

Meson production at HERA



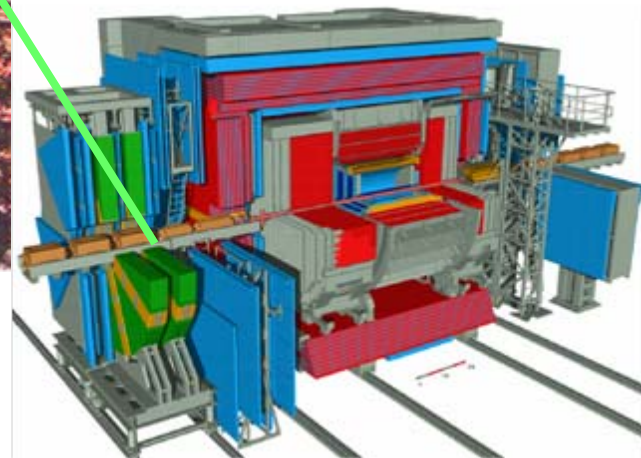
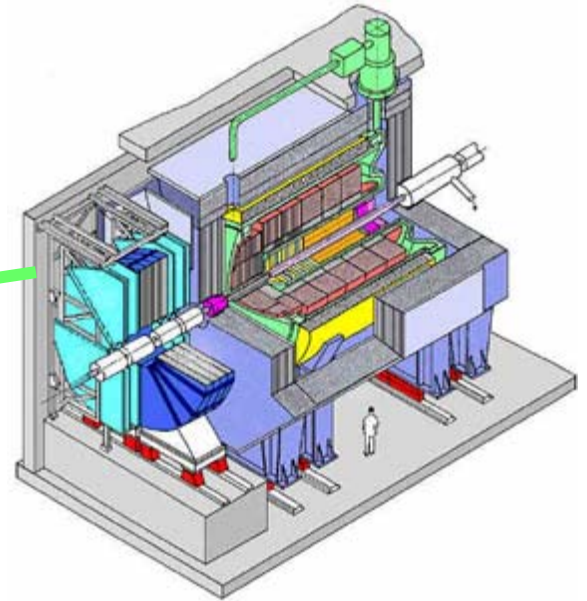
The H1 and ZEUS collaborations



Pierre Marage
Université Libre de Bruxelles



The HERA collider

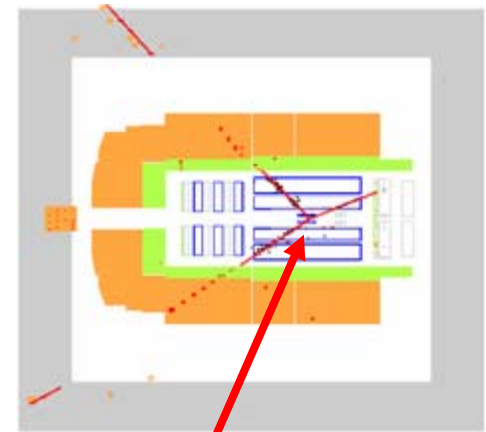
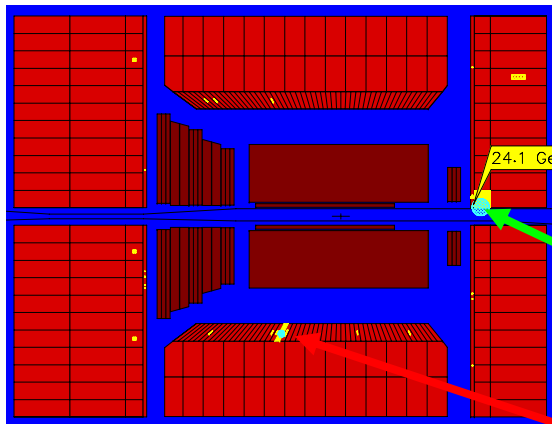


820 / 920 GeV p 27.5 GeV e^+ / e^-

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

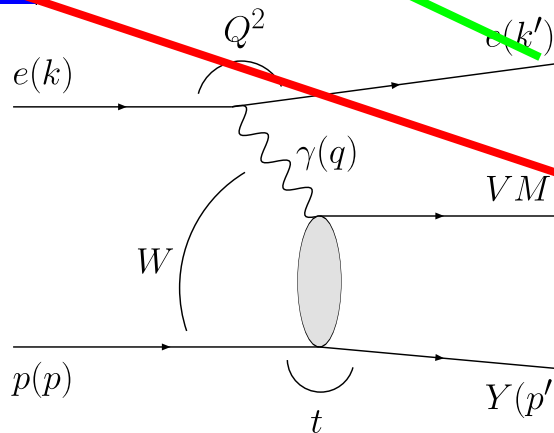
1992 – 2007 $\sim 500 \text{ pb}^{-1} / \text{exp.}$

Introduction



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

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



γ ρ ω ϕ J/ψ $\psi(2s)$ Y

p $p.$ diss. (M_Y)

A QCD laboratory

M_V 0 – 10 GeV

Q^2 0 – 80 GeV² (photoproduction & DIS)

W 30 – 300 GeV

$|t|$ 0 – 30 GeV² (small $|t| < 1.5$ GeV² & 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

ρ, ϕ (DIS), J/Ψ (photoprod.), large $|t|$

VI. Summary and conclusions

Spectroscopy

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

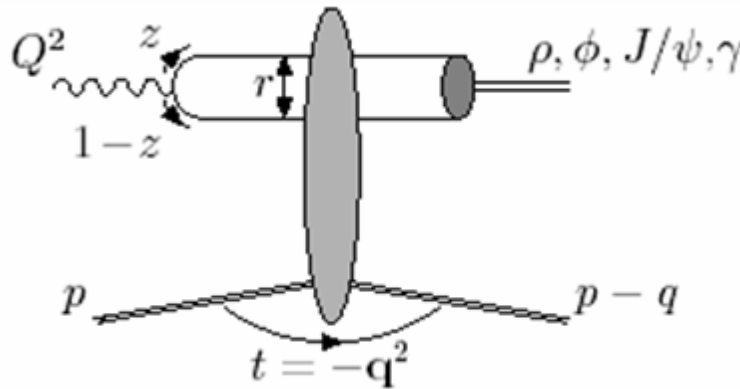
I. VM diffractive production

Interpretation frameworks

QCD factorisation

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

Factorisation theorem



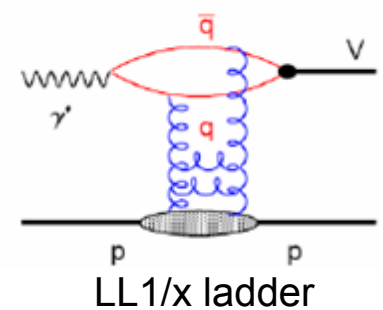
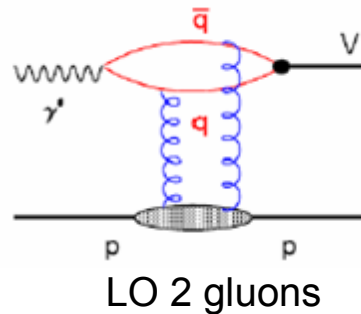
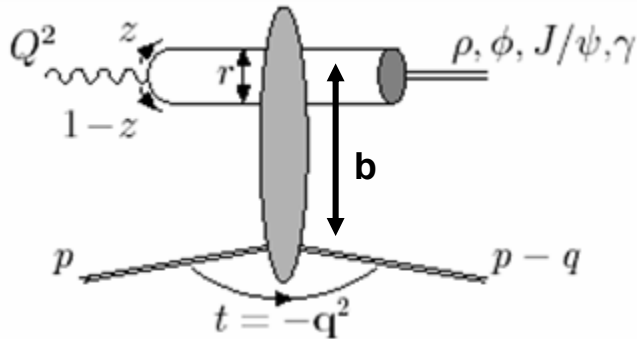
step 1. γ fluctuation into $q\bar{q}$ dipole γ WF $\Psi_\gamma(z, k_t)$

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

step 3. pair recombination into VM

for σ_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 : $z \square 1-z \square 1/2 \rightarrow 1/r \square 1/4 (Q^2 + M_V^2)$
 ((A_T : see below))

+ vertex factorisation

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

Energy dependence

2. W dependence

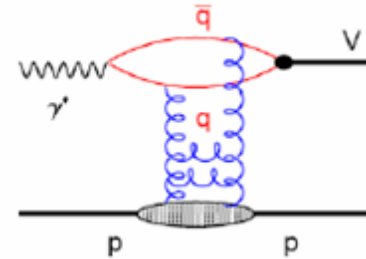
Regge-like parameterisation (high energy) $\sigma_{tot}(h-h) \propto s^{\alpha(0)-1}$

(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

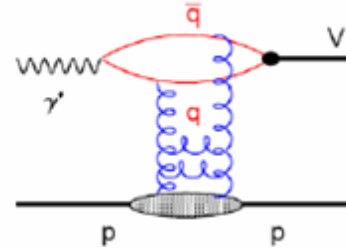
hard scale → **δ , $\alpha(0)$ large, with universal (Q^2+M^2) dep.**

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 $\rightarrow$ **α' small**

Transverse, soft contributions

5. transverse amplitudes

transverse γ (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 $R = \sigma_L / \sigma_T : R(W), R(t), \text{Re} / \text{Im contributions (disp. rel.)}$

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

→ possibly finite size effects also in σ_L

Beyond $LLQ^2, 1/x$

2 main – complementary – extensions

1. Hard scattering

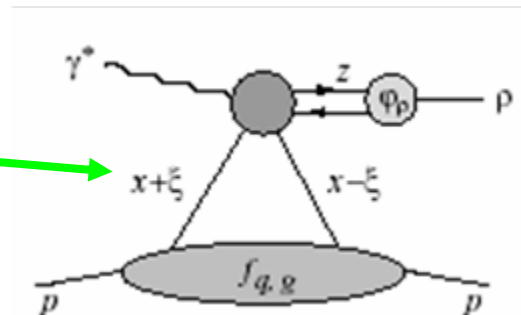
Beyond $LL1/x$ (where 2 gluons have the same x)

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

GPD (Generalised Parton Distributions)

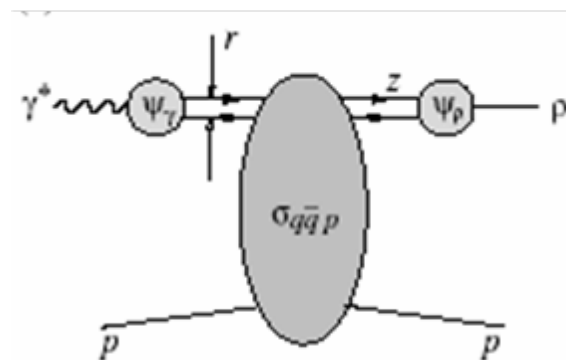
- large scale requested (Q^2, M_V)
- **relax $1/x$** requirement : also valid at **low energy** (Hermes, Compas, JLab); role of quarks

+ NLO



2. Dipole scattering

- large $1/x \Rightarrow$ factorisation
- **relax large scale** : also valid at **low Q^2**
 - σ (dip-p) universal : DIS, DDIS, VM production
- + include **saturation**



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

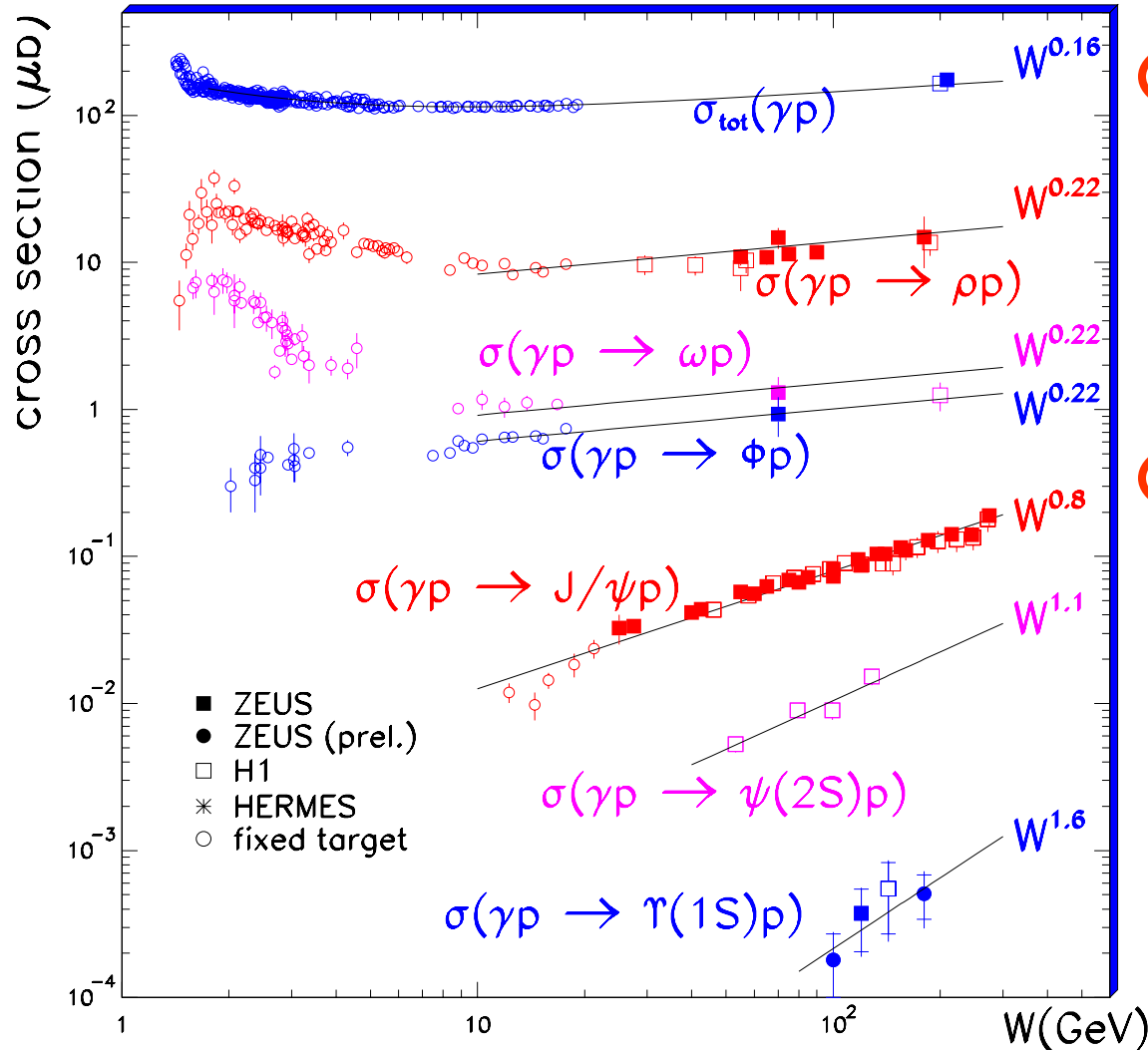
II. From soft to hard : mass

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

W dependences

t dependences

all VM photoproduction



soft

σ_{tot}
 ρ, ω, ϕ

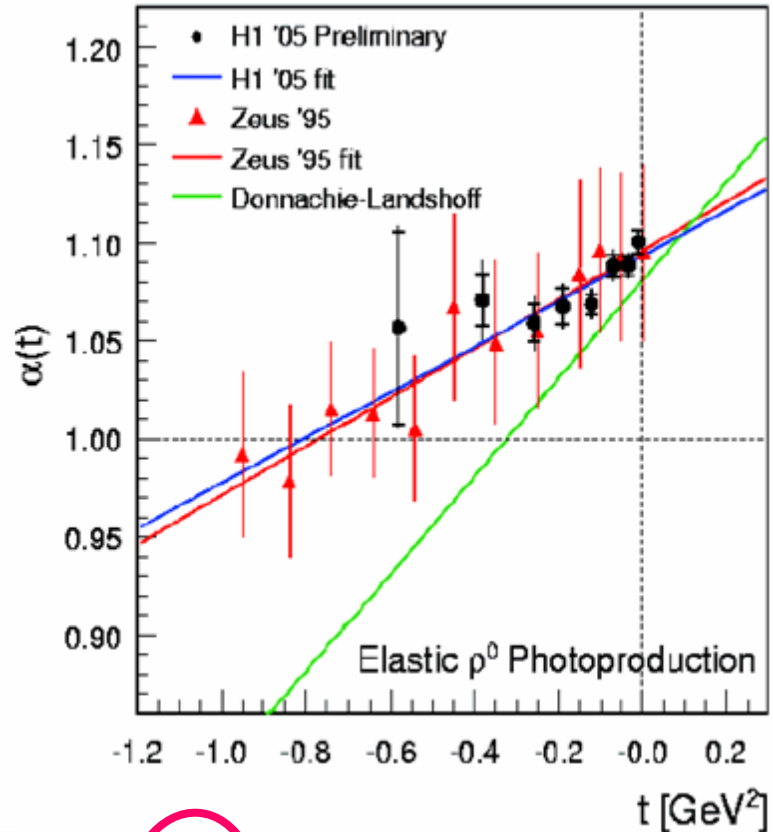
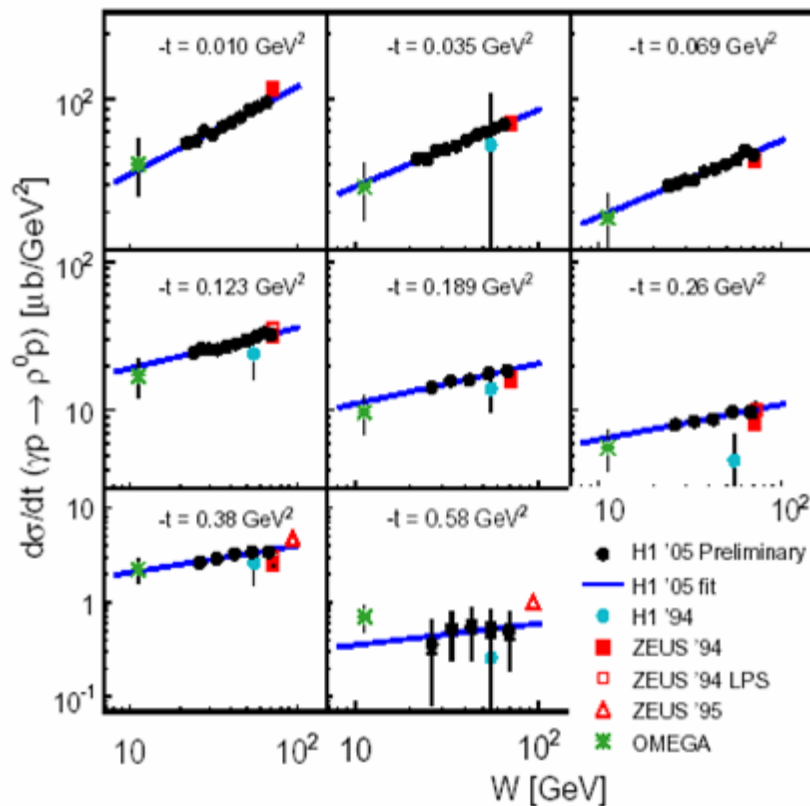
hard

J/ψ

skewing, $\text{Re} \rightarrow$ **GPD**

Υ

ρ, ω, ϕ W dependence



ZEUS
H1

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

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

soft intercept

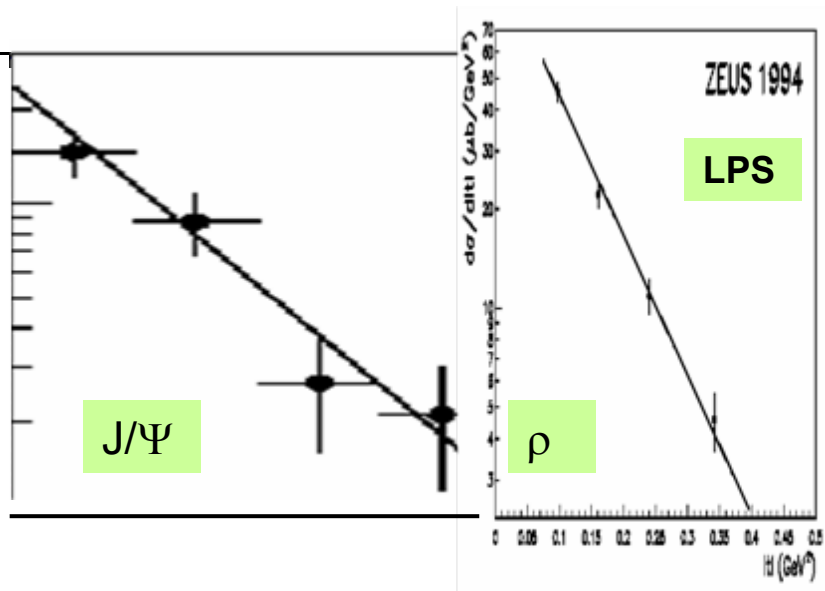
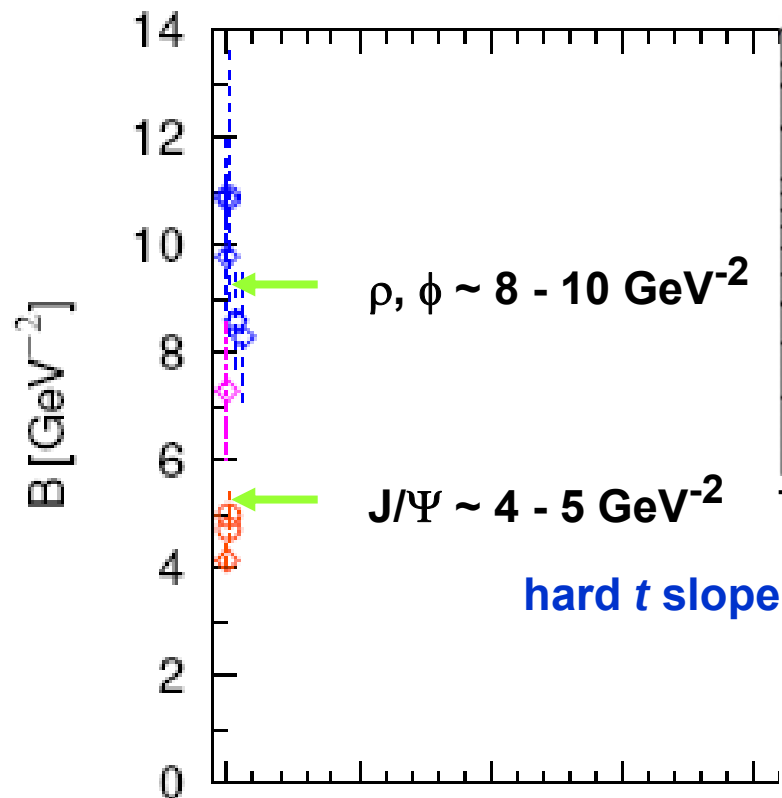
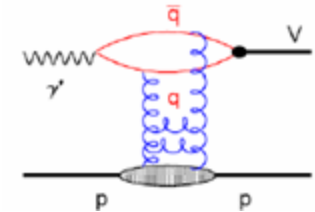
lower slope than h-h

-> rescattering effects ?

ρ , J/Ψ , t dependence

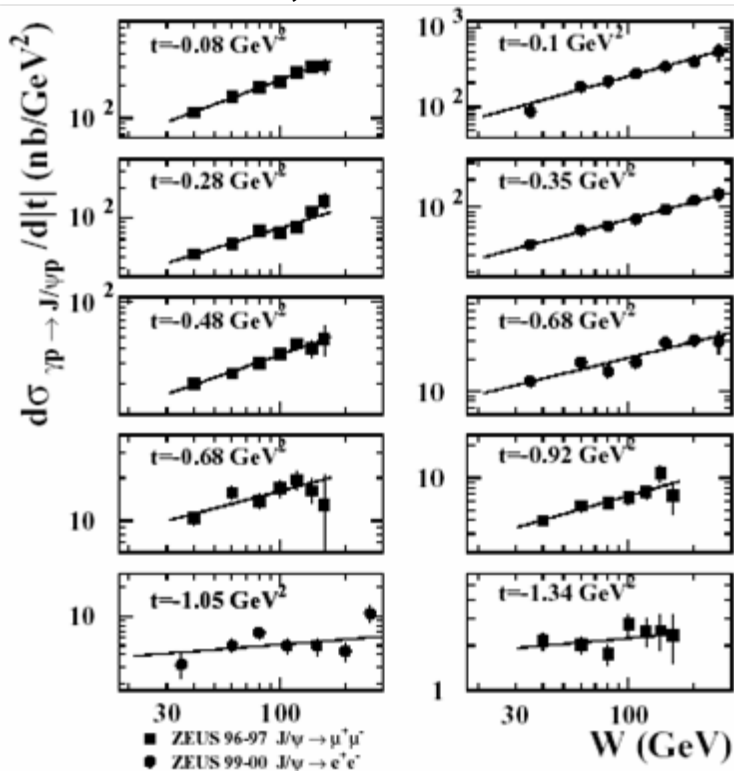
exponential slopes $\leftrightarrow$ **size of the dipole**

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



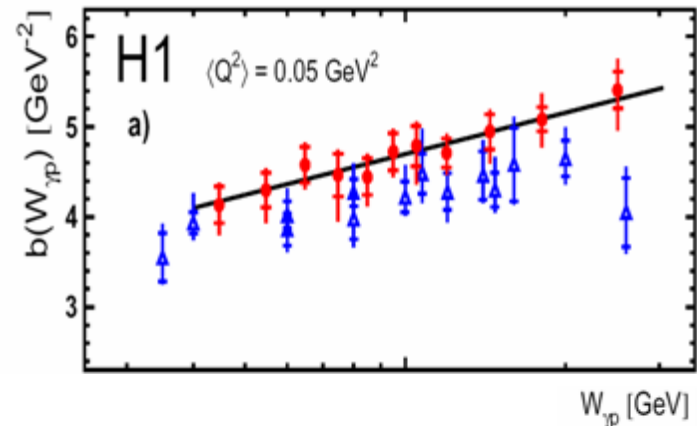
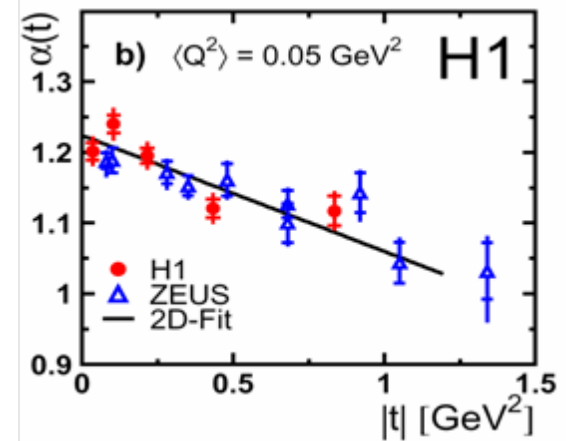
J/Ψ, W dependence, shrinkage

ZEUS 1996-97, 1999-2000



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

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

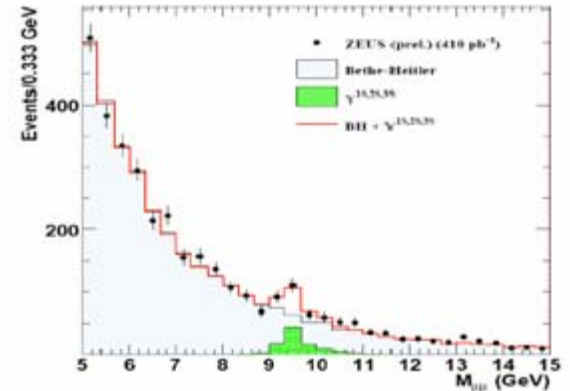
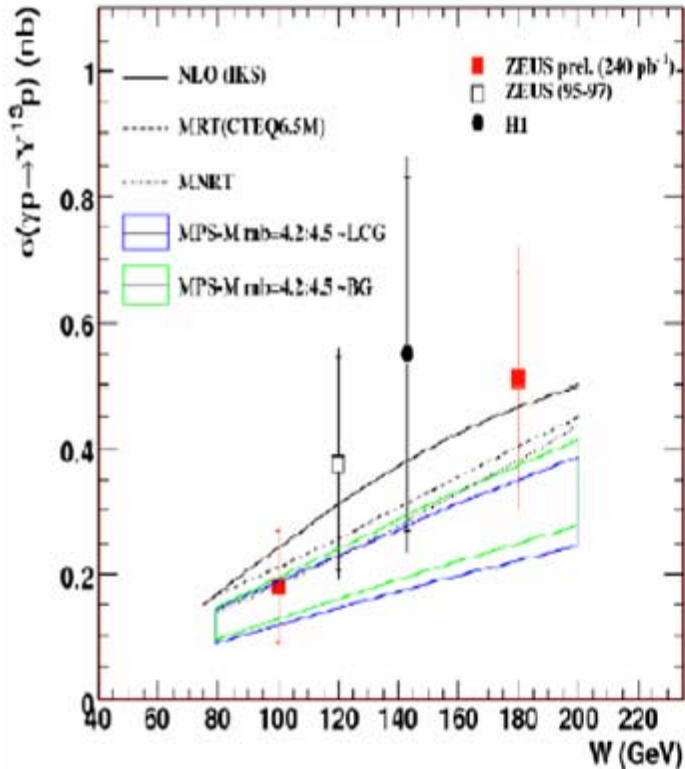


Upsilon

Zeus HERA 1+2

very hard W dependence

$$\delta \sim 1.6$$



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.)

Great progress !

skewing and GPD, NLO calculations, dipole calc.

III. From soft to hard : Q^2

(DVCS, ρ , ϕ , J/Ψ)

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

W dependences

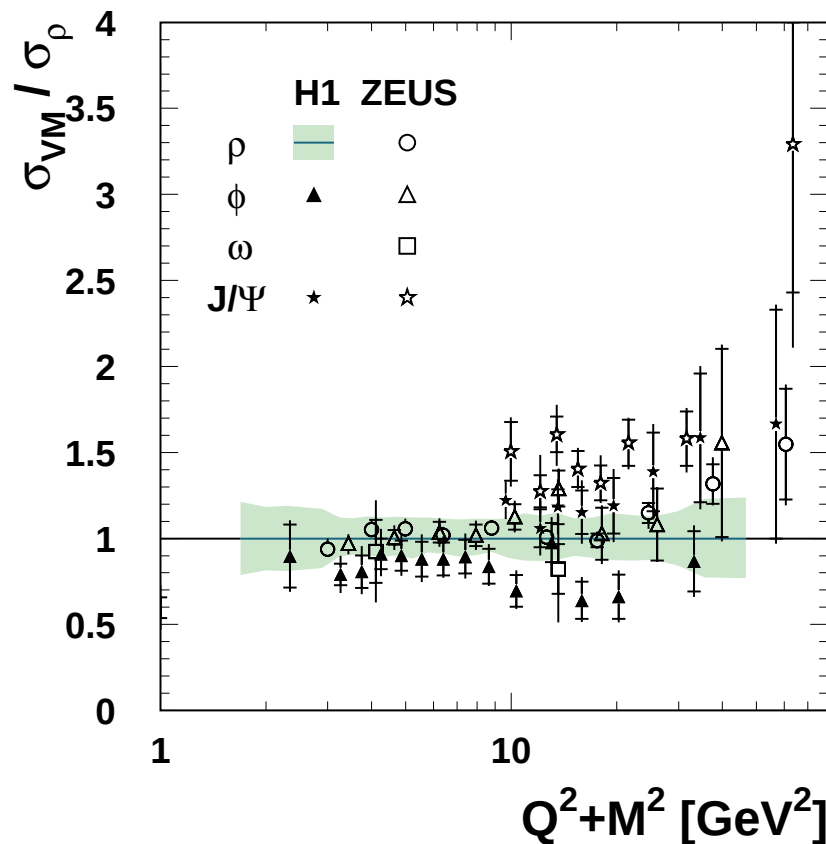
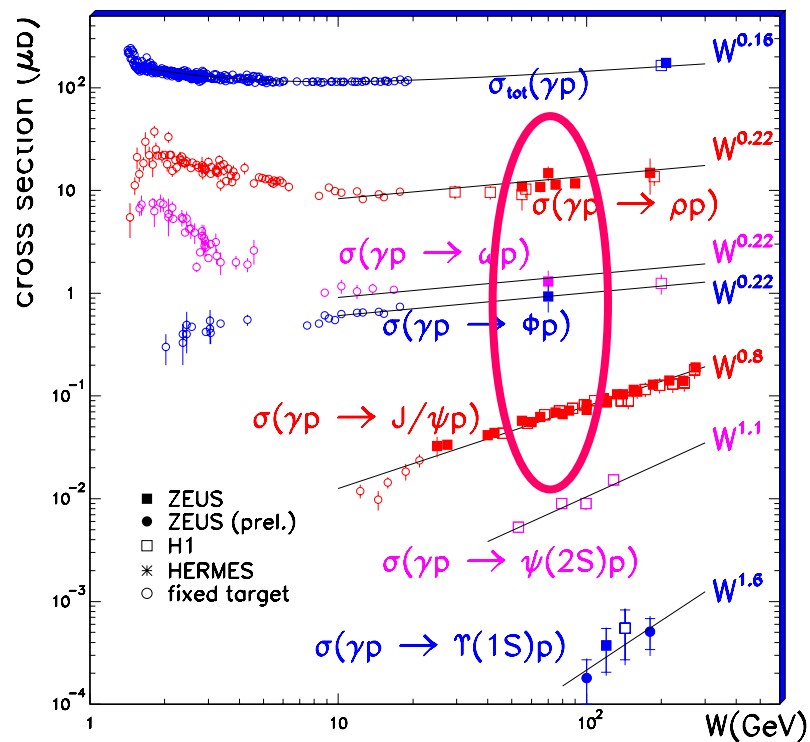
t dependences

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

Quark content weighted cross sections

(qualitatively) striking !

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

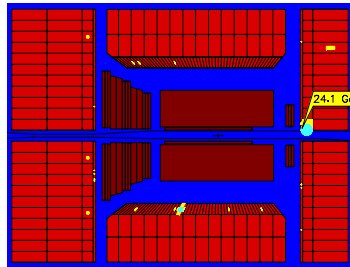


2. Deeply Virtual Compton Scattering

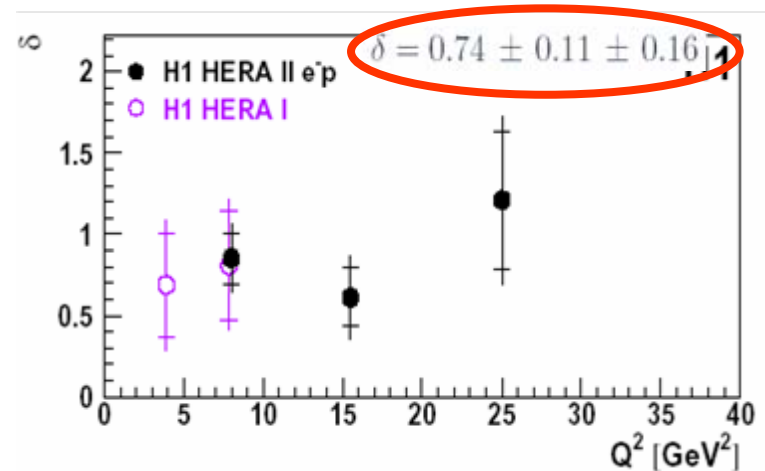
DIS domain :

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

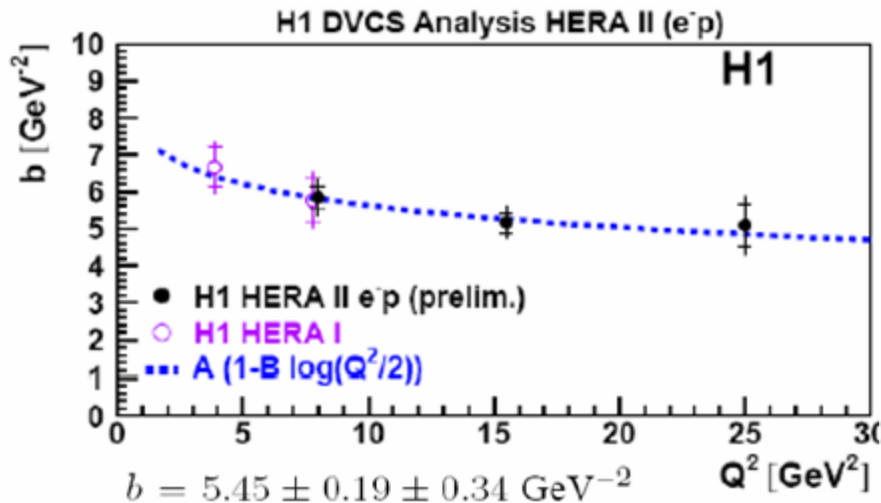
$$\text{i.e. } \gamma^* p \rightarrow \gamma p$$



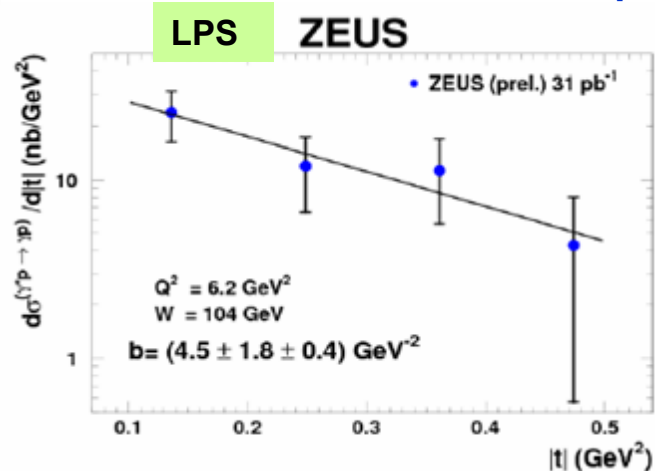
(no WF uncertainties $\leftrightarrow$ light VM)



hard W dependence



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

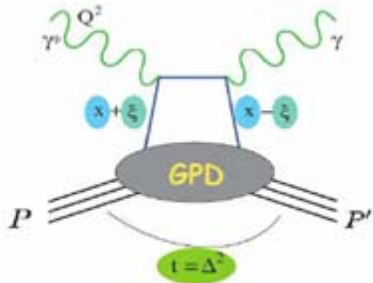


slope not soft, but steeper than J/Y ?

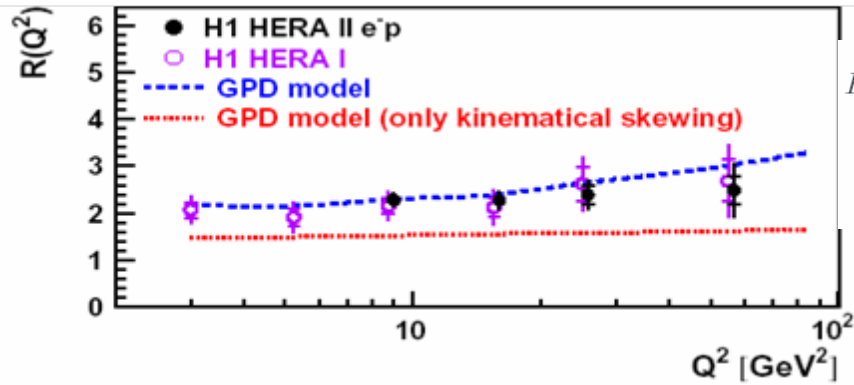
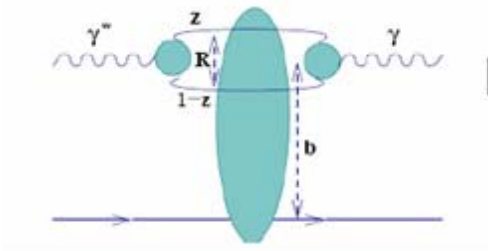
DVCS, models

GPD

kin. skewing
not sufficient



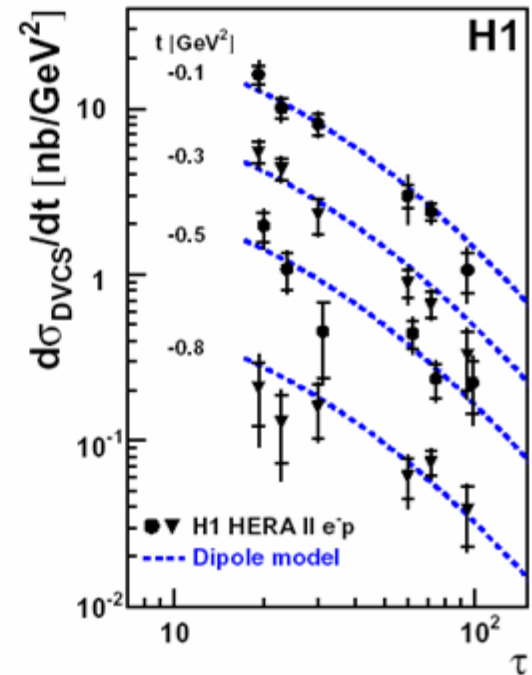
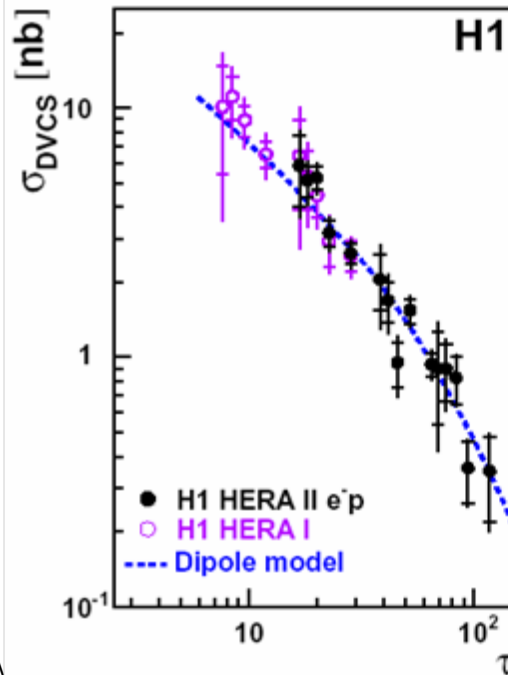
Dipoles + geom. scaling



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

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

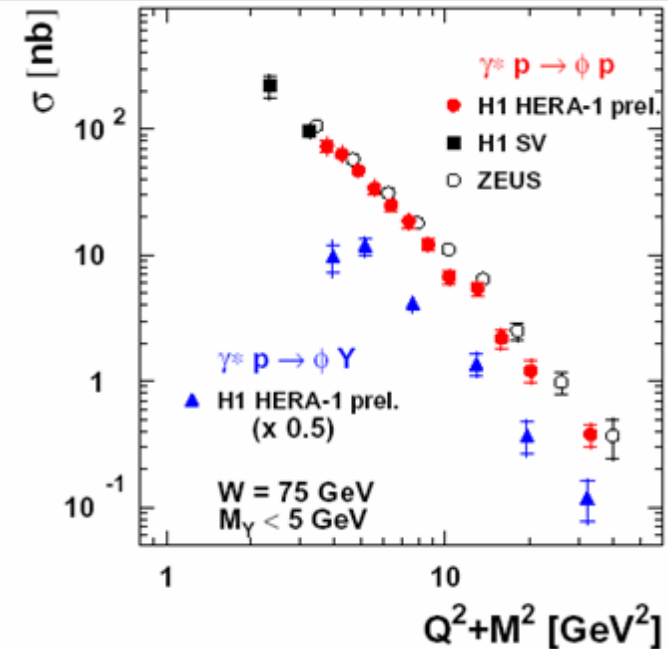
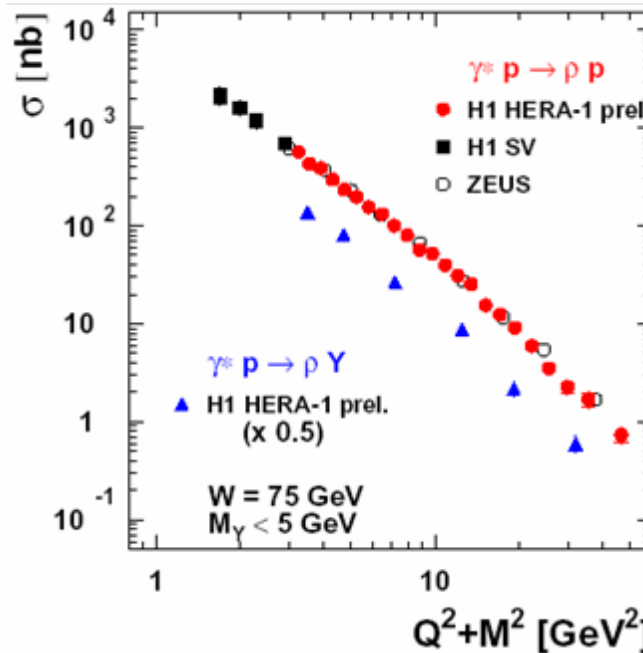
skewing



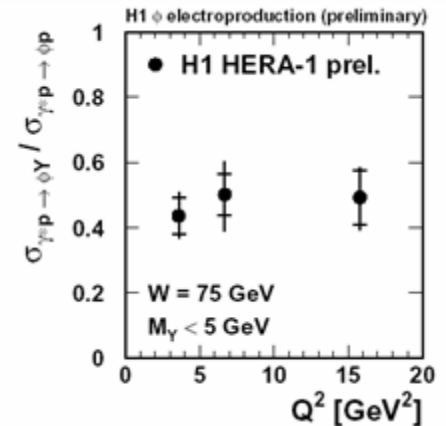
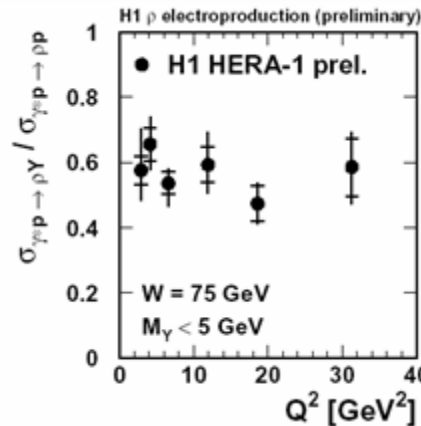
3. ρ and ϕ , elastic and p. dissoc.

ZEUS and H1 - HERA-1
large data sets

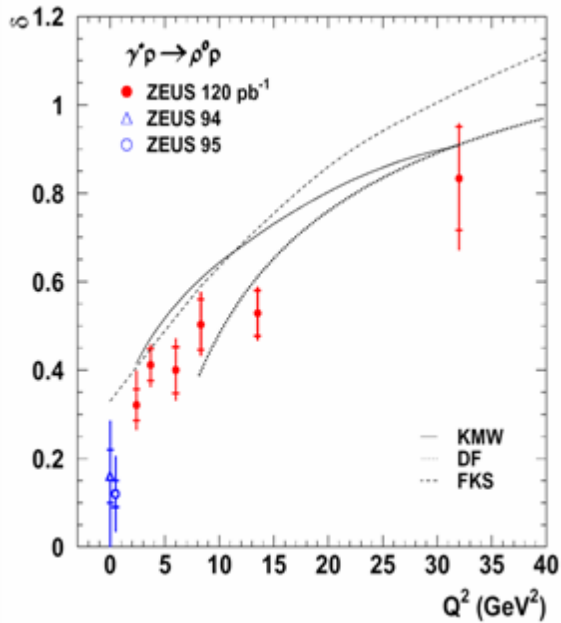
transition to hard diffr.
(+ soft features)



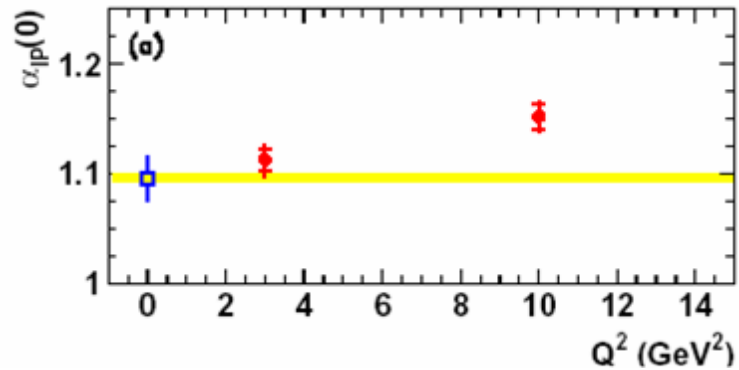
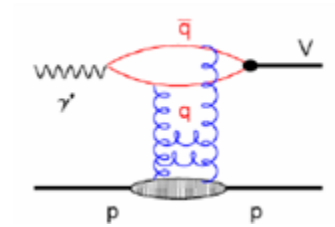
p.diss. / el. : no Q^2 dep. ($Q^2 > 2.5 \text{ GeV}^2$)
proton vertex factorisation



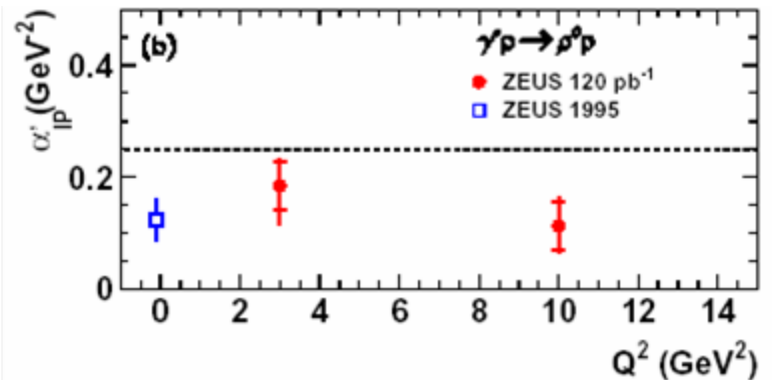
ρ , W dependence



hardening with Q^2



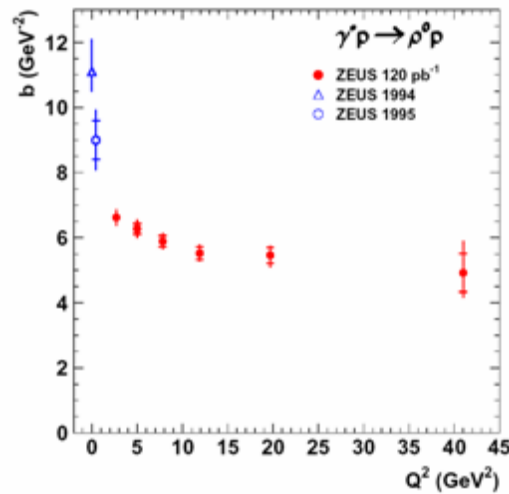
$\alpha' \sim 0.10\text{-}0.15 \text{ GeV}^{-2}$, indep. of Q^2 ?



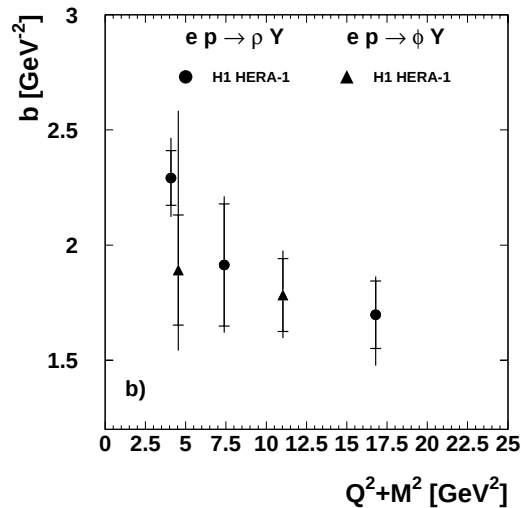
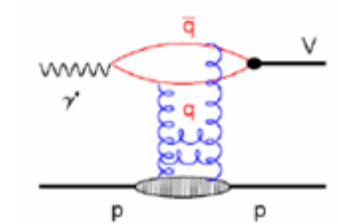
ρ , t dependence

t slope
hardening with Q^2

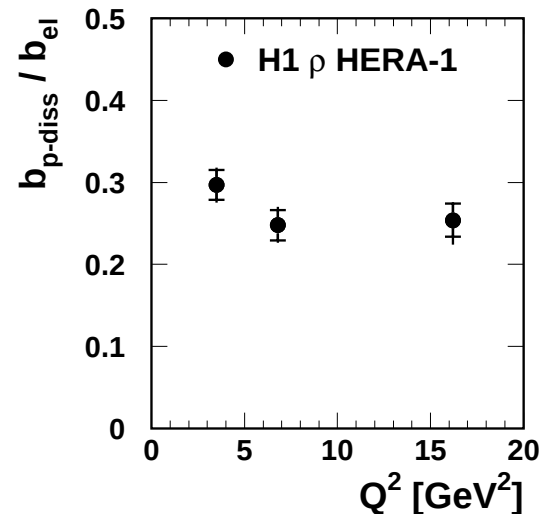
Difficult measurements:
background subtraction
other VM and incl. diff., p. diss.



elastic



proton dissociation

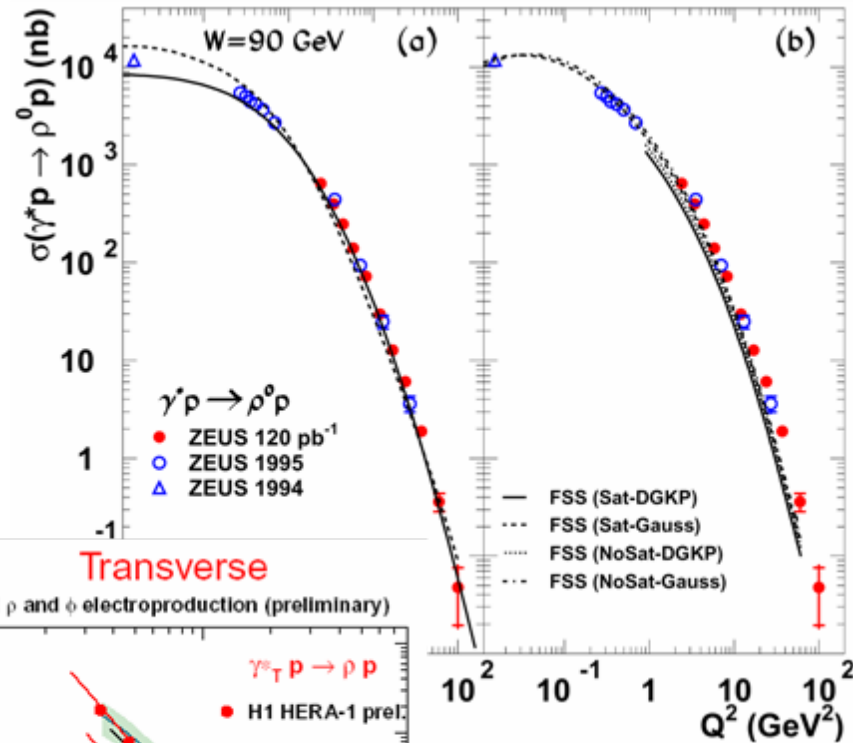


factoris. : p.diss. / el. slope indep. of Q^2

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

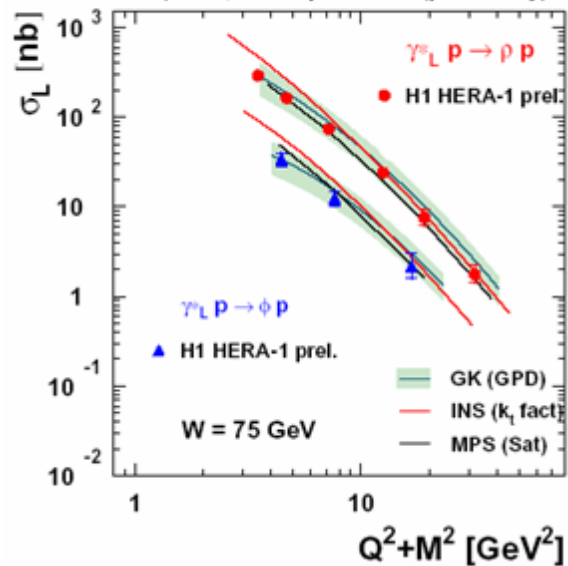
universal dipole

-> small Q^2



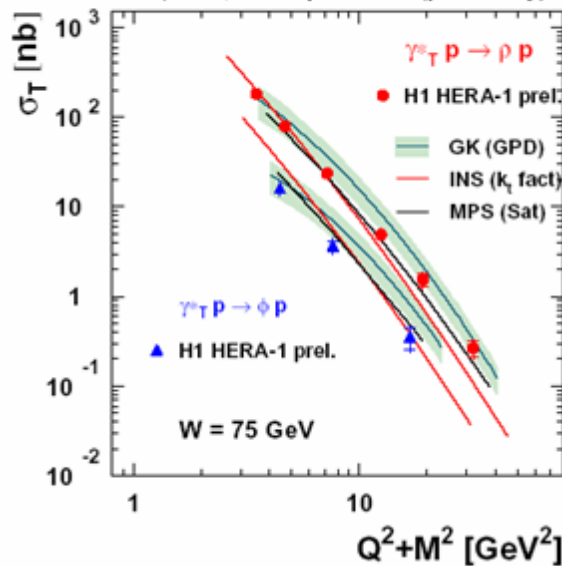
Longitudinal

H1 ρ and ϕ electroproduction (preliminary)



Transverse

H1 ρ and ϕ electroproduction (preliminary)



polarised cross sections

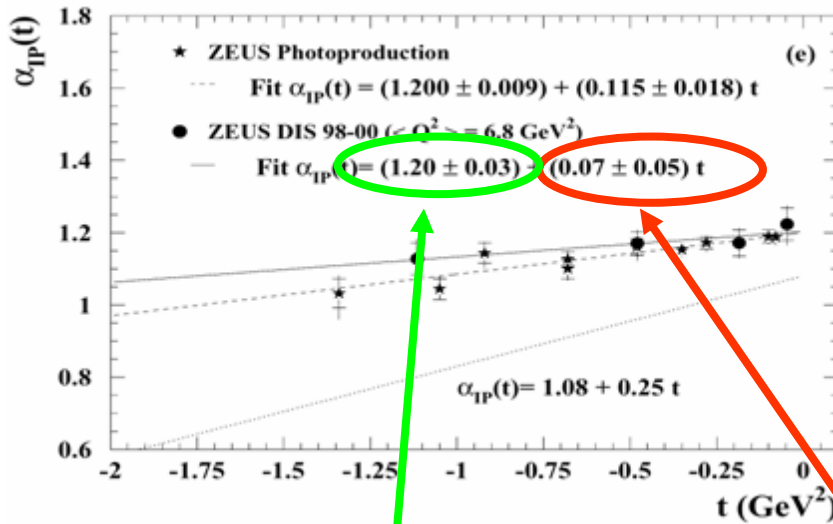
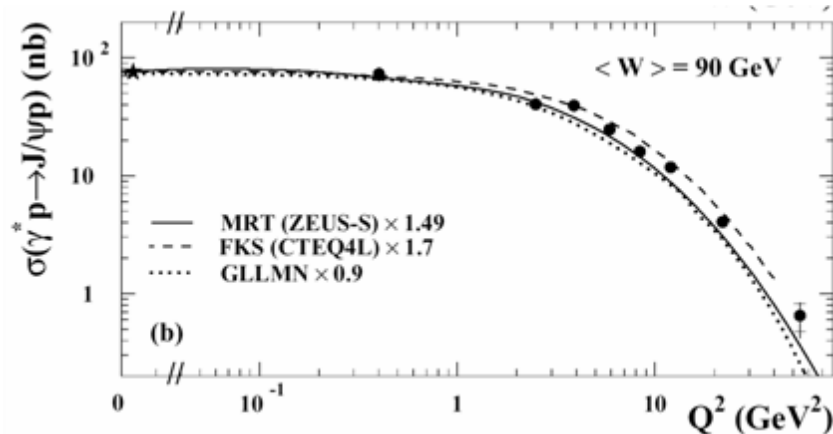
GPD, unintegrated k_t ,

dipole + saturation

4. J/Ψ, hard scales

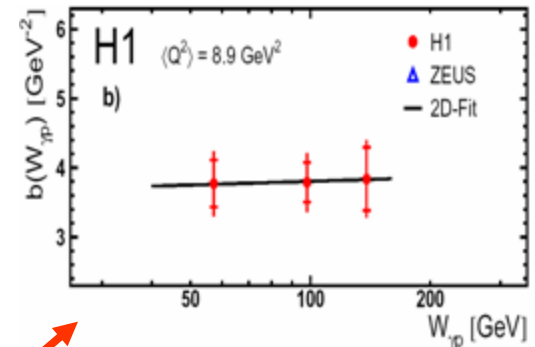
J/Ψ hard in photoproduction

→ $Q^2 = \text{second hard scale}$



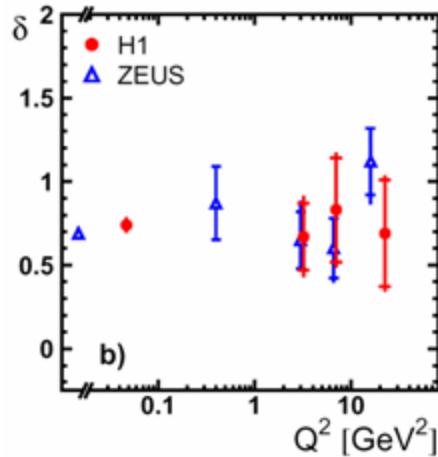
hard : $\alpha(0) = 1.20$

α' consistent with 0

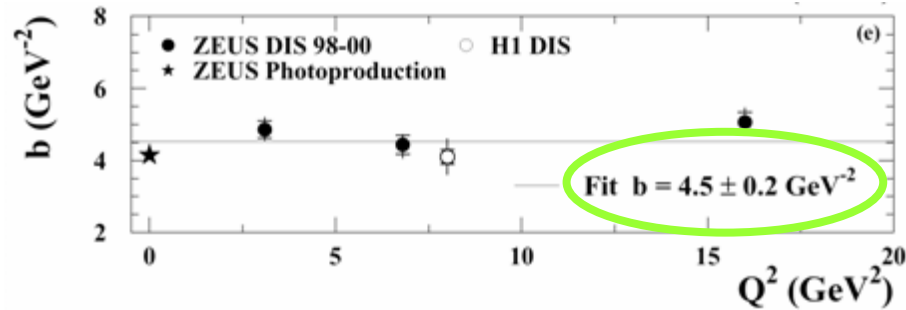


J/Ψ, Q² independence of $\alpha(0)$, b

δ

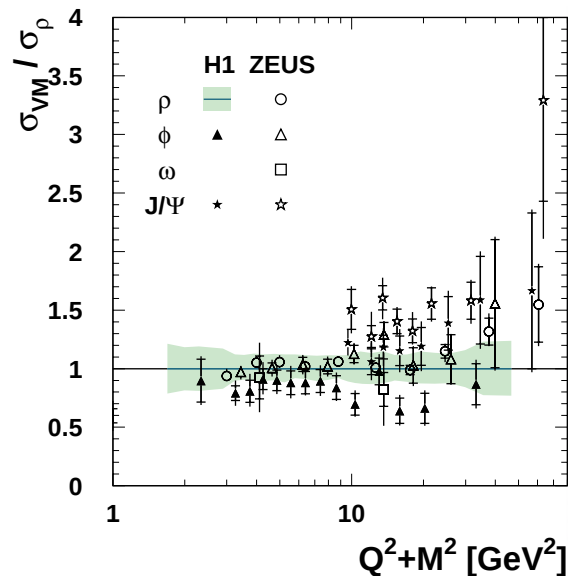


b slope

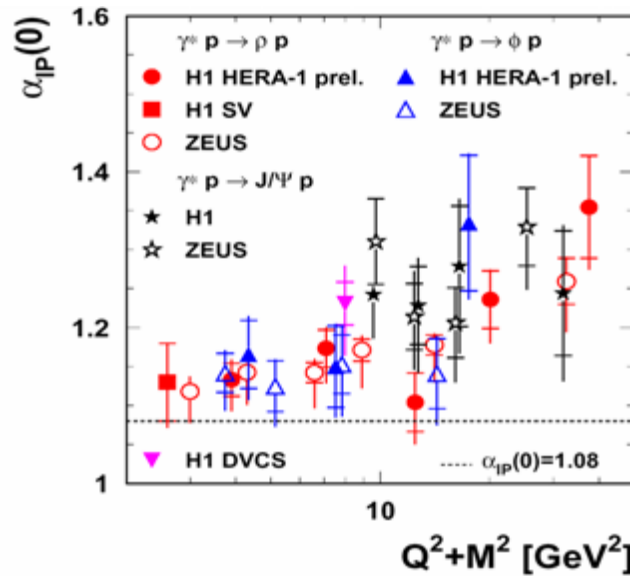


5. summary : universality ($Q^2 + M^2$) of hard diffraction

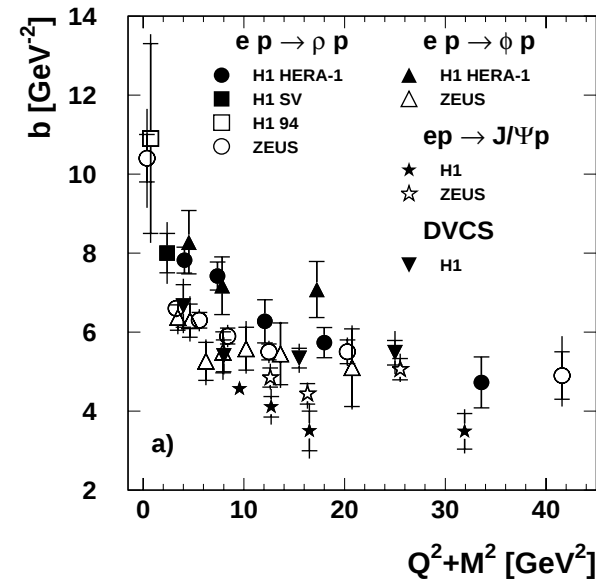
small dipoles, hard gluons



$d\sigma/dQ^2$



energy dep.



b slopes

IV. From soft to hard : t

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

universality (t)

t dependences

W dependences

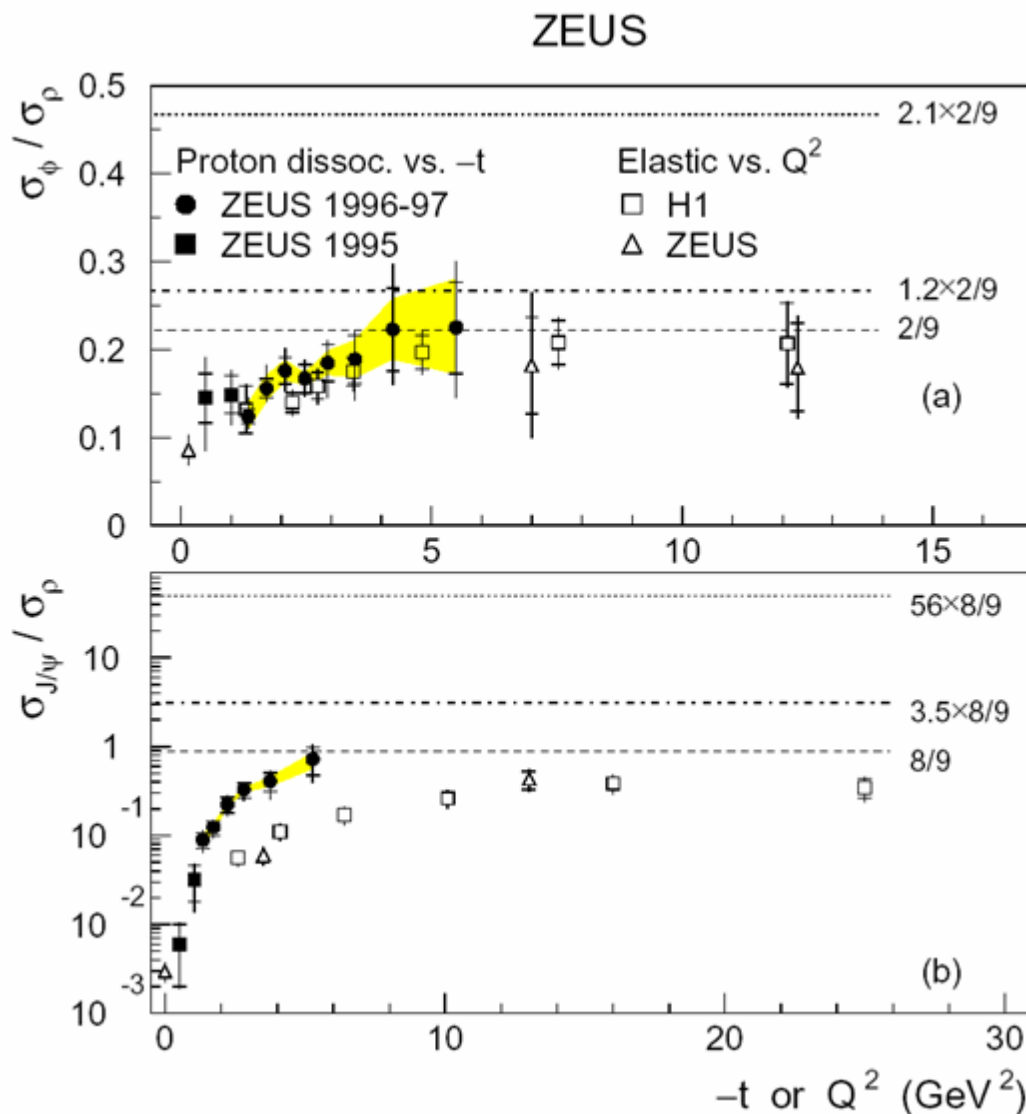
1. Universality (t)

Another hard scale

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

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

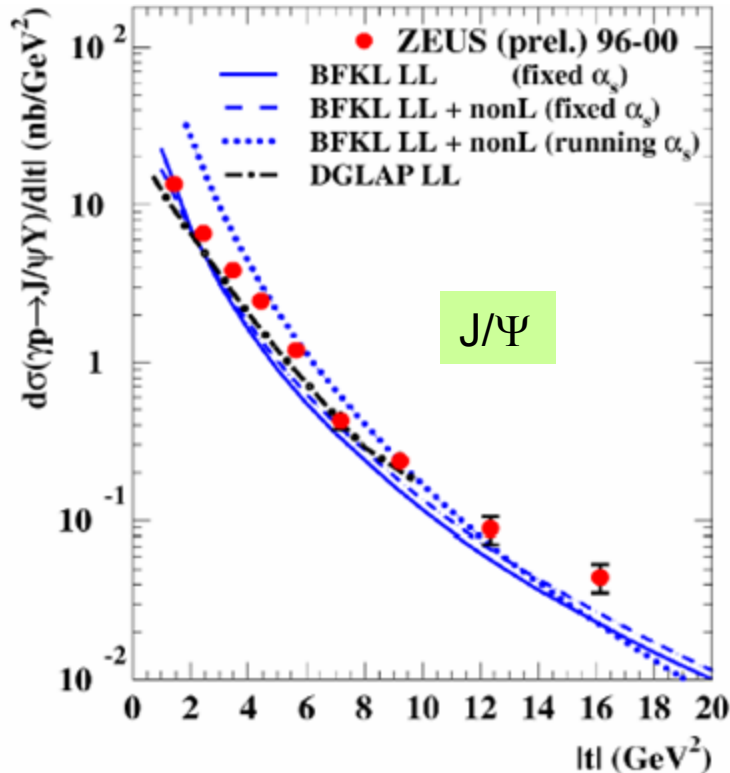
pQCD calculations
(BFKL, DGLAP)



2. ρ , J/Ψ , t dependences

Power like t dependences, exponential excluded at large $|t|$ (ρ , J/Ψ)

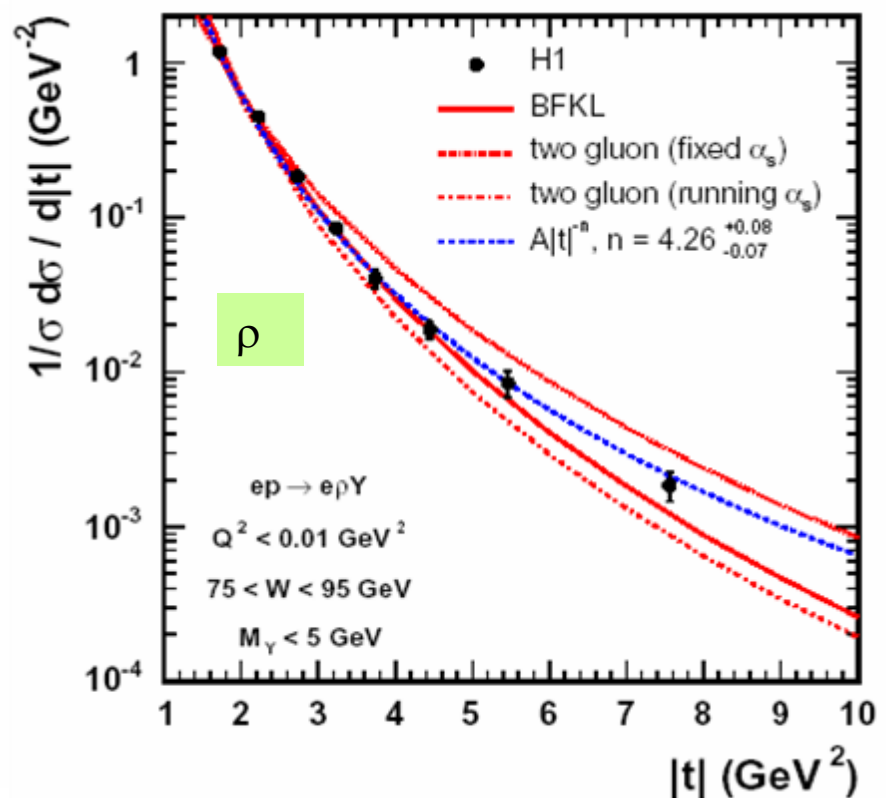
pQCD calculations



J/Ψ BFKL running α_s excluded

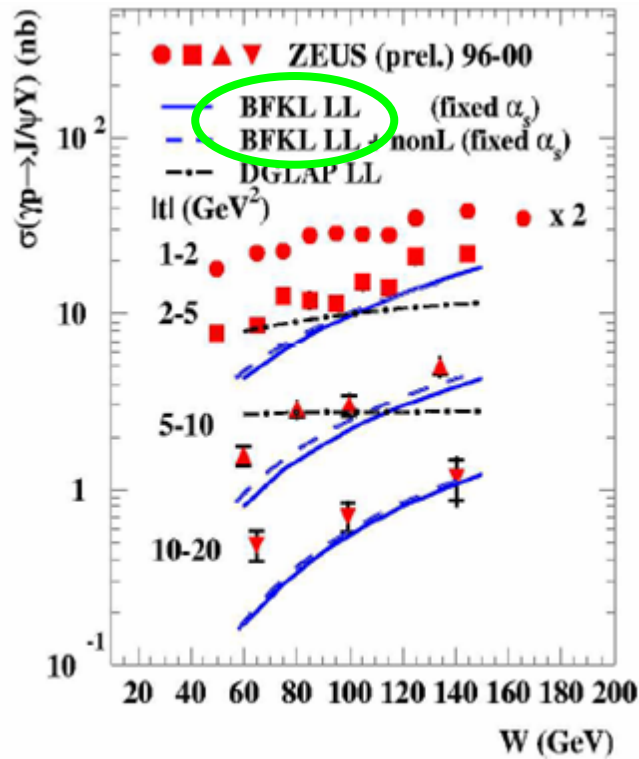
DGLAP OK ($t < M_{\Psi}^2$)

see also helicity below



BFKL favoured

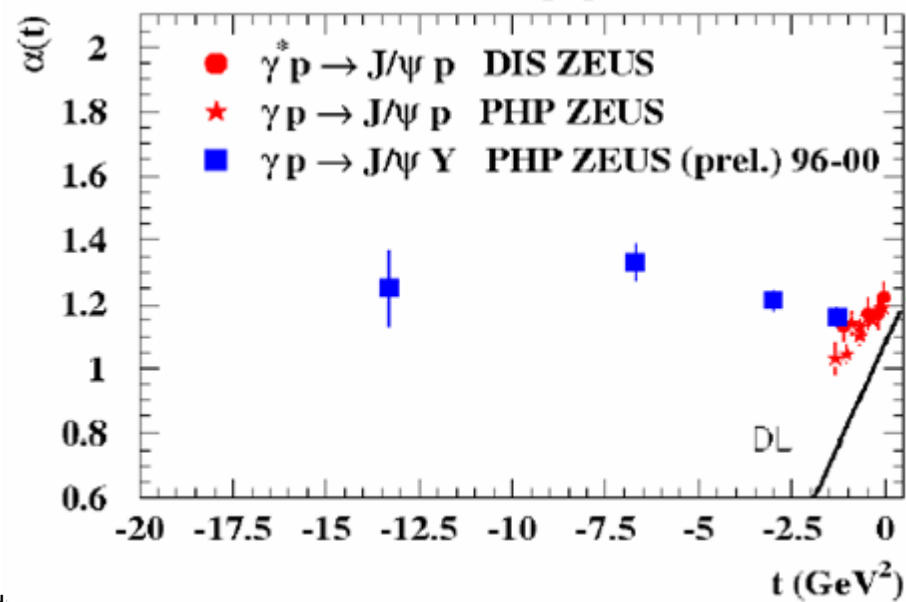
J/ψ, W dependence, shrinkage



rise of σ with W described by **BFKL**, not by DGLAP

Shrinkage

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



V. Helicity amplitudes

(Q^2, W, t, m)

ρ, ϕ (DIS), J/Ψ (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}

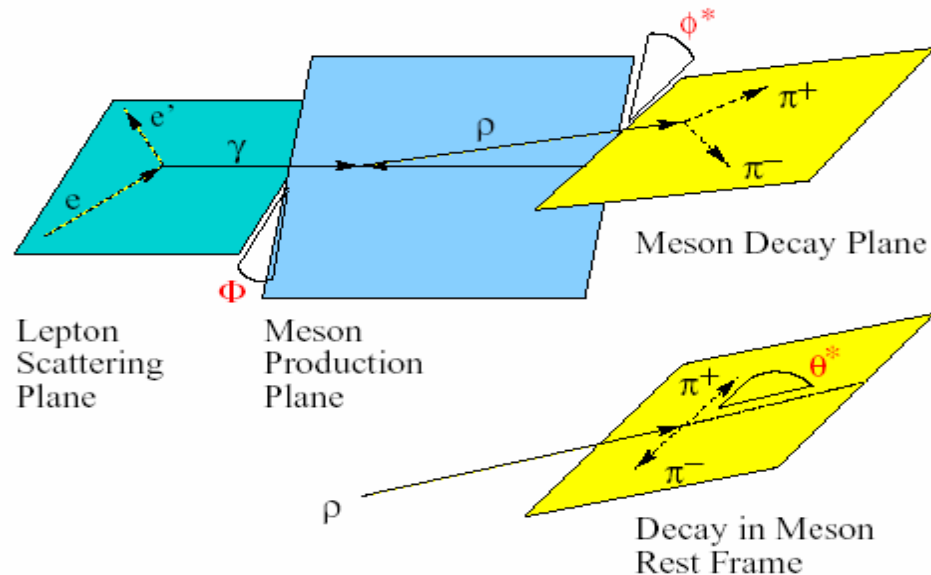
p QCD hierarchy ($|t| < Q^2$)

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 ρ, ϕ (Q^2, W, t, m)



ρ and ϕ , spin density matrix elements (O^2)

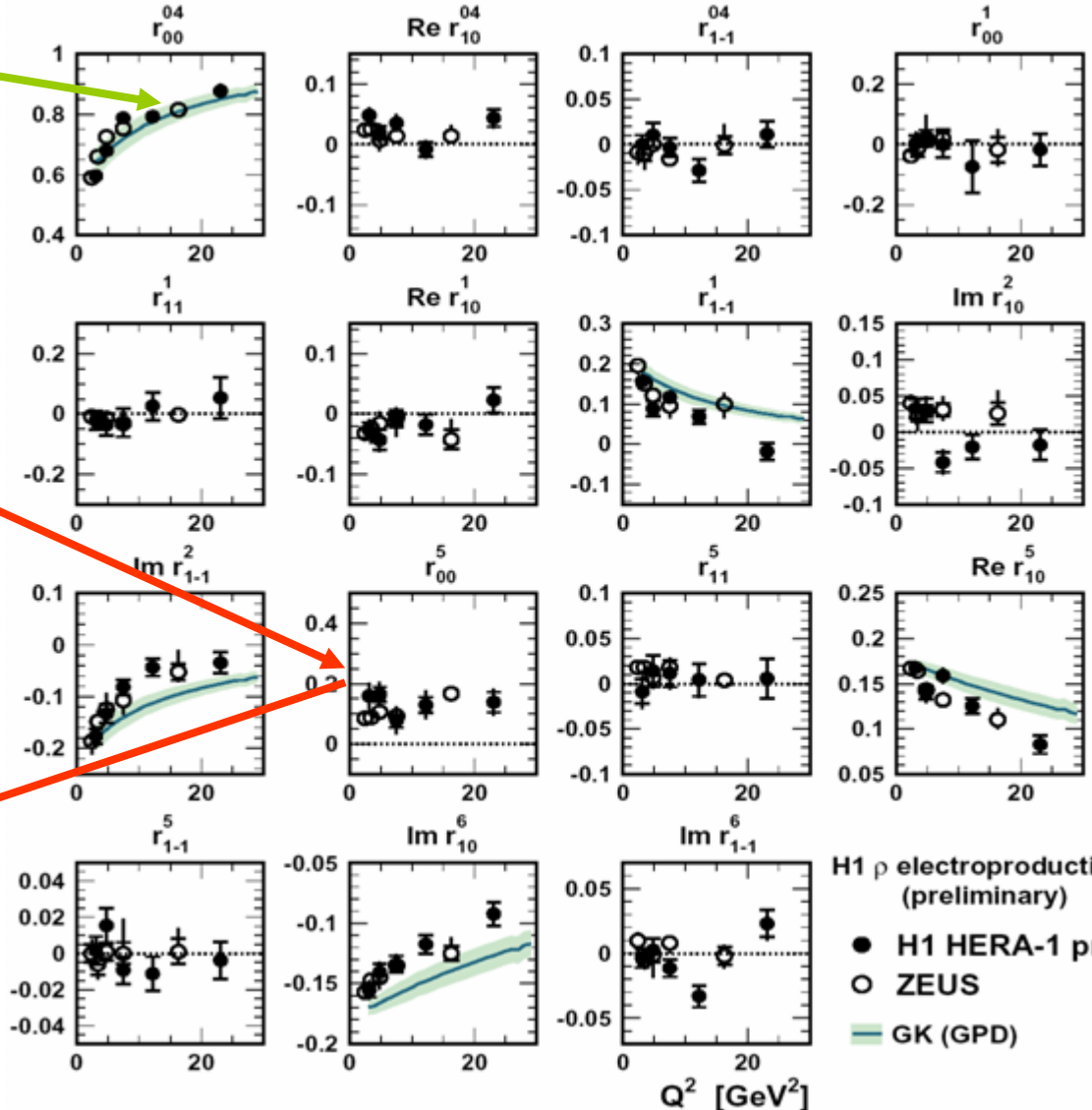
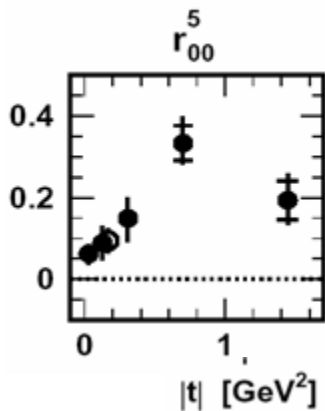
5 SCHC elements

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}

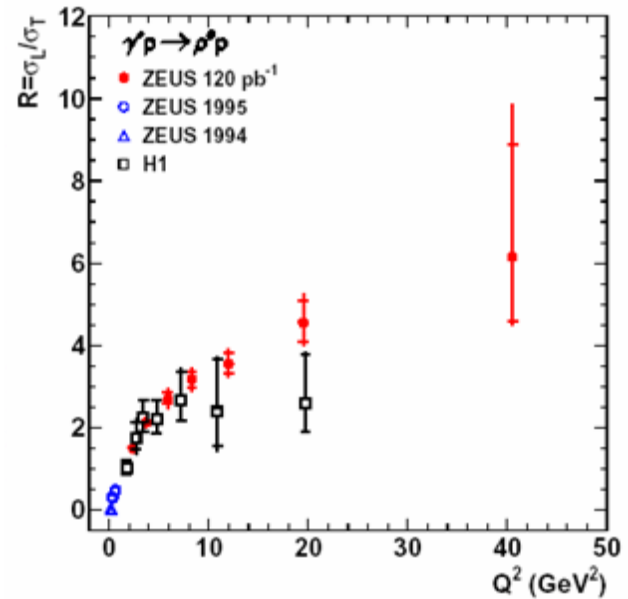


H1 ρ electroproduction (preliminary)

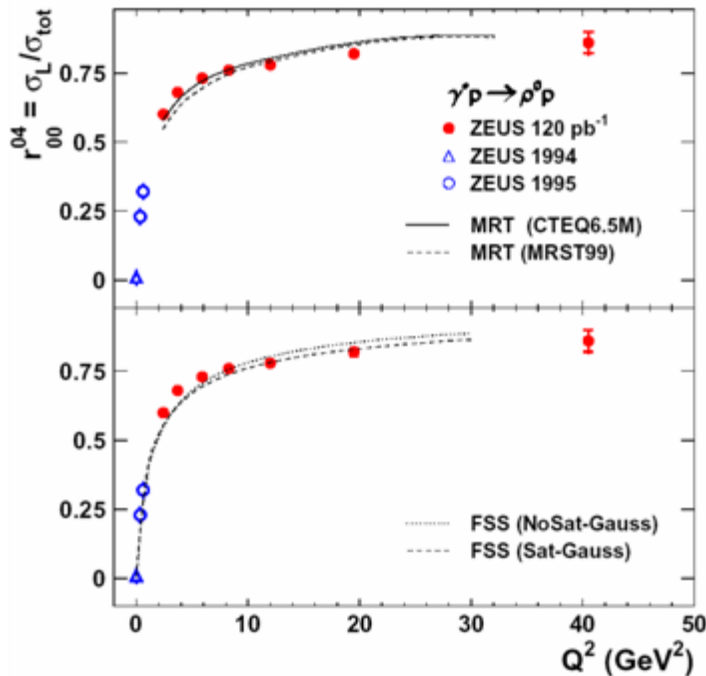
- H1 HERA-1 prel.
- ZEUS
- GK (GPD)

ρ and ϕ , $R = \sigma_L / \sigma_T (Q^2)$

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

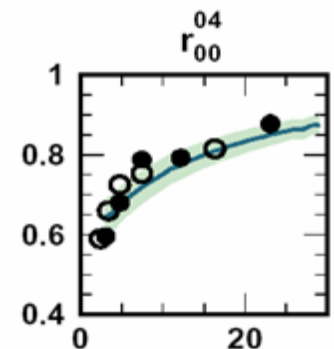


Q^2 dependence of gluons
(MRT – parton hadron duality)



dipole + saturation

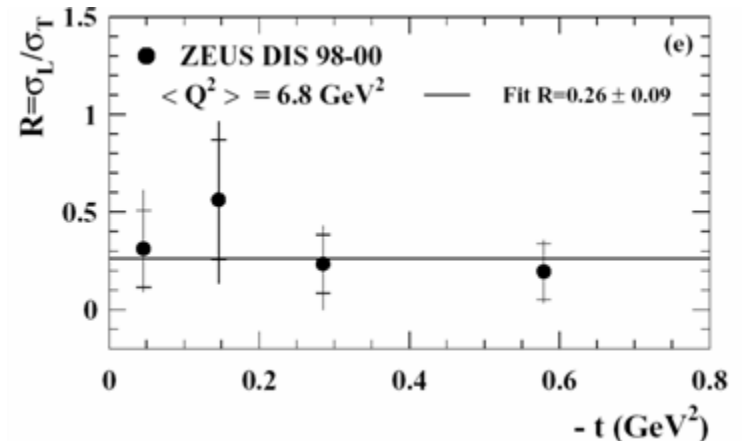
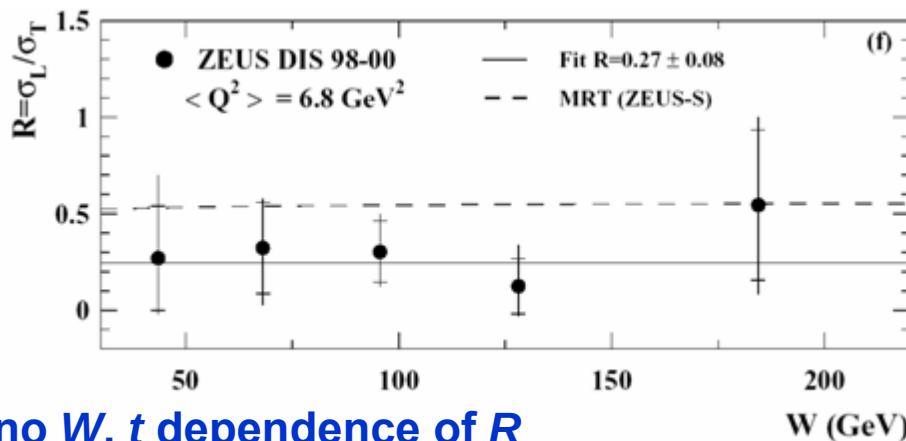
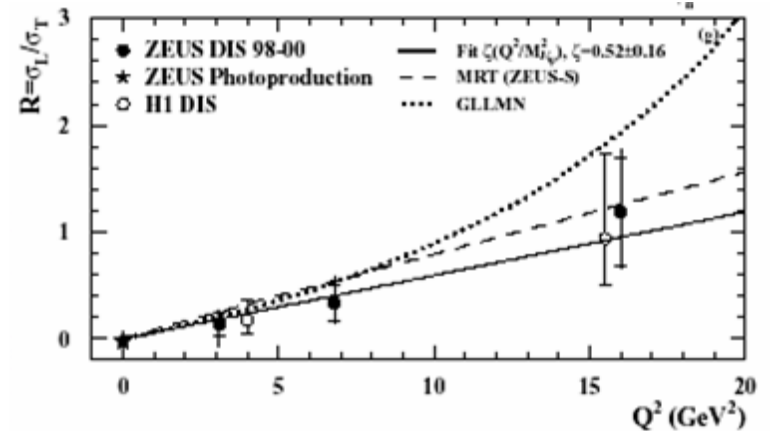
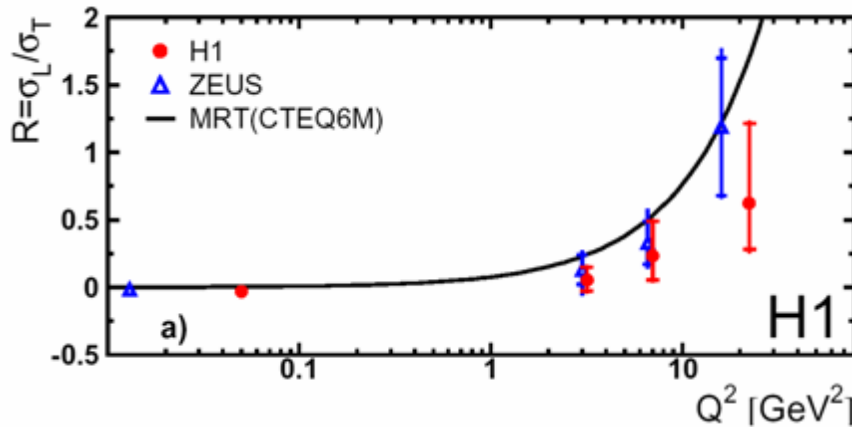
GPD



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

non-relativistic model for J/Ψ : $z \sim 1/2 \rightarrow$ **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 ρ, ϕ



no W, t dependence of R

large $|t|$, ρ (photoproduction)

“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

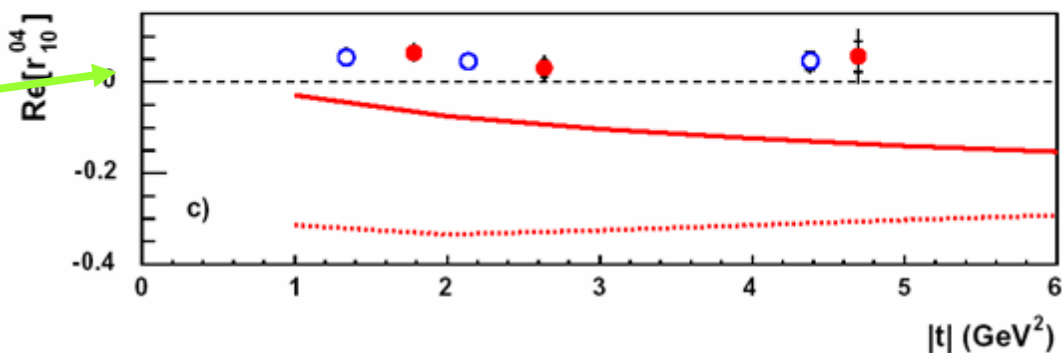
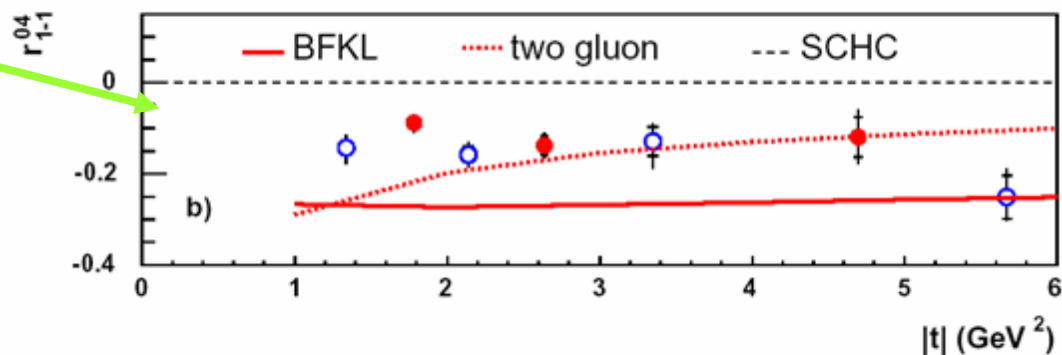
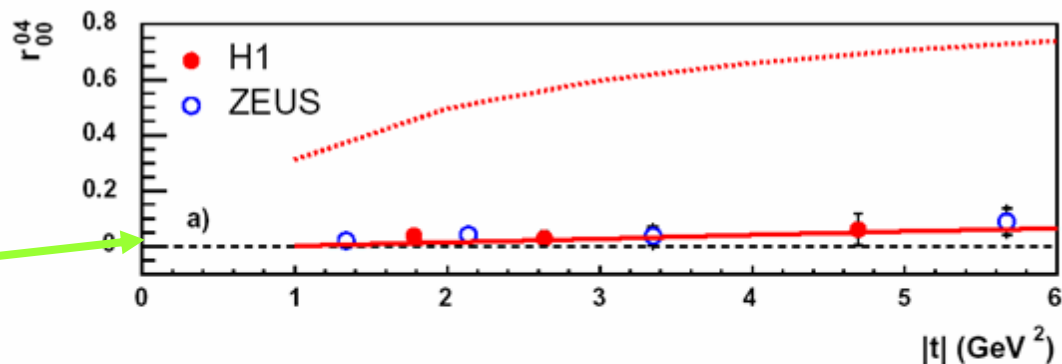
(due to constituent quark mass)

→ no orbital momentum needed for Ψ_T

→ SCHC

BFKL model describes data well
(except sign of)

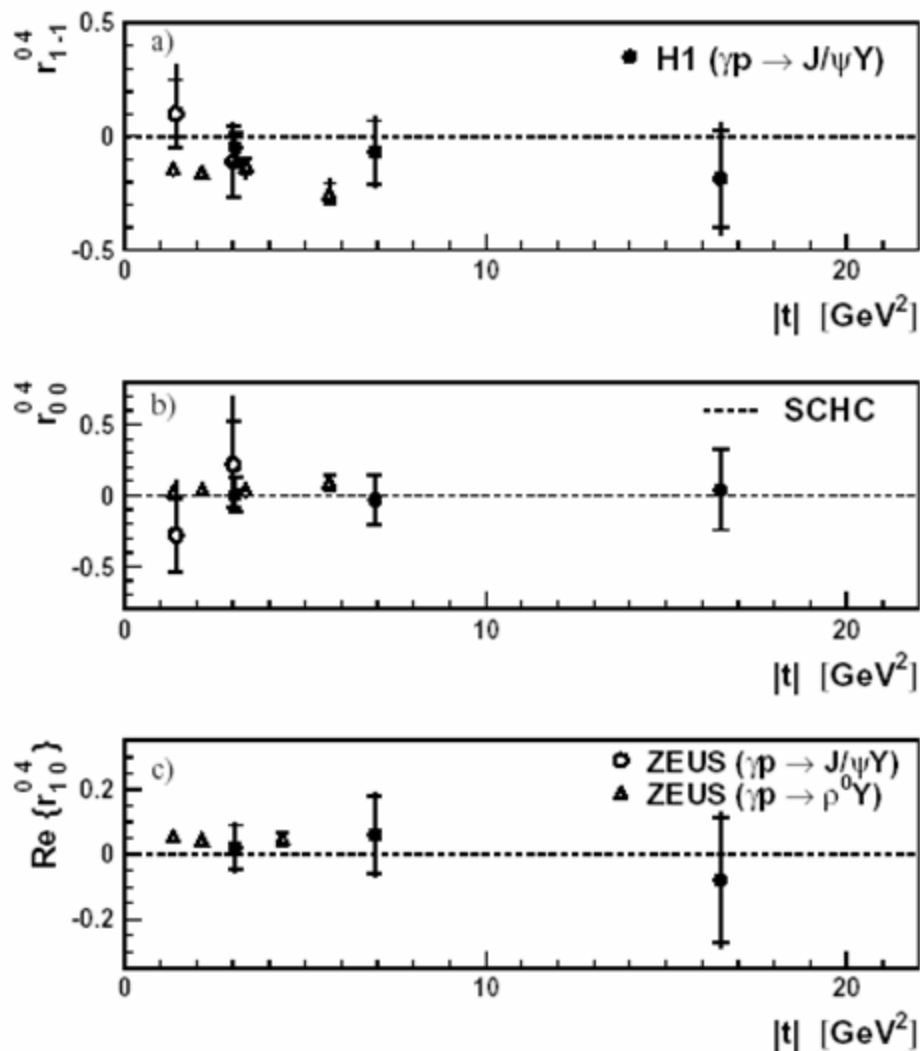
cf. also t and W dependences



large $|t|$, J/Ψ (photoproduction)

no helicity flip

cf. non-relativistic model



VI. Summary and conclusions on vector mesons

Summary

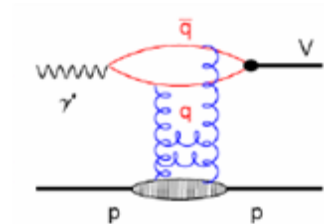
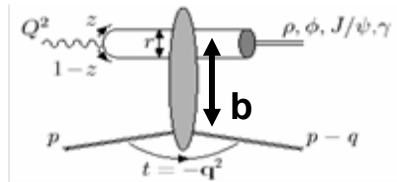
Enormous progress

- experiments

DVCS light VM (ρ, ϕ) J/Ψ Y
 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:

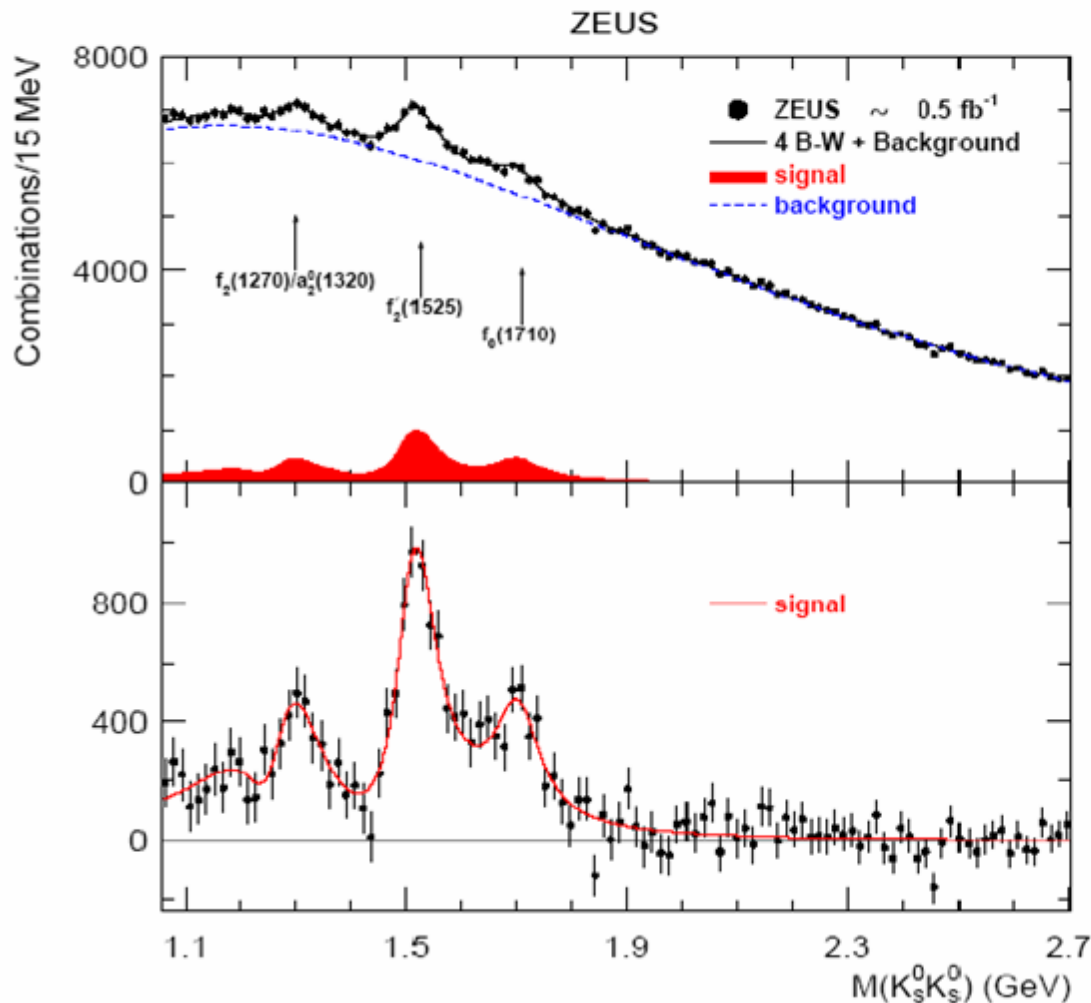
lightest glueball $J^{PC} = 0^{++}$ in mass range 1450-1750 MeV

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

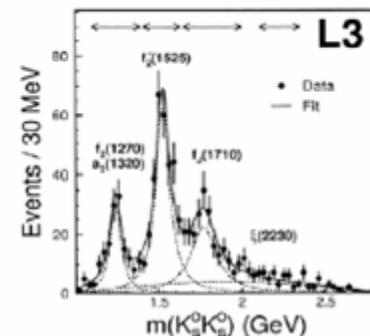
(Slides from F. Corriveau at PHIPSI08 – Frascati 2008. Many thanks to him !)

$K_S^0 K_S^0$ 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 5σ
significance

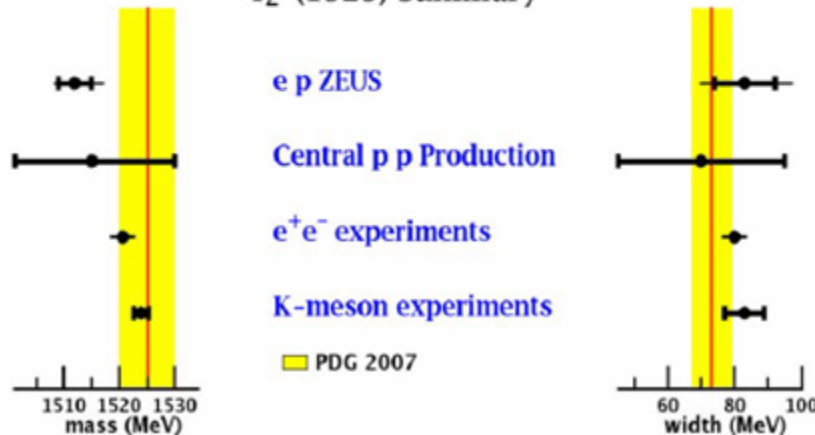
consistent with
 $J^{PC}=0^{++}$

glueball candidate



	Fit		PDG 2007 Values	
	$\chi^2/ndf=86/97$			
in MeV	Mass	Width	Mass	Width
$f_2(1270)$	1268 ± 10	176 ± 17	1275.4 ± 1.1	$185.2^{+3.1}_{-2.5}$
$a_2^0(1320)$	1257 ± 9	114 ± 14	1318.3 ± 0.6	107 ± 5
$f_2'(1525)$	$1512 \pm 3^{+2}_{-0.6}$	$83 \pm 9^{+5}_{-4}$	1525 ± 5	73^{+6}_{-5}
$f_0(1710)$	$1701 \pm 5^{+5}_{-3}$	$100 \pm 24^{+8}_{-19}$	1724 ± 7	137 ± 8

$f_2'(1525)$ summary



$f_0(1710)$ summary

