Graduiertenkolleg *30 June 1999*

Universität Regensburg

Applications of QCD in Studies of Diffractive Processes at HERA

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Physikalisches Institut

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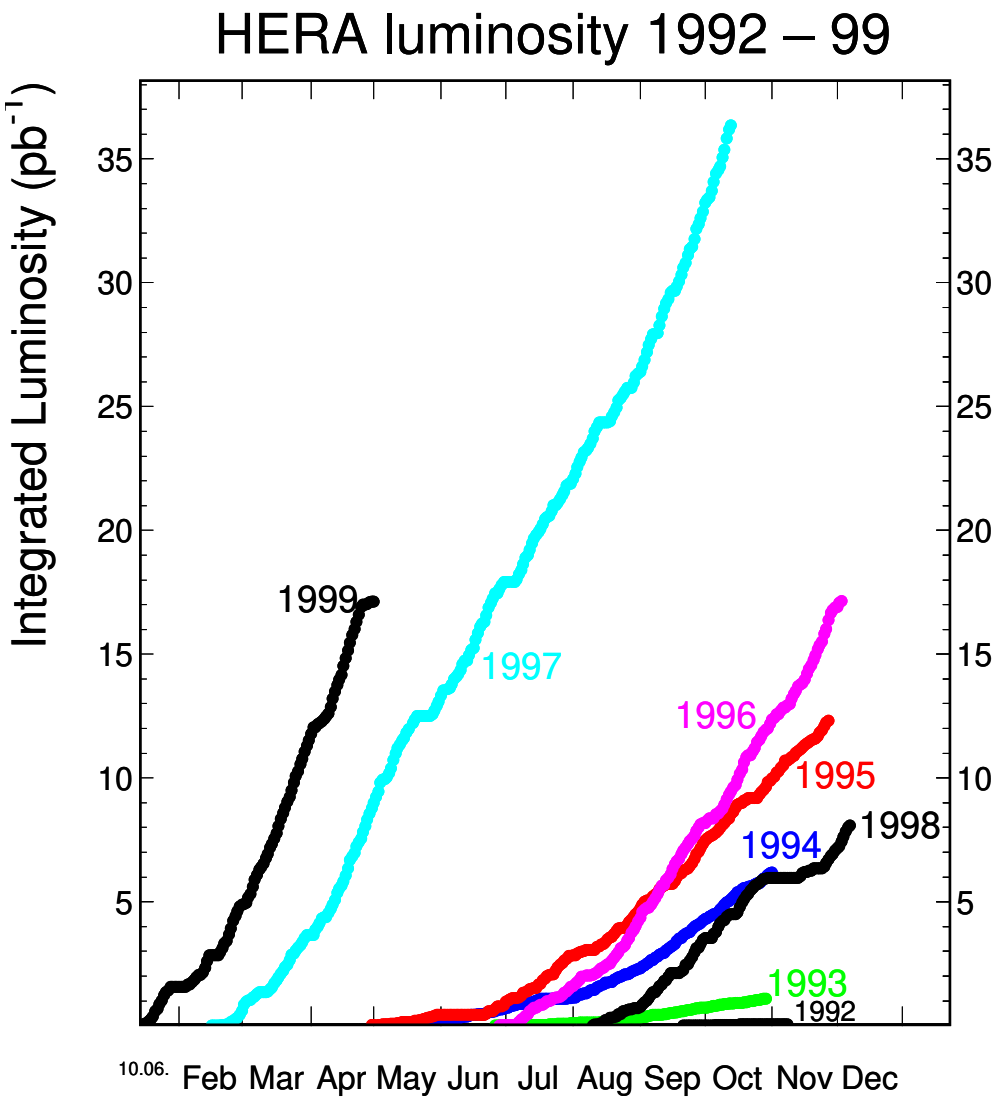
HERA Luminosity History



Luminosity upgrade in 2000

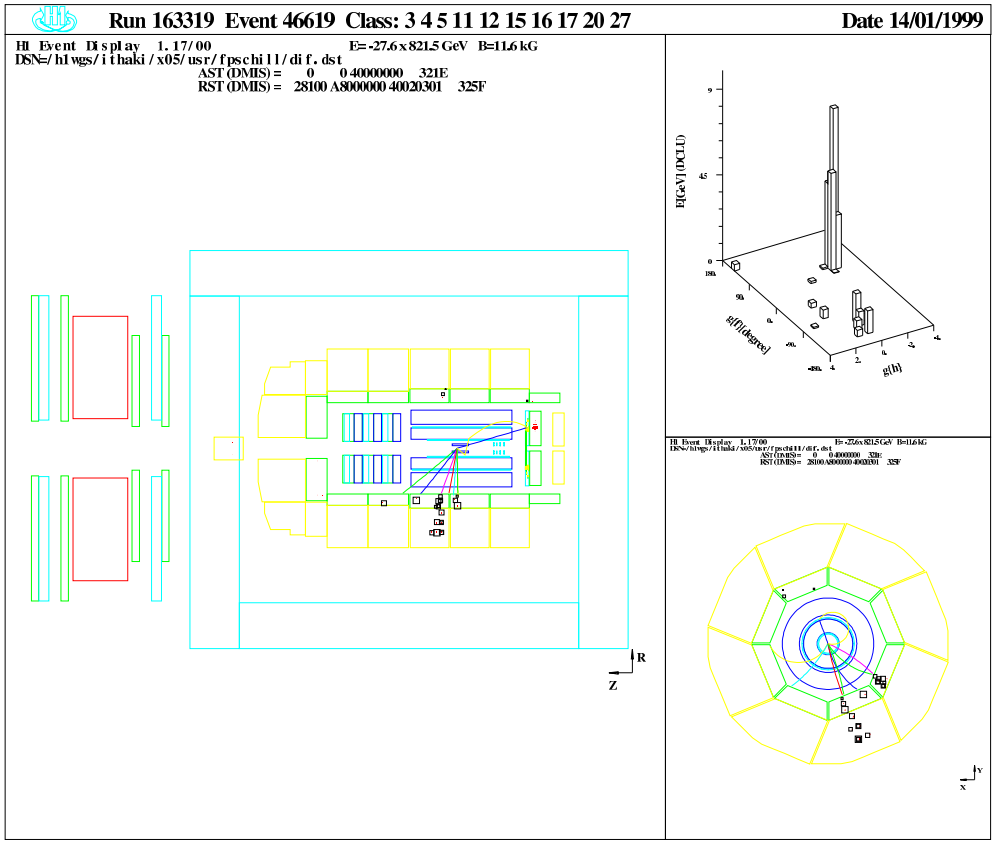
with a goal of 1 fb^{-1} by 2005

We expect an increase of a factor 20

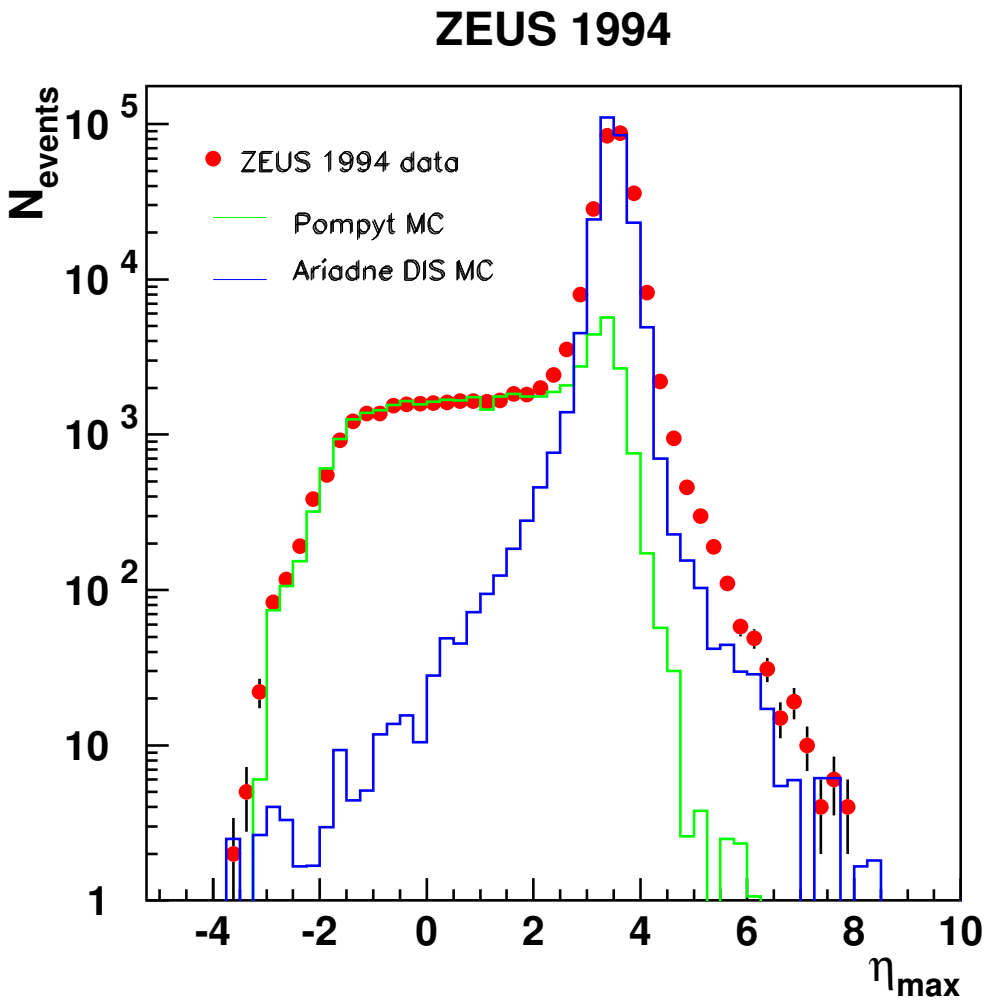
over the present integrated luminosity

Candidate for Inclusive Diffraction

Rapidity-Gap Signature



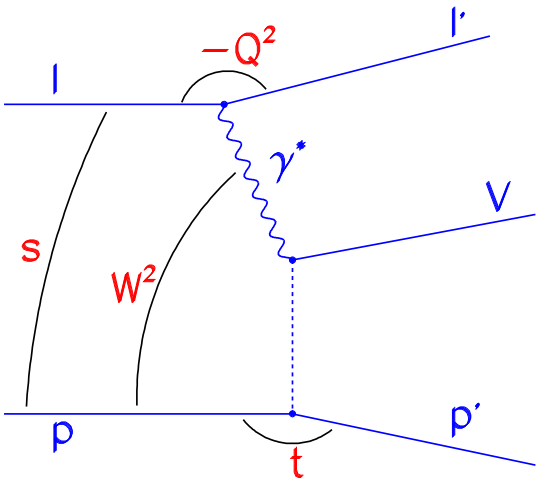
Rapidity-Gap Analysis



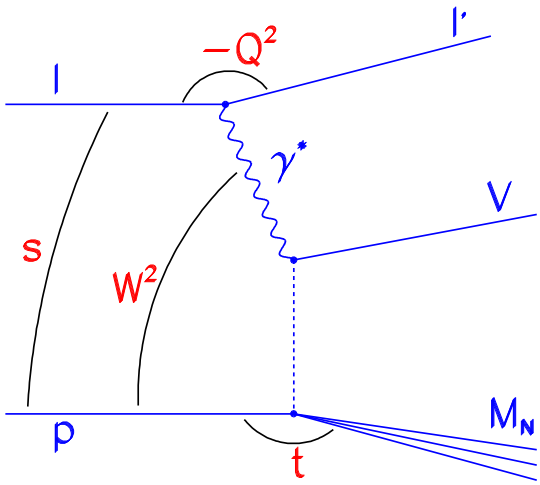
⇒ Recent review by A. Hebecker
LANL preprint hep-ph/9905226

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): ≃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)

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

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

$\Rightarrow$ 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"

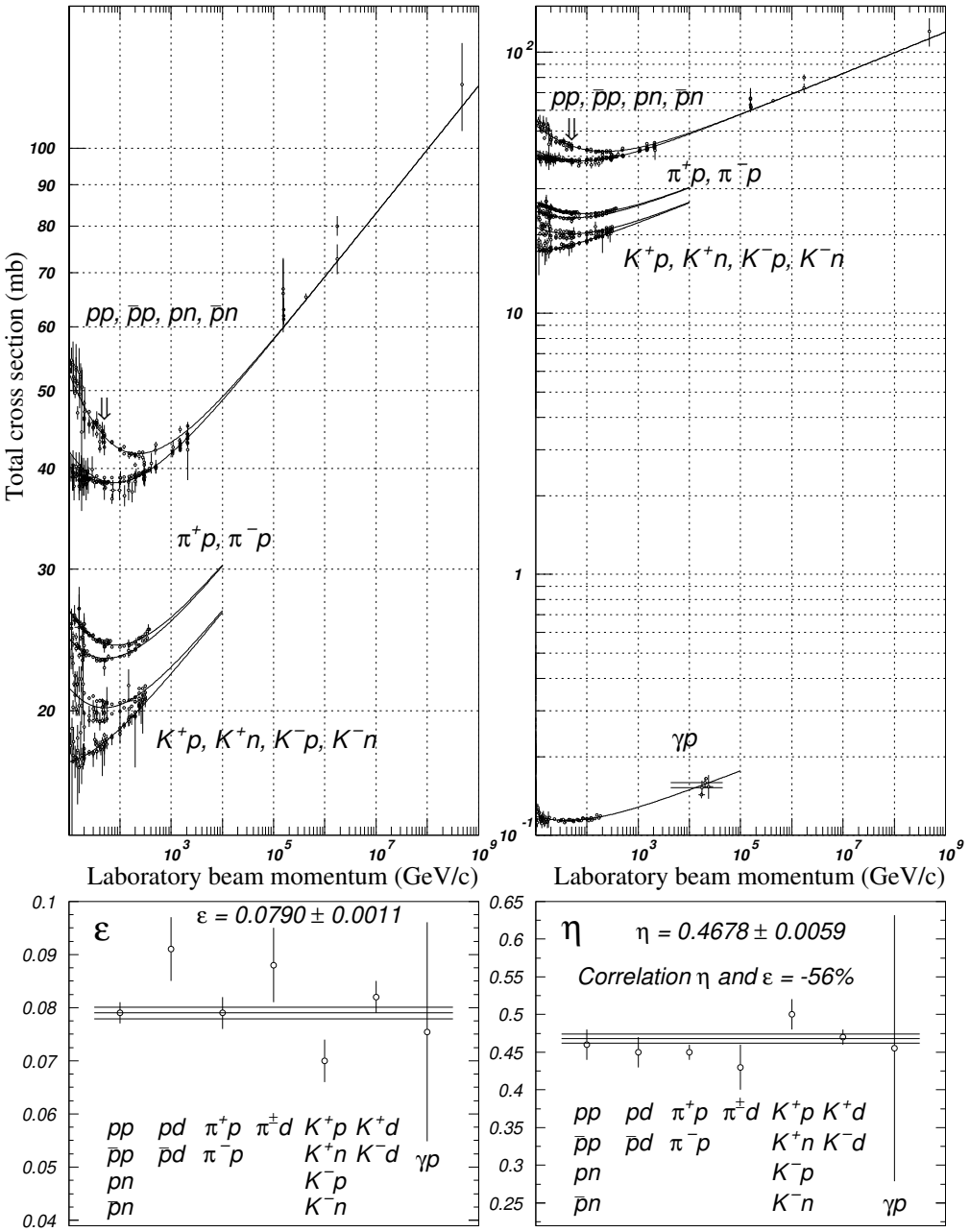
$$\frac{d\sigma}{dt} \propto e^{b\,t} \text{ with } b = b_0 + 2\,\alpha'_{I\!P} \ln\frac{s}{s_0}$$

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

Total Cross Sections

Donnachie + Landshoff, PL B296 (1992) 227

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

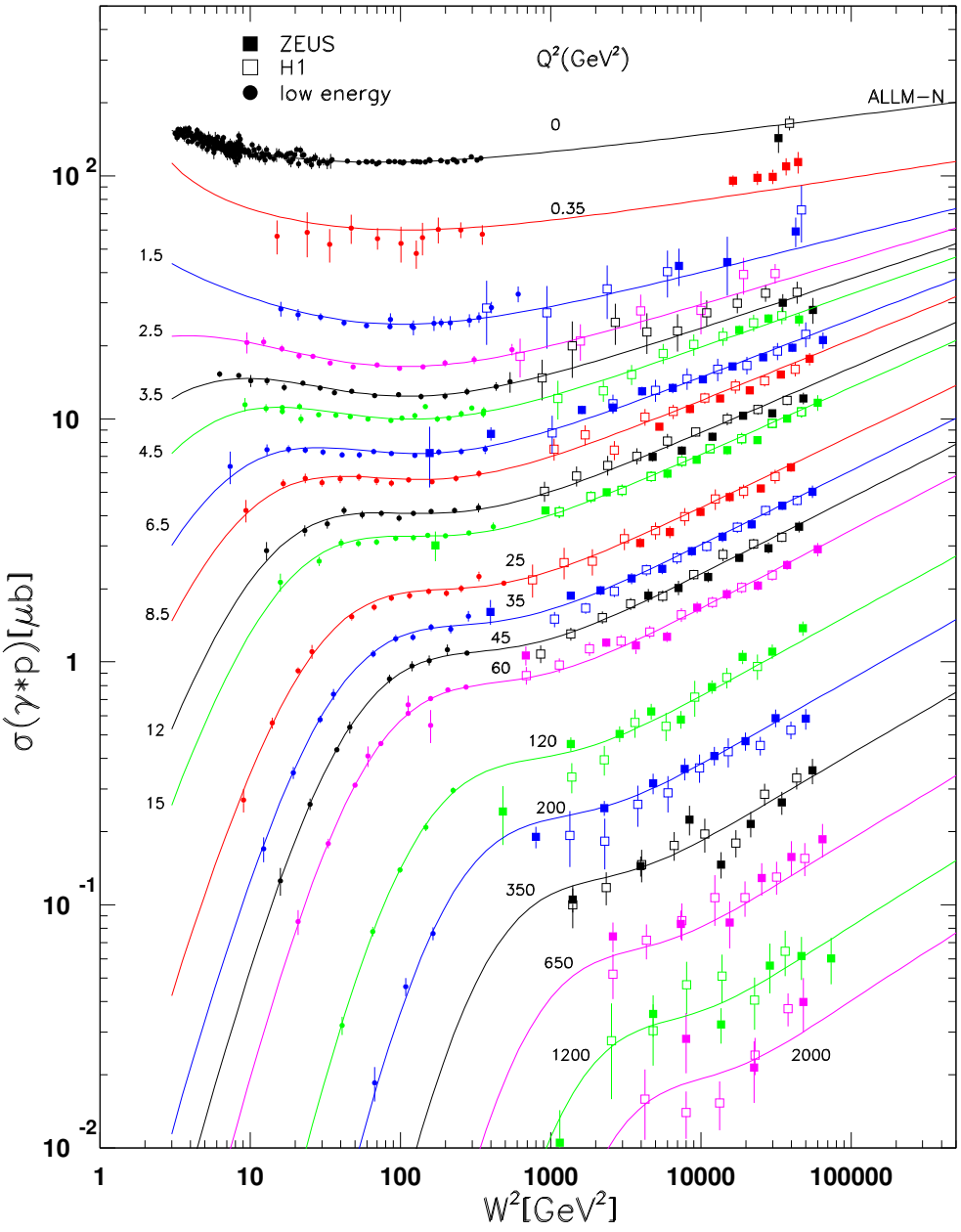


PDG 1996

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

Total Photon-Proton Cross Sections

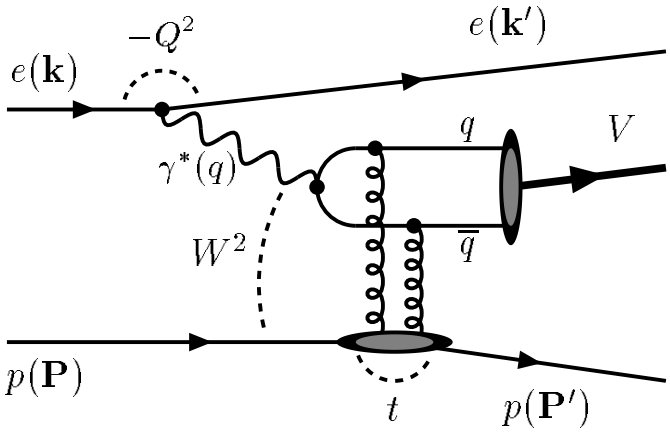
$$\sigma^{tot}_{\gamma^* p} \approx \frac{4\pi^2\alpha}{Q^2(1-x)} F_2(x,Q^2)$$



$\Rightarrow$ 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 !

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

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

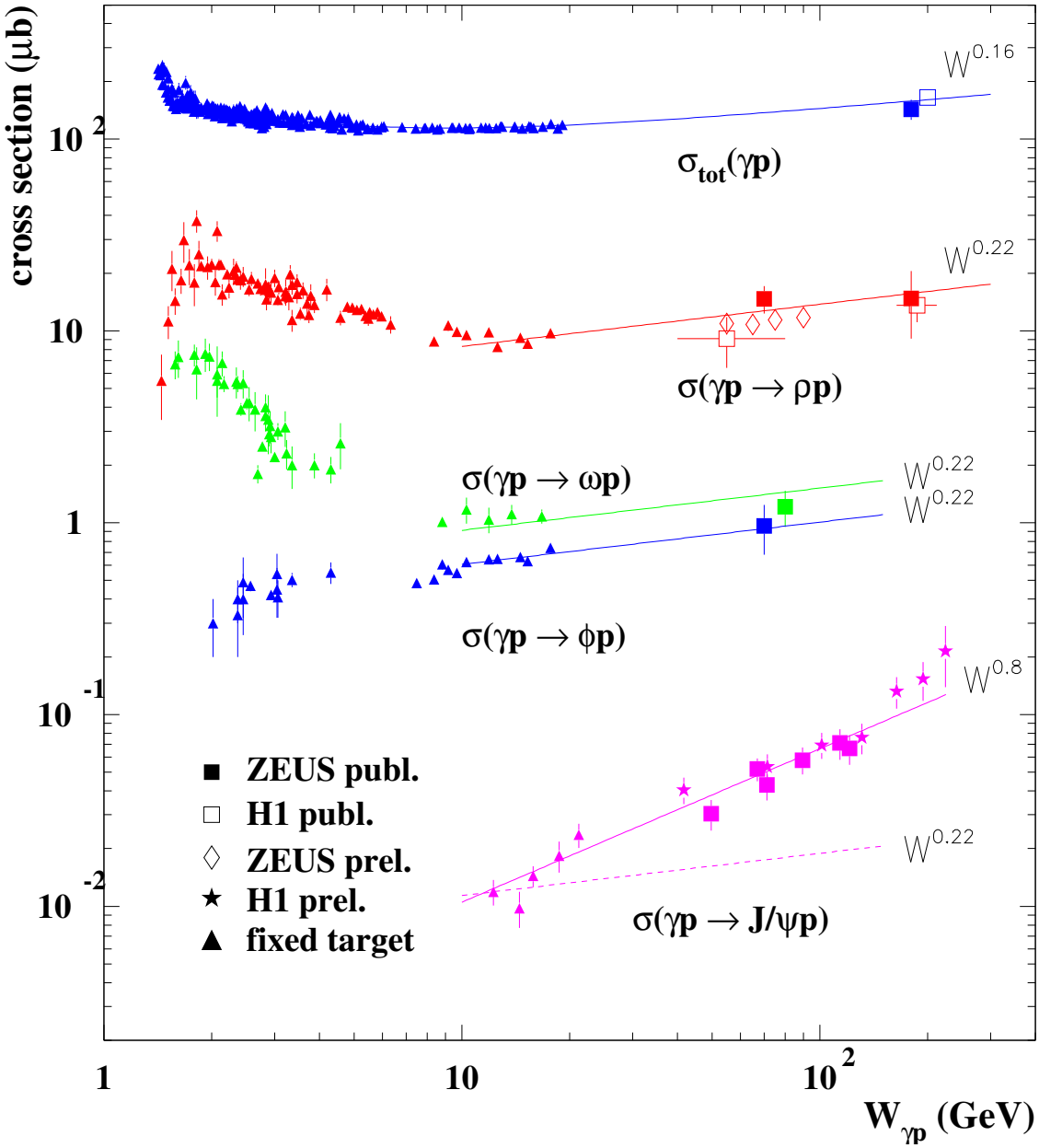
Ryskin, Z.Phys. C57 (1993) 89 (J/ψ Photoproduction)

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

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

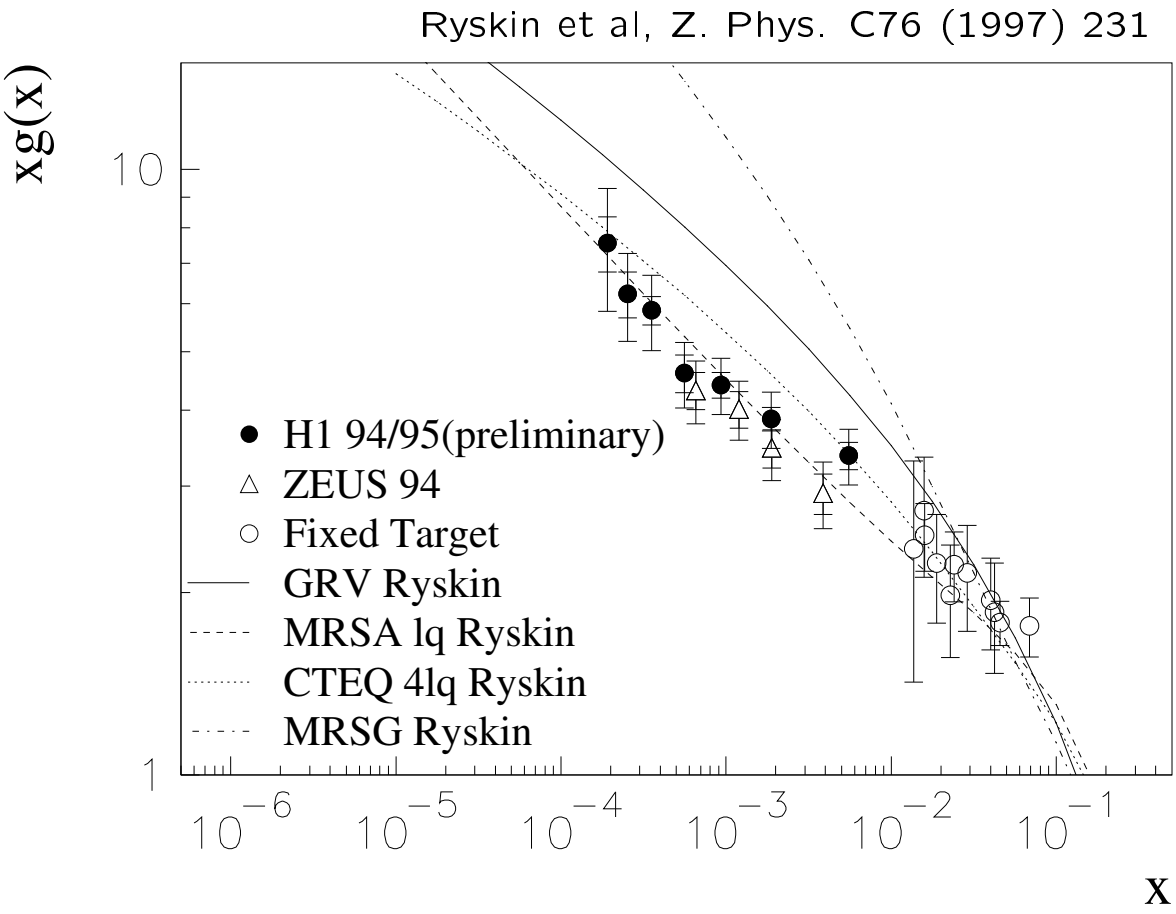
What experimental signatures for the region of pQCD validity ?

Elastic Vector-Meson Photoproduction Cross Sections



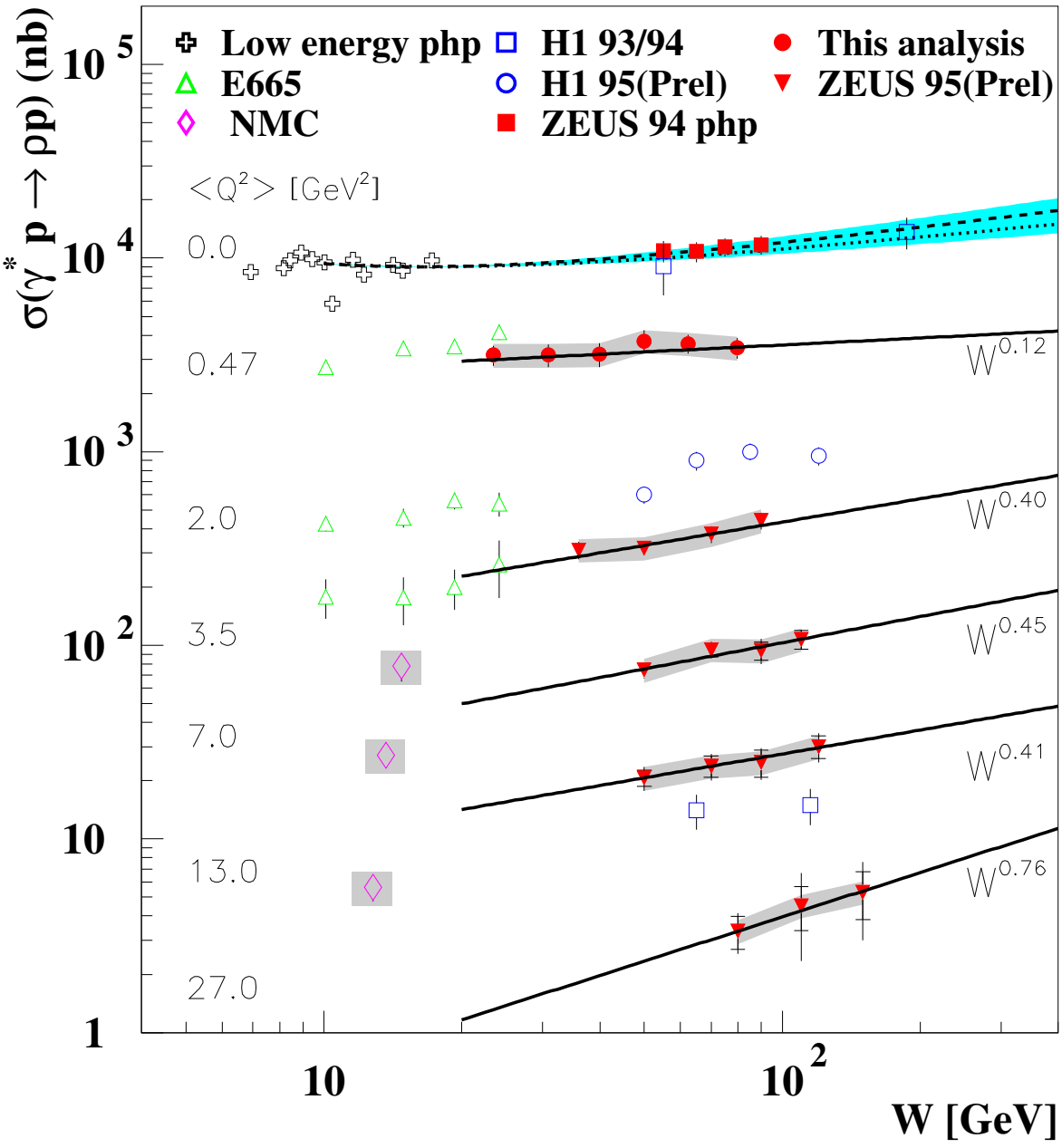
⇒Energy dependence for the J/ψ much steeper !

Elastic J/ψ Cross Sections



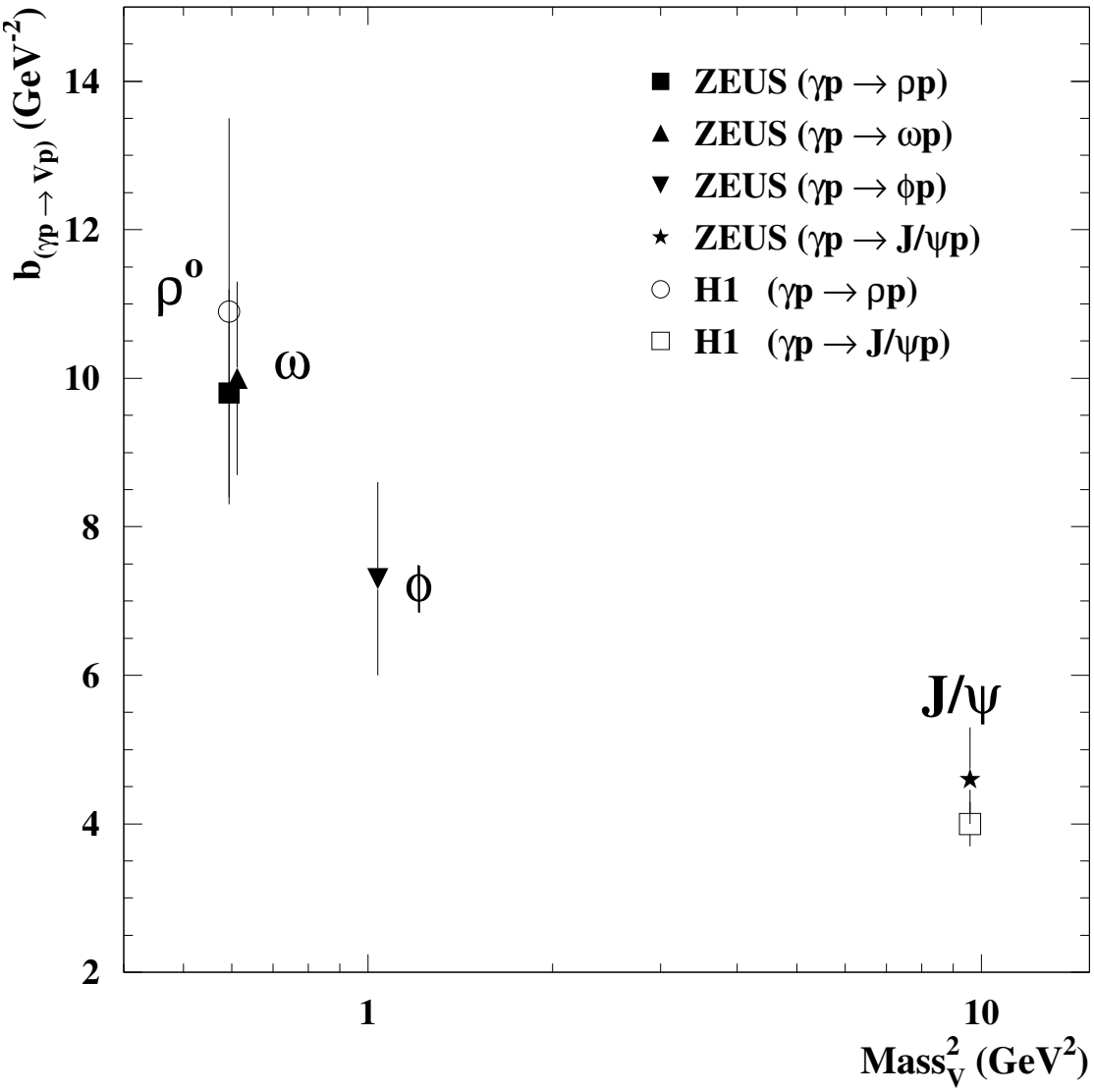
$\Rightarrow$ Can derive shape of gluon distribution !!

Elastic ρ^0 Cross Sections



$\Rightarrow$ Steepening with Q^2?

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

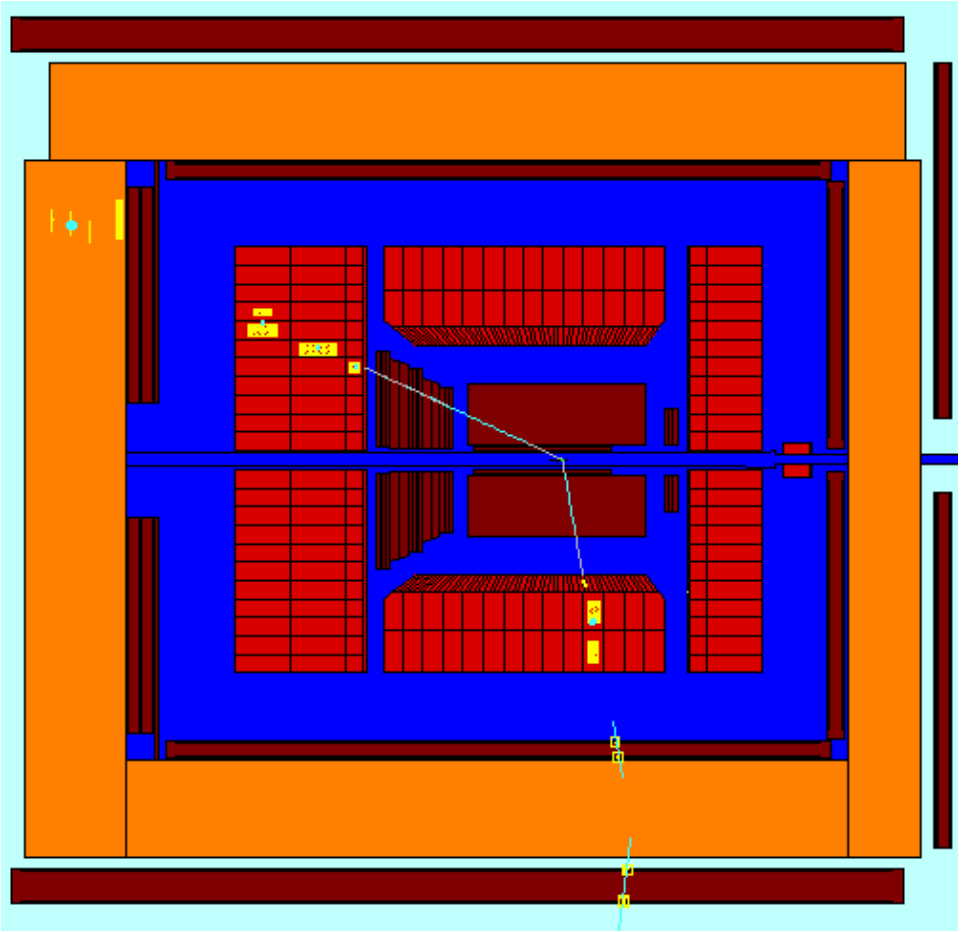


$$b = b_p + b_{J/\psi}: \quad b_{J/\psi} < 1\,\mathrm{GeV}^2$$

ZEUS Υ Signal

ZEUS: Phys. Lett. B437 (1998) 432

Measurement of Elastic Υ photoproduction at HERA



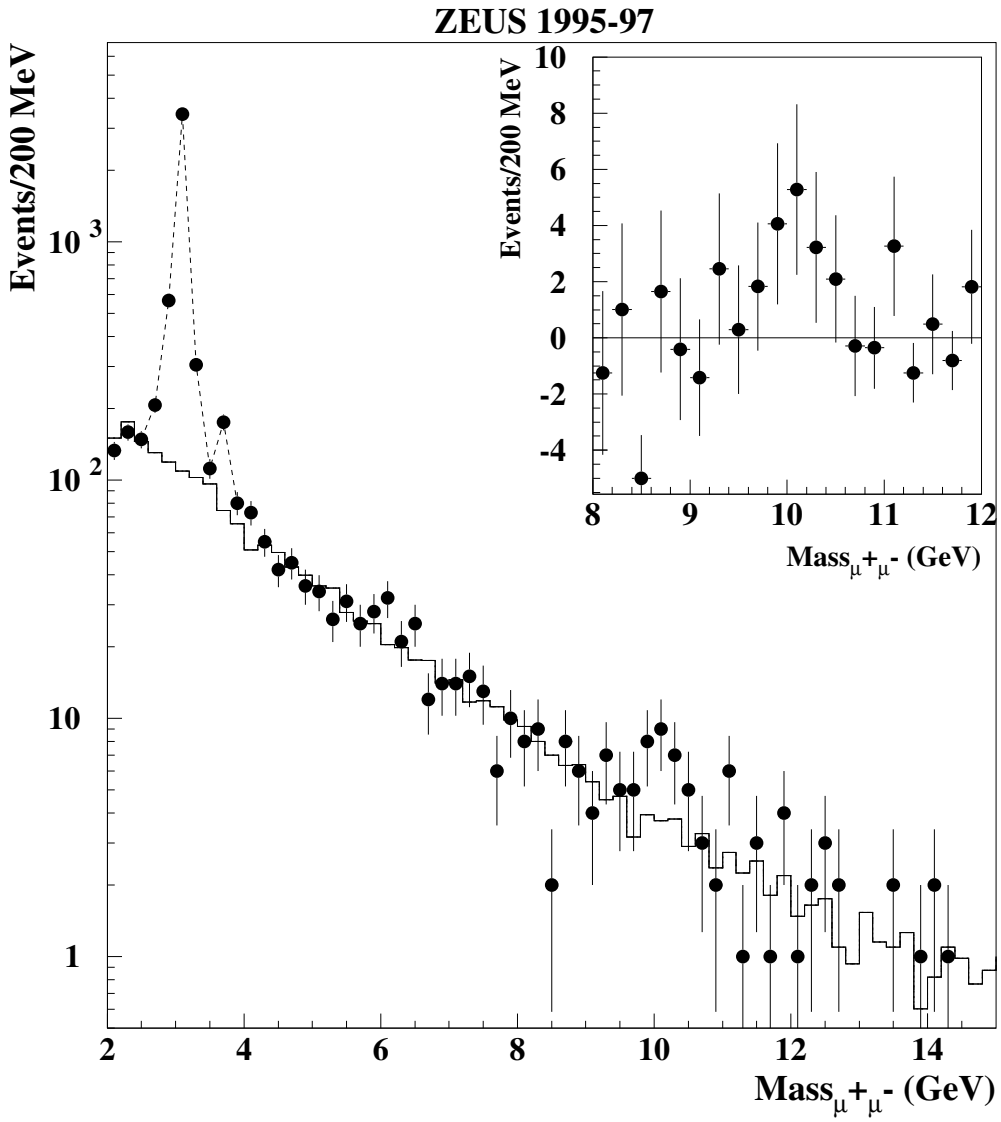
Example of elastic $\mu^+\mu^-$ photoproduction

Observation of Υ Photoproduction

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

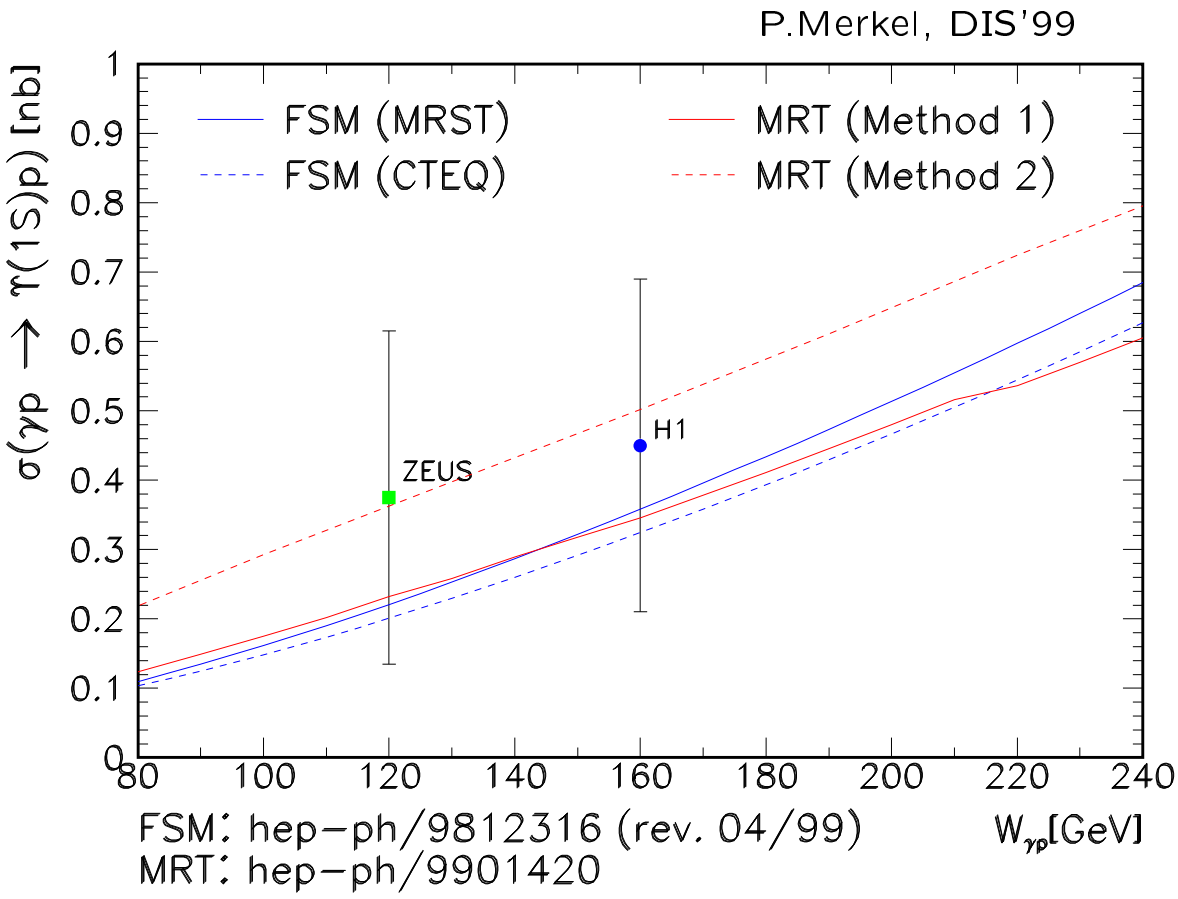
$$\gamma p \to \mu^+ \mu^- \, p$$

$80 < W < 280$ GeV $Q^2 < 1$ GeV^2



The Υ resonances are not resolved !

Υ Cross Section Calculations

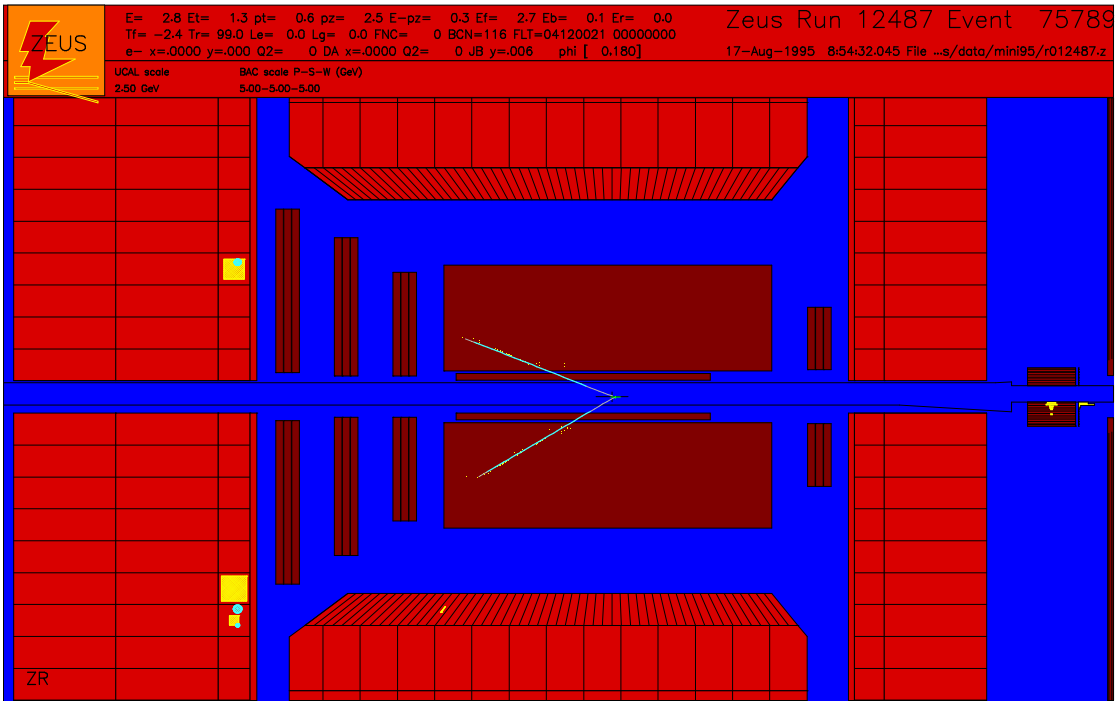


$\Rightarrow$ Sensitive to off-diagonal parton distributions !

Diffractive Production of ρ^0 Mesons

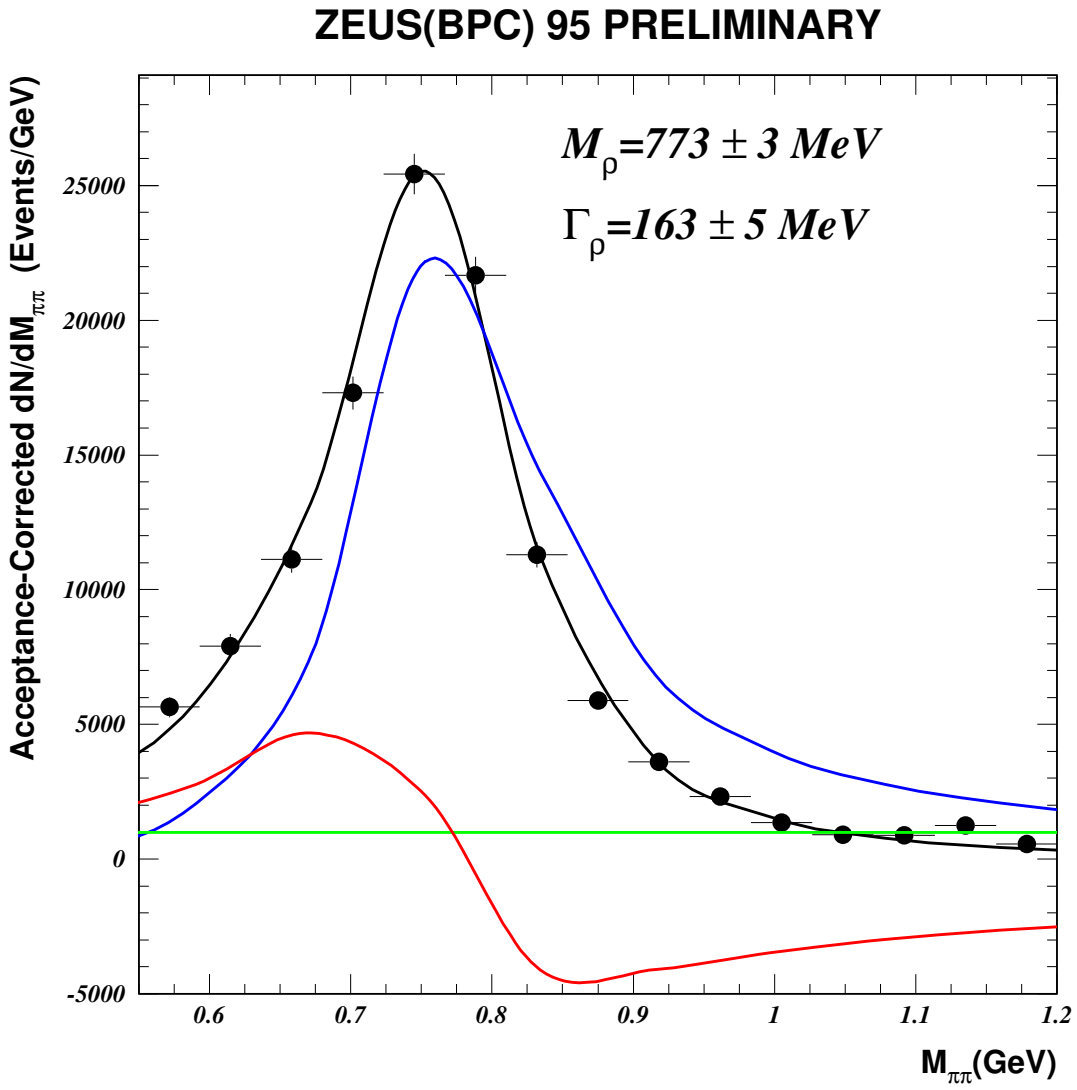
ZEUS: Eur. Phys. J. C6 (1999) 603

(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
$5k$ events	$3k$ events

$\pi^+\pi^-$ Invariant Mass Spectrum

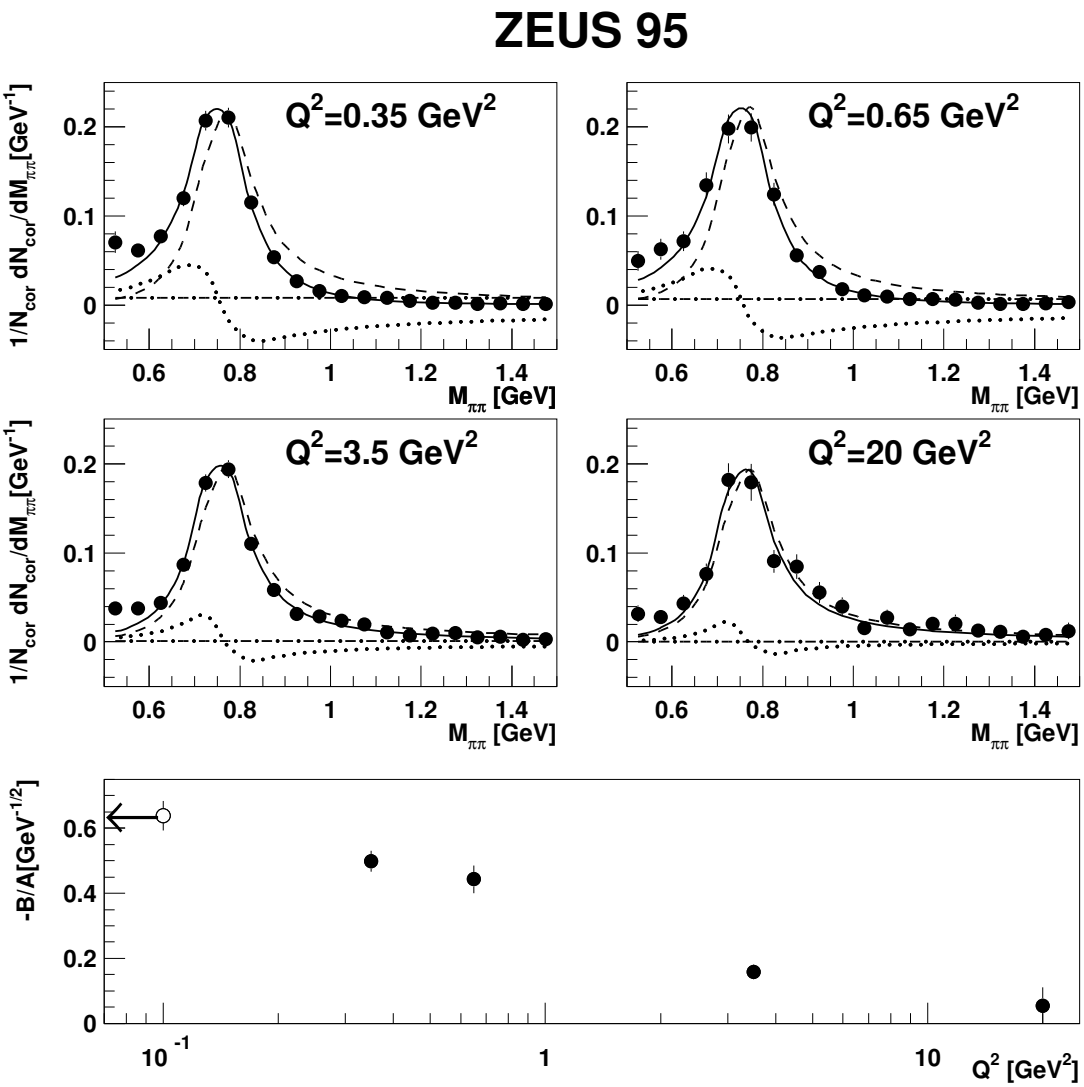


$$\frac{dN}{dM_{\pi\pi}} = \left| A \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} + B \right|^2$$

$\pi^+\pi^-$ Mass Spectrum Skewing

ZEUS: Eur. Phys. C6 (1999) 603

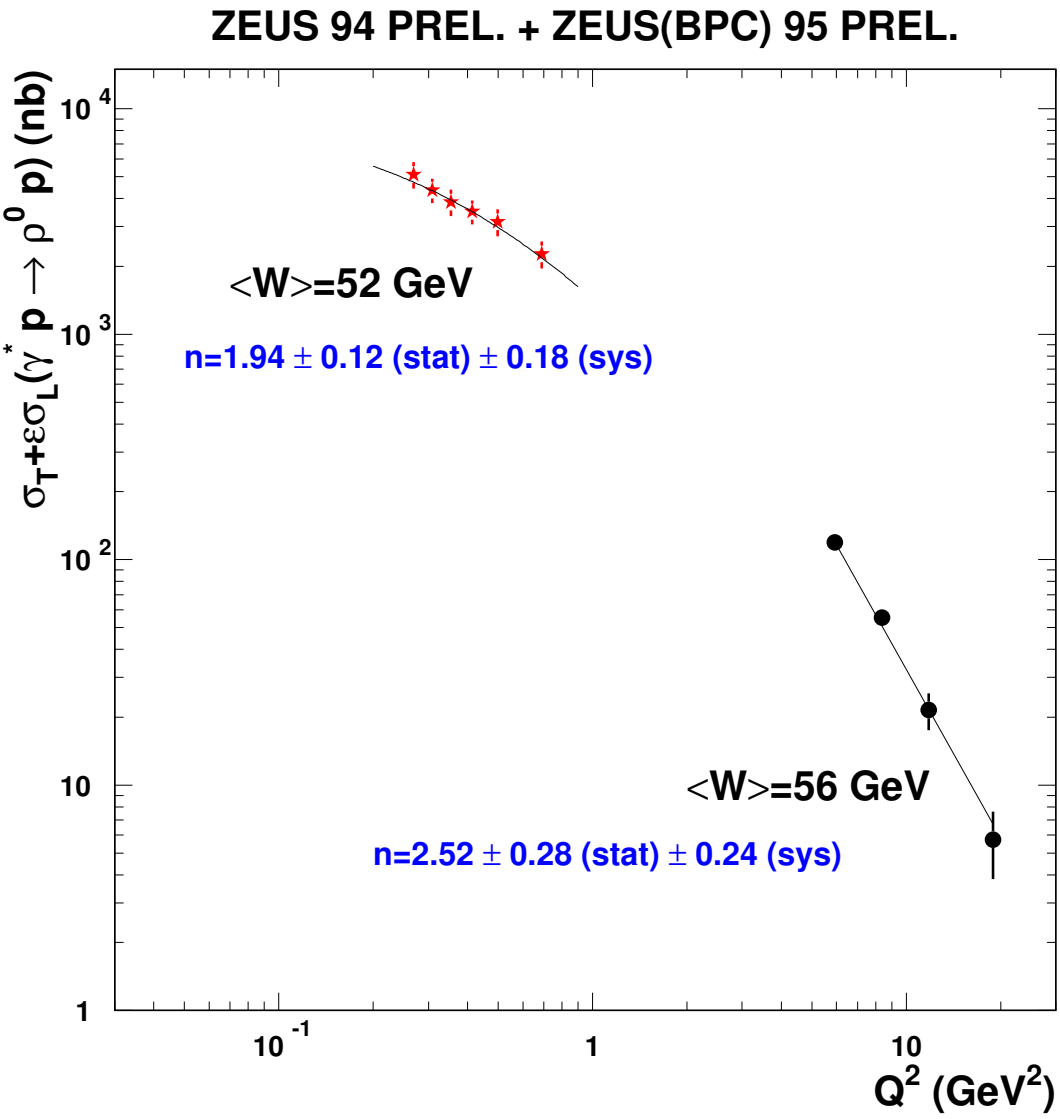
$$\frac{dN}{dM_{\pi\pi}} = \left| A\frac{\sqrt{M_{\pi\pi}M_\rho\Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + iM_\rho\Gamma_\rho} + B \right|^2$$



$\Rightarrow$ Skewing disappears at high Q^2

$\sigma_T + \epsilon\,\sigma_L(\gamma^* p \to \rho^0 p)$

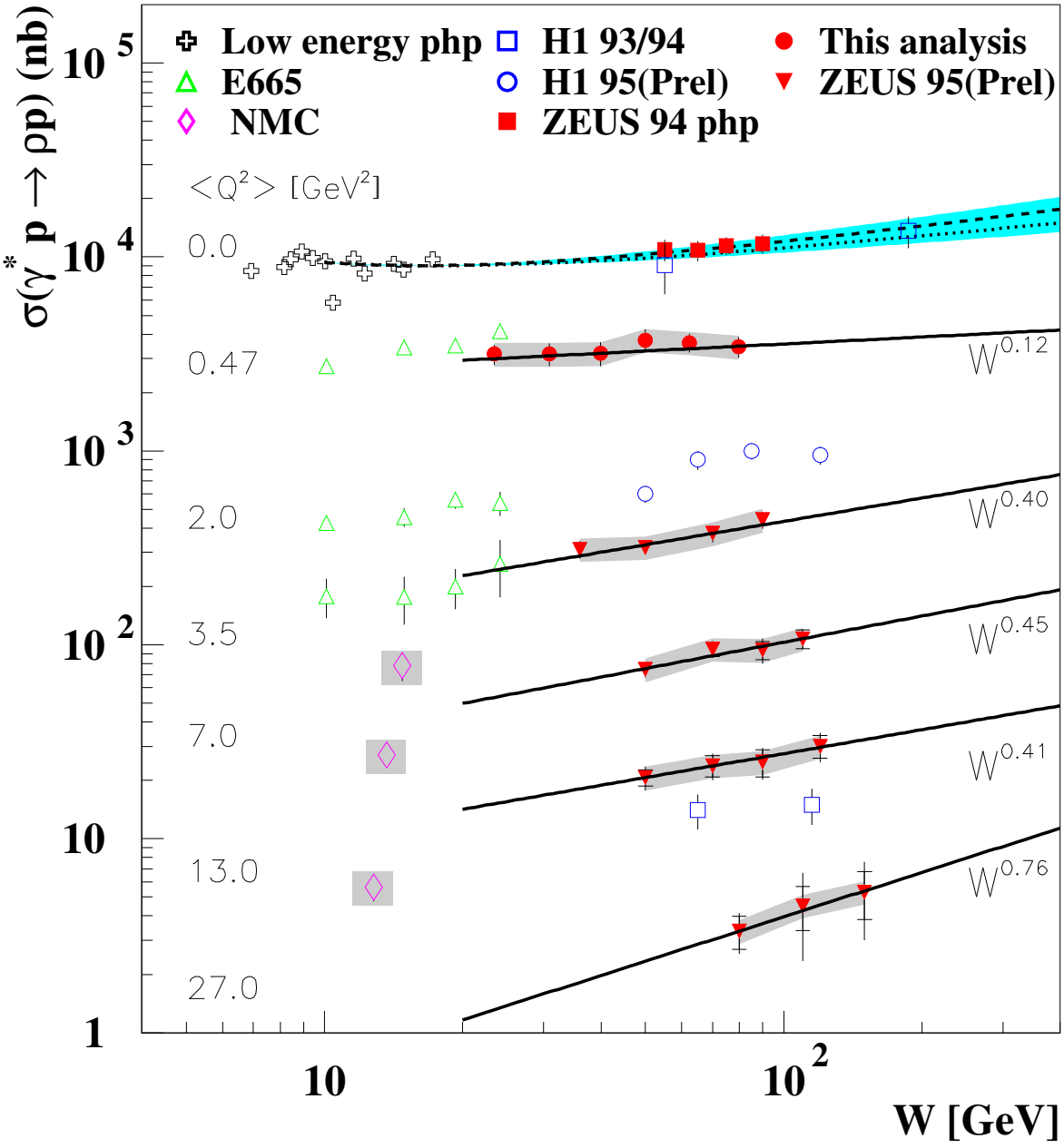
T.Monteiro, DIS'97



Fit to the shape $(Q^2 + M_\rho^2)^{-n}$

but notice the mixture of σ_L and σ_T ($\epsilon \approx 1$) ...

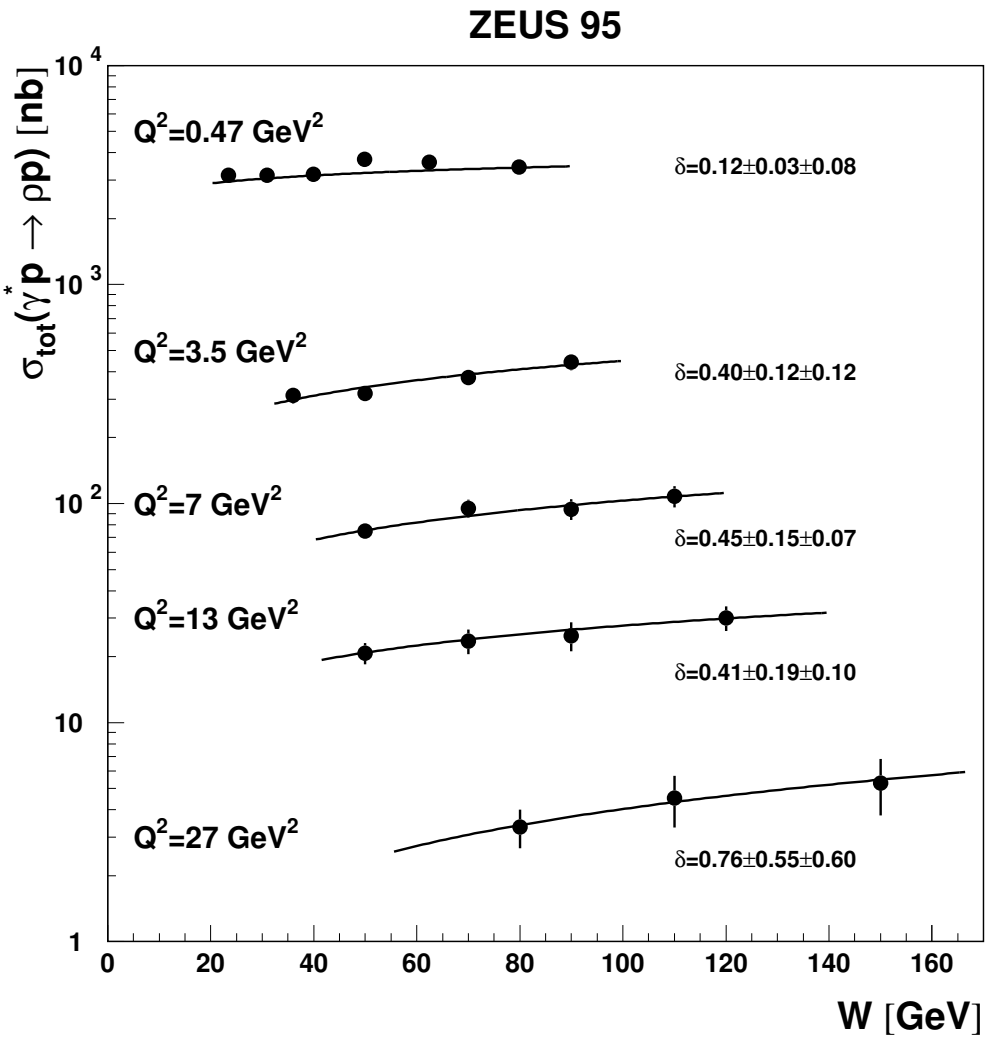
Elastic ρ^0 Cross Sections (I)



$\Rightarrow$ Steepening with Q^2?

Elastic ρ^0 Cross Sections (II)

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

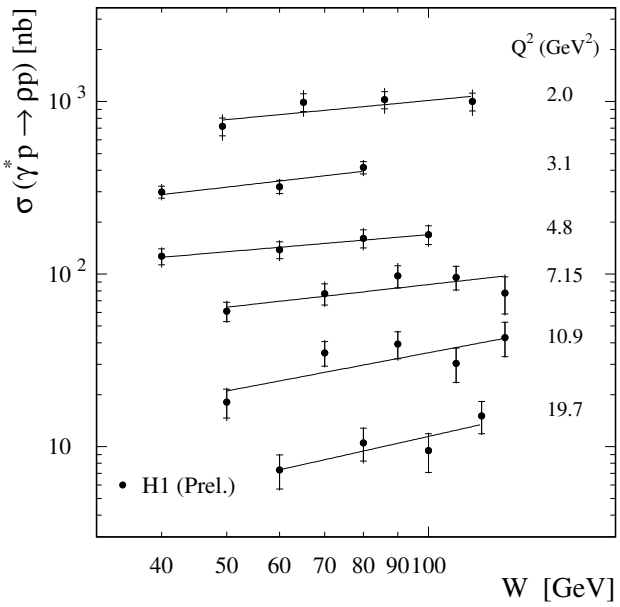


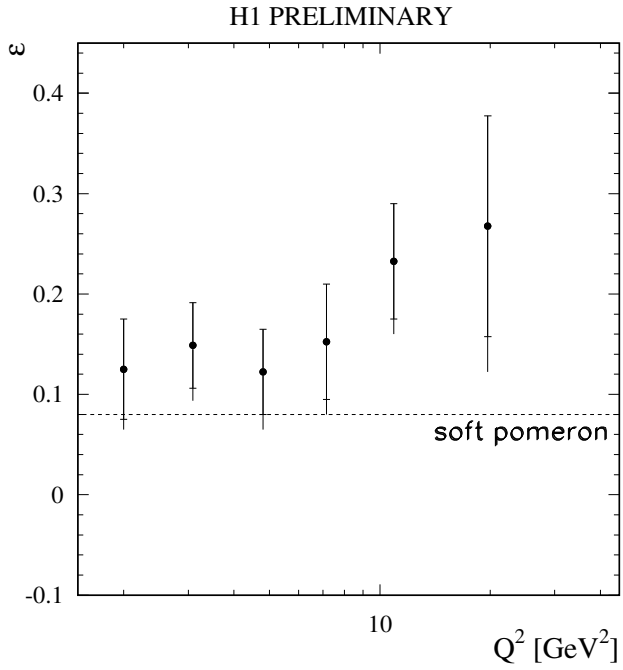
$\Rightarrow$ Steepening with Q^2 expected in pQCD

$\Rightarrow \approx 2\sigma$ effect

Elastic ρ^0 Cross Sections (III)

H1: hep-ex/9902019



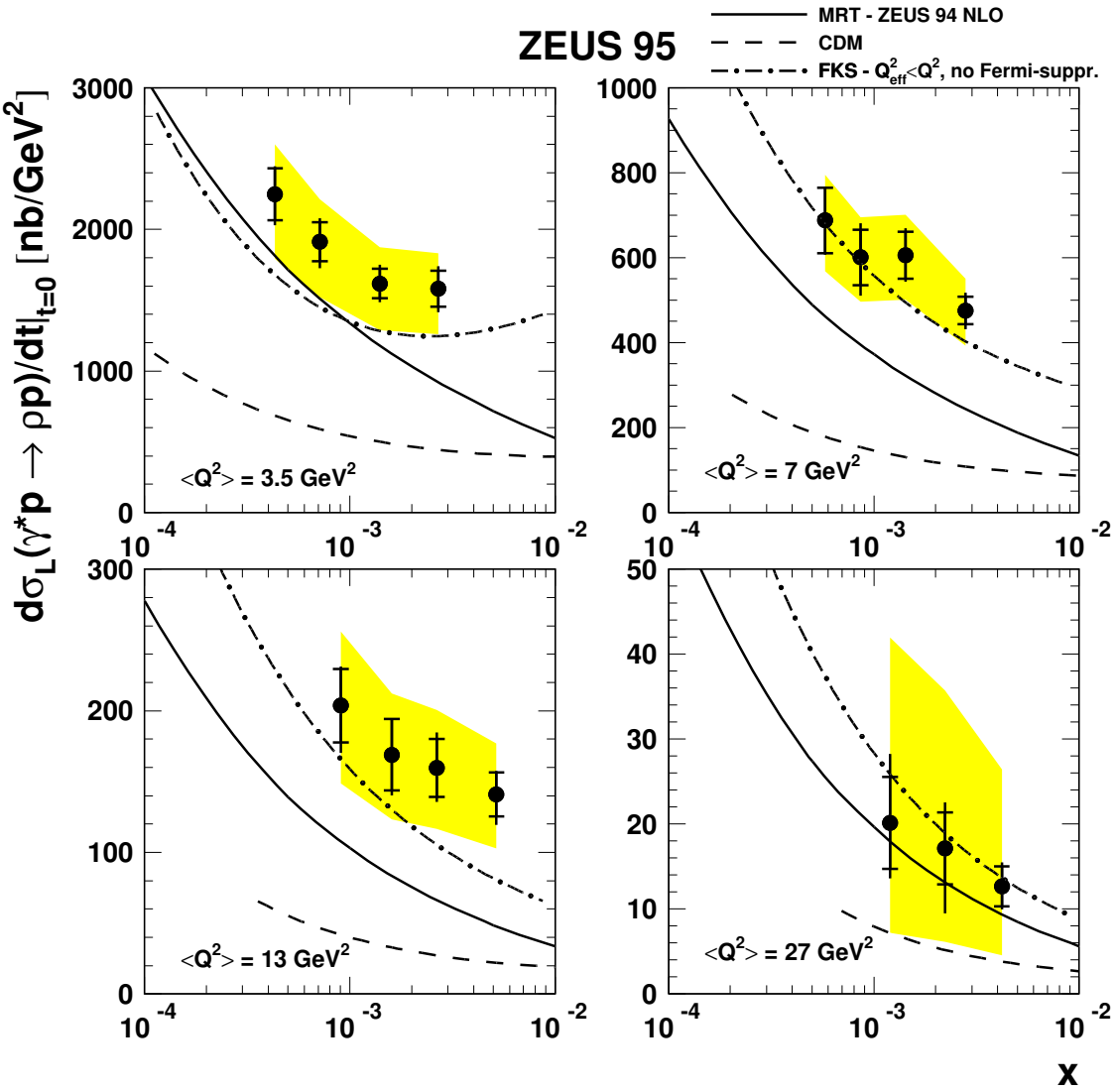


⇒ H1 data consistent and with similar sensitivity

Elastic ρ^0 Cross Sections (IV)

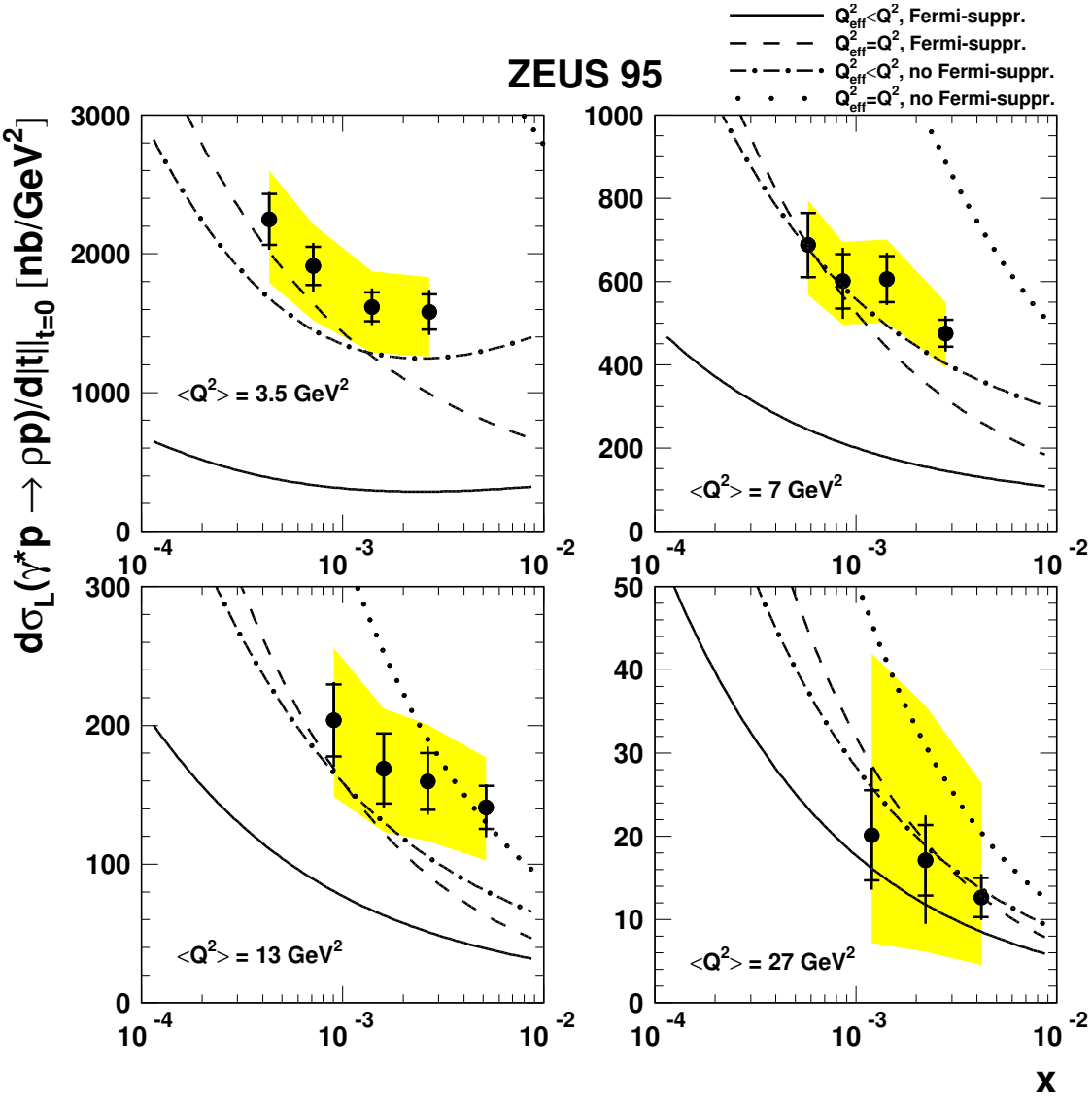
ZEUS longitudinal cross sections compared to models

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



Elastic ρ^0 Cross Sections (V)

ZEUS longitudinal cross sections compared to FKS

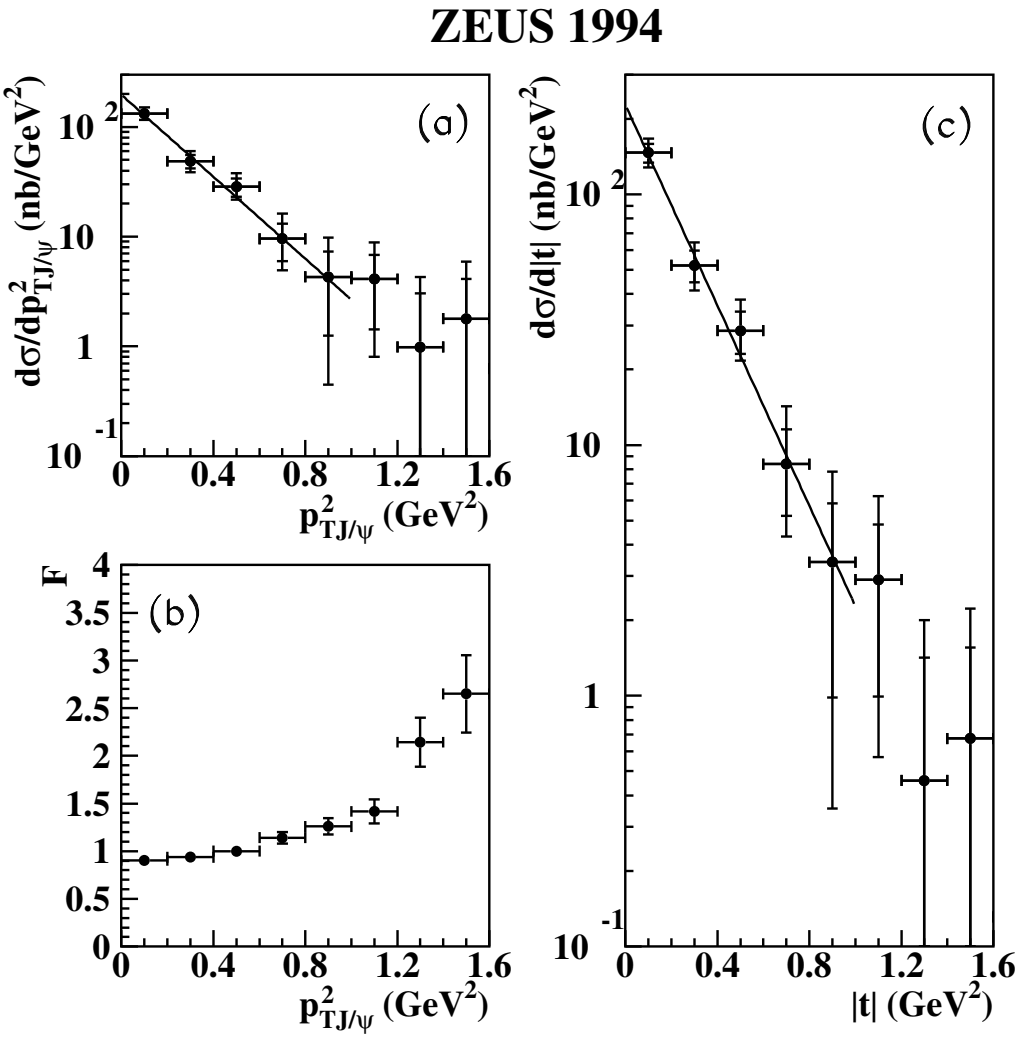


$\Rightarrow$ Effects of rescaling and of ρ^0 wave function comparable but with differing x dependence

$\Rightarrow$ Present experimental accuracy allows distinction

The Exponential Slope in $|t|$

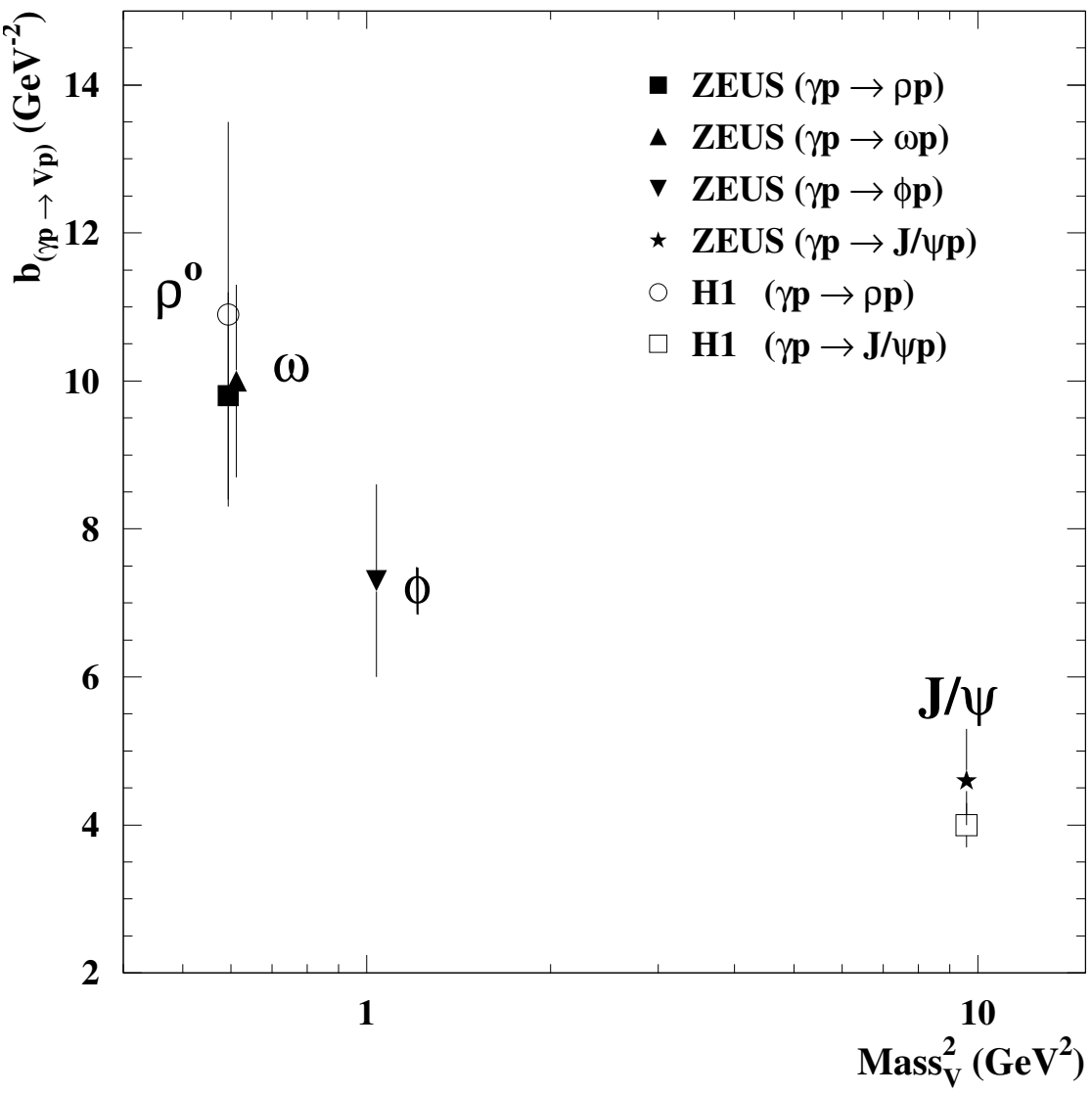
Photoproduction of J/ψ Mesons



$$b_{J/\psi} = 4.6 \pm 0.4\,(stat)^{+0.4}_{-0.6}\,(sys)\ \text{GeV}^{-2}$$

(Reminder : $b_{\rho^0} = 9.8 \pm 0.8\,(stat) \pm 1.1\,(sys)\ \text{GeV}^{-2}$)

t-Slope vs M^2_{VM}

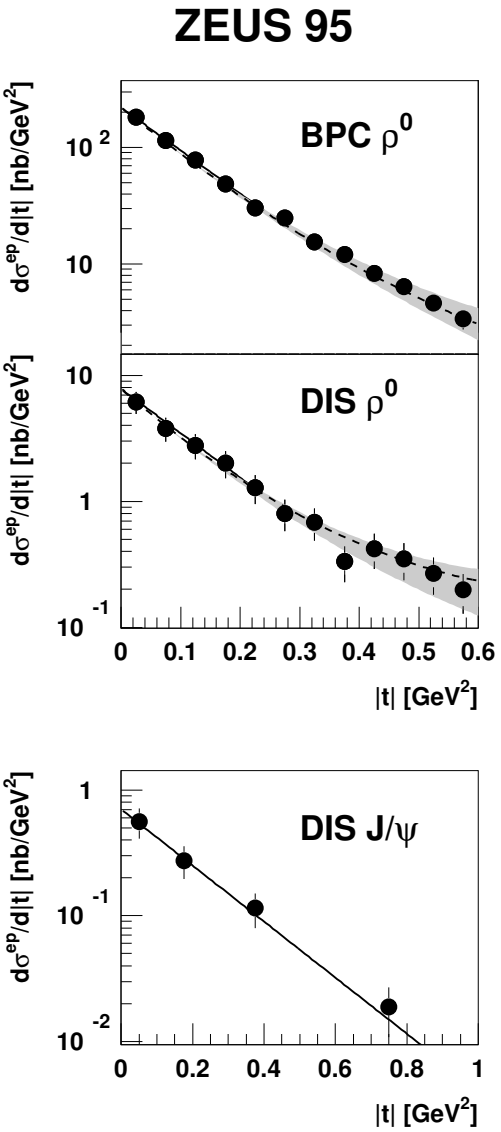


$$b = b_p + b_{J/\psi}: \quad b_{J/\psi} < 1\,\mathrm{GeV}^2$$

t-Distributions

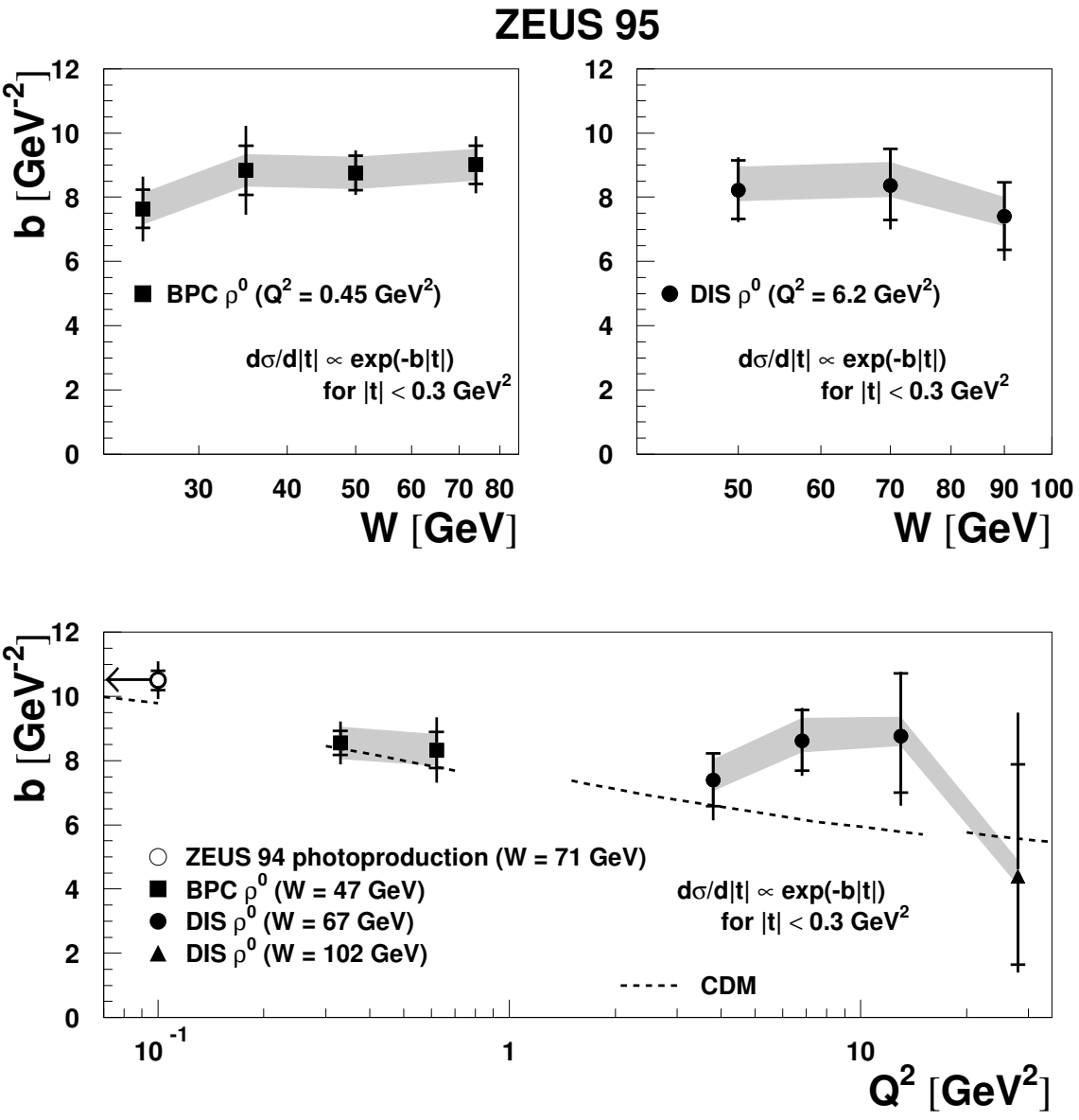
Systematic uncertainties

in determining the exponential slope b



$\Rightarrow$ Uncertainty in dissociative contribution dominates

Exponential slope b for ρ^0

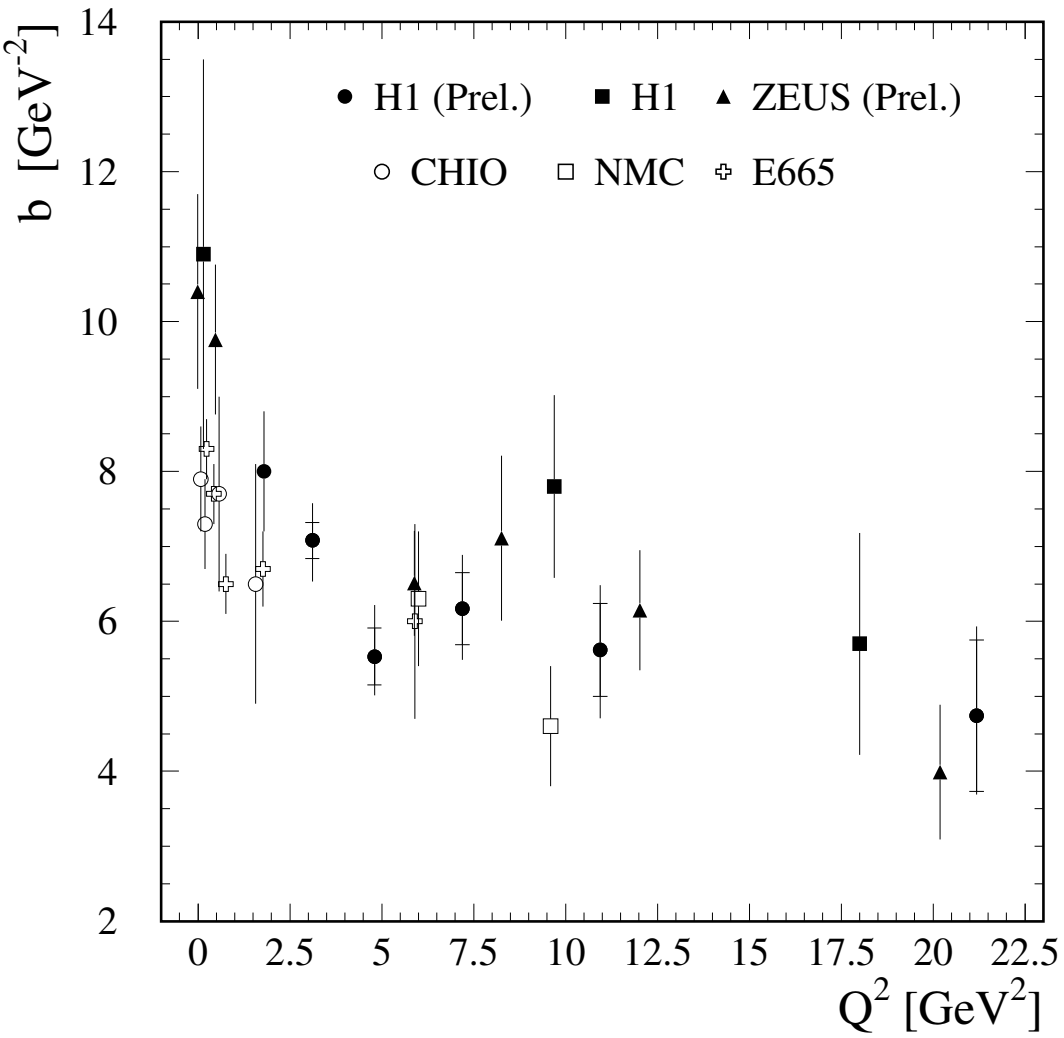


$\Rightarrow$ Inconclusive on shrinkage

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

New values for b from H1 for ρ^0

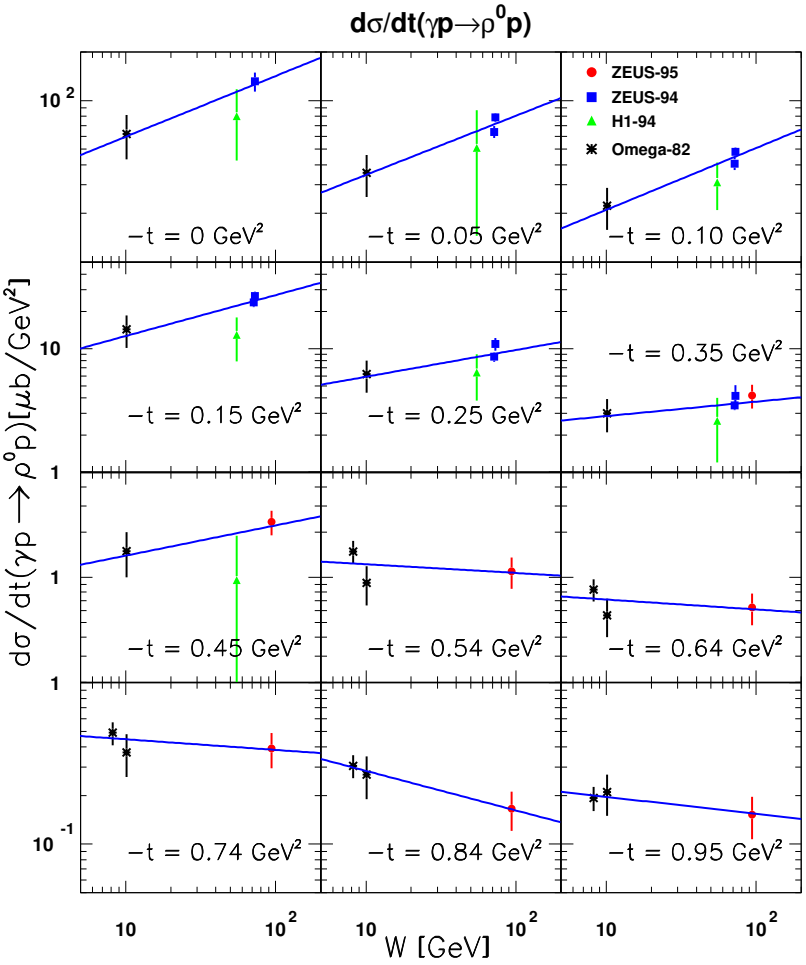
H1: hep-ex/9902019



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

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

ZEUS 1995 preliminary

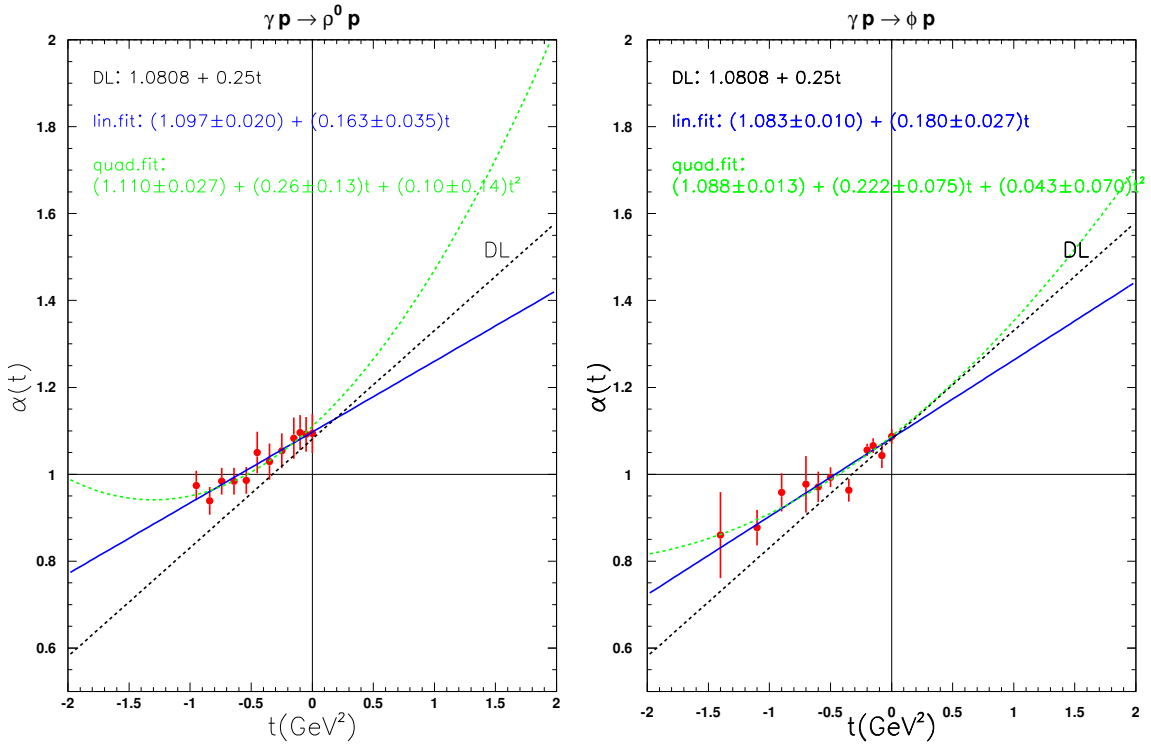


$$\sigma \propto W^{4(\alpha_{I\!P}(t)-1)}, \quad \alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$$

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

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

ZEUS 1995 preliminary

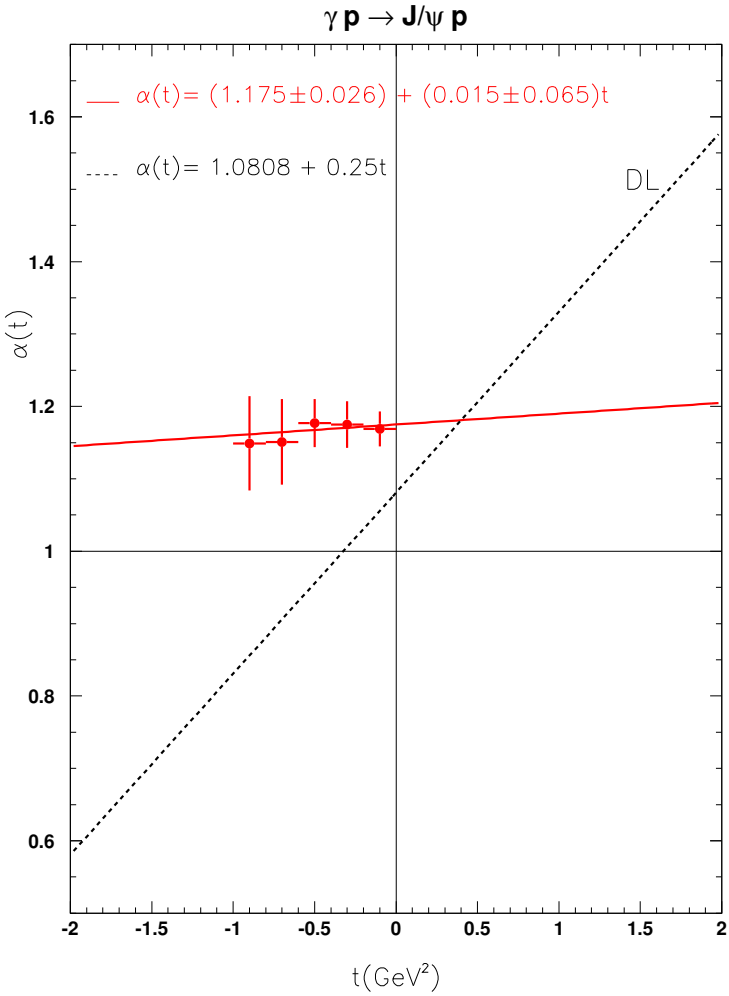


	$\alpha_{I\!P}(0)$	$\alpha'_{I\!P}$
ρ^0:	1.097 ± 0.020	0.163 ± 0.035 GeV^{-2}
ϕ:	1.083 ± 0.010	0.180 ± 0.027 GeV^{-2}

$\Rightarrow$ 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}

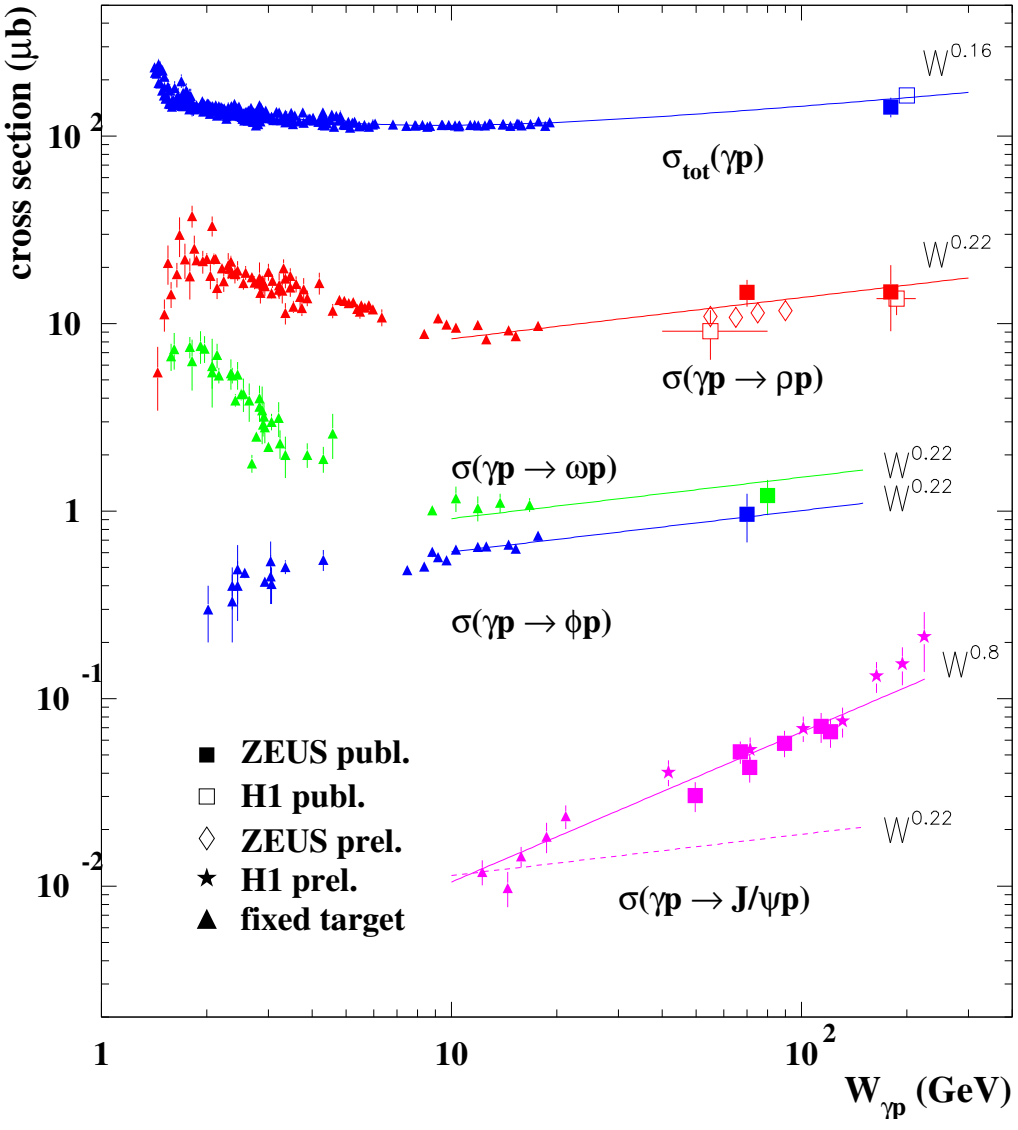
$\Rightarrow$ Shrinkage absent for J/ψ !

Vector Meson Production Ratios

If direct e–m coupling to quarks without form factors

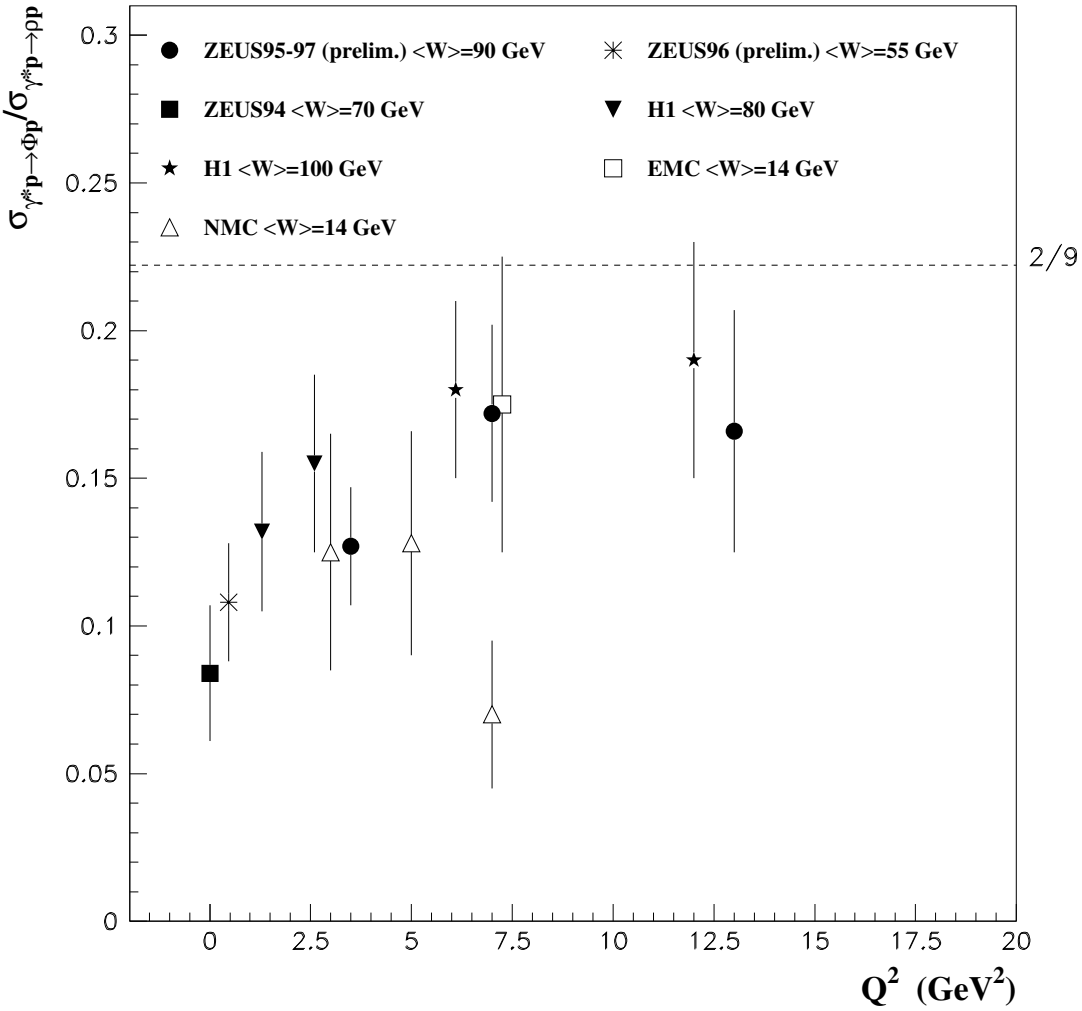
$$\rho^0 \;:\; \omega \;:\; \phi \;:\; J/\psi \;:\; \Upsilon$$

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



Ratio of ϕ to ρ^0

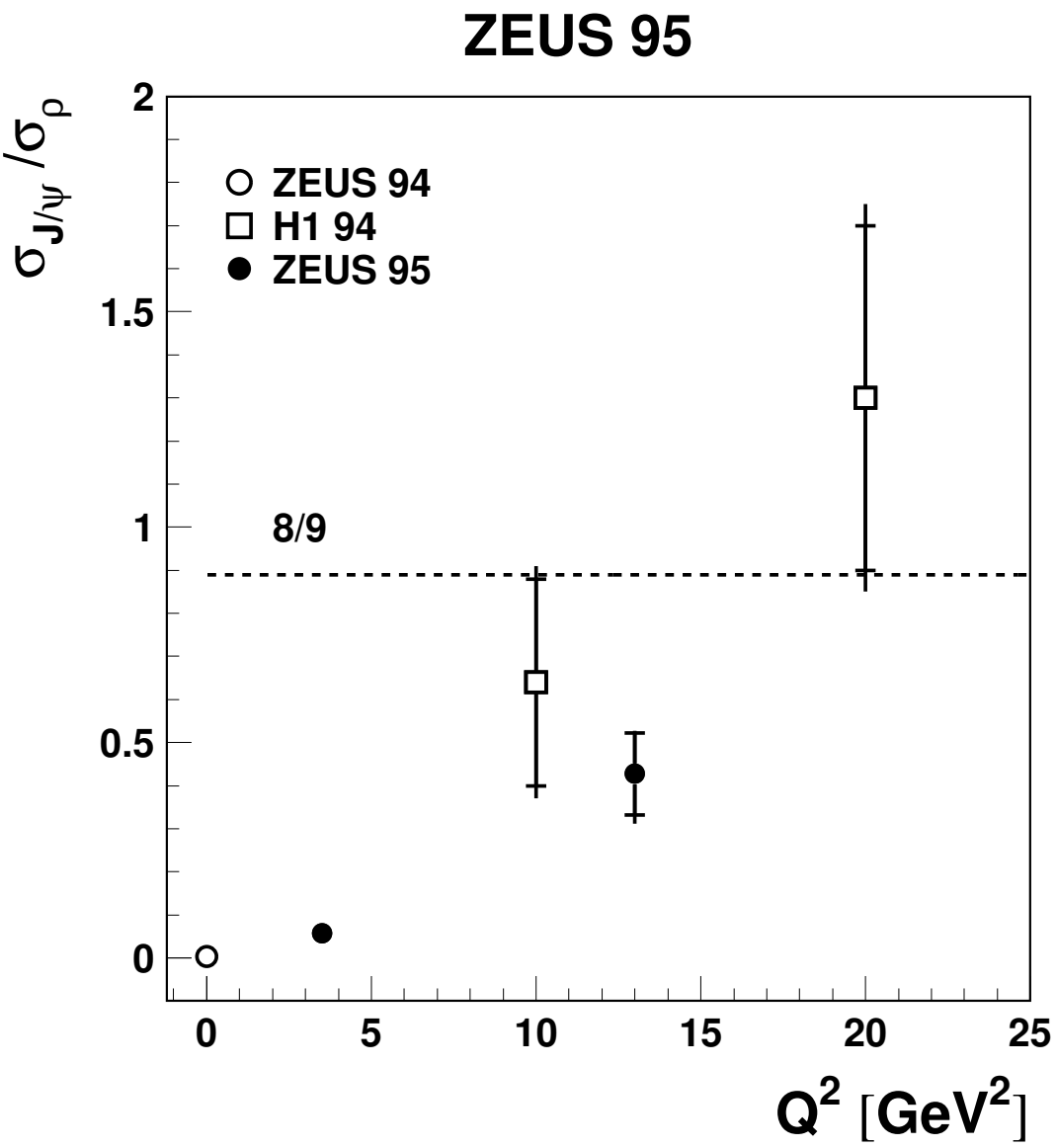
ZEUS ICHEP Abstract 793



$\Rightarrow \phi/\rho^0$ ratio rising with Q^2

Ratio of J/ψ to ρ^0

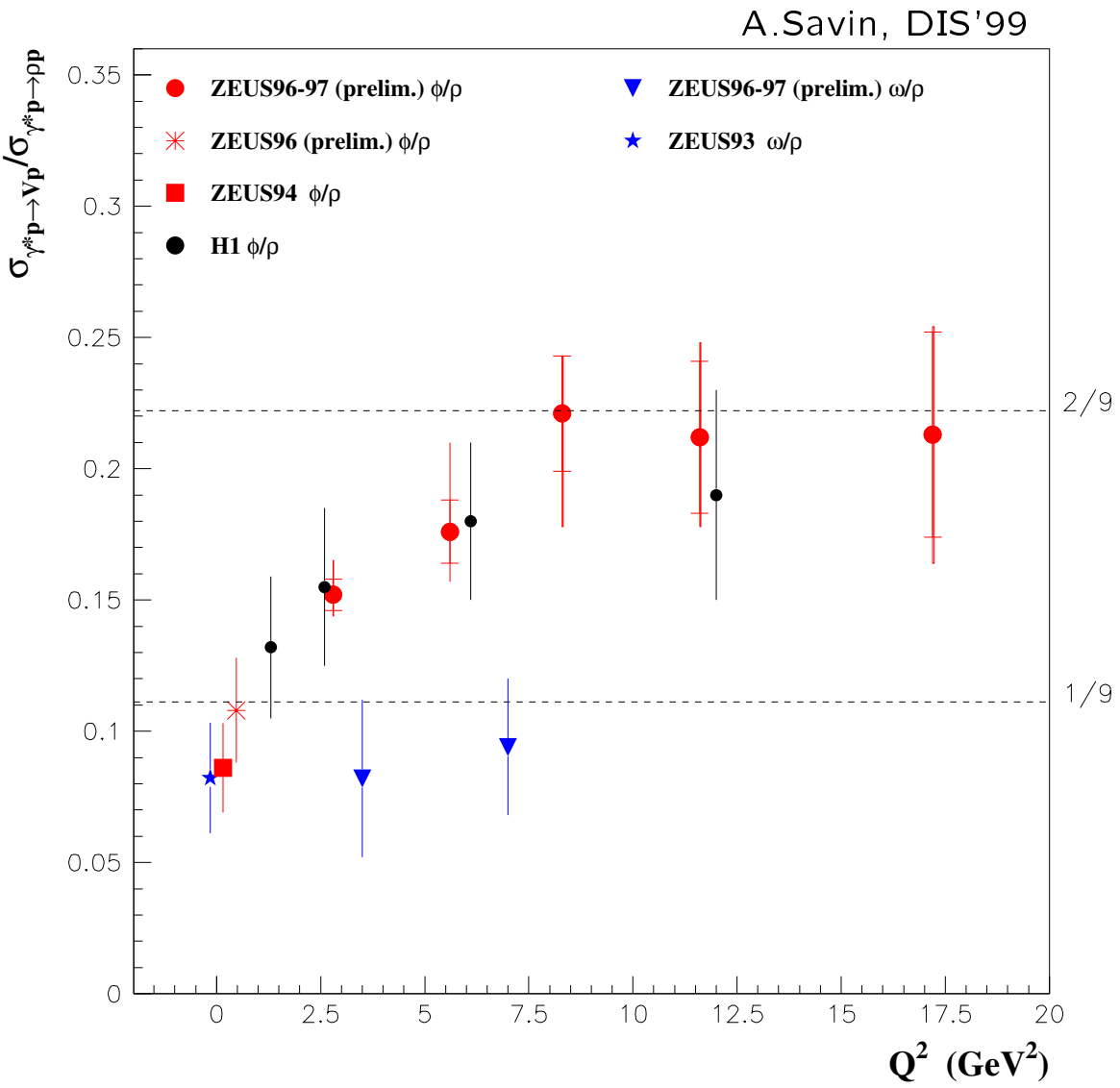
ZEUS: Eur. Phys. J. C6 (1999) 603



$\Rightarrow$ $J/\psi/\rho^0$ ratio rising with Q^2

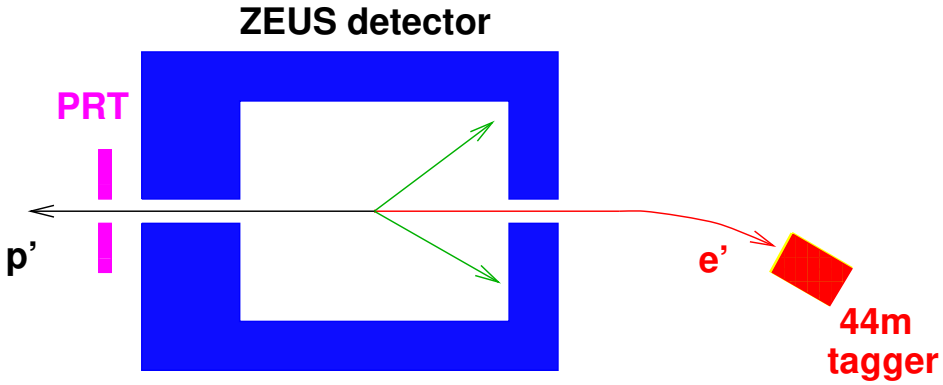
Flavor symmetry requires higher Q^2 than for ϕ

Ratio of ω to ρ^0



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

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}

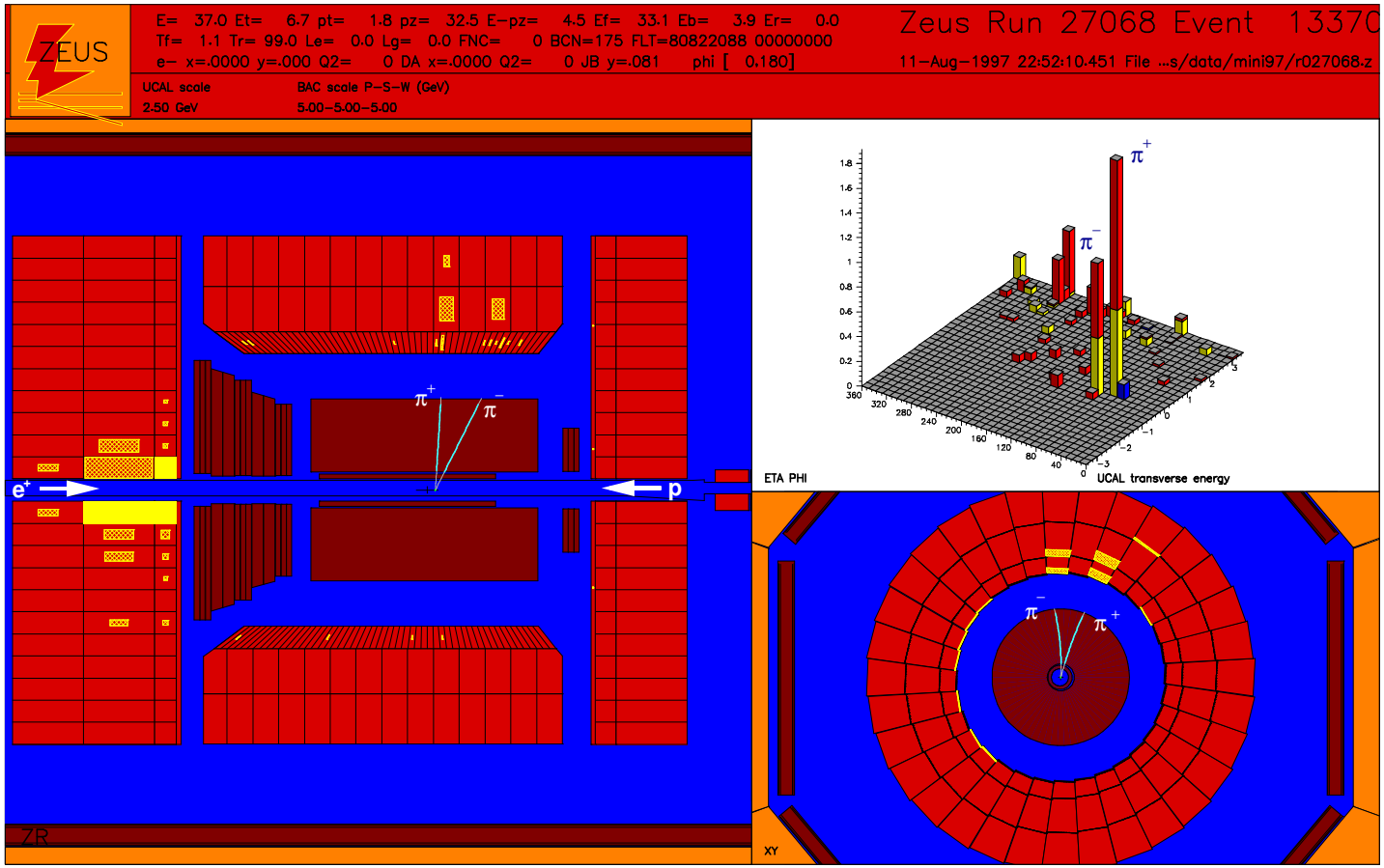
Elastic kinematic limit for ρ^0 $\longrightarrow$ $2 \cdot 10^{-8} < |t| < 2$ GeV^2

ZEUS 1996/97 preliminary

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

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

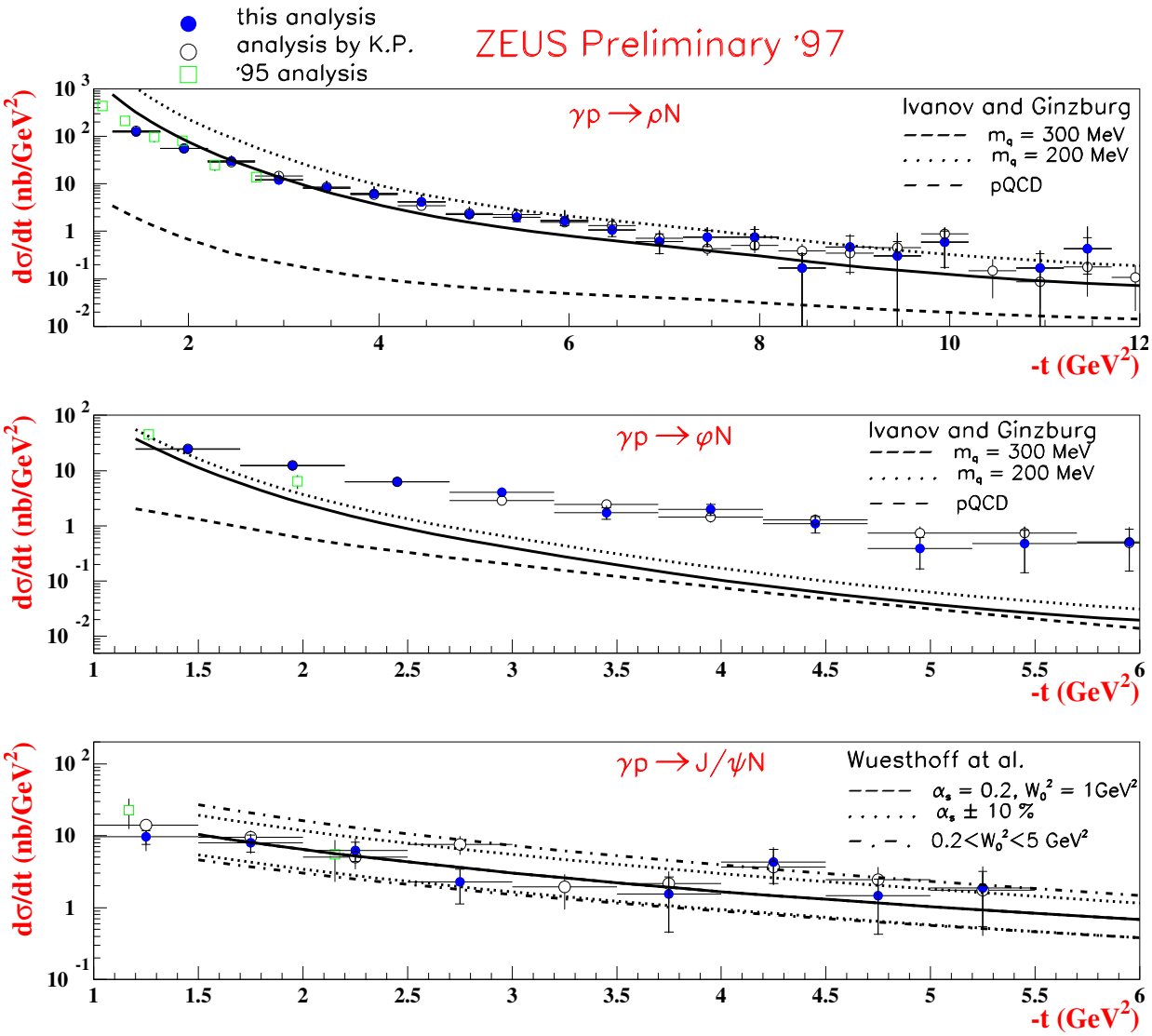
Candidate Event for Diffractive ρ^0 Photoproduction at High $|t|$



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

High $|t|$ VM Cross Sections $\frac{d\sigma}{dt}$

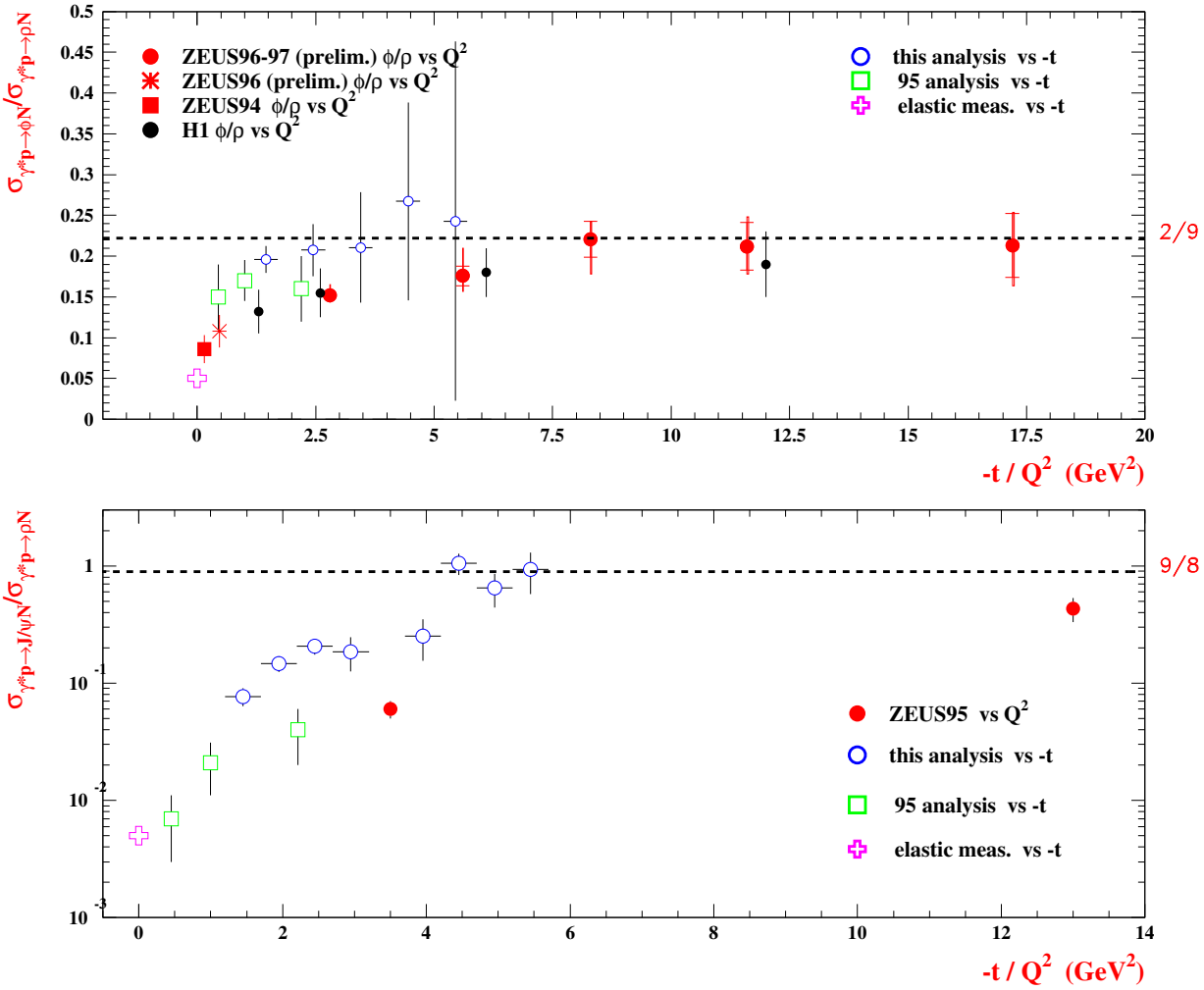
ZEUS 1995-97 preliminary



$\Rightarrow$ Very hard spectrum at high $|t|$!

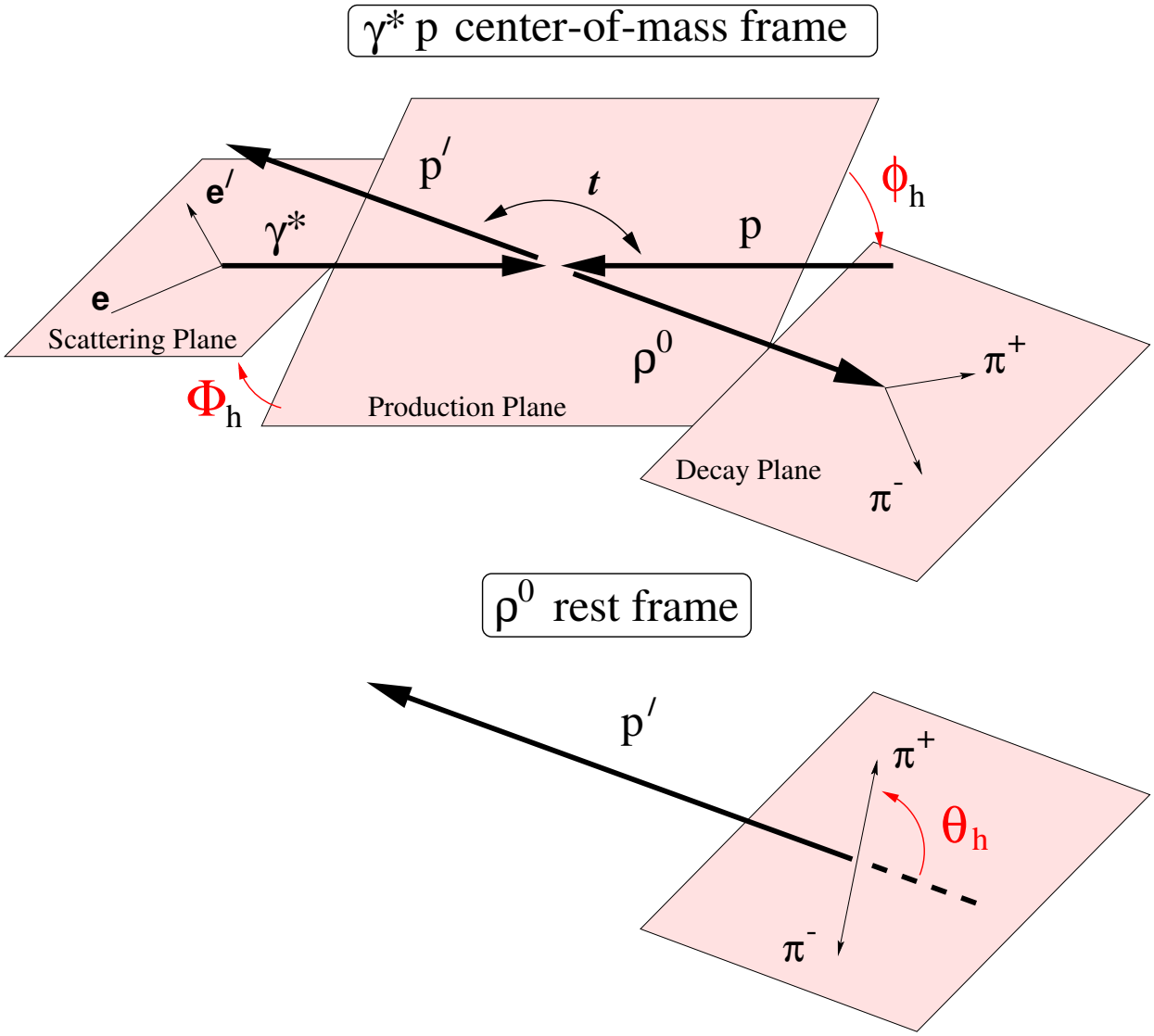
VM Production Ratios at High $|t|$

ZEUS 1995-97 preliminary



⇒ Supports idea of point-like coupling at high $|t|$!

Helicity Structure of Diffractive Processes



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

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

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

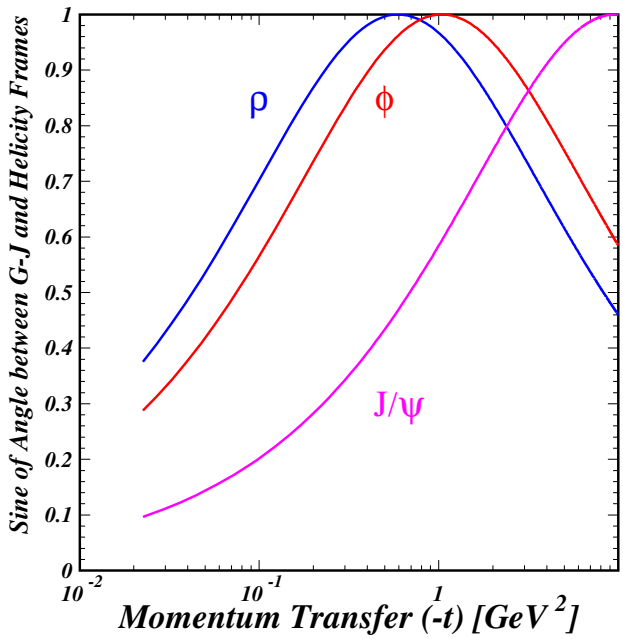
$$r_{ik}^{\alpha} = \begin{cases} \dfrac{\rho_{ik}^{\alpha}}{1+\epsilon R} & \alpha = 1-3 \text{ (Trans.)} \\ \dfrac{\sqrt{R}\,\rho_{ik}^{\alpha}}{1+\epsilon R} & \alpha = 5-8 \text{ (L/T int.)} \end{cases}$$

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



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

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

3-D Decay-Angle Distribution

(15 linearly independent parameters)

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

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

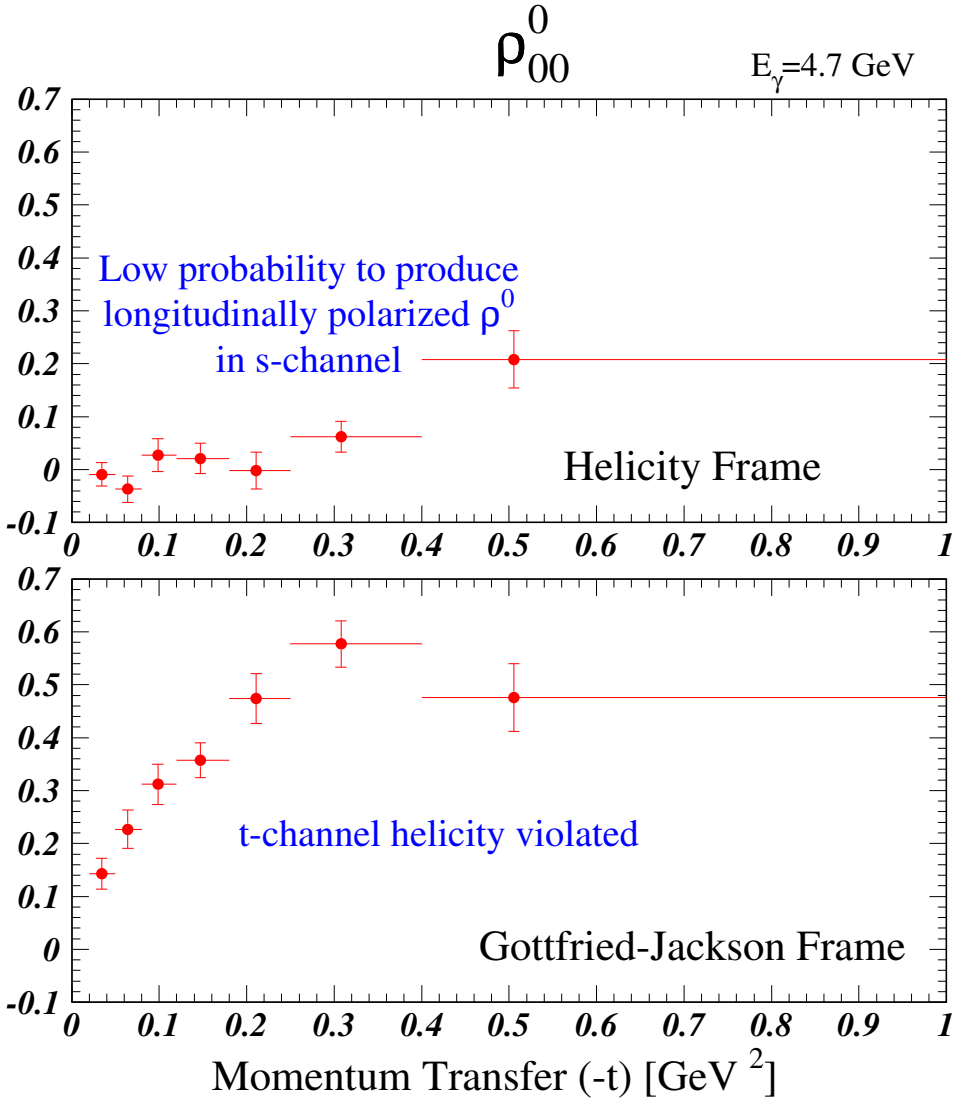
$$-\varepsilon\cos 2\Phi_h(\ r^1_{11}\sin^2\theta_h + r^1_{00}\cos^2\theta_h$$
$$-\sqrt{2}\,\mathrm{Re}\, r^1_{10}\ \sin 2\theta_h\cos\phi_h$$
$$-r^1_{1-1}\sin^2\theta_h\cos 2\phi_h\ )$$
$$-\varepsilon\sin 2\Phi_h(\ \sqrt{2}\,\mathrm{Im}\, r^2_{10}\ \sin 2\theta_h\sin\phi_h$$
$$+\mathrm{Im}\, r^2_{1-1}\sin^2\theta_h\sin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

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

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

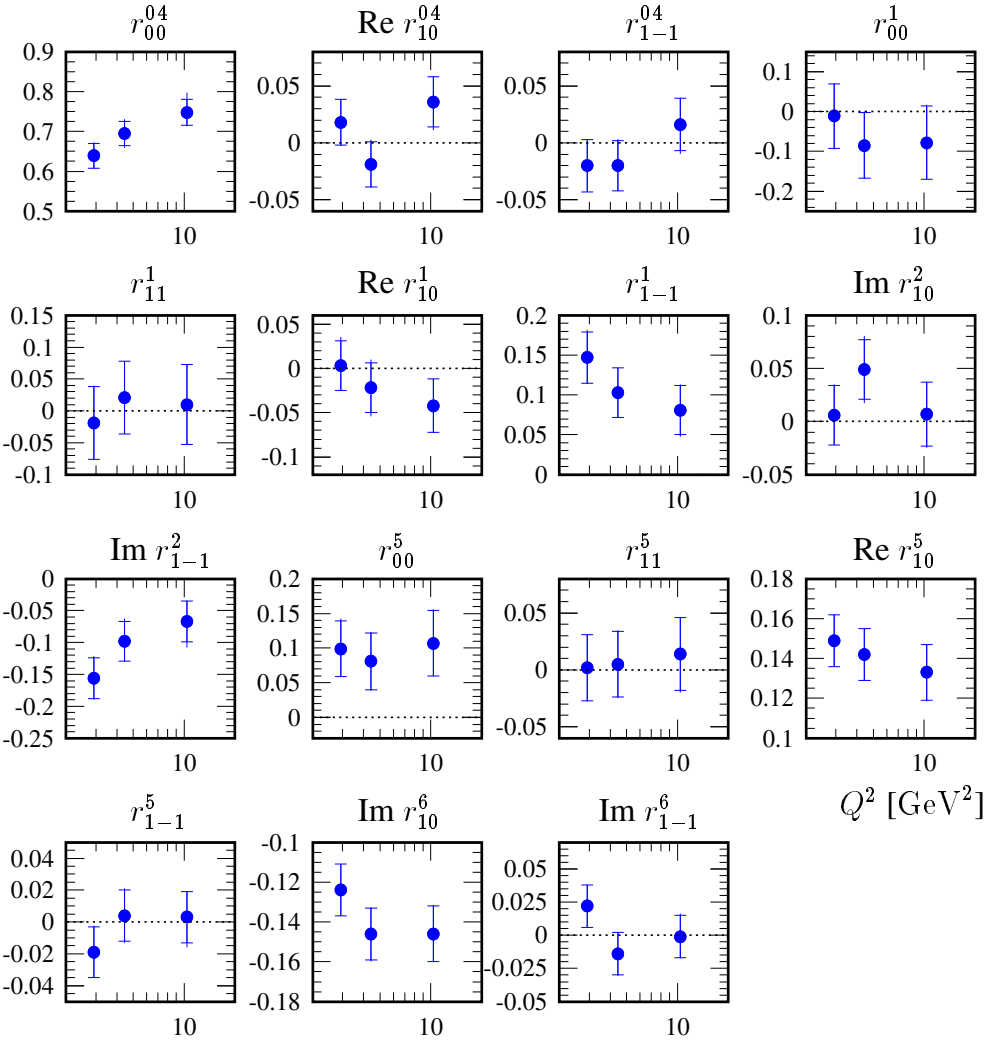
Gilman et al PL B31 (1970) 387

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

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

H1 hep-ex/9902019

submitted to Eur.Phys. C

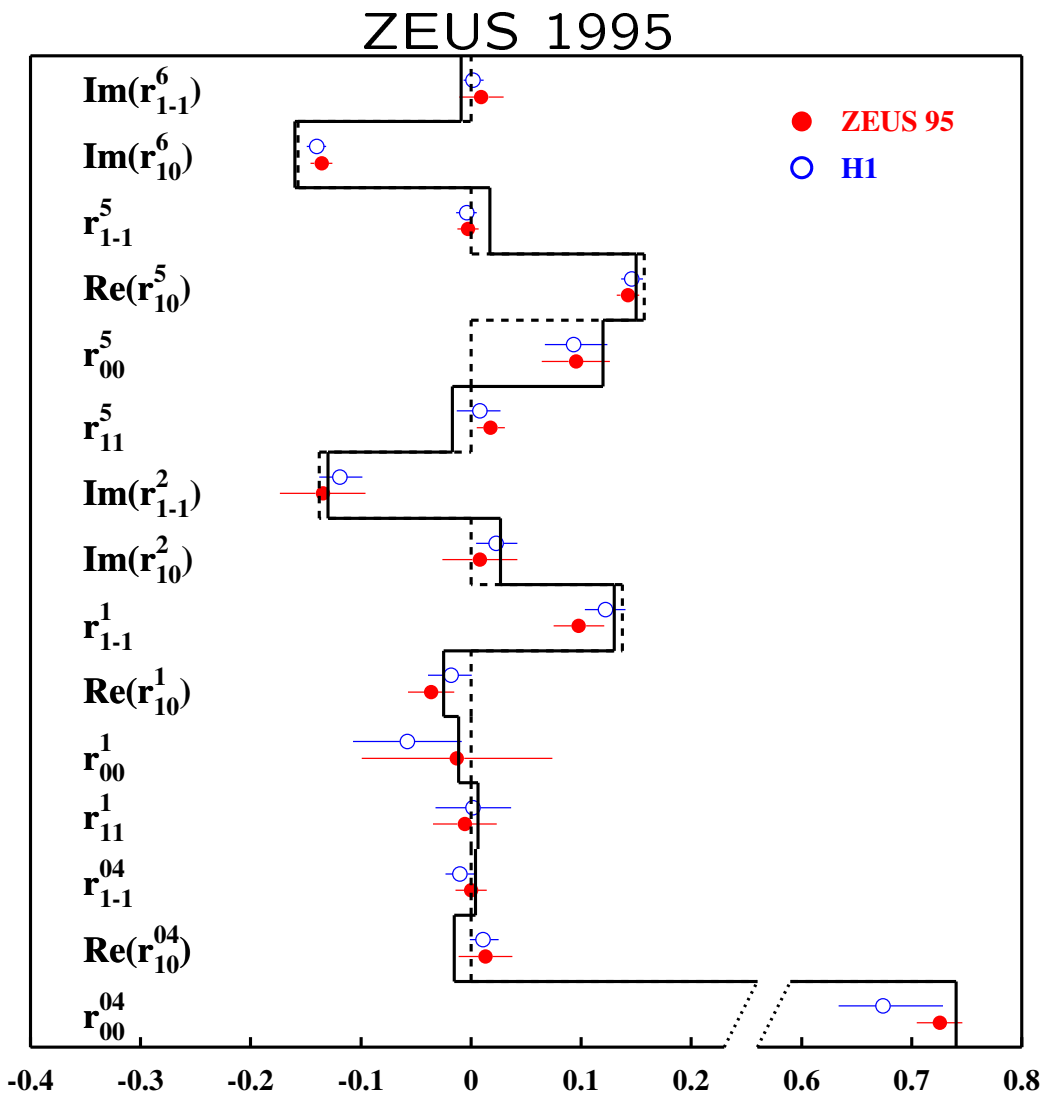


Dotted lines are SCHC values

$\Rightarrow$ 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

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

$\Rightarrow$ A là Martin, Ryskin, Teubner

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

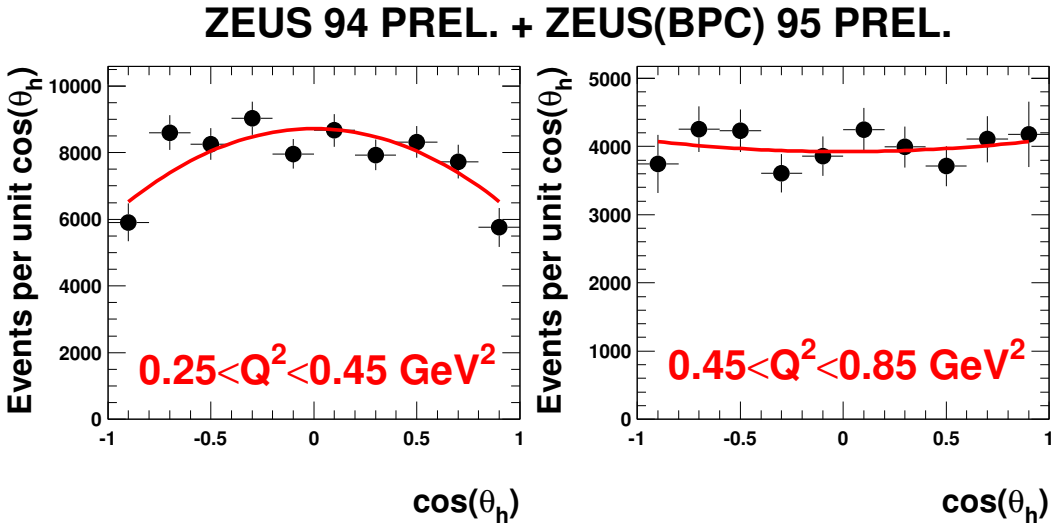
☞ Amplitude to produce longitudinal ρ's from transverse photons rendered experimentally accessible via its interference with the dominant helicity-conserving longitudinal amplitude

☞ 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

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

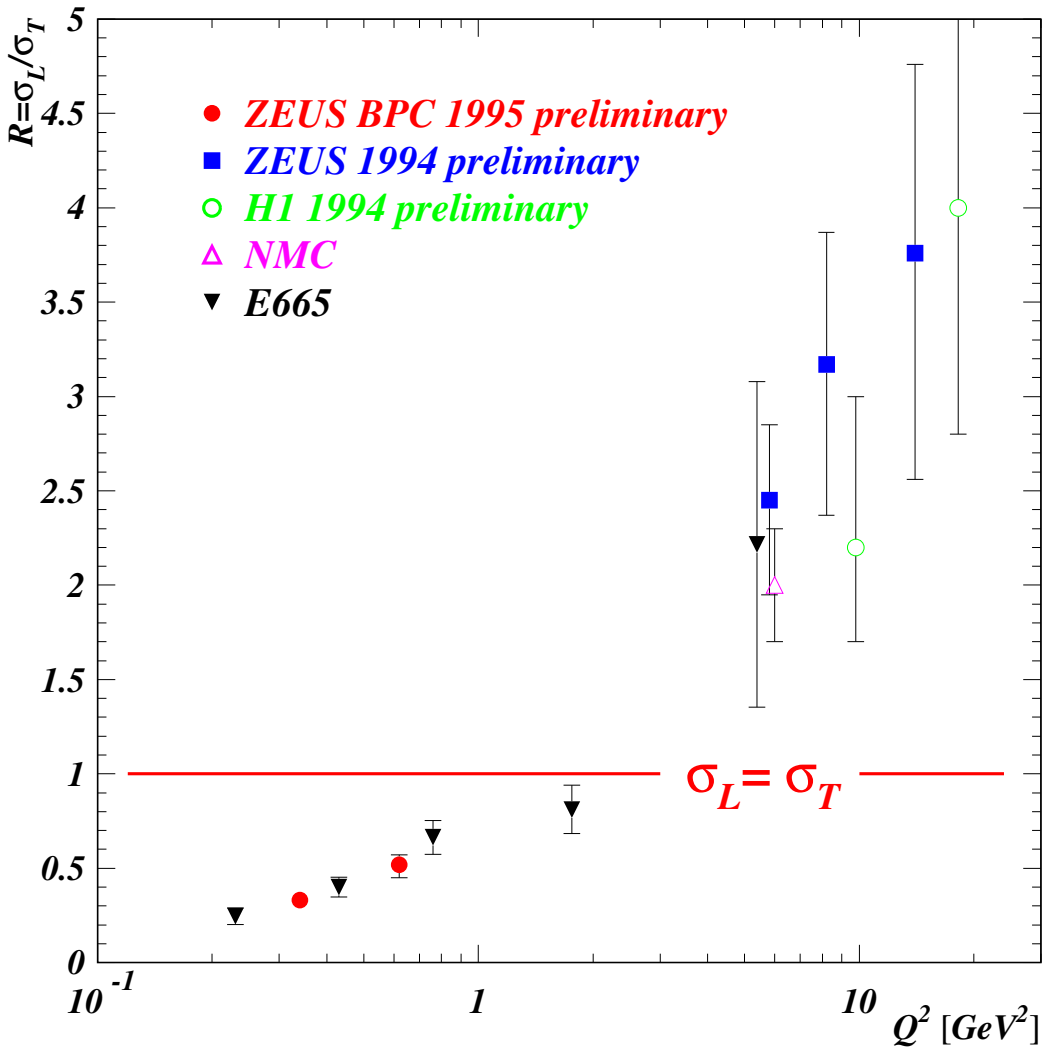


Q^2 (GeV^2)	r_{00}^{04}
0.34	0.24 ±0.02(stat)
0.62	0.34 ±0.03(stat)
5.8	$0.71^{+0.03}_{-0.04}$(stat)$^{+0.01}_{-0.01}$(sys)
8.2	$0.76^{+0.04}_{-0.04}$(stat)$^{+0.00}_{-0.02}$(sys)
14	$0.79^{+0.04}_{-0.05}$(stat)$^{+0.02}_{-0.01}$(sys)

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

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

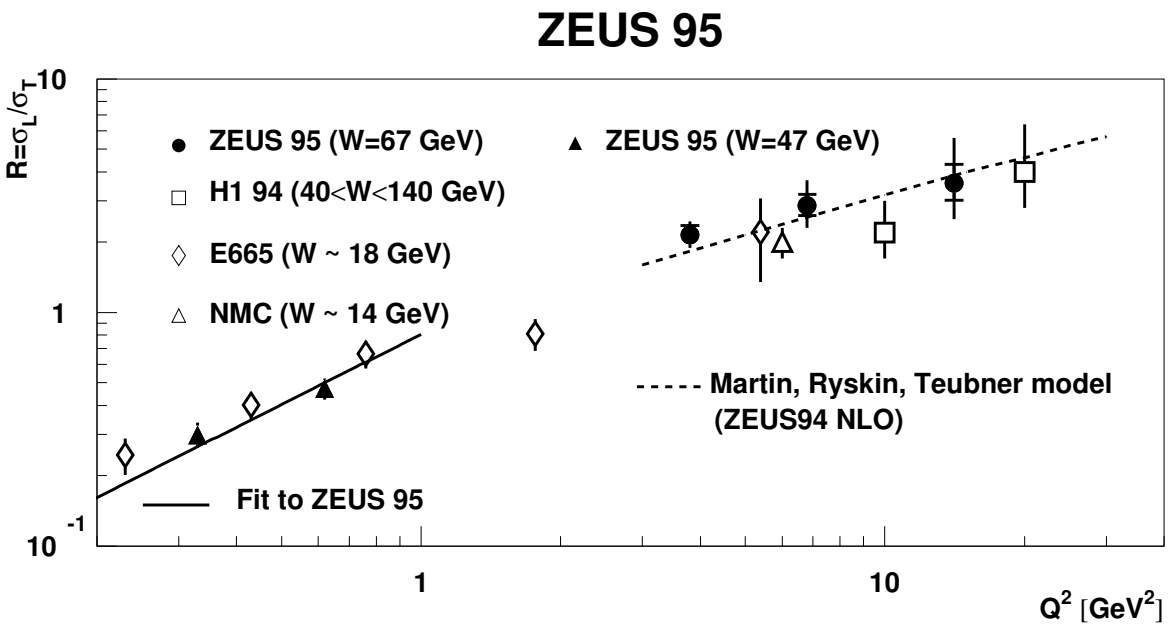
Δ now known to be small !

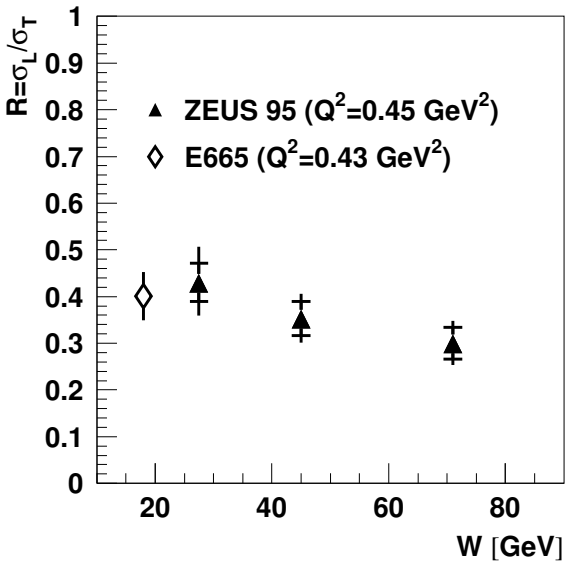


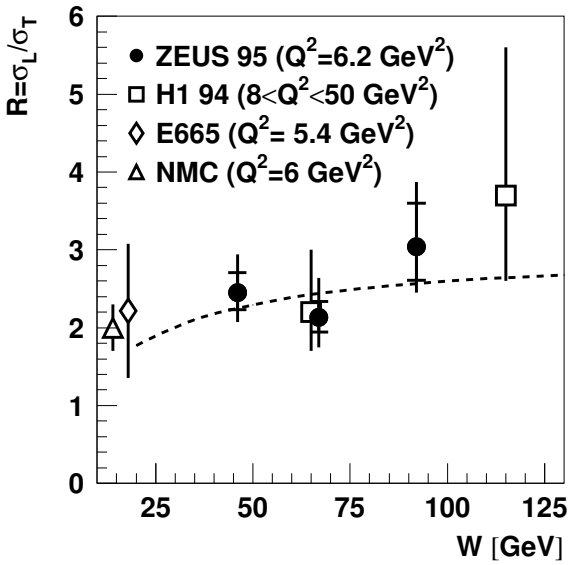
$\Rightarrow \sigma_L$ increases and becomes dominant

R vs Q^2 and W for ρ^0

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



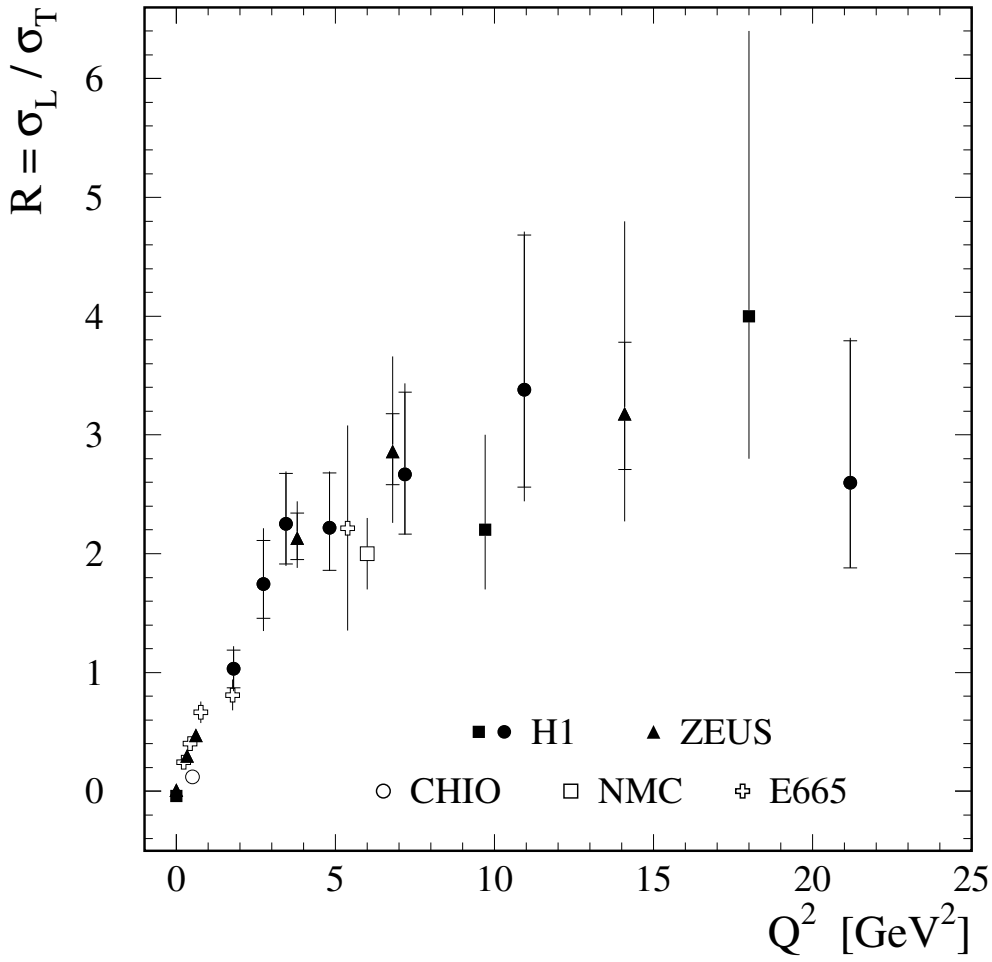




$\Rightarrow$ Do σ_T and σ_L have similar W dependence ?

R vs Q^2 (H1 DIS ρ^0)

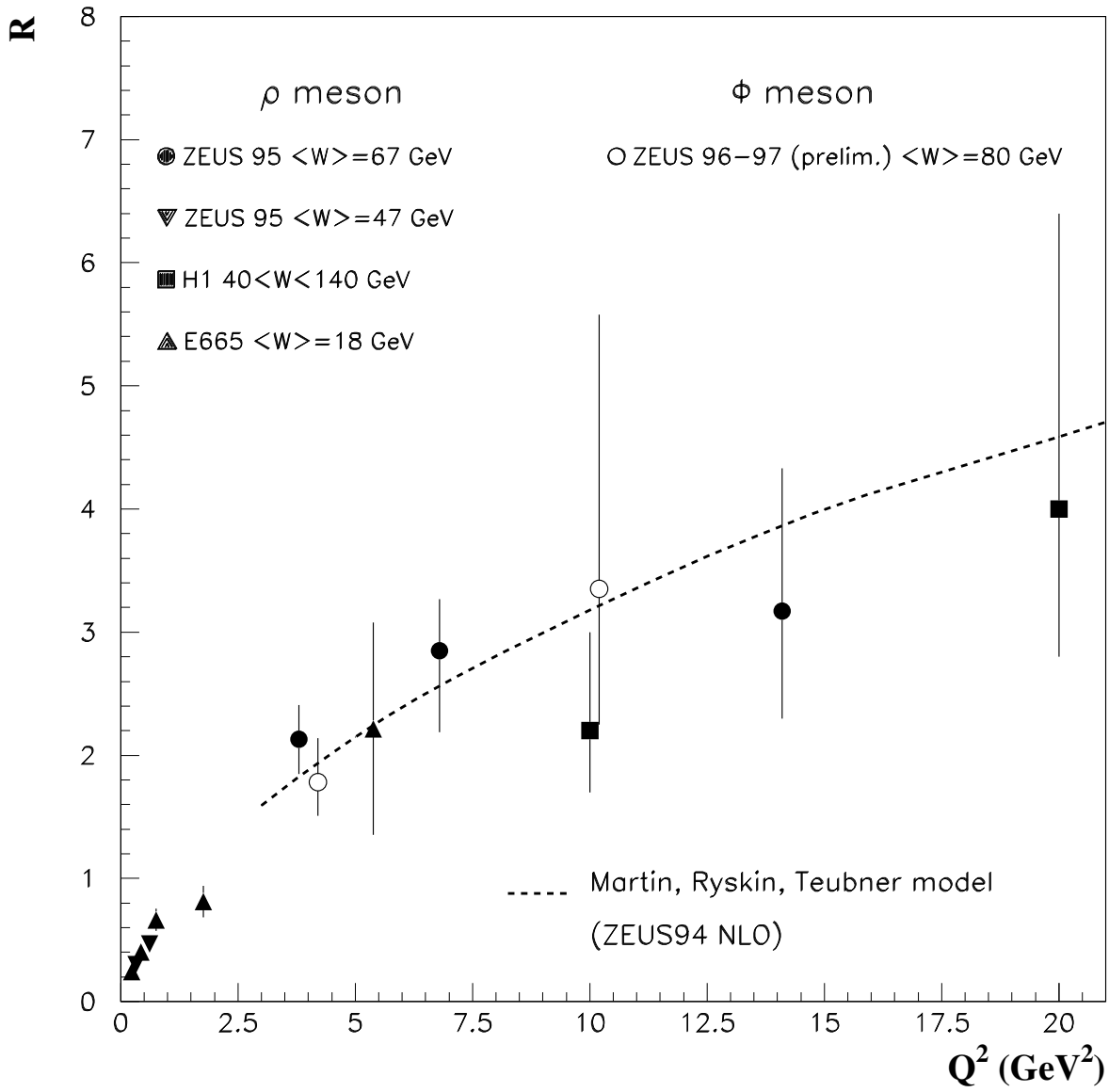
H1 hep-ex/9902019



$\Rightarrow$ σ_L/σ_T levelling off ??

R vs Q^2 (ZEUS DIS ϕ prel.)

ZEUS ICHEP Abstract 793

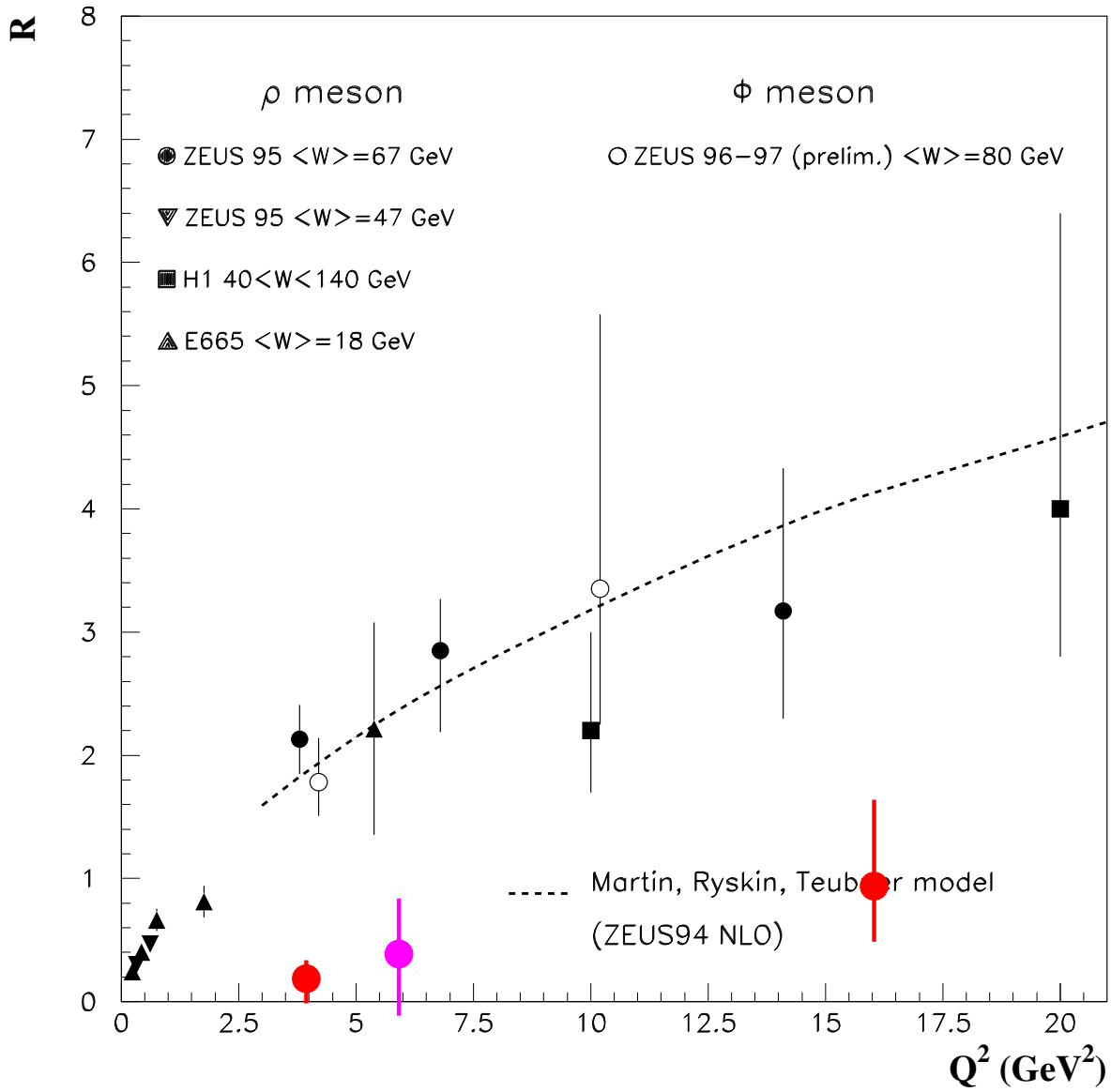


$\Rightarrow$ ϕ behaves like ρ^0 !!

R vs Q^2 for J/ψ

H1 hep-ex/9903008

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



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

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: $T_{\lambda_\pi \pi \lambda_\gamma}$

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

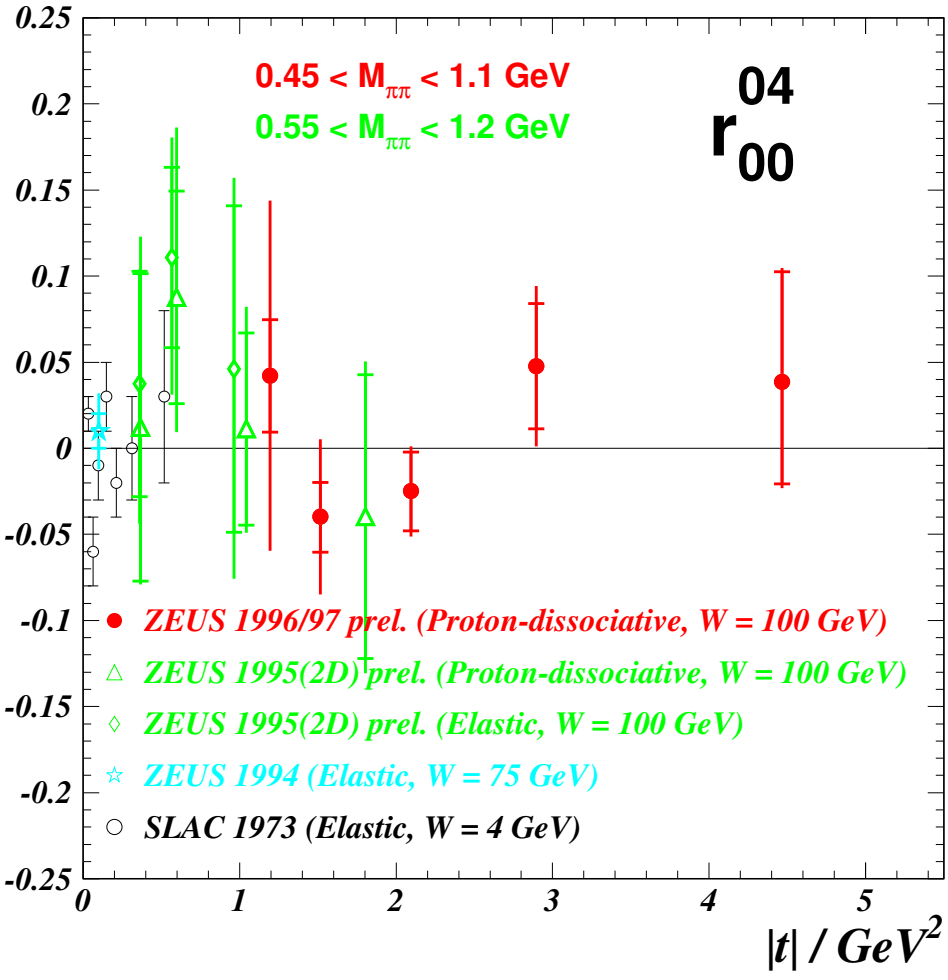
At low Q^2, Φ_h poorly measured, so integrate over it:

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

High-$|t|$ 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

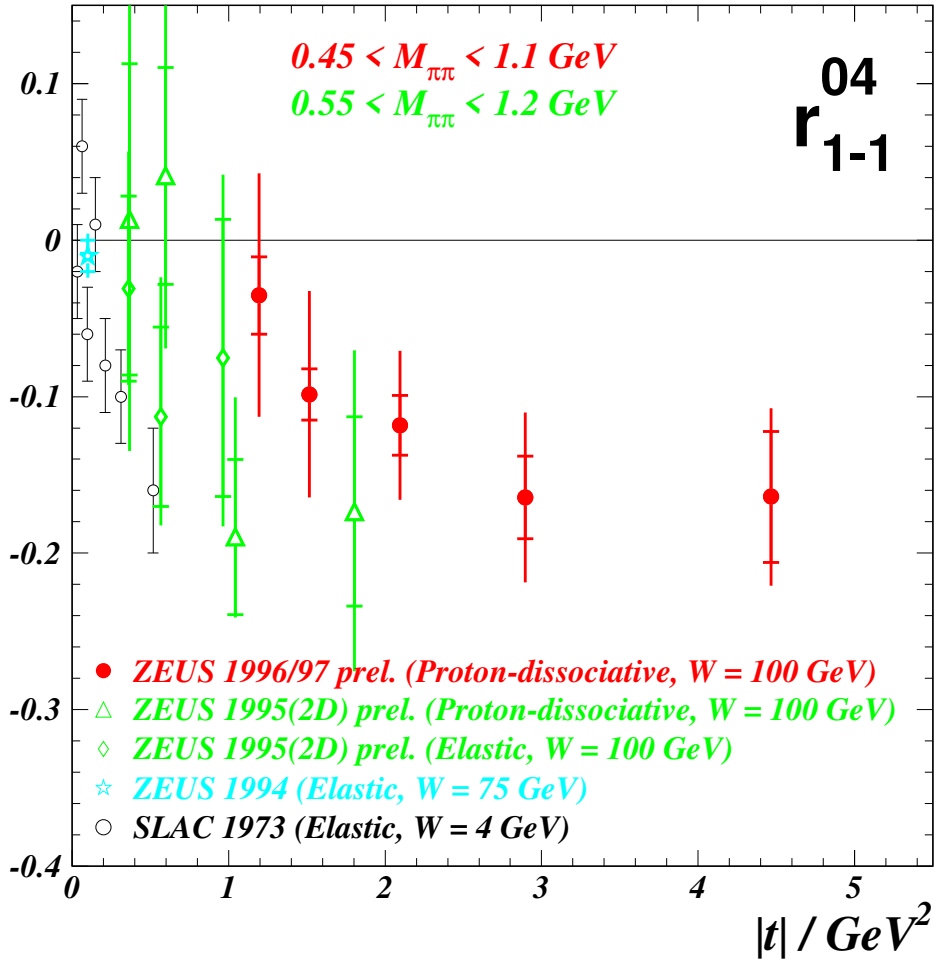


Long. pol. does *NOT* dominate at high $|t|$

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*

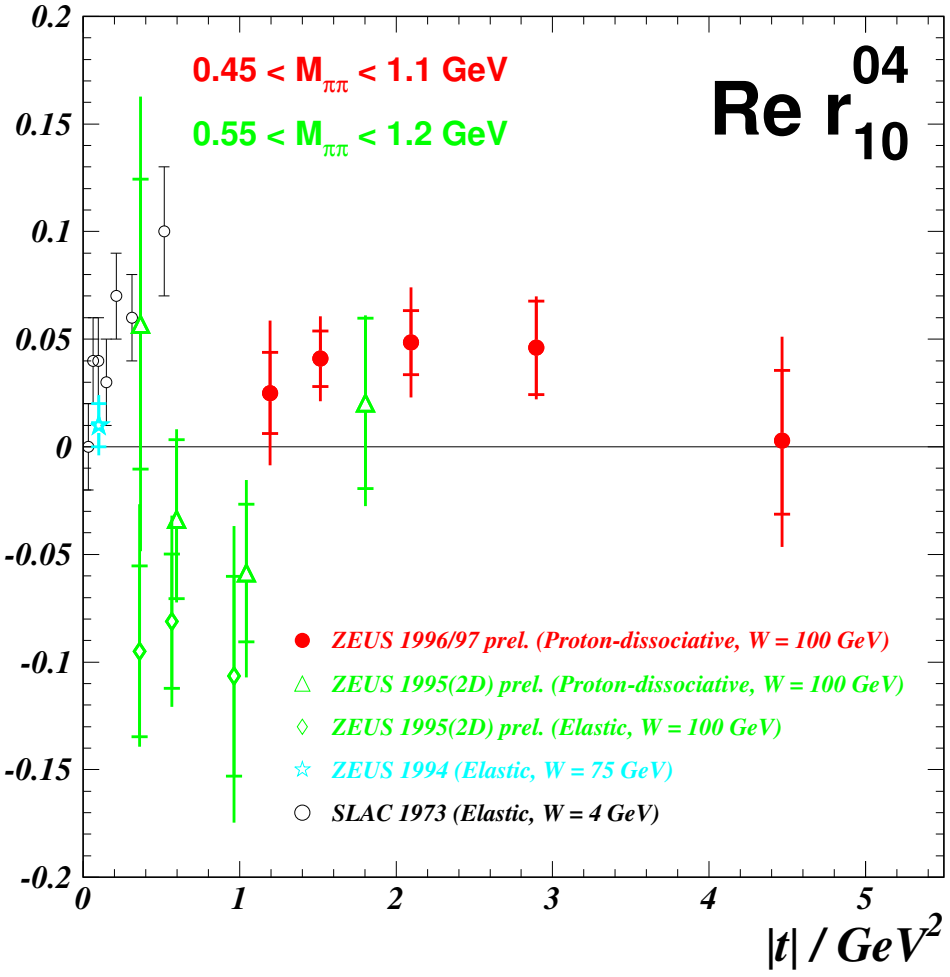


Clear double-flip contribution (But is it the ρ^0?)

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

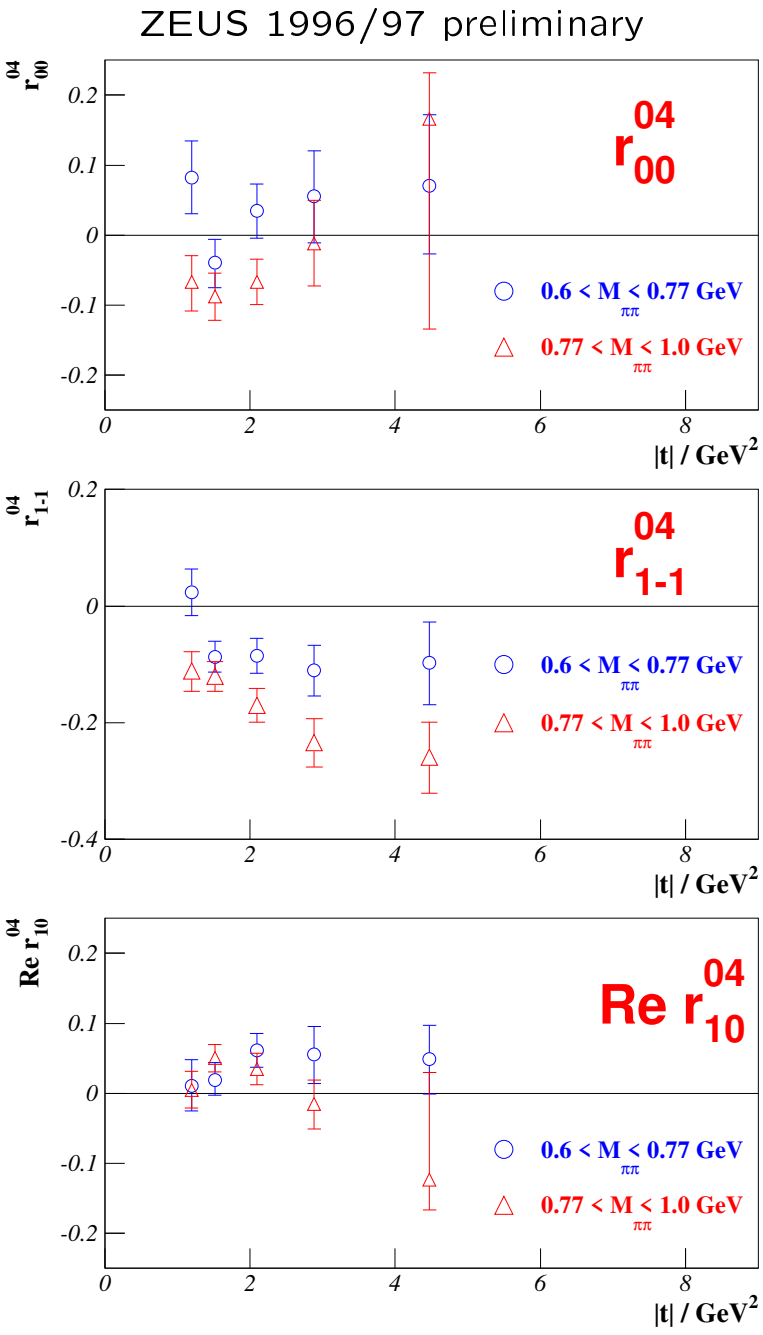


Indication of single-flip contribution (Is it the ρ^0?)

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

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