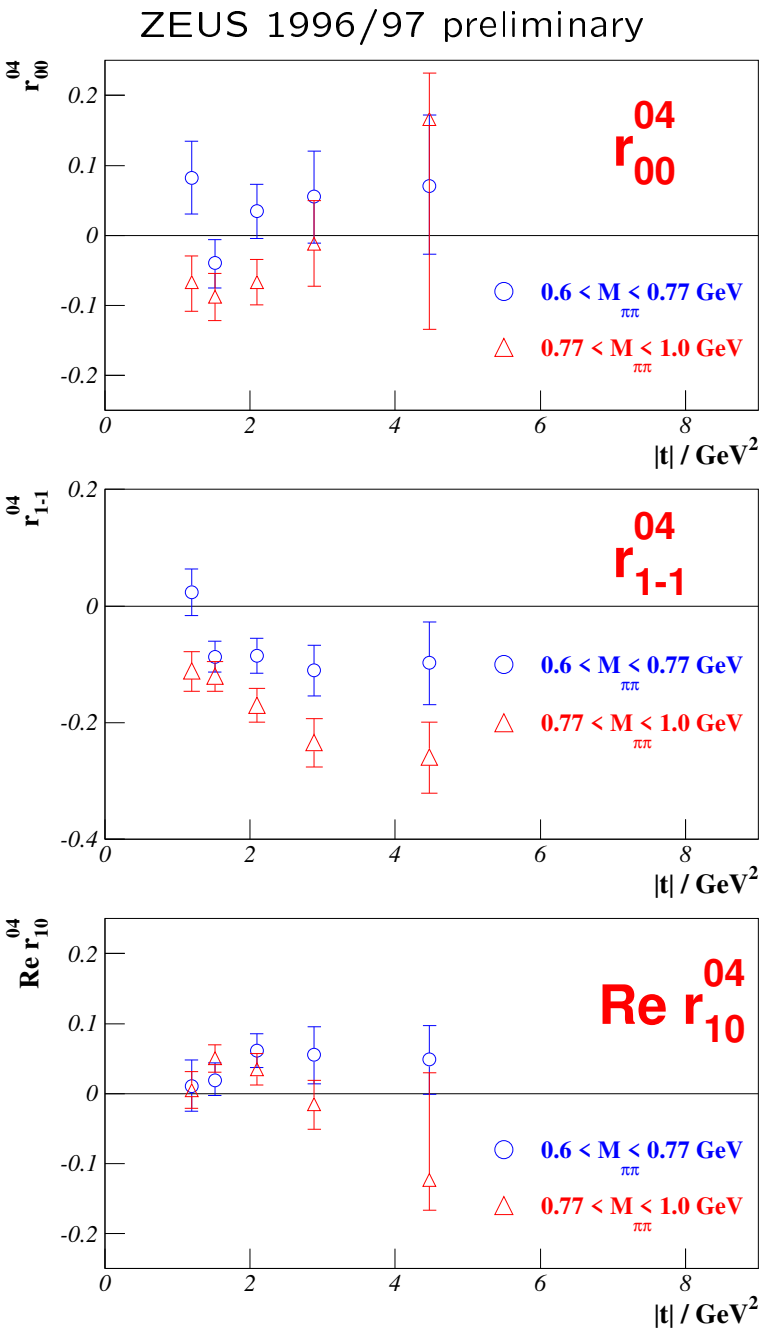


Indication of single-flip contribution (Is it the ρ^0?)

Helicity Analysis (IV)

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

Are production and decay independent??



Single-flip contribution depends on mass region !

Summary

Results presented on:

☞ Observation of Υ photoproduction

$\Rightarrow$ Rate much higher than naive LO calculation

$\Rightarrow$ Perhaps first look at ODPD's

☞ Elastic ρ^0, ϕ, J/ψ electroproduction

$\Rightarrow$ ρ^0 helicity structure (good-bye SCHC !)

$\Rightarrow$ $R = \dfrac{\sigma_L}{\sigma_T}$ versus Q^2 and W

☞ VM photoproduction at high $|t|$

$\Rightarrow$ Hard $|t|$ distribution

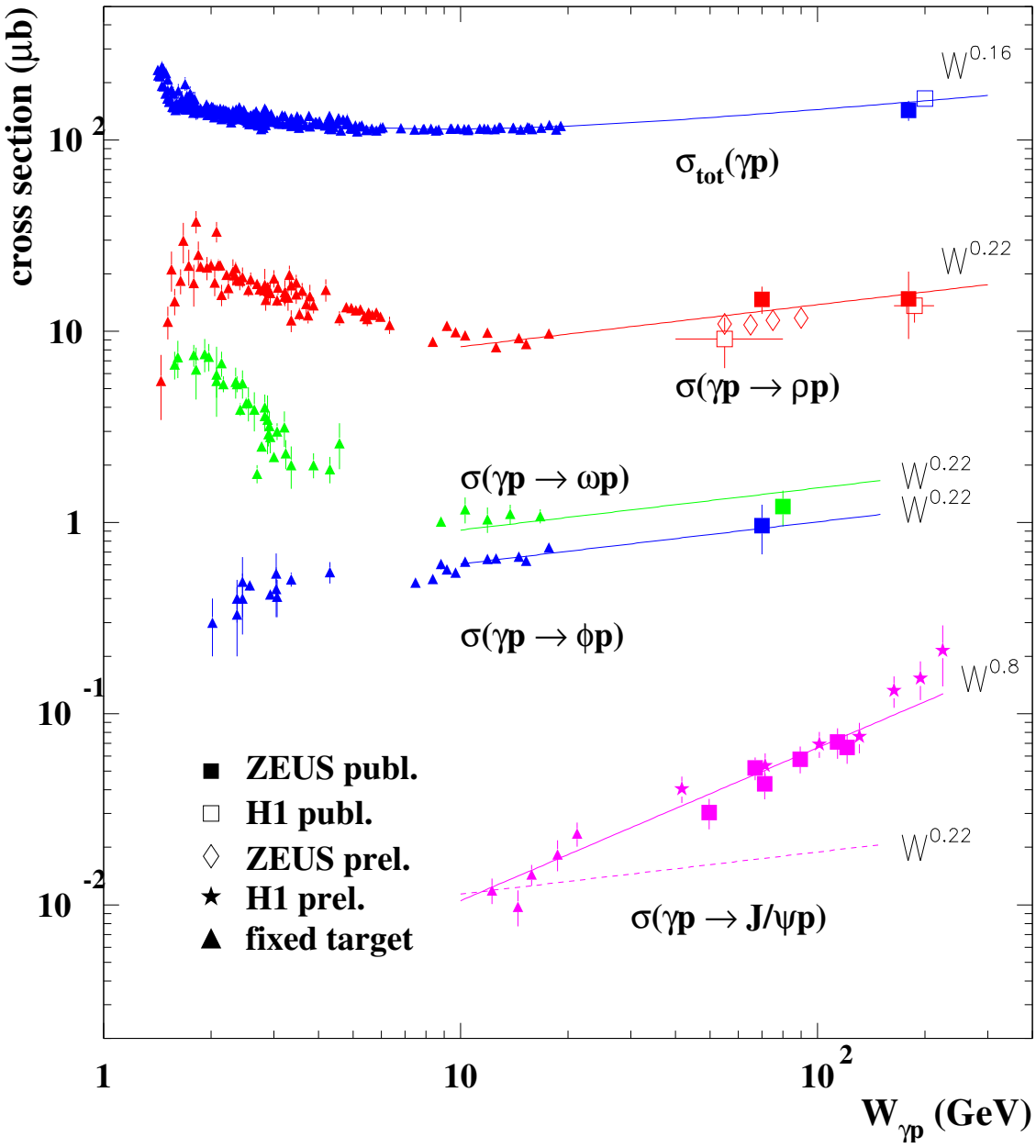
$\Rightarrow$ ρ^0 predominantly transversely polarized

$\Rightarrow$ Violation of SCHC confirmed at high W, $|t|$

Concluding Remark

These recent results are a small subset of an increasing wealth of data supporting descriptions of diffractive processes based on perturbative QCD

Elastic Vector-Meson Photoproduction Cross Sections



$\omega : \phi = 1 : 2$??

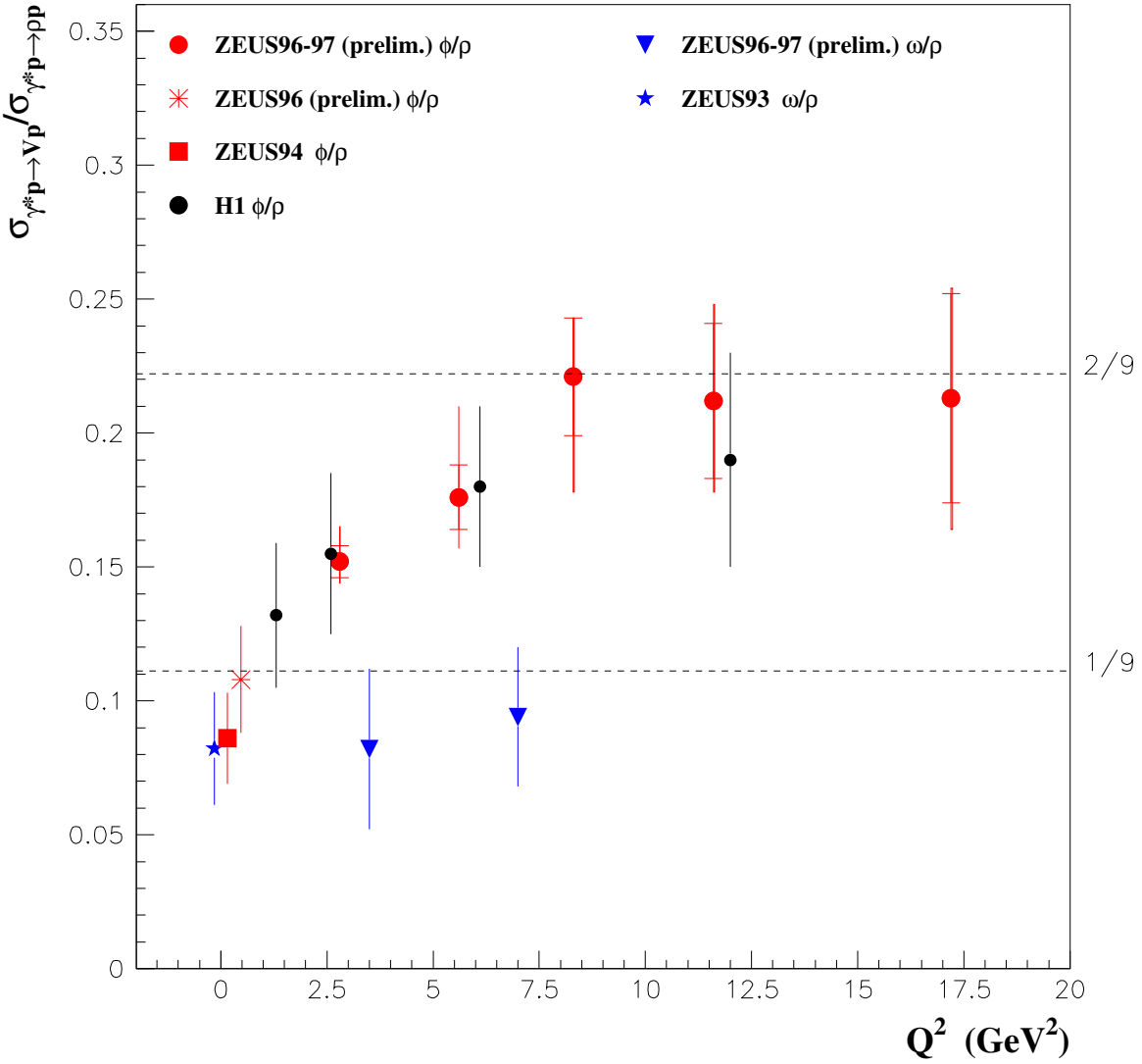
Vector Meson Production Ratios

If direct e–m coupling to quarks without form factors

$$\rho^0 \;:\; \omega \;:\; \phi \;:\; J/\psi \;:\; \Upsilon$$

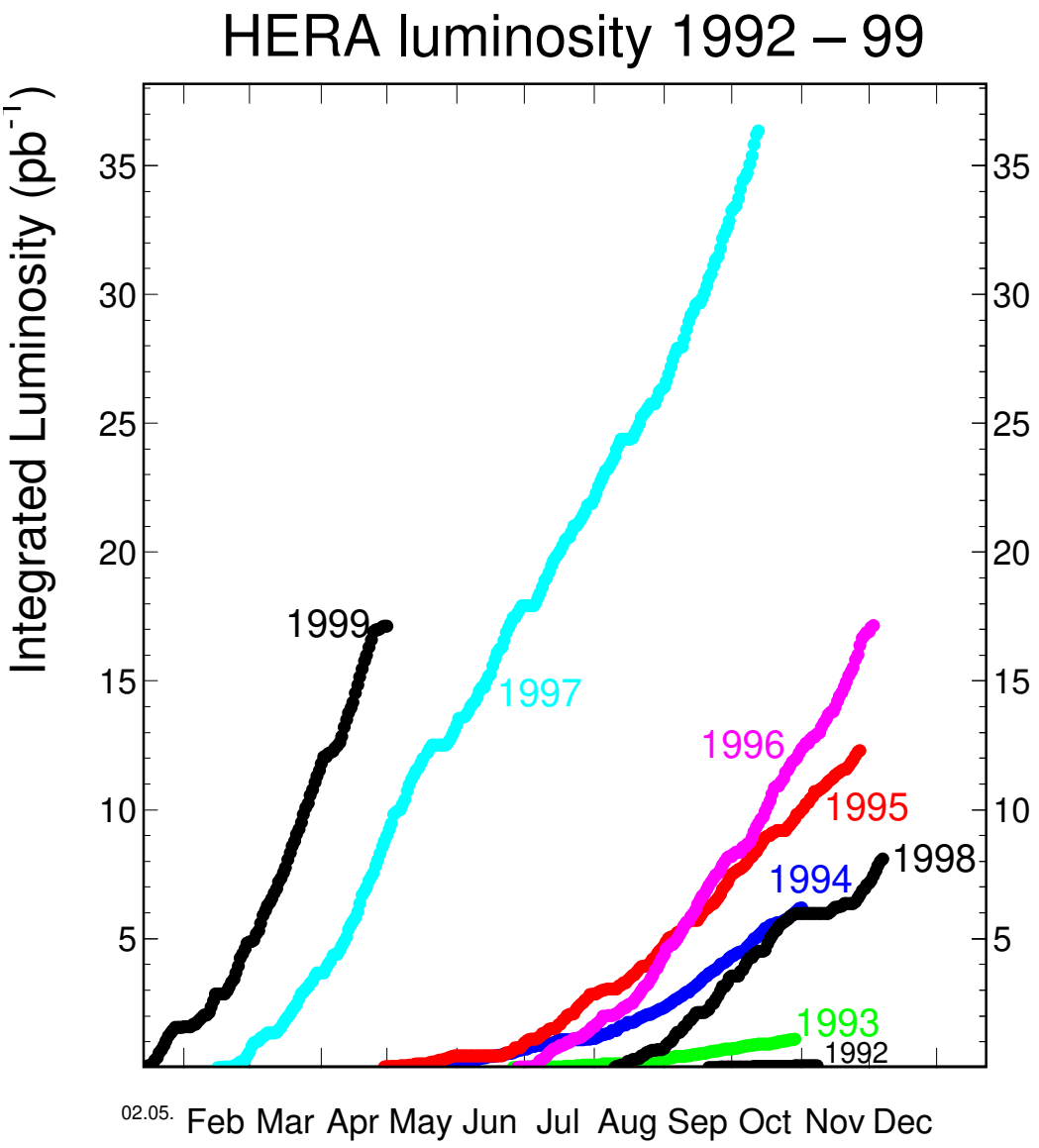
$$9 \;:\; 1 \;:\; 2 \;:\; 8 \;:\; 2$$

A.Savin, DIS'99



$\Rightarrow$ Supports idea of point-like coupling at high Q^2 !

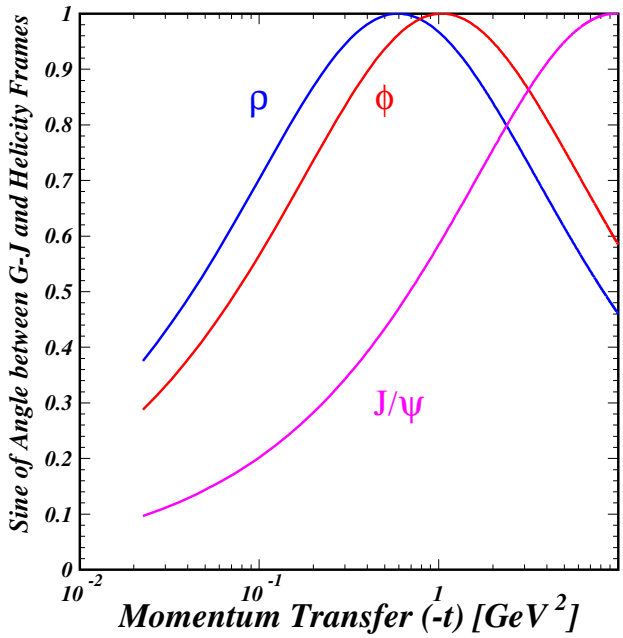
HERA Integrated Luminosity



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



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

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