Experimental Results on Exclusive Vector Mesons and Heavy Quarkonium

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H1 and ZEUS Collaborations

- Introduction and Motivation
- Elastic Vector Meson production
- Proton Dissociation
- high |t|
- Summary

Motivation

Investigation of vacuum-exchange processes

- Vacuum –exchange is complicated. Bulk of hadronic processes not calculable from first principles. Using high energy hard diffraction events we hope to learn more about the fundamental properties of strong force.

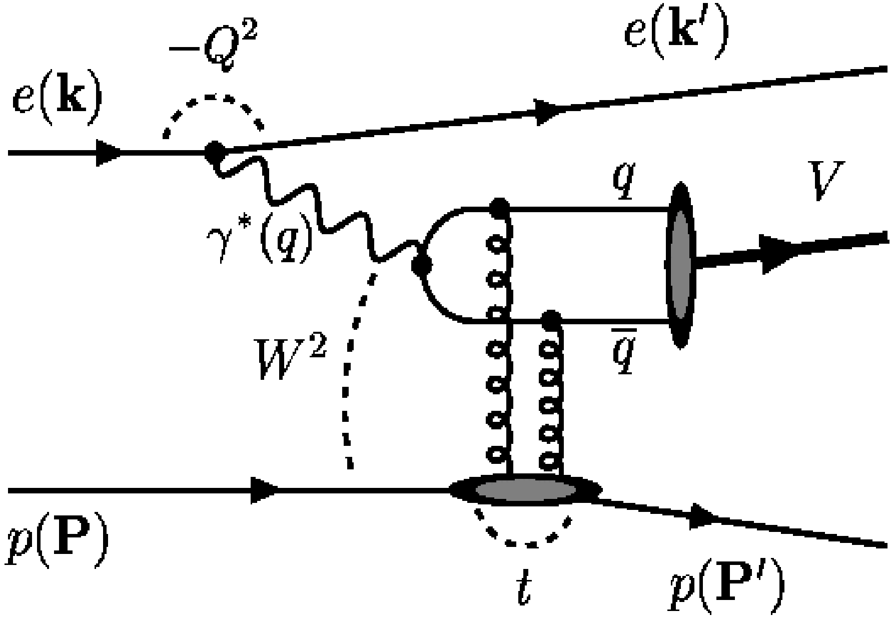
Exclusive Vector Mesons

- Study properties of the strong interaction and identify kinematic areas where pQCD is applicable:
Look for soft-> hard transitions using the scales Q^2, M_V^2, $|t|$
-Study of energy dependence is an important tool

- Dipole separation ~ $[Q^2+m_q^2]^{-1/2}$
Do we observe scaling in $[Q^2+M^2]$?

- Exclusive VM channel allows study of helicity structure using decay angles. Do we see helicity transfer, universal scaling behaviour, VM structure?

Vector Meson Production at HERA

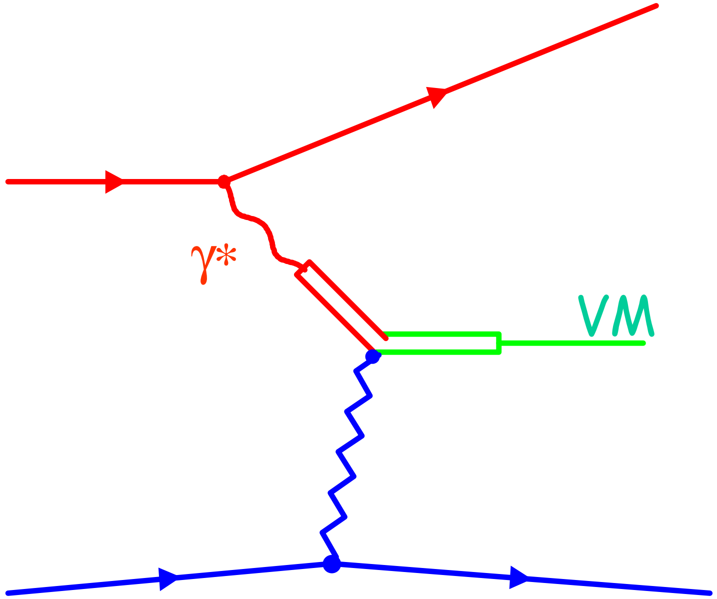


- Experimentally clean process
  - wide kinematic range

HERA -> simultaneous control of different scales: Q^2, t, M^2

VM	Vector Meson	$\rho, \omega, \phi, J/\Psi, \Psi', \Upsilon$
$W^2 = (q+p)^2$	γp COM energy	$20 < W < 290$ GeV
$Q^2 = -q^2 = (k-k')^2$	γ^* virtuality	$0 < Q^2 < 100$ GeV^2
$t = (p-p')^2$	4-mom. transfer	$-1 < t < 0$ GeV^2 (exclusive)
	at p vertex	$-30 < t < 0$ GeV^2 (p. diss)

VMD and Regge Theory



VMDominance:

- photon fluctuates into VM before interaction (VM retains γ^* helicity SCHC)
- VM scatters off proton (soft interaction)

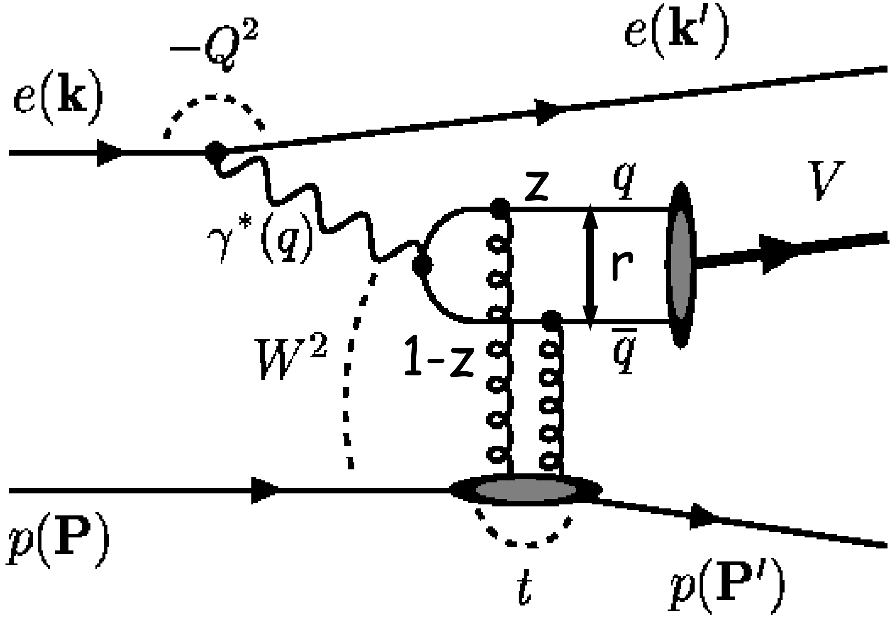
Regge theory:

Successful parameterisation of soft processes by Regge trajectories

$\alpha_{IP}(t)=\alpha_{IP}(0)+\alpha_{IP}'t$ soft pomeron $\alpha_{IP}(0)=1.08$, $\alpha_{IP}' = 0.25\ \mathrm{GeV}^{-2}$

- Intercept describes weak energy dependence of cross section
  $\sigma \sim W^{\delta}$ $\delta \sim 0.2$ $\delta = 2\,(\alpha_{IP}(0) - 1)$
- Small scattering angles $d\sigma/dt \sim e^{b(W)t}$
- shrinkage $b(W) = b_0 + 4\alpha' \ln(W/W_0)$

Dipole Picture in Proton Rest Frame



- γ^* -> qq (wave function
- qq scattering off proton
- VM formed after interaction

- γ^* -> qq (wave function parameterisations exist DGKP,NNPZ etc.)
- dipole cross section from proton. Lowest order colour singlet exchange 2 gluons.
- r: transverse separation of dipoles r ~ $[z(1-z)Q^2+m_q^2]^{-1/2}$
- Large Q^2 or m_q^2 small dipole resolve short distances -> pQCD
- Large dipole (small Q^2 and m_q^2) -> non-perturbative

pQCD predictions

$\sigma_L \,|_{t=0} \sim \alpha_s^2(Q_{eff}^2)/Q^6 \; |xG(x,Q_{eff}^2)|^2$

MRT: Phys. Rev. D62 (2000) 14022.

FKS: Phys. Rev. D57 (1998) 512.

1. Fast rise with energy from rise of gluon density $W^{\sim 0.8}$ [$W^2 \sim 1/x$]
   Q^2 dependence slower than $1/Q^6$ due to xG
2. Longitudinal cross section asymptotically dominant ($R = \sigma_L/\sigma_T = Q^2/M^2$)
3. Q^2 dependence less than $1/Q^6$ due to gluon density
4. Approximate Flavour symmetry due to universal hard 2g-dipole scatter
   $\rho : \omega : \phi : J/\Psi$ = 9 (9) : 1 (0.8) : 2 (2.4) : 8 (28)
   modification proportional to mass due to dipole-VM transition
5. Transverse $\sigma_T \sim Q^{-8}$: large dipole sizes due to endpoint effects make problems for predictions for light VMs
6. Universal t-dependence $\sim e^{-4|t|}$. No shrinkage (2g)

Confront models with data ->

Elastic VM in photoproduction (Q^2=0, |t|~0)

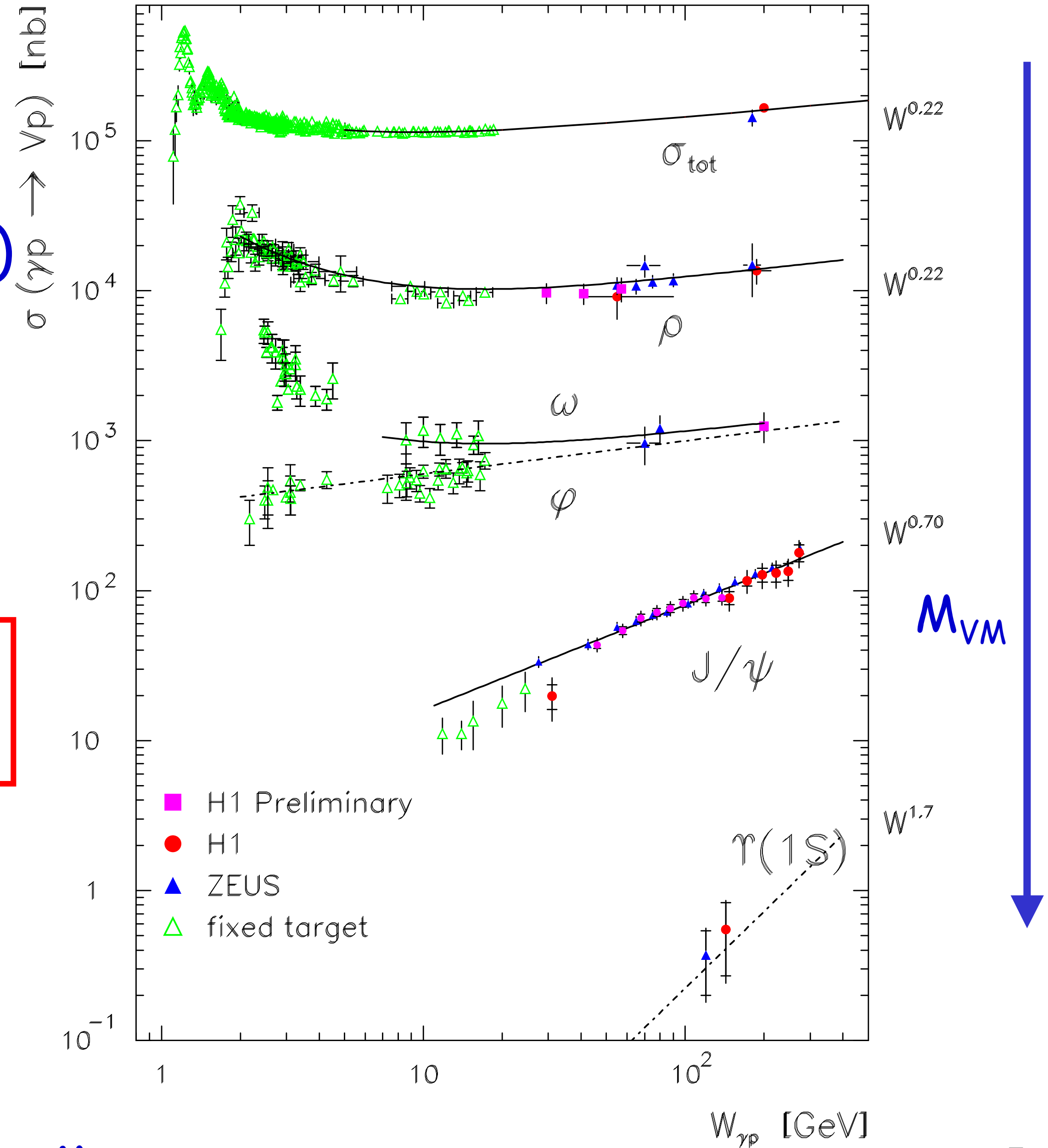
W-dependence:

Fit $\sigma^{el}(W) \sim W^{\delta} = 2\, \alpha_{IP}(< t >)$

δ = 0.22 ρ^0, ω, ϕ "soft"

δ = 0.8 for J/Ψ "hard"

$\Rightarrow$ VM mass - hard scale to apply pQCD?



Elastic J/Ψ Mesons in Photoproduction

Fast rise with W:

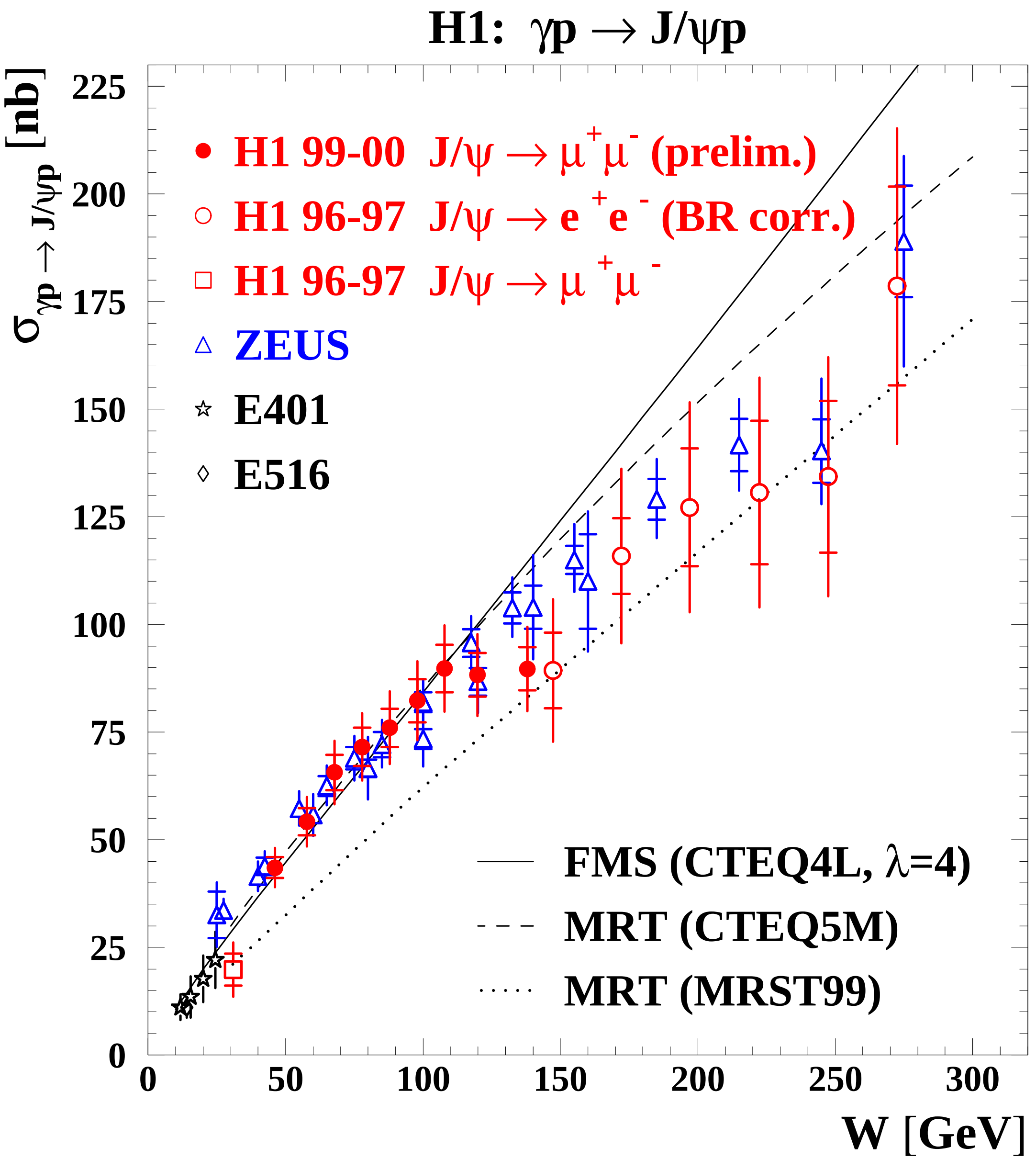
W^{δ} $\delta \sim 0.7$

pQCD models with $M_{J/\Psi}$ as hard scale give qualitative description of data

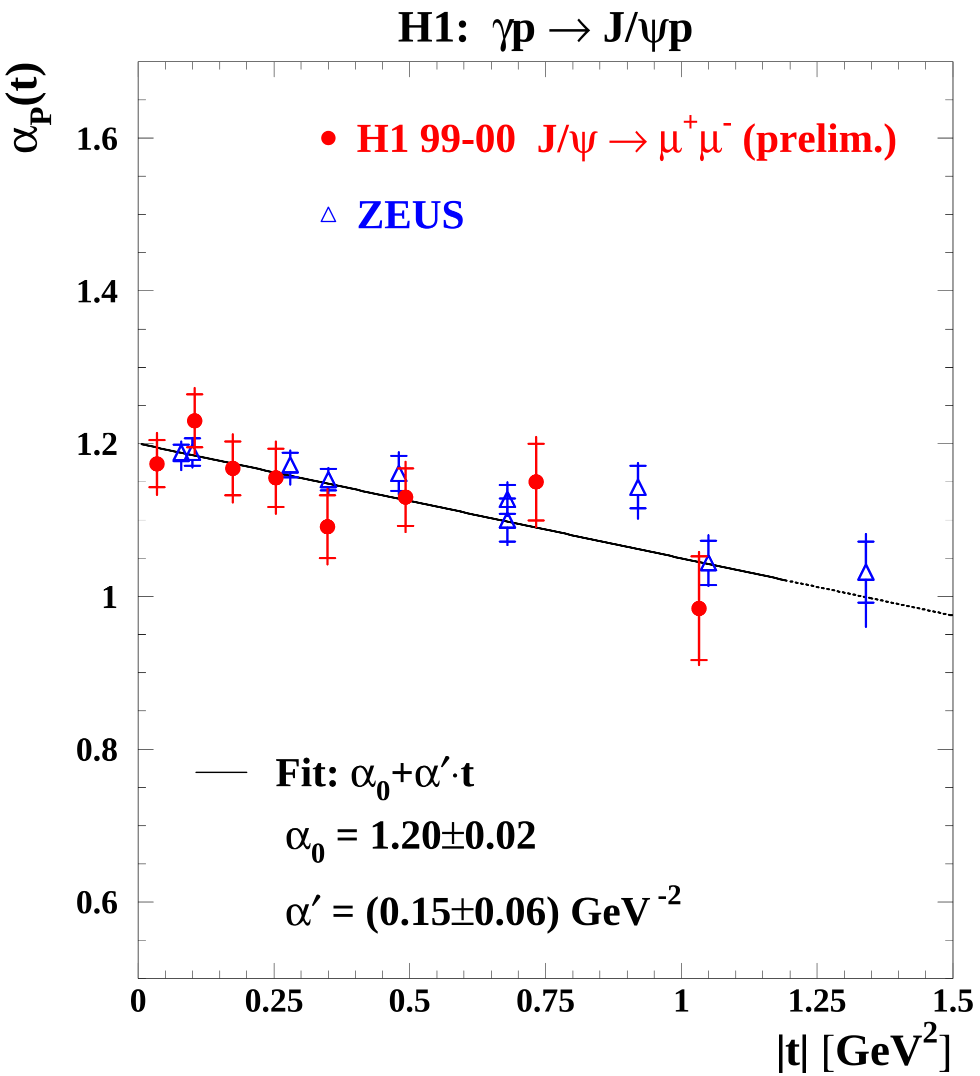
Extraction of gluon density?

$\sigma_L \sim [\, xG(x,Q_{eff}^2)]^2$

Choice of Q_{eff}^2?
NLO effects?



Pomeron Trajectory for J/Ψ in γp

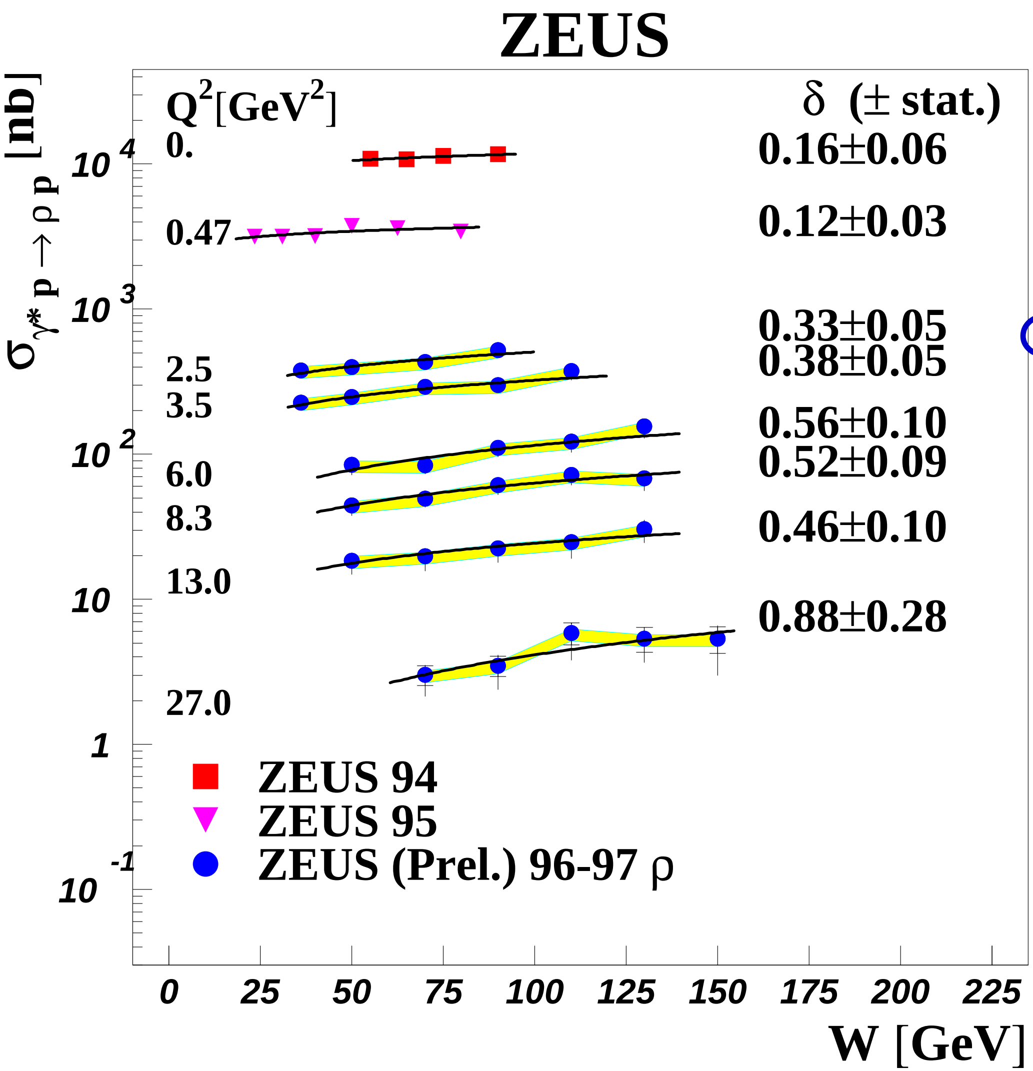


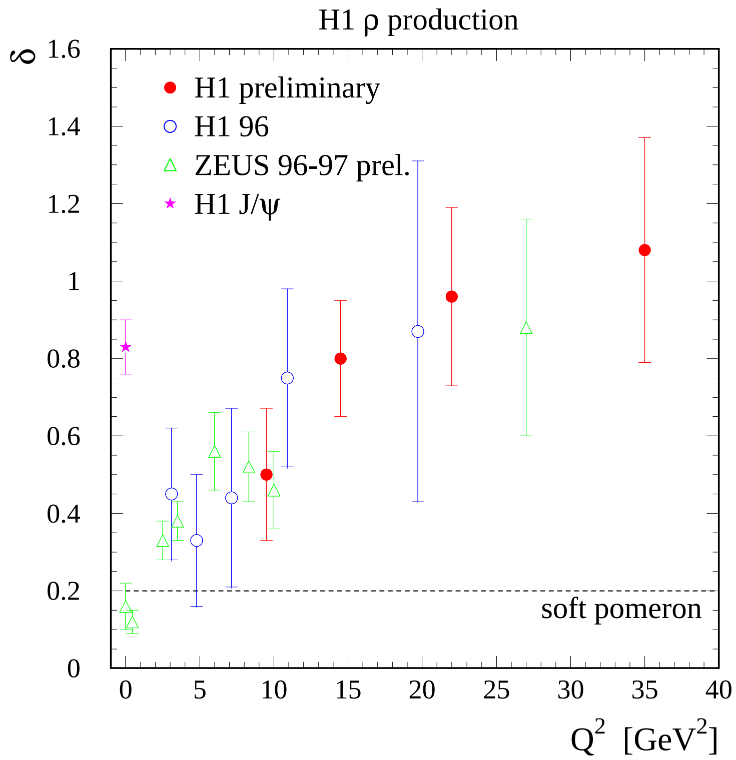
Measure W-dependence in bins of t

⇒ "soft" Pomeron alone excluded

-Shrinkage observed

W-dependence of elastic ρ^0 in bins of Q^2



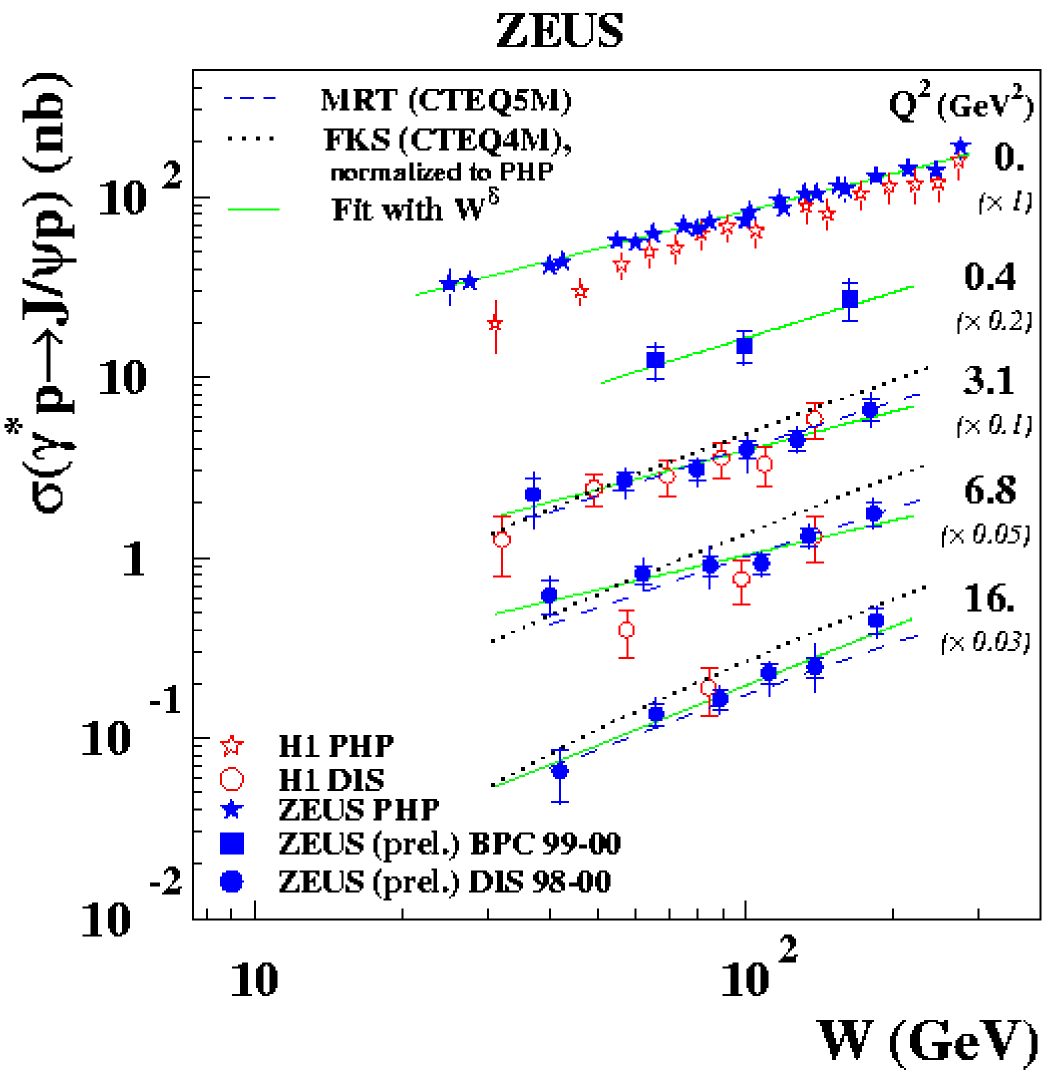


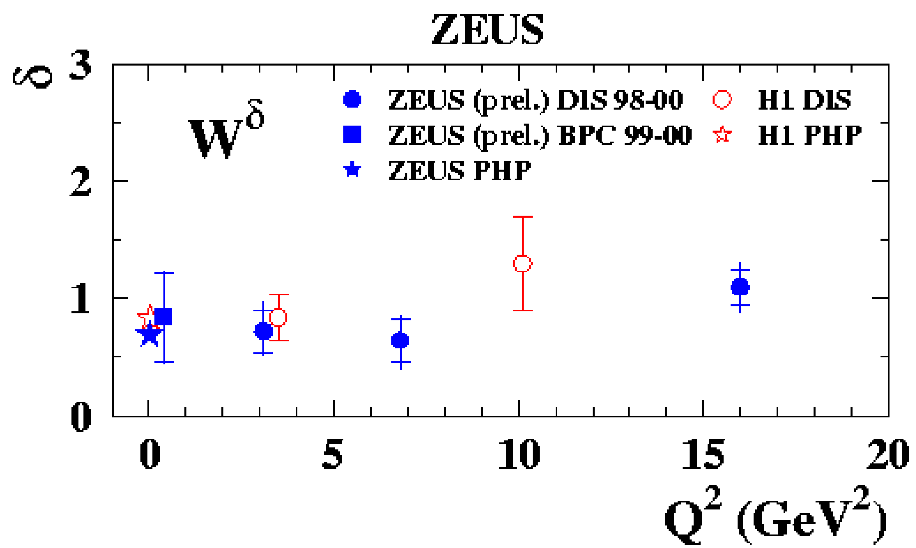
->W-dependence steepens vs Q^2

-Smooth transition soft-> hard

$\Longrightarrow$ Q^2 hard scale for pQCD?

W-dependence of elastic J/Ψ in bins of Q^2

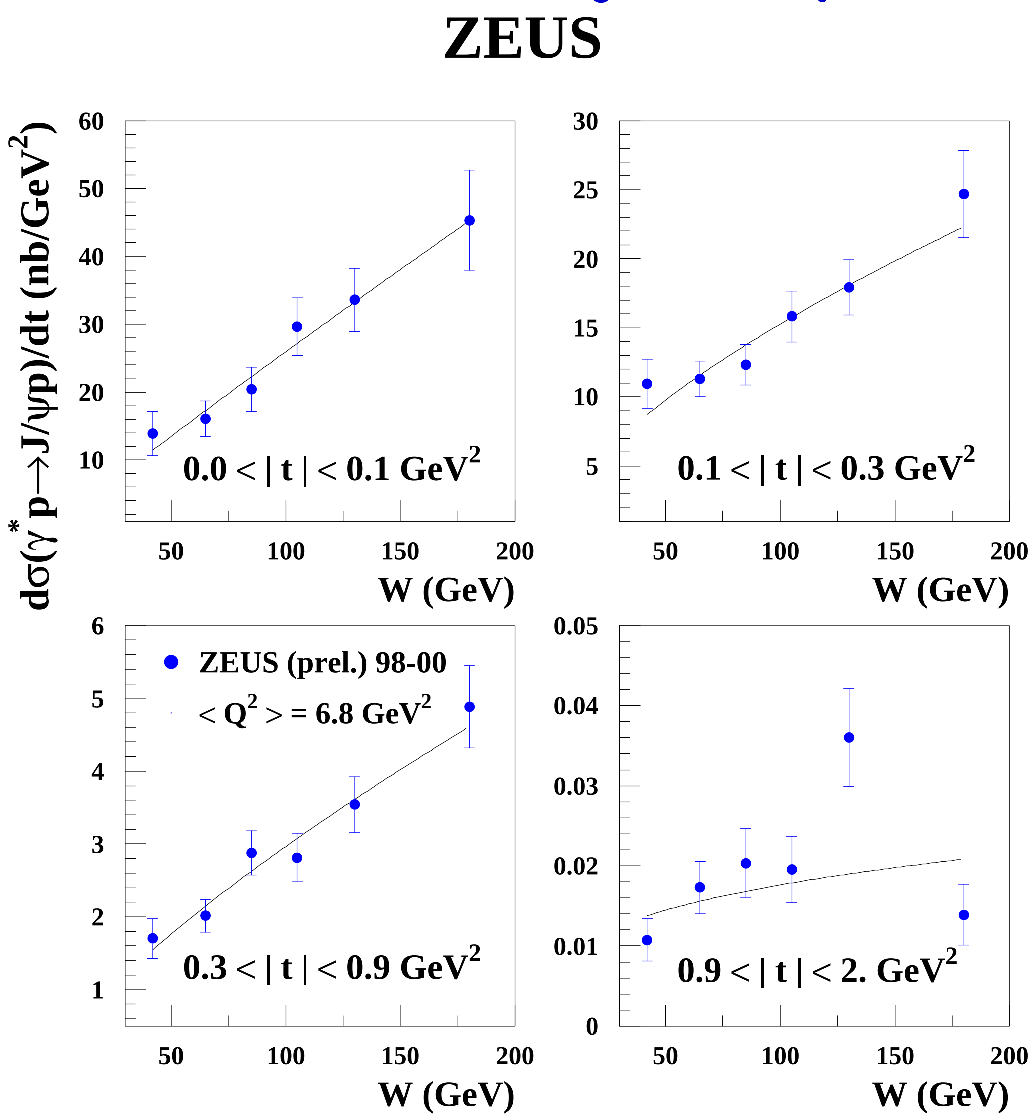


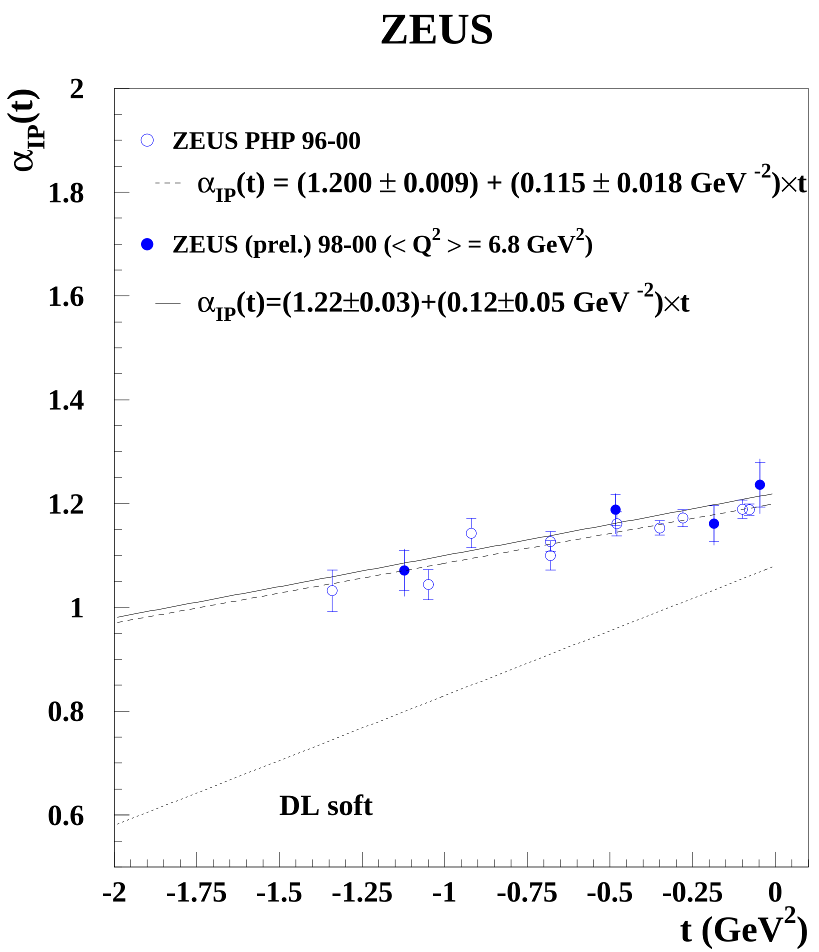


- δ flat in Q^2 for J/Ψ ($\delta \sim 0.7$)
- J/Ψ "hard" process

pQCD models using xG give qualitative description

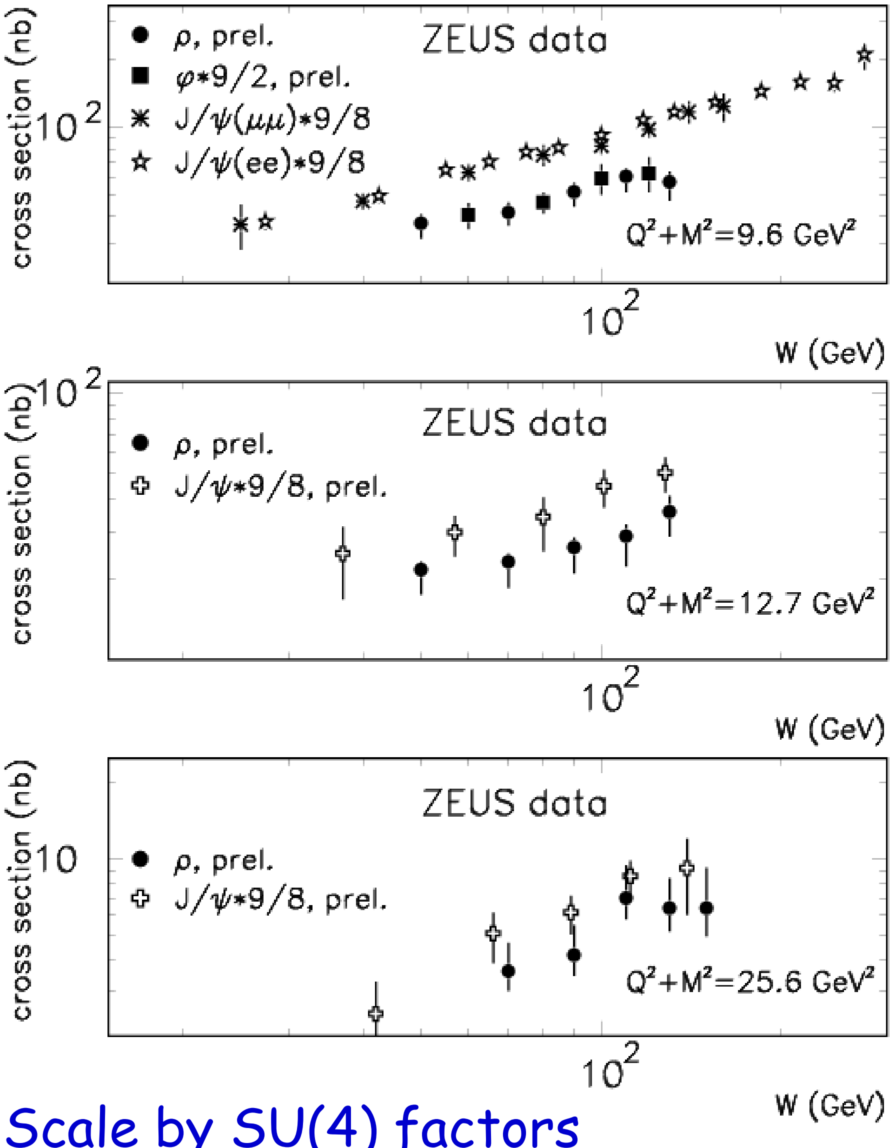
Pomeron trajectory for J/Ψ in Electroproduction



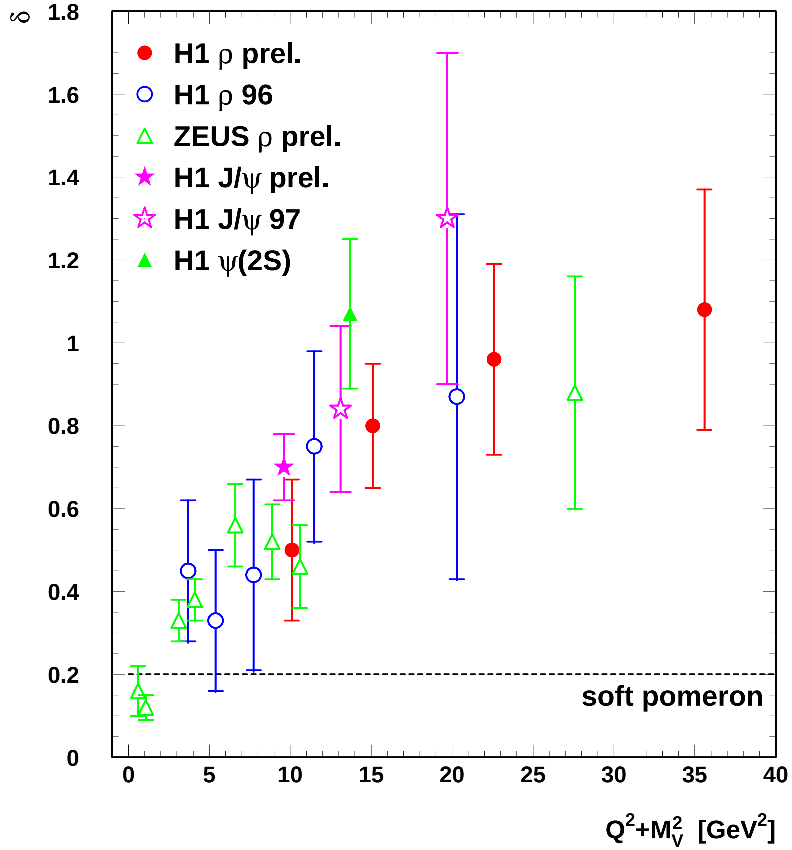


- increasing precision at high Q^2
- trajectory consistent with γp

Is Q^2+M^2 a universal scale for W-dependence?

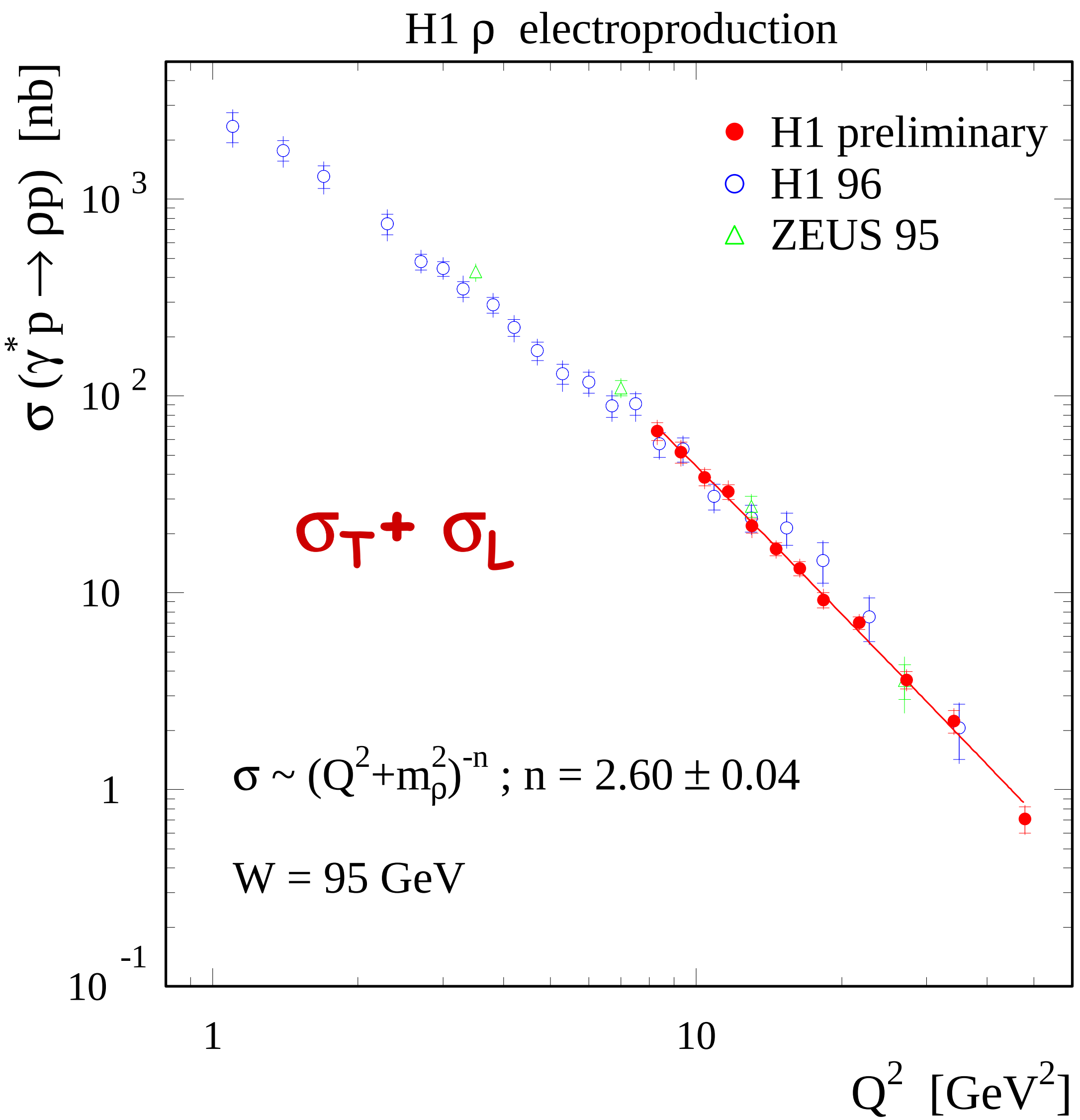


Scale by SU(4) factors
ρ : ω : ϕ : J/Ψ = 9 : 1 : 2 :8



- SU(4) scaling works for ρ,φ,ω not for J/Ψ
- but W dependences similar

Q^2 Dependence of ρ^0 Production



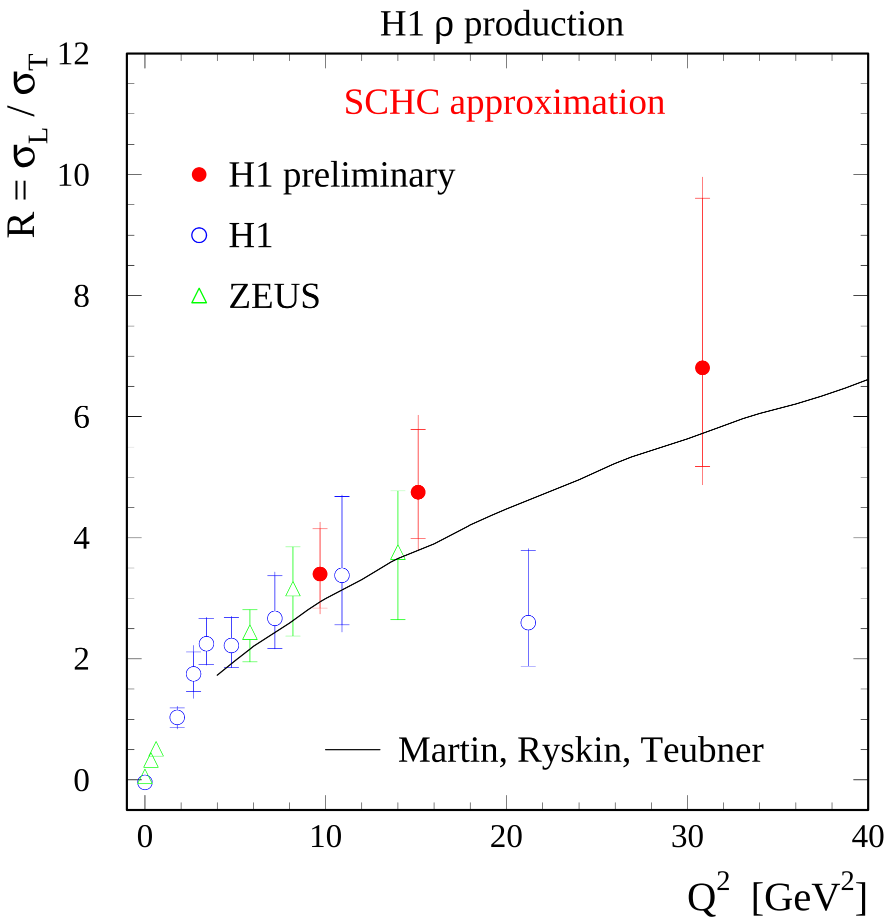
Fit:

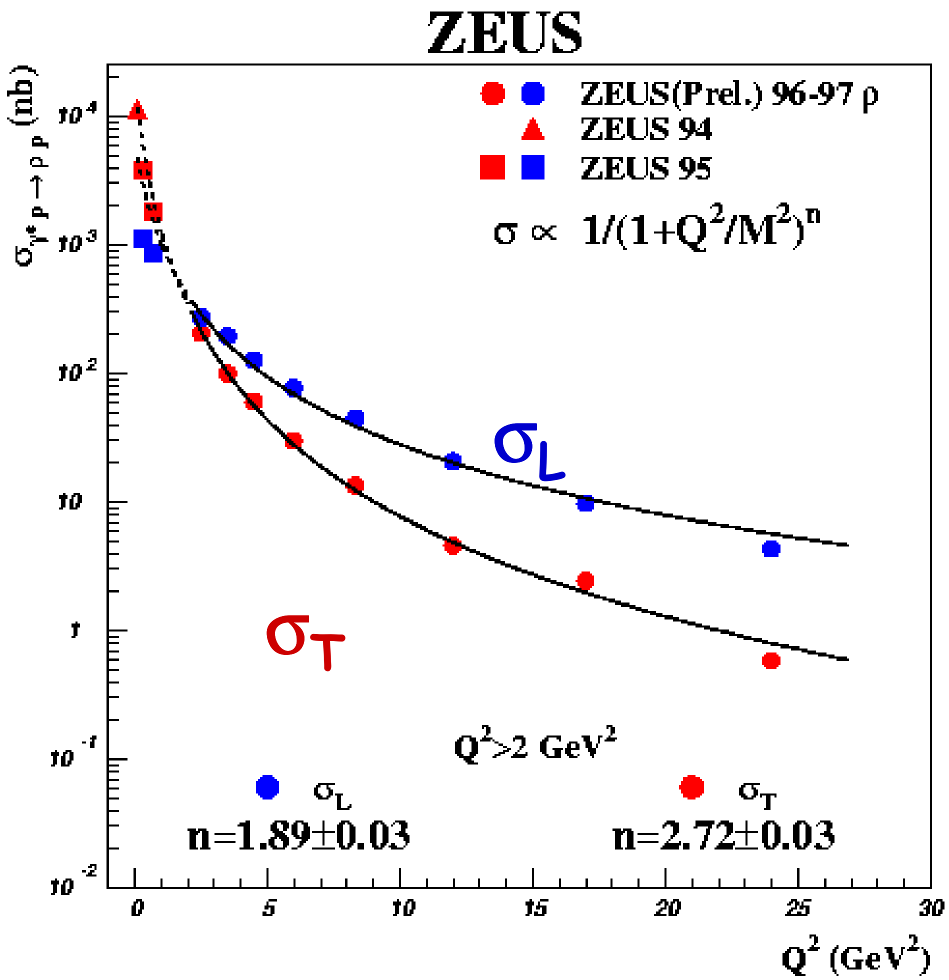
$\sigma(Q^2) \sim (Q^2+M^2)^{-n}$

H1: $n = 2.6 \pm 0.04$

- Parameterisation fails at lower Q^2
- VM wave function effects?

Measurement of $R=\sigma_L/\sigma_T$ vs Q^2 for ρ^0

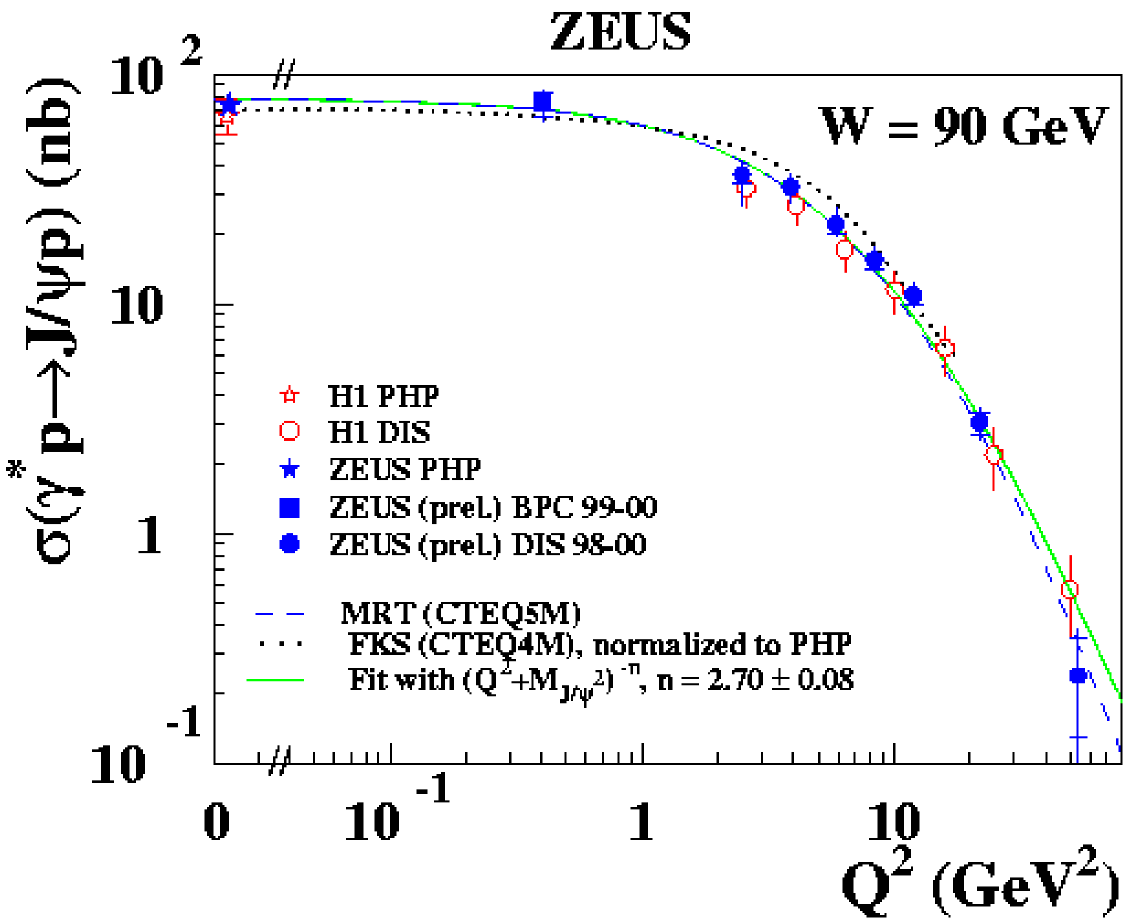


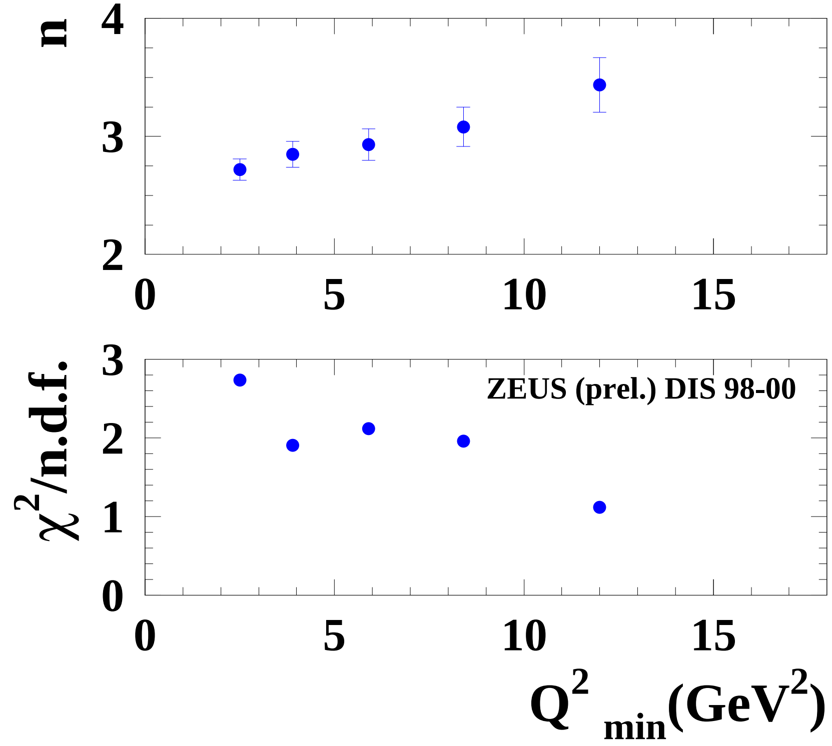


pQCD: $\sigma_L \sim \alpha_s^2/Q^6 \cdot [xG]^2$

Gluon density expected to weaken $1/Q^6$ dependence

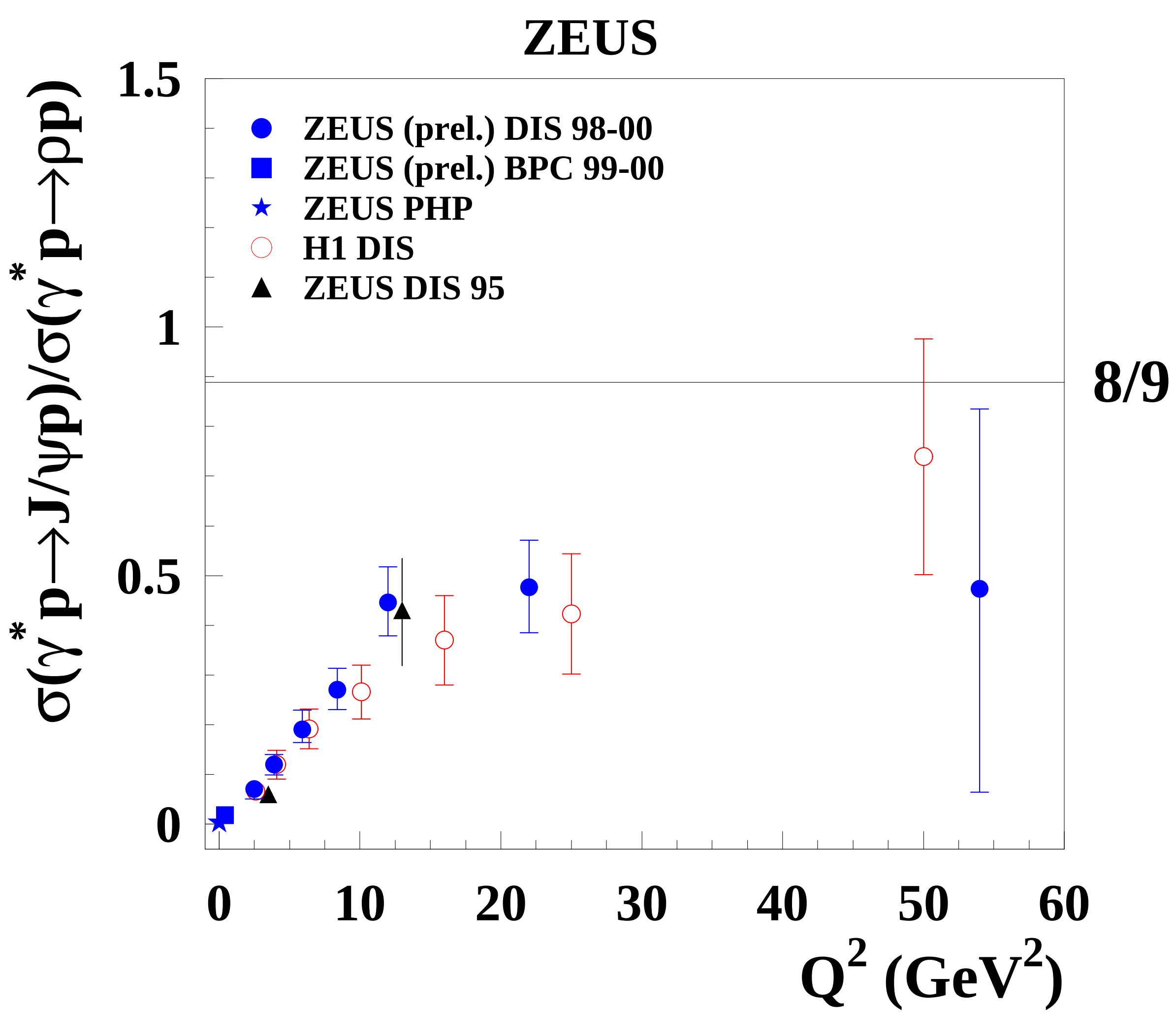
Q^2 Dependence of J/Ψ Electroproduction





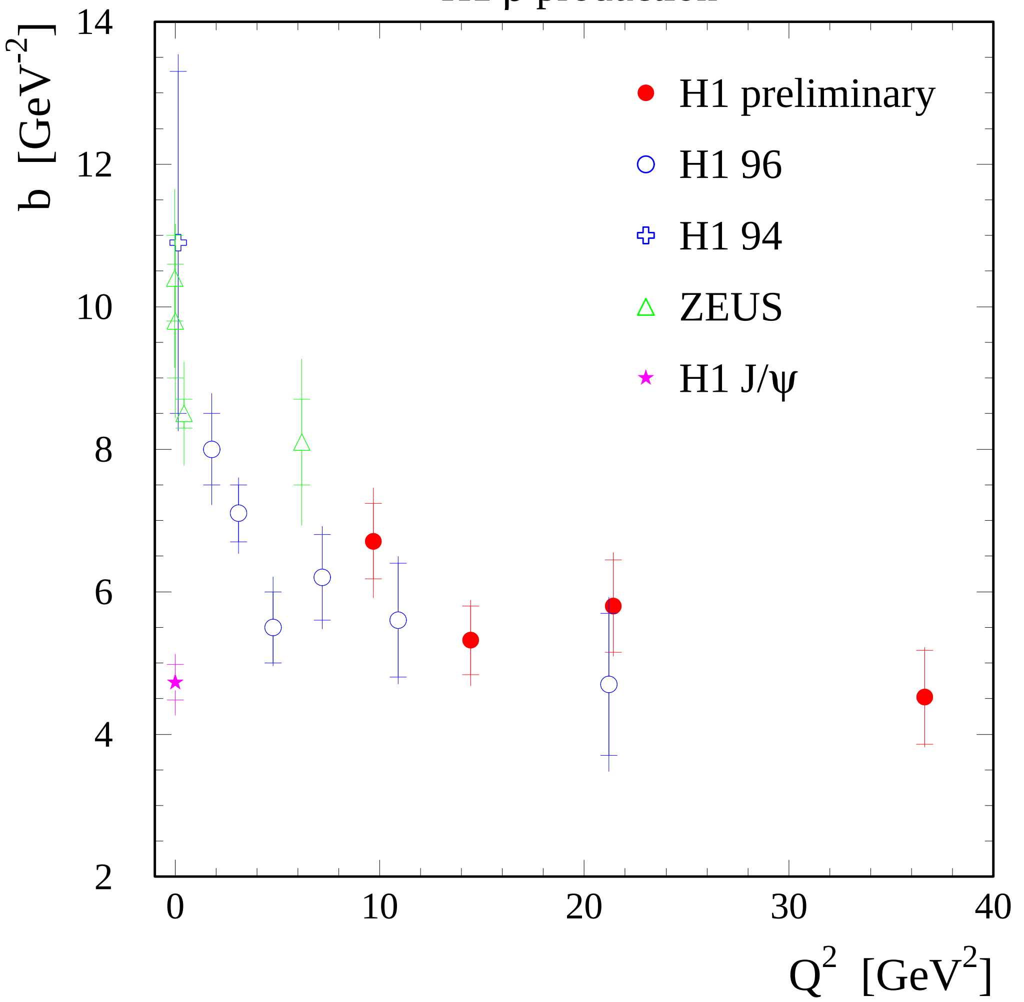
- Fit describes data, although χ^2 improves with increasing Q^2_{min}
- pQCD gives reasonable description

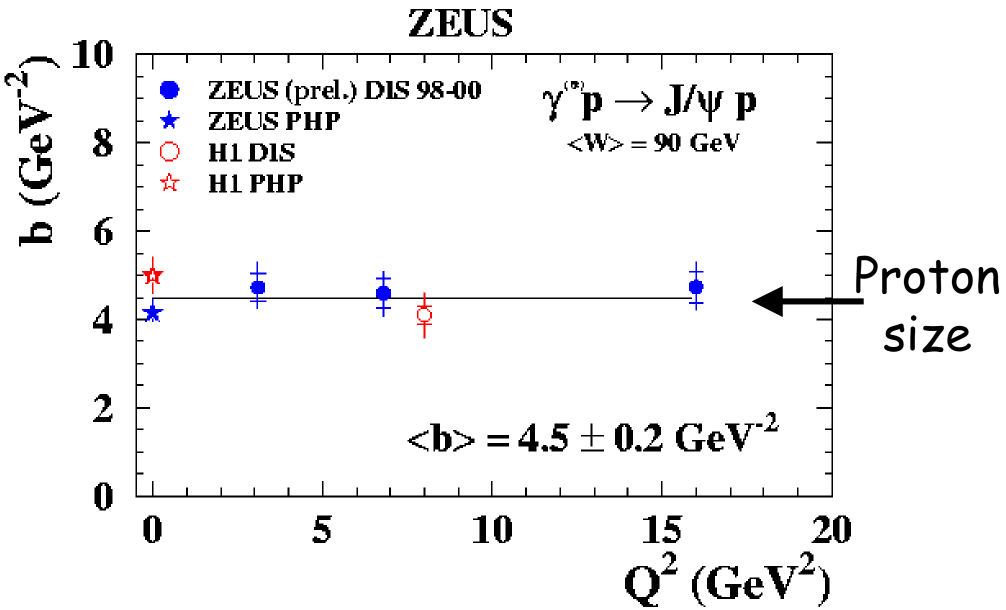
Ratio of J/Ψ and ρ^0 vs Q^2 – SU(4) scaling?



- Ratio increases with Q^2
- Approaching SU(4) value
- Far from enhancement (~3) due to mass predicted by pQCD

b(Q^2) in elastic electroproduction for ρ^0 and J/Ψ





Size of ρ^0 shrinks with Q^2 while J/Ψ is already point-like at $Q^2 \sim 0$

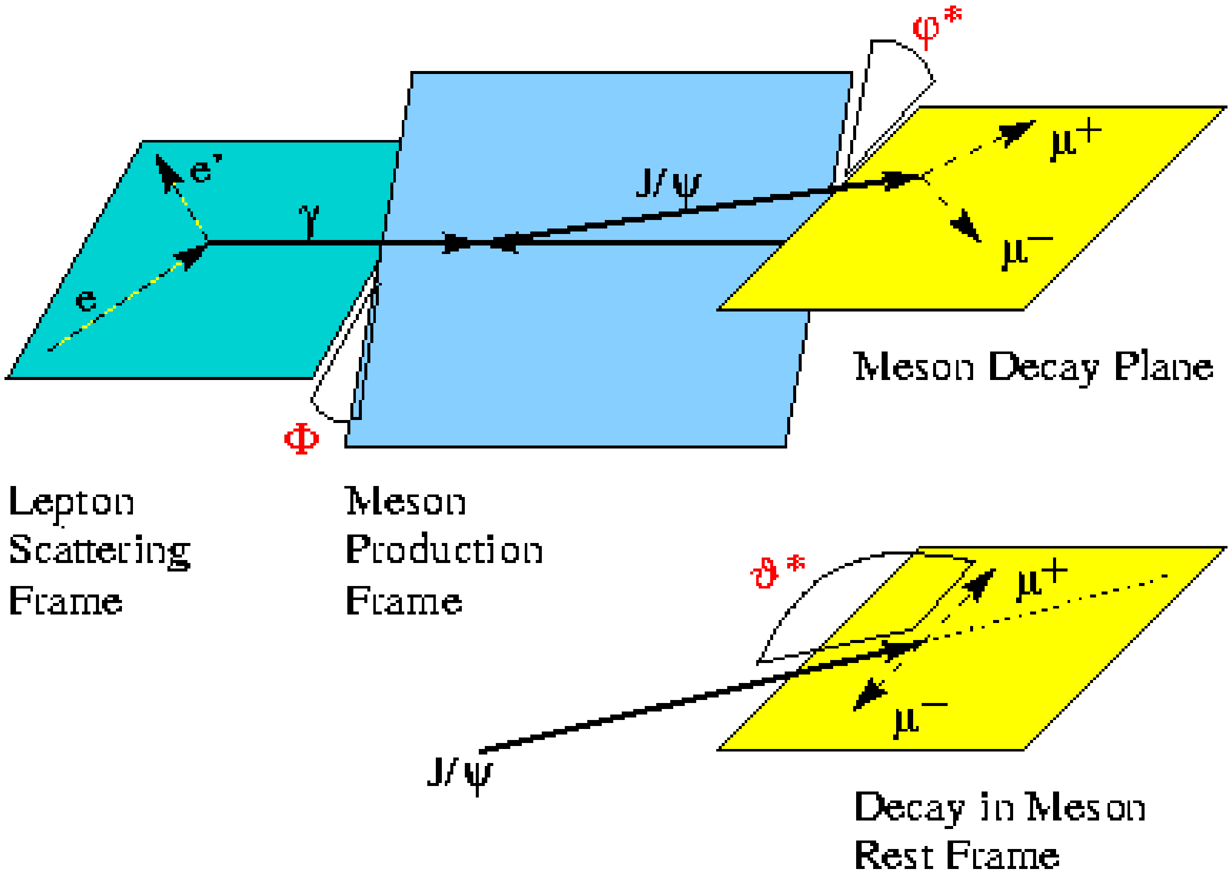
t-slope is the fourier transform of the spatial extension of the VM

"$b=b_p+b_{VM}$"

"universal" t dependence if Q^2 or M^2 is large?

Helicity

Information about polarisation of VM obtained in helicity frame

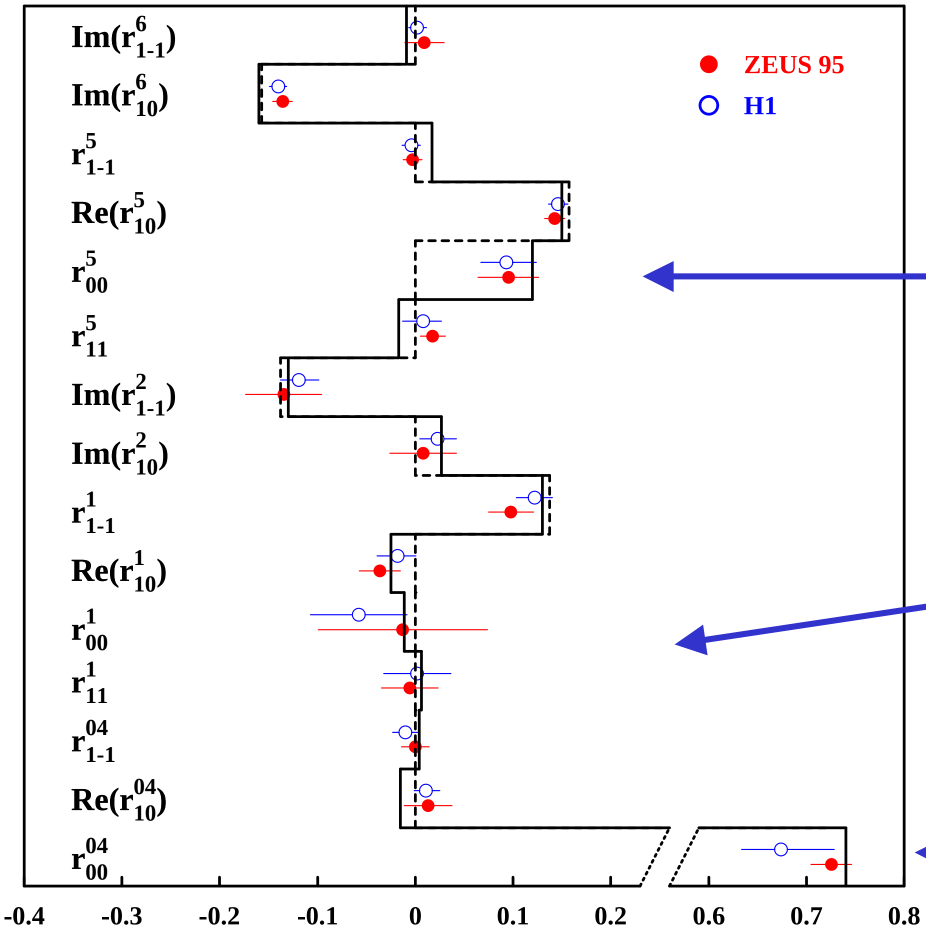


Angles Φ,ϕ,ϑ sensitive to products of helicity amplitudes:

$$T_{\lambda_{VM}\lambda_\gamma}$$

s-channel helicity conversation (SCHC) - helicity of photon transferred to VM.

What have we learned so far?



Results for ρ,ϕ electroproduction

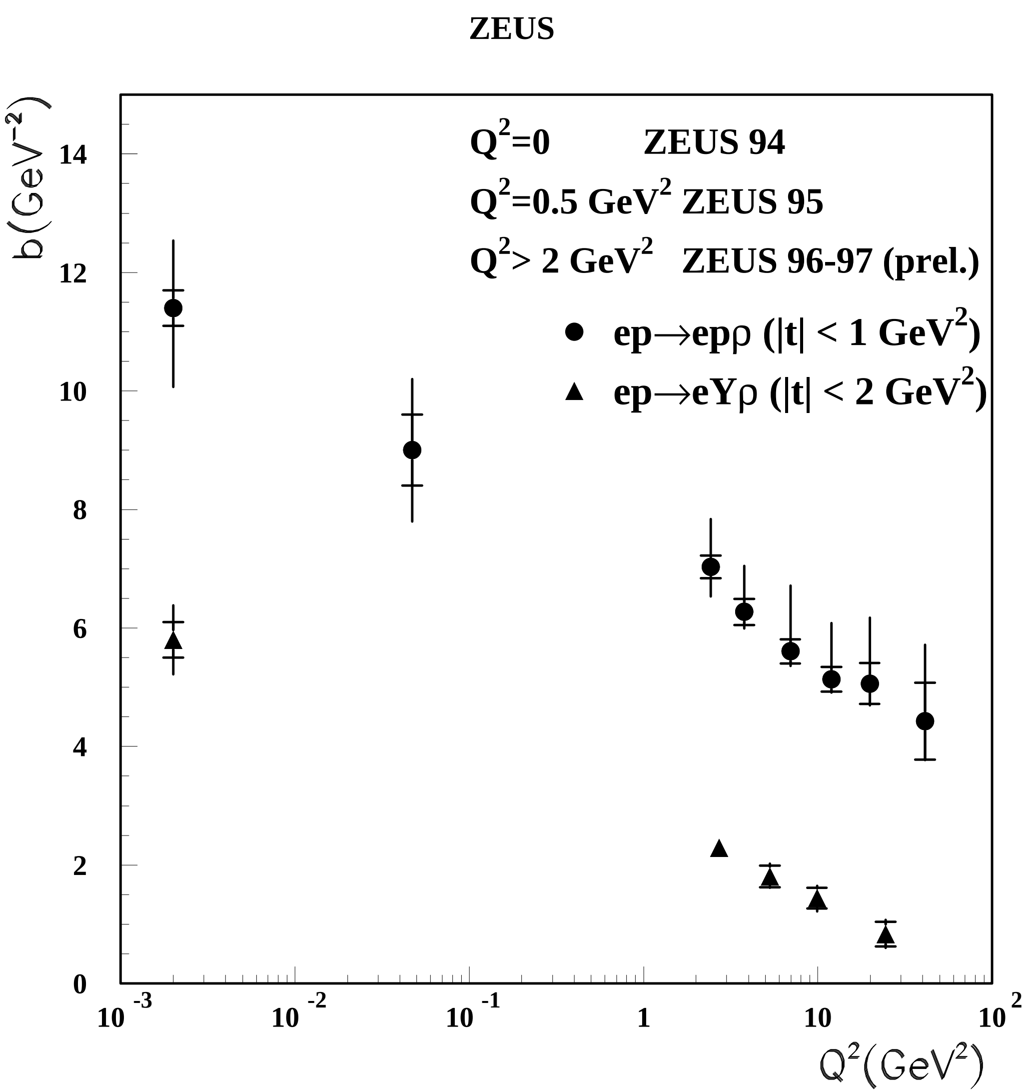
Small violation of SCHC r^5_{00} indicating dominant single flip amplitude is T_{01}

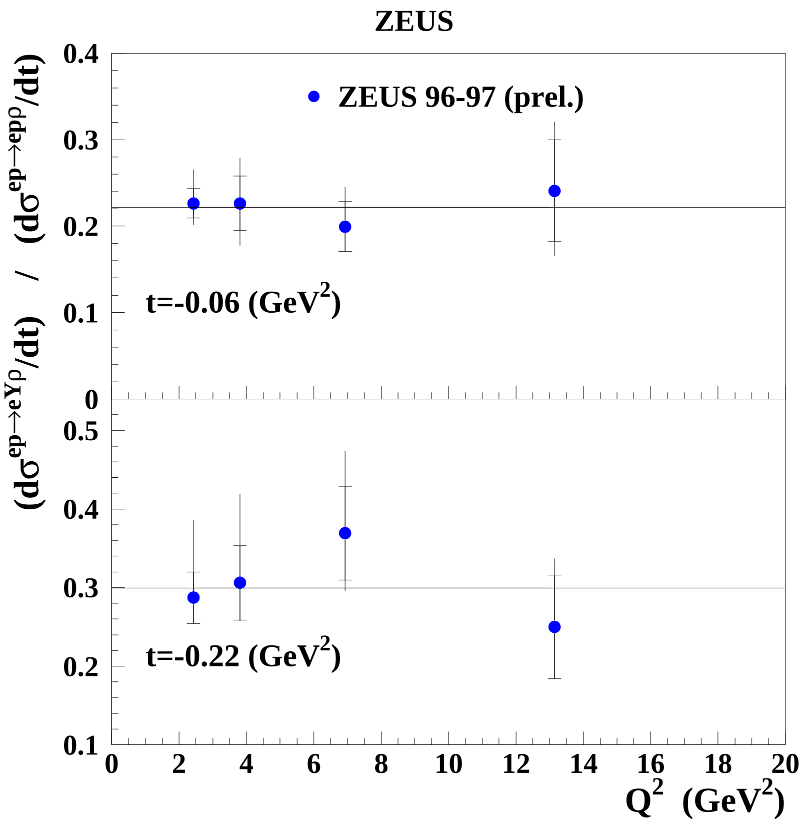
SCHC compatible for matrix elements describing single(T_{10}) or double helicity flip (T_{1-1})

Dominance of T_{00} over T_{11} for non-flip amplitude

- Described by pQCD (Ivanov and Kirschner) based on 2g exchange
- SCHC violation requires longitudinal momentum of photon to be shared asymmetrically by qq

Proton Dissociation ρ^0 Eletroproduction (low-|t|)



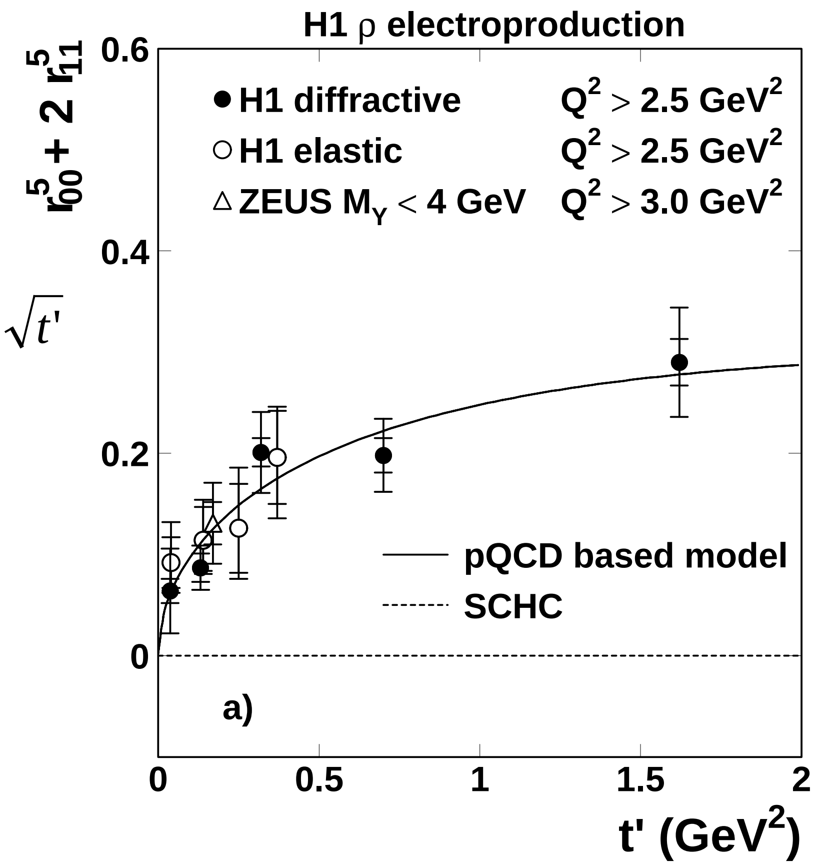


⇒ Consistent with vertex factorisation

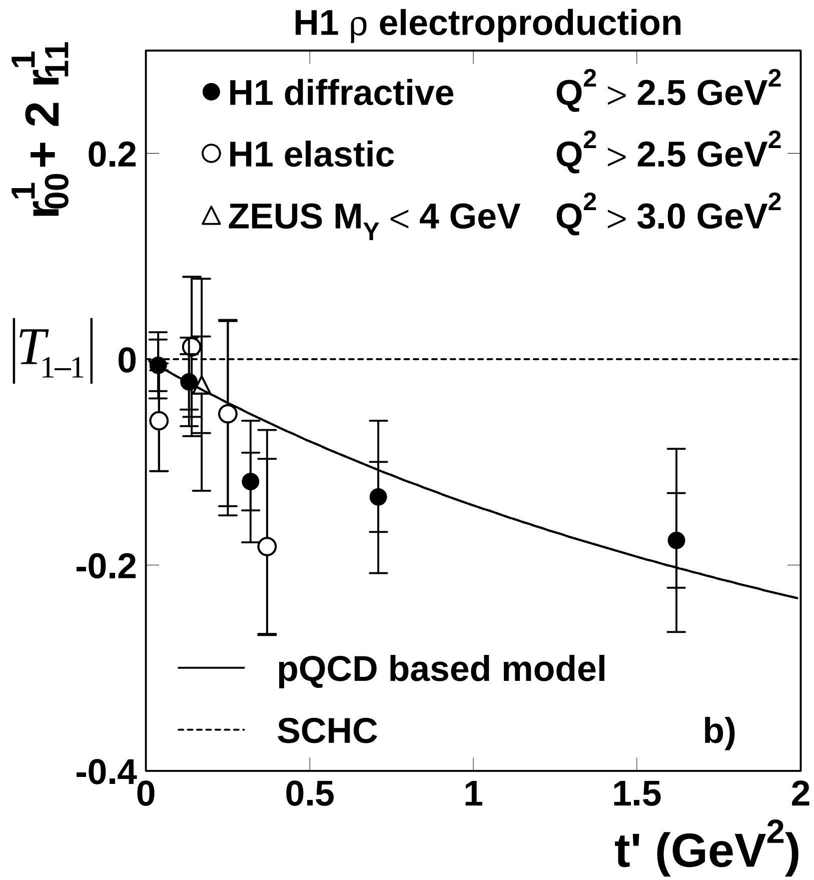
i.e. probability for p-dissociation is independent of projectile

SCHC for ρ^0 proton dissociation

$$\frac{|T_{01}|}{|T_{00}|} \propto \sqrt{t'}$$



$$|T_{01}| >> |T_{1-1}|$$

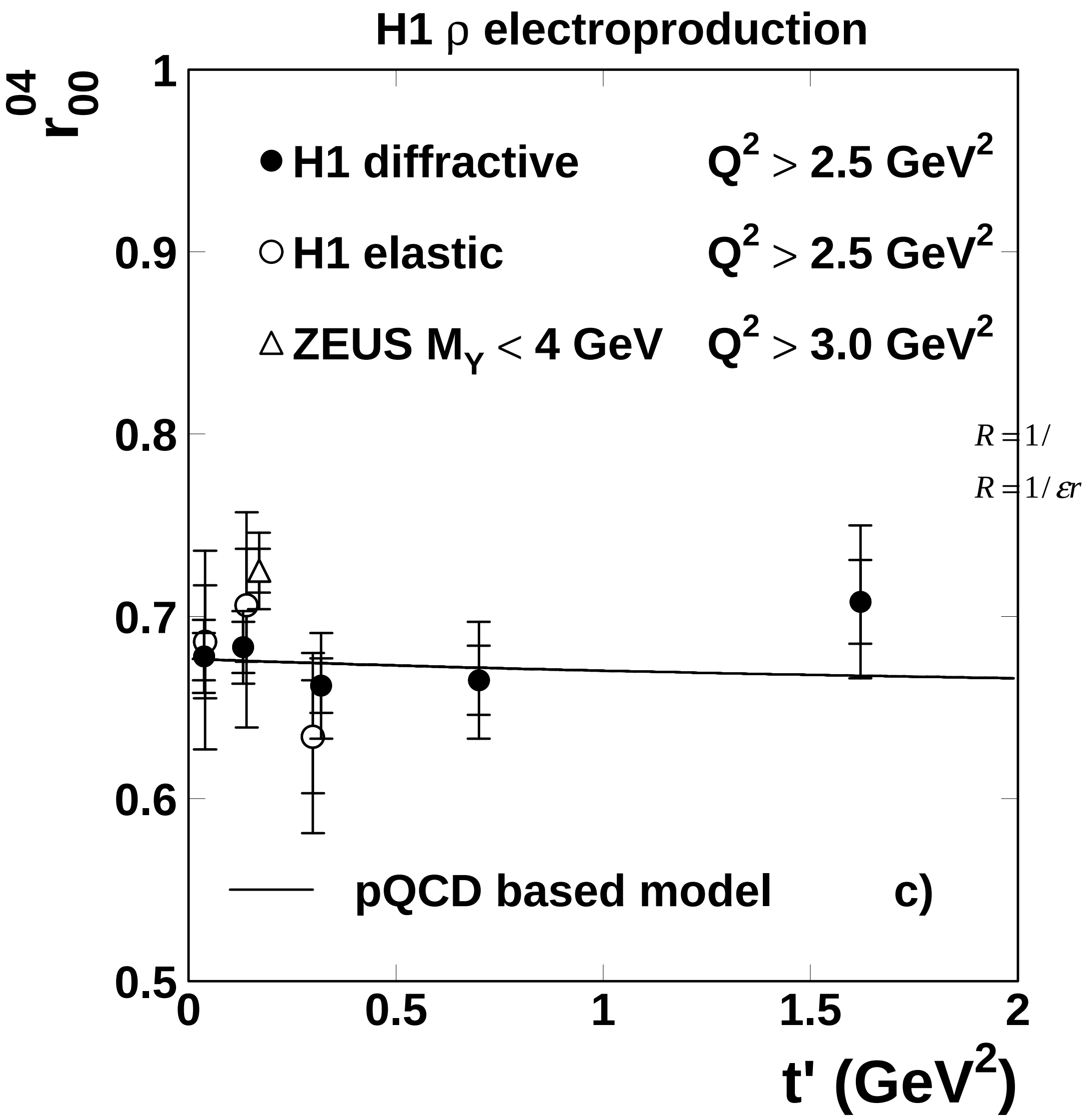


- SCHC–breaking observed for dissociation process

$t' = |t| - |t|_{min}$

- described by pQCD based on 2g exchange where photon longitudinal momentum shared asymmetrically by qq

R for ρ^0 proton dissociation



- $R = 1/\varepsilon\, r^{04}/(1-r^{04})$
- $r^{04} \sim (|T_{00}|^2 + |T_{11}|^2)$

- No dependence of r^{04} (R) on t

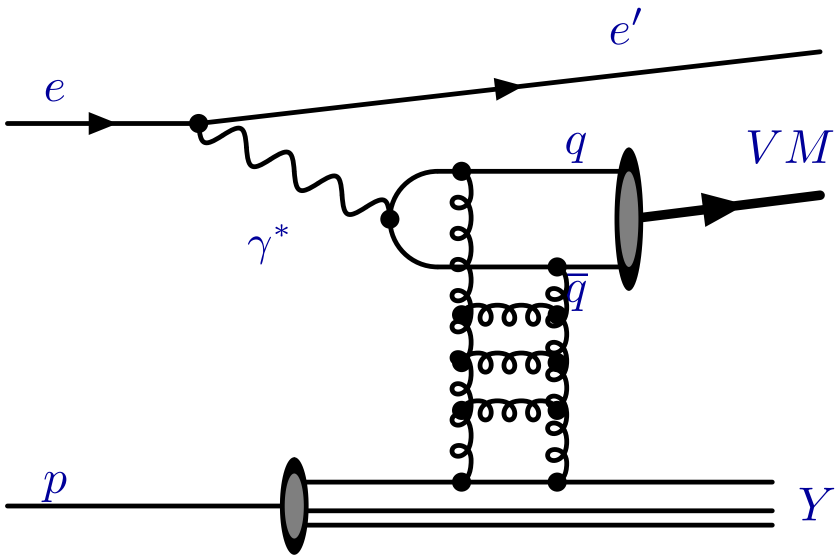
  $\Rightarrow$ b-slopes for σ_L and σ_T
  SCHC amplitudes are similar

- non-perturbative contributions to σ_T small?

  -> described by pQCD based on 2g exchange

High-|t| Vector Meson Production

- calculations for `hard' BFKL pomeron   Bartels, Forshaw et al.
- gluon ladder couples to a single parton within proton
- BFKL LLA: $W^{1.2}$ steep rise $\alpha'_{IP} < 0.1\ \mathrm{GeV}^{-2}$ little shrinkage
- t-dependence $d\sigma/dt \sim |t|^{-n}$, $n \sim 3$ (n increases with t)

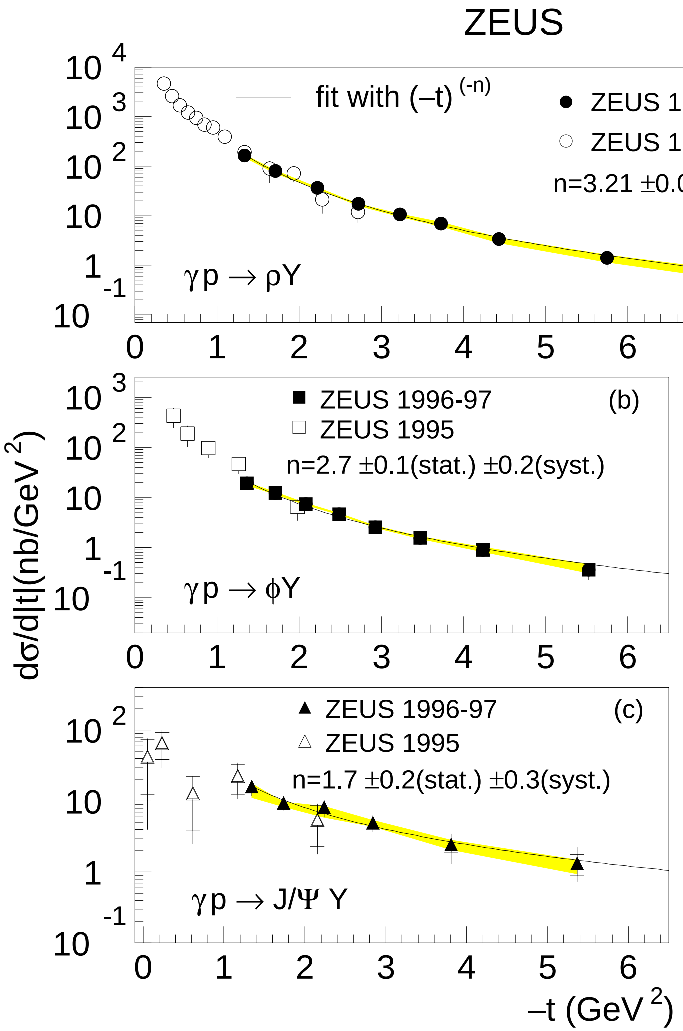


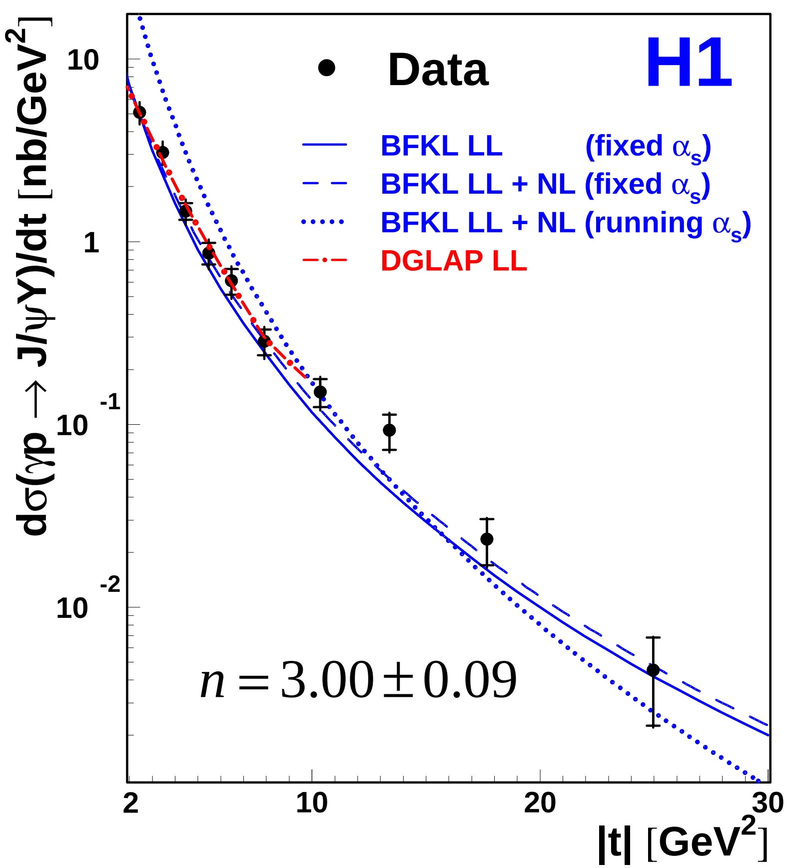
-In region $|t| < M^2$ DGLAP evolution possible through K_T ordering in ladder   Gotsman, Maor et al.

-$|t| \gg M^2$, no phase space for DGLAP evolution. Unordered K_T from BFKL evolution

Do we approach the BFKL region at HERA?

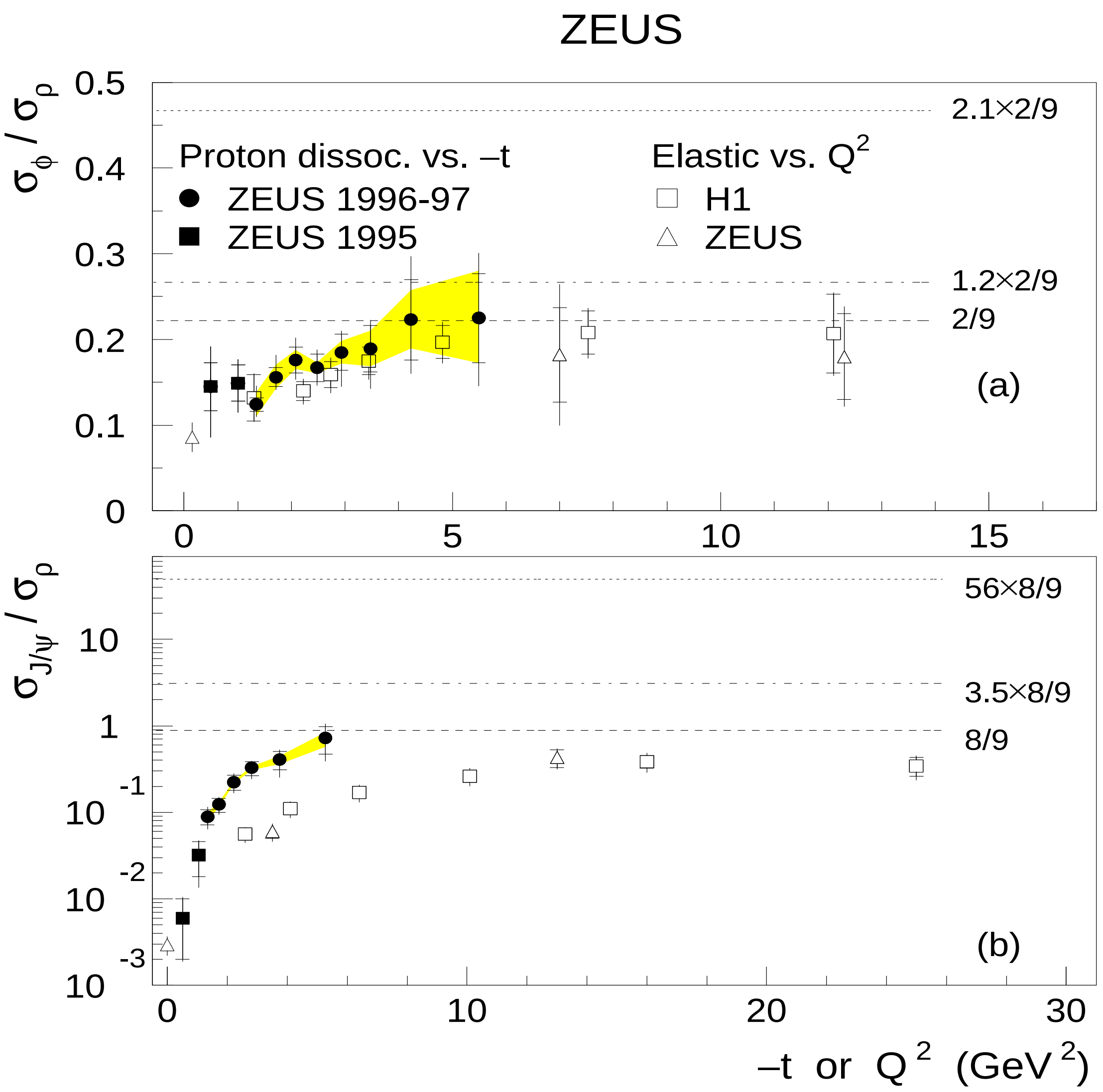
Proton-dissociation in γp. at high |t|





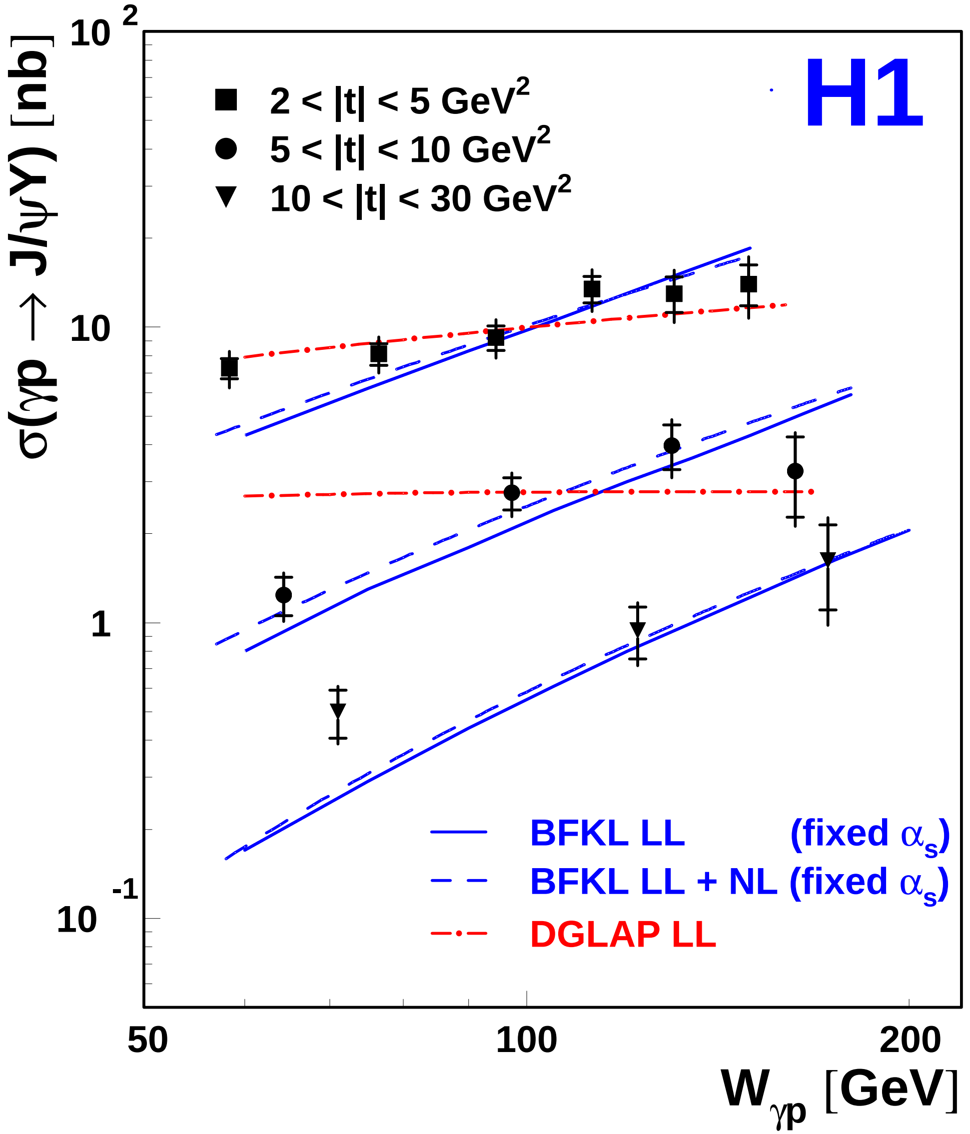
- $d\sigma/dt = A\,t^{-n}$ good fit (n increases with $|t|_{min}$)
- DGLAP good description (valid for $|t| < M^2$)
- BFKL describes data only with fixed α_s (why?)

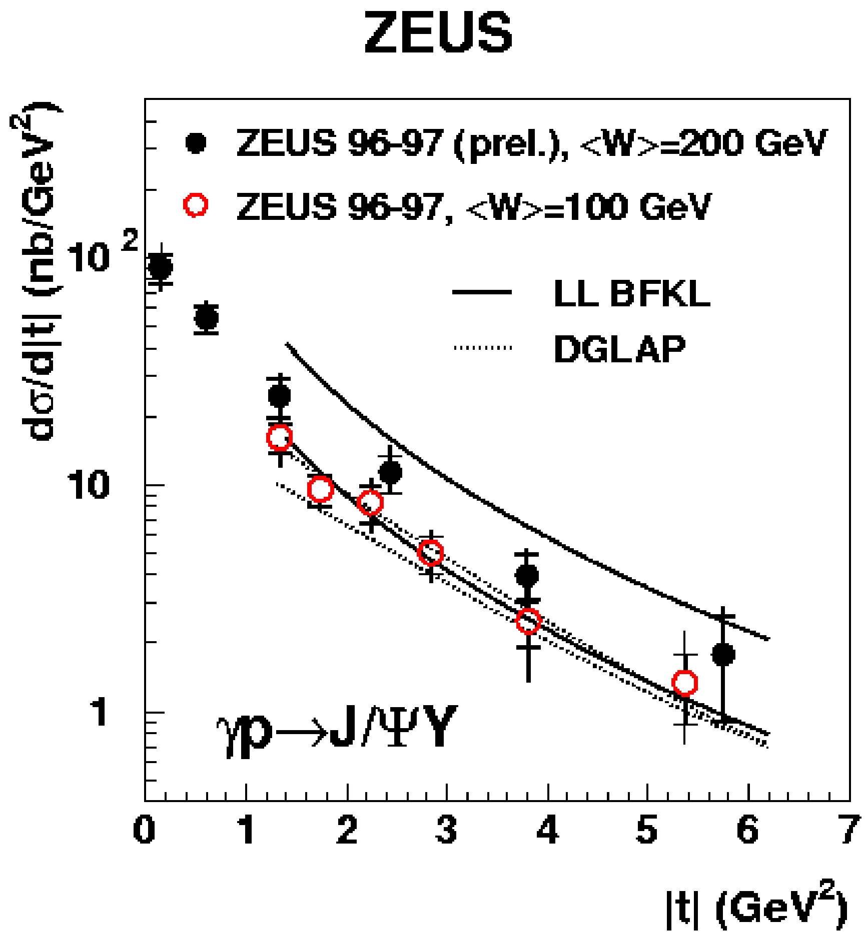
VMs at High t: σ_V/σ_ρ and SU(4)



Indication of flavor independence of VM production at high |t|?

High |t| J/Ψ: W-dependence





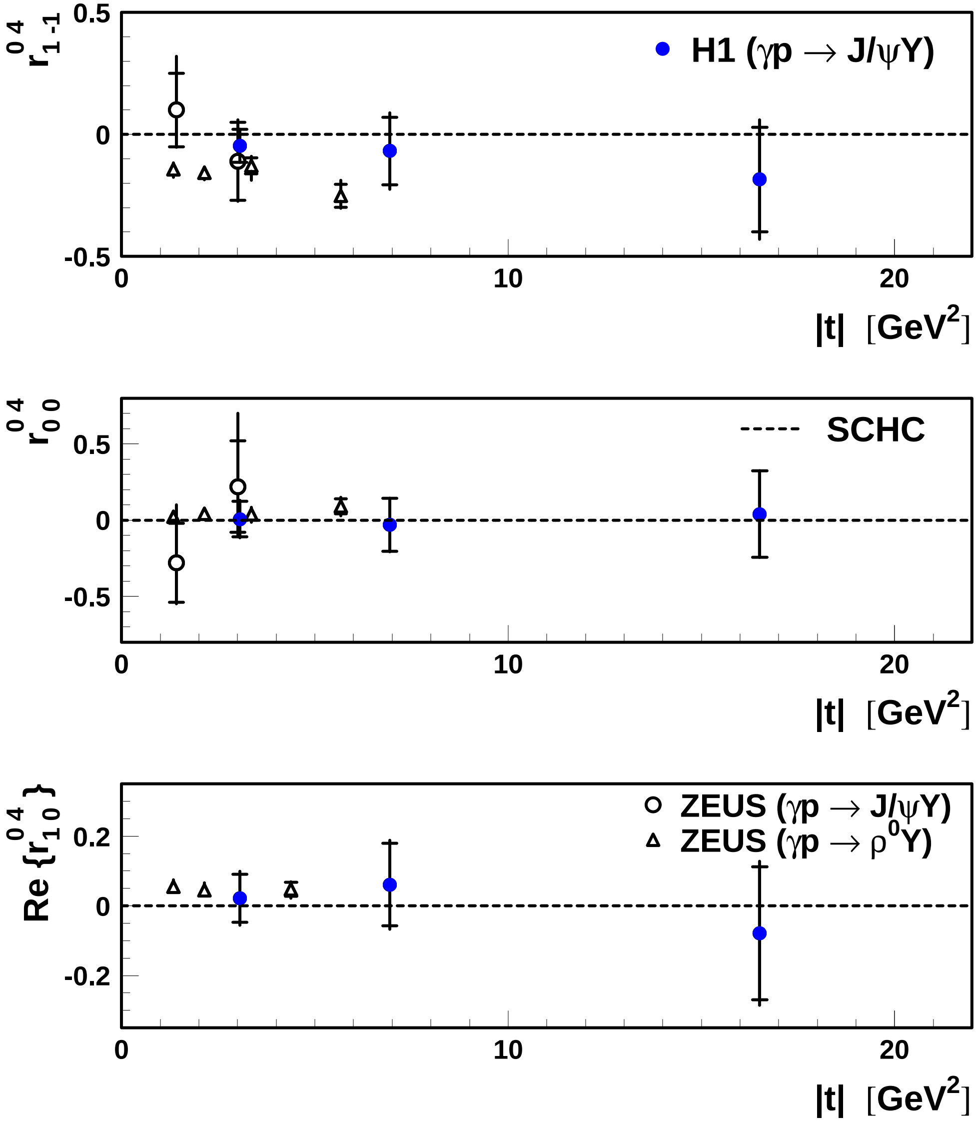
- W-dependence doesn't change with t
- LL BFKL predicts stronger rise with W
- DGLAP W rise flattens with t

SCHC at high |t| in γp proton dissociation

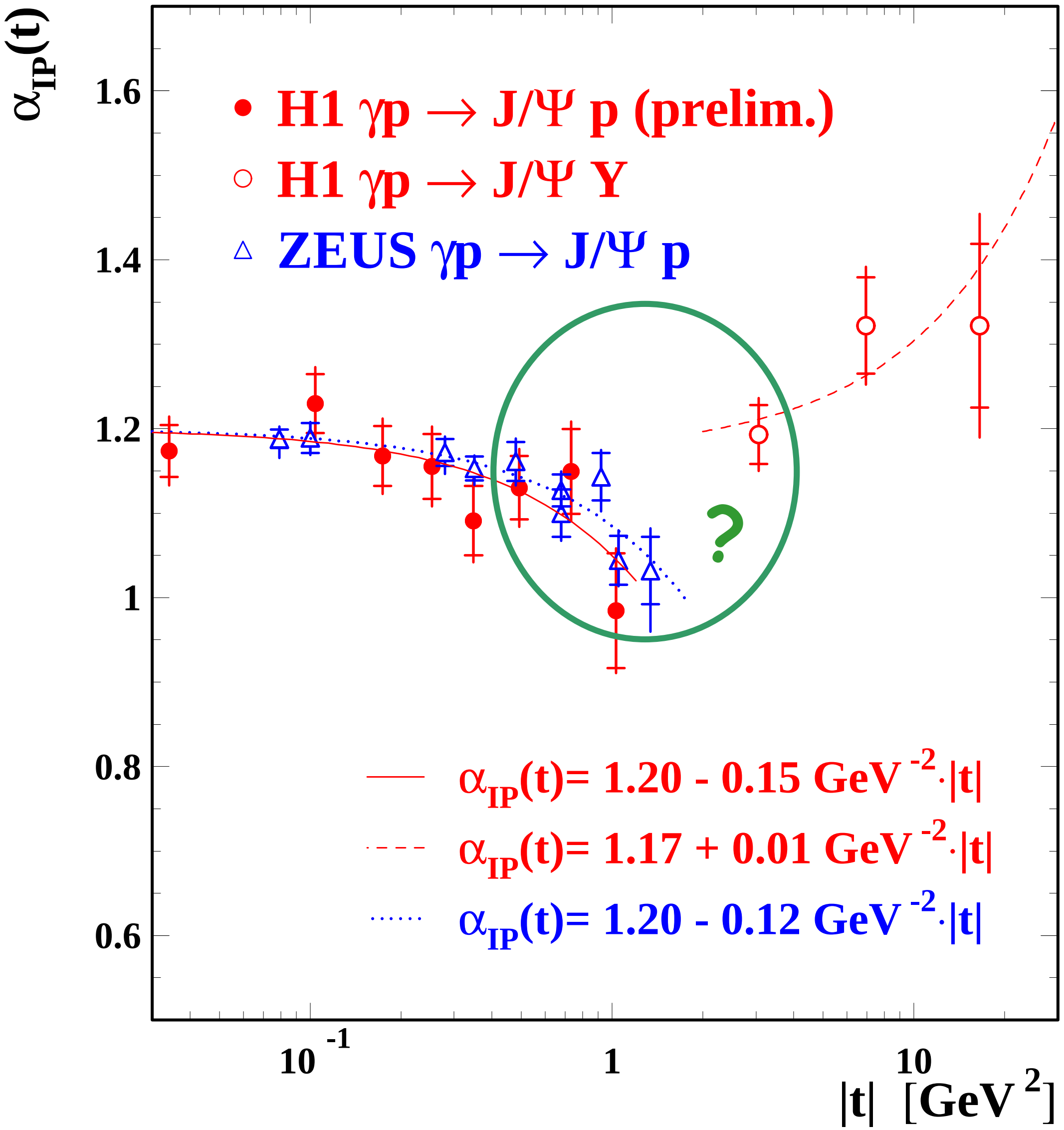
- ρ^0 shows small SCHC breaking - due to asymmetric sharing of γ momentum by qq

- J/Ψ consistent with SCHC within stats. for all t

Non-relativistic approximation for J/Ψ wave function z=1/2, r=0 satisfactory for present data



Pomeron trajectory Dependence on |t|



J/Ψ elastic:
moderate shrinkage

J/Ψ p-dissociation:
shrinkage consistent with zero.

Different "Pomeron" for p-diss and elastic?

Is this the BFKL Pomeron?

Summary

- Diffractive VM production at HERA allows to study the dynamics of vacuum-exchange processes
- Transition from soft to hard behaviour observed in Q^2 and/or M^2
- Analysis of helicity structure allows detailed investigations of scaling and VM structure
- VM production at high $|t|$ shows hard behaviour in t and W dependence (BFKL?)

QCD has had many successes but

Recent results raise difficult questions

HERA II will continue to do so

Looking forward to the challenge!