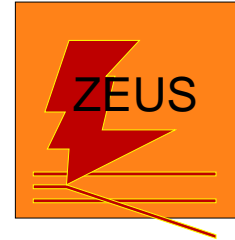


On behalf of H1 and ZEUS Collaborations



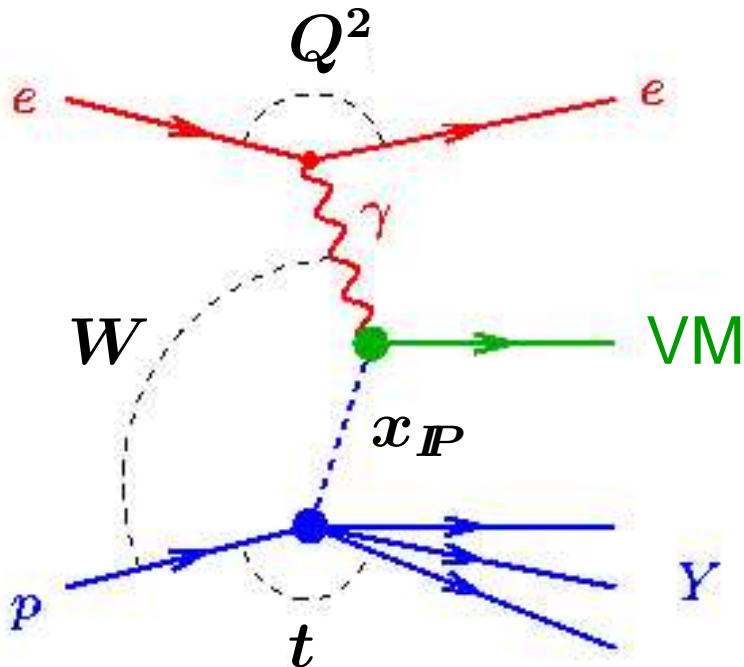
Diffractive electroproduction of ρ and ϕ mesons at HERA

2009 Europhysics Conference on High Energy Physics

16-22 July 2009 Krakow, Poland

Diffractive Vector Meson Production

$$e + p \rightarrow e + VM (= \rho, \phi, J/\psi, \dots, \text{or } \gamma) + Y (\text{or } p)$$



Q^2 Photon Virtuality

W γp CMS energy

t 4-momentum transfer squared

$x_{\mathbb{P}}$ Momentum fraction of the colour singlet exchange

Regge Theory

= Soft \mathbb{P} omeron exchange

$$\sigma \propto \left(\frac{W}{W_0}\right)^{4(\alpha_{\mathbb{P}}(t)-1)}$$

$$\alpha_{\mathbb{P}}(t) = 1.08 + 0.25 t \text{ (DL)}$$

Light VM at low Q^2 and low $|t|$

pQCD Models

Exchange of ≥ 2 gluons

$$\sigma \propto (xG(x, Q^2))^2$$

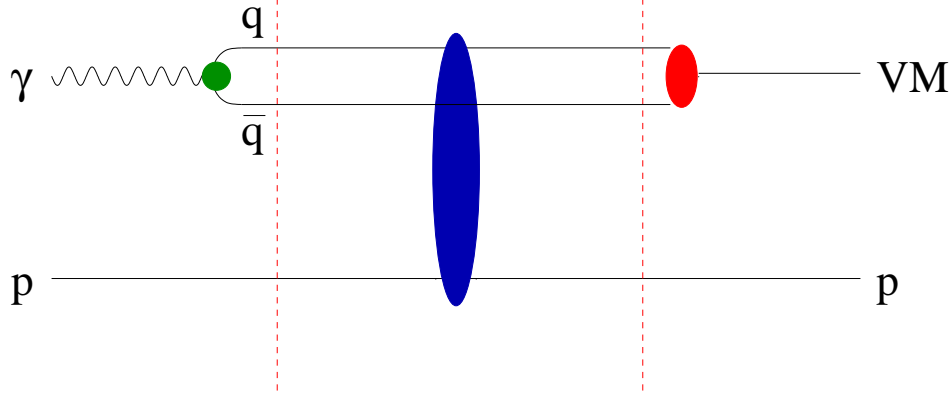
Steep rise of $xG(x, Q^2)$

Requires hard scale: Q^2, t or m_q

\implies Investigate transition between soft and hard regimes

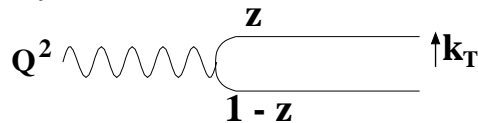
Perturbative QCD approaches

Dipole approach (k_t factorisation)



$$\mathcal{A} = \Psi_{q\bar{q}}^\gamma \otimes \sigma_{q\bar{q}-p} \otimes \Psi_{q\bar{q}}^V$$

Scanning radius decrease with increasing Q^2 or $M_V^2 \rightarrow \mu^2 = z(1-z)(Q^2 + M_V^2)$



$$\rightarrow \sigma_L \propto \frac{Q^2/M_V^2}{(Q^2 + M_V^2)^4} [\alpha_s(\mu^2) G(x, \mu^2)]^2$$

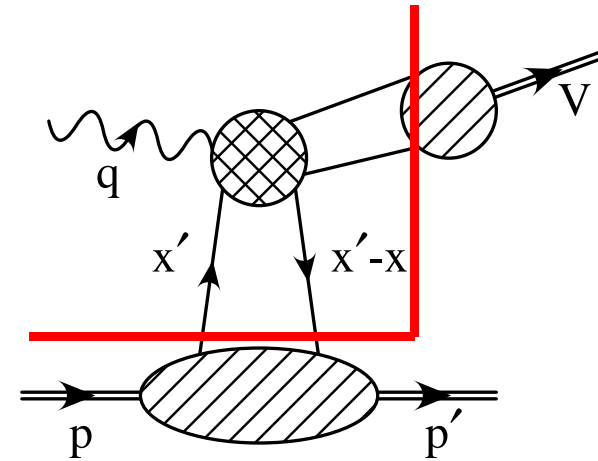
with $z \simeq 1/2 \rightarrow \mu^2 \simeq 1/4(Q^2 + M_V^2)$

$$\rightarrow \sigma_T \propto \frac{1}{(Q^2 + M_V^2)^4} [\alpha_s(\mu^2) G(x, \mu^2)]^2$$

with $z = 0, 1$ endpoints contributions

\rightarrow hard scale damped

Collinear factorisation theorem



$$\mathcal{A}_L = f(x, x', t, \mu) \otimes H \otimes \Psi^V$$

where f_i : non-forward PDF ($x' \neq x$)

\rightarrow Generalized Parton Density

Theorem proven for σ_L ; often assumed for σ_T

Collins, Frankfurt & Strikman [hep-ph/9611433]

Dipole - Saturation:

Kowalski, Motyka, Watt (KMW) [hep-ph/0606272]

Marquet, Peschanski, Soyez (MPS) [hep-ph/0702171]

Dipole - k_T factorisation:

Ivanov, Nikolaev, Savin (INS) [hep-ph/0501034]

Collinear - GPD:

Goloskokov, Kroll (GK) [hep-ph/07083569]

Parton hadron duality:

Martin, Ryskin, Teubner (MRT) [hep-ph/9609448]

VM theory: Main features / expectations

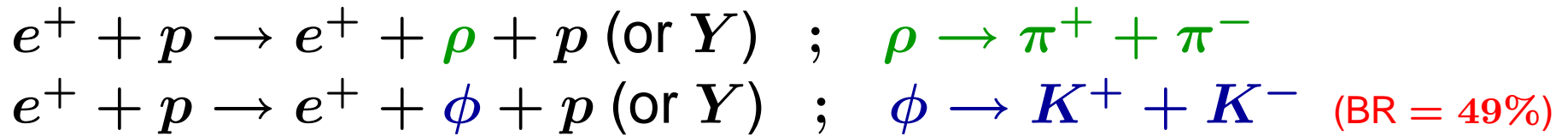
$\sigma(Q^2)$: $\sigma_L \propto Q^{-6}$; $\sigma_T \propto Q^{-8}$ **but** modified by gluon pdf Q^2 depend., quark Fermi motion and virtuality, $\alpha_s(Q^2)$, higher order.
→ Naive $R = \sigma_L/\sigma_T \propto Q^2/M_V^2$ also modified.

$\sigma(W)$: ● For σ_L at high Q^2 and heavy VM, hard (universal) W depend. expected from $1/x$ hard gluon pdf evolution.
● For light VM, delayed approach to hard pQCD regime (σ_T).

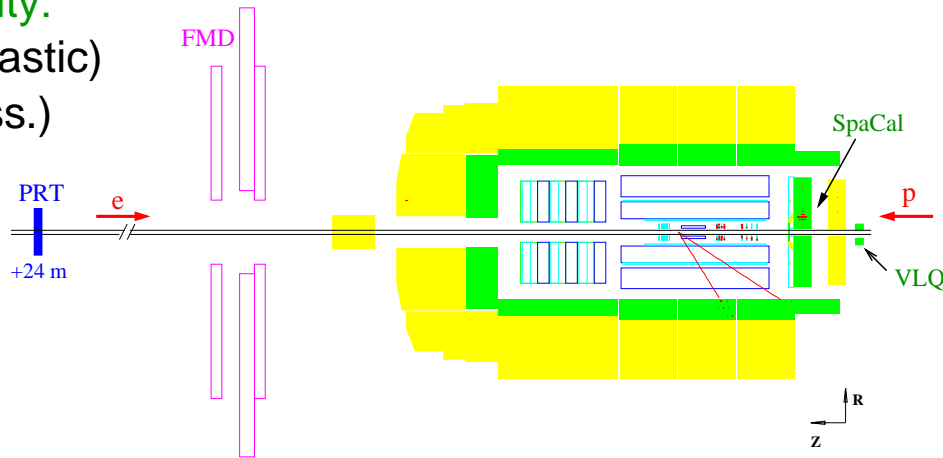
$d\sigma/dt$: $\propto \exp(-b|t|)$ for low $|t|$, where $b = b_{q\bar{q}} \otimes b_{\mathbf{P}} \otimes b_p$
● Expect common b for σ_L at high Q^2 and heavy VM.
→ Naive universality of b vs. $\mu^2 = 1/4(Q^2 + M_V^2)$
● Larger dipole in σ_T than in σ_L → expect $b_T > b_L$
→ Delayed universality of b vs. μ^2

Helicity amplitudes: see later

Data Selection



Forward activity:
 NOTAG (\simeq elastic)
 TAG (\simeq p diss.)



H1: ρ and ϕ

elastic and p diss. channels

1996-2000 data: 51 pb^{-1}

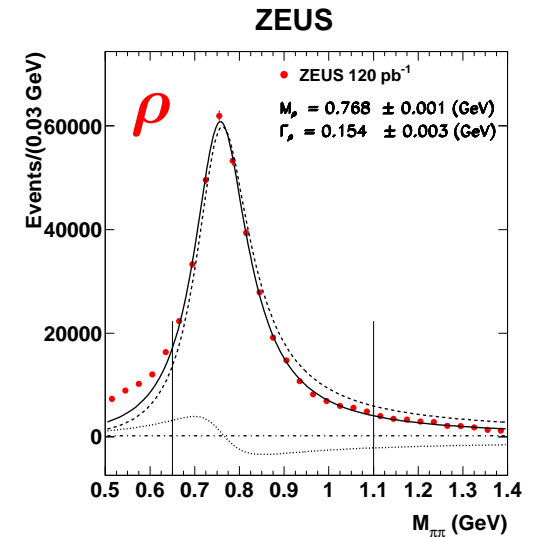
$2.5 < Q^2 < 60 \text{ GeV}^2$

$35 < W < 180 \text{ GeV}$

elastic: $|t| < 0.5 \text{ GeV}^2$

p diss.: $|t| < 3 \text{ GeV}^2$

H1prelim-08-013 & H1prelim-09-017



ZEUS: ρ

mostly elastic channel

1996-2000 data: 119 pb^{-1}

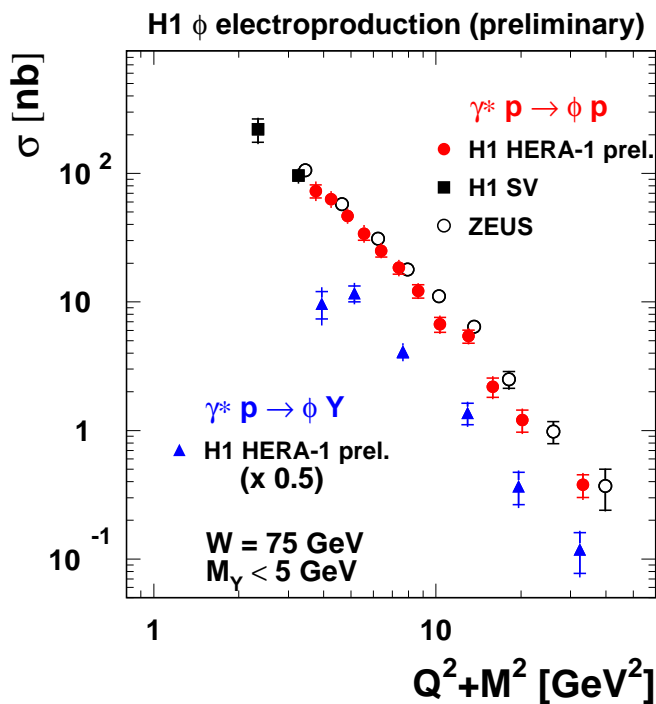
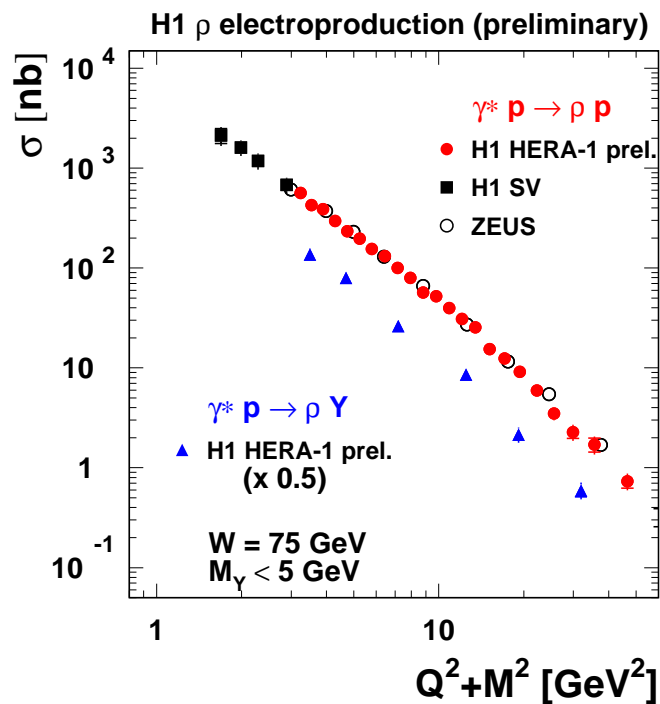
$2 < Q^2 < 160 \text{ GeV}^2$

$32 < W < 180 \text{ GeV}$

$|t| < 1 \text{ GeV}^2$

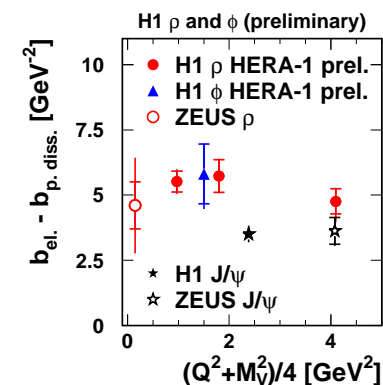
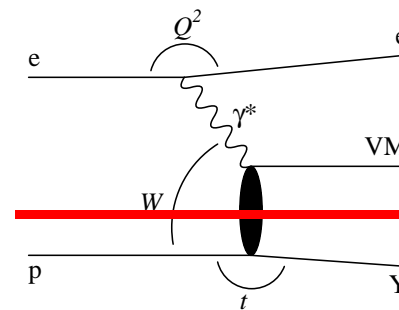
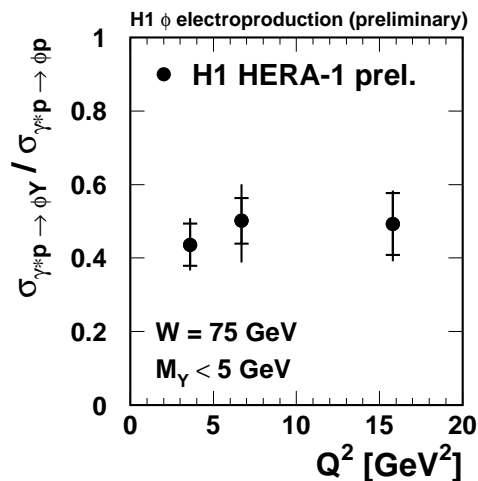
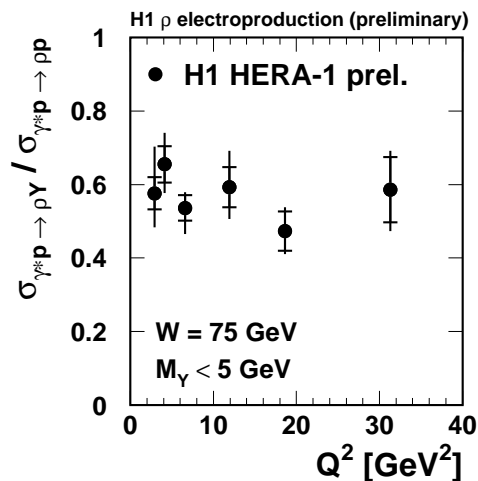
DESY-07-118 (PMC Physics A 1,6)

Light VM Cross-sections : Q^2 dependence



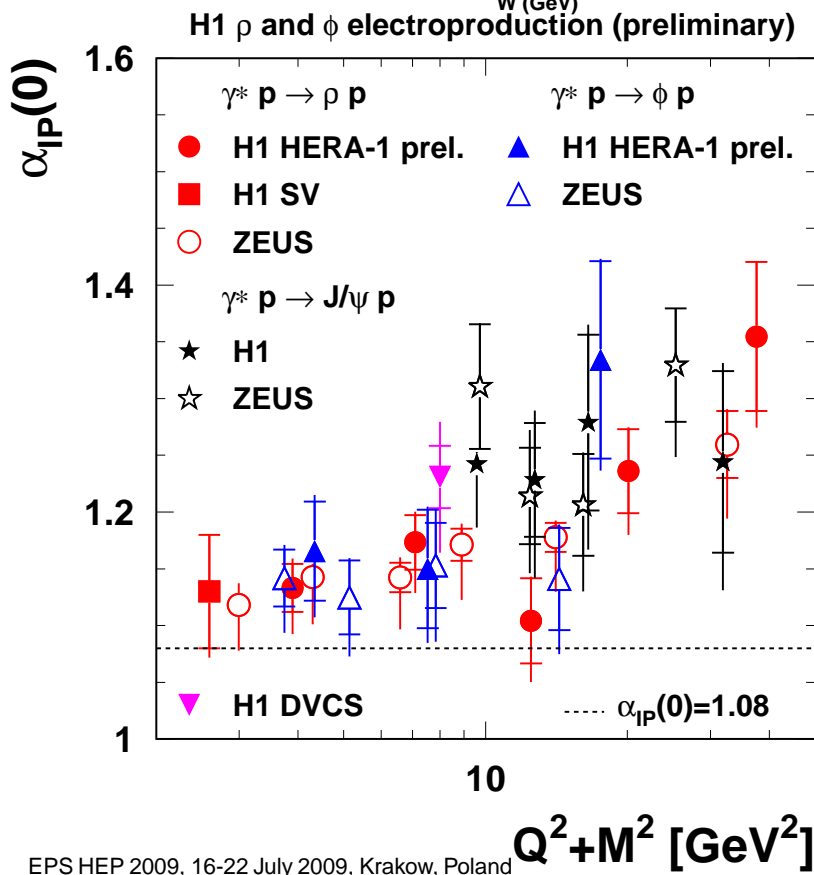
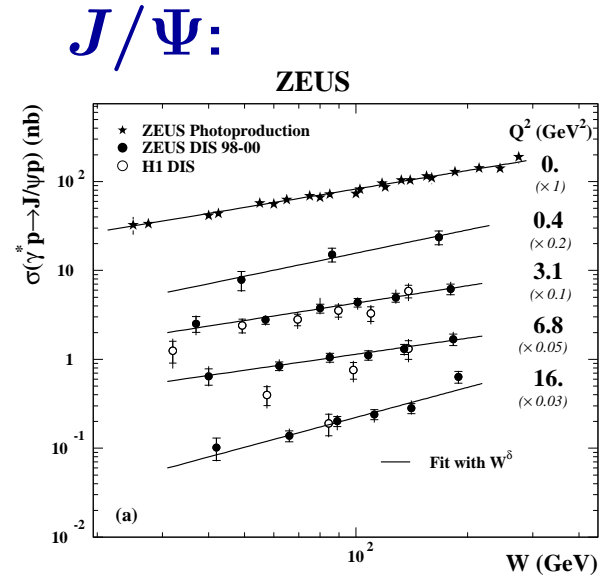
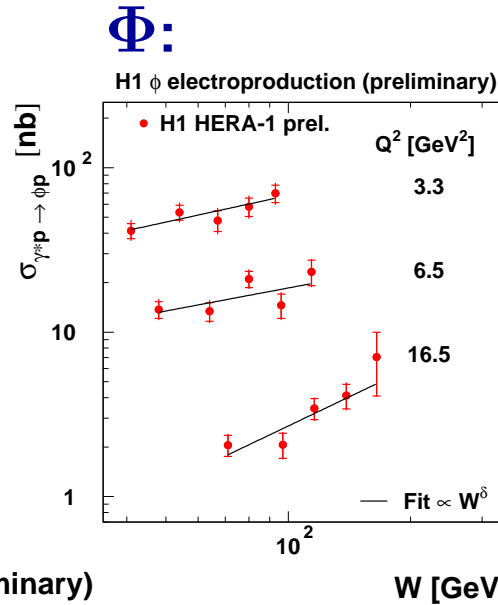
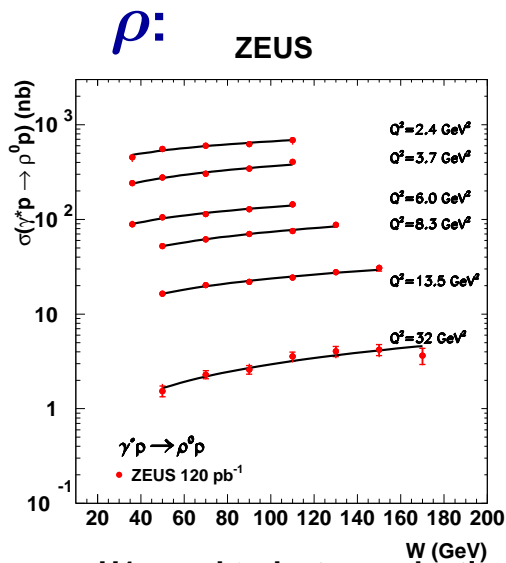
- High precision for elastic cross-sections
- First ϕ p-diss. cross-section
- H1 Zeus relative agreement

Test of vertex ("Regge") factorisation:



- p.diss/el : no Q^2 dep.
 - t -depend. : no Q^2 dep.
- vertex factorisation

Soft to hard transition: Q^2



$$\alpha_{IP}(0) = 1 + \delta/4 + \alpha'_{IP}/\langle |t| \rangle$$

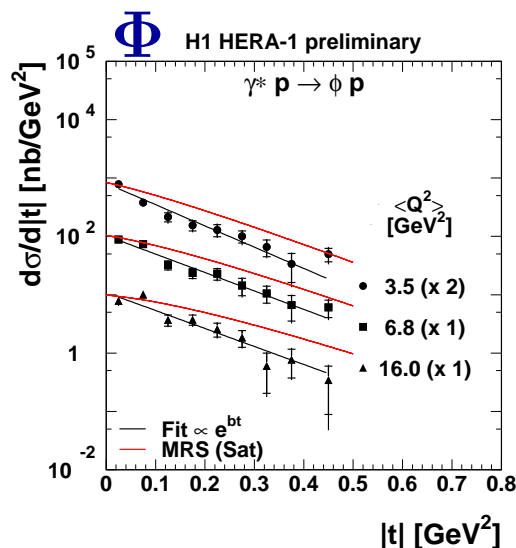
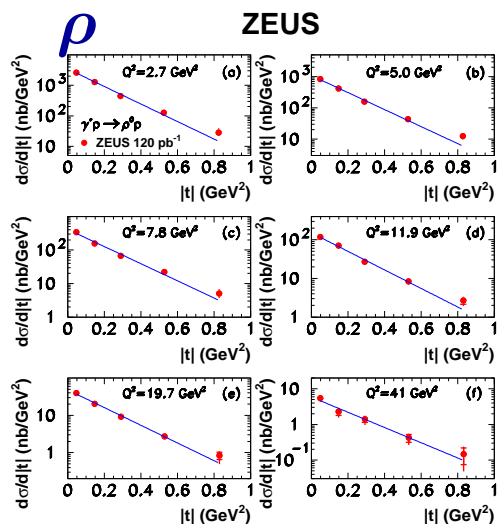
$$\alpha'_{IP} = 0 - 0.25 \text{ GeV}^{-2}$$

- Common hardening of $\alpha_{IP}(0)$ with $Q^2 + M^2$ for all VM and DVCS

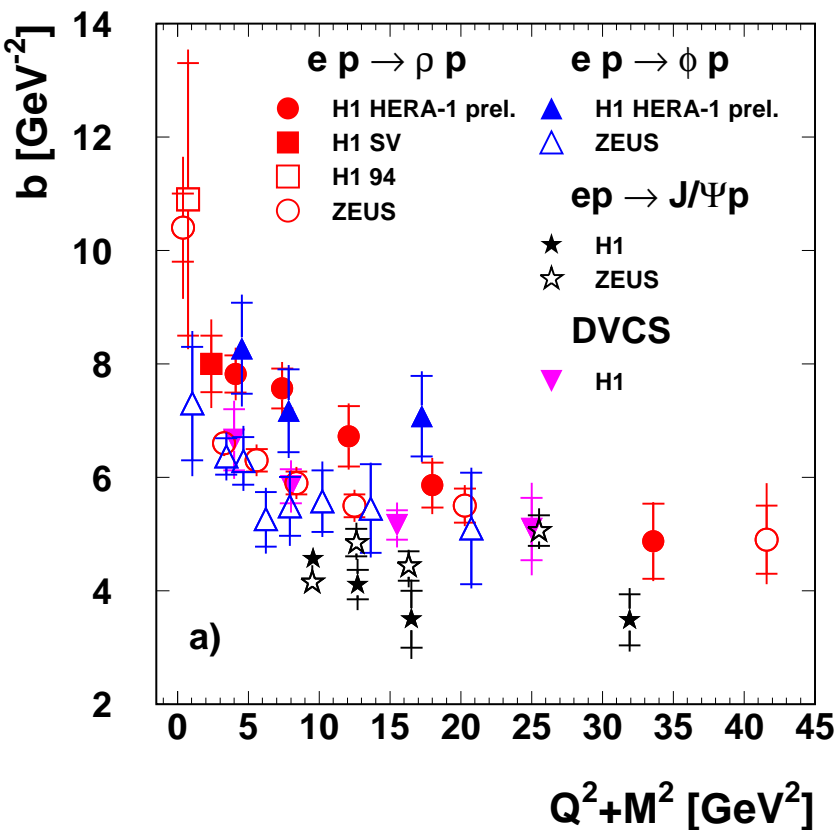
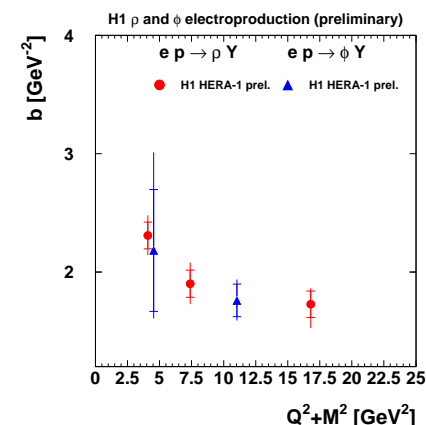
⇒ Transition from soft to hard regime with $Q^2 + M^2$

- Soft contributions (in σ_L ?) up to $Q^2 \sim 20 \text{ GeV}^2$ for ρ and ϕ

t dependences: Universality and hard diffraction



Proton dissociation:



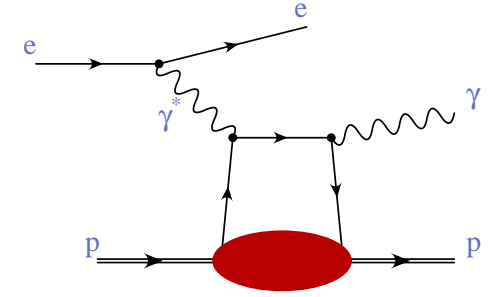
fit $e^{-b|t|}$: $b = b_p \otimes b_{q\bar{q}} \otimes b_{\mathbb{P}}$
 $\rightarrow b \propto q\bar{q}$ dipole size

- b_ρ and b_ϕ decrease $Q^2 + M^2$
- Common value with J/ψ for $Q^2 + M^2 > 20 \text{ GeV}^2$
- Large dipole for light VM at low Q^2

\Rightarrow Transition from soft to hard regime with $Q^2 + M^2$

Note on the scale and universality

DVCS is like DIS (at LO):



Photon interacts directly with a resolved quark

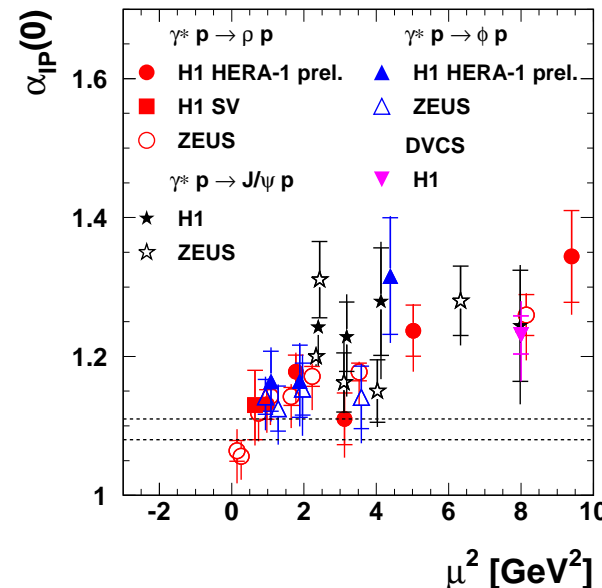
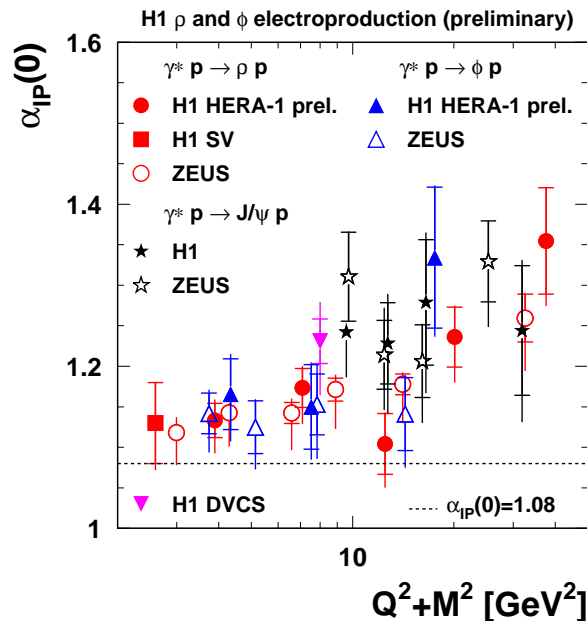
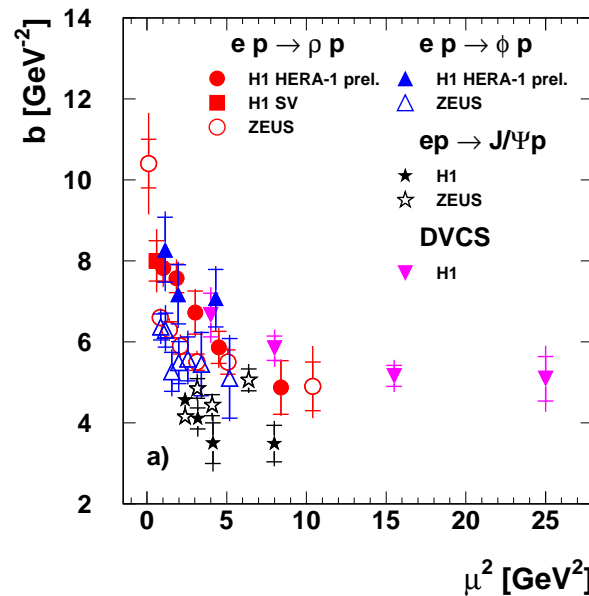
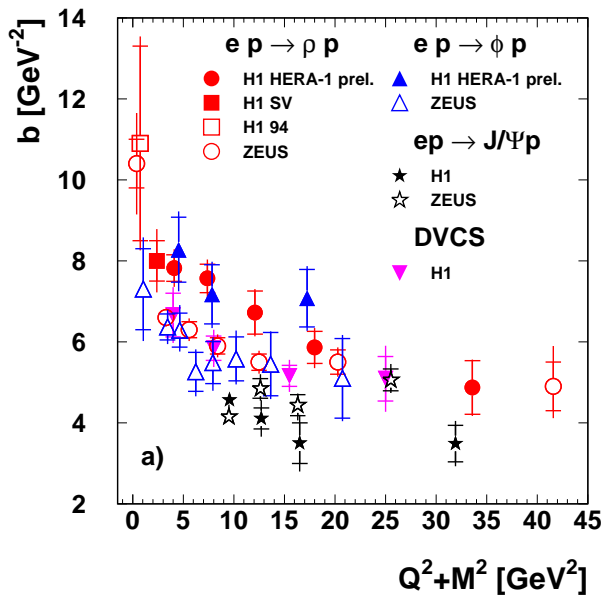
→ Hard scales are:

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

for VM: $\mu^2 = \frac{Q^2 + M^2}{4}$

→ Universality vs μ^2 :

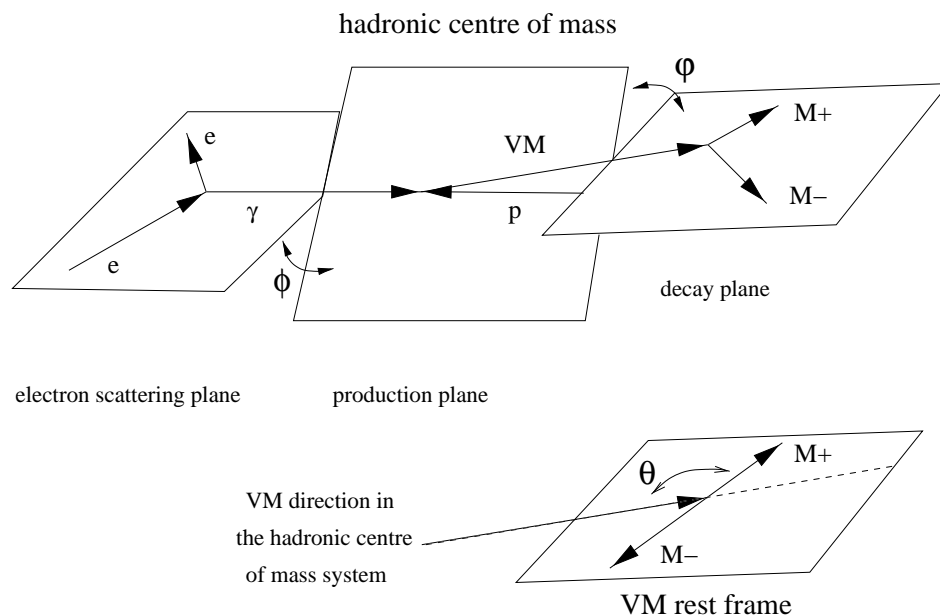
Soft/hard transition around $\mu^2 \sim 5 \text{ GeV}^2$



SPIN DENSITY MATRIX ELEMENTS

$$\theta^*, \Phi, \varphi \iff 15 \text{ SDMEs} : r_{kl}^{ij} \propto T_{\lambda'_\rho \lambda'_\gamma} T_{\lambda_\rho \lambda_\gamma}$$

$T_{\lambda_\rho \lambda_\gamma}$: helicity amplitudes



No helicity flip: $T_{00} : \gamma_L \rightarrow \rho_L$

$T_{11} : \gamma_T \rightarrow \rho_T$

Single flip: $T_{01} : \gamma_T \rightarrow \rho_L$

$T_{10} : \gamma_L \rightarrow \rho_T$

Double flip: $T_{1-1} : \gamma_T \rightarrow \rho_T$

s -Channel Helicity Conservation (SCHC): $T_{01} = T_{10} = T_{1-1} = 0$

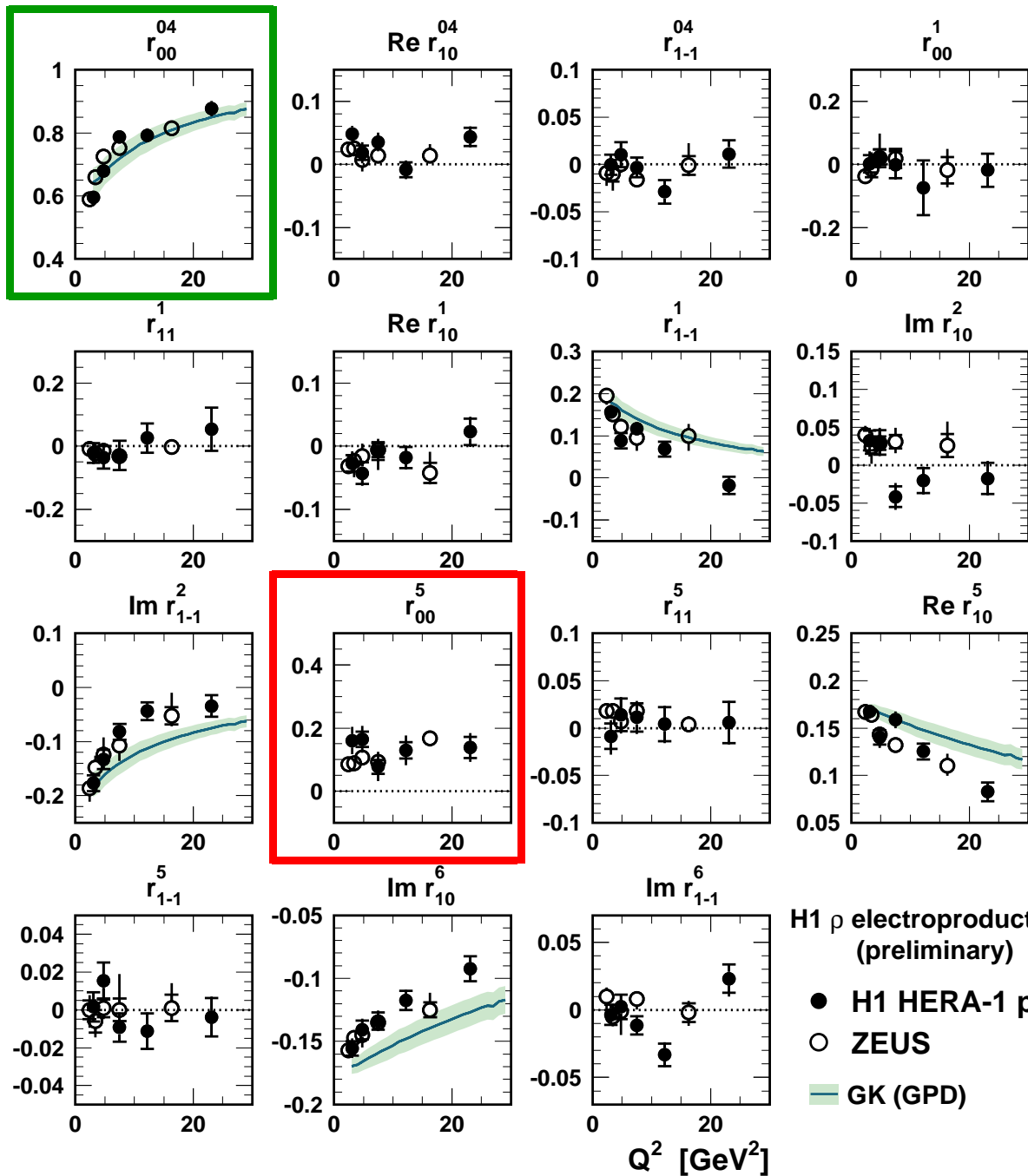
pQCD models: ● SCHC violation (single flip $\propto \sqrt{|t|}$, double $\propto |t|$)

D. Yu Ivanov and
R. Kirschner

[[hep-ph/9807324](https://arxiv.org/abs/hep-ph/9807324)]

● Hierarchy: $|T_{00}| > |T_{11}| > |T_{01}| > |T_{10}| > |T_{1-1}|$

ρ Polarisation - SDMEs vs. Q^2



- r_{00}^{04} increases with Q^2
- ↔ similar effects for r_{1-1}^1 , $\text{Im } r_{1-1}^2$, $\text{Re } r_{10}^5$ and $\text{Im } r_{10}^6$ (in SCHC)
- ↔ Fair description by GK (GPD) model

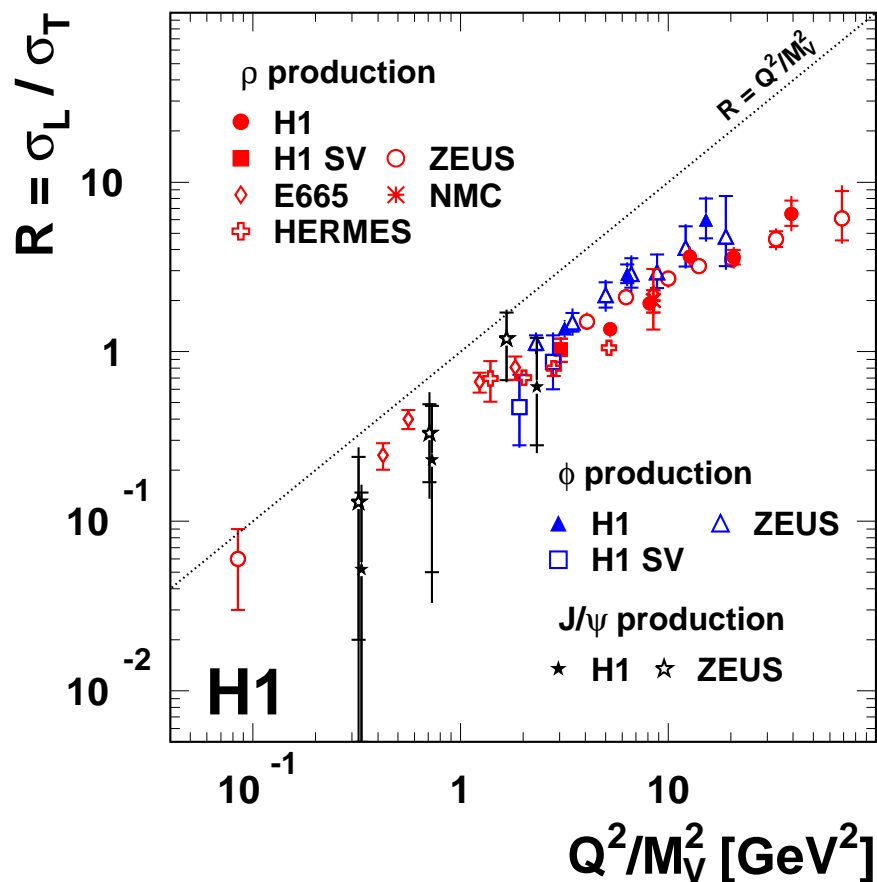
- r_{00}^5 violates SCHC
- Other SDME $\simeq 0$

H1 ρ electroproduction (preliminary)

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

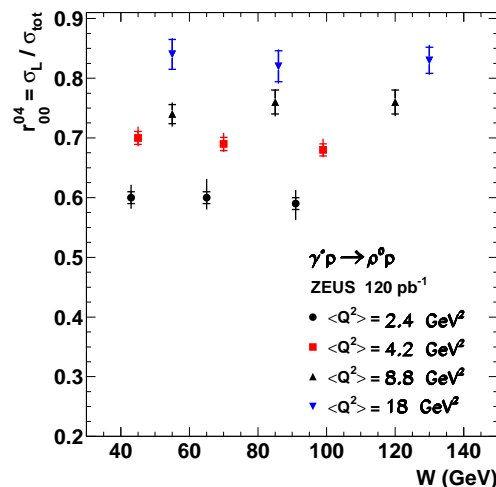
ρ and ϕ Polarisation - $R = \sigma_L / \sigma_T$

$$R_{SCHC} = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - \epsilon r_{00}^{04}} = \frac{|T_{00}|^2}{|T_{11}|^2} + \text{non SCHC corrections in H1 case}$$

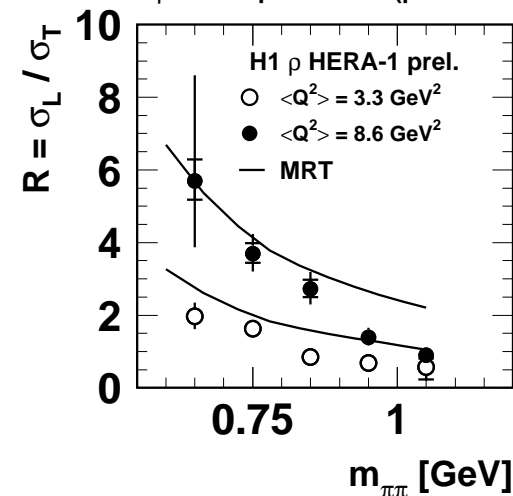


● ρ : no W dependance of R

ZEUS



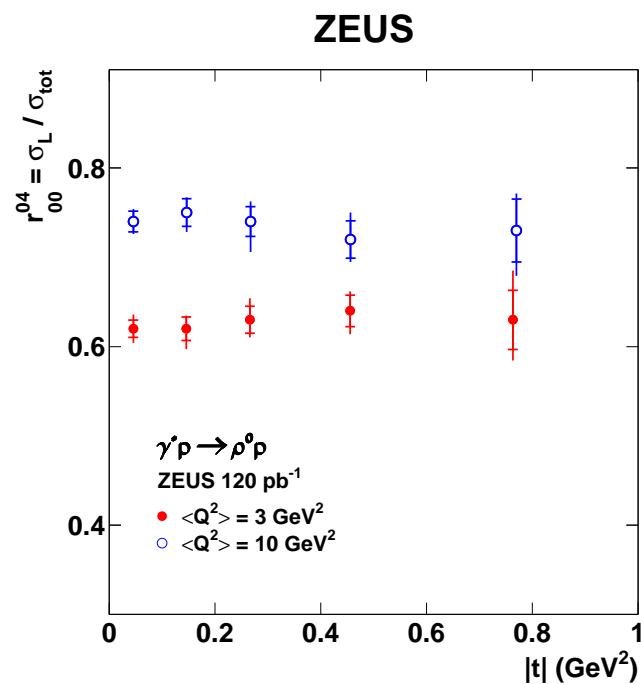
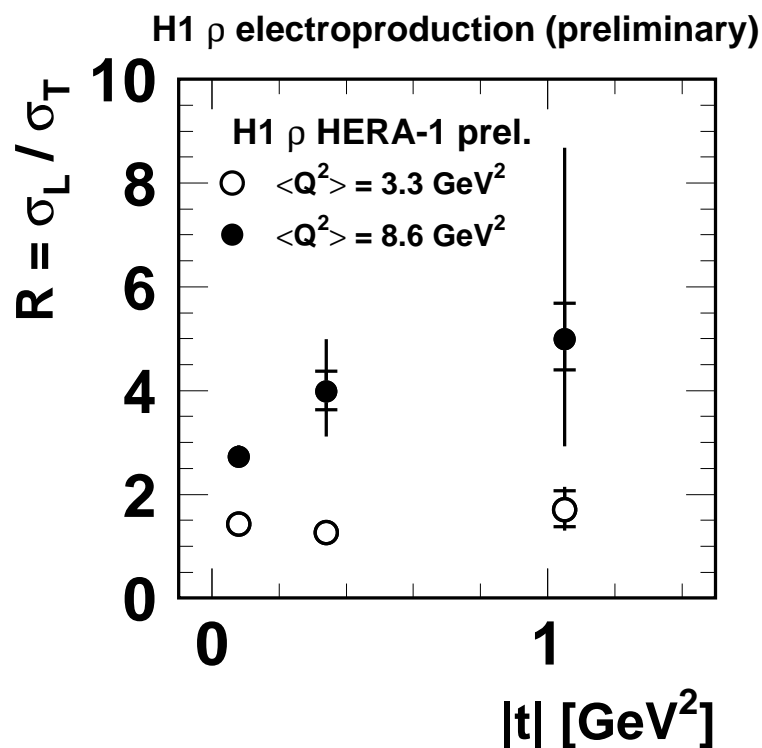
H1 ρ electroproduction (preliminary)



- Formal pQCD: $R \propto Q^2 / M^2$
- Scaling for all VM with Q^2 / M_V^2
- Damping at large Q^2

- Strong invariant mass dependance in ρ case
- formal pQCD: $R \propto Q^2 / M^2$ but M being diquark mass cf Martin, Ryskin, Teubner calculation

ρ and ϕ Polarisation - $R(t)$ and $b_L - b_T$



$$R(t) \propto \frac{\sigma_L}{\sigma_T} \exp(-(b_L - b_T)|t|)$$

- **H1:** $(b_L - b_T) < 0$ by 1.5σ for $Q^2 > 5 \text{ GeV}^2$

- also a t dependance of T_{11}/T_{00} - see later

→ Small difference of transverse size of $q\bar{q}$ dipoles from transverse and longitudinal photons

ρ and ϕ Polarisation - Cross-sections

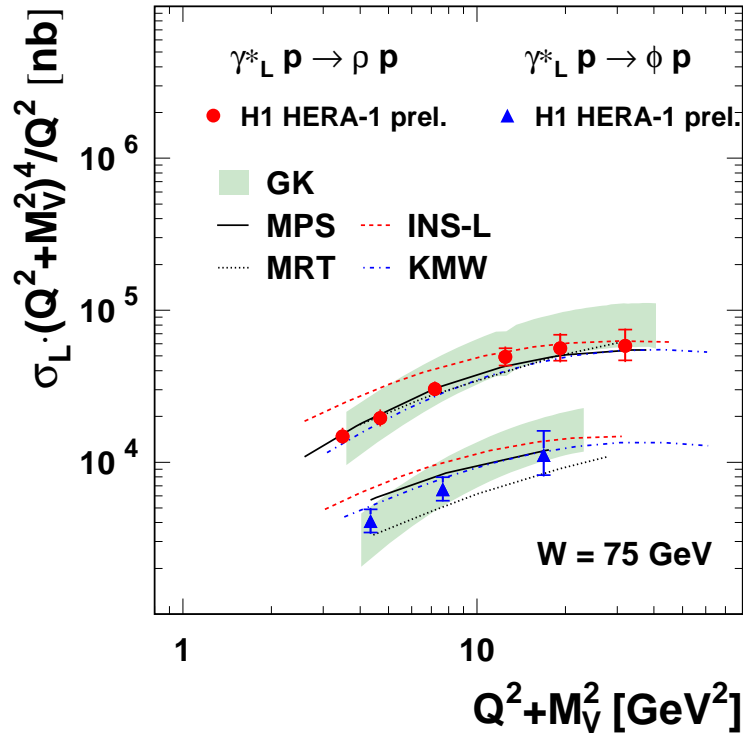
Longitudinal

$$\sigma_L \propto \frac{Q^2/M_V^2}{(Q^2+M_V^2)^4} [\alpha_s(\mu^2) G(x, \mu^2)]^2$$

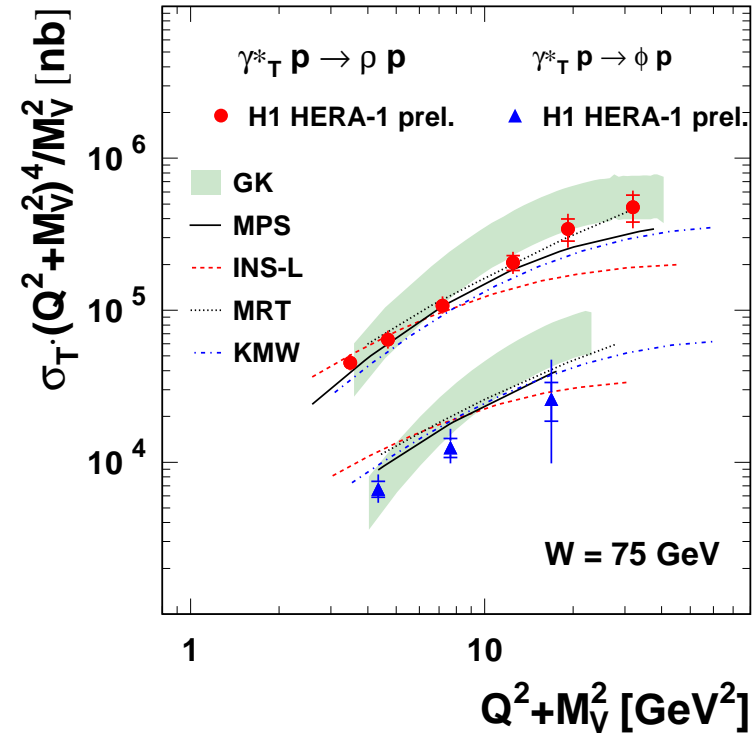
Transverse

$$\sigma_T \propto \frac{1}{(Q^2+M_V^2)^4} [\alpha_s(\mu^2) G(x, \mu^2)]^2$$

H1 ρ and ϕ electroproduction (preliminary)



H1 ρ and ϕ electroproduction (preliminary)



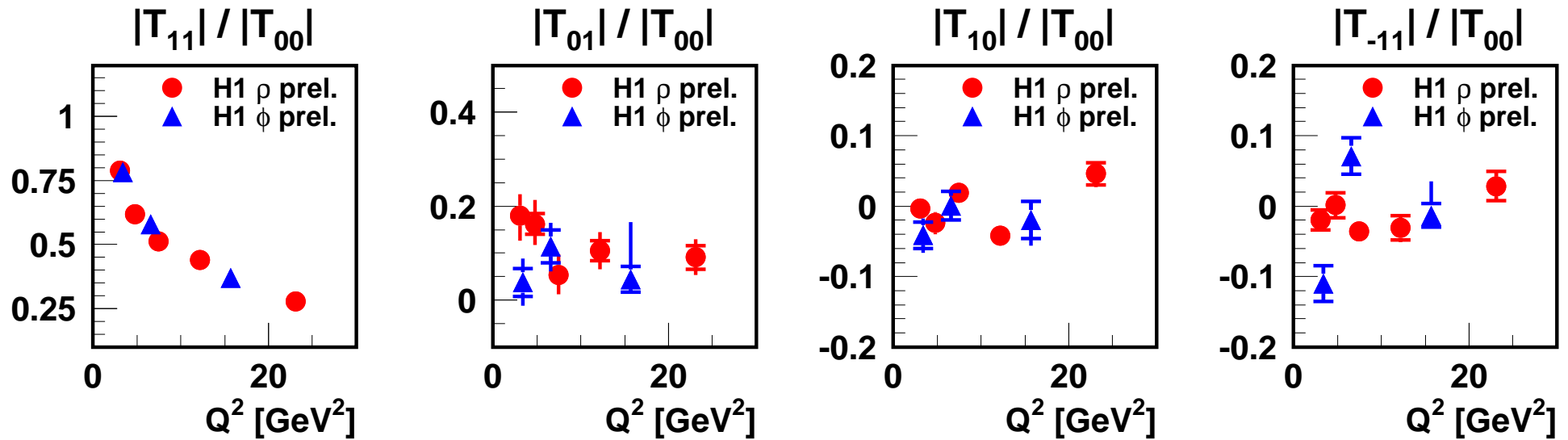
- Different $Q^2 + M^2$ dependences of σ_L and σ_T ($\sigma_L = 0$ at $Q^2 = 0$)
 - Good description by models with some differences
 - Effect of Q^2 dependences of $[\alpha_s(\mu^2) G(x, \mu^2)]^2$ visible
- N.B.: data at fixed $W \rightarrow$ varying x with $Q^2 + M_V^2$

Polarisation - Amplitude ratios vs. Q^2

pQCD (IK):

- $T_{11}/T_{00} \propto \frac{M}{Q} \frac{1+\gamma}{\gamma}$
- $T_{10}/T_{00} \propto -\frac{M \sqrt{|t|}}{Q^2} \frac{\sqrt{2}}{\gamma}$
- $T_{01}/T_{00} \propto \frac{\sqrt{|t|}}{Q} \frac{1}{\sqrt{2}\gamma}$

γ : gluon anomalous dim.



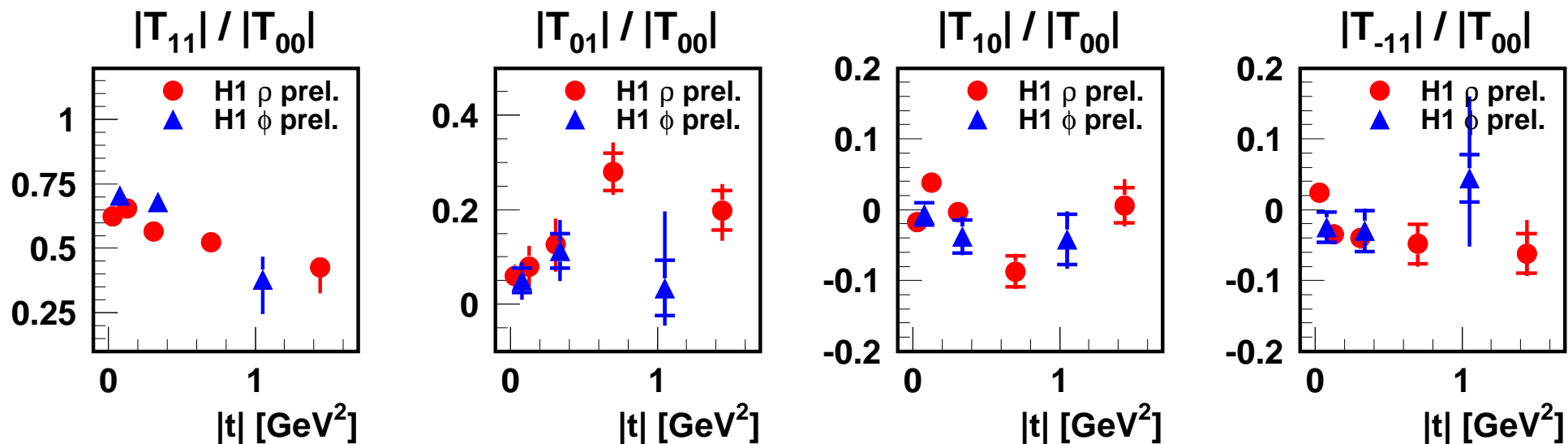
- T_{11}/T_{00} decreases with $Q^2 \leftrightarrow \sigma_L/\sigma_T$ increases with Q^2
- $T_{01}/T_{00} > 0 \leftrightarrow$ SCHC violation
- T_{10}/T_{00} and T_{-11}/T_{00} are small
 $\Rightarrow |T_{00}| > |T_{11}| > |T_{01}| > |T_{10}|, |T_{-11}| \leftrightarrow$ hierarchy observed

Polarisation - Amplitude ratios vs. $|t|$

pQCD (IK):

- $T_{11}/T_{00} \propto \frac{M}{Q} \frac{1+\gamma}{\gamma}$
- $T_{10}/T_{00} \propto -\frac{M}{Q^2} \frac{\sqrt{|t|}}{\gamma} \frac{\sqrt{2}}{\gamma}$
- $T_{01}/T_{00} \propto \frac{\sqrt{|t|}}{Q} \frac{1}{\sqrt{2}\gamma}$

γ : gluon anomalous dim.



- T_{11}/T_{00} decreases with $|t|$ (cf. $b_L - b_T$)
- T_{01}/T_{00} increases with $|t| \leftrightarrow$ SCHC violation increases with $|t|$
- T_{10}/T_{00} and T_{-11}/T_{00} are small but some $|t|$ dependence

CONCLUSIONS

Important progresses in precision of VM measurements and understanding of the underlying dynamics for ρ , ϕ .

→ Global picture emerges together with J/ψ and DVCS data.

Cross-section measurements:

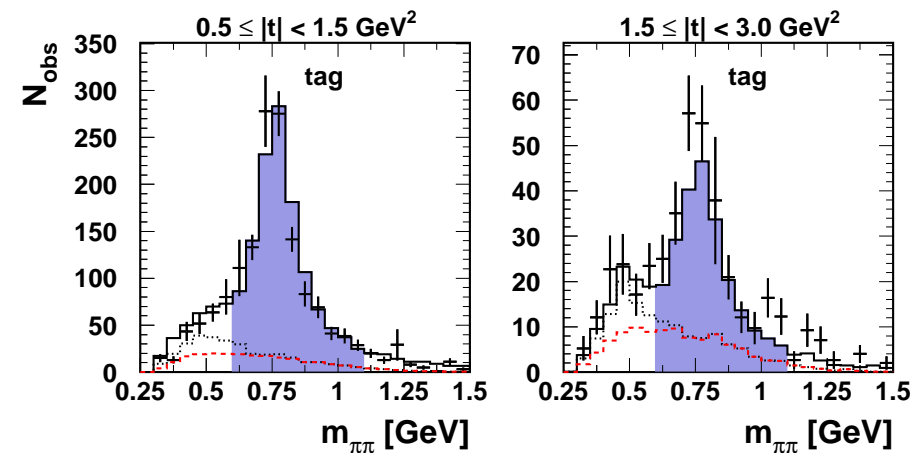
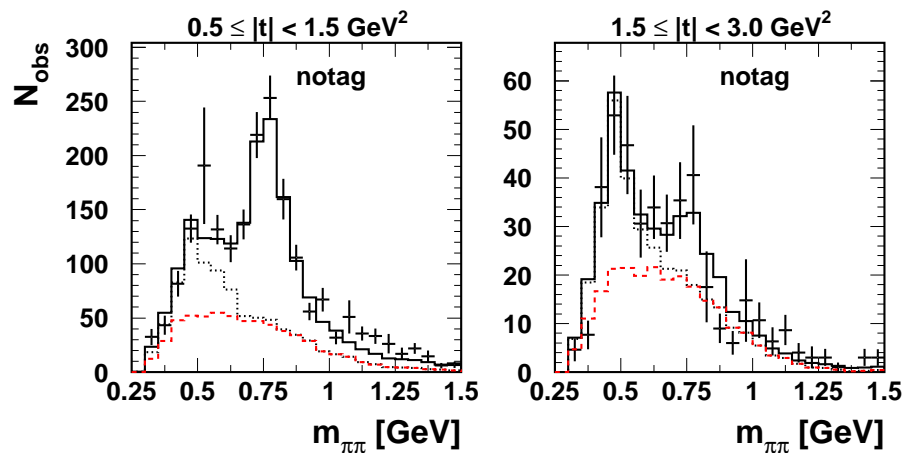
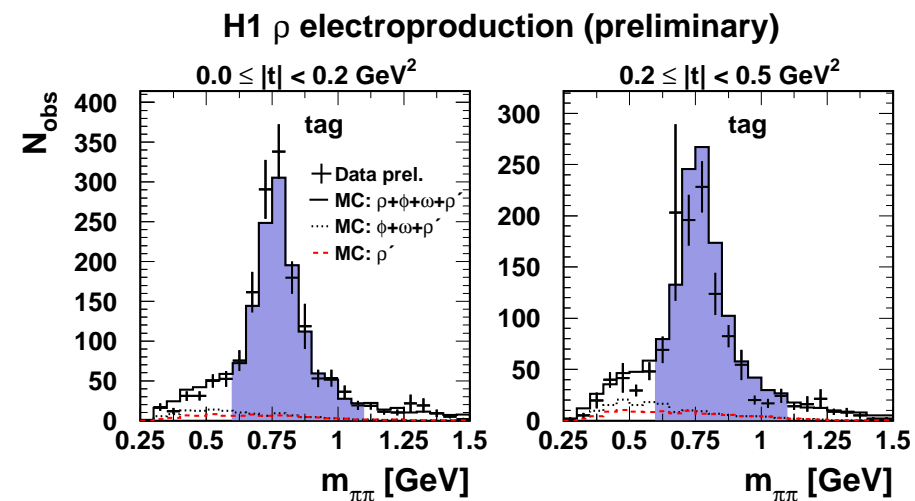
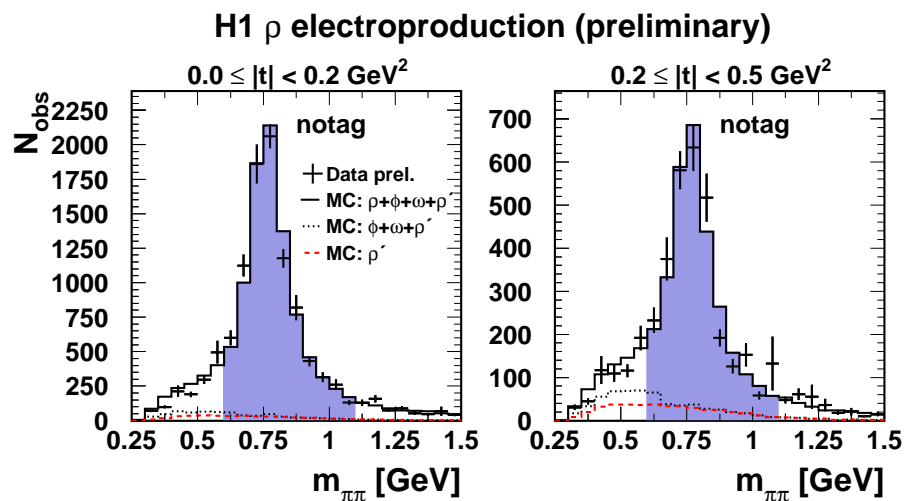
- Hard regime reached only around $\mu^2 = \frac{Q^2 + M^2}{4} = 5 \text{ GeV}^2$ as observed in measurements of $\alpha_{\mathbb{P}}(0)$ and b -slopes.
 - Possible soft component in σ_L up to "high" Q^2 for light VM.
- p diss. / elastic ratio: proton vertex factorisation observed

Polarisation properties:

- Polarised cross-section and amplitude ratios have been extracted
- σ_L/σ_T increases with Q^2 and maybe with $|t|$ at high Q^2
 - ↔ $|t|$ depend. expected in pQCD from \neq dipole in σ_L and σ_T .
- Violation of SCHC: significant T_{01}/T_{00} increases with $|t|$
- σ_L/σ_T decreases with ρ invariant mass
 - ↔ Predicted by MRT / limited influence of VM wave function.

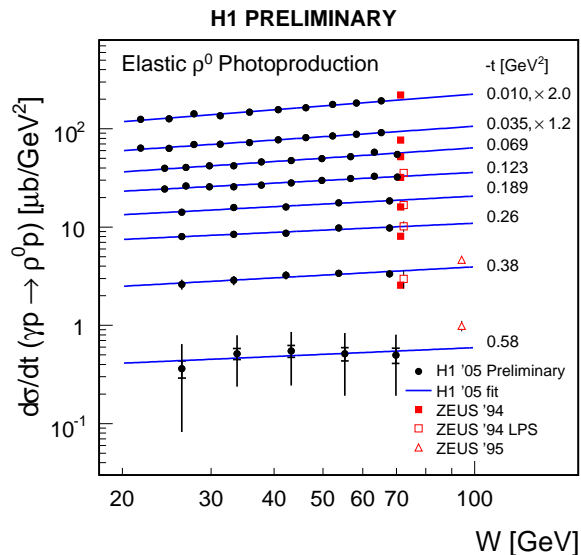
pQCD models: GPD and dipole ones describe main features, but differences in details

H1 background subtraction



Shrinkage : α'_{IP} measurements

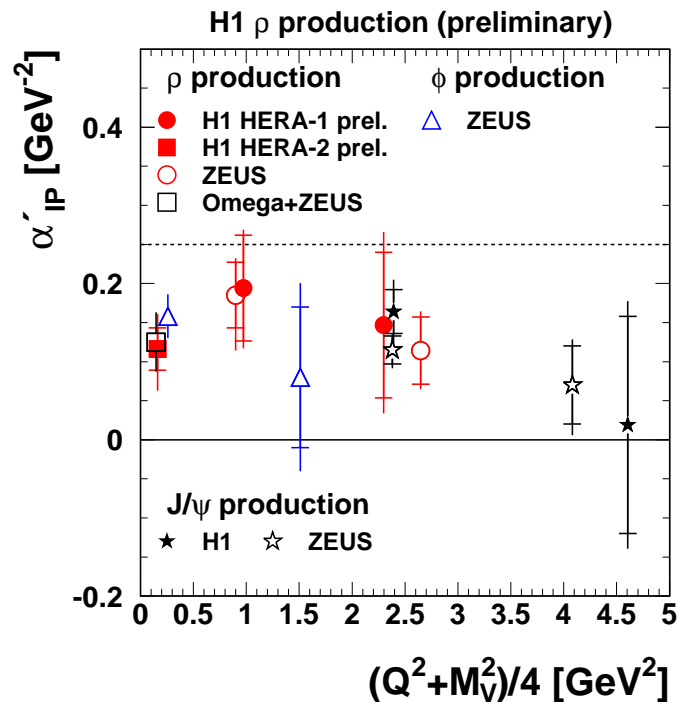
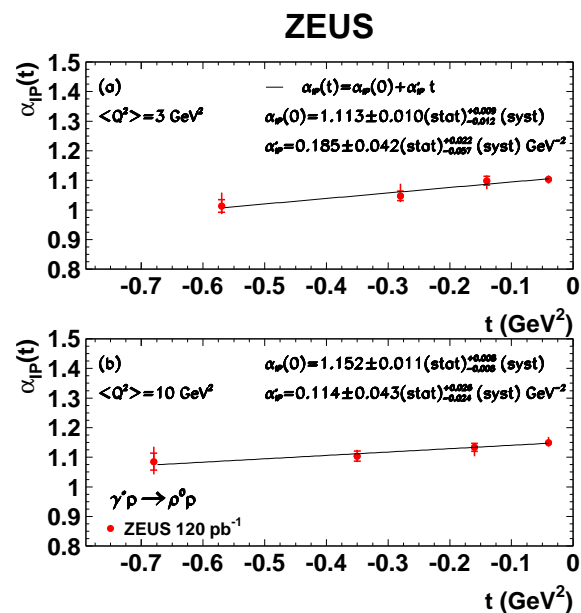
H1 ρ photoproduction:



$$\frac{d\sigma}{dt}(W) \propto e^{b_0 t} W^{4(\alpha_P(t)-1)}$$

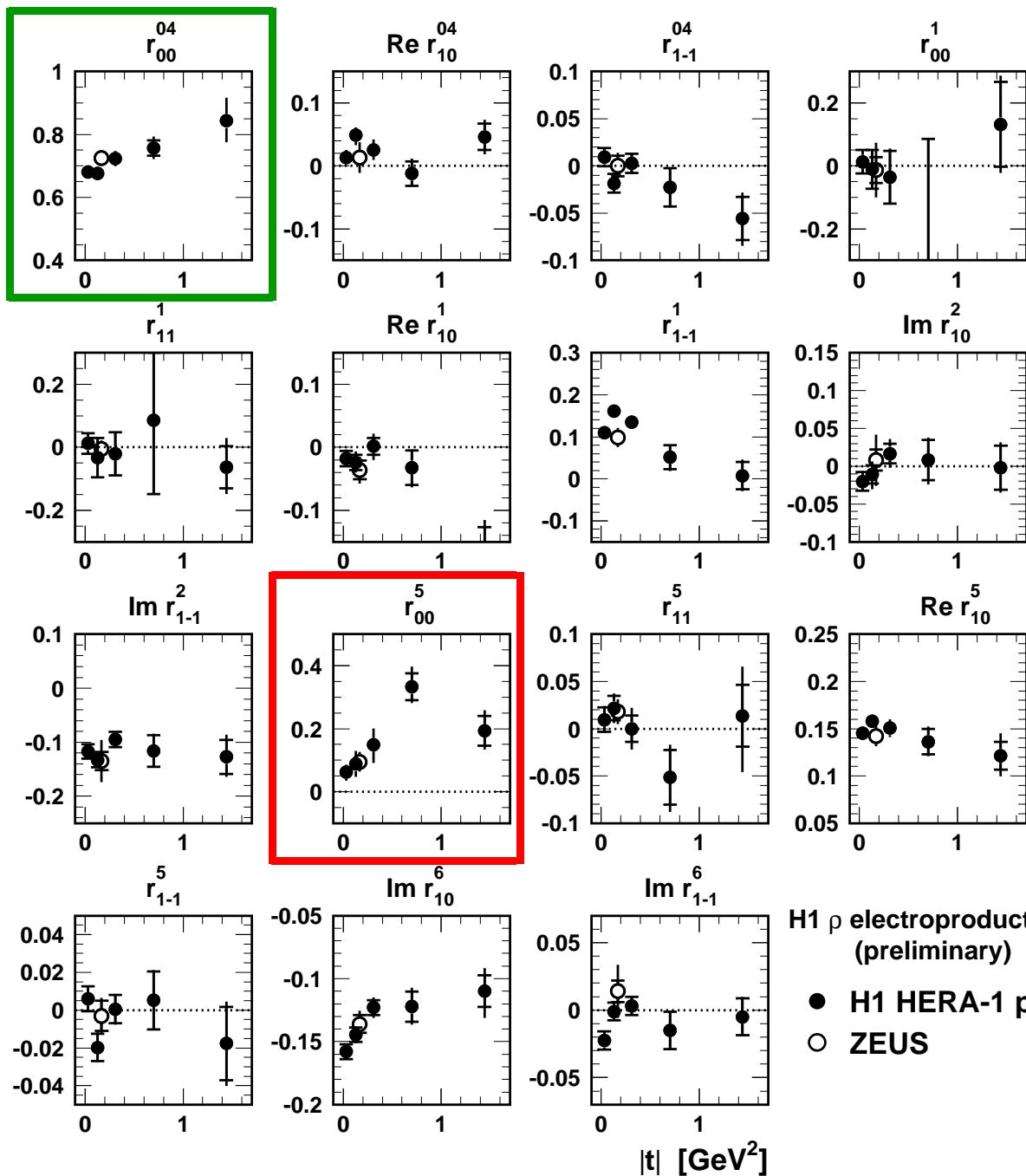
1. Study W depend. in bins of t :
→ Fit: $W^\delta \rightarrow \alpha_P(t) = 1 + \delta/4$
2. Study $\alpha_P(t)$ trajectories:
→ Fit: $\alpha_P(t) = \alpha_P(0) + \alpha'_{IP} t$

ZEUS ρ electroproduction:



⇒ For all VM, α'_{IP} smaller than 0.25 (DL, $p\bar{p}$)
(cf BFKL, multiple IP exchange)

ρ Polarisation - SDMEs vs. $|t|$



● r_{00}^5 increases with $|t|$
 ↔ SCHC violation increases with $|t|$

● r_{00}^{04} increases with $|t|$
 ↔ similar effects for r_{1-1}^1 ,
 $\text{Im } r_{1-1}^2$, $\text{Re } r_{10}^5$ and
 $\text{Im } r_{10}^6$ (in SCHC)

H1 ρ electroproduction
 (preliminary)

● H1 HERA-1 prel.
 ○ ZEUS

Polarisation - Retrieving Amplitude ratios

Assume purely imaginary amplitudes \longrightarrow phase = ± 1 !

\longrightarrow Extract $|T_{11}|/|T_{00}|$, $|T_{01}|/|T_{00}|$, $|T_{10}|/|T_{00}|$ and $|T_{-11}|/|T_{00}|$ from fit to the 15 SDMEs:

$$\begin{aligned}
 r_{00}^{04} &= B (\varepsilon + \beta^2) \\
 \text{Re } r_{10}^{04} &= B/2 (2\varepsilon\delta + \beta\alpha - \beta\eta) \\
 r_{1-1}^{04} &= B (\alpha\eta - \varepsilon\delta^2) \\
 r_{00}^1 &= -B \beta^2 \\
 r_{11}^1 &= B \alpha\eta \\
 \text{Re } r_{10}^1 &= B/2 \beta(\eta - \alpha) \\
 r_{1-1}^1 &= B/2 (\alpha^2 + \eta^2) \\
 \text{Im } r_{10}^2 &= B/2 \beta(\alpha + \eta) \\
 \text{Im } r_{1-\Gamma}^2 &= B/2 (\eta^2 - \alpha^2) \\
 r_{00}^5 &= \sqrt{2} B \beta \\
 r_{11}^5 &= B/\sqrt{2} \delta(\alpha - \eta) \\
 \text{Re } r_{10}^5 &= B/(2\sqrt{2}) (2\beta\delta + \alpha - \eta) \\
 r_{1-1}^5 &= B/\sqrt{2} \delta(\eta - \alpha) \\
 \text{Im } r_{10}^6 &= -B/(2\sqrt{2}) (\alpha + \eta) \\
 \text{Im } r_{1-\Gamma}^6 &= B/\sqrt{2} \delta(\alpha + \eta)
 \end{aligned}$$

$$\begin{aligned}
 \alpha &= |T_{11}|/|T_{00}| \\
 \beta &= |T_{01}|/|T_{00}| \\
 \delta &= |T_{10}|/|T_{00}| \\
 \eta &= |T_{-11}|/|T_{00}|
 \end{aligned}$$

$$B = \frac{1}{N_T + \varepsilon N_L} = \frac{R}{1 + \varepsilon R}$$

$$N_T = \alpha^2 + \beta^2 + \eta^2$$

$$N_L = 1 + 2\delta^2$$