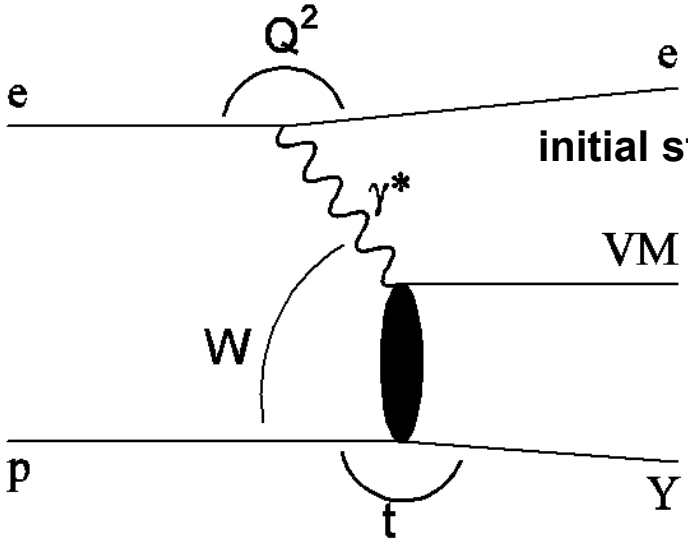
DIS 2009

DVCS and Vector Meson production with H1

Soft and hard diffraction, spin dynamics and QCD

X. Janssen and P. Marage
Université Libre de Bruxelles

DVCS and VM production



initial state : real and virtual photons

final state VM : γ, ρ, ϕ, J/ψ, ψ(2s), Υ

final state baryonic system: p, p. diss. (M_Y)

Q^2	0 – 80 GeV²	photoproduction & DIS	
$W \approx \sqrt{(Q^2/x)}$	30 – 300 GeV		
$\left\|t\right\| \approx \left\|p_{t,miss}\right\|^2 = \left\|\vec{p}_{t,e} + \vec{p}_{t,VM}\right\|$		small |t| (< 0.5 – 3 GeV²)	large |t| (2 < |t| < 10-30 GeV²)

$d\sigma$ / dQ^2, dW, dt

spin dynamics (helicity amplitudes, ang. distrib.), **Re/Im ampl.** (DVCS)

elast. / proton diss.; Regge factorisation

>14 publ. H1 papers + preliminary results on DVCS, ρ photoprod., ρ and ϕ electroproduction

H1 studies

Reaction		Q^2 dep.	W dep.	t dep.	spin dyn.	el.&p.d.	data	status	talk
***Small* |t| (< 0.5 – 3 GeV^2)**									
DVCS	$\gamma^* \to \gamma$	v	v	v	Re / Im	el / pd	hera-2	(1); **prel.**	
light VM	$\gamma \to \rho$		α' meast.		-	-	2005	**prel.**	**B. List**
	$\gamma^* \to \rho, \phi$	v	v	v	v	el / pd	hera-1	**prel.**	
heavy VM	$\gamma \to J/\psi$		v	v	v	el.	99-2000	(2)	
	$\gamma^* \to J/\psi$	v	v	v	v	el.	99-2000	(2)	
***Large* |t| (> 2 GeV^2)**									
photon	$\gamma \to \gamma$		?	v	v	-	99-2000	(3)	**T. Hreus**
light VM	$\gamma \to \rho$		?	v	v	-	2000	(4)	
heavy VM	$\gamma \to J/\psi$		?	v	v	-	hera-1	(5)	

(1) A. Aktas et al., Phys.Lett.B659 (2008) 796-806.
(2) A. Aktas et al., Eur. Phys. J. C46 (2006) 585-603
(3) F.D. Aaron et al., Phys. Lett. B672 (2009) 219-226
(4) A. Aktas et al., Phys. Lett. B 638 (2006) 422
(5) A. Aktas et al., Phys Lett B568 (2003) 205-218

In this talk, emphasis on unpublished data HERA-1 O(100 pb^{-1}); HERA-2 O(350 pb^{-1})

Content

I. QCD approaches

GPD and dipole models

II. Light VM

Event selection

III. Small $|t|$: Q^2 dependences

total and polarised cross sections; Q^2 dep. of gluon distributions

IV. Small $|t|$: W dependences

hard dependence for J/ψ; hardening with Q^2 for light VM

universality : $\alpha_{IP}(0)$ (Q^2)

V. Small $|t|$: t dependences

a. - Q^2 dependence of b slopes (el. and p. diss.)

- universality (DVCS, ρ and ϕ, J/ψ); VM form factor

b. Regge factorisation $b_{el} - b_{p.diss.}$

Content

VI. Effective pomeron trajectory : α'

VII. Small $|t|$: spin density matrix elements; helicity amplitudes

a. light VM and J/ψ : SCHC; ρ, ϕ : + SCHC violation

b. $R(Q^2)$ - universality

c. ρ $R(t)$; $b_L - b_T$ $R(m_{\pi\pi})$

d. ρ, ϕ helicity amplitudes ratios: Q^2 and t dependences

phases between helicity amplitudes

e. DVCS : Re / Im amplitudes (BCA)

VIII. Large $|t|$: tests of DGLAP / BFKL dynamics

a. t dependences

b. W dependences

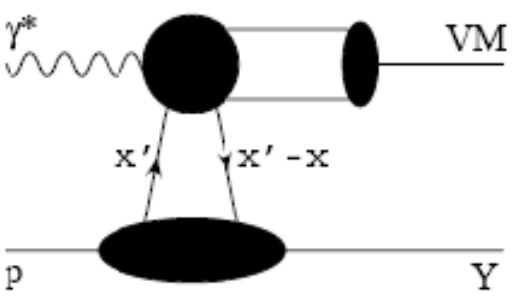
c. spin density matrix elements

IX. Summary and conclusions

I. QCD and models

Photon and VM production in QCD

collinear factorisation



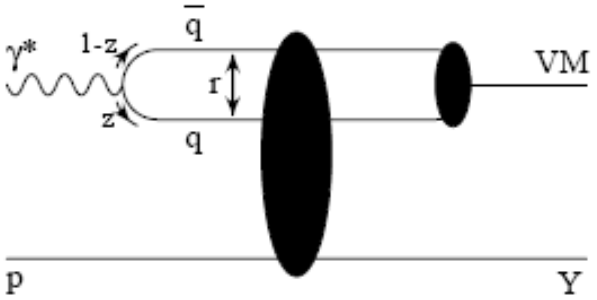
GPD

$$T_L^{\gamma^* p \to Vp}(x;t) = \Sigma_{i,j} \int_0^1 dz \int dx'\, f_{i/p}(x', x'-x, t; \mu) \cdot H_{i,j}(Q^2 x'/x, Q^2, z; \mu) \cdot \Psi_j^V(z;\mu)$$

long. mom. transfer needed for γ^* -> γ, VM (“skewing”)

hard scale, all x, σ_L and heavy Q

p rest frame factorisation



dipole

$$T^{\gamma^* p \to Vp}(x;t) = \int_0^1 dz \int d^2\mathbf{r}\, \Psi^\gamma(z,\mathbf{r}) \cdot \sigma^{q\bar{q}-p}(x,\mathbf{r};t) \cdot \Psi^V(z,\mathbf{r})$$

photo- and electroprod., low x

complementary information

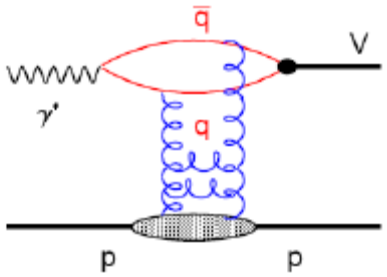
parton correlations in proton

universal q qbar dipole interactions

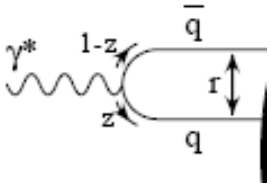
Photon and VM production in QCD

Dipole model

pQCD : 2 gluon exchange, gluon ladder



dipole-proton cross section depends on transverse size of dipole
(=> small J/ψ cross sections – colour transparency)



Scale $\mu^2 \sim z(1-z)(Q^2+M^2)$

- **long. amplitudes and heavy quarks** (non-relat. WF):

$z \sim 1-z \sim 0.5 \Rightarrow \mu^2 \sim (Q^2+M^2)/4$

-> long. ampl. become comparable to J/ψ for $Q^2 > 9$ GeV^2

NB + finite size effects ($z \neq 0.5$) => delayed hard behaviour

- **transverse amplitudes** : **larger transverse size** of dipole

$z, 1-z < 0.5 \Rightarrow \mu^2 < (Q^2+M^2)/4$

transverse scale < longitudinal scale - effect on *W* dep., *b* slopes

Models

Huge number of models and calculations !

ref. for the small $|t|$ data presented here

DVCS

(dipole) C. Marquet, R. Peschanski and G. Soyez, Phys. Rev. **D76** (2007) 034011

(GPD) K. Kumericki, D. Mueller and K. Passek-Kumericki, Eur. Phys. J. **C58** (2008) 193

ρ and ϕ, small t

(GK) S.V. Goloskokov and P. Kroll, Eur. Phys. J. **C53** (2008) 367

(MRT) A.D. Martin, M.G. Ryskin and T. Teubner, Phys. Rev. **D55** (1997) 4329

(INS) I.P. Ivanov, N.N. Nikolaev and A.A. Savin, Phys. Part.Nucl. **37** (2006) 1

(IK) D.Yu. Ivanov and R. Kirschner, Phys. Rev. **D58** (1998) 114026

(KMW) H. Kowalski, L. Motyka and G. Watt, Phys. Rev. **D74** (2006) 074016

(MPS) C. Marquet, R. Peschanski and G. Soyez, Phys. Rev. **D76** (2007) 034011

(FS) L. Frankfurt and M. Strikman, Phys. Rev. **D66** (2002) 031502

J/ψ, small t

(MRT) A.D. Martin, M.G. Ryskin and T. Teubner, Phys. Rev. **D62** (2000) 014022
various pdf's

II. Light VM (ρ, ϕ): event selection

Event selection and backgrounds

Elastic events : no tag in forward detectors, $|t| < 0.5$ GeV^2

Proton dissociation : tag events, $|t| < 3$ GeV^2

Light VM electroproduction: backgrounds

ρ mesons

$\omega, \phi \rightarrow \pi^+ \pi^- \pi^o$

estim. : MC with measured cross sections

$\rho' \rightarrow \rho \pi \pi \rightarrow \pi^+ \pi^- \pi^o \pi^o$

$\rightarrow \pi^+ \pi^- +$ undetected γ's

(ρ' generic for diffractively produced states heavier than ρ)

estim. = **from data** (correlation between directions of $\pi^+ \pi^-$ and missing γ's) + MC

---> **larger |t|** since large $p_{t,miss}$

---> elastic sample most affected (little genuine elast. prod. at large |t|)

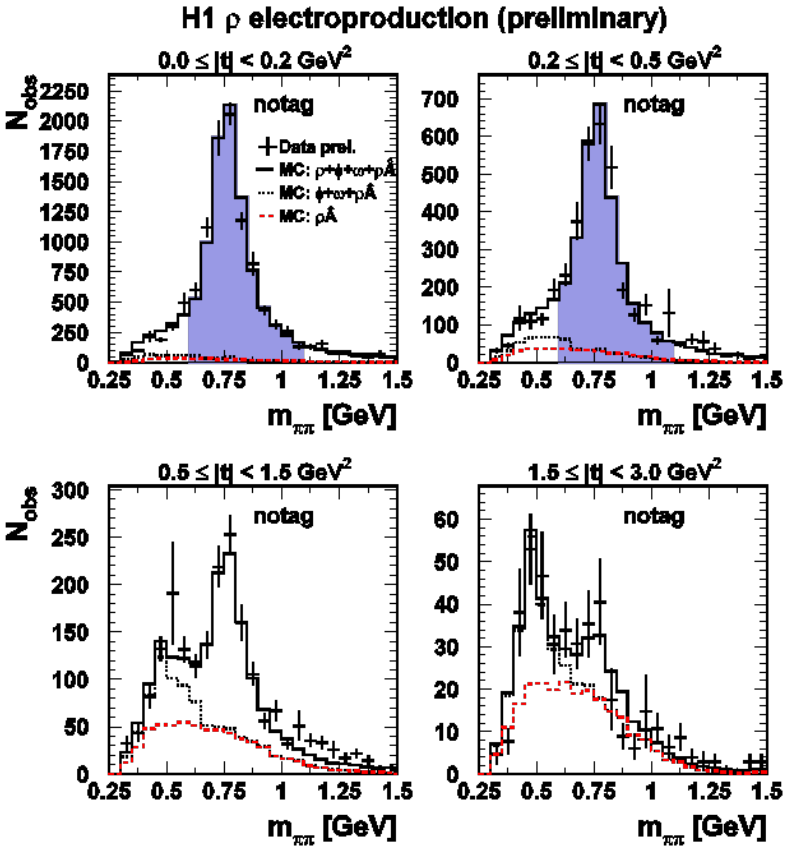
---> effect on |t| slopes

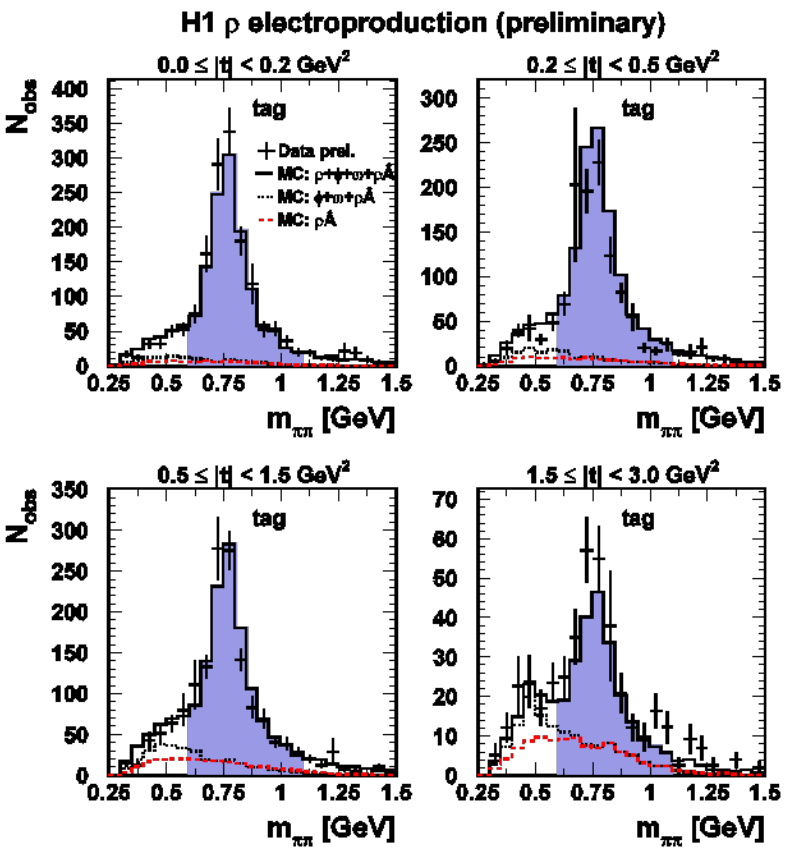
---> effect on spin density matrix elements (uniform background)

ϕ mesons

ω, ρ' (from ρ anal.), ρ, $\pi^+ \pi^-$

ρ : $m_{\pi\pi}$ mass shapes

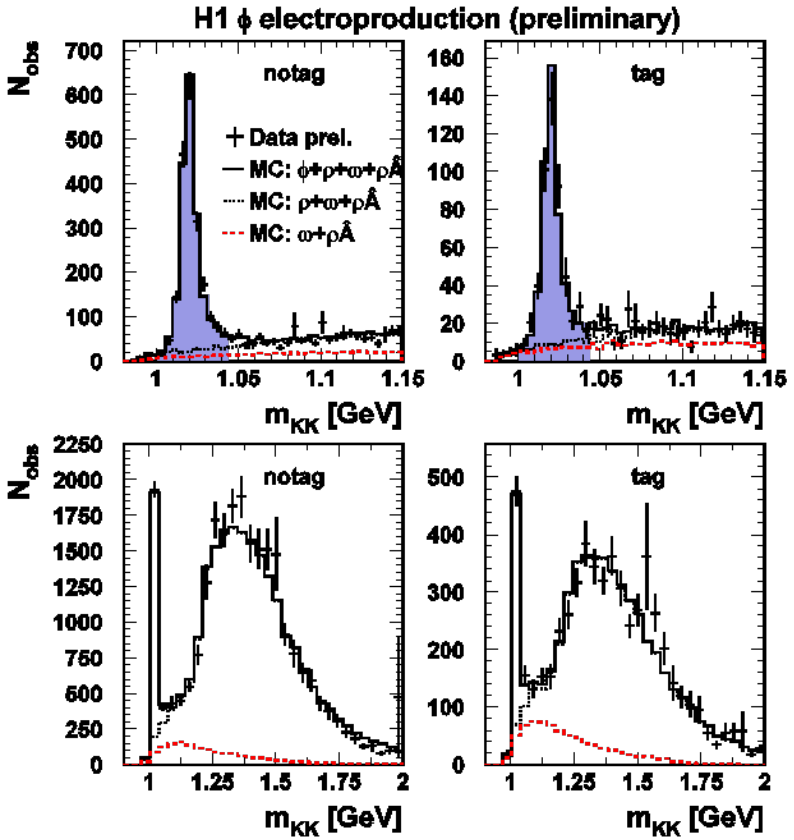




ρ' contribution is obtained from $0.6 < m_{\pi\pi} < 1.1$ GeV and extrapolated to **full mass range**

mass distributions, for different bins in t and Q^2 (not shown), very well described with contributions of the **various backgrounds**

ϕ : m_{KK} mass shapes

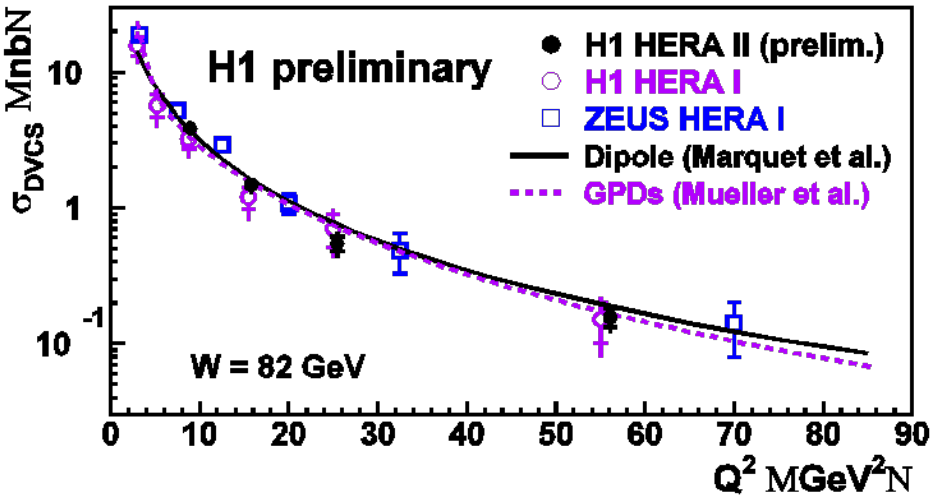


III. DVCS and VM Q^2 dependences

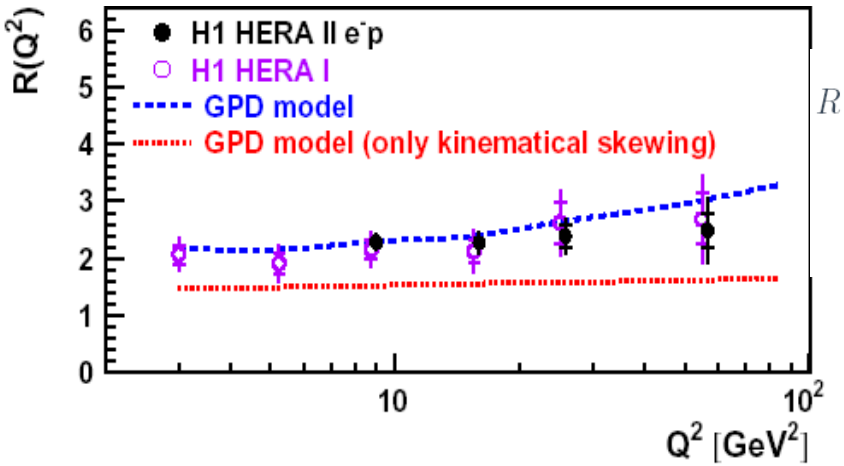
DVCS

GPD and dipole models

(HERA-2 data)

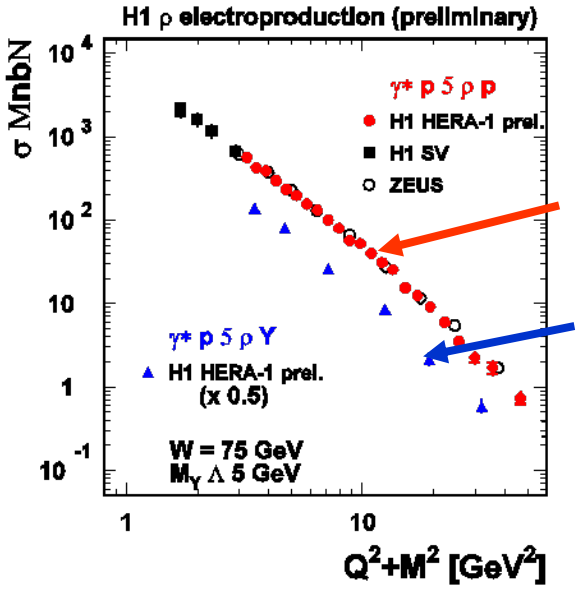


GPD's take into account skewing – but kinematic **skewing is not sufficient**



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

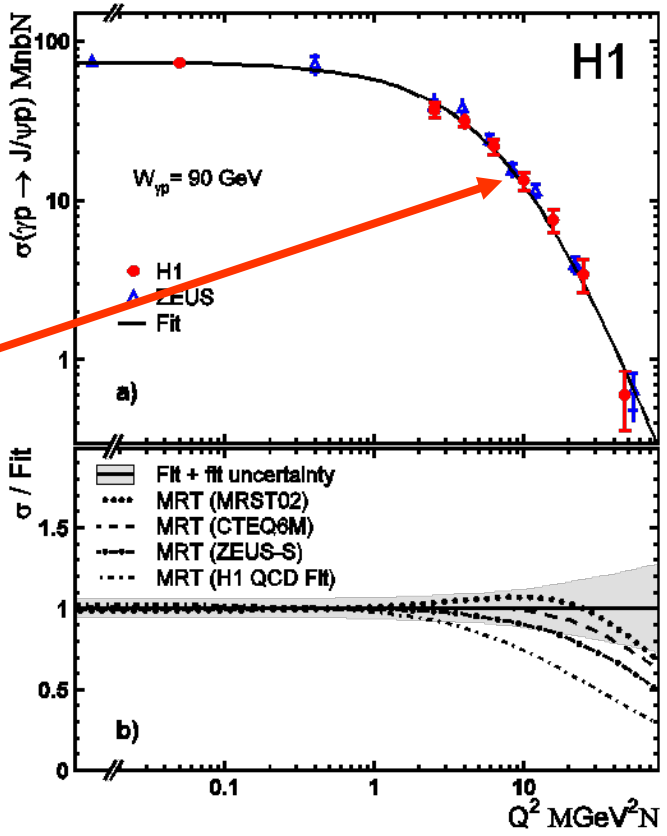
ρ and ϕ (el. and p. diss.), J/ψ



HERA-1 data

ρ el.

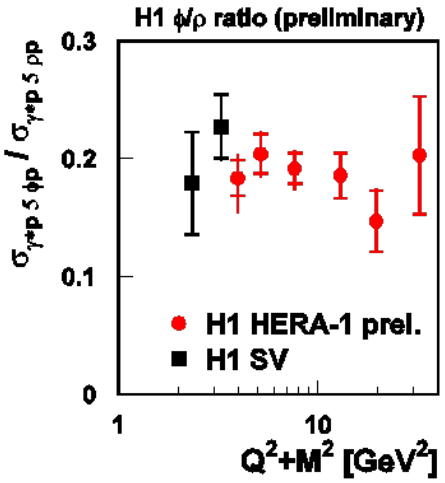
ρ p.d.



J/ψ

1999-2000 data

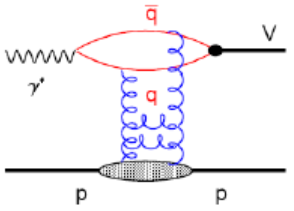
(excellent agreement with ZEUS)



ϕ/ρ

universal dipole – proton cross sections

=> **universal ($Q^2 + M^2$) dep.**



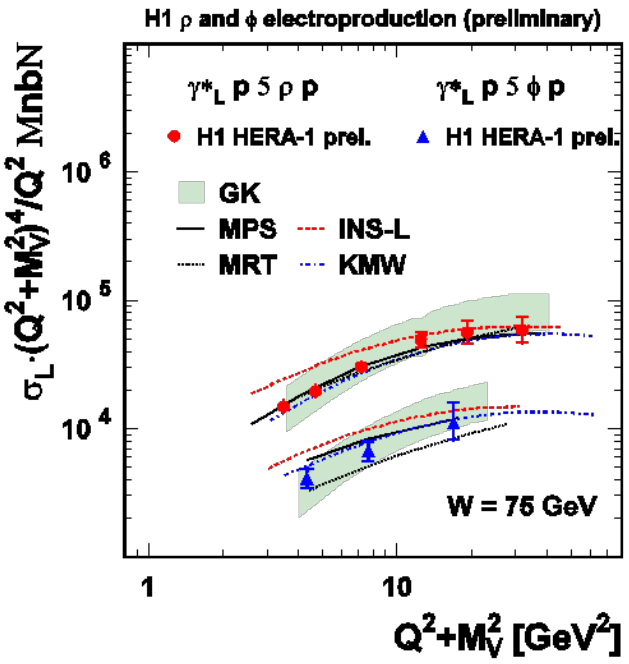
Polarised distributions

$\sigma_L \propto Q^2 \,|\, xG(x) \,|^2 \,/\, (Q^2 + M_V^2)^4 \;\Rightarrow$ formally $\sigma_L \propto 1/Q^6, \quad \sigma_T \propto 1/Q^8, \quad R = \sigma_L / \sigma_T \propto Q^2 / M_V^2$

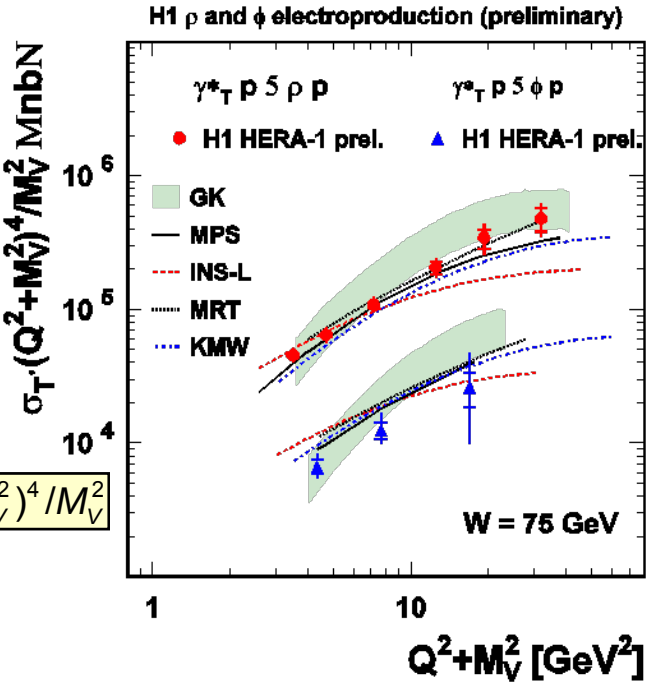
but Q^2 dependence of gluon density xG(x)

Scaled presentation (I. Ivanov)

(σ_L and σ_T obtained from σ_{tot} using measurement of R - see below)



$\sigma_L \cdot (Q^2 + M_V^2)^4 / Q^2$



$\sigma_T \cdot (Q^2 + M_V^2)^4 / M_V^2$

faster increase with Q^2 at small x than formal expectation - effect of **gluon density increase**

(NB fixed W => variable value of x in plots)

Variable success of various GPD and dipole models

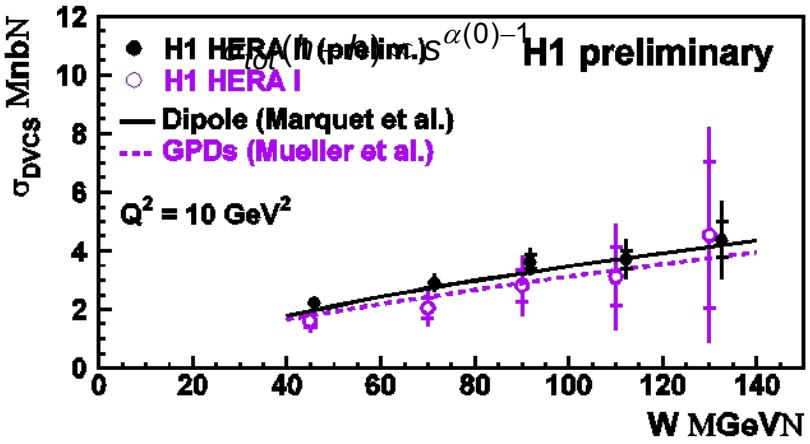
IV. W dependences

W dependences

power law dependence: W^{δ}

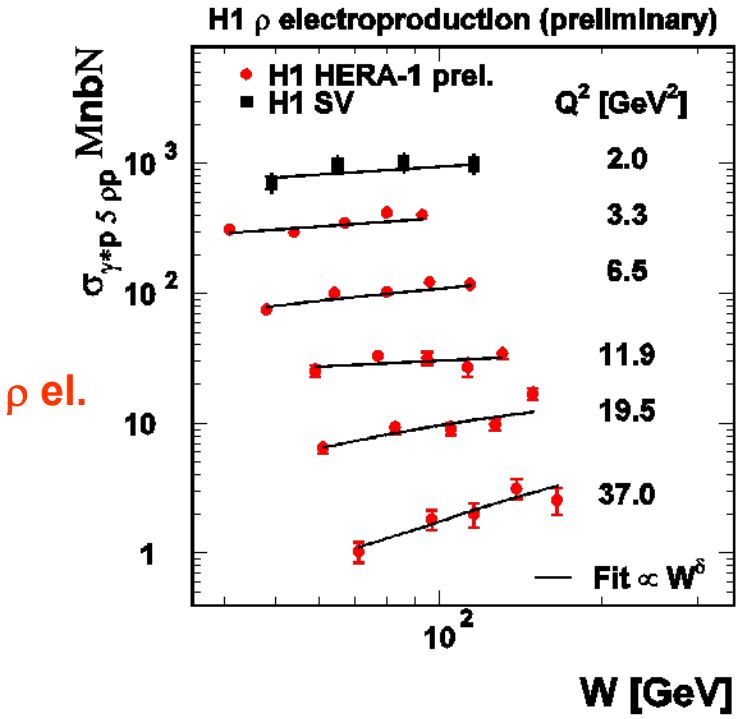
cf. high energy *h*–*h* interactions **(Regge)**

DVCS

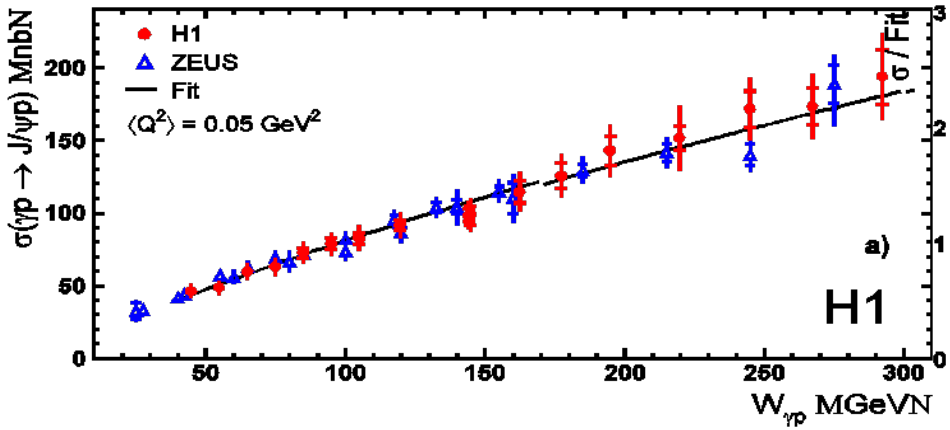


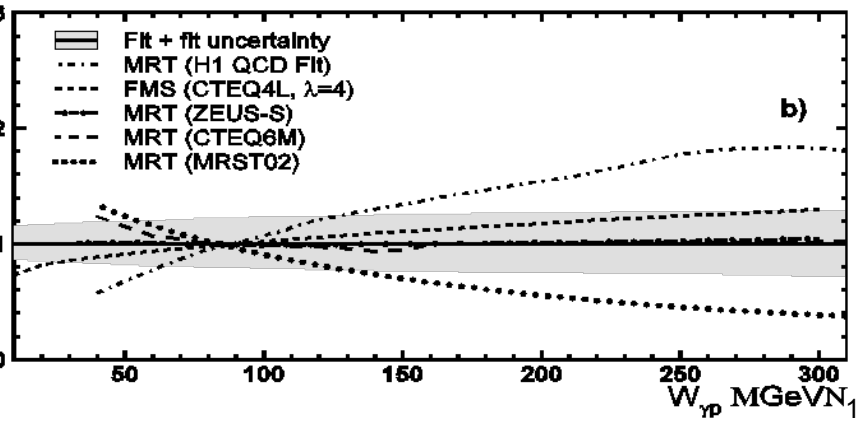
$\sim W^{\alpha(0)-1}$

ρ el.



J/ψ





$\alpha_P(0)$

high energy *h–h* interactions :

$$\sigma_{tot}(h-h) \propto s^{\alpha(t)-1}$$

$$\alpha(t) = \alpha(0) + \alpha' t$$

$\alpha(0) \approx 1.08$ ("soft")

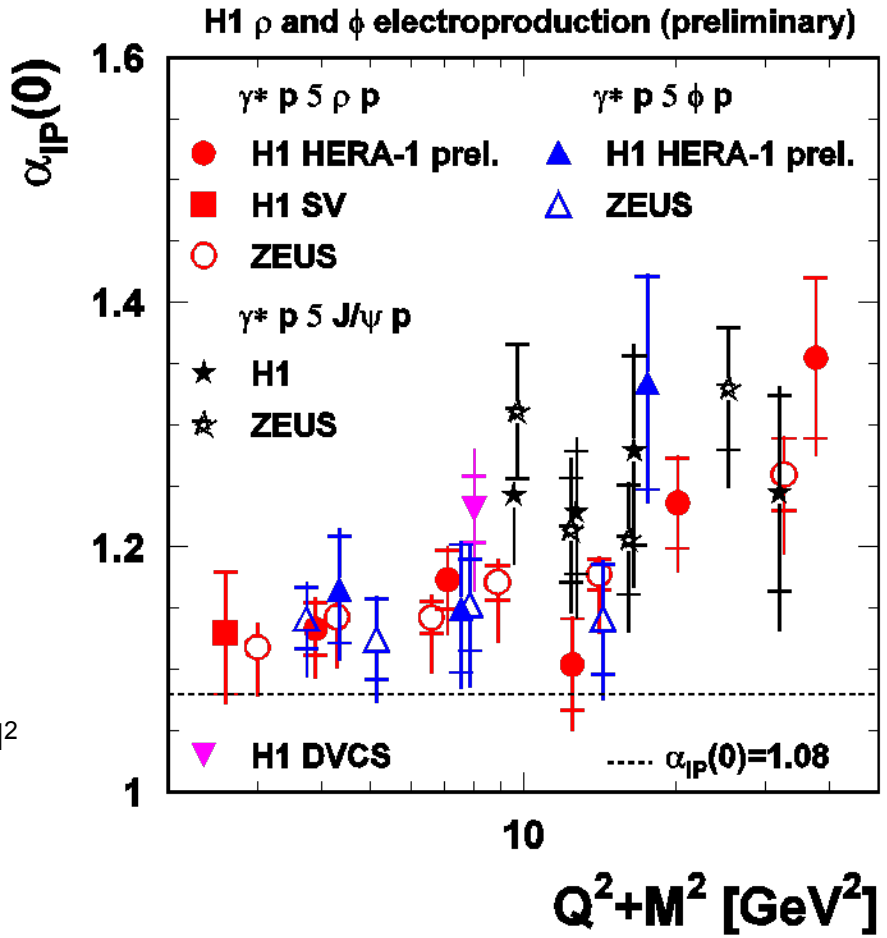
$\alpha' \approx 0.25$ GeV^{-2}

VM production

$\sigma \sim |x\,G(x)|^2$ -> **"hard" W dependence**
hardening of gluons with scale (quark mass, Q^2)

-> **$\alpha(0)$ increase** with Q^2

-> **universality** : ρ, ϕ similar to J/ψ at large Q^2+M^2



NB scale ? $\mu^2 = (Q^2 + M^2)/4$ for VM (dipole)

$\mu^2 = Q^2$ for DVCS – see discussion below

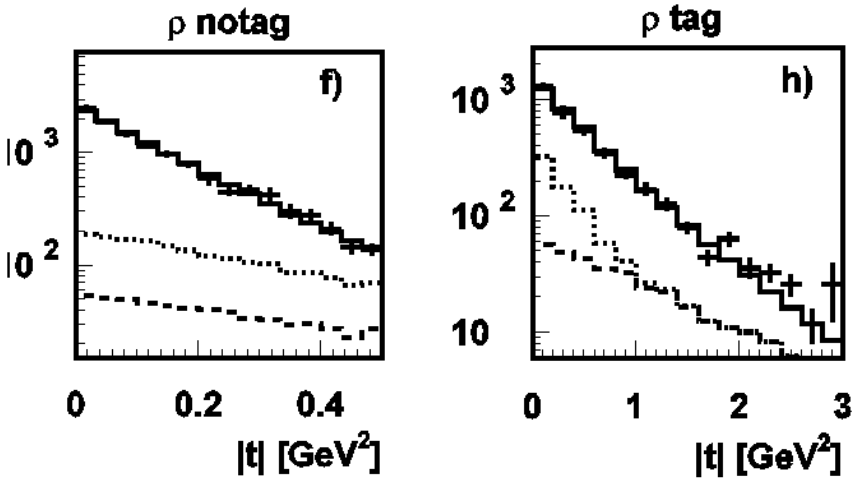
V. *t* dependences

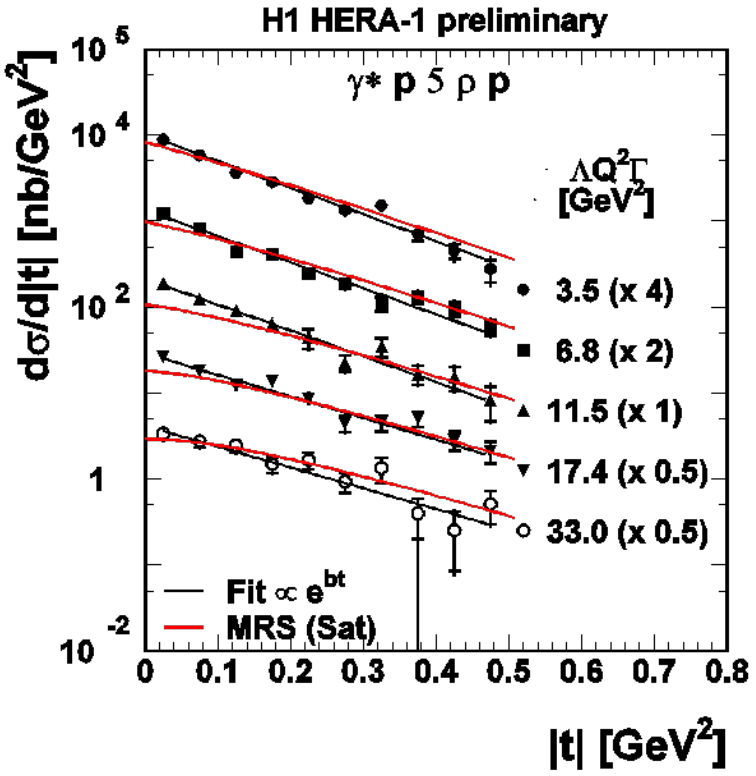
t dependences

exponential *t* dependence

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

- elastic |t| <0.5 GeV^2
- p. diss. |t| <3 GeV^2



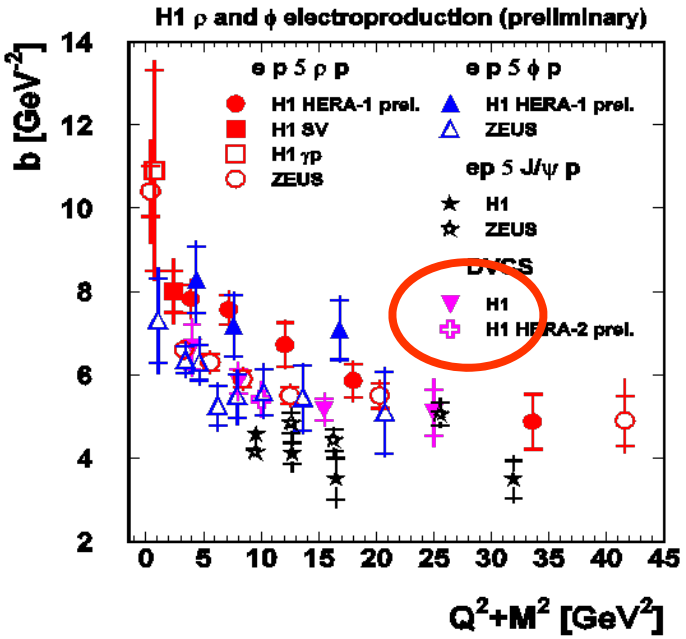


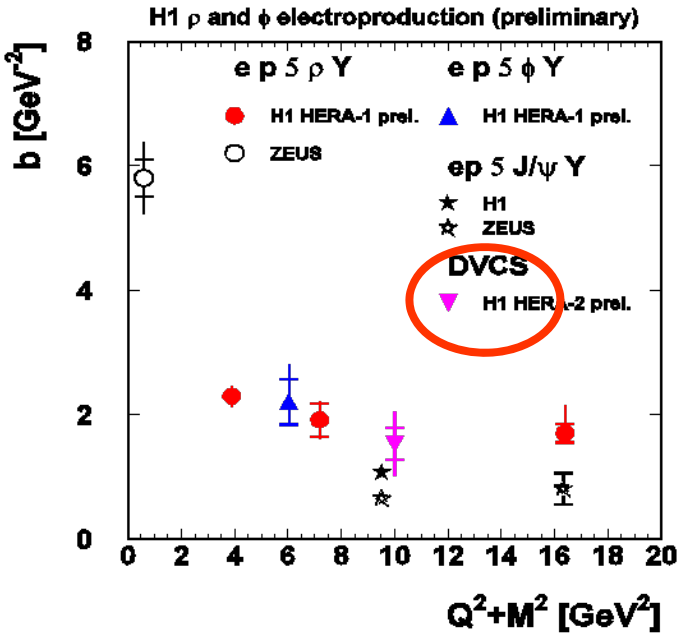
Elastic (p. diss.) slope extraction: exper. effects:

- **amount** and effective **slope** of **VM (ρ' etc.)** bg. (lower histo.)
- **amount** and **slope** of **p. diss.** (**el.**) bg. (upper histo.)

- MPS problematic
- two-gluon form factor model of FS gives good description (not shown), with Q^2 dependence of the form factor

b slopes





optical model $b = b_{dipole} + b_{exch} + b_Y \quad (+b_{VM})$

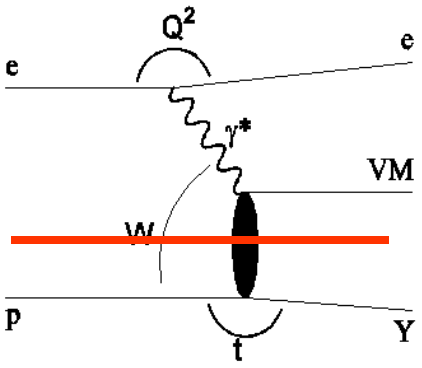
- ✓ ***b* decrease** with dipole size (Q^2, m_Q)
- ✓ **universal** scale dependence $\mu^2 = (Q^2 + M^2)/4$ for VM

  $\mu^2 = Q^2$ for DVCS

- ✓ b(ρ, ϕ at large Q^2) -> b (J/ψ) -> small room for VM form factor b_{VM}

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

Vertex ("Regge") factorisation

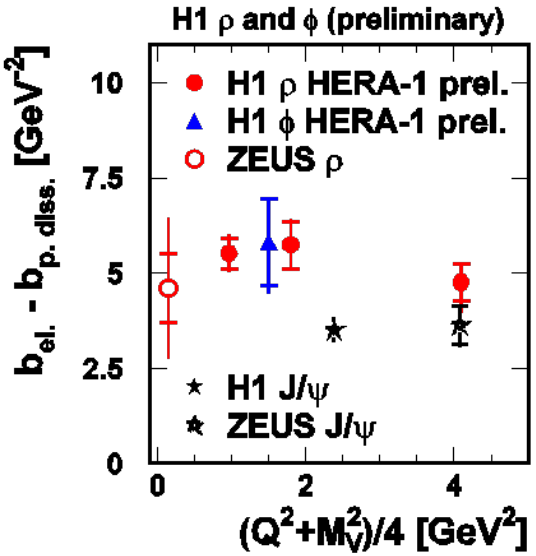


✓ $\frac{d\sigma / dt \text{ (p.diss.)}}{d\sigma / dt \text{ (elast.)}}(t=0)$ indep. of Q^2

(not shown)

✓ **$b_{el} - b_{pd}$ indep. of Q^2**

$b_{el} - b_{pd}$ = cte = 5.5 for ρ, ϕ
= 3.5 for J/ψ



VI. Slope of effective Regge trajectory

Shrinkage and Regge trajectory

W – t correlation

Regge : $\sigma \sim W^{\delta}$

t dependence of δ

$\delta = 4\,(\alpha(t) - 1) = 4\,(\alpha(0) + \alpha' t - 1)$

soft h-h scattering $\alpha' = 0.25\ \mathrm{GeV}^{-2}$

W dependence of diffractive peak ("shrinkage")

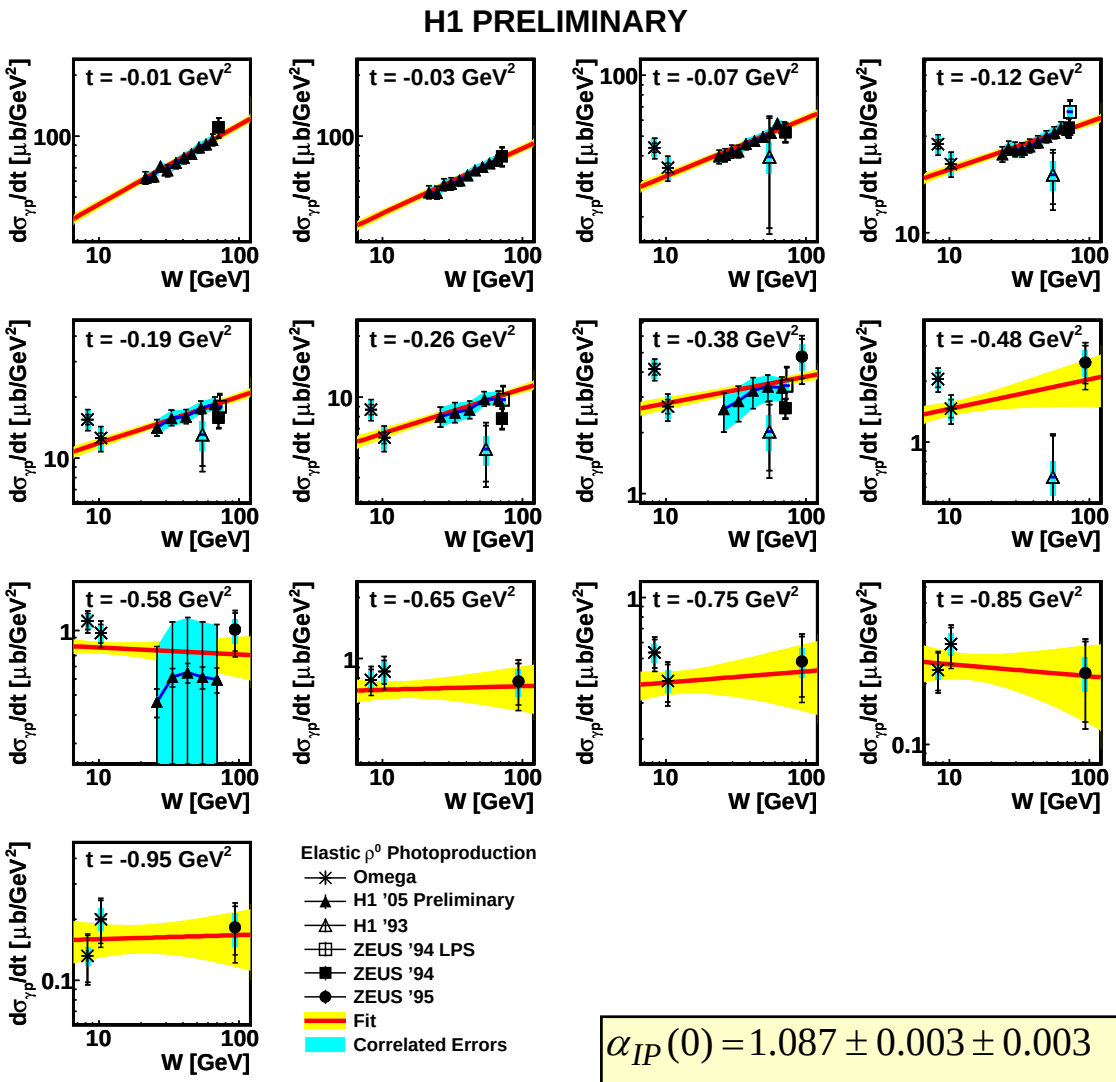
$$\frac{d\sigma}{dt}(W) = e^{bt} = e^{b_0 t}\, W^{4(\alpha(0)+\alpha' t-1)}$$

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

=> α' **measurement** through

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

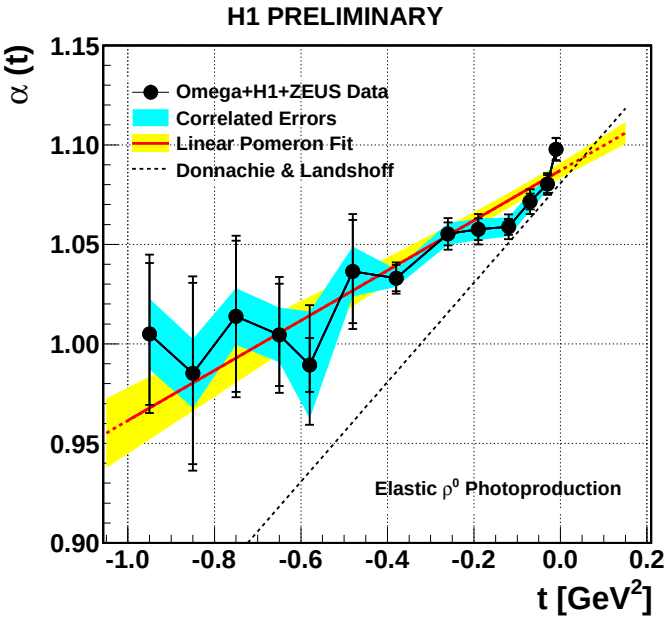
Regge trajectory (ρ photoprod.)



H1 prelim. 2005 data

High energy H1

Low energy Omega

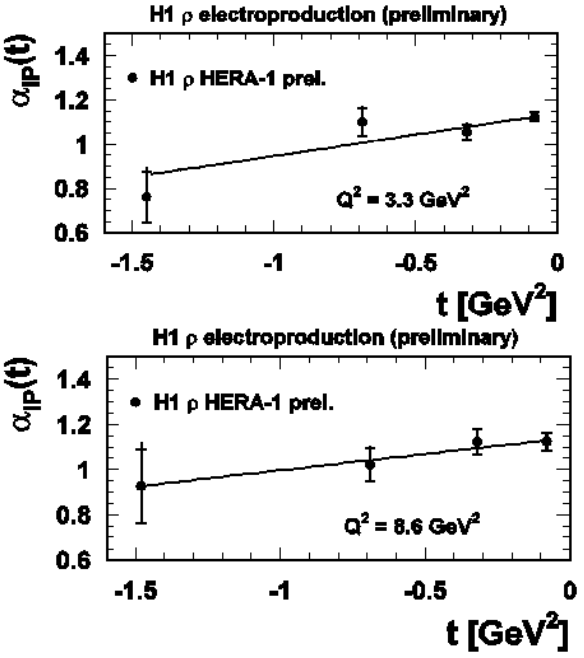


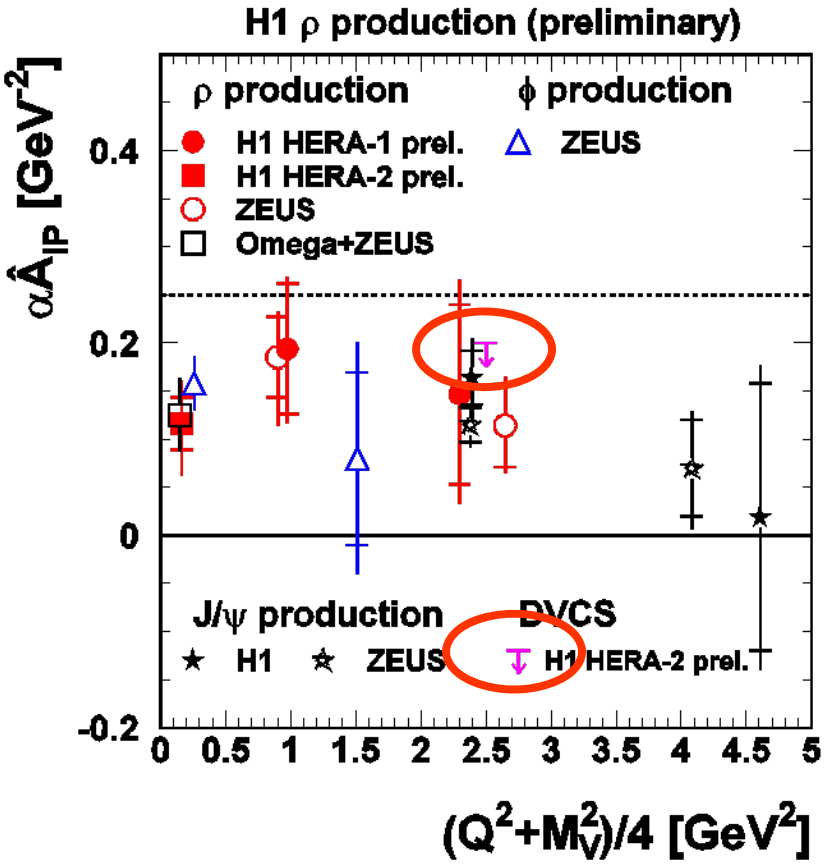
$$\alpha_{IP}(0) = 1.087 \pm 0.003 \pm 0.003$$

$$\alpha' = 0.126 \pm 0.013 \pm 0.012\ \mathrm{GeV}^2$$

Regge trajectory (small |*t*|)

ρ electroprod.





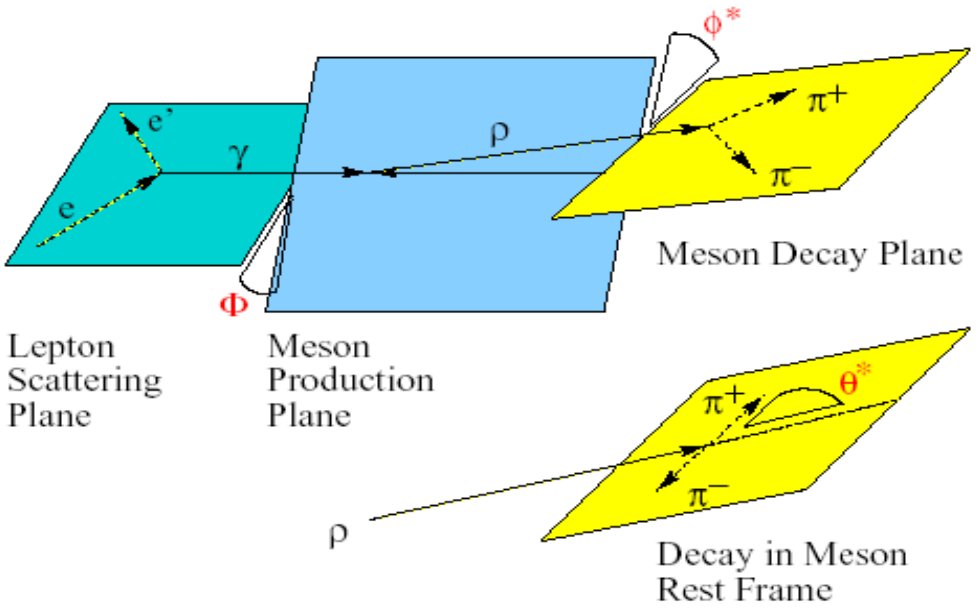
systematically: $\alpha' < 0.25$ GeV^{-2}

NB J/ψ $2 < |t| < 30$ GeV^2 : $\alpha' = -0.014 \pm 0.007 \pm 0.005$

VII. Amplitude studies

Spin density matrix elements

3 angles describe VM production and decay in helicity frame



→ **15 spin density matrix elements**
bilinear combinations of **5 helicity amplitudes $T_{\lambda VM,\lambda\gamma}$** (NPE is assumed)

SCHC T_{00} T_{11}
single flip T_{01} T_{10}
double flip $T_{-1\,1}$

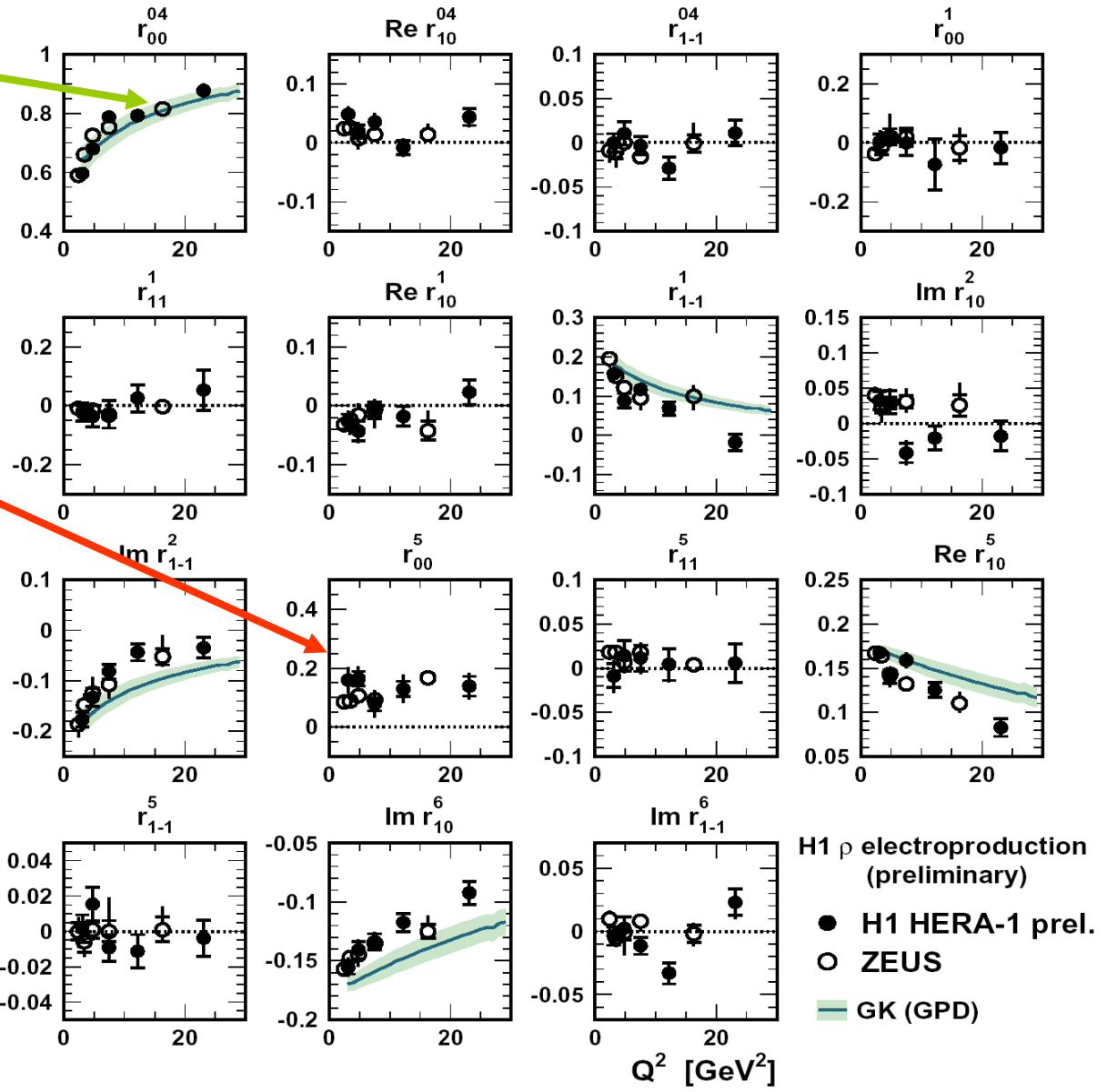
spin density matrix elements (Q^2) (ρ)

5 SCHC elements
compared to GPD calculations

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

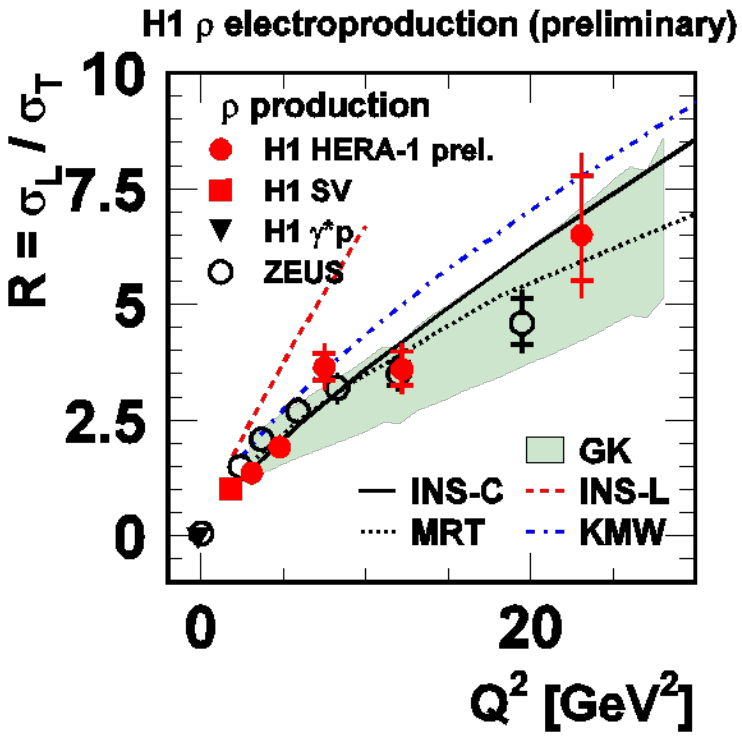
except $\sim T_{01} T_{00}^*$

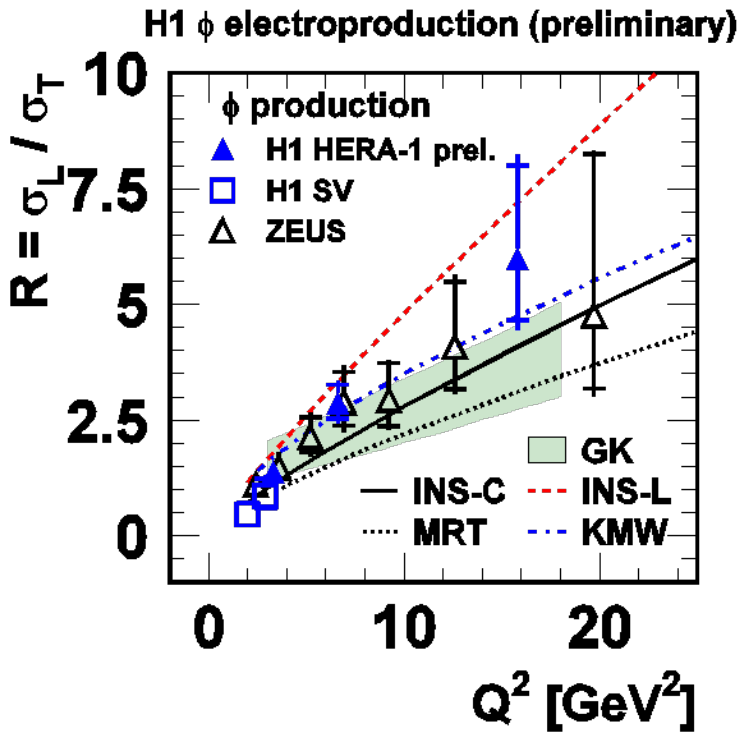
several models
(GPD, unintegrated k_t,
dipole + saturation)
can reproduce
general features of
SCHC amplitudes + hierarchy
but not details



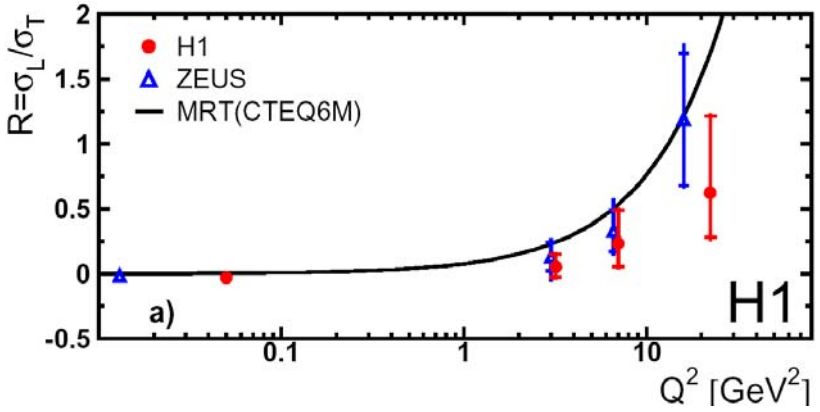
$R\,(Q^2)$ (ρ, ϕ)

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





scaling of R (Q^2)

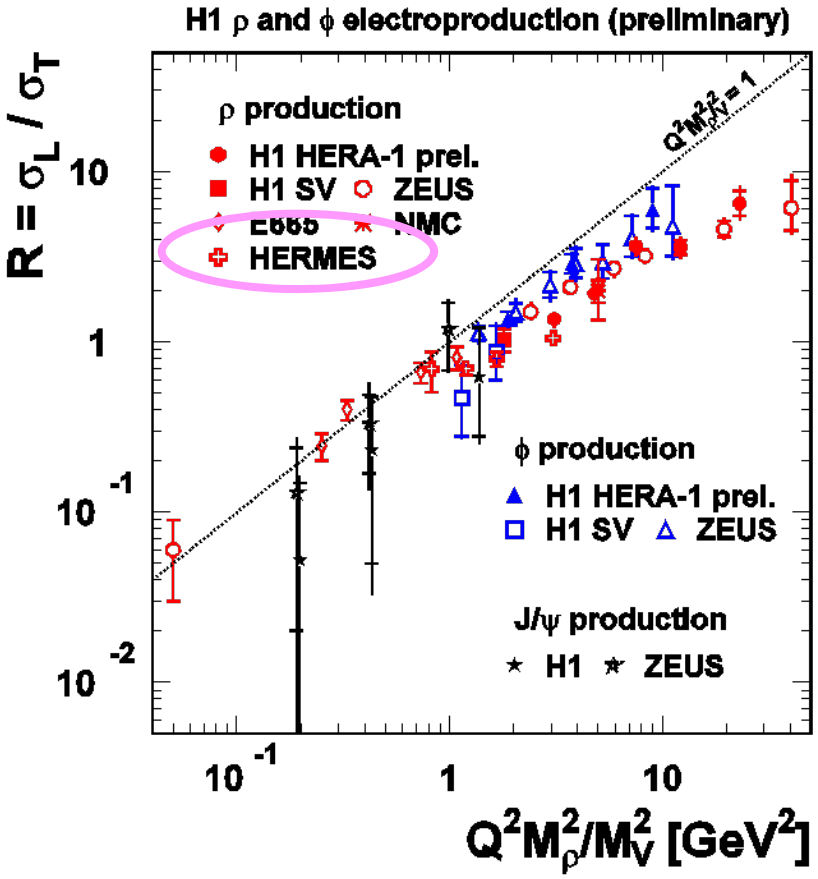


J/ψ

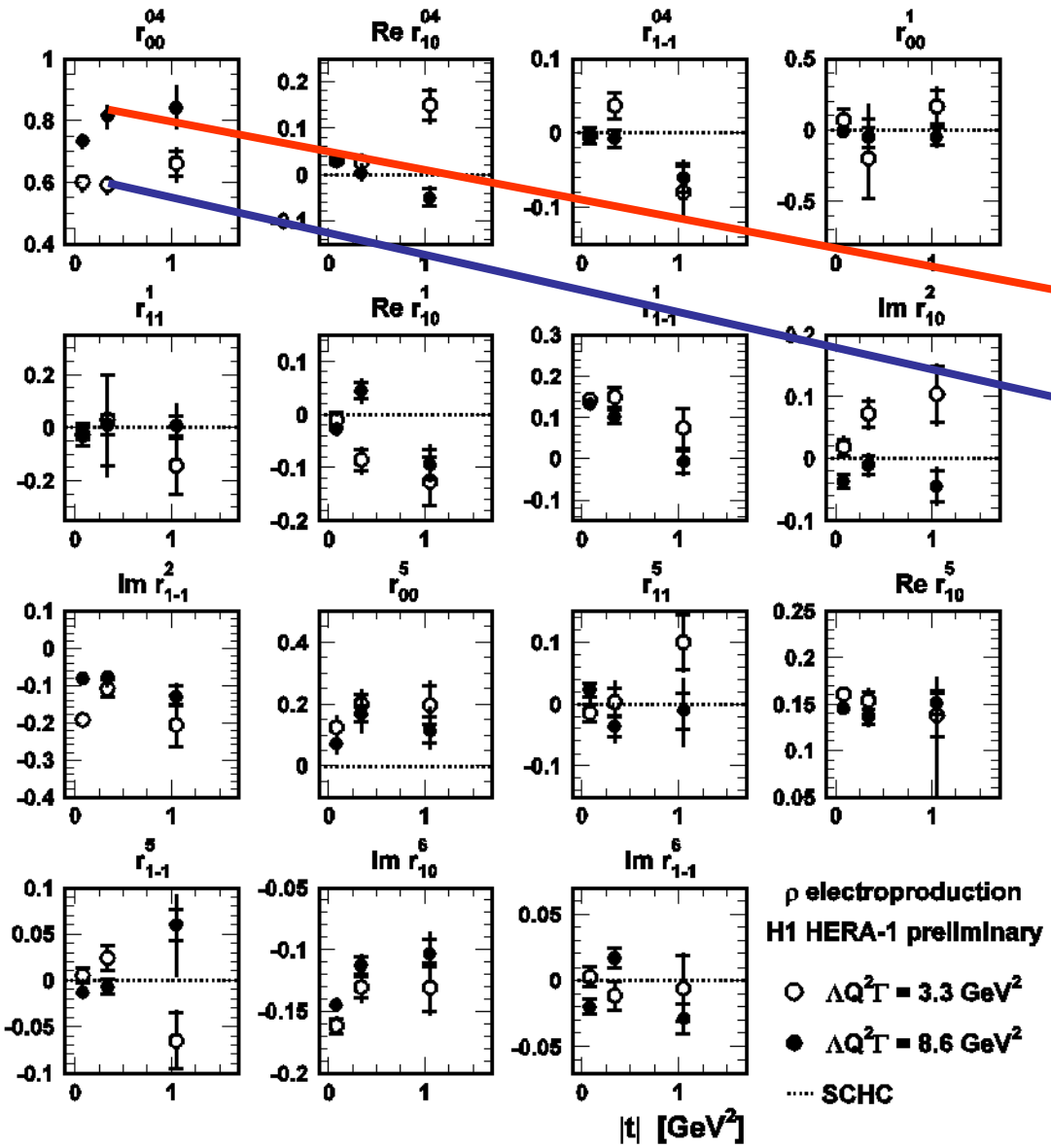
pQCD : formally $R \sim Q^2 / M^2$

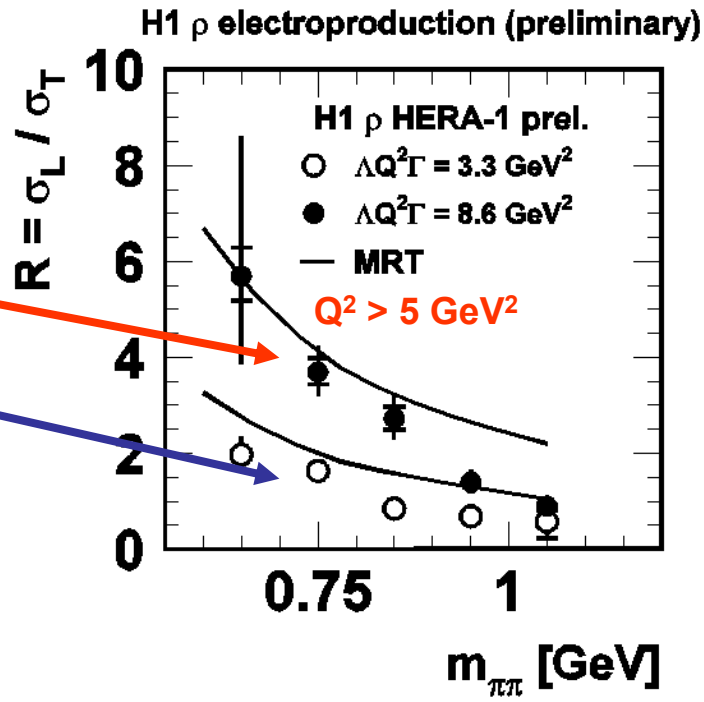
scaling plot : $Q^2 \cdot M^2_\rho / M^2_V$

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



SDME and R (t) (ρ)





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

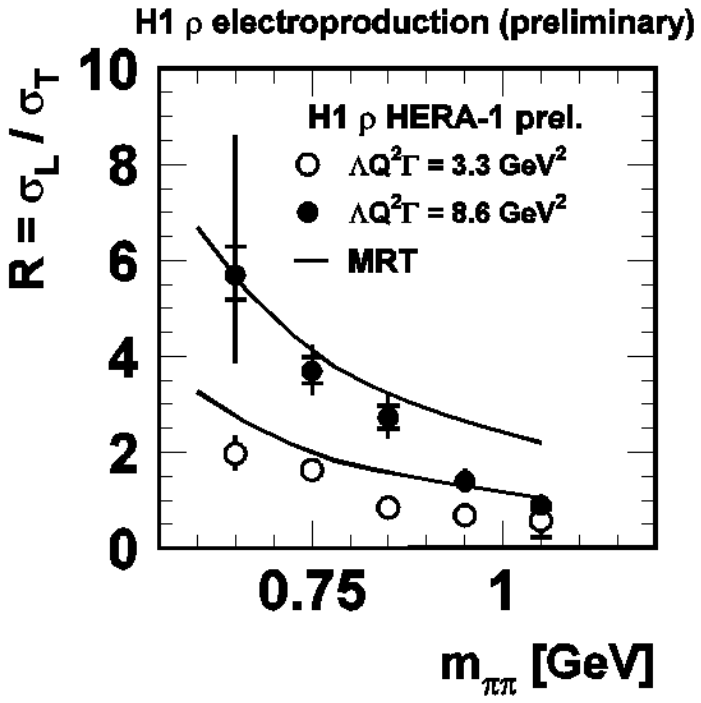
Q^2 > 5 GeV^2 :

b_L-b_T <0 1.5 σ

(stat. + syst.)

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

$R\,(m)$ (ρ)



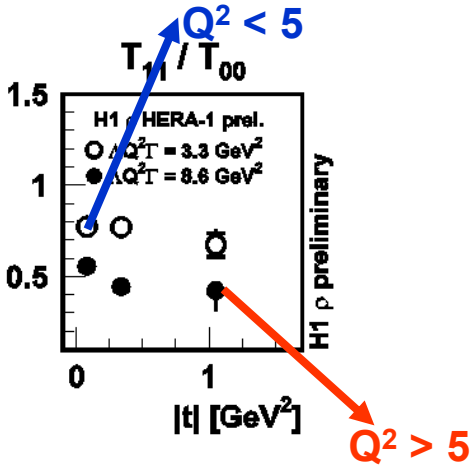
Decrease of R(m) is qualitatively consistent with formal pQCD calculations $R \sim Q^2 / M^2$

if *M* is diquark / dipion mass rather than resonance mass

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

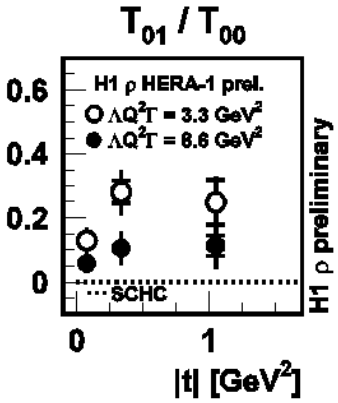
amplitudes ratios (t, Q^2) (ρ)

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

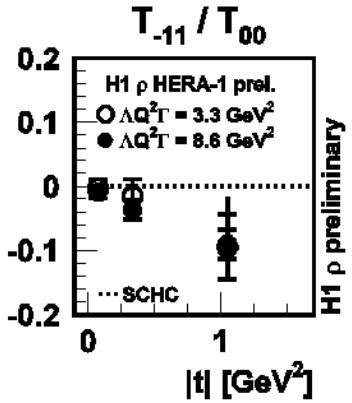


$$\frac{M}{Q}\,\frac{1+\gamma}{\gamma}$$

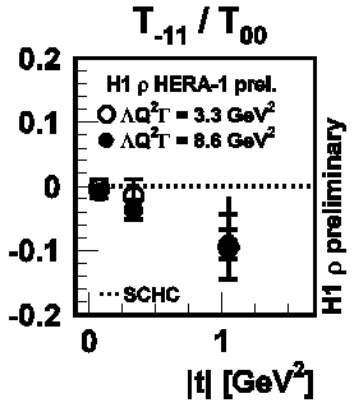
(Ivanov-Kirschner)



$$\frac{\sqrt{|t|}}{Q}\,\frac{1}{\sqrt{2}\gamma}$$



$$-\frac{M\sqrt{|t|}}{Q^2}\,\frac{\sqrt{2}}{\gamma}$$



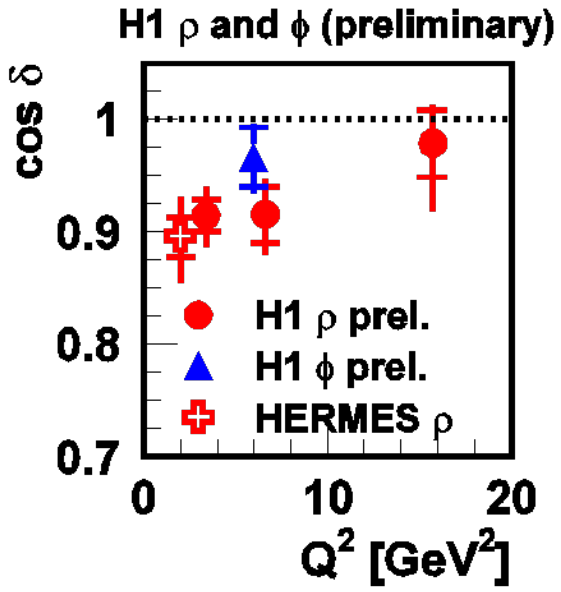
$$T_{-11}/T_{00} = \eta^0 + \eta^1,$$

$$\eta^0 = -\frac{\bar{\alpha}_S^2 |t|\, M}{\pi\, \alpha_S\, Q\, m_\rho^2}\,\frac{1}{4^\gamma\,\frac{\Gamma^2(\gamma+1)}{\Gamma(2\gamma+2)}\,xG(x,Q^2/4)}$$

$$\eta^1 = \frac{M\,|t|}{Q^3}\,\frac{2(\gamma+2)}{\gamma}.$$

- ✓ **Q^2 dependences** (higher twist) of all amplitude ratios
- ✓ expected ***t* dependences** of helicity flip amplitudes T_{01}/T_{00} T_{10}/T_{00} T_{-11}/T_{00}
- ➢ *t* dependence of T_{11}/T_{00} follows from proton rest frame factorisation
  (increase with $|t|$ of the two transverse amplitudes $|T_{01}/T_{00}|^2$ and $|T_{-11}/T_{00}|^2$
  implies the decrease of $|T_{11}/T_{00}|^2$)

SCHC amplitudes phases (Q^2) (ρ, ϕ)



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

phase difference decreases with Q^2

NB phase difference between amplitudes is related to different values of ρ = Re / Im,

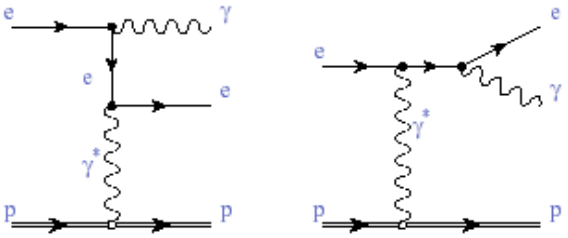
which are related through dispersion relations to the *W* evolutions

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

Beam charge asymmetry in DVCS

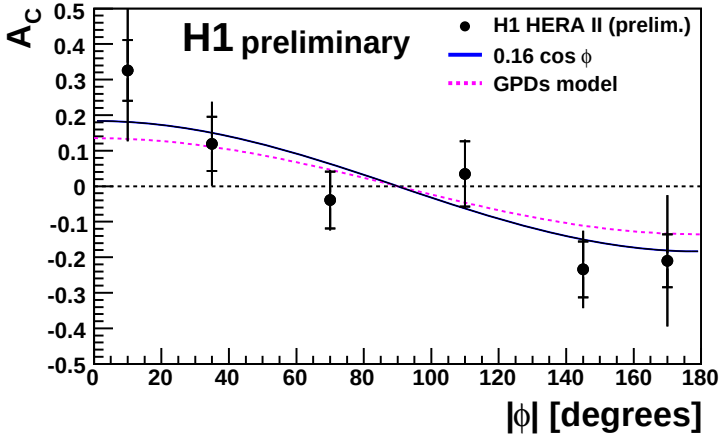
interference with Bethe-Heitler

→ access to **Re contributions**



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

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



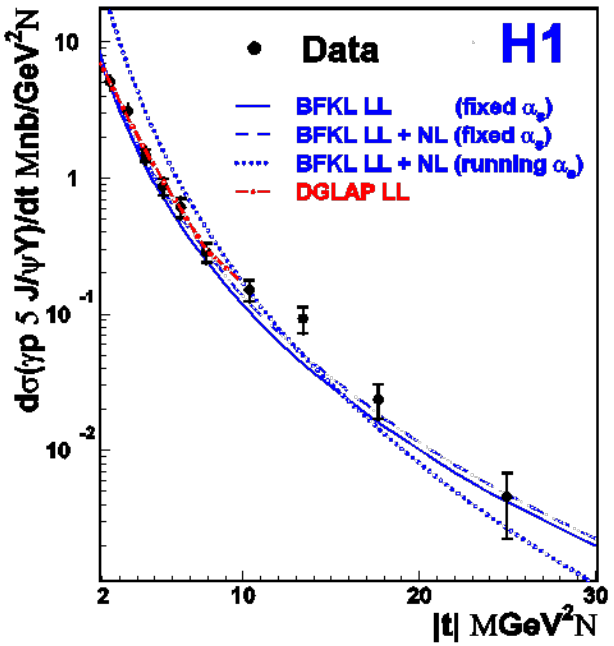
$\rho = \mathrm{Re}\ A_{DVCS}\ /\ \mathrm{Im}\ A_{DVCS} = 0.20 \pm 0.05 \pm 0.08$

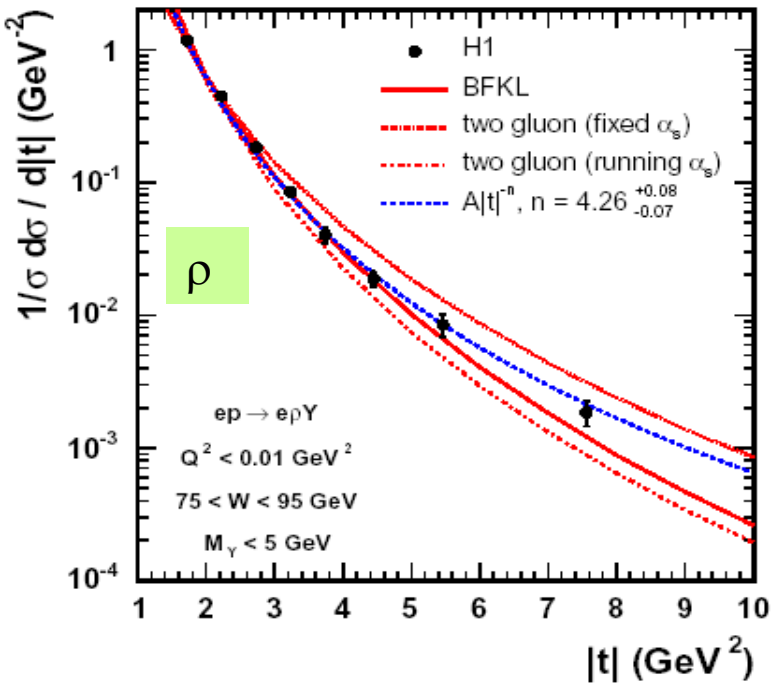
in agreement with dispersion relation analysis $\rho = \tan(\pi\ \delta(Q^2)/8) = 0.25 \pm 0.03 \pm 0.05$

VIII. Large |t|

t dependences

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





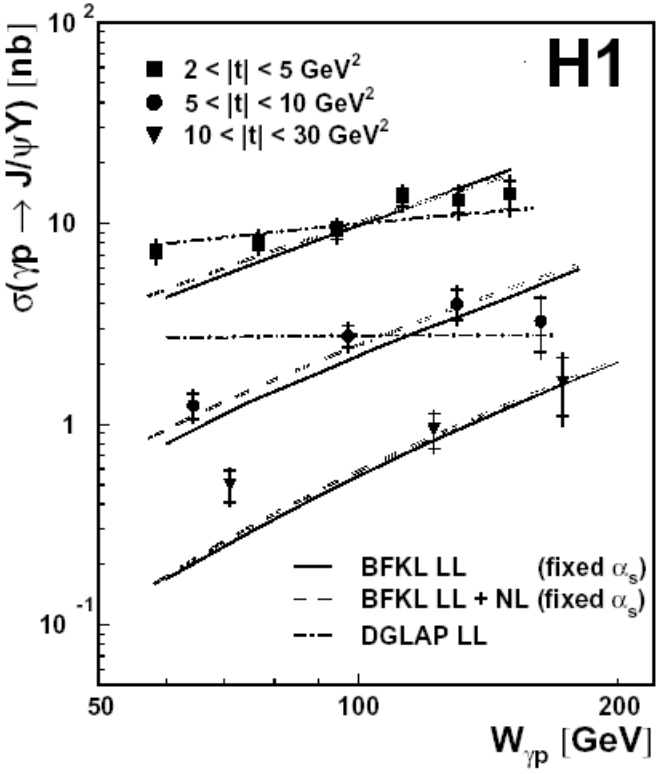
J/Ψ BFKL running α_s excluded

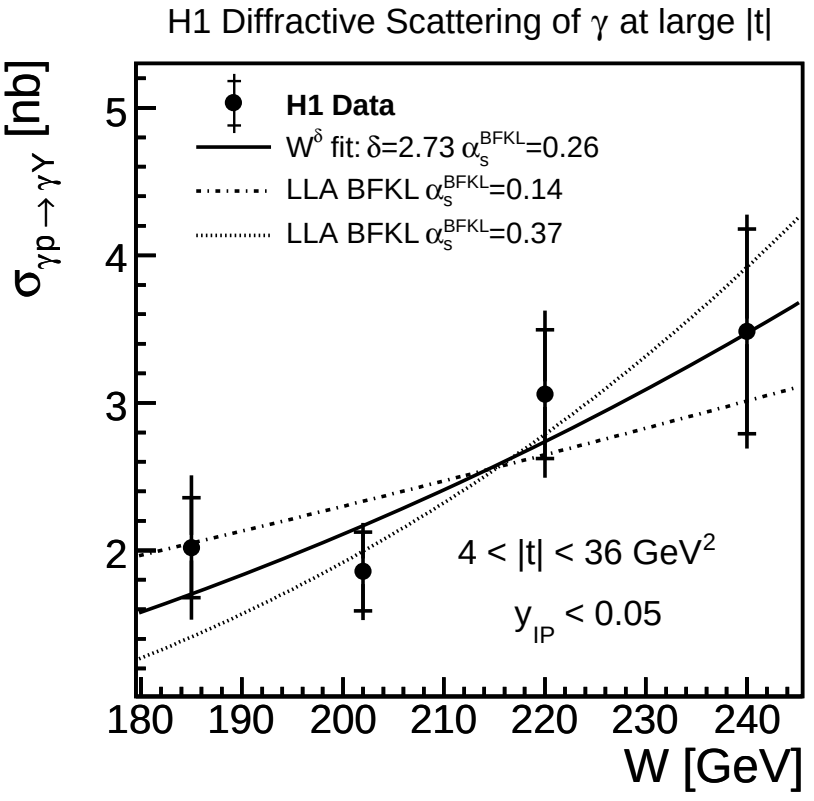
DGLAP OK ($t < M_\Psi^2$)

see also helicity below

BFKL favoured

W dependences





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

SDME (ρ)

"naïve" pQCD predicts large helicity flip, with long. ρ dominating at large $|t|$ (t ~ t)

But SCHC T → T dominates

+ double flip T → T

Reason :

chiral odd contribution in γ

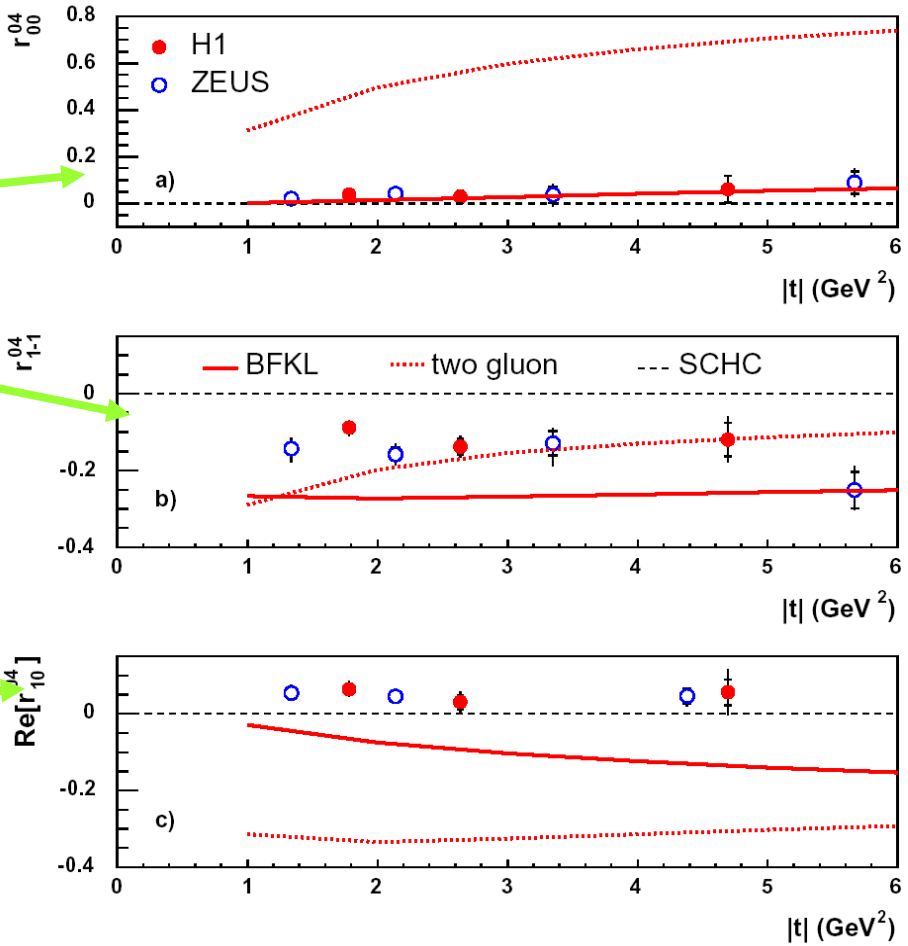
(due to constituent quark mass)

→ no orbital momentum needed for Ψ_T

→ SCHC

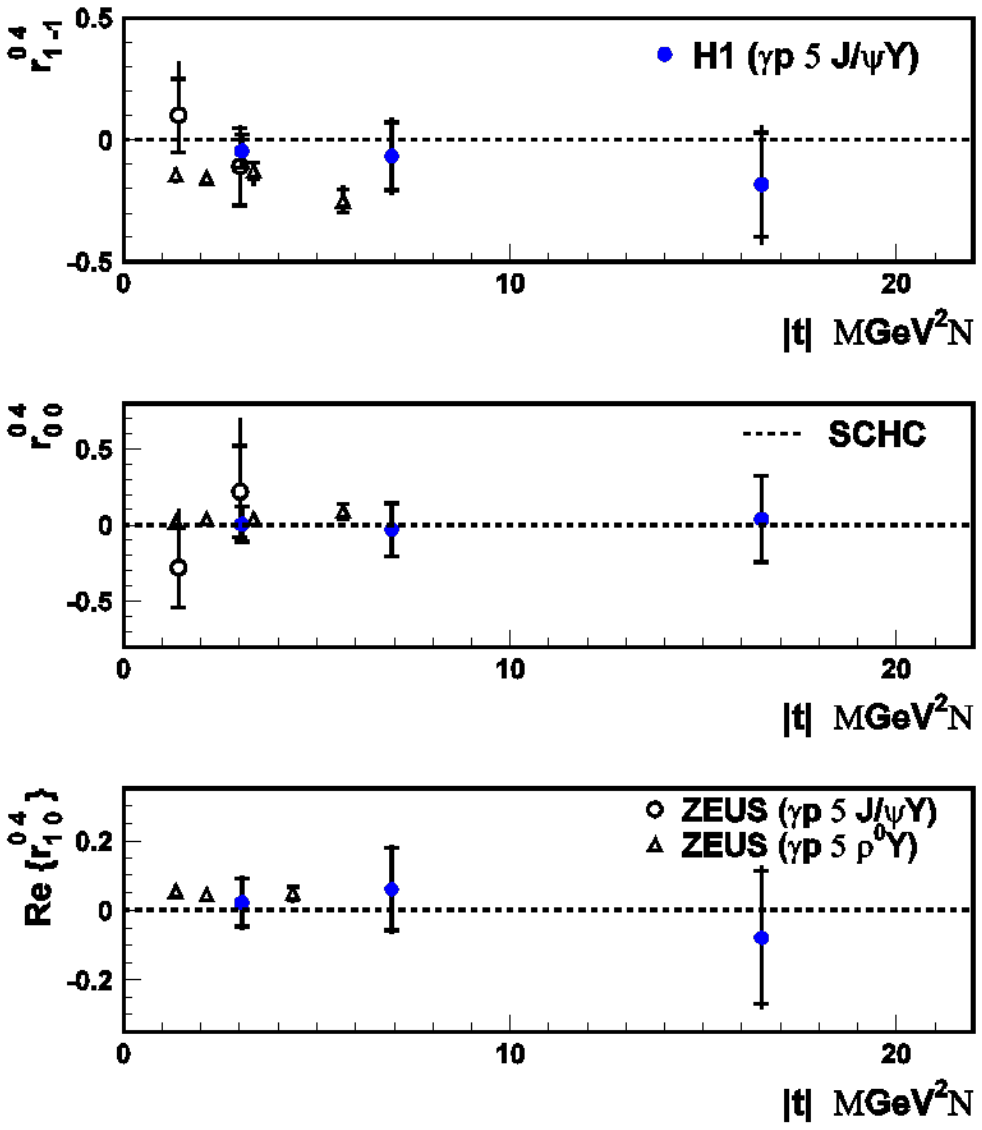
BFKL model describes data, except for sign of

cf. also t and W dependences



SDME (J/ψ)

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



IX. Summary and conclusions

Summary

Small |t| (electro- and photoproduction)

- ***Q²*, *W*, *t*** measurements of DVCS, ρ and φ, J/ψ production
  hard features for sufficient **$(Q^2 + M^2) \geq$ 10-20 GeV²**
- spin density matrix elements and **helicity amplitudes**
  BCA in DVCS -> Re/Im amplitudes
  ρ and φ **SCHC + helicity violations**
  ***Q²* and *t* dependences** of amplitudes qualitatively understood in **pQCD**
  indication of *t* dependence of $R(t)$ for $Q^2 > 5$ GeV² -> **$b_L - b_T \neq 0$ at 1.5 σ**
  $\cos(\delta) \neq 1$
  J/ψ **SCHC**, also at large |t|
  scaling of $R(Q^2)$ for various VM
- effective Regge trajectory
  intercept **$\alpha_{IP}(0)$ increases** with scale $Q^2 + M^2$ (DVCS, ρ and φ, J/ψ)
  slope **$0 < \alpha' < 0.25$ GeV^{-2}** for VM : ρ photoprod., ρ and φ, J/ψ; indication for $\alpha' < 0$ for J/ψ at large |t|
- GPD and dipole **models** describe main features, but differences in details

Large |t| (photoproduction)

- hard *W* dependences
- power-law dep. of t distributions
- SDME ρ : SCHC + doiuble flip (chiral odd contrib.)
  J/ψ : SCHC
- BFKL describe main features, DGLAP OK only for $|t| < m_\psi^2$

Conclusions

Very rich and varied landscape,

explored by ZEUS and H1, complementing lower energy experiments

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

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

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

Many thanks to the DIS09 convenors,

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

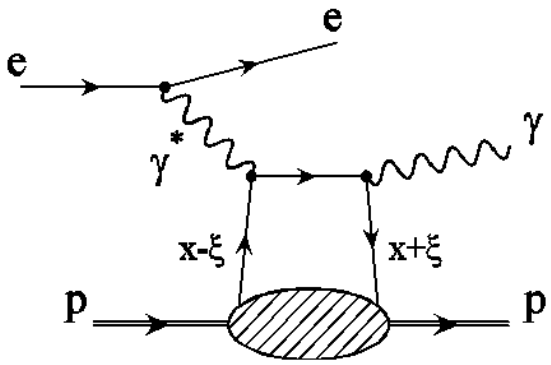
Backup

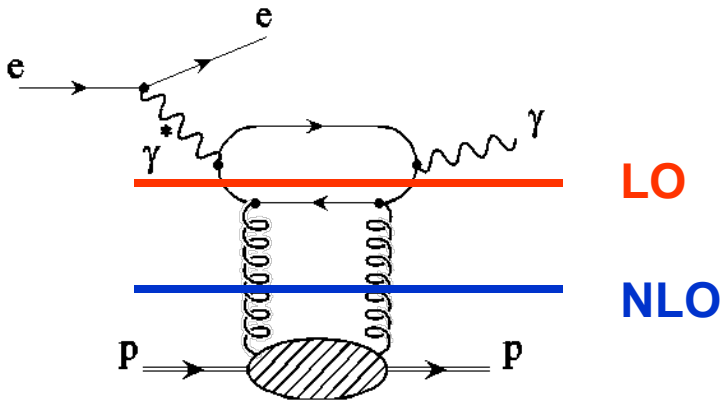
DVCS : remark on scales

DVCS and VM universality of W dependence ($a_P(0)$) and t dependence (b),
for scale taken as

$\mu^2 = Q^2$ for GPD (LO ~60% of cross section, NLO 40%)

$\mu^2 = (Q^2 + M^2)/4$ for dipole model (2 gluon exchange)





LO = quark sea - scale = Q^2

NLO = gluons - scale = $(Q^2 + M^2)/4$

NB separation between LO and NLO depends on factorisation scale

-> indication from data that DVCS scale ~ Q^2 rather than $(Q^2 + M^2)/4$?