

# Meson production at HERA



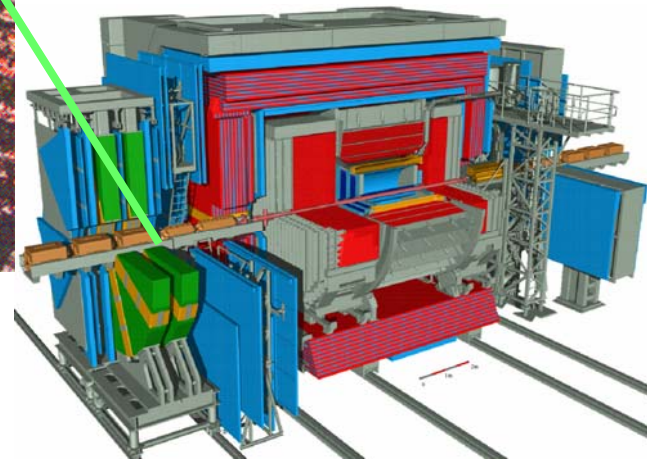
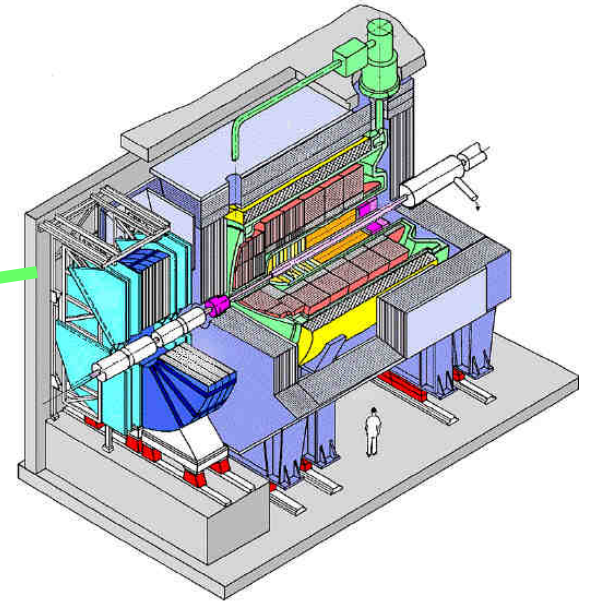
The H1 and ZEUS collaborations



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# The HERA collider

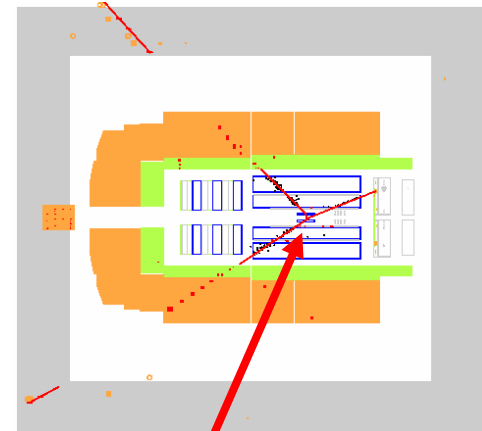
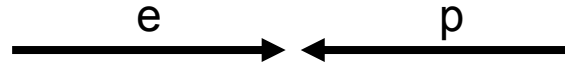
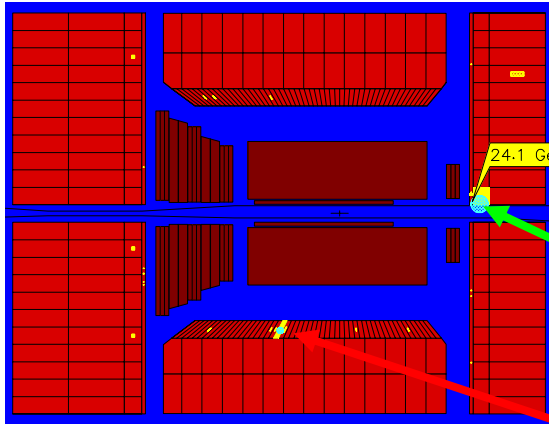


820 / 920 GeV p    27.5 GeV e<sup>+</sup> / e<sup>-</sup>

$\sqrt{s} = 300 / 320$  GeV

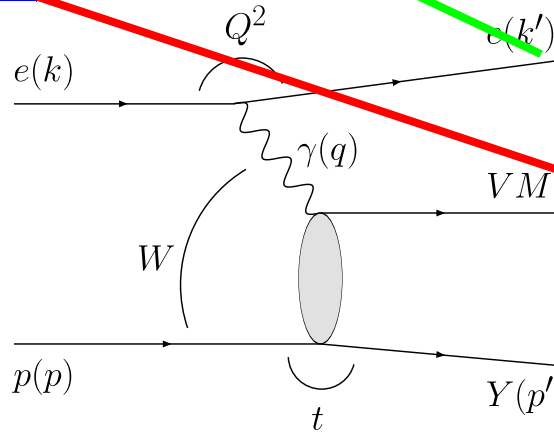
1992 – 2007    ~ 500 pb<sup>-1</sup> / exp.

# Introduction



$$x = Q^2 / W^2$$

$$|t| \approx p_{p,t}^2$$



$\gamma$   $\rho$   $\omega$   $\phi$   $J/\psi$   $\psi(2s)$   $Y$   
**p** **p. diss. (M\_Y)**

## A QCD laboratory

$M_V$	0 – 10 GeV
$Q^2$	0 – 80 GeV <sup>2</sup> (photoproduction & DIS)
$W$	30 – 300 GeV
$ t $	0 – 30 GeV <sup>2</sup> (small $ t  < 1.5$ GeV <sup>2</sup> & large $ t $ )

# Content

## Vector meson production and DVCS

- I. Interpretation frameworks
- II. From soft to hard : mass  
 $W, t$  dependences  
 $\sigma_{\text{tot}}, \rho, \omega, \phi, J/\Psi, Y$
- III. From soft to hard :  $Q^2$   
universality ( $Q^2 + M^2$ ),  $W, t$  dependences  
DVCS,  $\rho, \phi, J/\Psi$
- IV. From soft to hard :  $t$   
universality ( $t$ ),  $t, W$  dependences  
 $\rho, \phi, J/\Psi$
- V. Helicity amplitudes  
 $Q^2, W, t, m$  dependences  
 $\rho, \phi$  (DIS),  $J/\Psi$  (photoprod.), large  $|t|$
- VI. Summary and conclusions

## Spectroscopy

$K_S^0 K_S^0$  resonances (1270, 1525, 1710)

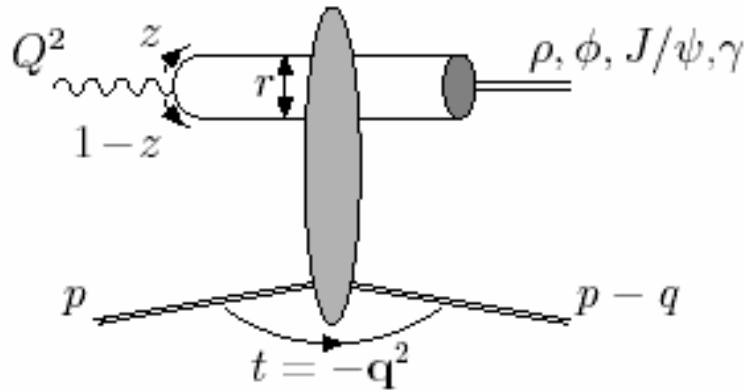
# **I. VM diffractive production**

## **Interpretation frameworks**

# QCD factorisation

( Large  $Q^2$ , large energy (LL $Q^2$ ,  $1/x$ ) -> basic ingredients )

## Factorisation theorem



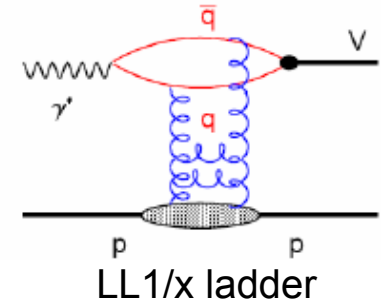
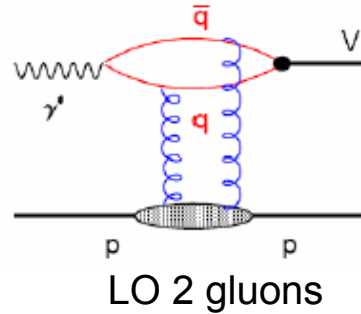
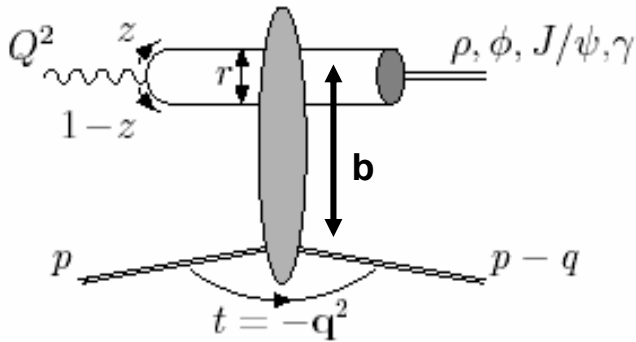
**step 1.**  $\gamma$  fluctuation into  $q\bar{q}$  dipole       $\gamma$  WF  $\Psi_\gamma(z, k_t)$

**step 2.** dipole – proton interaction       $A = \int dr^2 dz \Psi_\gamma \cdot \sigma(\text{dip} - p) \cdot \Psi_V$

**step 3.** pair recombination into VM

for  $\sigma_L$  + heavy quarks

# Dipole universality



## 1. universality of dipole cross section, depending on $(r, z, b)$

$\sigma(r)$ : “scanning radius” - colour transparency :  $r$  decreases with increased  $Q^2$ ,  $M_V$

→ in perturbative domain :

**universal scale**  $\bar{Q}^2 = z(1-z)(Q^2 + M_V^2)$

$A_L$  + heavy quarks :  $z \simeq 1-z \simeq 1/2 \rightarrow 1/r \simeq 1/4(Q^2 + M_V^2)$   
 ((  $A_T$  : see below ))

## + vertex factorisation

elastic – proton dissociation universality for  $Q^2$ ,  $W$ , hel. amplitudes

# Energy dependence

## 2. $W$ dependence

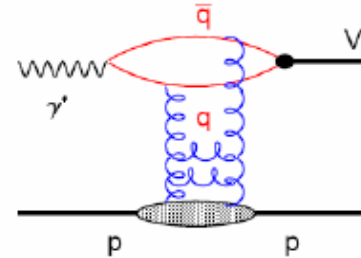
**Regge-like parameterisation** (high energy)  $\sigma_{tot}(h-h) \propto s^{\alpha(0)-1}$

(soft) pomeron trajectory :  $\alpha(t) = \alpha(0) + \alpha' t$

$$\alpha(0) \approx 1.08 \quad (1.07 \dots 1.11)$$

$$\alpha' \approx 0.25 \text{ GeV}^{-2}$$

VM production :  $\sigma \sim W^\delta \sim |x G(x)|^2$



**Hard scale** (large mass,  $Q^2$ ,  $|t|$ )

→ **hard** energy ( $1/x$ ) dependence of  $x G(x)$

(BFKL, low  $x$  DIS DGLAP)

i.e.  $\delta = 4(\alpha(t) - 1) = 4[\alpha(0) + \alpha' t - 1]$  **larger** than in soft interactions

**hard scale** →  $\delta, \alpha(0)$  large, with universal  $(Q^2+M^2)$  dep.

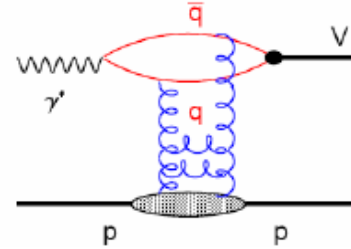


# $t$ dependences

## 3. $t$ dependence (moderate $|t|, \leq 1.5 \text{ GeV}^2$ )

exponential param. :  $\frac{d\sigma}{dt} \propto e^{-b|t|}$

$$b = b_{dip} \oplus b_{exch} \oplus b_Y$$



hard scale  $\rightarrow$   **$b$  smaller than soft, with universal  $(Q^2 + M^2)$  dep.**

## 4. $W$ - $t$ correlation

**shrinkage** of diffractive peak :

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

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

$W$  dependence as a function of  $t$

$t$  dependence as a function of  $W$

BFKL : shrinkage expected to be small

hard scale  $\rightarrow$   **$\alpha'$  small**

# Transverse, soft contributions

## 5. transverse amplitudes

transverse  $\gamma$  (light quarks) : contributions up of **end points ( $z \approx 0, 1$ )**

→ even for large  $Q^2$

scale  $z(1-z)(Q^2+M^2)$  can be **small**

**large** transverse dipoles, even for large  $Q^2$

→ **soft contributions, delayed pQCD expected**

visible in  $R = \sigma_L / \sigma_T$  :  $R(W)$ ,  $R(t)$ , Re / Im contributions (disp. rel.)

NB : also longitudinal extension of longitudinal wave function at moderate  $Q^2$

→ possibly finite size effects also in  $\sigma_L$

# Beyond LLQ<sup>2</sup>, 1/x

2 main – complementary – extensions

## 1. Hard scattering

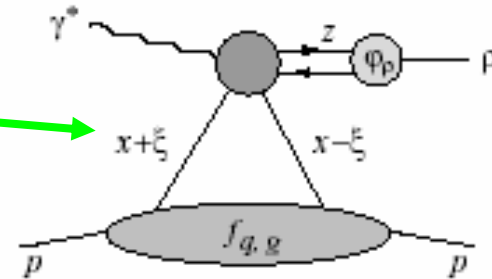
Beyond LL1/x (where 2 gluons have the same x)

- skewing :  $Q^2 \neq M^2 \Rightarrow x(\text{in}) \neq x(\text{out})$  (Y, DVCS)
- large Re / Im

## GPD (Generalised Parton Distributions)

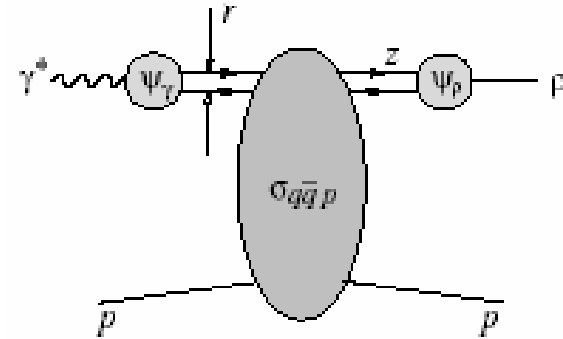
- large scale requested ( $Q^2, M_V$ )
- **relax 1/x** requirement : also valid at **low energy** (Hermes, Compas, JLab); role of quarks

## + NLO



## 2. Dipole scattering

- large 1/x => factorisation
- **relax large scale** : also valid at **low Q<sup>2</sup>**
- $\sigma$  (dip-p) universal : DIS, DDIS, VM production
- + include **saturation**



Also other approaches (2 pomerons, GVDM, ...)

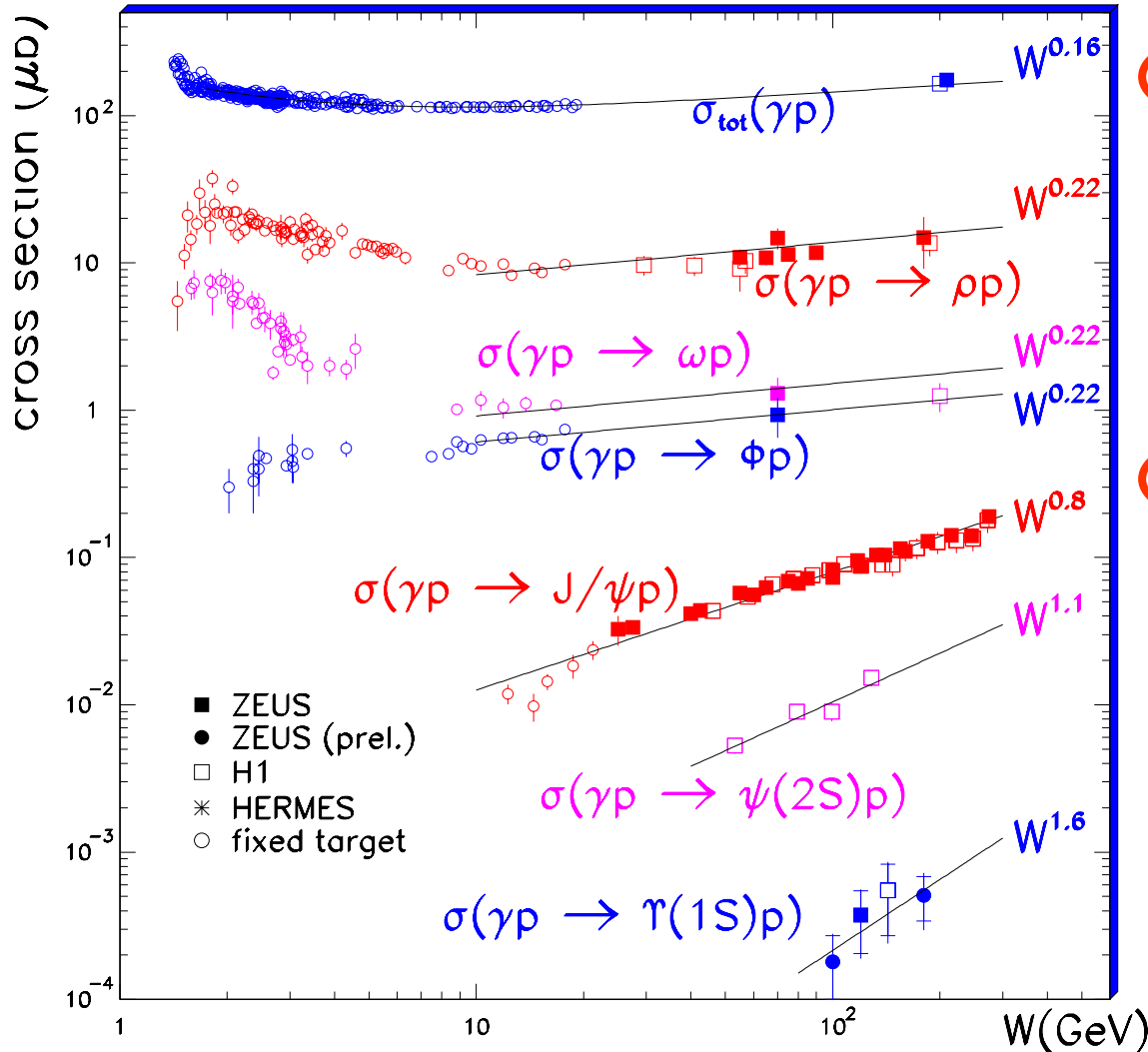
## II. From soft to hard : mass

$(\sigma_{\text{tot}}, \rho, \omega, \phi, J/\Psi, Y)$

***W* dependences**

***t* dependences**

# all VM photoproduction



**soft**

$\sigma_{\text{tot}}$   
 $\rho, \omega, \phi$

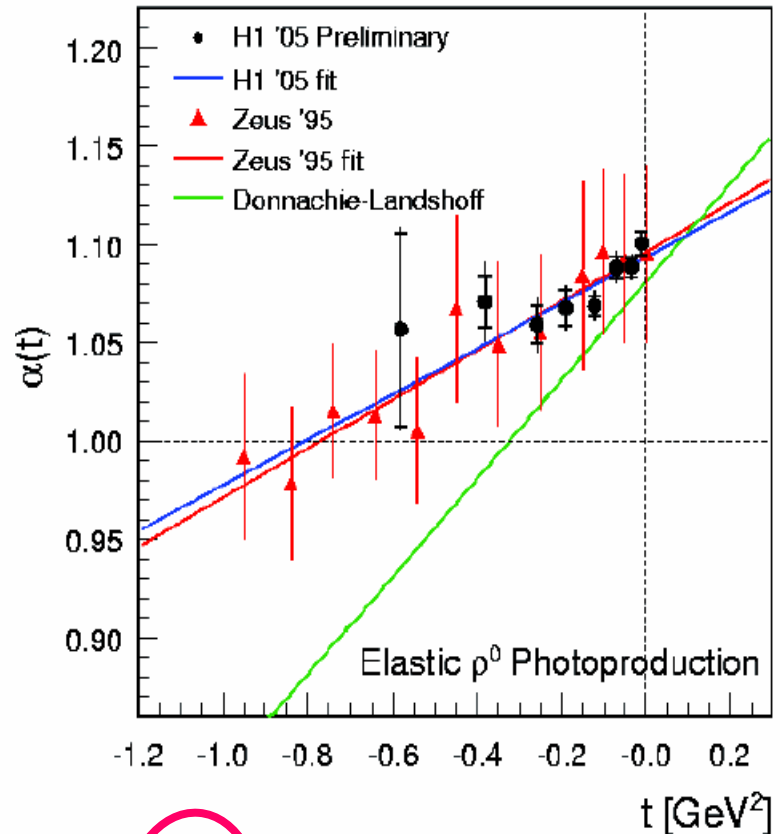
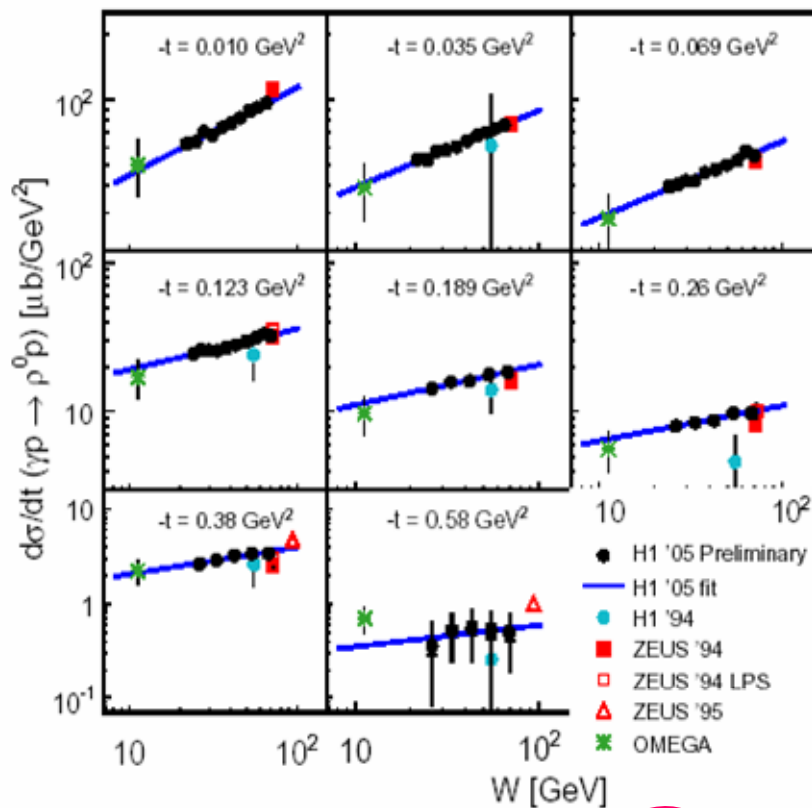
**hard**

$J/\psi$

skewing, Re  $\rightarrow$  **GPD**

$\Upsilon$

# $\rho, \omega, \phi$ $W$ dependence



ZEUS

$$\alpha_P(t) = (1.096 \pm 0.021) + (0.125 \pm 0.038) \text{ GeV}^{-2} \cdot t$$

H1

$$\alpha_P(t) = (1.093 \pm 0.003^{+0.008}_{-0.007}) + (0.116 \pm 0.027^{+0.036}_{-0.046}) \text{ GeV}^{-2} \cdot t$$

soft intercept

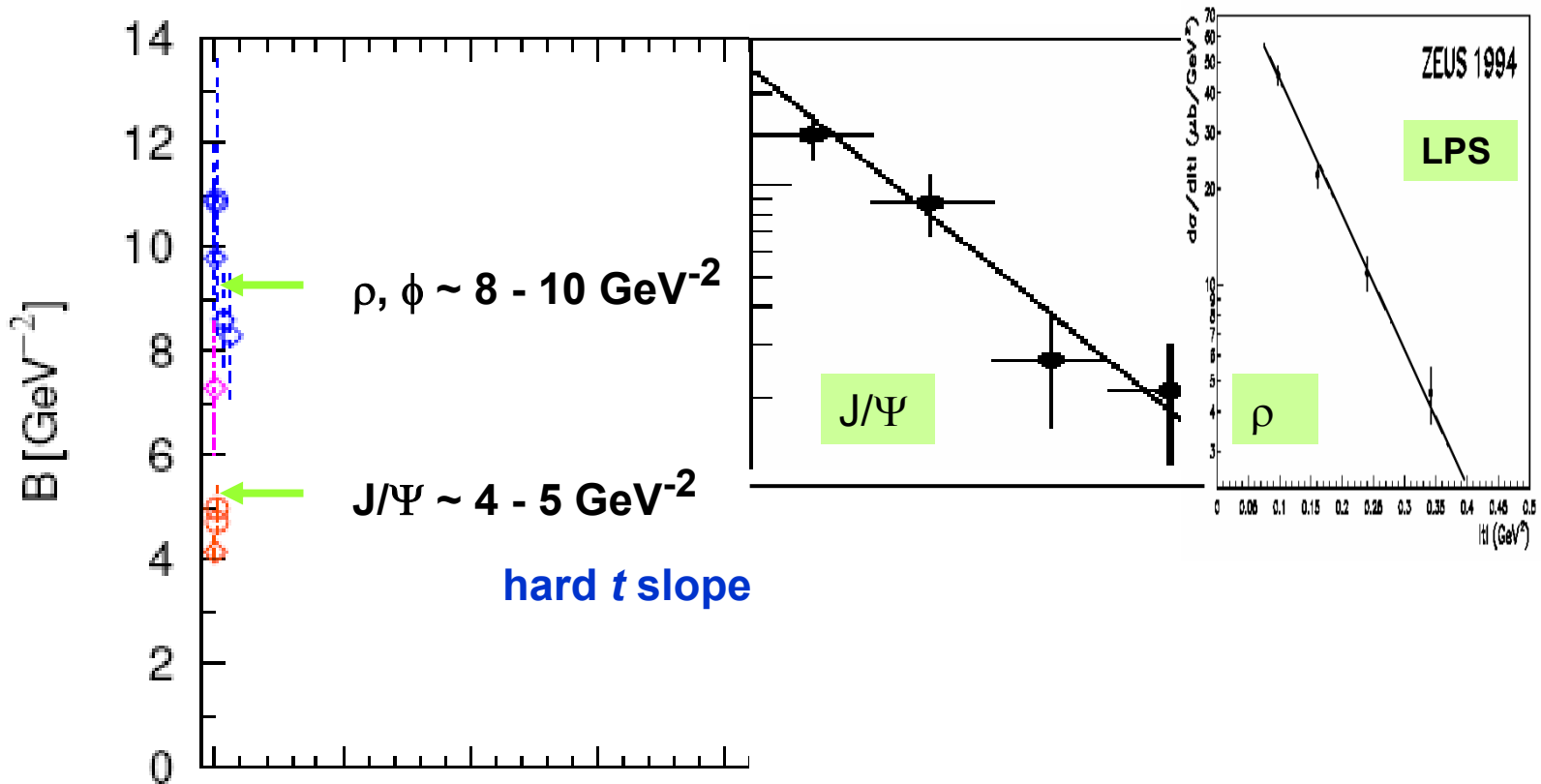
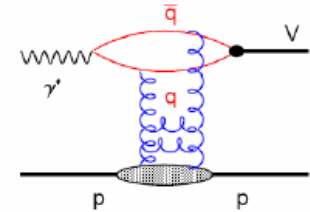
lower slope than h-h

-> rescattering effects ?

# $\rho$ , $J/\Psi$ , $t$ dependence

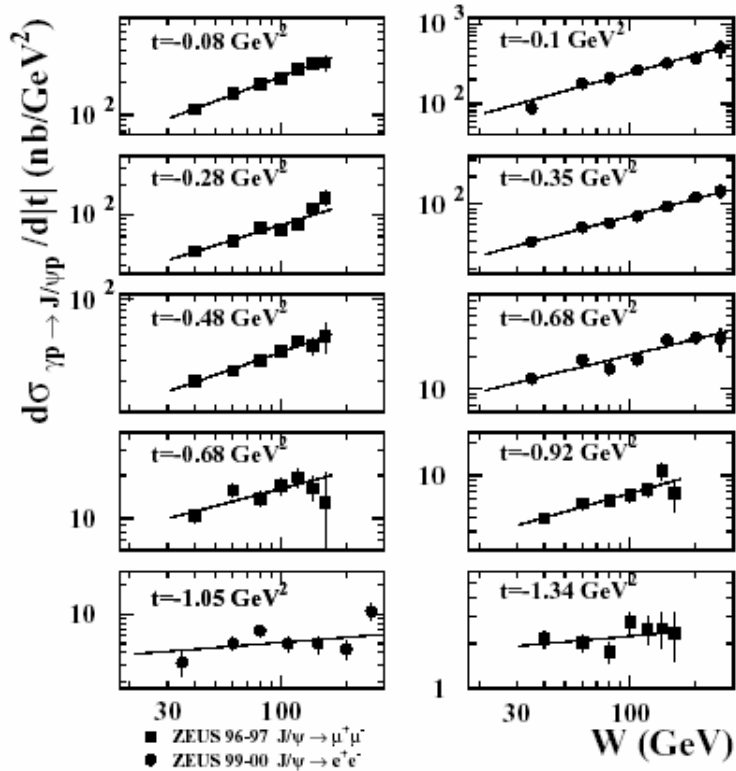
exponential slopes  $\leftrightarrow$  **size of the dipole**

heavy charm quark  $\rightarrow$  small dipole  $\rightarrow$  flatter  $t$  distribution, **smaller slope**



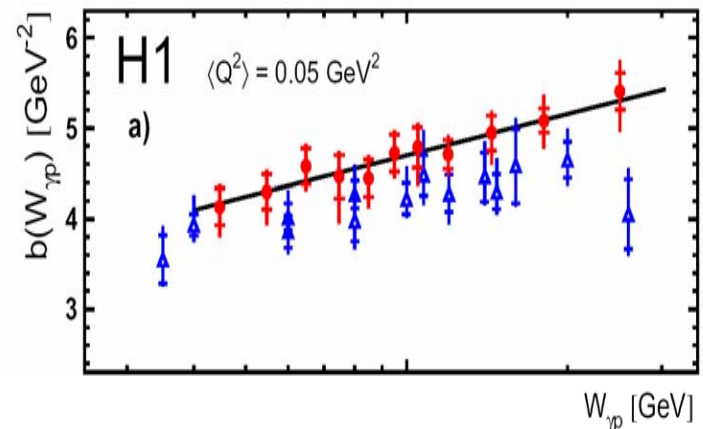
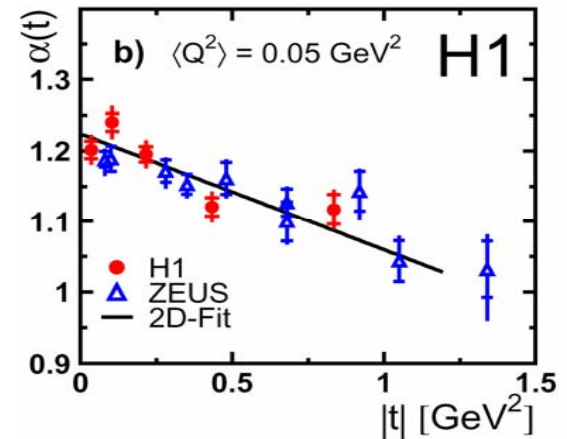
# J/Ψ, W dependence, shrinkage

ZEUS 1996-97, 1999-2000



hard intercept  $\alpha(0) \sim 1.20$

lower (?) slope  $\alpha' \sim 0.12 - 0.16 \text{ GeV}^{-2}$

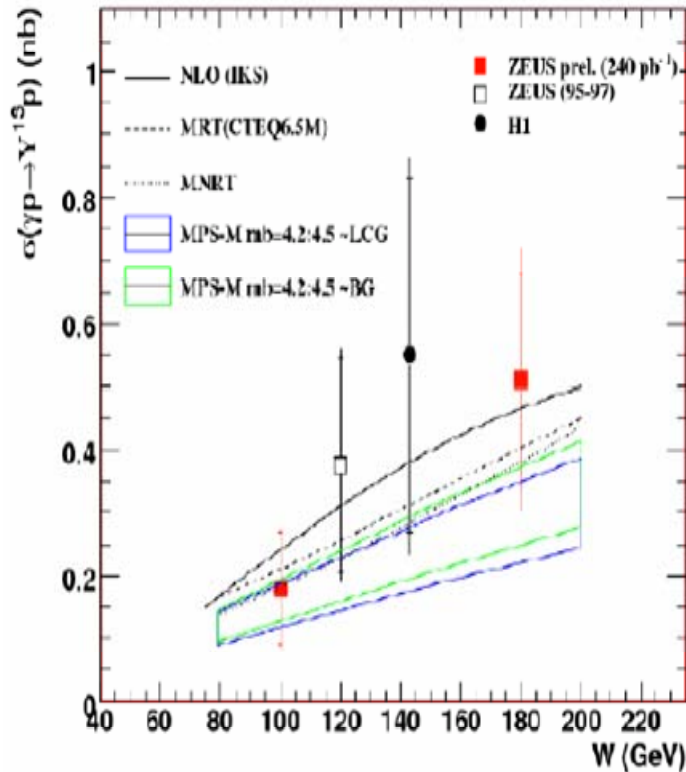




# Upsilon

very hard  $W$  dependence

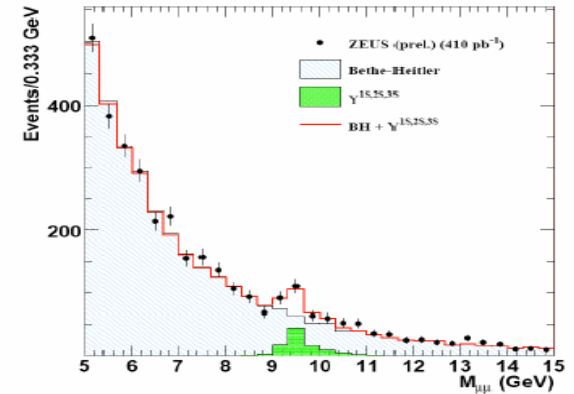
$$\delta \sim 1.6$$



Number of Upsilon candidates  $104 \pm 21$

NLO – Ivanov, Krasnikov, Szymanowski –  
 hep-ph/0412235  
 MRT – Martin, Ryskin, Teubner,  
 (based on CTEQ6.5M gluon)  
 MNRT – Martin, Nockles, Ryskin, Teubner  
 (based on diffractive  $J/\psi$  data alone)  
 MPS – color dipole approach calculation  
 by Magno Machado (private com.)

## Zeus HERA 1+2



Great progress !

skewing and GPD, NLO calculations, dipole calc.

# III. From soft to hard : $Q^2$

(DVCS,  $\rho$ ,  $\phi$ ,  $J/\Psi$ )

universality ( $Q^2 + M^2$ )

$W$  dependences

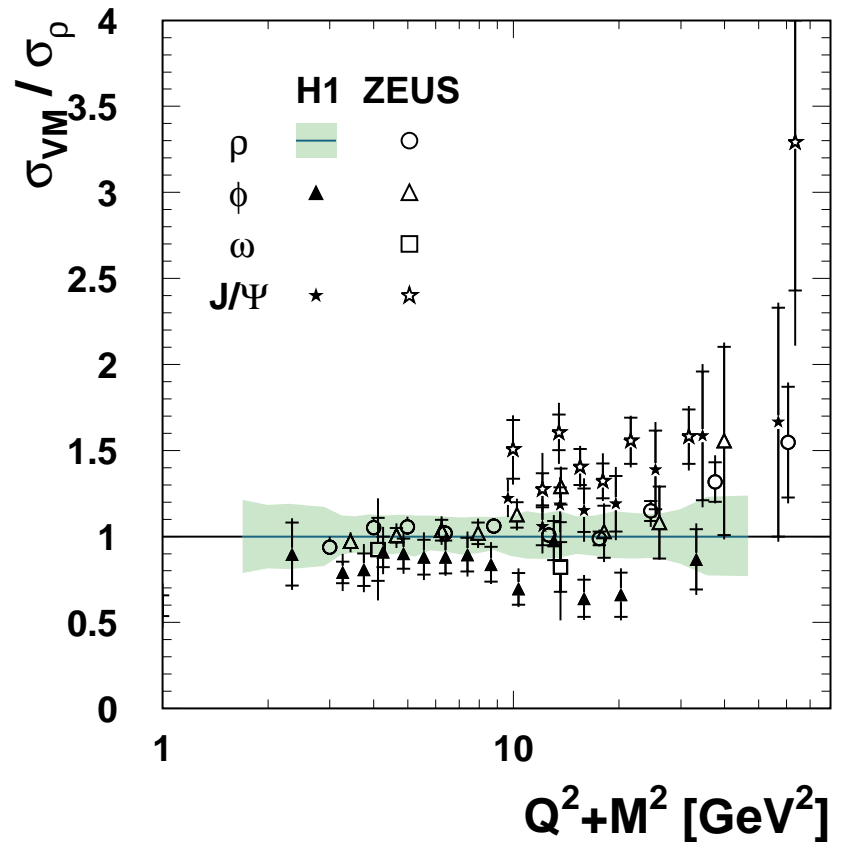
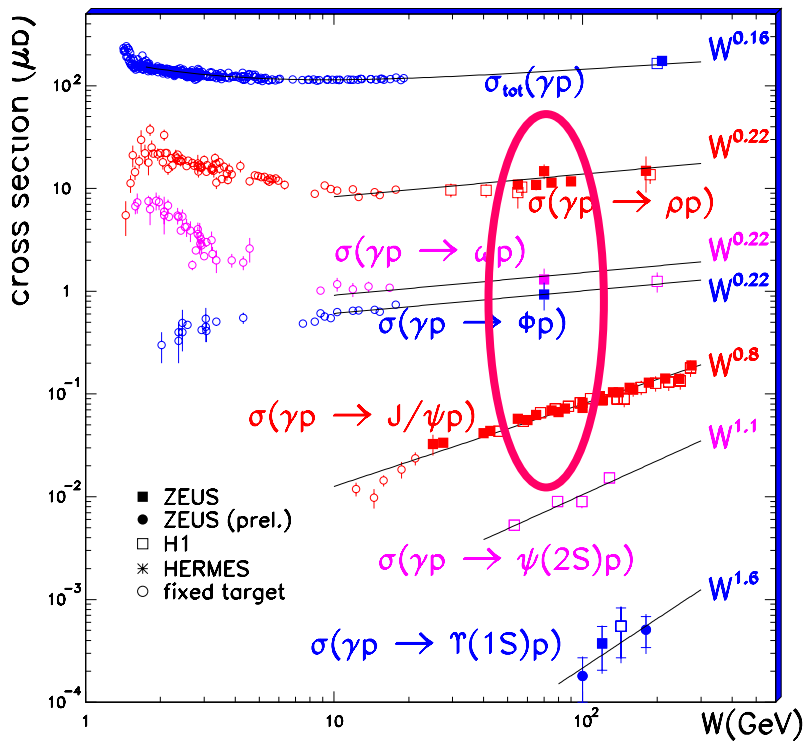
$t$  dependences

# 1. Universality ( $Q^2 + M^2$ )

Quark content weighted cross sections

(qualitatively) striking !

universal dipole cross section ( $Q^2 + M^2$ )

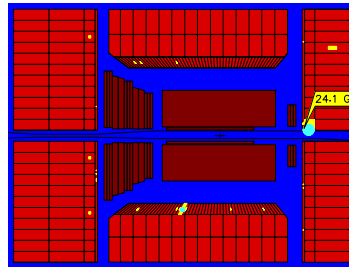


# 2. Deeply Virtual Compton Scattering

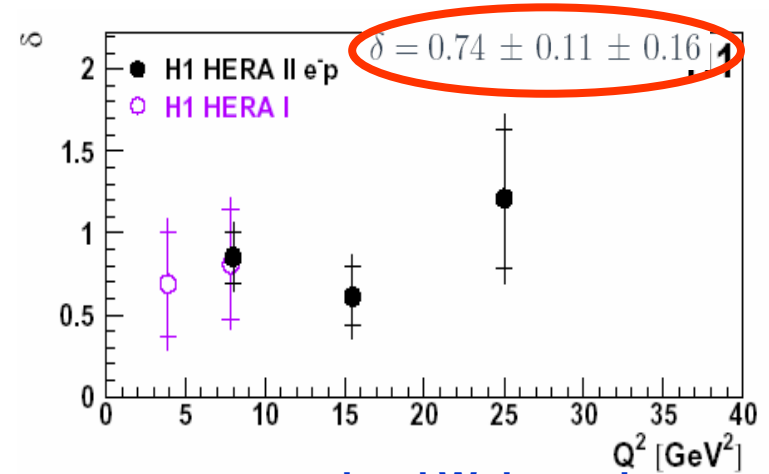
DIS domain :

$$e + p \rightarrow e + p + \gamma \text{ (real)}$$

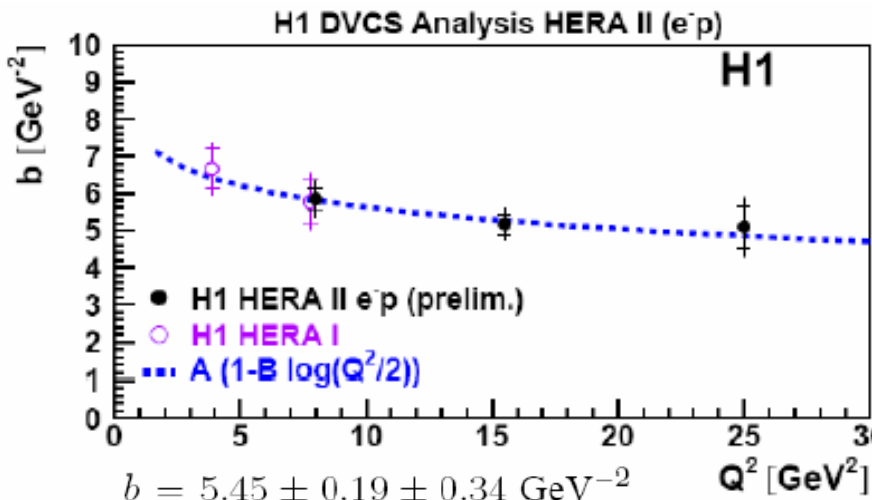
$$\text{i.e. } \gamma^* p \rightarrow \gamma p$$



( no WF uncertainties  $\leftrightarrow$  light VM )

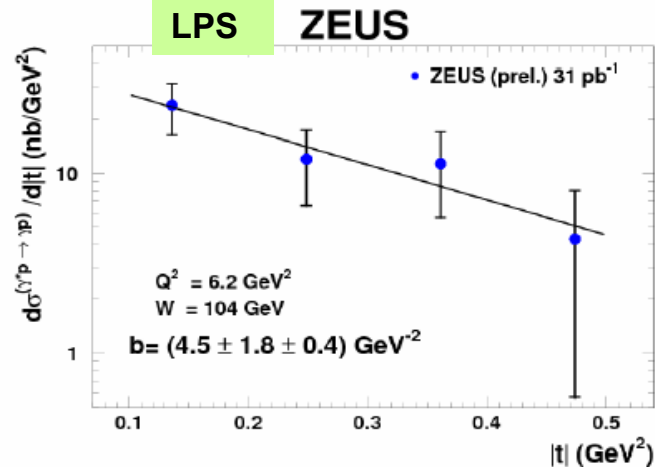


hard W dependence



$\Rightarrow \sqrt{\langle r_T^2 \rangle} = 0.65 \text{ fm}$   
 $\gg$  valence quarks value

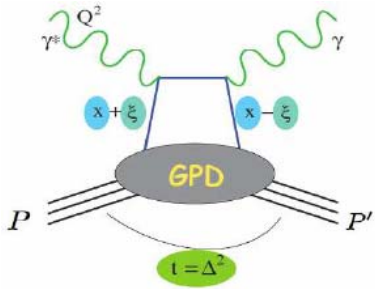
slope not soft, but steeper than J/Y ?



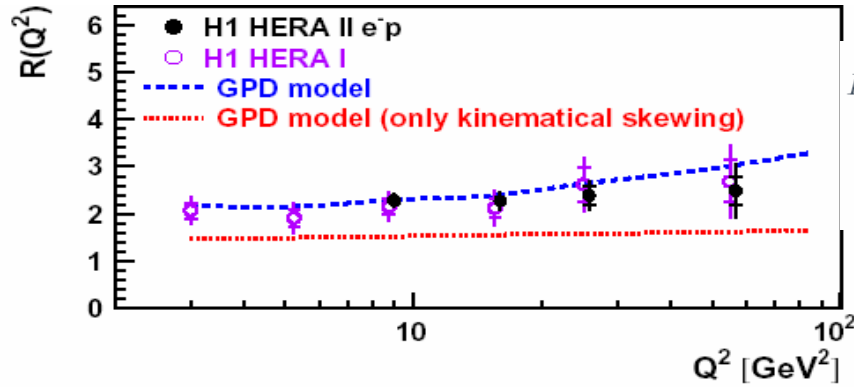
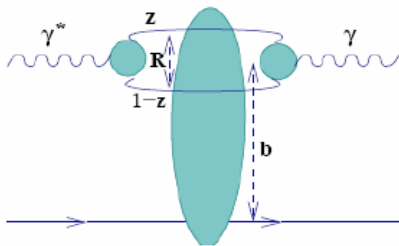
# DVCS, models

## GPD

kin. skewing  
not sufficient



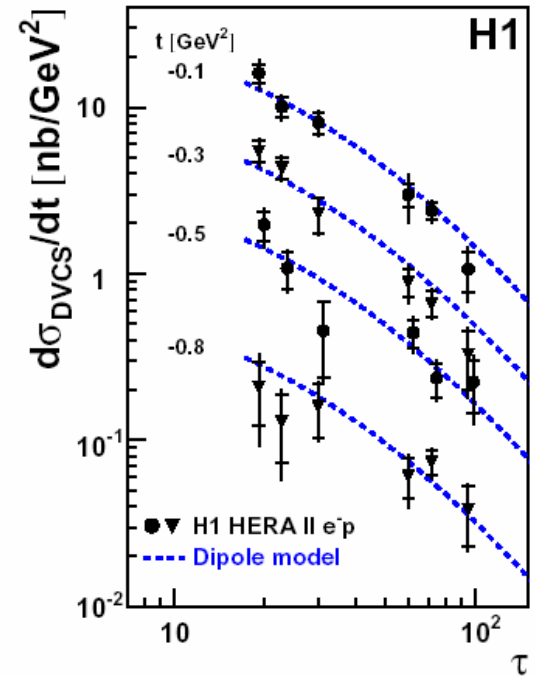
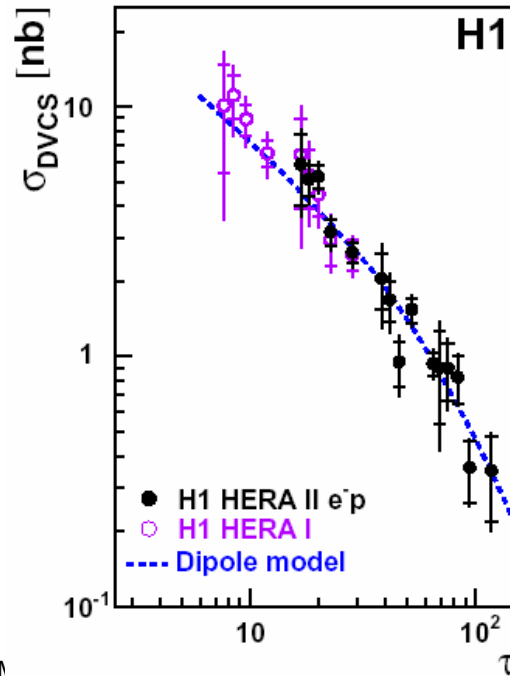
## Dipoles + geom. scaling



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

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

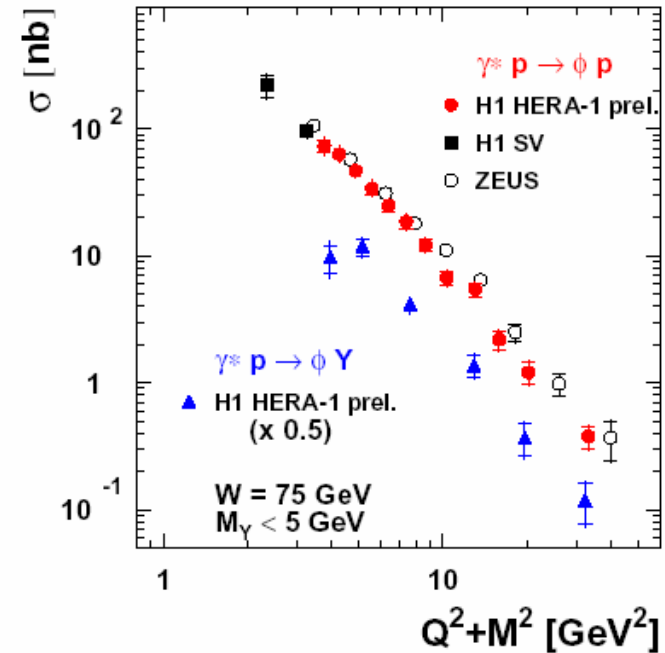
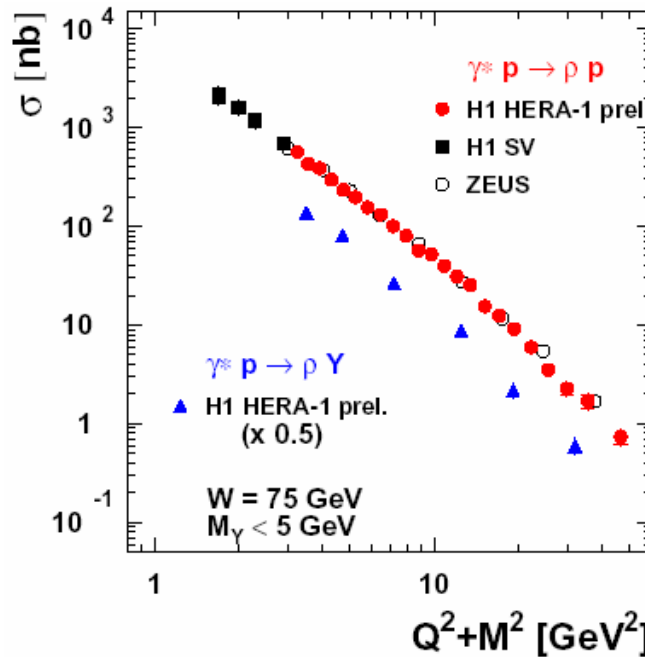
skewing



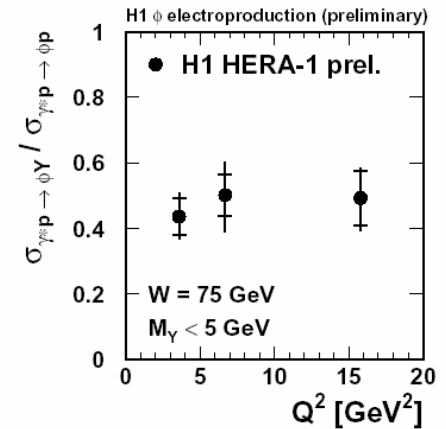
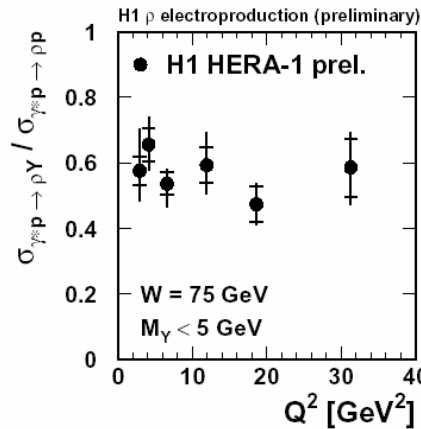
# 3. $\rho$ and $\phi$ , elastic and p. dissoc.

ZEUS and H1 - HERA-1  
large data sets

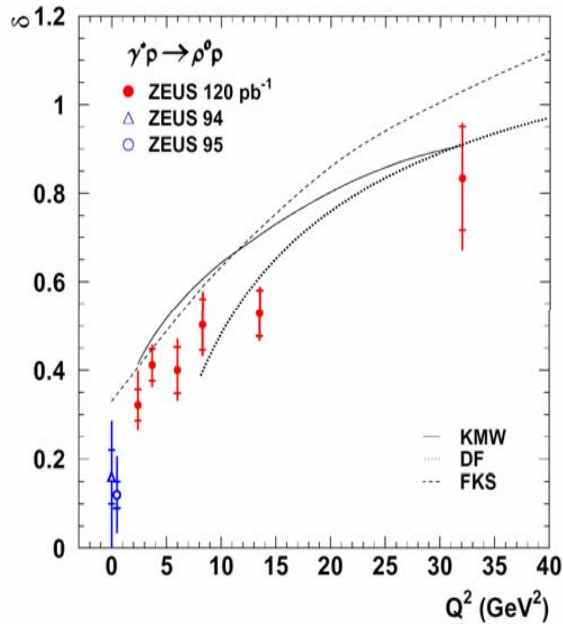
transition to hard diffr.  
(+ soft features)



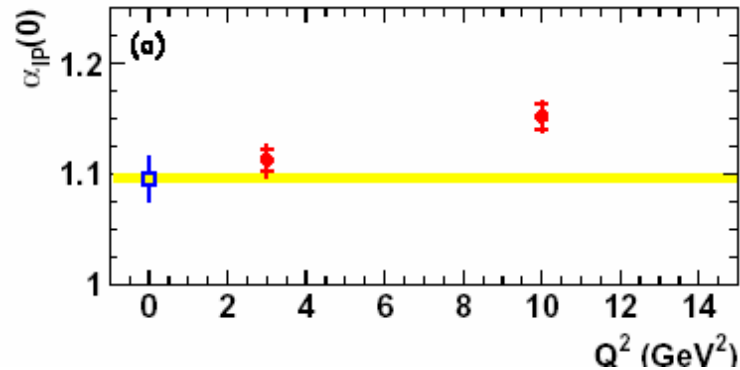
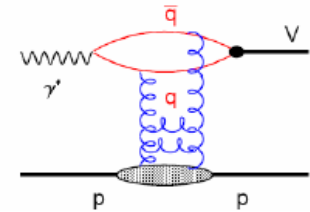
p.diss. / el. : no  $Q^2$  dep. ( $Q^2 > 2.5 \text{ GeV}^2$ )  
proton vertex factorisation



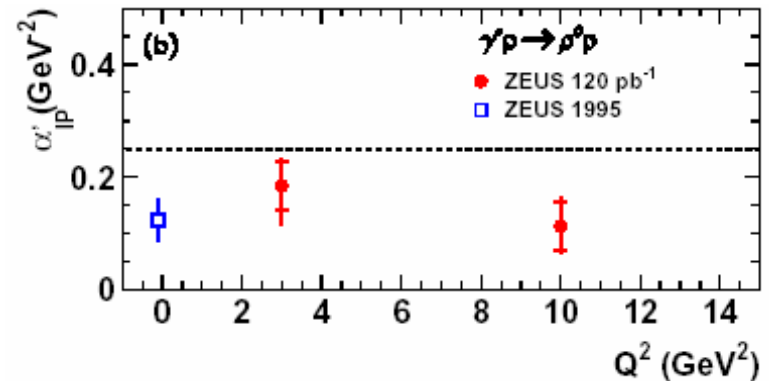
# $\rho$ , $W$ dependence



hardening with  $Q^2$



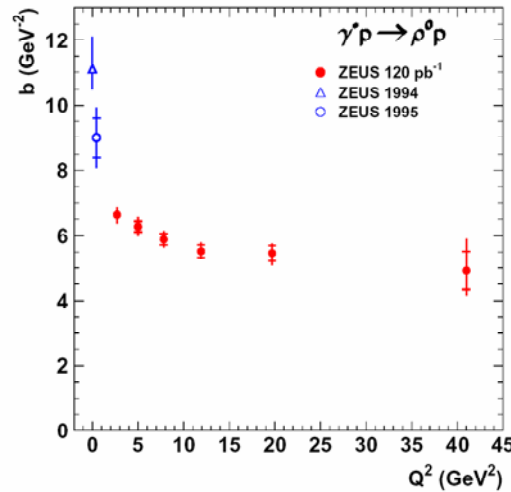
$\alpha' \sim 0.10-0.15 \text{ GeV}^{-2}$ , indep. of  $Q^2$  ?



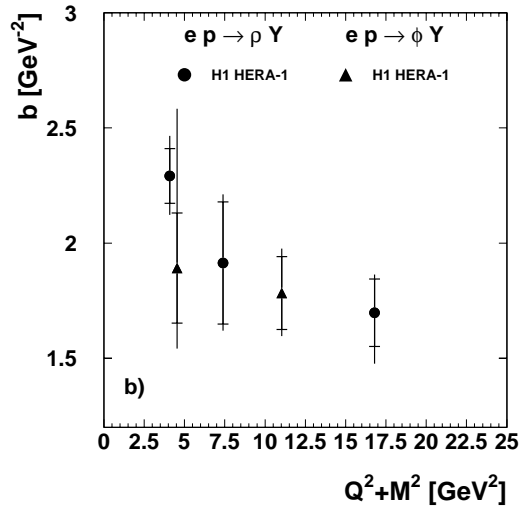
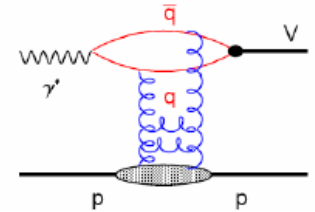
# $\rho$ , $t$ dependence

$t$  slope  
hardening with  $Q^2$

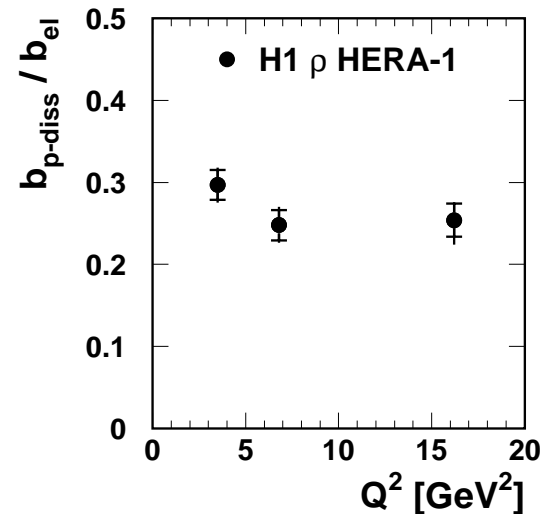
Difficult measurements:  
background subtraction  
other VM and incl. diff., p. diss.



elastic



proton dissociation



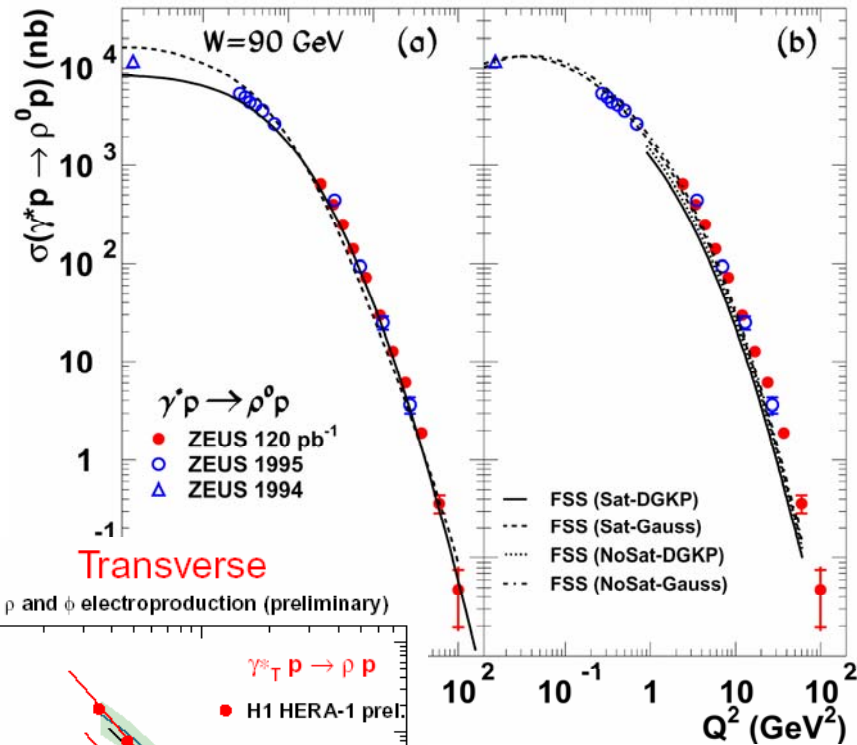
factoris. : p.diss. / el. slope indep. of  $Q^2$



# $\rho, d\sigma/dQ^2$

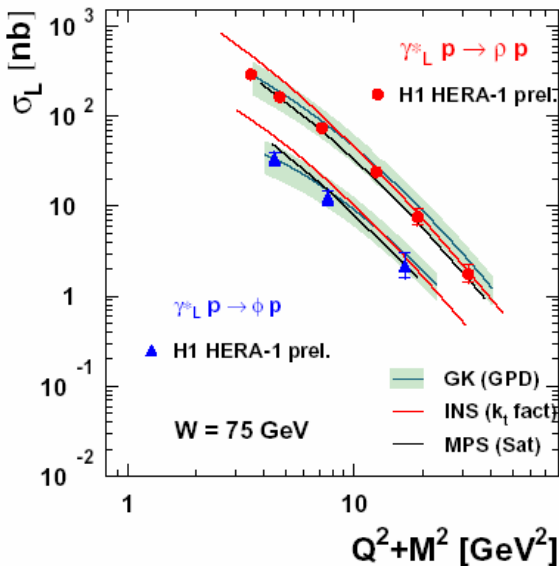
universal dipole

-> small  $Q^2$



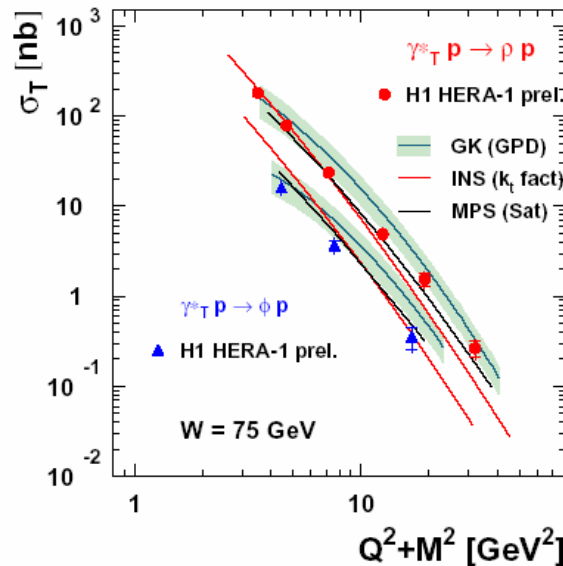
Longitudinal

H1  $\rho$  and  $\phi$  electroproduction (preliminary)



Transverse

H1  $\rho$  and  $\phi$  electroproduction (preliminary)



polarised cross sections

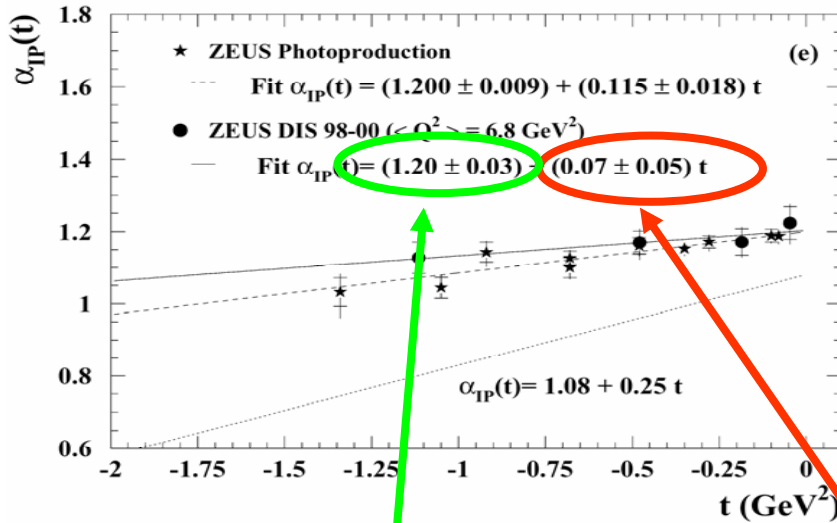
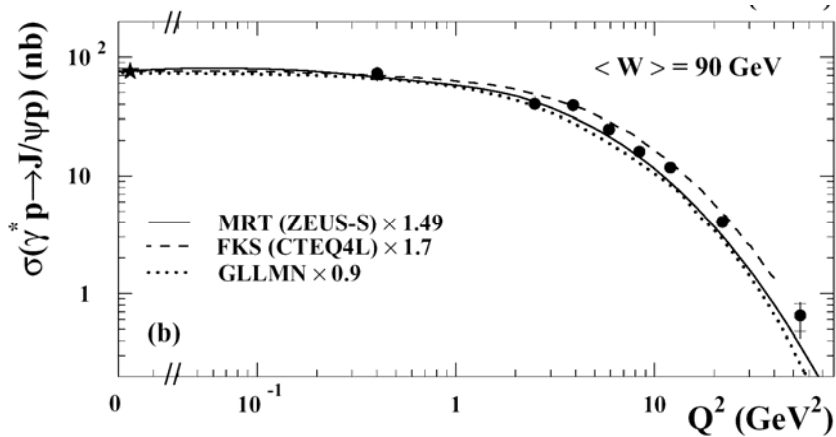
**GPD**, unintegrated  $k_t$ ,

dipole + saturation

# 4. J/Ψ, hard scales

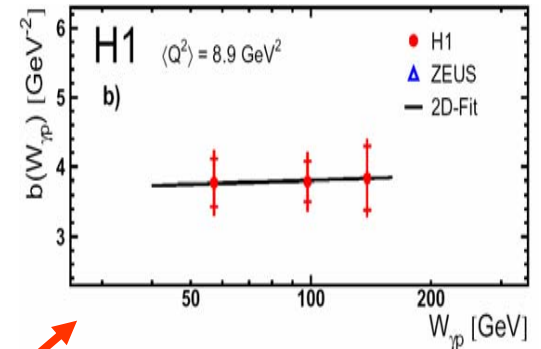
J/Ψ hard in photoproduction

→  $Q^2 = \text{second hard scale}$



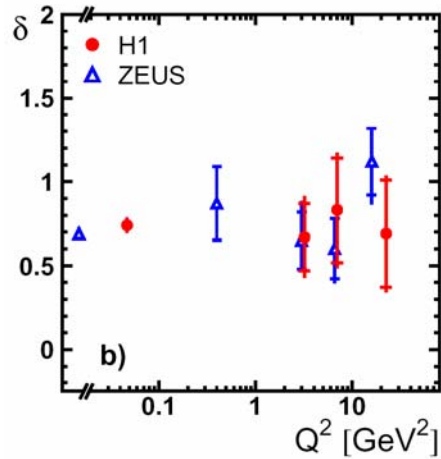
hard :  $\alpha(0) = 1.20$

$\alpha'$  consistent with 0

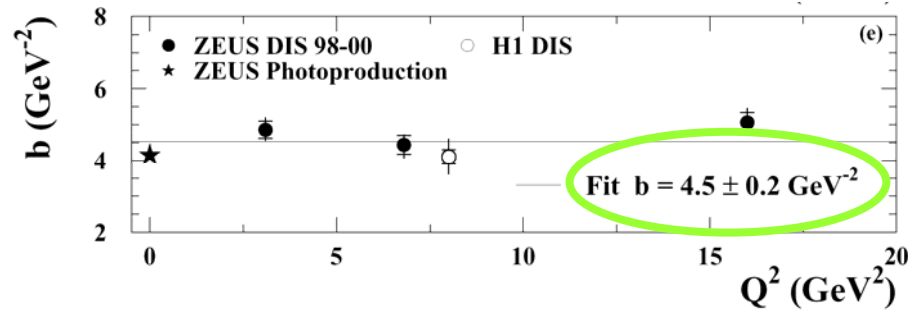


# $J/\Psi$ , $Q^2$ independence of $\alpha(0)$ , $b$

$\delta$

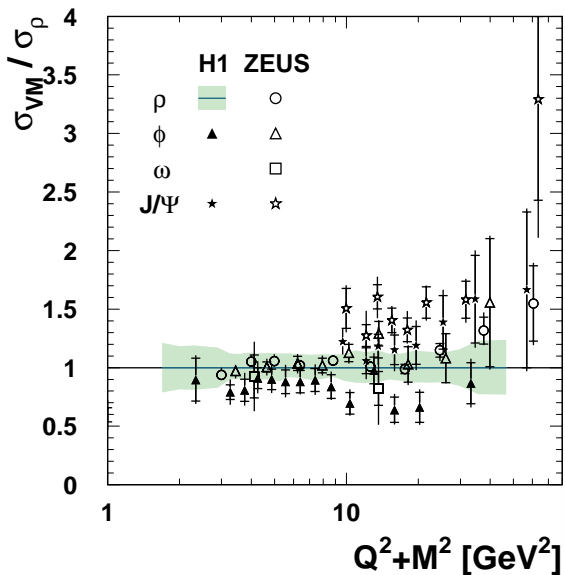


$b$  slope

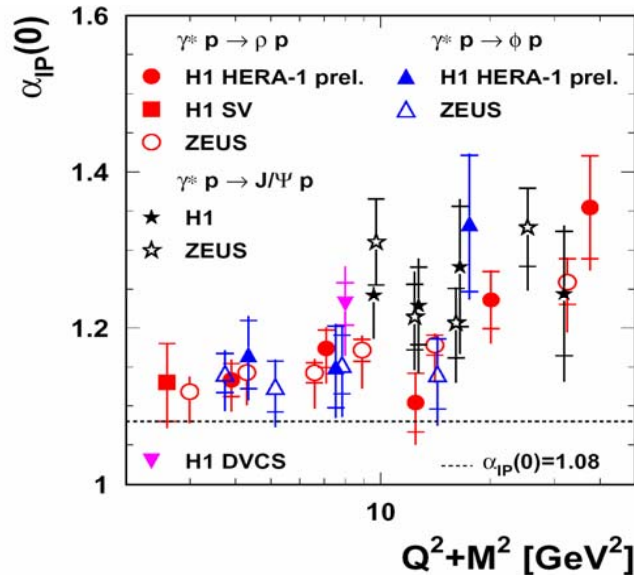


# 5. summary : universality ( $Q^2 + M^2$ ) of hard diffraction

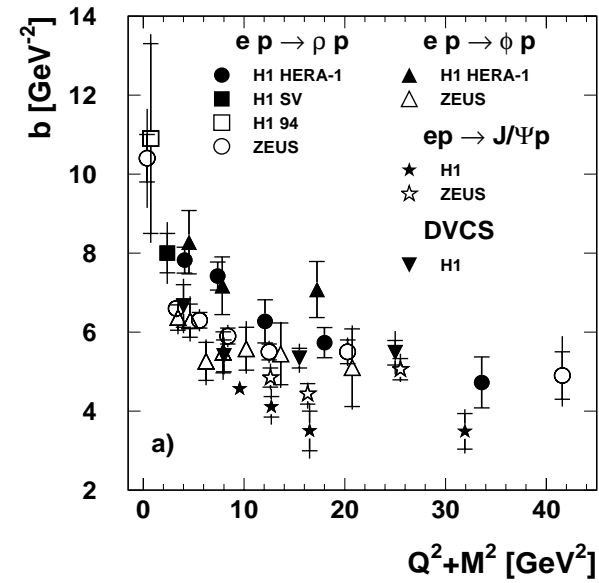
small dipoles, hard gluons



$d\sigma/dQ^2$



energy dep.



$b$  slopes

# IV. From soft to hard : $t$

$(\rho, \phi, J/\Psi)$

**universality ( $t$ )**  
 **$t$  dependences**  
 **$W$  dependences**

# 1. Universality ( $t$ )

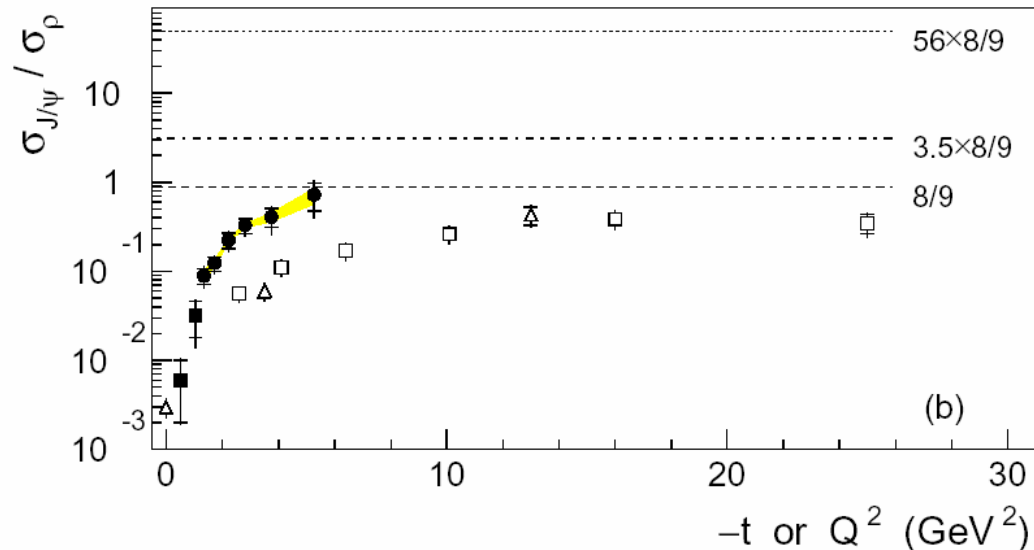
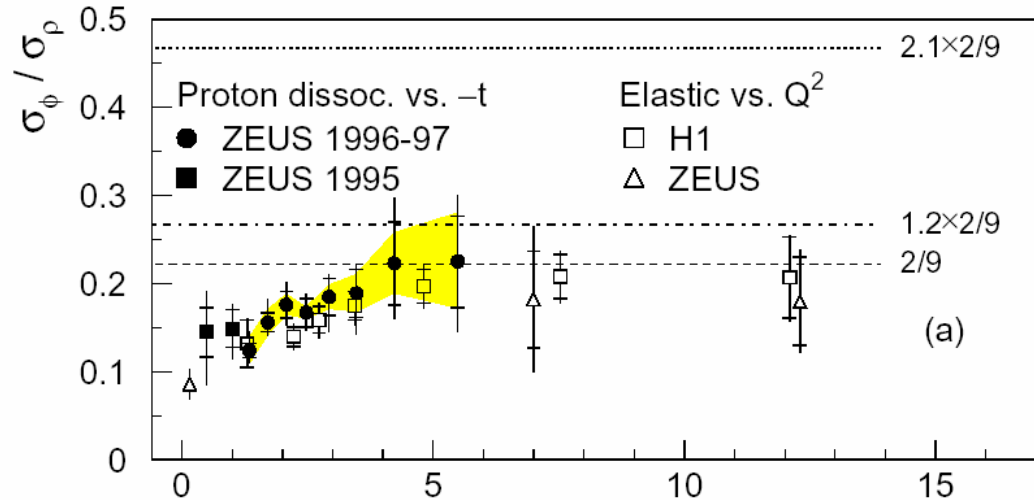
Another hard scale

large  $Q^2$  : large virtuality  
at the **photon** vertex

large  $|t|$  : large virtuality  
at the **proton** vertex

pQCD calculations  
(BFKL, DGLAP)

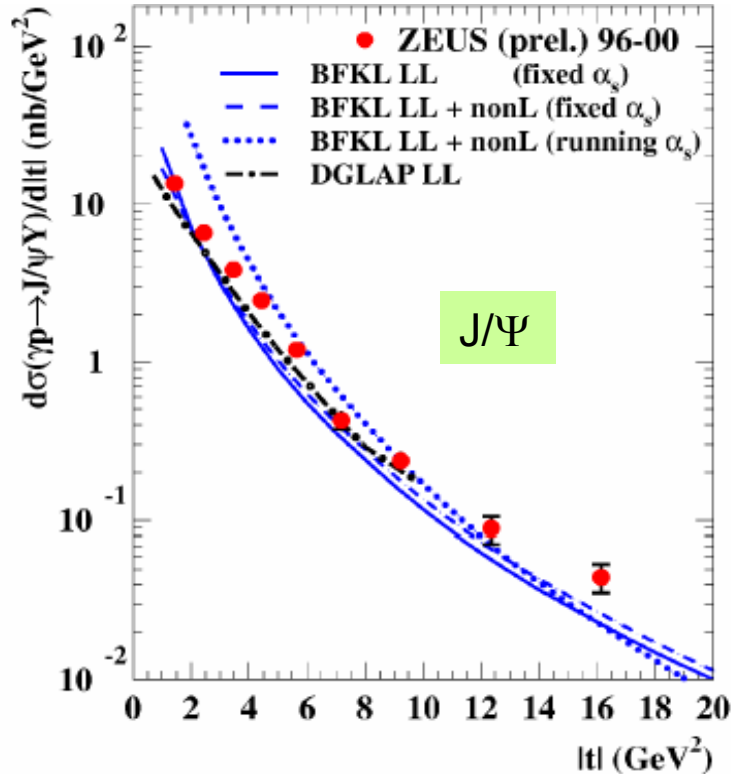
ZEUS



# 2. $\rho$ , $J/\Psi$ , $t$ dependences

Power like  $t$  dependences, exponential excluded at large  $|t|$  ( $\rho$ ,  $J/\Psi$ )

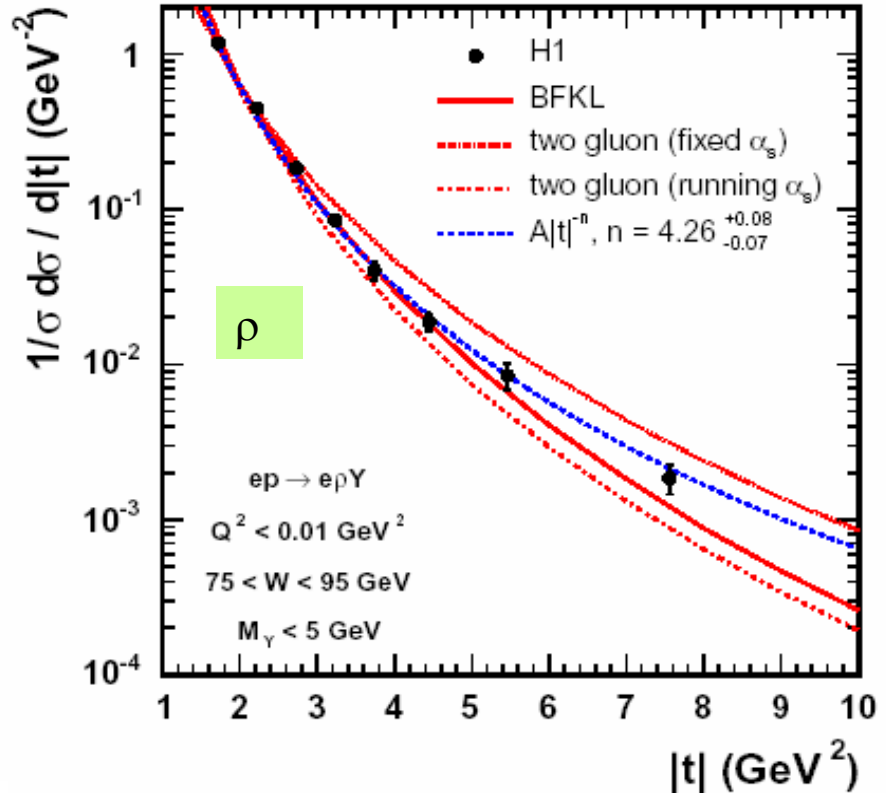
pQCD calculations



**J/ $\Psi$  BFKL running  $\alpha_s$  excluded**

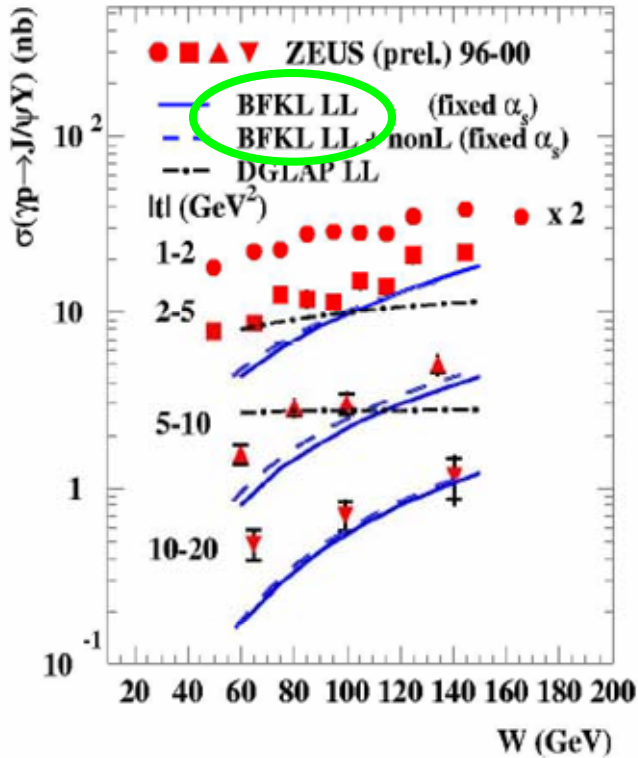
DGLAP OK ( $t < M_{\Psi}^2$ )

see also helicity below



**BFKL favoured**

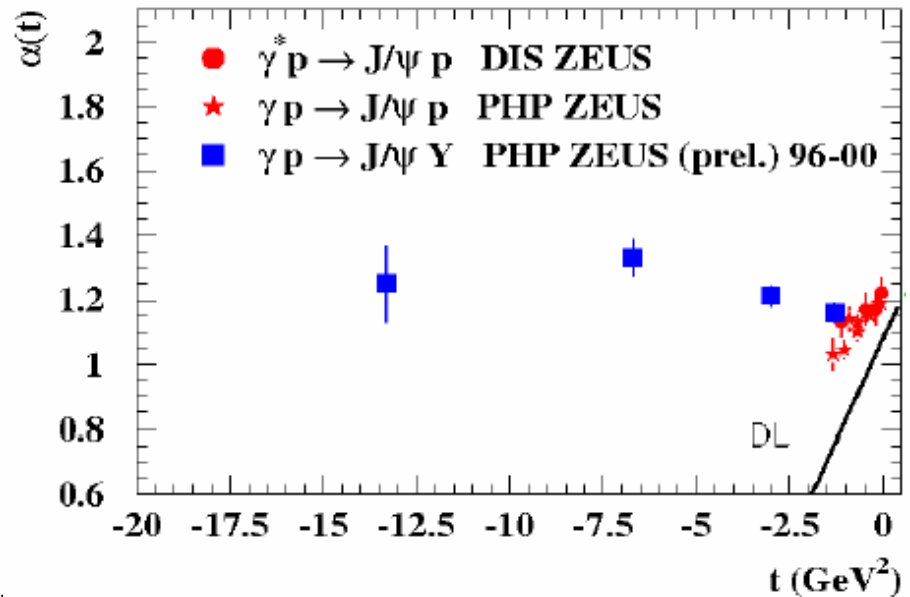
# J/ψ, W dependence, shrinkage



rise of  $\sigma$  with  $W$  described by BFKL, not by DGLAP

## Shrinkage

$\alpha'$  slope tends to become  $< 0$   
(and  $\alpha(0)$  smaller ?)





# V. Helicity amplitudes

$(Q^2, W, t, m)$

$\rho, \phi$  (**DIS**),  $J/\Psi$  (photoprod.), large  $|t|$

# spin density matrix elements

3 angles describe VM production and decay

→ **15 spin density matrix elements**

related to **helicity amplitudes**  $T_{\lambda\rho,\lambda\gamma}$

(NPE is assumed)

**SCHC**  $T_{00}$   $T_{11}$

**single flip**  $T_{01}$   $T_{10}$

**double flip**  $T_{-11}$

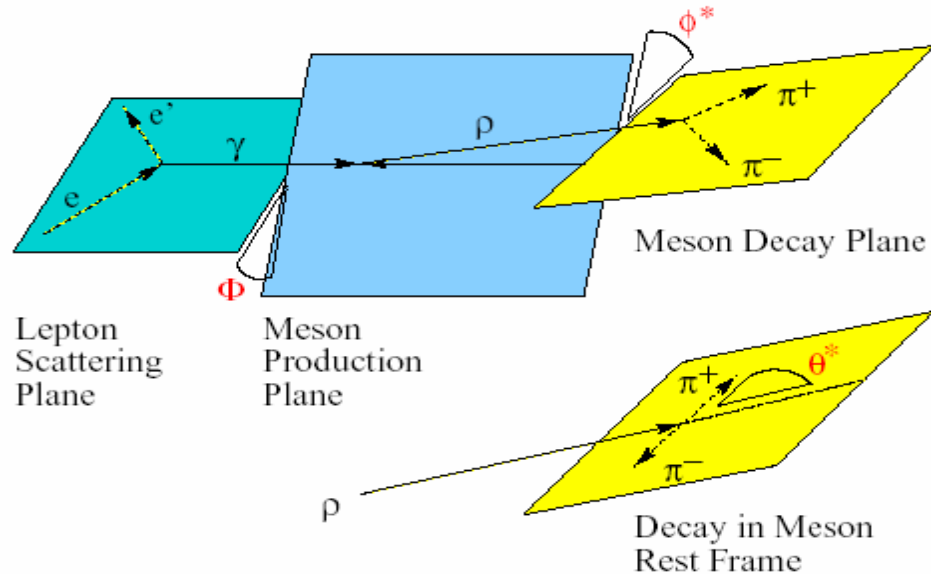
**p QCD hierarchy** ( $|t| < Q^2$ )

all amplitudes suppressed by factors  $1/Q$  w.r.t.  $T_{00}$

single spin flip  $\sim \sqrt{|t|}$

$T_{00} > T_{11} > T_{01} > T_{10}, T_{-11}$

**ZEUS, H1 HERA-1**  $\rho, \phi$  ( $Q^2, W, t, m$ )



# $\rho$ and $\phi$ , spin density matrix elements ( $Q^2$ )

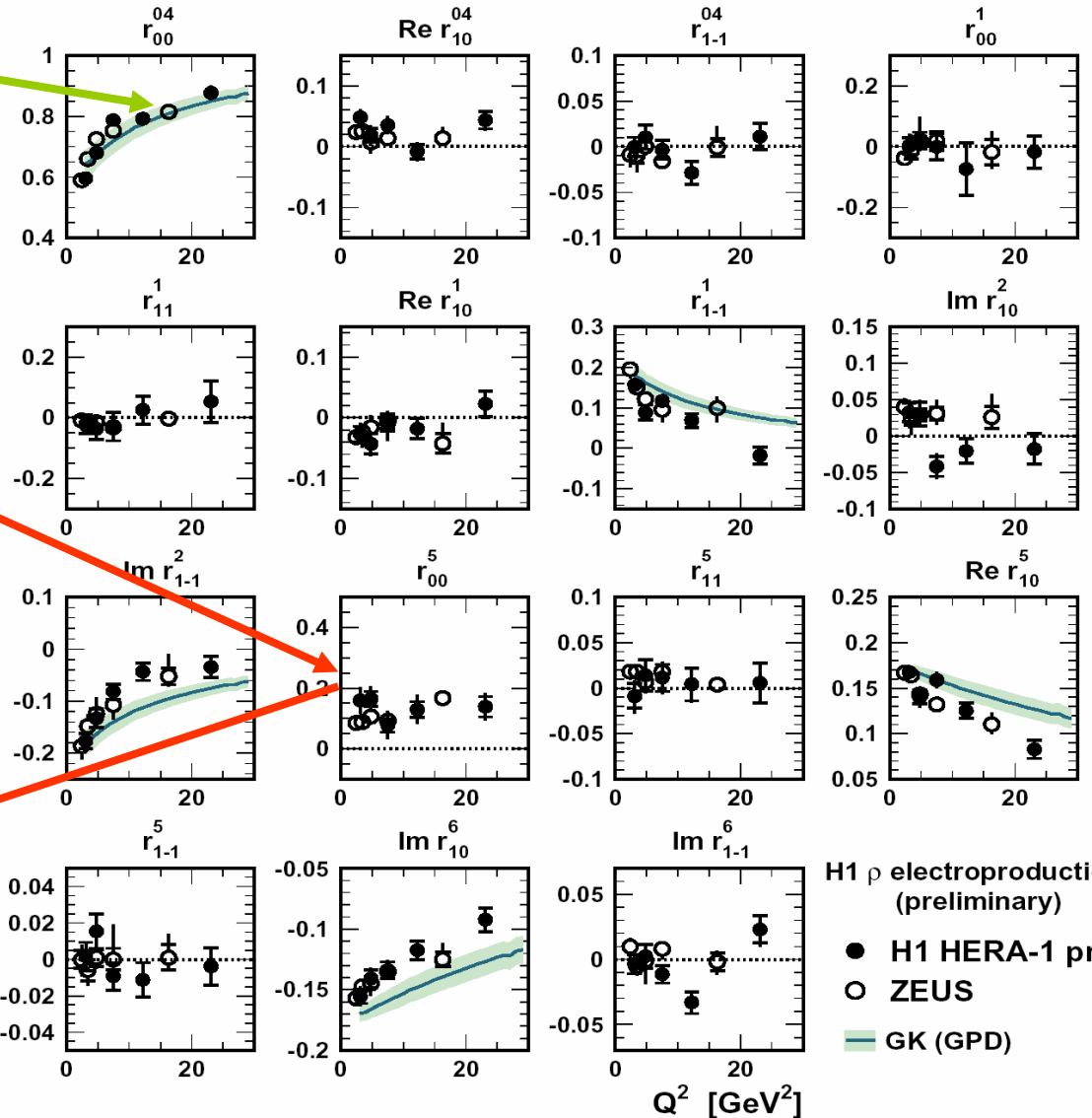
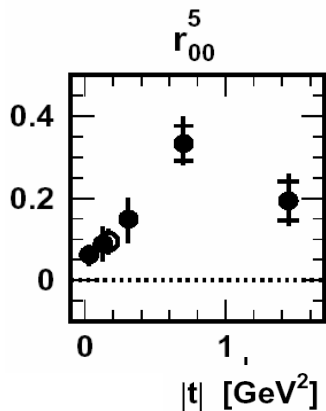
## 5 SCHC elements

compared to GPD calculations

Other elements (dashed lines) compatible with 0 or small

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

expected  $\sqrt{|t|}$  dependence of spin flip amplitude  $T_{01}$



H1  $\rho$  electroproduction (preliminary)

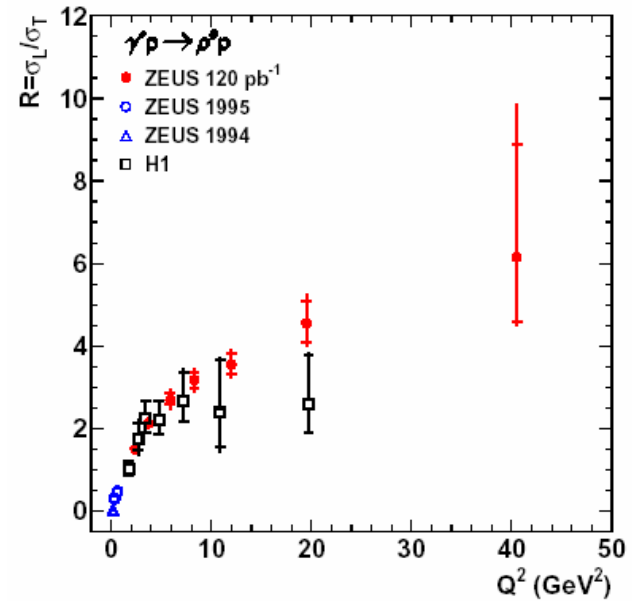
● H1 HERA-1 prel.

○ ZEUS

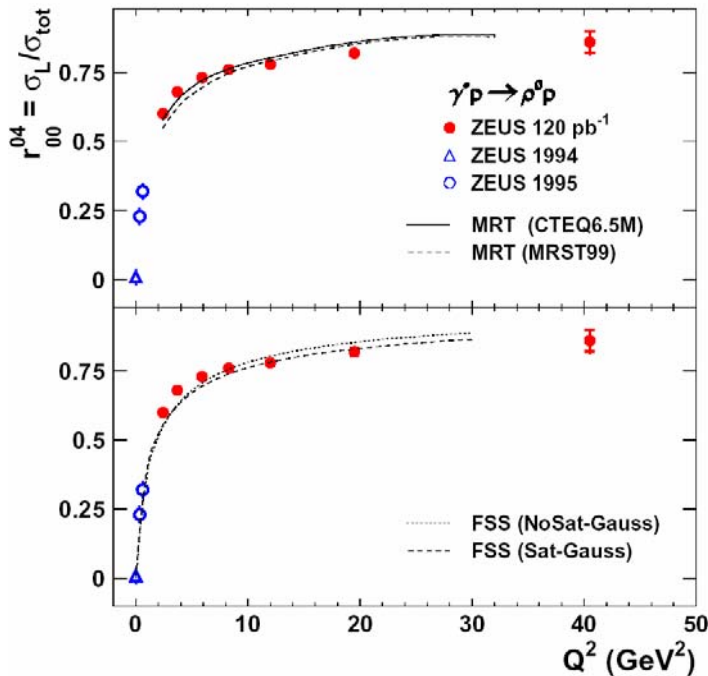
— GK (GPD)

# $\rho$ and $\phi$ , $R = \sigma_L / \sigma_T (Q^2)$

LO 2 gluon exchange :  $R \sim Q^2 / M^2$   
clearly **modified** !

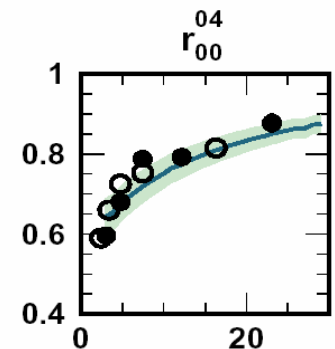


$Q^2$  dependence of gluons  
(MRT – parton hadron duality)



**dipole + saturation**

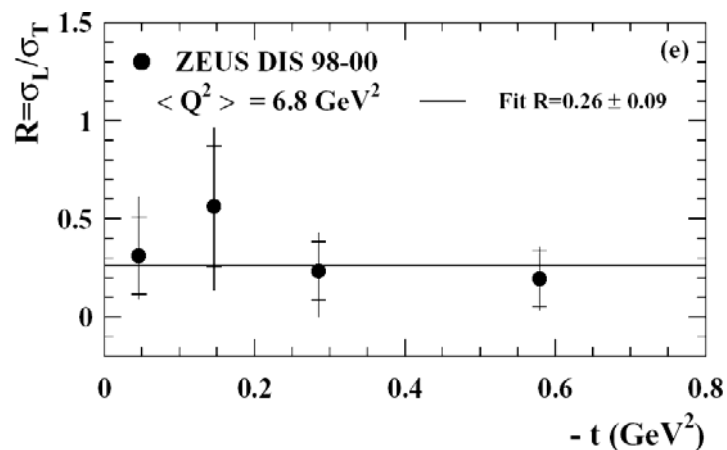
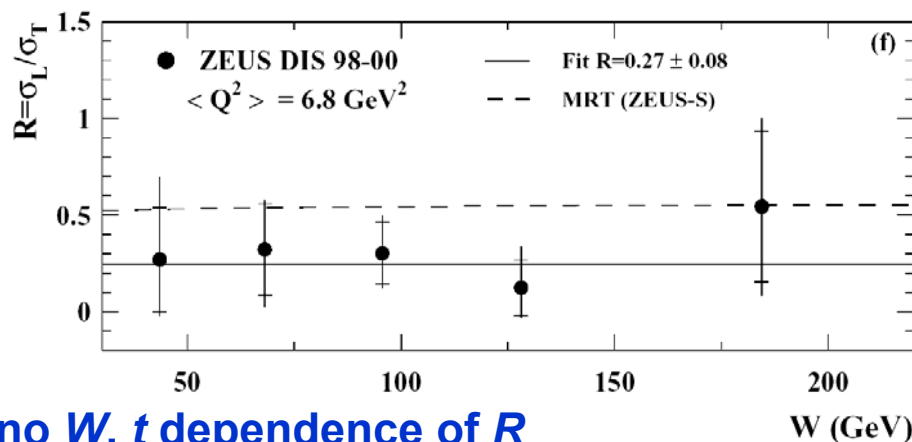
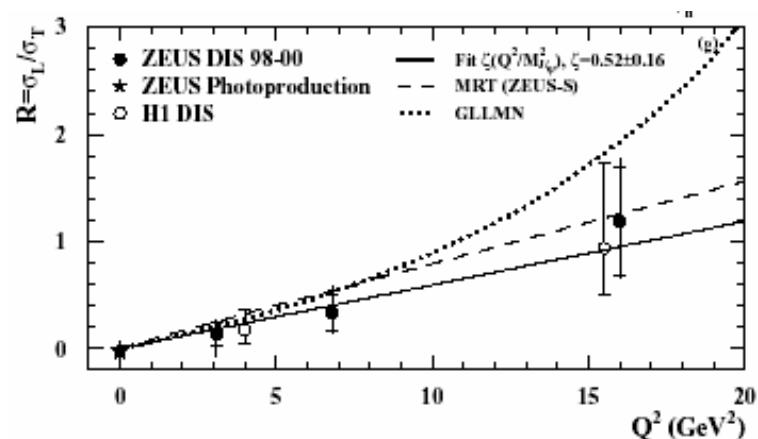
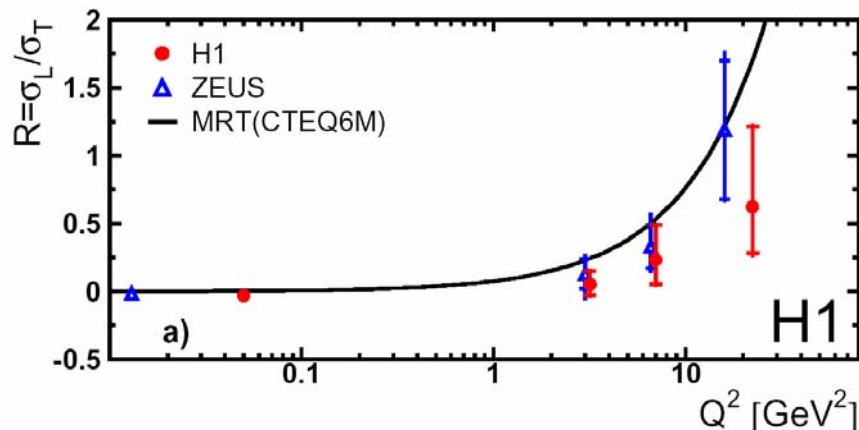
**GPD**



# $J/\Psi, R = \sigma_L / \sigma_T$

non-relativistic model for  $J/\Psi$  :  $z \sim 1/2 \rightarrow$  **no helicity flip**

basic scale for  $R$  given by  $R \sim Q^2 / M^2 \rightarrow$  much slower increase of  $R$  with  $Q^2$  than for  $\rho, \phi$



**no  $W, t$  dependence of  $R$**

# large $|t|$ , $\rho$ (photoproduction)

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

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

Reason :

**chiral odd contribution** in  $\gamma$

(due to constituent quark mass)

→ no orbital momentum needed for  $\Psi_T$

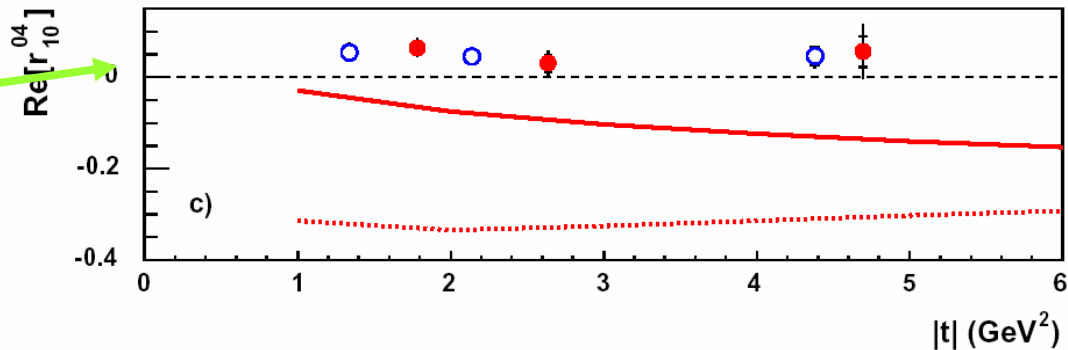
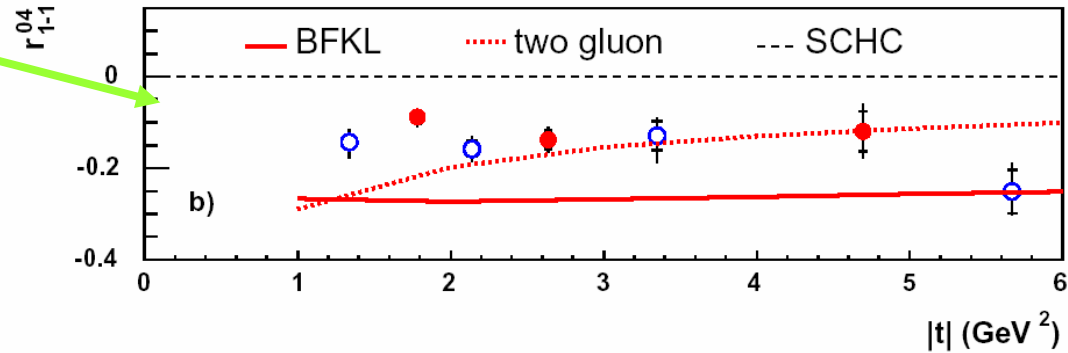
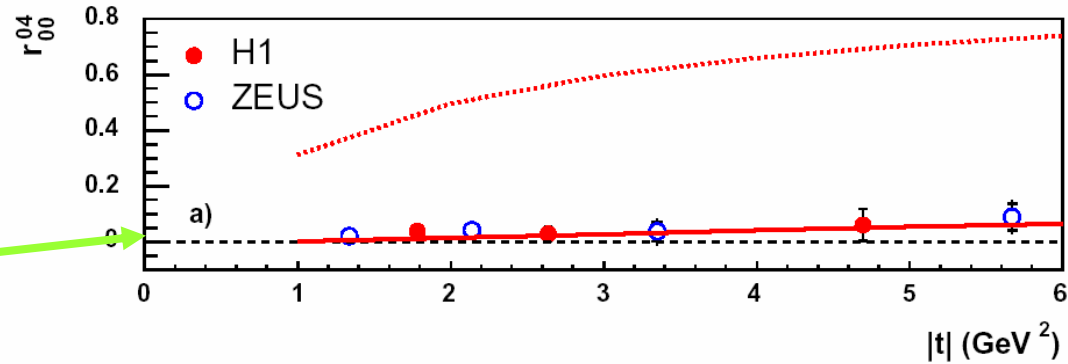
$\Psi_T$

→ SCHC

**BFKL model** describes data well

(except sign of )

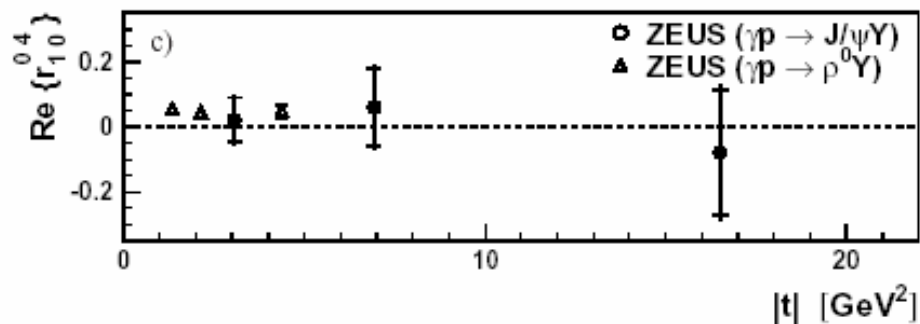
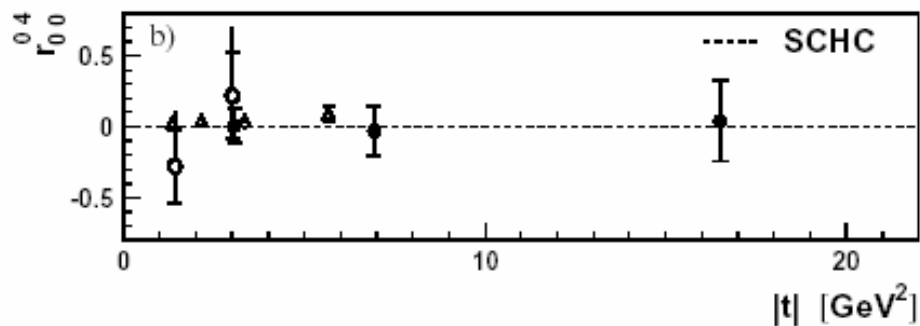
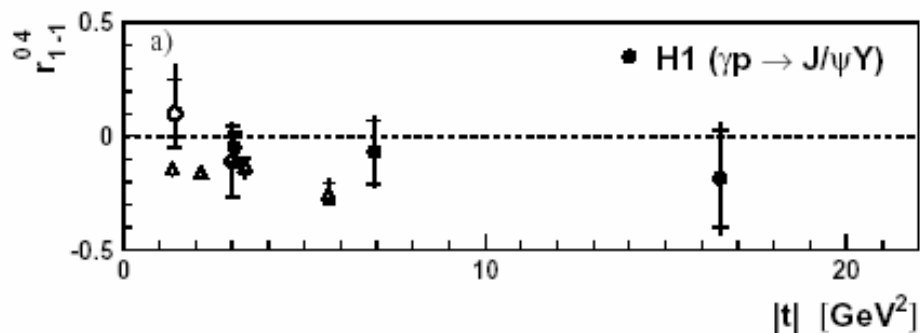
cf. also  $t$  and  $W$  dependences



# large $|t|$ , $J/\Psi$ (photoproduction)

no helicity flip

cf. non-relativistic model



# **VI. Summary and conclusions on vector mesons**



# Summary

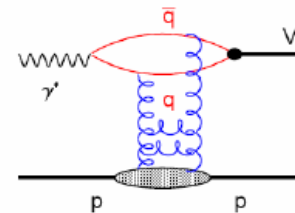
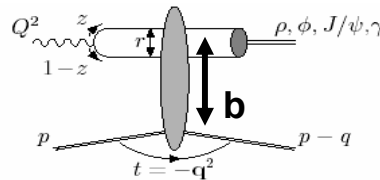
## Enormous progress

### - experiments

DVCS light VM ( $\rho, \phi$ )  $J/\Psi$   $\Upsilon$   
 $Q^2$   $W$   $t$  hel. amplitudes p.diss. / el.

### → Consistent QCD picture

- universal  $q\bar{q}$  dipoles
- gluon distribution in p



### - theory

- GPD
- NLO
- dipole + saturation
- ...

training ground / tests of several general ideas / techniques

**BUT** beyond semi-qualitative understanding, many **quantitative** descriptions still lacking

# VII. Spectroscopy

# Gluon and Quark States

The best known hadrons are well explained by the Standard Model

Particles made only from gluons, or from more than 3 quarks are not excluded

Since gluons carry both color and anti-color, 2 or 3 may form color singlet “glueballs”

## Lattice QCD calculations predict:

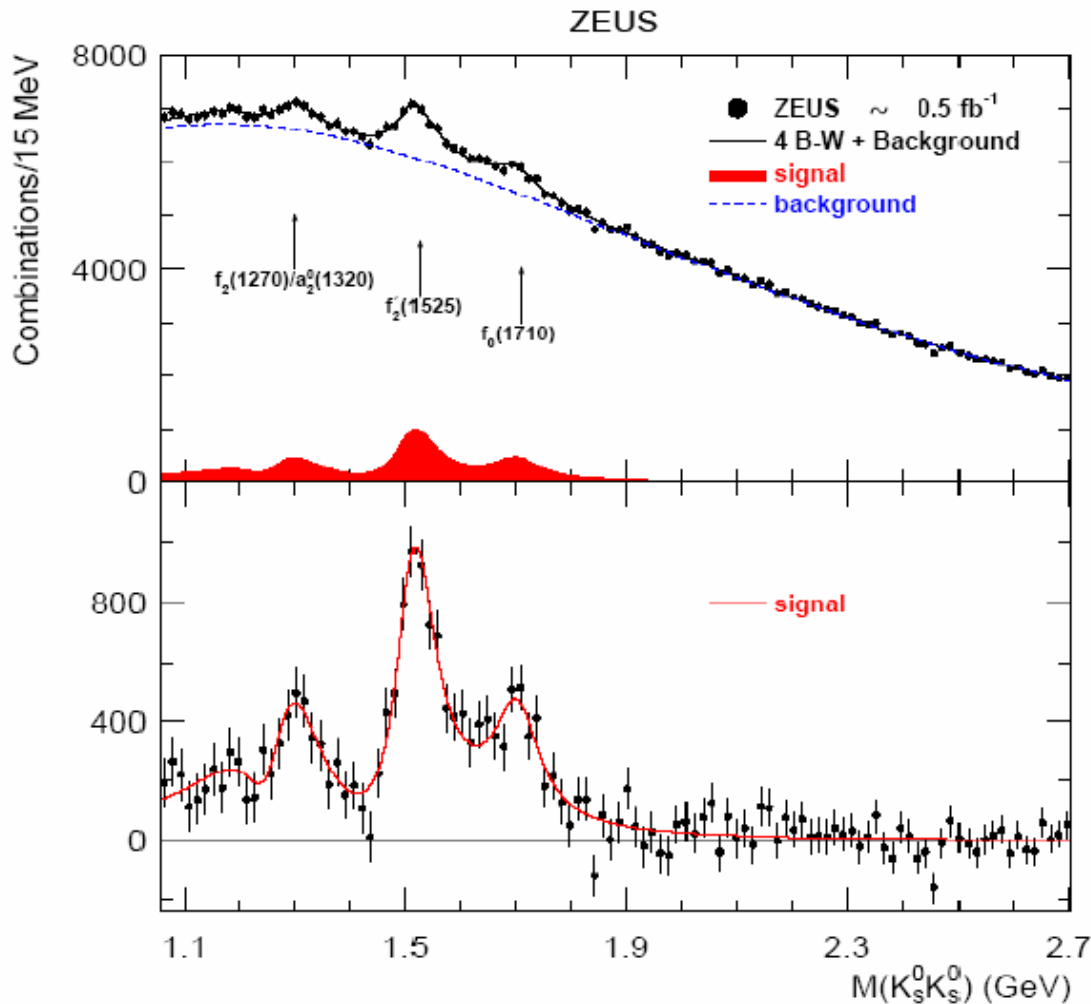
lightest glueball  $J^{PC} = 0^{++}$  in mass range 1450-1750 MeV

next:  $J^{PC} = 2^{++}$  in mass range 2300-2600 MeV

$K_s^0 K_s^0$  bound states:  $J^{PC} = 0^{++}$  (scalar),  $2^{++}$  (tensor), ..  
hence may couple to glueballs

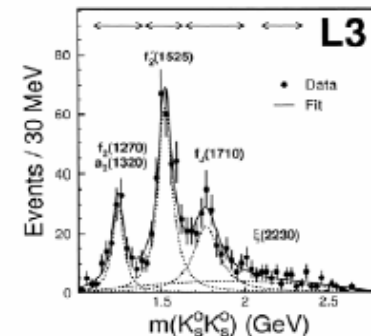
(Slides from F. Corriveau at PHIPSI08 – Frascati 2008. Many thanks to him !)

# $K_S^0 K_S^0$ Resonant States



Bret-Wigner functions, with interference terms included

states  $f_2'(1525)$  and  $f_0(1710)$  clearly seen



# $K_S^0 K_S^0$ Resonance Results

State  $f_0(1710)$ :

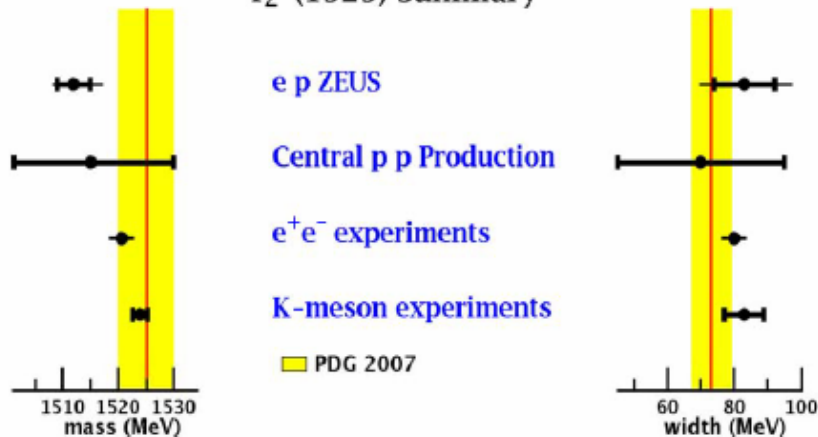
observed at  $5\sigma$  significance

consistent with  $J^{PC}=0^{++}$

glueball candidate  $\rightarrow$

in MeV	Fit		PDG 2007 Values	
	Mass	Width	Mass	Width
$f_2(1270)$	$1268 \pm 10$	$176 \pm 17$	$1275.4 \pm 1.1$	$185.2^{+3.1}_{-2.5}$
$a_2^0(1320)$	$1257 \pm 9$	$114 \pm 14$	$1318.3 \pm 0.6$	$107 \pm 5$
$f_2'(1525)$	$1512 \pm 3^{+2}_{-0.6}$	$83 \pm 9^{+5}_{-4}$	$1525 \pm 5$	$73^{+6}_{-5}$
$f_0(1710)$	$1701 \pm 5^{+5}_{-3}$	$100 \pm 24^{+8}_{-19}$	$1724 \pm 7$	$137 \pm 8$

$f_2'(1525)$  summary



$f_0(1710)$  summary

