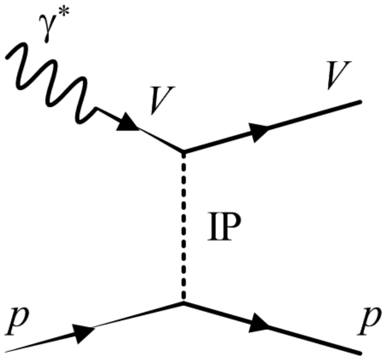
Exclusive processes at HERA

Robert Ciesielski (DESY)
on behalf of H1 and ZEUS Collaborations

$$\gamma^* p \to V p$$

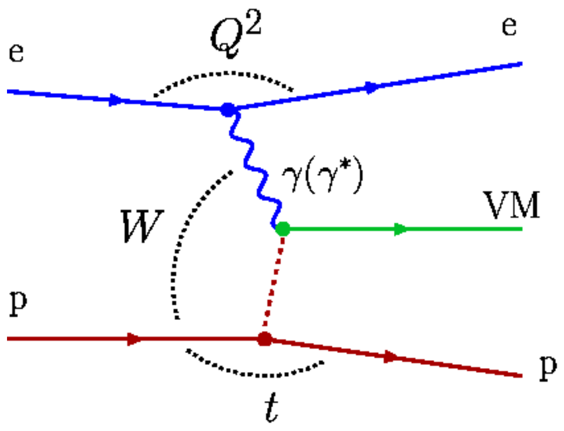
$$V = \rho, \omega, \varphi, J/\Psi, \Psi', \Upsilon, \gamma$$

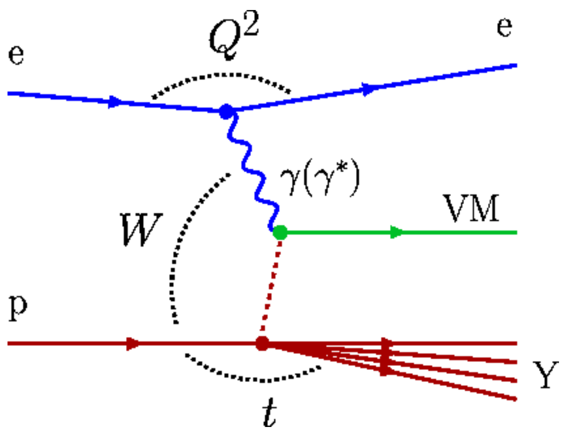


International Conference on High Energy Physics, ICHEP08
Philadelphia, July 29-August 5, 2008

Exclusive processes @HERA - VM Production, DVCS

HERA (DESY): collisions of 27.5 GeV *e* with 920 GeV *p* $(\sqrt{s}=318\,GeV)$





$\gamma^{(*)}p \rightarrow V\,p$

exclusive

$\gamma^{(*)}p \rightarrow V\,Y$

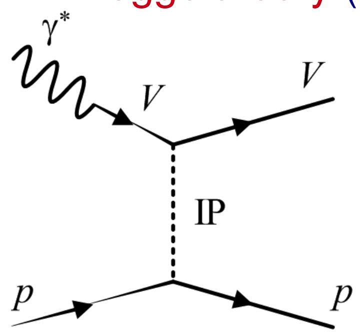
proton dissociative (dominates at higher-t)

VM : vector meson or real photon	$\rho, \omega, \varphi, J/\Psi, \Psi', \Upsilon, \gamma$
Q^2 : photon virtuality	$0 < Q^2 < 180\,GeV^2$
W : CM energy of the $\gamma^* p$ system ($x=Q^2/W^2$)	$20 < W < 290\,GeV$
t : (4-mom. transfer)^2 at the proton vertex	$\lvert t \rvert < 30\,GeV^2$

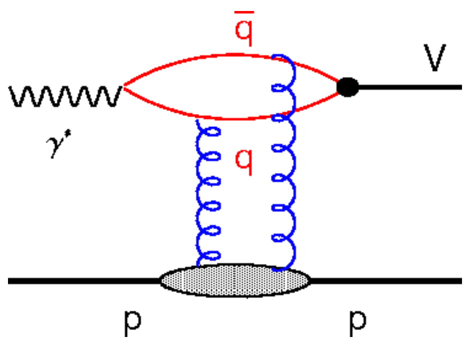
HERA data spans exceptionally wide range of kinematic variables

VM Production Mechanisms @ HERA

soft: VDM + Regge theory (hadron level)



hard: pQCD (parton level)



soft Pomeron exchange: $\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha_{IP}' \cdot t$

$\alpha_{IP}(0) = 1.08, \alpha_{IP}' = 0.25\, GeV^{-2}$

$$\frac{d\sigma}{dt} \propto e^{-b|t|} (W/W_0)^{4(\alpha_{IP}(t)-1)}$$

2-gluon exchange (LO):

$$\sigma_L \propto \alpha_s(Q^2)[xg(x, Q^2)]^2 / Q^6$$

- slow rise with W: $\delta \simeq 0.22$
- shrinkage of the diffractive peak with W: $b(W) = b(W_0) + 4\alpha_{IP}' \ln(W/W_0)$

  $b(W_0) \approx 10\, GeV^{-2}$

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

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

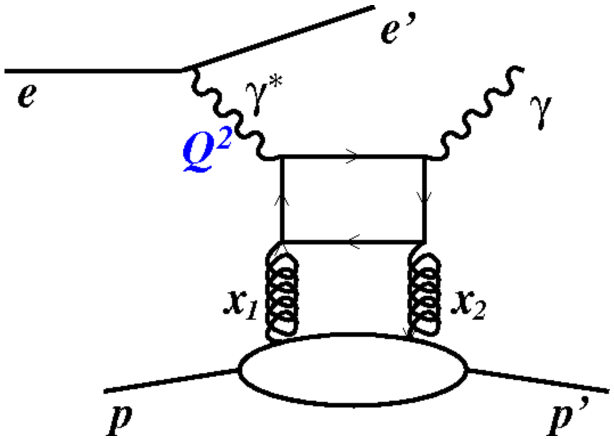
- fast rise with W: $\delta \simeq 0.7$

  ($x = Q^2/W^2$, gluon desity rises at low-x)
- universal t-dependence:

  $b_{2g} \approx 4-5\, GeV^{-2}$ and $\alpha_{IP}' \approx 0$

Change of regime expected with rising Q^2, M_{VM}^2 or t (hard scales of the process)

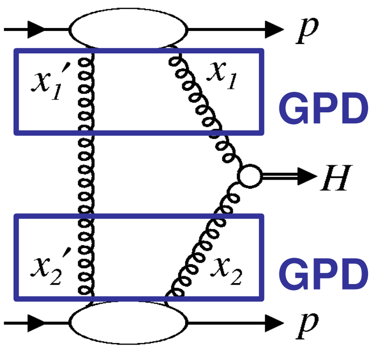
DVCS – Deeply Virtual Compton Scattering

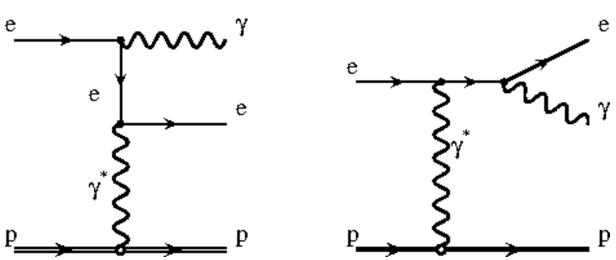


$$\gamma^* \, p \rightarrow \gamma \, p$$

Similar to VM production, but with real photon in the final state
- no VM wave-function uncertainty (non-perturbative part)
- easier access to GPDs - Generalised (skewed) PDFs

GPDs describe the correlations between two partons (x_1,x_2) which differ by longitudinal, $x=x_1-x_2$, and transverse, t, momentum at a given Q^2.
(~3D picture of the proton) Important for exclusive Higgs production @LHC



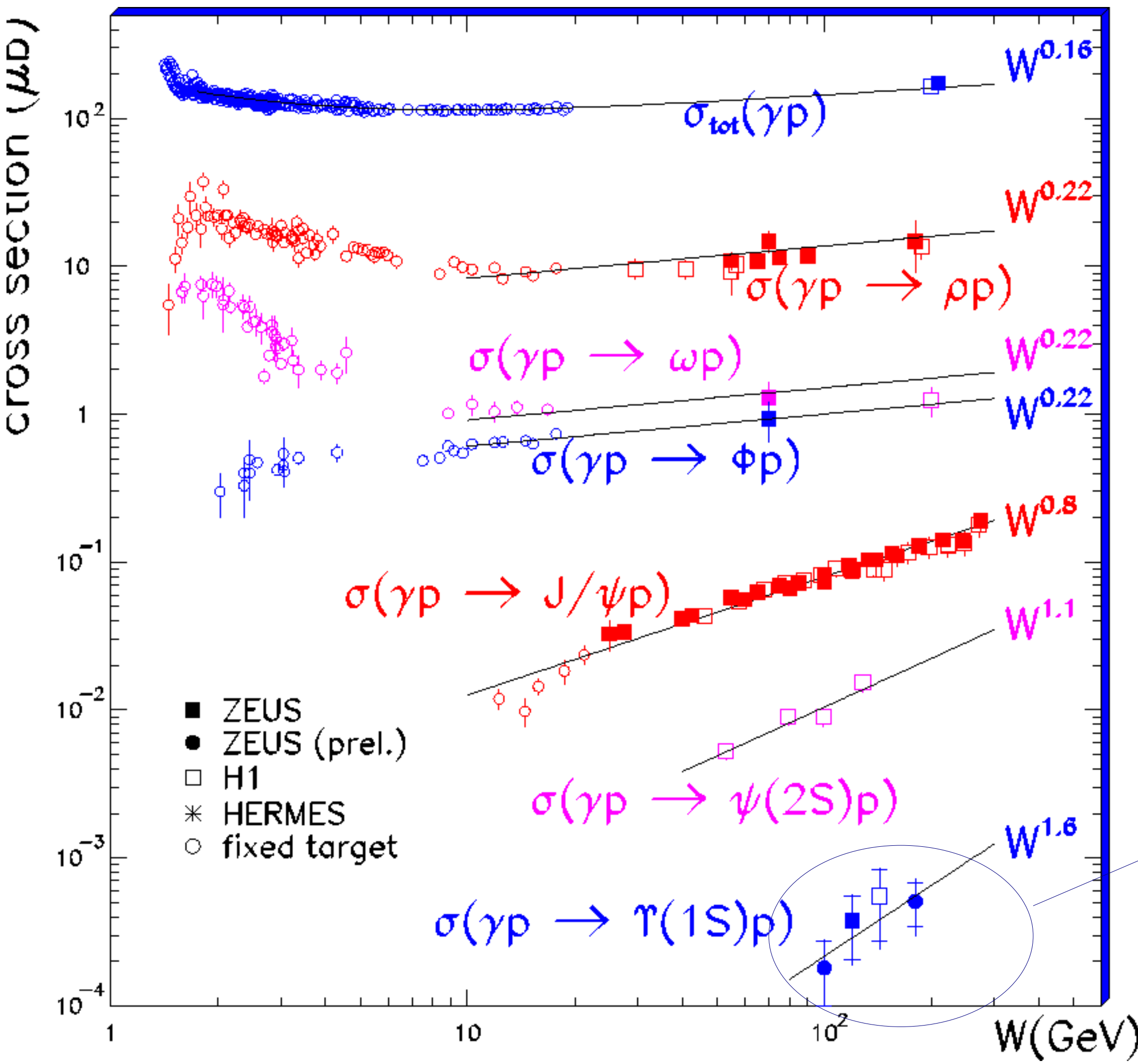


Irreducible QED background from $ep \rightarrow ep\,\gamma$ Bethe-Heitler process
Sensitive to the real part of the amplitude via the QCD-QED interference

$$\sigma = \sigma^{DVCS} + \sigma^{BH} \pm \sigma^{interf.}$$

Vector Mesons in Photoproduction [Q^2=0]

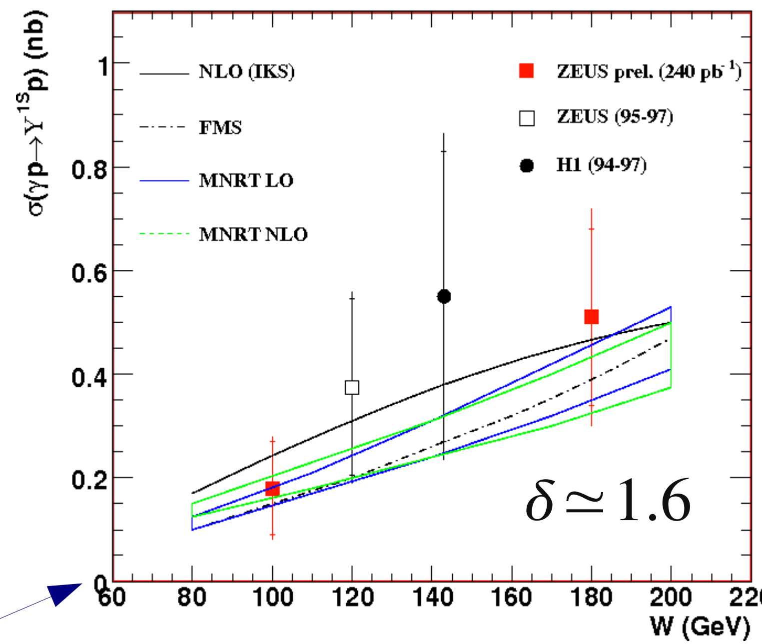
$\gamma\, p \rightarrow V\, p$



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

soft physics: $\delta \simeq 0.22$

$\gamma\, p \rightarrow \Upsilon\, p$

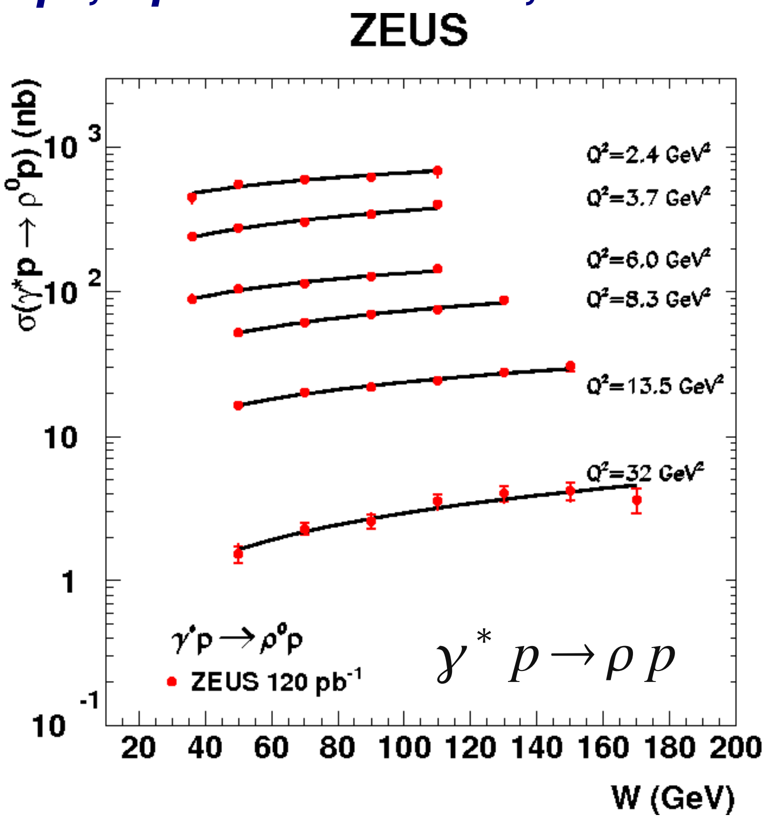


pQCD describes the steep rise of the cross section with M_{Υ} as a hard scale, sensitivity to gluon GPDs

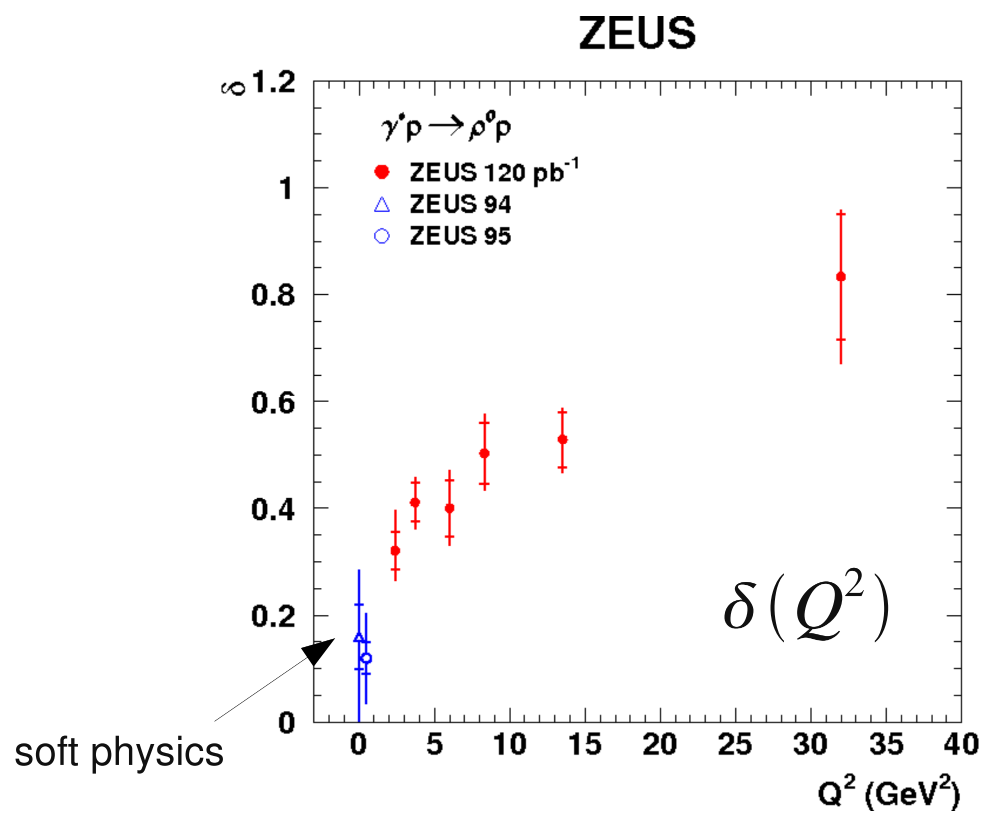
Process becomes harder (steeper W dependence) as M_{VM} becomes larger

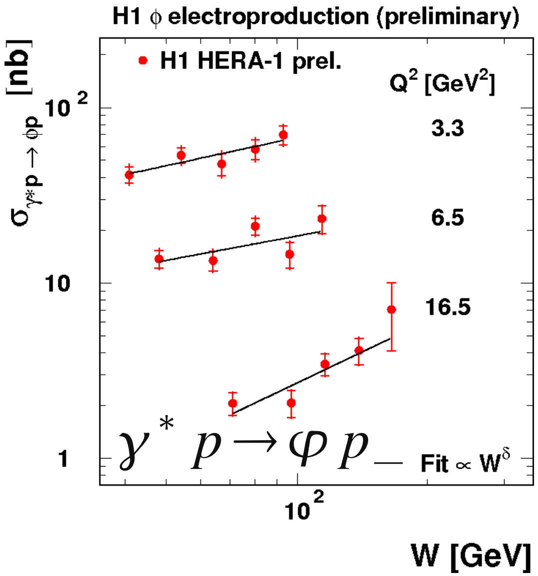
VM mass sets hard scale in photoproduction

ρ, φ mesons, W-dependence vs Q^2



$$\sigma(W) \propto W^{\delta} \text{ in bins of } Q^2$$





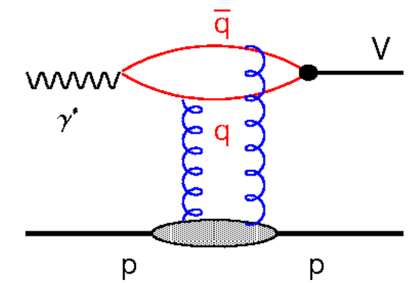
Steeper W dependence as Q^2 becomes larger

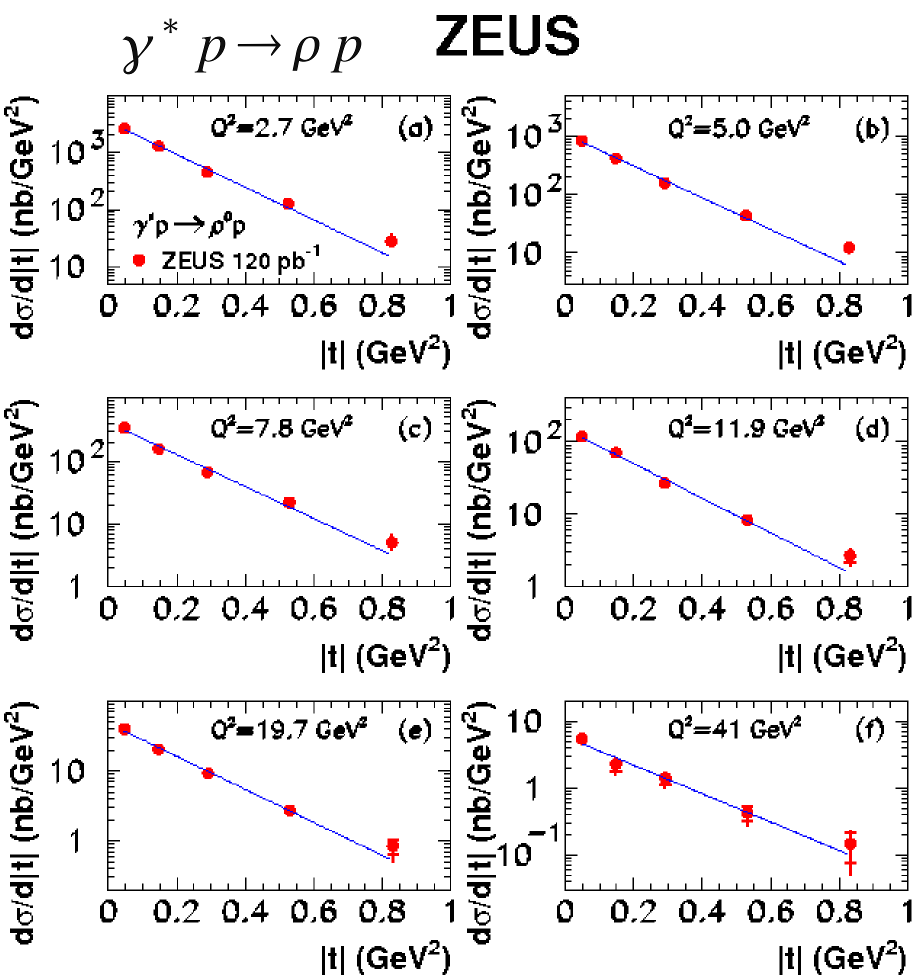
Q^2 sets hard scale for light vector mesons

ρ, φ mesons, t-dependence vs Q^2

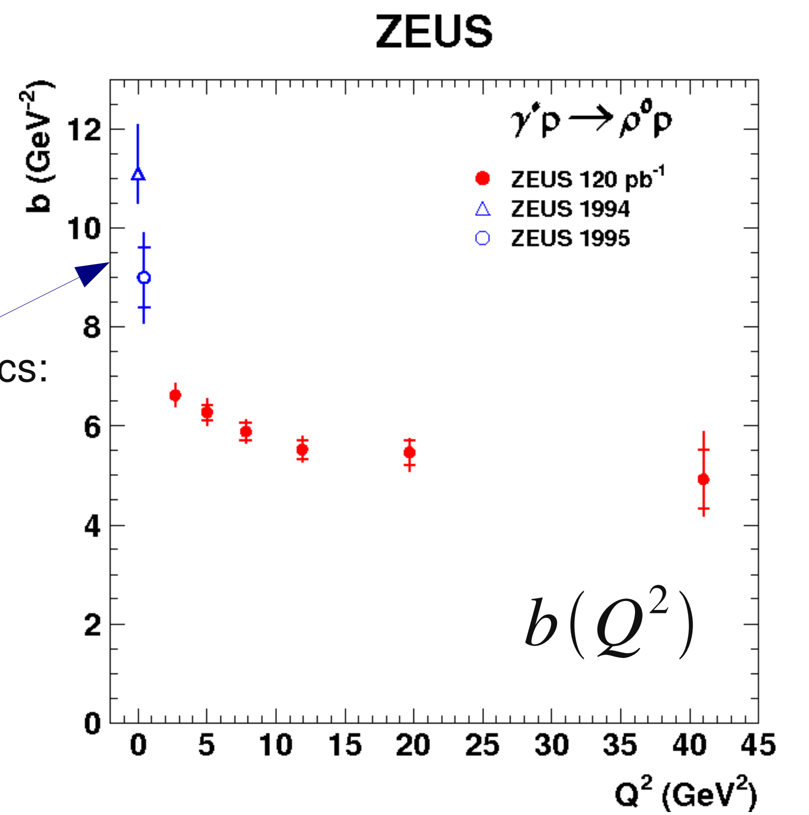
$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$ in bins of Q^2

b describes the transverse size of the interaction region $b \propto R_p^2 + R_{q\bar{q}}^2$





soft physics:



b slope decreases with Q^2: *b =10 → 5 GeV* $^{-2}$

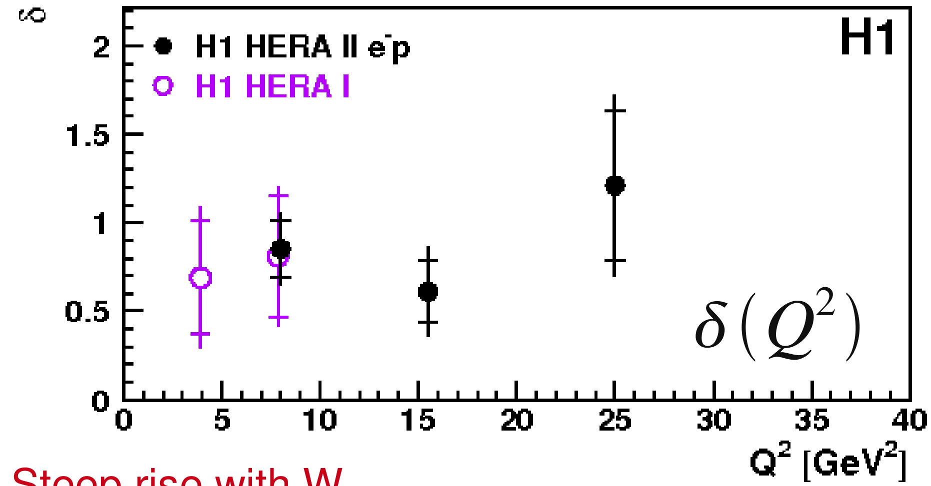
Transverse size of dipole decreases with Q^2

DVCS vs Q^2

$$\gamma^* p \to \gamma p$$

W dependence:

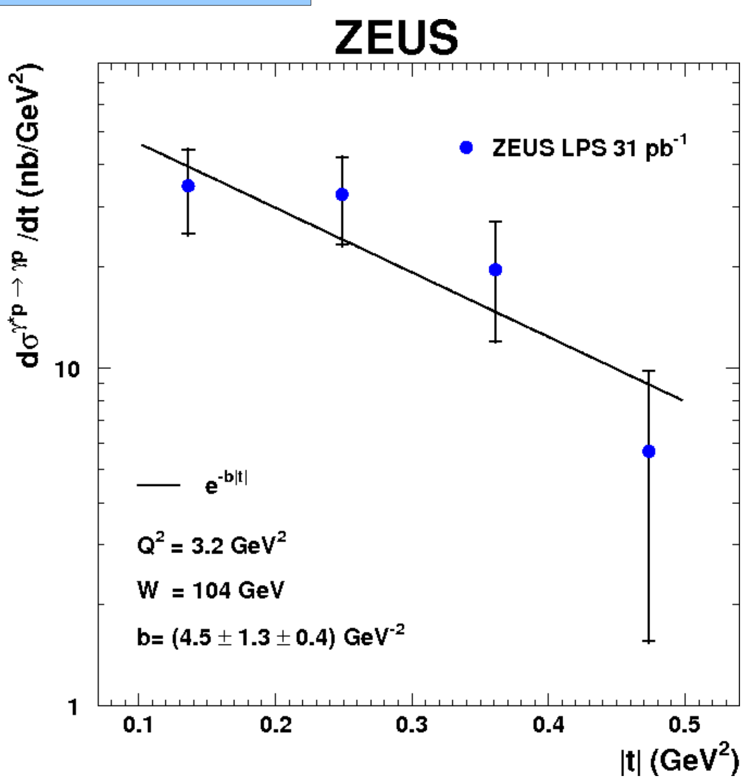
$$\sigma(W) \propto W^\delta$$



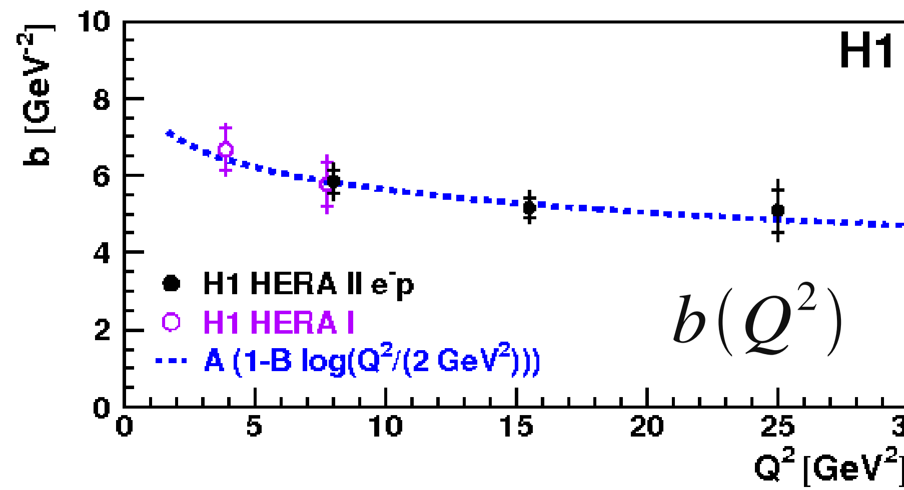
Steep rise with W,
no significant dependence of δ on Q^2 (within errors)

t dependence:

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

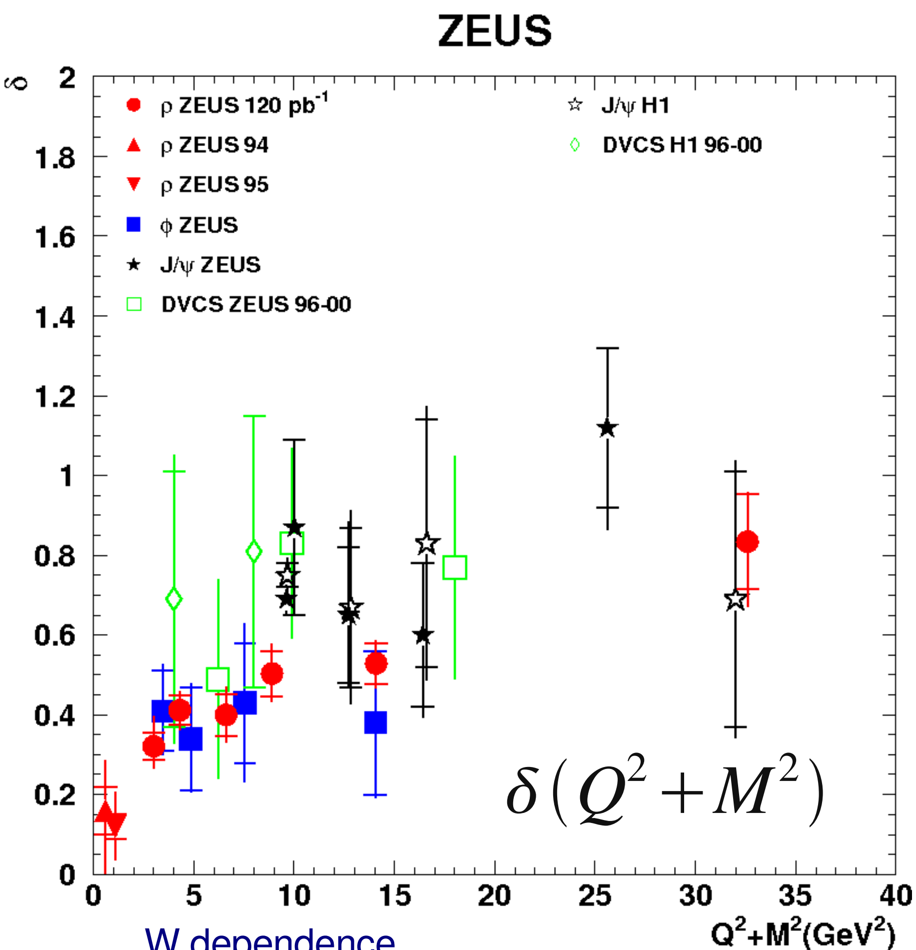


First direct measurement of t-dependence using the Leading Proton Spectrometer (proton tag, only elastic contribution)

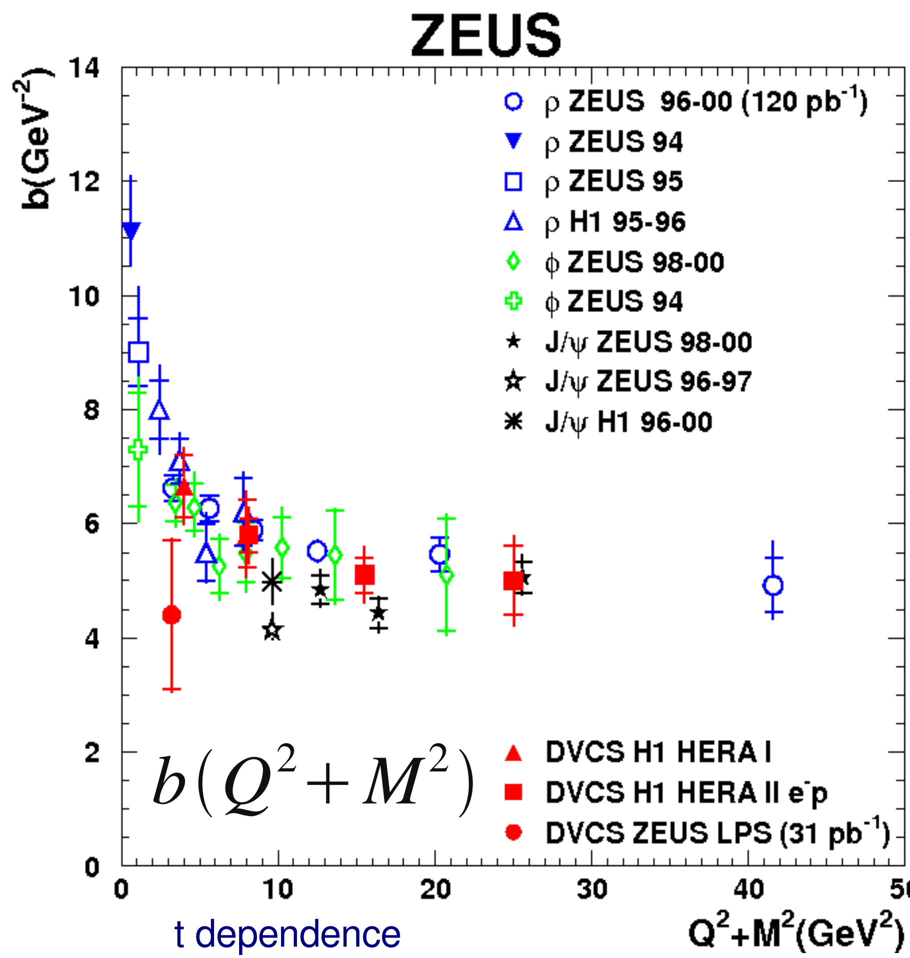


First measurement of
Q^2-dependence of the b slope

All VMs and DVCS, W and t-dependence vs Q^2+M^2



W dependence



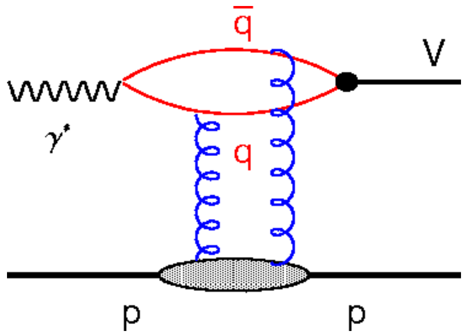
t dependence

Similar behaviour of δ and *b* with Q^2+M^2 for all VM (ρ, φ, J/ψ) and DVCS
Transition from *soft* to *hard* regime with increasing of hard scale

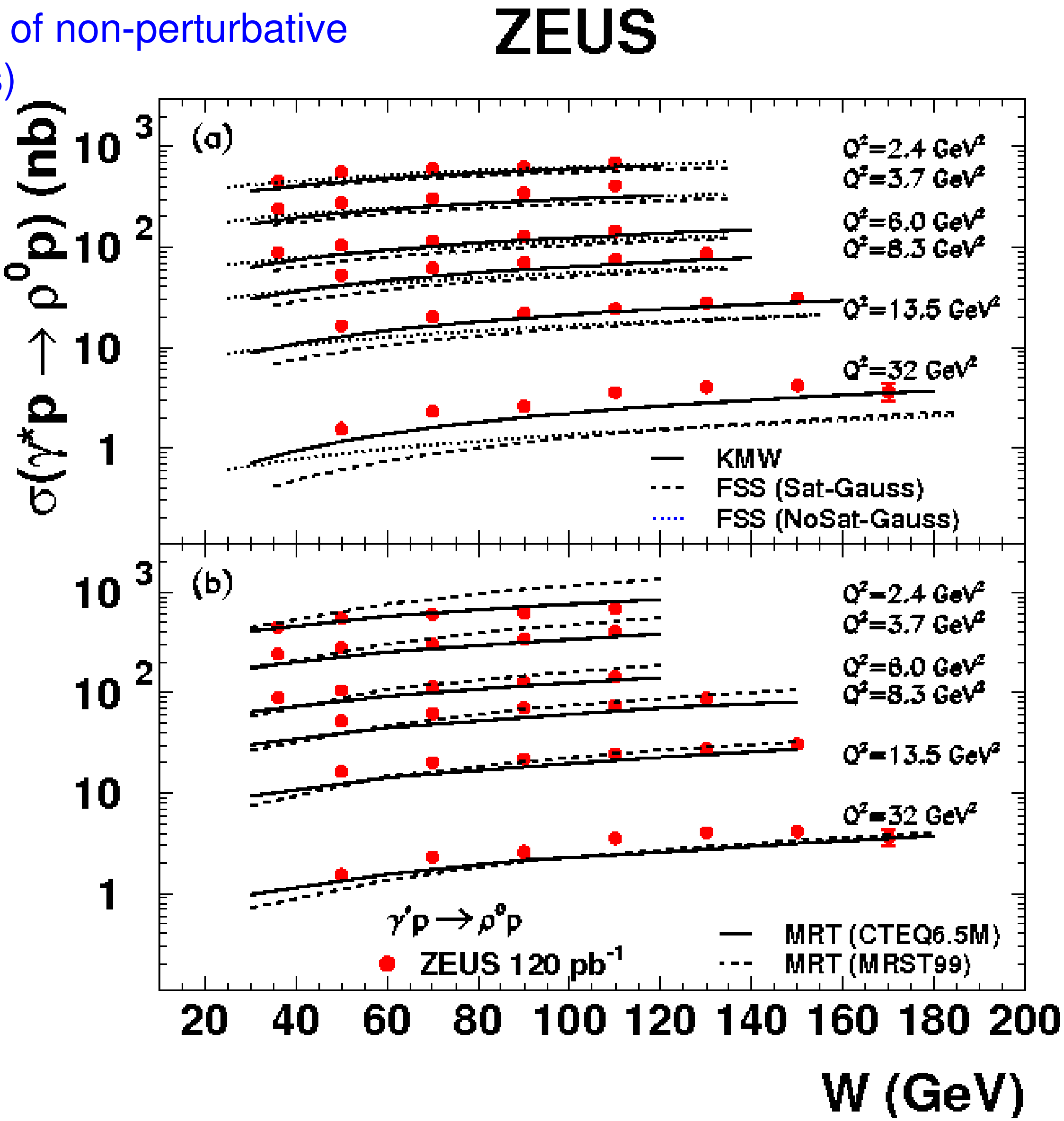
At higher Q^2+M^2: point-like dipole probes gluon cloud of the proton (pQCD region)

Comparison to theoretical models, ρ

High precision of data → improved understanding of non-perturbative quantites: VM wave-function, PDFs (low-x gluons)



$$A \propto \psi_{q\bar{q}}^{\gamma^*} \otimes \sigma_{q\bar{q}-p} \otimes \psi_{q\bar{q}}^{V}$$



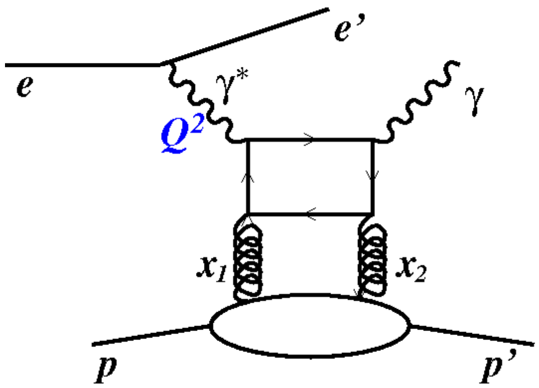
Models differ for $\sigma_{q\bar{q}-p}$ and $\psi_{q\bar{q}}^{V}$

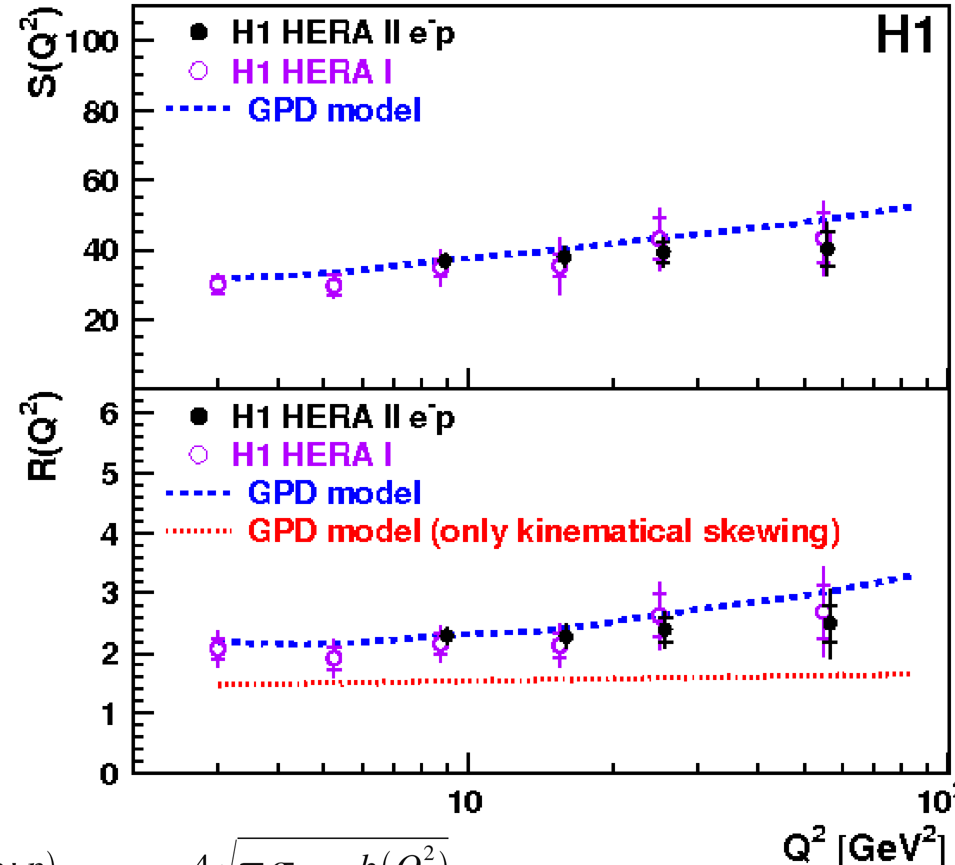
KMW - Kowalski-Motyka-Watt
FSS - Forshaw-Sandapen-Shaw
MRT - Martin-Ryskin-Teubner

Large differences between the models and PDF input. HERA data provide constrains

Comparison to theoretical models, DVCS

GPD model – A. Freund et al. (NLO QCD) with
GPD parametrisation by J. Pumplin et al.





Two dimentionless observables:

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

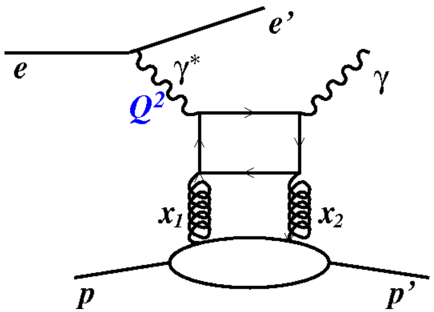
$$R = \frac{ImA(\gamma^* p \rightarrow \gamma p)_{t=0}}{ImA(\gamma^* p \rightarrow \gamma^* p)_{t=0}} = \frac{4\sqrt{\pi \sigma_{DVCS} b(Q^2)}}{\sigma_T(\gamma^* p \rightarrow X)\sqrt{(1+\rho^2)}}$$

S measures the Q^2 evolution of GPD

R measures the ratio of GPDs to PDFs ie. skewing effect (x_1-x_2),
R=1 if no skewing (x_1=x_2, GPDs →PDFs)

NLO pQCD model based on GPDs describes the $S(Q^2)$ and $R(Q^2)$.
Data has proven its potential to constrain gluon (and sea) GPDs.

DVCS – Beam Charge Asymmetry

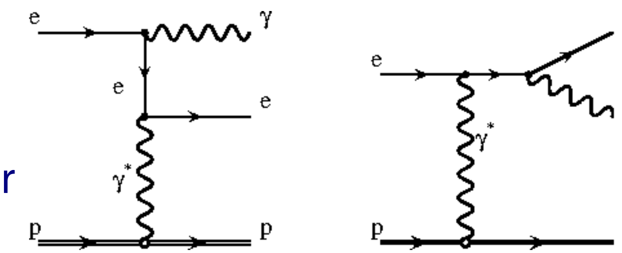


$\gamma^* p \rightarrow \gamma p$

DVCS

$ep \rightarrow ep\gamma$

QED Bethe-Heitler



The QCD-QED interference term is sensitive to the real part of the QCD amplitude,
It changes sign with lepton beam charge:

$$\sigma = \sigma^{DVCS} + \sigma^{BH} \pm \sigma^{interf.}$$

+ for incoming e^+ beam
- for incoming e^- beam

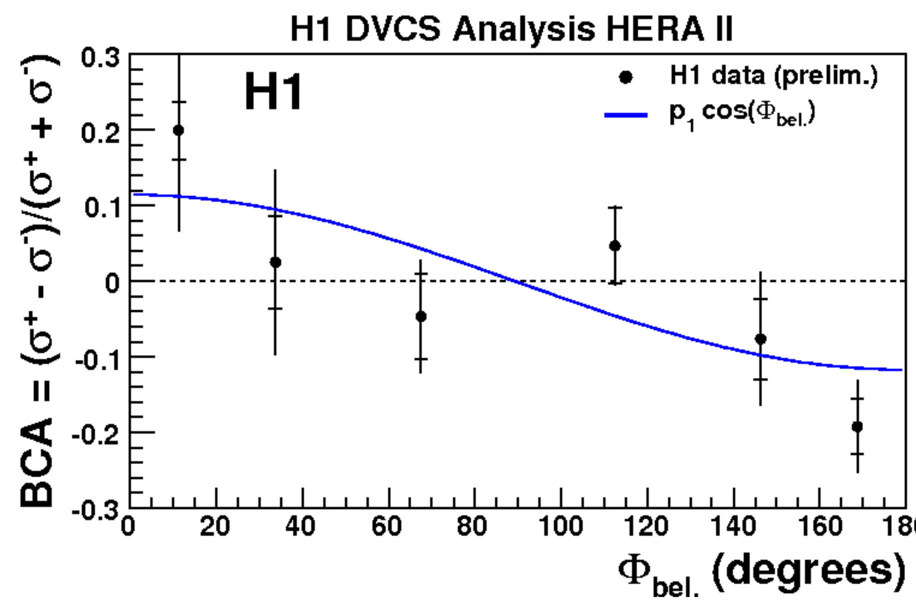
Beam Charge Asymmetry (BCA) vs ϕ

ϕ is the angle between two planes defined by incoming and outgoing electron and γ^* and outgoing proton

$$BCA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = p_1 \cdot \cos(\phi) + \ldots$$

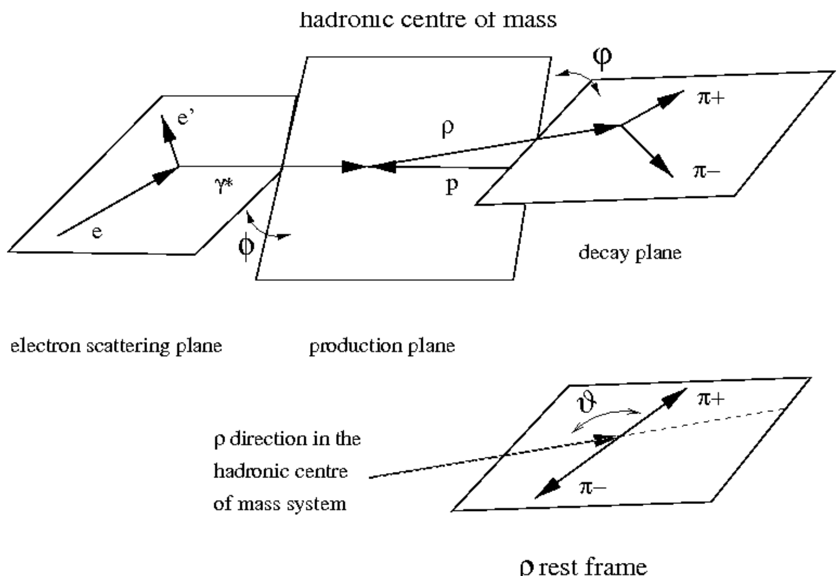
$p_1 = 0.17 \pm 0.03 \pm 0.05$ sensitive to GPDs

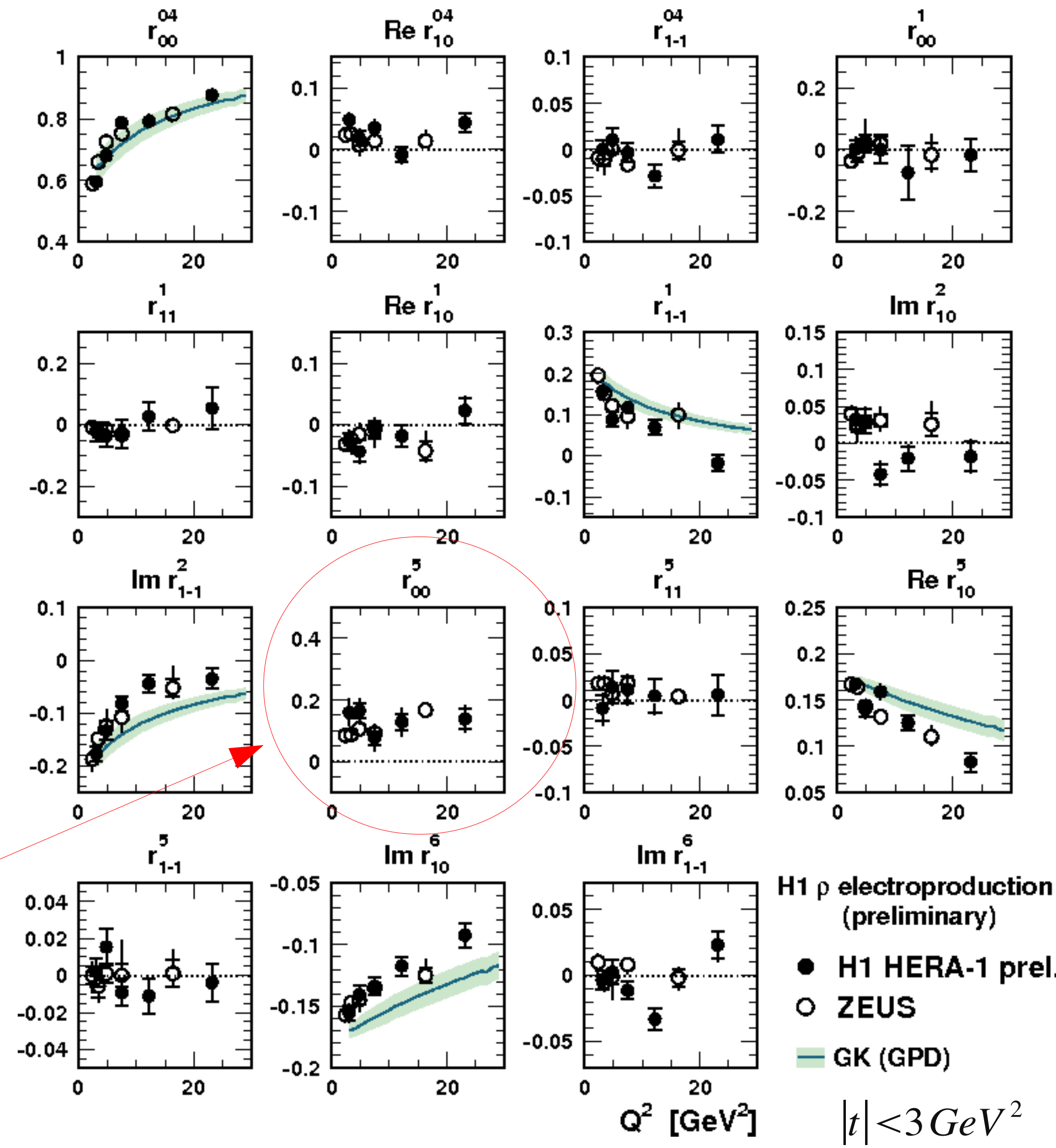
First measurement in the low-x region at HERA



ρ and φ mesons, Helicity Structure

Angular distributions → 15 Spin Density Matrix Elements r^{ij}_{kl} → helicity amplitudes $T_{\lambda_\gamma \lambda_{VM}}$





15 combinations of SDME measured in bins of Q^2 and t (not shown).

Test of *s-channel helicity conservation* (SCHC, observed in soft processes):
VM retains helicity of the photon, the only allowed transitions are: $T_{11}: \gamma_T \rightarrow V_T$, $T_{00}: \gamma_L \rightarrow V_L$

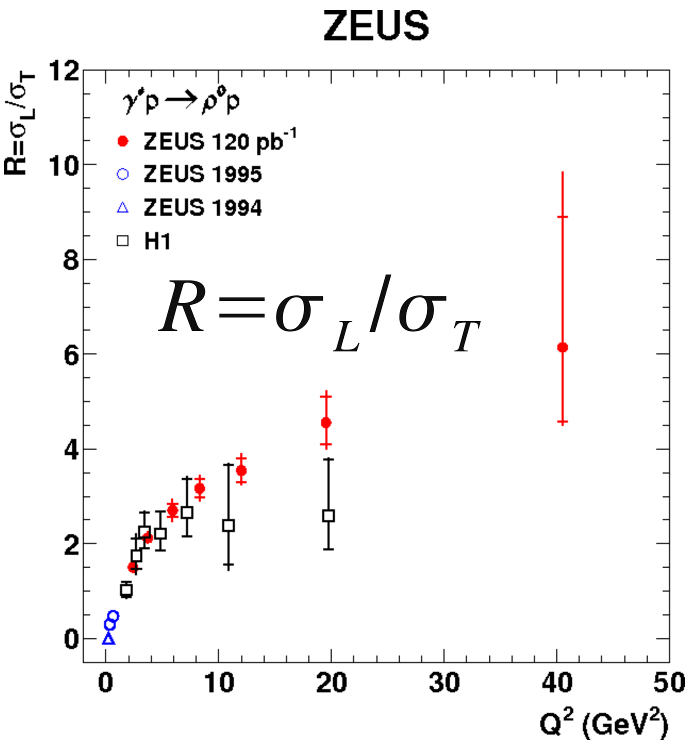
$r^5_{00} \propto T_{01}, T_{0-1}$ violates SCHC
(it measures single helicity flip, $\propto \sqrt{|t|}$)

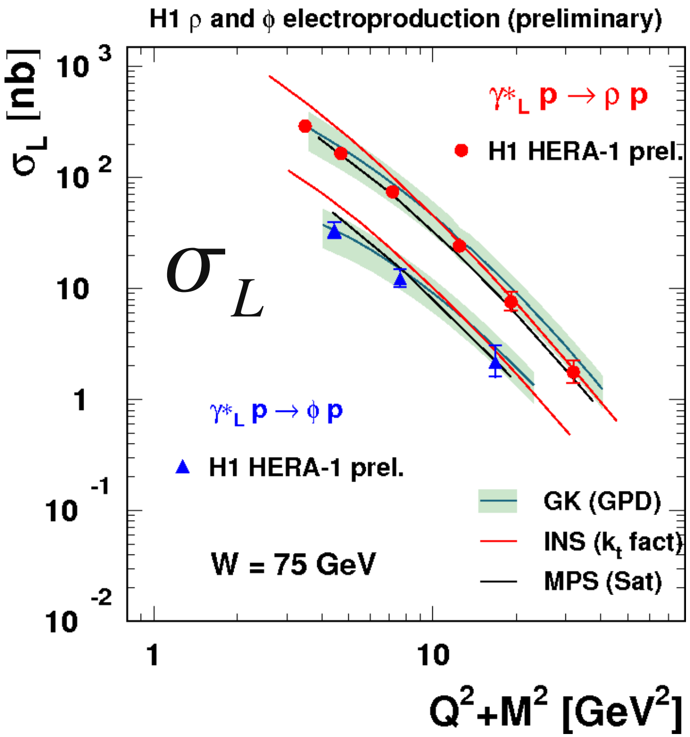
ρ and φ mesons, Polarised Cross Sections

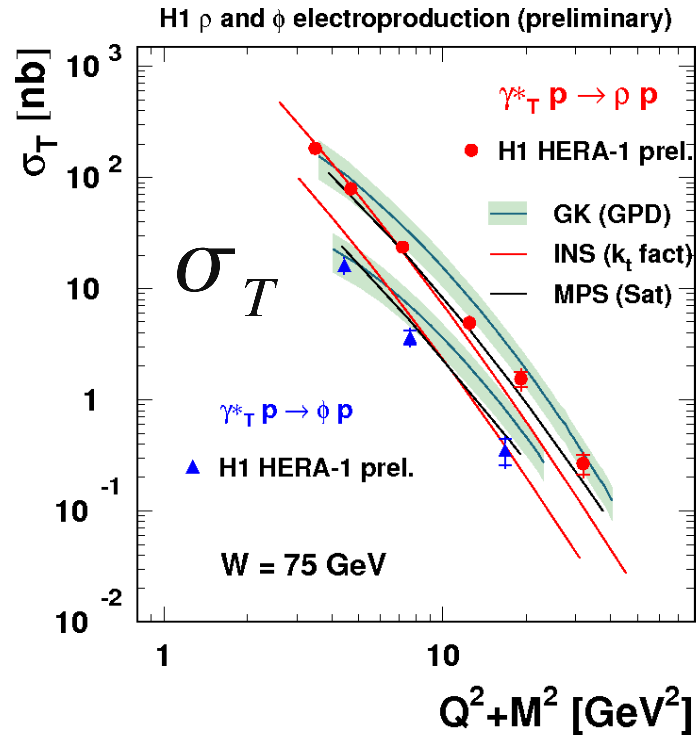
$$\sigma = \sigma_T + \epsilon \cdot \sigma_L \qquad \epsilon \simeq 0.996$$

Vector Meson production processes → unique opportunity to extract $R = \sigma_L / \sigma_T$

R measured from 1DIM angular distributions f($\cos\theta_h$, r^{04}_{00}), in SCHC approximation







R rises with Q^2. σ_L dominates at higher Q^2.

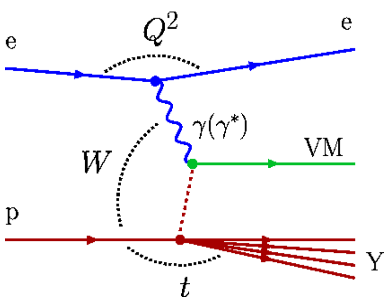
Not shown: R independent of W and t,
R decreases with $M\rho$

σ_L and σ_T have different Q^2+M^2 dependence.

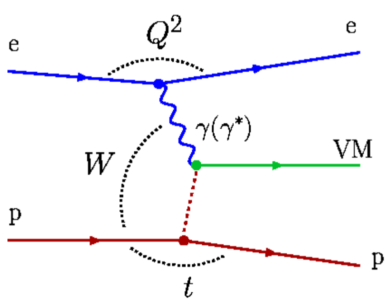
Models based on pQCD describe well σ_L, but not σ_T.

ρ and φ mesons, proton vertex factorisation

H1 test of proton vertex factorisation in DIS regime (shown already by ZEUS for Q^2=0)

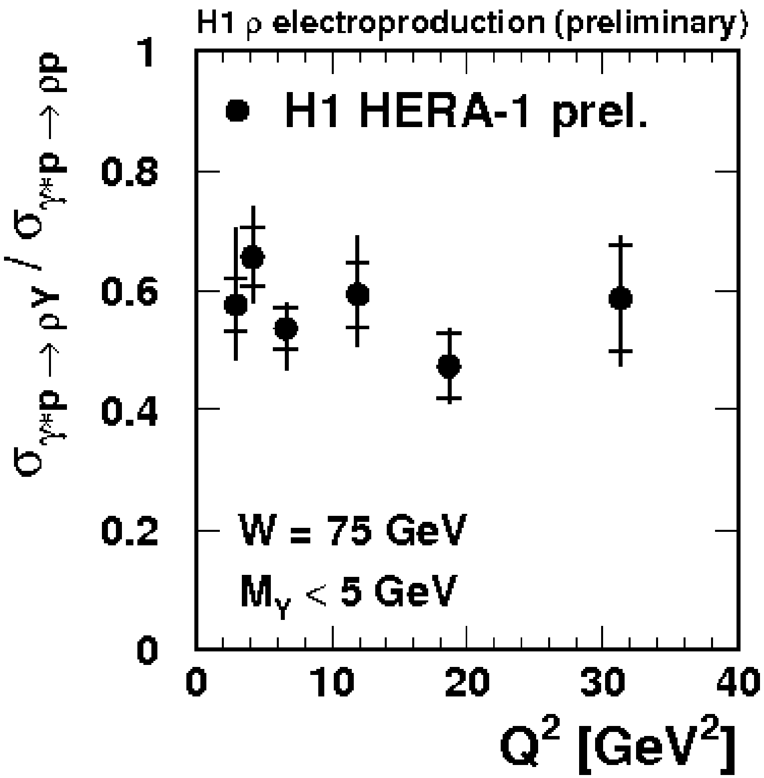


proton dissociative

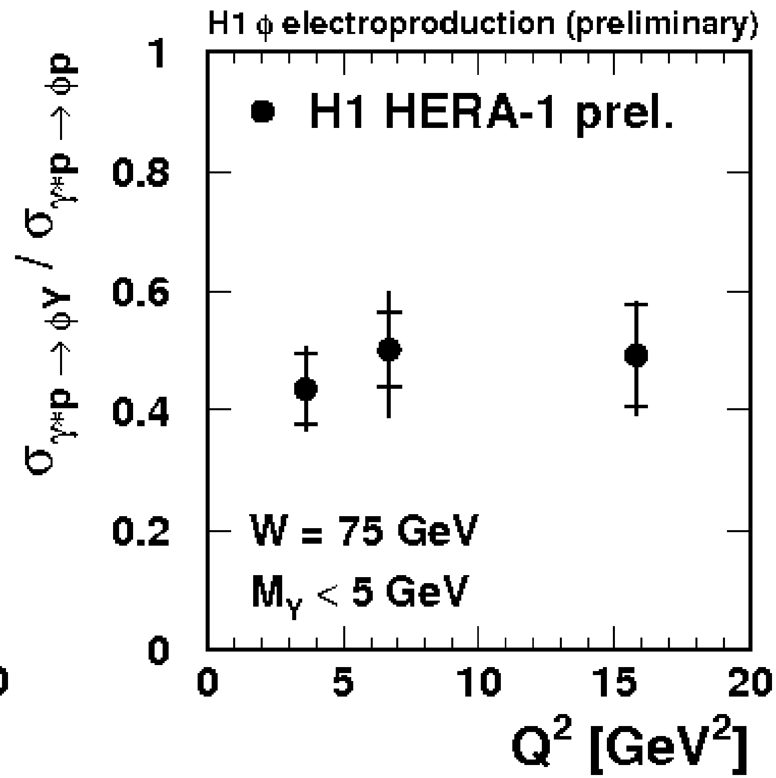


elastic

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



$\gamma^* p \rightarrow \varphi p$



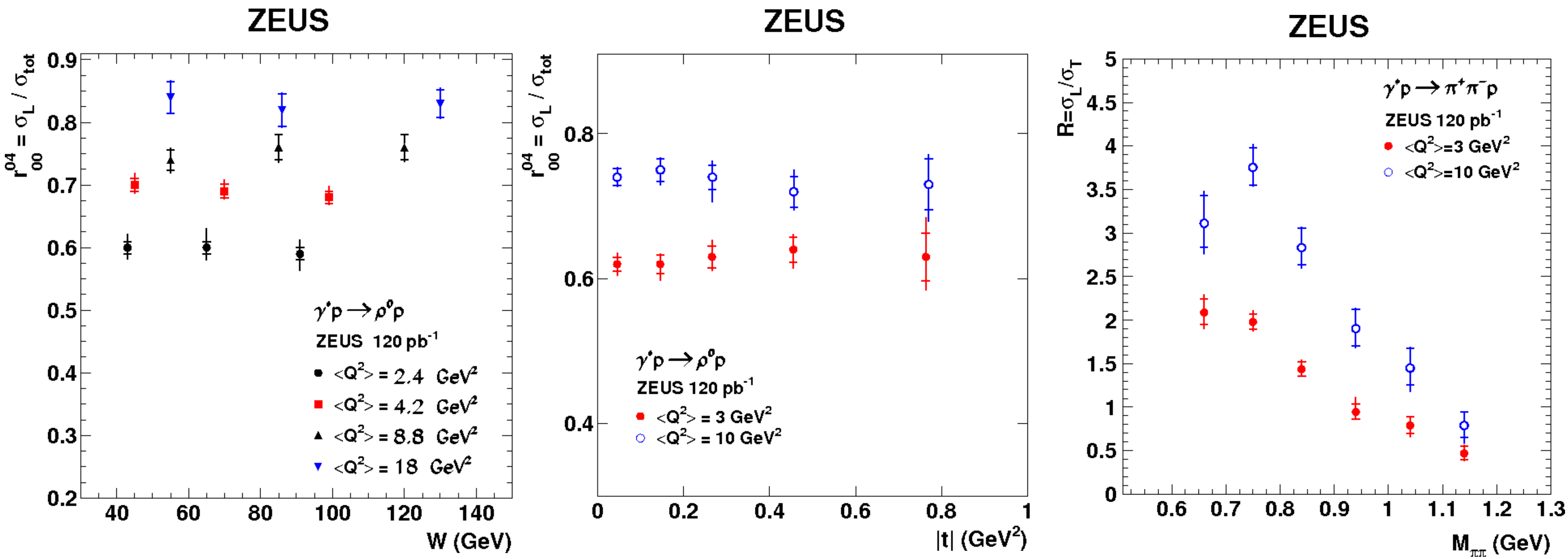
Ratio of p-diss to elastic cross sections consistent with no dependence on Q^2
Similar values for ρ and φ mesons (within errors)
Probability of proton dissociation is independent of the projectile

Summary

- New high statistics measurements of ρ, φ mesons and DVCS
- All observed features are compatible with the expectations of pQCD
  - The cross section is rising with W and the rise becomes steeper as Q^2 or M_v increases
  - The exponential slope of the t distribution is decreasing with Q^2 and levels off at about 5 GeV^{-2}
  - The ratio of cross sections induced by longitudinally and transversely polarised virtual photons increases with Q^2, but is independent of W and t
  - The violation of SCHC is observed for light vector mesons
  - Proton vertex factorisation is observed in DIS regime

- DVCS process is well described by pQCD+GPD model
- Non of the models is able to describe all the features of the data for light vector mesons

ρ and φ mesons, Polarised Cross Sections



Significant dependence of R on M_V

R consistent with no dependence on W and t.

σ_L and σ_T have the same W and t dependence

- the same transverse size of the interaction region (b_L=b_T)
- the same rise of the cross section with energy

... the large spatial configurations of a dipole for σ_T are suppresed in VM production?

ρ and φ mesons, Helicity Structure

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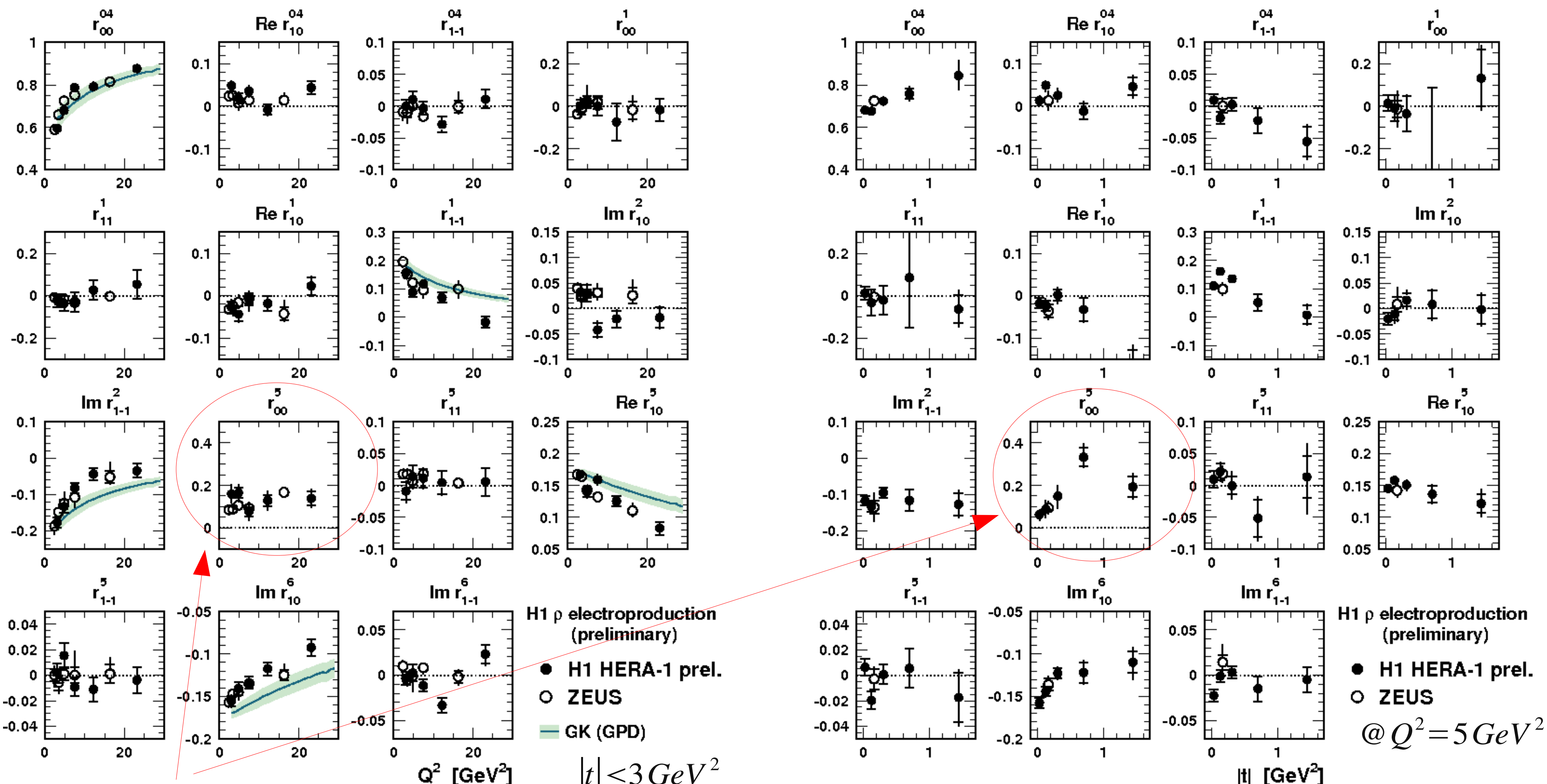
15 combinations of SDME measured in of bins Q^2 and t. Test of *s-channel helicity conservation*, SCHC.
(SCHC: VM retains helicity of the photon, the only allowed transitions are: $T_{11}: \gamma_T \to V_T, \quad T_{00}: \gamma_L \to V_L$)



$r^5_{00} \propto T_{01}, T_{0-1}$ violates SCHC (it measures single helicity flip, $\propto \sqrt{|t|}$)

Increased precision of recent HERA data allows to:

- Study the VM and DVCS dynamics within QCD
- Test QCD in the transition region *soft* → *hard*
- Given factorisation, test pQCD and constrain non-perturbative quantites