EPIC'99
8 April 1999

Indiana University
Cyclotron Facility

Results from ZEUS and H1 on Diffractive Processes

Workshop on Physics with an Electron/Polarized-Ion Collider

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Physics Institute
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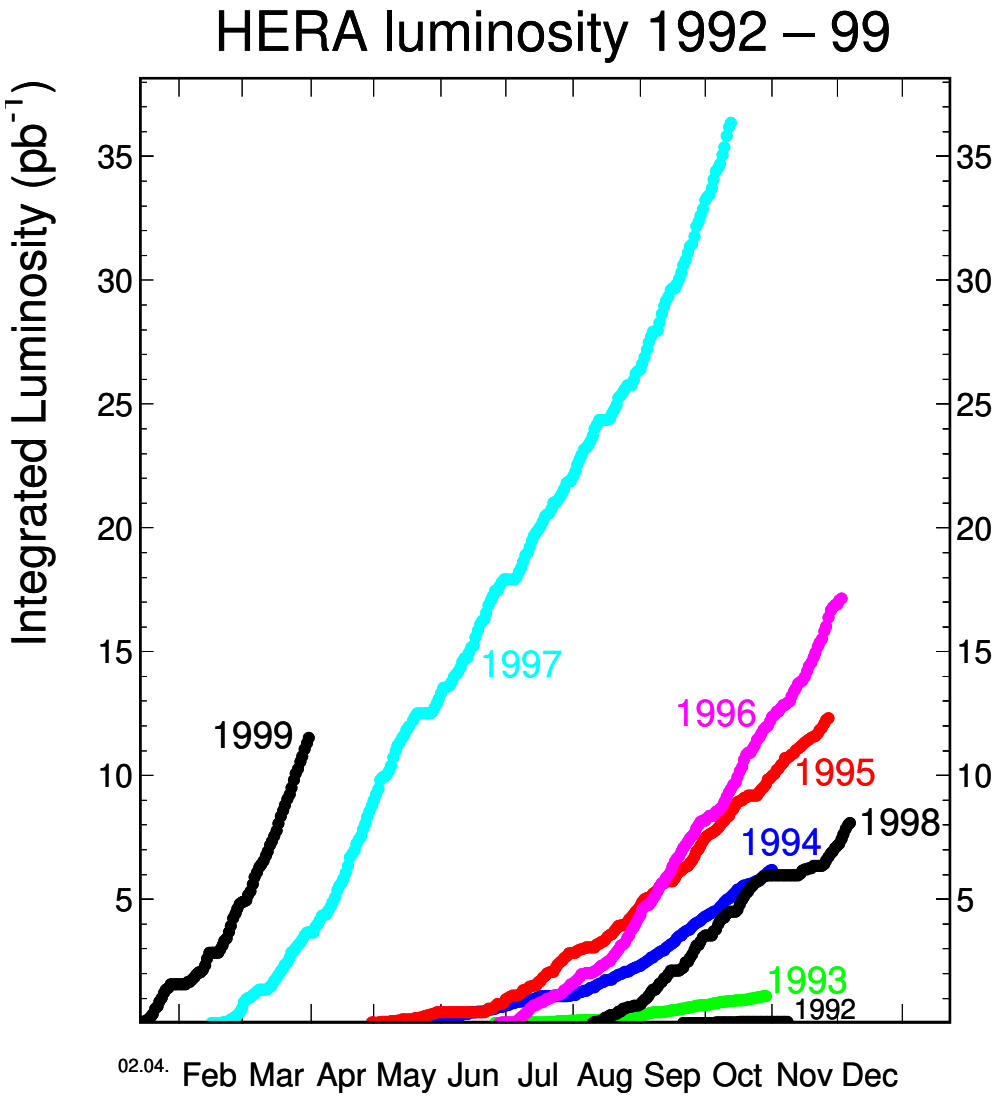
HERA Luminosity History



Luminosity upgrade in 2000

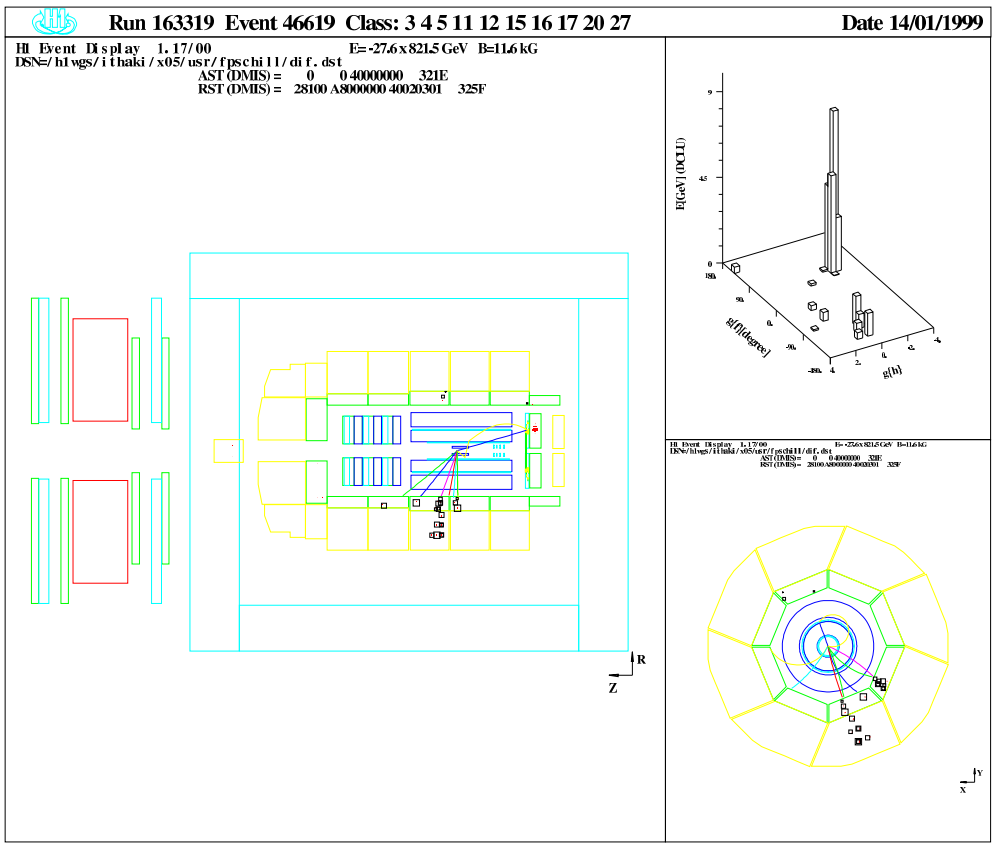
with a goal of 1 fb^{-1} by 2005

We expect an increase of a factor 20

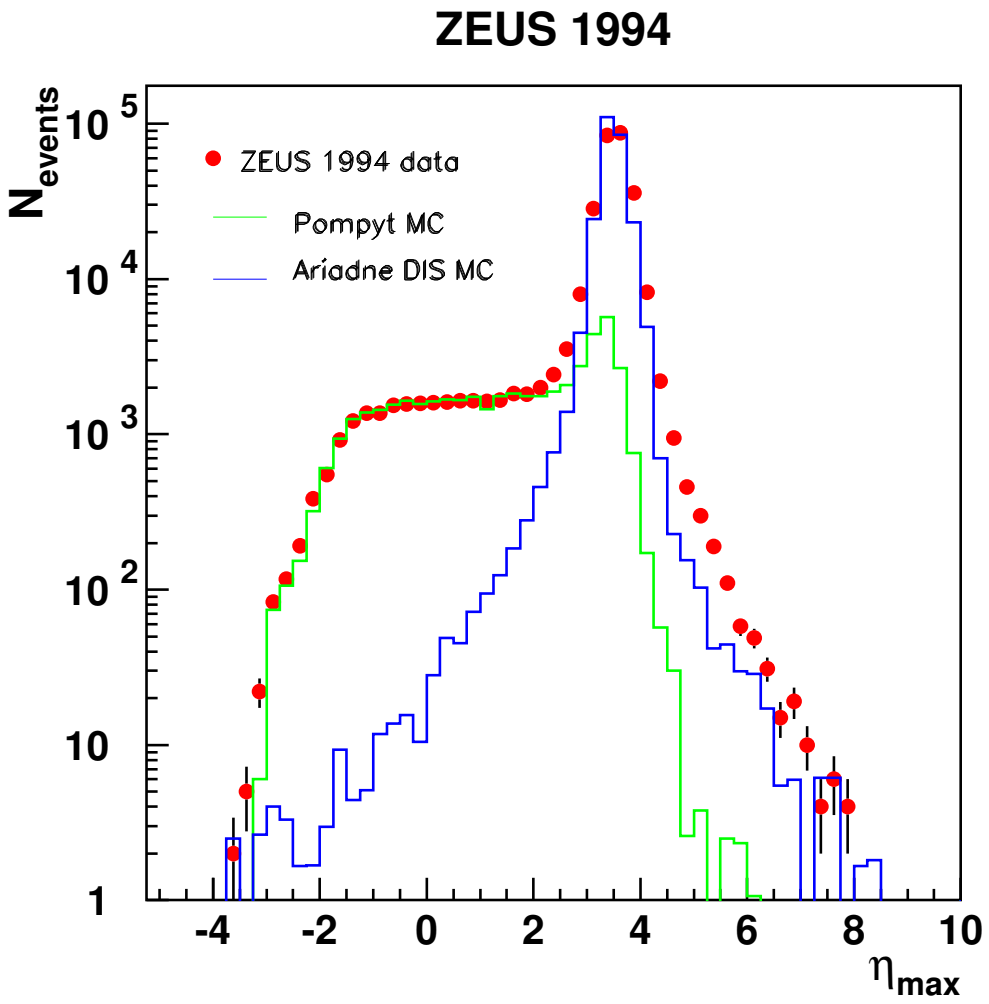
over the present integrated luminosity

Candidate for Inclusive Diffraction

Rapidity-Gap Signature

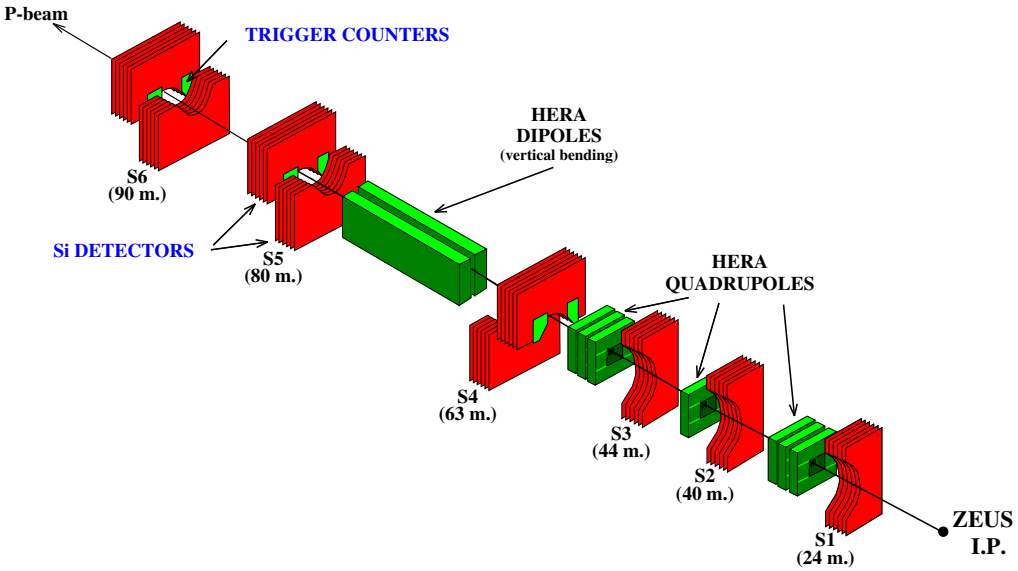


Rapidity-Gap Analysis

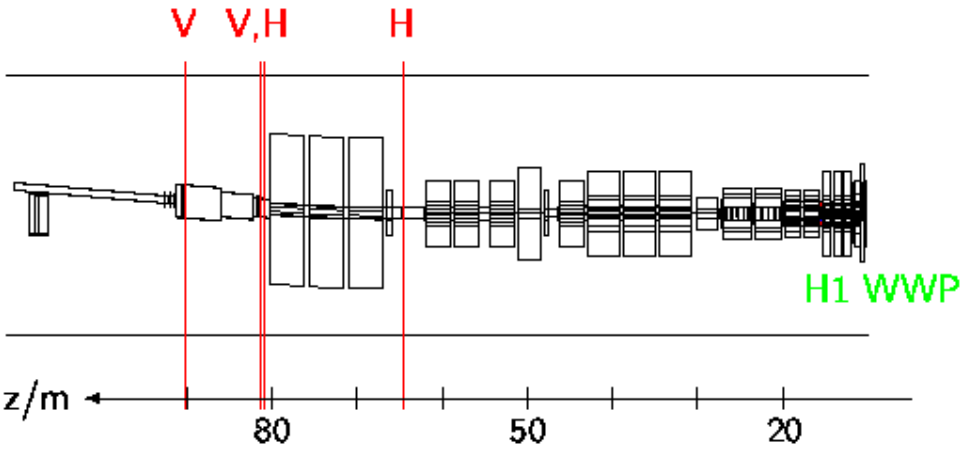


Leading Baryon Detectors

ZEUS



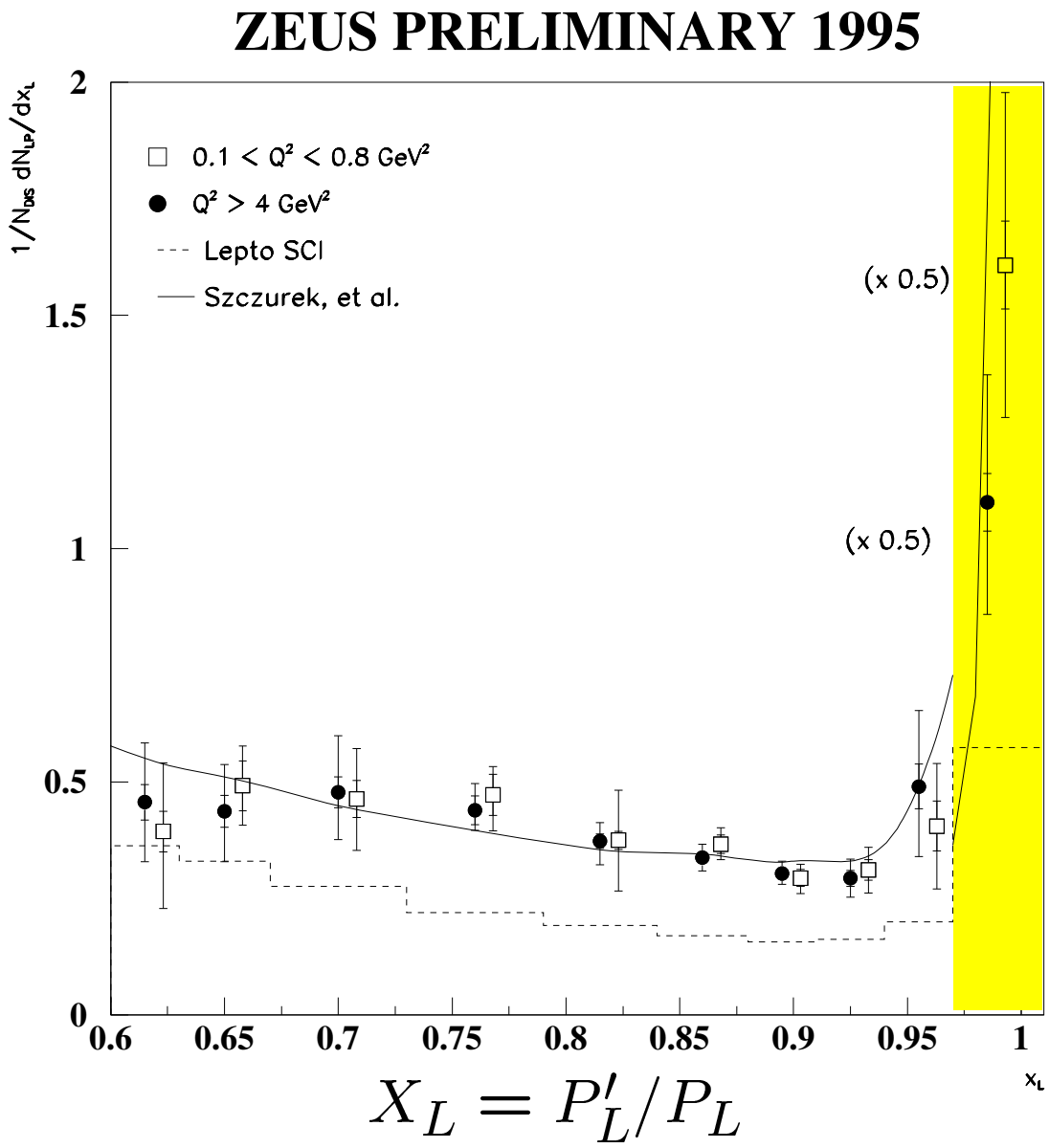
H1



Each experiment also operates forward neutron detectors

Q^2 Independence of Diffraction

Double Tag with the
Leading Proton Spectrometer
and the
Beam-Pipe Calorimeter



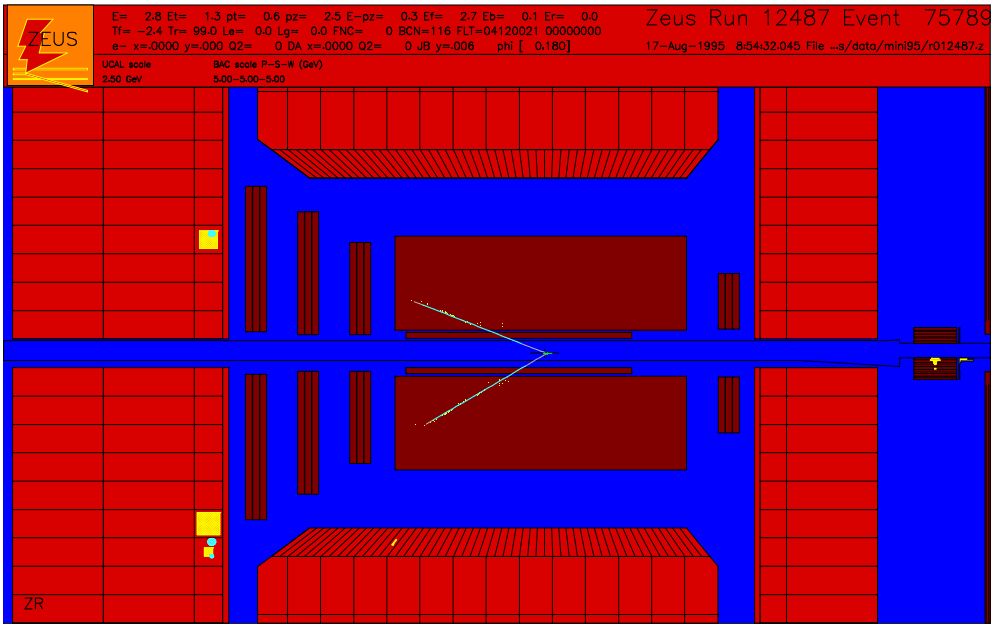
$$X_L = P'_L / P_L$$

$\Rightarrow$ X_L spectrum Q^2 unchanged even at very low Q^2

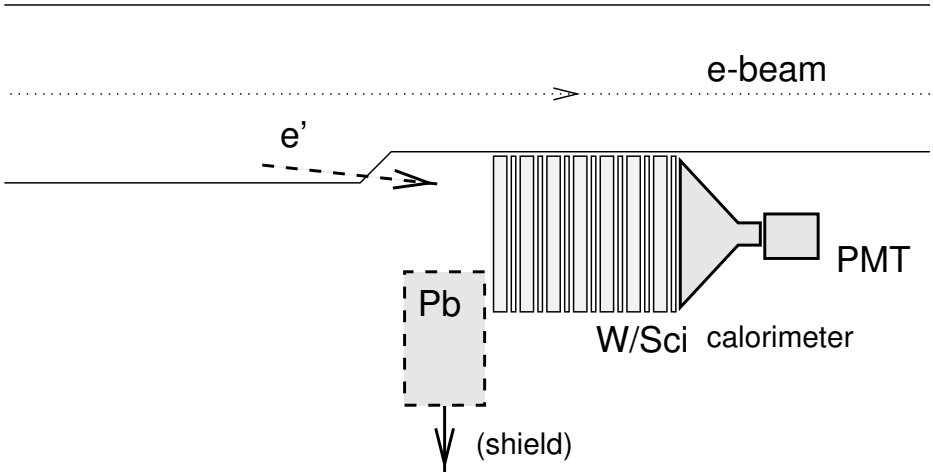
Special-Purpose Electron Detectors

ZEUS Beam Pipe Calorimeter

Elastic J/ψ Electroproduction $(0.1 < Q^2 < 0.8$ GeV$^2)$

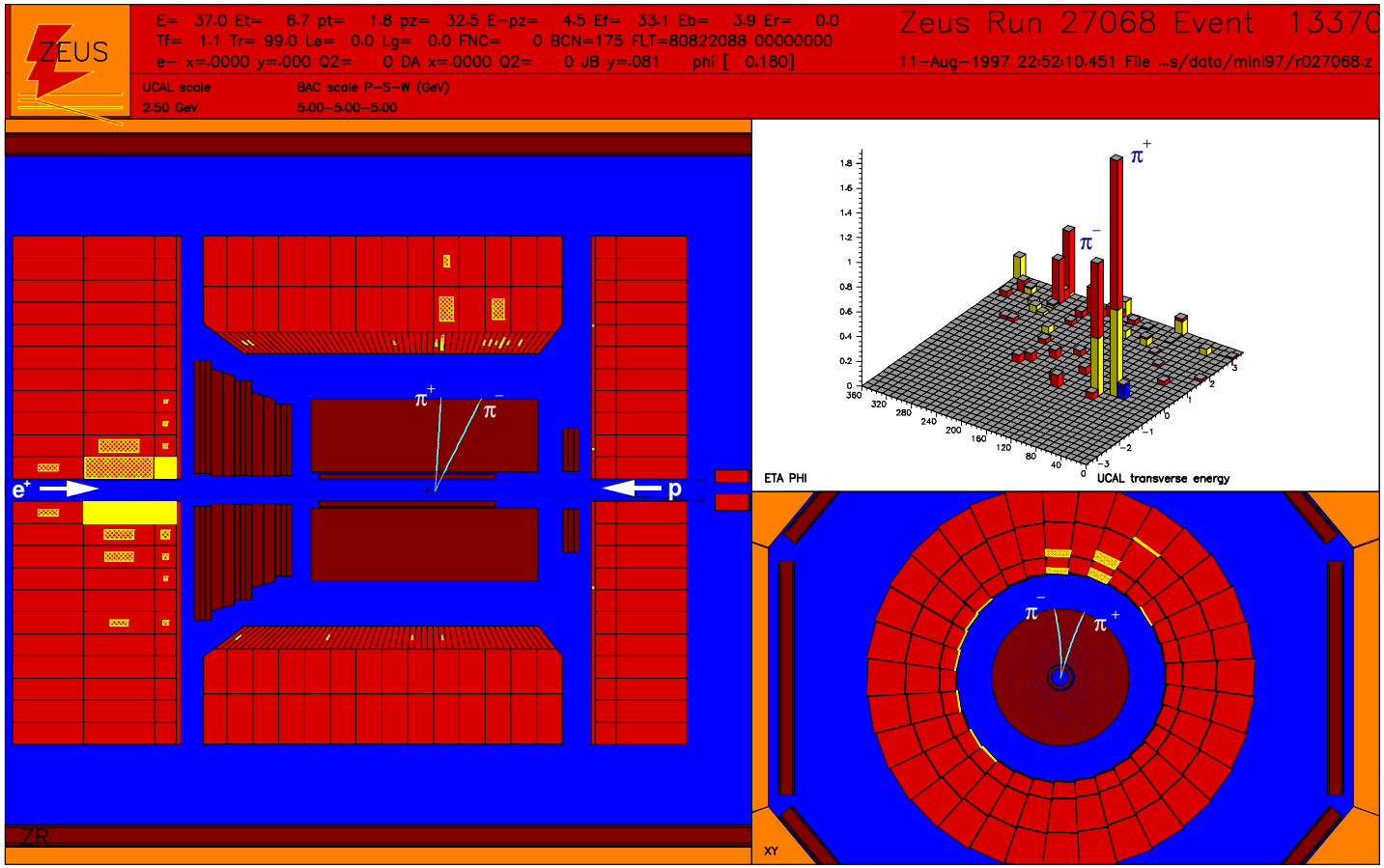


Photoproduction Tagger at 44m



Acceptance: $Q^2 < 0.01$GeV$^2 \Rightarrow t \simeq -P_T^2$(VM)

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

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:

$$\boxed{x < 0.06}$$

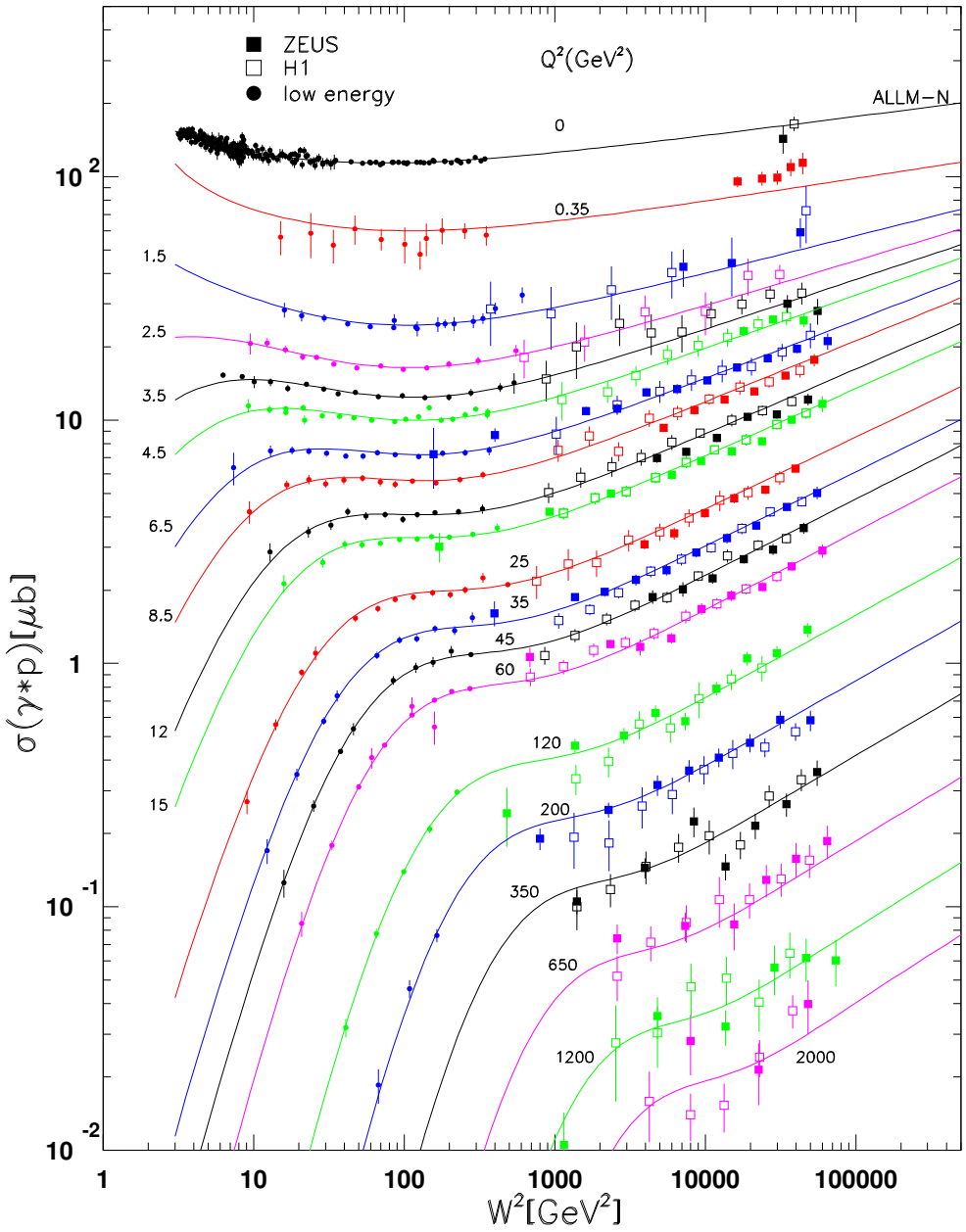
$$W^2 = Q^2\left[\frac{1}{x} - 1\right] + m_{\mathrm{p}}^2 \approx \frac{Q^2}{x}$$

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

Gilman, Hand conventions for virtual-photon flux definition

Total Photon-Proton Cross Sections

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



⇒ Steeply rising cross sections at high energy!

Regge Phenomenology

☞ Energy Dependence of Elastic Cross Sections

$\Rightarrow$ Exchange of the phenomenological Pomeron

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

$$\boxed{\alpha_{I\!P}(t) = 1.08 + 0.25\,t}$$

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

$$\propto W^{4\epsilon} = W^{0.32}$$

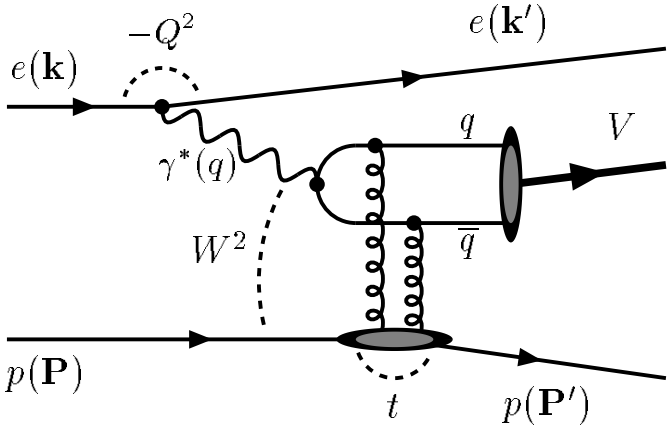
☞ "Shrinkage"

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

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

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

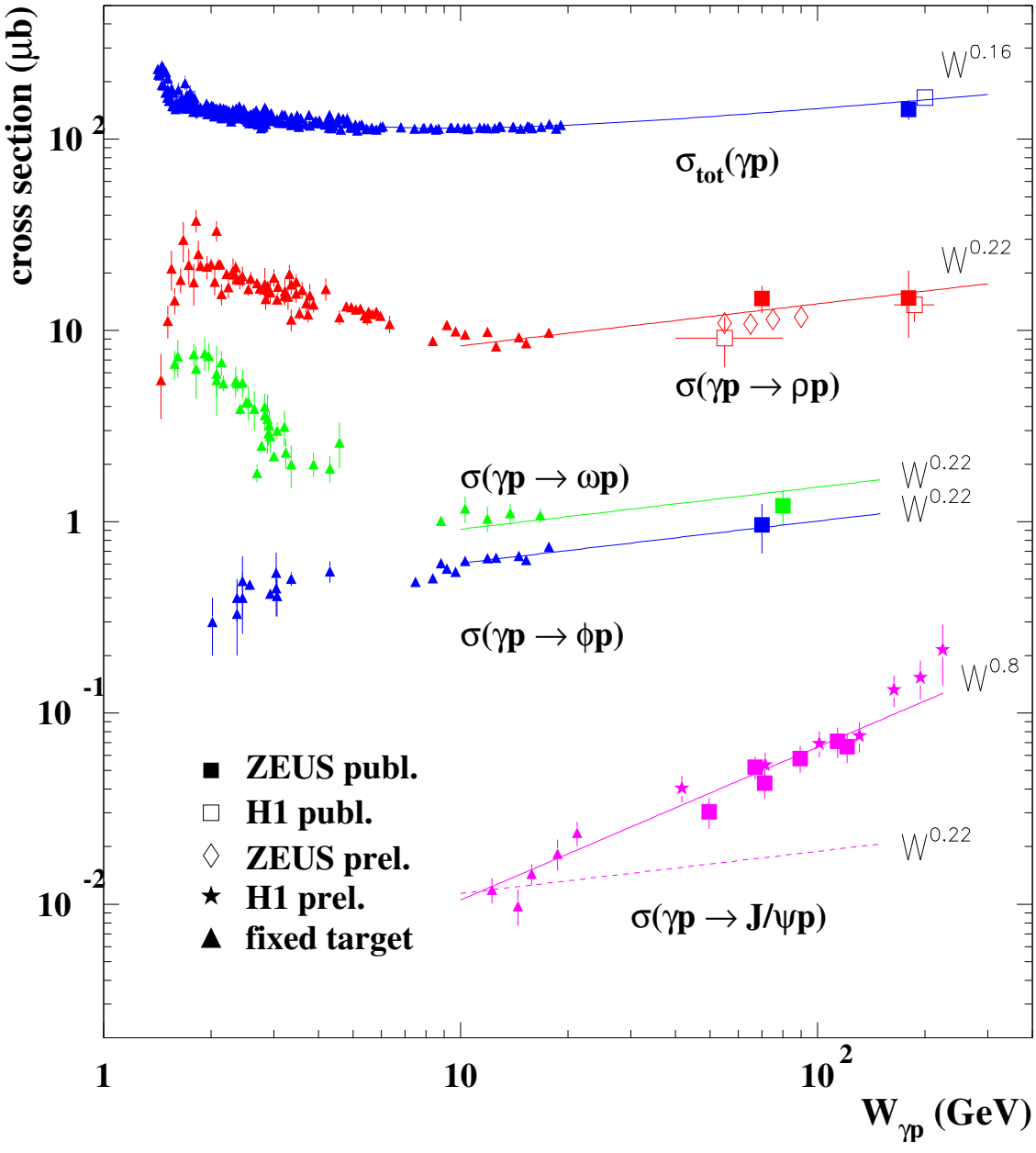
Ryskin, Z.Phys. C57 (1993) 89 (J/ψ Photoproduction)

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

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

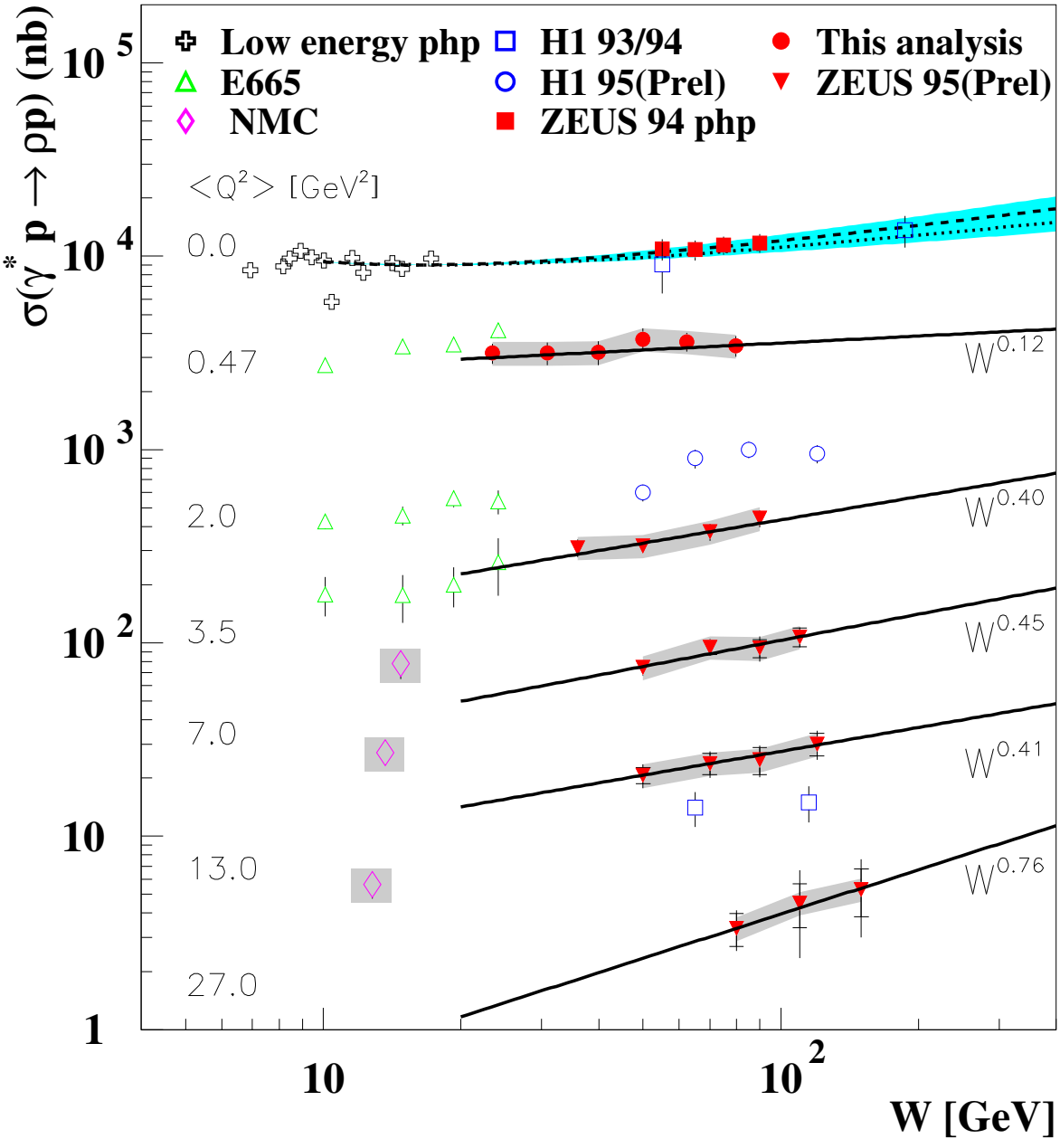
What experimental signatures for the region of pQCD validity ?

Elastic Vector-Meson Photoproduction Cross Sections



⇒Energy dependence for the J/ψ much steeper !

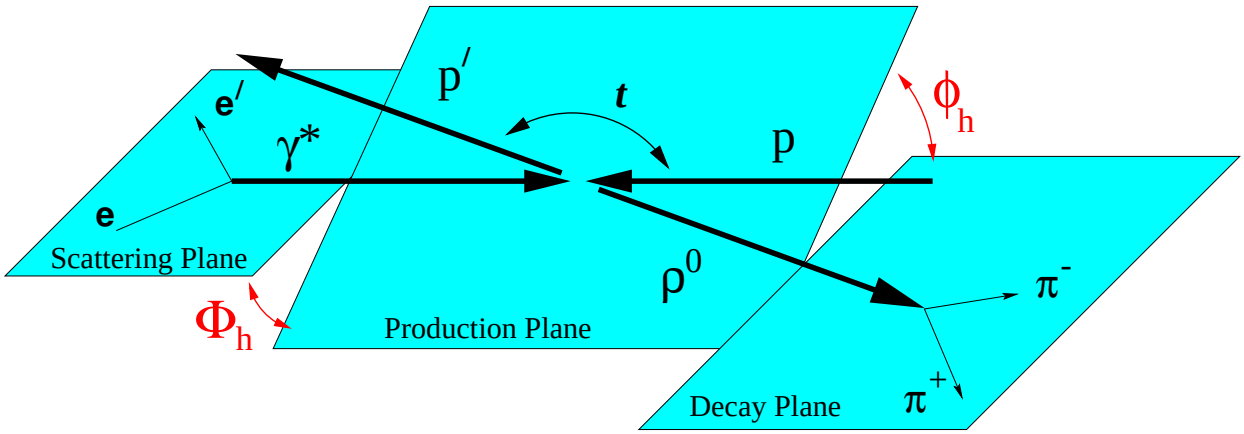
Elastic ρ^0 Cross Sections



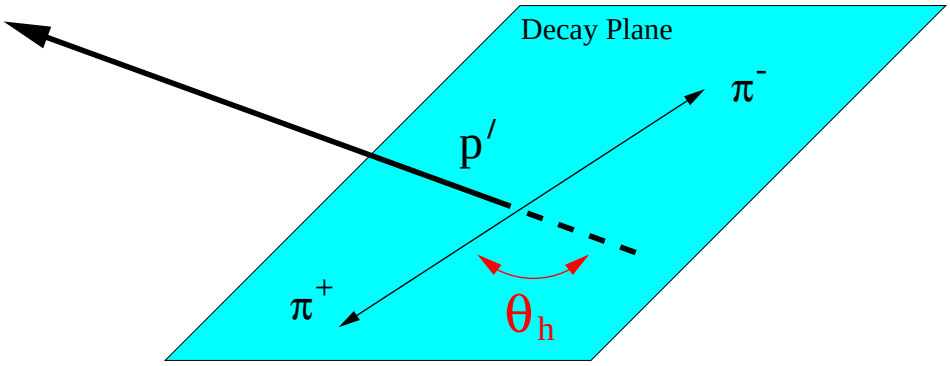
$\Rightarrow$ Steepening with Q^2?

Helicity Analyses

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

- 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!

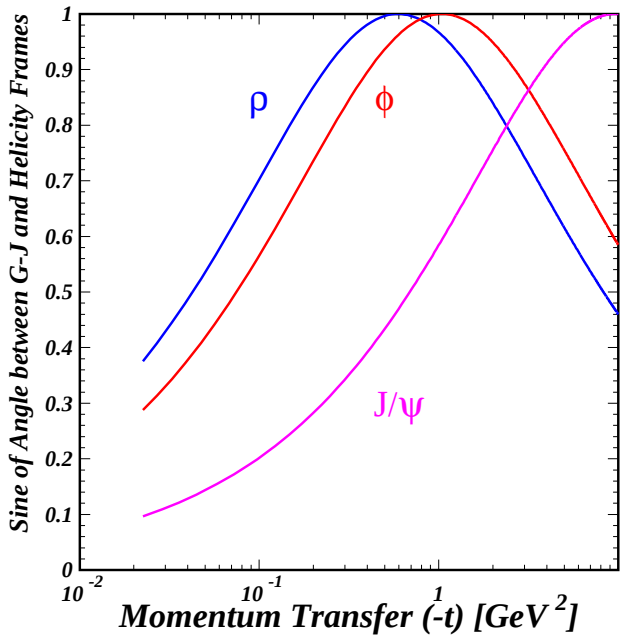
$$r^{\alpha}_{ik} = \begin{cases} \dfrac{\rho^{\alpha}_{ik}}{1+\epsilon R} & \alpha = 1 - 3 \text{ (Trans.)} \\ \dfrac{\sqrt{R}\,\rho^{\alpha}_{ik}}{1+\epsilon R} & \alpha = 5 - 8 \text{ (L/T int.)} \end{cases}$$

Constraints from hermiticity, parity conservation

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)

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

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

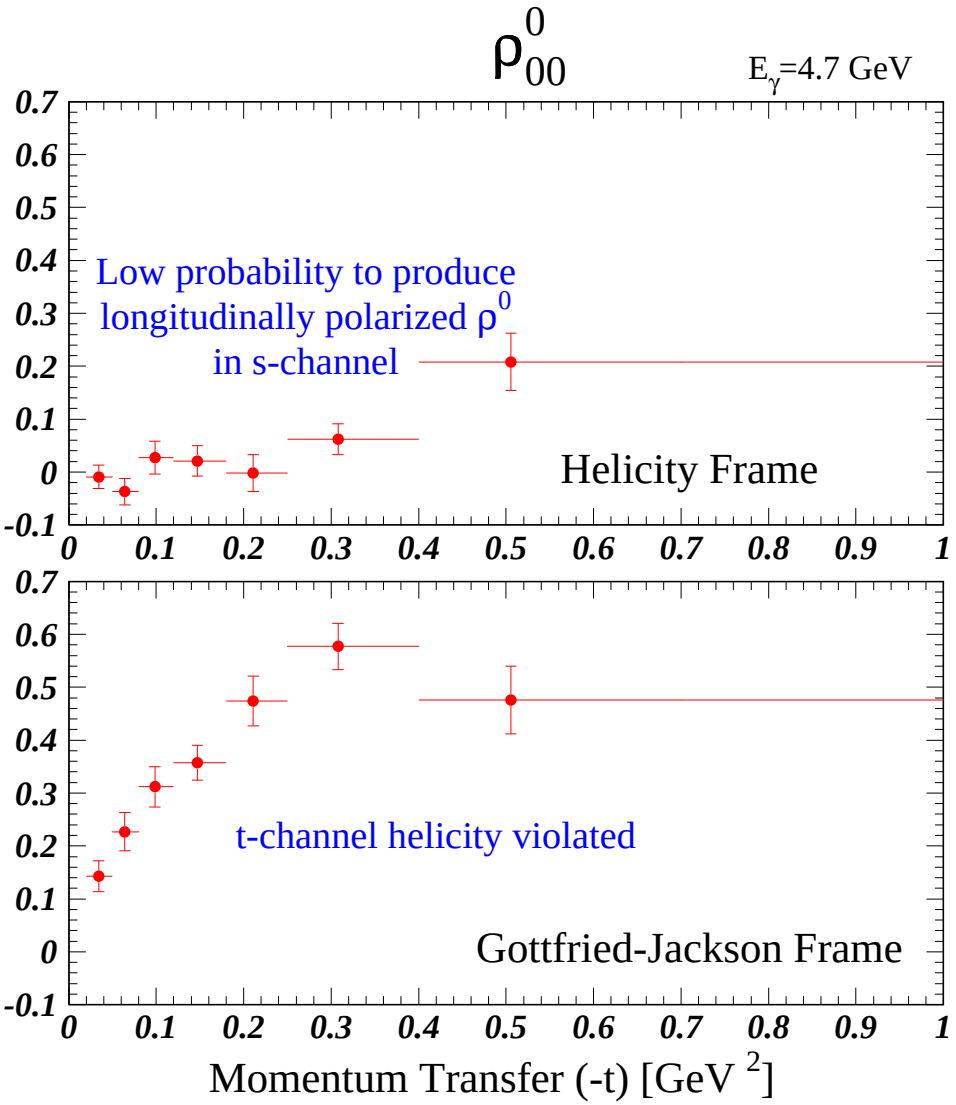
$$-\varepsilon\cos 2\Phi_h(\ r^1_{11}\sin^2\theta_h + r^1_{00}\cos^2\theta_h$$
$$-\sqrt{2}\,\mathrm{Re}\, r^1_{10}\ \sin 2\theta_h\cos\phi_h$$
$$-r^1_{1-1}\sin^2\theta_h\cos 2\phi_h\ )$$
$$-\varepsilon\sin 2\Phi_h(\ \sqrt{2}\,\mathrm{Im}\, r^2_{10}\ \sin 2\theta_h\sin\phi_h$$
$$+\mathrm{Im}\, r^2_{1-1}\sin^2\theta_h\sin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

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

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

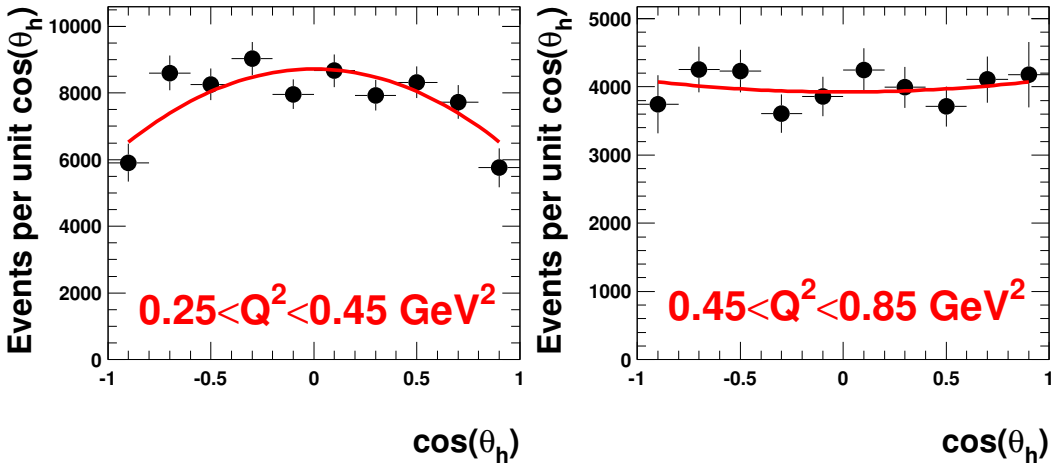
Gilman et al PL B31 (1970) 387

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

ρ^0 Electroproduction at HERA

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

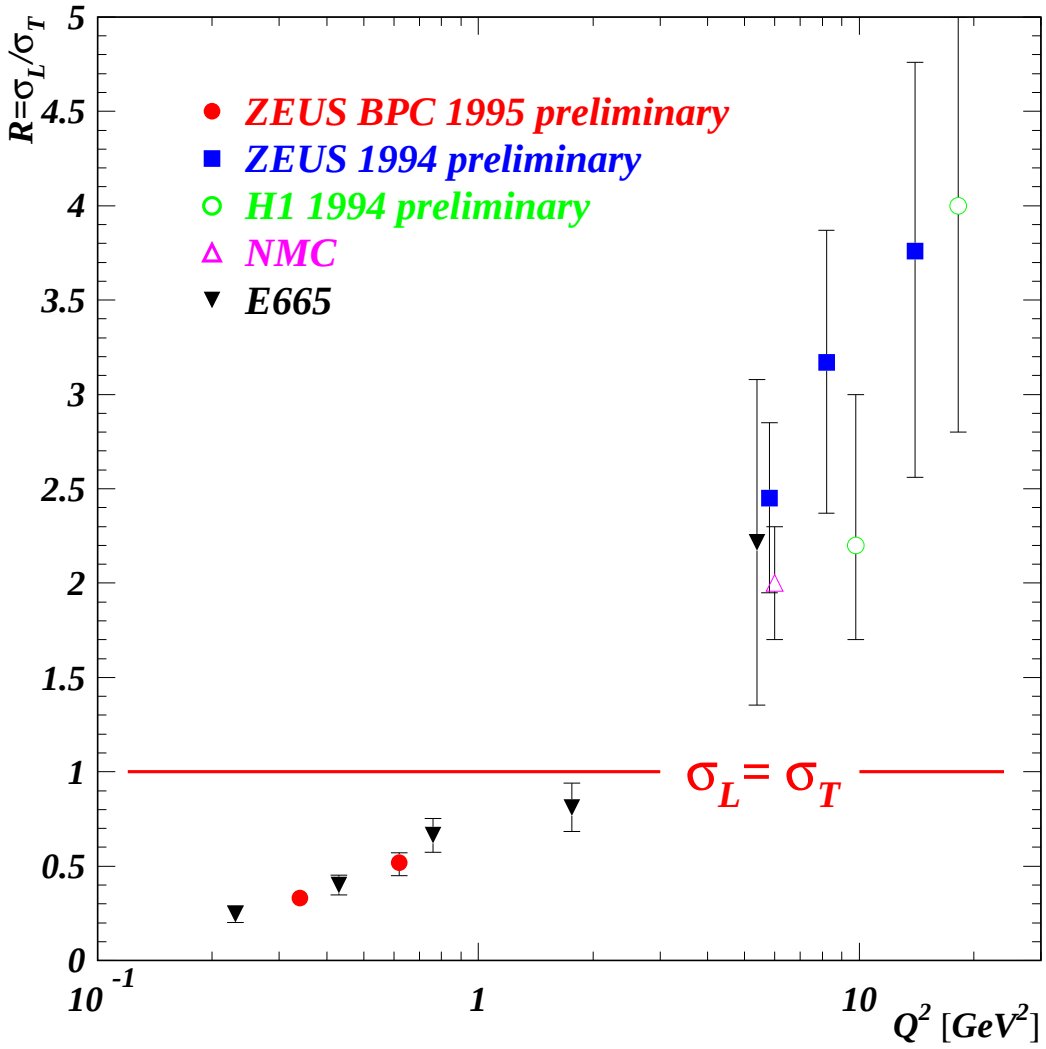
ZEUS 94 PREL. + ZEUS(BPC) 95 PREL.



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

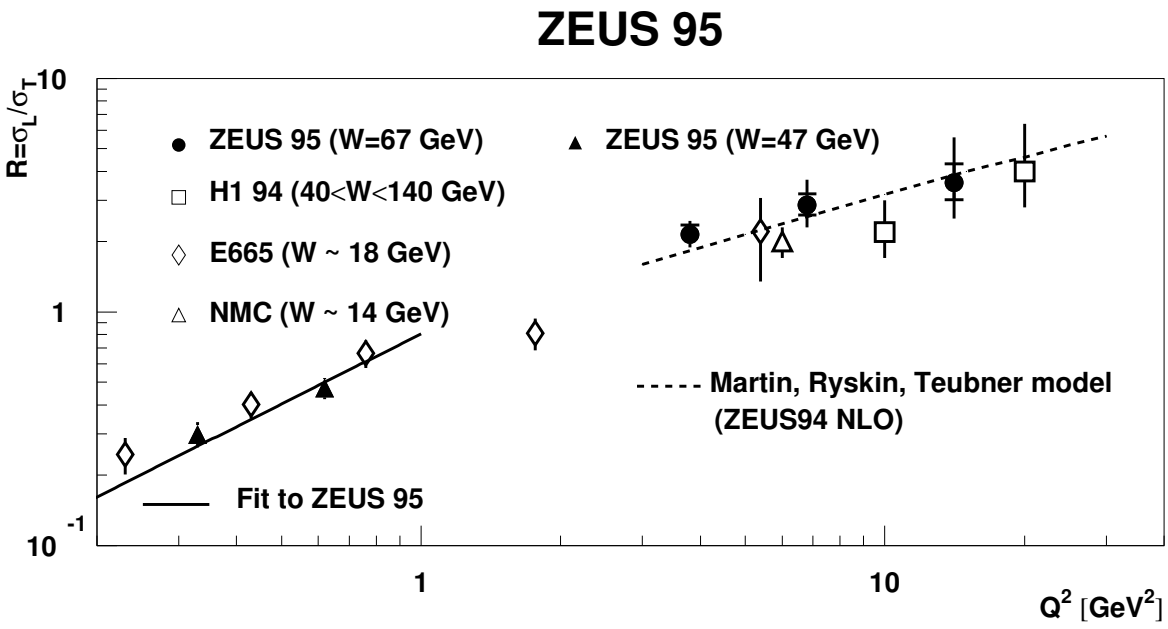
Assuming SCHC: $R = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - r_{00}^{04}}$

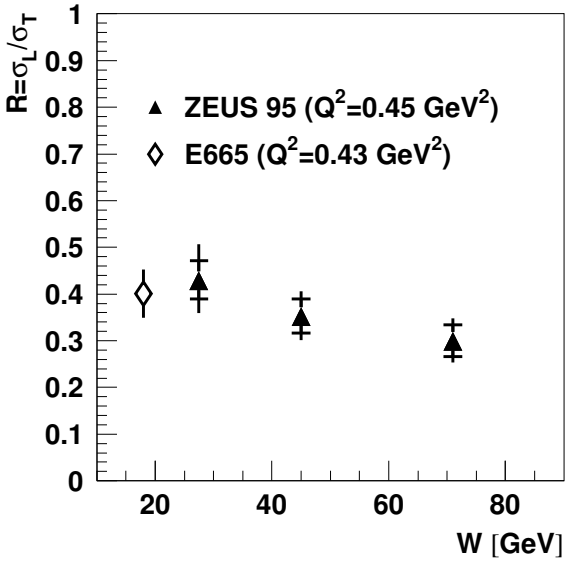


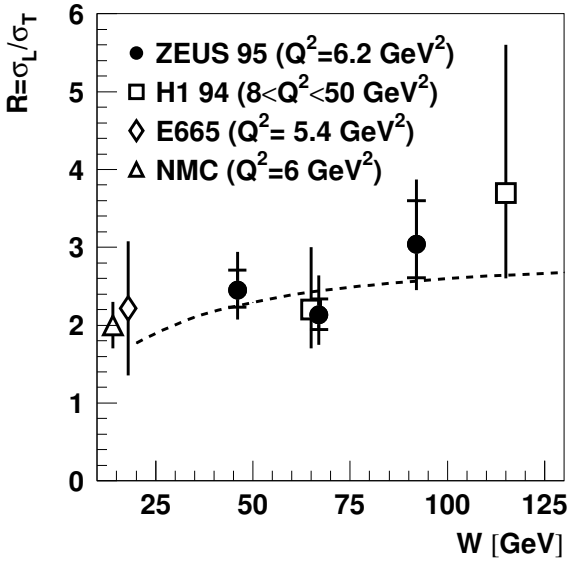
$\Rightarrow \sigma_L$ increases and becomes dominant

R vs Q^2 and W for ρ^0

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



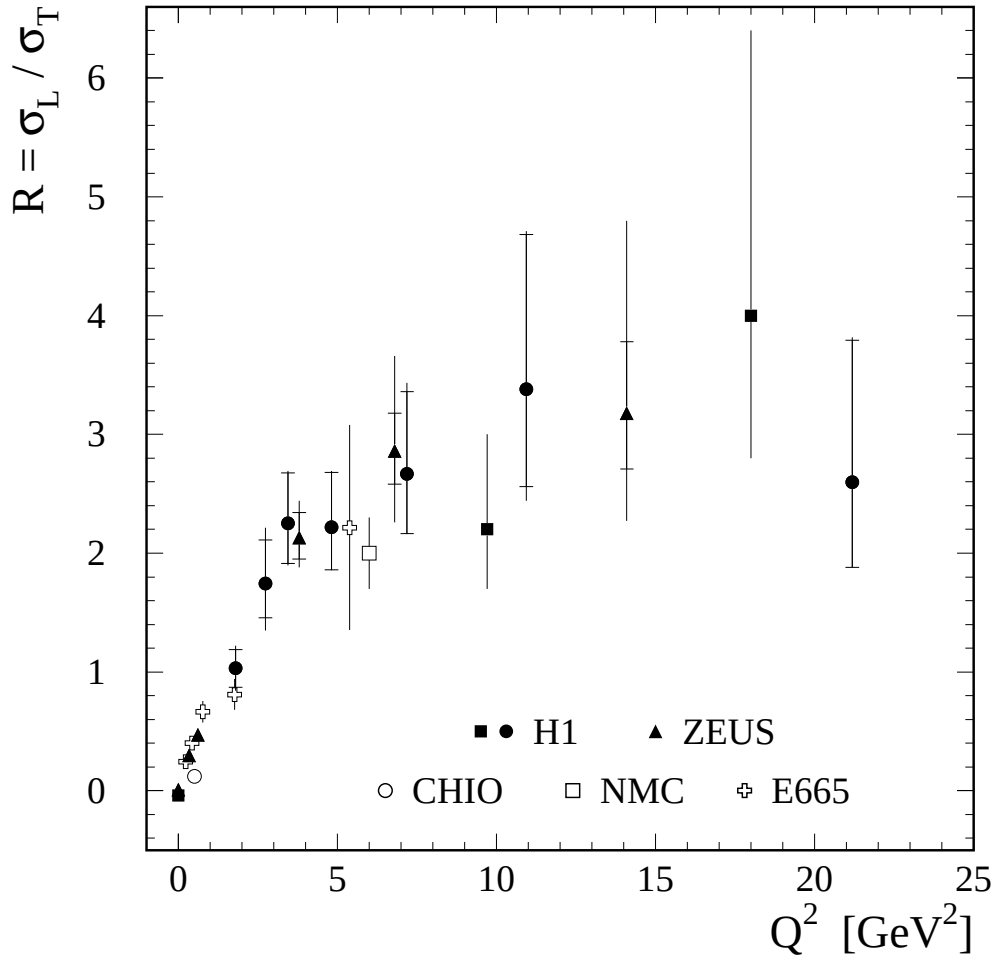




$\Rightarrow$ Do σ_T and σ_L have similar W dependence ?

R vs Q^2 (H1 DIS ρ^0)

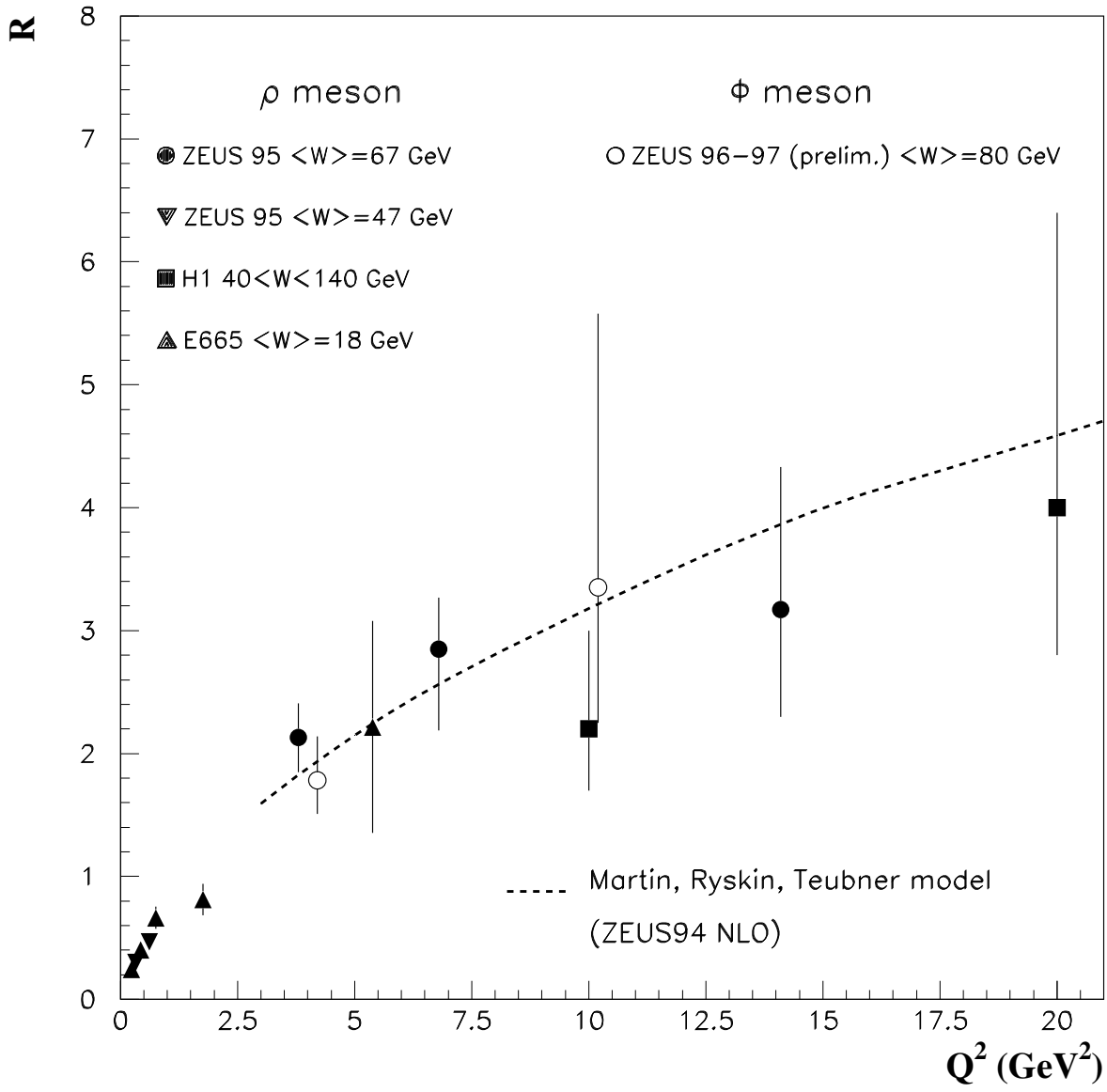
H1 hep-ex/9902019



$\Rightarrow$ σ_L/σ_T levelling off ??

R vs Q^2 (ZEUS DIS ϕ prel.)

ZEUS ICHEP Abstract 793

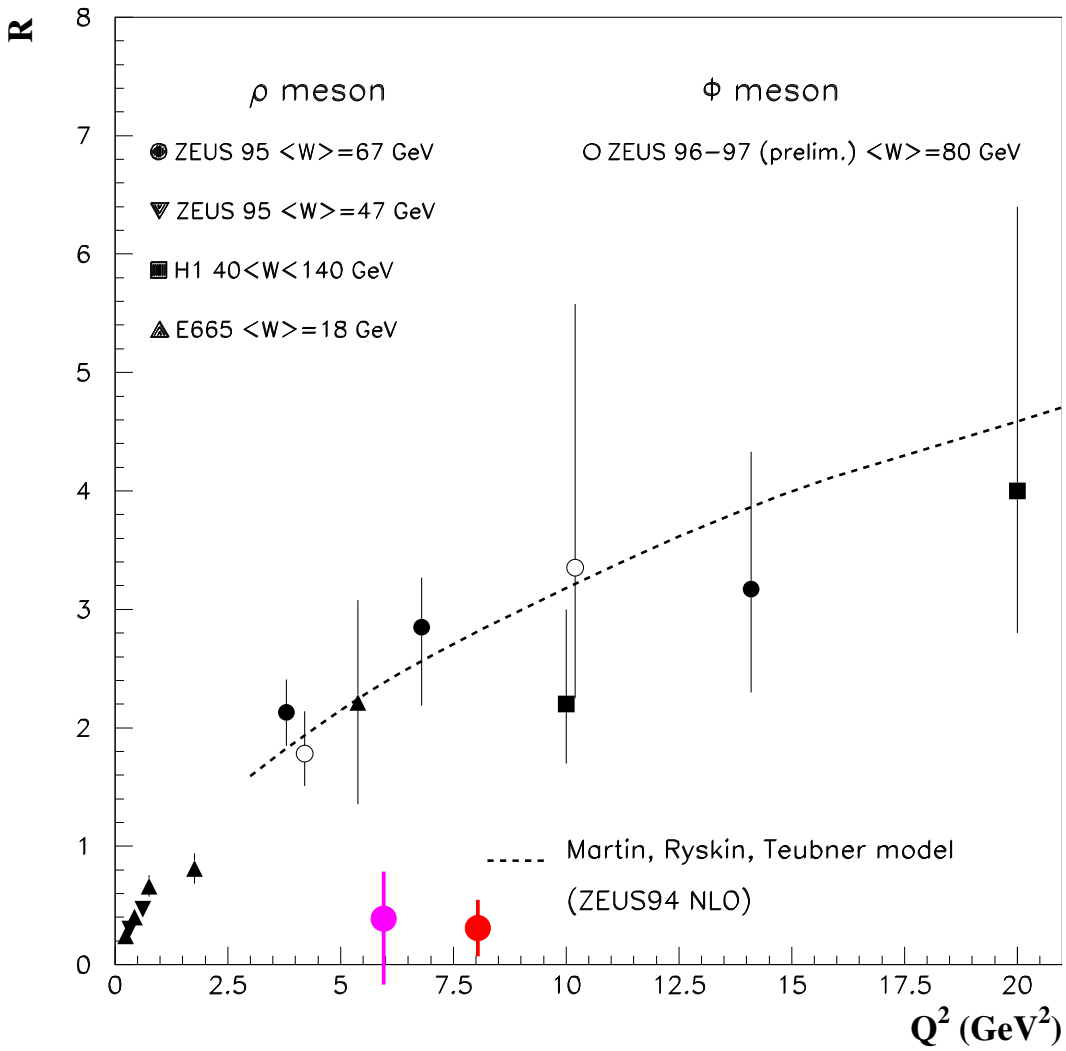


$\Rightarrow$ ϕ behaves like ρ^0 !!

R vs Q^2 for J/ψ

H1 ICHEP Abstract 572

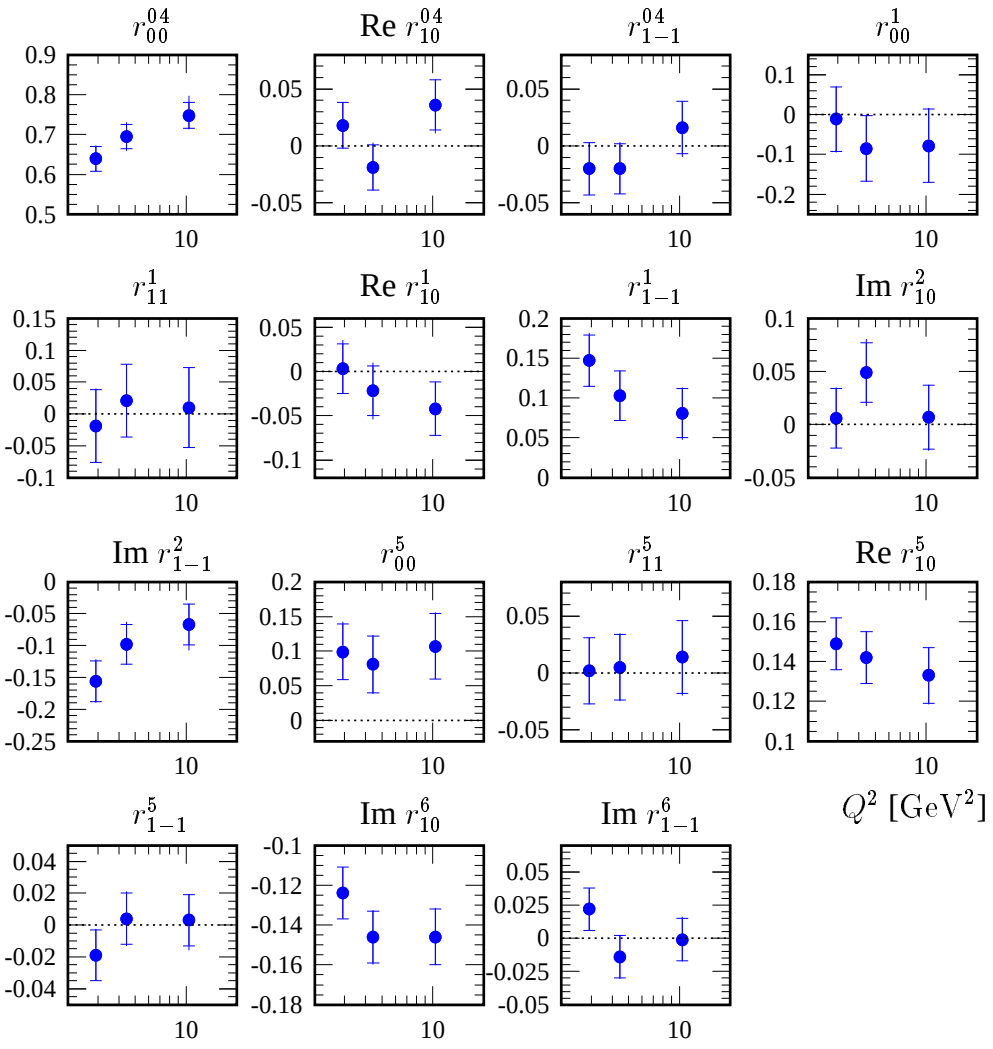
ZEUS Eur. Phys. J. C6 (1999) 603



$\Rightarrow$ R for J/ψ lower !!

15-Parameter Helicity-Angle Fit (I)

H1 hep-ex/9902019

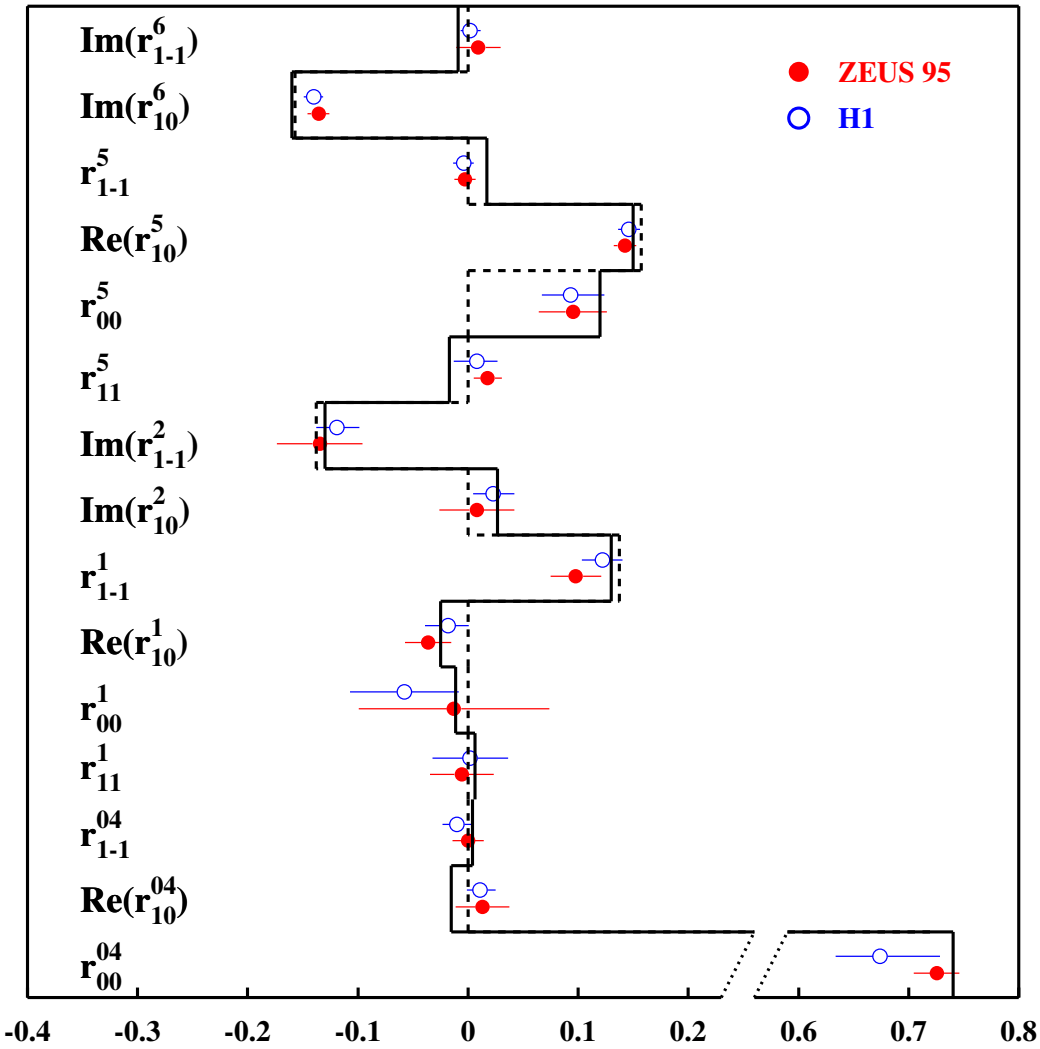


Dotted lines are SCHC values

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

15-Parameter Helicity-Angle Fit (II)

ZEUS ICHEP Abstract 792/792b

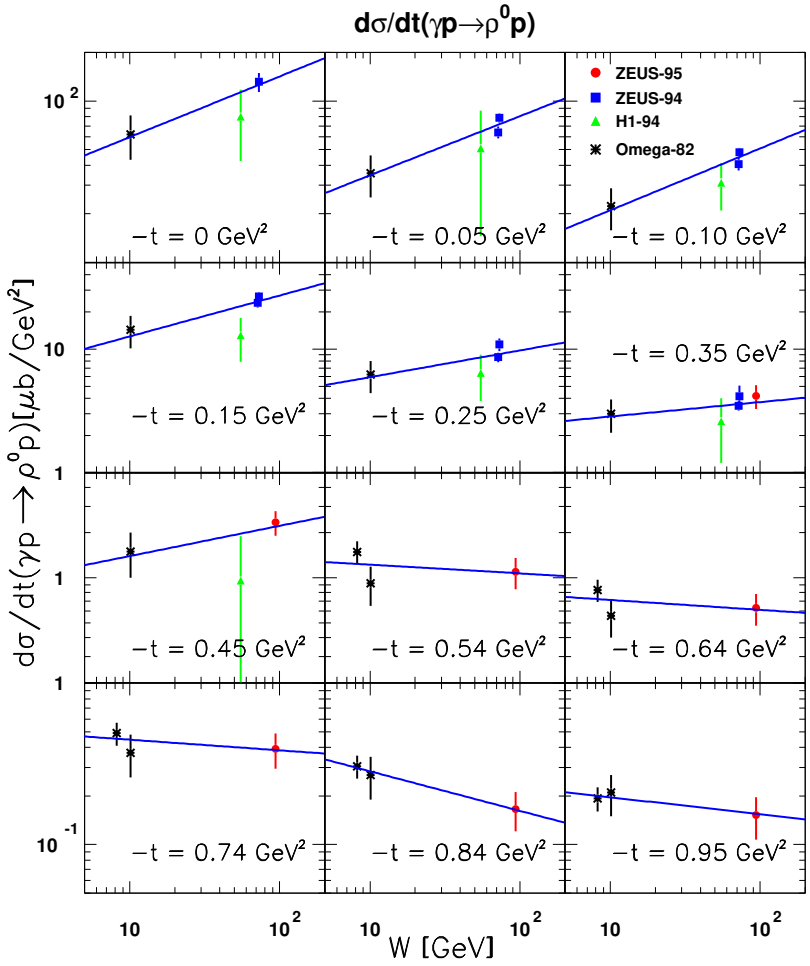


$\Rightarrow$ Agreement with Ivanov and Kirschner

(Phys. Rev. D58 (1998) 114026)

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

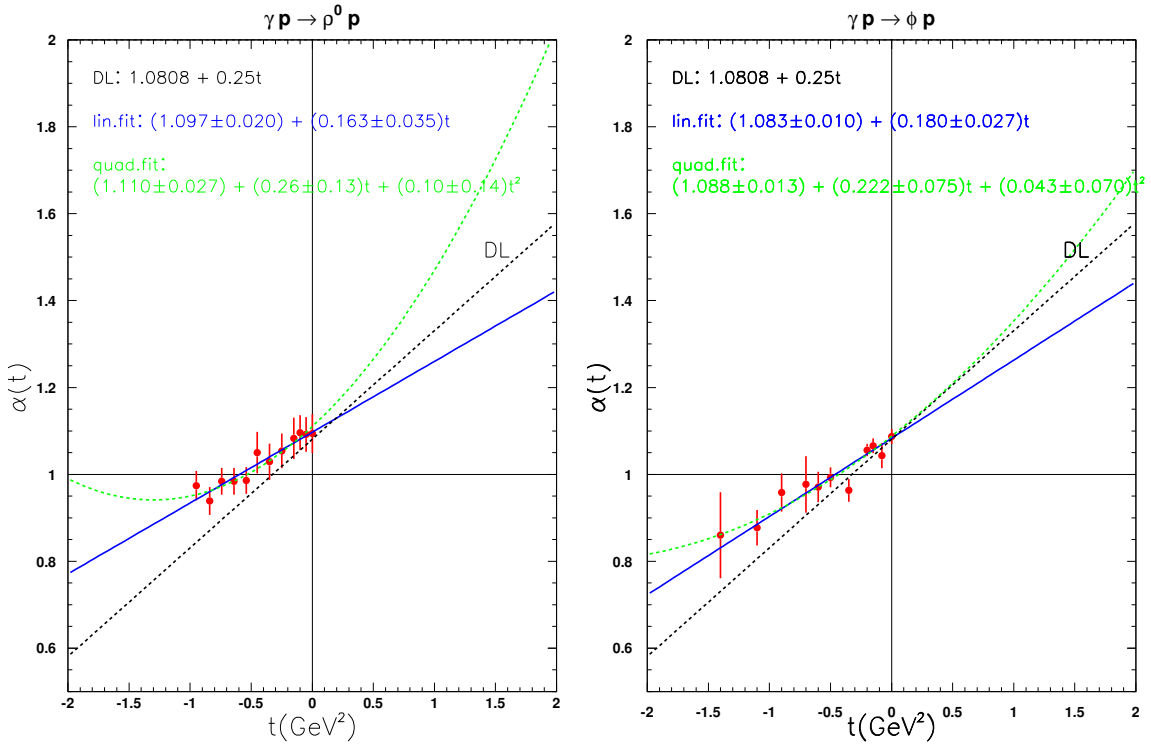
Determining $\alpha_{I\!P}(t)$ Using $\frac{\mathrm{d}\sigma}{\mathrm{d}t}(W)$



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

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

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

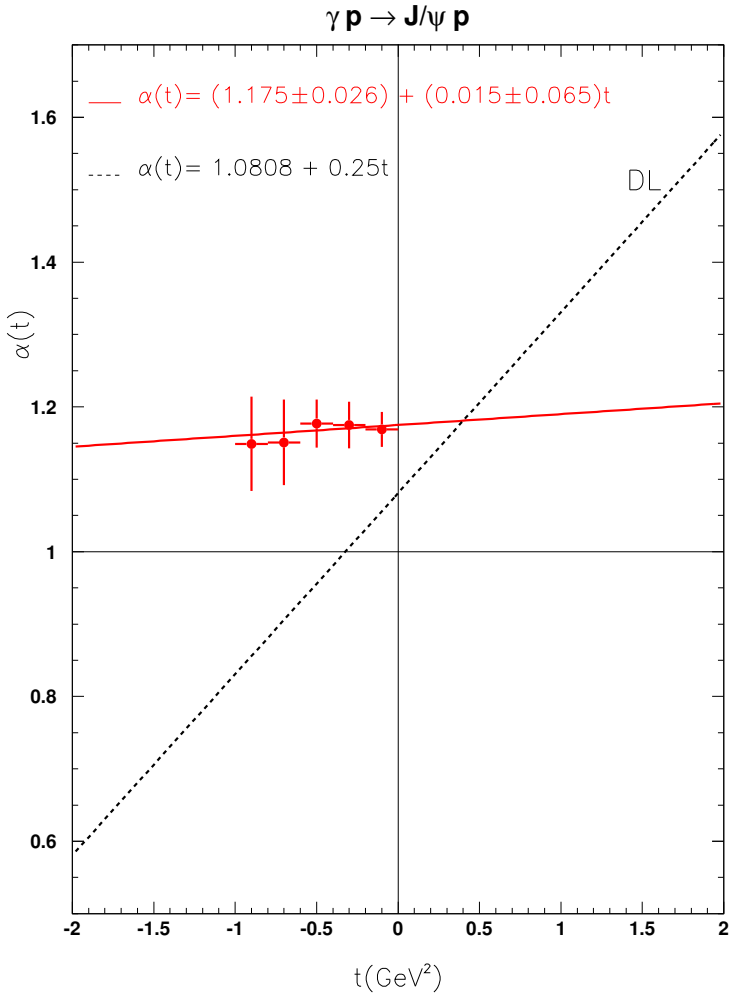


	$\alpha_{I\!P}(0)$	$\alpha'_{I\!P}$
ρ^0:	1.097 ± 0.020	0.163 ± 0.035 GeV^{-2}
ϕ:	1.083 ± 0.010	0.180 ± 0.027 GeV^{-2}

$\Rightarrow$ 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 !

Conclusions (I)

Investigations at HERA of
hard diffractive processes
encourage descriptions
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

Conclusions (II)

The kinematic region addressed by EPIC (4 x 40 GeV) is crucial to the new field of hard diffraction

Polarization at EPIC will allow unprecedented studies of the yet-to-be-understood helicity structure of diffractive processes