HERA-LHC
CERN
26-30/05/2008

Vector meson production and DVCS at HERA

From soft to hard diffraction

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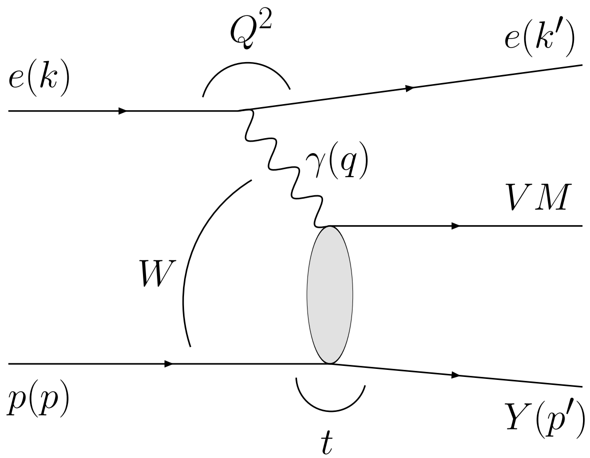
Introduction



γ ρ ω ϕ J/ψ ψ(2s) Υ

p p. diss. (M_Y)

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|)

dσ / d*Q^2*, d*W*, d*t*, helicity amplitudes (ang. distrib.)

> 30 H1 + ZEUS exp. papers + several “preliminary results”
mostly HERA-1 O(100 pb-1) – some HERA-2
huge number of theoretical papers
strong theory – experiment interactions

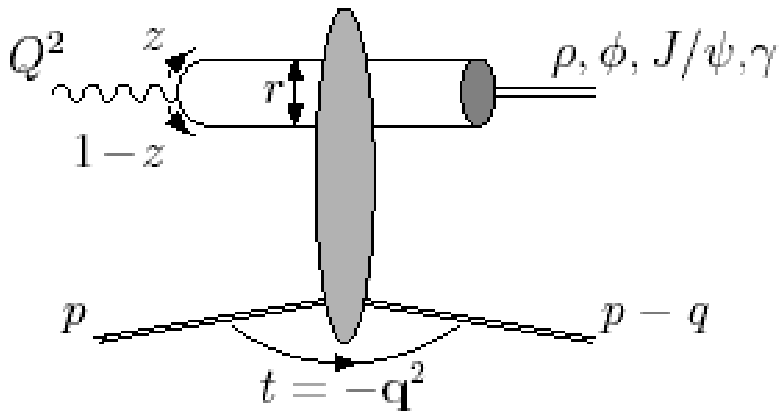
Content

I. Interpretation frameworks

QCD factorisation

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

Factorisation theorem



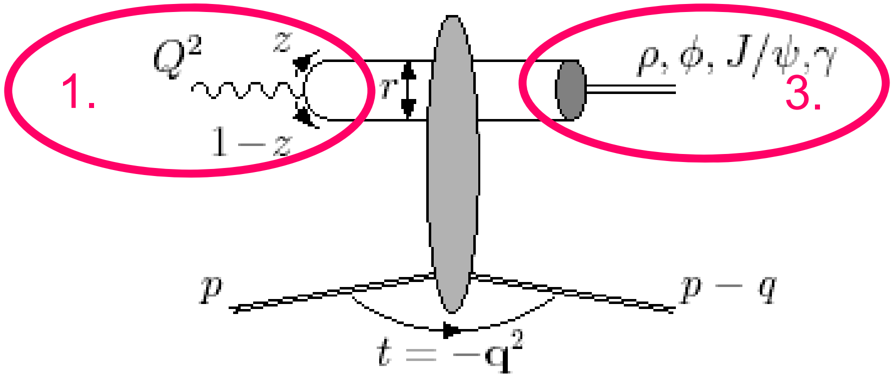
step 1. γ fluctuation into $q\bar{q}$ dipole

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

step 3. pair recombination into VM

for σ_L + heavy quarks

γ - VM wave functions



1. γ wave function

well known : $\Psi(z, k_t)$

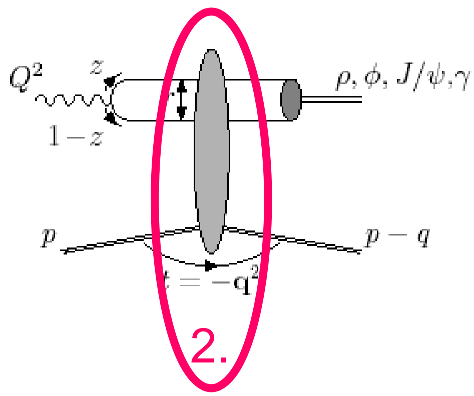
however : large |*t*| studies -> chiral odd contributions

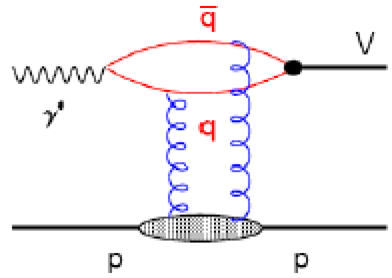
3. pair recombination into VM

- VM wave function description ?
- role on σ_L / σ_T and helicity amplitudes

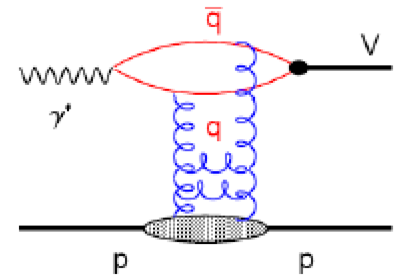
Dipole universality

2. dipole – proton interaction





LO 2 gluons



LL1/x ladder

1. universality of dipole cross section

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

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

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

((A_T : see below))

dependences

2. *W* dependence

Regge-like parameterisation

high energy *h–h* interactions : $\sigma_{tot}(h-h) \propto s^{\alpha(0)-1}$

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

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

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

- pQCD VM production : $\sigma \sim W^{\delta}$ $\delta = 4\,(\alpha(t) - 1) = 4\,(\alpha(0) + \alpha' t - 1)$

$\sigma \sim |x\,G(x)|^2$ -> **hard** cf. BFKL, low x DIS DGLAP

- **shrinkage** of diffractive peak : $\frac{d\sigma}{dt}(W) = e^{bt} = e^{b_0 t}\, W^{4(\alpha(0)+\alpha' t-1)}$

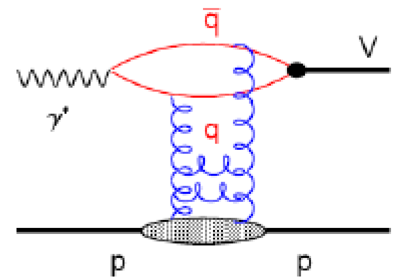
$b = b_0 + 4\alpha' \ln(W/W_0)$

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

BFKL : shrinkage expected to be small

→ **W^{δ} hard, $\alpha(0)$ large, universal (Q^2+M^2), α' small**

dependences



3. Q^2 dependence

(in the pert. domain) **universal ($Q^2 + M^2$)**

NB formally $\sigma_L \propto Q^2 \, | xG(x) |^2 \, / \, (Q^2 + M_V^2)^4 \sim 1/Q^6$

<u>but</u> gluon anomalous dim. slows down $xG(x) \propto (Q^2 / Q_0^2)^\gamma$

(especially at smaller Q^2, where γ is larger)

4. t dependence (moderate |t|, ≤ 1.5 GeV²)

$$\frac{d\sigma}{dt} \propto e^{-b|t|} \quad \text{with} \quad b = b_{dip} \oplus b_{exch} \oplus b_Y$$

→ decreases with increasing ($Q^2 + M^2$)

(in the pert. domain) **universal ($Q^2 + M^2$)**

5. vertex factorisation

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

transverse, soft contributions

6. 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.)

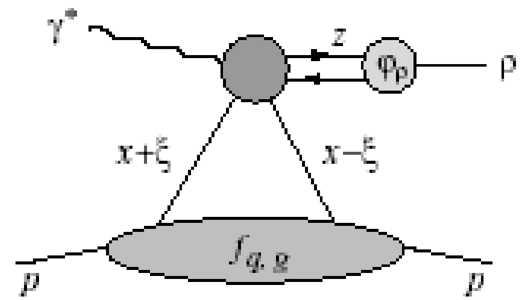
NB : also longitudinal extension of longitudinal wave function at moderate Q^2

→ possibly finite size effects also in σ_L

Beyond LLQ^2,1/x

2 mains – complementary – extensions

1. Hard scattering



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

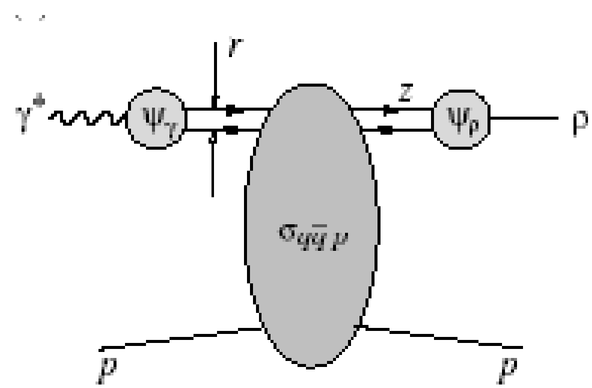
- skewing : $Q^2 \neq M^2$ => x(in) ≠ x(out) (Υ, DVCS)
- large Re / Im

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**

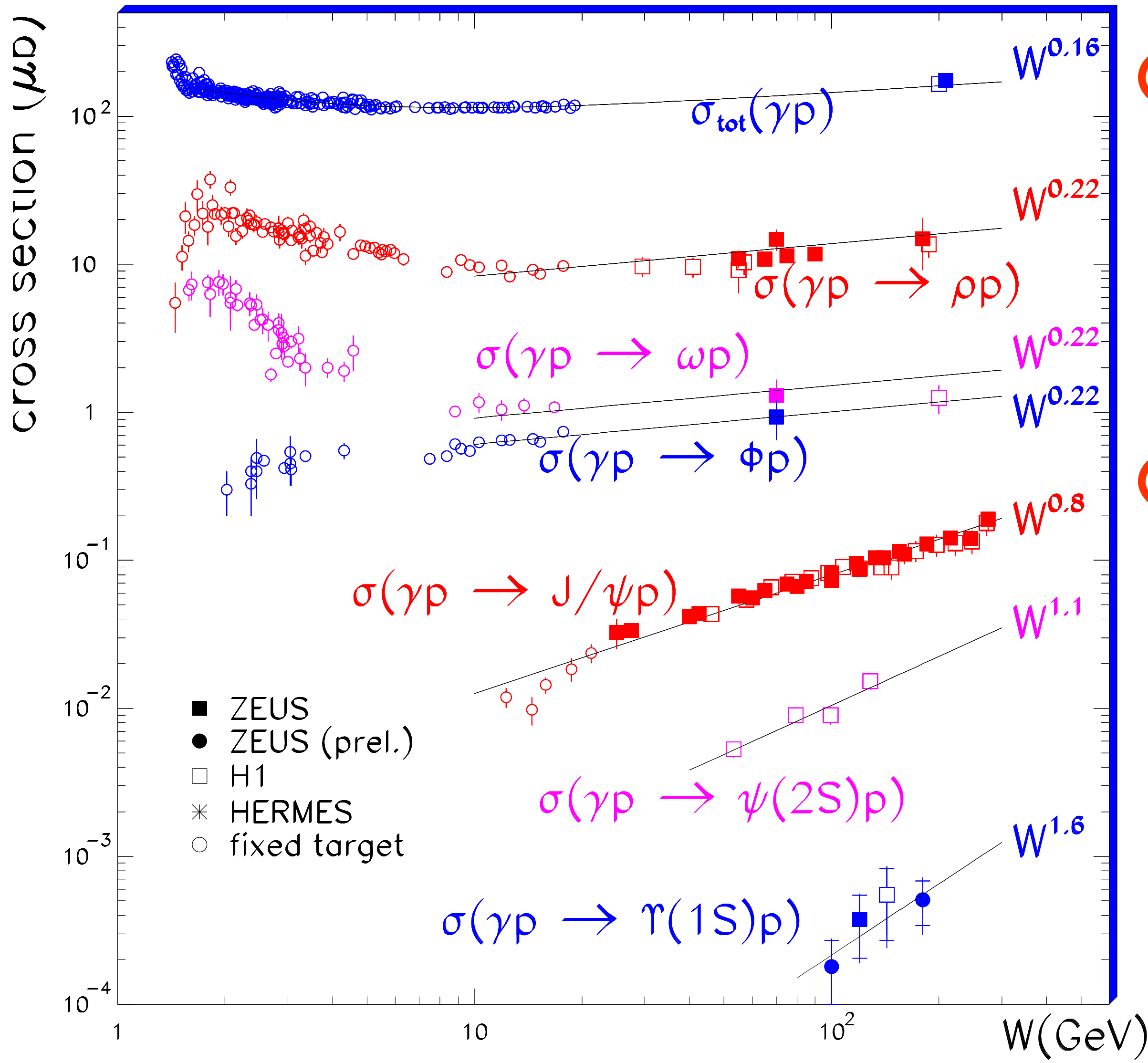
Also other approaches (2 pomerons, GVDM, ...)

II. From soft to hard : mass

(σ_{tot}, ρ, ω, ϕ, J/Ψ,Υ)

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

Photoproduction



soft

σ_{tot}

ρ, ω, φ

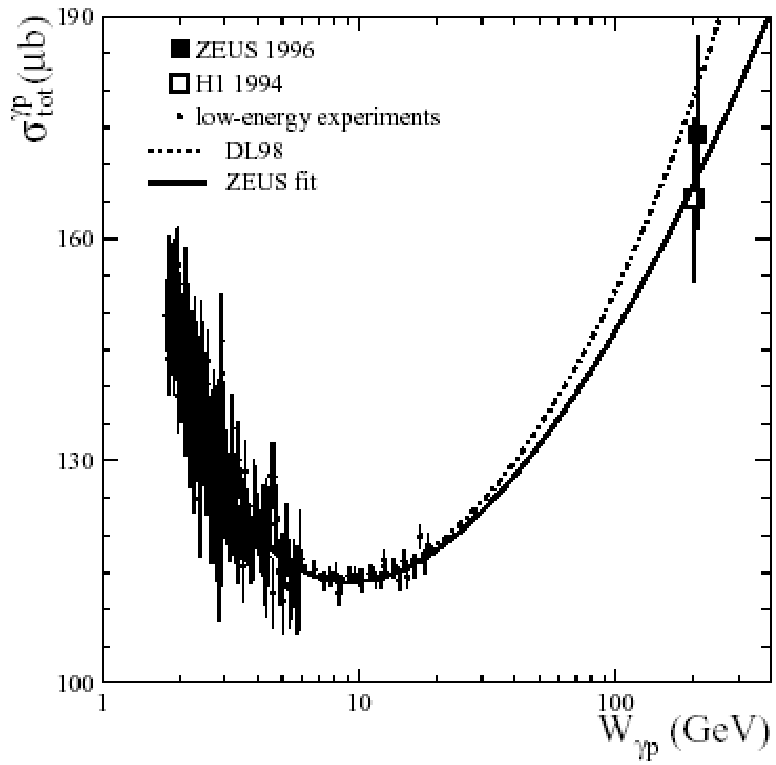
hard

J/Ψ

skewing, Re → GPD

Υ

σ_{tot}



H1 (W=200 GeV), 165 $\pm 2 \pm 11$ μb

ZEUS (W=209 GeV), 174 $\pm 1 \pm 13$ μb

Large systematic uncertainties

ZEUS

+ ratios at different *W*

-> prel. 2008

$$\varepsilon = 0.070 \pm 0.007(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.050(6\text{mT})$$

+ use of low energy run

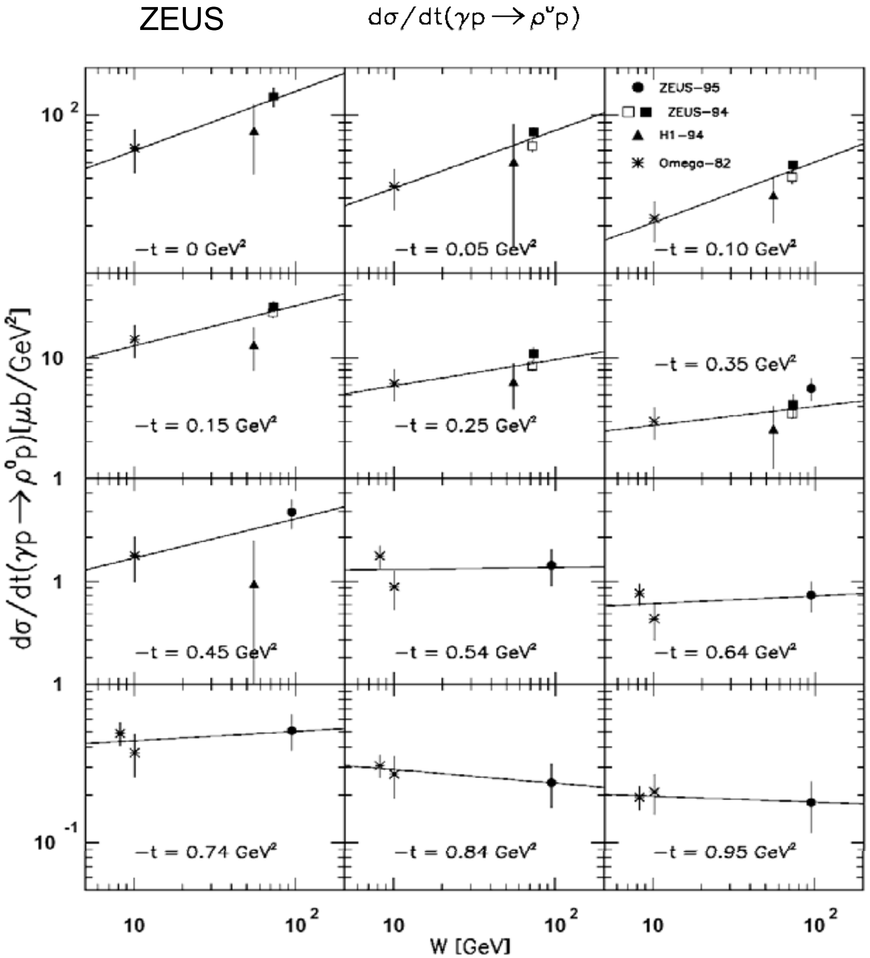
II.1 From soft to hard : mass
ρ, ω, ϕ

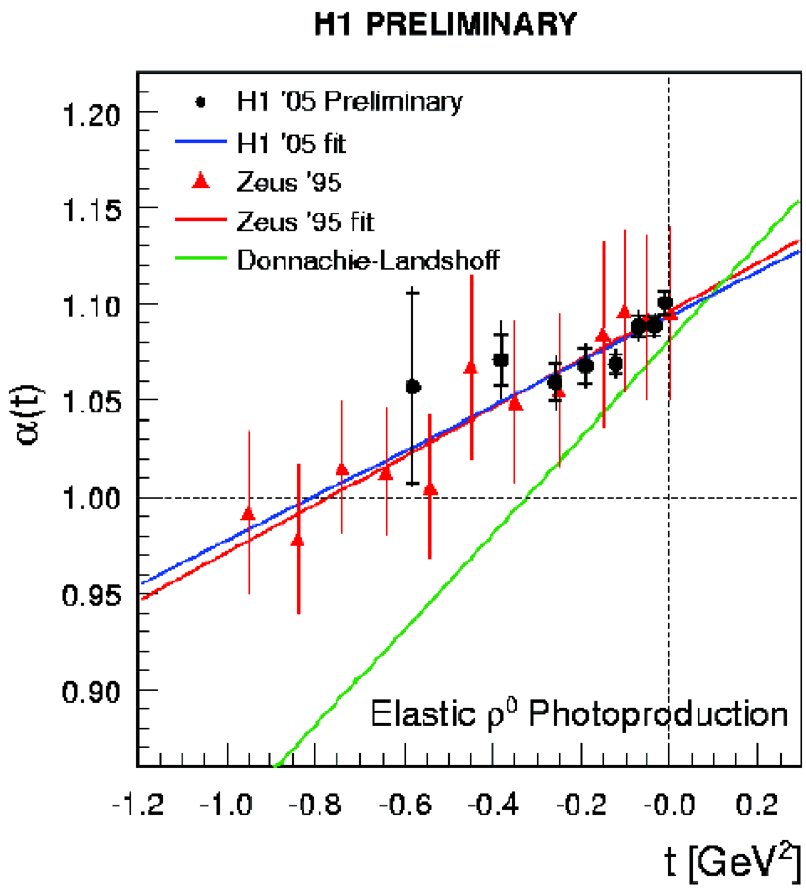
soft W dependence

W dependences + *t* evolution

→ intercept + slope (shrinkage) of trajectory

ZEUS





ρ, shrinkage

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 (?) $\alpha' \approx 0.12\ \text{GeV}^{-2} \neq 0.25\ \text{GeV}^{-2}$

Should we be surprised ?

II.2 From soft to hard : mass J/Ψ

J/Ψ, *W* dependence

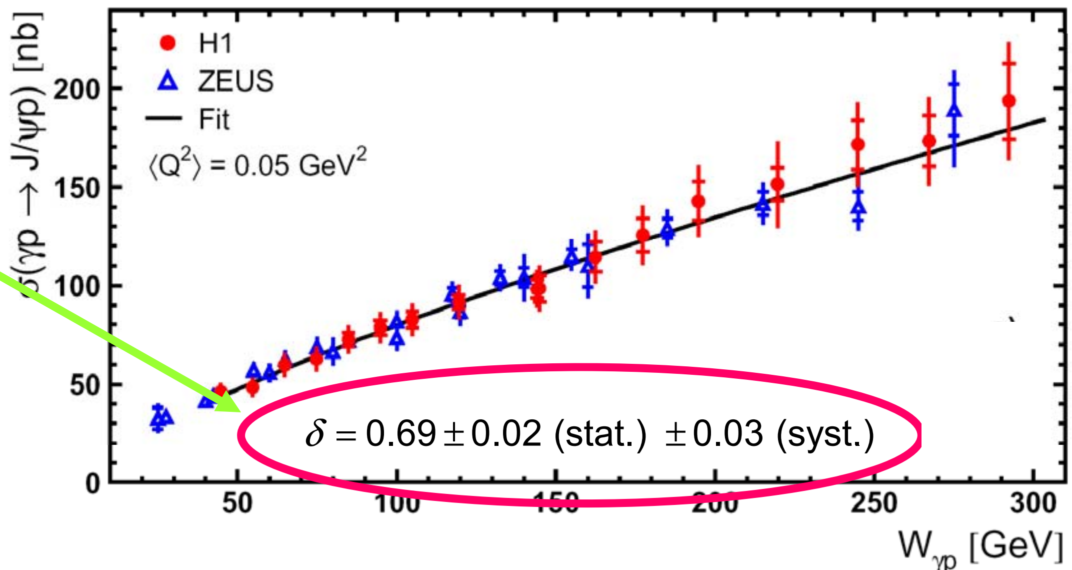
ZEUS, H1 1999-2000

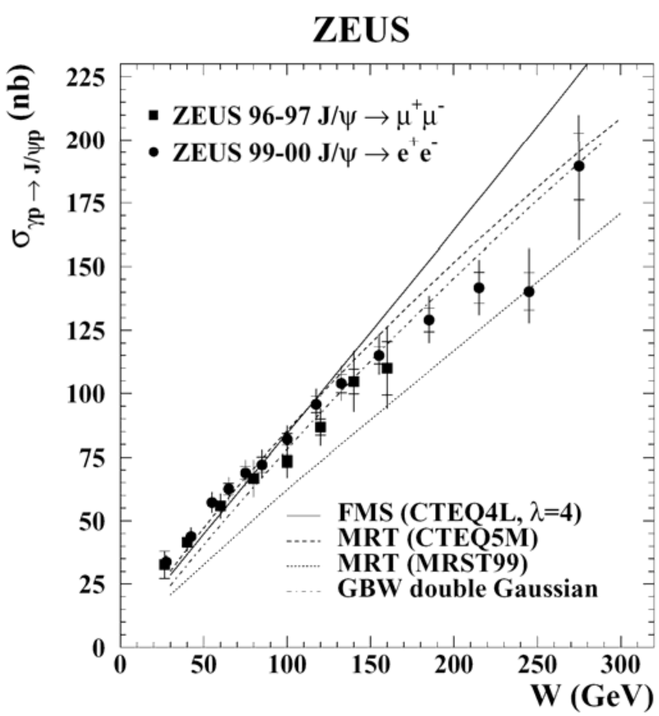
hard slope

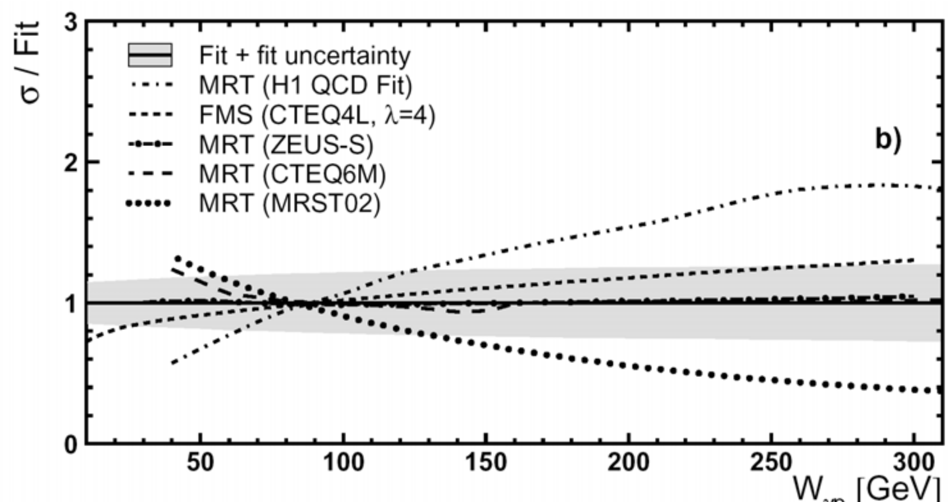
mass = hard scale

=> comparisons with theory

tests of pdf's



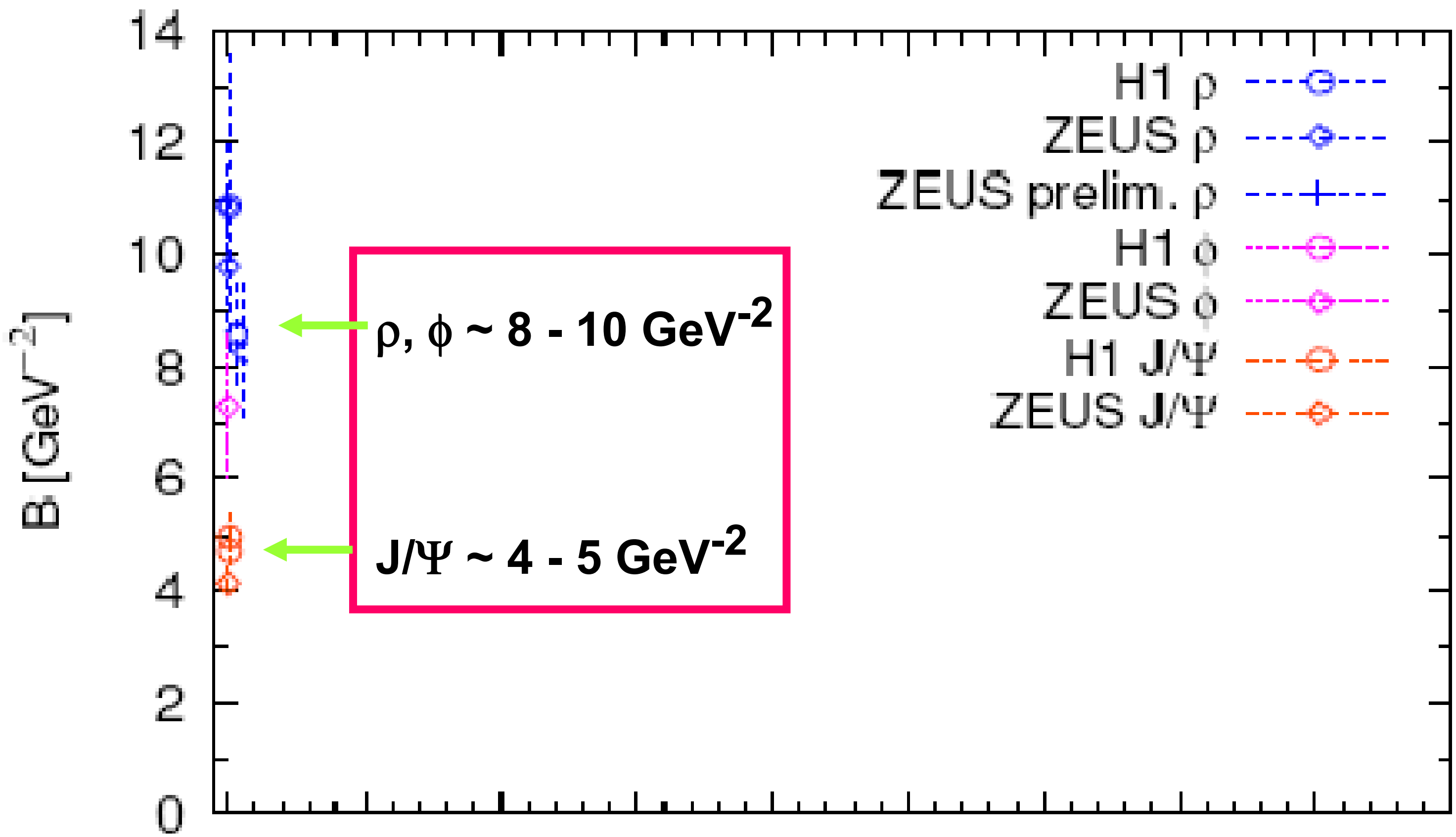




J/Ψ, *t* dependence

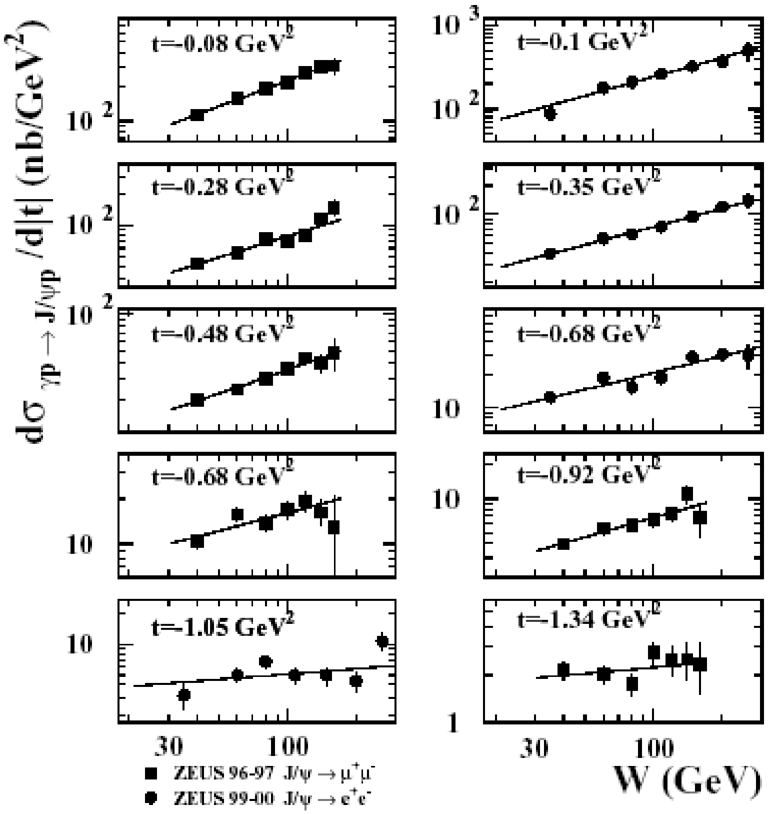
exponential slopes ↔ **size of the dipole**

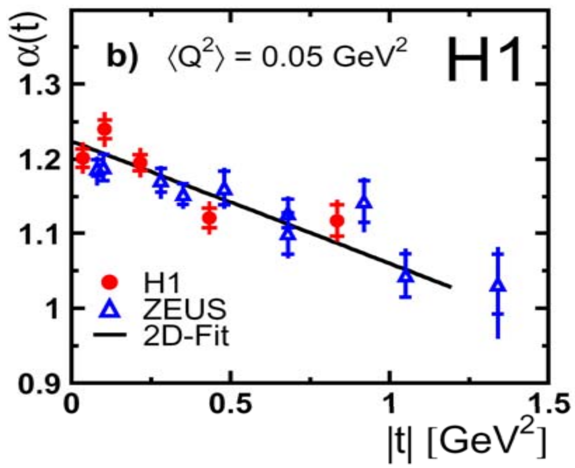
heavy charm quark -> small dipole -> flatter *t* distribution, smaller slope

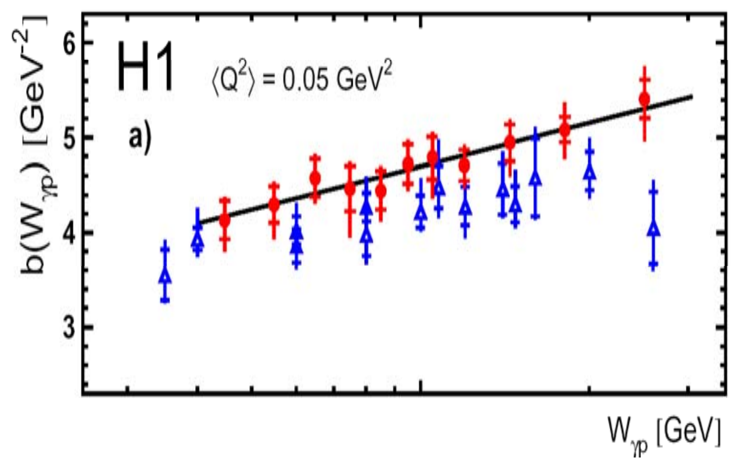


J/Ψ, *W* dependence, shrinkage

ZEUS 1996-97, 1999-2000







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

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

ZEUS

$$\alpha_{I\!P}(0) = 1.200 \pm 0.009^{+0.004}_{-0.010}$$
$$\alpha'_{I\!P} = 0.115 \pm 0.018^{+0.008}_{-0.015}\ \mathrm{GeV}^{-2}$$

H1

α_0	α' [GeV^{-2}]
$1.224 \pm 0.010 \pm 0.012$	$0.164 \pm 0.028 \pm 0.030$

II.3 From soft to hard : mass Upsilon

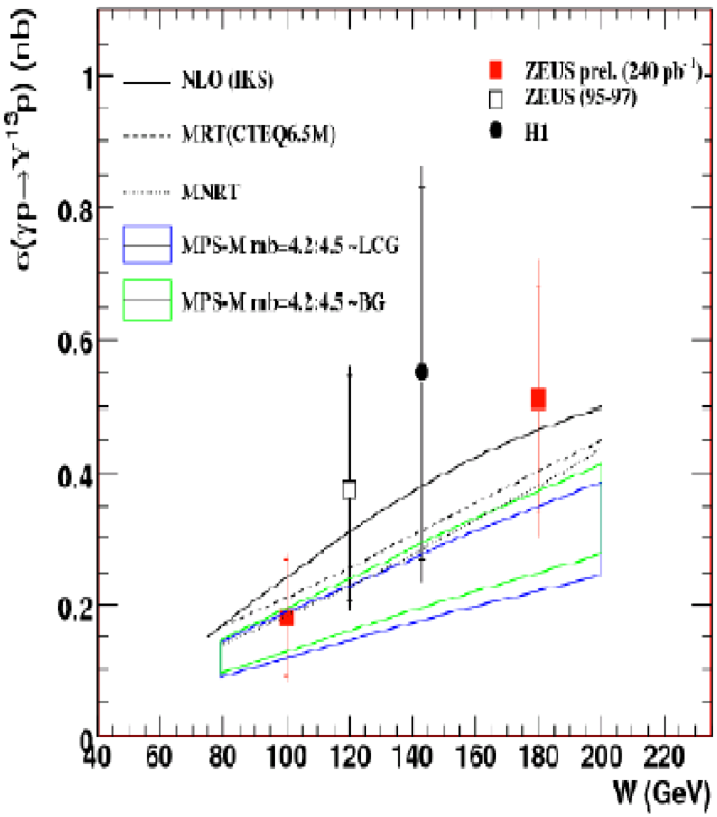
Upsilon

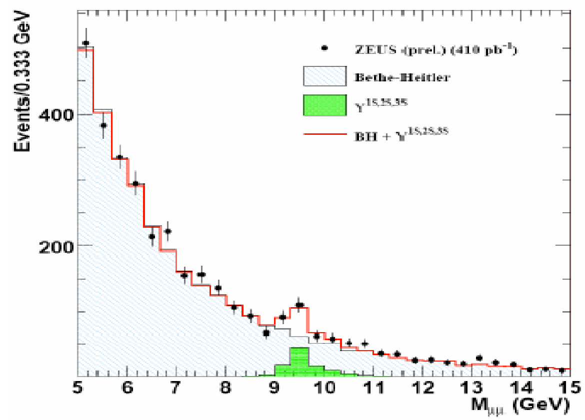
Zeus HERA 1+2

very hard *W* dependence

$\delta \sim 1.6$

Number of Upsilon candidates 104 ± 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/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)

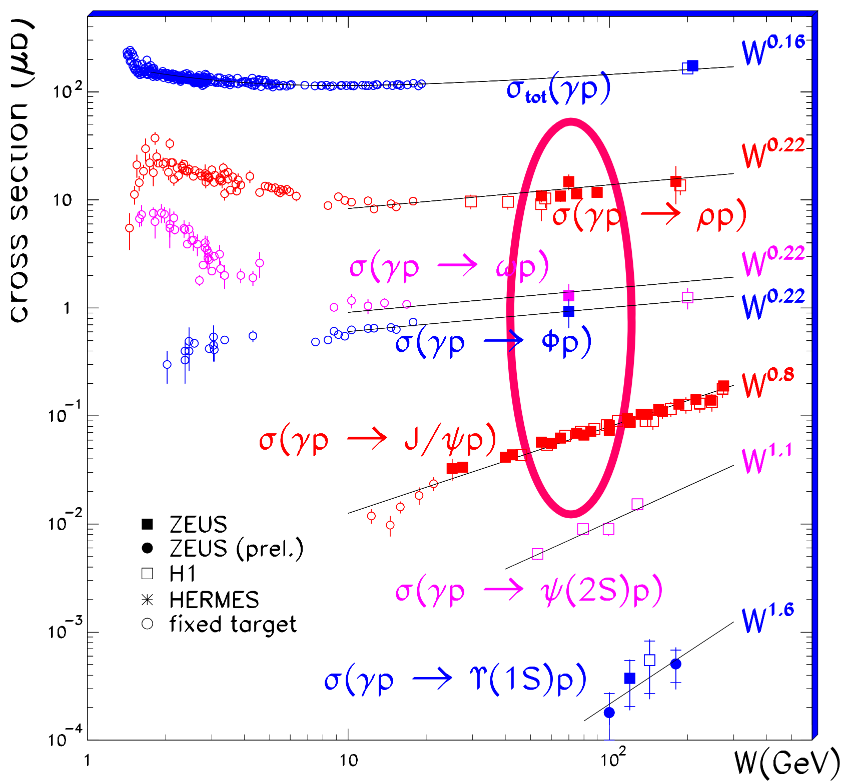
universality ($Q^2 + M^2$)
***W* dependences**
***t* dependences**

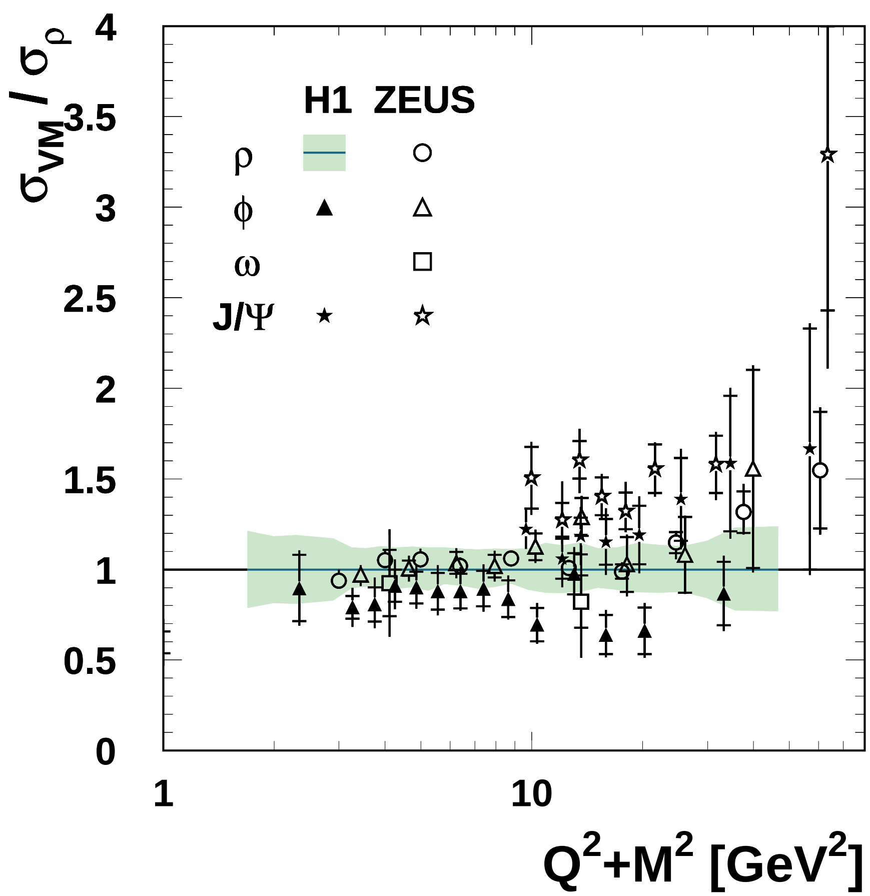
Universality ($Q^2 + M^2$)

Cross section comparison :

support to the dipole approach ideas

(qualitatively) striking !





III.1 From soft to hard : Q^2
DVCS

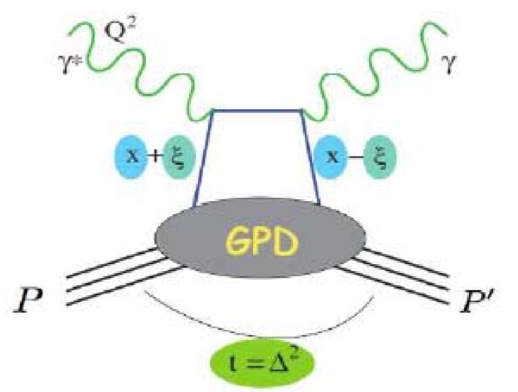
Deeply Virtual Compton Scattering

DIS domain : e + p → e + p + γ (real)

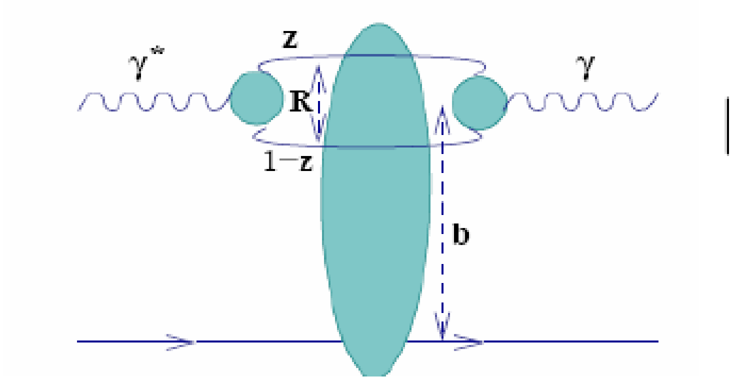
i.e. γ* p → γ p

2 complementary approaches :

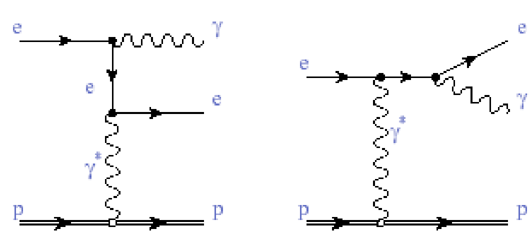
GPD



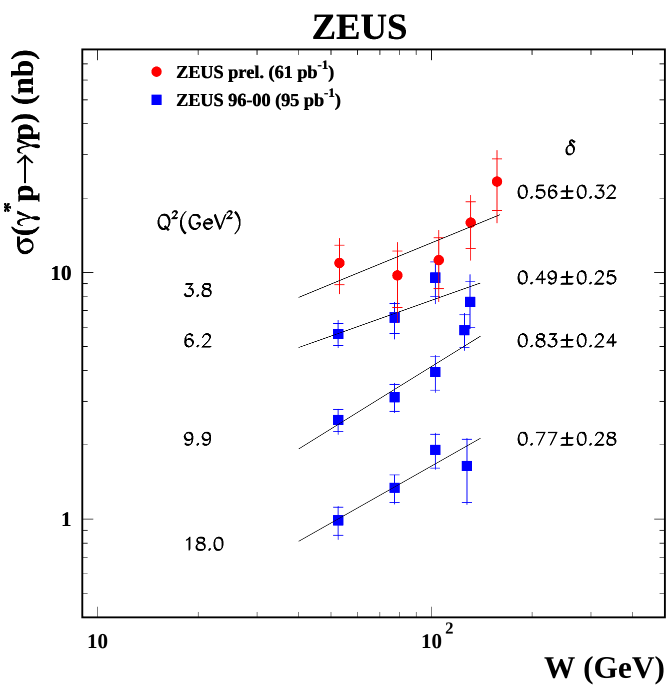
Dipole

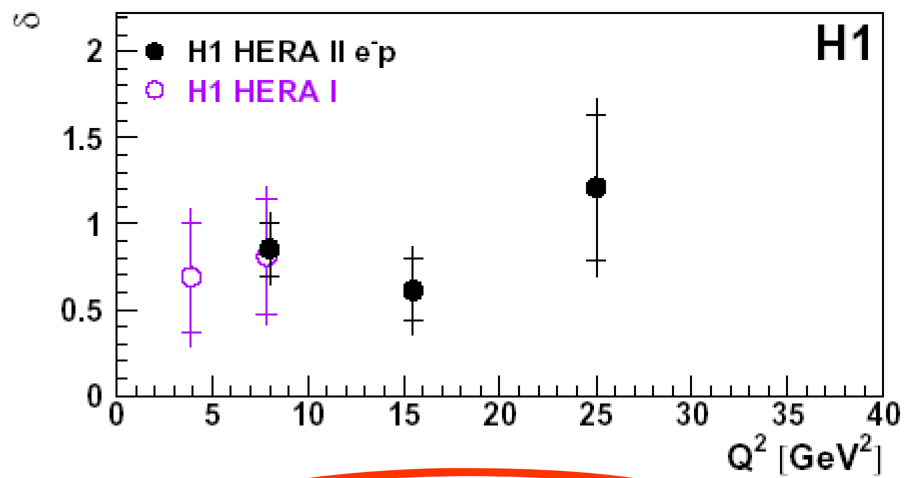


+ no WF uncertainties in calculations ↔ light VM
+ interference with Bethe-Heitler → access to Re contributions



DVCS – *W* dependence

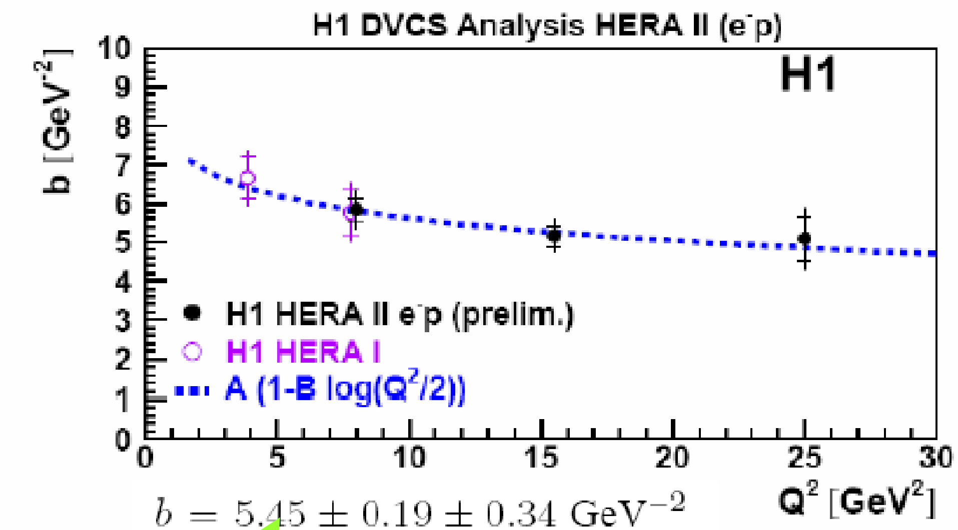




$\delta = 0.74 \pm 0.11 \pm 0.16$

hard

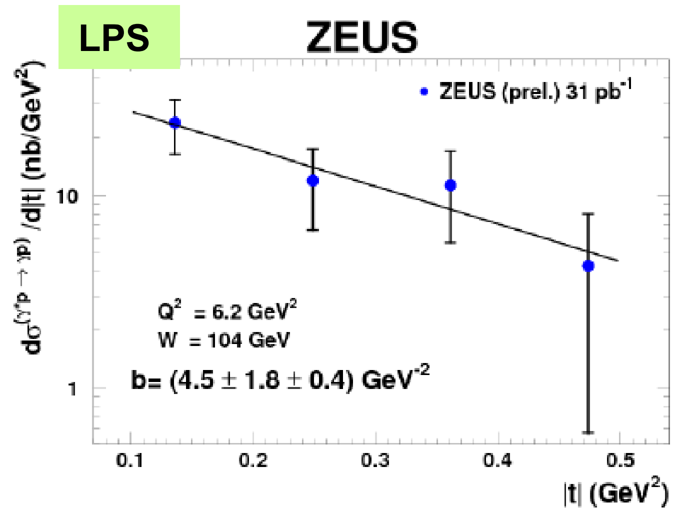
DVCS – *t* slope



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

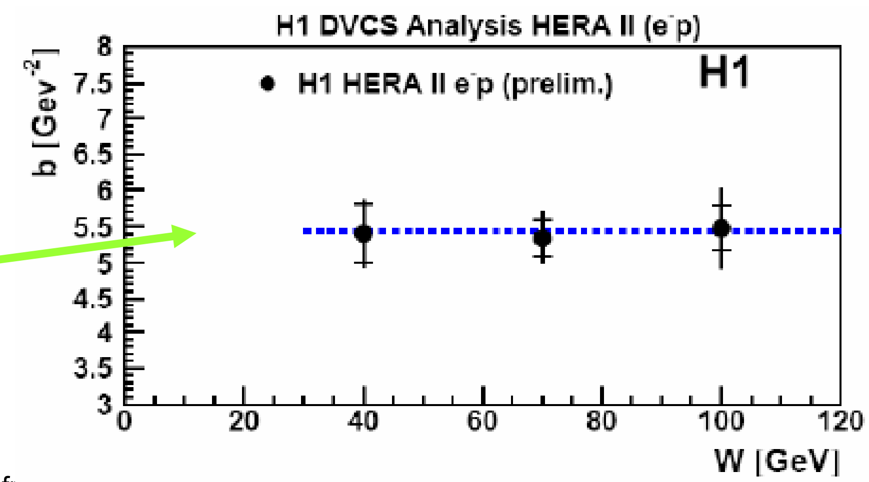
=> $\sqrt{\langle r_T^2 \rangle}$=0.65 fm

>> valence quarks value



slope not soft, but steeper than J/Ψ ?

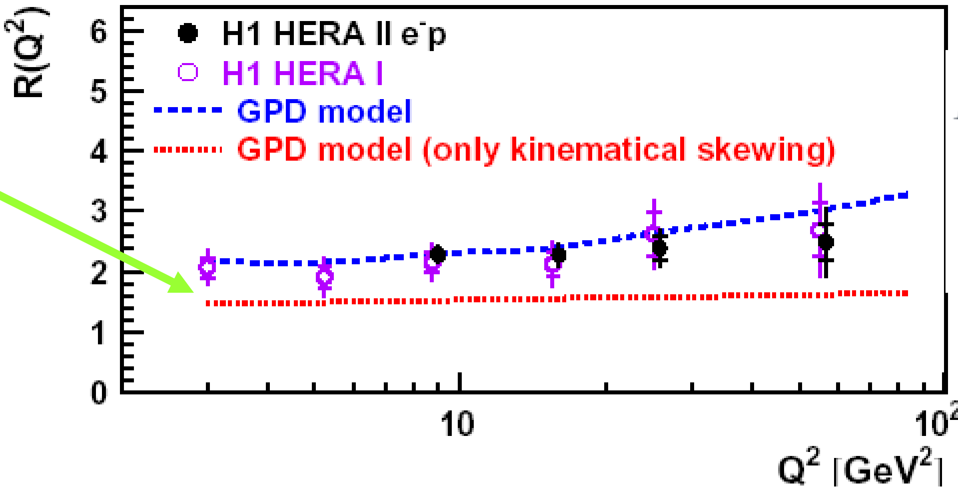
No shrinkage observed



DVCS – models

GPD

kin. skewing
not sufficient

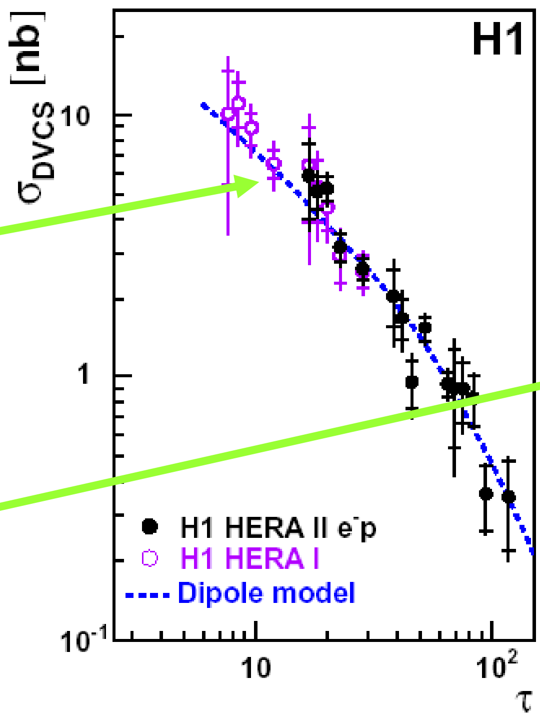


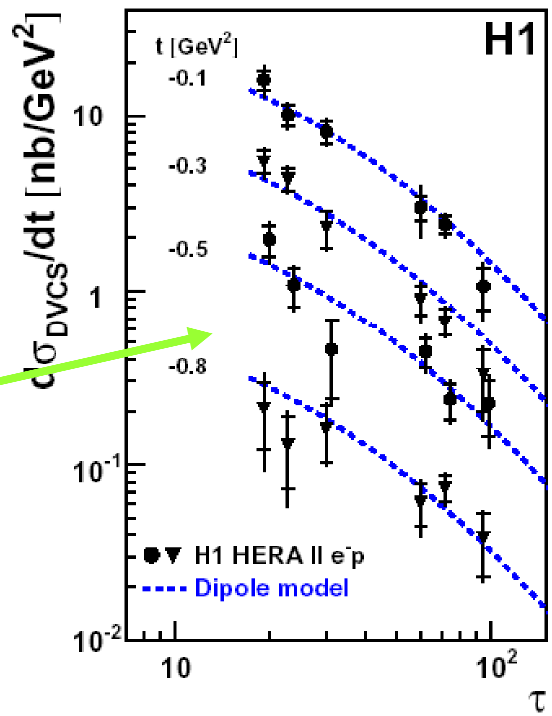
$$R = \frac{\mathcal{I}m\ A(\gamma^* p \to \gamma p)}{\mathcal{I}m\ A(\gamma^* p \to \gamma^* p)} = \frac{4\sqrt{\pi\ \sigma_{DVCS}\ b(Q^2)}}{\sigma_T(\gamma^* p \to X)\ \sqrt{(1+\rho^2)}}$$

Dipoles + geom. scaling

good description

no indication of *t* dependence
in saturation scale





III.2 From soft to hard : Q^2

ρ and ϕ

ρ and ϕ, elastic and p. dissoc.

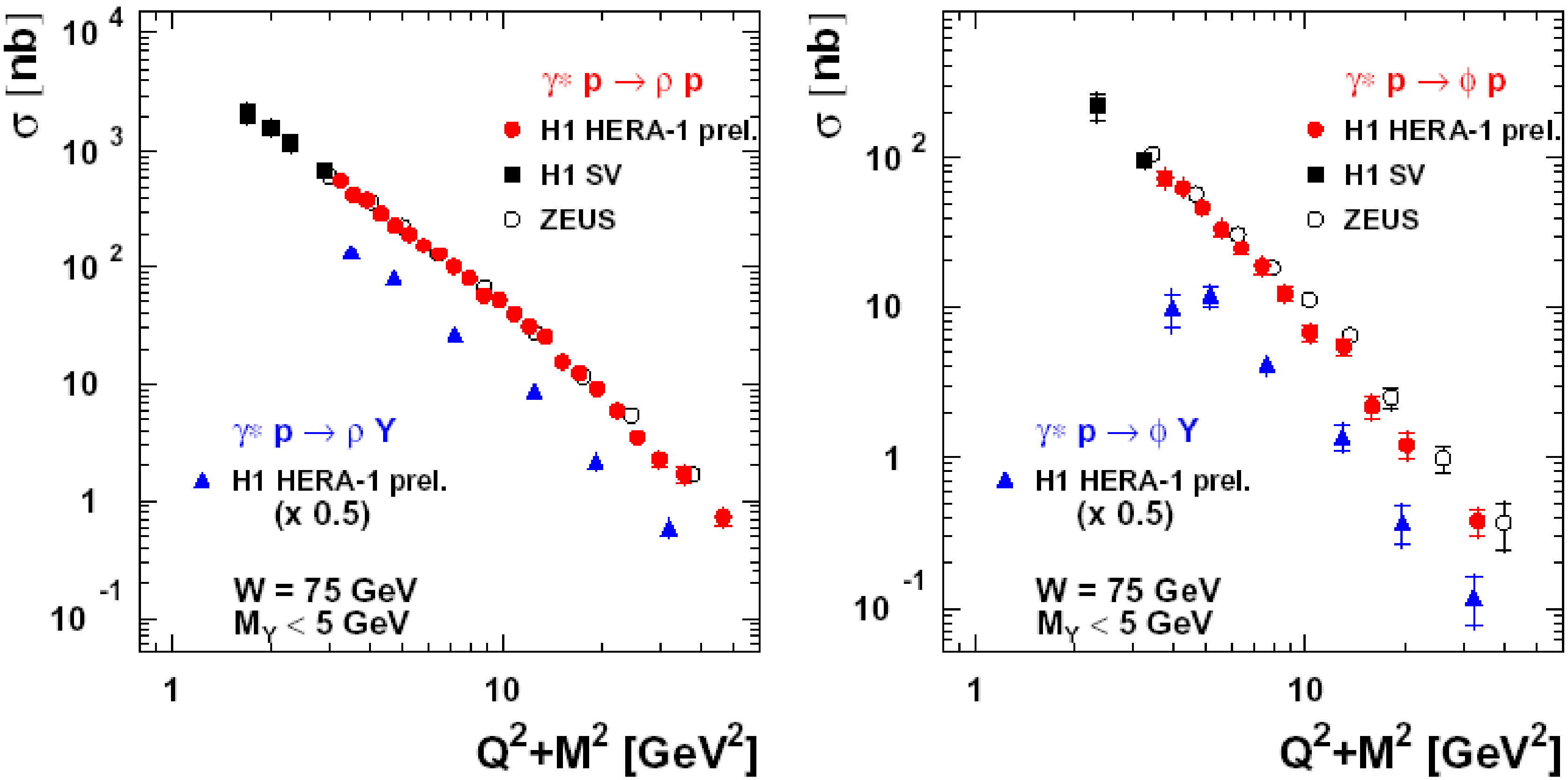
H1 and ZEUS HERA-1

large data sets

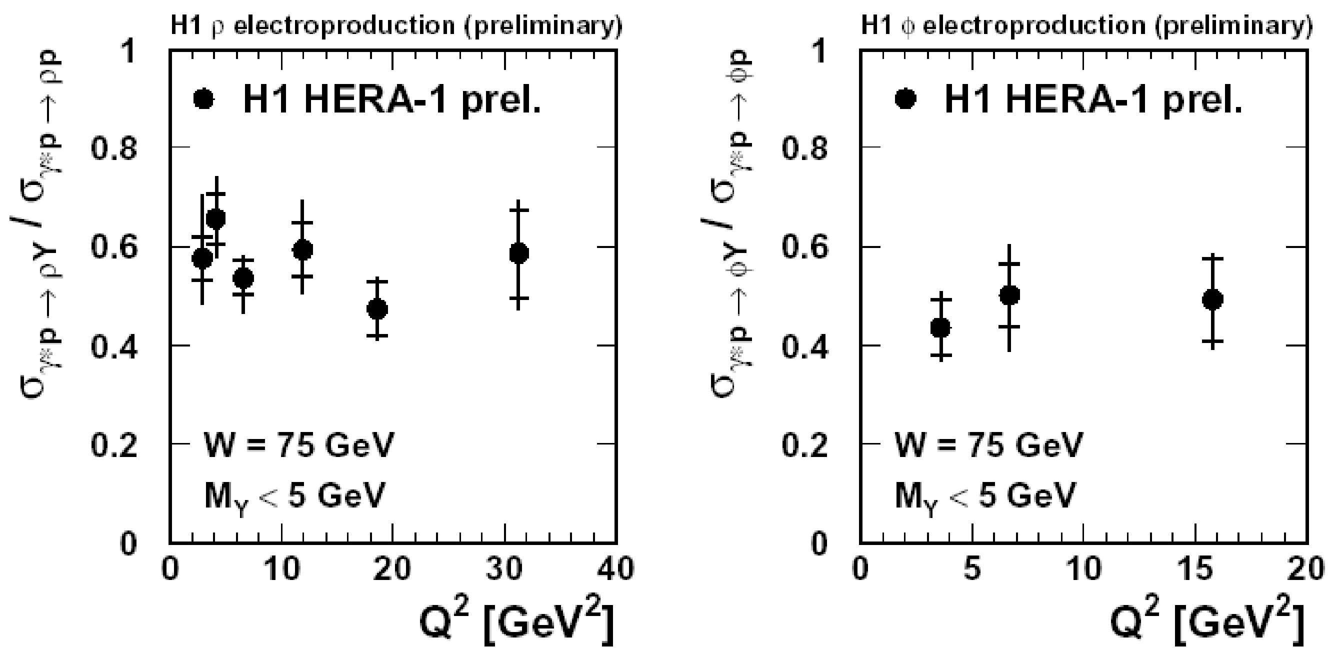
transition region $1.5 < Q^2 < 50$ GeV^2 (+ ZEUS $0.3 < Q^2 < 1$ GeV^2)

Q^2, W, t measurements

helicity amplitudes (15 SDME + kin. dependences)



ρ and φ, proton vertex factorisation



no Q^2 dependence ($Q^2 > 2.5$ GeV^2)

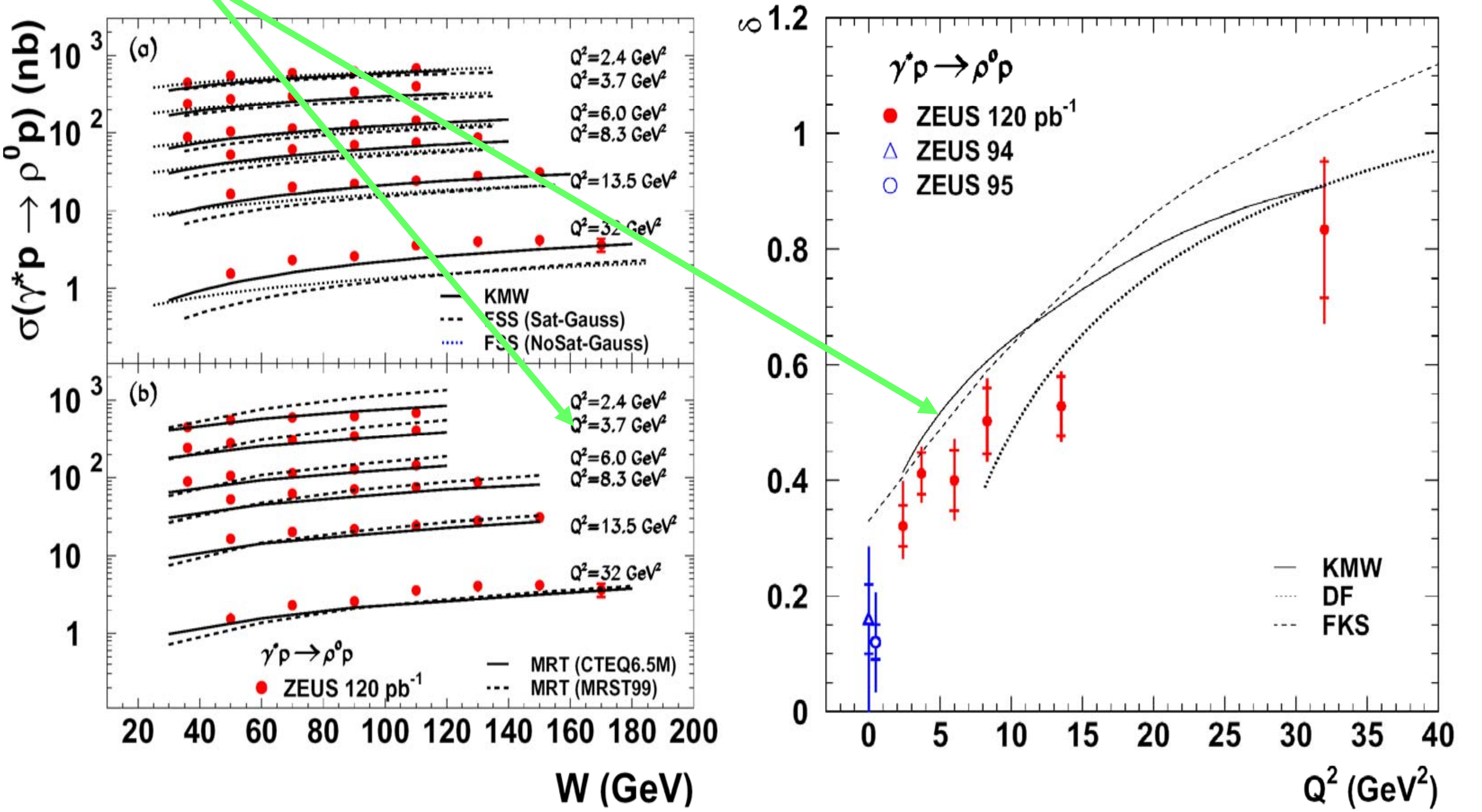
of proton dissociation ($M_Y < 5$ GeV) / elastic cross section ratio

(also t slopes ratios indep. of Q^2

matrix elements compatible for elastic and p. dissoc.)

ρ, *W* dependence

hardening of *W* dependence with Q^2

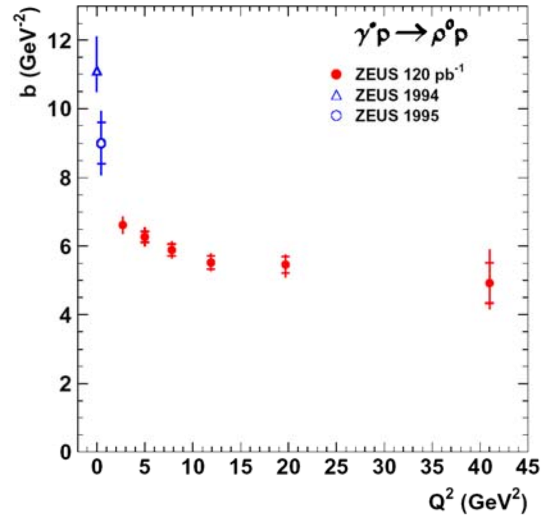


some sensitivity to pdf (MRT) – dipole + sat. preferred – no model perfect

ρ, *t* dependence

t dependence

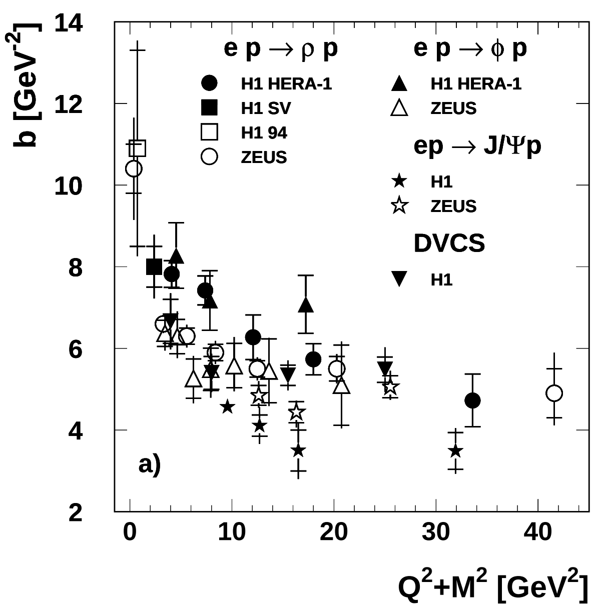
hardening with Q^2



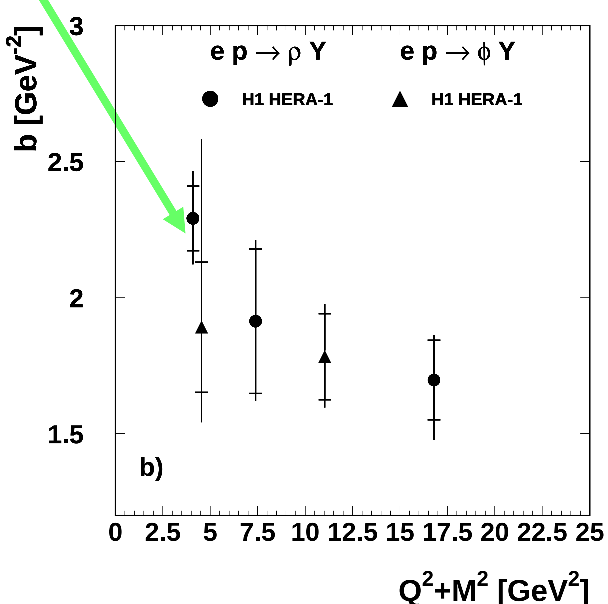
ZEUS HERA-1

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

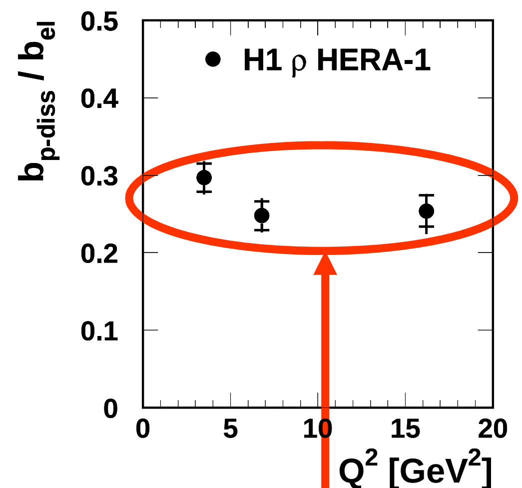
H1 HERA-1



elastic

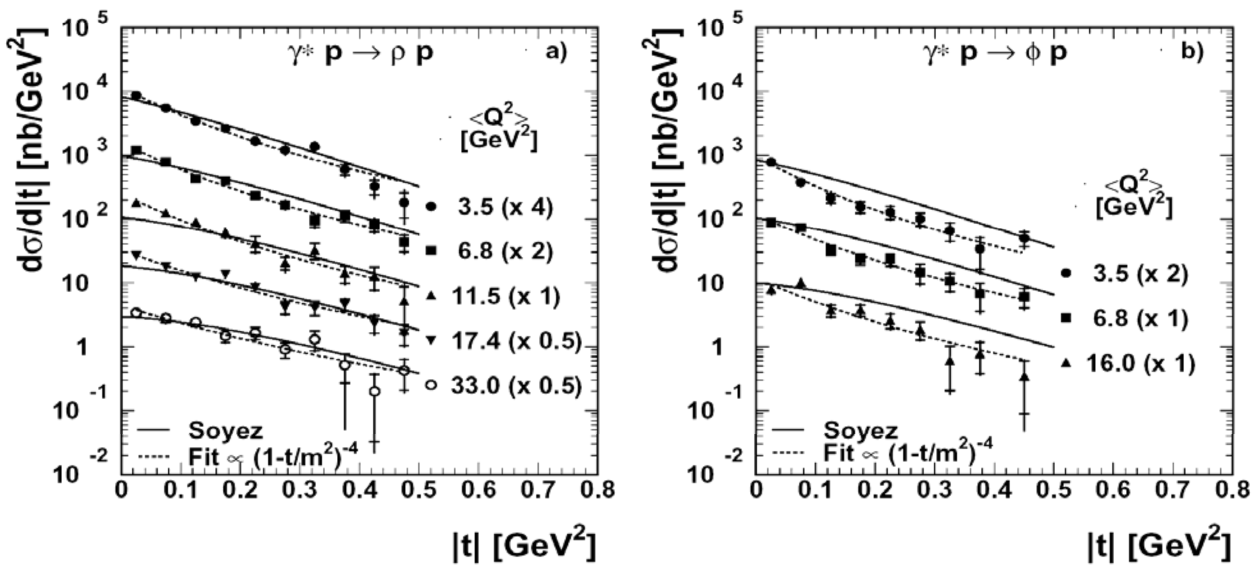


proton dissociation



ratio constant

ρ, *t* dependence



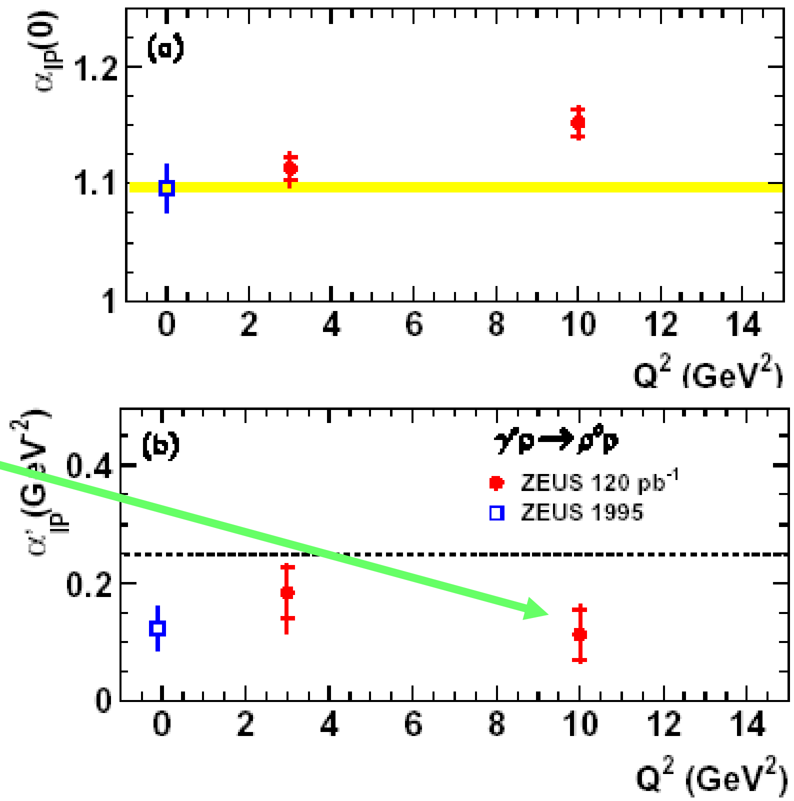
dipole + saturation

t dependent sat. scale

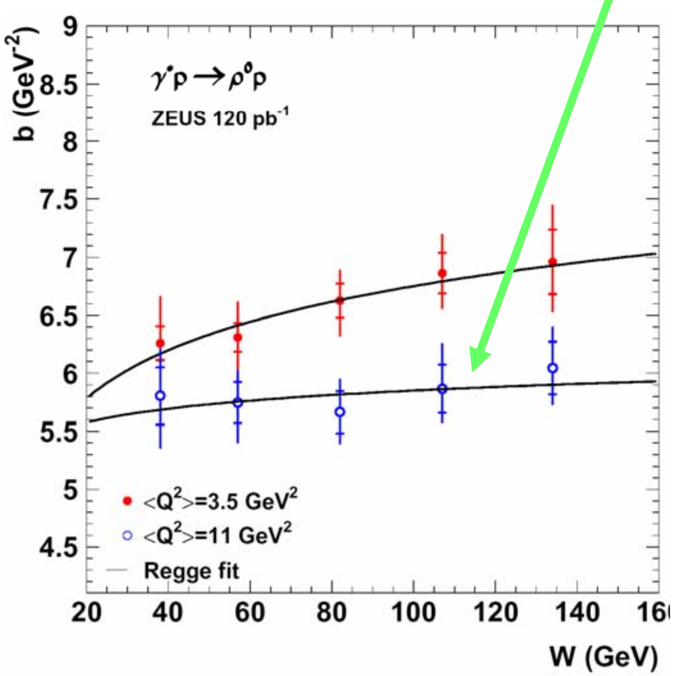
trend OK but not in detai

ρ, trajectory

intercept α(0) hardening with Q^2

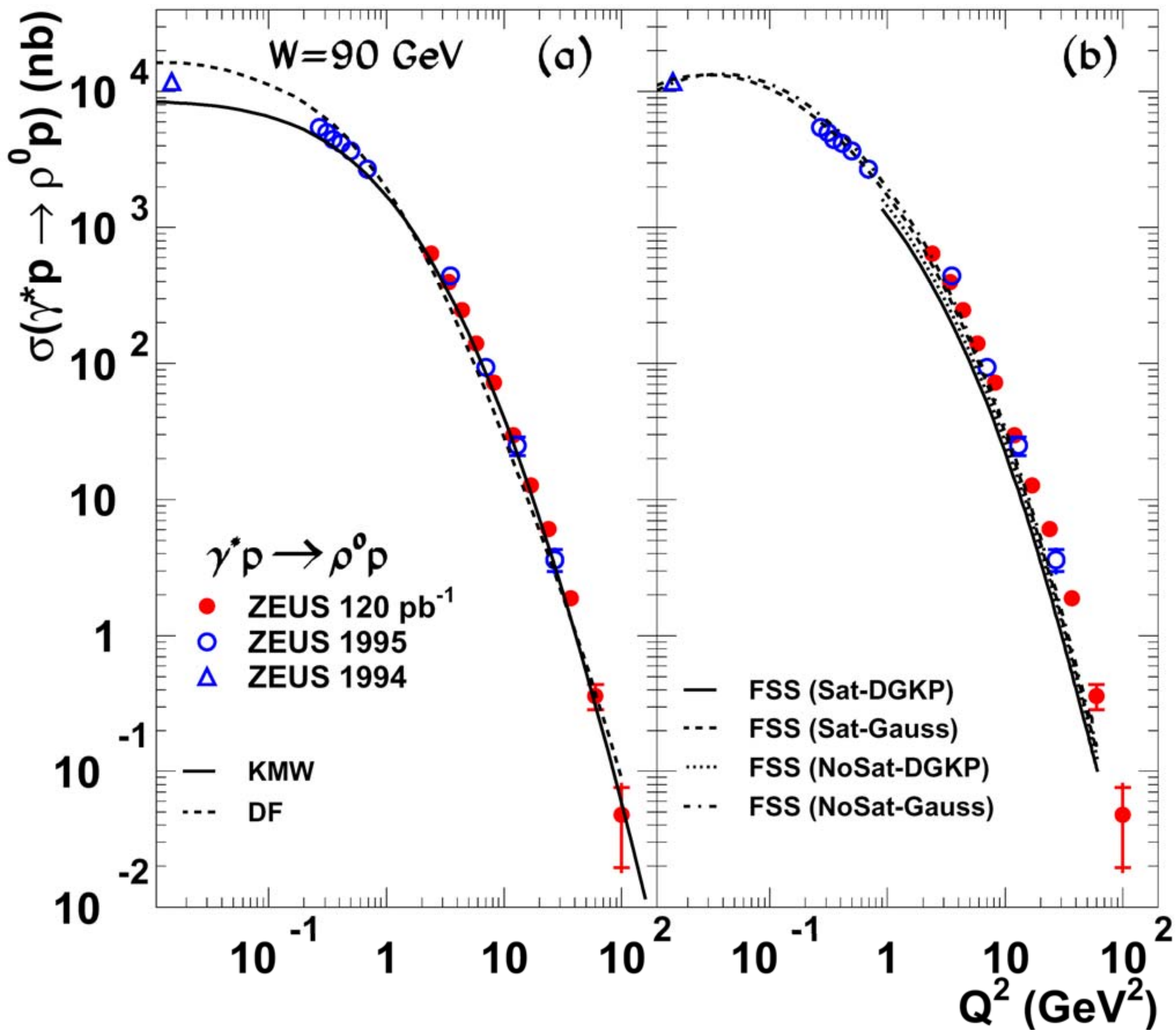


slope α' smaller than h-h, indication for decrease with Q^2 (but similar to photoprod.)



ρ, dσ/dQ²

ZEUS HERA-1



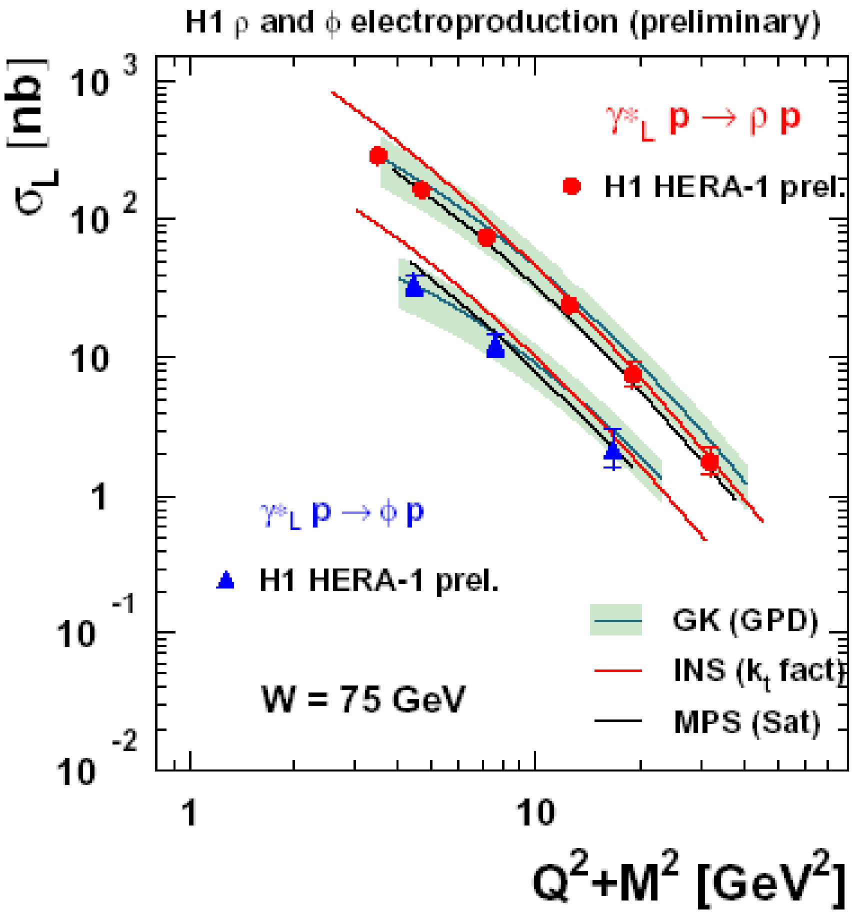
dipoles models

-> low Q2

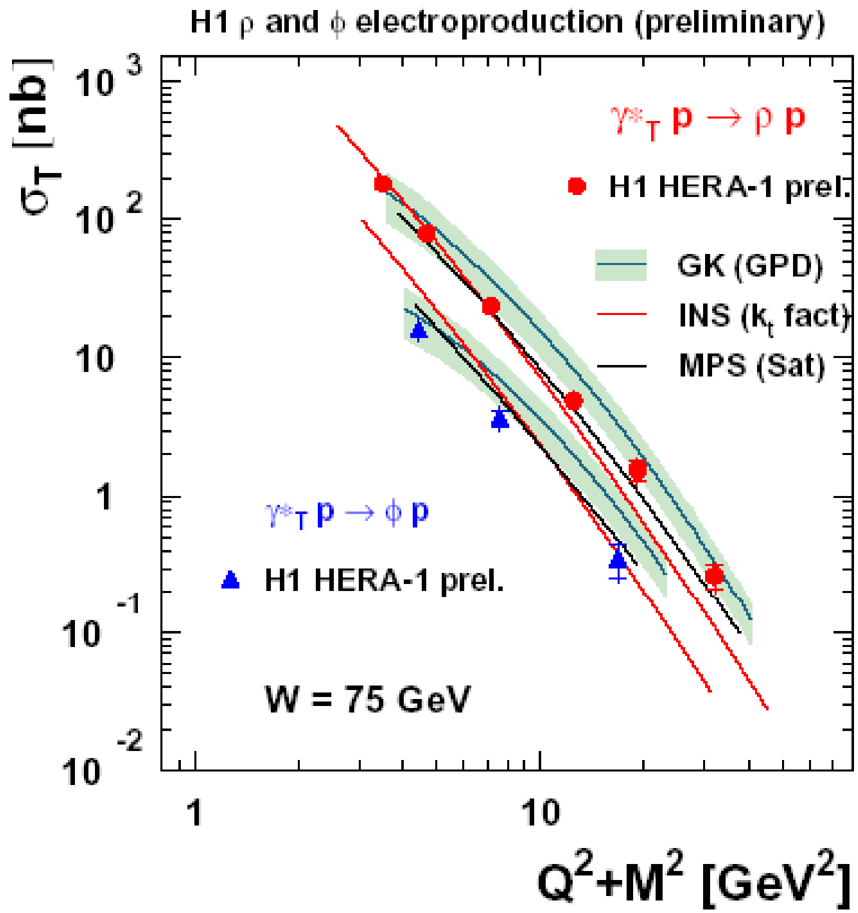
-> (some) WF sensitivity

ρ and ϕ, $d\sigma/dQ^2$ polarised cross sections

Longitudinal



Transverse



both for σ_L and σ_T

GPD OK for ρ – less for ϕ

k_t fact., dipole + saturation **too steep**

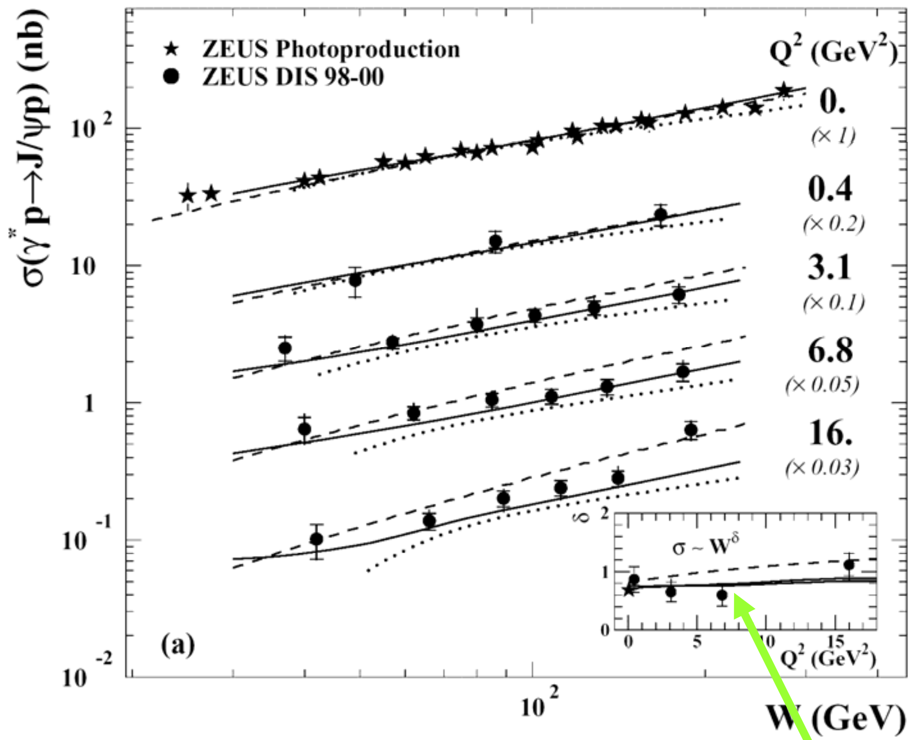
III.3 From soft to hard : Q^2
J/Ψ

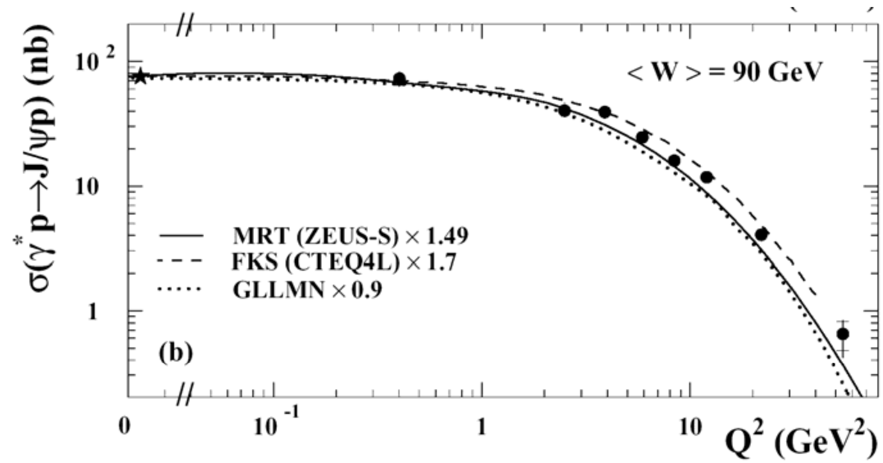
J/Ψ, *W* dependence

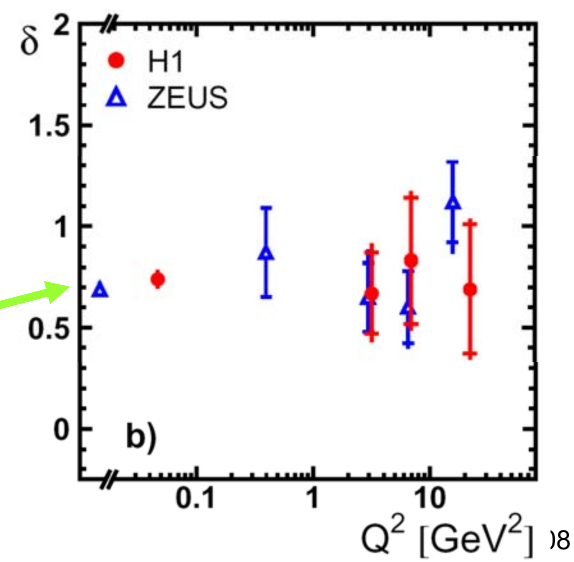
J/Ψ hard in photoproduction

With Q^2, second hard scale

-> predictions of $d\sigma/dQ^2$, *W* dep.





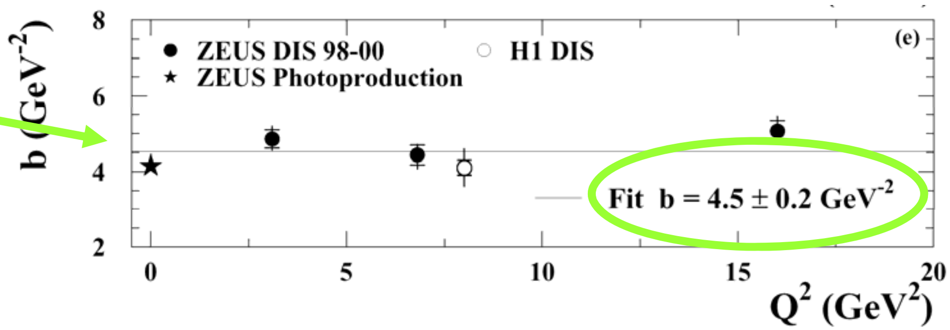


hard ($\alpha(0) = 1.20$), indep. of Q^2

J/Ψ, *t* dependence, shrinkage

t slope

- ZEUS : no **Q^2 dependence**

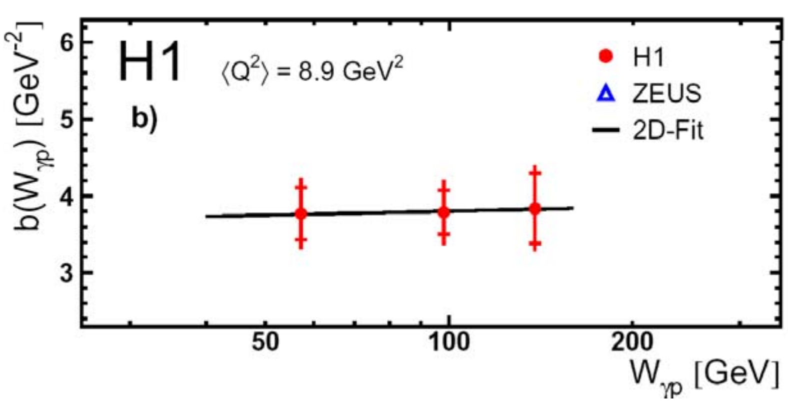


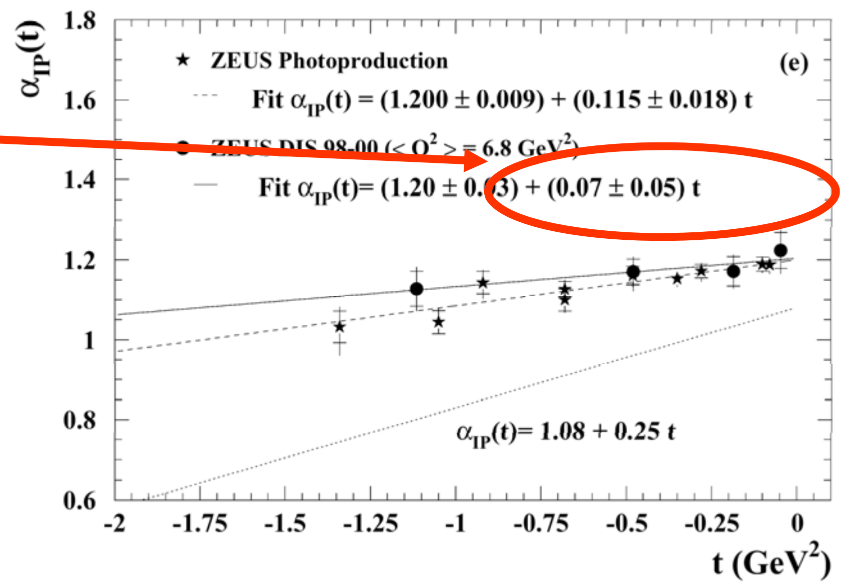
- H1 : slightly smaller in DIS

Q^2 [GeV^2]	b_0 [GeV^{-2}]	α_0	α' [GeV^{-2}]
$\lesssim 1$	$4.630 \pm 0.060^{+0.043}_{-0.163}$	$1.224 \pm 0.010 \pm 0.012$	$0.164 \pm 0.028 \pm 0.030$
$2-80$	$3.86 \pm 0.13 \pm 0.31$	$1.183 \pm 0.054 \pm 0.030$	$0.019 \pm 0.139 \pm 0.076$

shrinkage

α' smaller in DIS, consistent with 0

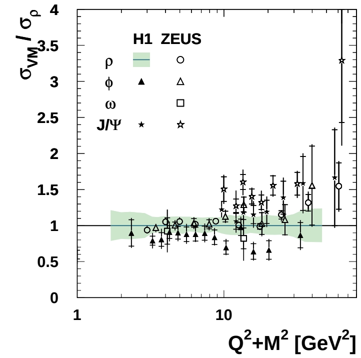




From soft to hard : Q^2

summary

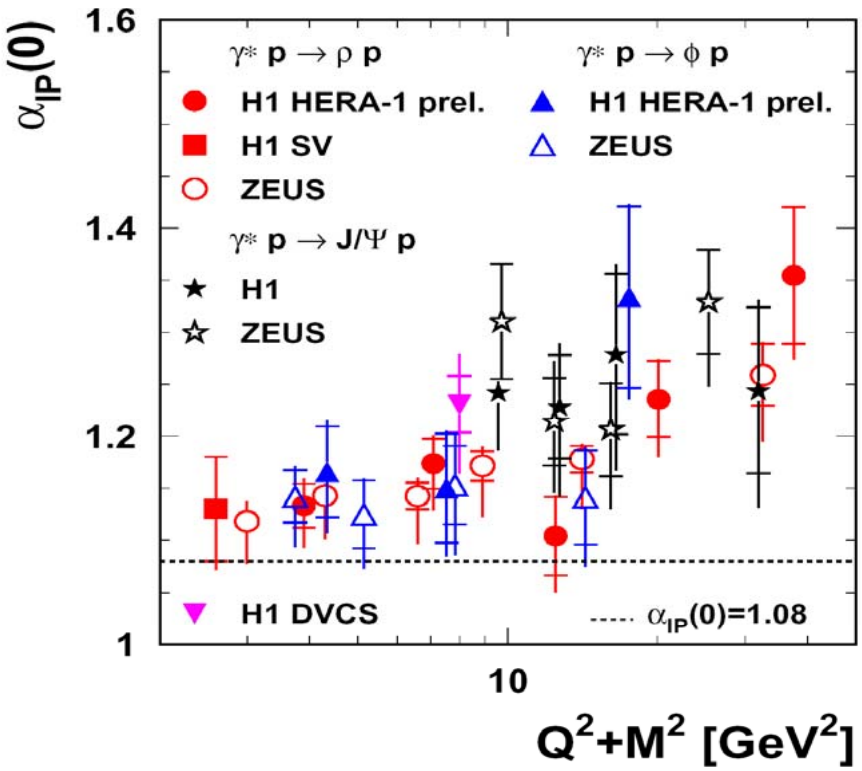
universality, onset of hard diffraction



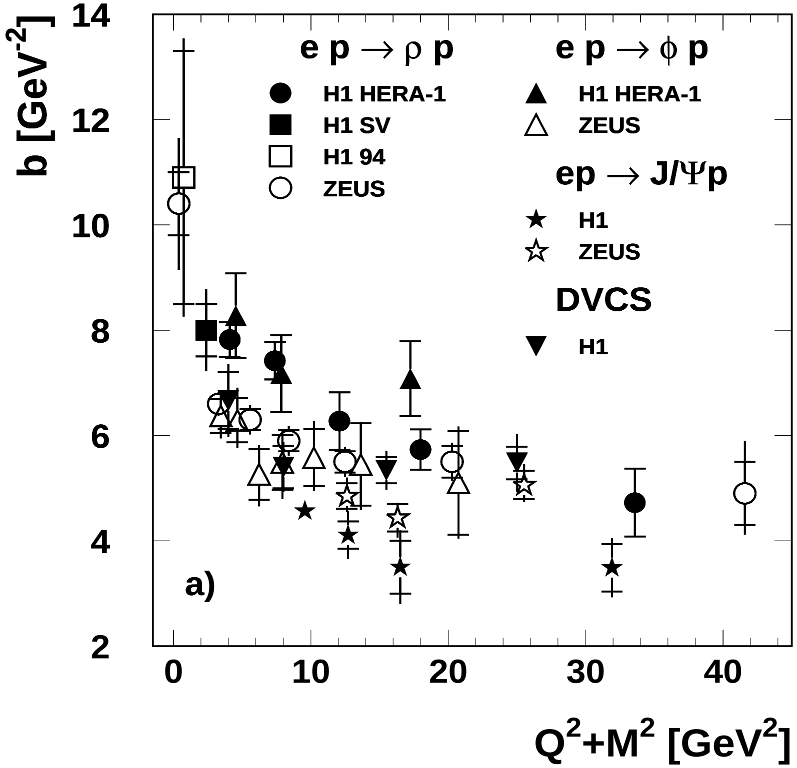
Universality ($Q^2 + M^2$) and onset of hard diffraction

(small dipoles, hard gluons)

hard energy dependences



hard *t* slopes



IV. From soft to hard : *t*

(ρ, ϕ, J/Ψ)

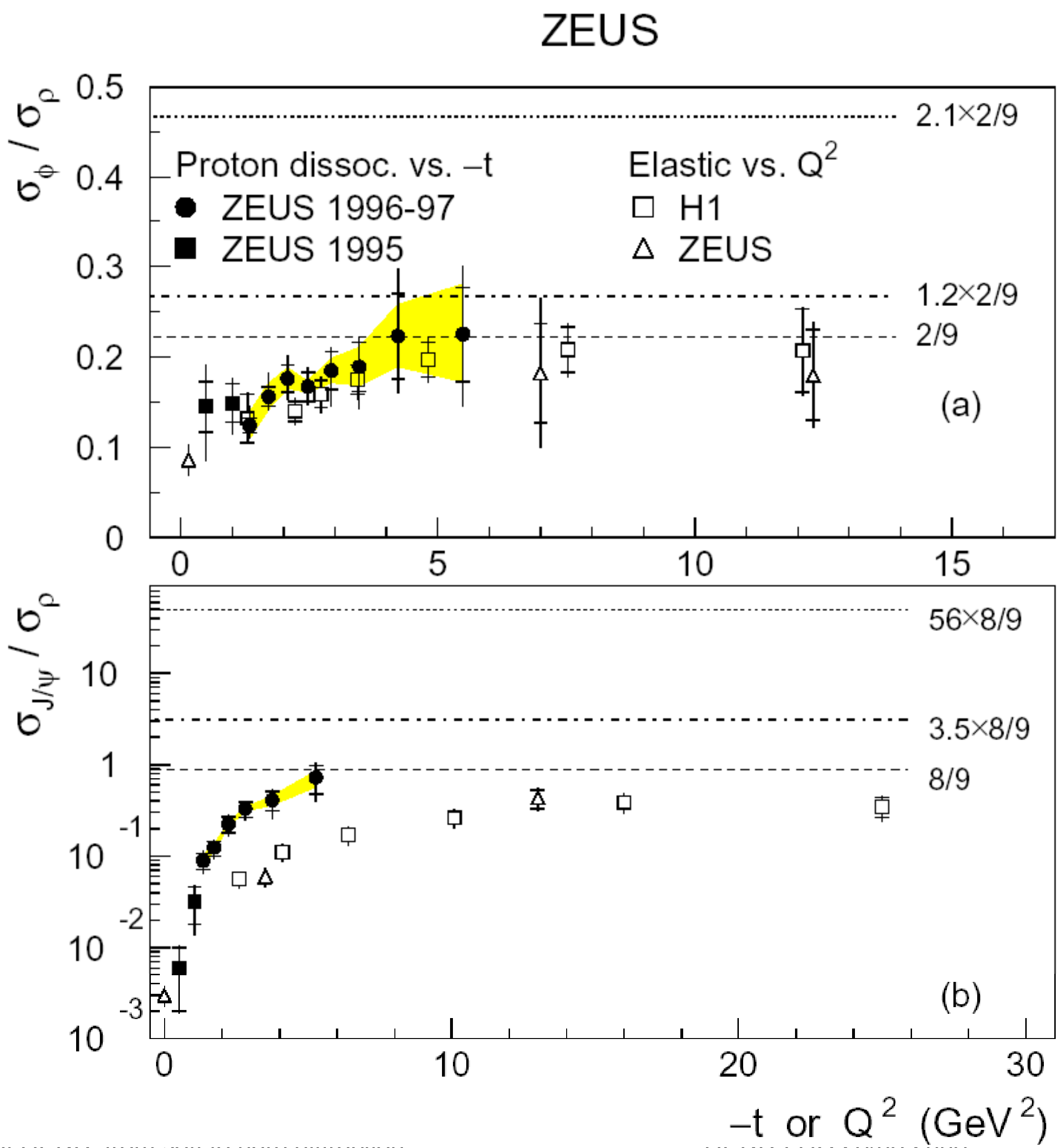
universality (*t*)
***t* dependences**
***W* dependences**

Universality (t)

Another hard scale

-> pQCD calculations

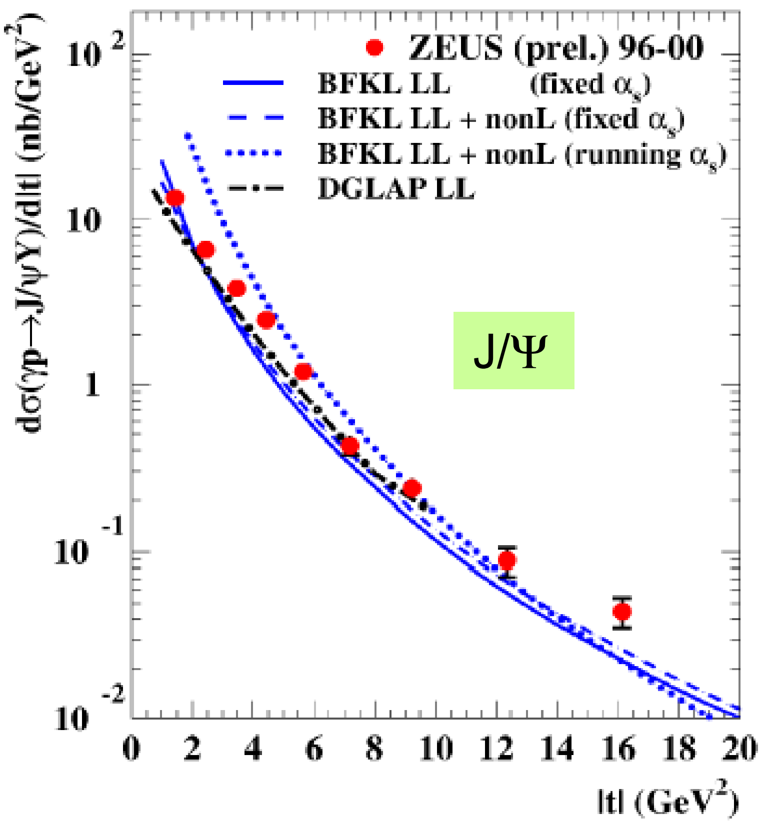
(BFKL, DGLAP)

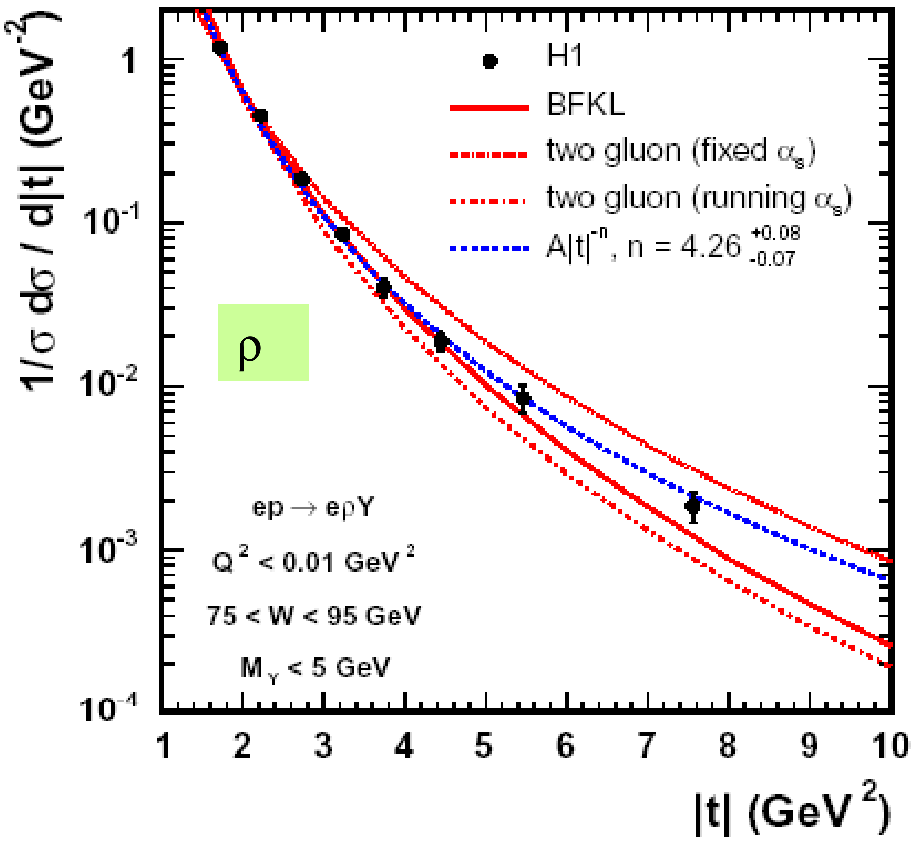


t dependences

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

pQCD calculations





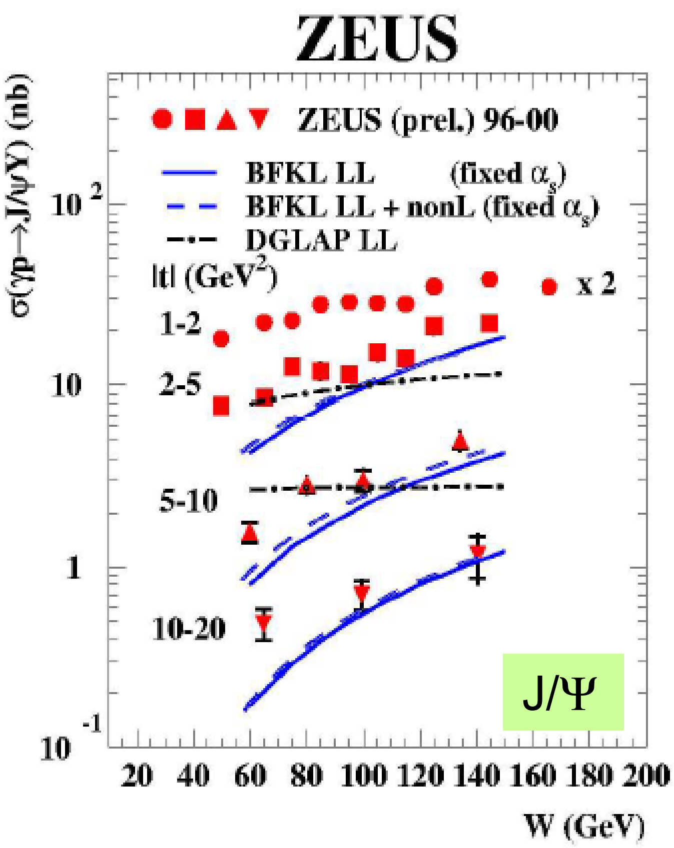
J/Ψ BFKL running α_s excluded

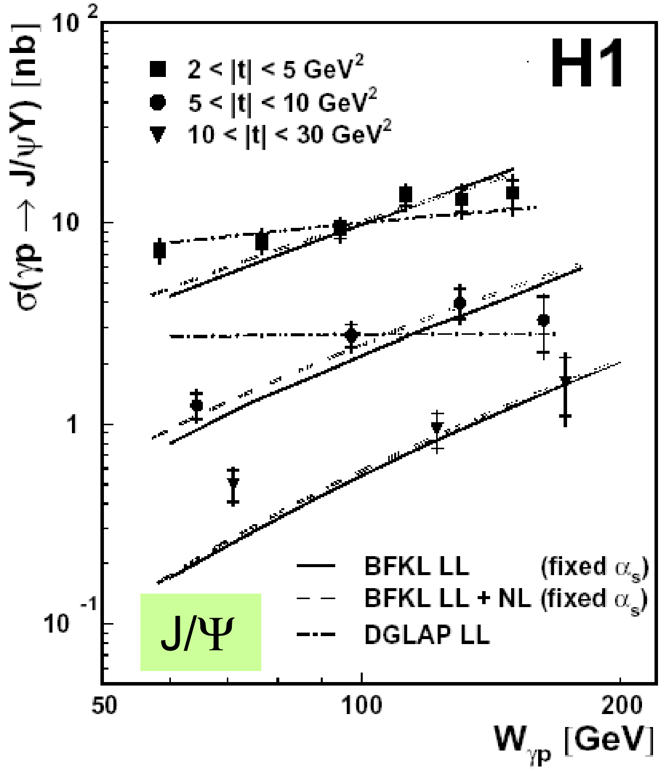
DGLAP OK ($t < M_\Psi^2$)

BFKL favoured

see also helicity below

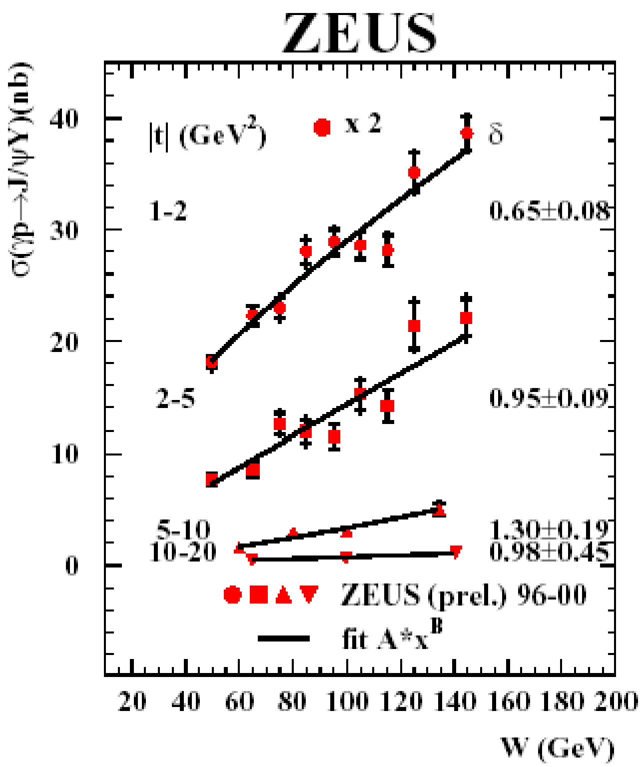
J/Ψ, *W* dependence

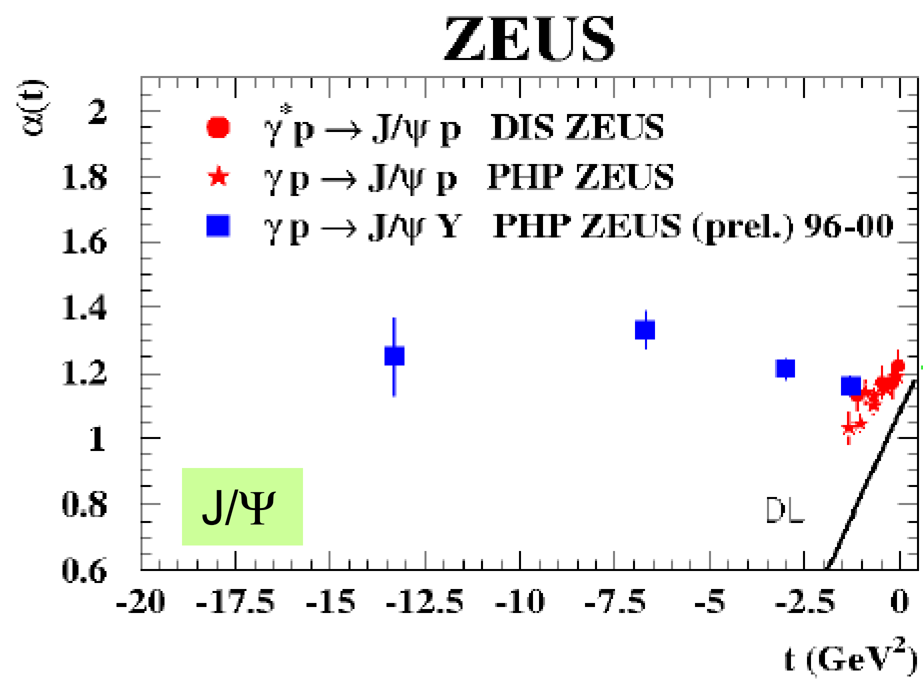




rise of σ with *W* **described by BFKL**, not by DGLAP

J/Ψ, shrinkage





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

ZEUS

$\gamma p \to J/\psi\, p$	(Eur. Phys. J. **C24**(2002)345)	$\alpha_{IP}(t) = 1.200 \pm 0.009 + (0.115 \pm 0.018)t$
$\gamma^* p \to J/\psi\, p$	(Nucl. Phys. **B695**(2004)3)	$\alpha_{IP}(t) = 1.20 \pm 0.03 + (0.07 \pm 0.05)t$
$\gamma p \to J/\psi\, Y$	(DIS2005)	$\alpha_{IP}(t) = 1.153 \pm 0.048 - (0.020 \pm 0.014)t$

H1

$$\alpha(0) = 1.167 \pm 0.048\ (\text{stat.}) \pm 0.024 (\text{syst.})$$
$$\alpha' = -0.0135 \pm 0.0074\ (\text{stat.}) \pm 0.0051\ (\text{syst.})\ \text{GeV}^{-2}$$

V. Helicity amplitudes

(Q^2, W, t, m)

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

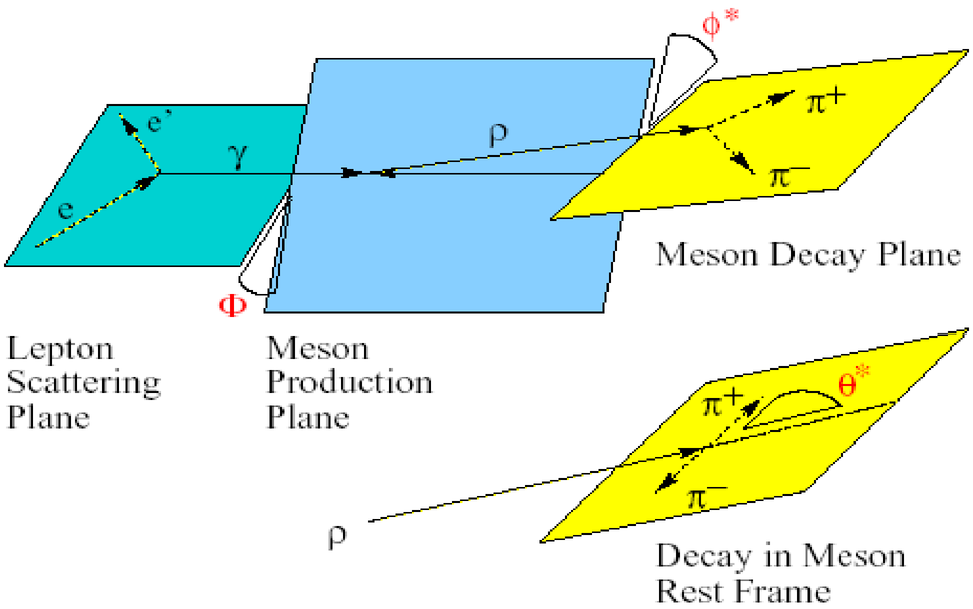
spin density matrix elements

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*)

V.1 Helicity amplitudes
ρ and φ

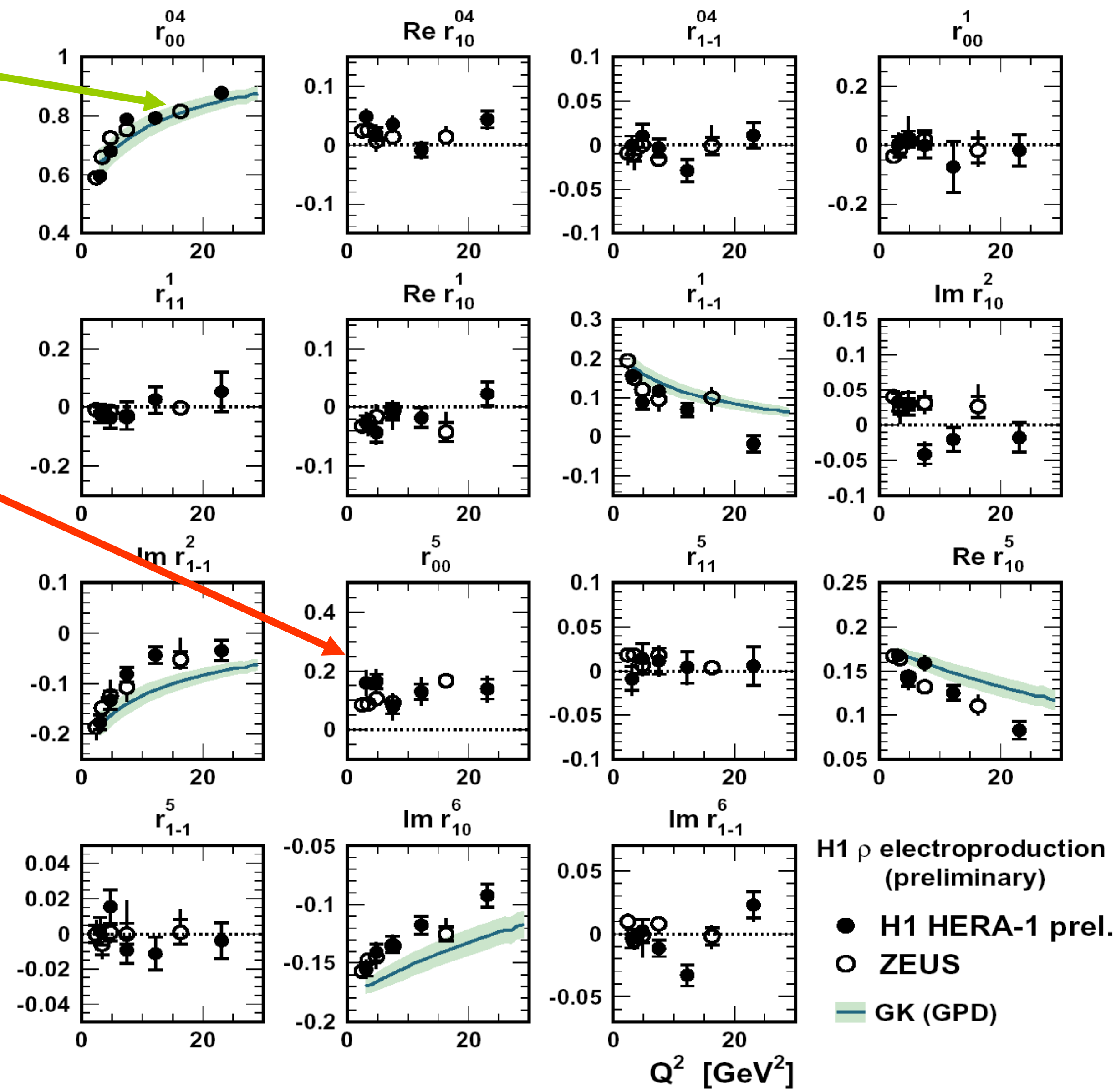
spin density matrix elements (Q^2)

5 SCHC elements

compared to GPD calculations

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

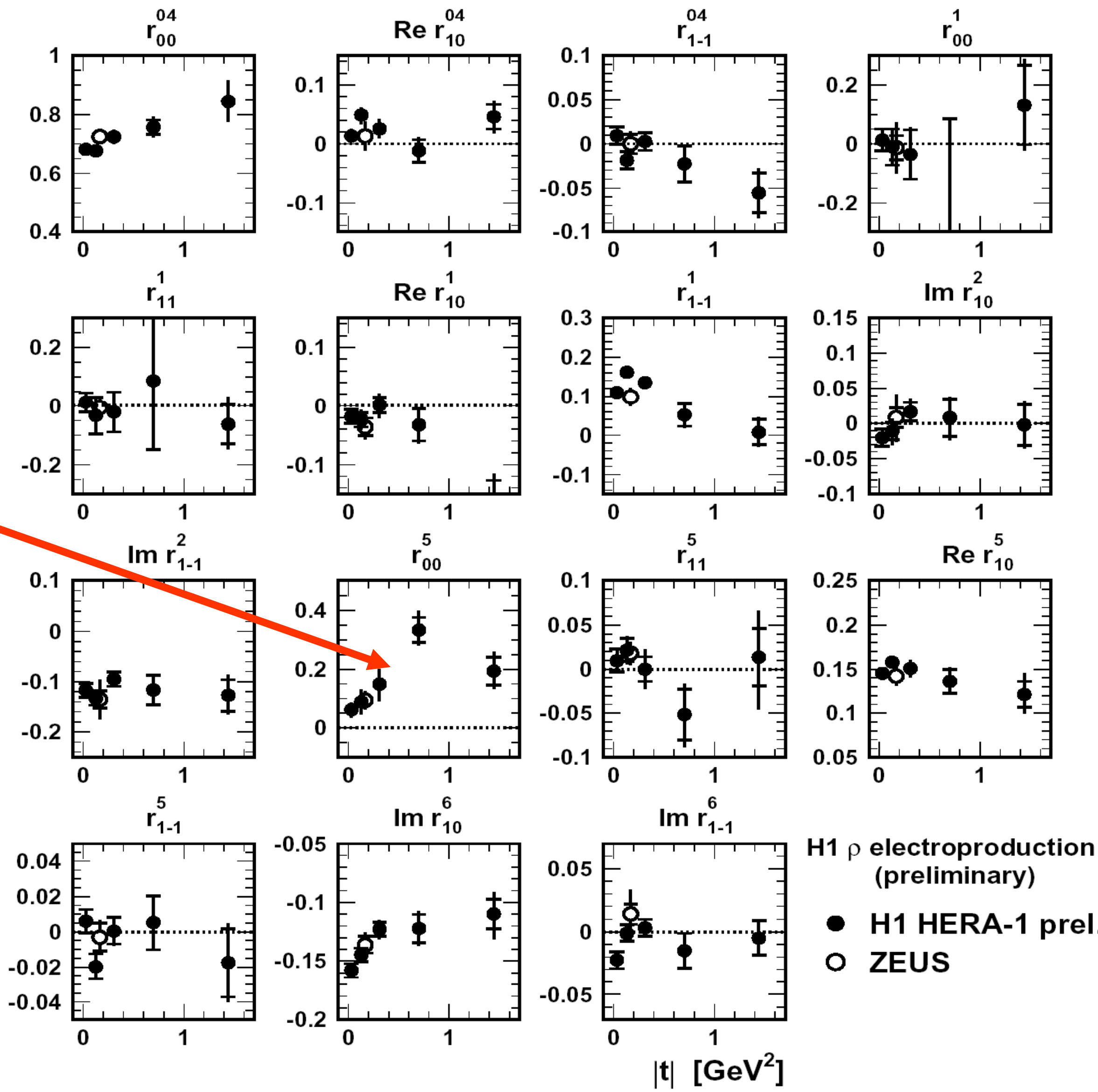
except ~ $T_{01}\, T_{00}^{*}$



several models
(GPD, unintegrated k_t,
dipole + saturation)
can reproduce
general features of
SCHC amplitudes + hierarchy
but not details

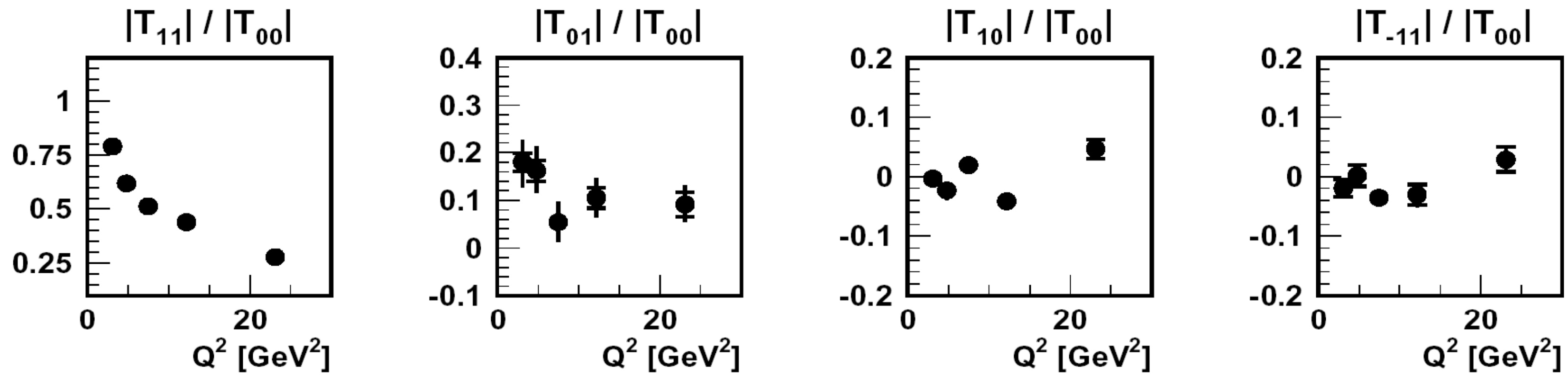
spin density matrix elements (t)

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



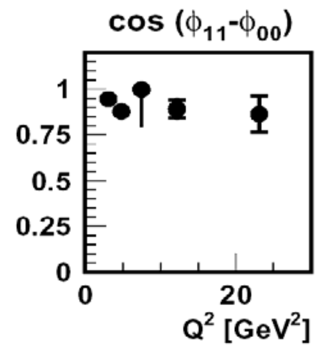
amplitudes ratios and phases

Extract **amplitude ratios** from matrix elements



pQCD predictions on ***Q*²*, t* and *M* dependences** of amplitude ratios

+ extraction of **phase** between T_{00} and T_{11}



more to come from H1 on matrix elements and amplitudes

separate low Q^2 (< 5) and high Q^2 (> 5 GeV²) **– transition region**

(finite size effects also in long. ampl.)

$R = \sigma_L / \sigma_T \ (Q^2)$

Under SCHC,

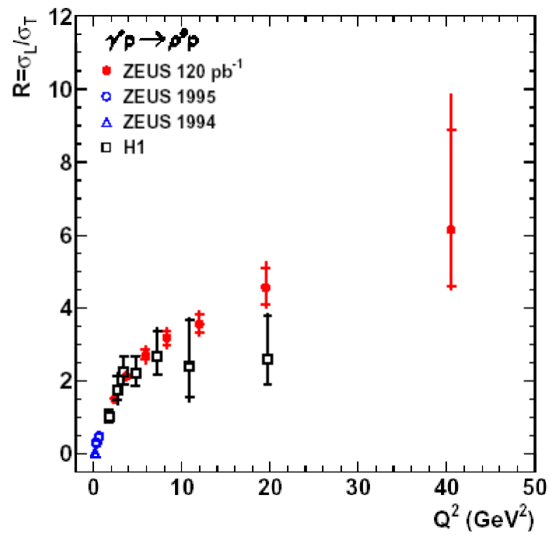
$$R = \sigma_L / \sigma_T \approx T_{00} / T_{11} \approx r^{04}_{00} / (1 - r^{04}_{00}) \qquad (\varepsilon \approx 1)$$

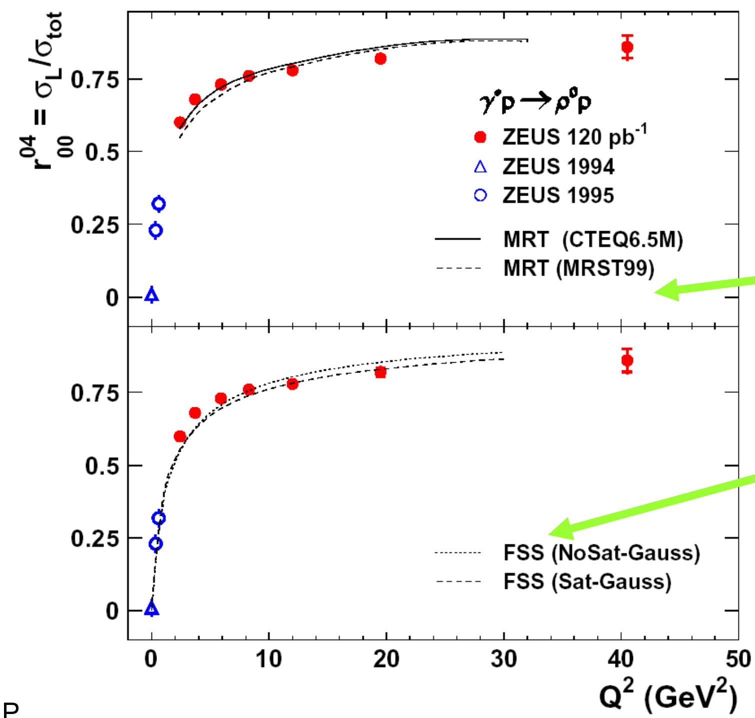
ZEUS uses the SCHC approx.

H1 takes into account hel. flip

LO 2 gluon exchange : ***R ~ Q²/ M²***

clearly **modified** !



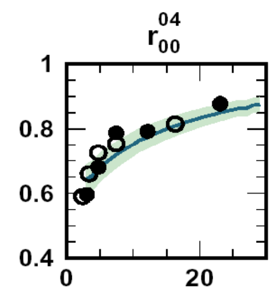


Q^2 dependence of gluons

(MRT – parton hadron duality)

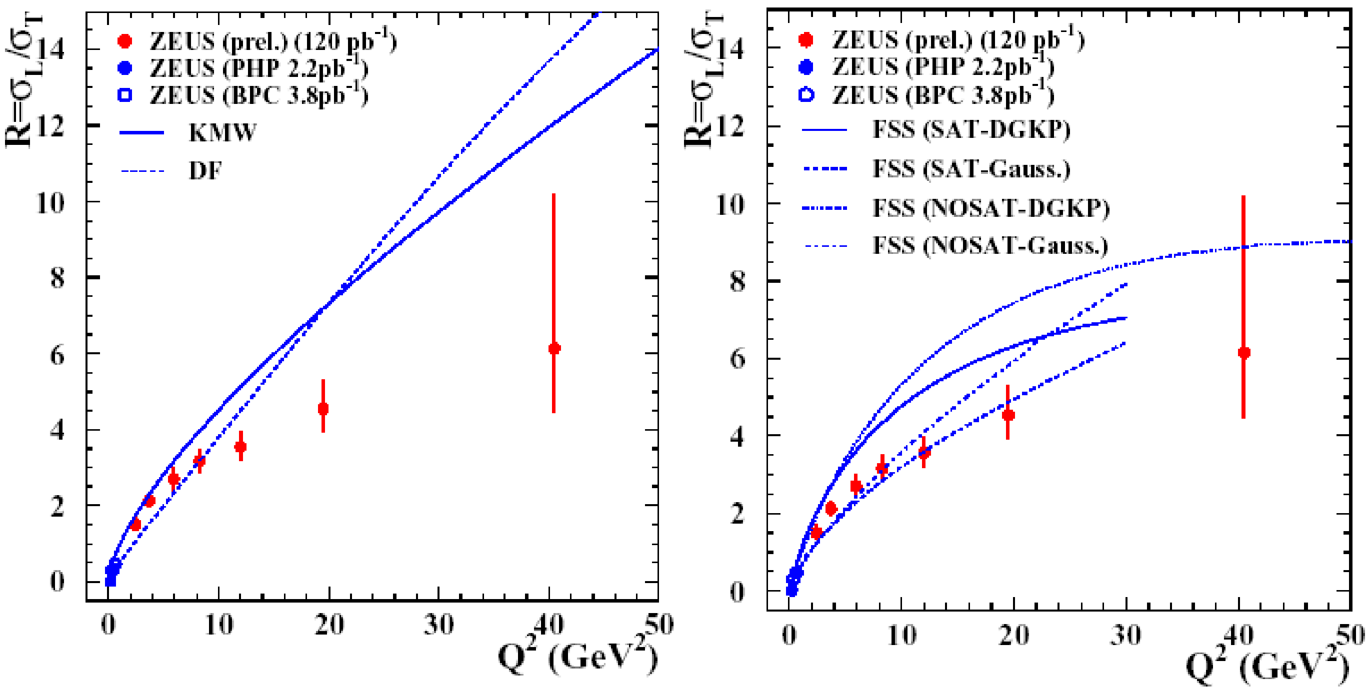
dipole + saturation

H1 : also GPD



$R = \sigma_L / \sigma_T$ (Q^2)

variety of dipole approaches

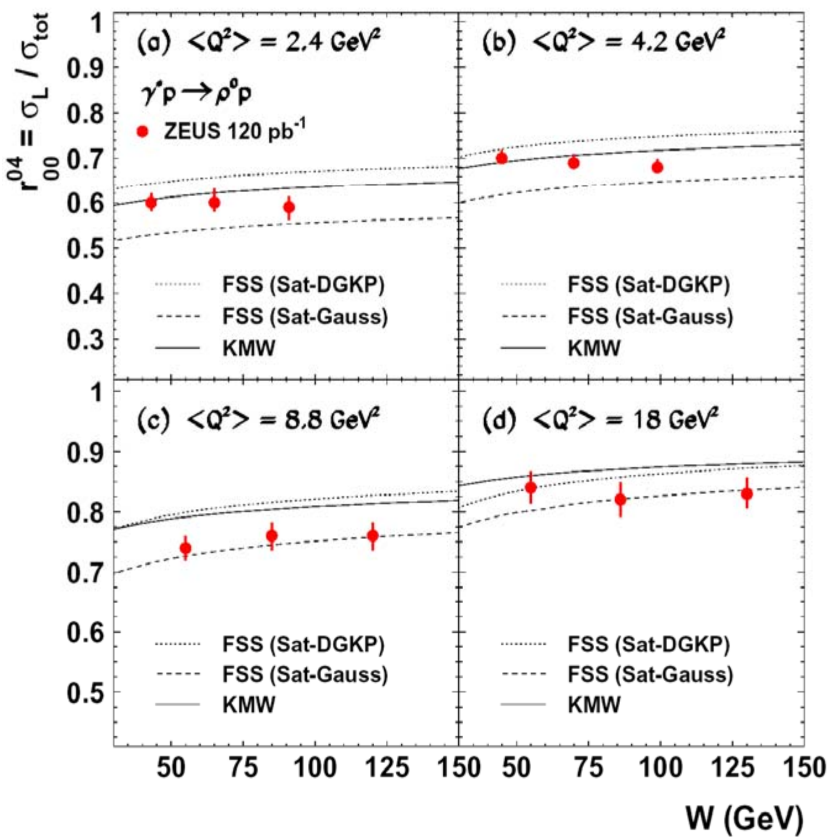


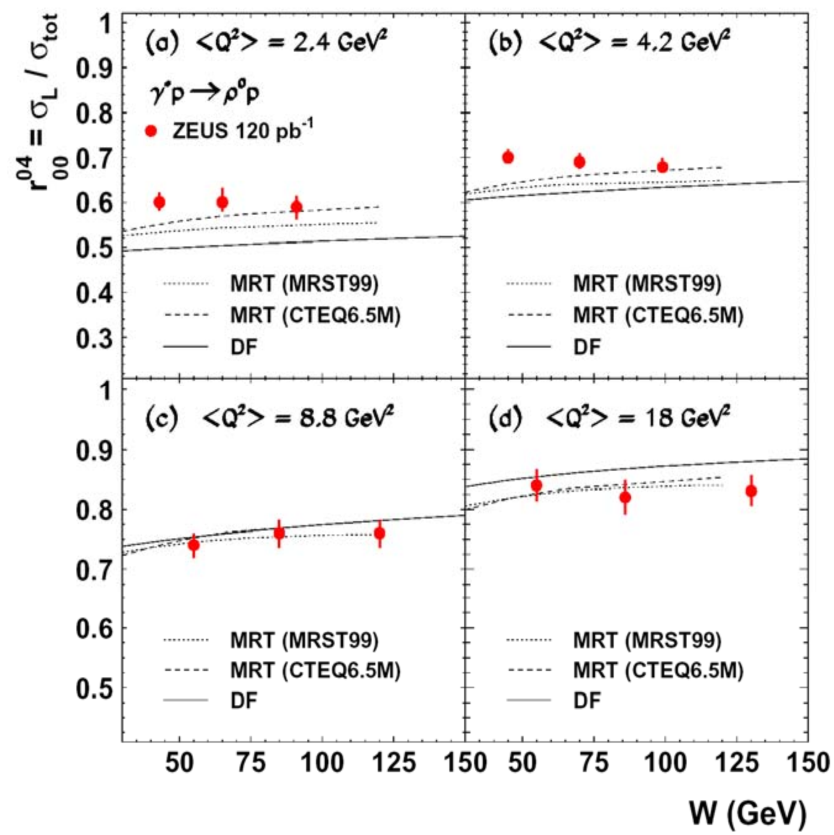
$R = \sigma_L / \sigma_T$ (W)

W* dependence of *R expected :

more large, soft dipoles for σ_T than σ_L => **σ_L harder than σ_T**

- predicted by most models (but problems with Q^2 absolute normalisations)
- **not seen** in data (but limited lever arm)





NB phase between T_{00} and T_{11} , i.e. different Re contributions

possibly related to **different *W* dependences** through dispersion relations

$R = \sigma_L / \sigma_T$ (t, m)

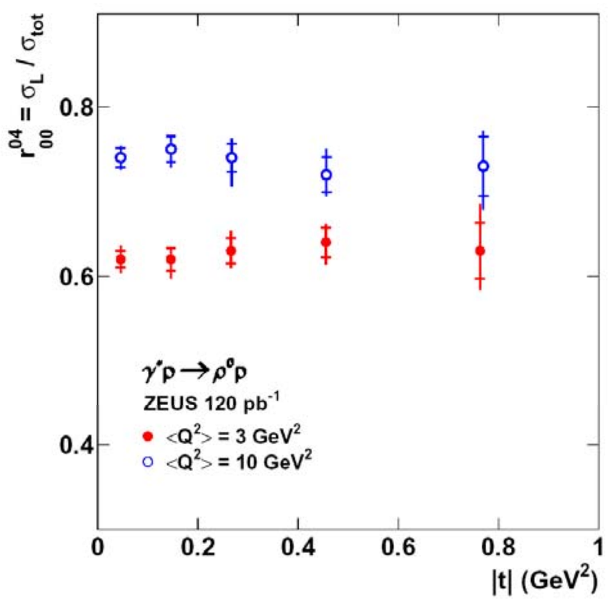
t* dependence of *R expected in dipole approach

transverse dipoles larger than longitudinal dipoles

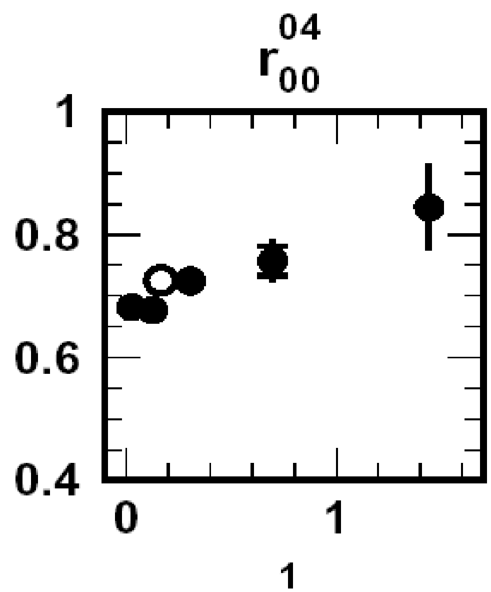
→ b_T **steeper than** b_L

→ R should increase with *t*

ZEUS : no t dependence of r^{04}_{00}

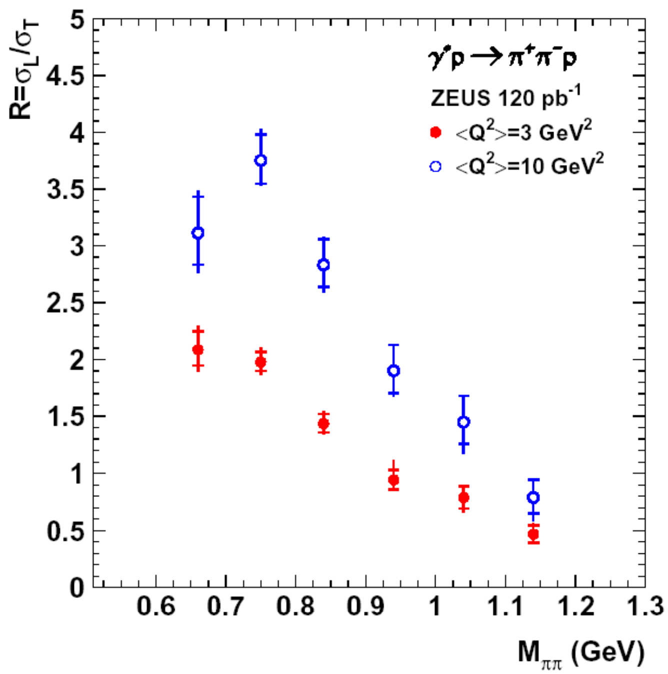


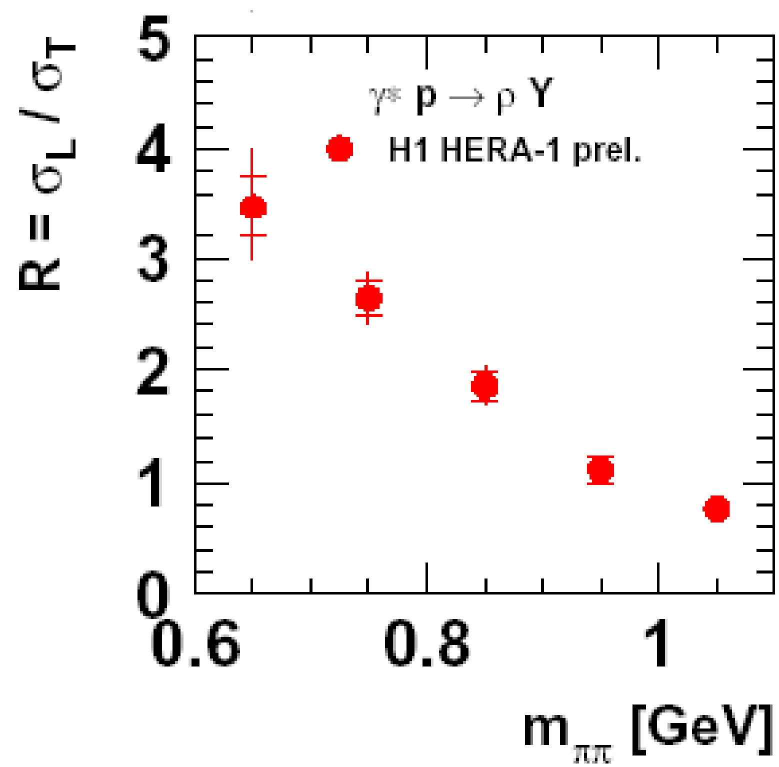
but H1



More to come from H1,
including effects on SCHC violation

ρ, $R = \sigma_L / \sigma_T$ (m)





cf. generic Q^2 / M^2 expected dependence

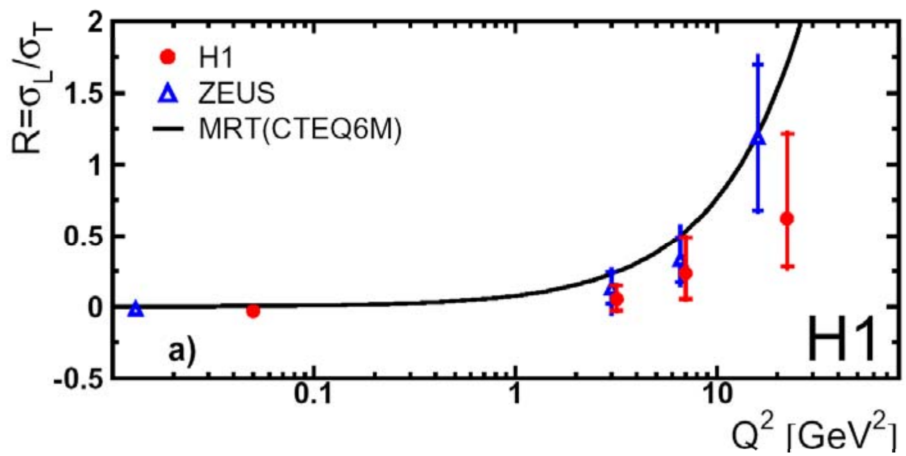
+ effect à la parton – hadron duality (i.e. weak effect of the resonance) ?

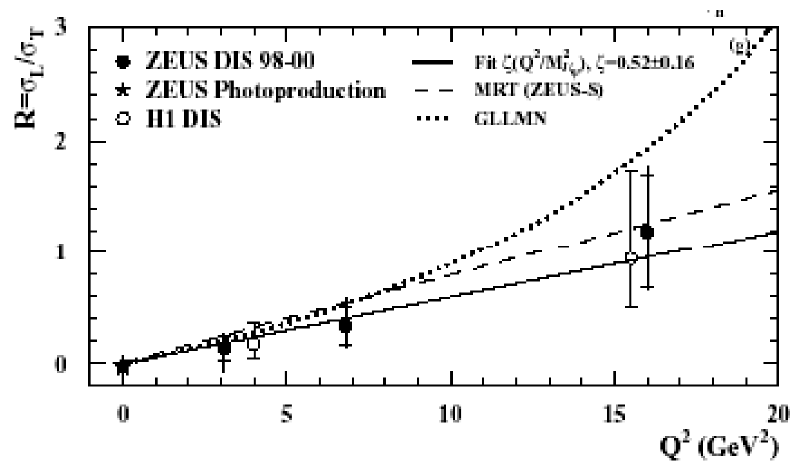
V.2 Helicity amplitudes
J/Ψ

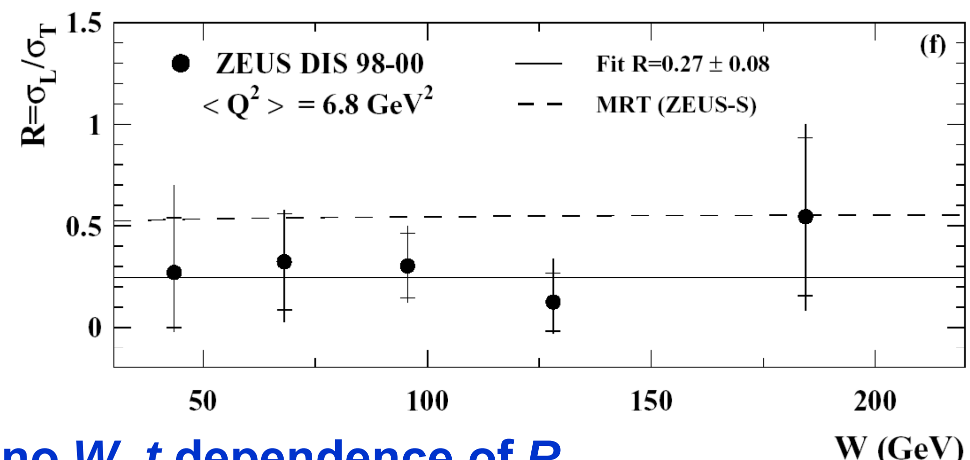
$R = \sigma_L / \sigma_T$

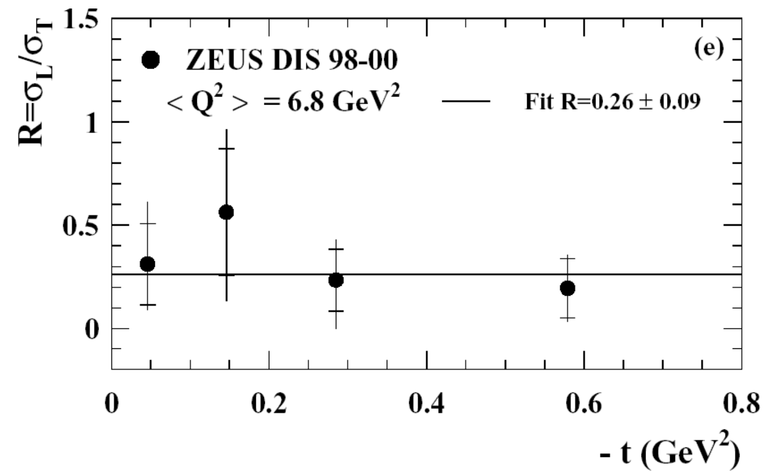
non-relativistic model for J/Ψ : $z \sim 1/2 \longrightarrow$ **no helicity flip**

basic scale for R given by $R \sim Q^2 / M^2 \longrightarrow$ much slower increase of R with Q^2 than for ρ, ϕ









no W, t dependence of R

V.3 Helicity amplitudes large |*t*|, ρ and J/Ψ

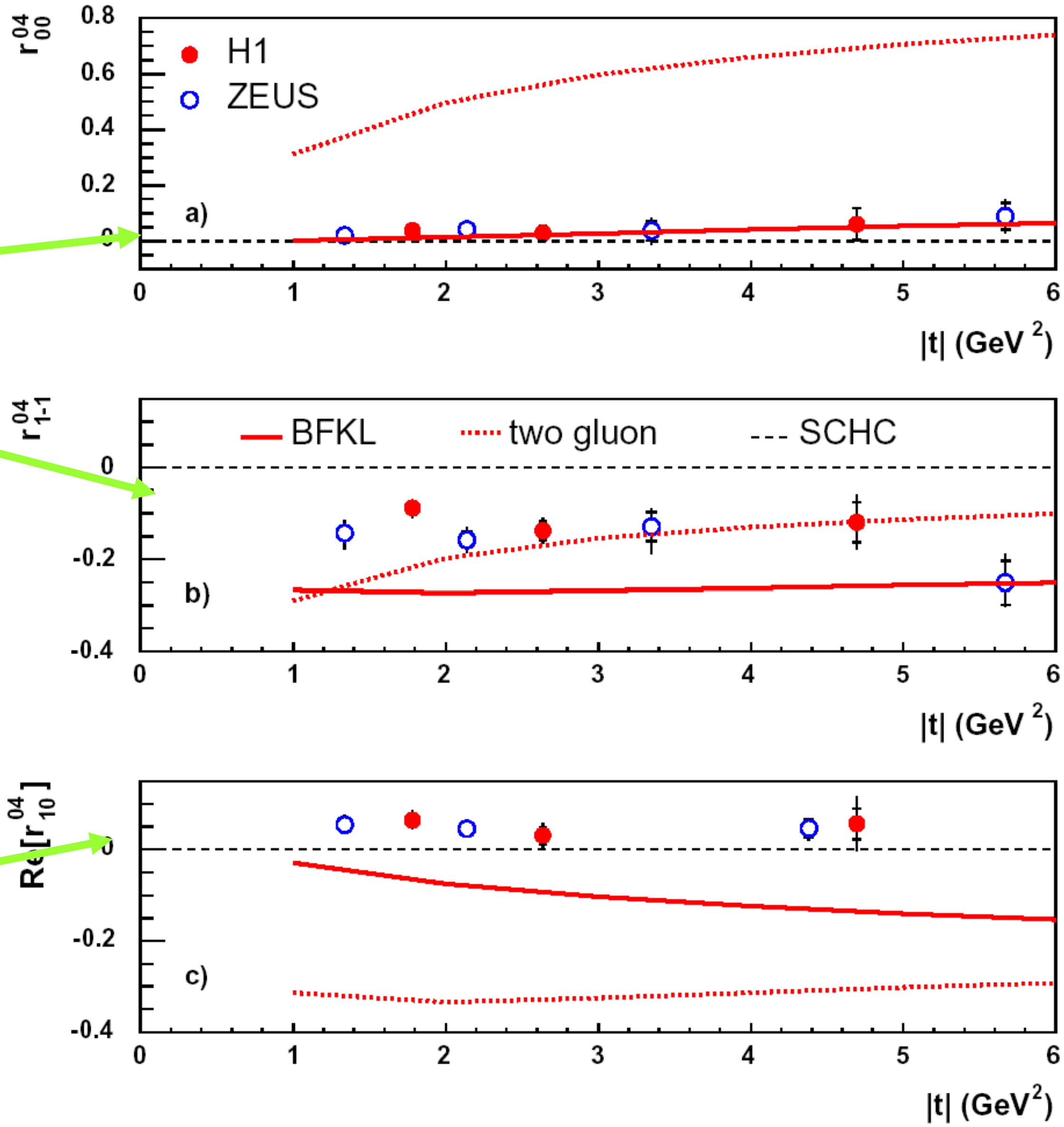
ρ (photoproduction)

"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

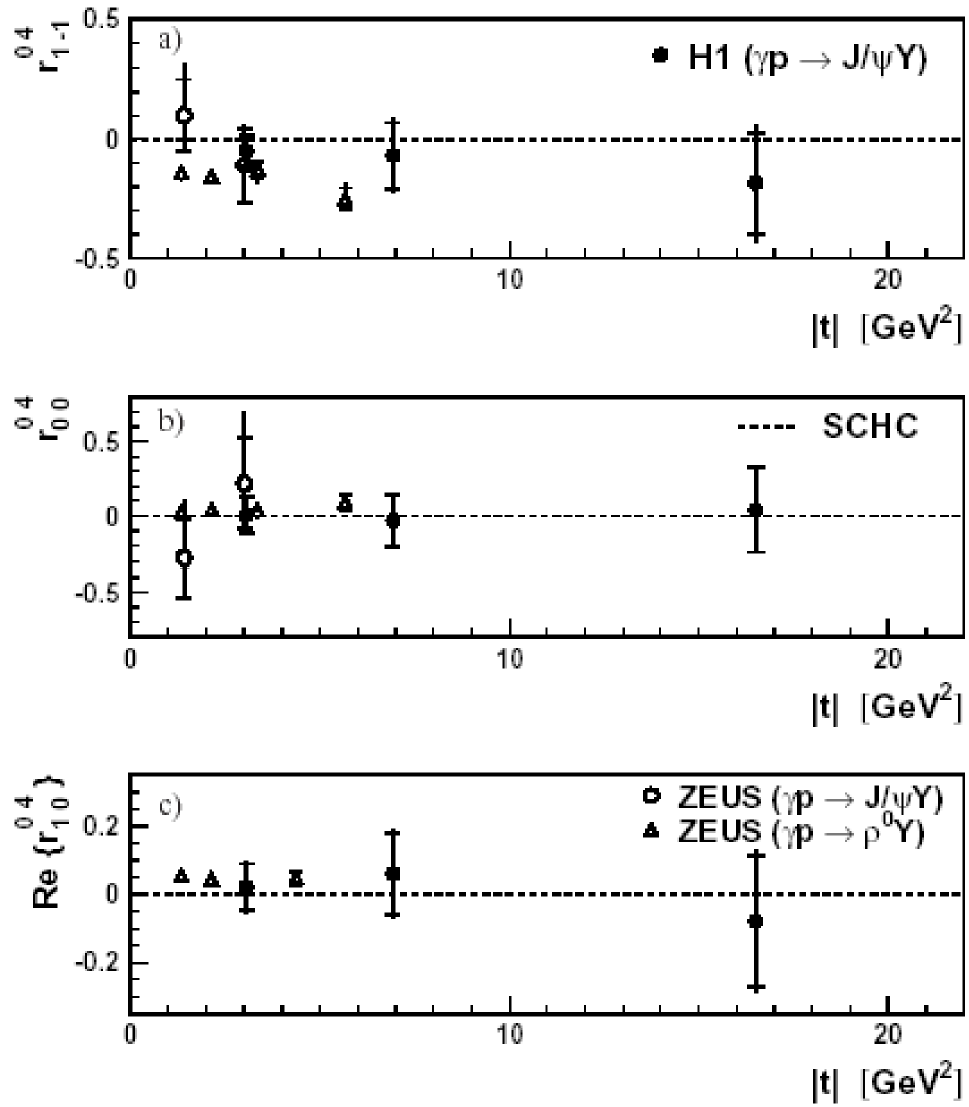
BFKL model describes data well
(except sign of)
cf. also t and W dependences



J/Ψ (photoproduction)

no helicity flip

cf. non-relativistic model



VI. Summary and conclusions

summary

Enormous progress

- experiments

DVCS, light VM, J/Ψ, Υ

- **Q^2** (but stat. limited Q^2 > 20 GeV^2) → **HERA-2** !?
- ***W*** (but limited lever arm)
- ***t*** (but p.diss. bg. (LPS/FPS/VFPS) + other VM bg.; stat. limited very large |*t*|)
- **ang. var.** (but other VM bg.; DVCS + FPS/VFPS)
- **p.diss. / el.** (but no clean meast - LPS/FPS/VFPS)
- **missing** **other VM, in part. ρ'**

- theory

DVCS, J/Ψ, Υ, large |*t*|, also light VM

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

training ground / tests of several general ideas / techniques

conclusions

Very rich and varied landscape,

of which semi-quantitative understanding thus achieved,

but detailed quantitative description of data still missing in most corners,

in particular :

- ***W* dependences** (esp. light VM)
- ***t* dependences, shrinkage**
- **detailed description of helicity amplitudes** (light VM)
- **generally, soft physics interplay**

Many thanks to the convenors,

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