Workshop on
Generalized Parton Distributions
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Vector Meson Production at HERA

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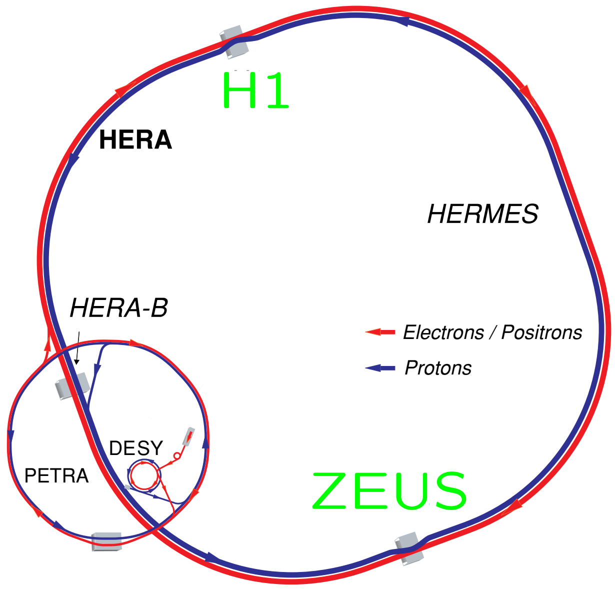
- Introduction
- New results in photo- and electroproduction
- Transition between soft and hard behaviour
- Comparisons between ρ, ϕ, J/ψ production
- VM production at large $|t|$
- Helicity studies
- Conclusions

The HERA ep Collider

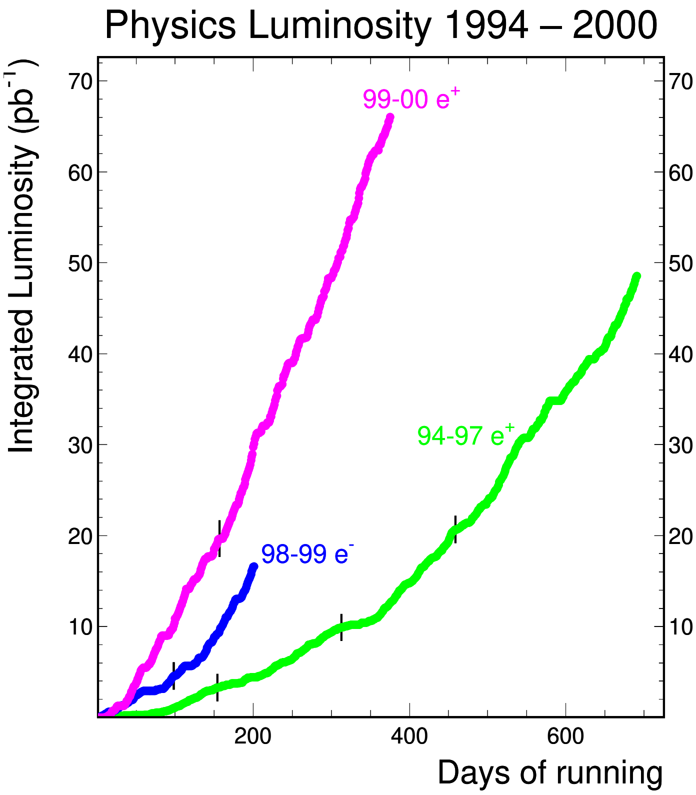


H1, ZEUS:

$e^{\pm} \Rightarrow \Leftarrow p$

27.5 GeV 920 GeV

$\sqrt{s} = 320$ GeV



1994 – 1997

e^+p at $\sqrt{s} = 300$ GeV

45 pb^{-1}

1998 – 1999

e^-p at $\sqrt{s} = 320$ GeV

16 pb^{-1}

1999 – 2000

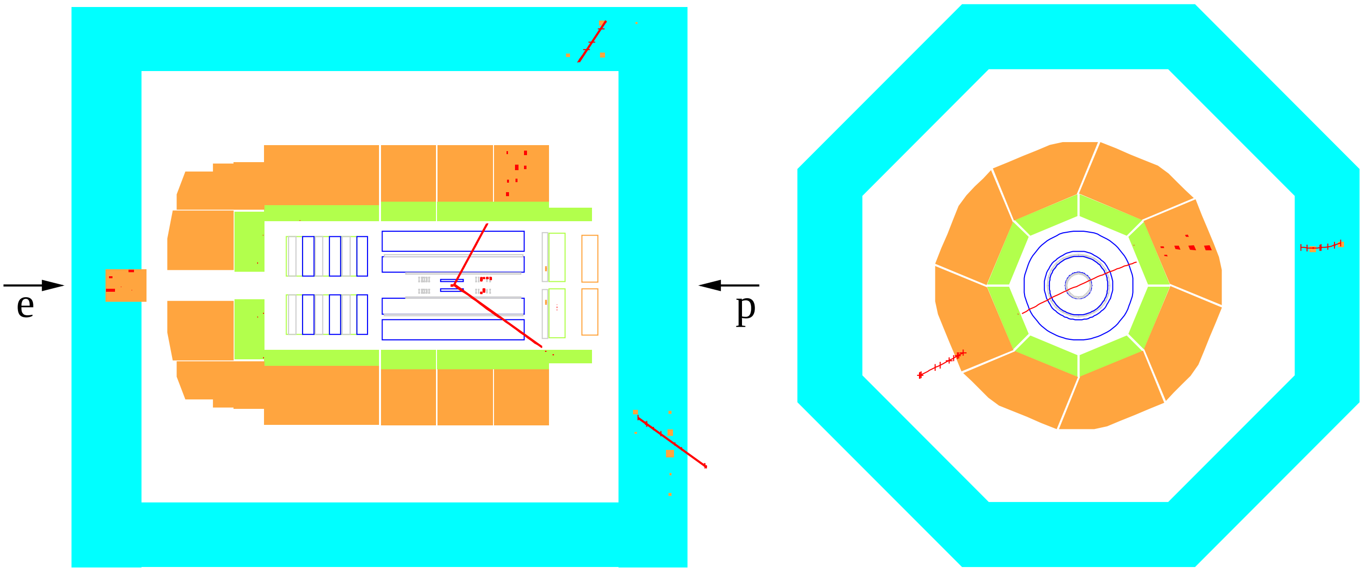
e^+p at $\sqrt{s} = 320$ GeV

68 pb^{-1}

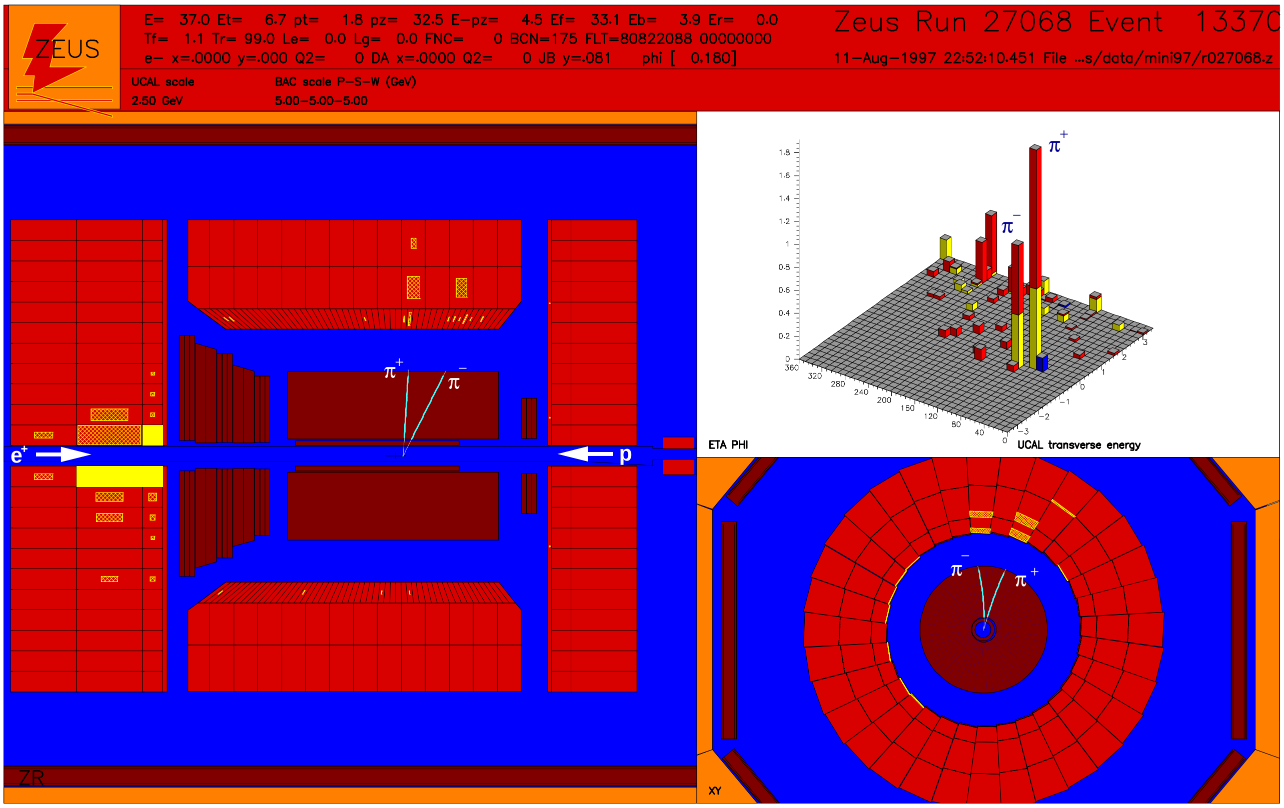
Half the HERA-I Luminosity collected in 99-00

The H1 and ZEUS Experiments

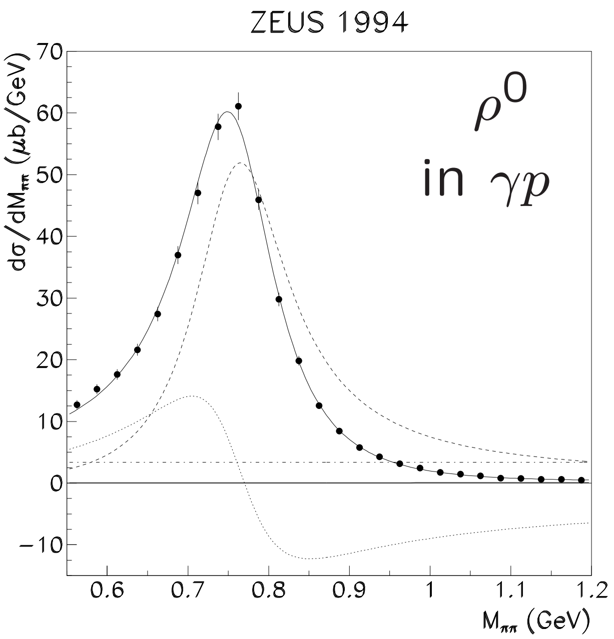
Υ-Candidate in H1:

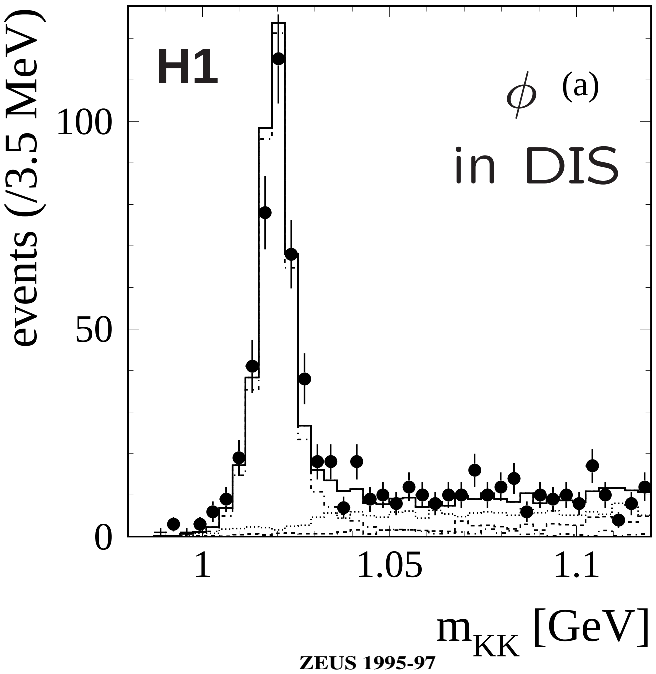


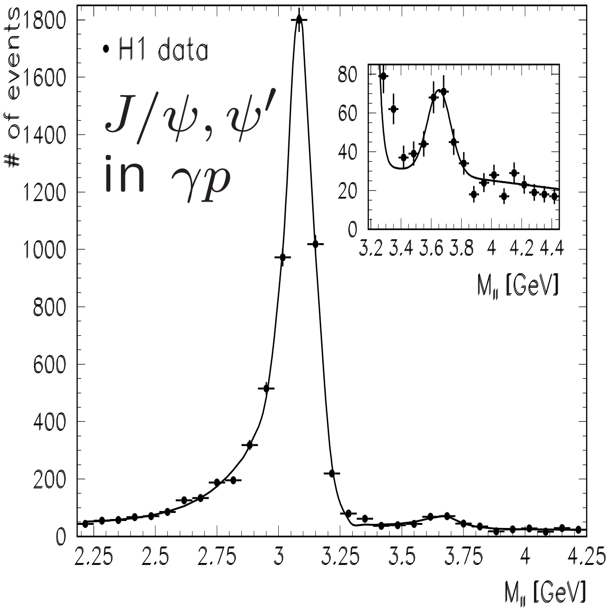
ρ^0-Candidate at high $|t|$ in ZEUS:

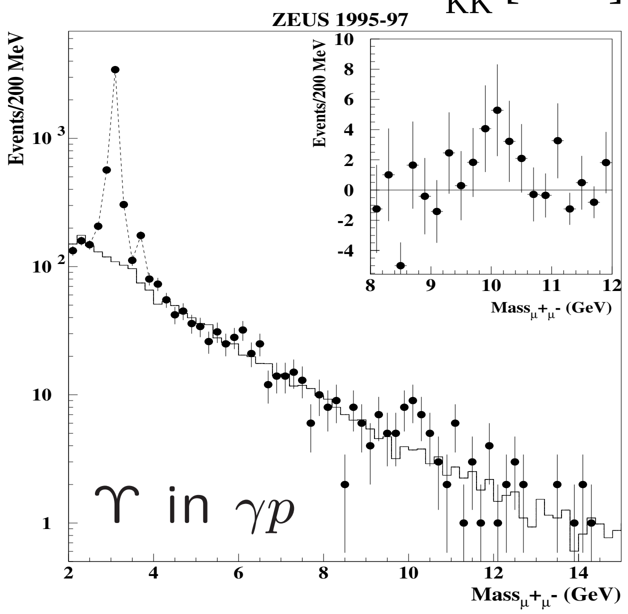


Vector Meson Signals



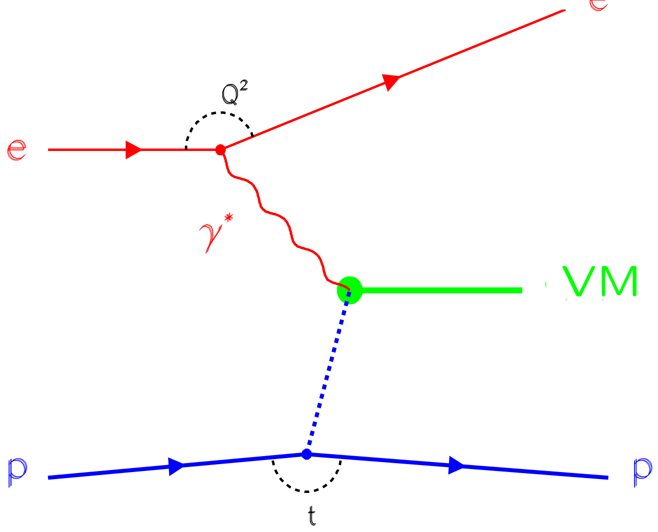




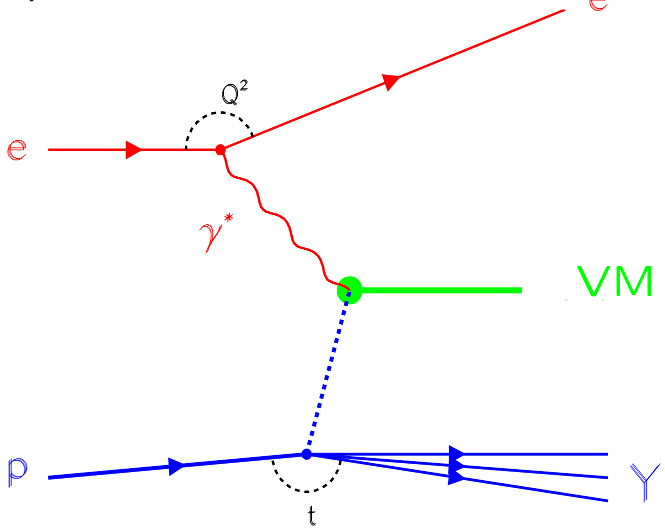


Diffractive Vector Meson Production at HERA

elastic



proton dissociative



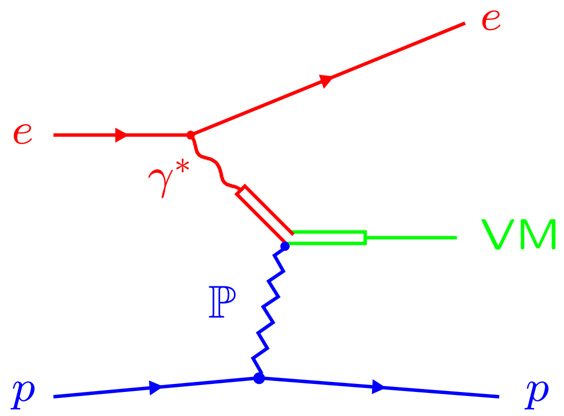
Q^2	γ^* Virtuality	$0 < Q^2 < 100\ \mathrm{GeV}^2$
$W_{\gamma p}$	CM Energy of $\gamma^* p$ system	$20 < W_{\gamma p} < 290\ \mathrm{GeV}$
t	(4-mom. transfer at p vertex)^2	$0 < \lvert t\rvert < 20\ \mathrm{GeV}^2$
VM	Vector Meson	$\rho^0,\ \omega,\ \phi,\ J/\psi,\ \psi',\ \Upsilon$

$\Rightarrow$ HERA: Simultaneous control of different scales (Q^2, t, M_{VM})

$\Rightarrow$ At large $|t|$: proton dissociation process dominates

Diffractive Vector Meson Production Models

Regge Approach



Soft Pomeron exchange

$\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}\, t$

$\alpha_{\mathbb{P}}(0) = 1.08,\ \alpha'_{\mathbb{P}} = 0.25\,\mathrm{GeV}^{-2}$

$$\frac{d\sigma}{dt} \propto e^{b_0 t} \left(\frac{W_{\gamma p}}{W_0}\right)^{4(\alpha_{\mathbb{P}}(t)-1)}$$

$$b = b_0 + 4\alpha'_{\mathbb{P}} \ln\left(\frac{W_{\gamma p}}{W_0}\right)$$

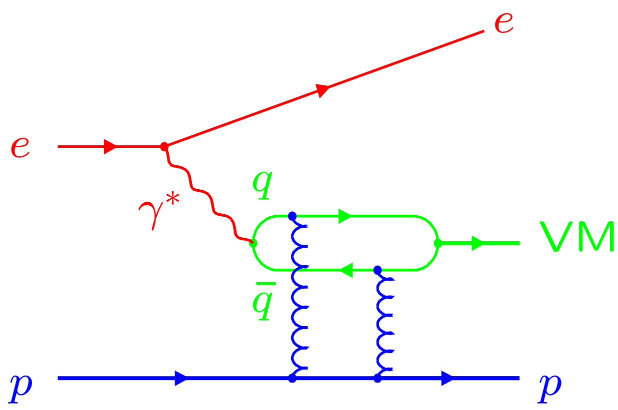
Slow rise $\sigma \propto W_{\gamma p}^{0.22\ldots0.32}$

Shrinkage: $b = b(W_{\gamma p})$

SCHC

Works for light VM
at $Q^2 \approx 0$, $t \approx 0$

pQCD Approach



Exchange of ≥ 2 gluons

At large $|t|$: $\frac{d\sigma}{dt} \propto |t|^{-n}$

$\sigma \propto [xg(x,Q^2)]^2$

Steep rise due to $xg(x,Q^2)$

Less or no shrinkage

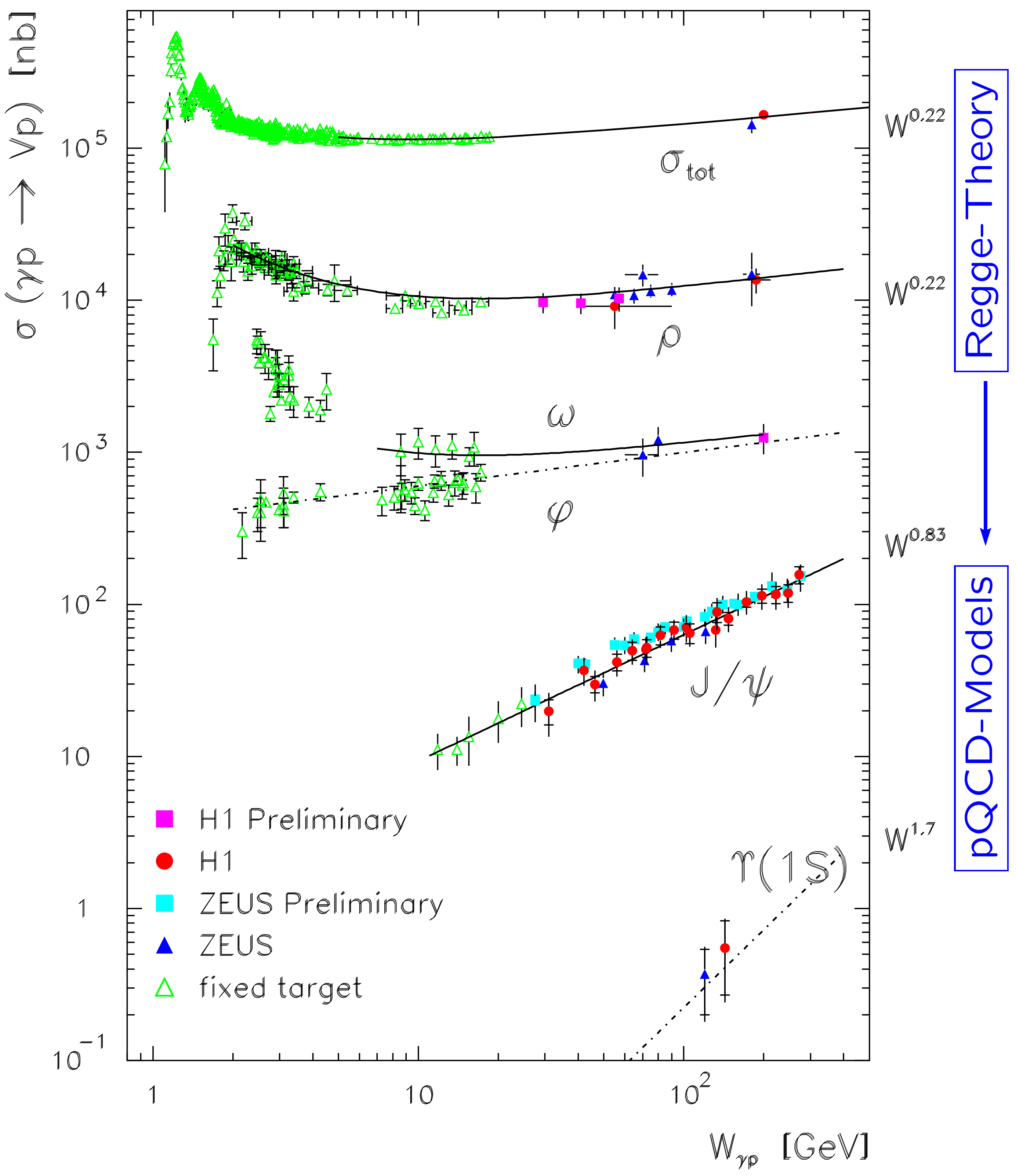
Requires 'hard' scale:
Q^2, M_V^2
What about t?

Transition between soft and hard regimes:

VM at HERA: Testbed for pQCD scales

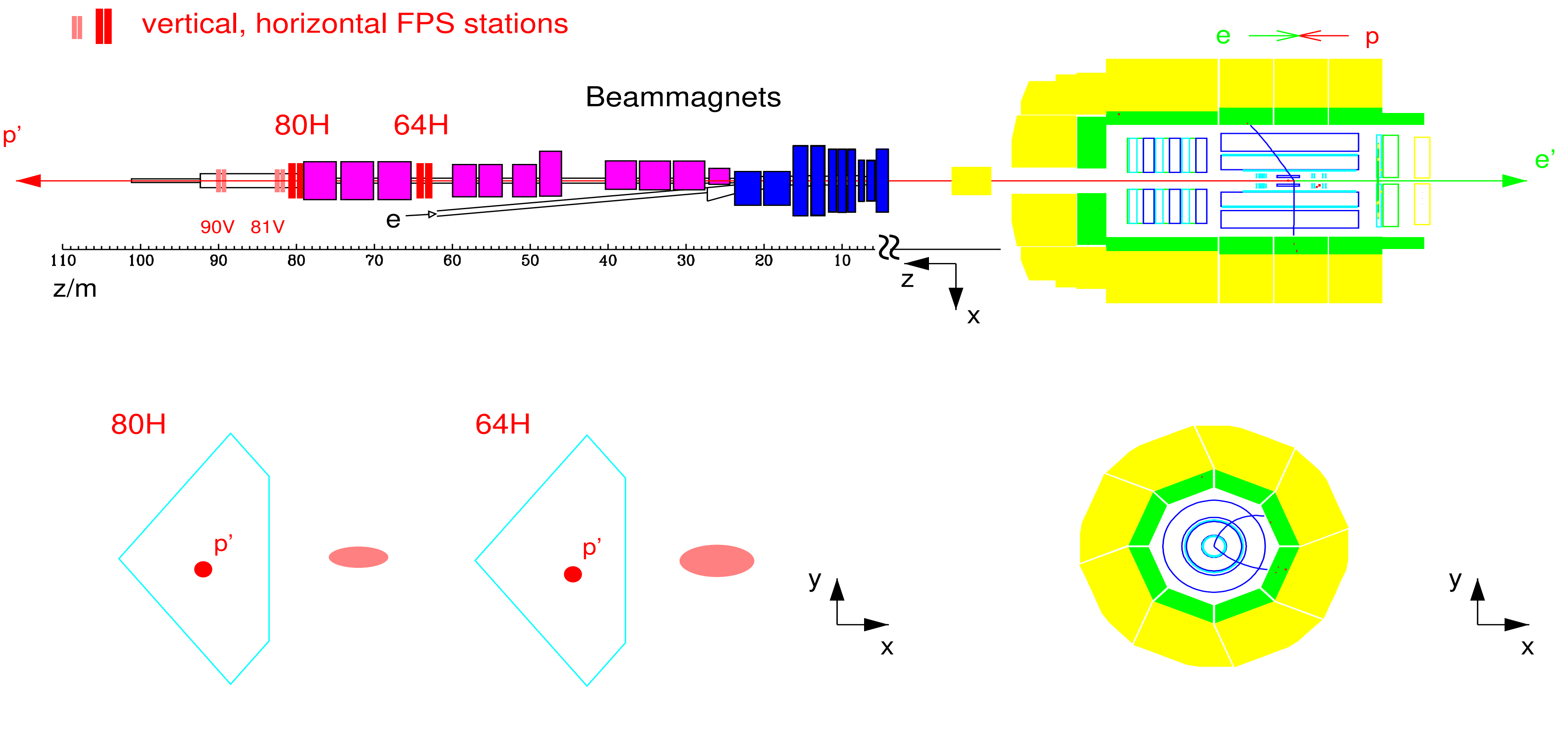
$$Q^2, M_V^2, t$$

VM Cross Sections in Photoproduction



Increasing M_V^2: Transition from 'soft' to 'hard'

ρ^0 Production with a Leading Proton



reconstructed proton track
(intercepts)

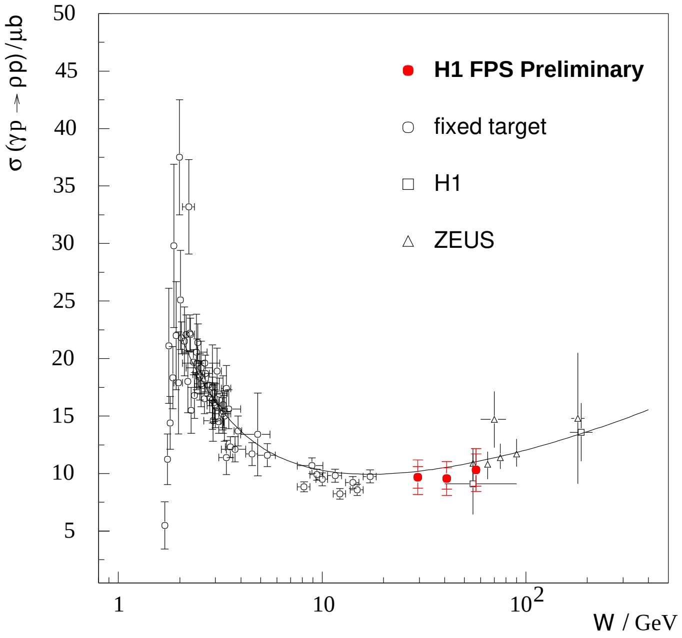
reconstructed pion tracks

Use beam optics for complete kinematic reconstruction of scattered p.

Elastic ρ^0 with a Leading p

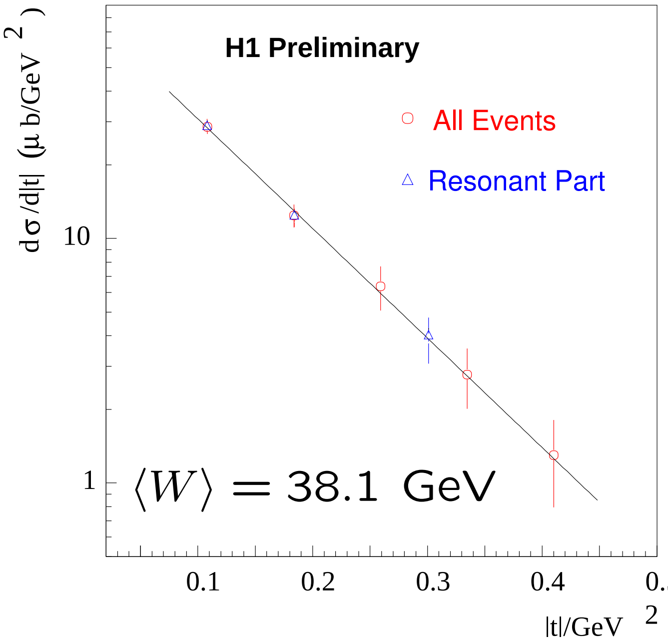
Using H1 Forward Proton Spectrometer (FPS)

Energy Dependence:



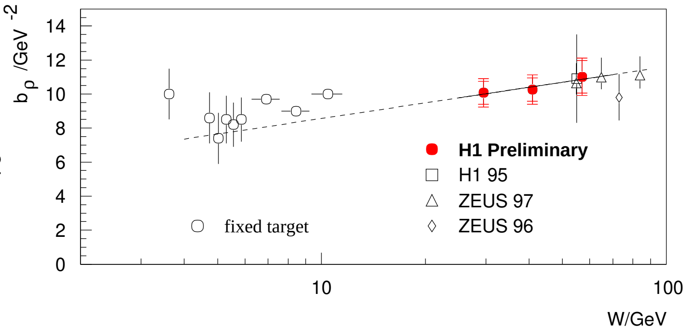
$$\sigma(\gamma p \rightarrow \rho^0 p) \propto W^{0.22}$$

Diffractive Slope:



$$b = 10.31 \pm 0.77 \pm 0.52 \text{ GeV}^{-2}$$

Trajectory:



Line: $b_\rho(W) = b_0 + 4\alpha'_{\mathbb{P}} \ln(W)$
with $\alpha'_{\mathbb{P}} = 0.25$ GeV^{-2}

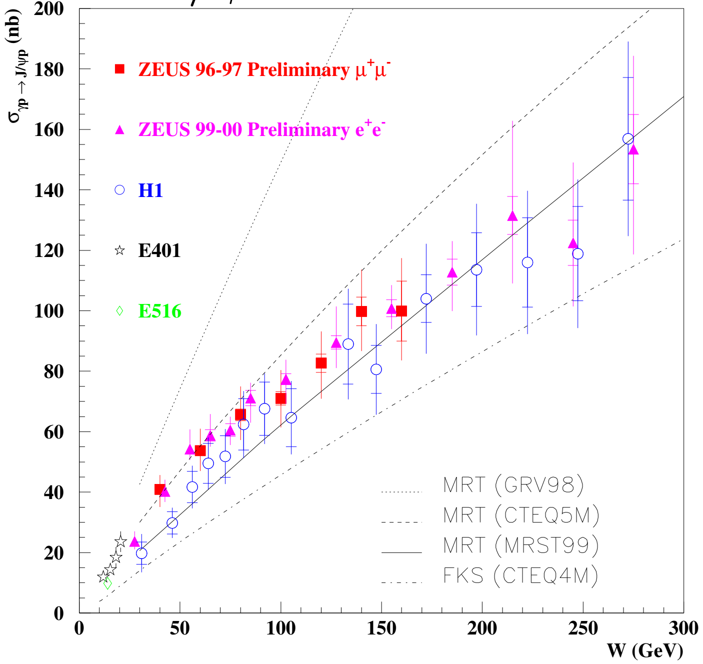
- Full kinematic reconstruction of proton
- Direct selection of elastic component
- Extended kinematic HERA range

ρ^0-photoproduction is entirely ‘soft’

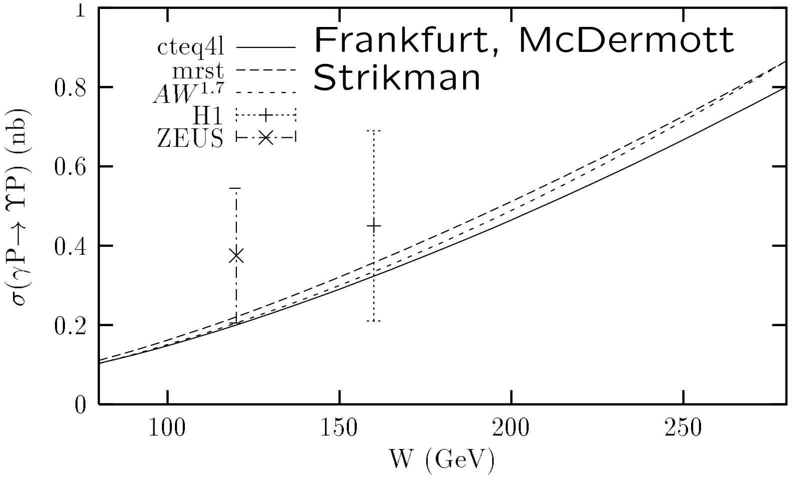
Heavy Vector Mesons in Photoproduction

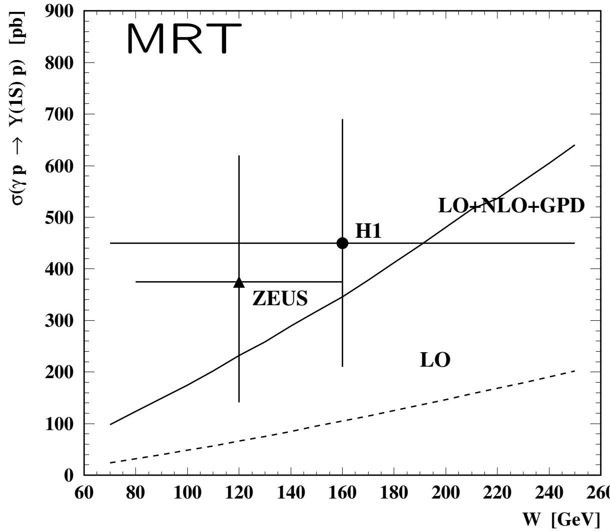
Energy Dependence

J/ψ-Production



Υ-Production

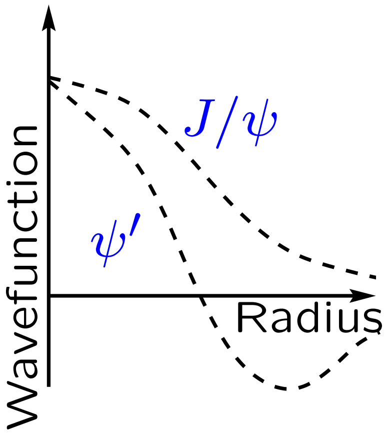


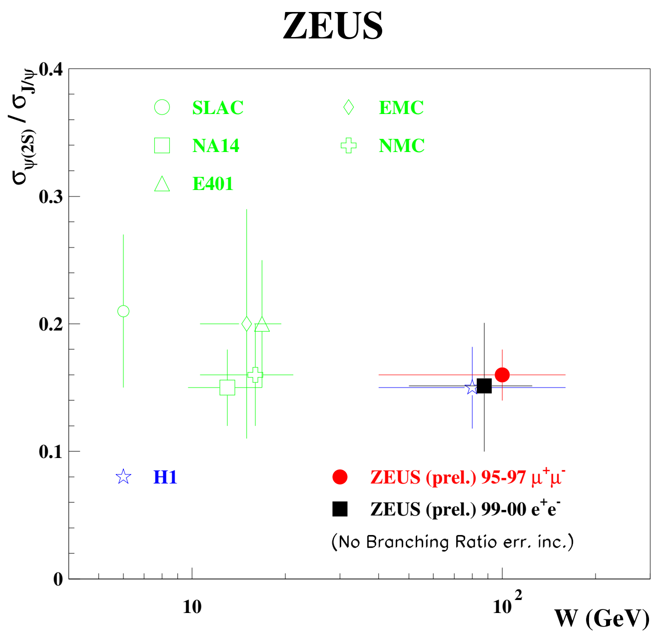


- J/ψ: Steep rise ($W^{\sim 0.8}$) measured
- Good description by QCD
- Υ: $W^{\sim 1.7}$ predicted using GPD
- Effects from GPD: Factor 2-2.5
- MRT and FMS approaches are quite different

J/ψ and Υ photoproduction are mostly ‘hard’

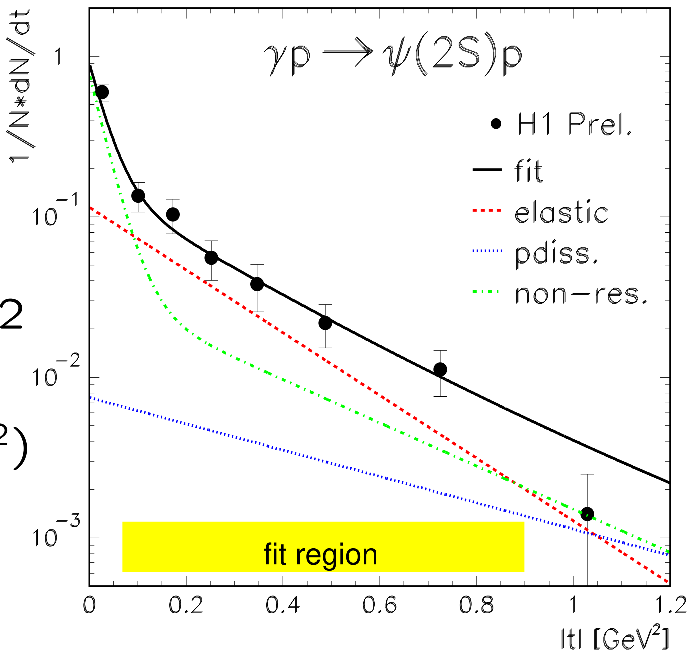
ψ' Photoproduction





$\sigma_{\psi'}/\sigma_{J/\psi} \sim 0.17$

pQCD-calculations:
lower than data
non-pert. contributions?



$b_{\psi'} = 4.5 \pm 1.2^{+1.4}_{-0.7}$ GeV^{-2}

($b_{J/\psi} = 4.73 \pm 0.25^{+0.30}_{-0.39}$ GeV^{-2})

b is sensitive to node

— Optical Interpretation: $b \propto r_p^2 + r_{VM}^2$: $b_{\psi'} > b_{J/\psi}$

+ QCD Picture with Wavefunction: $b_{\psi'} \lesssim b_{J/\psi}$
(Kopeliovich, Nemchik et al.)

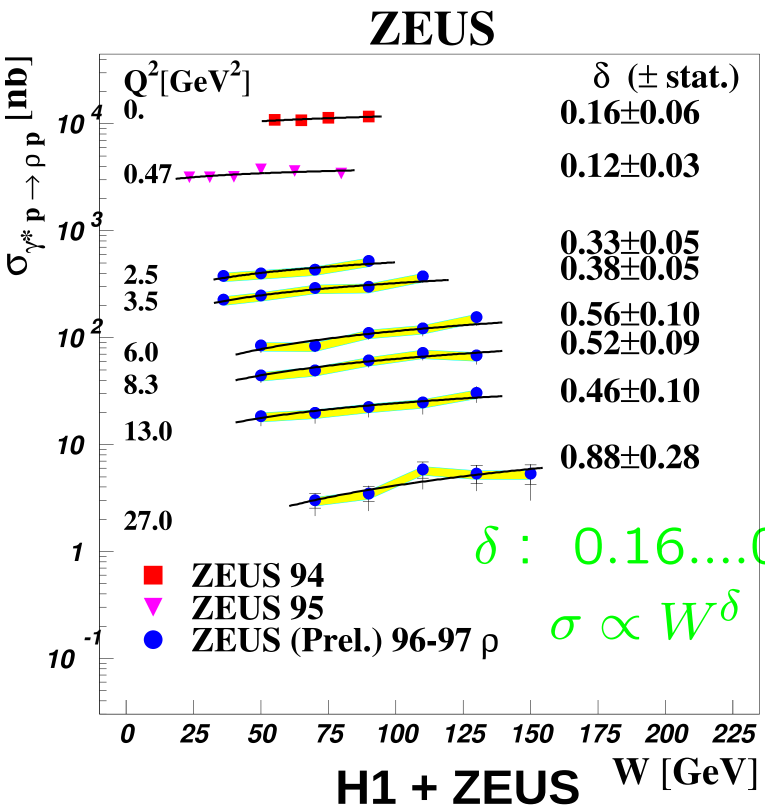
Ratio and slopes correctly described

Need to take wave functions into account

Transition with Q^2

Elastic Electroproduction

$\gamma^* p \rightarrow \rho p$



Slope rising with Q^2

Transition

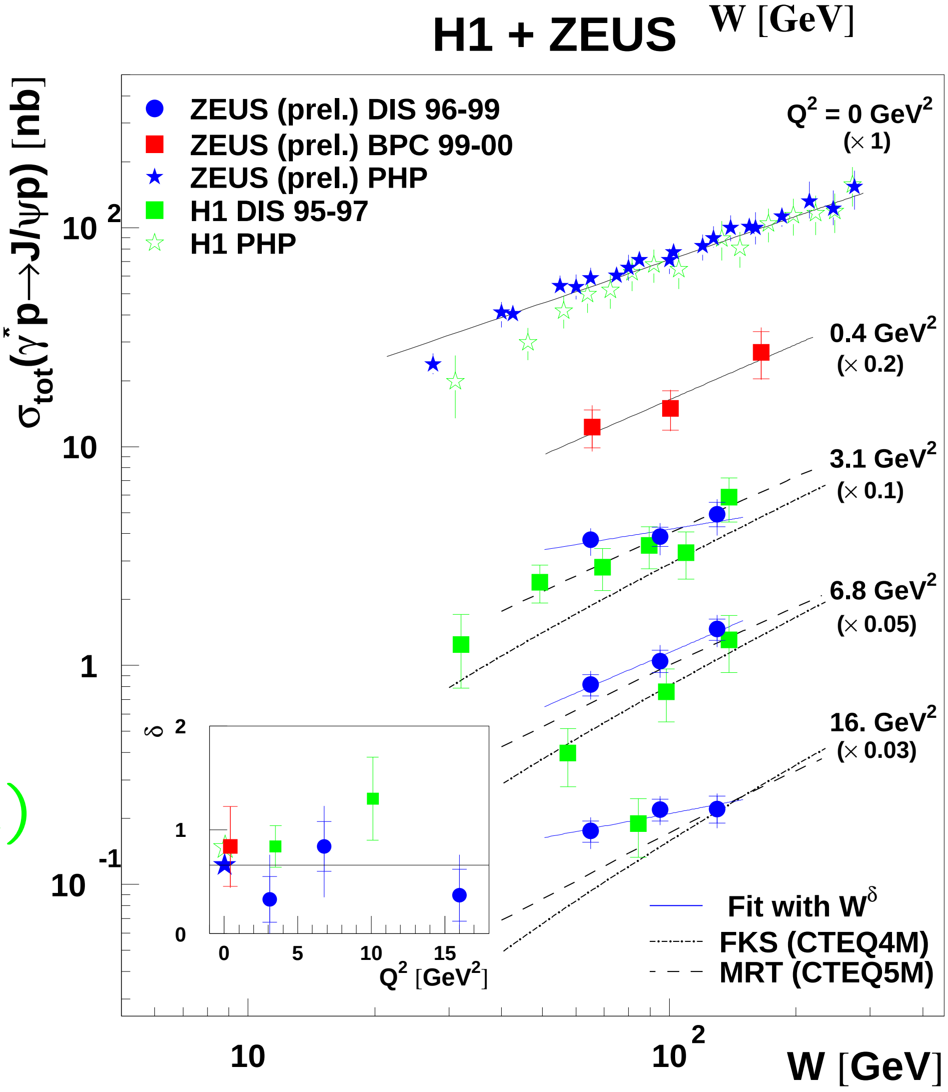
soft $\rightarrow$ hard

δ : 0.16....0.88

$\sigma \propto W^\delta$

$\gamma^* p \rightarrow J/\psi p$

New data in transition region (ZEUS)



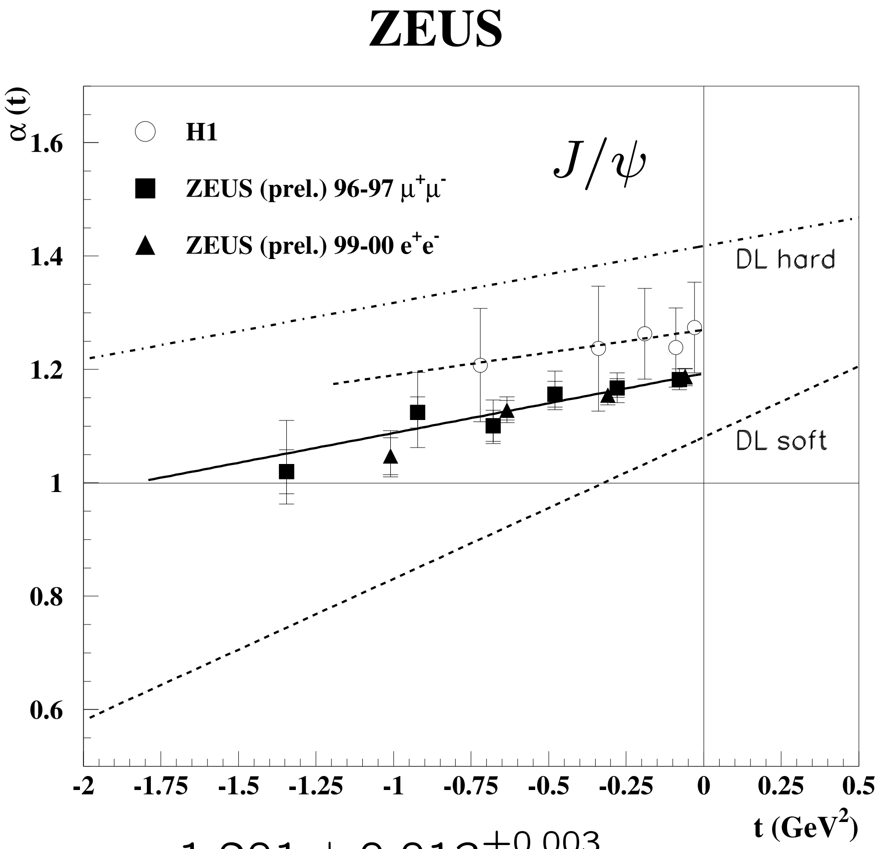
Steep rise already at $Q^2 \sim 0$

Increasing Q^2: No effect (yet)

Mass provides hard scale

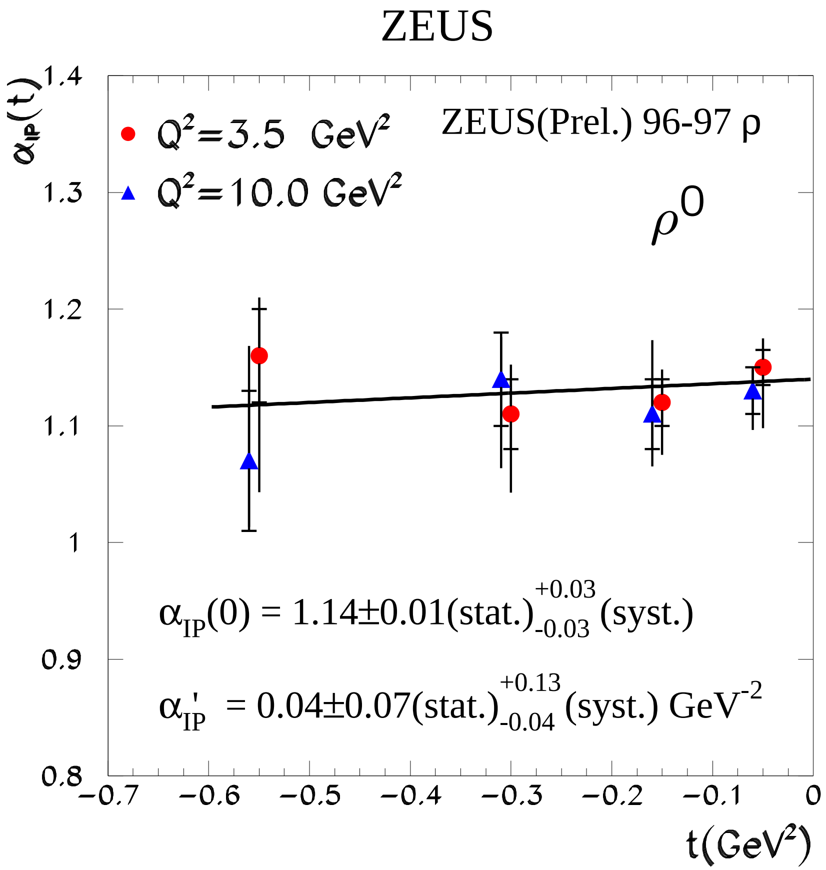
Trajectories at Large M_V^2 or Large Q^2

Photoproduction $\gamma p \to J/\psi\, p$



$$\alpha_{\mathbb{P}} = 1.201 \pm 0.013^{+0.003}_{-0.011}$$
$$\alpha'_{\mathbb{P}} = 0.126 \pm 0.029^{+0.015}_{-0.028}\ \text{GeV}^{-2}$$

Electroproduction $\gamma^* p \to \rho\, p$



Measured values of $\alpha'_{\mathbb{P}}$ smaller than soft pomeron ($\alpha'_{\text{soft }\mathbb{P}}$=0.25 GeV^{-2})

ρ-Electroproduction: still large uncertainties

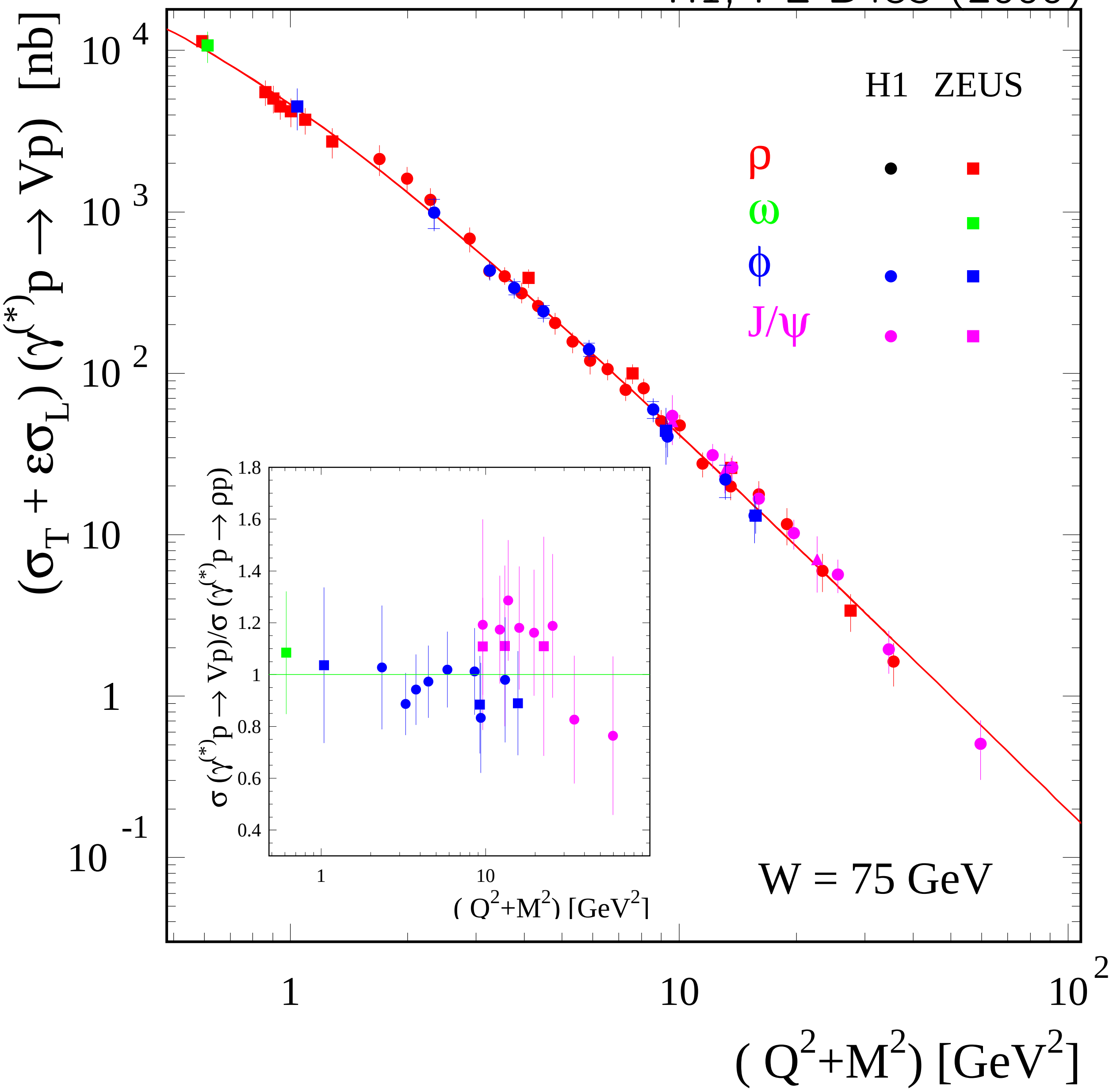
Approximate Flavour Independence

Interplay between Q^2 and M_V^2 scales:

Elastic VM total cross sections

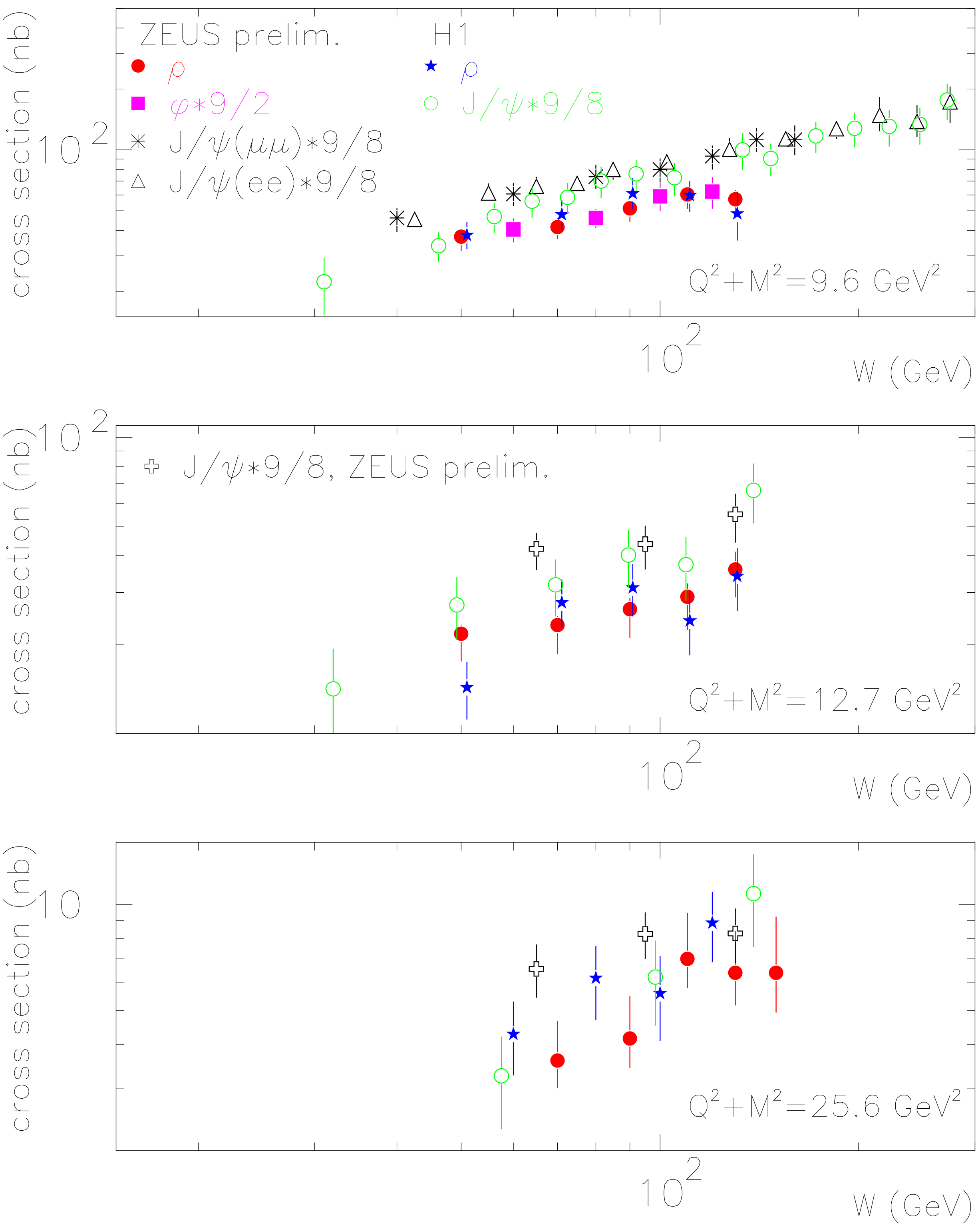
$\sigma_\rho : \sigma_\omega : \sigma_\phi : \sigma_{J/\psi} = 9 : 1 : 2 : 8$

H1, PL B483 (2000)



Universal $Q^2 + M_V^2$ dependence

Energy Dependence with $Q^2 + M_V^2$



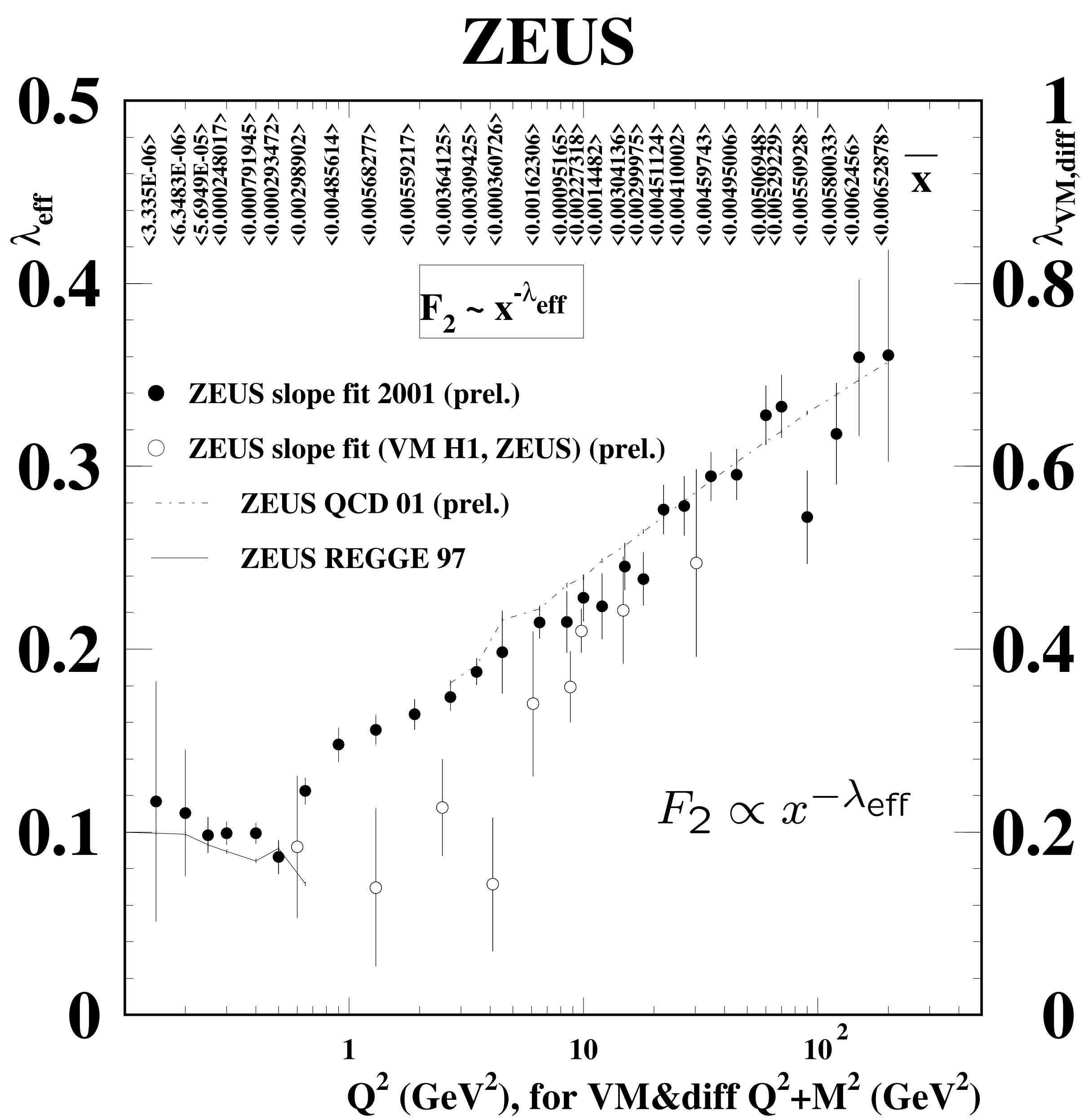
- More recent data $\rightarrow$ better precision
- J/ψ enhanced by $\sim 30\%$ above ρ, ϕ

Comparison with Inclusive DIS

Fit to VM cross section

$$A \cdot x^{-\lambda_V}$$

at different values of $M_V^2 + Q^2$

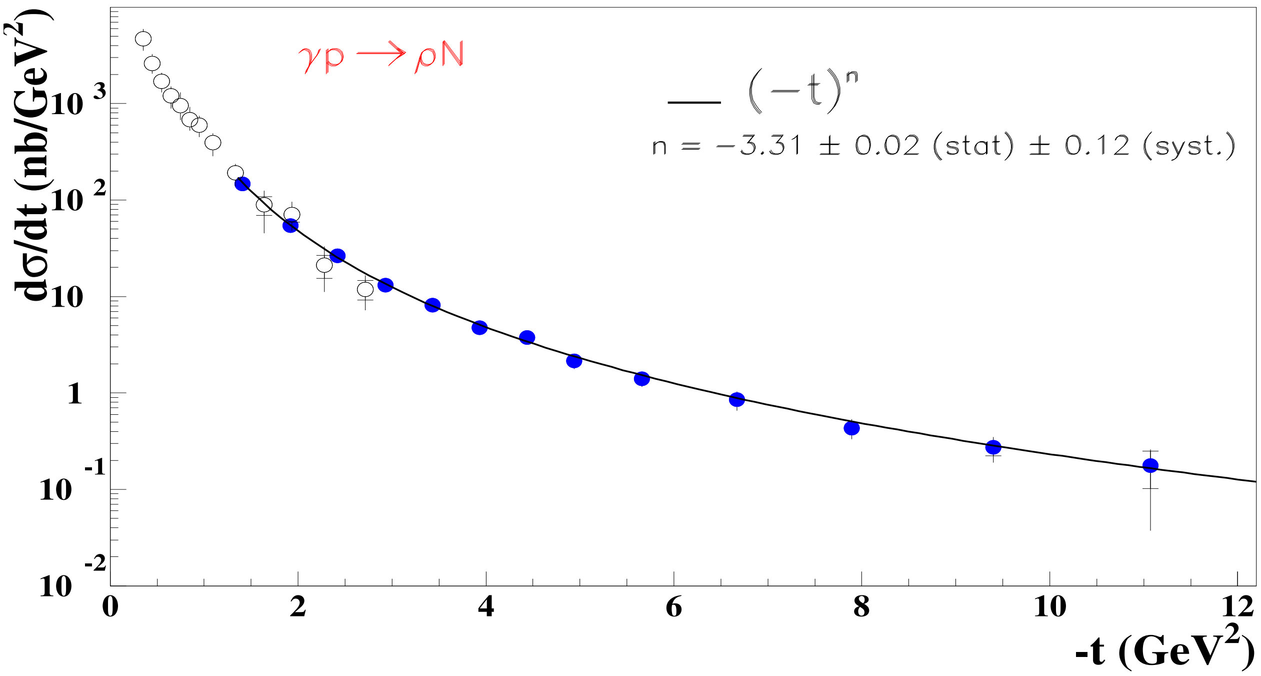


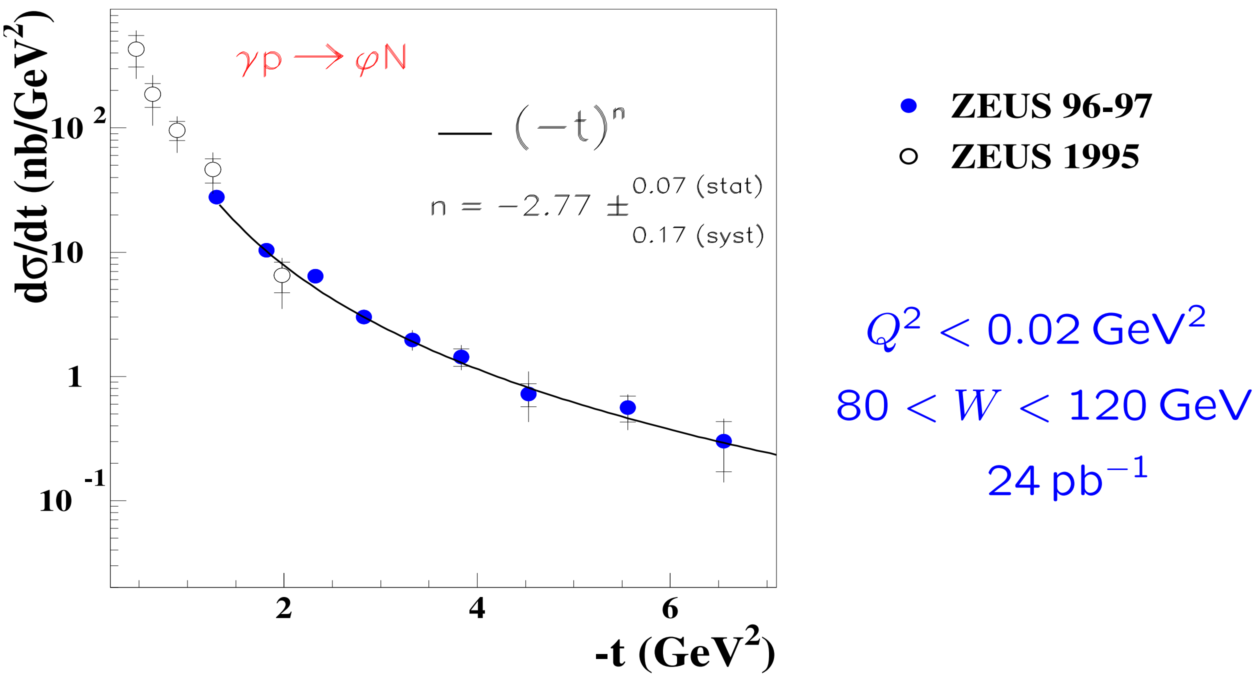
VM Production at high $|t|$

Proton-Dissoc. Photoproduction of ρ, ϕ

Does $|t|$ also provide a hard scale?

ZEUS 96 - 97 Preliminary



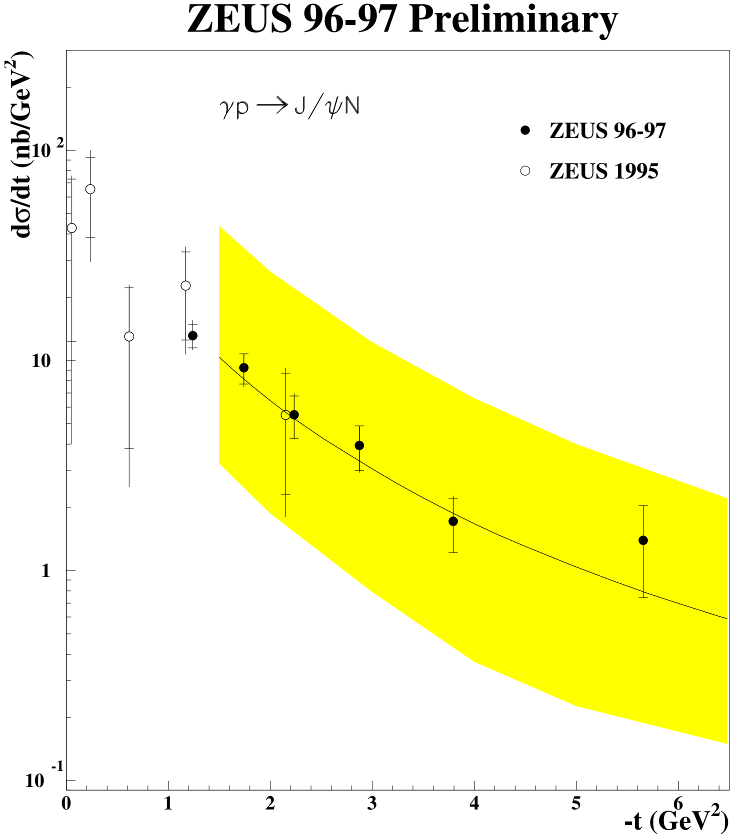


- t dependence at high $|t| \propto (-t)^n$
- $n \sim -3$ for both ρ and ϕ mesons

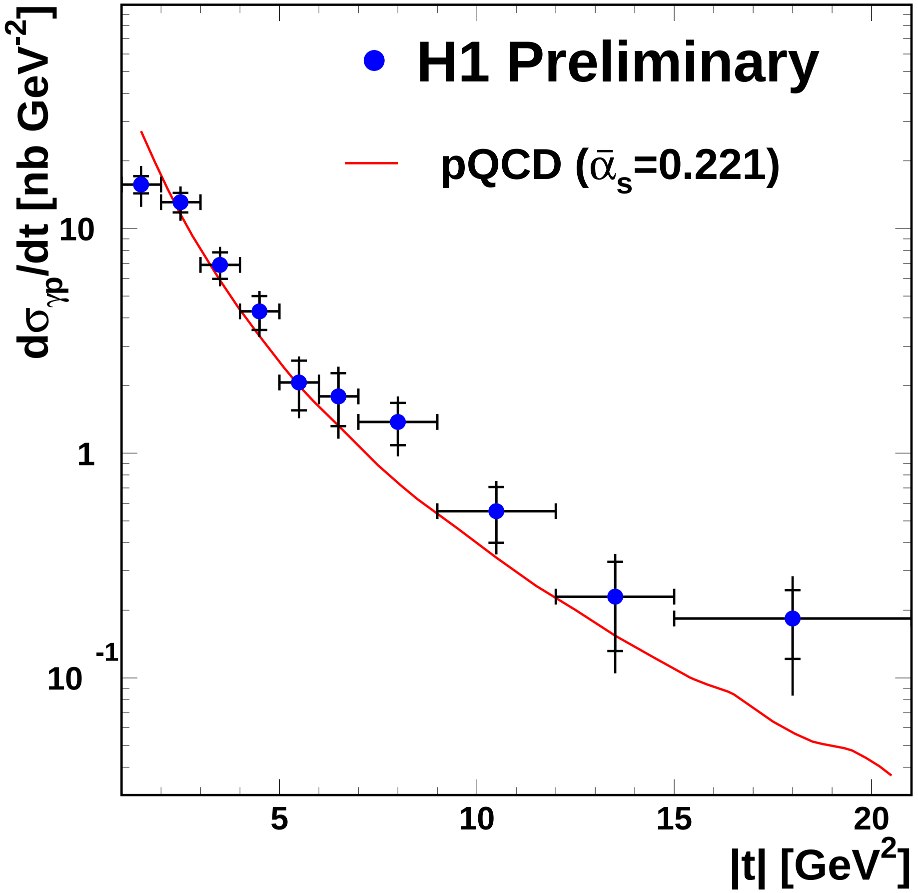
J/ψ production at high $|t|$

Proton-Dissoc. Photoproduction: $\gamma p \to J/\psi X$

$Q^2 < 0.02\,\mathrm{GeV}^2$; $80 < W < 120\,\mathrm{GeV}$



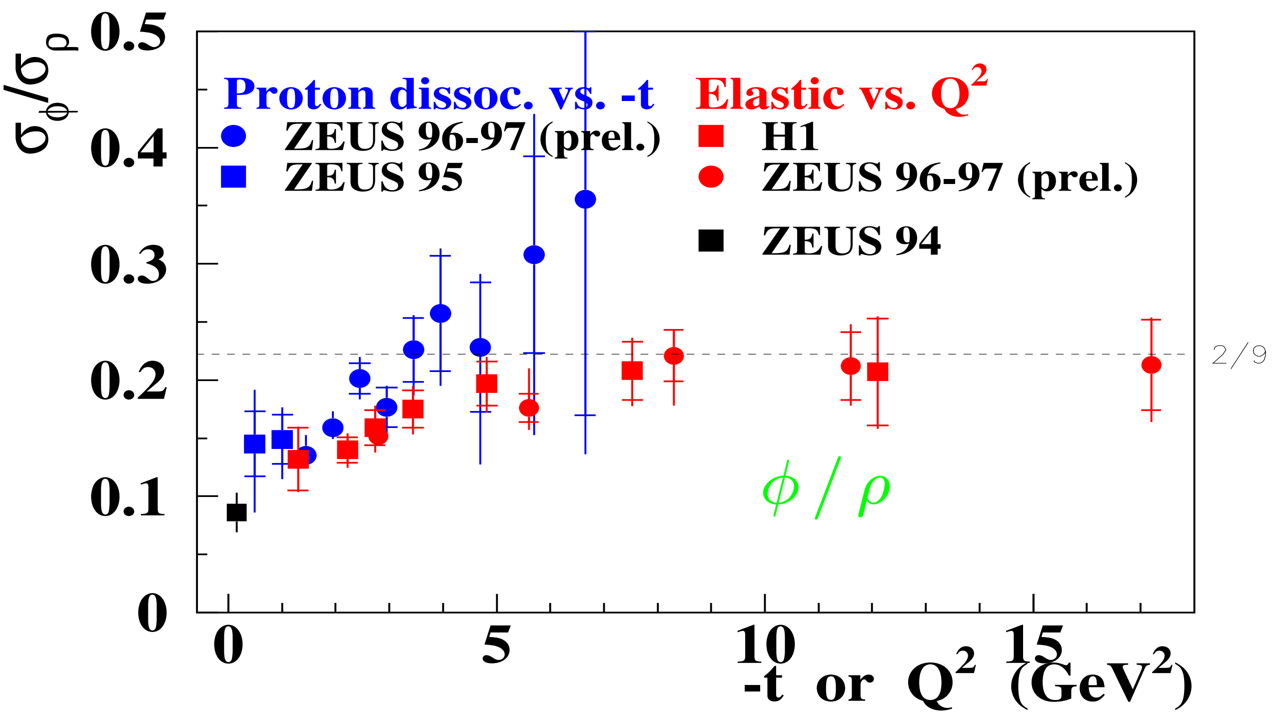
$Q^2 < 1\,\mathrm{GeV}^2$; $50 < W < 160\,\mathrm{GeV}$

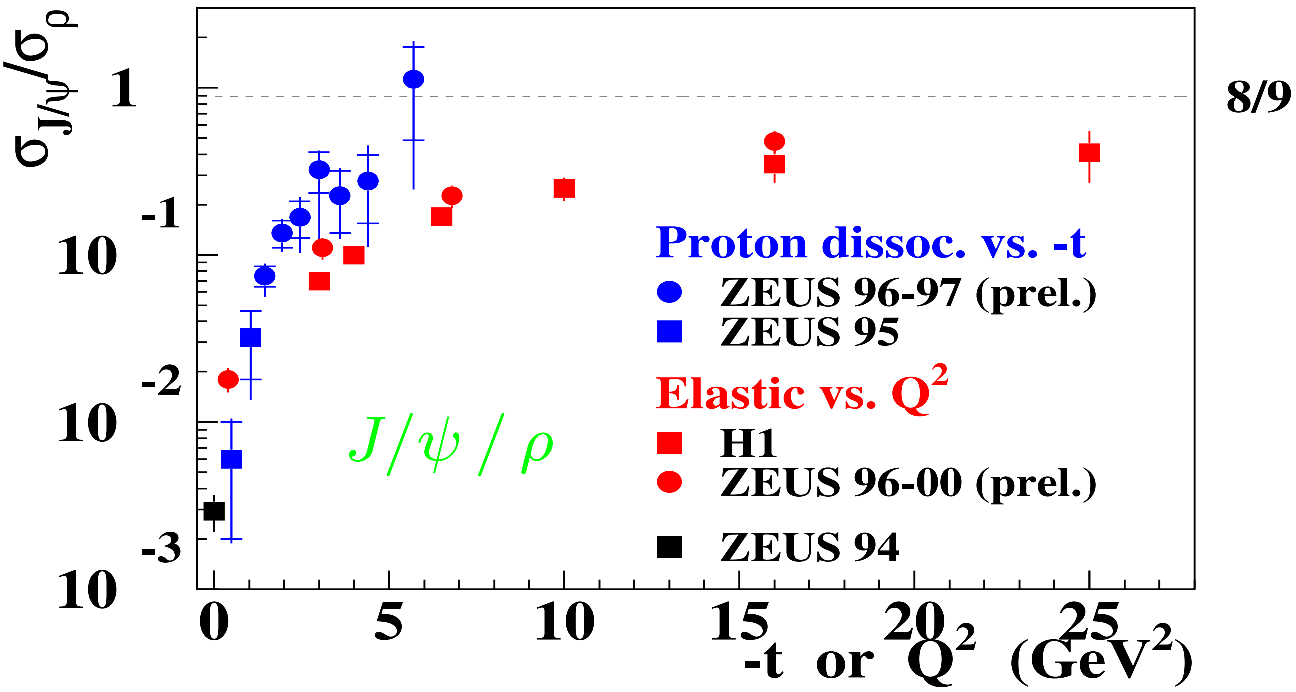


- t-dependence $\propto t^{-1.7}$, even flatter than for ρ and ϕ
- Data well reproduced by LO BFKL model (Forshaw, Ryskin 1995)
- Large normalization uncertainty: Choice of $\bar{\alpha}_s$

Comparison of $|t|$ and Q^2

VM Production Cross Section Ratios





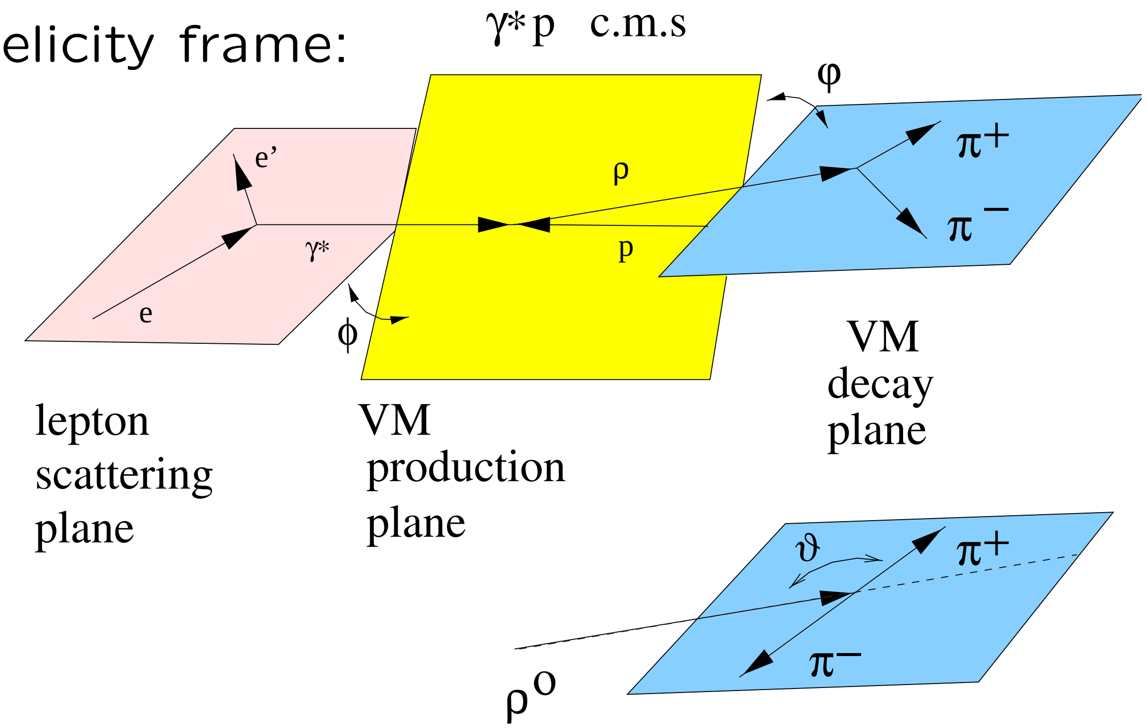
- Small $|t|$, Q^2: Rise in $|t|$ steeper than in Q^2
- Large $|t|$, Q^2: $|t|$ shows hard scale behaviour

Helicity Studies

- Study transitions between γ and VM helicity states

$\Rightarrow$ pQCD provides quantitative predictions (Ivanov, Kirschner)

Helicity frame:



Decay angular distributions: $W(\vartheta, \varphi, \Phi)$

15 combinations of spin density ME: $r_{ij}^{\alpha\beta}$

Products of helicity amplitudes: $T_{\lambda_{VM}\lambda_\gamma}$

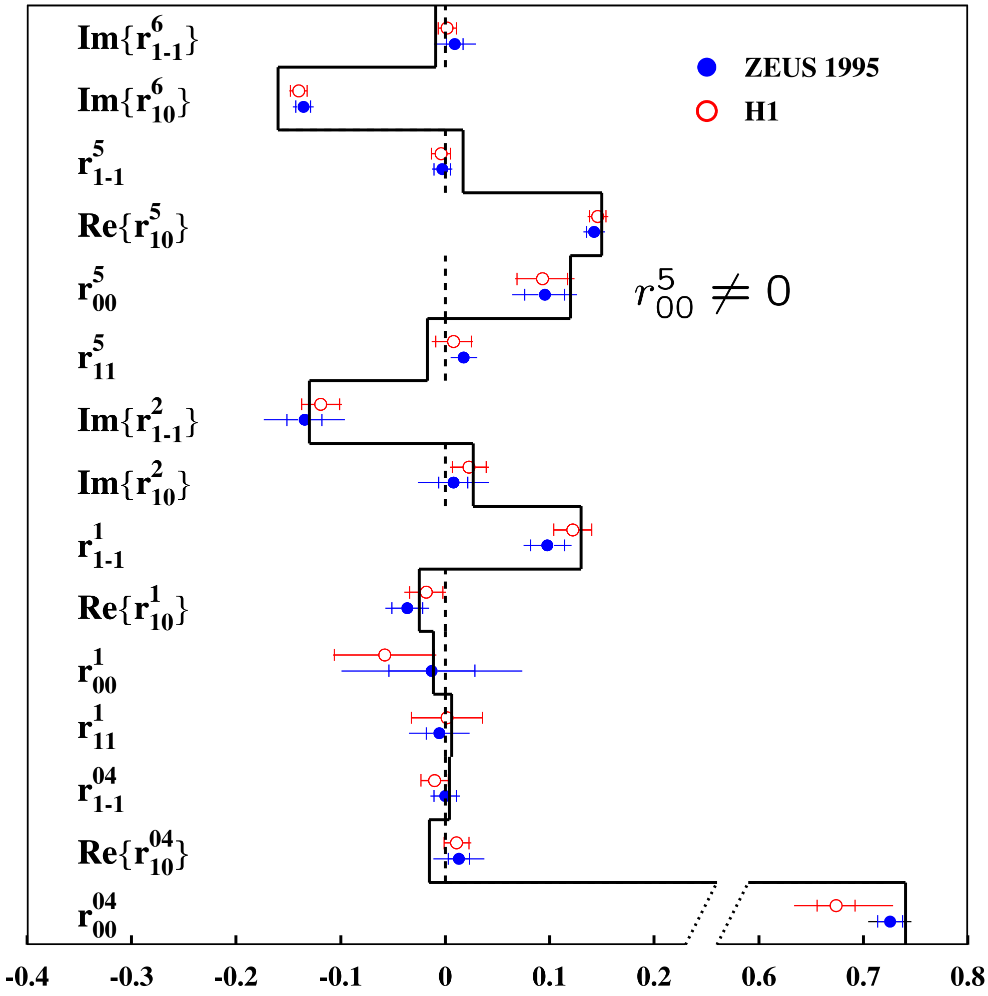
$$R = \frac{\sigma_L}{\sigma_T} = \frac{T_{00}^2 + 2T_{10}^2}{T_{01}^2 + T_{11}^2 + T_{1-1}^2}$$

- s-Channel Helicity Conservation: Expect $\gamma_T \to \rho_T$ and $\gamma_L \to \rho_L$ transitions only

Spin Density Matrix Elements

Elastic Electroproduction $\gamma^* p \rightarrow \rho^0 p$

ρ^0: ZEUS/EPJ C12 (2000) 393
H1/PL B483 (2000) 360
ϕ: H1/EPJ C13 (2000) 371



- $r^5_{00} \propto \mathrm{T}_{00}\mathrm{T}^*_{01} + \mathrm{T}_{01}\mathrm{T}^*_{00} \neq 0$

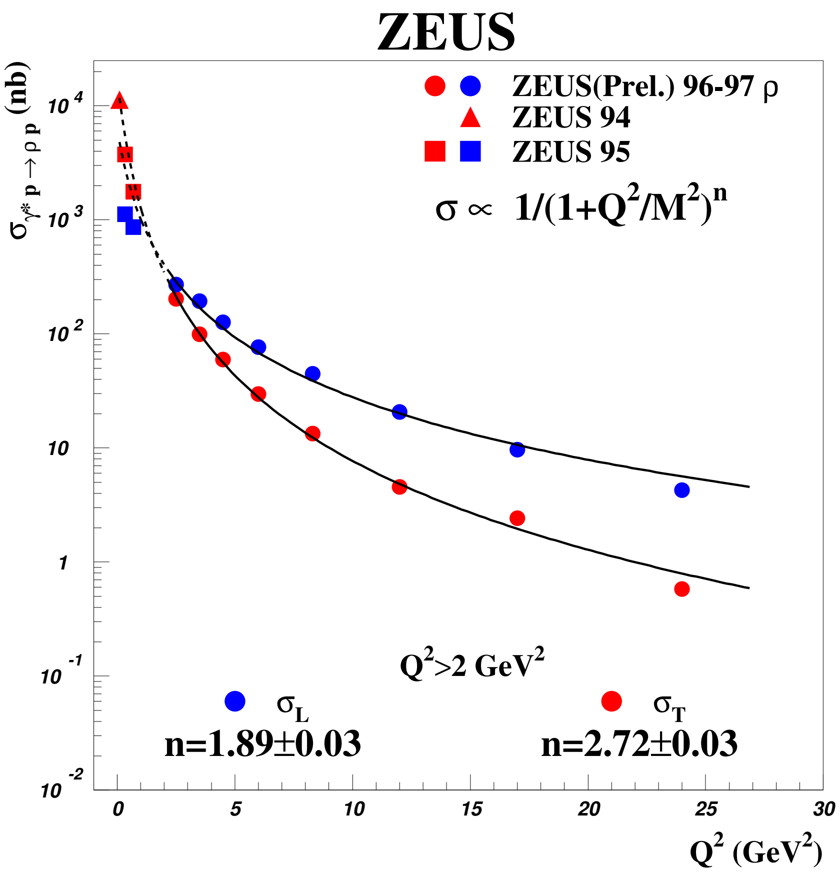
$\Rightarrow \gamma_T \rightarrow \rho_L$ transition measured

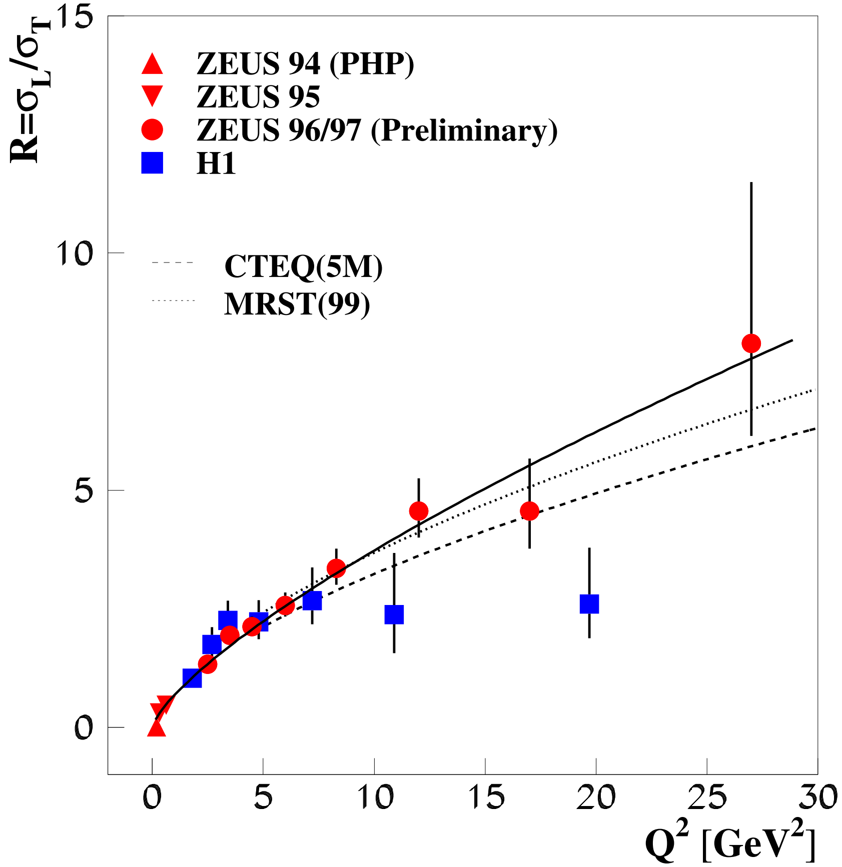
- Breaking of SCHC:

$\Rightarrow$ predicted by model using pQCD

Q^2 dependence of σ_L and σ_T

Elastic Electroproduction: $\gamma^* p \to \rho^0 p$ Evaluate θ-distributions $W(\vartheta)$





- σ_L increasingly dominant at large Q^2
- σ_T still significant at large Q^2
- Rise of R expected in pQCD

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

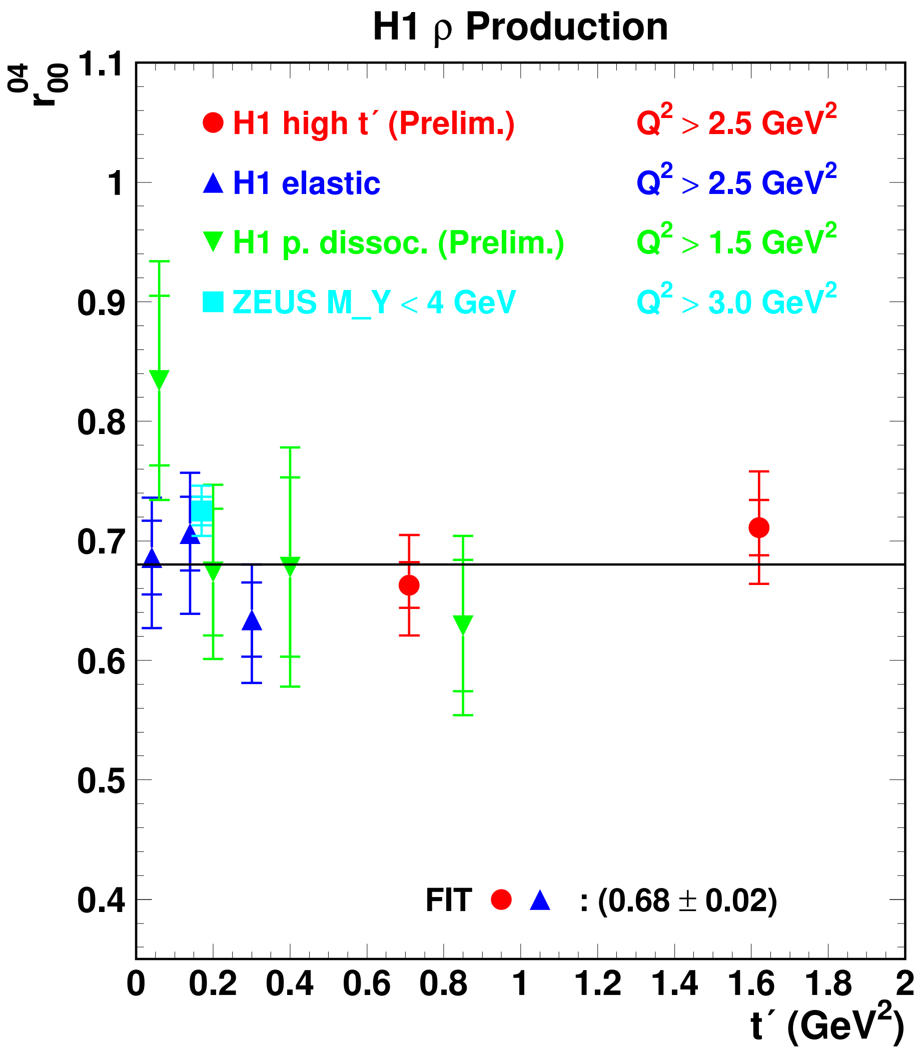
Helicity Amplitudes with $|t|$

Proton-Dissoc. Electroproduction: $\gamma^* p \rightarrow \rho^0 X$

($2.5 < Q^2 < 30\,\text{GeV}^2$, $40 < W < 140\,\text{GeV}$, $6\,\text{pb}^{-1}$)

Evaluate θ-Distributions $W(\vartheta)$ in bins of $|t|$:

$$W(\cos(\vartheta)) \propto 1 - r_{00}^{04} + (3r_{00}^{04} - 1)\cos^2\vartheta$$



$$r_{00}^{04} \propto |T_{01}|^2 + |T_{00}|^2$$

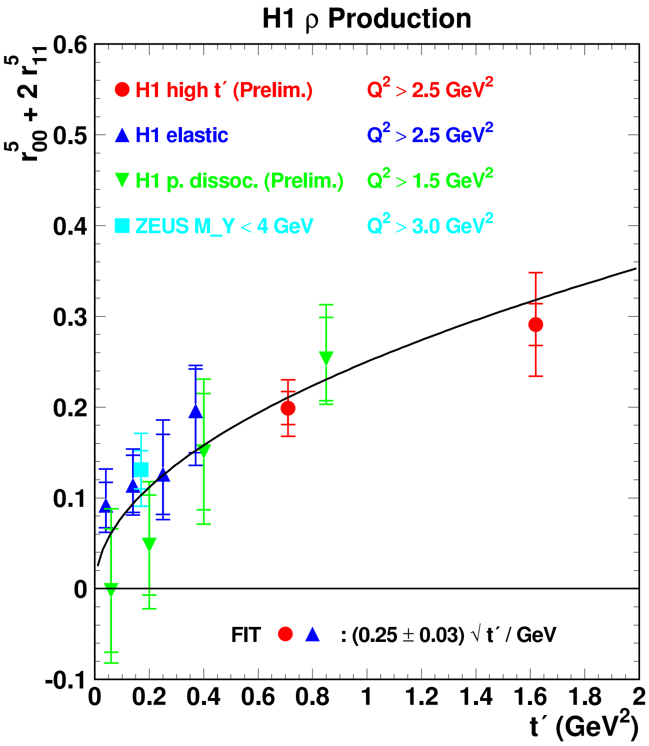
$$R = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}}$$

- Flat $|t|$-dependence
- Proton dissociation data similar to elastic data
  $\rightarrow$ Factorization of diffractive vertices

Helicity Amplitudes with $|t|$

Electroproduction: $\gamma^* p \to \rho^0 X$

Evaluate Φ-Distributions $W(\Phi)$ in bins of $|t|$



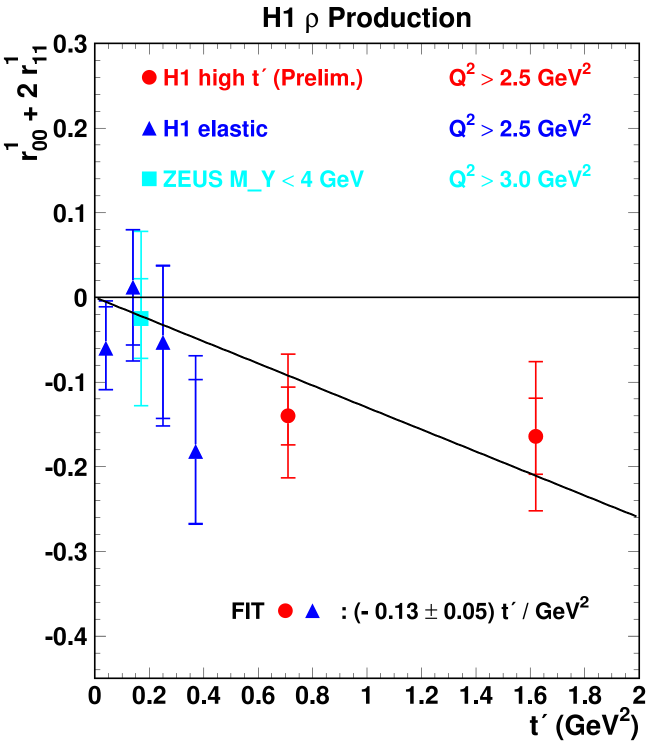
$W(\cos(\Phi)) \Rightarrow r^5_{00} + 2r^5_{11}$

$r^5_{00} \propto T_{00}T^*_{01}$

$r^5_{11} \propto T_{10}T^*_{11} + T_{10}T^*_{1-1}$

SCHC violation at large $|t|$

Curve: $\sqrt{t}$-fit



$W(\cos(2\Phi)) \Rightarrow r^1_{00} + 2r^1_{11}$

$r^1_{00} \propto -|T_{01}|^2$

$r^1_{11} \propto T_{1-1}T^*_{11} + T_{11}T^*_{1-1}$

Contributions:

r^1_{00} : $\gamma_T \to \rho_L$ dominant

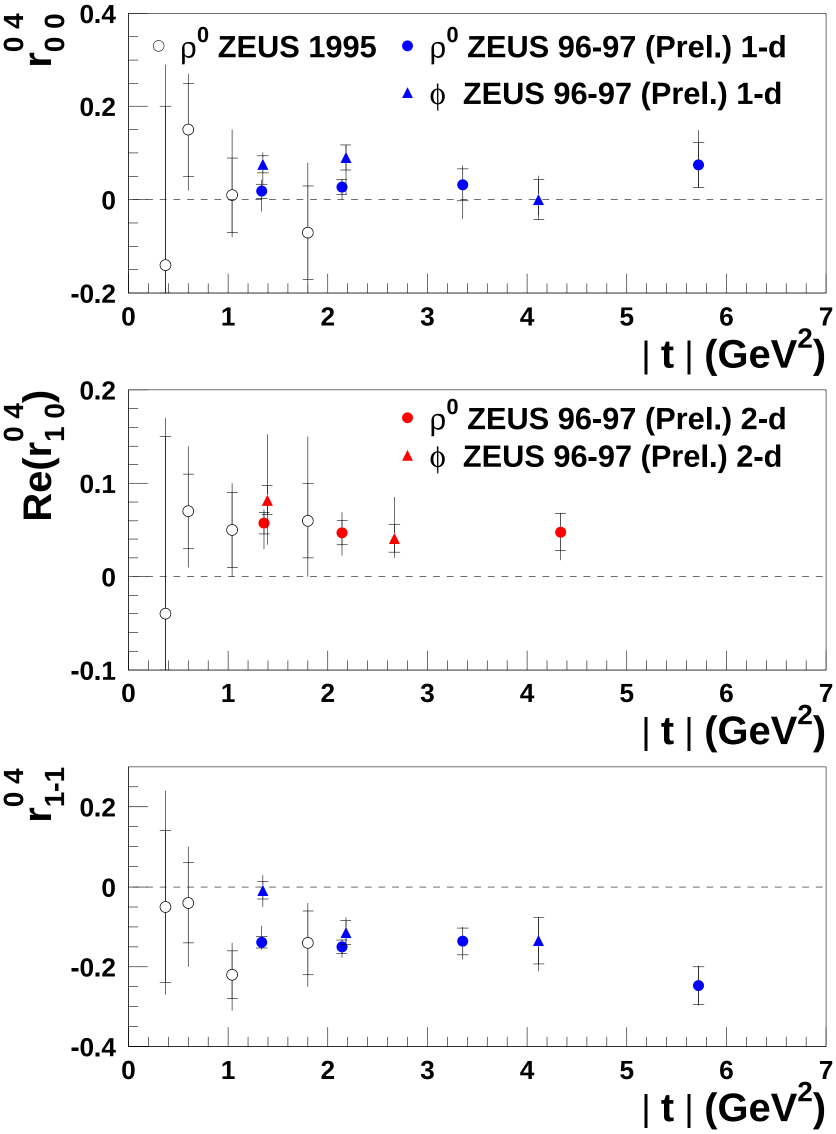
r^1_{11} : double-flip ?

Data described by pQCD-inspired fits

Helicity Amplitudes with $|t|$

Proton-Diss. Photoproduction of ρ and ϕ:

Evaluate $W(\varphi, \vartheta)$



$W(\cos^2\vartheta)$:

$r^{04}_{00} \propto |T_{01}|^2$

$W(\sin 2\vartheta \cos\varphi)$:

$Re(r^{04}_{10}) \propto Re(T_{11}T^*_{01})$

$\gamma_T \to \rho_L$: several %

$W(\sin^2\vartheta \cos 2\varphi)$:

$r^{04}_{1-1} \propto Re(T_{11}T^*_{1-1})$

Non-zero double-flip

- Results for ρ and ϕ mesons similar
- Flat t-dependence
- SCHC violated also at large $|t|$

Summary

Diffractive vector meson production at HERA is an ideal testing ground of pQCD

- New results on Vector Meson Production:
  Higher precision in larger kinematic region

- pQCD describes the data in general
  (in the presence of a hard scale)
  Need additional corrections, soft contributions (?), wave function effects ...

- Vector Meson Universality:
  Universal dependence on $M^2 + Q^2$
  SU(4)-symmetry (ρ^0, ϕ), $|t|^{-n}$-dependence

- VM Production Ratios:
  $|t|$ is confirmed as a hard scale variable
  $|t|$-behaviour somewhat different than Q^2

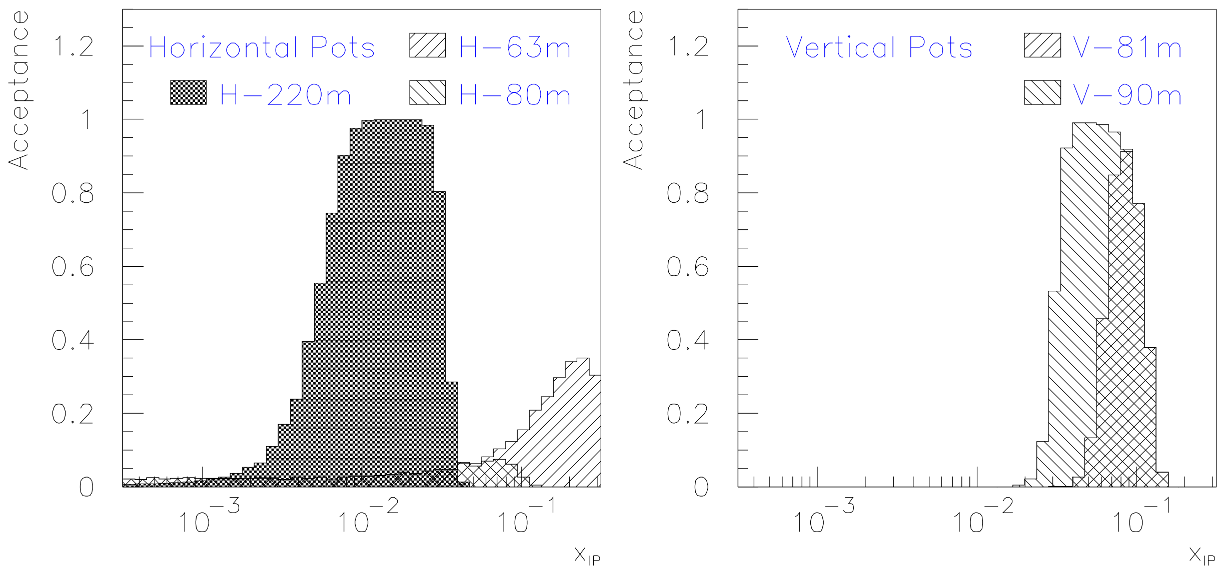
- $\gamma p \rightarrow J/\psi X$ at very large $|t|$:
  Reproduced by LO BFKL calculation

- Helicity studies:
  New data available at larger values of $|t|$

Outlook

- HERA-I: Analyses of recent data underway, look out for publications
- HERA-II: Upgrade machine and detectors
  - Expect 5 times higher luminosity
  - Further extend the kinematic range to higher Q^2, t, M_V^2 with better precision

- Upgrade example (H1): New forward beam-line instrumentation (VFPS)
  - Much increased acceptance



  - Full reconstruction of scattered proton
  - Direct measurement of elastic component

More data exploring the transition region between soft and hard diffraction is underway