MESON 2008
Krakow
06-10/06/2008

Meson production at HERA

The H1 and ZEUS collaborations

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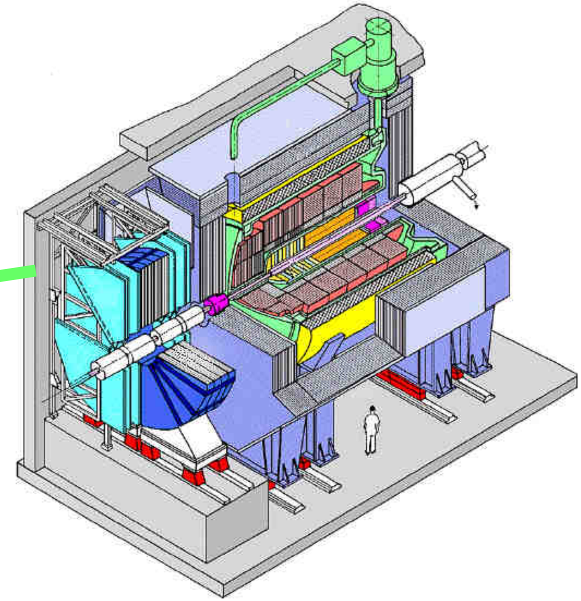
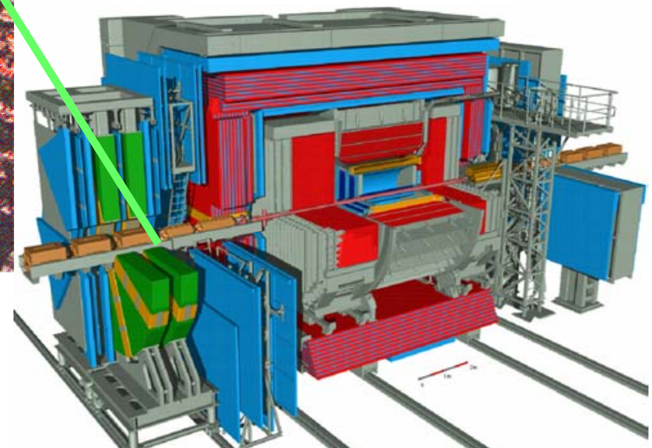
The HERA collider



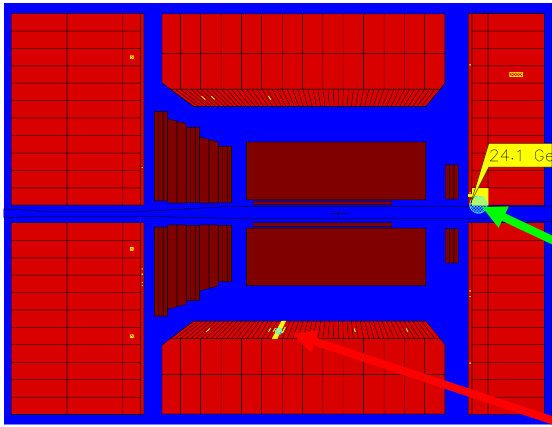


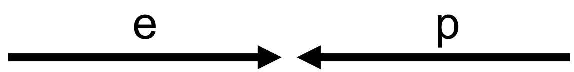
820 / 920 GeV p   27.5 GeV e^+ / e^-

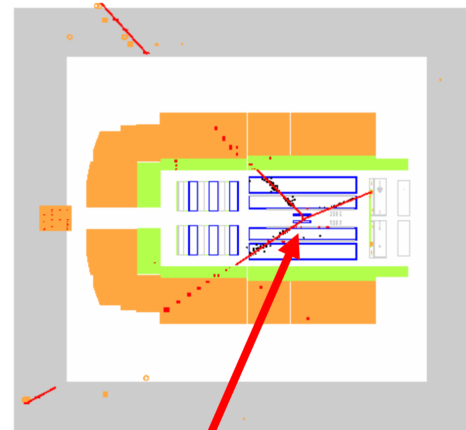
$\sqrt{s}$ = 300 / 320 GeV

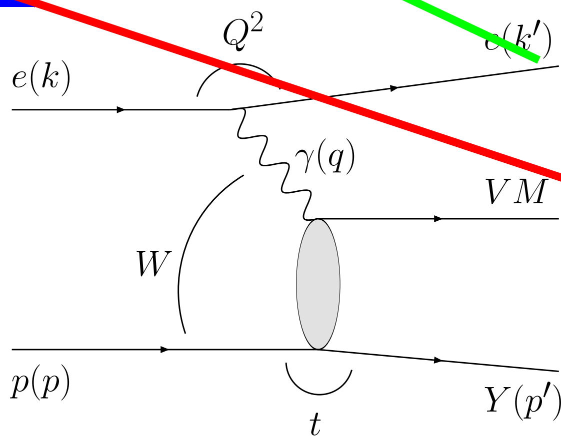
1992 – 2007   ~ 500 pb^{-1} / exp.

Introduction









$x = Q^2 / W^2$

$|t| \simeq p^2_{p,t}$

γ ρ ω ϕ **J/ψ** **ψ(2s)** Υ

p **p. diss. (M_Y)**

A QCD laboratory

M_V 0 – 10 GeV

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

W 30 – 300 GeV

|*t*| 0 – 30 GeV^2 (small |t| < 1.5 GeV^2 & large |t|)

Content

Vector meson production and DVCS

I. Interpretation frameworks

II. From soft to hard : mass

W, t dependences

σ_{tot}, ρ, ω, ϕ, J/Ψ,Υ

III. From soft to hard : *Q^2*

universality ($Q^2 + M^2$), *W, t* dependences

DVCS, ρ, ϕ, J/Ψ

IV. From soft to hard : *t*

universality (*t*), *t, W* dependences

ρ, ϕ, J/Ψ

V. Helicity amplitudes

Q^2, *W, t, m* dependences

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

VI. Summary and conclusions

Spectroscopy

$K^0_S K^0_S$ resonances (1270, 1525, 1710)

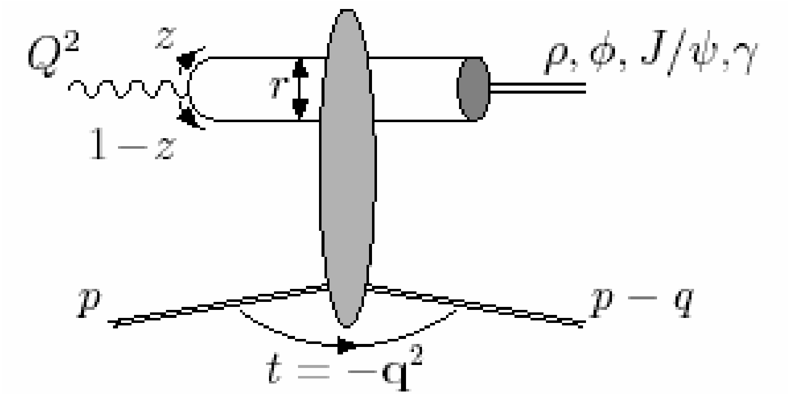
I. VM diffractive production

Interpretation frameworks

QCD factorisation

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

Factorisation theorem



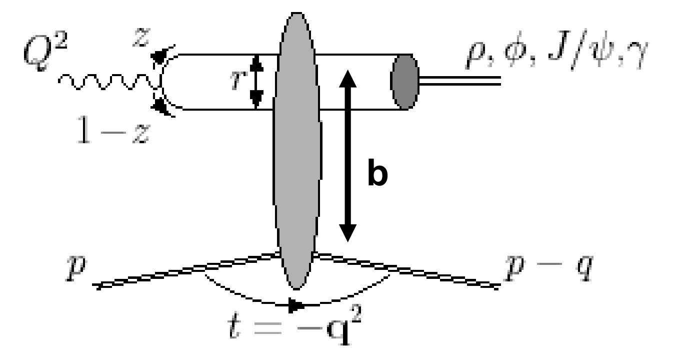
step 1. γ fluctuation into $q\bar{q}$ dipole γ WF Ψ_γ (z, k_t)

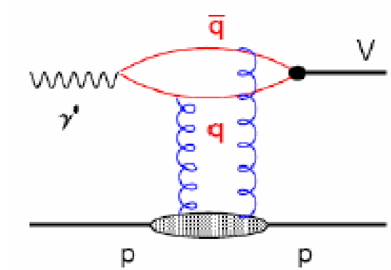
step 2. dipole – proton interaction $A = \int dr^2\, dz\, \Psi_\gamma \cdot \sigma(dip-p) \cdot \Psi_V$

step 3. pair recombination into VM

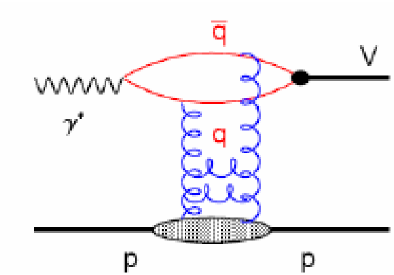
for σ_L + heavy quarks

Dipole universality





LO 2 gluons



LL1/x ladder

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

σ(r) : "scanning radius" - colour transparency : *r* decreases with increased Q^2, M_V

→ in perturbative domain :

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

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

((A_T : see below))

+ vertex factorisation

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

Energy dependence

2. *W* dependence

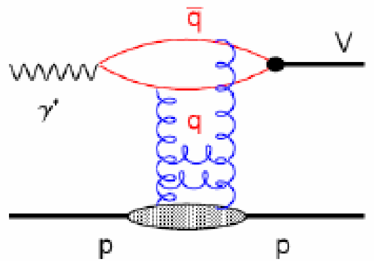
Regge-like parameterisation (high energy) $\sigma_{tot}(h-h) \propto s^{\alpha(0)-1}$

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

$\alpha(0) \simeq 1.08$ (1.07 ... 1.11)

$\alpha' \simeq 0.25$ GeV^{-2}

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



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

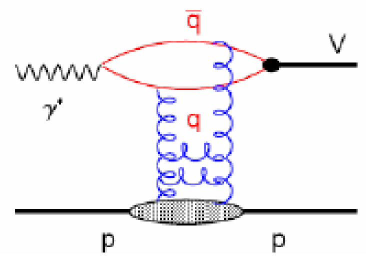
$\longrightarrow$ hard energy (1/x) dependence of x G(x) (BFKL, low x DIS DGLAP)

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

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

t dependences

3. *t* dependence (moderate |t|, ≤ 1.5 GeV²)



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

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

hard scale → **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 → **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 $R = \sigma_L / \sigma_T$: $R(W)$, $R(t)$, Re / 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

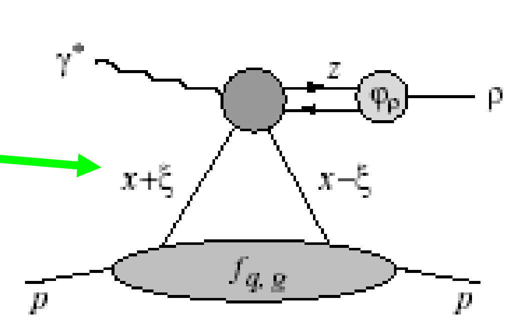
2 main – complementary – extensions

1. Hard scattering

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

– skewing : $Q^2 \neq M^2$ => x(in) ≠ x(out) (Υ, 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

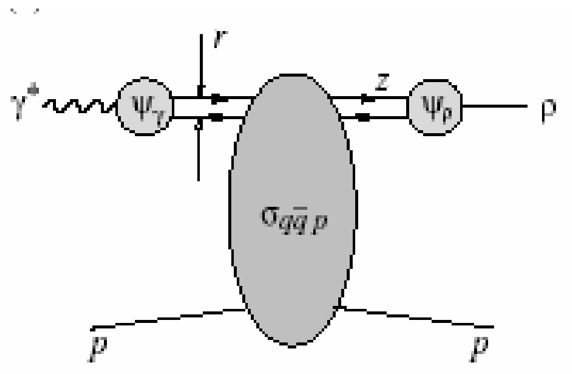
2. Dipole scattering

– large 1/x => factorisation

– **relax large scale** : also valid at low Q^2

σ (dip-p) universal : DIS, DDIS, VM production

+ include **saturation**



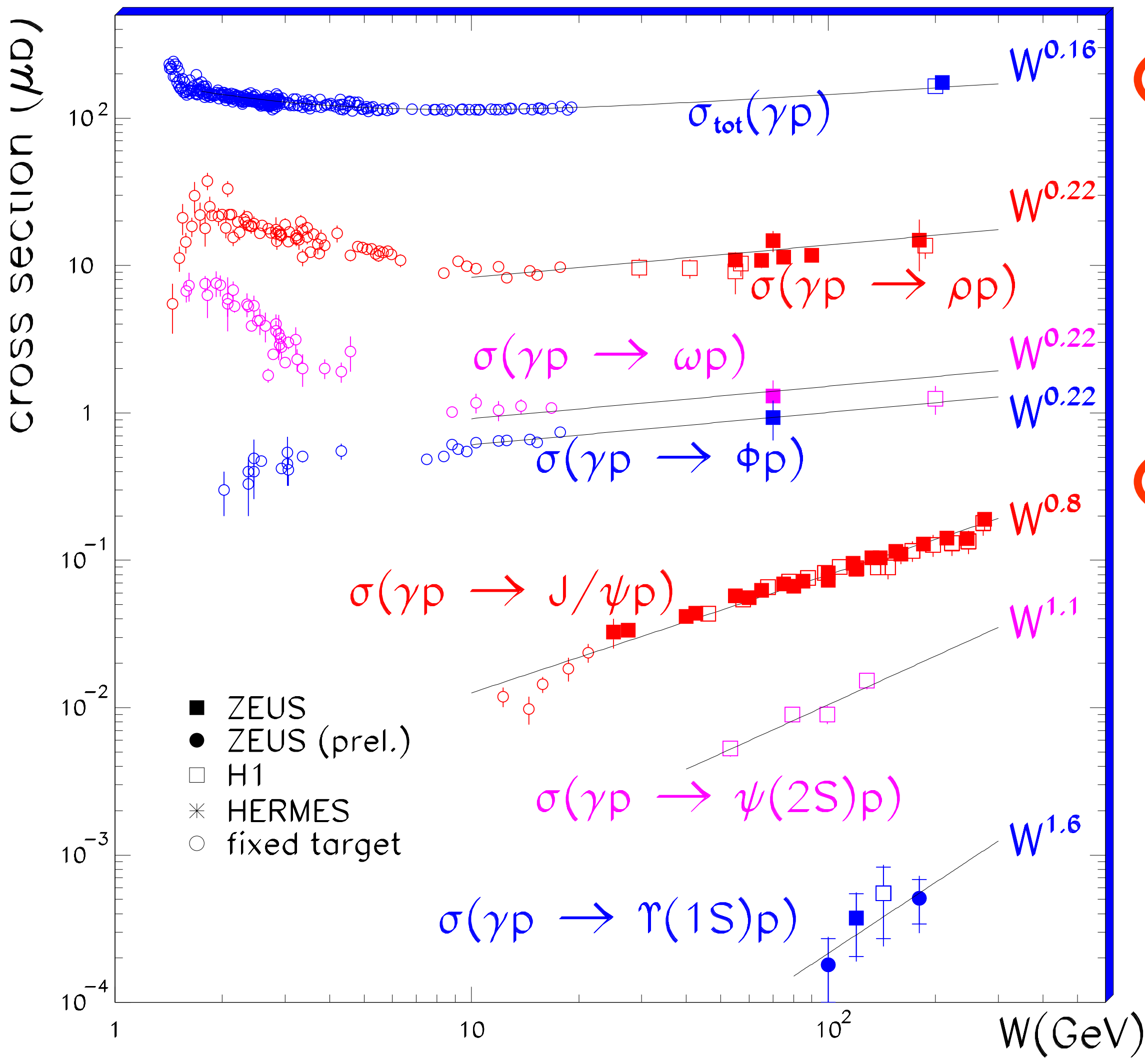
Also other approaches (2 pomerons, GVDM, ...)

II. From soft to hard : mass

(σ_{tot}, ρ, ω, ϕ, J/Ψ,Υ)

W **dependences**
t **dependences**

all VM photoproduction



soft

σ_{tot}

ρ, ω, φ

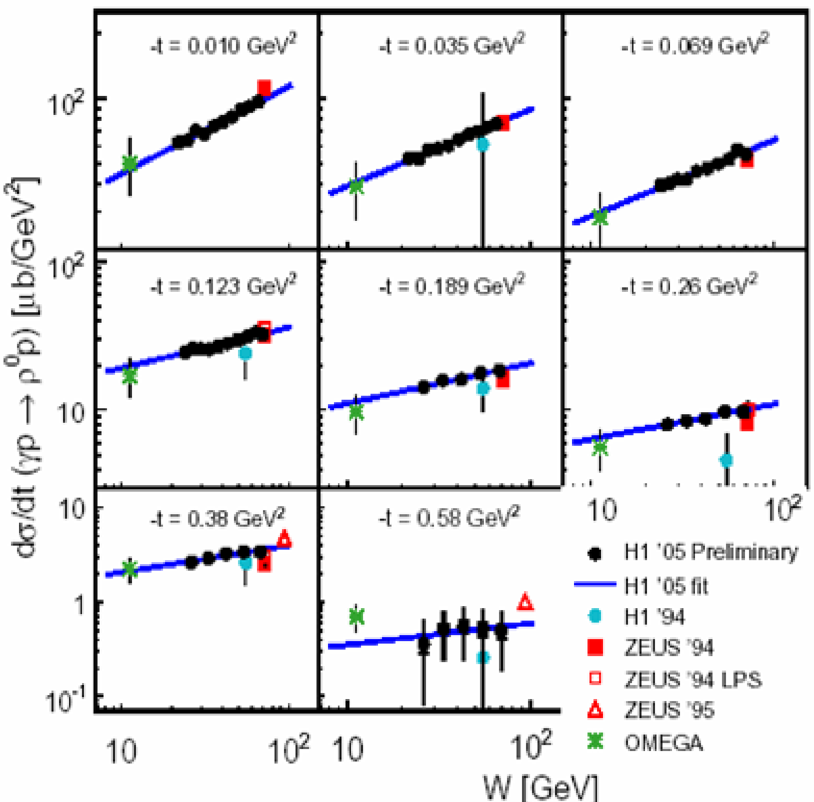
hard

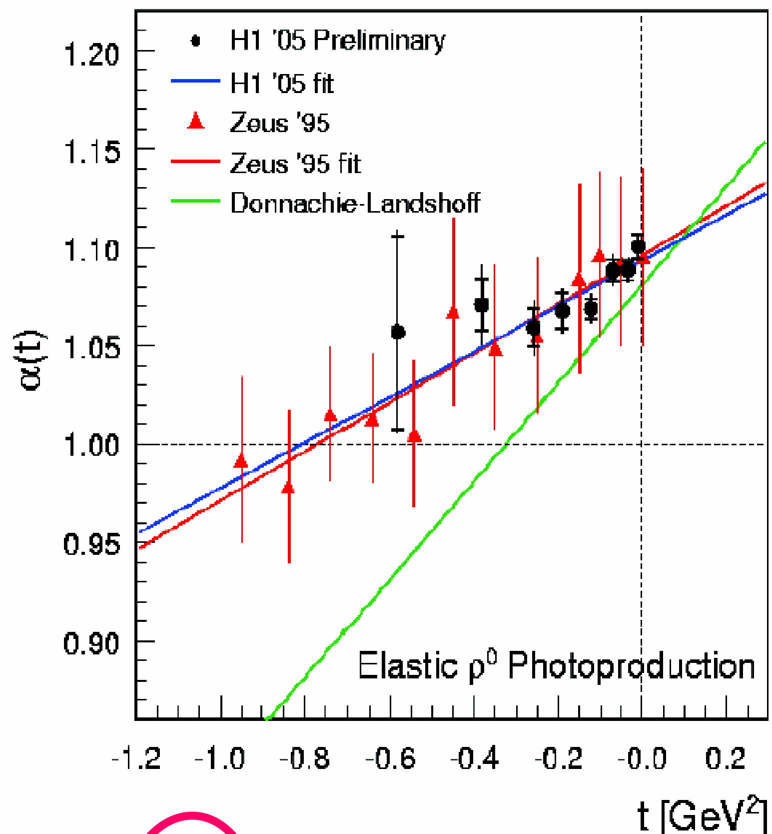
J/Ψ

skewing, Re → GPD

Υ

ρ, ω, φ *W* dependence





ZEUS $\alpha_{\mathbb{P}}(t) = (1.096 \pm 0.021) + (0.125 \pm 0.038)\ \mathrm{GeV}^{-2} \cdot t$

H1 $\alpha_{\mathbb{P}}(t) = (1.093 \pm 0.003\ ^{+0.008}_{-0.007}) + (0.116 \pm 0.027\ ^{+0.036}_{-0.046})\ \mathrm{GeV}^{-2} \cdot t$

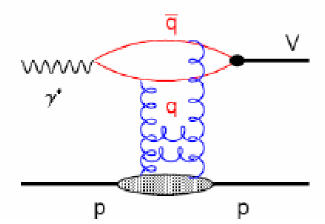
soft intercept

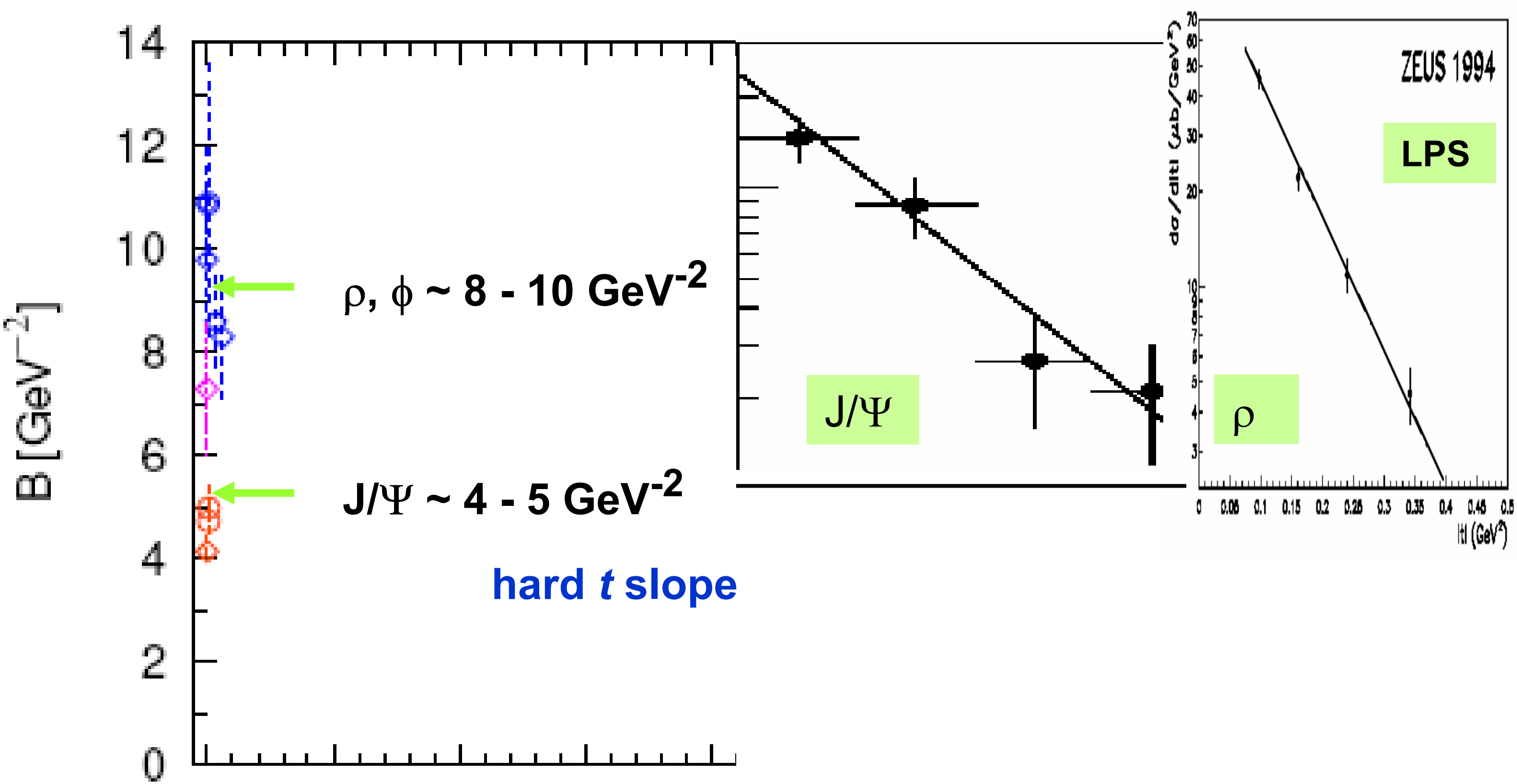
lower slope than h-h
-> rescattering effects ?

ρ, J/Ψ, *t* dependence

exponential slopes ↔ **size of the dipole**

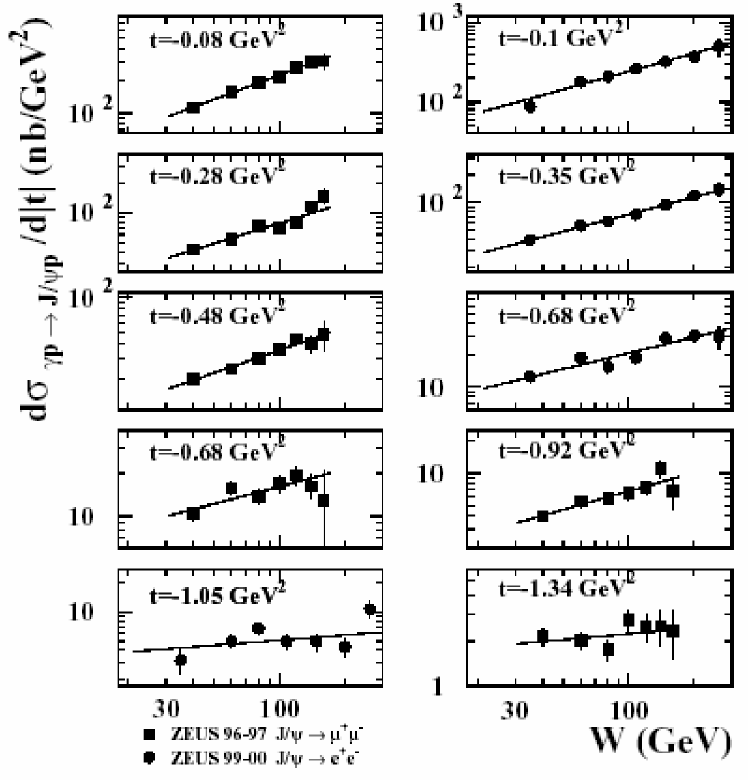
heavy charm quark -> small dipole -> flatter *t* distribution, **smaller slope**

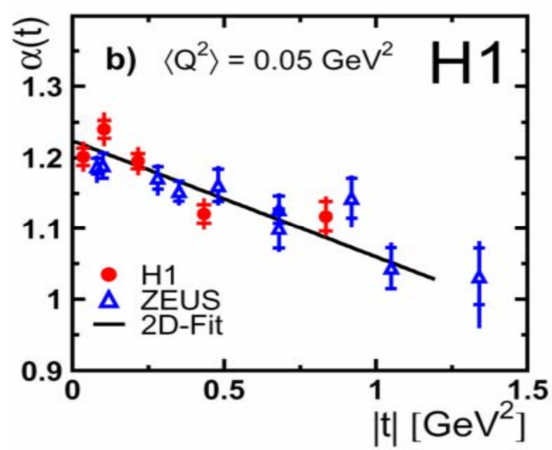


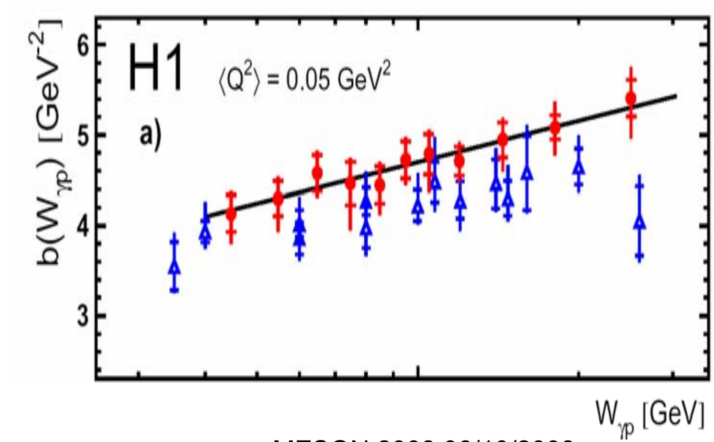


J/Ψ, *W* dependence, shrinkage

ZEUS 1996-97, 1999-2000







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

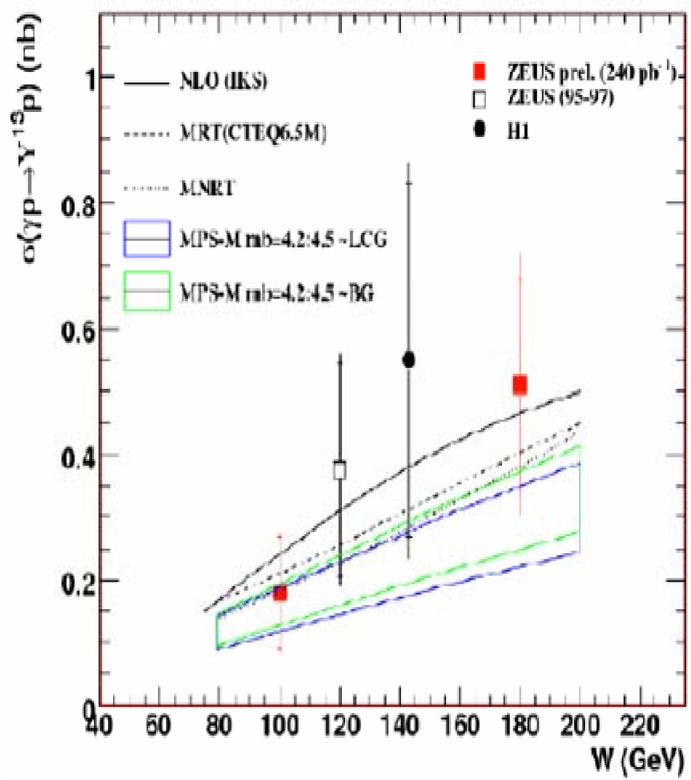
lower (?) slope $\alpha' \sim 0.12$ - 0.16 GeV^{-2}

Upsilon

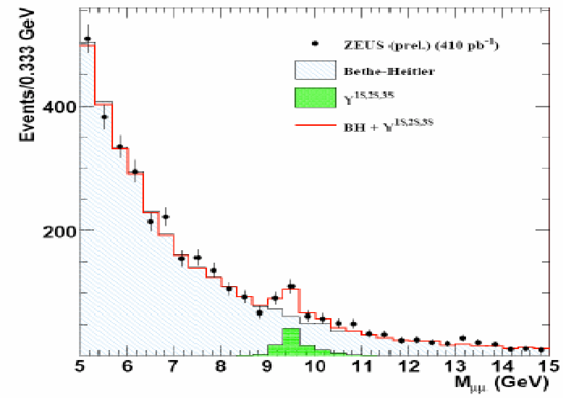
very hard *W* dependence

$\delta \sim 1.6$

Number of Upsilon candidates 104 ± 21



Zeus HERA 1+2



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

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

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

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

Great progress !

skewing and GPD, NLO calculations, dipole calc.

III. From soft to hard : Q^2

(DVCS, ρ, ϕ, J/Ψ)

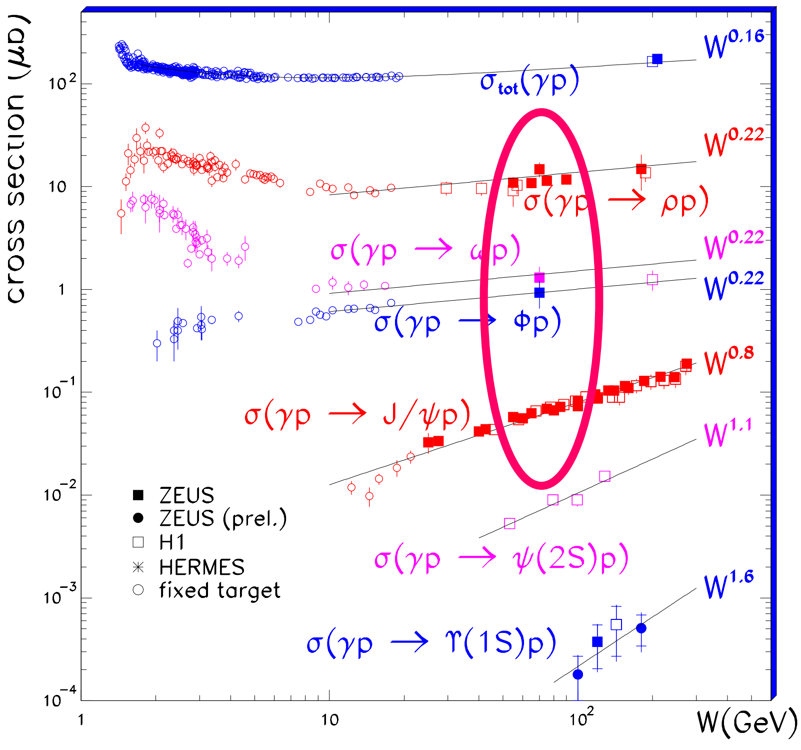
universality ($Q^2 + M^2$)
W dependences
t dependences

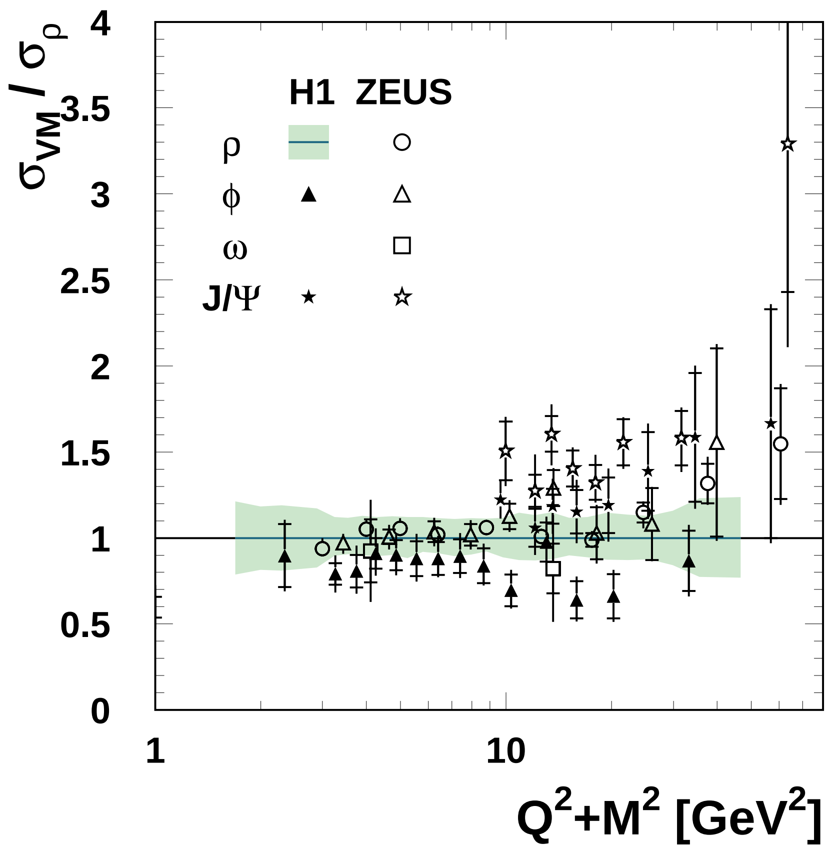
1. Universality ($Q^2 + M^2$)

Quark content weighted cross sections

(qualitatively) striking !

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



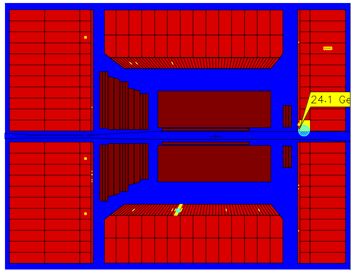


2. Deeply Virtual Compton Scattering

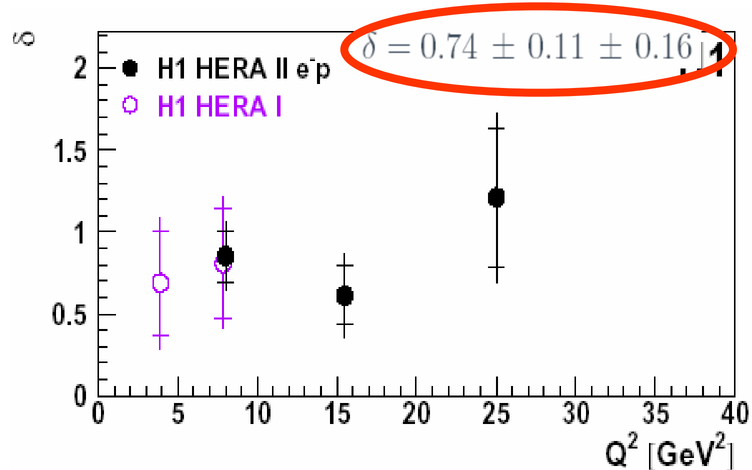
DIS domain :

e + p → e + p + γ (real)

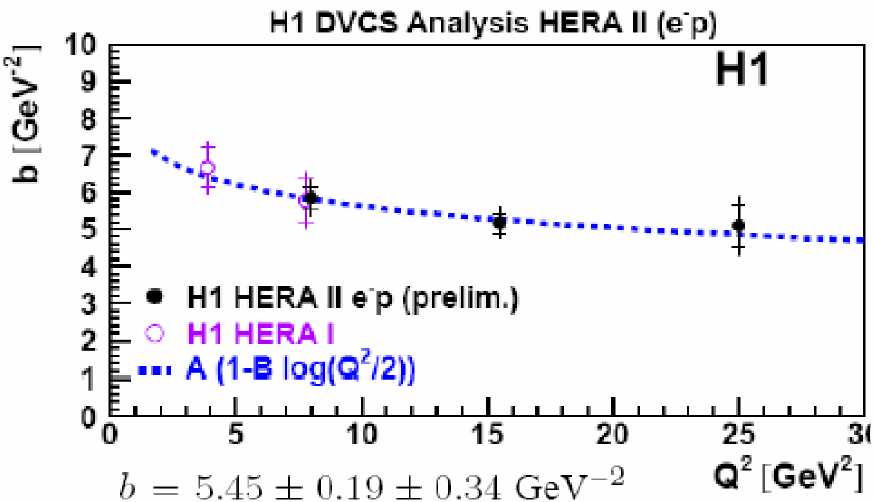
i.e. γ* p → γ p



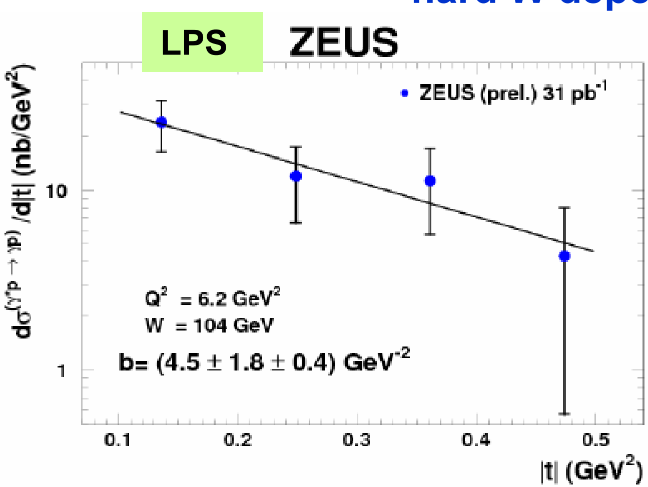
(no WF uncertainties ↔ light VM)



hard W dependence



$b = 5.45 \pm 0.19 \pm 0.34\ \mathrm{GeV}^{-2}$



=> $\sqrt{\langle r_T^{\,2} \rangle}$=0.65 fm

>> valence quarks value

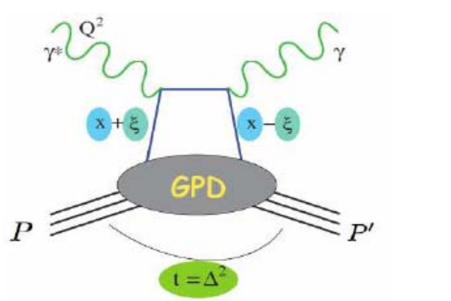
slope not soft, but steeper than J/Y ?

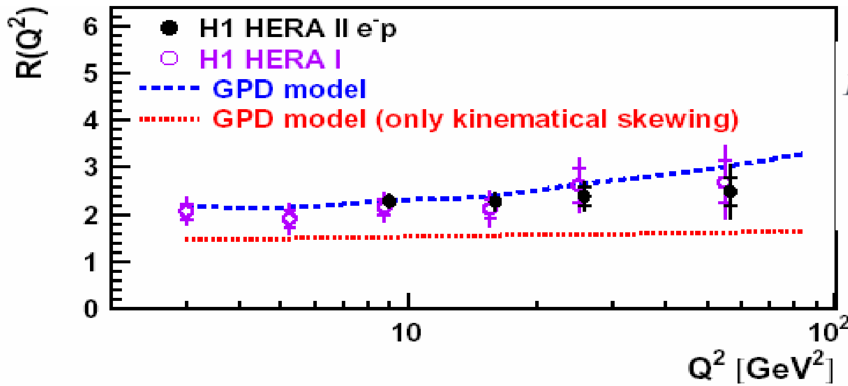
DVCS, models

GPD

kin. skewing

not sufficient

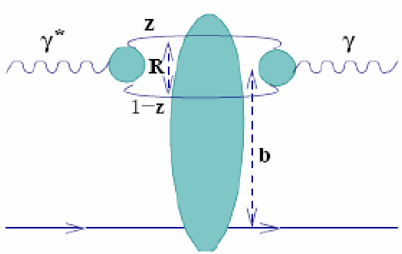


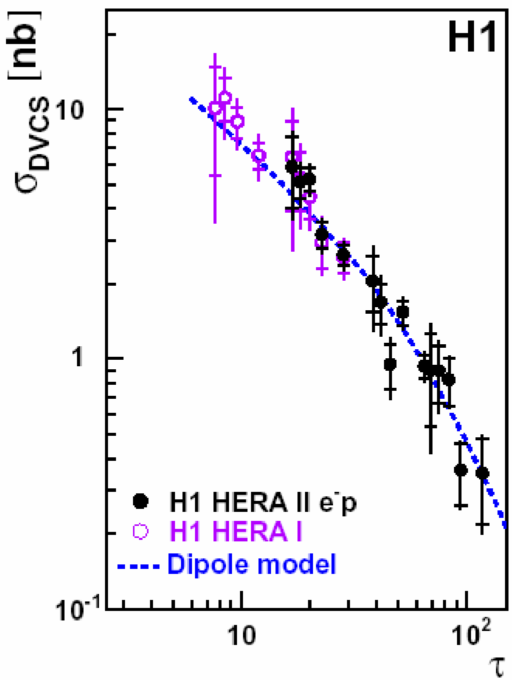


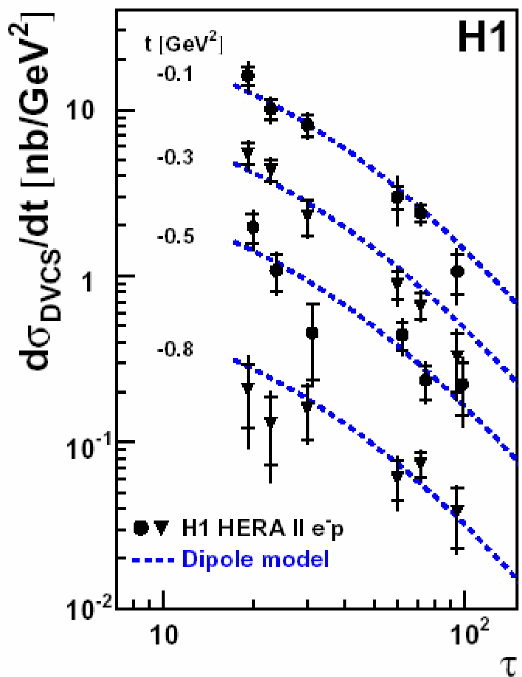
$$R = \frac{\mathcal{I}m\ A(\gamma^* p \to \gamma p)}{\mathcal{I}m\ A(\gamma^* p \to \gamma^* p)} = \frac{4\sqrt{\pi}\ \sigma_{DVCS}\ b(Q^2)}{\sigma_T(\gamma^* p \to X)\ \sqrt{(1+\rho^2)}}$$

skewing

Dipoles + geom. scaling



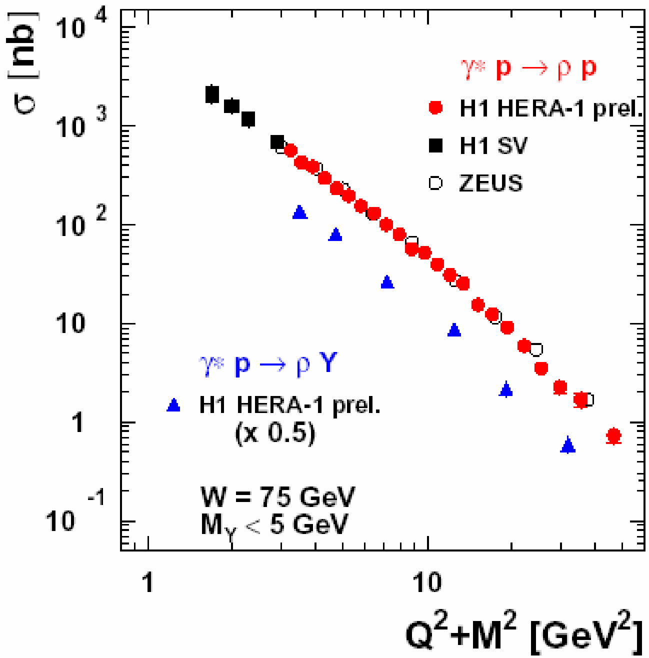


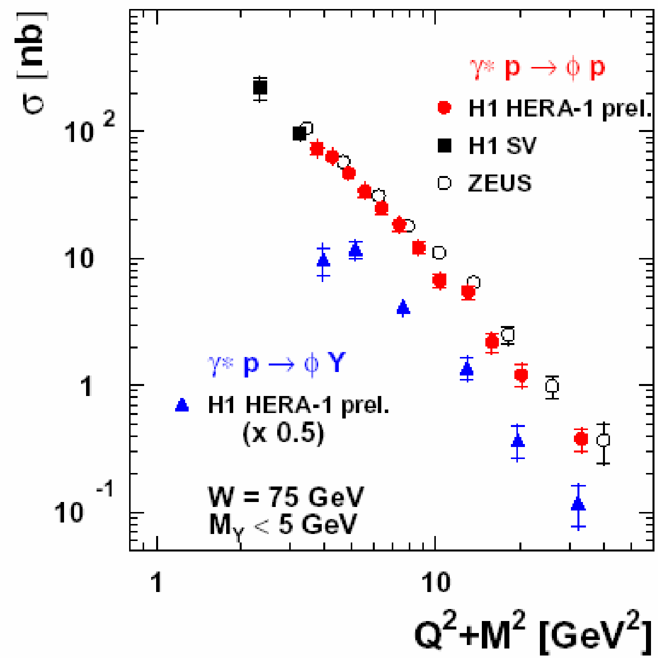


3. ρ and ϕ, elastic and p. dissoc.

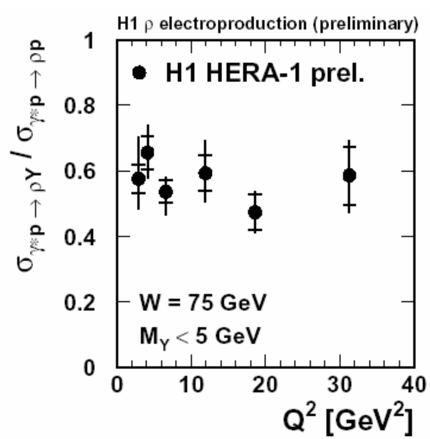
ZEUS and H1 - HERA-1
large data sets

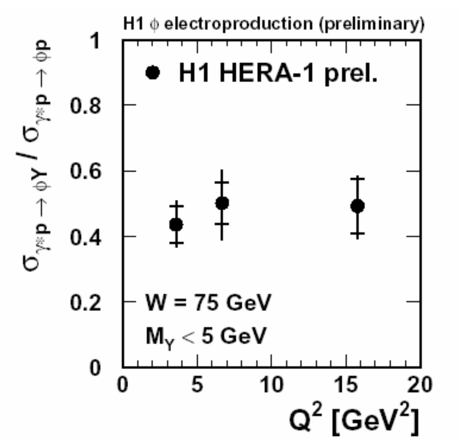
transition to hard diffr.
(+ soft features)



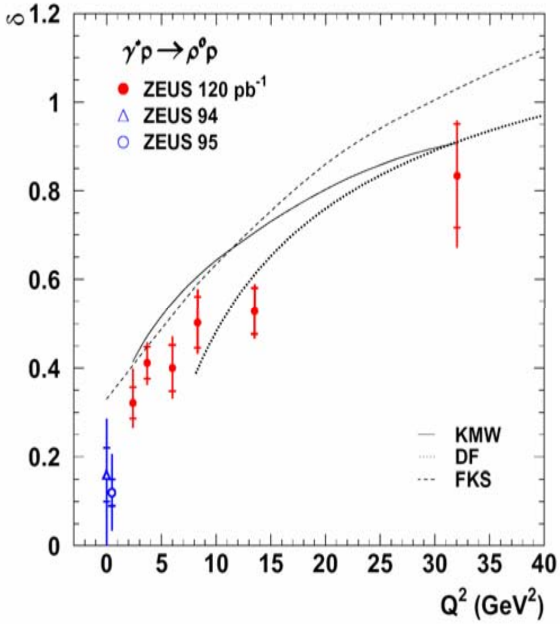


p.diss. / el. : no Q^2 dep. ($Q^2 > 2.5$ GeV^2)
proton vertex factorisation

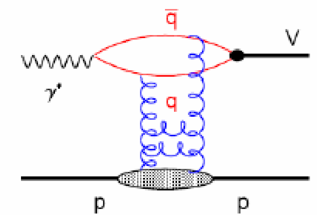


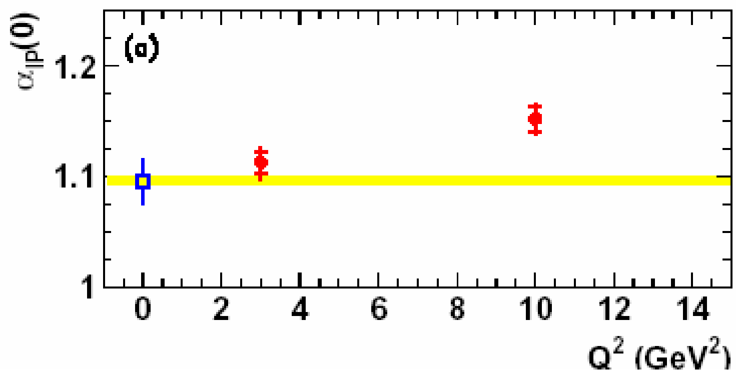


ρ, *W* dependence

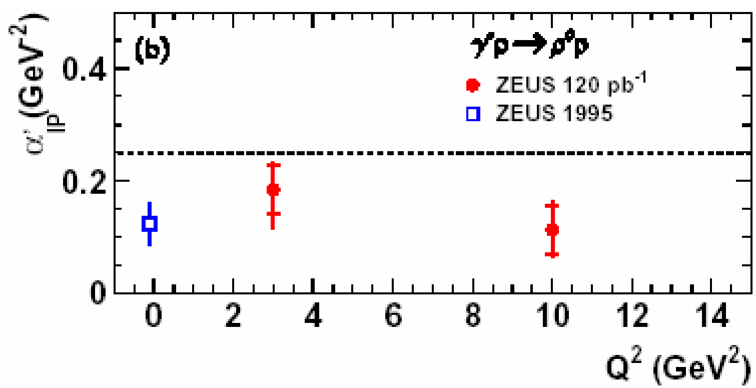


hardening with Q^2





α' ~ 0.10-0.15 GeV^{-2}, indep. of Q^2 ?



ρ, *t* dependence

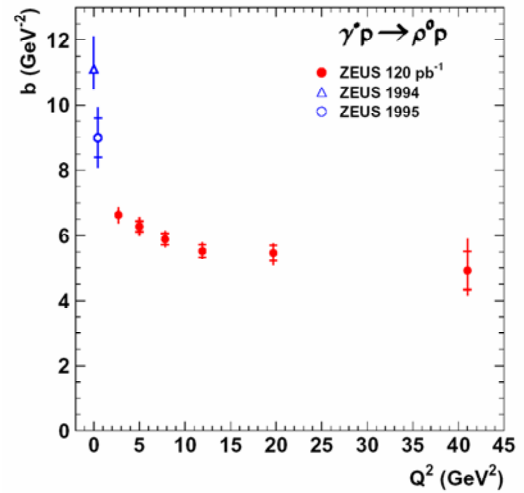
***t* slope**

hardening with Q^2

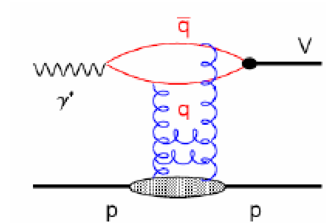
Difficult measurements:

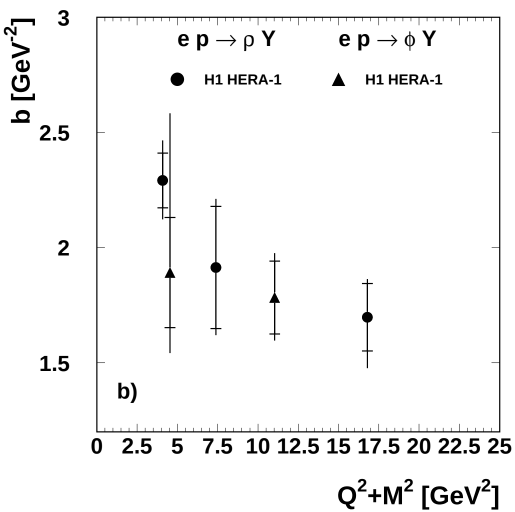
background subtraction

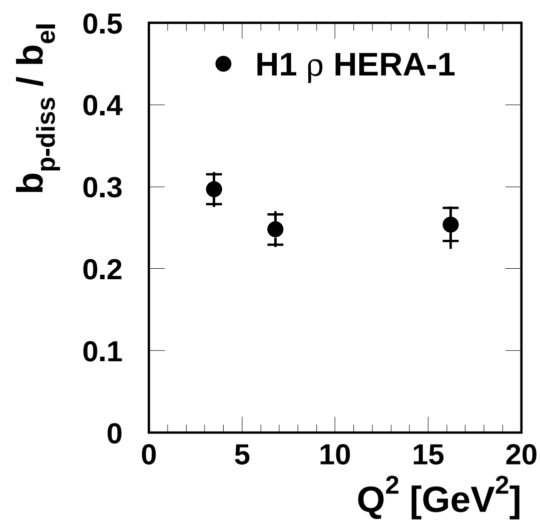
other VM and incl. diffr., p. diss.



elastic



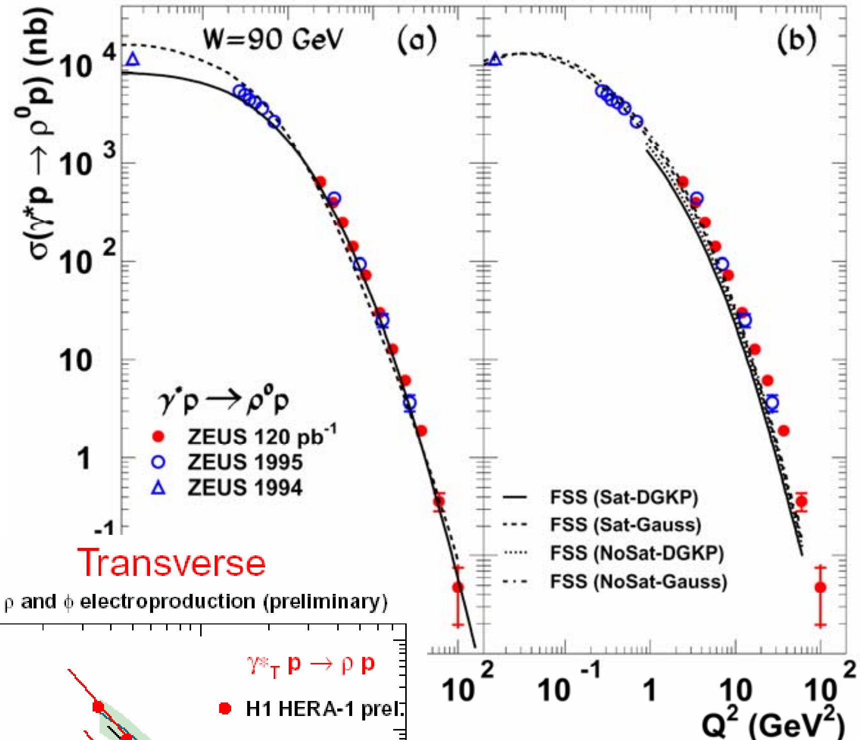




proton dissociation

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

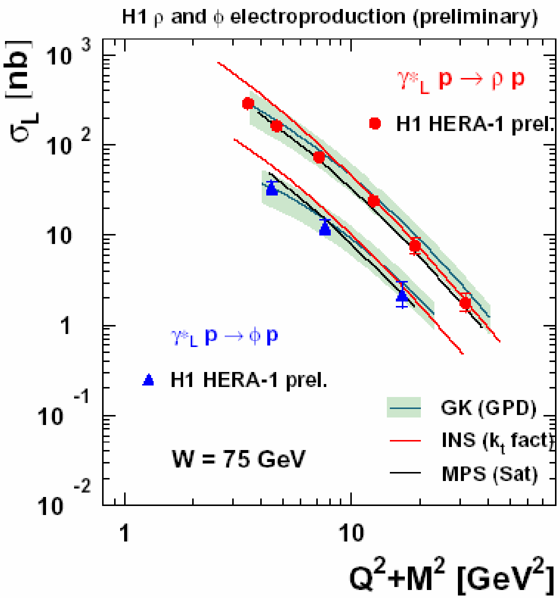
ρ, dσ/dQ²



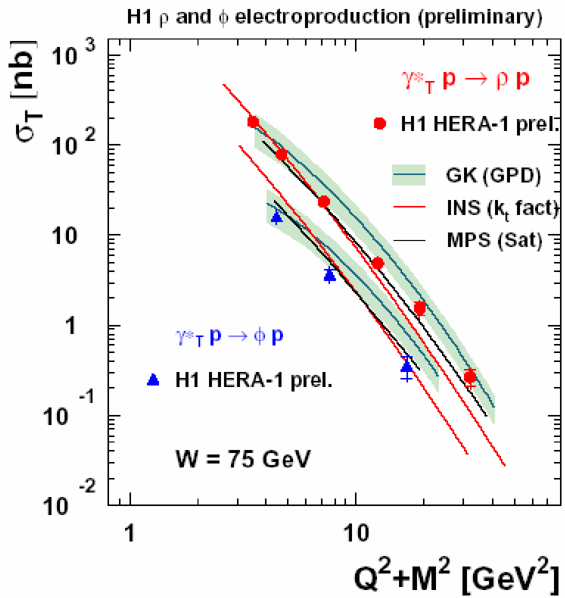
universal dipole

-> small Q^2

Longitudinal



Transverse



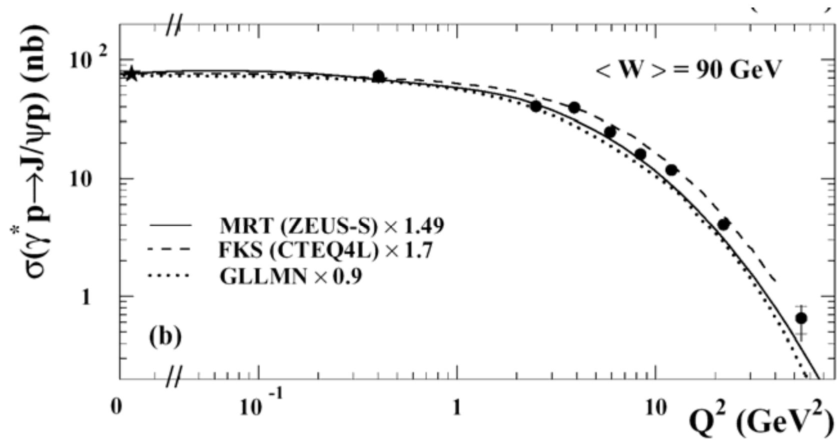
polarised cross sections

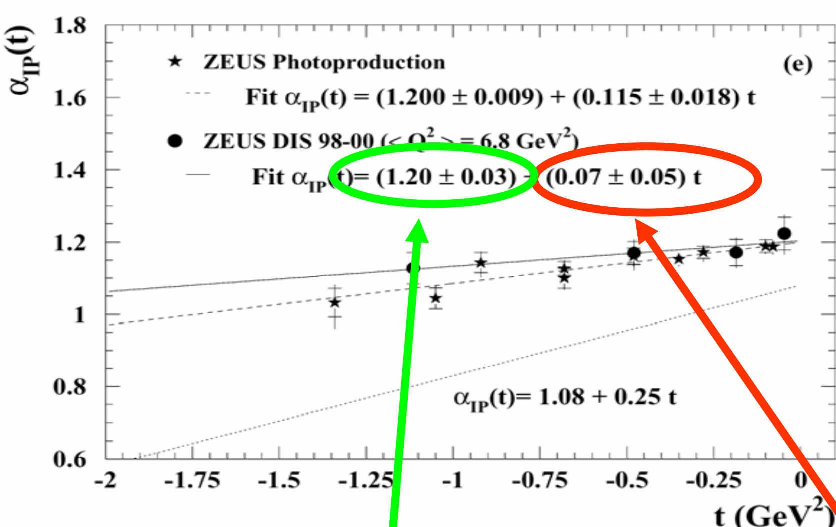
GPD, unintegrated k_t,

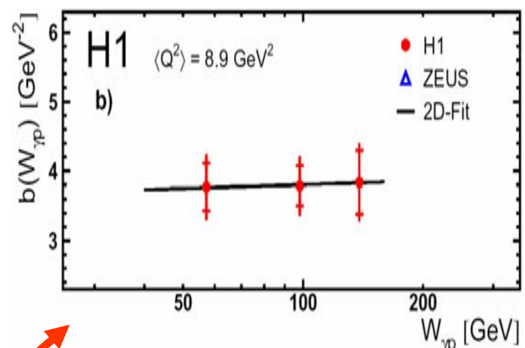
dipole + saturation

J/Ψ hard in photoproduction

→ Q^2 = second hard scale





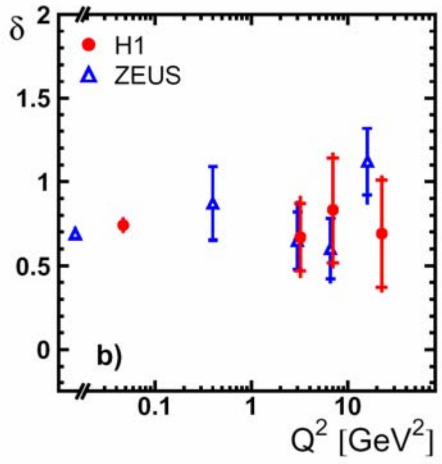


hard : $\alpha(0) = 1.20$

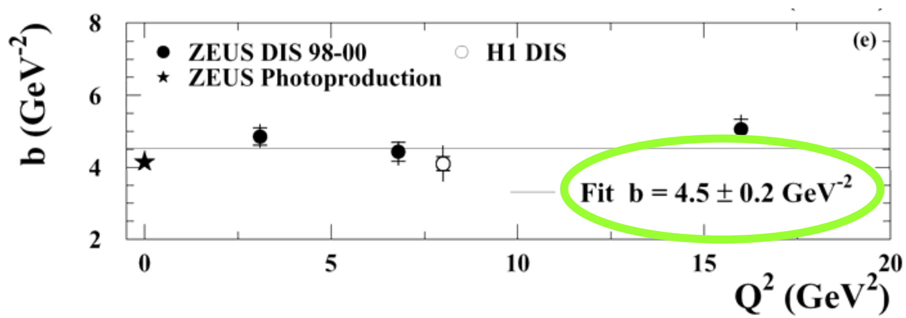
α' **consistent with 0**

J/Ψ, Q^2 independence of $\alpha(0)$, *b*

δ

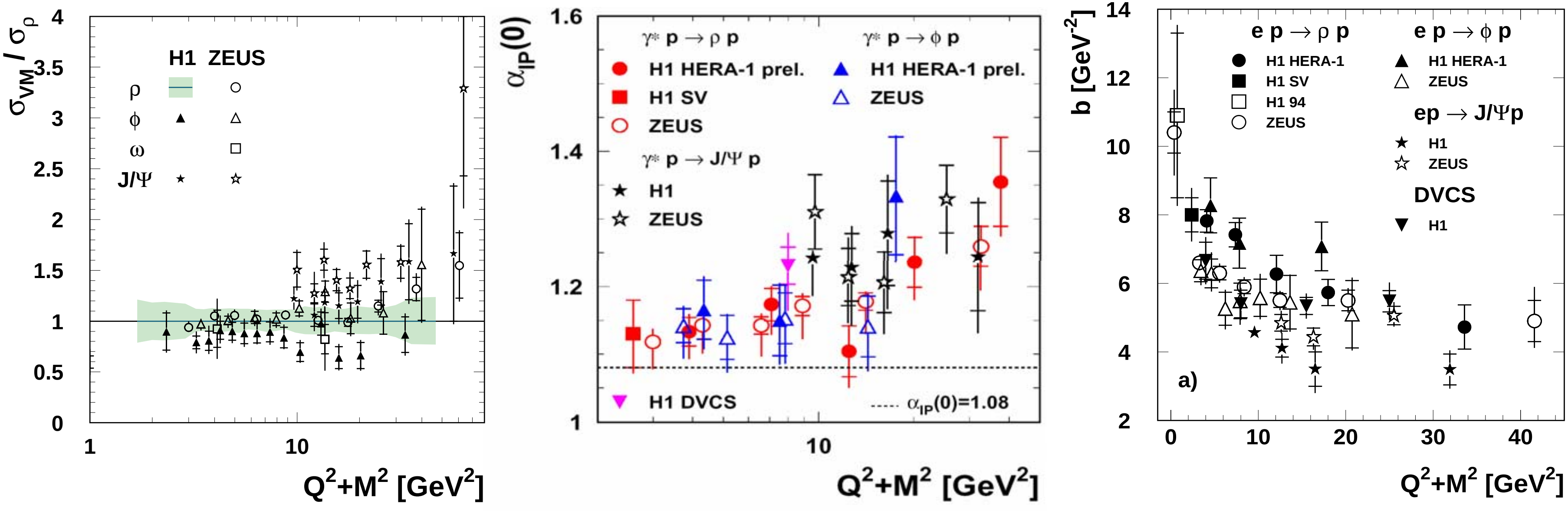


***b* slope**



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

small dipoles, hard gluons



dσ/dQ² energy dep. *b* slopes

IV. From soft to hard : *t*

(ρ, ϕ, J/Ψ)

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

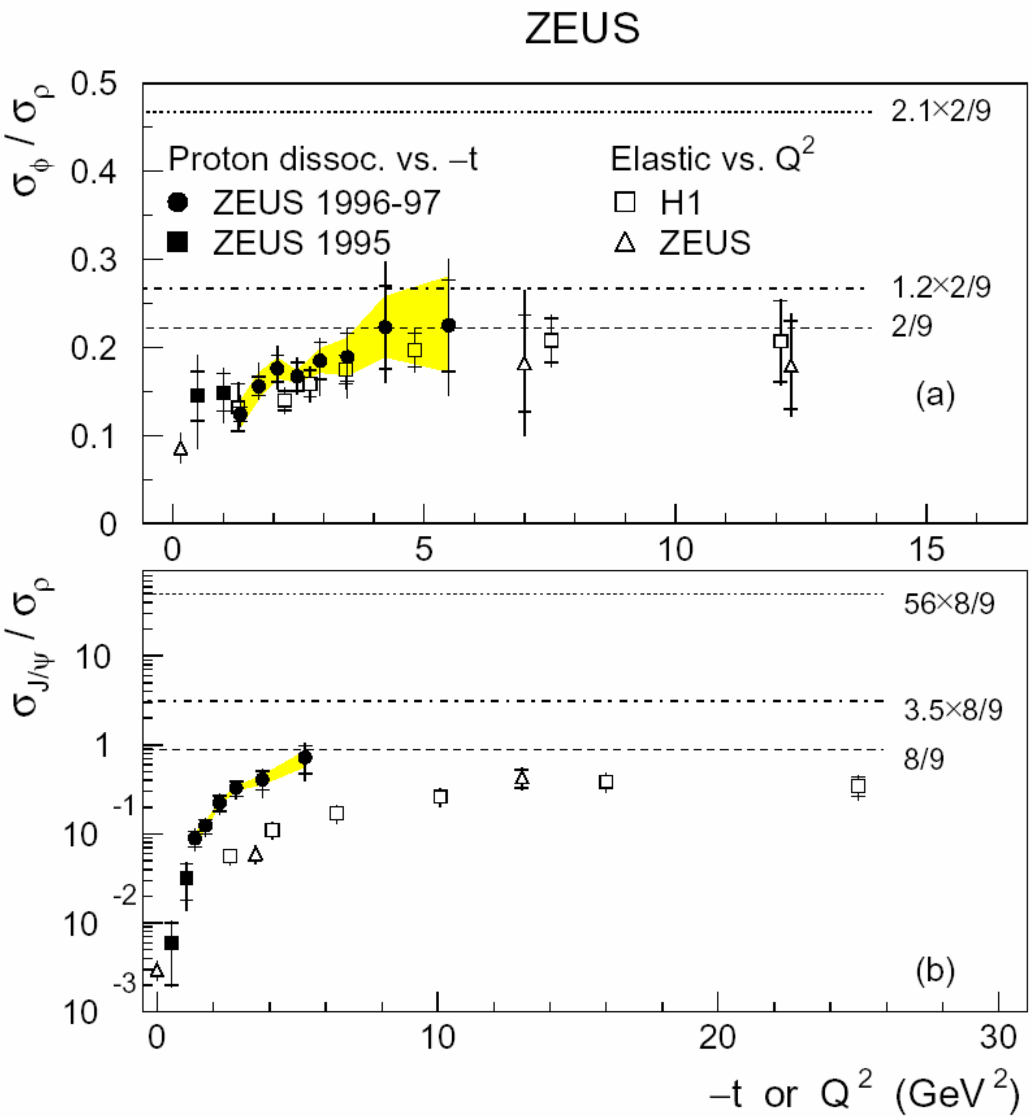
1. Universality (t)

Another hard scale

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

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

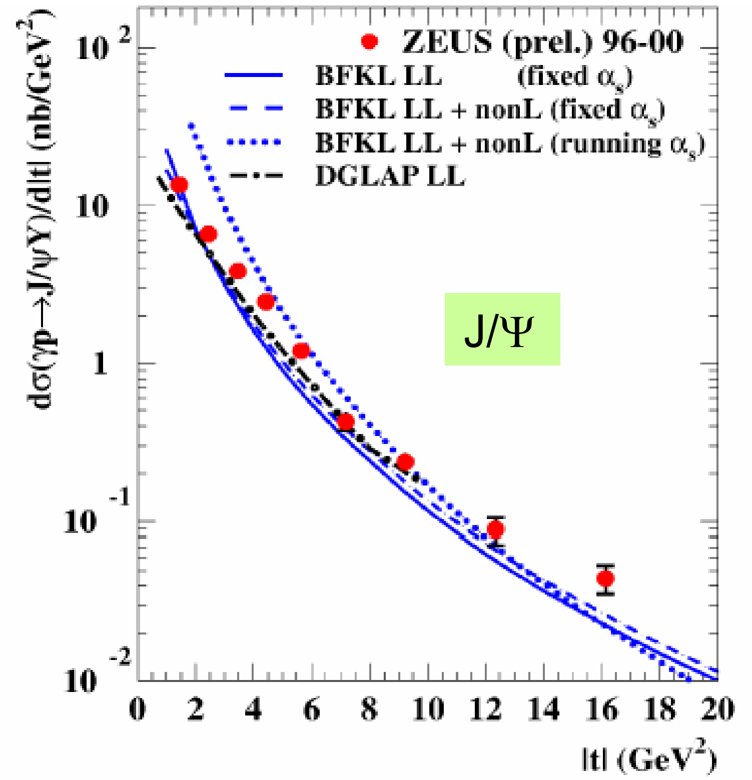
pQCD calculations
(BFKL, DGLAP)

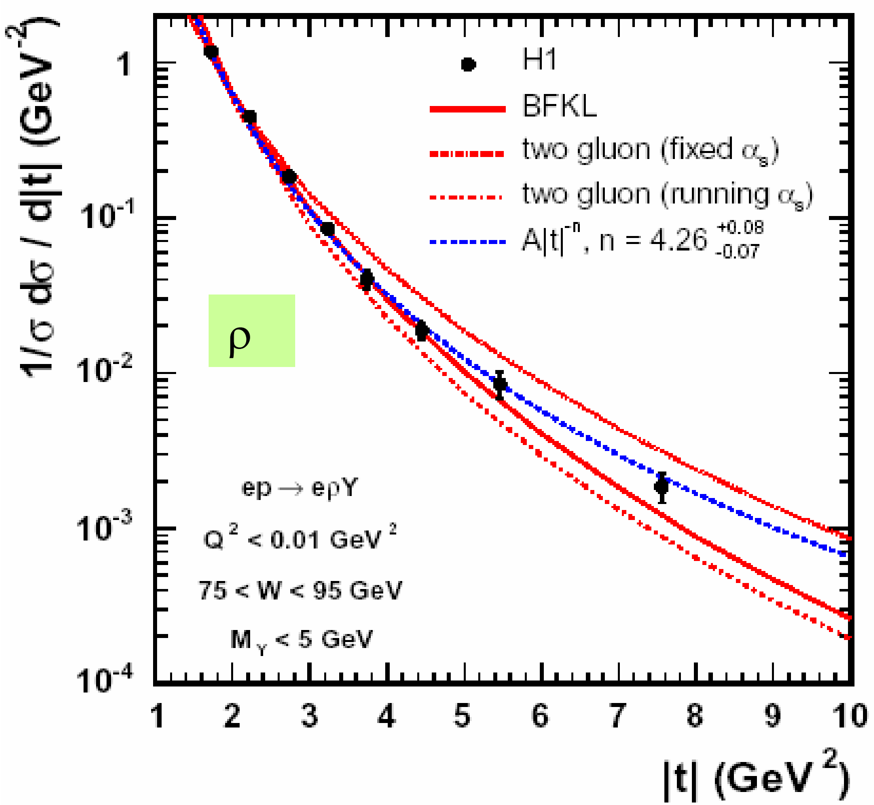


2. ρ, J/Ψ, *t* dependences

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

pQCD calculations





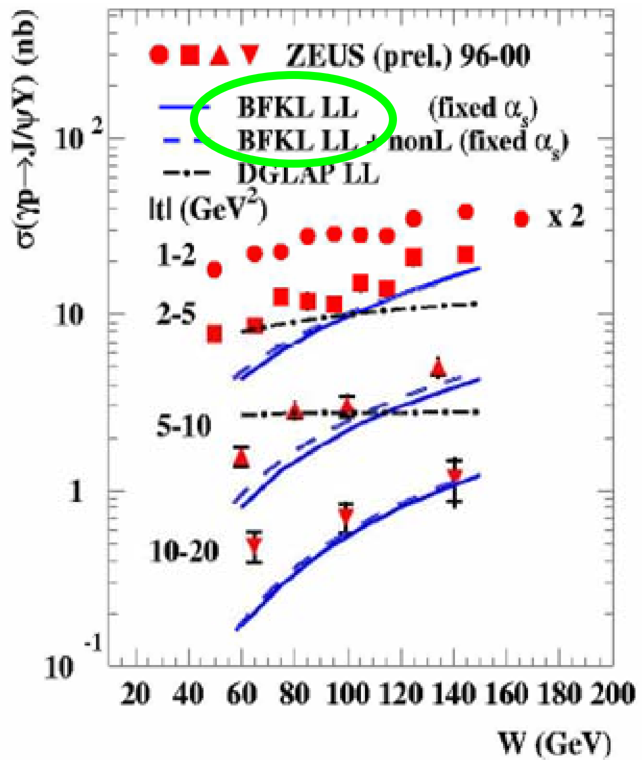
J/Ψ BFKL running α_s excluded

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

BFKL favoured

see also helicity below

J/Ψ, *W* dependence, shrinkage

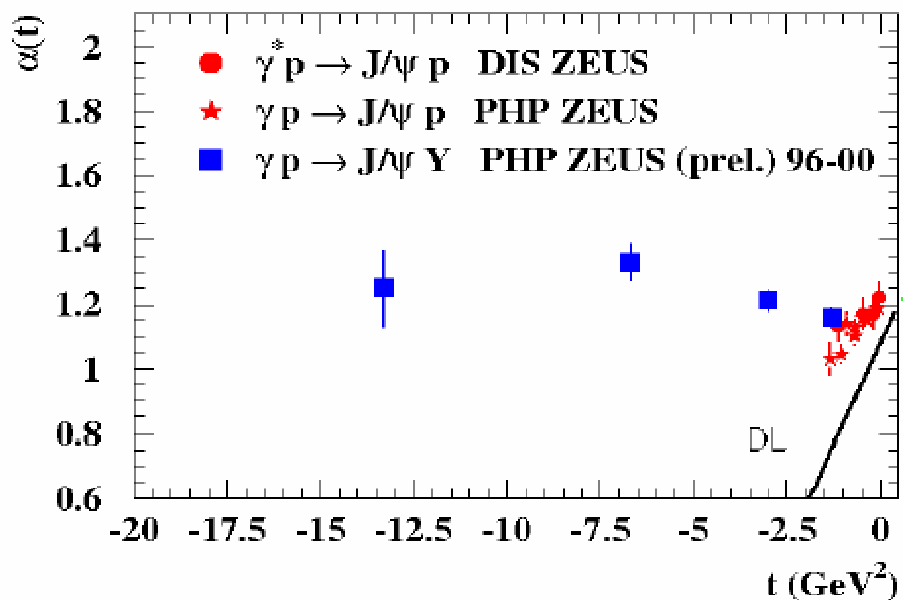


rise of σ with *W* **described by BFKL**, not by DGLAP

Shrinkage

α' slope tends to **become < 0**

(and α(0) smaller ?)



V. Helicity amplitudes

(Q^2, W, t, m)

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

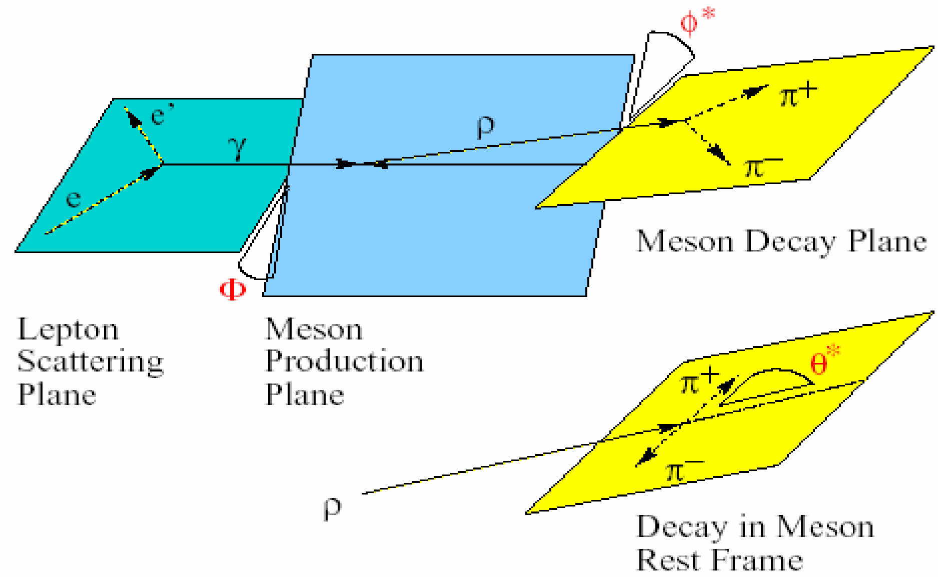
spin density matrix elements

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 $T_{-1\,1}$

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

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

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

$T_{00} > T_{11} > T_{01} > T_{10}, T_{-1\,1}$

ZEUS, H1 HERA-1 ρ, φ (Q^2, W, t, m)

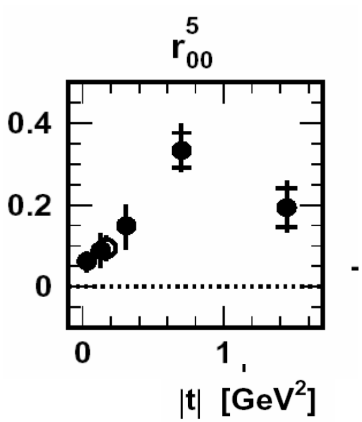
ρ and φ, spin density matrix elements (Q^2)

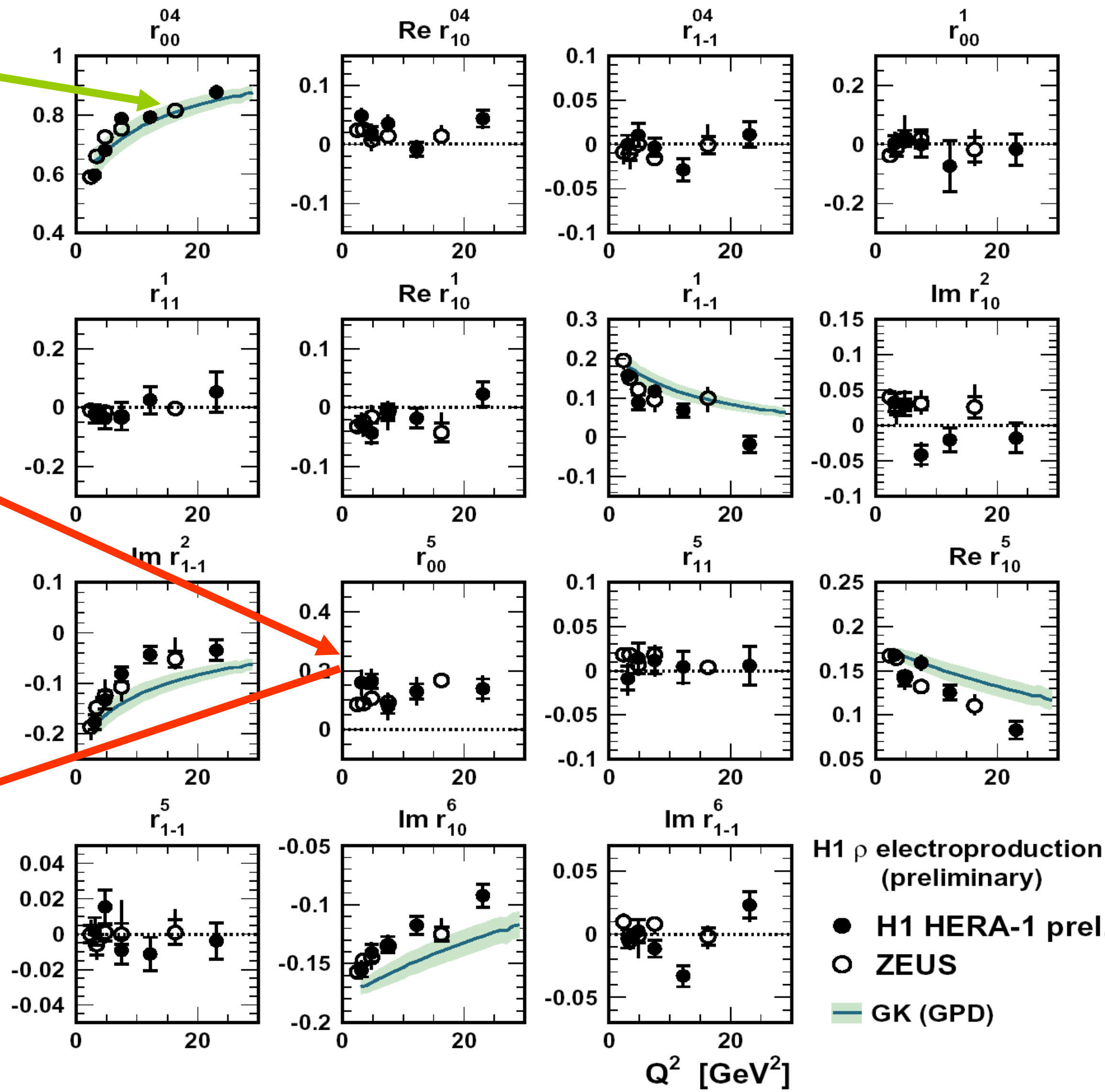
5 SCHC elements compared to **GPD** calculations

Other elements (dashed lines) compatible with 0 or small)

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

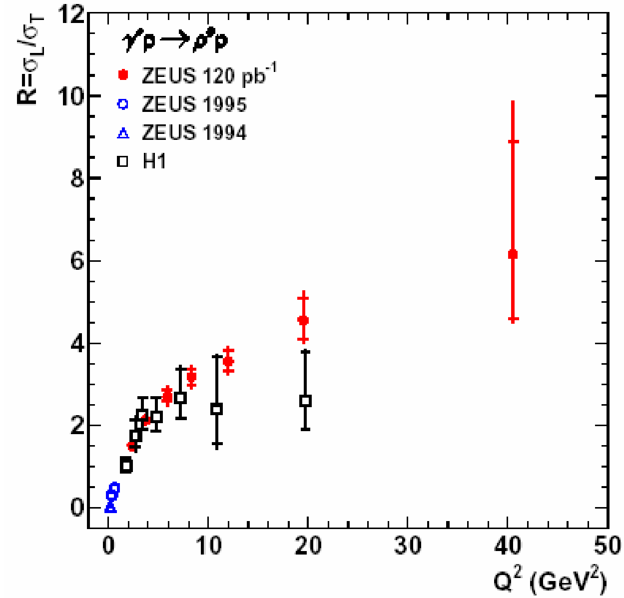
expected $\sqrt{|t|}$ dependence of **spin flip** amplitude T_{01}



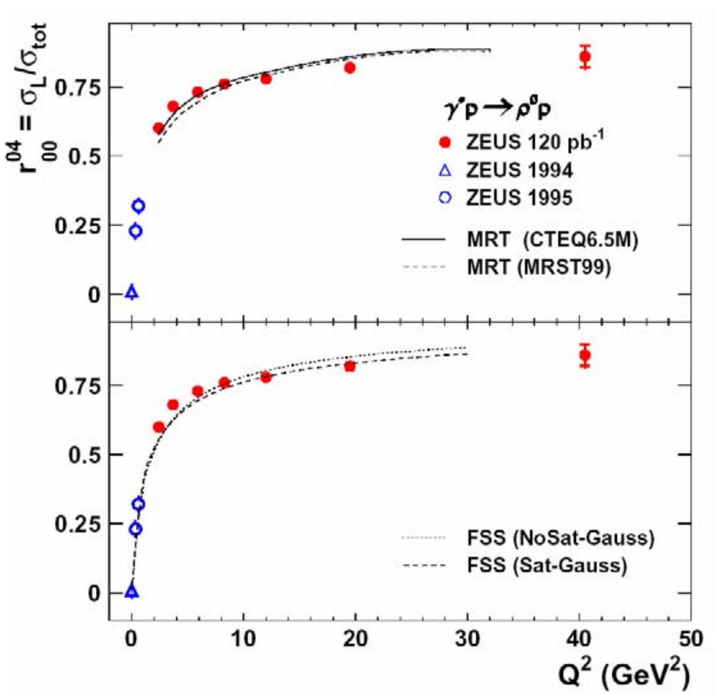


ρ and ϕ, $R = \sigma_L / \sigma_T$ (Q^2)

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

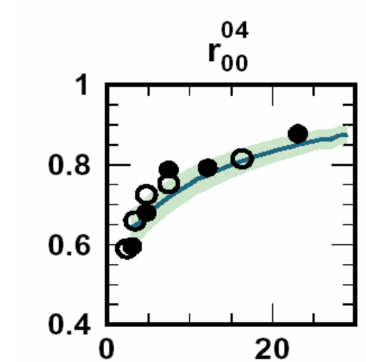


Q^2 dependence of gluons
(MRT – parton hadron duality)



dipole + saturation

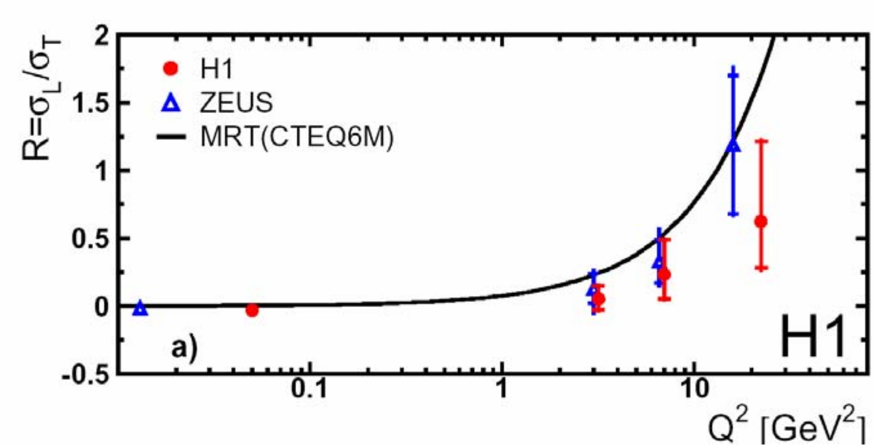
GPD

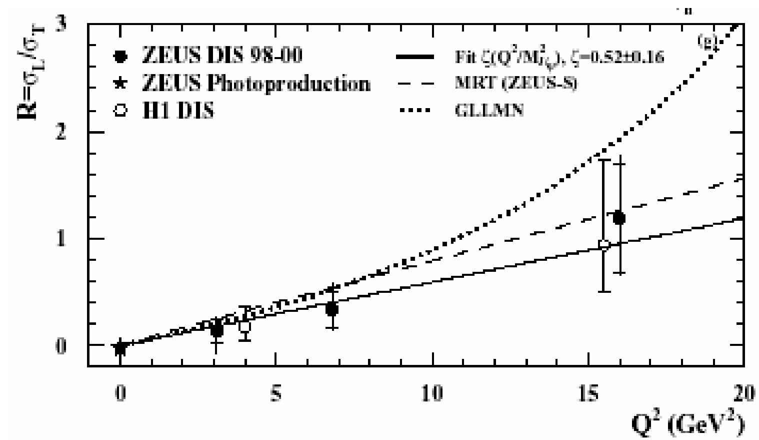


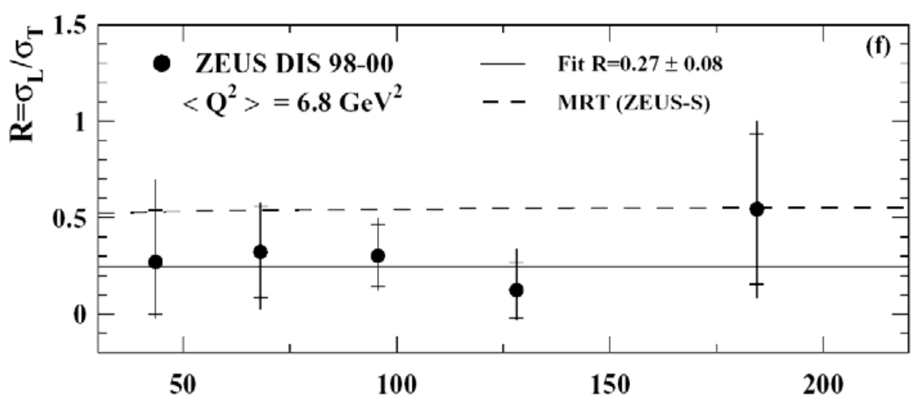
J/Ψ, $R = \sigma_L / \sigma_T$

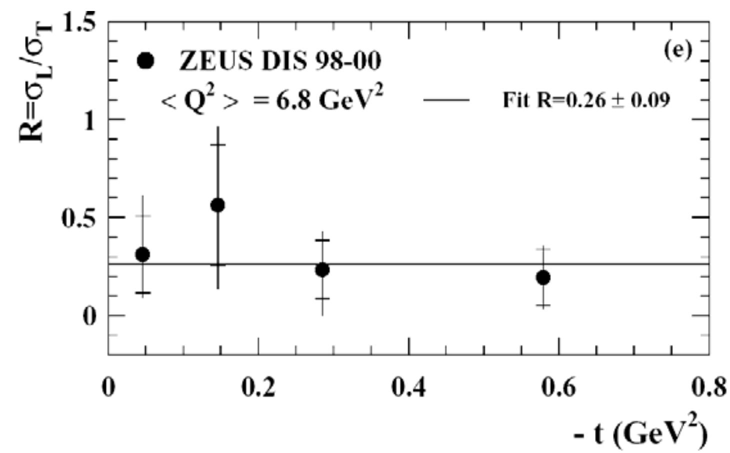
non-relativistic model for J/Ψ : z ~ 1/2 ⟶ **no helicity flip**

basic scale for R given by $R \sim Q^2 / M^2$ ⟶ 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 ~ *t*)

But SCHC T → T dominates

+ double flip T → T

Reason :

chiral odd contribution in γ

(due to constituent quark mass)

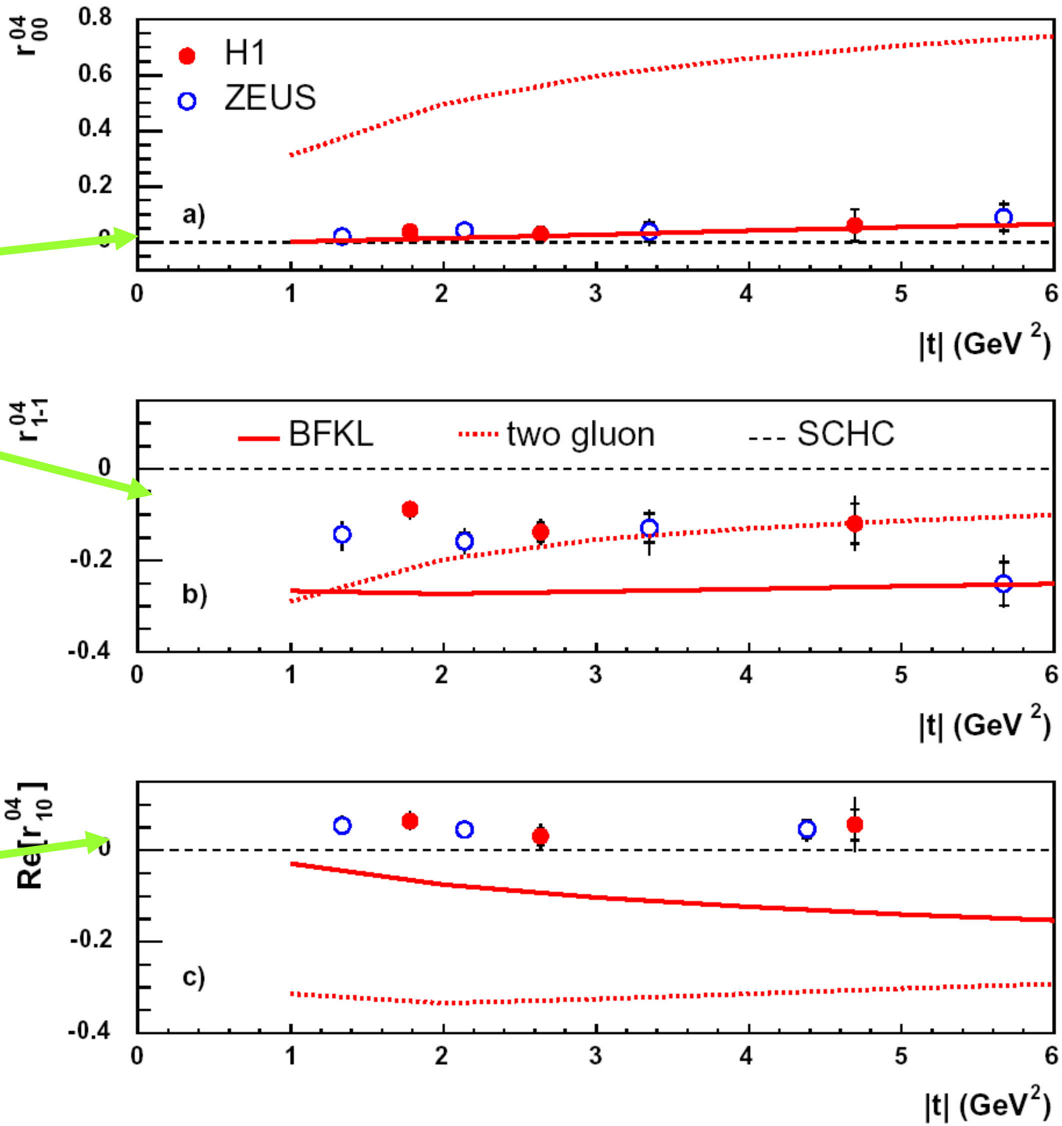
→ no orbital momentum needed for Ψ_T

→ SCHC

BFKL model describes data well

(except sign of)

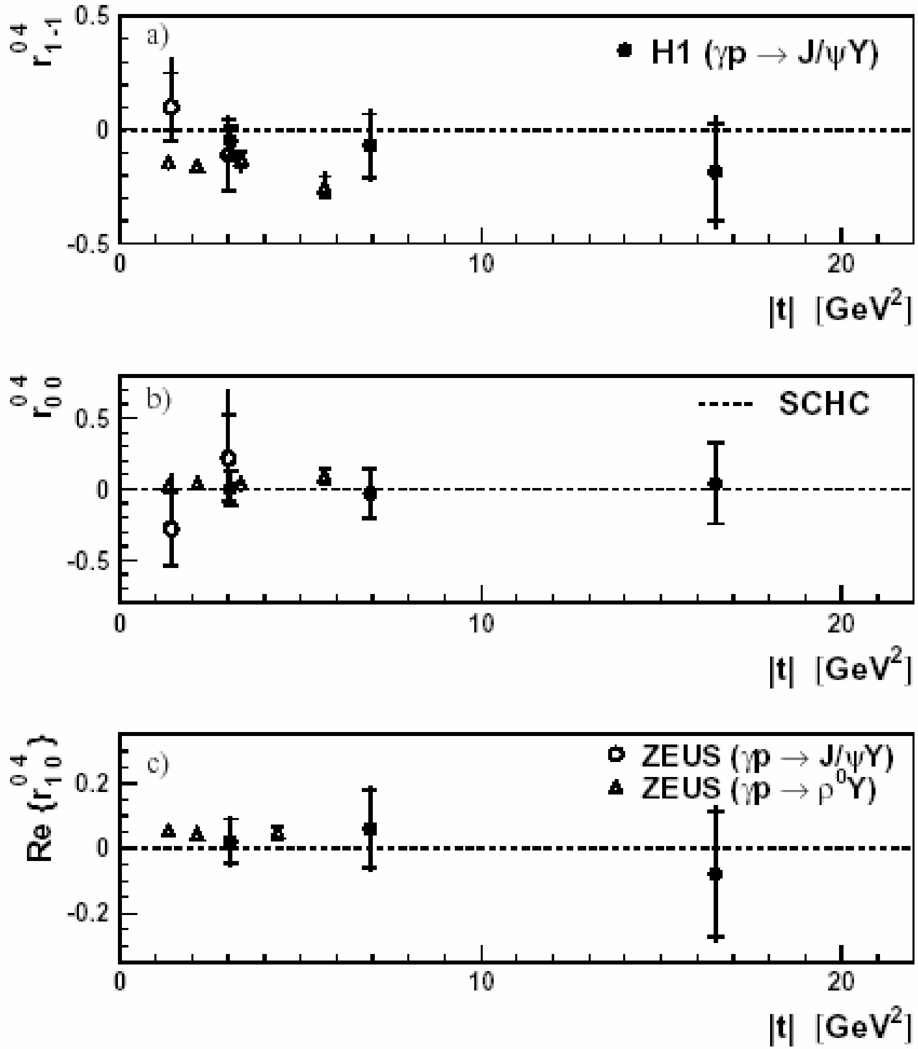
cf. also *t* and *W* dependences



large |*t*|, J/Ψ (photoproduction)

no helicity flip

cf. non-relativistic model



VI. Summary and conclusions on vector mesons

Summary

Enormous progress

- experiments

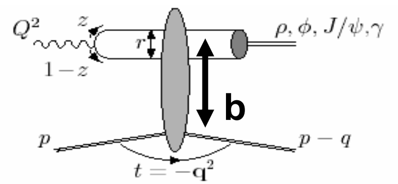
DVCS light VM (ρ, ϕ) J/Ψ Υ

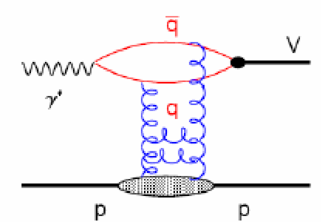
Q^2 W t hel. amplitudes p.diss. / el.

→ **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:

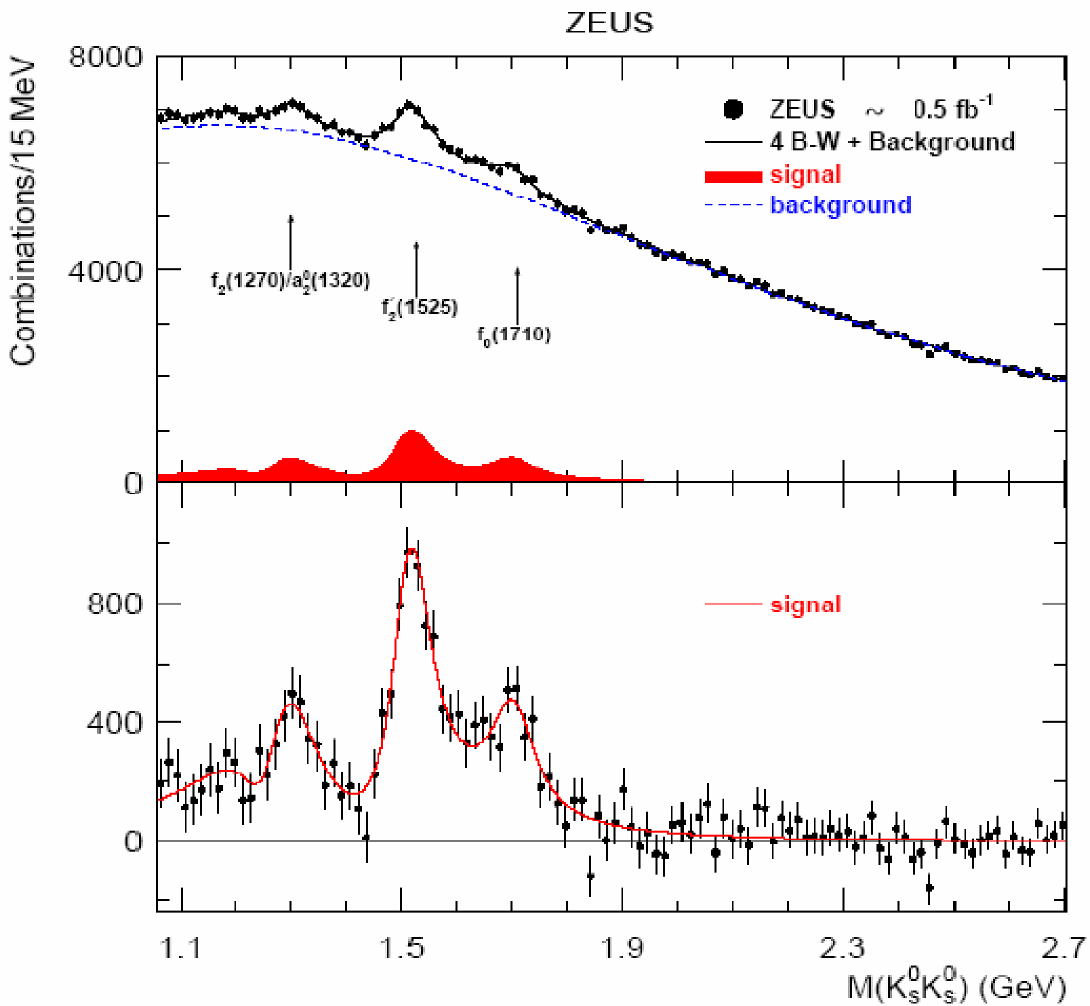
lightest glueball $J^{PC} = 0^{++}$ in mass range 1450-1750 MeV

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

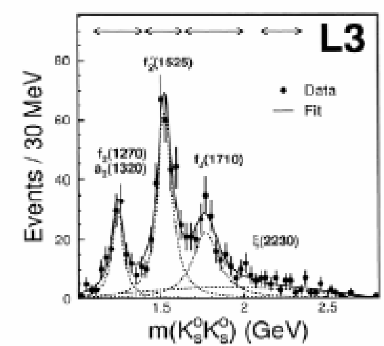
(Slides from F. Corriveau at PHIPSI08 – Frascati 2008. Many thanks to him !)

$K_s^0 K_s^0$ 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 $\chi^2/ndf = 86/97$		PDG 2007 Values	
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