



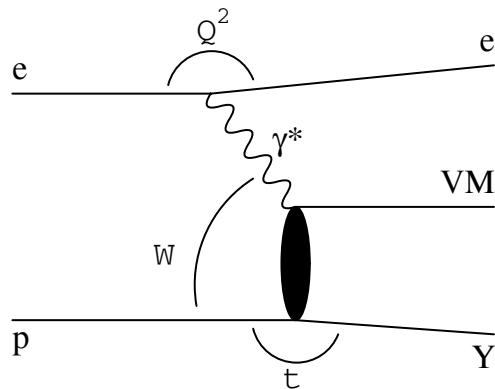
Exclusive (hard) diffraction at HERA (DVCS and Vector Mesons)



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The HERA harvest



initial state : real and virtual photons

final state VM : $\gamma, \rho, \phi, J/\psi, \psi(2s), Y$

final state baryonic syst.: p, p. diss.

M_V 0 – 10 GeV

Q^2 0 – 80 GeV²

$W \approx \sqrt{(Q^2/x)}$ 30 – 300 GeV

$|t| = |p_{t,miss}|^2$ 0 – 30 GeV²

photoproduction & DIS

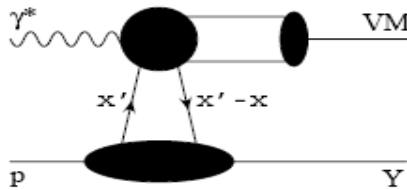
small ($< 0.5 - 3 \text{ GeV}^2$) & large $|t|$ ($2 < |t| < 10-30 \text{ GeV}^2$)

> 30 H1 + ZEUS published exp. papers most recent results (2008-2009)

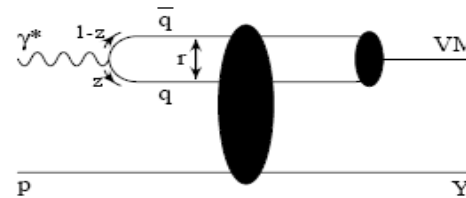
- DVCS ZEUS (LPS) + H1 DESY-08-132 + H1-prelim-09-014
- ρ photoprod. H1 H1-prelim-09-016
- ρ and ϕ electroprod. H1 DESY-09-093 (to appear soon)
- Y photoprod. ZEUS DESY-09-036
- real γ at large $|t|$ H1 DESY-08-077

Context

QCD frameworks



collinear factorisation (GPD)



proton rest frame factorisation (dipole approach)

scale $\mu^2 = z(1-z)(Q^2 + M^2)$

- long. amplitudes $z \approx 1-z \approx 0.5 \Rightarrow \mu^2 \approx (Q^2 + M^2)/4$
- transv. amplitudes $\mu^2 < (Q^2 + M^2)/4$

Content

DVCS

$d\sigma / dQ^2, dW, dt$ (small t)

VM helicity amplitudes

elast. / proton diss.; Regge factorisation

$d\sigma / dW, dt$ (large t); helicity amplitudes

Event selection and backgrounds

Photoprod. ($Q^2 \sim 0$) / electroprod. ($Q^2 > 1 \text{ GeV}^2$) : absence / presence of electron cand.

VM selection : 2 tracks + inv. mass selection

elastic events : LPS (ZEUS) or no tag in forward detectors (H1, Zeus) $|t| < 0.5 \text{ GeV}^2$

proton dissociation : tag events, $|t| < 3 \text{ GeV}^2$

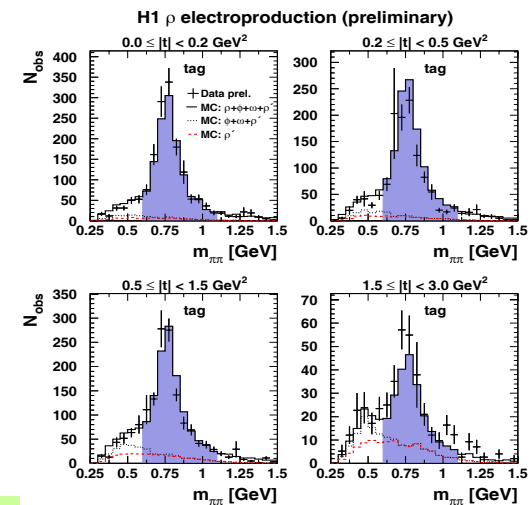
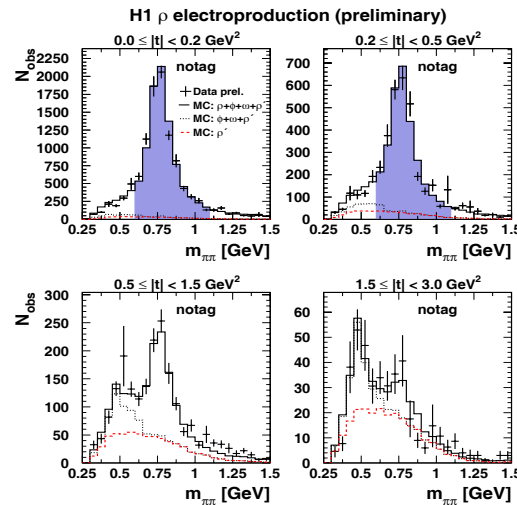
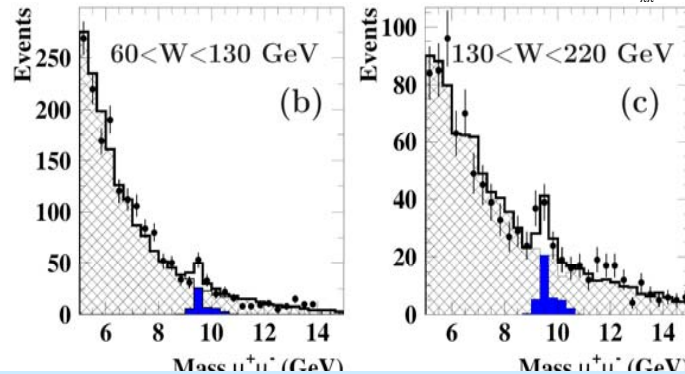
backgrounds:

elastic \leftrightarrow p. diss. events

other VM's (ρ')

continuum

Y

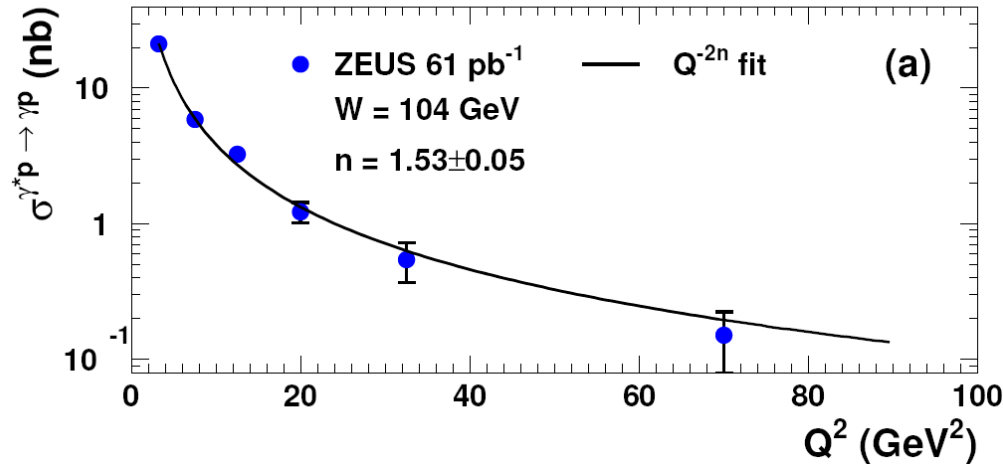


ρ

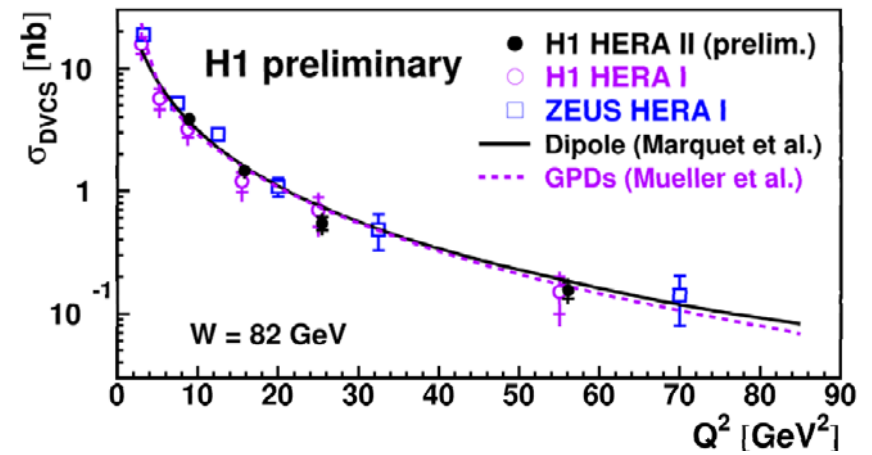
DVCS

Q² dependence

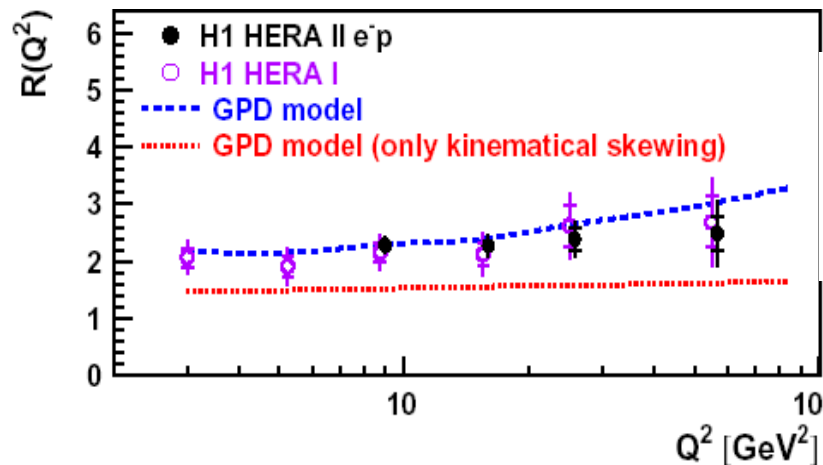
ZEUS LPS



GPD and dipole models



GPD take into account
skewing
but kin. skewing is
not sufficient



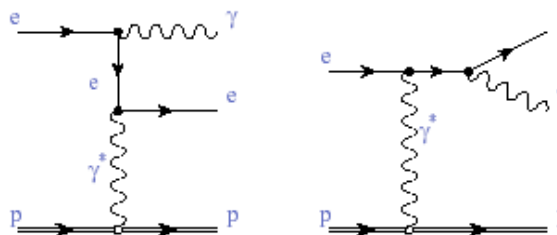
$$R = \frac{\text{Im} A(\gamma^* p \rightarrow \gamma p)}{\text{Im} A(\gamma^* p \rightarrow \gamma^* p)}$$

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

Re / Im (BCA)

interference with Bethe-Heitler

→ access to **Re contributions**



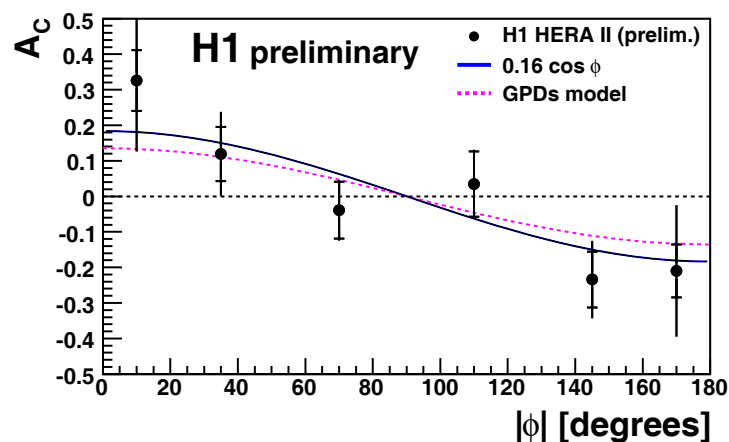
Beam charge asymmetry (e^+ vs. e^-)

$$A_C = \frac{d\sigma^+/d\phi - d\sigma^-/d\phi}{d\sigma^+/d\phi + d\sigma^-/d\phi} = 2A_{BH} \frac{\text{Re}A_{DVCS}}{|A_{DVCS}|^2 + |A_{BH}|^2} \cos \phi.$$

$$\rho = \text{Re} A_{DVCS} / \text{Im} A_{DVCS} = 0.20 \pm 0.05 \pm 0.08$$

in agreement with dispersion relation analysis

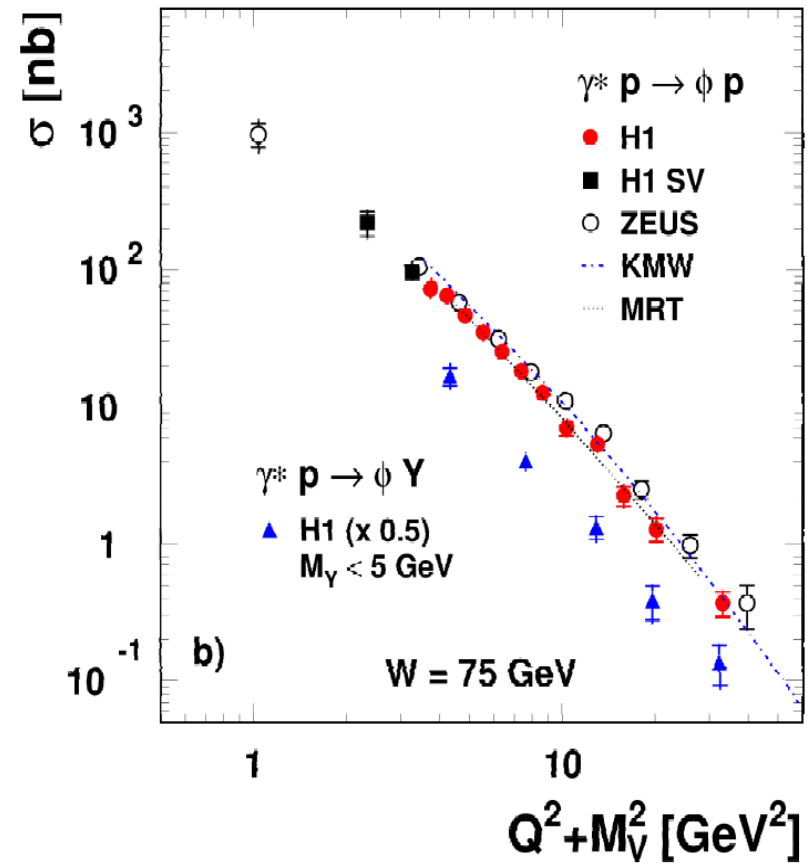
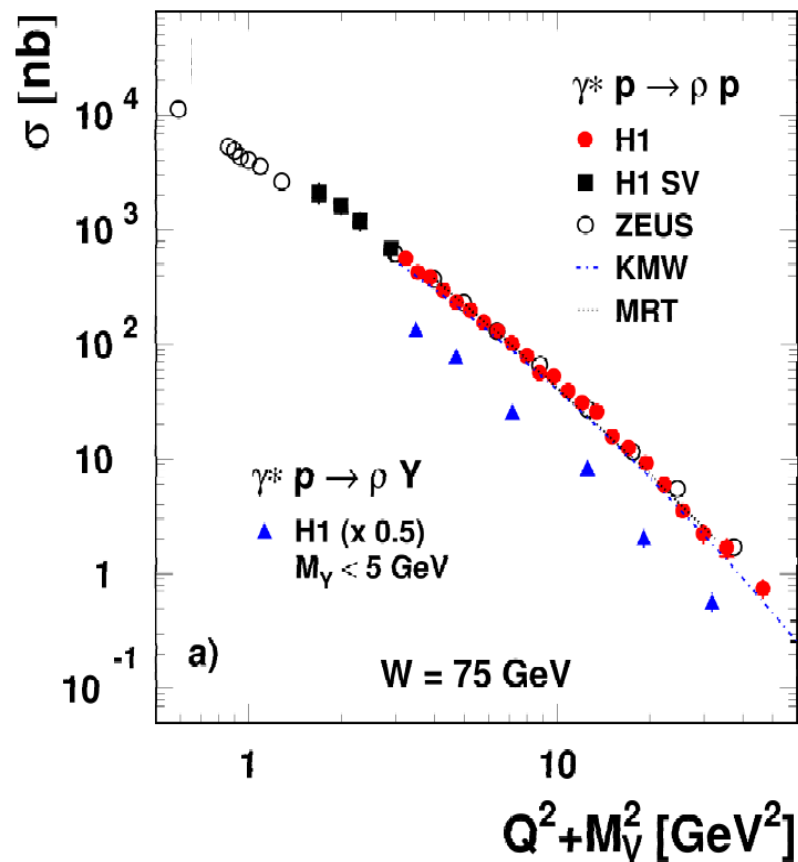
$$\rho = \tan(\pi \delta(Q^2) / 8) = 0.25 \pm 0.03 \pm 0.05$$



W, t dependences; effective Regge trajectory : see below

Q^2 dependences (VM)

ρ and ϕ (el. and p. diss.)



Excellent ZEUS-H1 agreement on total cross sections

(also for ϕ with ZEUS p. diss. bg. subtraction as for ρ)

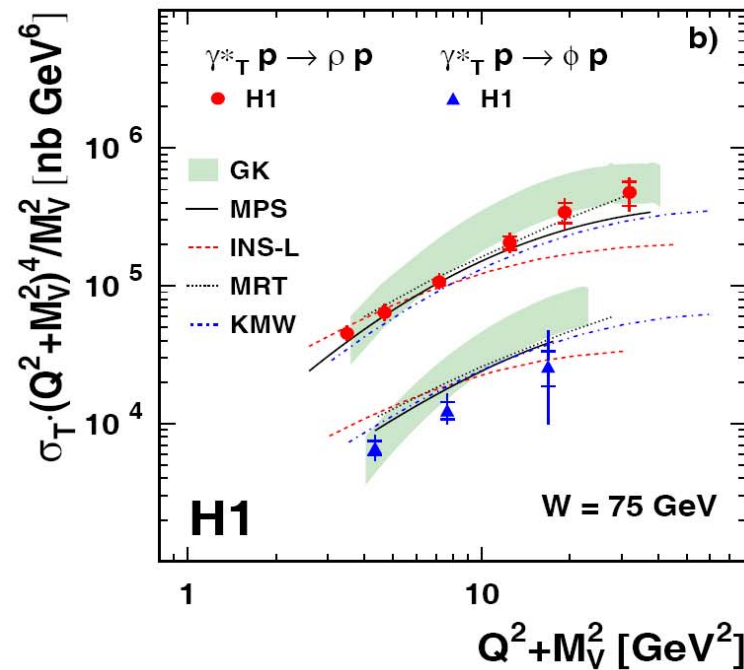
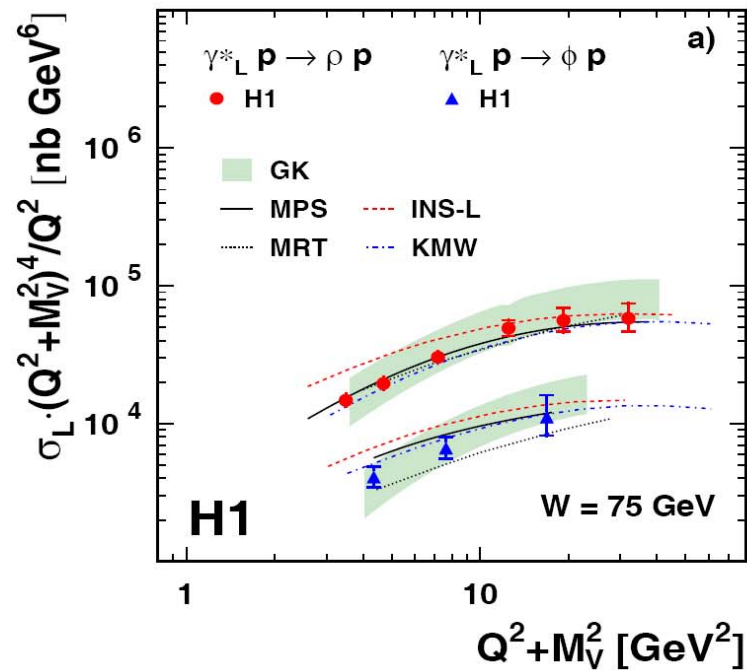
ρ and ϕ – polarised cross sections

$$\sigma_L \propto |xG(x)|^2 / (Q^2 + M_V^2)^4$$

$$R = \sigma_L / \sigma_T \propto Q^2 / M_V^2$$

$$\Rightarrow \text{formally } \sigma_L \propto 1/Q^6, \quad \sigma_T \propto 1/Q^8$$

but Q^2 dependence of $|xG(x)|^2$ (and of R)



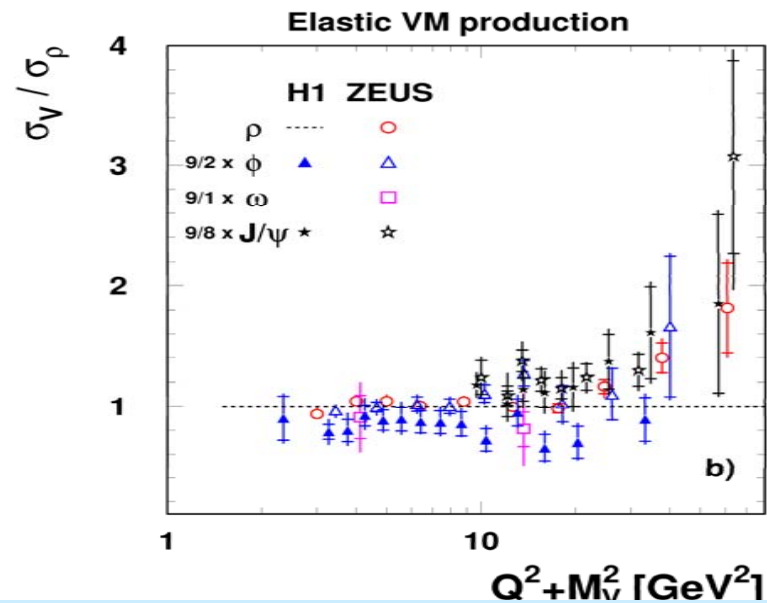
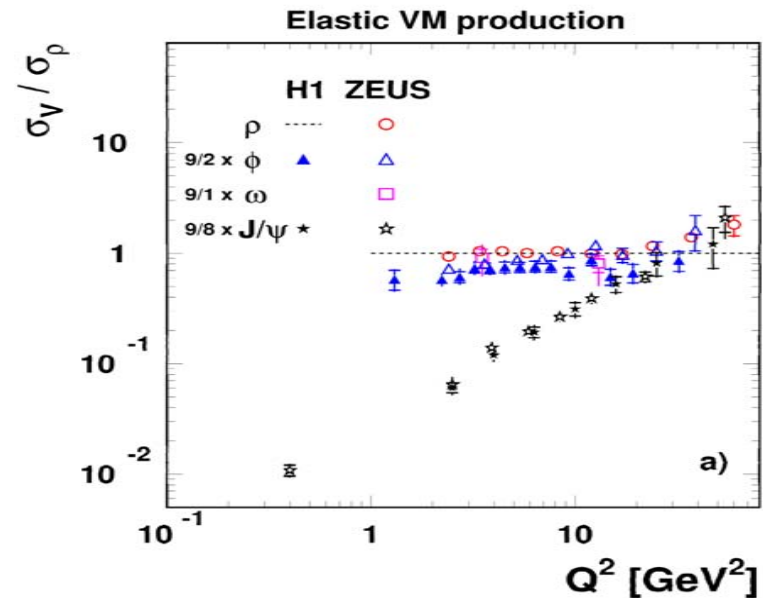
NB fixed W , varying x

(approximate) universality

Cross sections scaled by
quark charge content

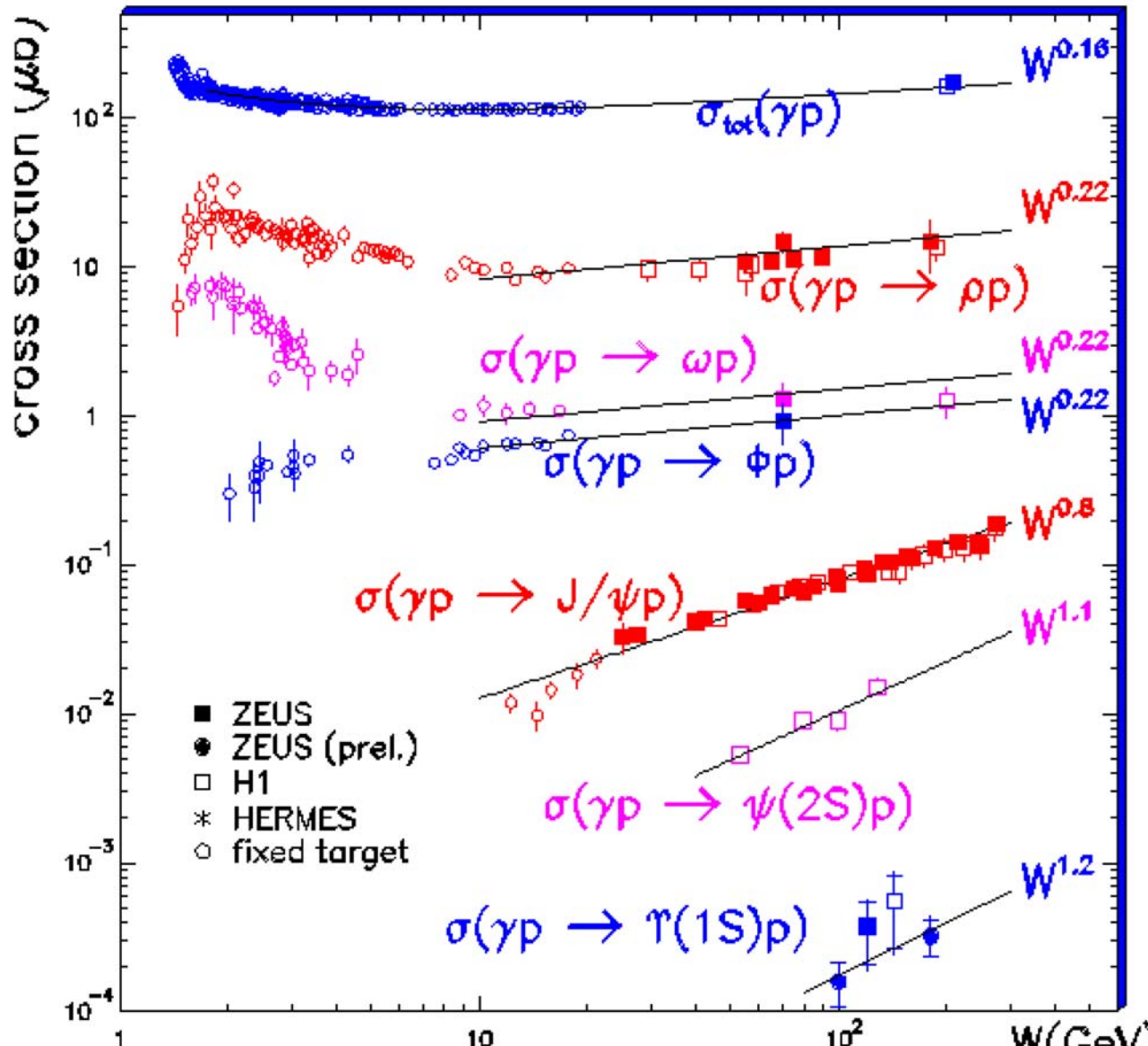
Very strong Q^2 dependence

approximate universality
as a function of Q^2+M^2



W dependences

Photoproduction : mass dependence



$$\sigma \propto W^\delta$$

soft

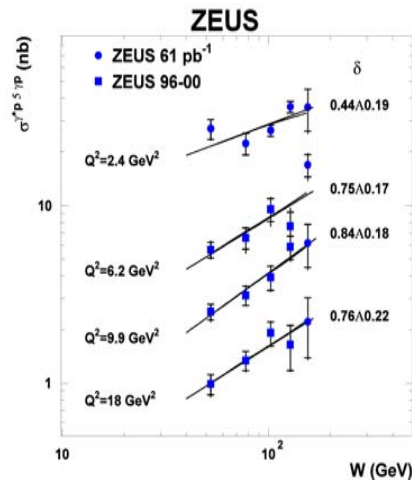
σ_{tot}
 ρ, ω, ϕ

hard

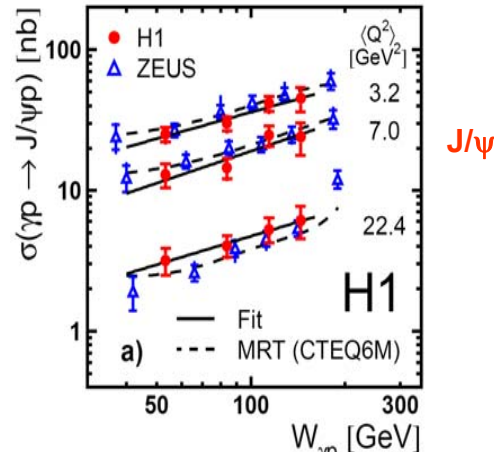
J/ Ψ

Υ
(skewing,
Re \rightarrow GPD)

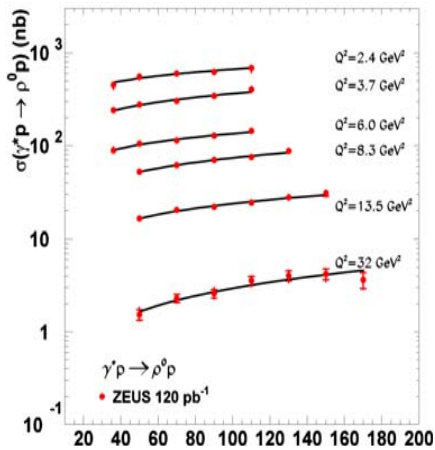
DVCS and electroprod.: Q^2 dependence



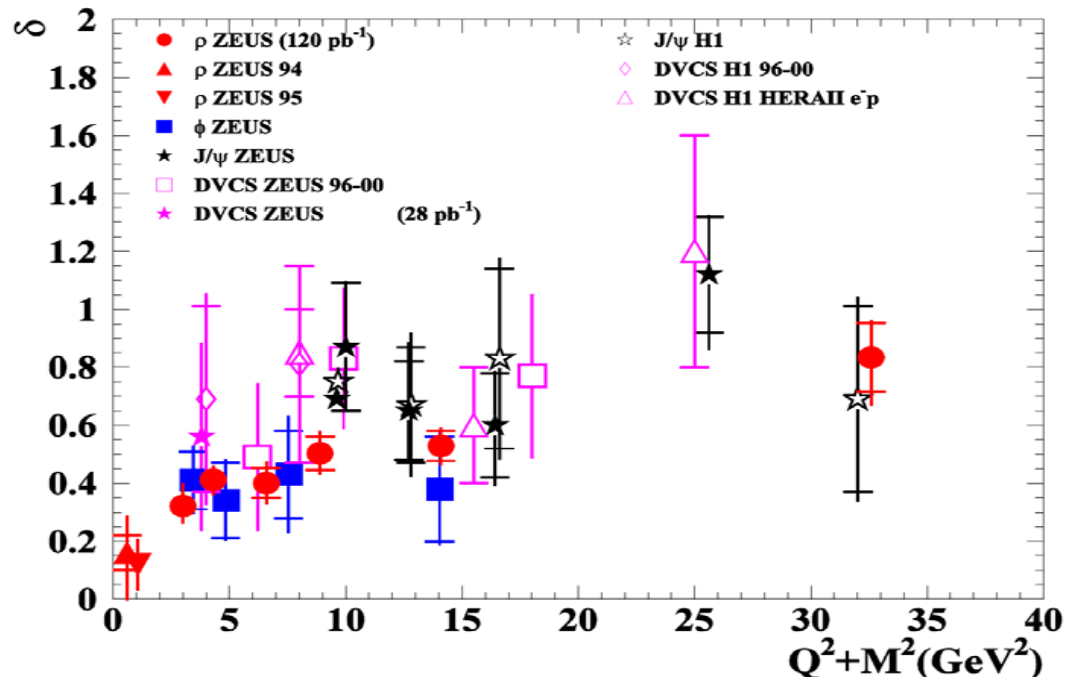
DVCS



J/ψ



ρ

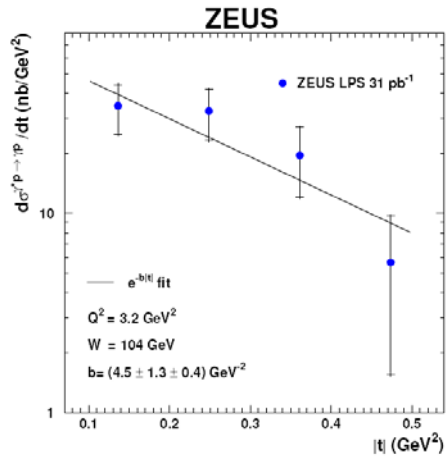


see below – effective Regge trajectory

t dependences

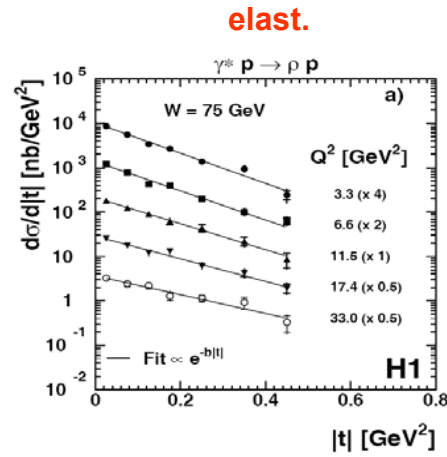
t dependences

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

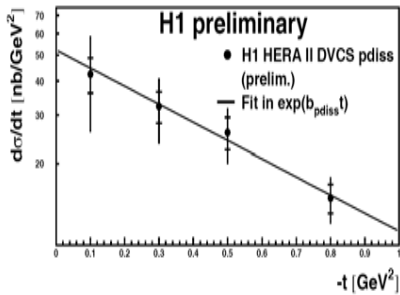
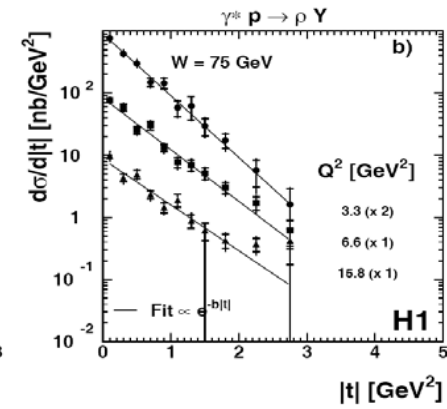


**DVCS
(LPS)**

ρ

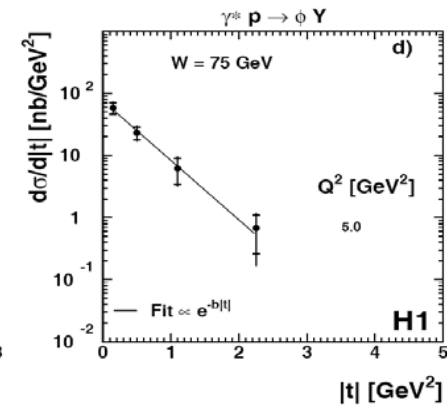
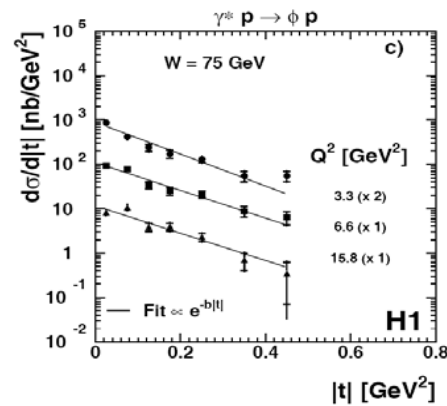


p. diss.

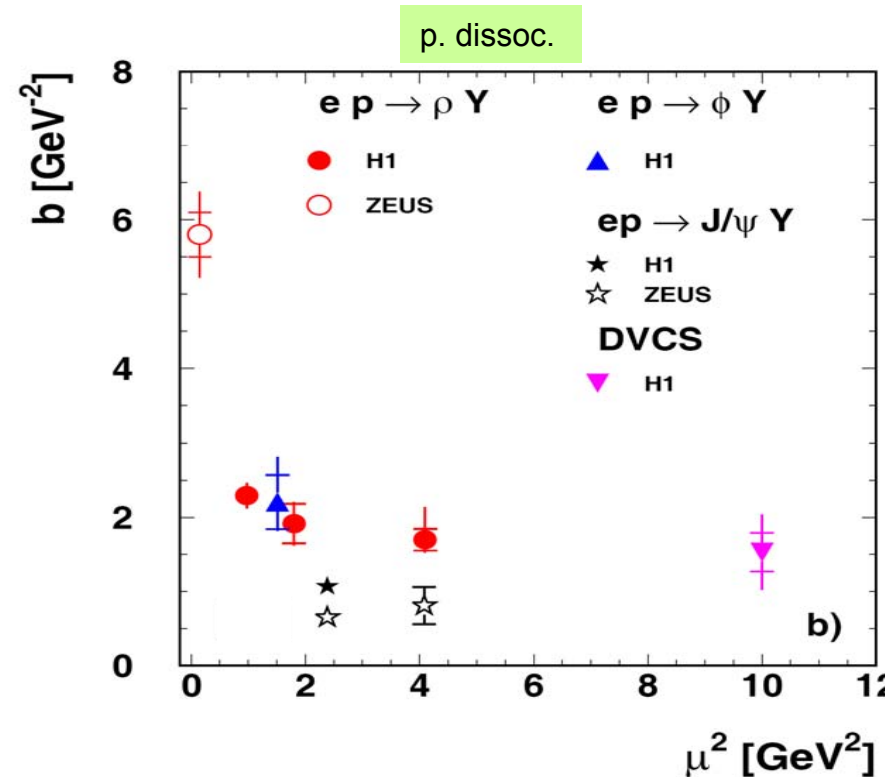
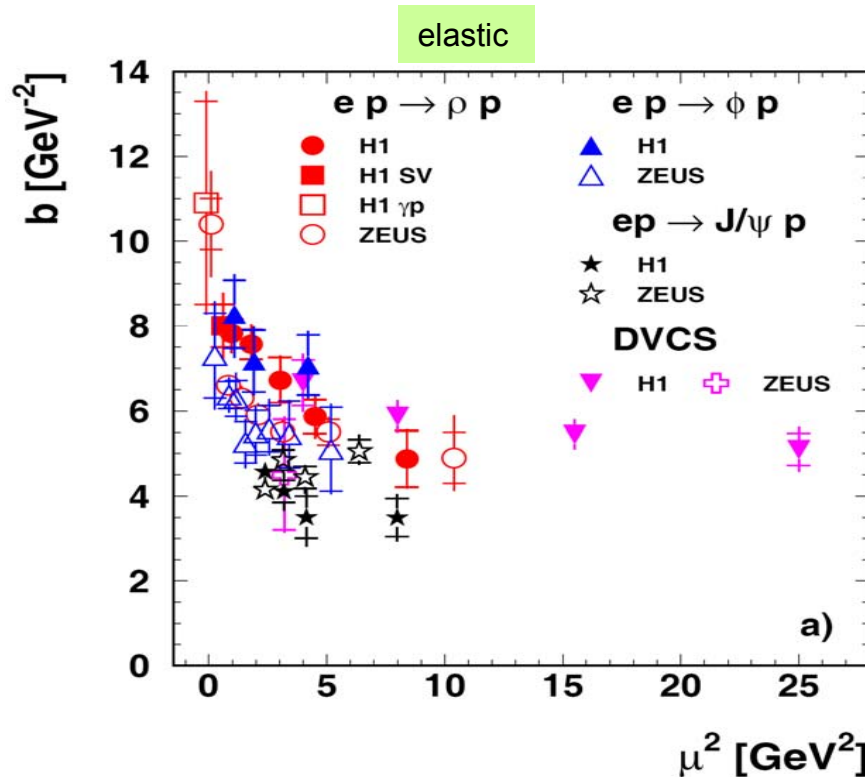


**DVCS
(p. diss.)**

ϕ



b slopes



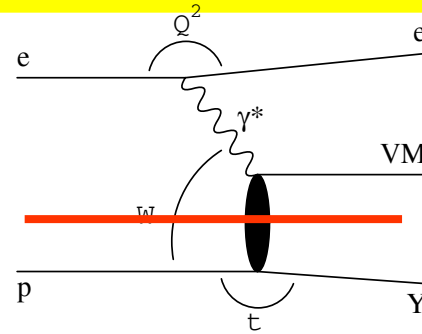
optical model

$$b = b_{dipole} + b_{exch} + b_Y (+b_{VM})$$

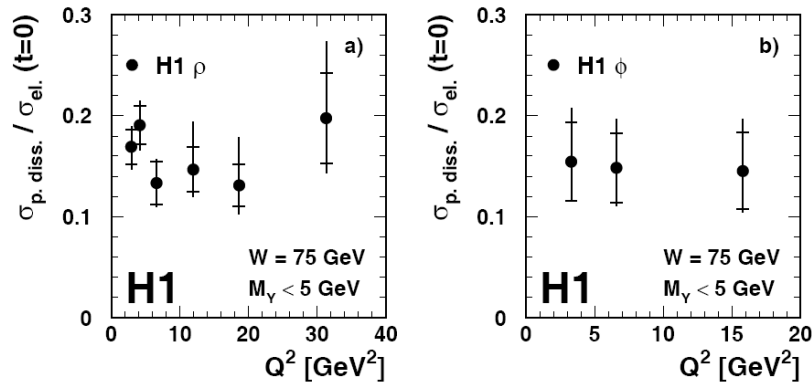
- b decrease with **dipole size** (Q^2 , m_q)
- **universal scale dependence** for $\mu^2 > 5 \text{ GeV}^2$ $\mu^2 = (Q^2 + M^2)/4$ for VM
 $\mu^2 = Q^2$ for DVCS
- $b(\rho, \phi \text{ at large } Q^2) \rightarrow b(J/\psi) \rightarrow$ small room for VM form factor b_{VM}

$b_{el} - b_{pd}$ and Regge factorisation

Vertex (“Regge”) factorisation



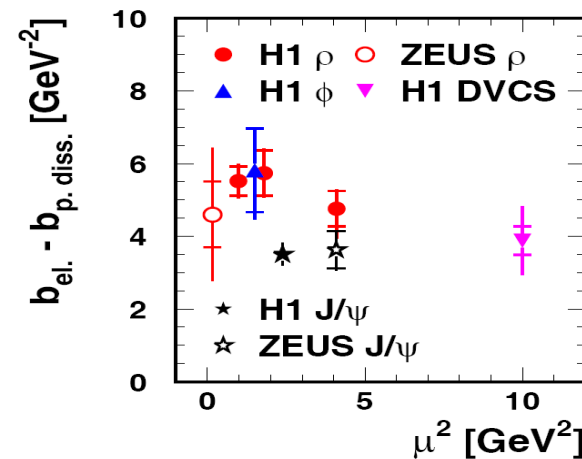
➤ $\frac{d\sigma / dt (\text{p.diss.})}{d\sigma / dt (\text{elast.})} (t=0)$ indep. of Q^2



➤ $b_{el.} - b_{p.diss.}$

$b_{el.} - b_{p.diss.} \sim \text{cte} (?) \sim 5.5$ for ρ, ϕ
 $= 4$ for DVCS ($\mu^2 = Q^2$)
 $= 3.5$ for J/ψ

-> factorisation for $\mu^2 > 5 \text{ GeV}^2$?



Effective Regge trajectory

Effective trajectory

✓ **W dependence**

$$\sigma \sim W^\delta \quad \delta = 4 (\alpha(t) - 1) \quad \alpha(t) = \alpha(0) + \alpha' t$$

✓ **shrinkage of diffractive peak**

W – t correlation

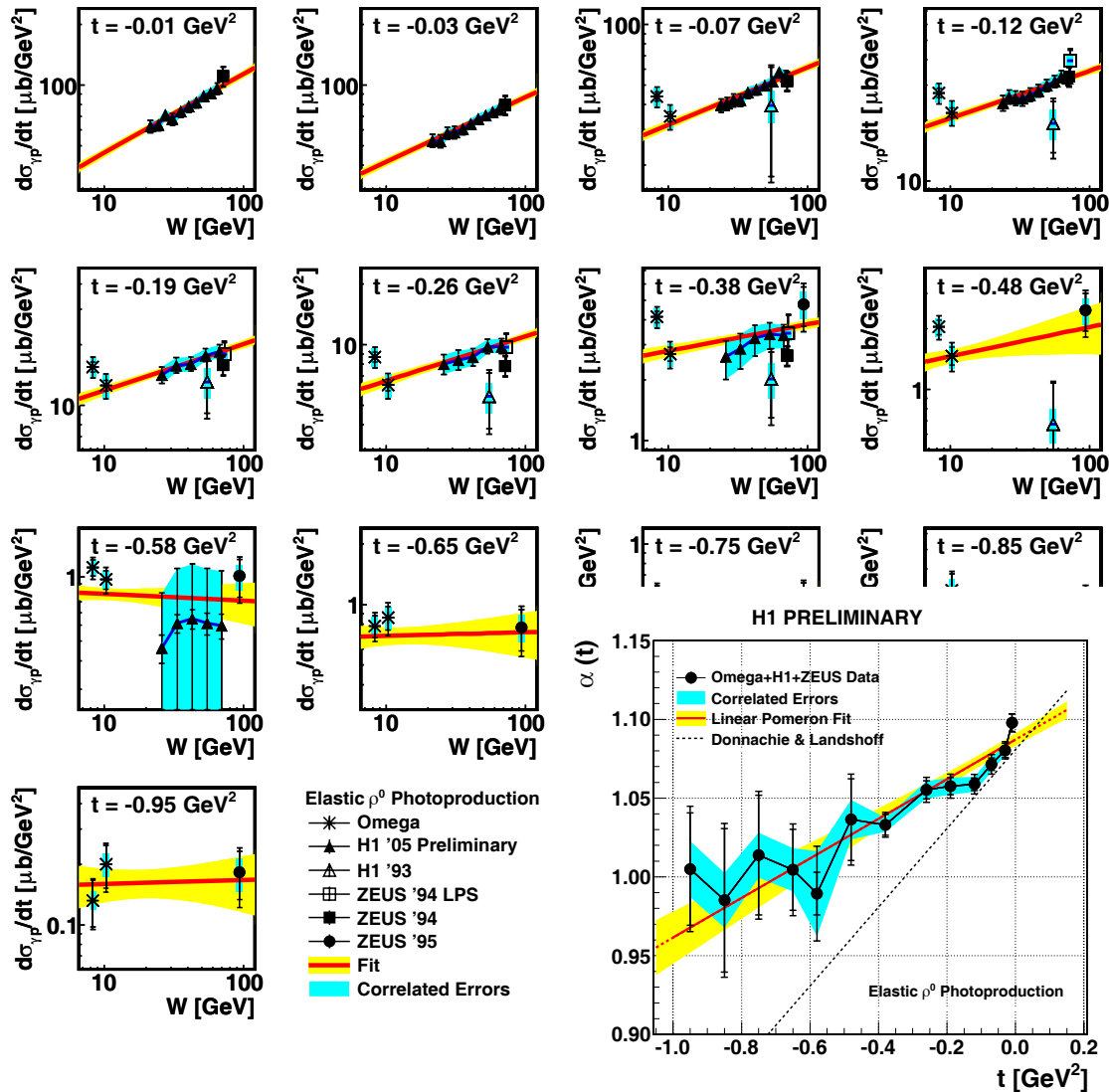
t dependence as a function of *W* *W* dependence as a function of *t*

$$\frac{d\sigma}{dt}(W) = e^{bt} = e^{b_0 t} W^{4(\alpha(0) + \alpha' t - 1)}$$

$$b = b_0 + 4 \alpha' \ln(W / W_0)$$

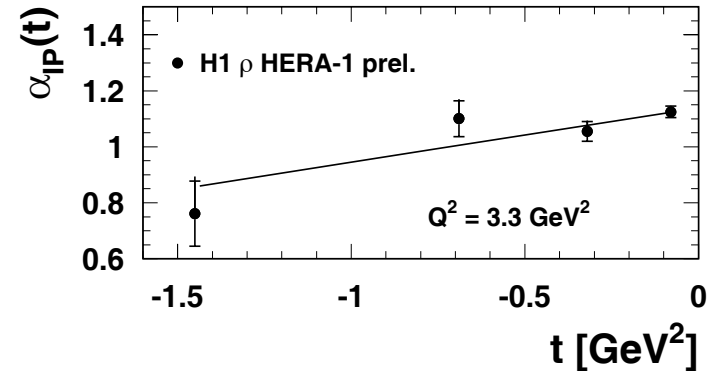
Shrinkage

H1 PRELIMINARY

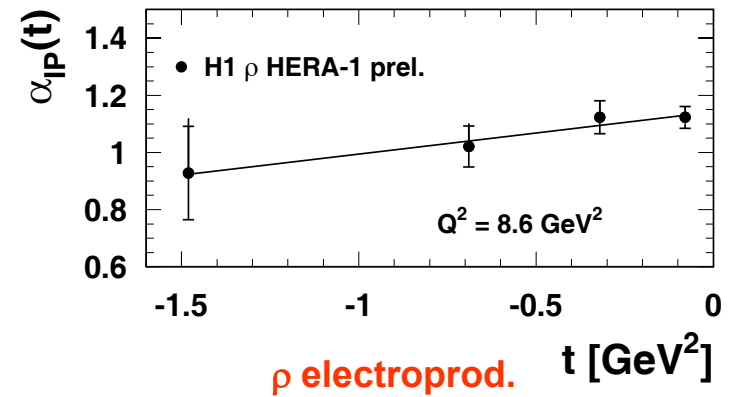


ρ photoprod.

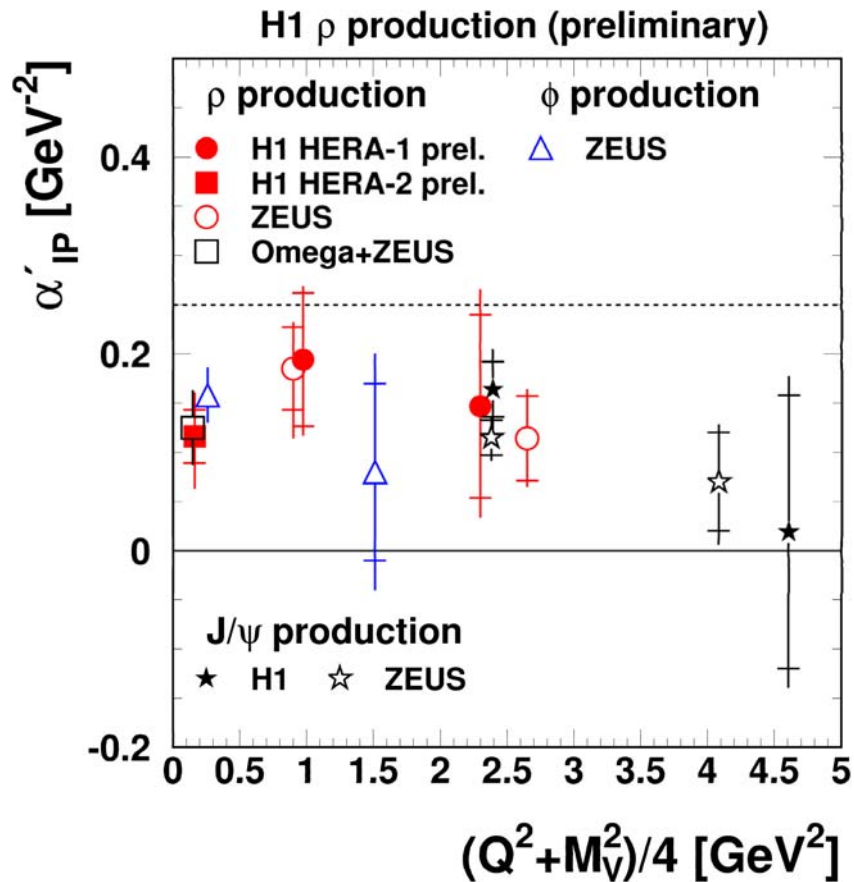
H1 ρ electroproduction (preliminary)



H1 ρ electroproduction (preliminary)



α' slope



hadron-hadron inter. : $\alpha' = 0.25 \text{ GeV}^{-2}$

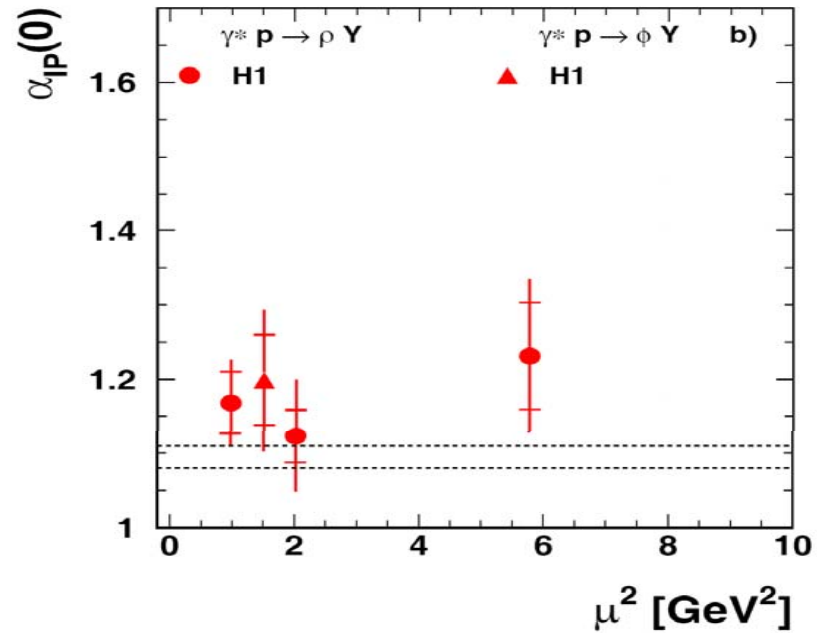
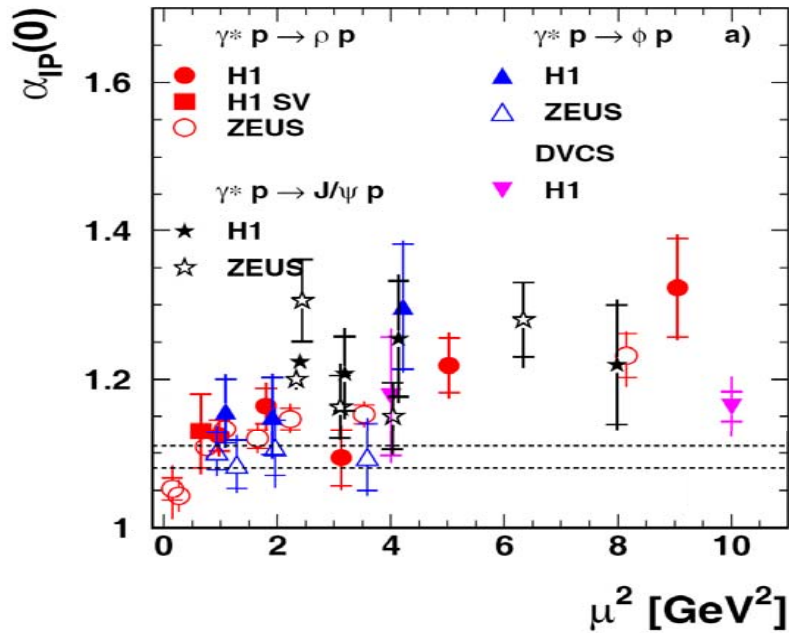
H1 DVCS : $\alpha' = 0.03 \pm 0.09 \pm 0.11 \text{ GeV}^{-2}$

NB J/ ψ $2 < |t| < 30 \text{ GeV}^2$ photoprod.,

$$\alpha' = -0.02 \pm 0.01 \pm 0.01 \text{ GeV}^{-2} \text{ (H1 + ZEUS)}$$

$\alpha_P(0)$

$$\sigma \propto W^\delta \quad \delta = 4(\alpha(t) - 1) \quad \alpha(t) = \alpha(0) + \alpha' t$$

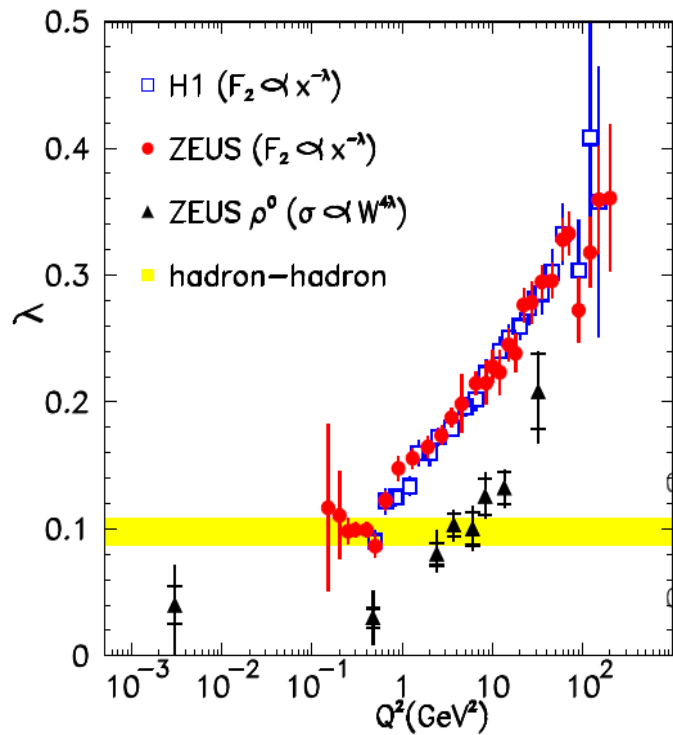


$$\mu^2 = (Q^2 + M^2)/4 \text{ for VM} \quad \mu^2 = Q^2 \text{ for DVCS}$$

hardening with Q^2 and mass (dipole size)

light VM : getting similar to J/ψ for μ^2 larger than about **5 GeV²**

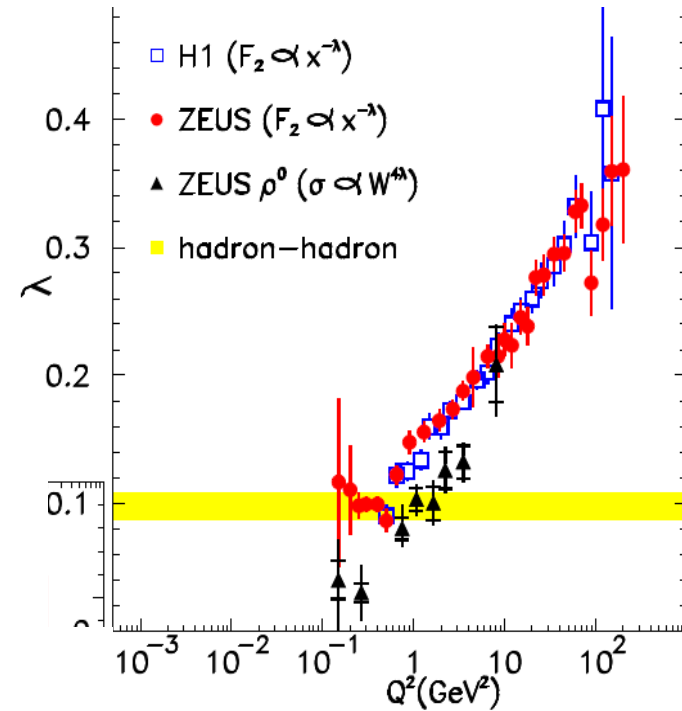
Remark on scales



$$Q_{eff}^2 = Q^2$$

April 2009 ,28

A. Levy: Exclusive VM, DIS09,
Madrid



$$Q_{eff}^2 = \frac{Q^2 + M^2}{4}$$

24

Helicity amplitudes

spin density matrix elements

3 angles describe VM production and decay

→ **15 spin density matrix elements**

bilinear combinations of

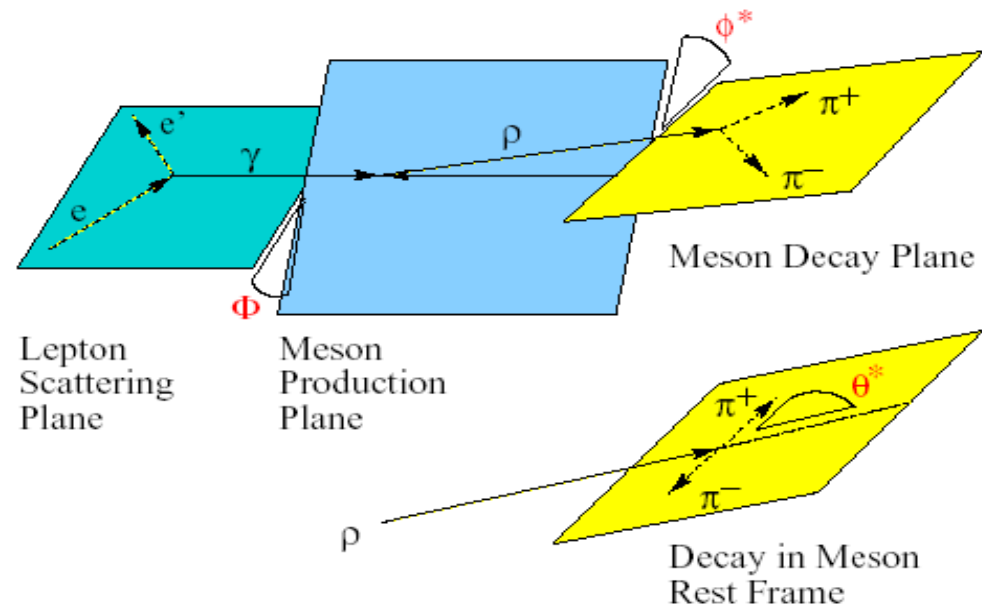
helicity amplitudes $T_{\lambda\rho,\lambda\gamma}$

(NPE is assumed)

SCHC T_{00} T_{11}

single flip T_{01} T_{10}

double flip T_{-11}



spin density matrix elements (Q^2) (ρ)

5 SCHC elements

compared to GPD calculations

Other elements (dashed lines) compatible with 0 or small

except $\sim T_{01} T_{00}^*$

several models

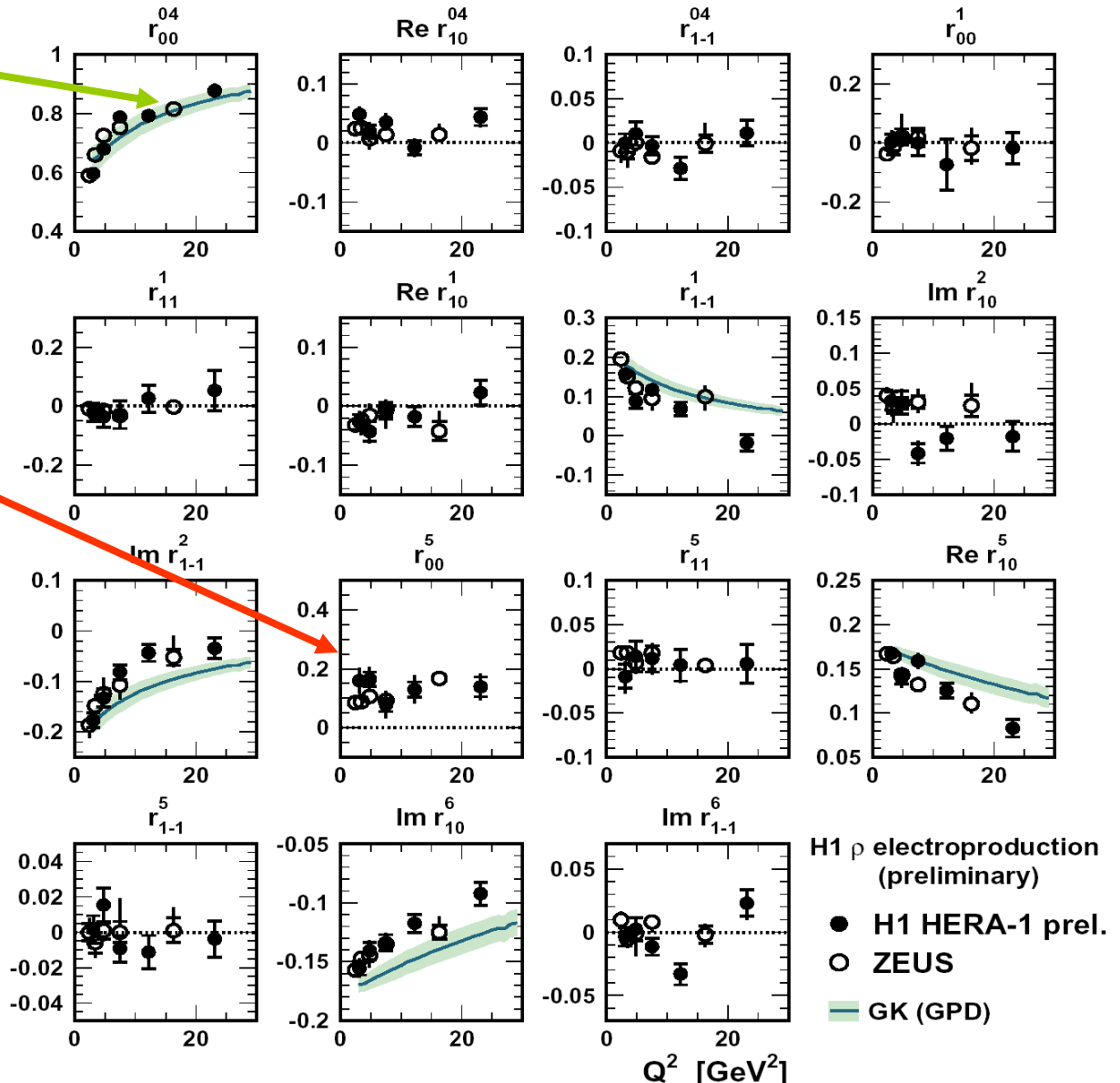
(GPD, unintegrated k_t ,

dipole + saturation)

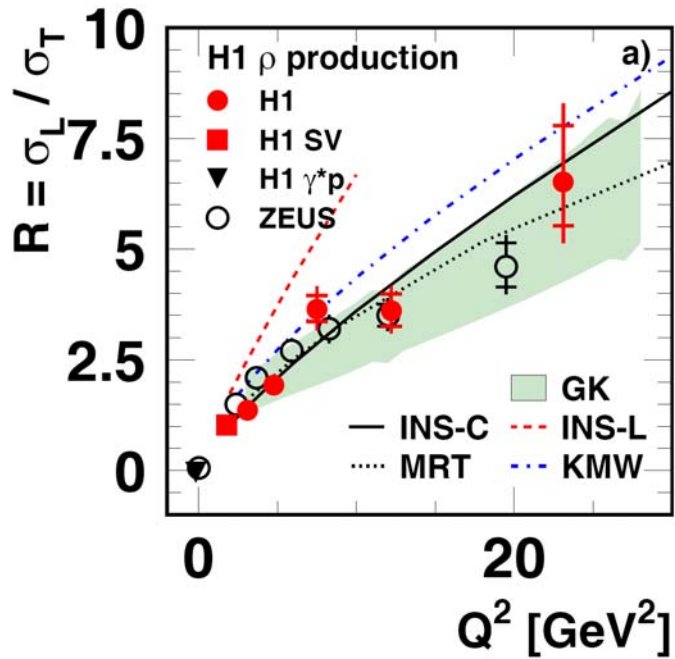
can reproduce

general features of
SCHC amplitudes + hierarchy

but not details



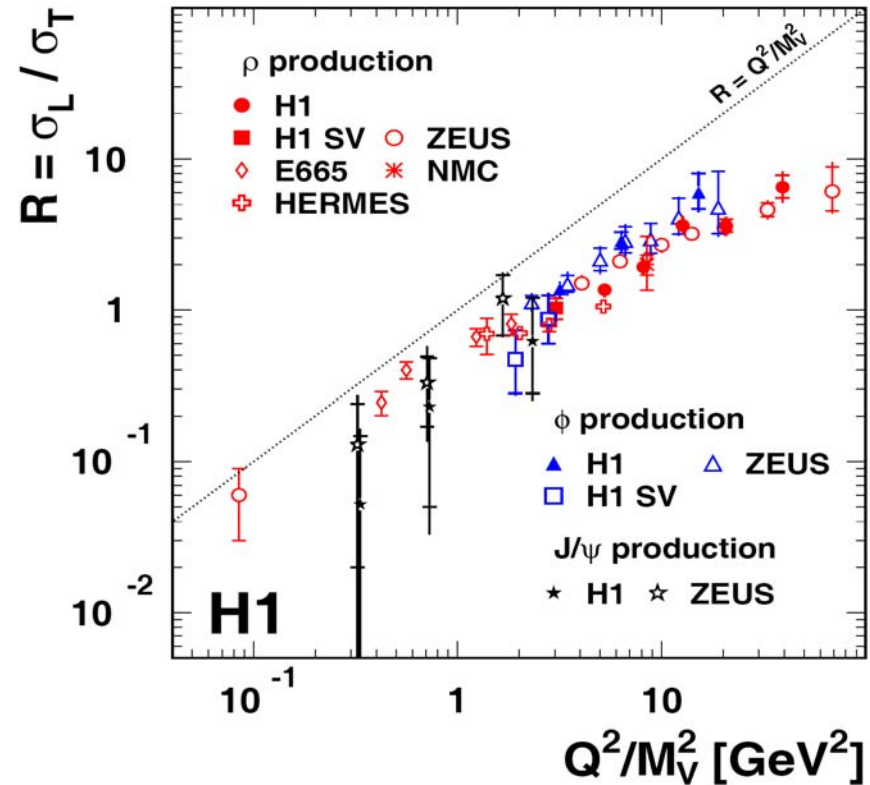
$R(Q^2) ; Q^2 / M^2$



pQCD : formally $R \sim Q^2 / M^2$
 scaling plot (Q^2 / M_V^2)

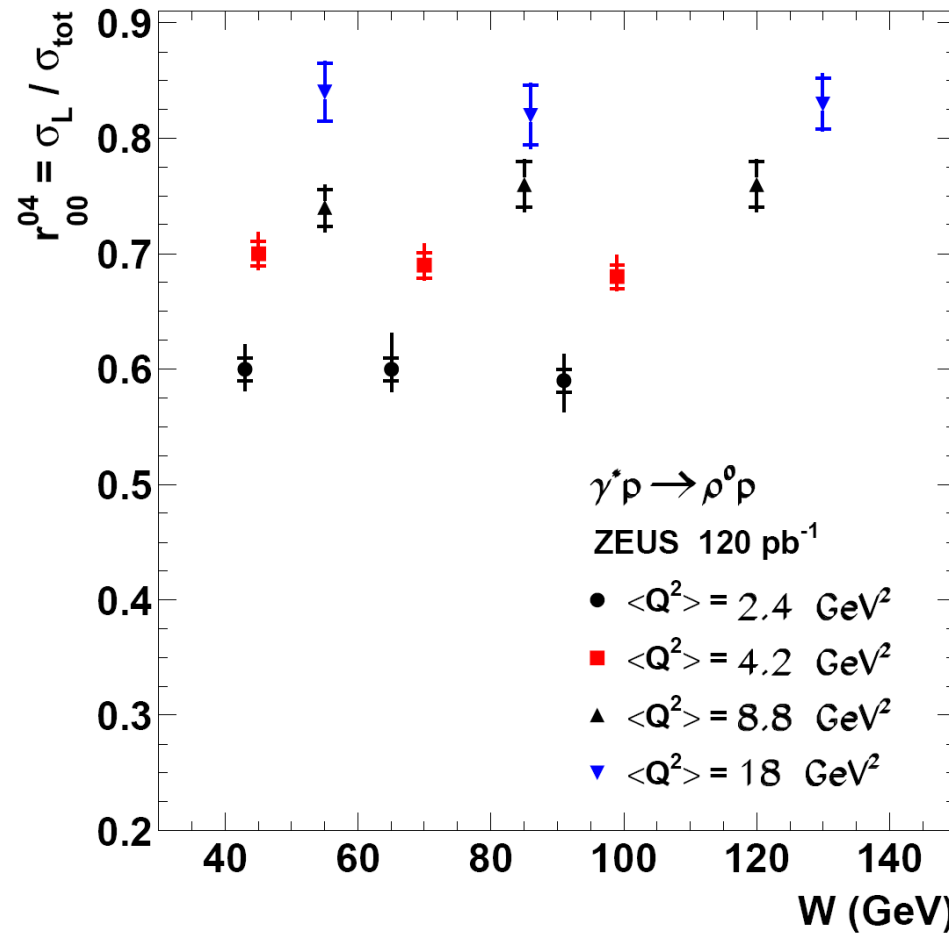
- scaling OK
- lower than 1
- damping at large Q^2

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

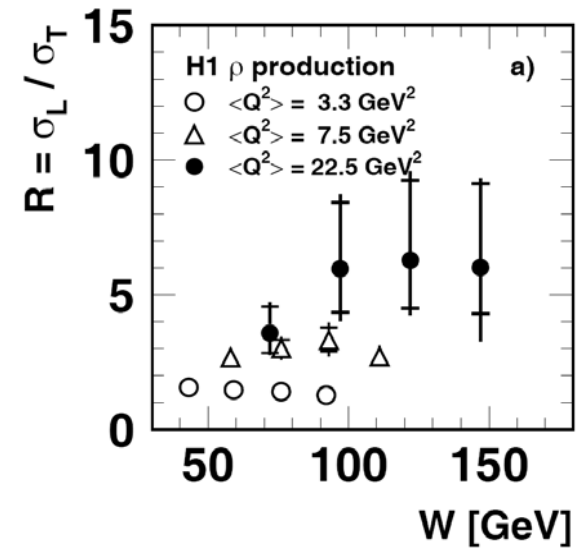


R(W)

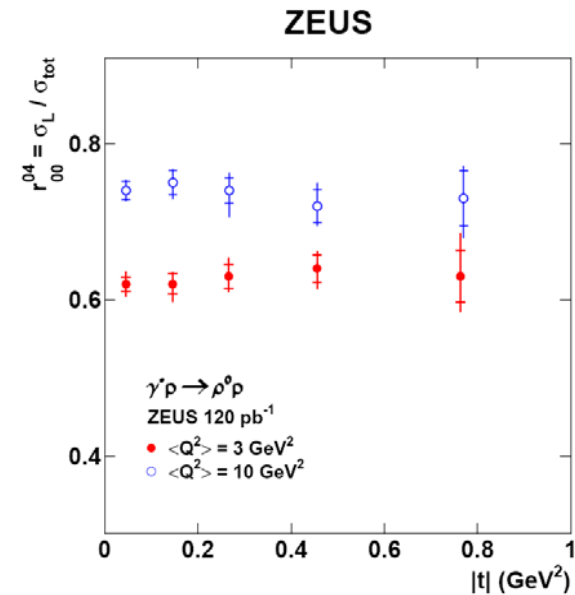
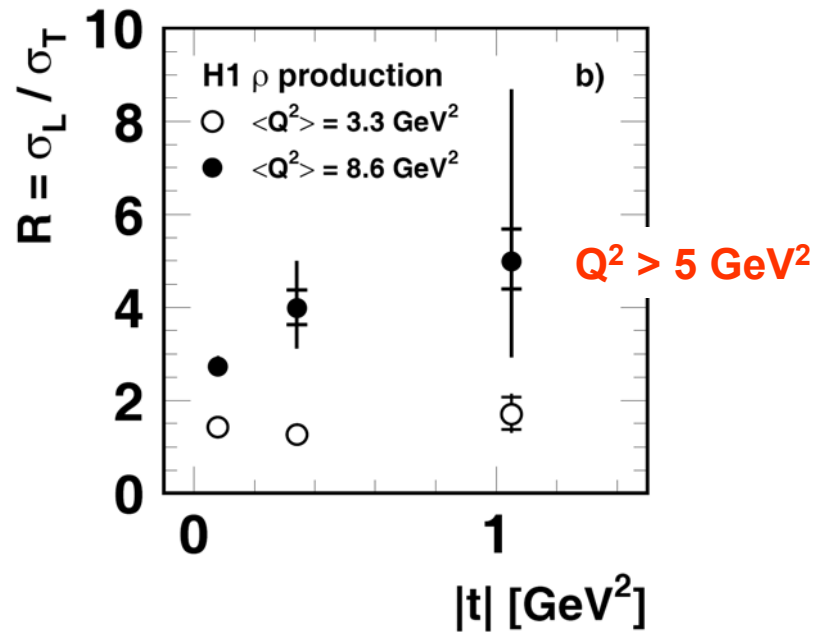
ZEUS



No W dependence of σ_L / σ_T



$R(t) ; b_L - b_T$



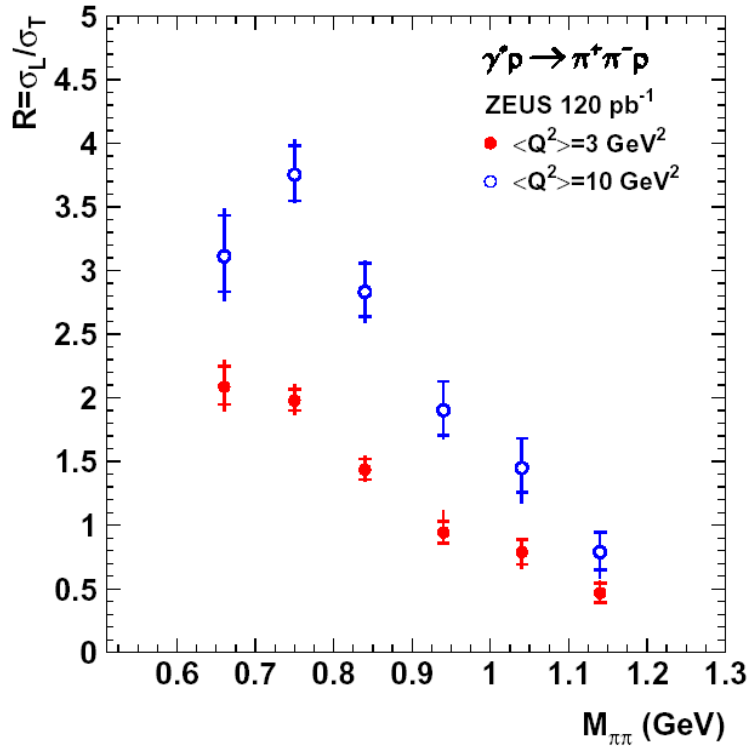
$$R(t) = \frac{\sigma_L}{\sigma_T} \propto \exp[-(b_L - b_T)|t|]$$

H1 $Q^2 > 5 \text{ GeV}^2$: $b_L - b_T < 0$ 1.5σ (stat. + syst.)

also t dependence of T_{11} / T_{00} – see below

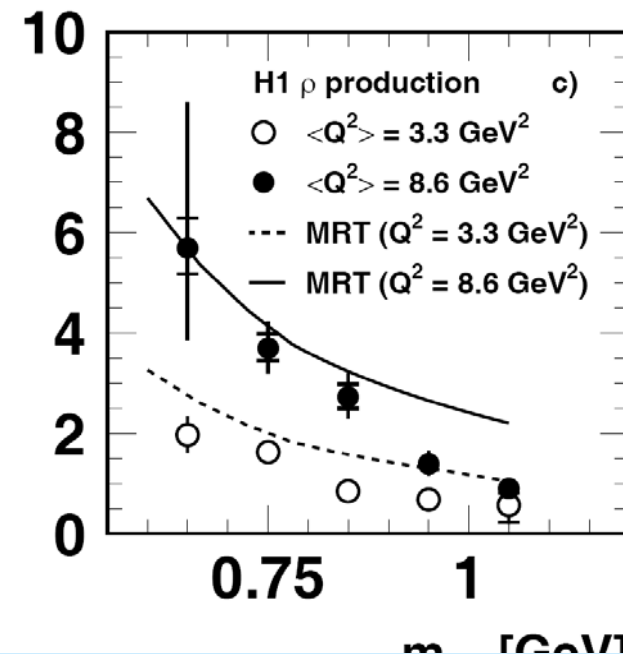
indication that transverse size of dipoles from transverse photons is larger than from longitudinal photons

$R(m) (\rho)$



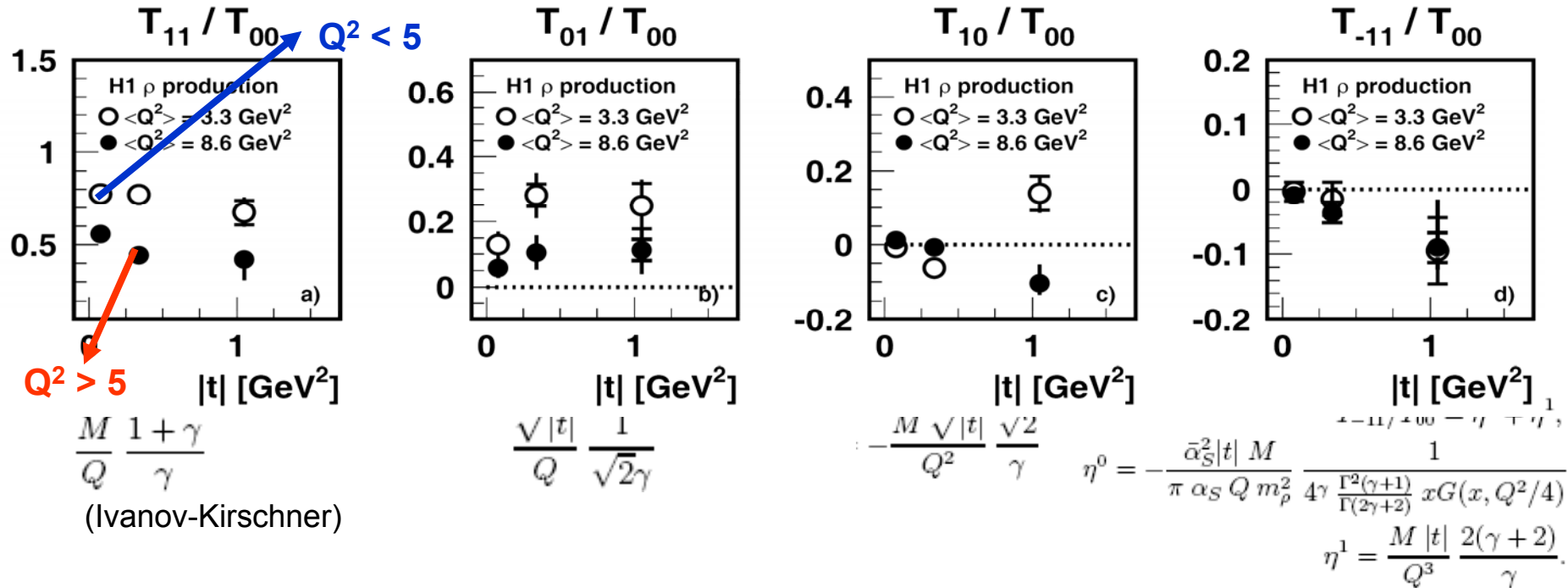
Decrease of $R(m)$ is qualitatively consistent with formal pQCD calculations $R \sim Q^2 / M^2$ if M is **diquark / dipion mass** rather than resonance mass

Support to models (MRT) with small relevance of the VM WF



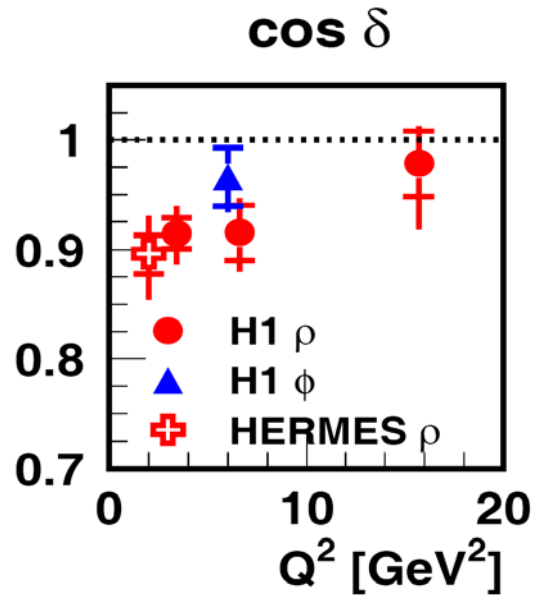
amplitudes ratios (t, Q^2) (ρ)

Global fit of 15 SDME \rightarrow 4 **amplitude ratios** (supposed to be purely imaginary)



- ✓ **Q^2 dependences** (higher twist) of all amplitude ratios
- ✓ **t dependences** of helicity flip amplitudes T_{01}/T_{00} T_{10}/T_{00} T_{-11}/T_{00}
NB **double flip amplitude** \rightarrow gluon polarisation
- **t dependence** of T_{11}/T_{00} - cf. $R(t)$: different slopes for L and T – here **3 σ effect**

SCHC amplitudes phases (Q^2) (ρ , ϕ)



phase between T_{00} and $T_{11} \neq 0$

phase difference decreases with Q^2

NB phase difference related to different values of $\rho = \text{Re} / \text{Im}$,

which are related through dispersion relations to the W evolutions

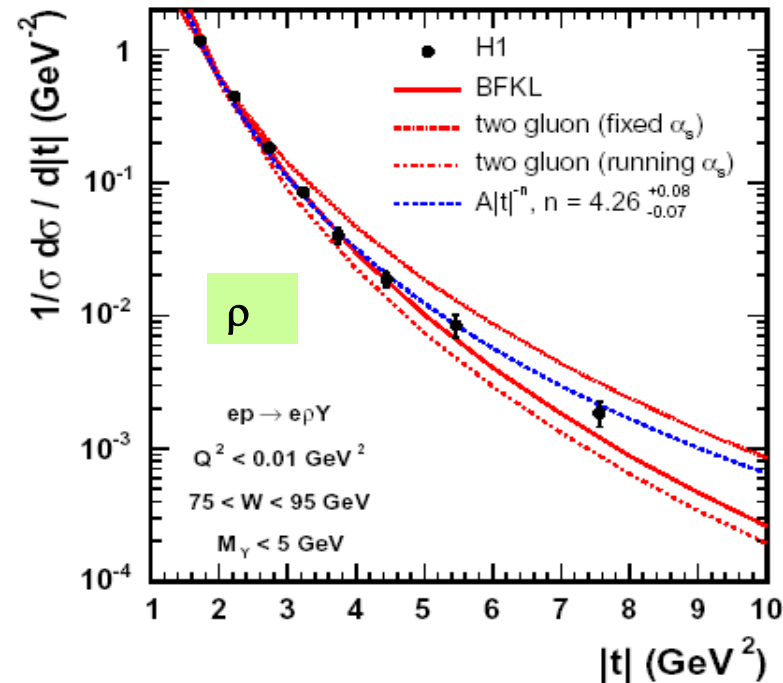
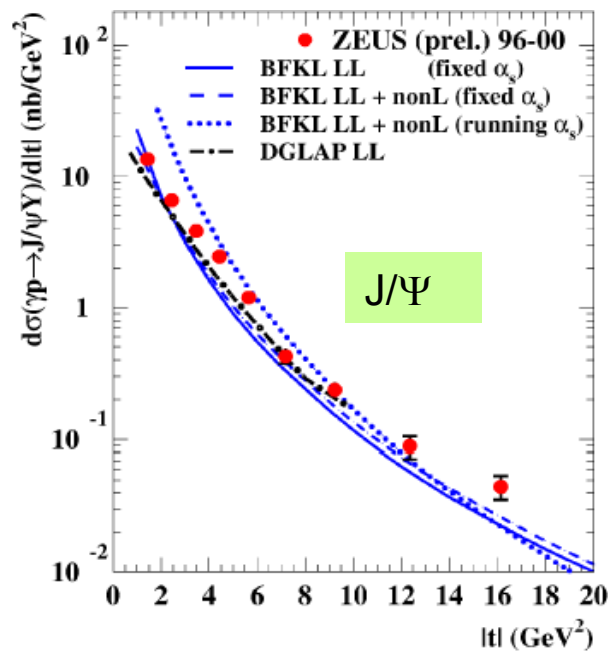
-> indication of different **W evolution** of transverse and longitudinal amplitudes ?

Large $|t|$

t dependences

Power like t dependences for real γ , ρ , J/Ψ

Quote measured powers for photon, rho, jpsi



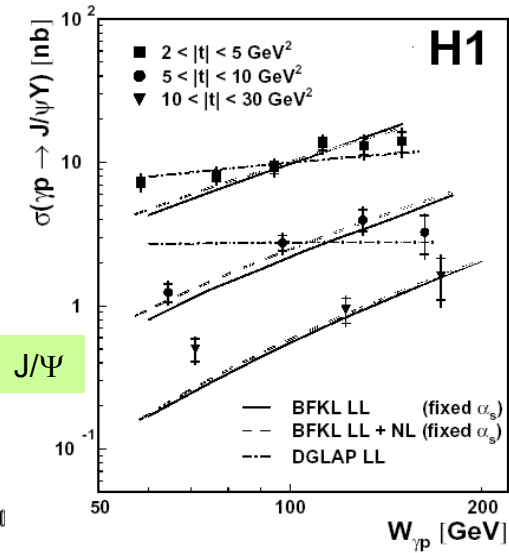
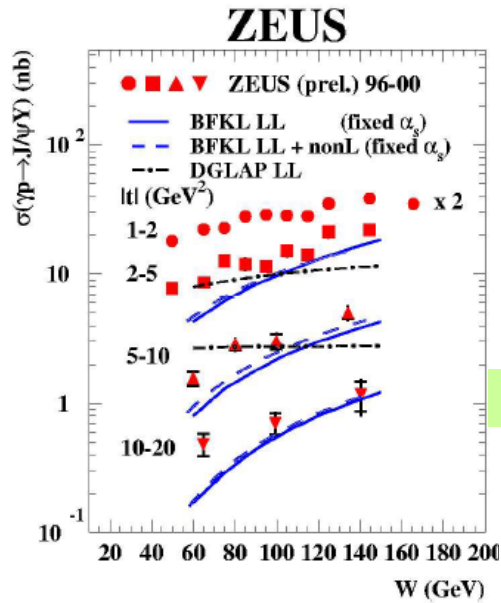
J/Ψ BFKL running α_s excluded

DGLAP OK ($t < M_\Psi^2$)

see also helicity below

BFKL favoured

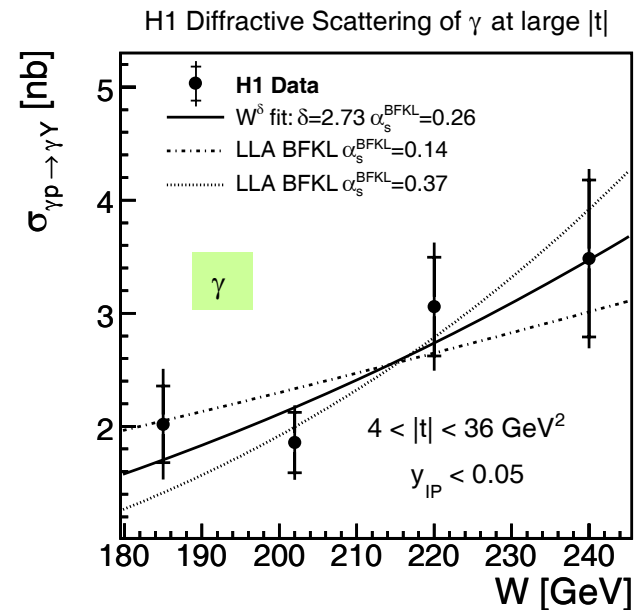
W dependences



rise of σ with W described by **BFKL**, not by DGLAP at large $|t|$

J/ψ

BFKL pred.



SDME (ρ)

“naïve” pQCD predicts large helicity flip, with long. ρ dominating at large $|t|$ (spin flip $\sim t$)

But SCHC $T \rightarrow T$ dominates + double flip $T \rightarrow T$

Reason :

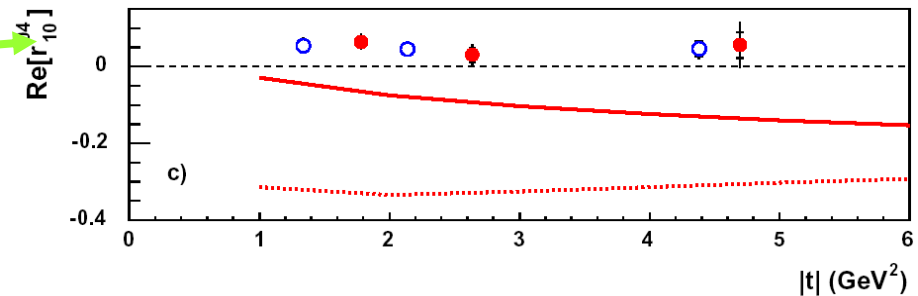
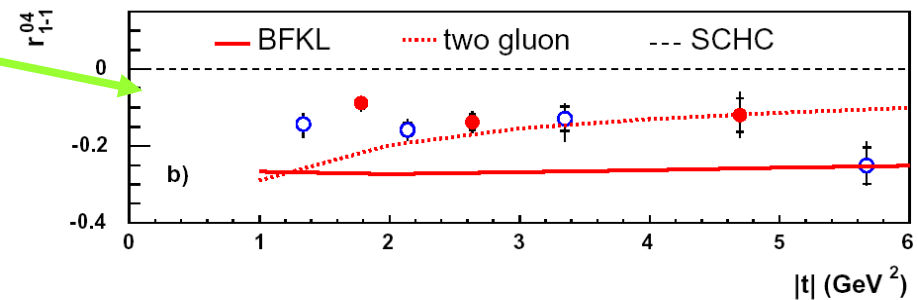
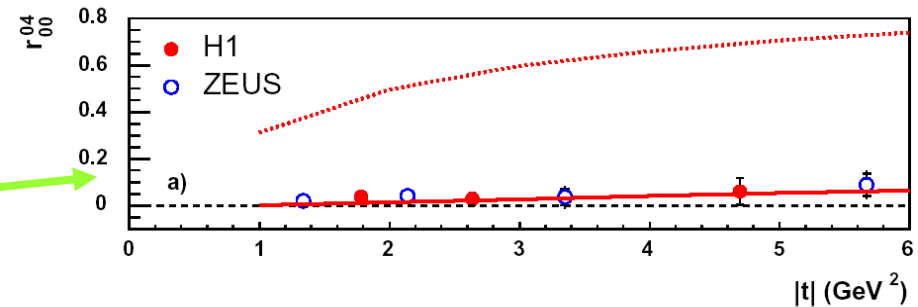
chiral odd contribution in γ

(due to constituent quark mass)

→ no orbital momentum needed for Ψ_T

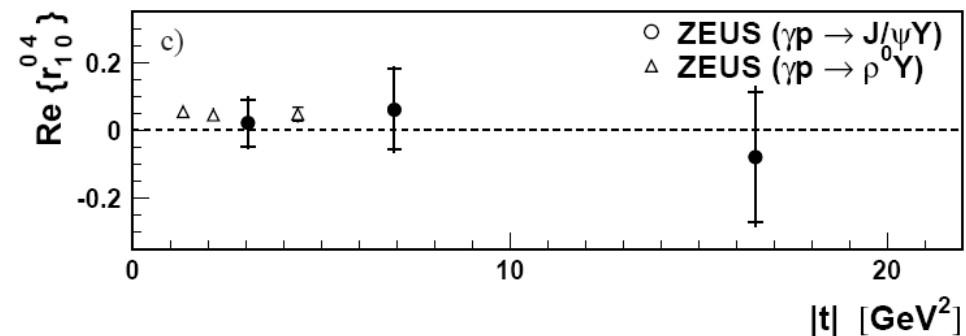
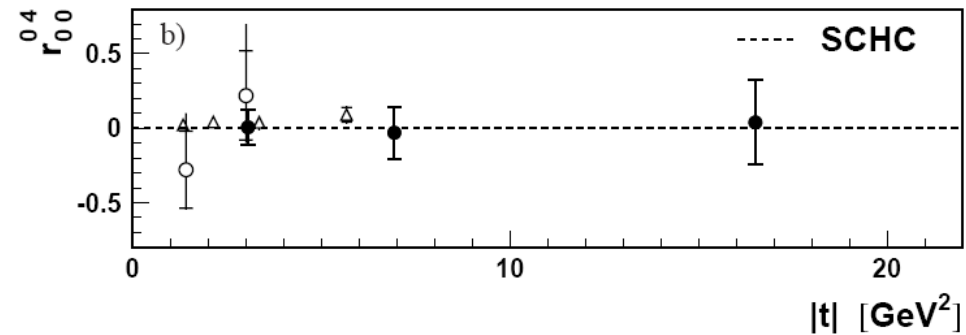
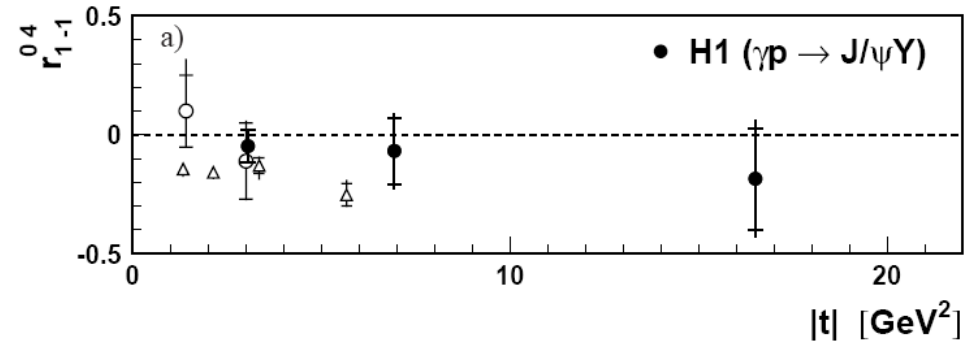
→ SCHC

BFKL model describes data, except for sign of ρ
cf. also t and W dependences



SDME (J/ψ)

SDME compatible with SCHC,
as expected from models
and compact J/ψ WF



Summary and conclusions

summary

Measurements of kinematic and angular distributions of real γ , ρ and ϕ , J/ψ , in photo- and electroprod., small and large $|t|$

➤ **DVCS**

Q^2 , W , t dependences; **beam charge asymmetry** -> Re/Im amplitudes

➤ **VM at small $|t|$**

Q^2 , W , t dependences of DVCS, ρ and ϕ , J/ψ

hard features for $Q^2 + M^2 \geq 10\text{-}20 \text{ GeV}^2$

helicity amplitudes

SCHC + helicity violations

Q^2 and t dependences understood in QCD

indication of $b_L - b_T \neq 0$

$\cos(\delta) \neq 1$

effective Regge trajectory

$\alpha_{\text{pom}}(0)$ increases with scale. $\alpha' < 0.25 \text{ GeV}^{-2}$

GPD and dipole models describe main features, but differences in details

➤ **VM at large $|t|$**

W , t dependences; **helicity amplitudes**

BFKL describes main features, but differences in details

conclusions

Very rich and varied landscape,

explored by ZEUS and H1, complementing lower energy experiments

A semi-quantitative understanding is achieved in a QCD framework,

in the two complementary approaches of GPD's and dipole models

and, at large $|t|$, in the BFKL framework

Many thanks to the organisers,

and to all those to whom I borrowed data – plots – ideas