European Center for Theoretical Studies *31 August 1998*

Trento, Italy

Hard Diffractive Leptoproduction of Vector Mesons

Workshop
on
Coherent QCD Processes
with
Nucleons and Nuclei

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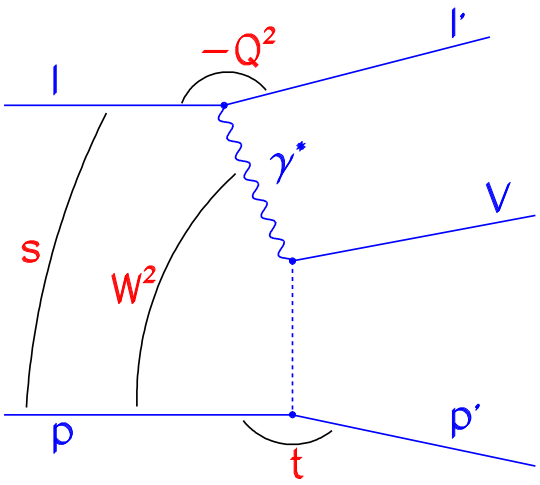
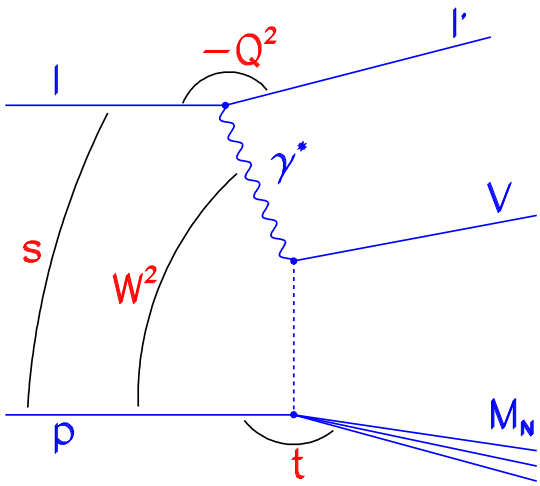
Universität Bonn

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)

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

Signatures for Hard Processes

☞ Energy Dependence of Elastic Cross Sections

⇒ Exchange of the phenomenological Pomeron

$$\frac{d\sigma}{d|t|} \propto e^{-b_0|t|}\left(\frac{s}{s_0}\right)^{2(\alpha_{I\!P}(t)-1)} \qquad \alpha_{I\!P}(t) = 1.08 + 0.25\,t$$

$$\left.\frac{d\sigma}{d|t|}\right|_{t=0} \propto \left(\frac{s}{s_0}\right)^{2(\alpha_{I\!P}(0)-1)} \propto W^{4\epsilon} = W^{0.32}$$

⇒ Exchange of a gluon ladder

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

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

☞ Pointlike couplings; small-size $q\bar{q}$ configurations

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

⇒ $b \propto R_{\mathrm{p}}^2 + R_{\mathrm{VM}}^2$ (Elastic)

⇒ Only longitudinally polarized configurations pointlike !!

☞ Absence of ρ^0 mass spectrum skewing

Skewing is interesting ($\sigma_{\pi p}^{tot}$?), but not due to hard process

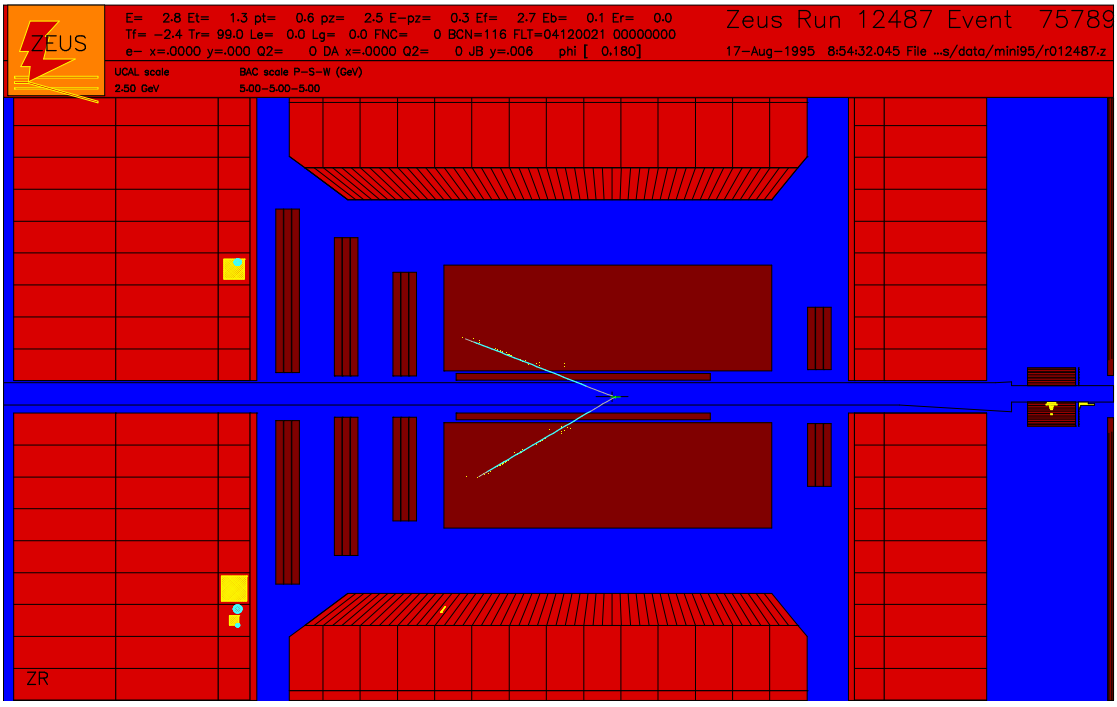
☞ Absence of shrinkage

$\alpha'_{I\!P} > 0$? (Gribov, JETP Lett. 41 (1961) 667)

Diffractive Production of ρ^0 Mesons

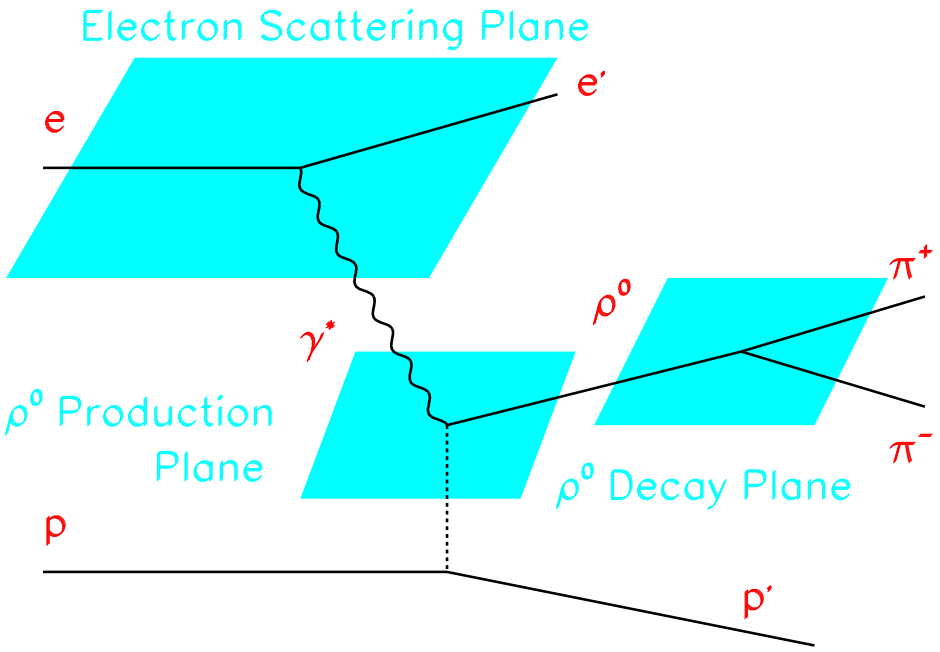
ZEUS: hep-ex/9808020

(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

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^+

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

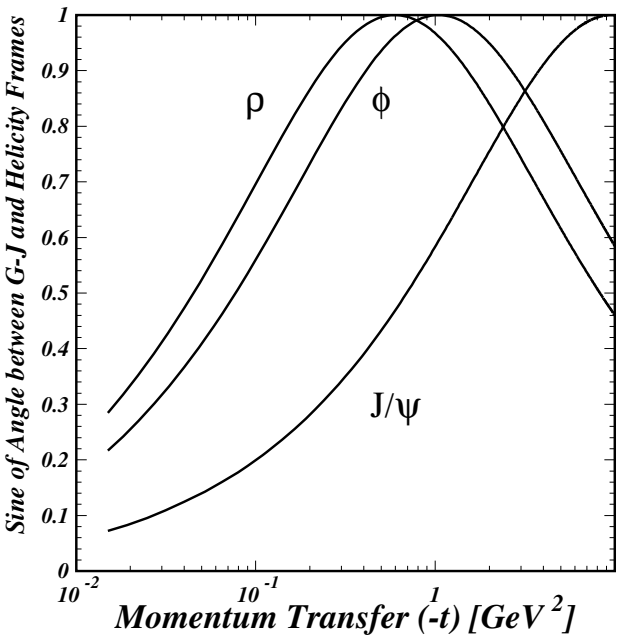
$$r^{\alpha}_{ik} = \begin{cases} \dfrac{\rho^{\alpha}_{ik}}{1+\epsilon R} & \alpha = 1-3 \text{ (Trans.)} \\ \dfrac{\sqrt{R}\,\rho^{\alpha}_{ik}}{1+\epsilon R} & \alpha = 5-8 \text{ (L/T int.)} \end{cases}$$

Constraints from hermiticity, parity conservation

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)

3-D Decay-Angle Distribution

(15 linearly independent parameters)

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

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

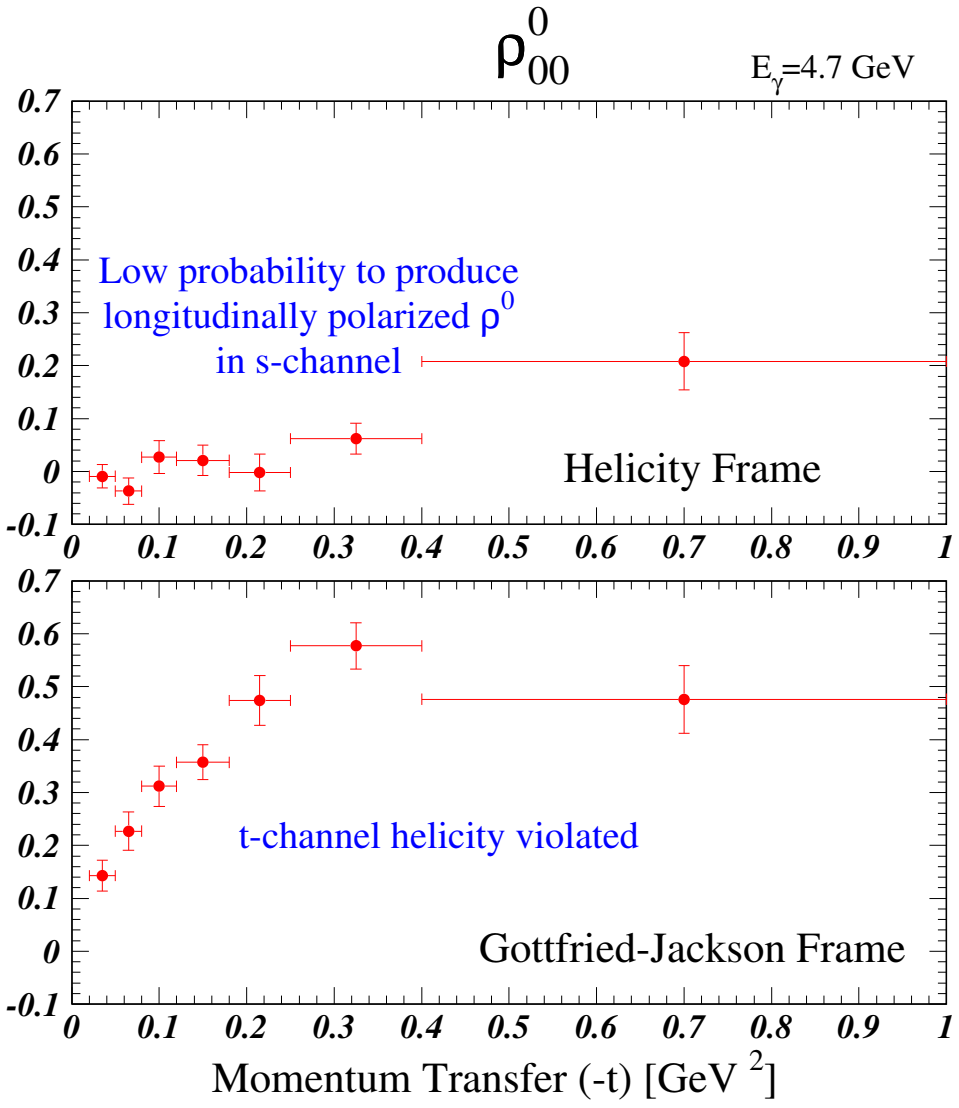
$$-\varepsilon\cos 2\Phi_h(\ r^1_{11}\sin^2\theta_h + r^1_{00}\cos^2\theta_h$$
$$-\sqrt{2}\,\mathrm{Re}\, r^1_{10}\ \sin 2\theta_h\cos\phi_h$$
$$-r^1_{1-1}\sin^2\theta_h\cos 2\phi_h\ )$$
$$-\varepsilon\sin 2\Phi_h(\ \sqrt{2}\,\mathrm{Im}\, r^2_{10}\ \sin 2\theta_h\sin\phi_h$$
$$+\mathrm{Im}\, r^2_{1-1}\sin^2\theta_h\sin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

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

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
- 3k $\rho^0 \to \pi^+\pi^-$ reconstructed in bubble chamber



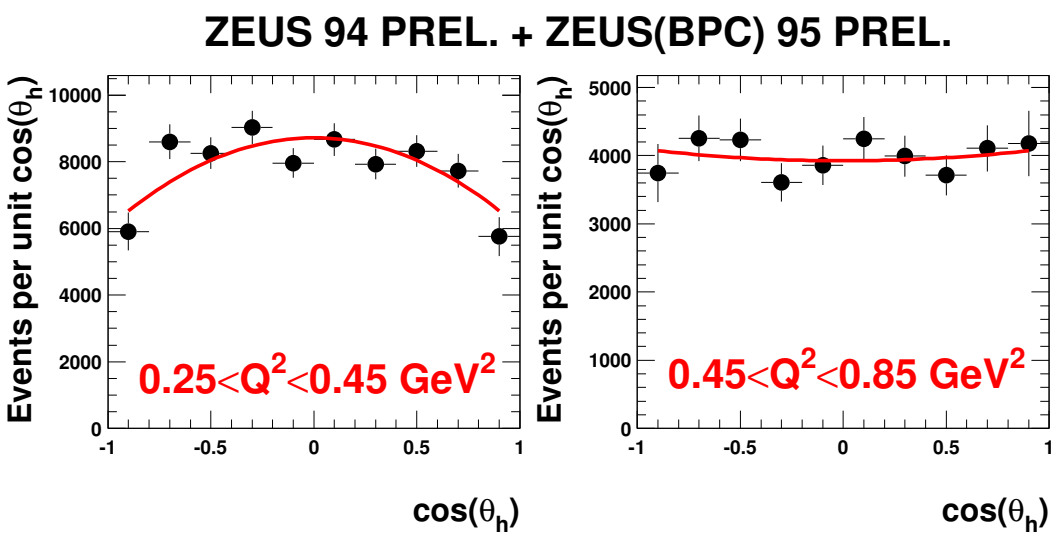
Inconsistent with t-channel exchange of spin 0 object

Gilman et al PL B31 (1970) 387

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

ρ^0 Electroproduction at HERA

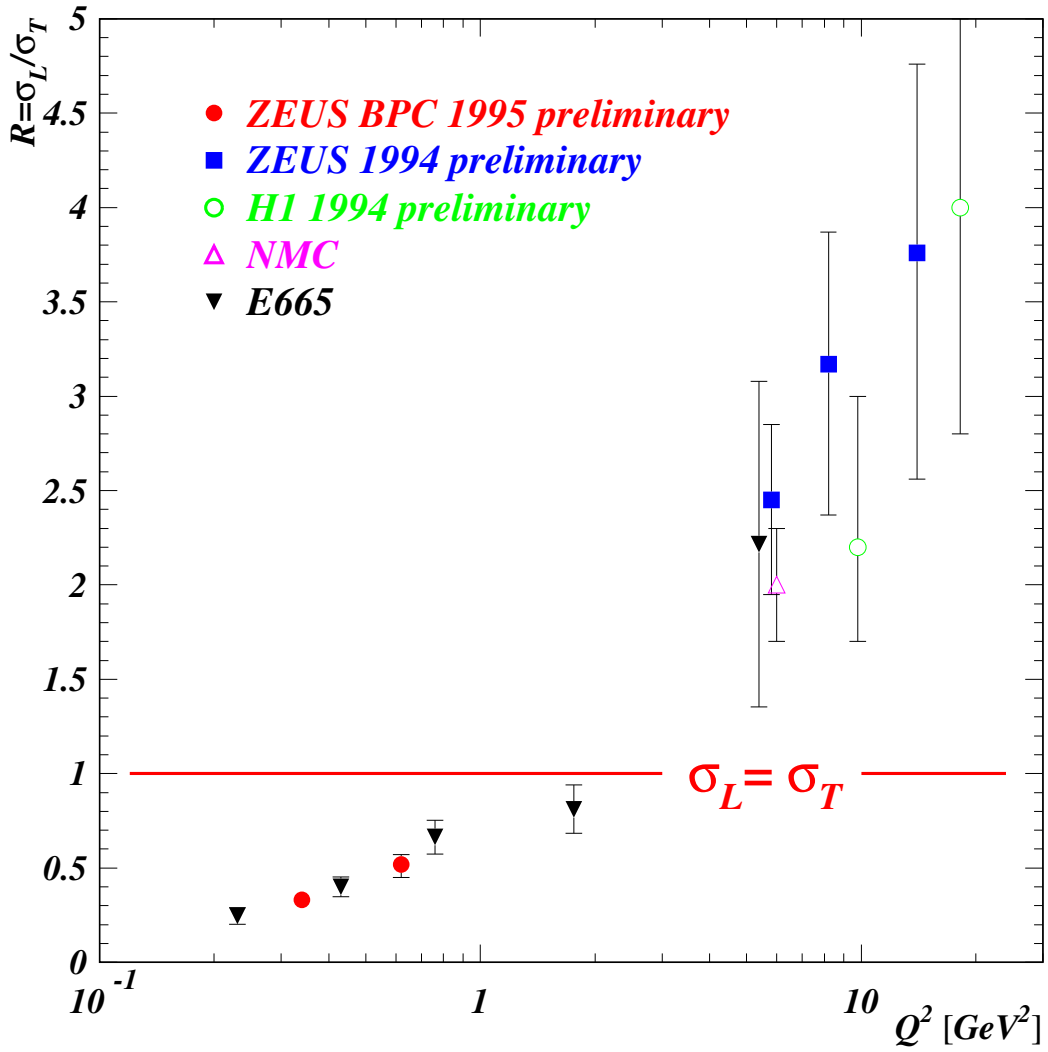
$$\frac{dN}{d\cos\theta_h} \propto 1 - r_{00}^{04} + (3r_{00}^{04} - 1)\cos^2\theta_h$$



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

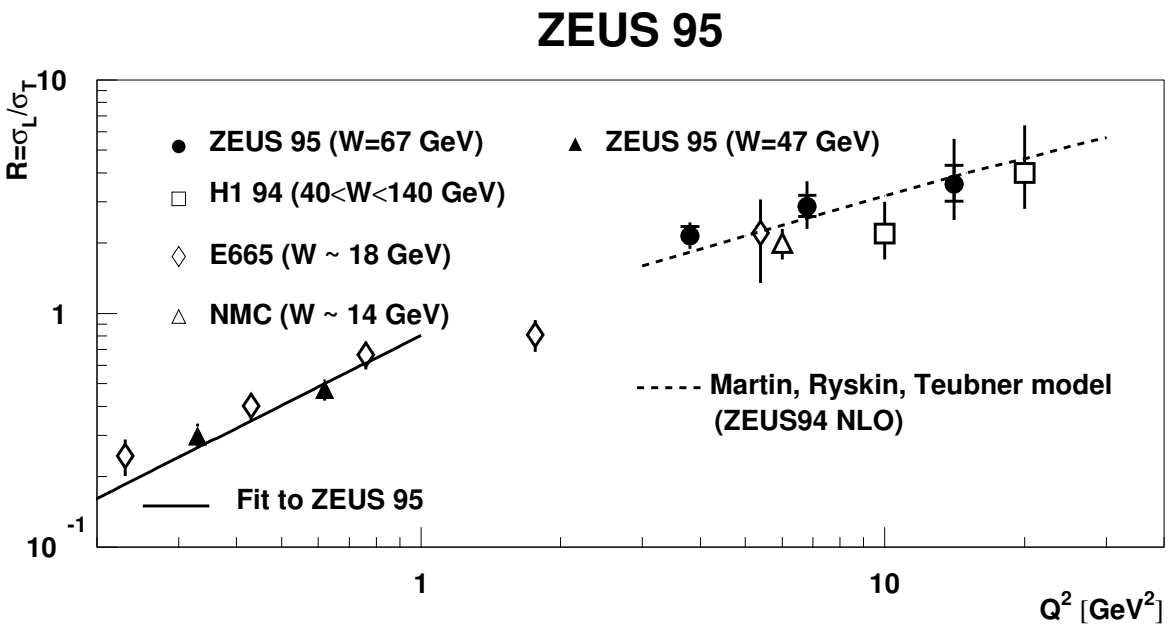
Assuming SCHC: $R = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}$

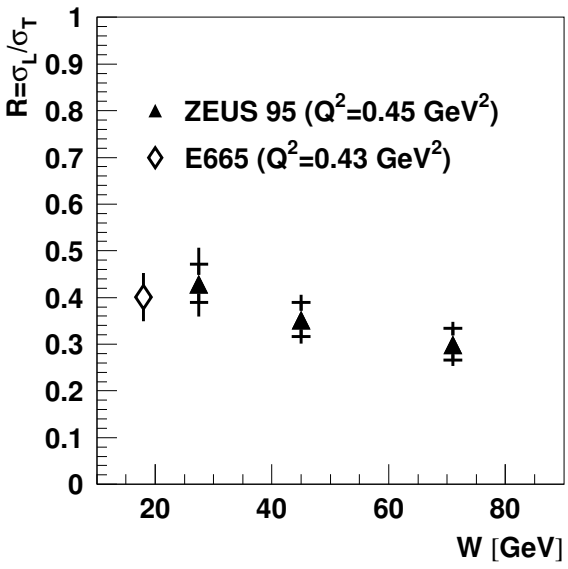


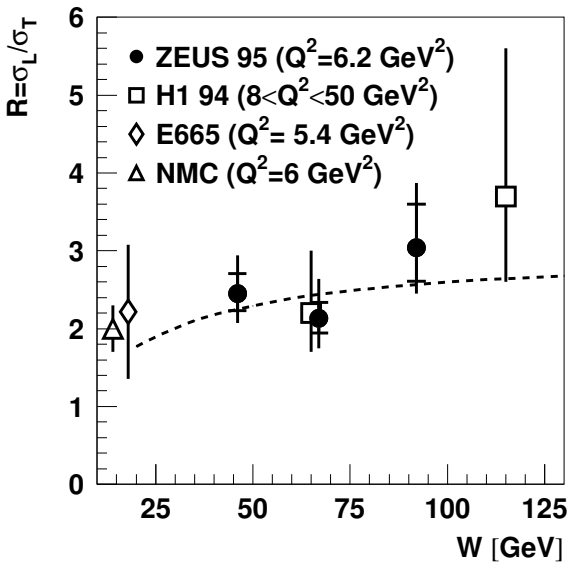
$\Rightarrow$ σ_L increases and becomes dominant

R vs Q^2 and W for ρ^0

ZEUS: hep-ex/9808020



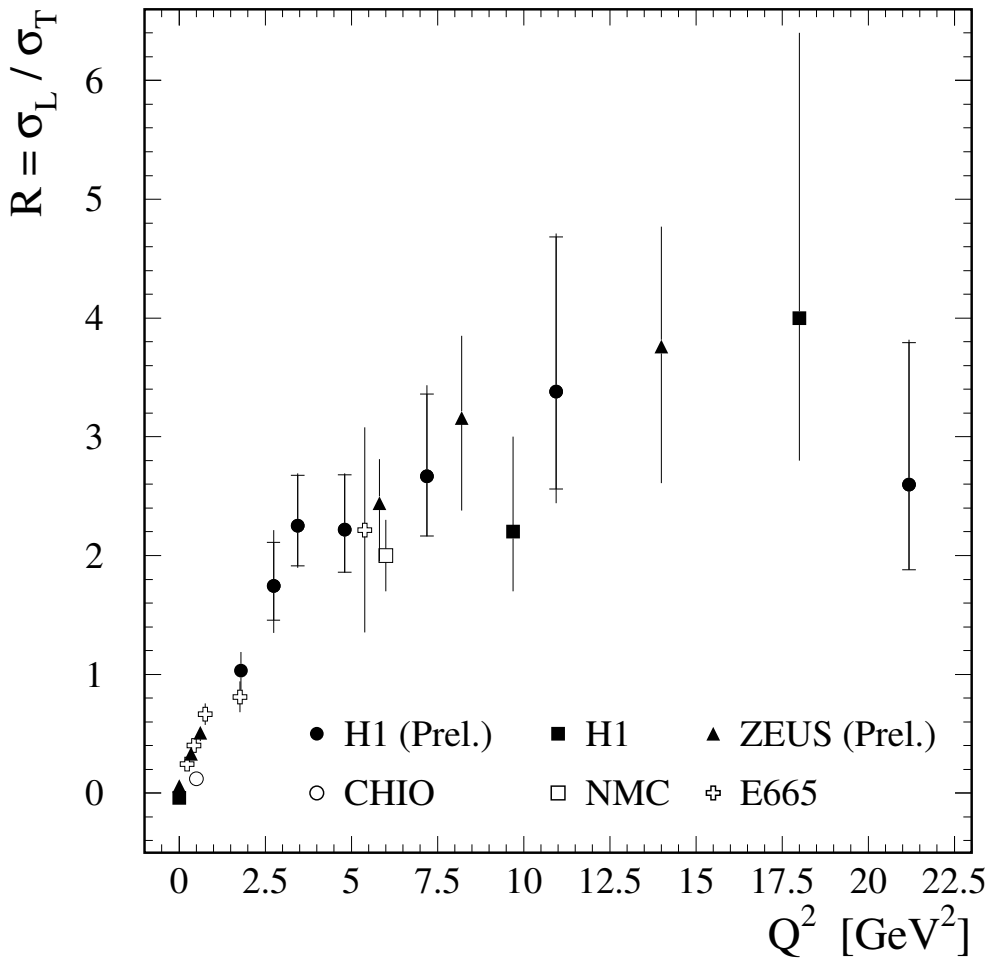




$\Rightarrow$ Do σ_T and σ_L have similar W dependence ?

R vs Q^2 (H1 DIS ρ^0 prel.)

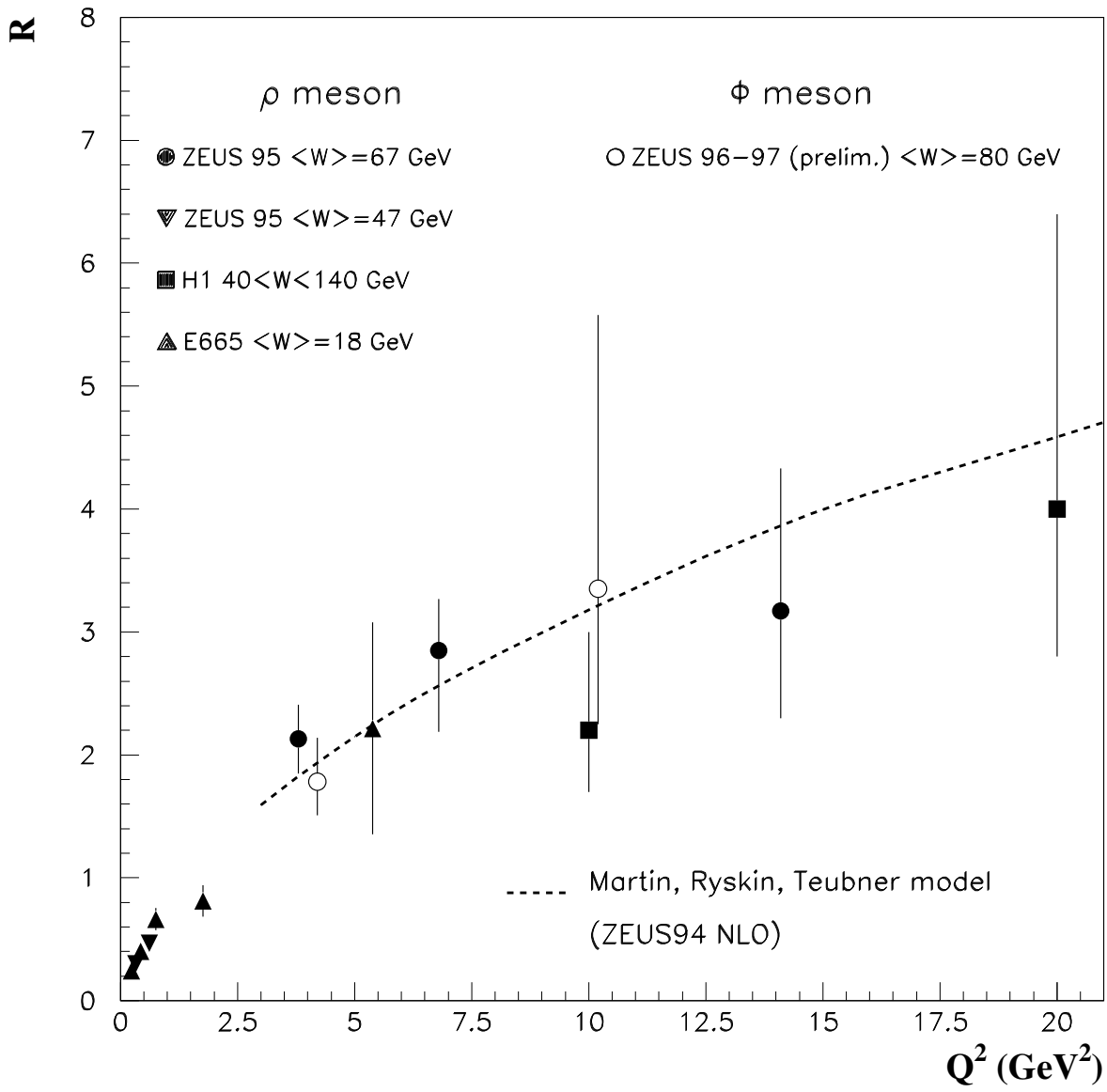
H1 ICHEP Abstract 564



$\Rightarrow$ σ_L/σ_T levelling off ??

R vs Q^2 (ZEUS DIS ϕ prel.)

ZEUS ICHEP Abstract 793

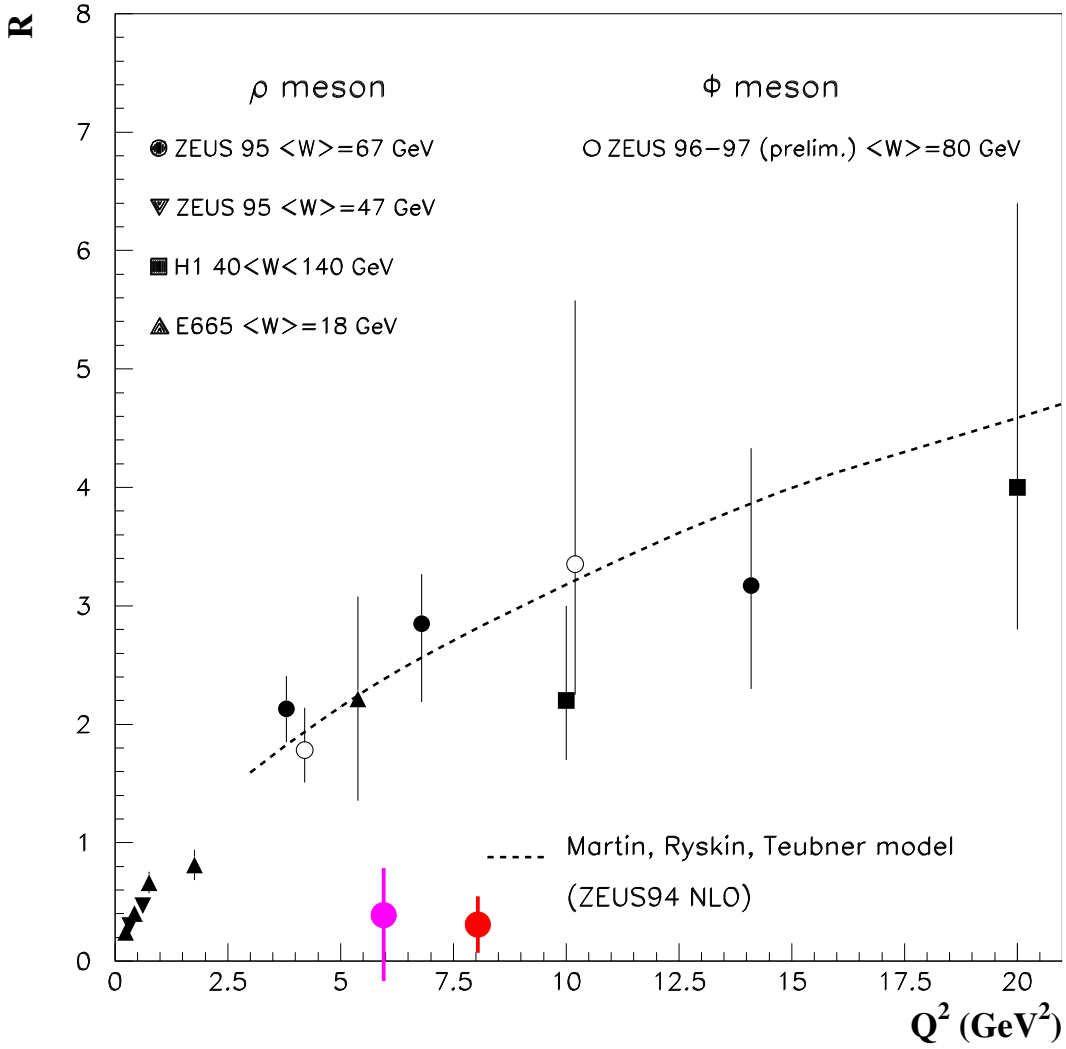


$\Rightarrow$ ϕ behaves like ρ^0 !!

R vs Q^2 for J/ψ

H1 ICHEP Abstract 572

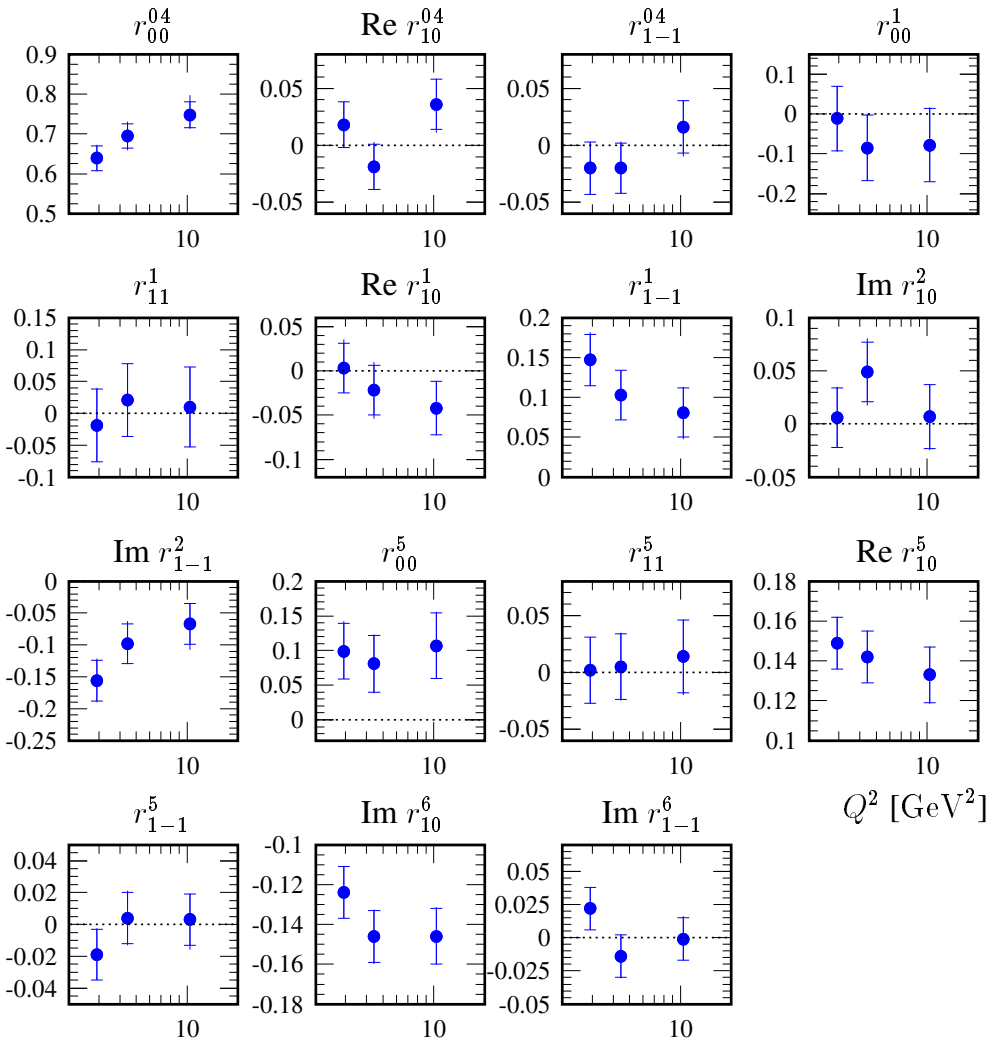
ZEUS hep-ex/9808020



$\Rightarrow$ R for J/ψ lower !!

15-Parameter Helicity-Angle Fit (I)

H1 ICHEP Abstract 564

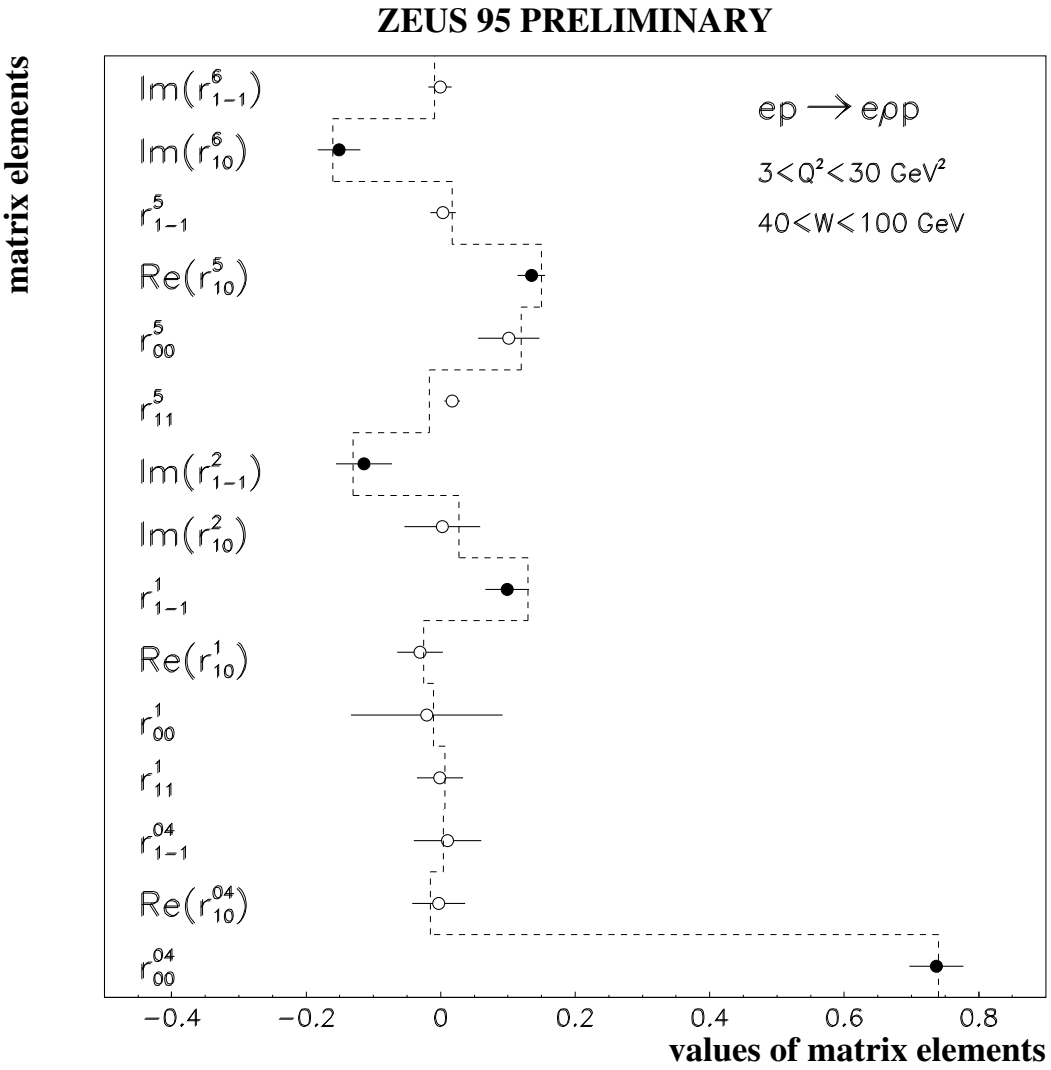


Dotted lines are SCHC values

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

15-Parameter Helicity-Angle Fit (II)

ZEUS ICHEP Abstract 792/792b



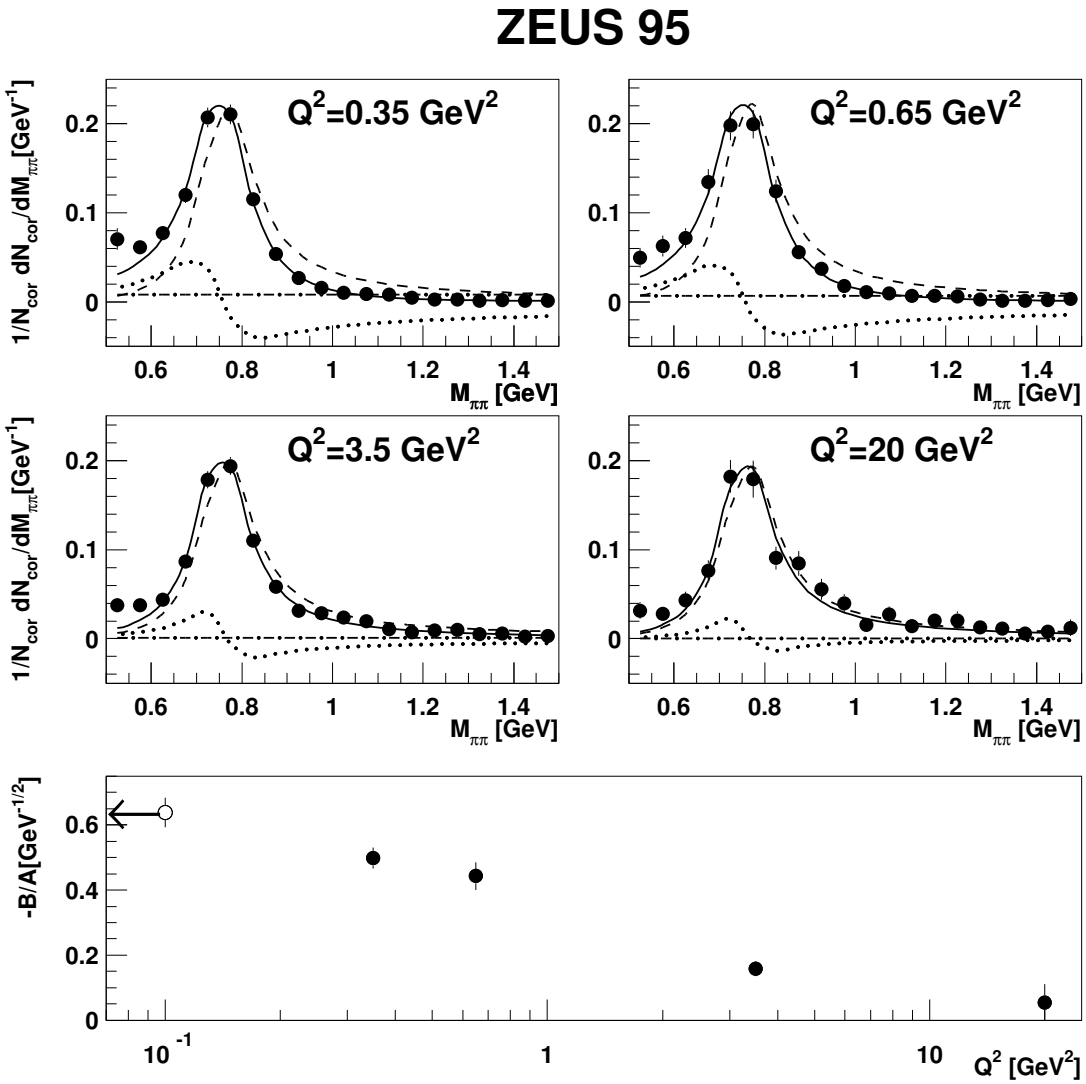
$\Rightarrow$ Agreement with Ivanov and Kirschner!! (hep-ph/9807324)

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

$\pi^+\pi^-$ Mass Spectrum Skewing (I)

ZEUS ICHEP Abstract 792

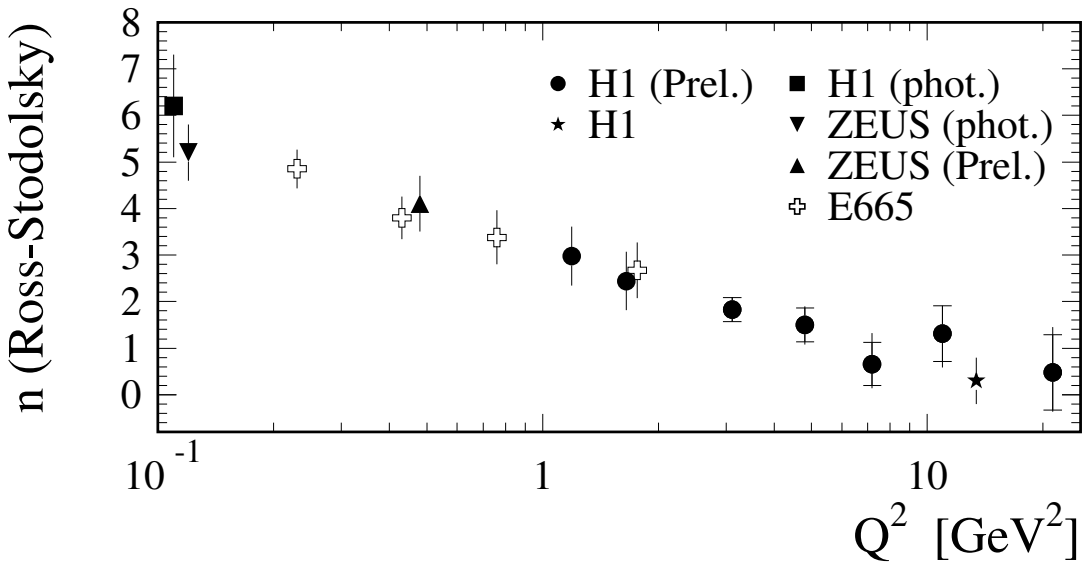
$$\frac{dN}{dM_{\pi\pi}} = \left| A\frac{\sqrt{M_{\pi\pi}M_\rho\Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + iM_\rho\Gamma_\rho} + B \right|^2$$

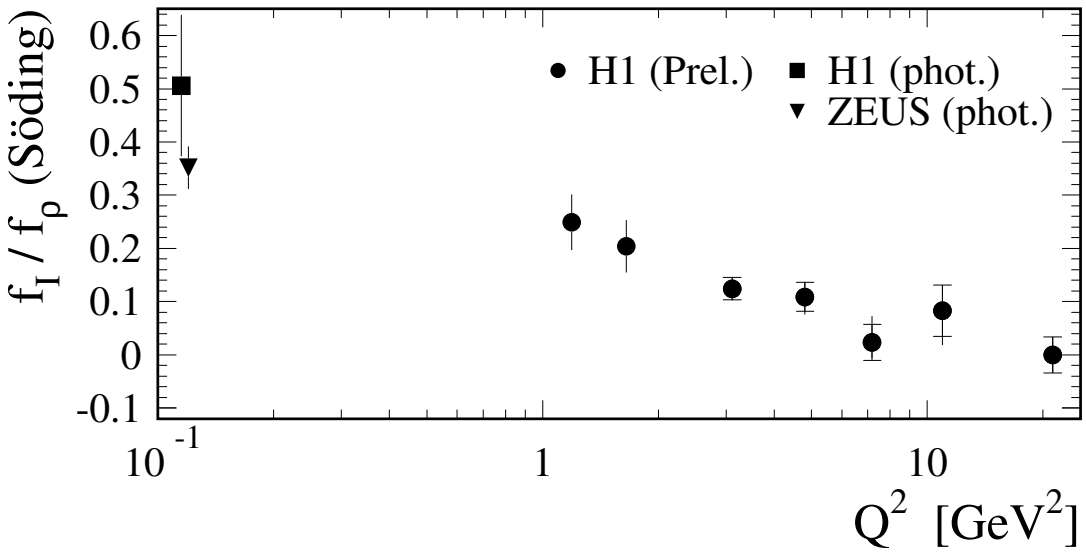


$\Rightarrow$ Skewing disappears at high Q^2

$\pi^+\pi^-$ Mass Spectrum Skewing (II)

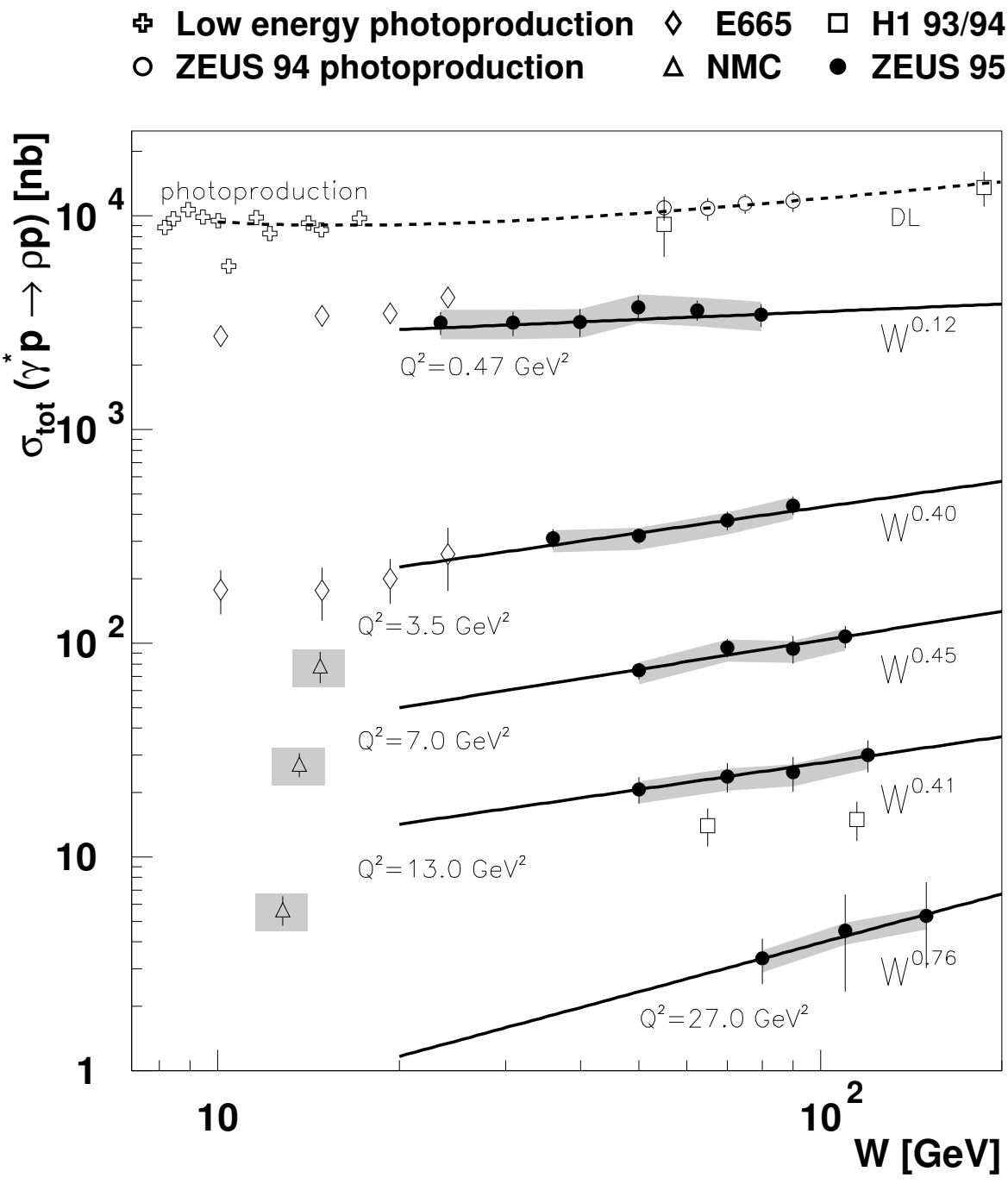
H1 ICHEP Abstract 564





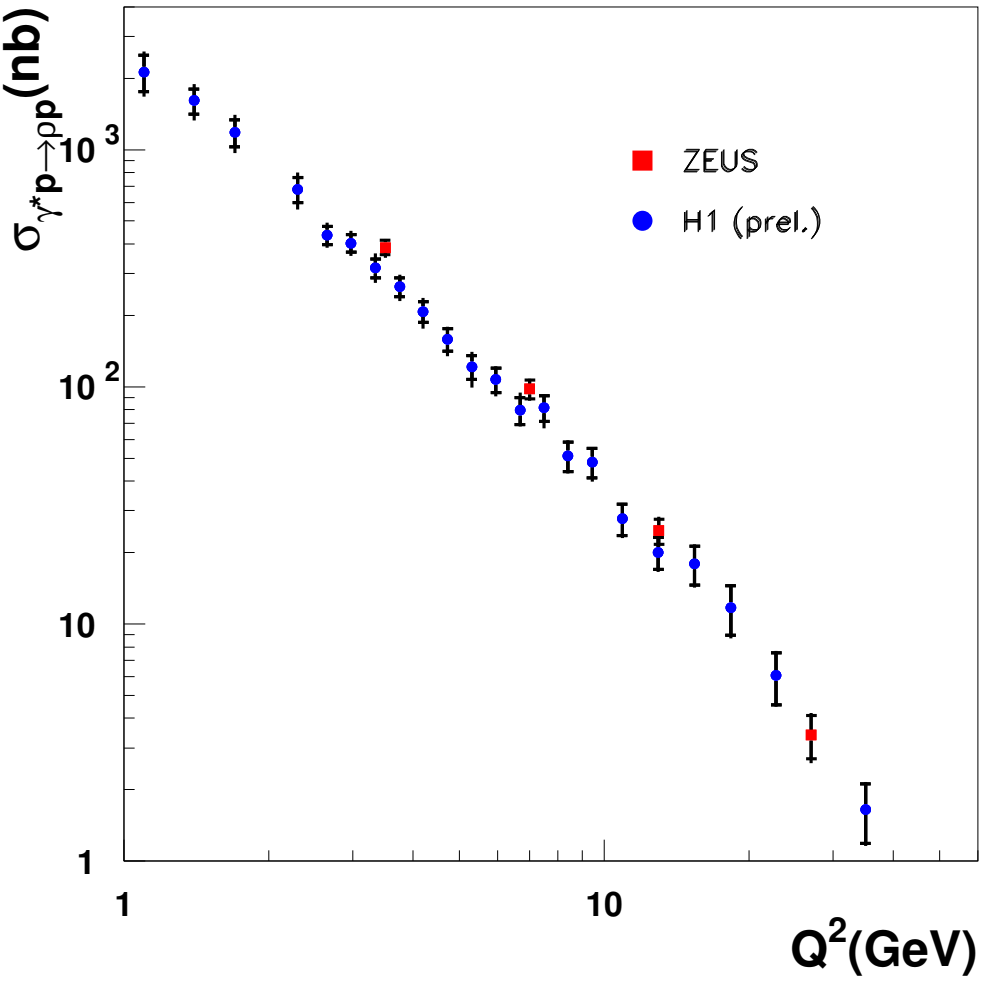
$\Rightarrow$ Consistency between ZEUS, H1, and E665

Elastic ρ^0 Cross Sections (I)



$\Rightarrow$ Disagreement ZEUS/H1? E665/NMC?

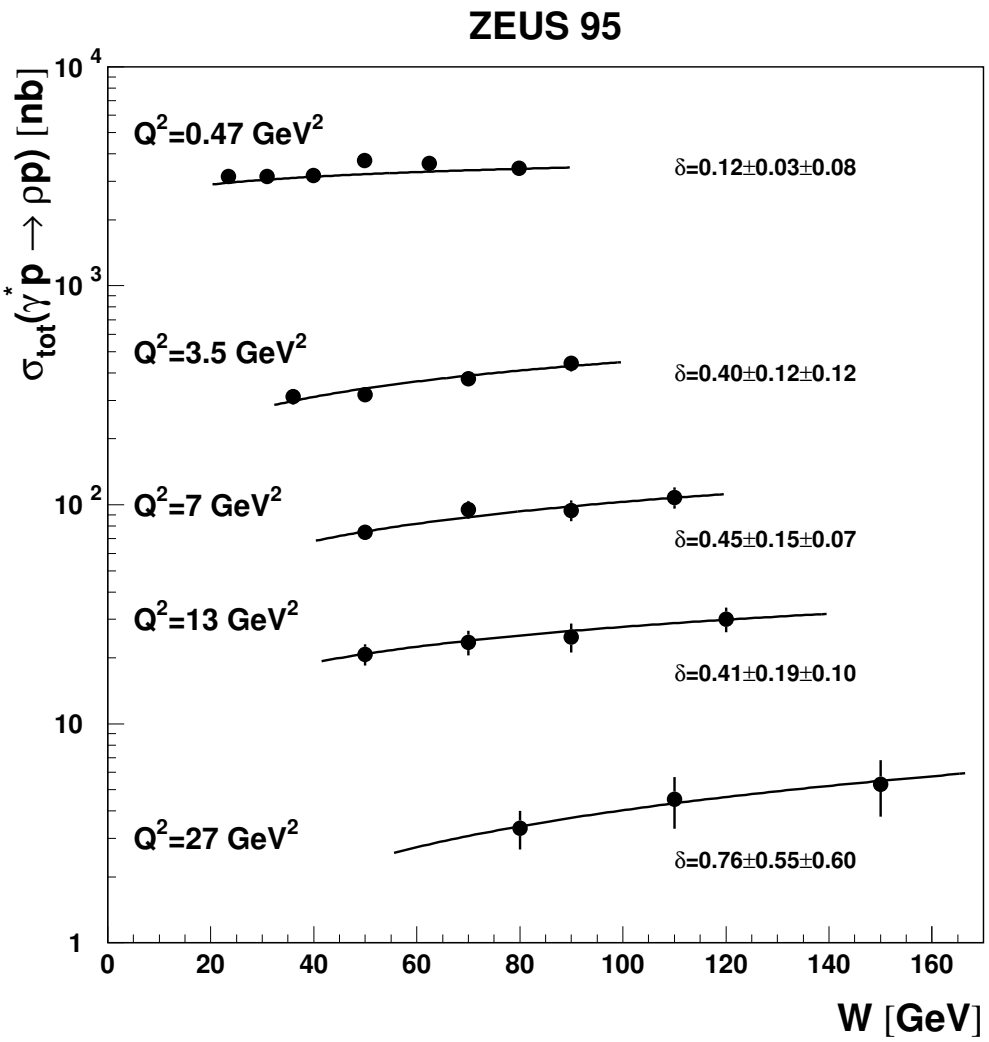
Elastic ρ^0 Cross Sections (II)



$\Rightarrow$ Beautiful measurement of Q^2 dependence by H1 !!

$\Rightarrow$ ZEUS/H1 inconsistency gone !!

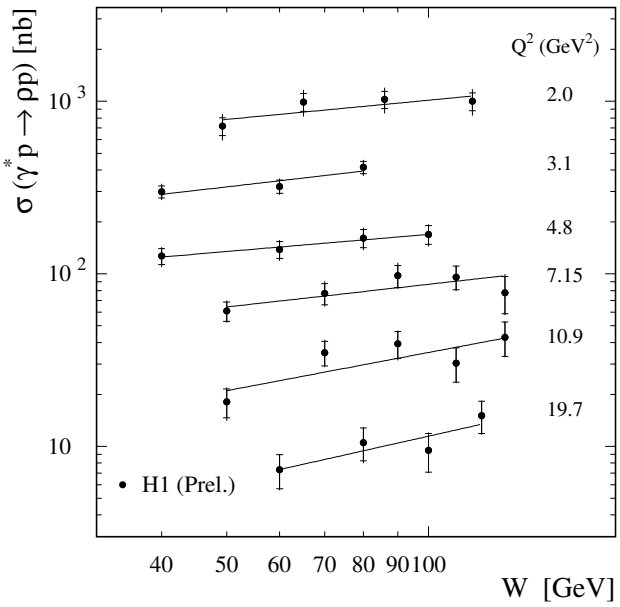
Elastic ρ^0 Cross Sections (III)

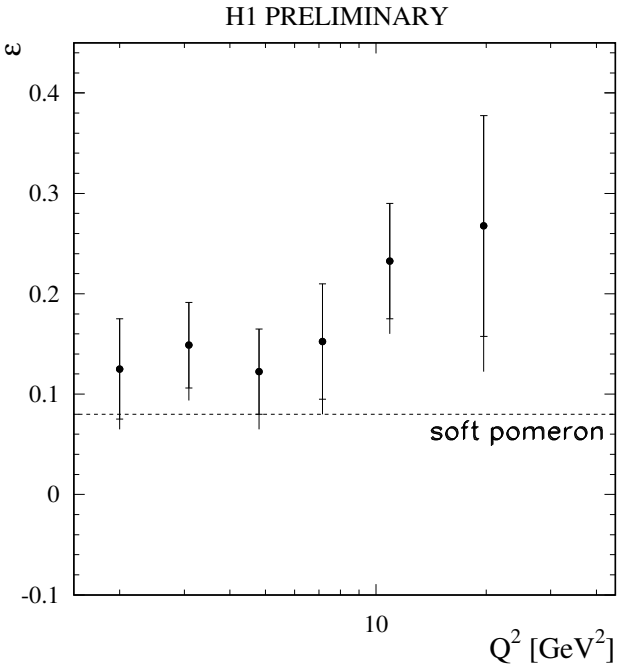


$\Rightarrow$ Steepening with Q^2 expected in pQCD

$\Rightarrow \approx 2\sigma$ effect

Elastic ρ^0 Cross Sections (IV)



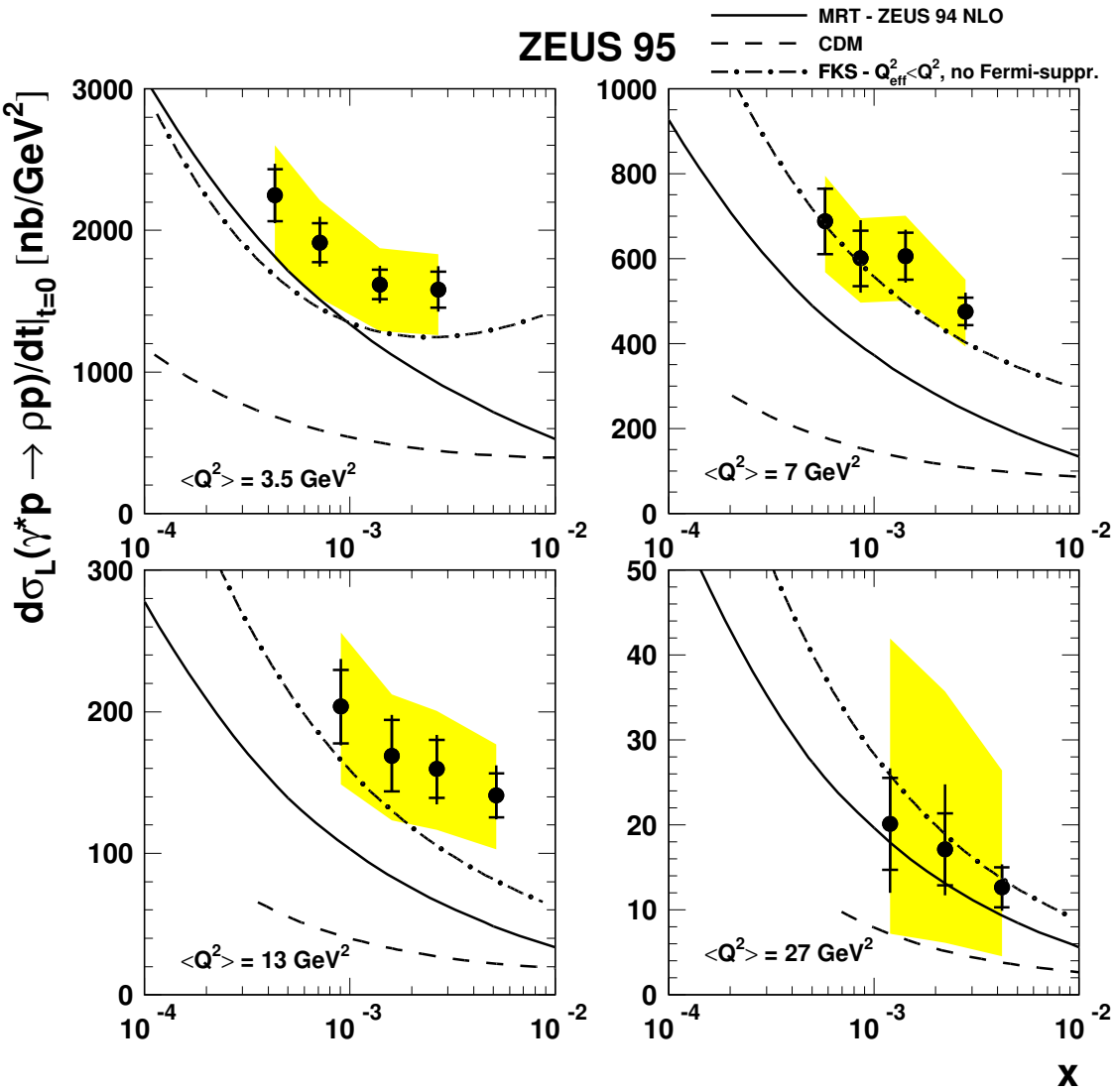


⇒ H1 data consistent and with similar sensitivity

Elastic ρ^0 Cross Sections (V)

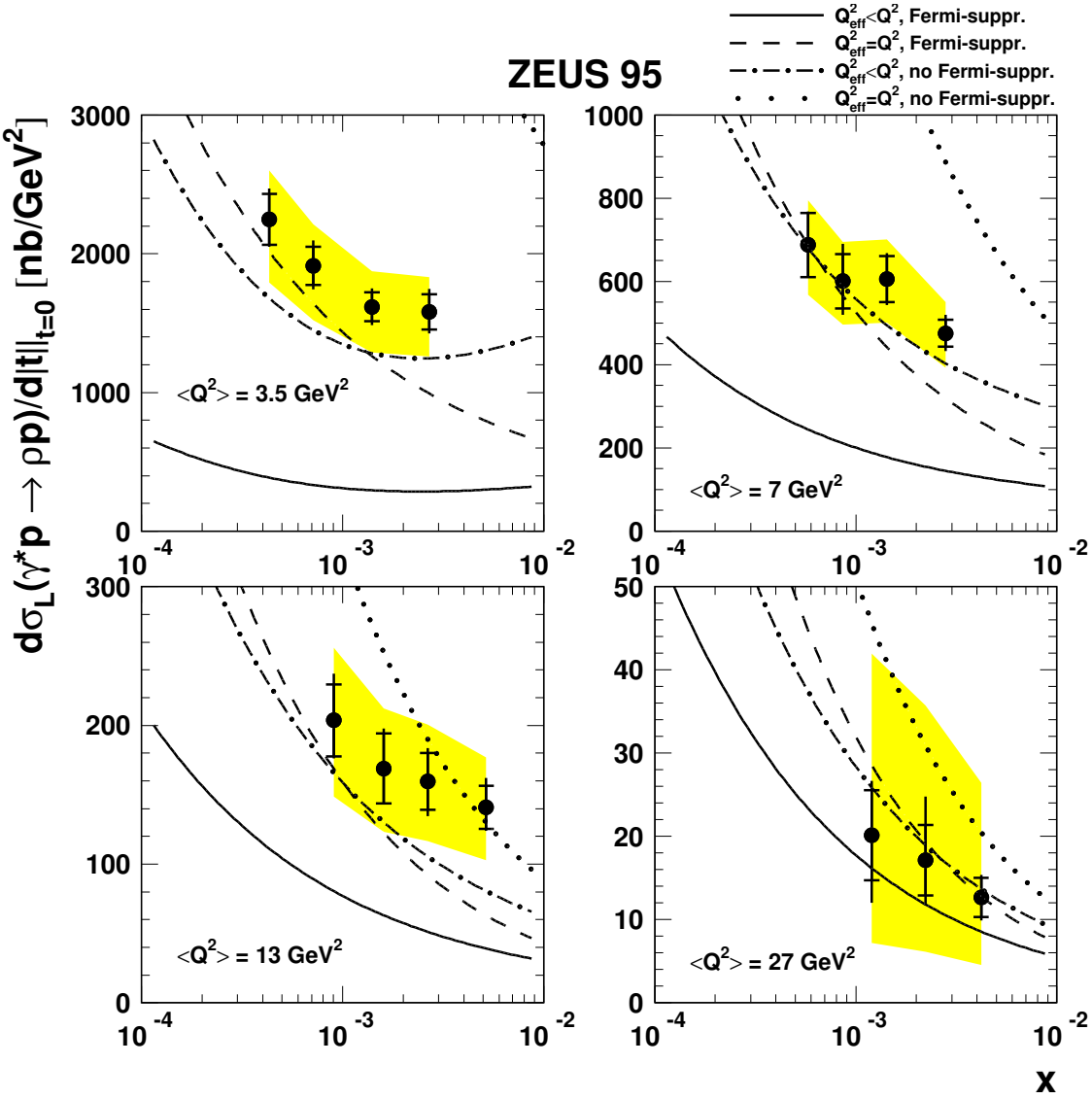
ZEUS longitudinal cross sections compared to models

(hep-ex/9808020)



Elastic ρ^0 Cross Sections (VI)

ZEUS longitudinal cross sections compared to FKS



$\Rightarrow$ Effects of rescaling and of ρ^0 wave function comparable but with differing x dependence

$\Rightarrow$ Present experimental accuracy allows distinction

Elastic ϕ Cross Sections (I)

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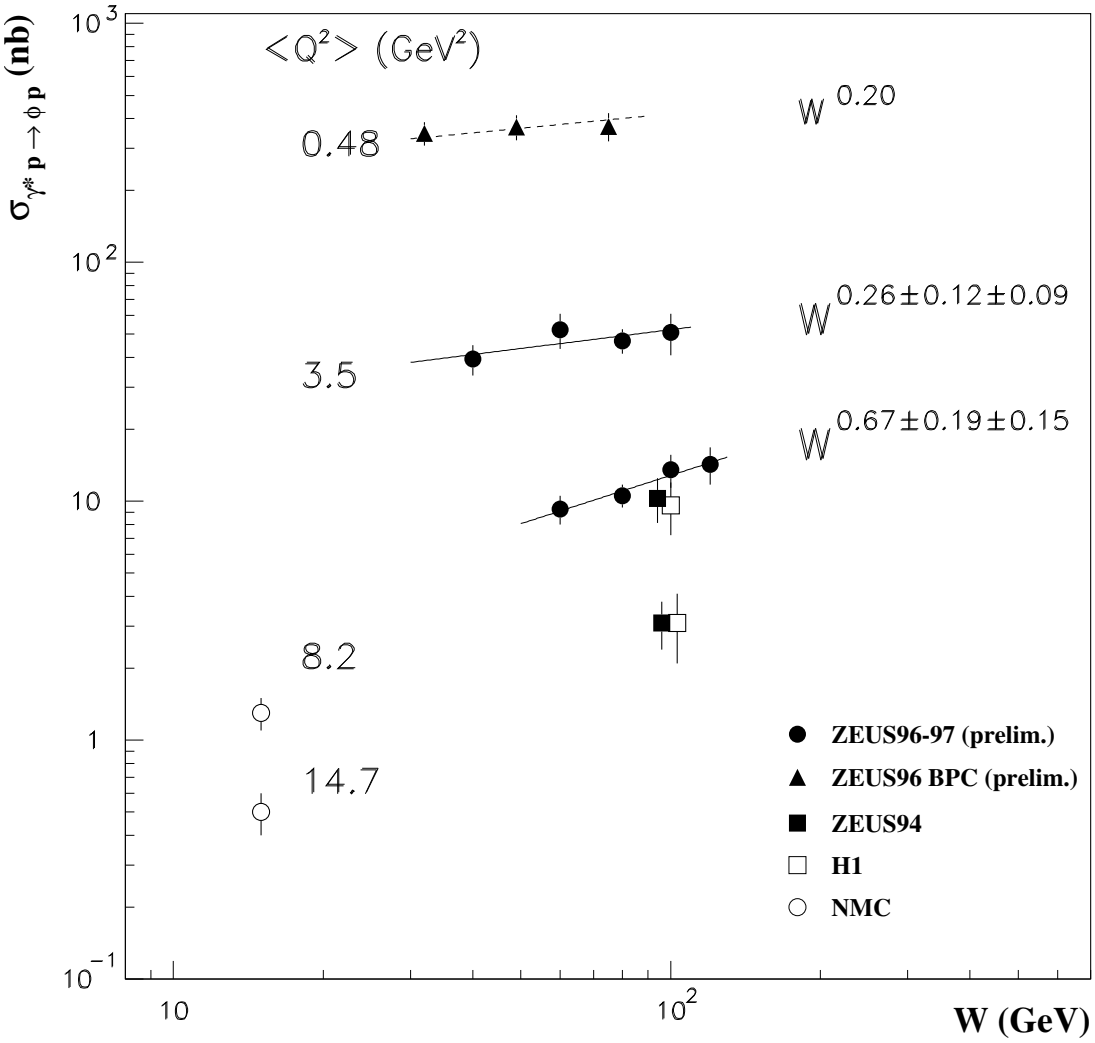

$\Rightarrow$ More evidence that W dependence steepens with Q^2

Elastic ϕ Cross Sections (II)

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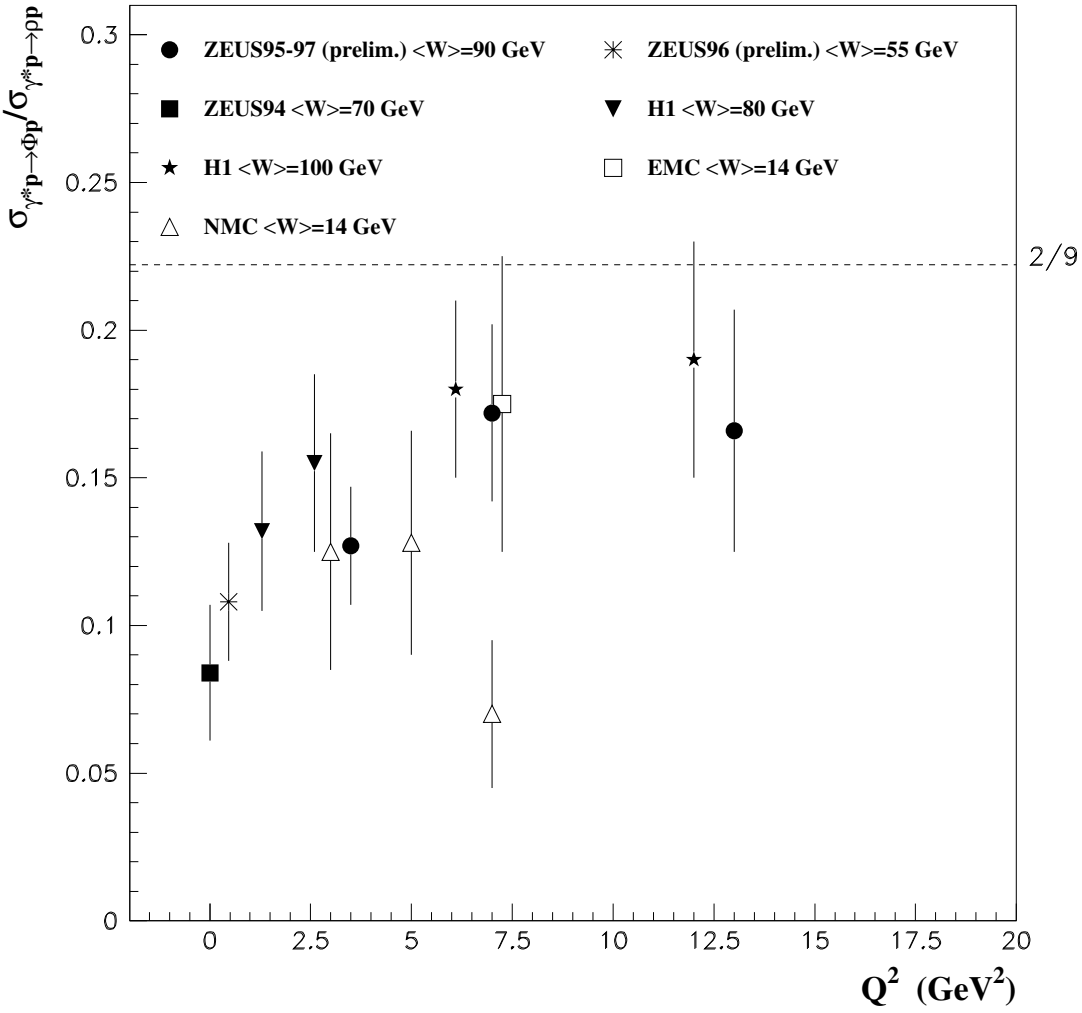
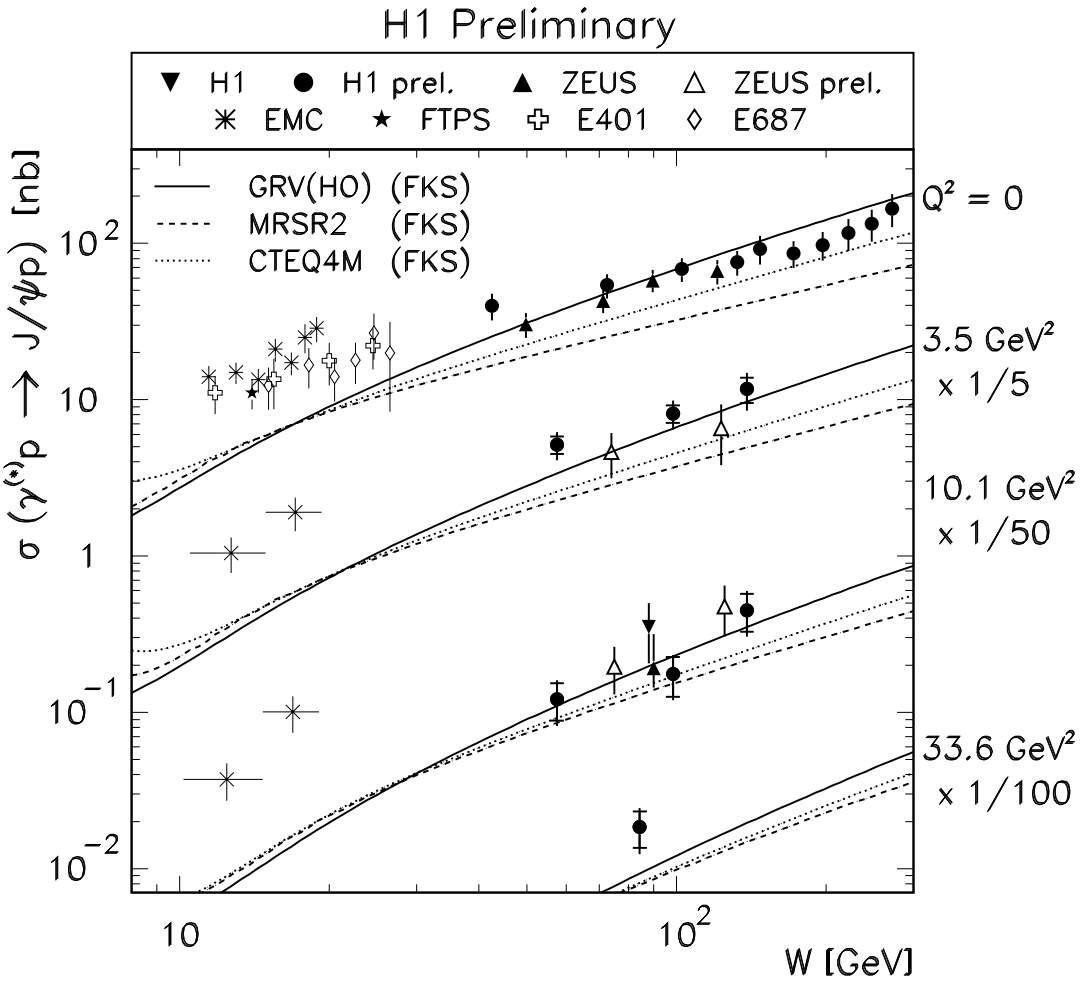


$\Rightarrow$ ϕ/ρ^0 ratio rising with Q^2

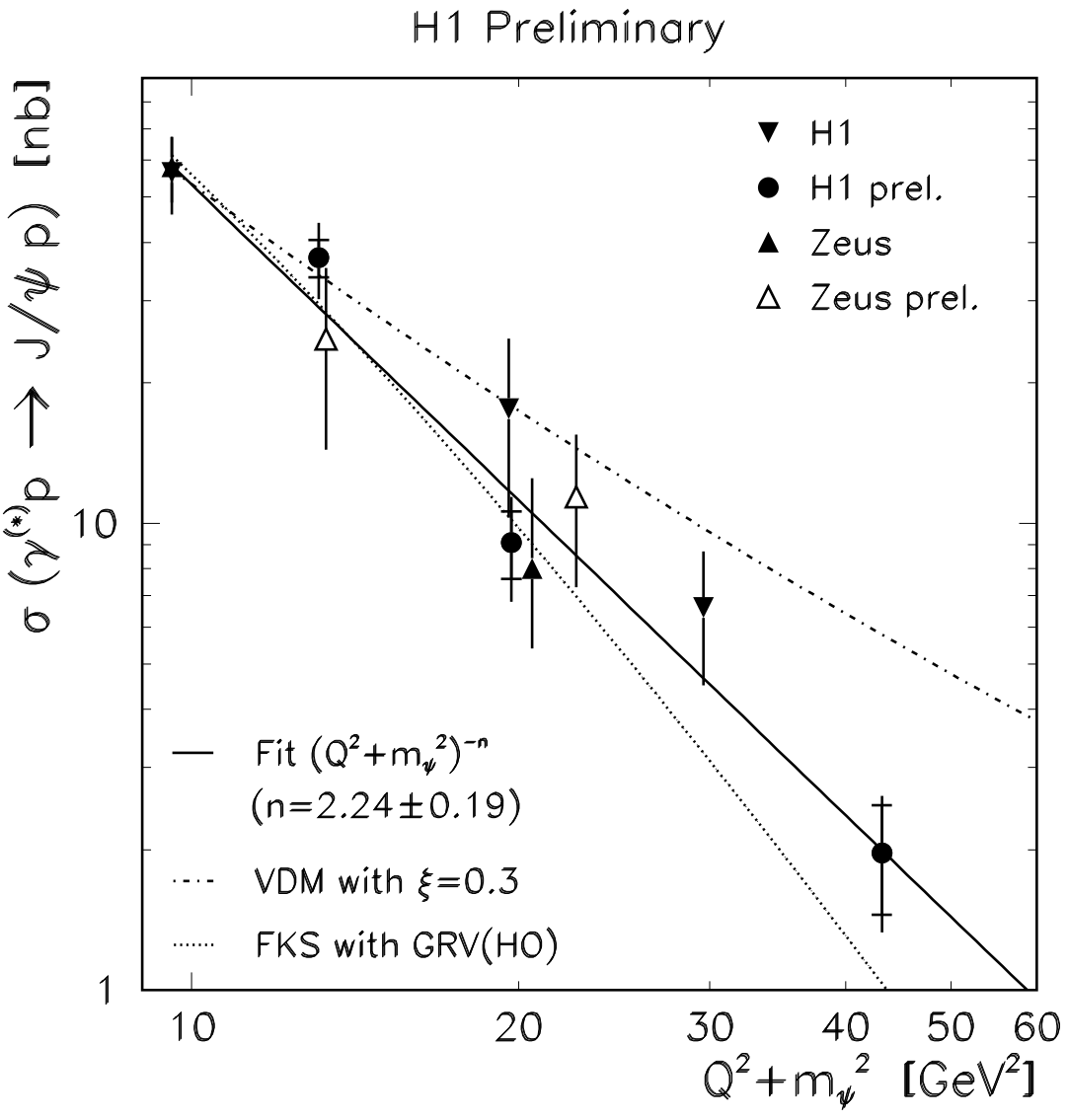
Elastic J/ψ Cross Sections (I)

H1 ICHEP Abstract 572



Elastic J/ψ Cross Sections (II)

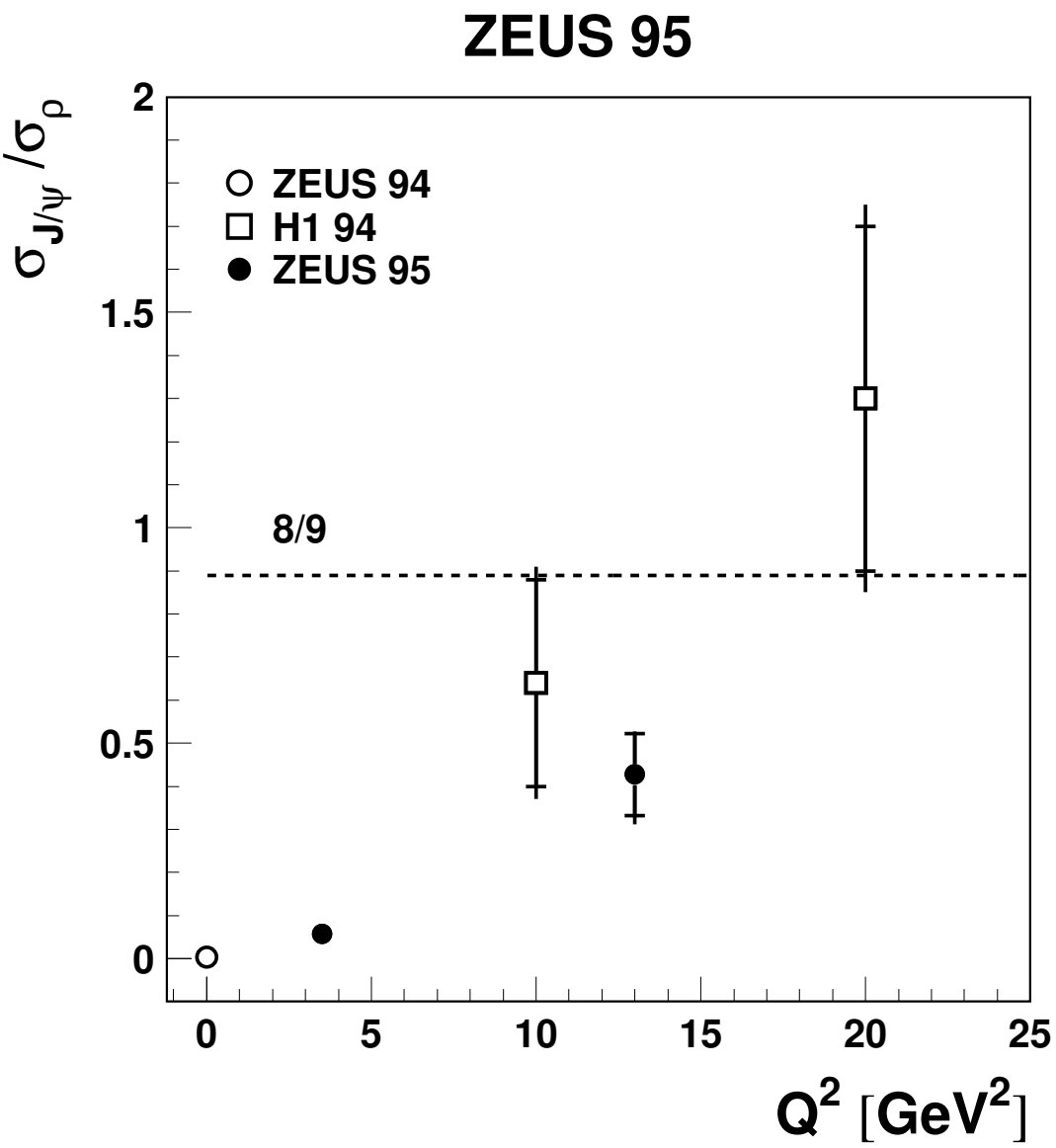
H1 ICHEP Abstract 572



$\Rightarrow$ How much rescaling necessary ?

Elastic J/ψ Cross Sections (III)

ZEUS hep-ex/9808020



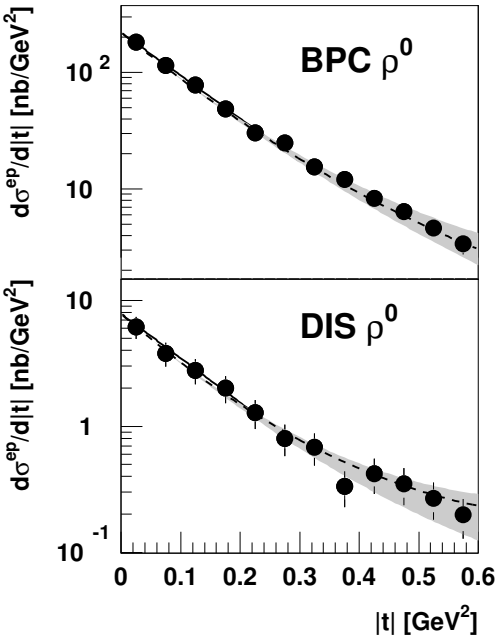
$\Rightarrow$ $J/\psi/\rho^0$ ratio rising with Q^2
Flavor symmetry requires higher Q^2 than for ϕ

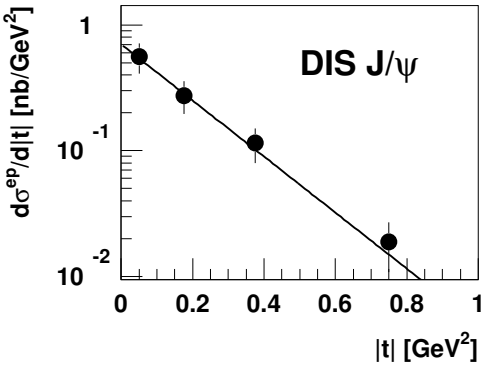
t-Distributions

Systematic uncertainties

in determining the exponential slope b

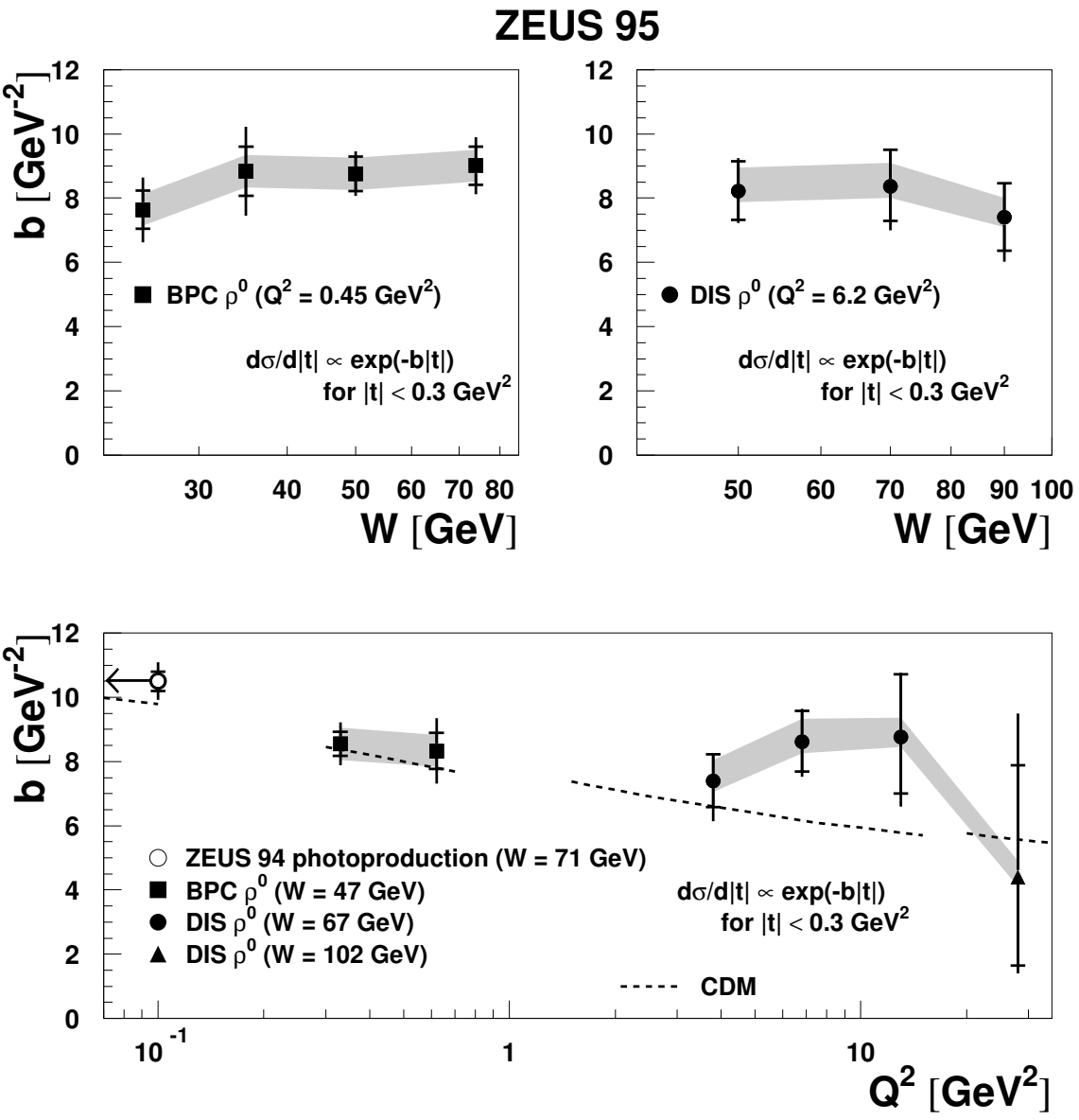
ZEUS 95





$\Rightarrow$ Uncertainty in dissociative contribution dominates

Exponential slope b for ρ^0

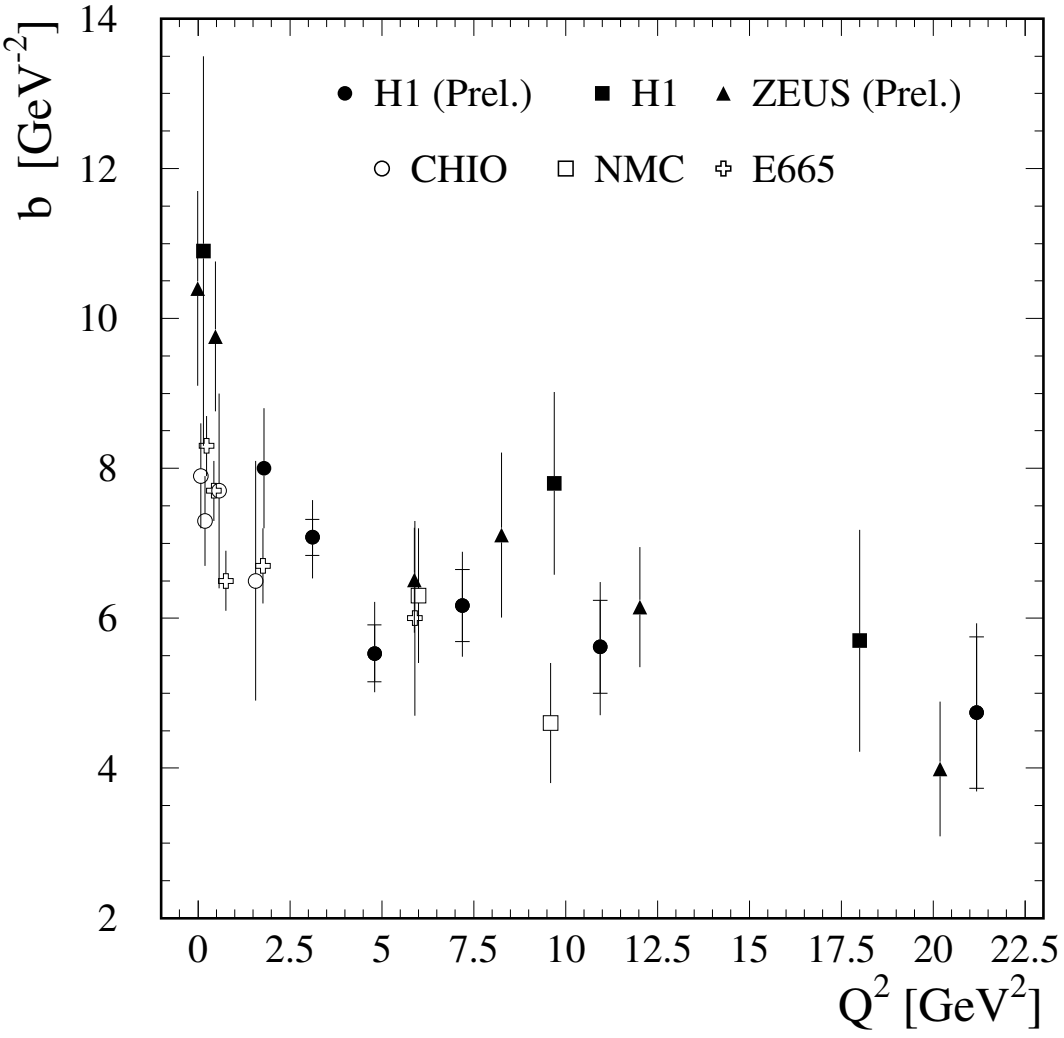


$\Rightarrow$ Inconclusive on shrinkage

$\Rightarrow$ b at high Q^2 smaller than for photoproduction

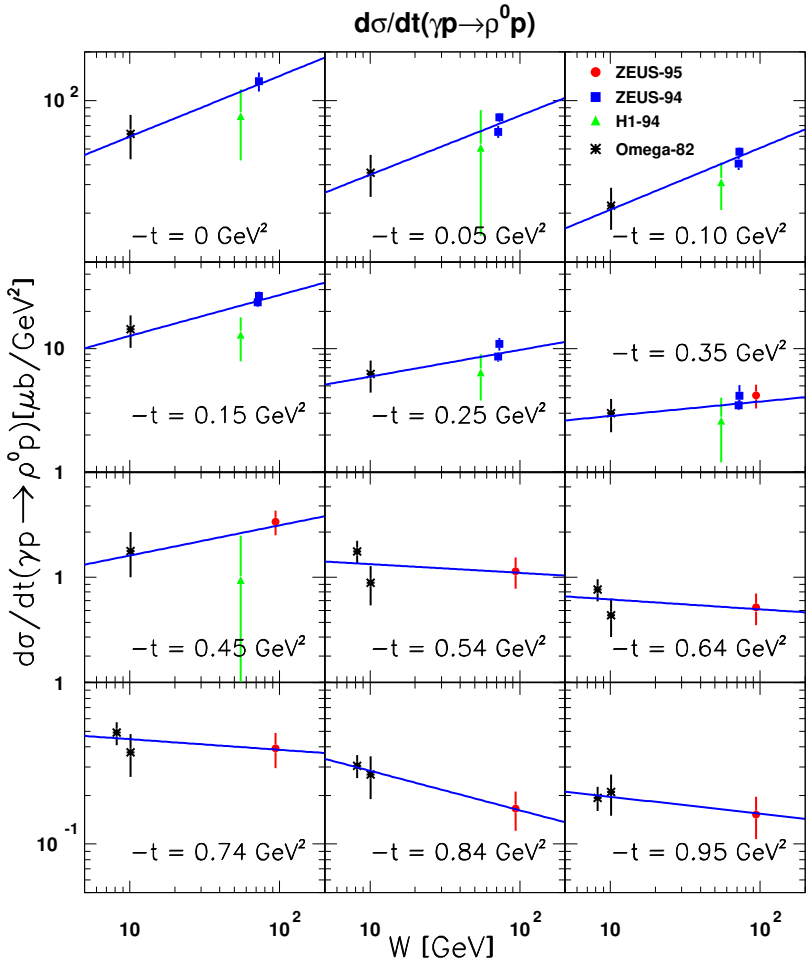
New values for b from H1 for ρ^0

H1 ICHEP Abstract 564



$\Rightarrow$ Over what Q^2 range is b falling??

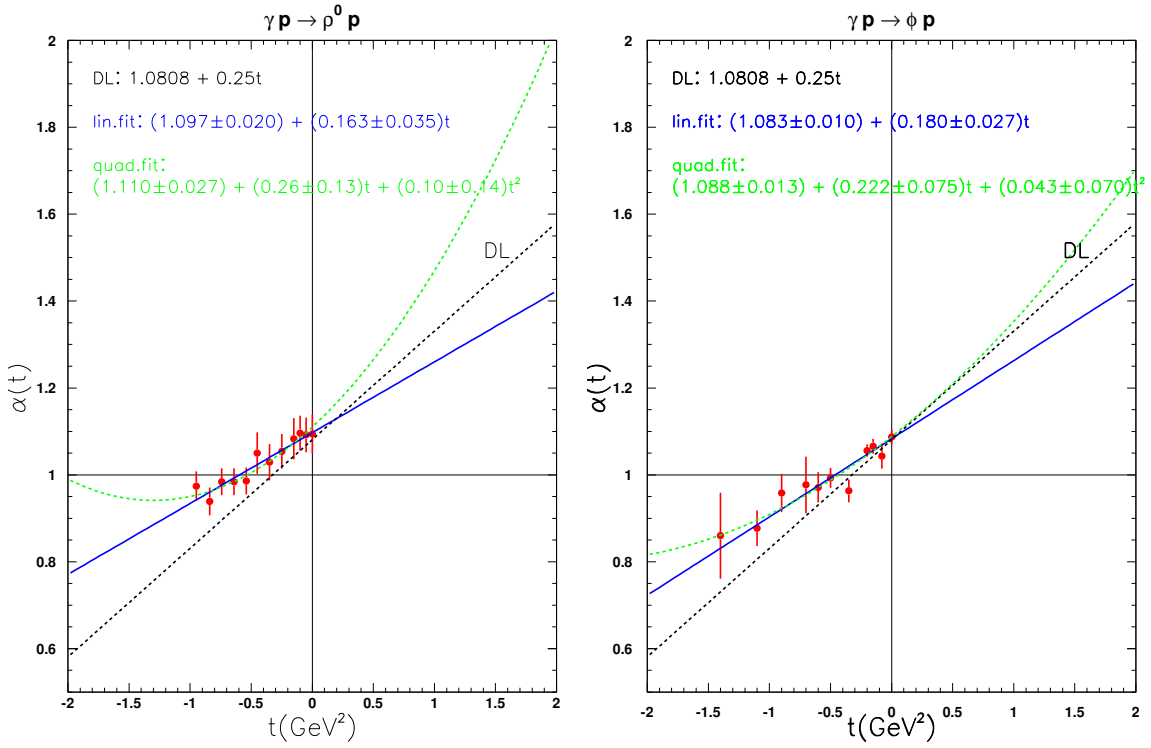
Determining $\alpha_{I\!P}(t)$ Using $\frac{\mathrm{d}\sigma}{\mathrm{d}t}(W)$



$$\sigma \propto W^{4(\alpha_{I\!P}(t)-1)}, \quad \alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$$

$\Rightarrow$ Sensitive to transition between rising and falling energy dependence

Measuring $\alpha_{I\!P}(t)$ with ρ^0 and ϕ

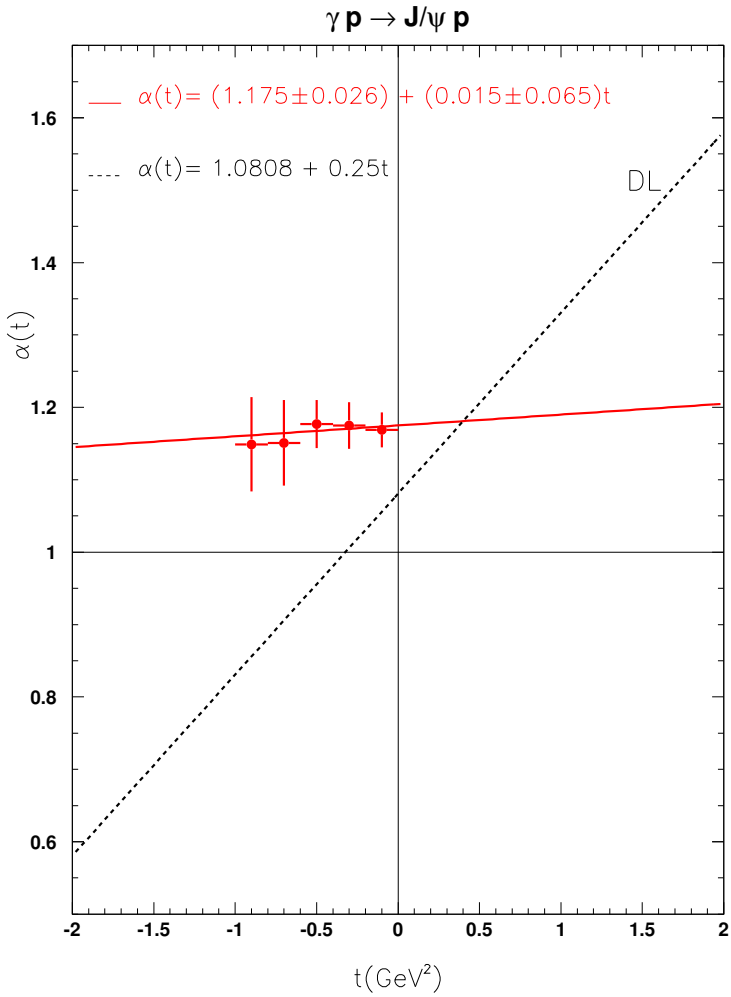


	$\alpha_{I\!P}(0)$	$\alpha'_{I\!P}$
ρ^0:	1.097 ± 0.020	0.163 ± 0.035 GeV^{-2}
ϕ:	1.083 ± 0.010	0.180 ± 0.027 GeV^{-2}

$\Rightarrow$ Shrinkage similar to hadronic cross sections

Measuring $\alpha_{I\!P}(t)$ with J/ψ Mesons

A. Levy, Phys. Lett. B424 (1998) 191



	$\alpha_{I\!P}(0)$	$\alpha'_{I\!P}$
J/ψ:	1.175 ± 0.026	0.015 ± 0.065 GeV^{-2}

$\Rightarrow$ **Shrinkage absent for J/ψ !**

Summary

We have new results on:

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

$\Rightarrow$ Helicity structure (good-bye SCHC !)

$\Rightarrow$ $R = \frac{\sigma_L}{\sigma_T}$ versus Q^2 (Small for J/ψ !)

$\Rightarrow$ x, Q^2, t dependence (improved accuracy)

☞ $\alpha_{I\!P}(t)$ for ρ^0, ϕ, and J/ψ

$\Rightarrow$ Shrinkage for ρ^0, ϕ similar to hadronic xsecs

$\Rightarrow$ J/ψ exhibits no such shrinkage

Thanks to the organizers for a timely workshop!!