LISHEP 98 *Rio de Janeiro*

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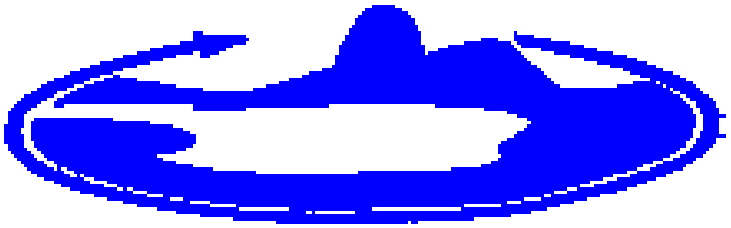
Scale Issues in High-Energy Diffractive Vector-Meson Production



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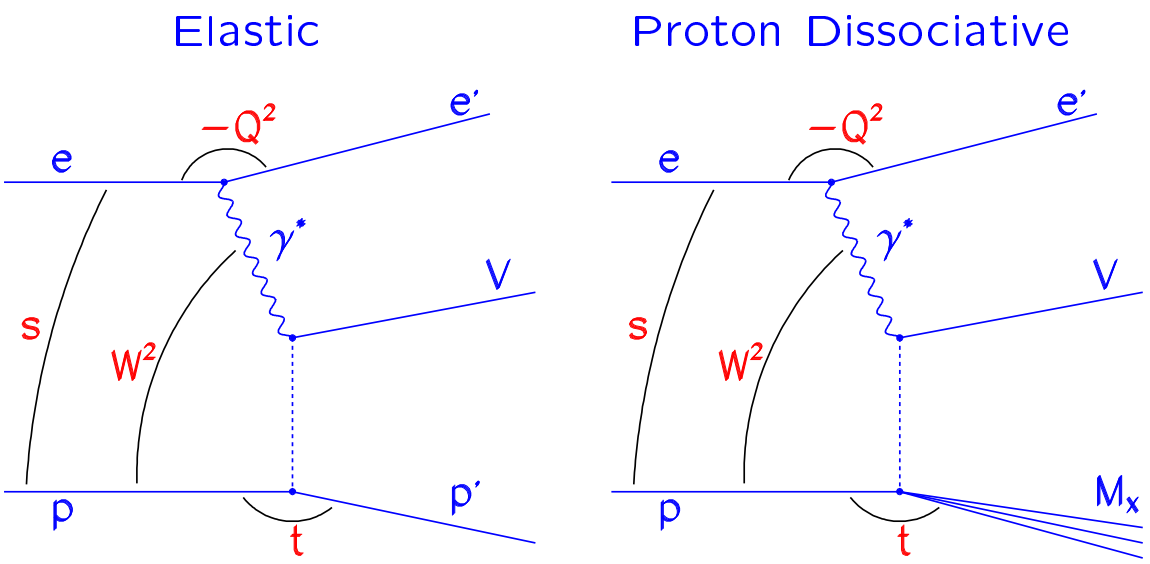
Diffractive Electroproduction of Vector Mesons



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

W: Center–of–mass energy of γ^*–p system (20 – 240 GeV)

Q^2: Photon Virtuality (10^{-10} – 20 GeV^2)

t: Square of Momentum Transfer at the Proton Vertex ($|t| < 13$ GeV^2)

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 ?

Signatures for pQCD

☞ Energy Dependence of Elastic Cross Sections

⇒ Exchange of the phenomenological Pomeron

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

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

⇒ 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

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

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

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

⇒ Only longitudinally polarized configurations pointlike !!

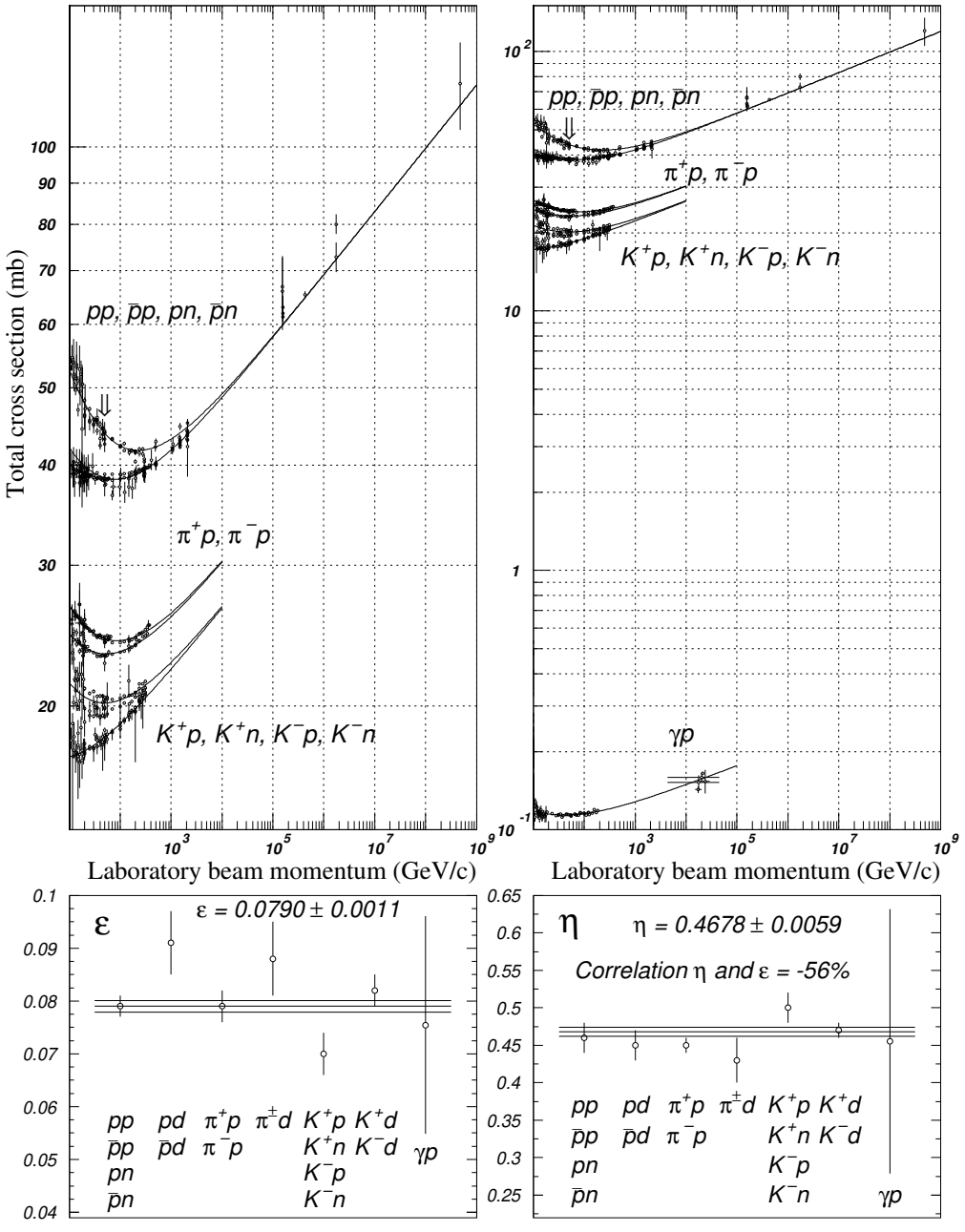
☞ Absence of ρ^0 mass spectrum skewing

Skewing is interesting ($\sigma_{\pi p}^{tot}$?), but not pQCD

☞ Absence of shrinkage

Total Cross Sections

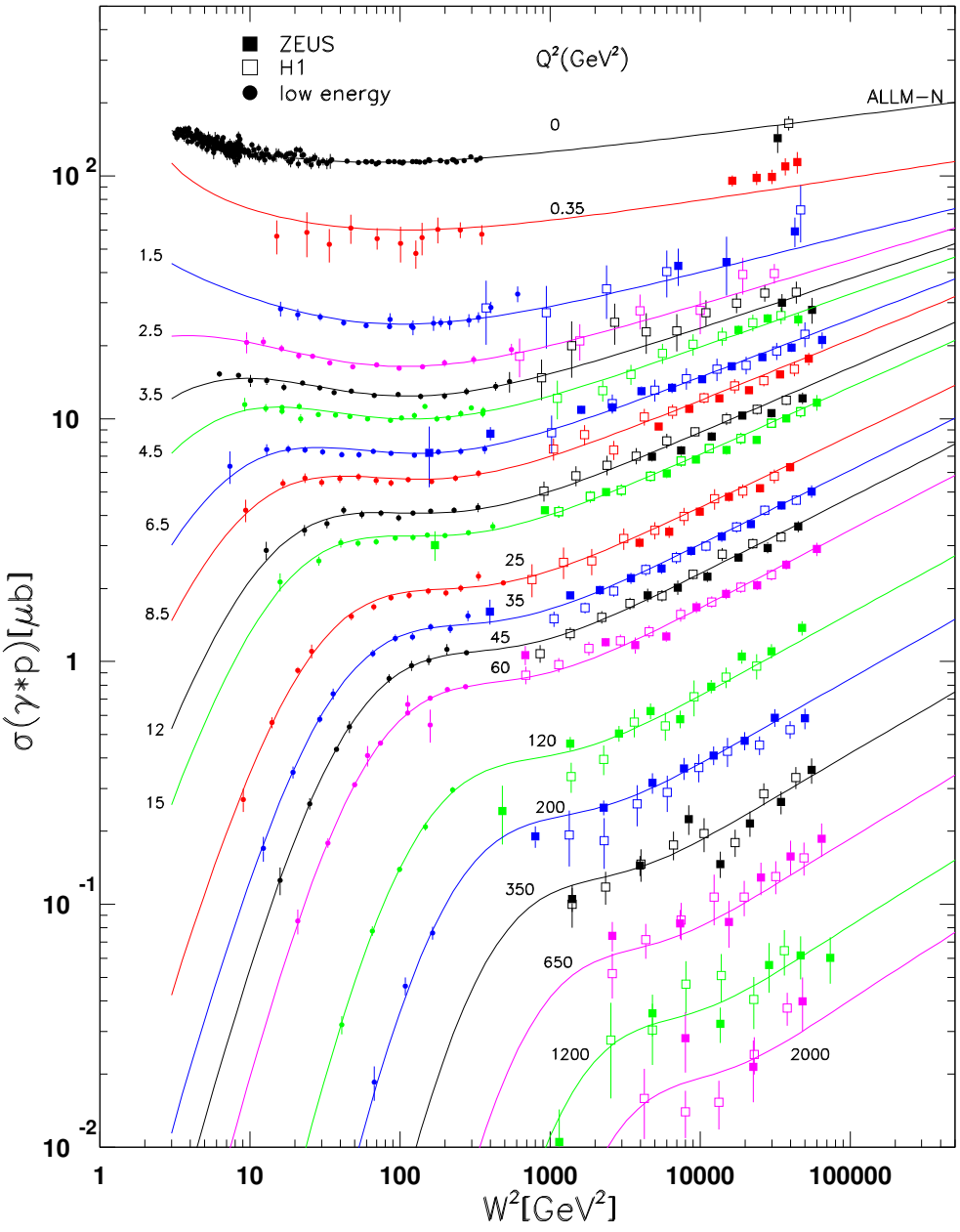
$$\sigma^{tot} = X\, s^{\epsilon} + Y\, s^{\eta}$$



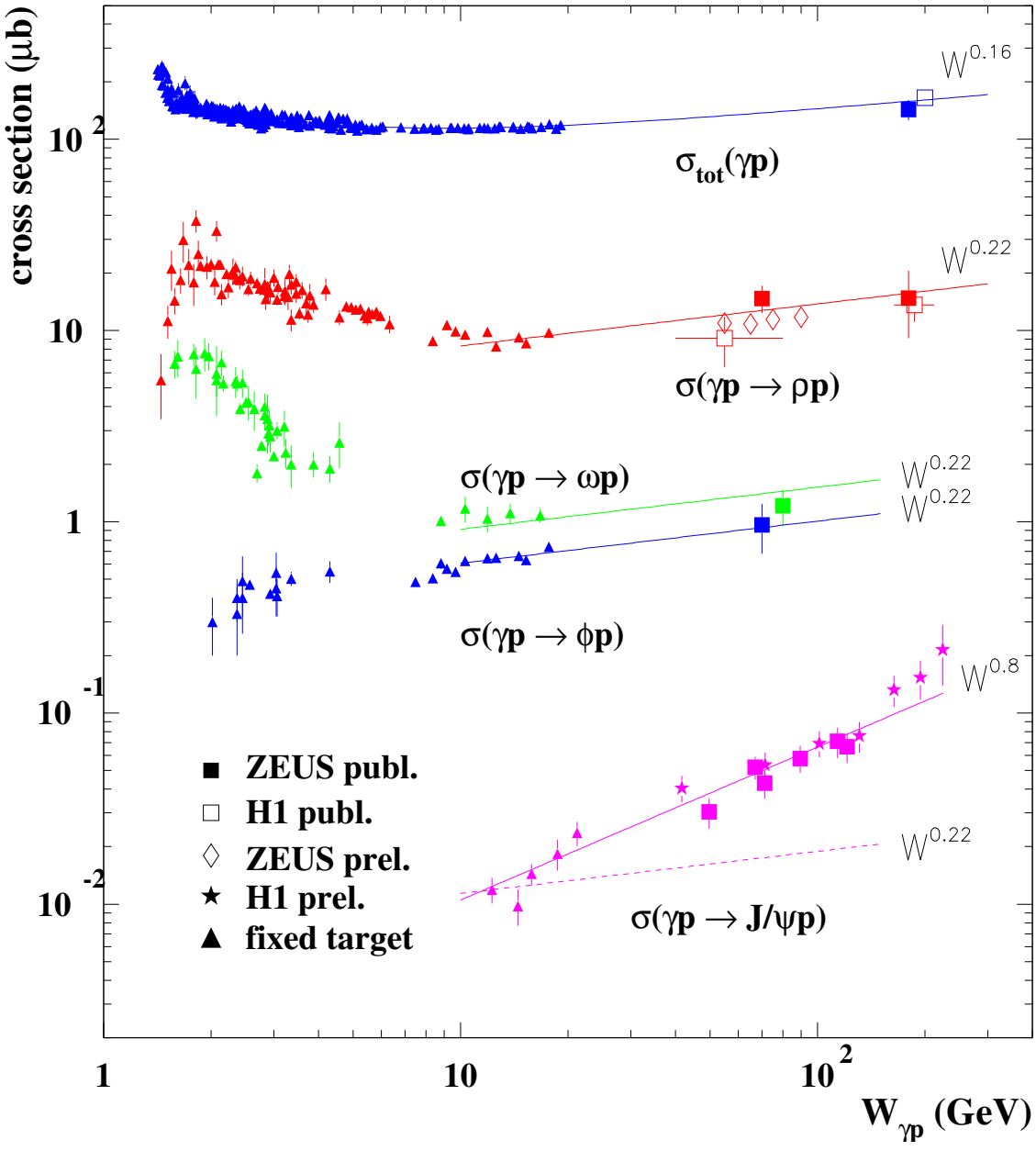
$\epsilon = 0.0790 \pm 0.0011$ $\eta = 0.4678 \pm 0.0059$

Total Photon-Proton Cross Sections

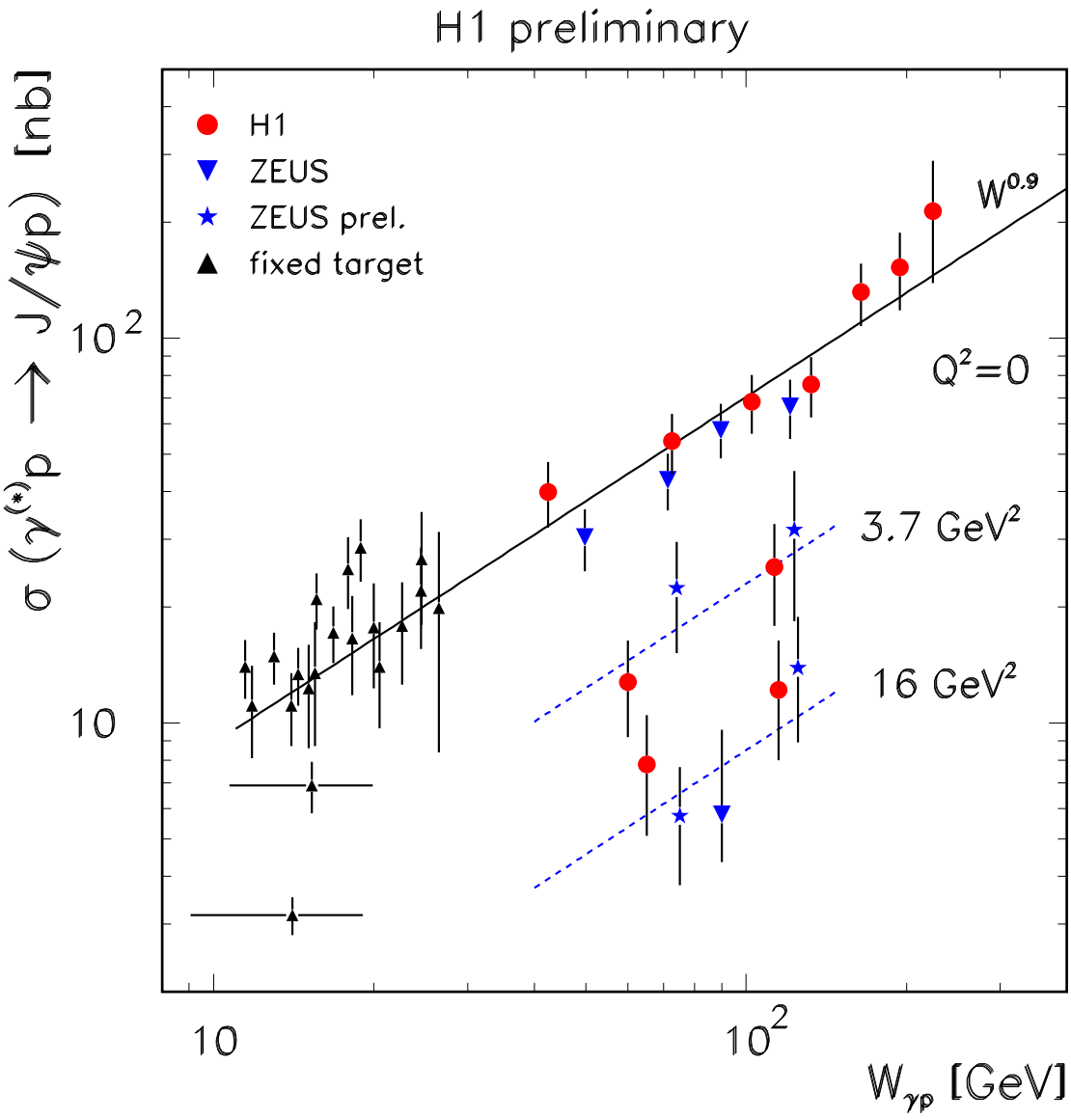
$$\sigma^{tot}_{\gamma^* p} \approx \frac{4\pi^2\alpha}{Q^2(1-x)} F_2(x,Q^2)$$



Elastic Vector-Meson Photoproduction Cross Sections

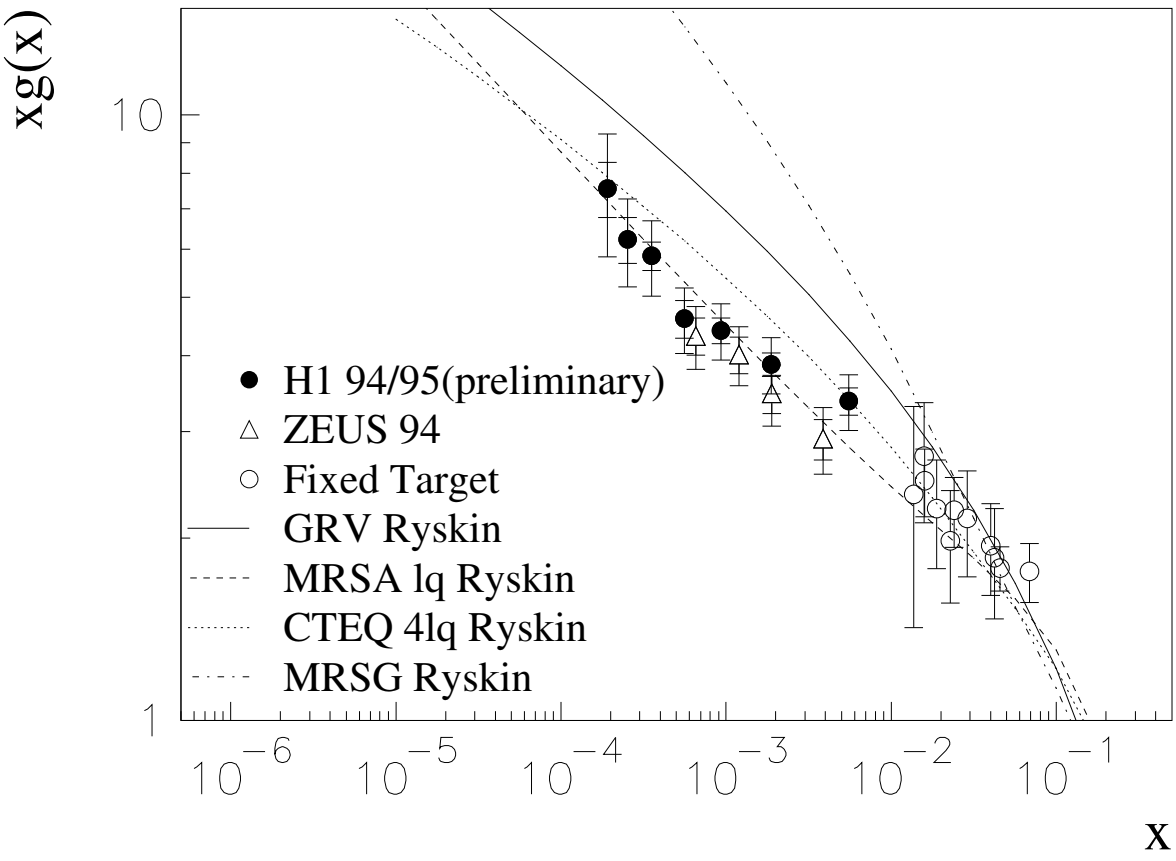


Elastic J/ψ Cross Sections



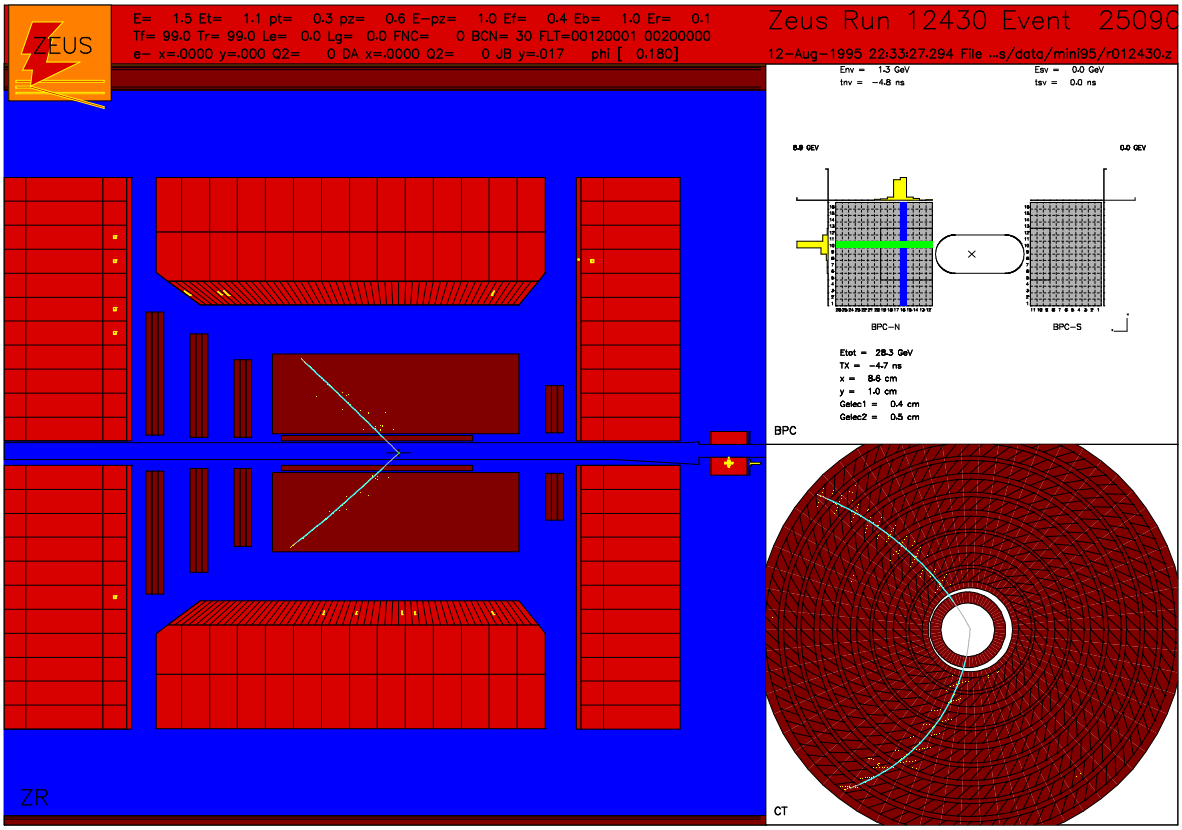
$\Rightarrow$ See talk by Lee West

Elastic J/ψ Cross Sections



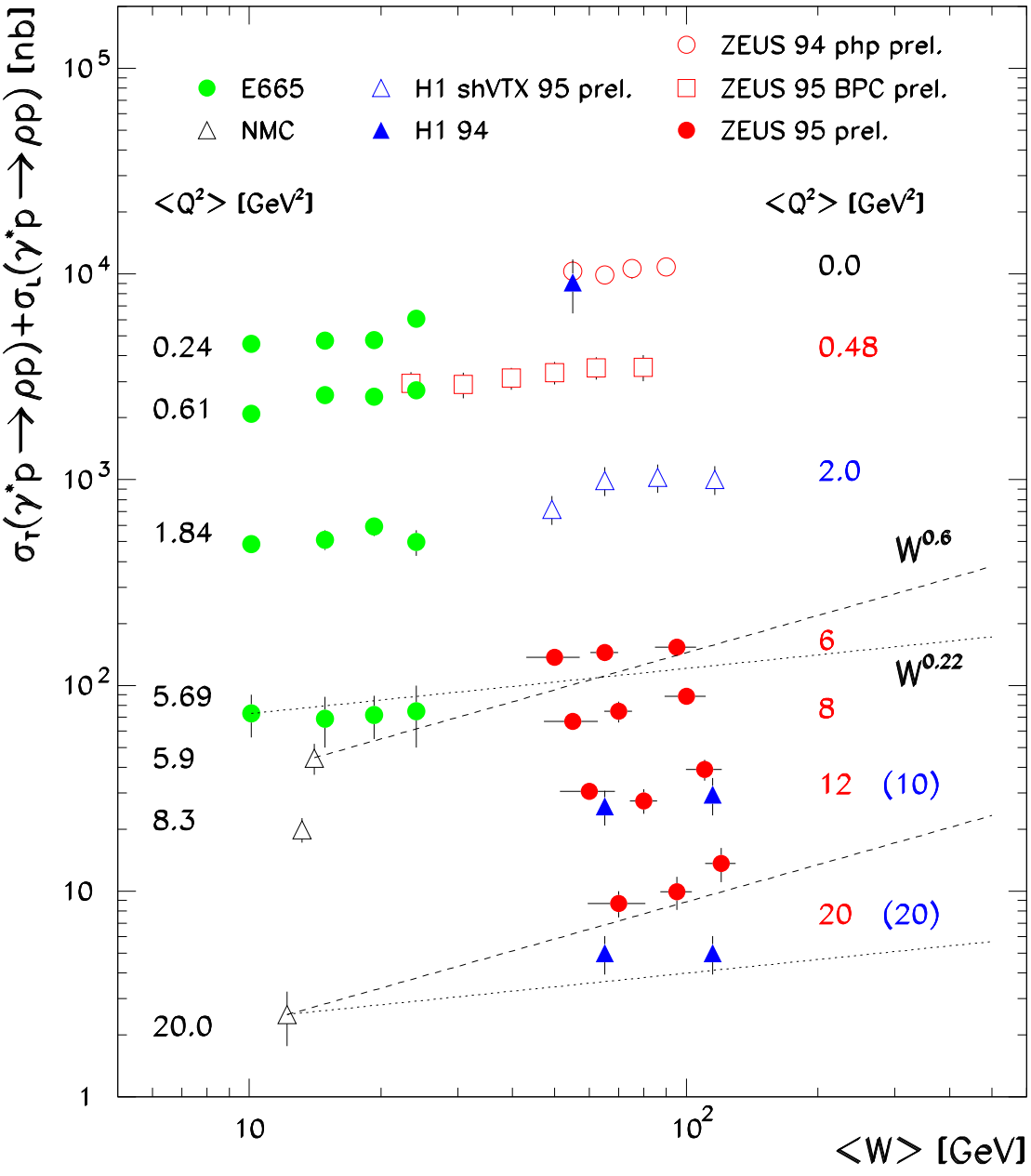
$\Rightarrow$ Can derive shape of gluon distribution !!

Diffractive Production of ρ^0 Mesons

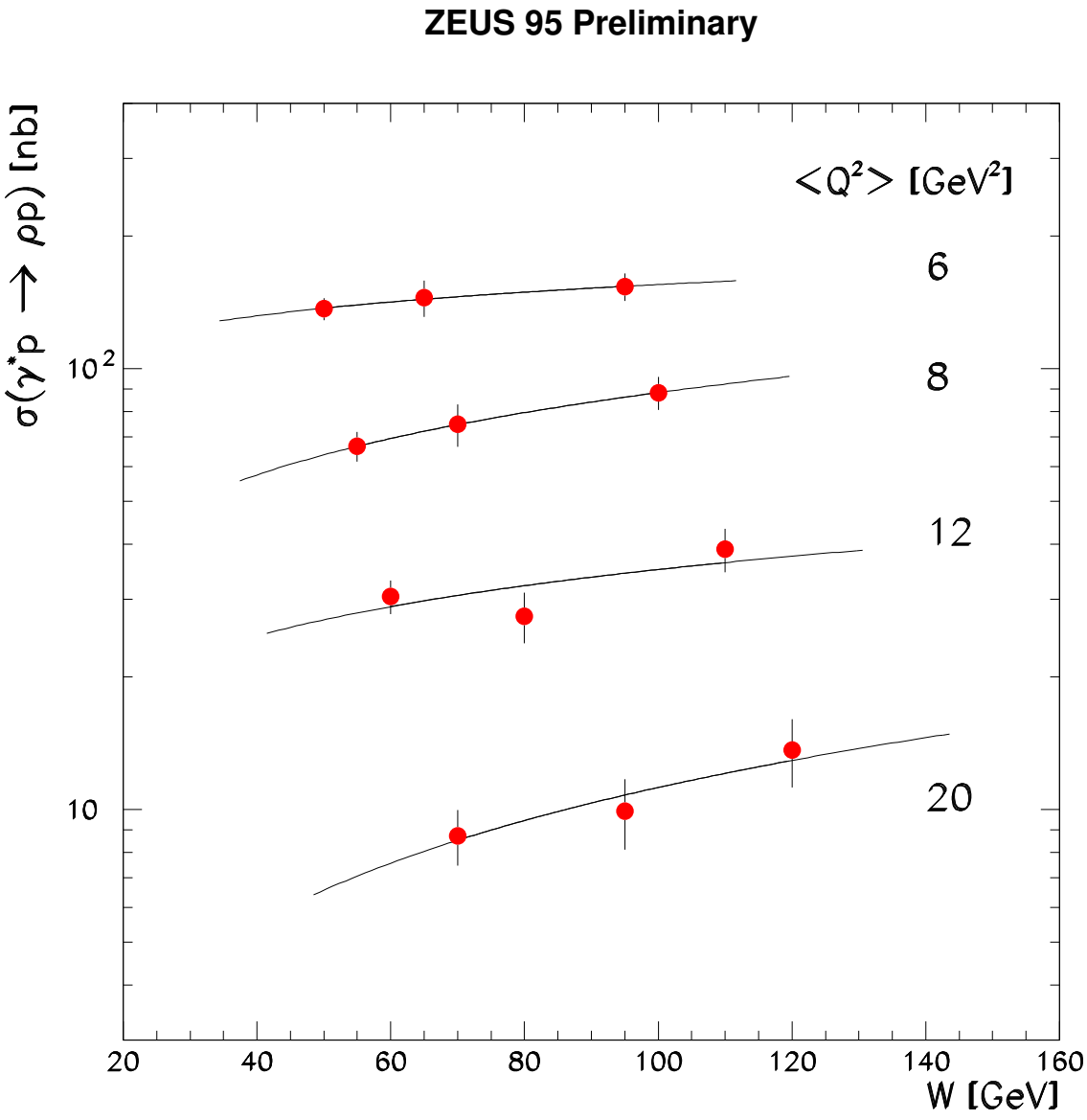


e^+ in BPC	e^+ in UCAL
1995: 3.8 pb^{-1}	1995: 6 pb^{-1}
$0.25 < Q^2 < 0.85$ GeV^2	$5 < Q^2 < 30$ GeV^2
$20 < W_{\gamma^* p} < 90$ GeV	$34 < W_{\gamma^* p} < 144$ GeV
$\approx$ 6000 events	$\approx$ 2000 events

Elastic ρ^0 Cross Sections at High Q^2

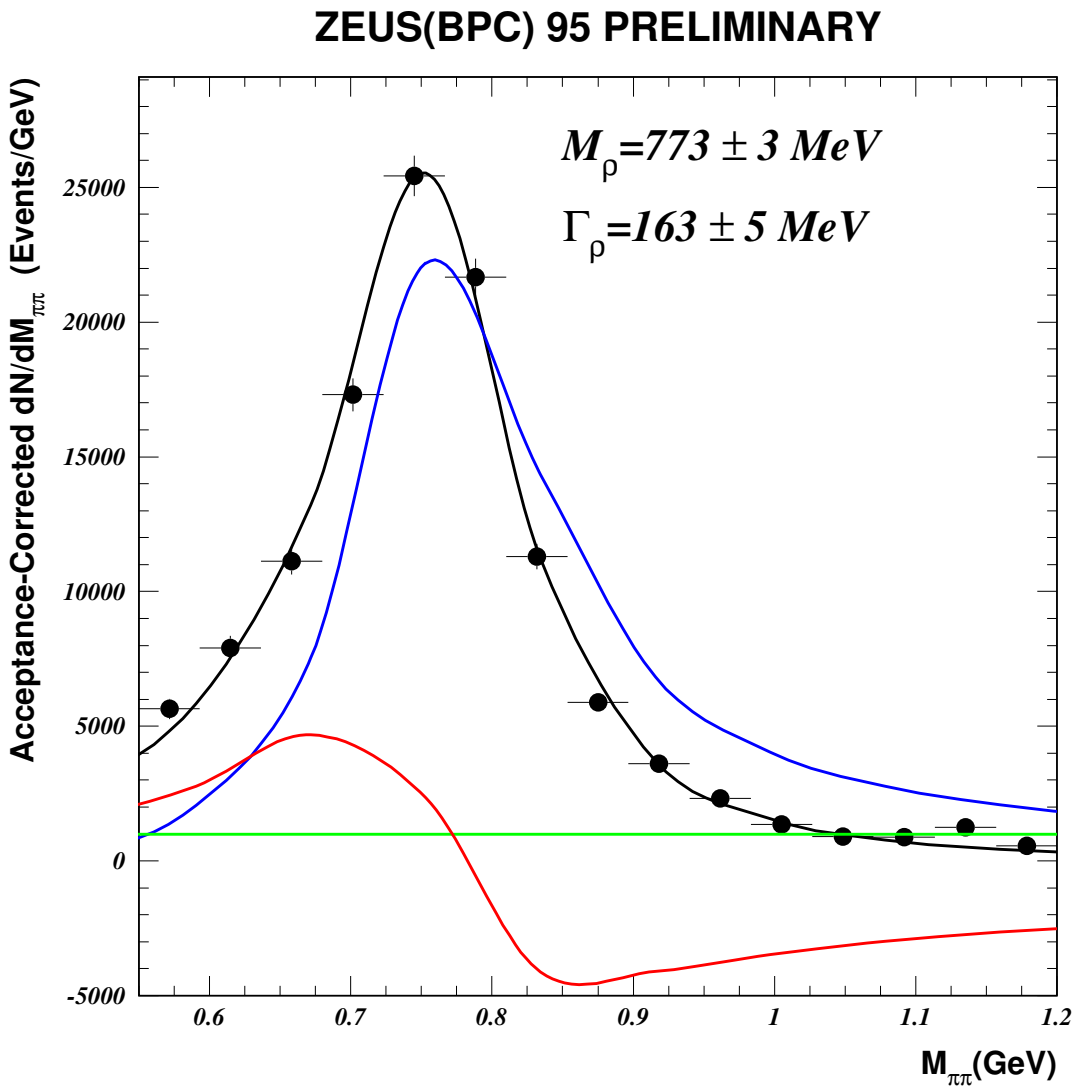


Elastic ρ^0 Cross Sections at High Q^2



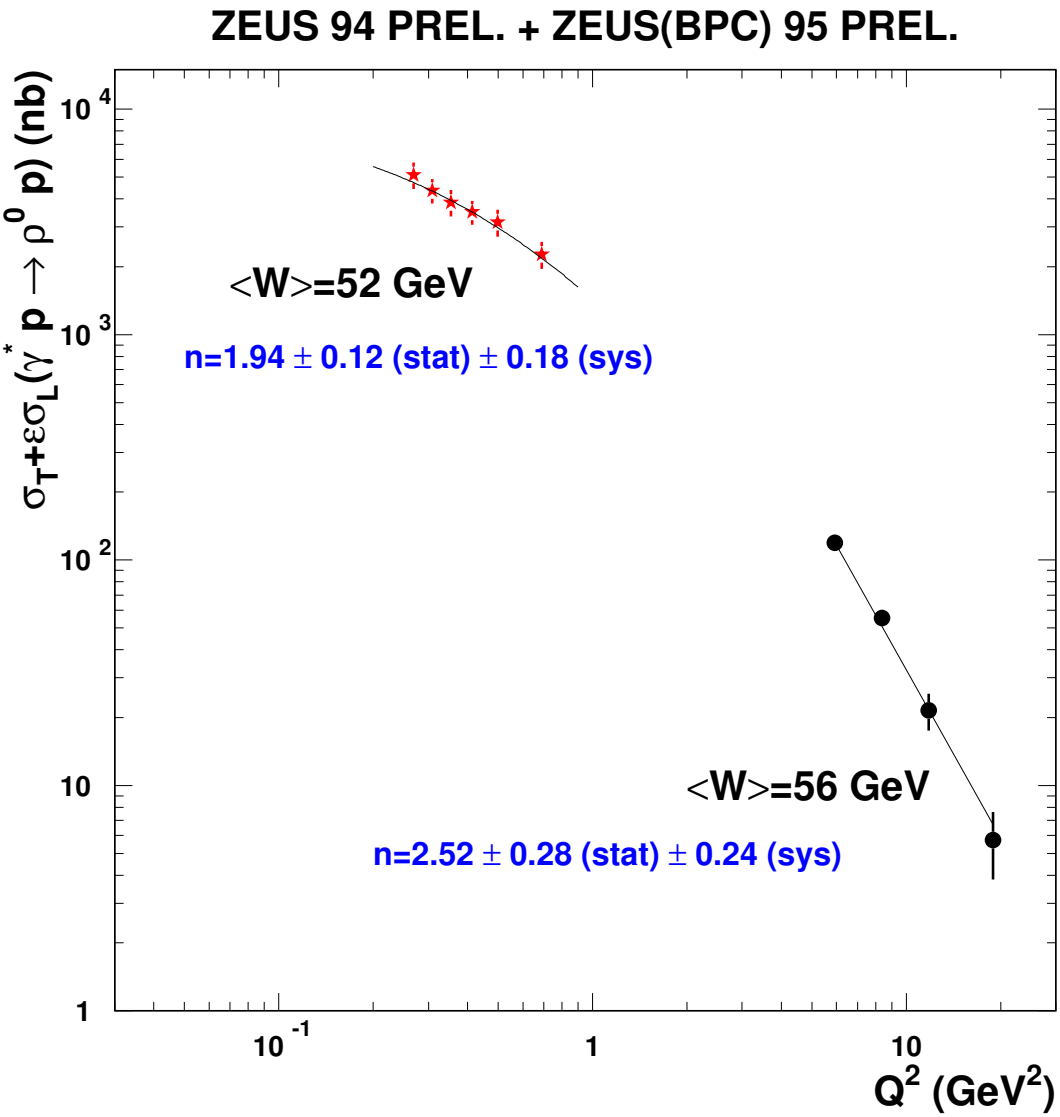
$\Rightarrow$ Steepening with Q^2 expected in pQCD

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



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

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

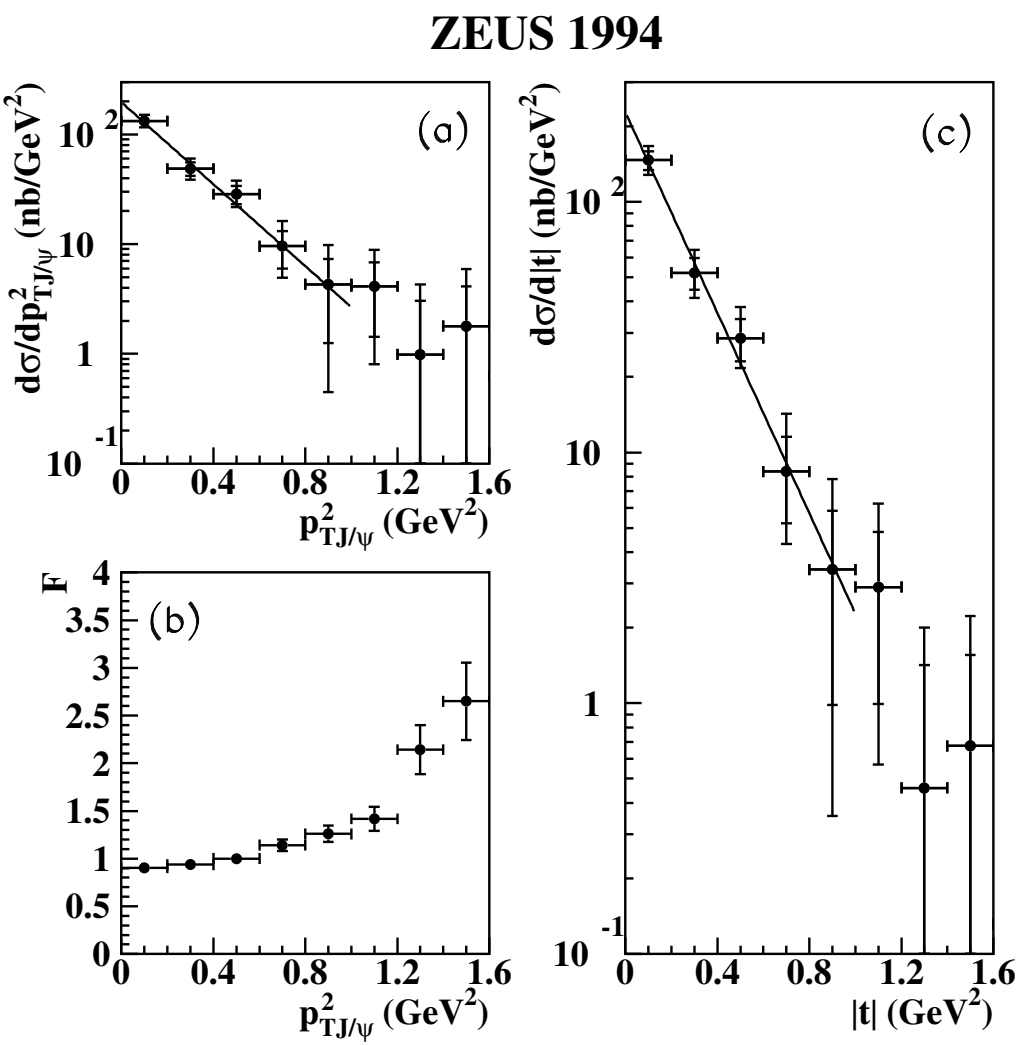


Fit to the shape $(Q^2 + M_\rho^2)^{-n}$

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

Photoproduction of J/ψ Mesons

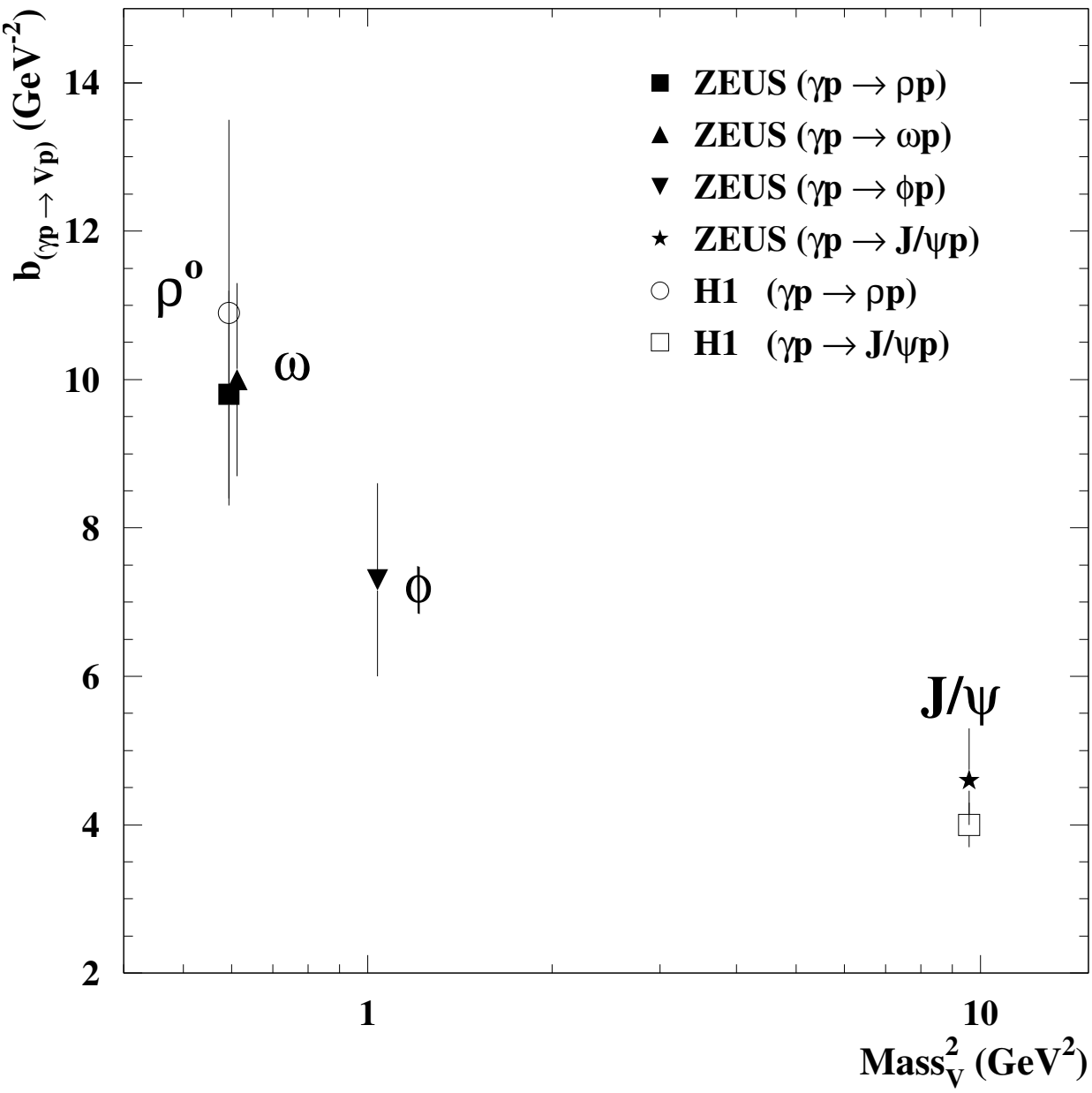
The Exponential Slope in $|t|$



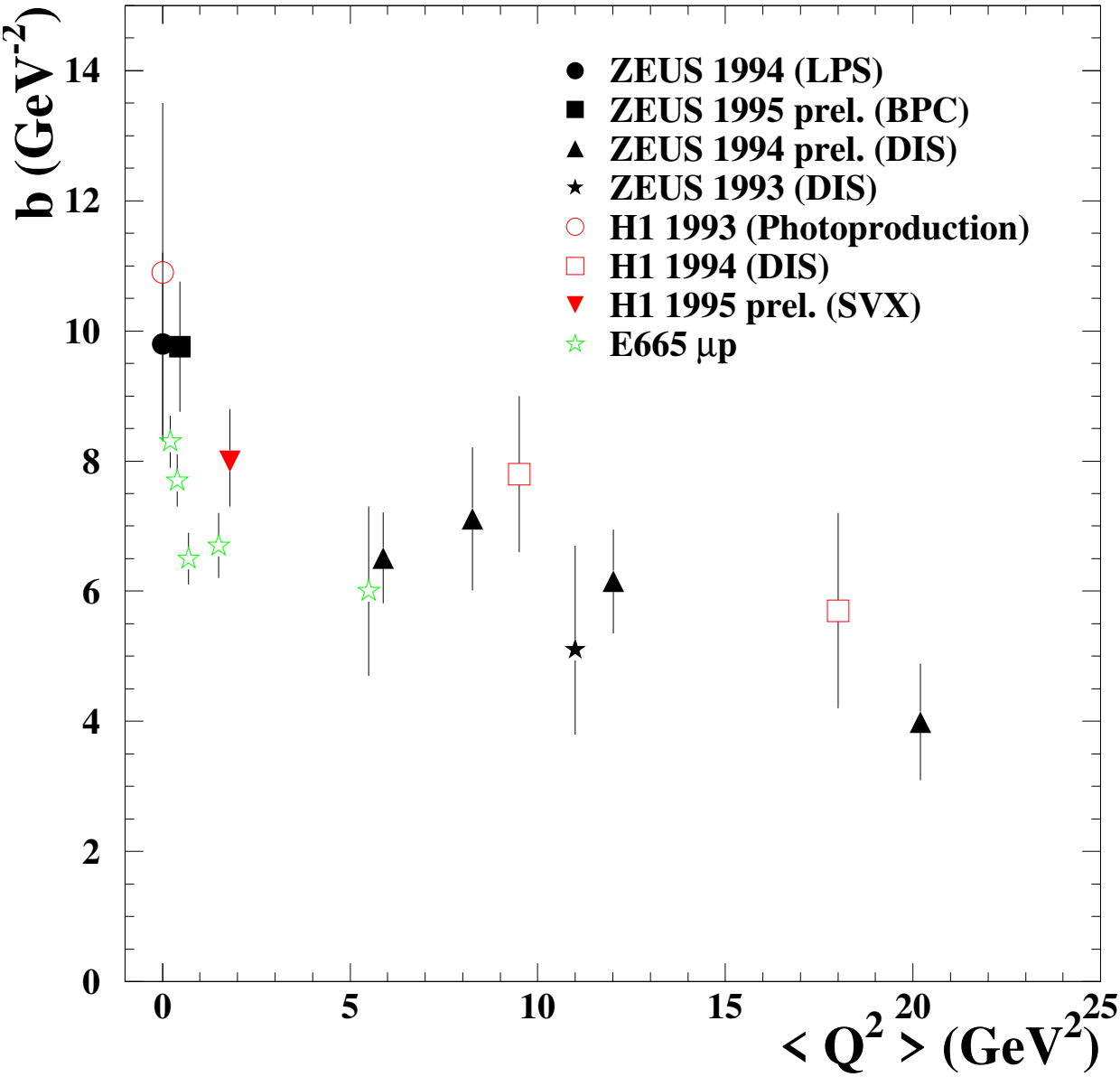
$$b_{J/\psi} = 4.6 \pm 0.4\,(stat)^{+0.4}_{-0.6}\,(sys)\ \text{GeV}^{-2}$$

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

t-Slope for ρ^0 Mesons vs M^2_{VM}



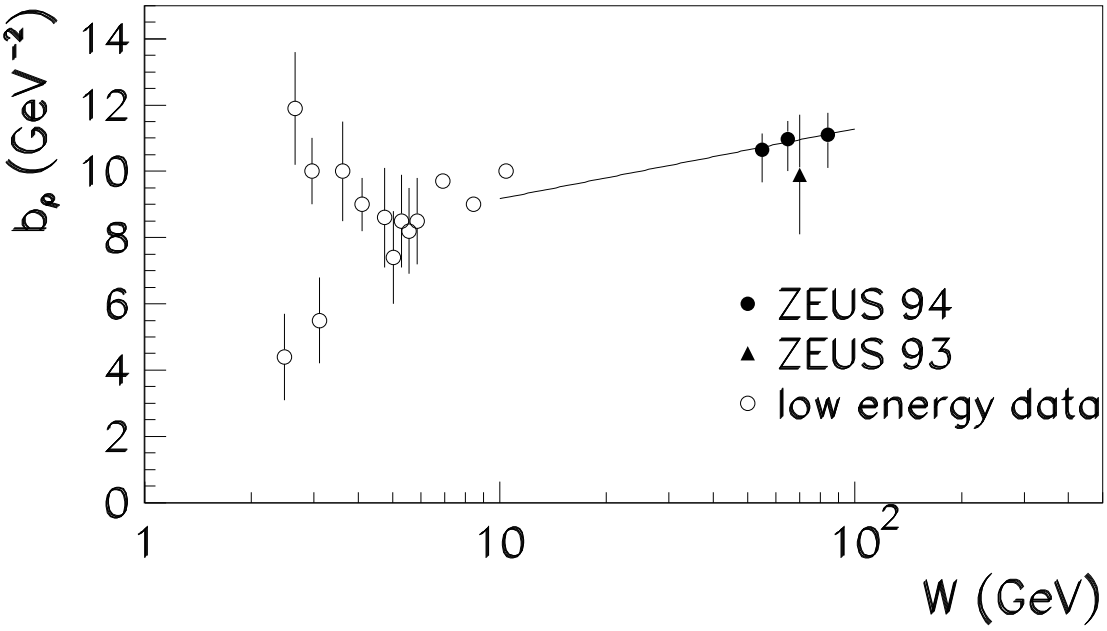
t-Slope for ρ^0 Mesons vs Q^2



$\Rightarrow$ The shrinking photon !!

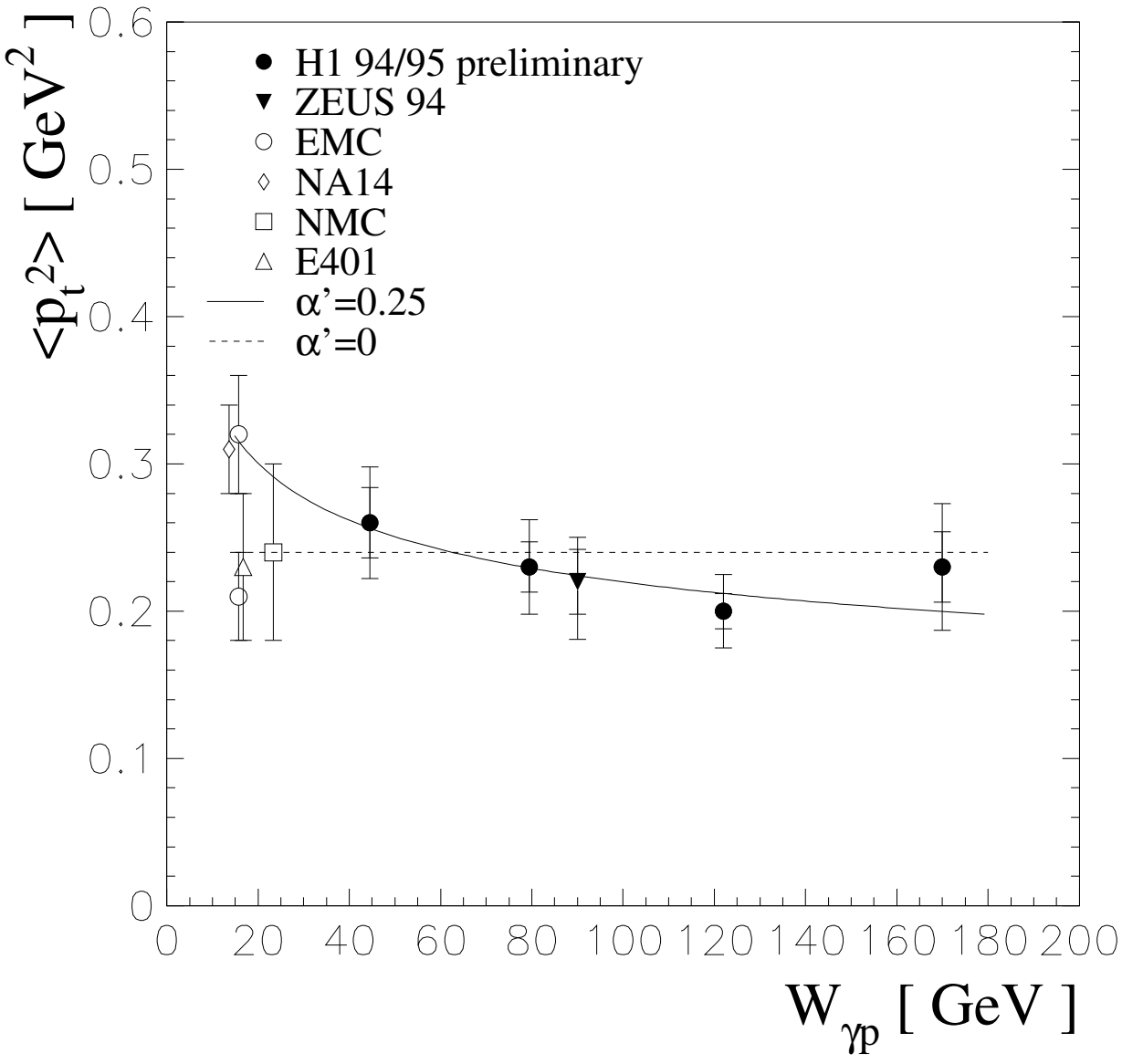
t-Slope for ρ^0 Mesons vs W

Does the t-slope depend on energy?



$\Rightarrow$ Test for shrinkage inconclusive

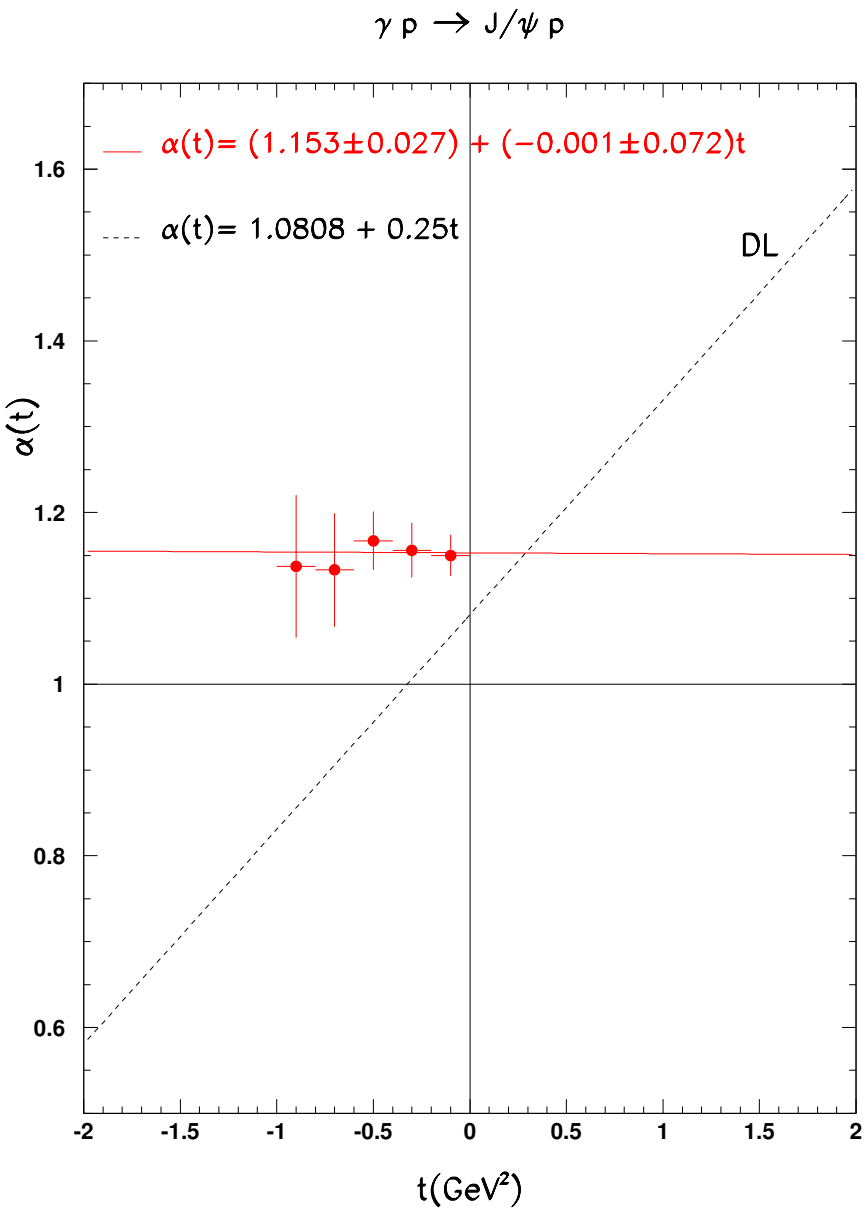
Elastic J/ψ Cross Sections



$\Rightarrow$ Again inconclusive on shrinkage

The Case Against Shrinkage

A. Levy, hep-ph/9712519

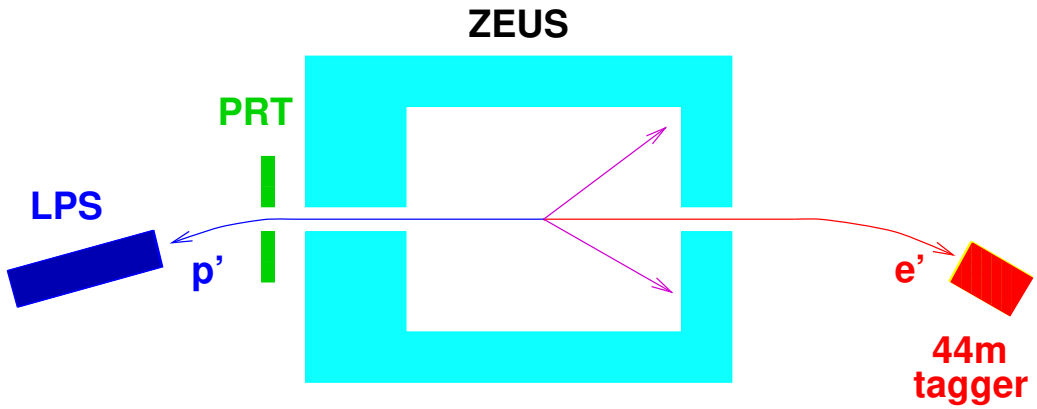


$\Rightarrow$ Inconsistent with $\alpha'_{I\!P} = 0.25$

$\Rightarrow$ Concludes pQCD applicable

High-$|t|$ Photoproduction

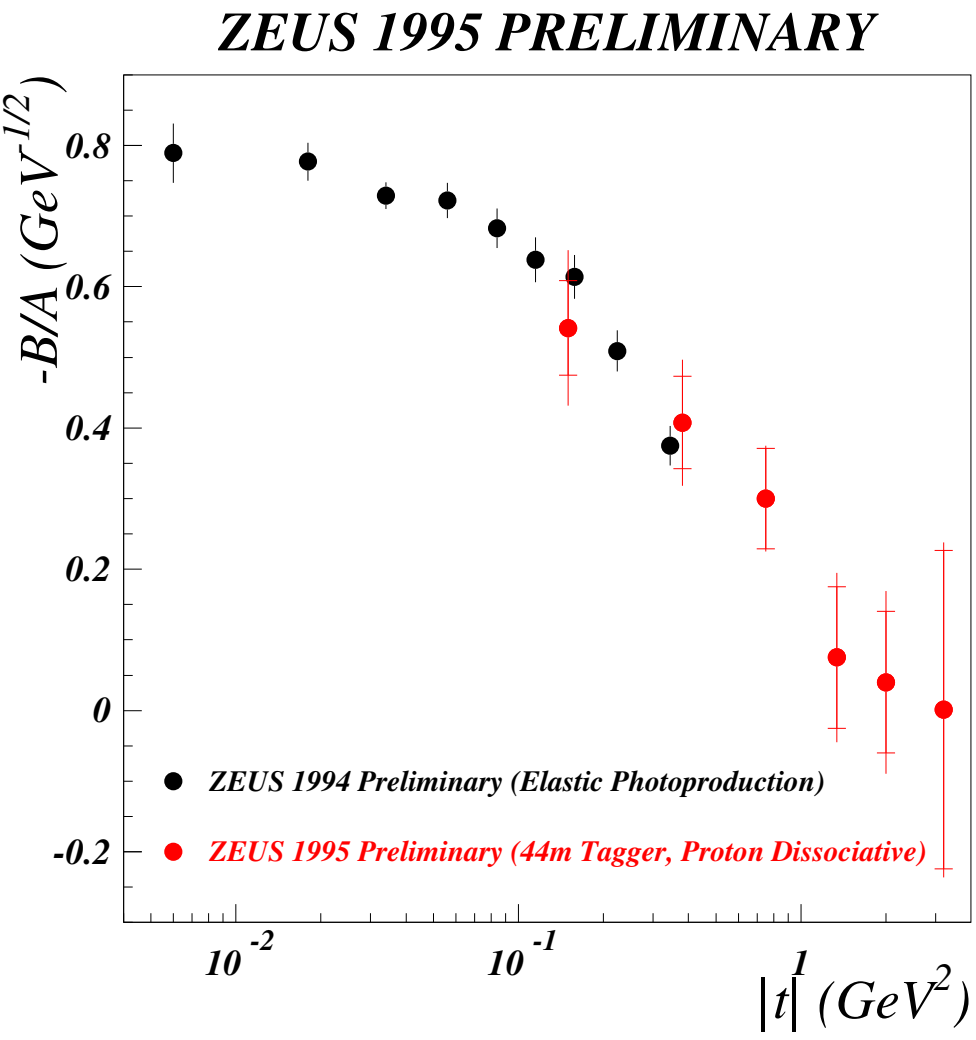
$$|t| \approx Q^2 + p_T^2(\rho^0)$$



e^+ in 44m Tagger	Untagged Sample
1995: 2.1 pb^{-1}	1994: 2.2 pb^{-1}
$10^{-5} < Q^2 < .01$ GeV^2	$10^{-10} < Q^2 < 4$ GeV^2
$85 < W_{\gamma^* p} < 105$ GeV	$50 < W_{\gamma^* p} < 100$ GeV
$\lvert t\rvert < 4$ GeV^2	$\lvert t\rvert < 0.5$ GeV^2
$\approx 3k$ events	$\approx 80k$ events
(primarily proton dissociative)	(primarily elastic)

ρ^0 Mass Spectrum Skewing vs. $|t|$

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

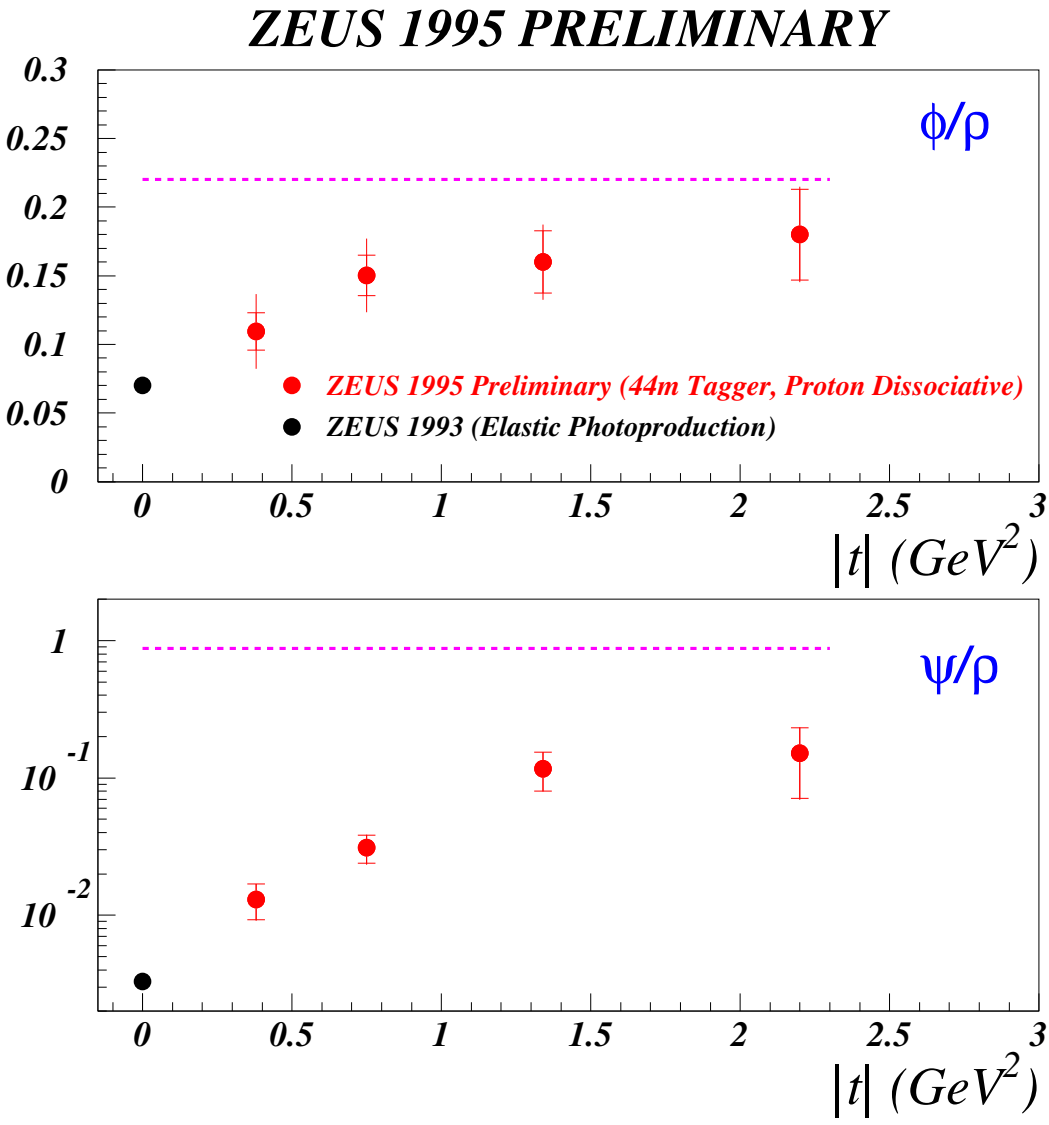


Vector Meson Production Ratios

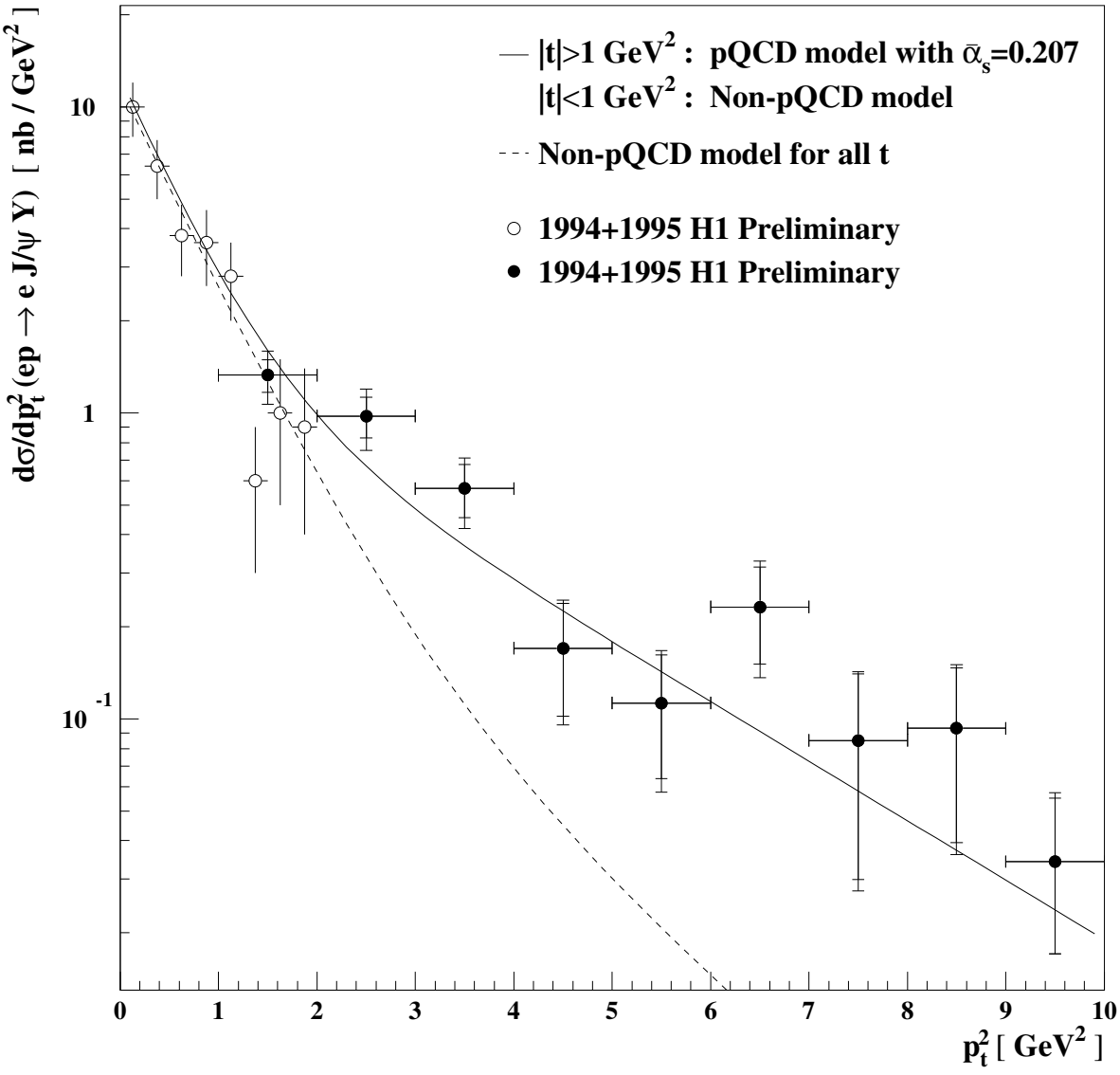
If direct e–m coupling to quarks without form factors

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

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

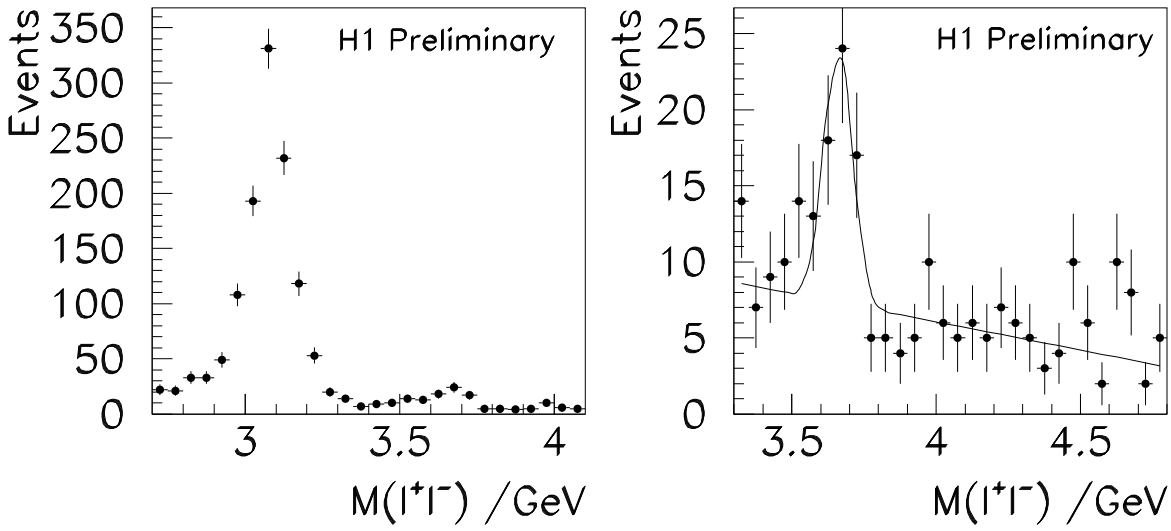


J/ψ Photoproduction at High $|t|$



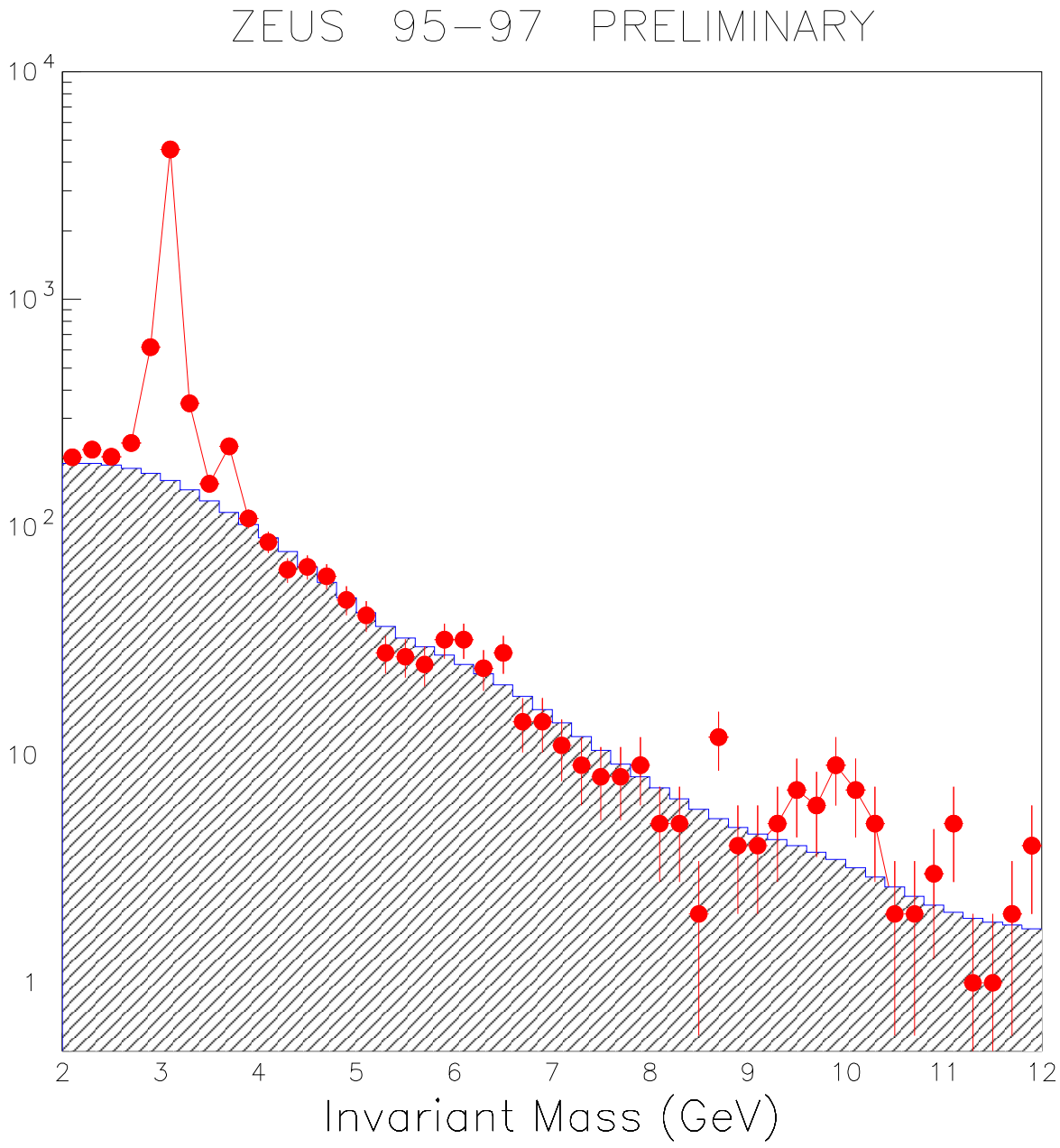
$\Rightarrow$ pQCD works at high $|t|$!!

J/ψ(2S) Signal from H1

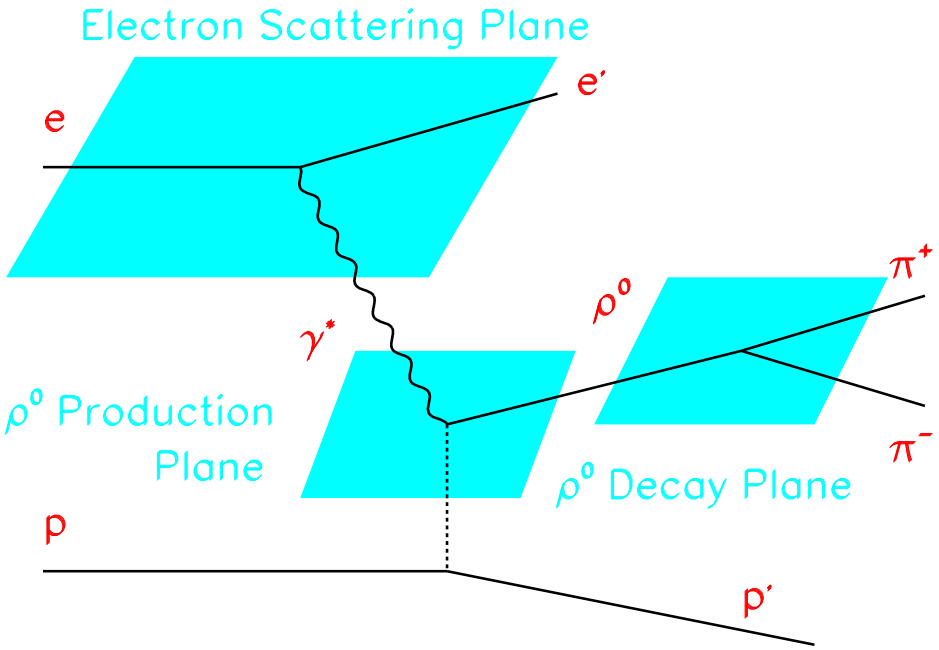


Striking effects expected for radially excited states in the color dipole model

Preliminary Υ Signal from ZEUS



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:
   $W(\theta,\phi) = W^0(\theta,\phi) \pm P_\gamma^c\ W^3(\theta,\phi)$
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

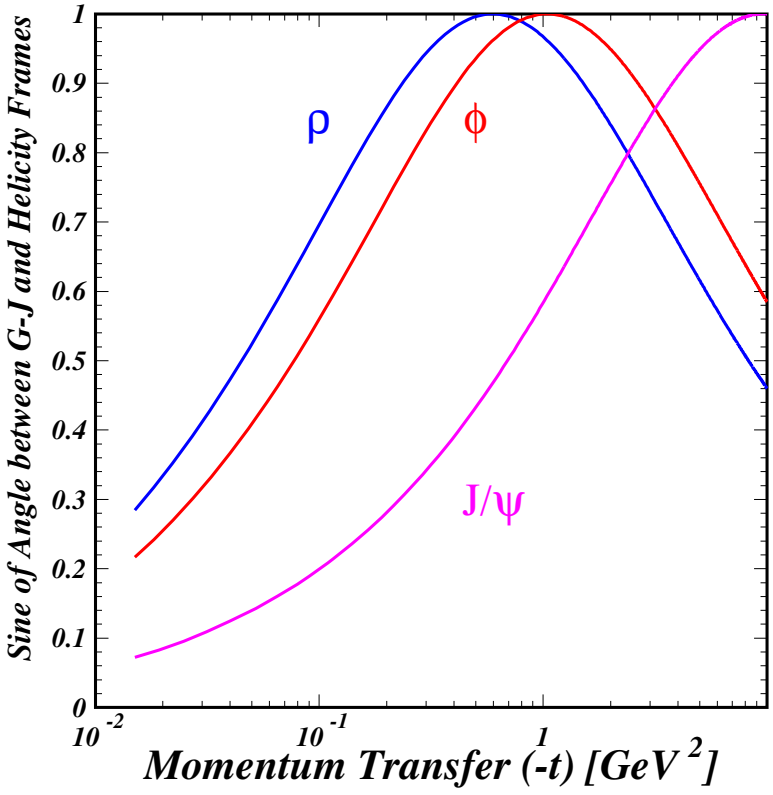
$$r^{04}_{ik} = \frac{\rho^0_{ik} + \epsilon R \rho^4_{ik}}{1 + \epsilon R}$$

$$r^{\alpha}_{ik} = \begin{cases} \frac{\rho^{\alpha}_{ik}}{1+\epsilon R} & \alpha = 1-3 \\ \frac{\sqrt{R}\,\rho^{\alpha}_{ik}}{1+\epsilon R} & \alpha = 5-8 \end{cases}$$

The Choice of Frame

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

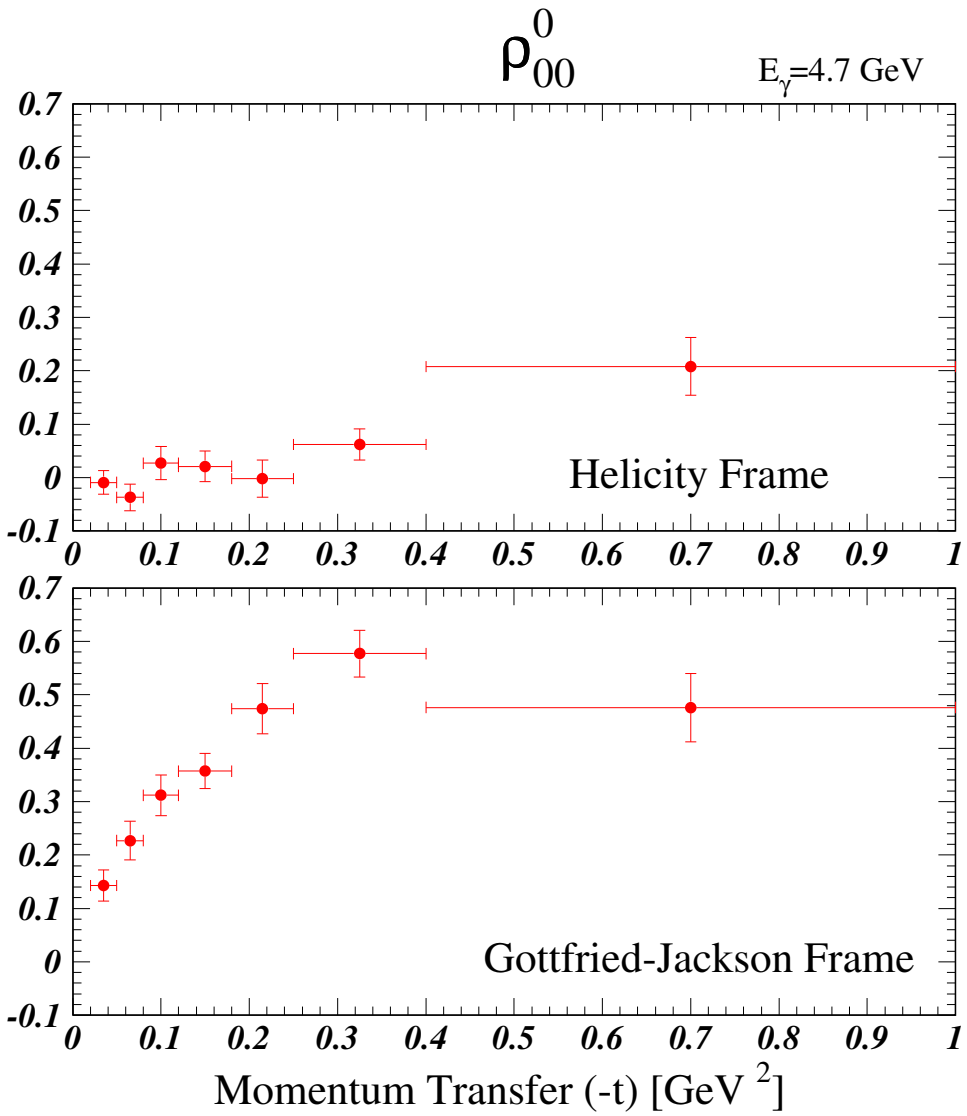
The angle χ between the two frames: $\cos\chi = \left(\frac{m_\rho^2 + t}{m_\rho^2 - t}\right)$



$\Rightarrow$ ρ^0 most sensitive to deviation from SCHC

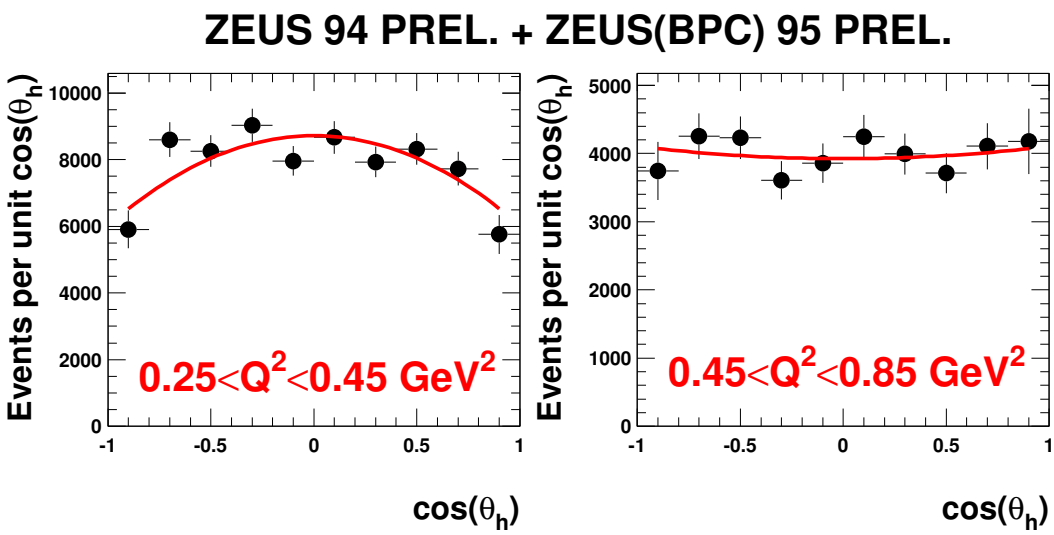
SCHC in ρ^0 Photoproduction

- 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



ρ^0 Electroproduction at HERA

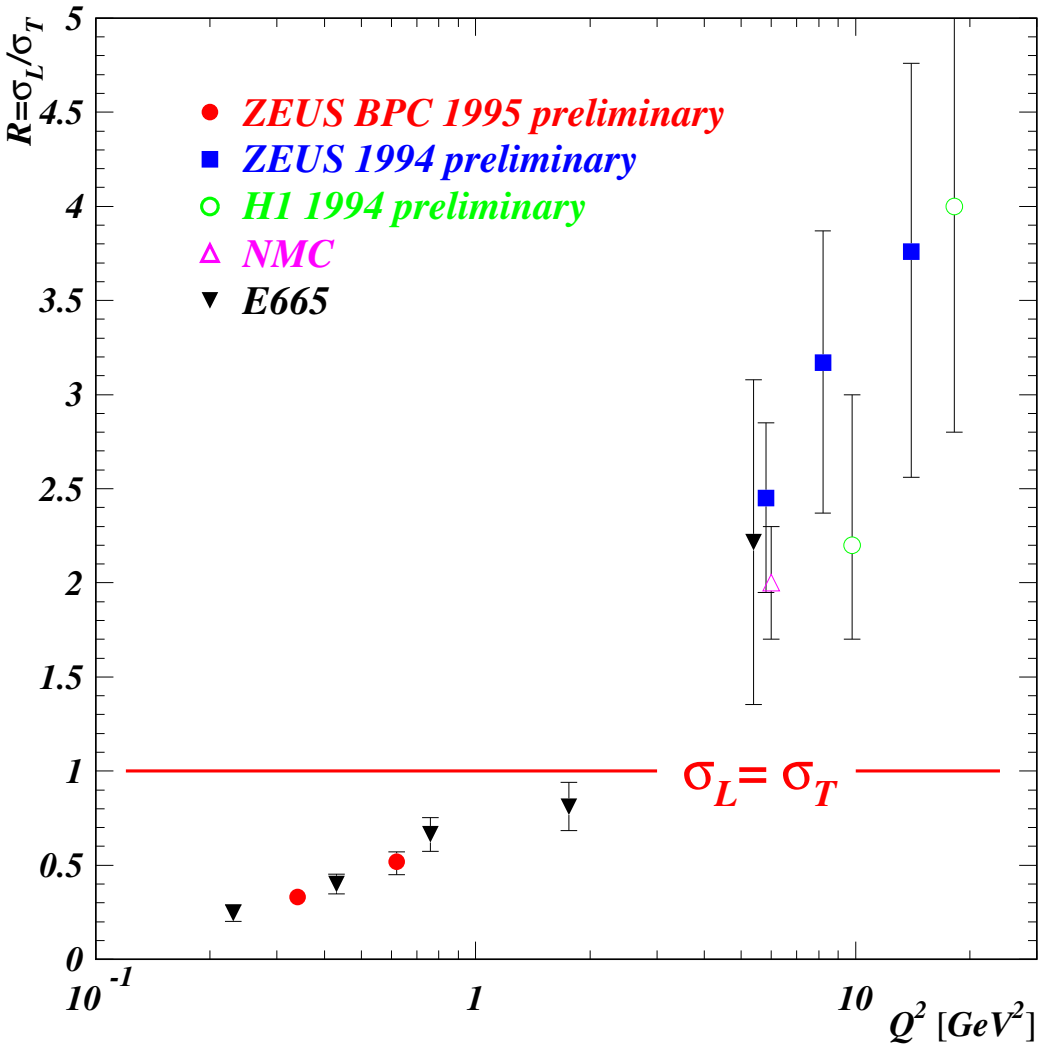
$$\frac{dN}{d\cos\theta_h} \propto 1 - r_{00}^{04} + (3r_{00}^{04} - 1)\cos^2\theta_h$$



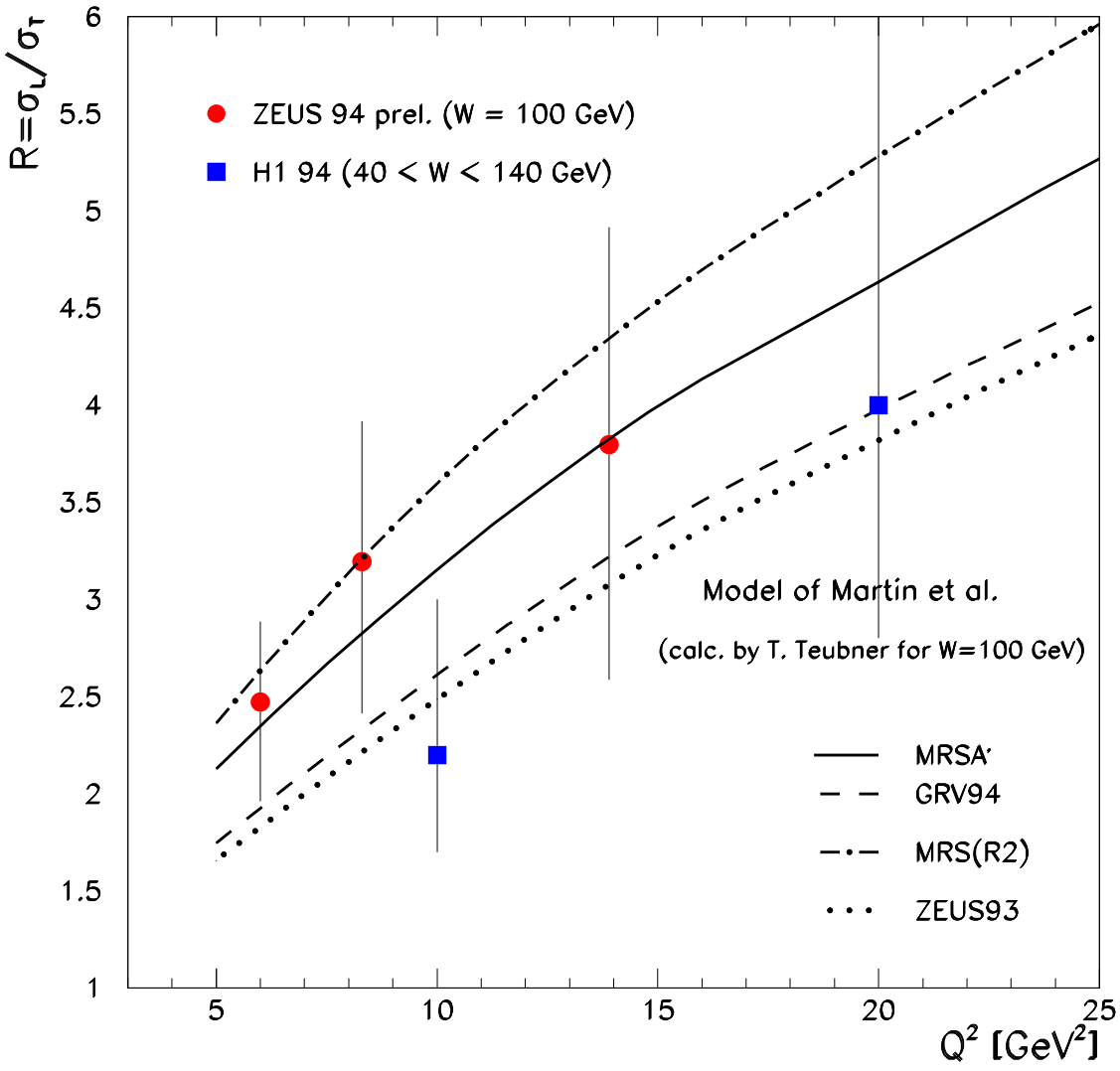
Q^2 (GeV^2)	r_{00}^{04}
0.34	0.24 ±0.02(stat)
0.62	0.34 ±0.03(stat)
5.8	$0.71^{+0.03}_{-0.04}$(stat)$^{+0.01}_{-0.01}$(sys)
8.2	$0.76^{+0.04}_{-0.04}$(stat)$^{+0.00}_{-0.02}$(sys)
14	$0.79^{+0.04}_{-0.05}$(stat)$^{+0.02}_{-0.01}$(sys)

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

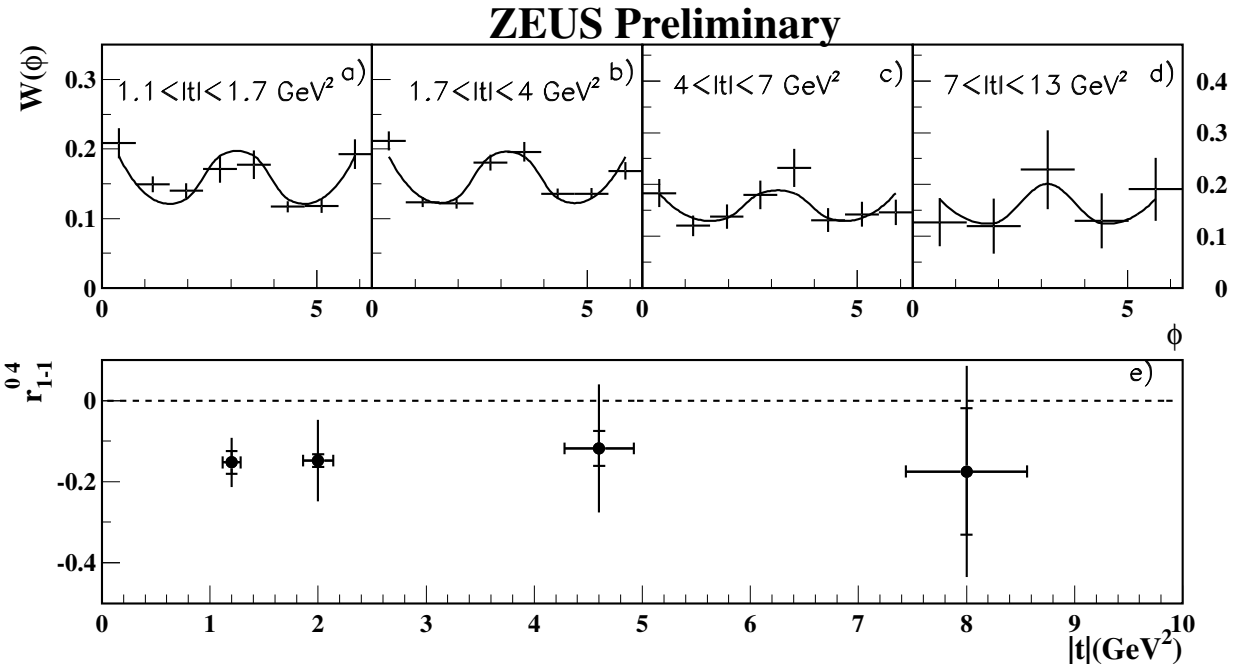
Assuming SCHC: $R = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}$



pQCD Calculation of R



SCHC at High $|t|$



But the ρ^0 is tricky (r_{ik} depend on $m_{\pi\pi}$)

Discrepancy not observed for the ϕ

$\Rightarrow$ see Jim Whitmore's talk

Conclusions

These 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

These studies are statistics–limited