Photons@LHC
CERN, 22-25 April 2008

Exclusive Vector Mesons and DVCS at HERA

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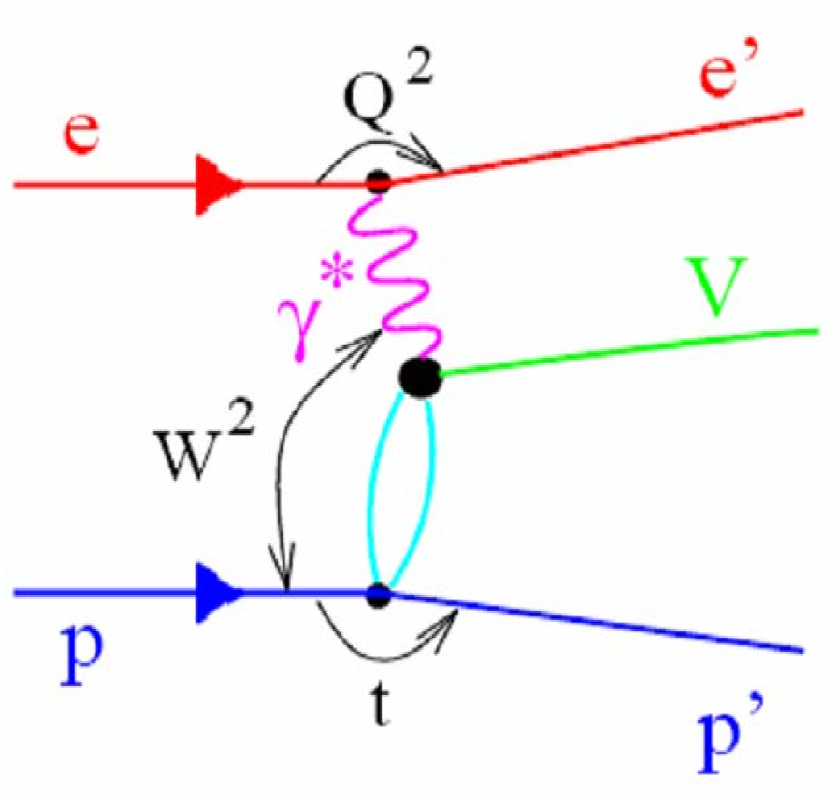
On behalf of the H1 and ZEUS Collaborations



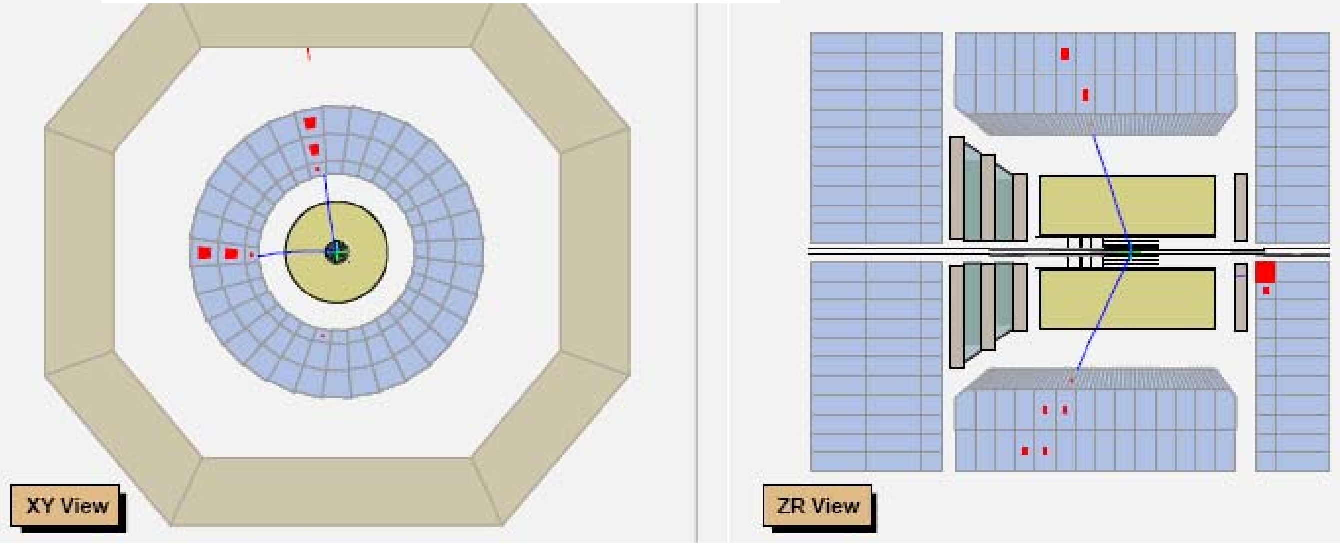
$V=(\rho, \omega, \phi, J/\psi, \psi(2s), \Upsilon, \gamma)$

- $Q^2=-(e-e')^2$ - photon virtuality
- W - γ^*p center of mass energy
- $t=(p-p')^2$ –momentum transfer squared at the proton vertex

- no quantum numbers exchanged in the interaction
- the proton stays intact (or dissociates)

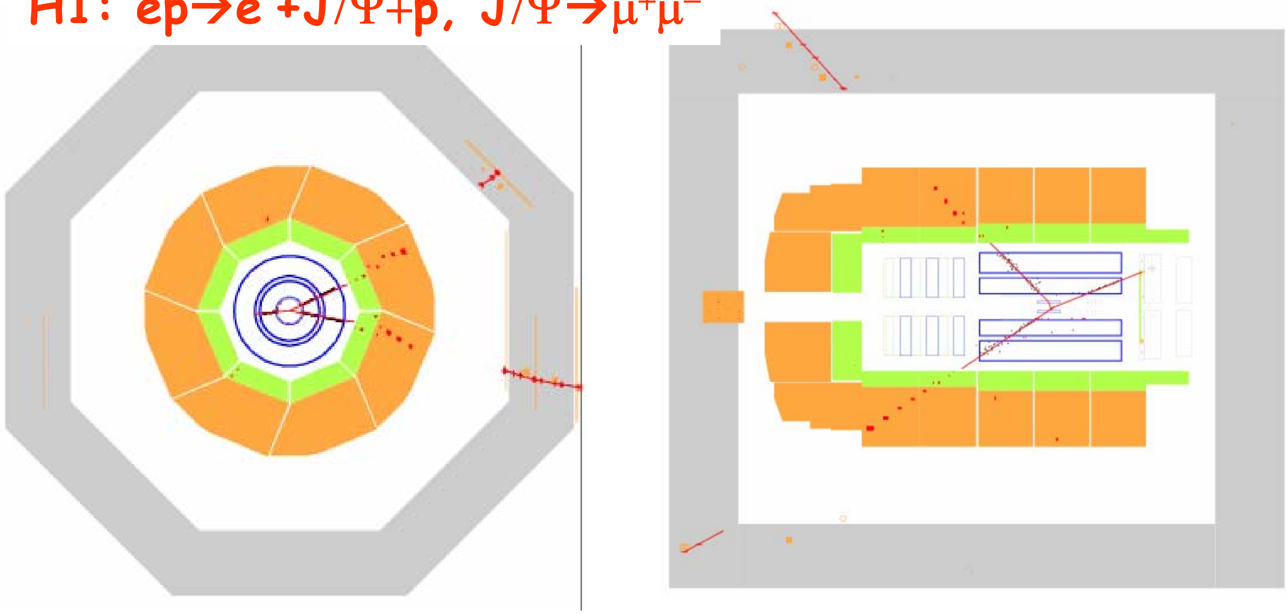
Exclusive Vector meson production - clean experimental signatures

ZEUS: $ep \rightarrow e' + \rho^0 + p$, $\rho \rightarrow \pi^+\pi^-$

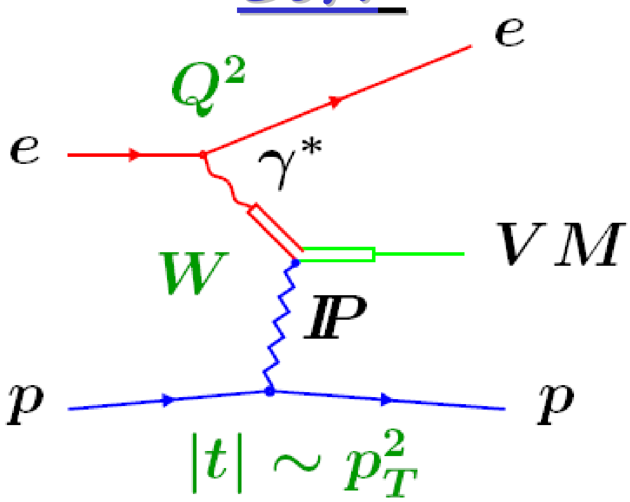


- scattered $e^{+/-}$ reconstructed in e/m calorimeters (DIS) or undetected (photoproduction)
- scattered p undetected
- decay products of VM
- nothing else in the central detector

H1: $ep \rightarrow e' + J/\Psi + p$, $J/\Psi \rightarrow \mu^+\mu^-$



"Soft"



Regge theory and VDM model

$$\sigma \propto W^{\delta}$$

-Weak energy dependence, δ~0.2

$$\delta = 4(\alpha_{IP}(t) - 1)$$

$\alpha_{IP}(t)=1.08+0.25 \cdot t$ (DL)

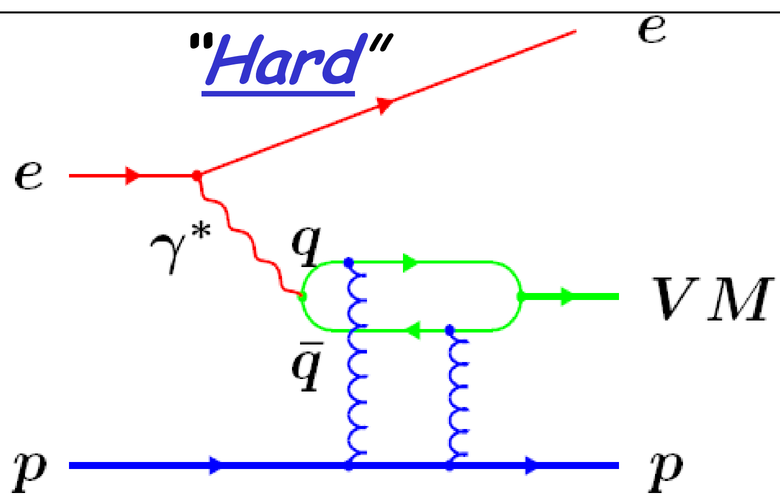
$$\frac{d\sigma}{dt} \propto e^{-bt}$$

-Shrinkage of diffractive peak

b-slope is closely related to the size of interaction

$$b(W) = b_0 + 2\alpha' \ln(W^2 / W_0^2);\ b_0 \sim 10\, GeV^{-2}$$

"Hard"



in presence of hard scale: Q^2, m_q or t

pQCD description (exchange of ≥2 gluons)

-Fast increase of cross section with energy due to gluon density in proton

Increasing *W* is similar to going to small *x*

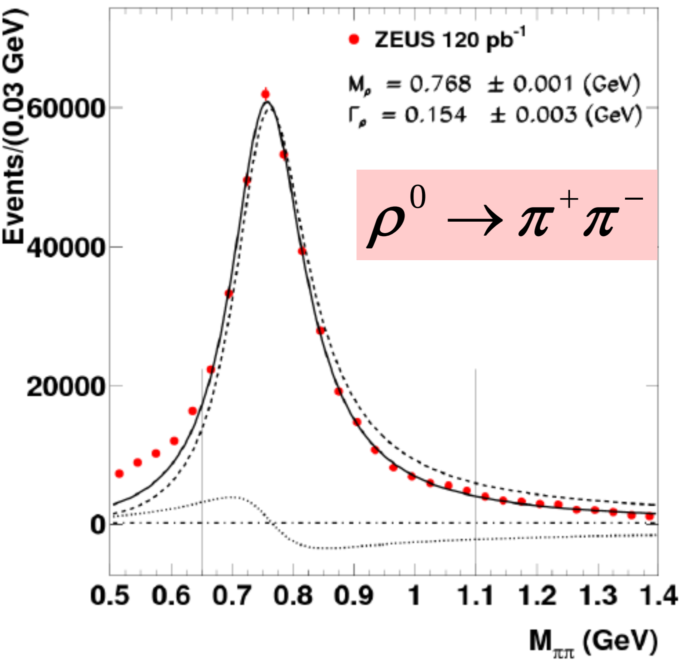
$$W^2 \propto \frac{1}{x}$$

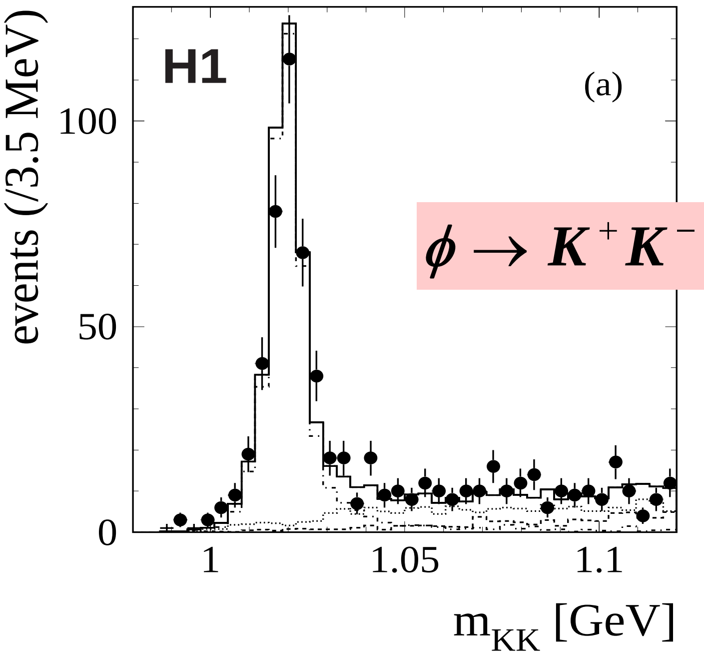
$$\sigma \sim \left| x\ g(x,Q^2) \right|^2$$

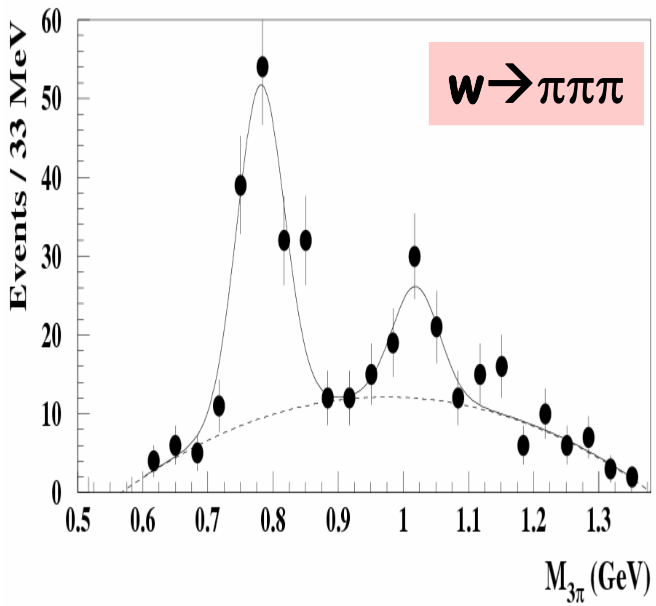
- **Expect δ to increase from soft (~0.2) to hard (~0.8)**
- **Expect b to decrease from soft (~10 GeV^{-2}) to hard (~4÷5 GeV^{-2})**

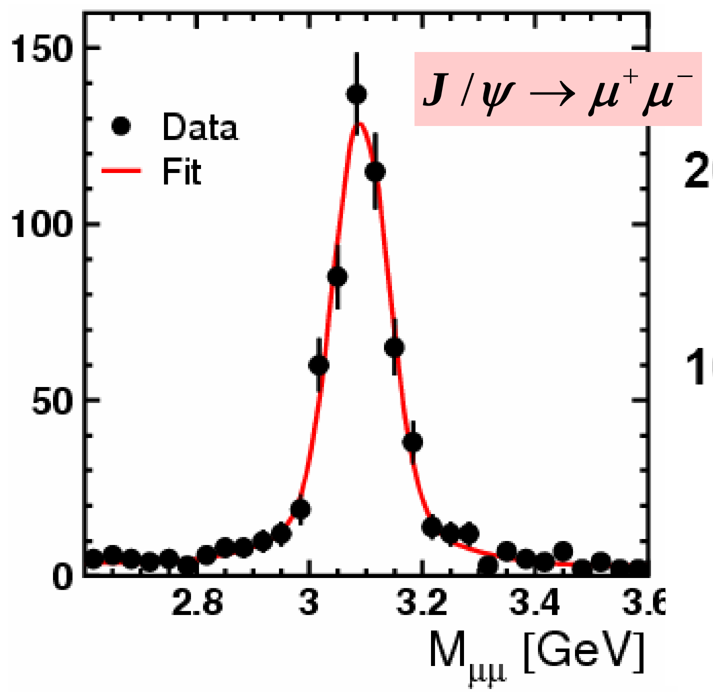
With HERA data it is possible to access both the 'soft' and the 'hard' regimes and investigate the transition from "soft" to "hard" Pomeron exchange processes with increasing of Q^2, VM mass (M_{VM}) or t.

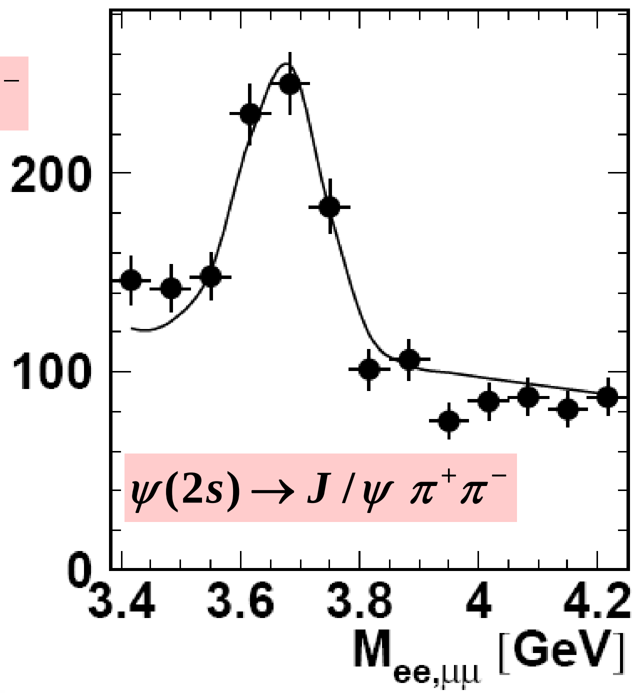
Vector Mesons mass distributions

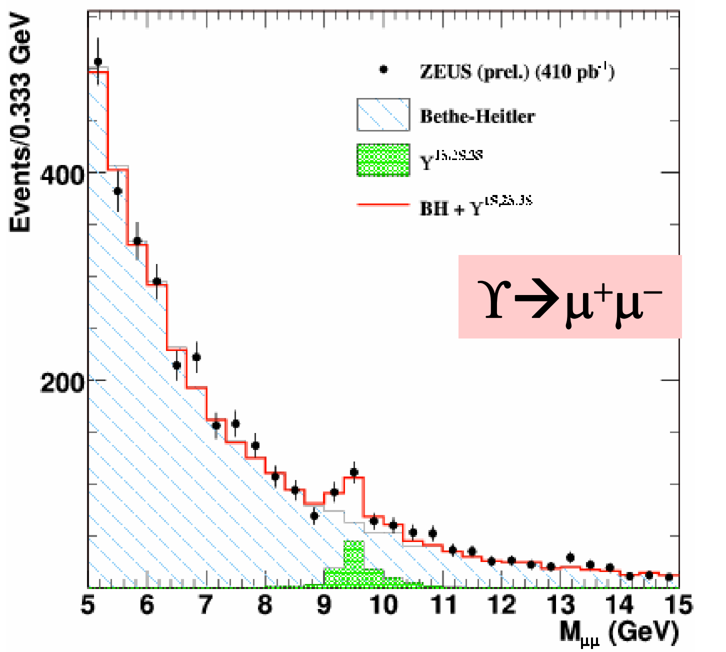




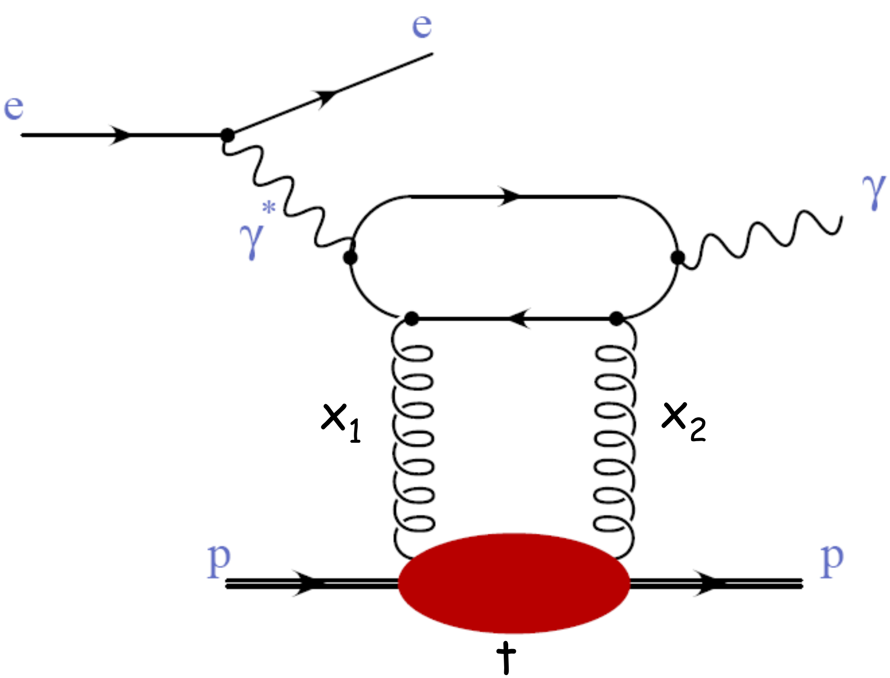




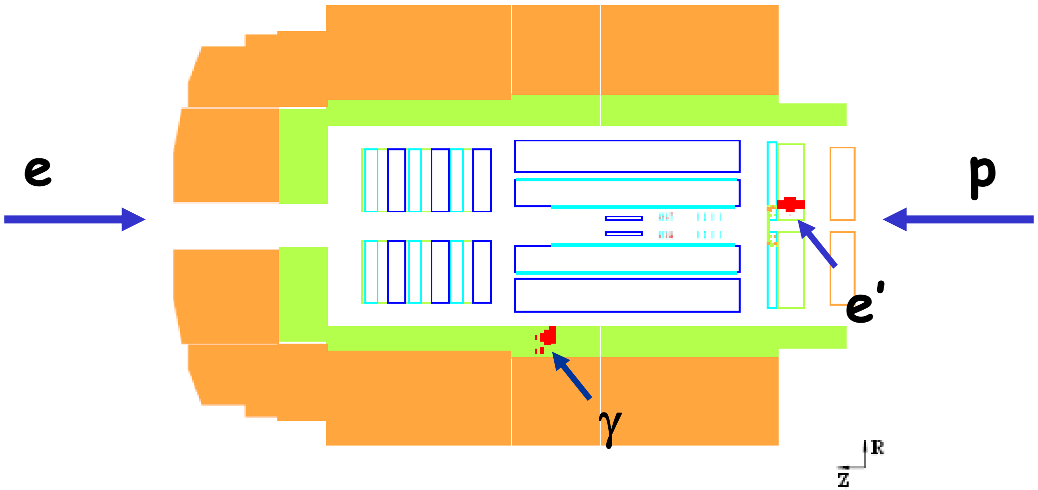




Deeply Virtual Compton Scattering (DVCS)



$\gamma^* p \rightarrow \gamma + p$

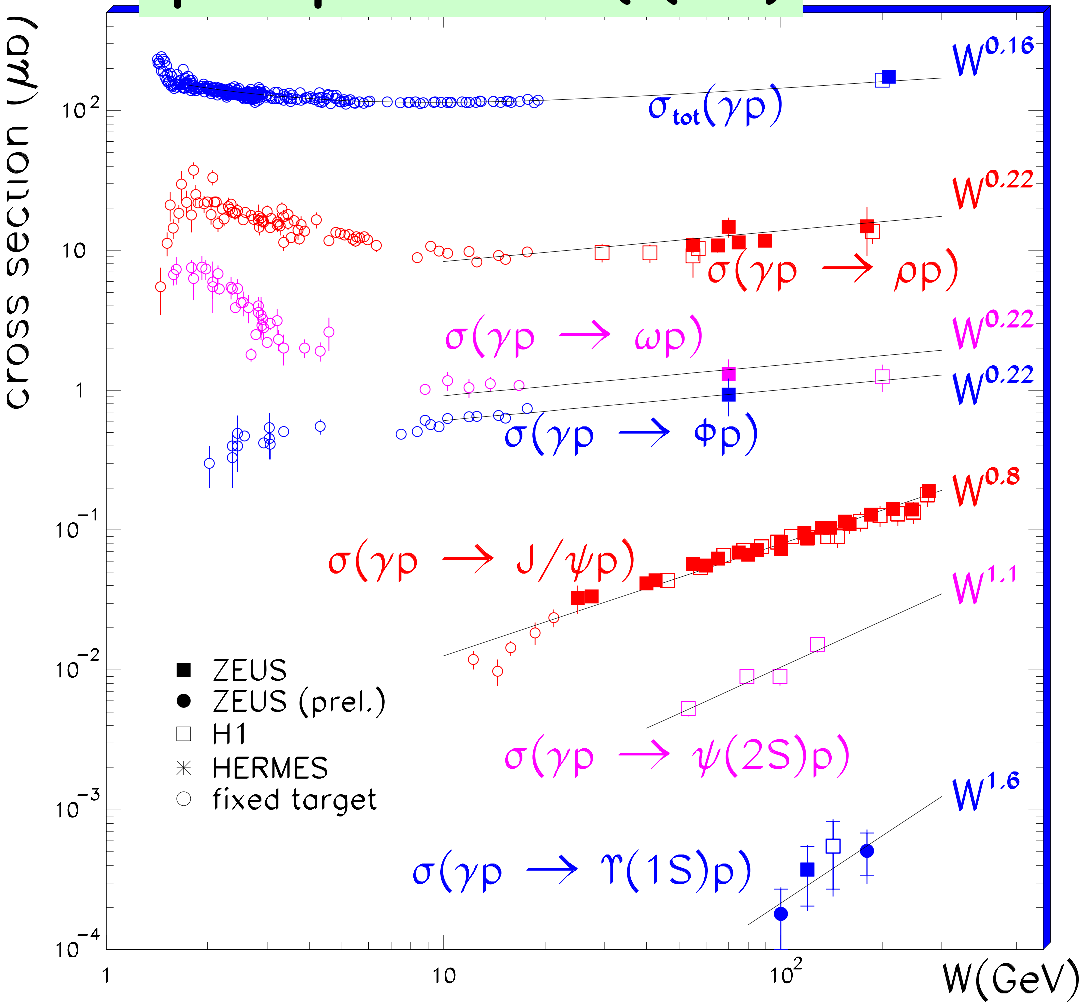


-elastic scattering of virtual photon off a proton
-clean experimental signature
-fully calculable in QCD
-no uncertainty due to VM wave function
-access to generalized (skewed) parton distributions- GPD(x_1,x_2)

GPDs describe the correlations between two partons (x_1,x_2) which differ by longitudinal (x_1-x_2) and transverse (t) momentum at given Q^2

Elastic photoproduction of Vector mesons $\gamma p \to V+p$ ($V=\rho,\phi,\omega,J/\Psi,\Upsilon$)

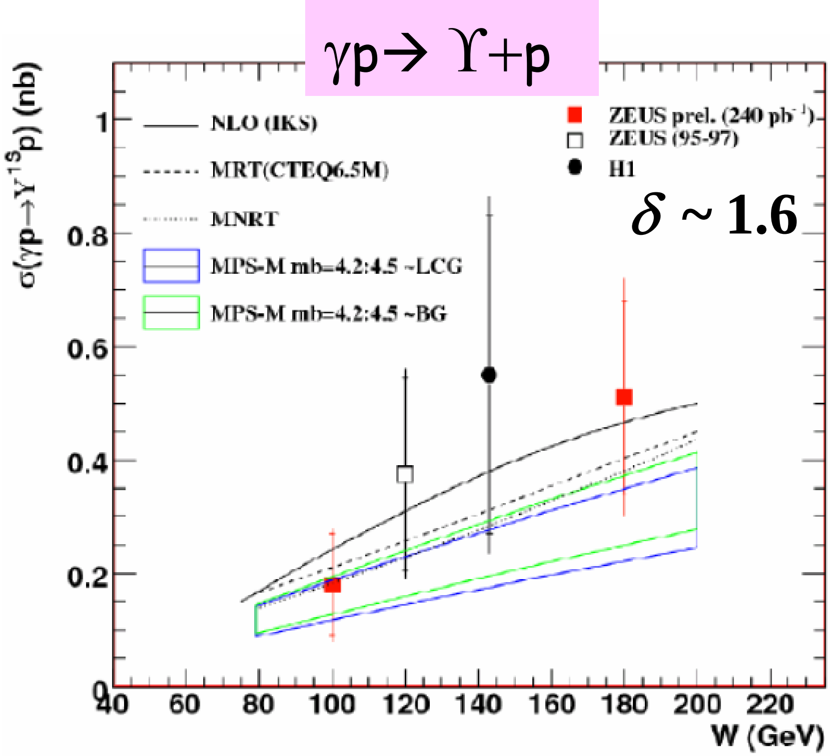
'photoproduction' (Q^2~0)



$$\sigma(W) \propto W^{\delta}$$

Prediction for Soft physics: δ~0.2

$\gamma p \to \Upsilon + p$

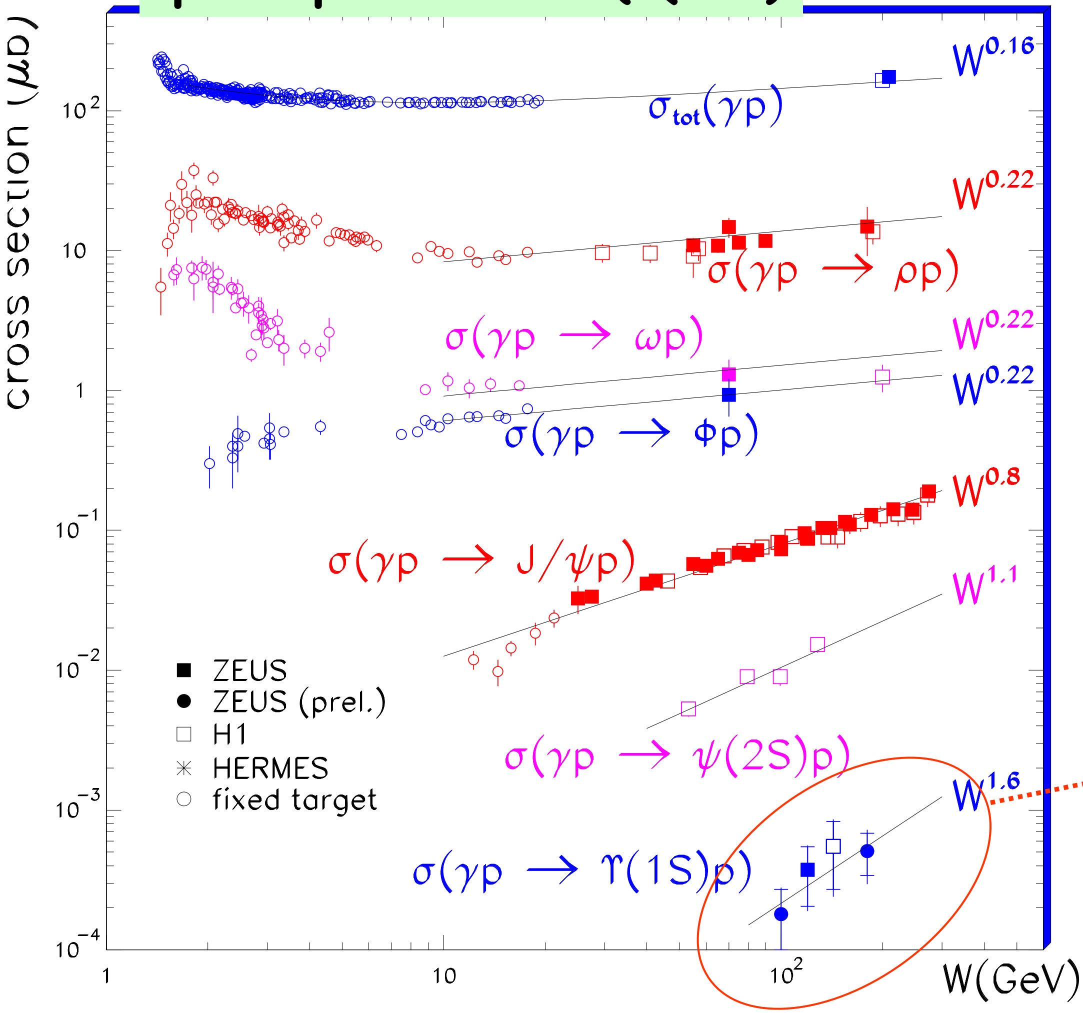


Process becomes hard (steeper W dependence) as M_{VM} becomes larger (J/ψ, Υ)

VM mass sets hard scale of interaction

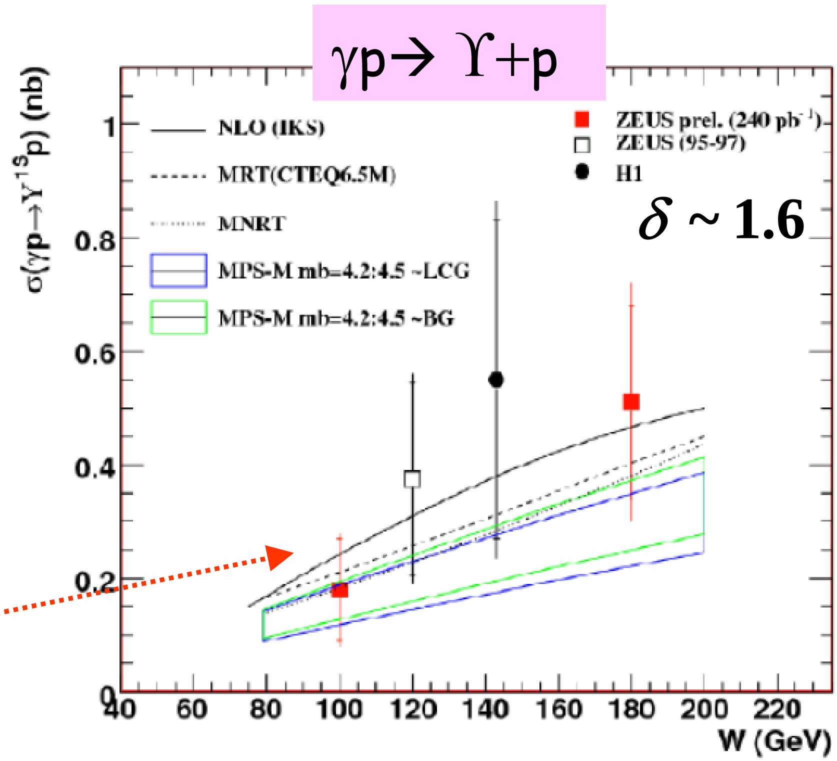
Elastic photoproduction of Vector mesons $\gamma p \to V+p$ ($V=\rho,\phi,\omega,J/\Psi,\Upsilon$)

'photoproduction' ($Q^2 \sim 0$)



$$\sigma(W) \propto W^{\delta}$$

Prediction for Soft physics: $\delta \sim 0.2$



NLO – Ivanov , Krasnikov , Szymanowski – hep-ph/0412235

MRT – Martin, Ryskin, Teubner, (based on CTEQ6.5M gluon)

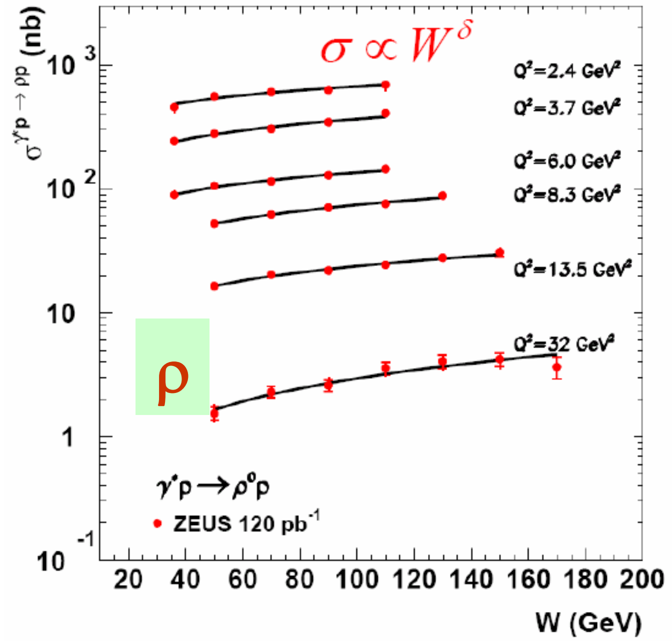
MNRT – Martin, Nockles, Ryskin, Teubner (based on diffractive J/ψ data alone)

MPS – color dipole approach calculation by Magno Machado (private com.)

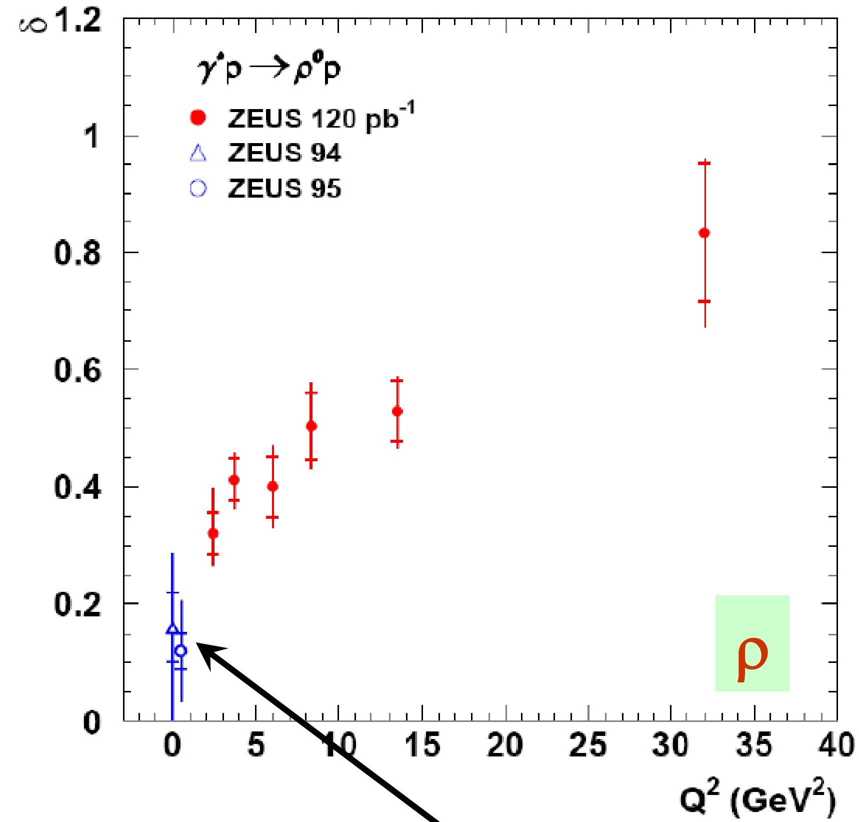
Process becomes hard (steeper W dependence) as M_{VM} becomes larger (J/ψ, Υ)

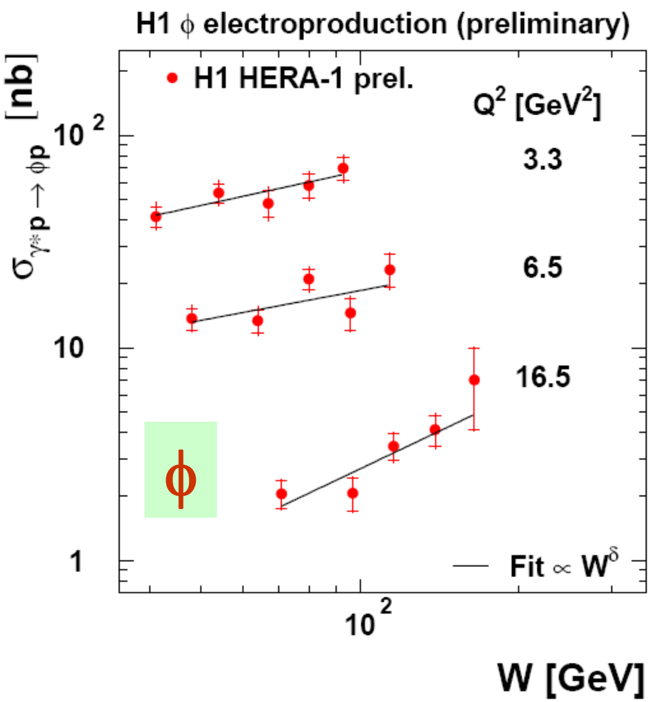
VM mass sets hard scale of interaction

Elastic Electroproduction of ρ,ϕ-mesons $\gamma^* p \to \rho p$, ϕp



$$\sigma_{\gamma p}(W) \propto W^{\delta}$$



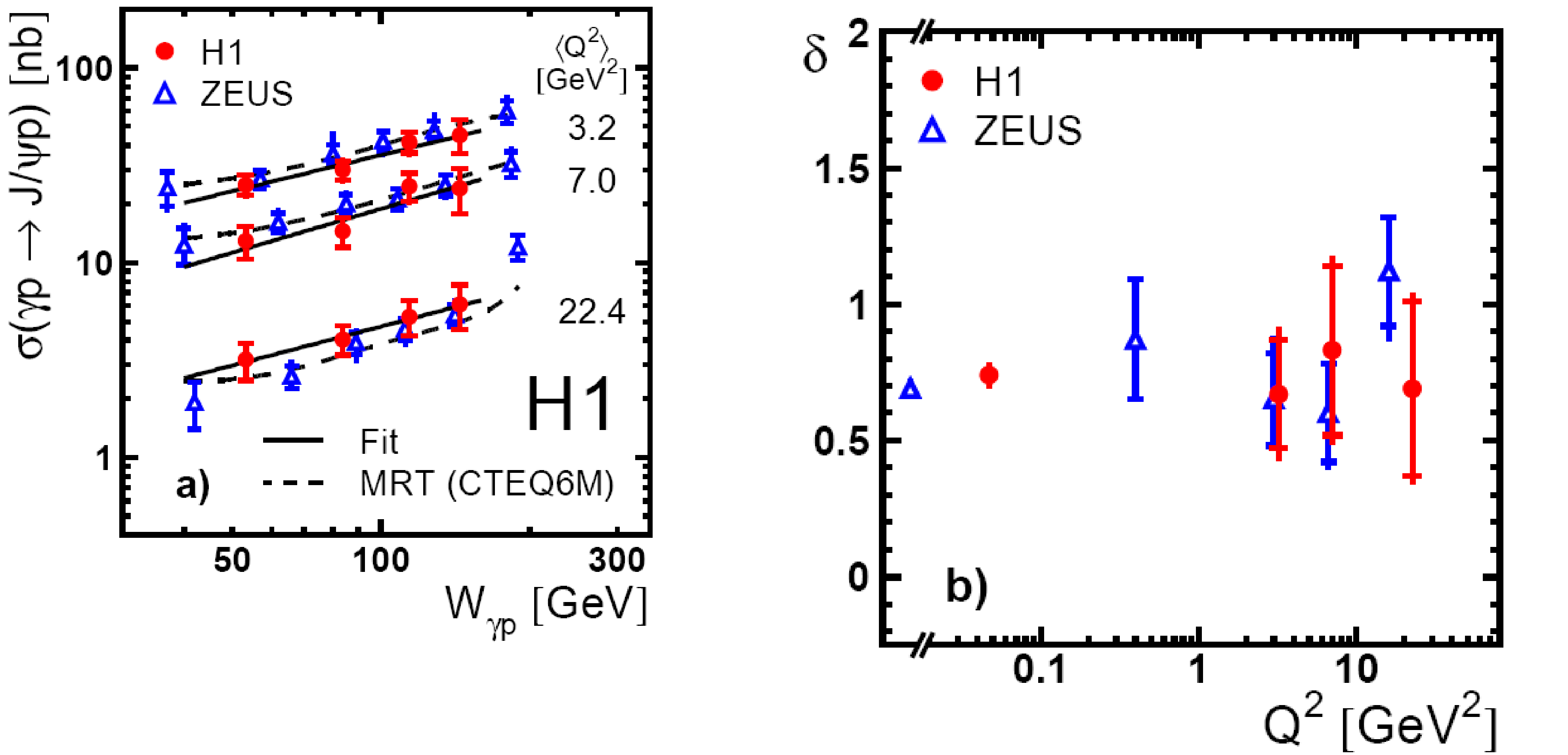


Prediction for Soft physics: δ~0.2

Energy dependence gets steeper with Q^2

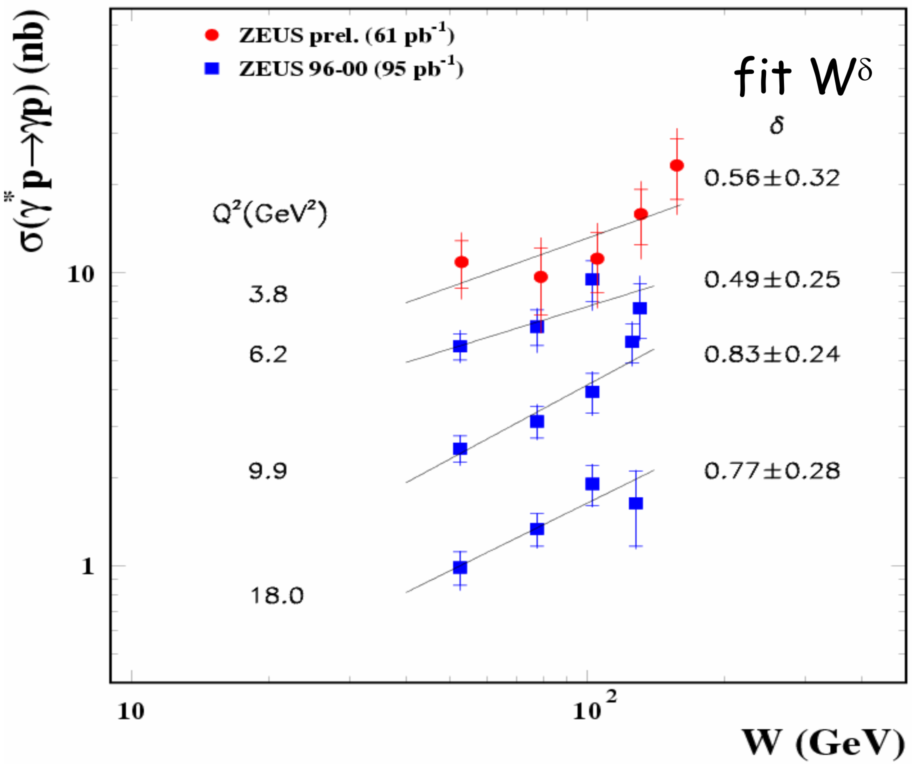
➔ for ρ,ϕ–production Q^2 sets the hard scale

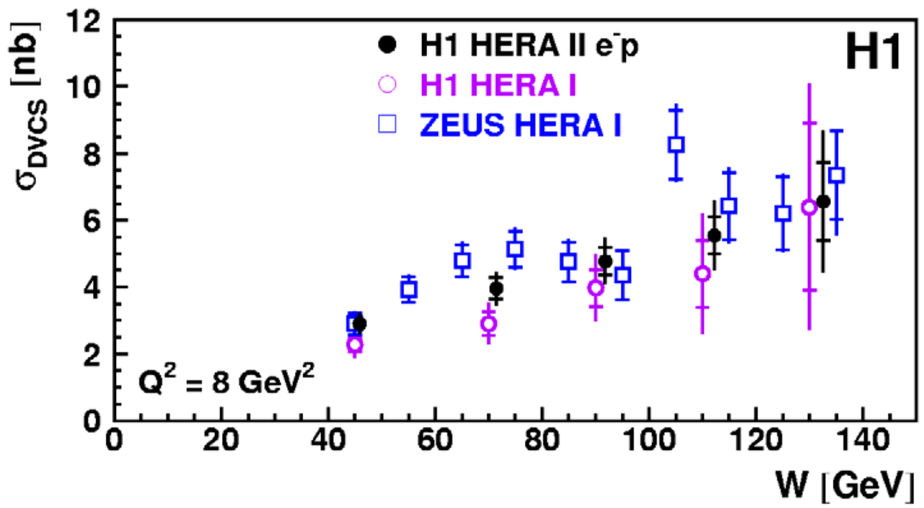
Elastic Electroproduction of J/ψ-mesons $\gamma^* p \rightarrow J/\psi + p$

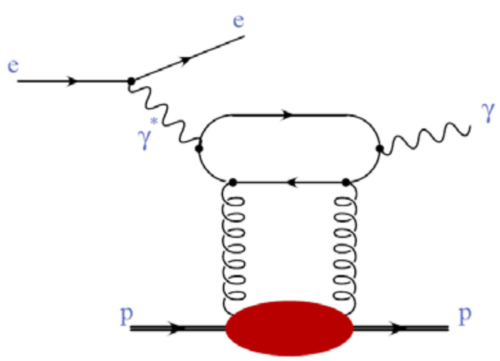


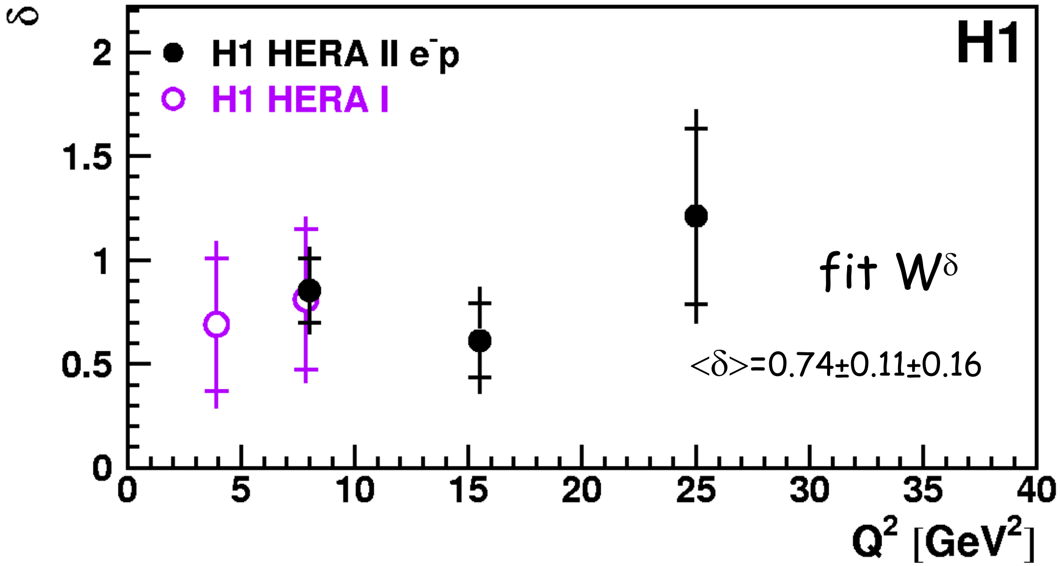
- Strong energy dependence
- No significant change with Q^2

➔ for J/ψ the mass is the dominant scale



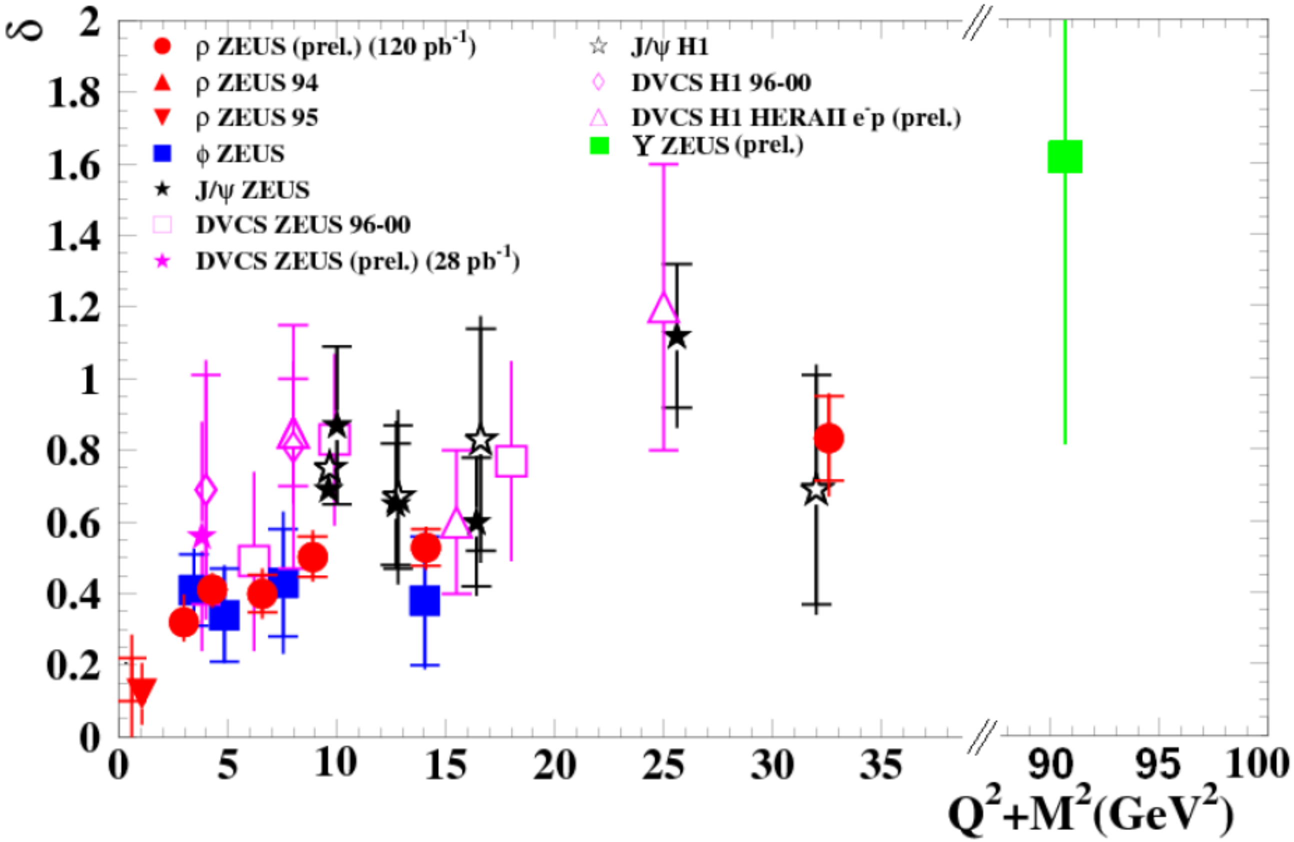






-steep rise with energy, even at lowest Q^2 and no significant Q^2 dependence
(may suggest that the most sensitive part to soft scale is the wave function)

DVCS and Elastic VM production- energy dependence

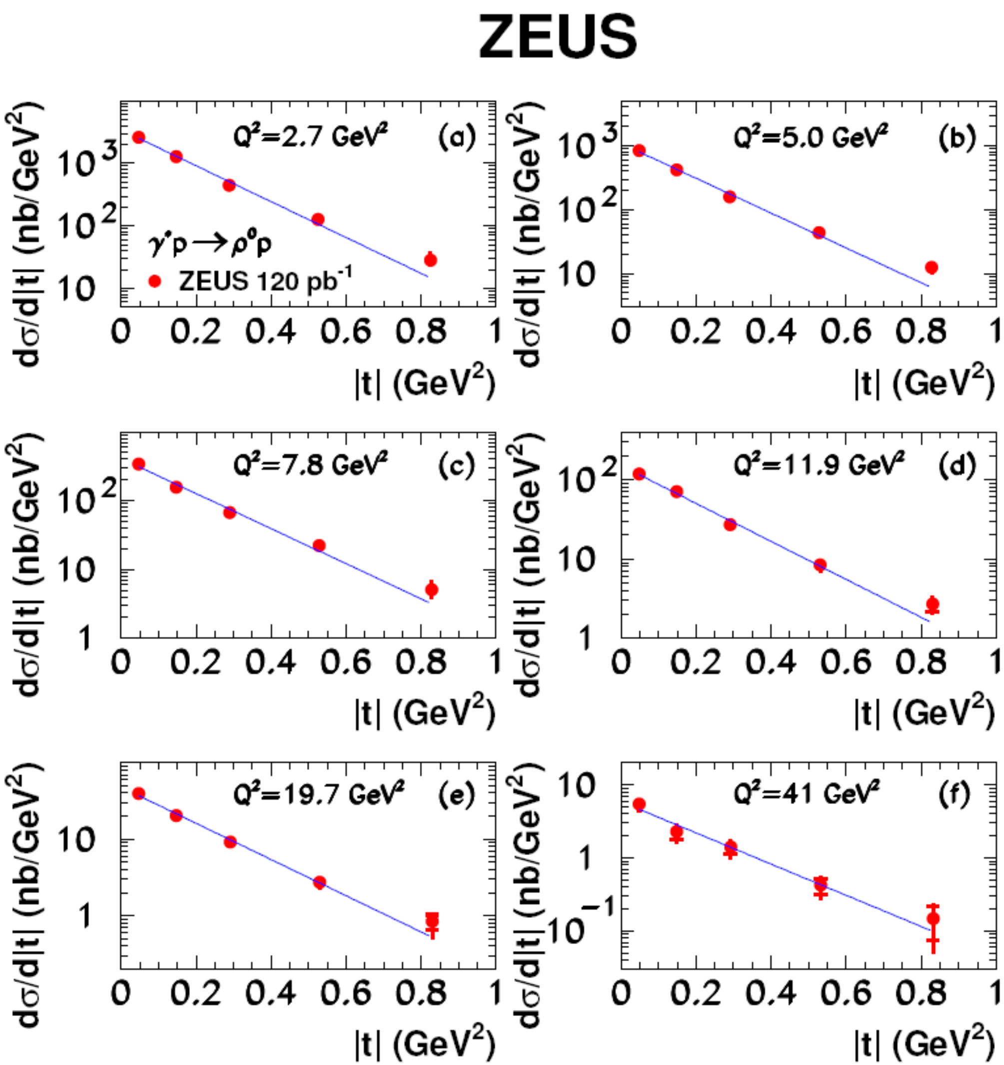


$$\sigma(W) \propto W^{\delta}$$

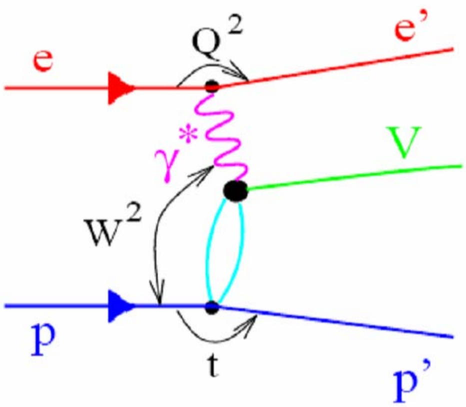
- similar behavior for DVCS and all VMs !
- steep slope observed for all VM in the presence of hard scale (Q^2+M^2)
- Transition from soft to hard regime with increasing of hard scale

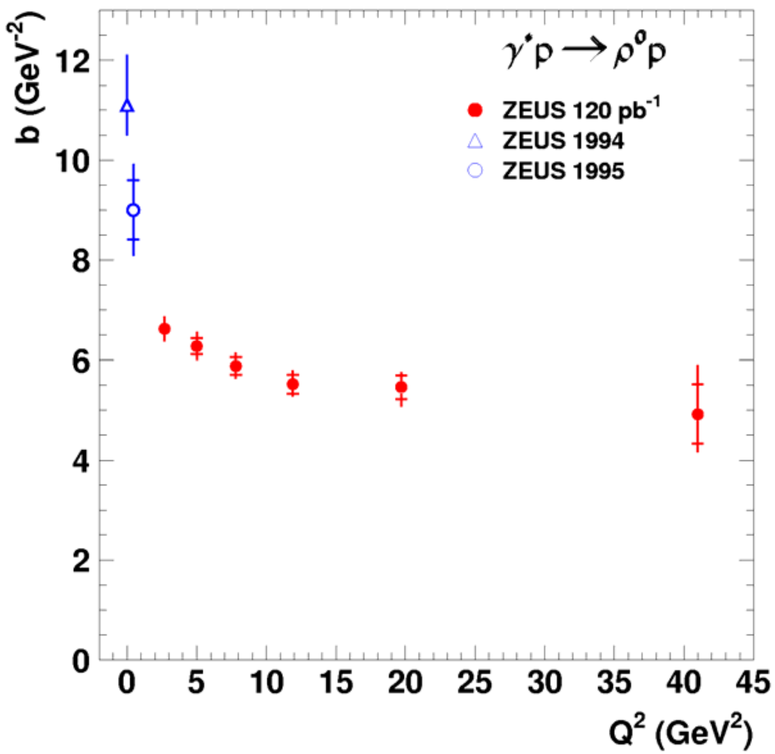
b : the t-slope parameter: $\gamma^* p \to \rho p$

b characterize the size of interaction,
expect ***b*** to decrease from 'soft' to 'hard'



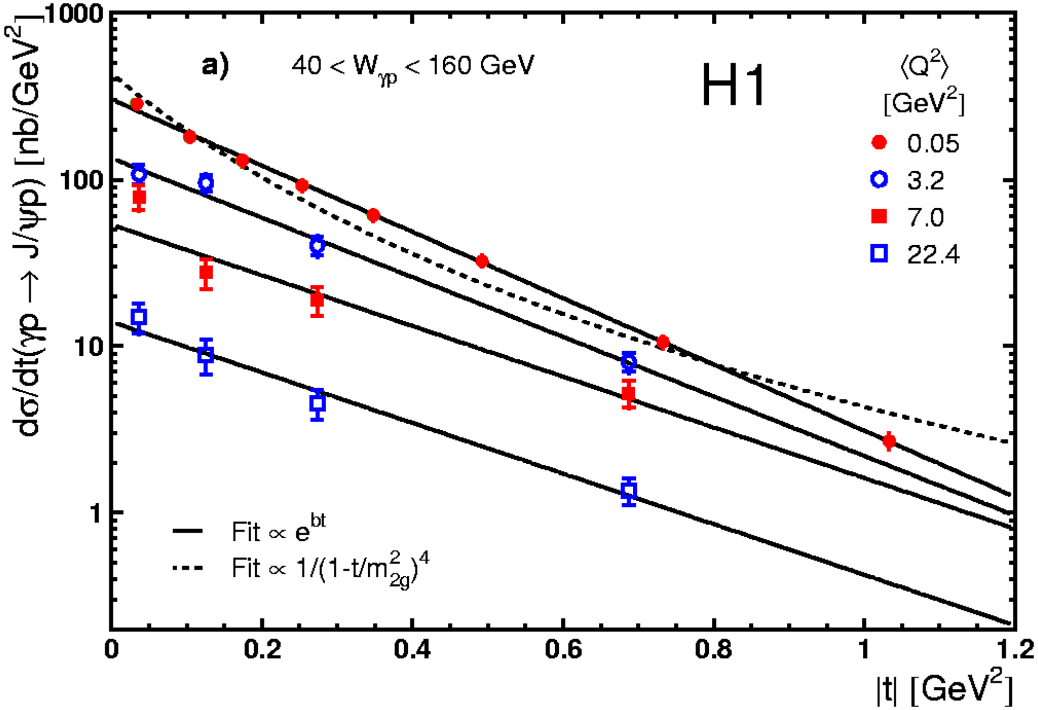
$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

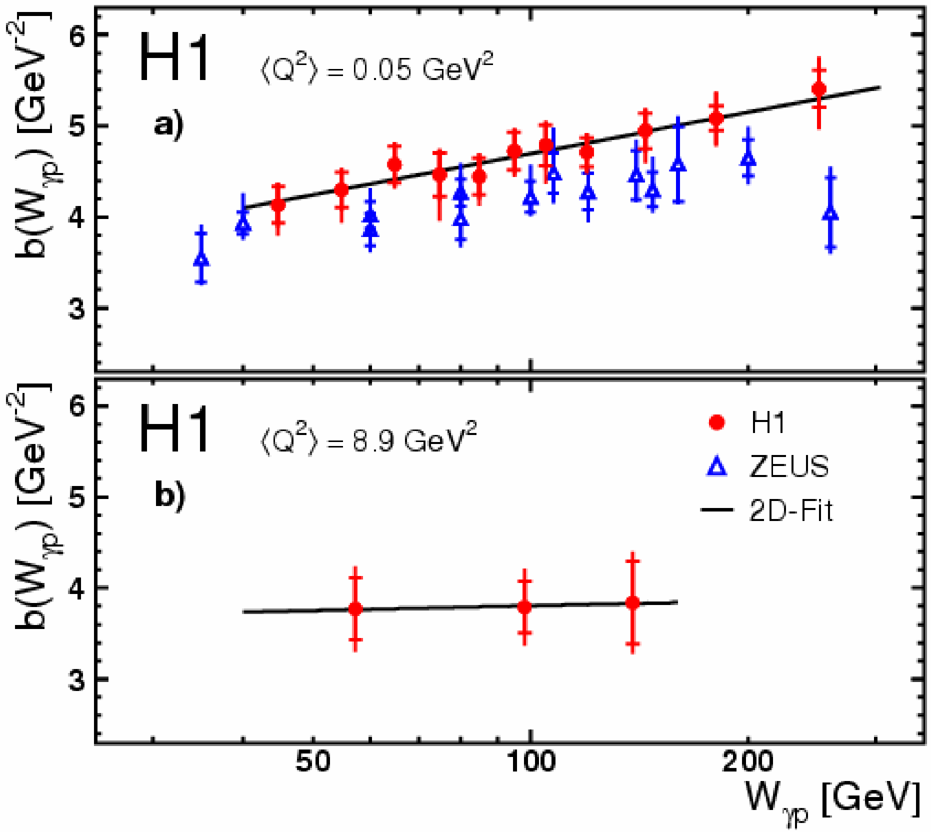


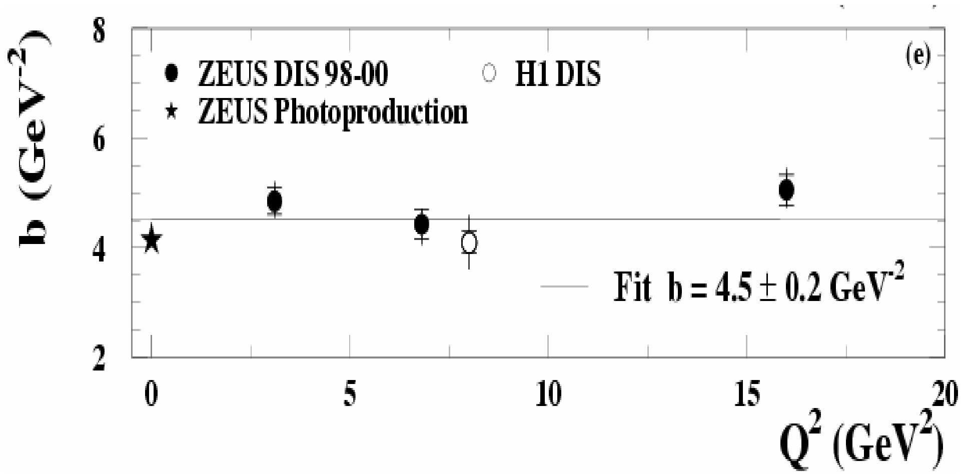


b-slope decreases with increasing Q^2
from ~10 GeV^{-2} to ~5 GeV^{-2}

b : the t-slope parameter $\gamma^* p \to J/\psi + p$







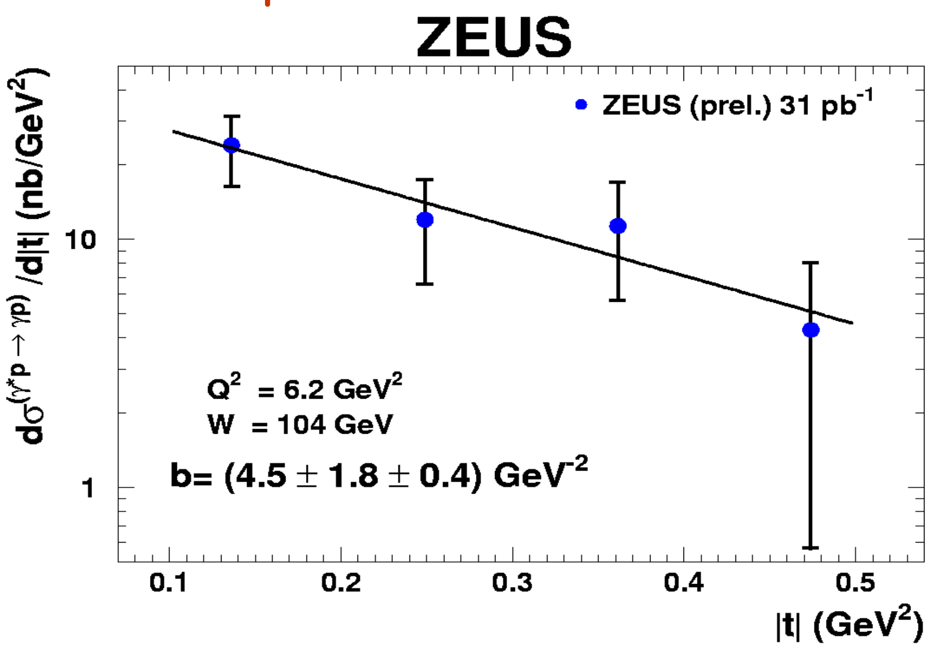
- b increases with W for photoproduction (shrinkage)
- for higher Q^2 no W dependence of b
- **b= 4.5±0.2 GeV^{-2}** (ZEUS)

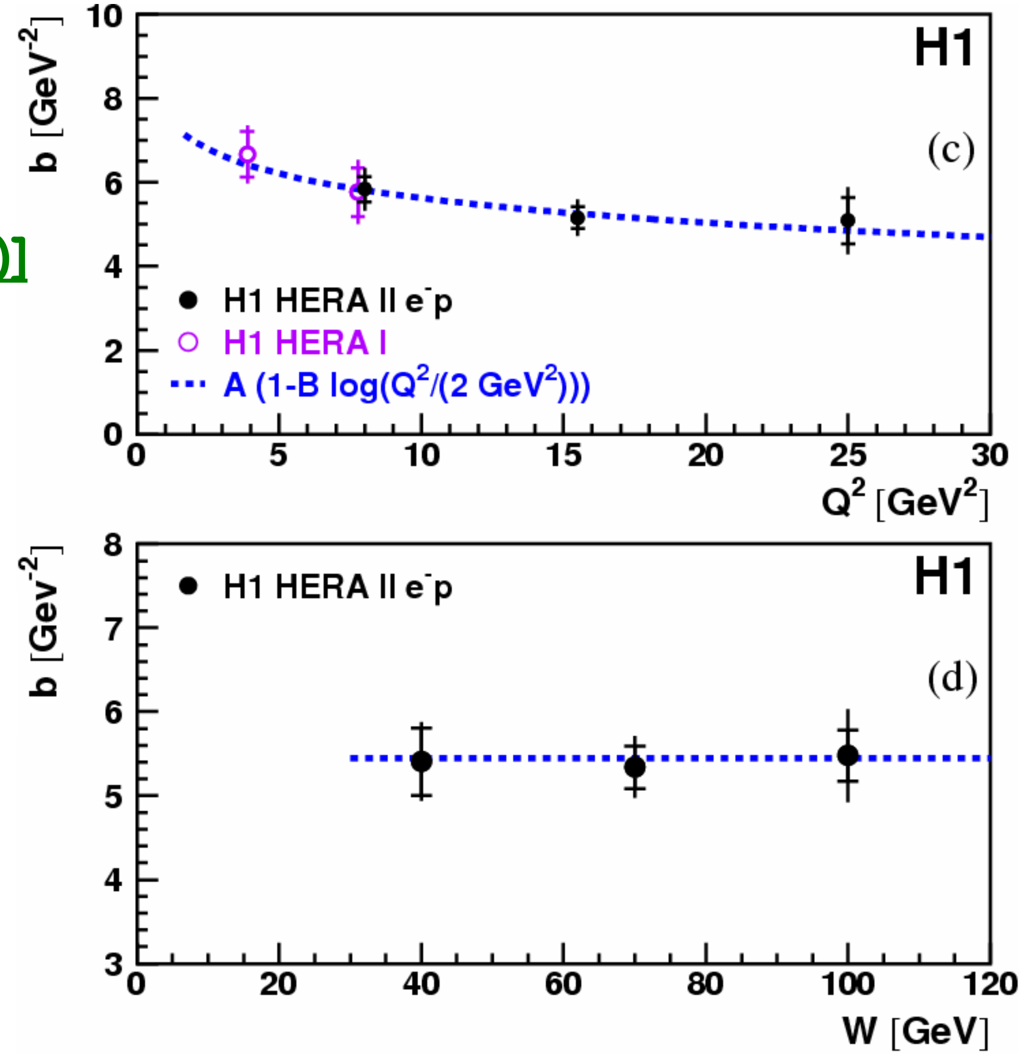
b : the t-slope parameter-DVCS $\gamma^* p \to \gamma p$

- measure t-dependence as function of Q^2 and W

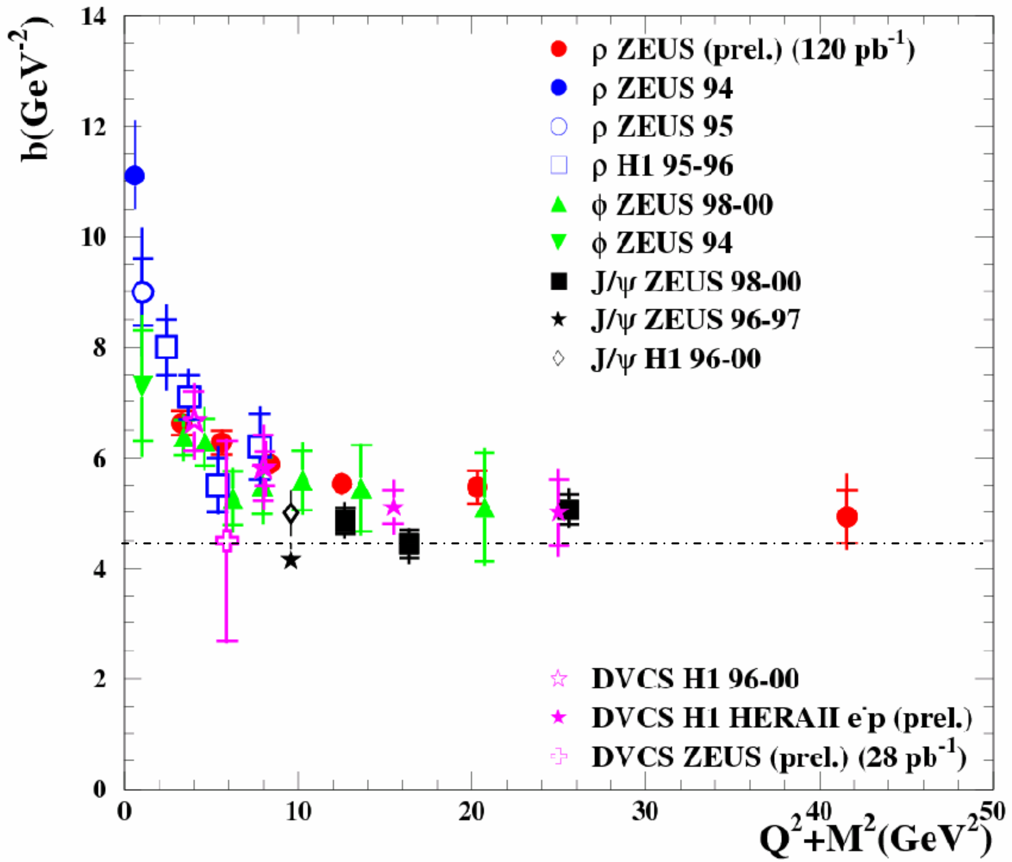
- **Q^2 dependence:** $b(Q^2)=A[1-B\cdot \log(Q^2/2)]$
  $A=6.98 \pm 0.54$ GeV^{-2} ; $B=0.12 \pm 0.03$
- **no W dependence of b**
  $b=5.45 \pm 0.19 \pm 0.34$ GeV^{-2}

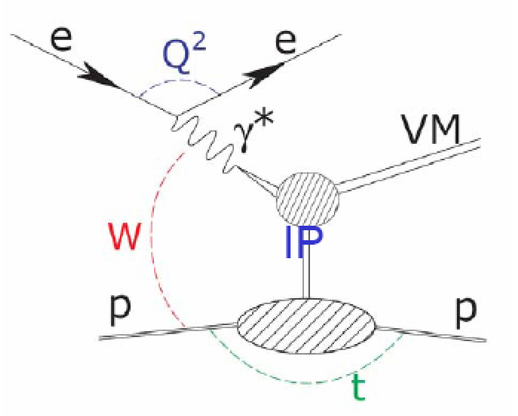
- direct t measurement using Leading Proton Spectrometer





VM production and DVCS: t-slope $b(Q^2+M^2)$





$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

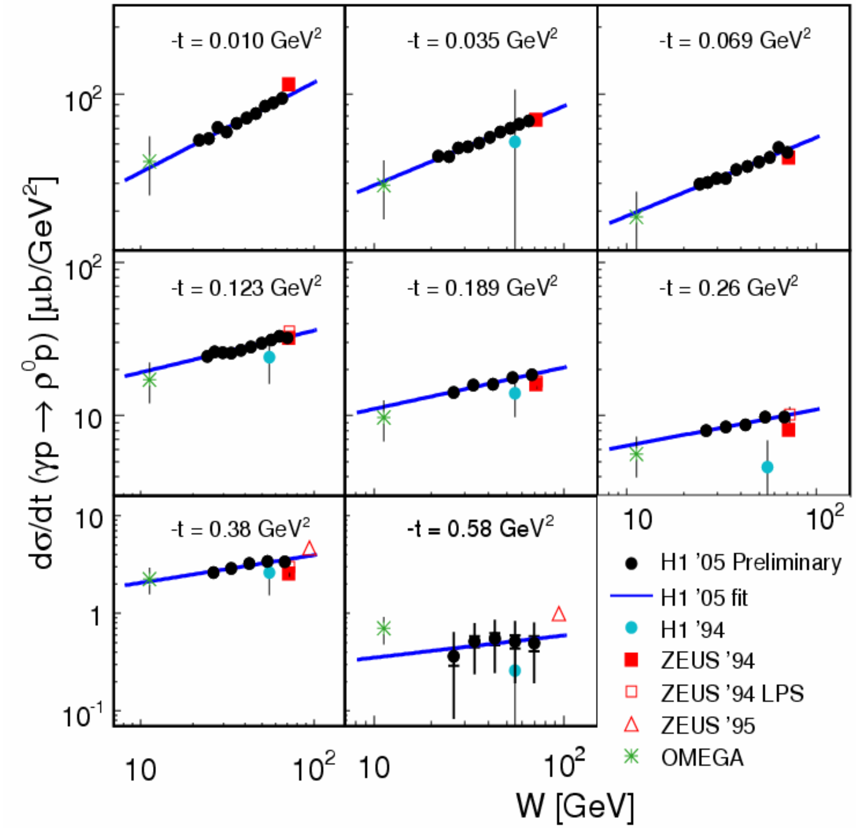
Similar behavior of slope with scale Q^2+M^2 for $\rho,\phi,J/\psi$,DVCS

-***b*** characterize the size of interaction, expect ***b*** to decrease from 'soft' to 'hard'
-***b*** decreases with Q^2+M^2 from ~10 GeV^{-2} (soft process) to ~4÷5 GeV^{-2} (hard process)

➔size of scattered VM getting smaller with Q^2+M^2

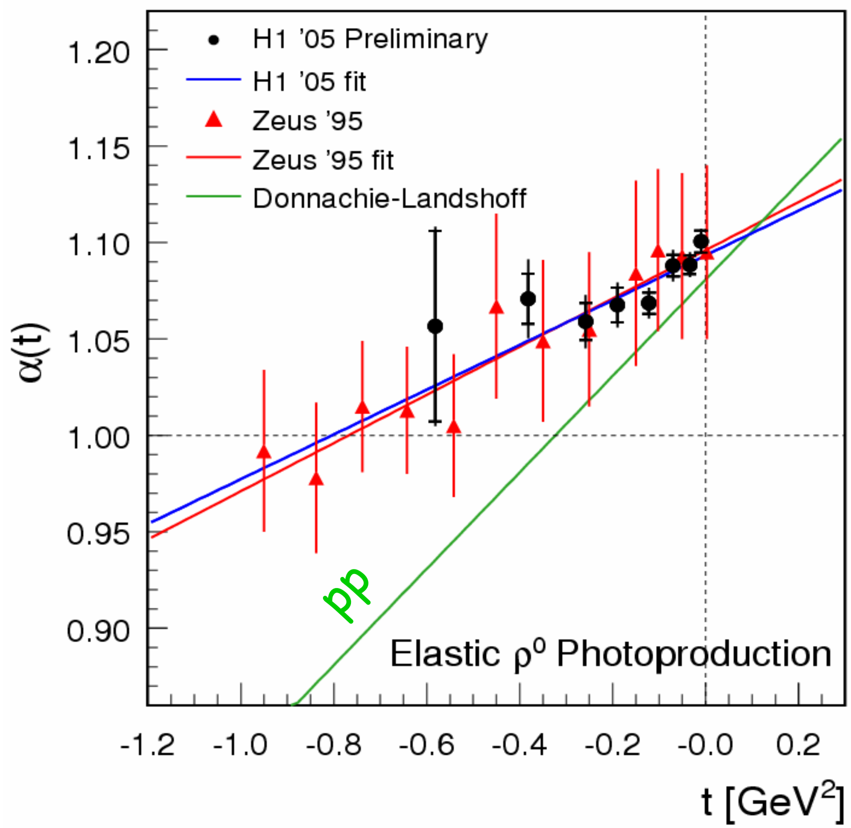
➔transverse extension of hard gluons in proton r_g~0.6 fm $\langle r^2\rangle=2\cdot b\cdot(\hbar c)2$ smaller compared to charge radius of the proton~0.8 fm

Effective Pomeron trajectory ($\gamma p \rightarrow \rho p$)



$$\frac{d\sigma}{dt} \propto \exp(b_0 t) \cdot W^{4(\alpha_{IP}(t)-1)}$$

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP} \cdot t$$



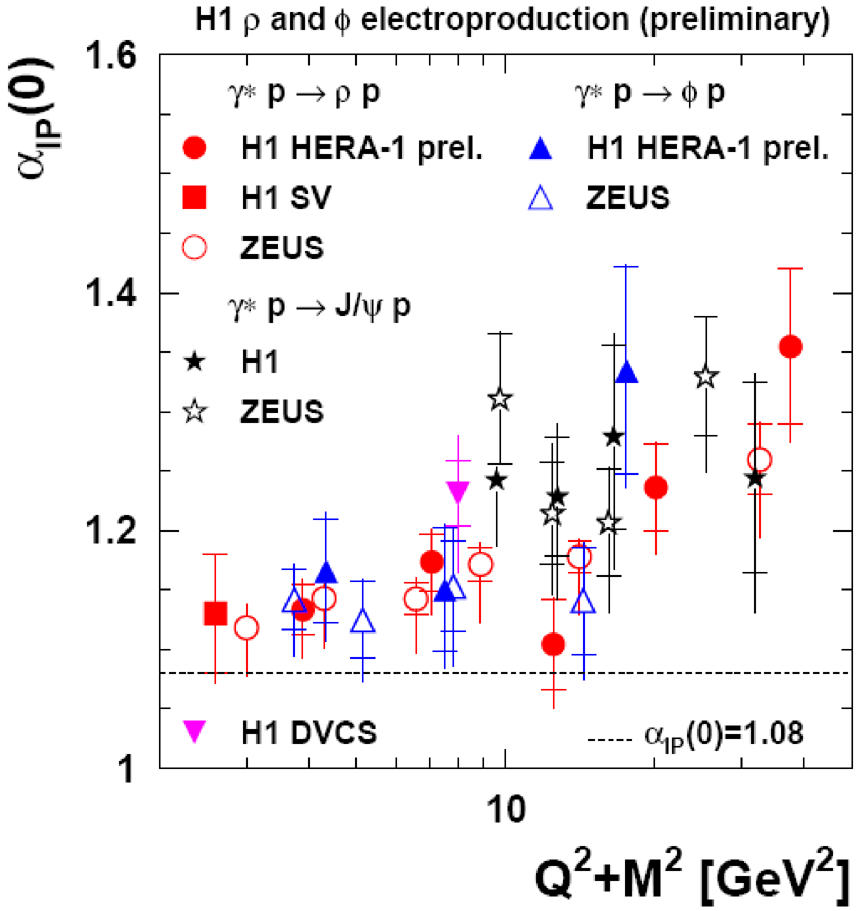
H1:
$\alpha_P(0) = 1.093 \pm 0.003^{+0.008}_{-0.007}$
$\alpha'_P = 0.116 \pm 0.027^{+0.036}_{-0.046}\ \mathrm{GeV}^{-2}$

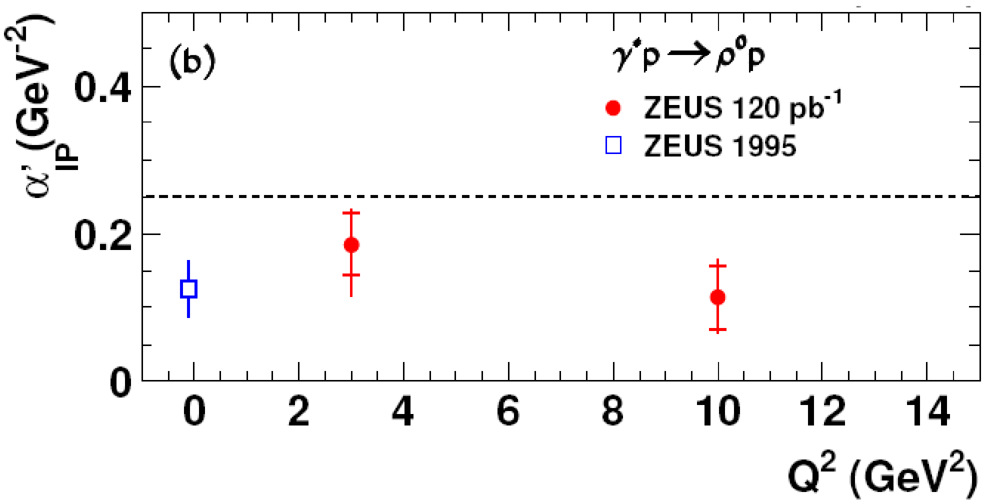
ZEUS:
$\alpha_P(0) = 1.096 \pm 0.021$
$\alpha'_P = 0.125 \pm 0.038\ \mathrm{GeV}^{-2}$

$\alpha_{IP}(0)$ consistent with 1.08 from soft pp scattering;
α'_{IP} ~twice smaller than 0.25 GeV^{-2}

➔two soft Pomeron trajectories ?
Size of two proton system grows twice faster with s than a single proton in γp ?

Effective Pomeron Trajectory ($\gamma^* p \rightarrow \rho p$) vs Q^2, Q^2+M^2





-With increasing of the scale (Q^2+M^2) the intercept $\alpha_{IP}(0)$ grows

➔ hardening of gluon distribution with the hard scale long.polarized γ_L^*

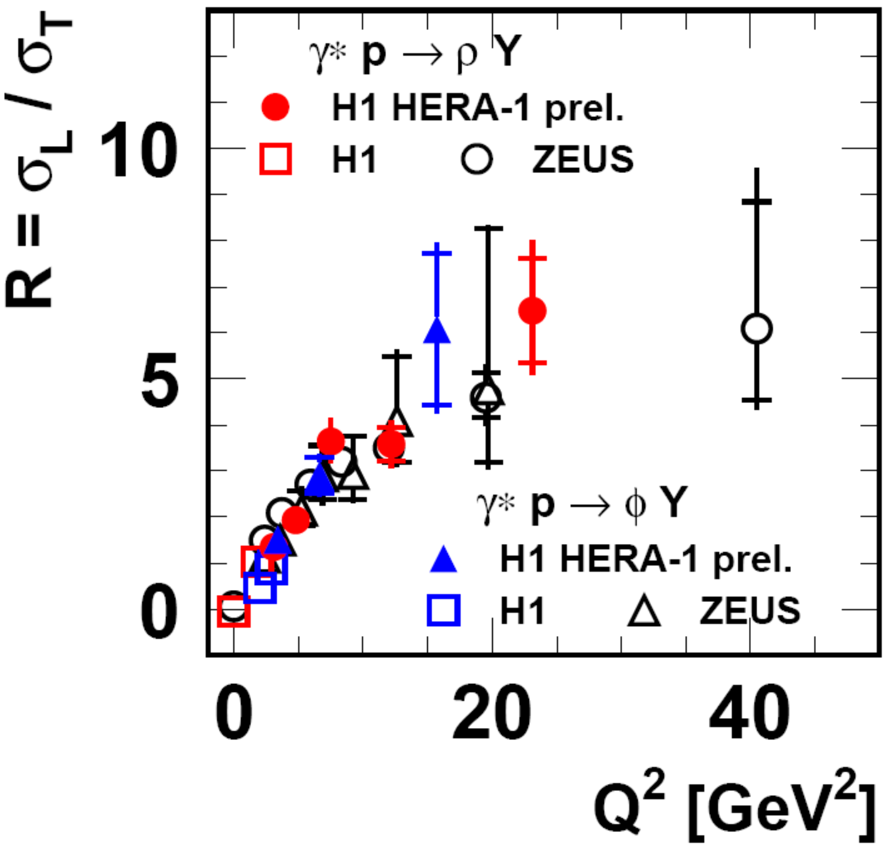
$$\sigma_{tot} = \sigma_T + \varepsilon \cdot \sigma_L$$

transv. polarized γ_T^*

small spatial configuration (large k_T)
steep rise with W
dominates at high Q^2

large spatial configuration (small k_T)
slow rise with W

calculate σ_L/σ_{Tot}, σ_L/σ_T from the spin density matrix elements, assume s-channel helicity conservation ***(SCHC):*** $R = \sigma_L / \sigma_T = r_{00}^{04} / \varepsilon(1 - r_{00}^{04})$ (at HERA kinematics $\varepsilon \approx 1$)



$R=\sigma_L/\sigma_T$: increase with Q^2

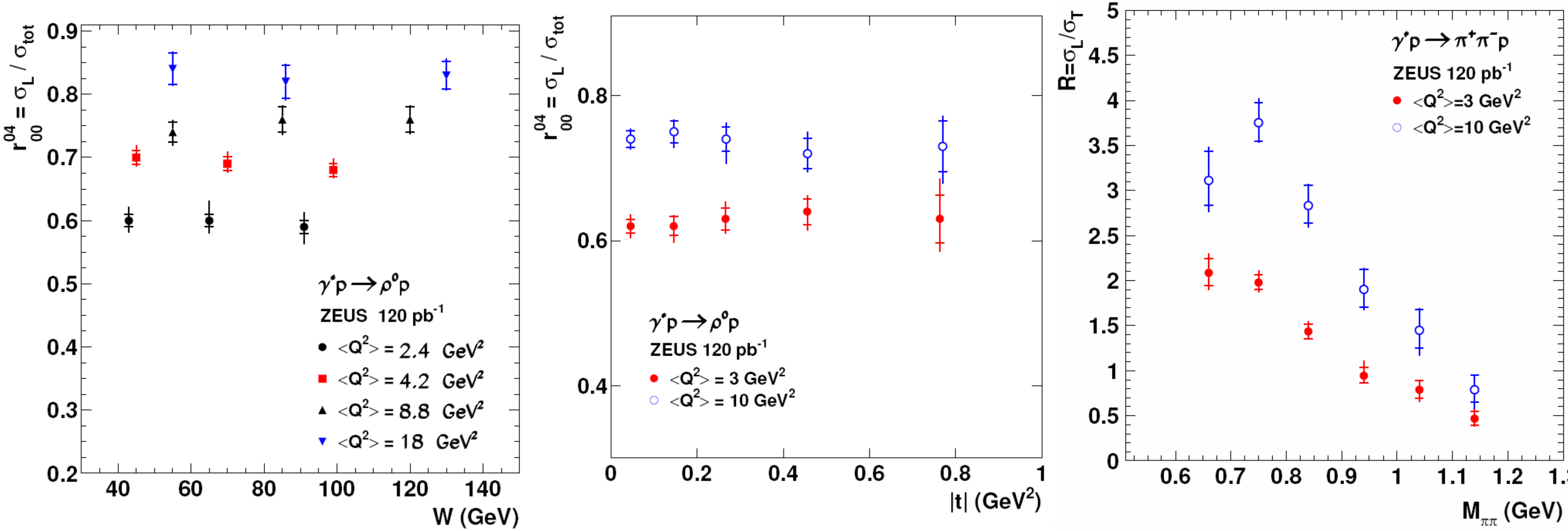
➔QCD expectation
as the scale gets harder σ_L dominates

-similar for ρ and ϕ

Elastic ρ-mesons in DIS: Polarised cross section ratios

$$\sigma_{tot} = \sigma_T + \varepsilon \cdot \sigma_L$$

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

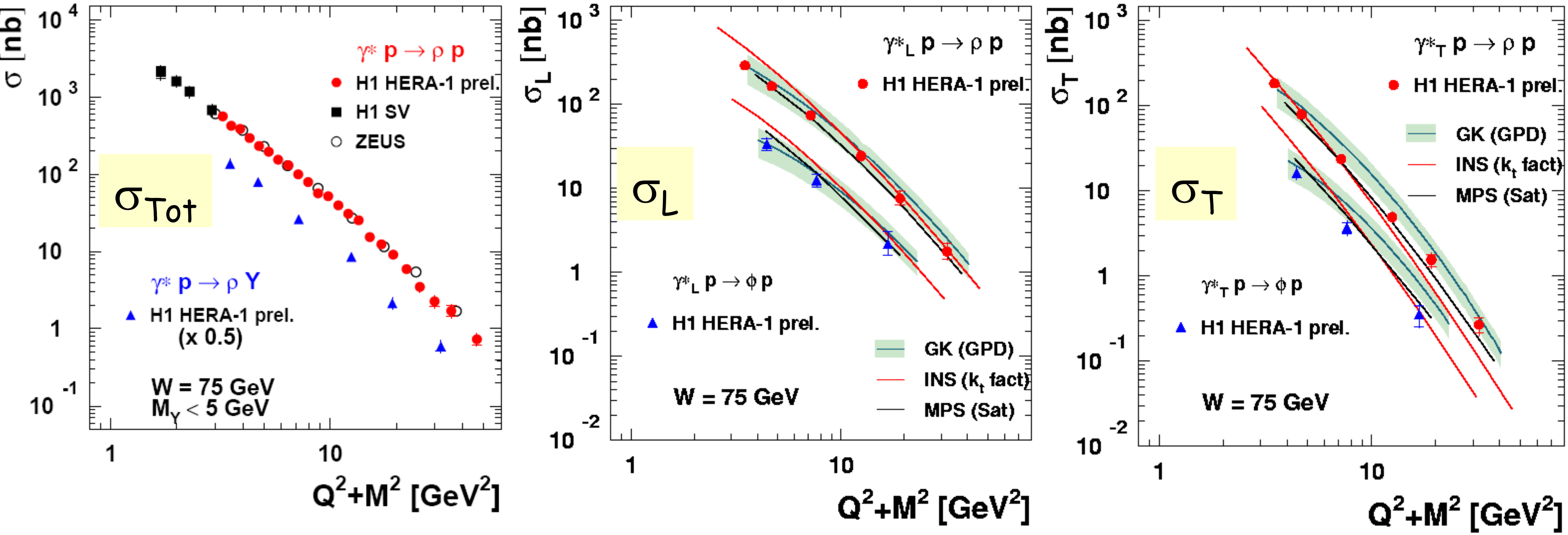


σ_L/σ_{tot}: independent of W; independent of t

- σ_L and σ_T have the same |t| dependence → $b_L \approx b_T$
- the typical dipole size contribution to ρ production independent of the photon polarisation
- large-size configurations of γ^*_T are suppressed

strong dependence of R with invariant mass

Elastic ρ,ϕ-mesons in DIS: Polarised cross sections σ_L, σ_T



- Steep decrease of cross section with increasing Q^2,
  - similar for proton-dissociation cross-section

$$\sigma_{Tot} \propto (Q^2+M^2)^{-n}, \quad n(Q^2) \cong 2.15 + 0.007 \cdot Q^2 \quad \text{(H1)}$$

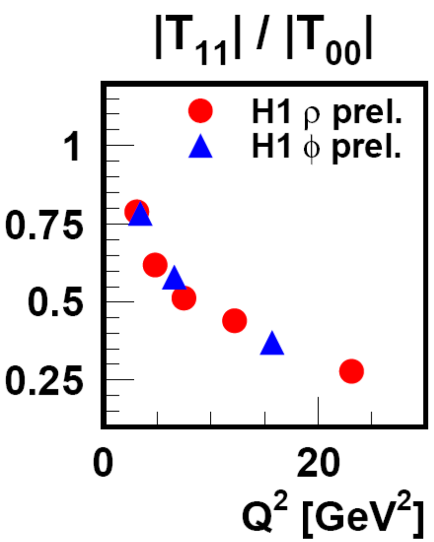
- Different Q^2+M^2 dependences of σ_L and σ_T ($\sigma_L=0$ at $Q^2=0$)
- Good description of σ_L by GK model (GPD); σ_T not described
- similar for ρ and ϕ

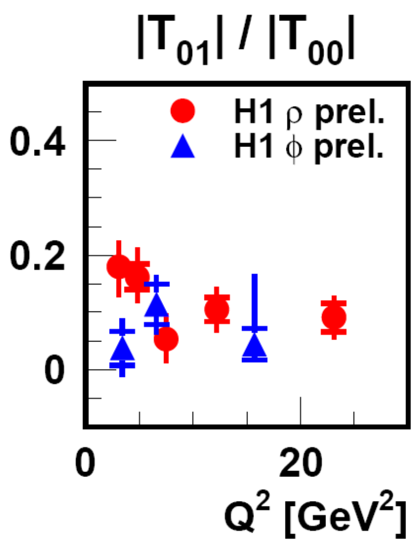
Models:

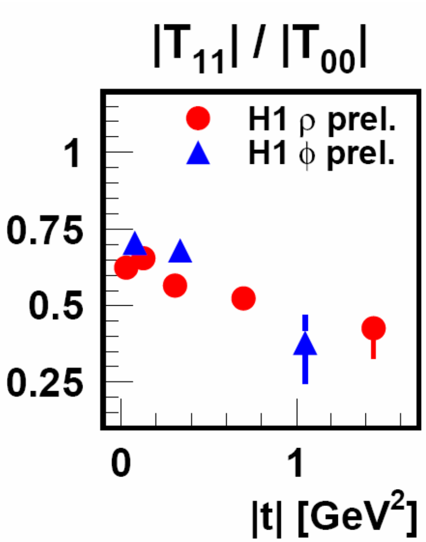
GK	Goloskokov, Kroll
INS	Ivanov, Nikolaev, Savin
MPS	Marquet, Peschanski, Soyez

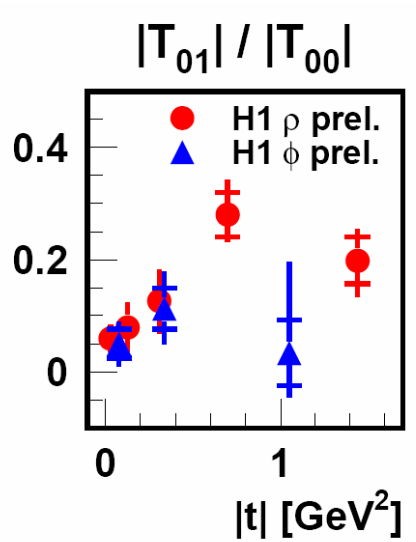
Extract $|T_{11}|/|T_{00}|$, $|T_{01}|/|T_{00}|$, $|T_{10}|/|T_{00}|$, $|T_{1-1}|/|T_{00}|$ from fit to the 15 SDMEs:

No helicity flip:	T_{00}: $\gamma_L \rightarrow \rho_L$; T_{11}: $\gamma_T \rightarrow \rho_T$
Single flip:	T_{01}: $\gamma_T \rightarrow \rho_L$; T_{10}: $\gamma_L \rightarrow \rho_T$
Double flip:	T_{1-1}: $\gamma_T \rightarrow \rho_T$









- $|T_{11}|/|T_{00}|$ decreases with Q^2
  decreases with t

σ_L/σ_T **increases with Q^2**

- $|T_{01}|/|T_{00}|>0$, increases with t

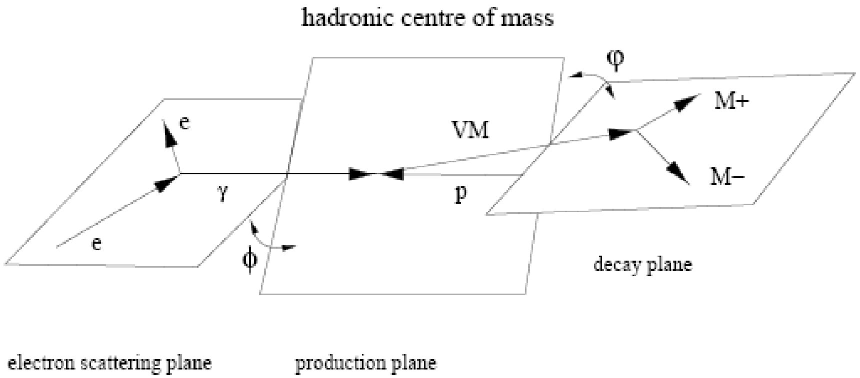
SCHC violation increases with t

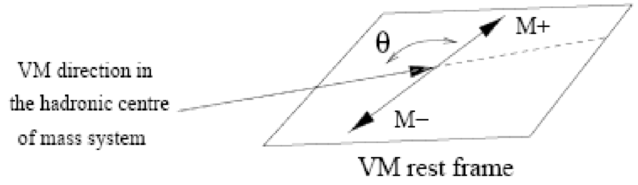
σ_L/σ_T **mainly constant with t**

- $|T_{10}|/|T_{00}|$ and $|T_{-11}|/|T_{00}|$ are small

Hierarchy $|T_{00}| > |T_{11}| > |T_{01}| > |T_{10}| > |T_{1-1}|$ is observed

Decay angular distributions





Helicity angles:

θ_h, ϕ_h- angles of decay particles in meson rest frame

φ– angle between scattering and production plane

Angular distributions are related to the spin of γ^* and meson

Angular distribution→ 15 spin density matrix elements r_{ij}^{kl} → helicity amplitudes $T_{\lambda_{VM}\lambda_{\gamma}}$

No helicity flip: T_{00}: $\gamma_L \to \rho_L$; T_{11}: $\gamma_T \to \rho_T$
Single flip: T_{01}: $\gamma_T \to \rho_L$; T_{10}: $\gamma_L \to \rho_T$
Double flip: T_{1-1}: $\gamma_T \to \rho_T$

- **s-channel helicity conservation (SCHS):**

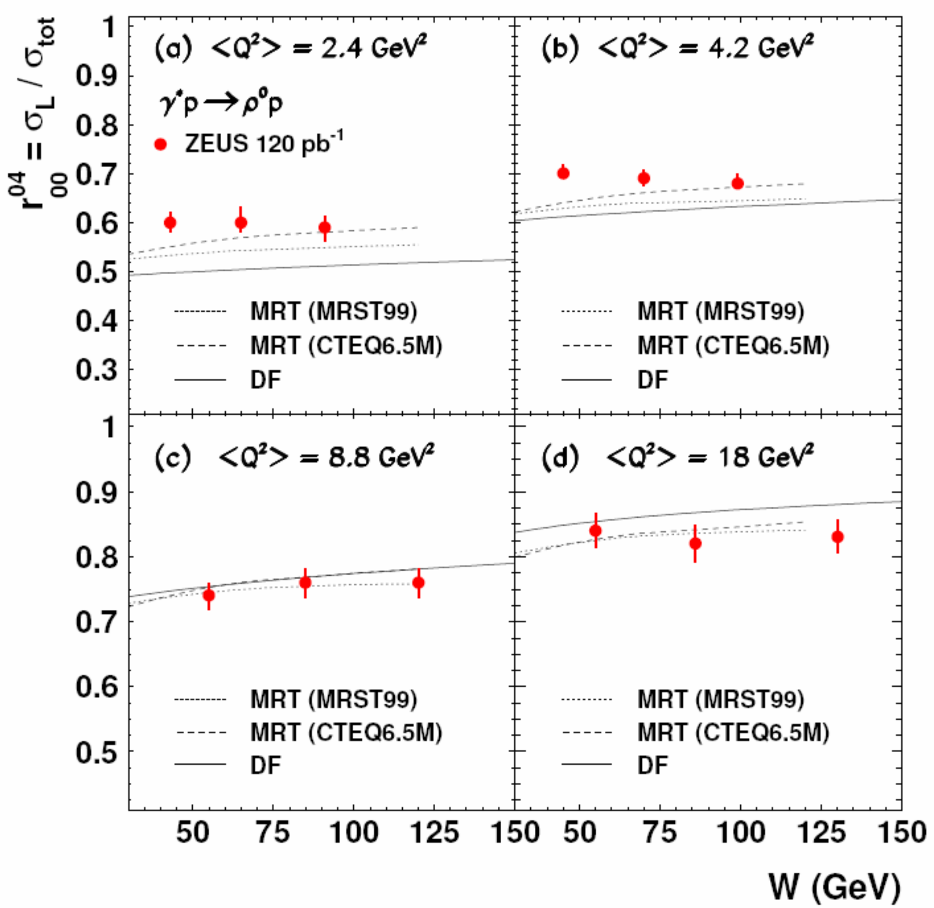
-the VM retains the γ^* helicity; $T_{01} = T_{10} = T_{1-1} = 0$
-$R = \sigma_L/\sigma_T$ is related to the spin density matrix elements r_{00}^{04}

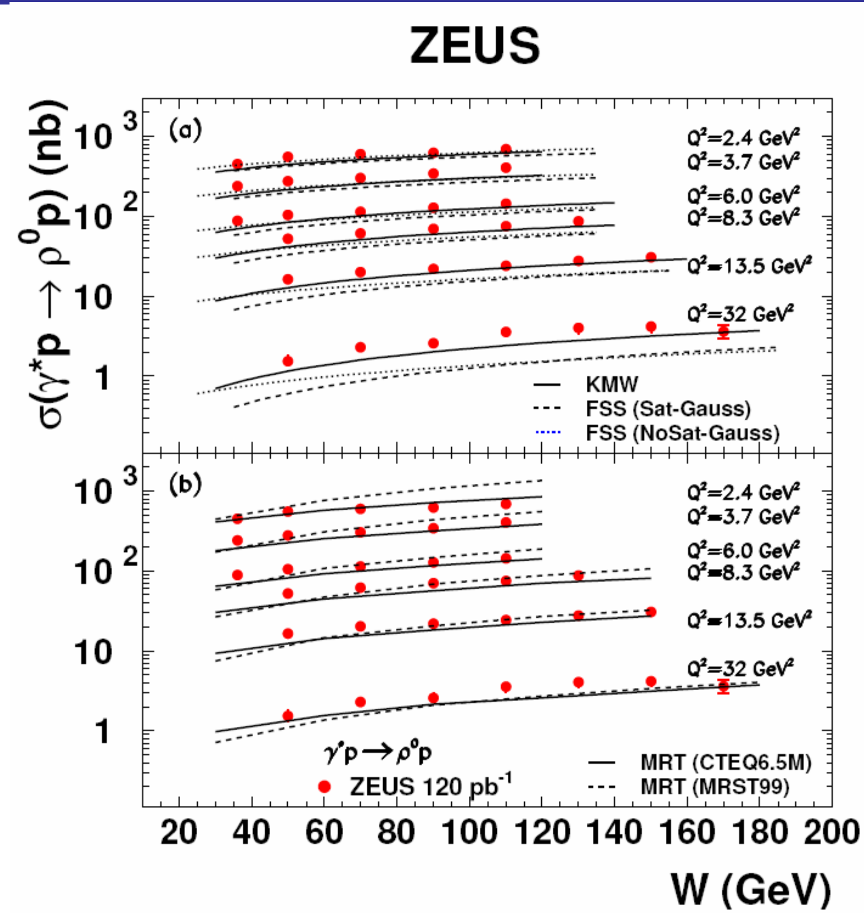
- **pQCD models**

- -the orbital angular momentum of $q\bar{q}$ can be modified through the transfer of transverse momentum carried by gluons
-the helicity of the outgoing VM can be different from that of the incoming γ^*, helicity flip between photon and meson is possible: single flip $\propto \sqrt{|t|}$,double flip $\propto |t|$
-Hierarchy: $|T_{00}| > |T_{11}| > |T_{01}| > |T_{10}| > |T_{1-1}|$

ρ^0 – production : comparison to theory calculations

Experiments reach the precision level where we can improve our understanding of the VM wave function and Gluon Density in the proton.



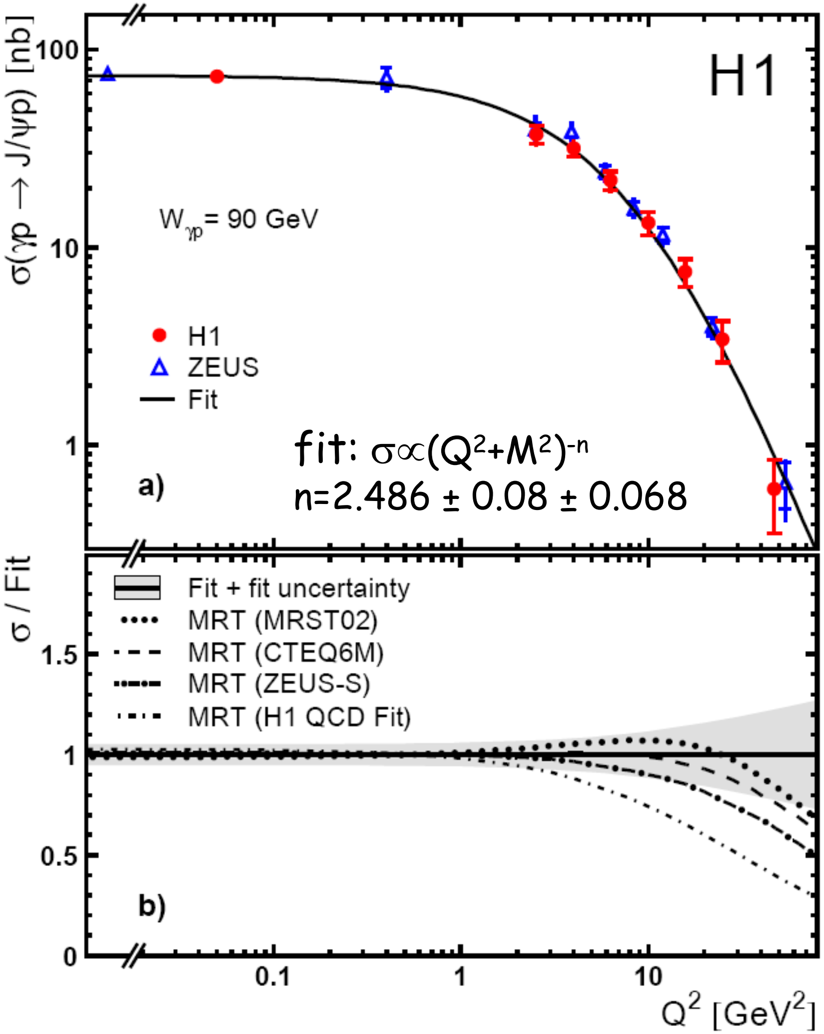


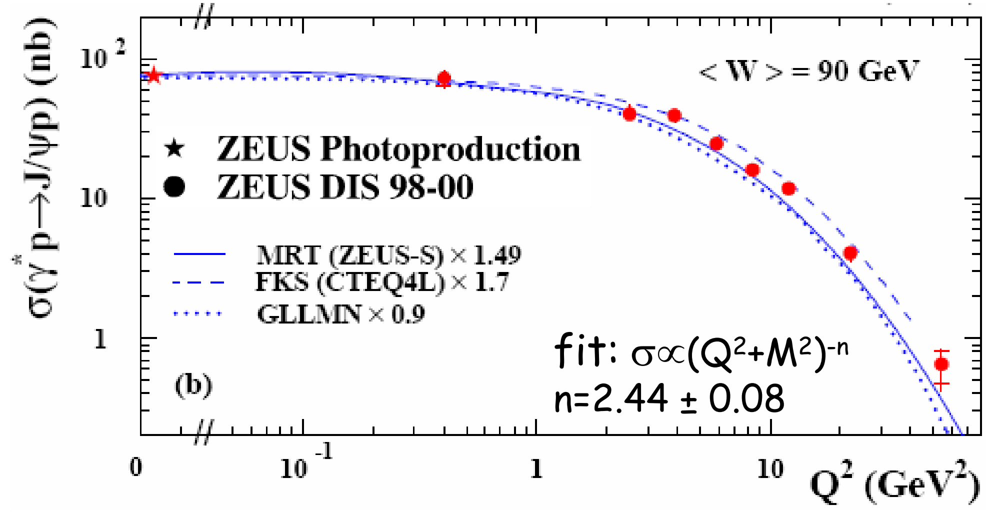
Large differences between the models and between the different PDFs
➔ HERA data provide constrains

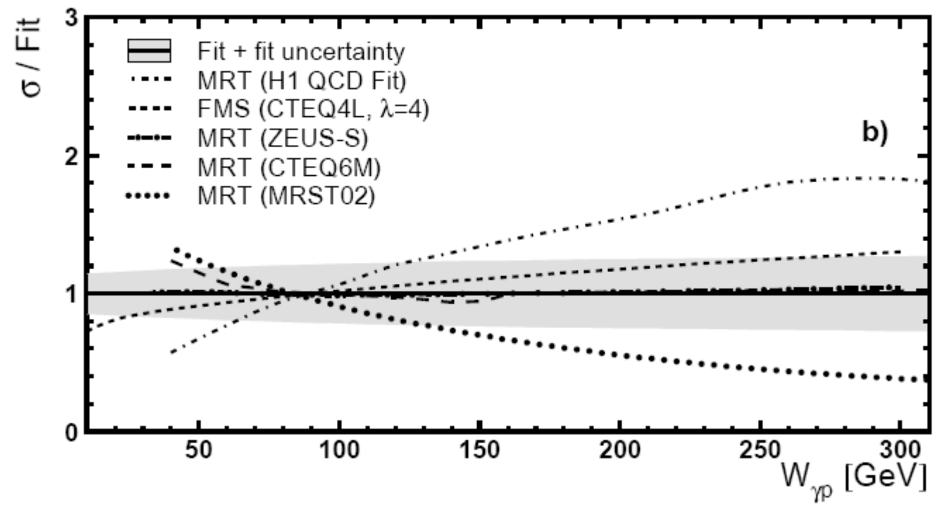
Models differ in assumptions on wave functions, corrections applied to LO calculations, assumption on GPDs

MRT	Martin-Ryskin-Teubner
FSS	Forshaw-Sandapen-Shaw
KMW	Kowalski-Motyka-Watt
DF	Dosch-Ferreira
FKS	Frankfurt-Koepf-Strikman

J/ψ– production : comparison to theory calculations







-qualitatively described by models
-sensitive to models
-sensitive to gluon density at low x

MRT- Martin,Ryskin,Teubner
FKS – Frankfurt, Koepf, Strikman
FMS – Frankfurt, McDermott,Strikman
GLLMN - Gotsman et al.

DVCS: QCD interpretation in terms of GPD

Two dimensionless observables:

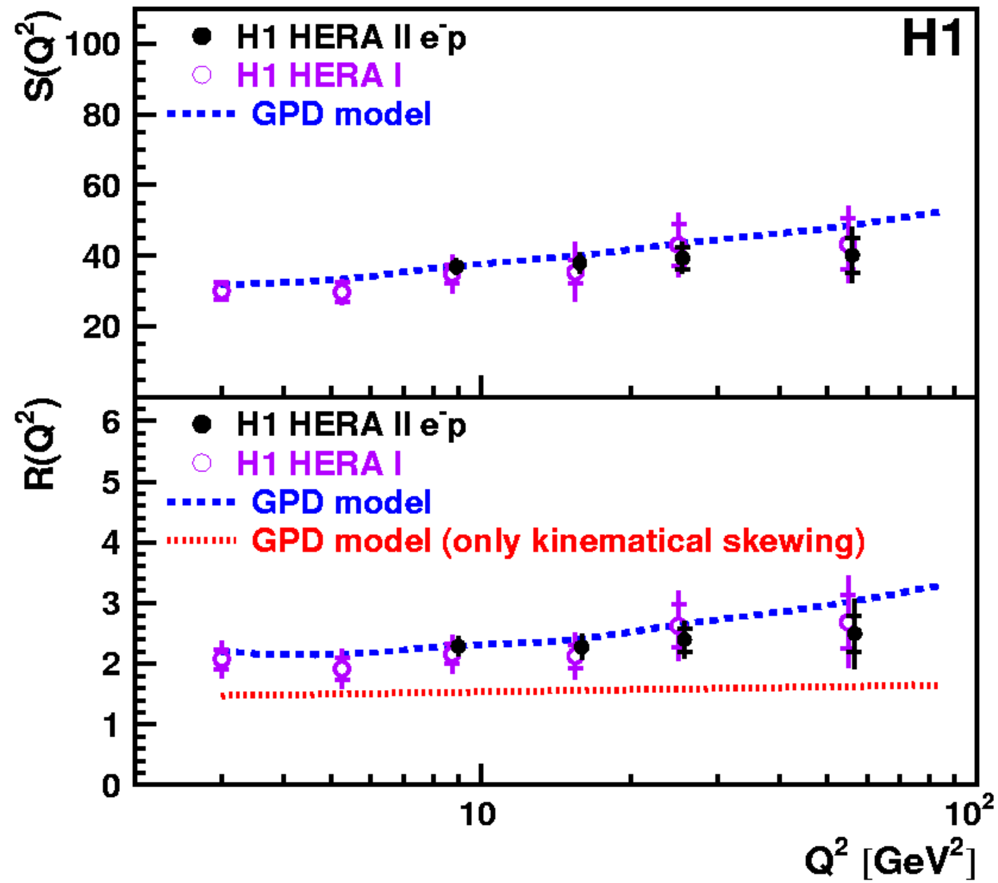
$$S = \sqrt{\frac{\sigma_{DVCS}\, Q^4\, b(Q^2)}{1+\rho^2}}$$

gives Q^2 evolution of GPD: (correct Q^2 dependence of the propagator and of *b)*

evolution of S with Q^2 observed; described by NLO QCD

$$R = \frac{Im\, A(\gamma^* p \to \gamma p)}{Im\, A(\gamma^* p \to \gamma^* p)} = \frac{4\sqrt{\pi \sigma_{DVCS}\, b(Q^2)}}{\sigma_T(\gamma^* p \to X)\sqrt{1+\rho^2}}$$

R ~ skewing effects, R=1 if no skewing
Result: R is around 2

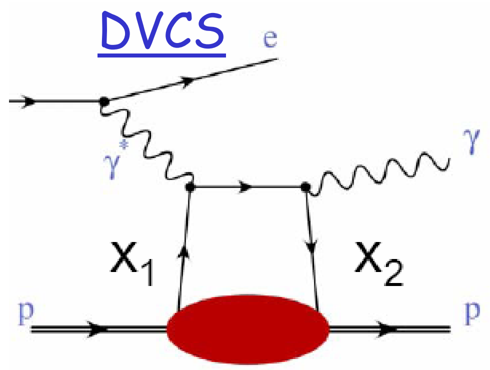


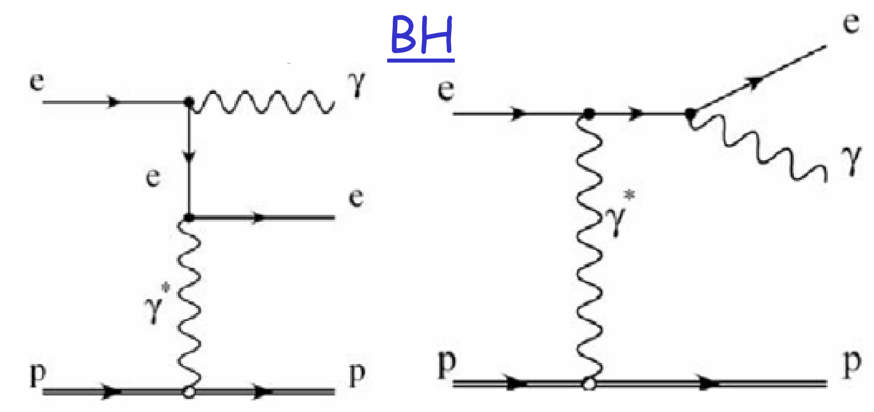
\`GPD model' - A.Freund et al. (NLO QCD)
GPD parameterisation: J.Pumplin et al.

NLO QCD model (based on GPD) describes Q^2 dependence of S and R
Set constrains on gluon and sea GPDs

DVCS: Beam Charge Asymmetry (BCA)

Interference between DVCS (QCD) and Bethe-Heitler (QED) processes

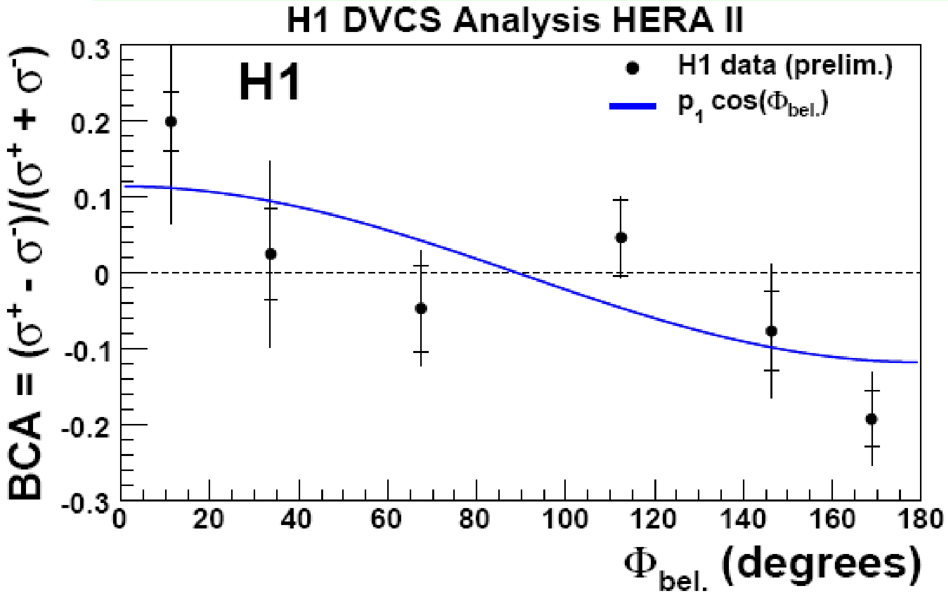


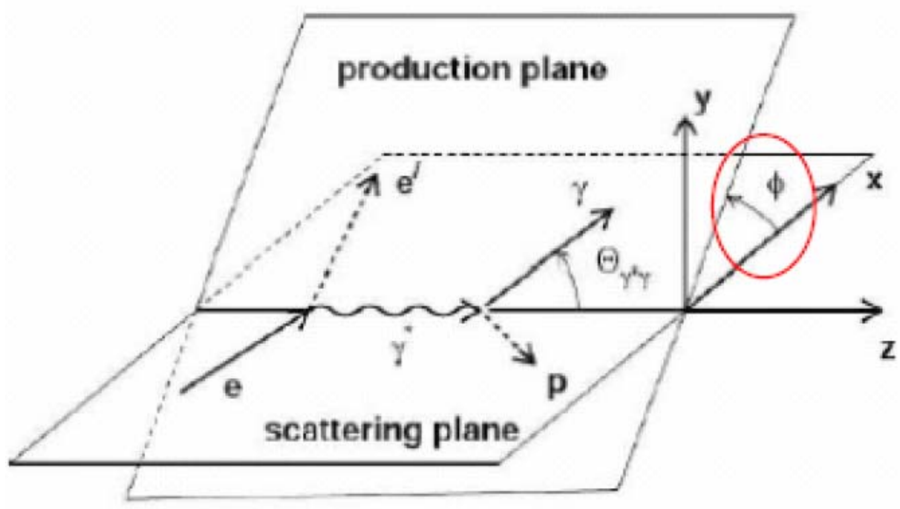


$d\sigma^{\pm}=d\sigma^{BH}+d\sigma^{DVCS}\pm$ interference

(+/-) is a beam lepton charge

$BCA=(\sigma^{+}-\sigma^{-})/(\sigma^{+}+\sigma^{-})= p_1\cdot\cos(\phi)+\ldots$; $p_1 \sim GPD$ ➔ information about GPD





Summary

New high statistics measurements of Vector mesons in DIS and photoproduction and DVCS process at HERA:

- W-dependence of cross section becomes stronger with increasing of hard scale Q^2+M^2
- The exponential slope of t-distribution decreases with Q^2+M^2 and levels off at about b~4÷5 GeV^{-2}
- The ratio of the longitudinally and transverse cross sections σ_L/σ_T increases with Q^2 and is independent of W
- Effective Pomeron trajectory has smaller slope than that extracted from soft hadron-hadron scattering
- W and t dependence of DVCS indicate hard process. Good agreement with NLO QCD predictions, based on GPD model
- DVCS beam charge asymmetry measured, process is sensitive to GPDs

All these features are compatible with expectations of perturbative QCD, set constrains on gluon PDFs and GPDs