DIS 2009

DVCS and Vector Meson production with H1

Soft and hard diffraction, spin dynamics and QCD

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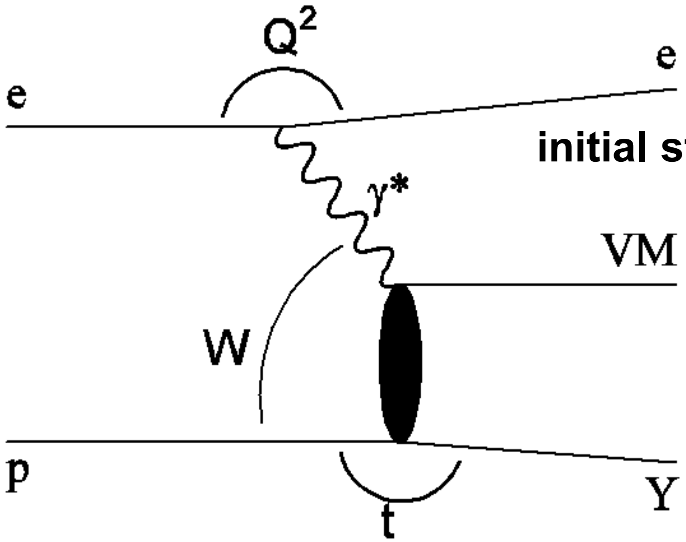
DVCS and VM production



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 GeV^2 photoproduction & DIS

$W \approx \sqrt{(Q^2/x)}$ 30 – 300 GeV

$|t| \approx |p_{t,miss}|^2 = |\vec{p}_{t,e} + \vec{p}_{t,VM}|$ small |t| (< 0.5 – 3 GeV^2)   large |t| (2 < |t| < 10-30 GeV^2)

dσ / d*Q*^{2}, d*W*, d*t*

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	γ^* **->** γ	v	v	v	Re / Im	el / pd	hera-2	(1); **prel.**	
light VM	γ **->** ρ		α' meast.		-	-	2005	**prel.**	**B. List**
	γ^* **->** ρ, ϕ	v	v	v	v	el / pd	hera-1	**prel.**	
heavy VM	γ **-> J/**ψ		v	v	v	el.	99-2000	(2)	
	γ^* **-> J/**ψ	v	v	v	v	el.	99-2000	(2)	
***Large* |*t*| (> 2 GeV^2)**									
photon	γ **->** γ		?	v	v	-	99-2000	(3)	**T. Hreus**
light VM	γ **->** ρ		?	v	v	-	2000	(4)	
heavy VM	γ **-> J/**ψ		?	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In this talk, emphasis on unpublished data HERA-1 O(100 pb^{-1}); HERA-2 O(350 pb^{-1})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

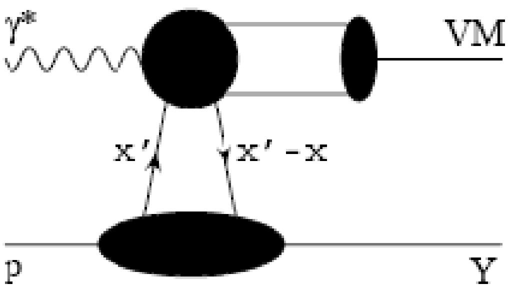
c. spin density matrix elements

IX. Summary and conclusions

I. QCD and models

Photon and VM production in QCD

collinear factorisation



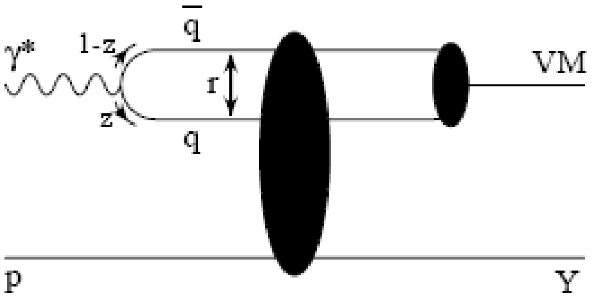
GPD

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

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

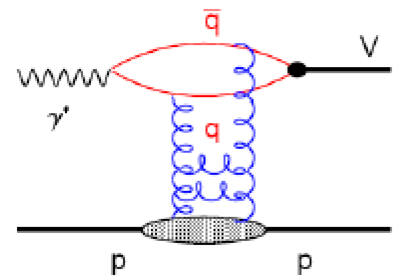
complementary information

parton correlations in proton

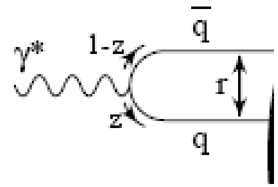
universal q qbar dipole interactions

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 $\mu^2 \simeq z(1-z)\,(Q^2+M^2)$

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

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

-> 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

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

estim. : MC with measured cross sections

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

$\to \pi^+ \pi^- +$ 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|)

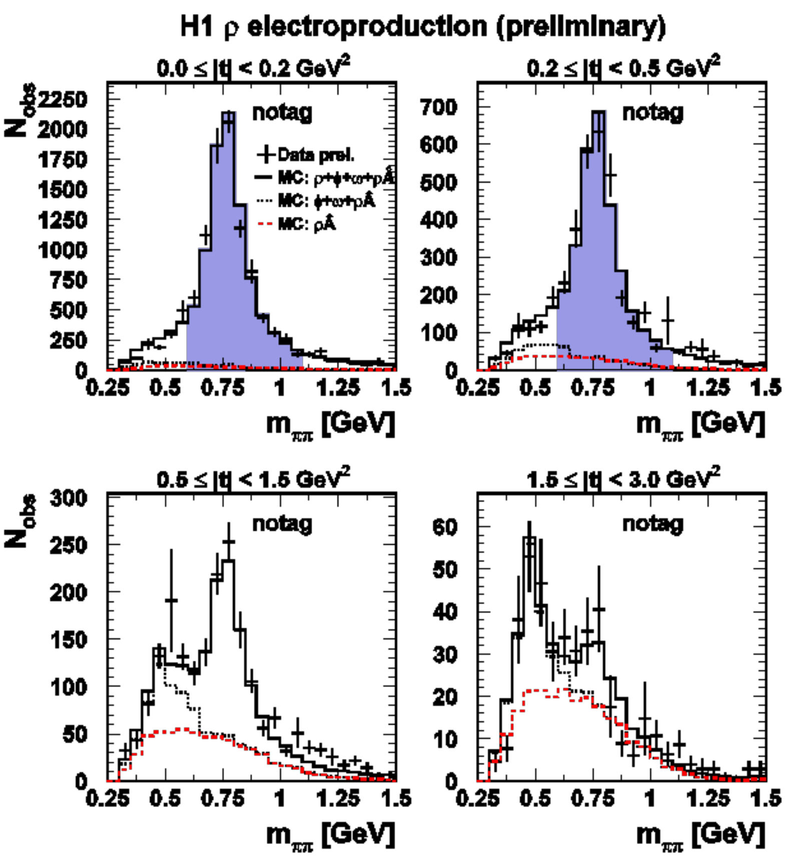
---> effect on |t| slopes

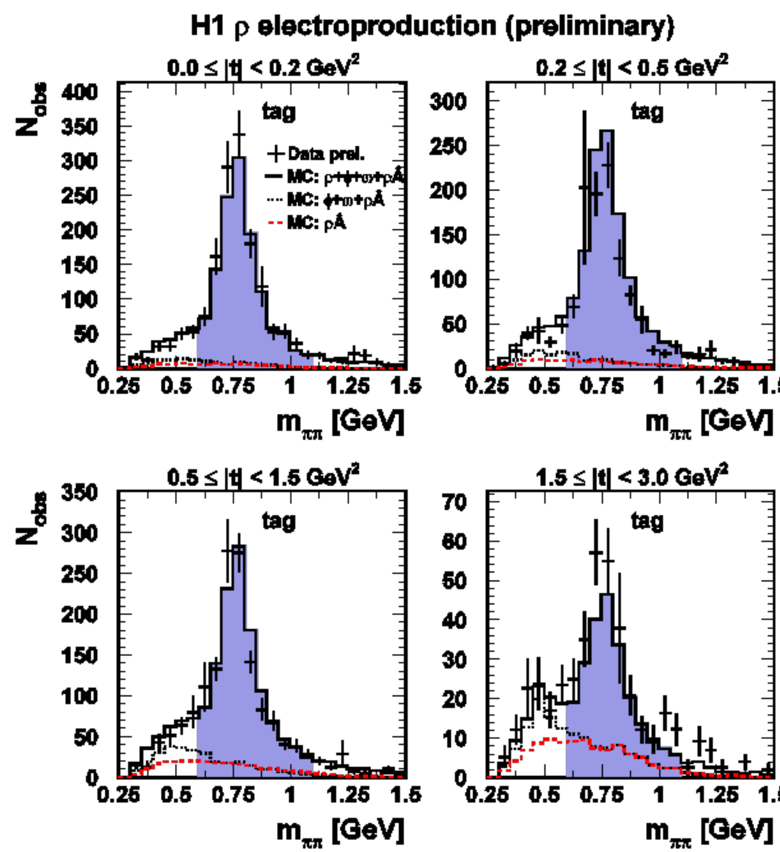
---> effect on spin density matrix elements (uniform background)

ϕ mesons

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

ρ : $m_{\pi\pi}$ mass shapes

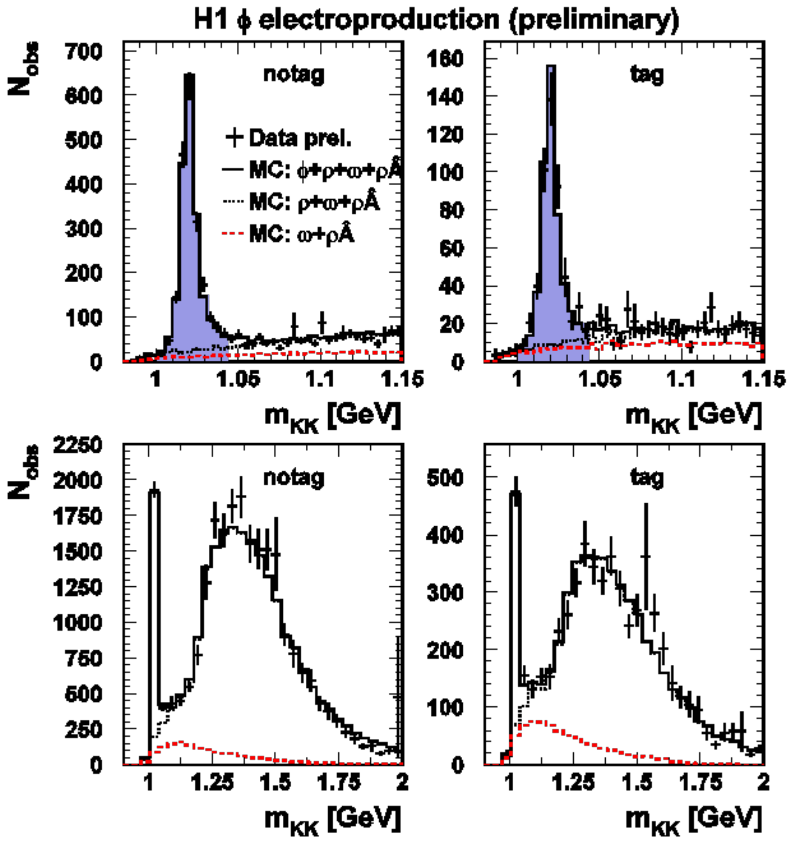




ρ' contribution is obtained from $0.6 < m_{\pi\pi} < 1.1$ GeV and extrapolated to **full mass range**

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

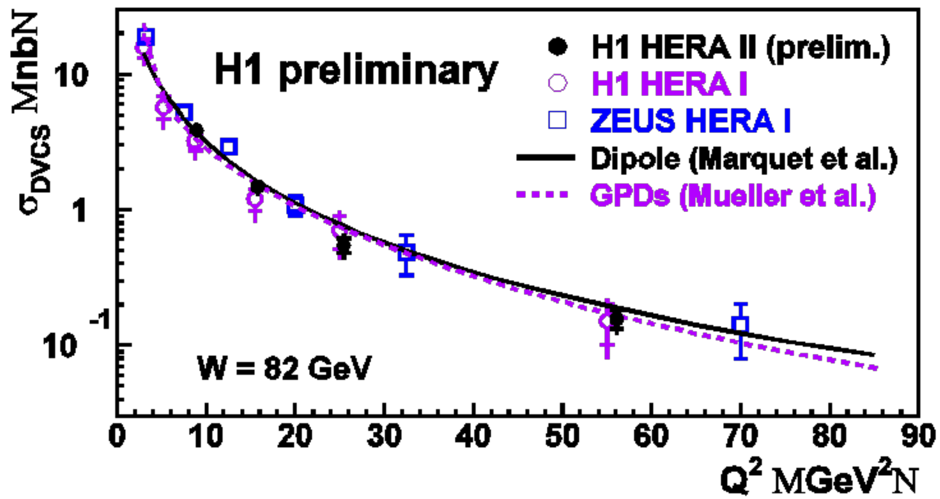


III. DVCS and VM Q^2 dependences

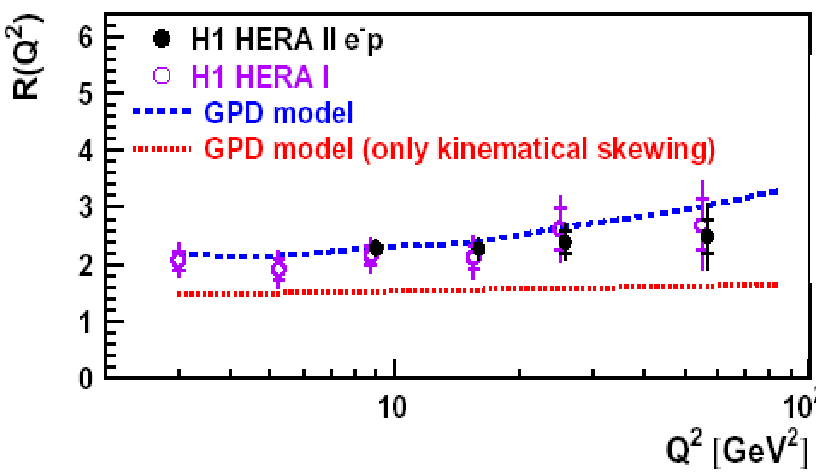
DVCS

GPD and dipole models

(HERA-2 data)

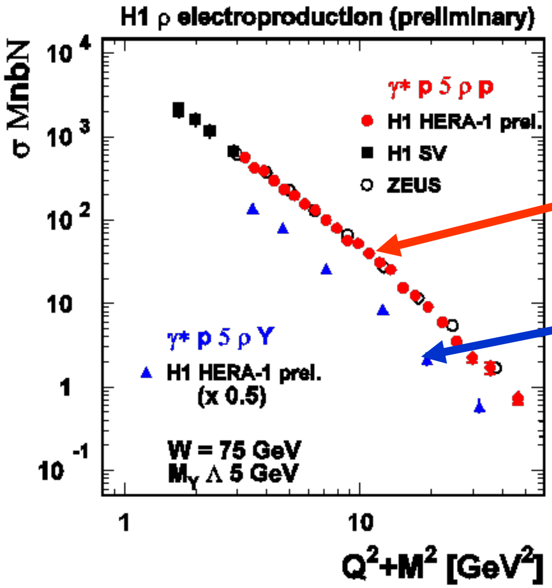


GPD's take into account skewing – but kinematic **skewing is not sufficient**



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

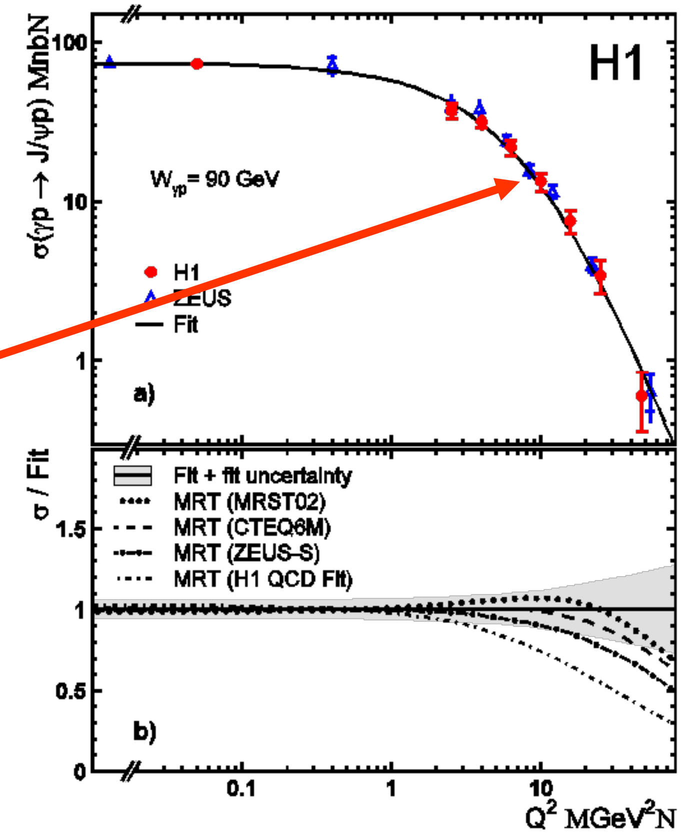
ρ and φ (el. and p. diss.), J/ψ



HERA-1 data

ρ el.

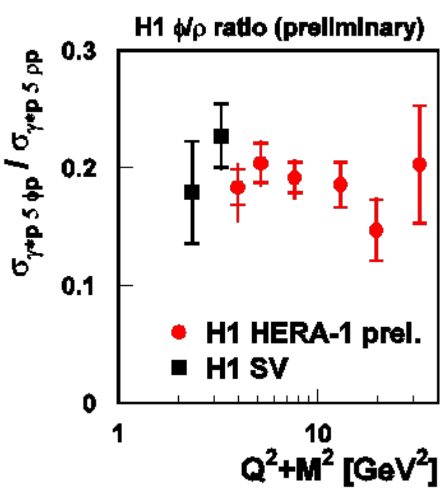
ρ p.d.



J/ψ

1999-2000 data

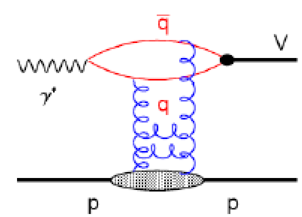
(excellent agreement with ZEUS)



φ/ρ

universal dipole – proton cross sections

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



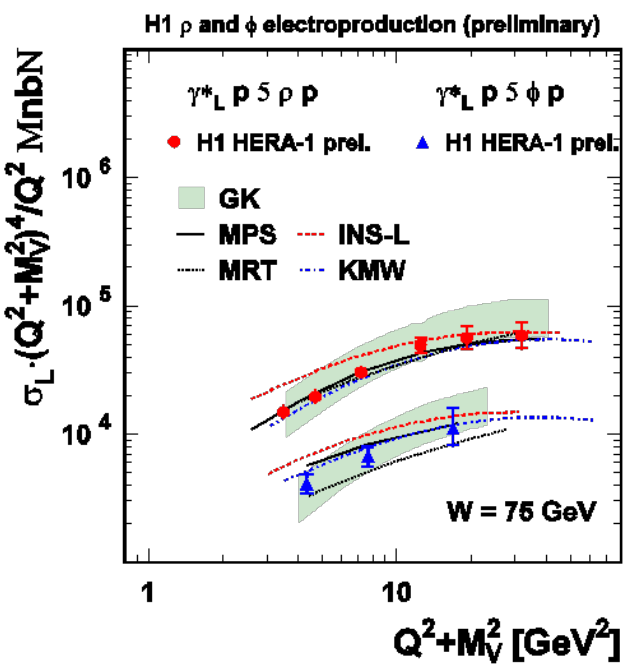
Polarised distributions

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

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

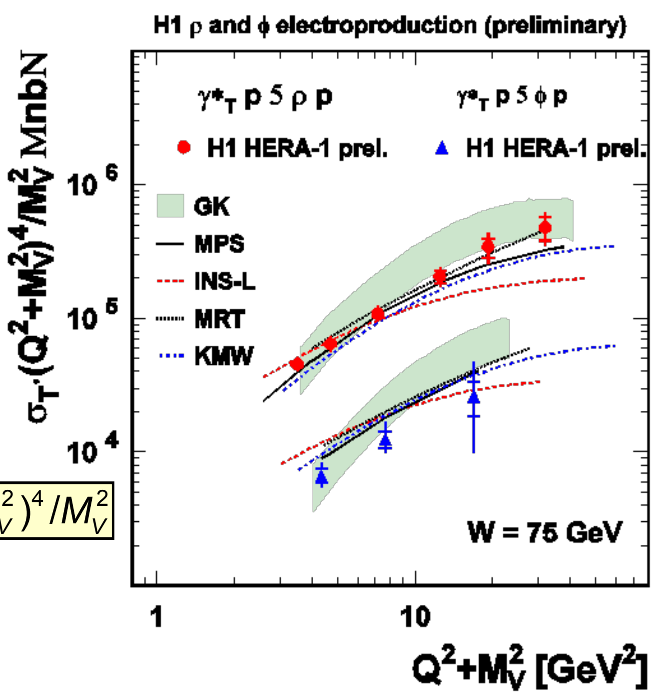
Scaled presentation (I. Ivanov)

(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

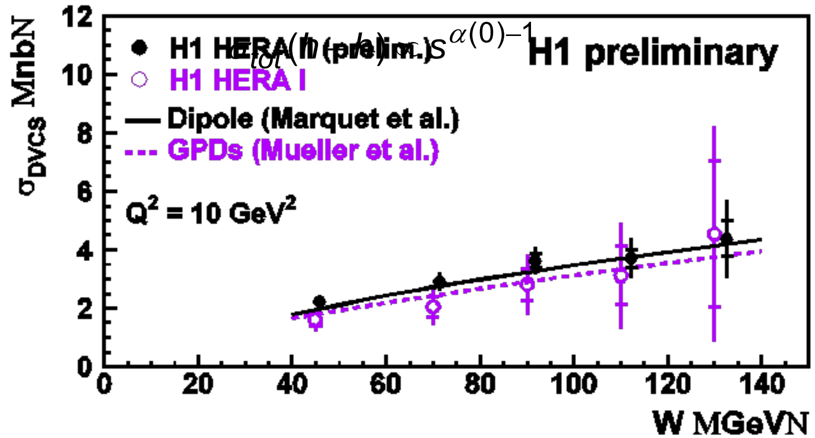
W dependences

power law dependence: W^{δ}

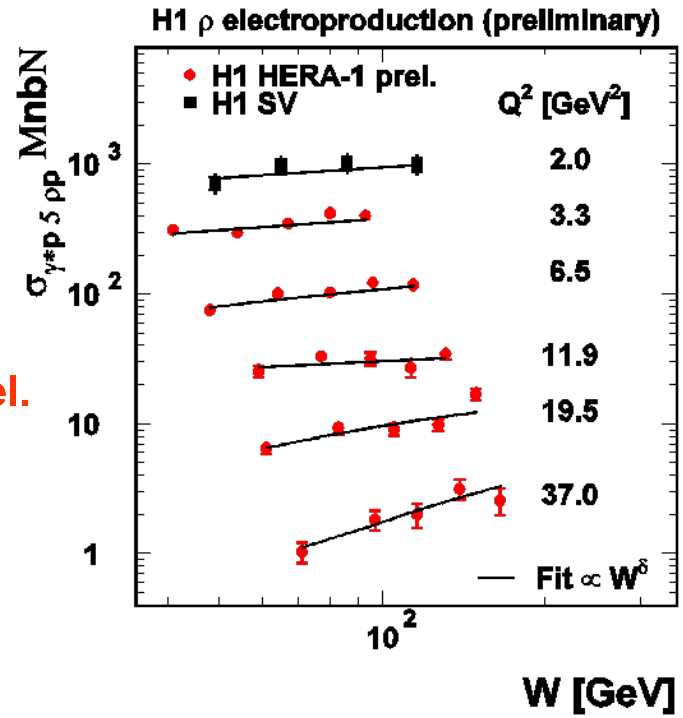
cf. high energy *h–h* interactions **(Regge)**

$\sigma_{tot}(h-h) \propto s^{\alpha(0)-1}$

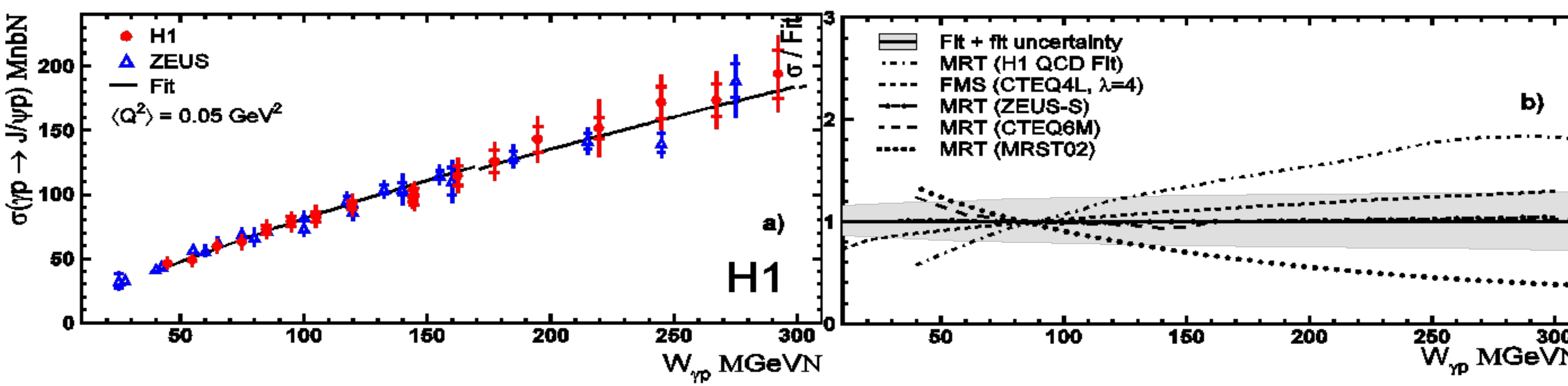
DVCS



ρ el.



J/ψ



$\alpha_P(0)$

high energy *h–h* interactions :

$$\sigma_{tot}(h-h) \propto s^{\alpha(t)-1}$$
$$\alpha(t) = \alpha(0) + \alpha' t$$
$$\alpha(0) \simeq 1.08 \quad (\text{"soft"})$$
$$\alpha' \simeq 0.25 \text{ GeV}^{-2}$$

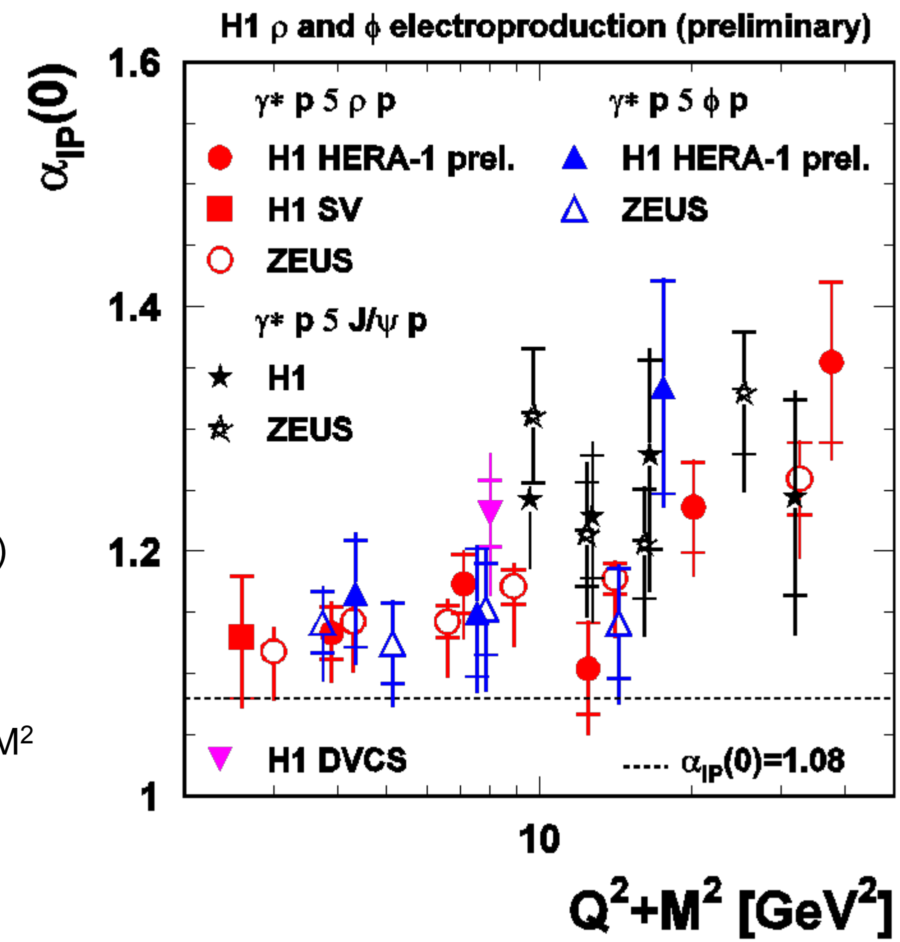
VM production

$\sigma \sim |x\,G(x)|^2$ -> **“hard” W dependence**

hardening of gluons with scale (quark mass, Q^2)

-> **α(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

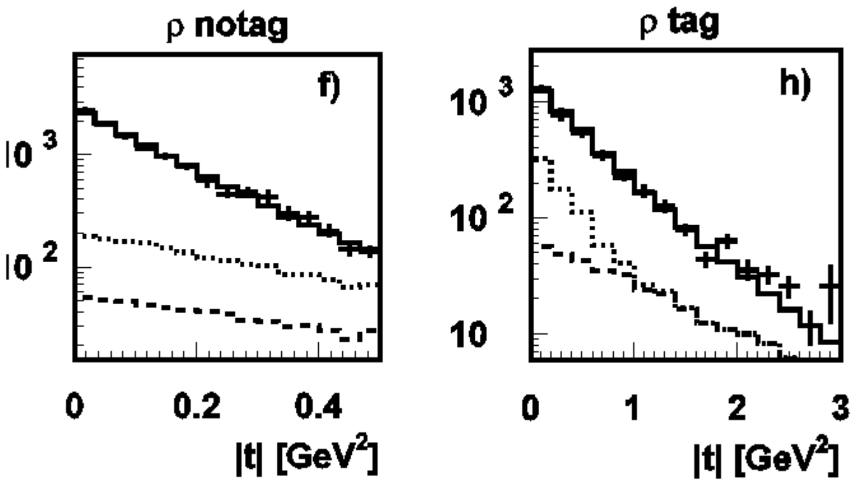
V. *t* dependences

t dependences

exponential *t* dependence

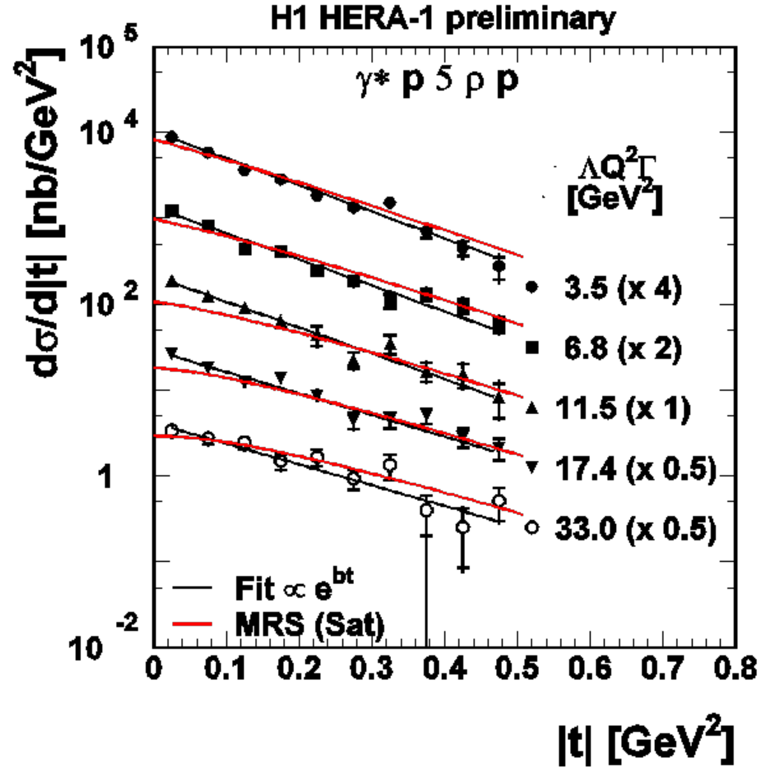
$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

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



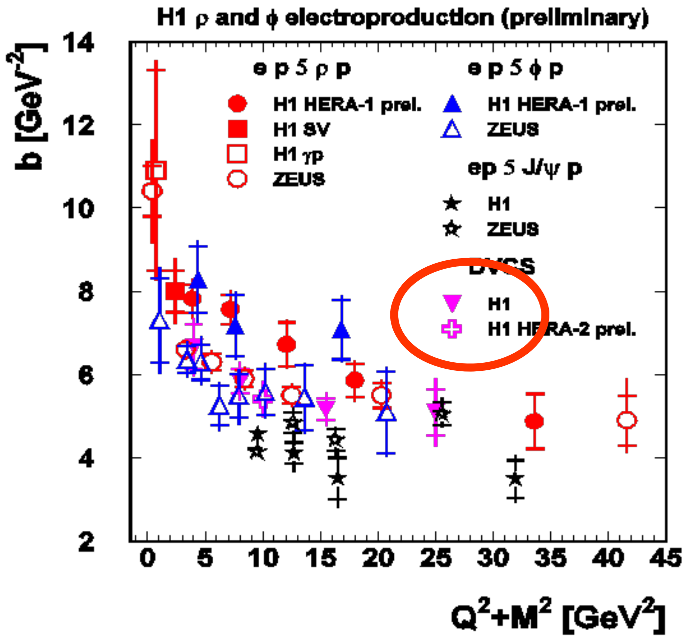
Elastic (p. diss.) slope extraction: exper. effects:

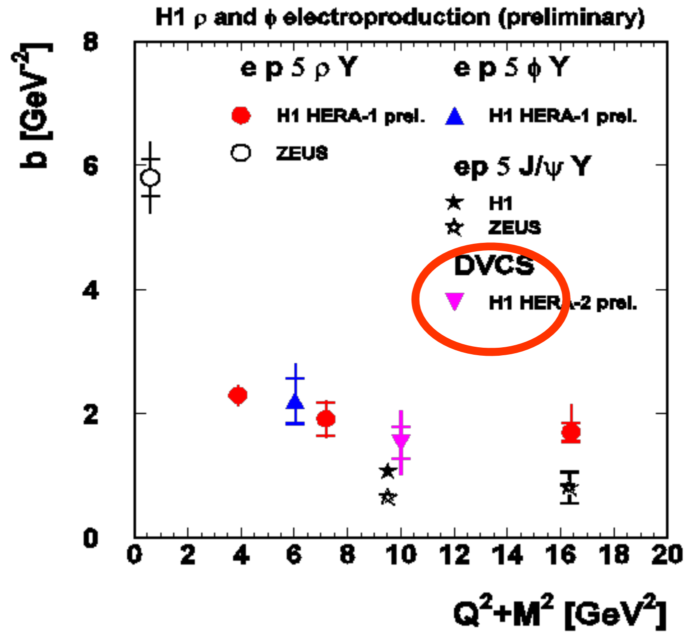
- **amount** and effective **slope** of **VM (ρ' etc.)** bg. (lower histo.)
- **amount** and **slope** of **p. diss.** (**el.**) bg. (upper histo.)



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

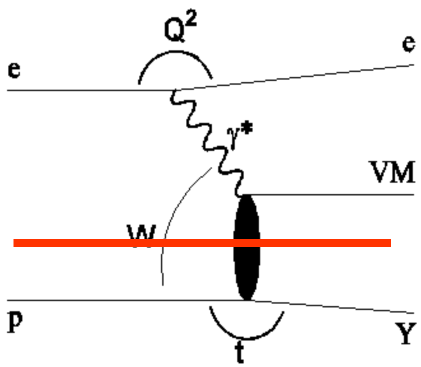
- ✓ ***b* decrease** with dipole size (Q^2, m_Q)
- ✓ **universal** scale dependence $\mu^2 = (Q^2 + M^2)/4$ for VM

  $\mu^2 = Q^2$ 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

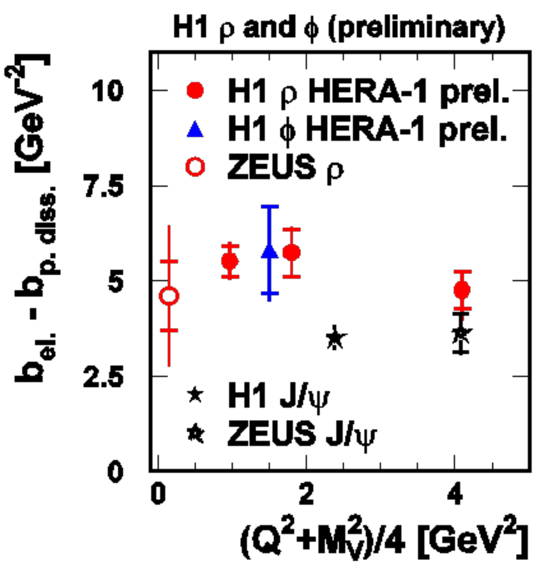
Vertex ("Regge") factorisation



✓ $\dfrac{d\sigma/dt\ (\text{p.diss.})}{d\sigma/dt\ (\text{elast.})}(t=0)$ 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 **α' = 0.25 GeV^{-2}**

W dependence of diffractive peak ("shrinkage")

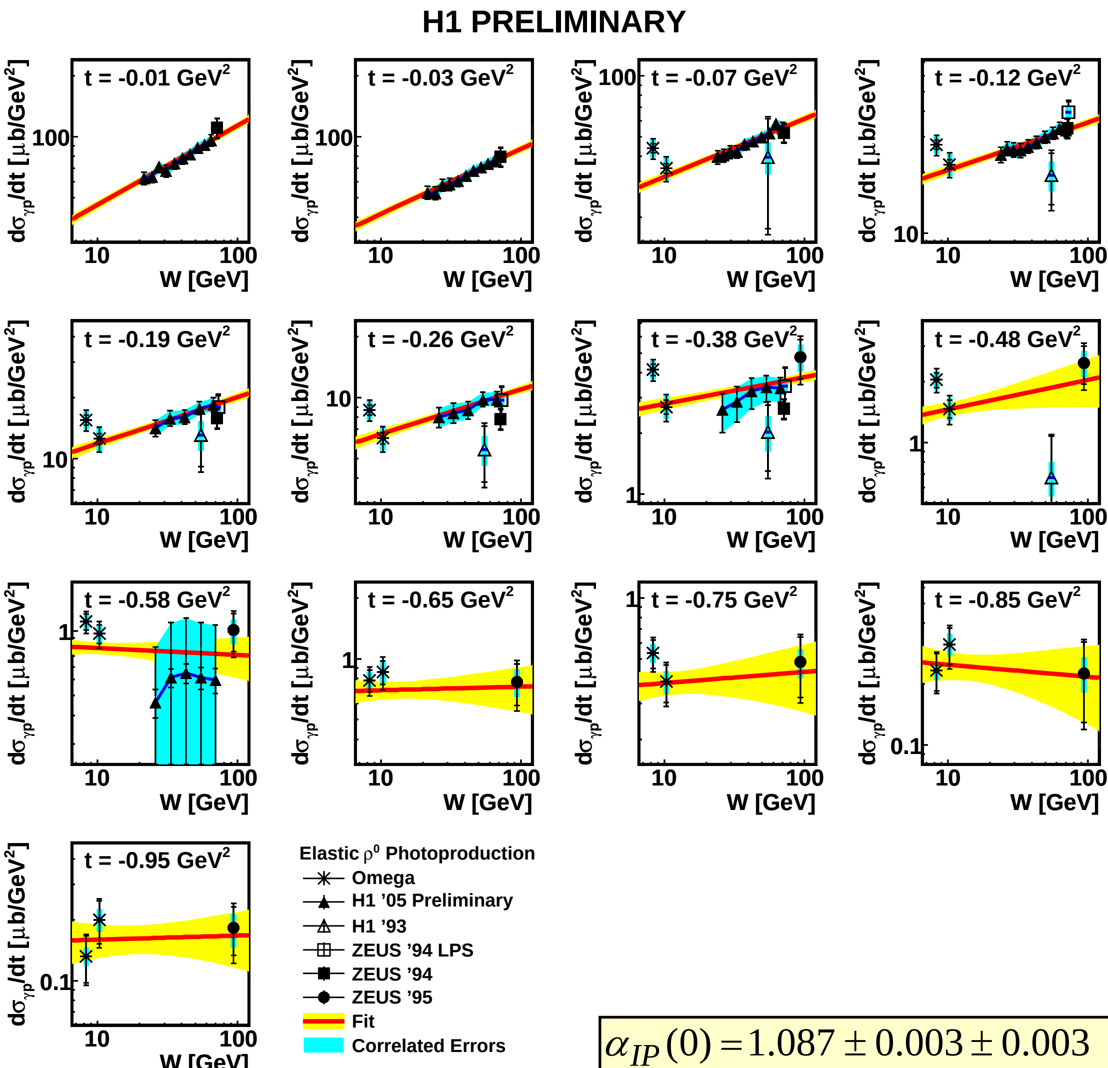
$$\frac{d\sigma}{dt}(W) = e^{bt} = e^{b_0 t}\, W^{4(\alpha(0)+\alpha' t-1)}$$

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

=> α' **measurement** through

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

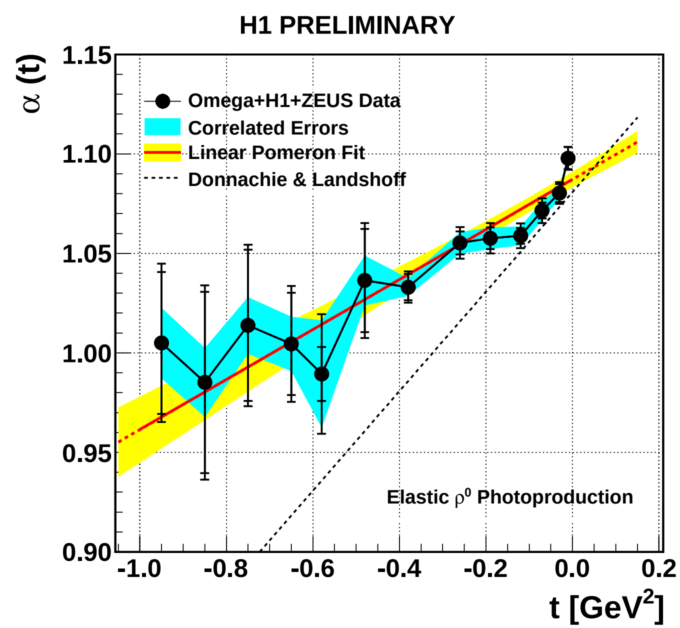
Regge trajectory (ρ photoprod.)



H1 prelim. 2005 data

High energy H1

Low energy Omega

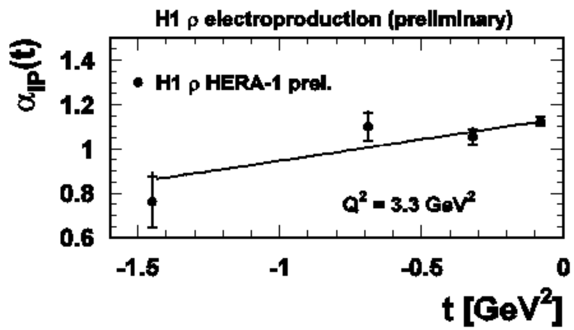


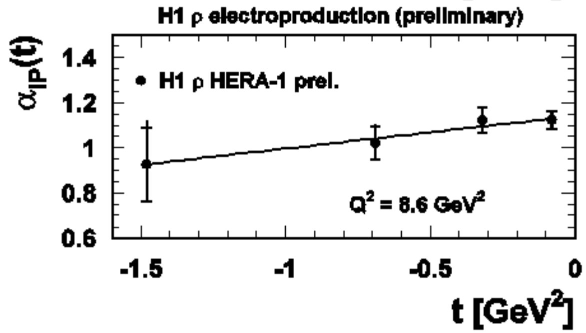
$$\alpha_{IP}(0) = 1.087 \pm 0.003 \pm 0.003$$

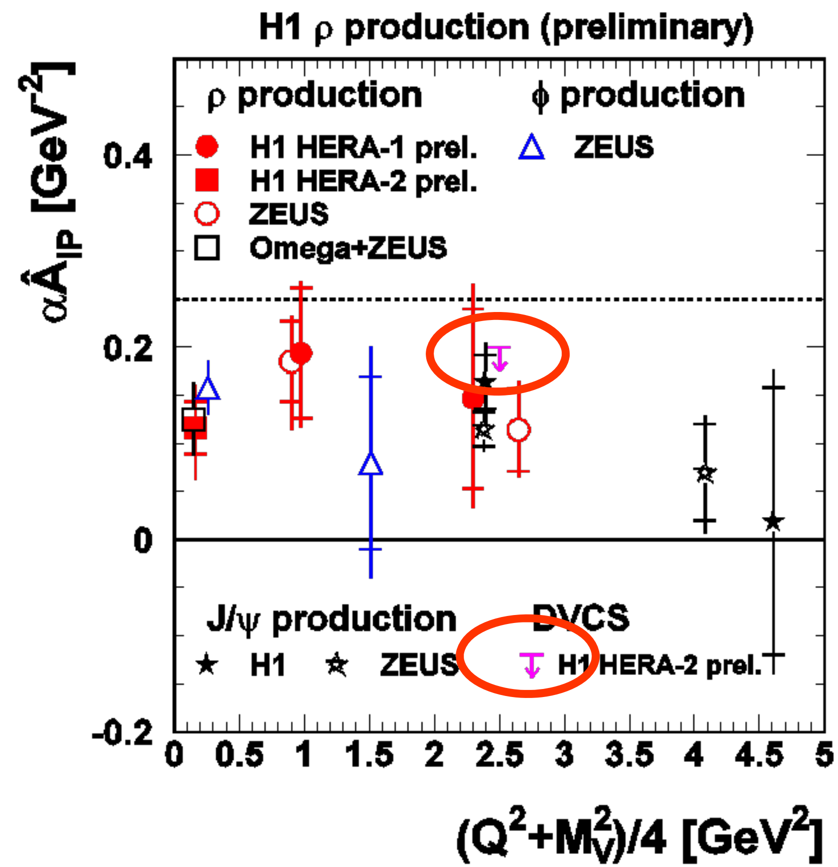
$$\alpha' = 0.126 \pm 0.013 \pm 0.012\ \mathrm{GeV}^2$$

Regge trajectory (small |t|)

ρ electroprod.







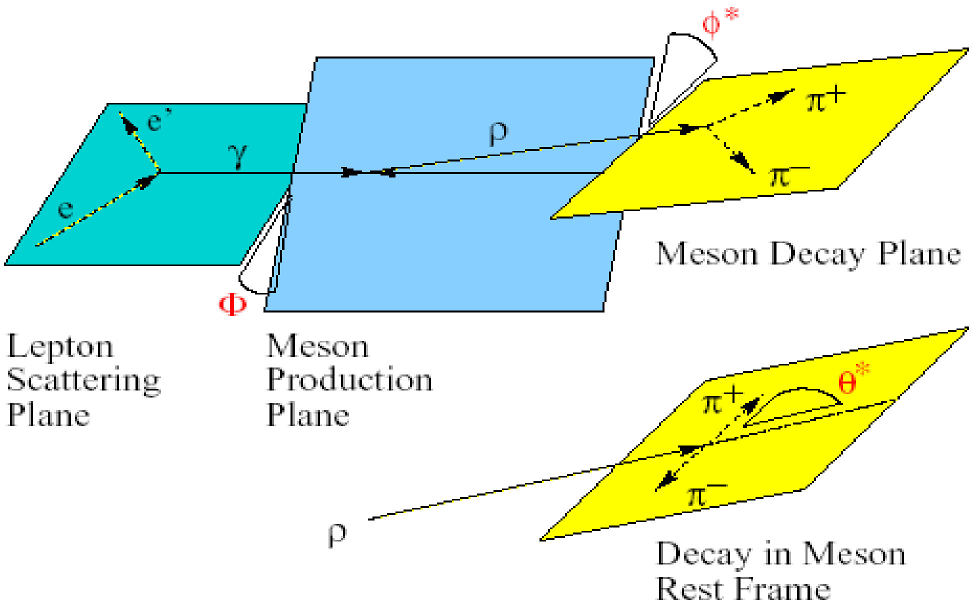
systematically: α' **< 0.25 GeV^{-2}**

NB J/ψ 2 < |t| < 30 GeV^2 : α' = - 0.014 ± 0.007 ± 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}

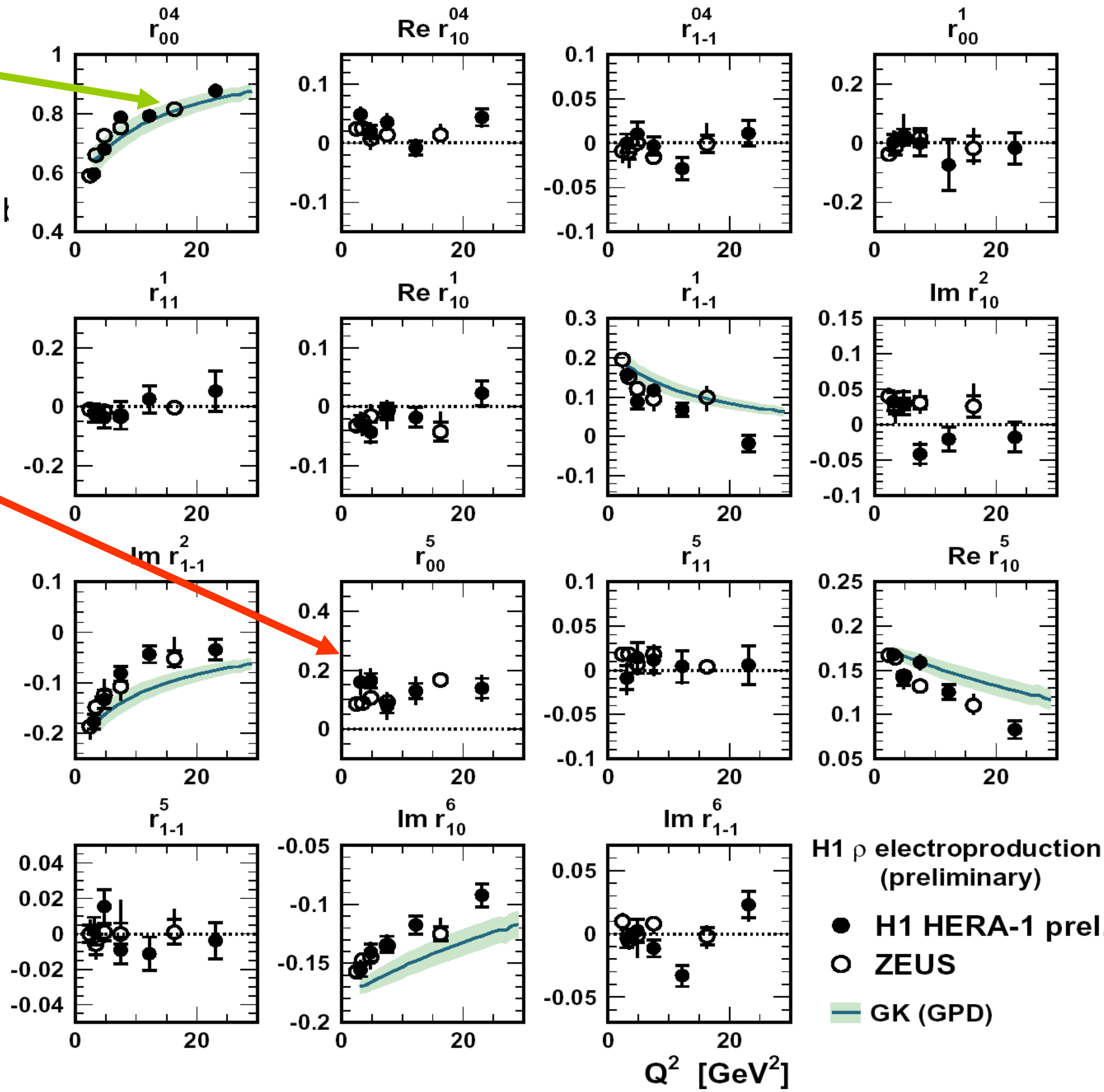
double flip $T_{-1\,1}$

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

5 SCHC elements
compared to GPD calculations

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

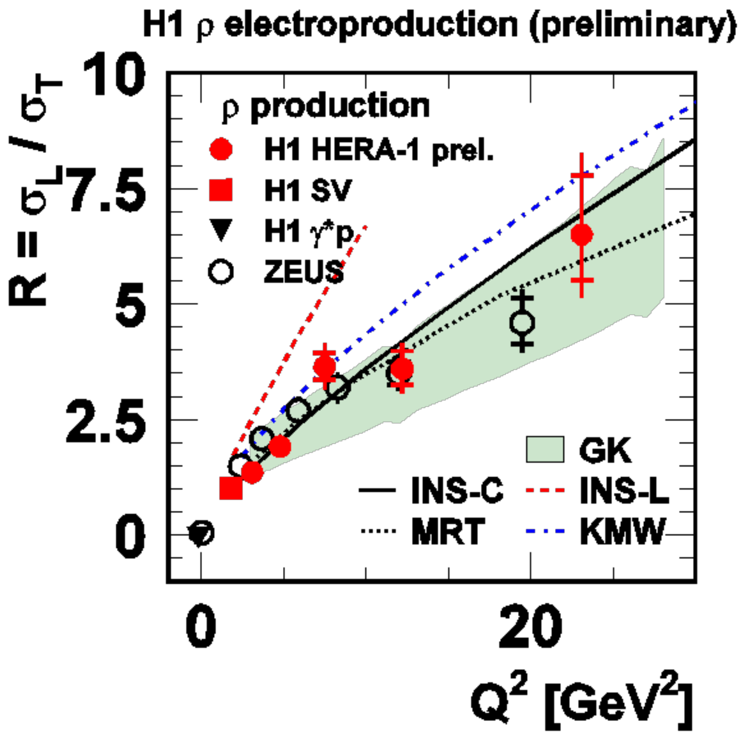
except **~ $T_{01}\, T_{00}^*$**

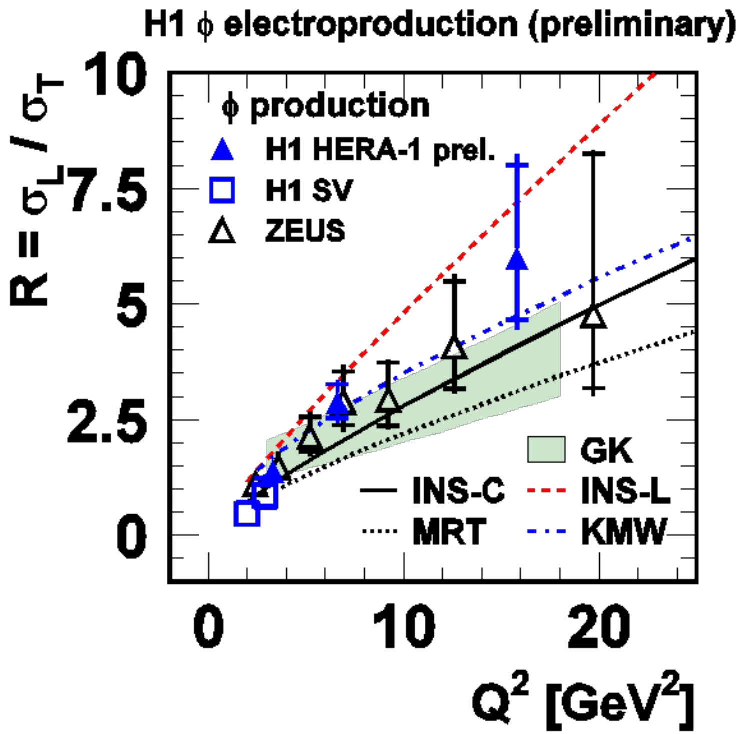


several models
(GPD, unintegrated k_t,
dipole + saturation)
can reproduce
general features of
SCHC amplitudes + hierarchy
but not details

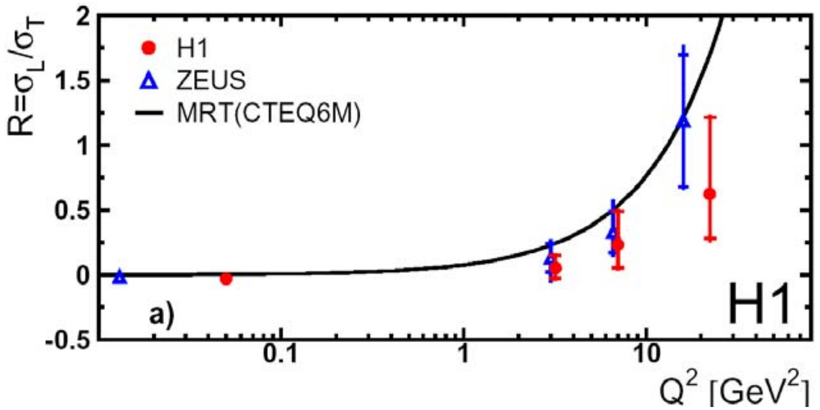
R (Q^2) (ρ, φ)

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

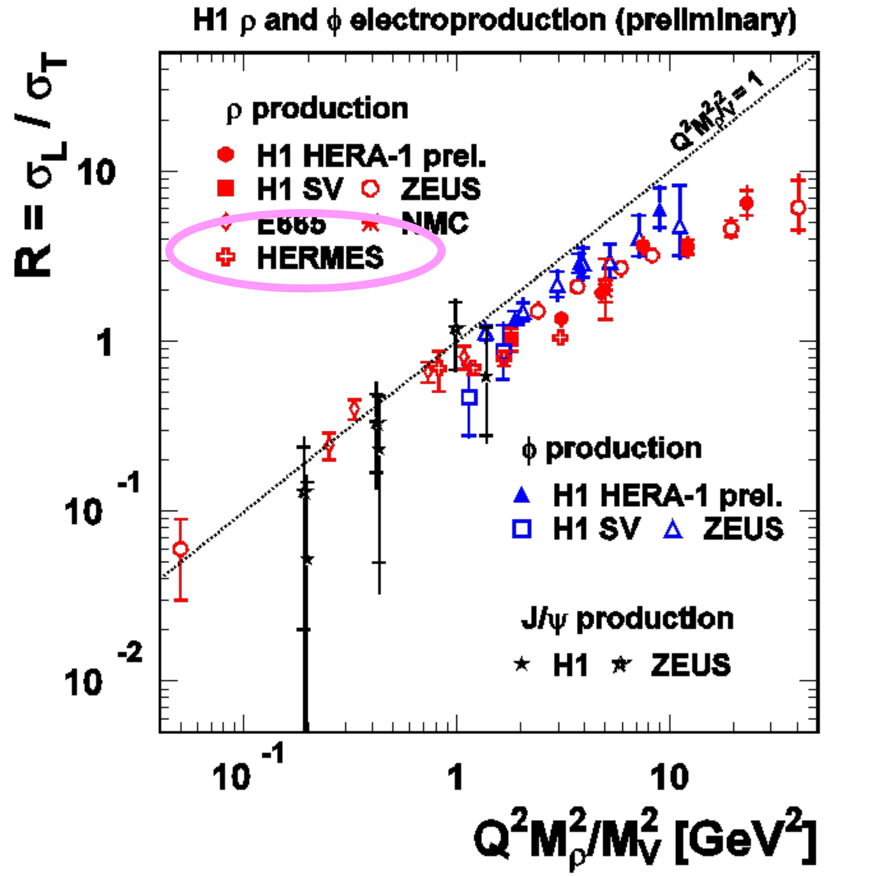




scaling of *R* (Q^2)



J/ψ

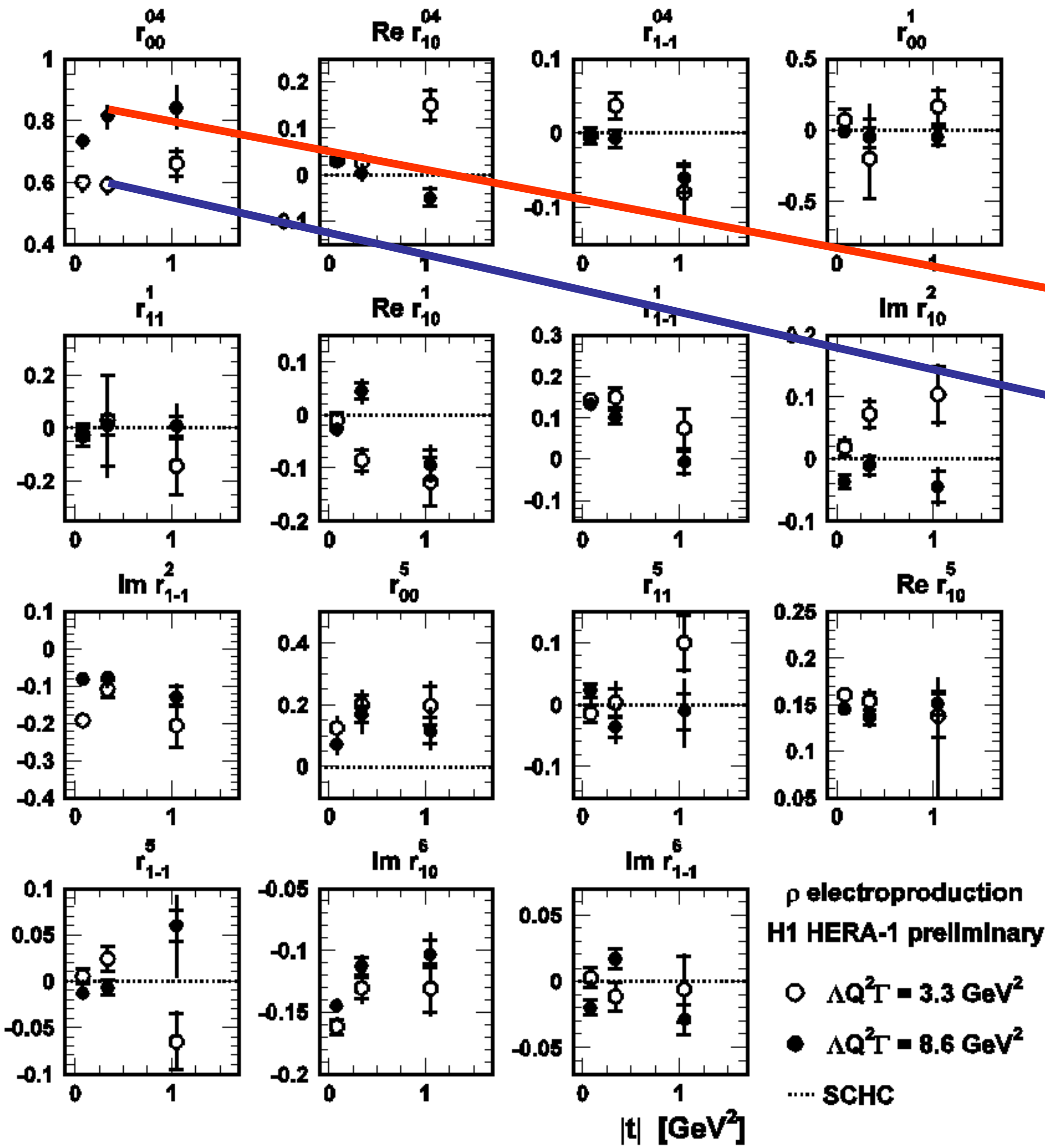


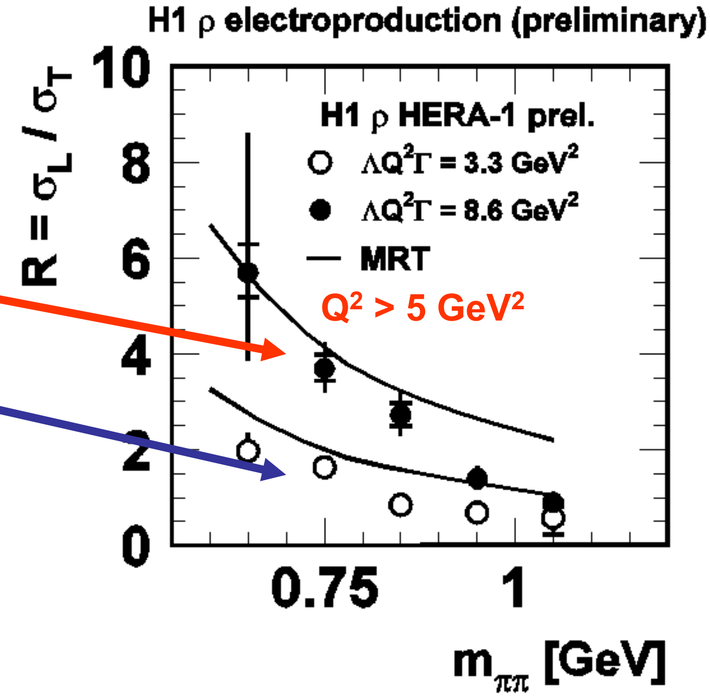
pQCD : formally **$R \sim Q^2 / M^2$**

scaling plot : **$Q^2 \, . \, M^2_\rho / M^2_V$**

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

SDME and R (t) (ρ)





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

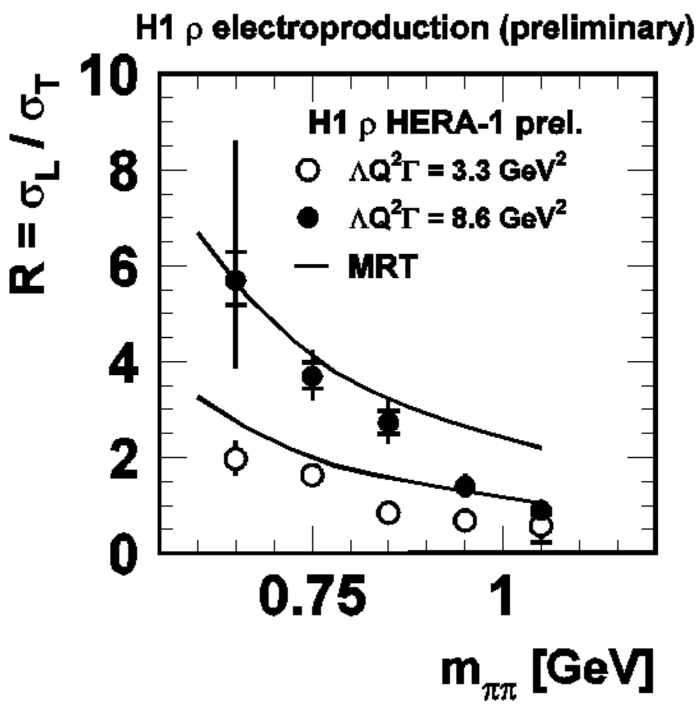
$Q^2 > 5$ GeV^2 :

$b_L - b_T < 0$ 1.5 σ

(stat. + syst.)

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

R (*m*) (ρ)



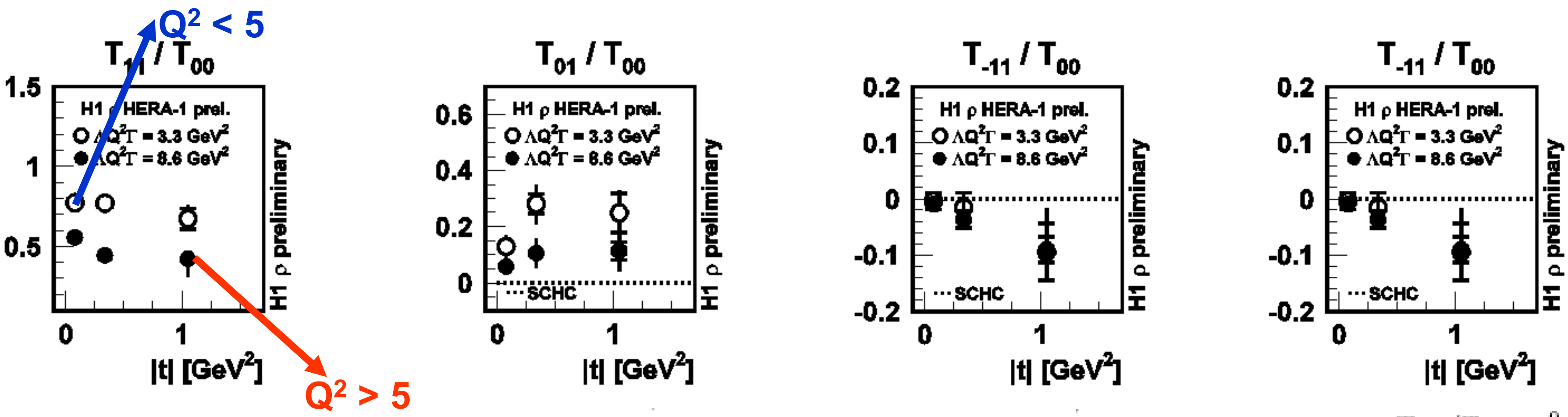
Decrease of R(m) is qualitatively consistent with formal pQCD calculations ***$R \sim Q^2 / M^2$***

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)

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

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

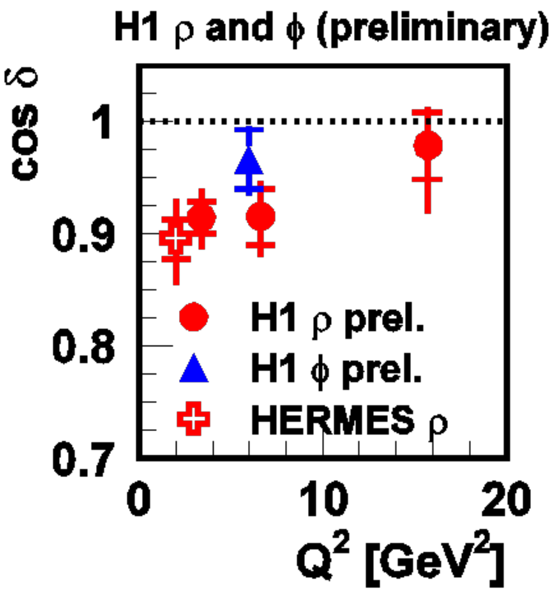
$$T_{-11}/T_{00} = \eta^0 + \eta^1,$$

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

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

- ✓ **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} ≠ 0

phase difference decreases with Q^2

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

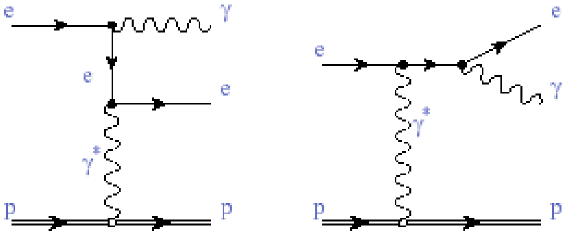
which are related through dispersion relations to the *W* evolutions

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

Beam charge asymmetry in DVCS

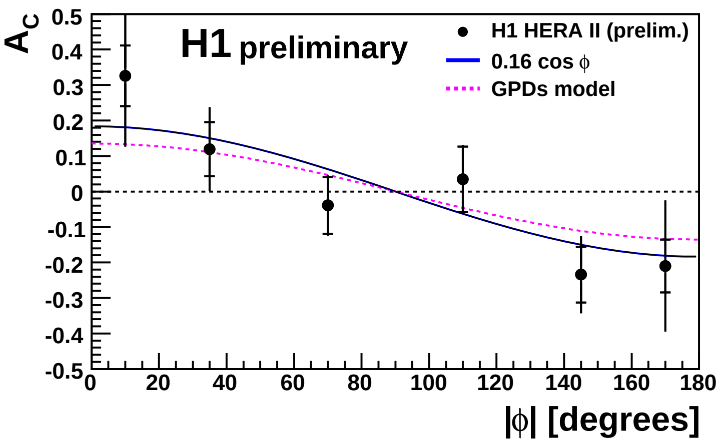
interference with Bethe-Heitler

→ access to **Re contributions**



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

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



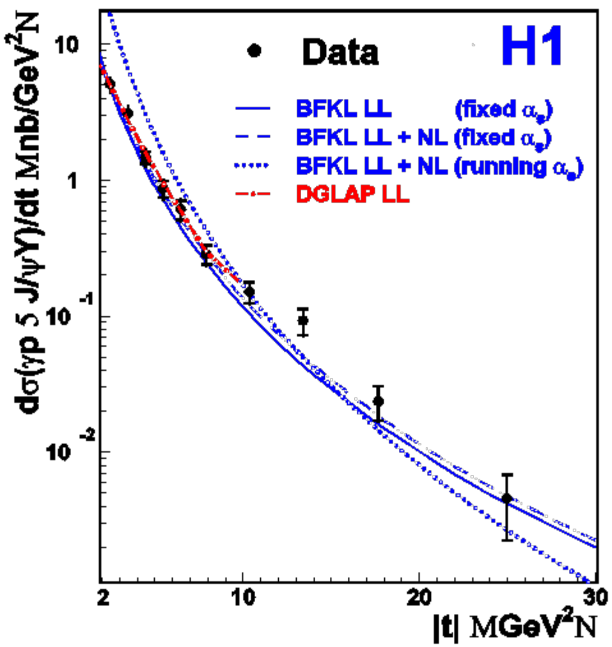
$$\rho = \mathrm{Re}\ A_{DVCS} \,/\, \mathrm{Im}\ A_{DVCS} = 0.20 \pm 0.05 \pm 0.08$$

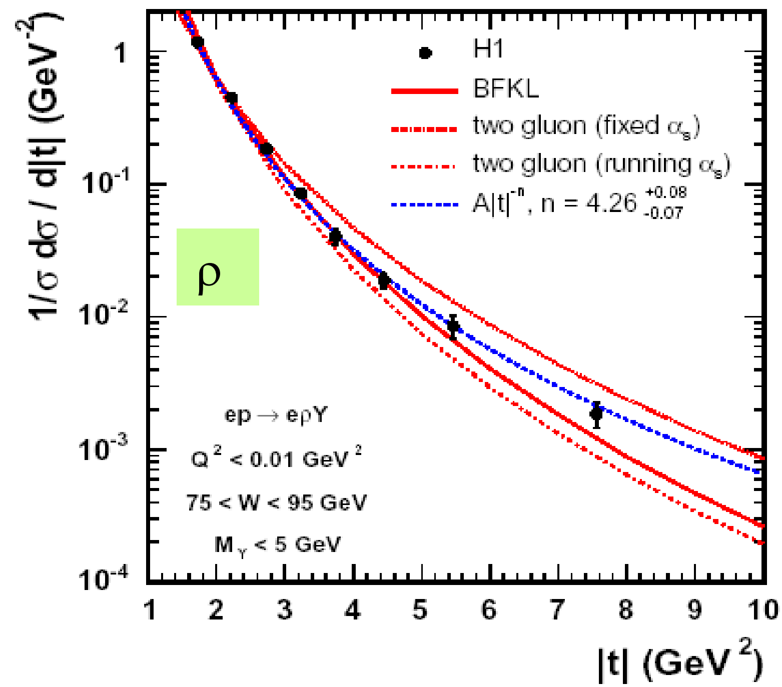
in agreement with dispersion relation analysis $\rho = \tan\,(\pi\,\delta(Q^2)\,/\,8) = 0.25 \pm 0.03 \pm 0.05$

VIII. Large |t|

t dependences

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





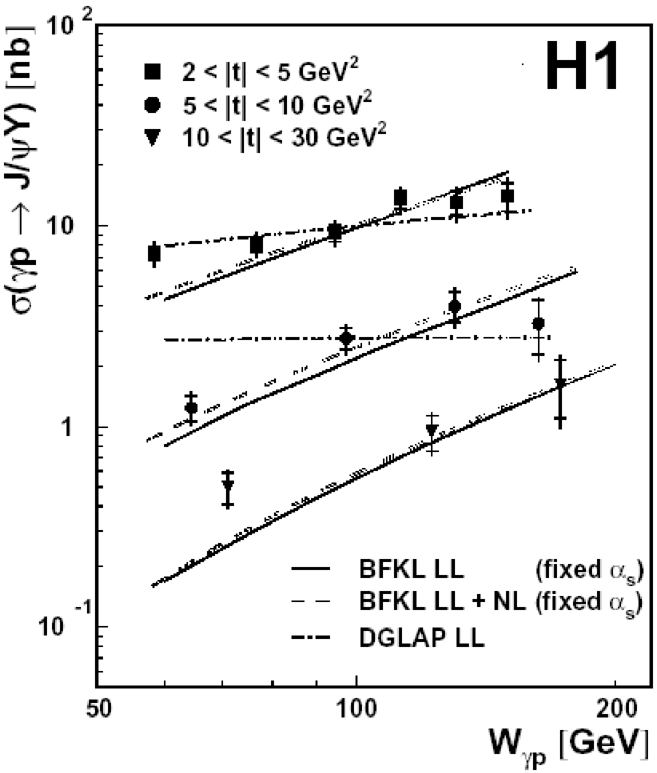
J/Ψ BFKL running α_s excluded

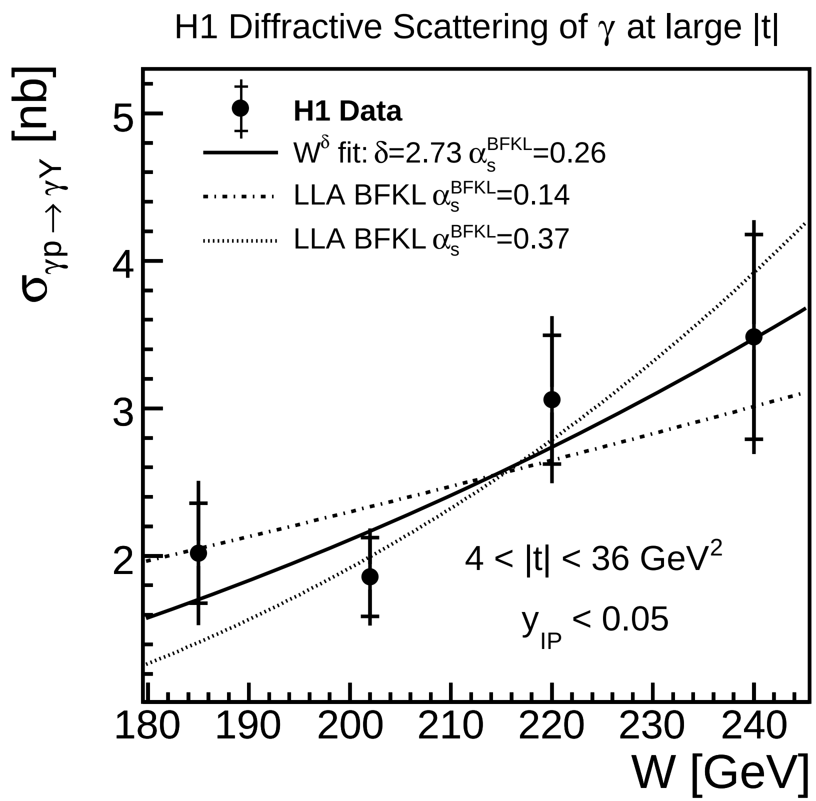
DGLAP OK ($t < M_\Psi^2$)

see also helicity below

BFKL favoured

W dependences





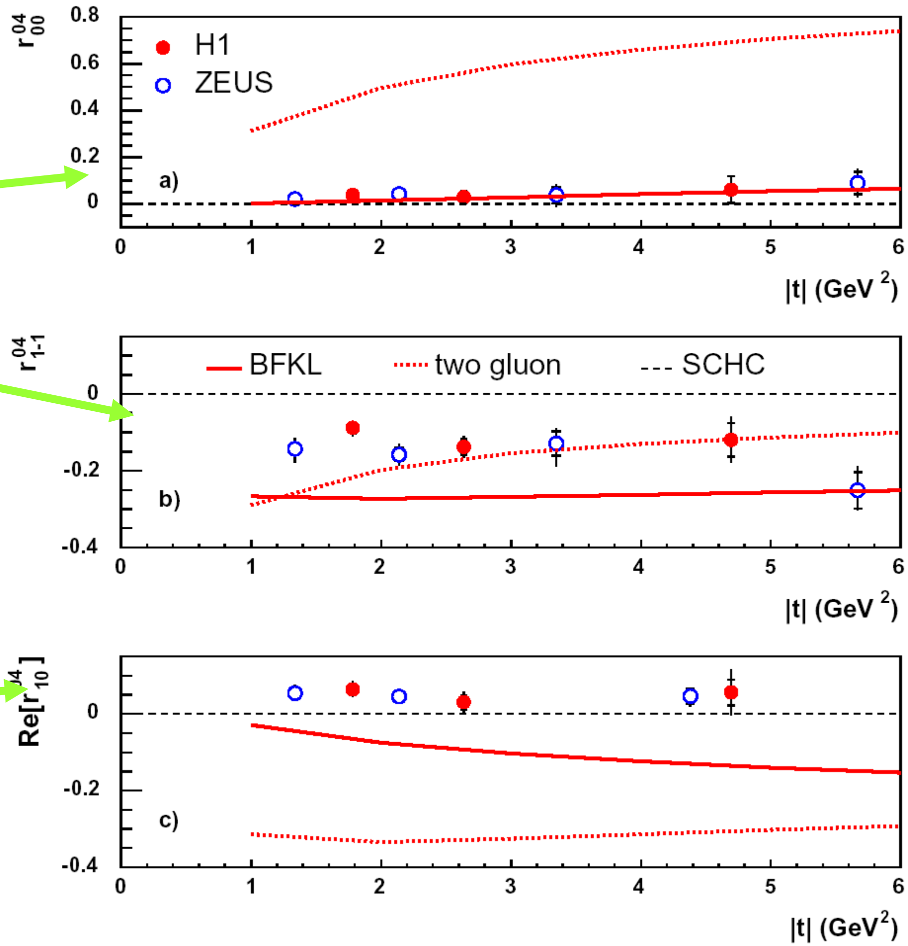
rise of σ with *W* described by BFKL, not by DGLAP

SDME (ρ)

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

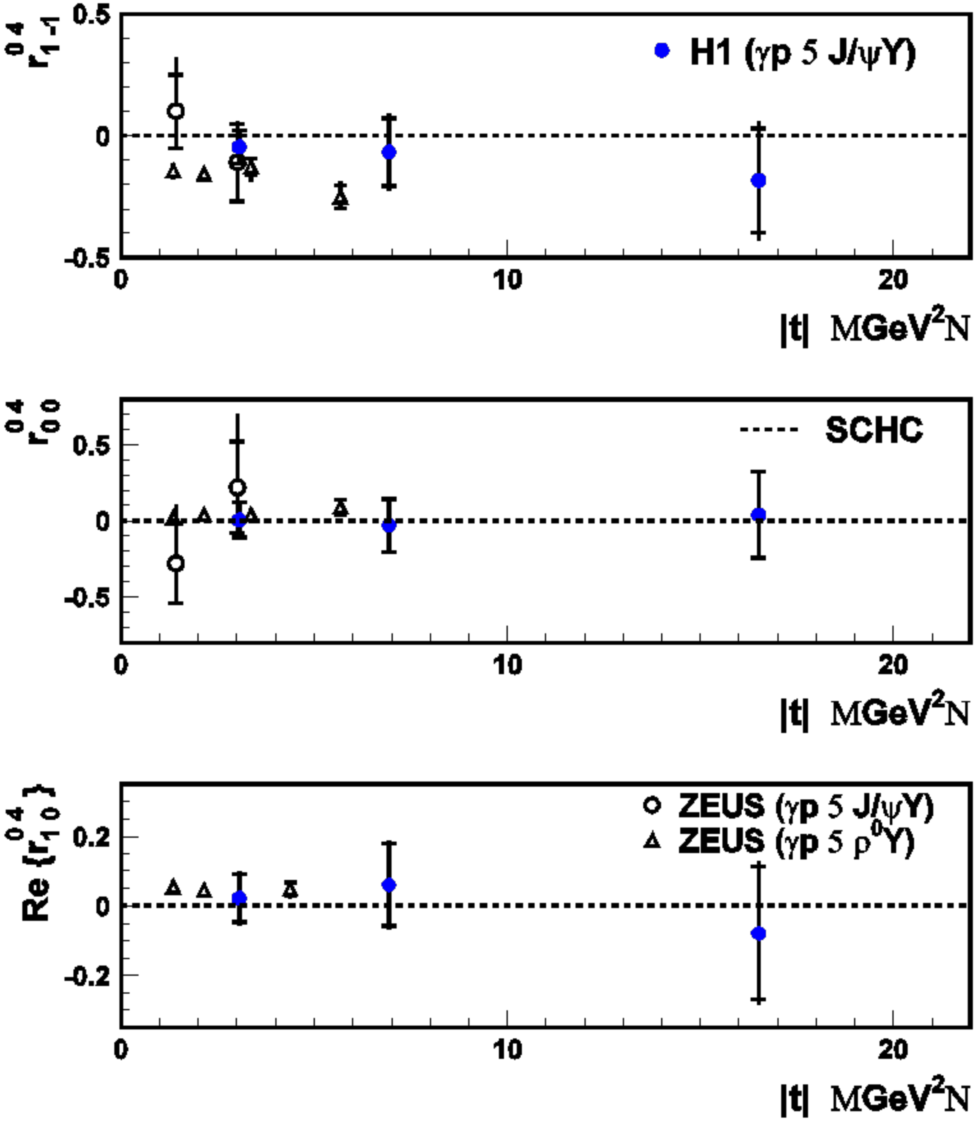
But SCHC T → T dominates
+ double flip T → T
Reason :
chiral odd contribution in γ
(due to constituent quark mass)
→ no orbital momentum needed for Ψ_T
→ SCHC

BFKL model describes data,
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**

  Q^2 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

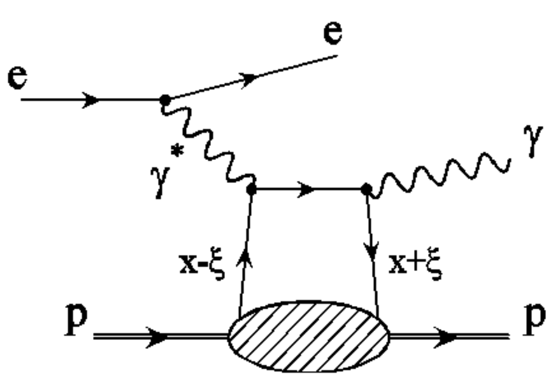
Backup

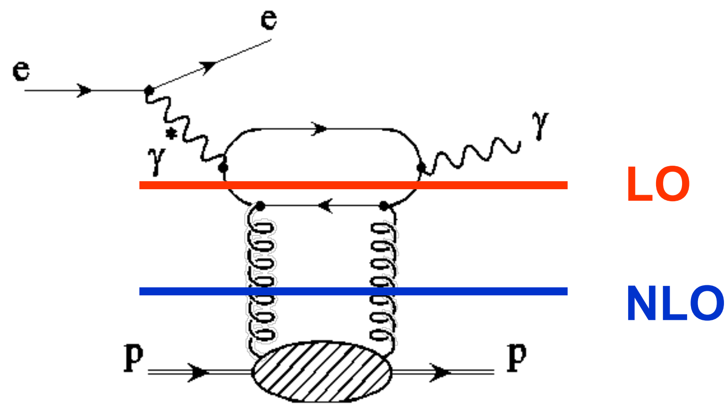
DVCS : remark on scales

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 $(Q^2 + M^2)/4$?