

Vector Meson production and DVCS at H1(HERA)

L. Favart

I.I.H.E.
Université Libre de Bruxelles

The logo of the Université Libre de Bruxelles (ULB) is a dark grey square with the letters 'ULB' in white, bold, sans-serif font.

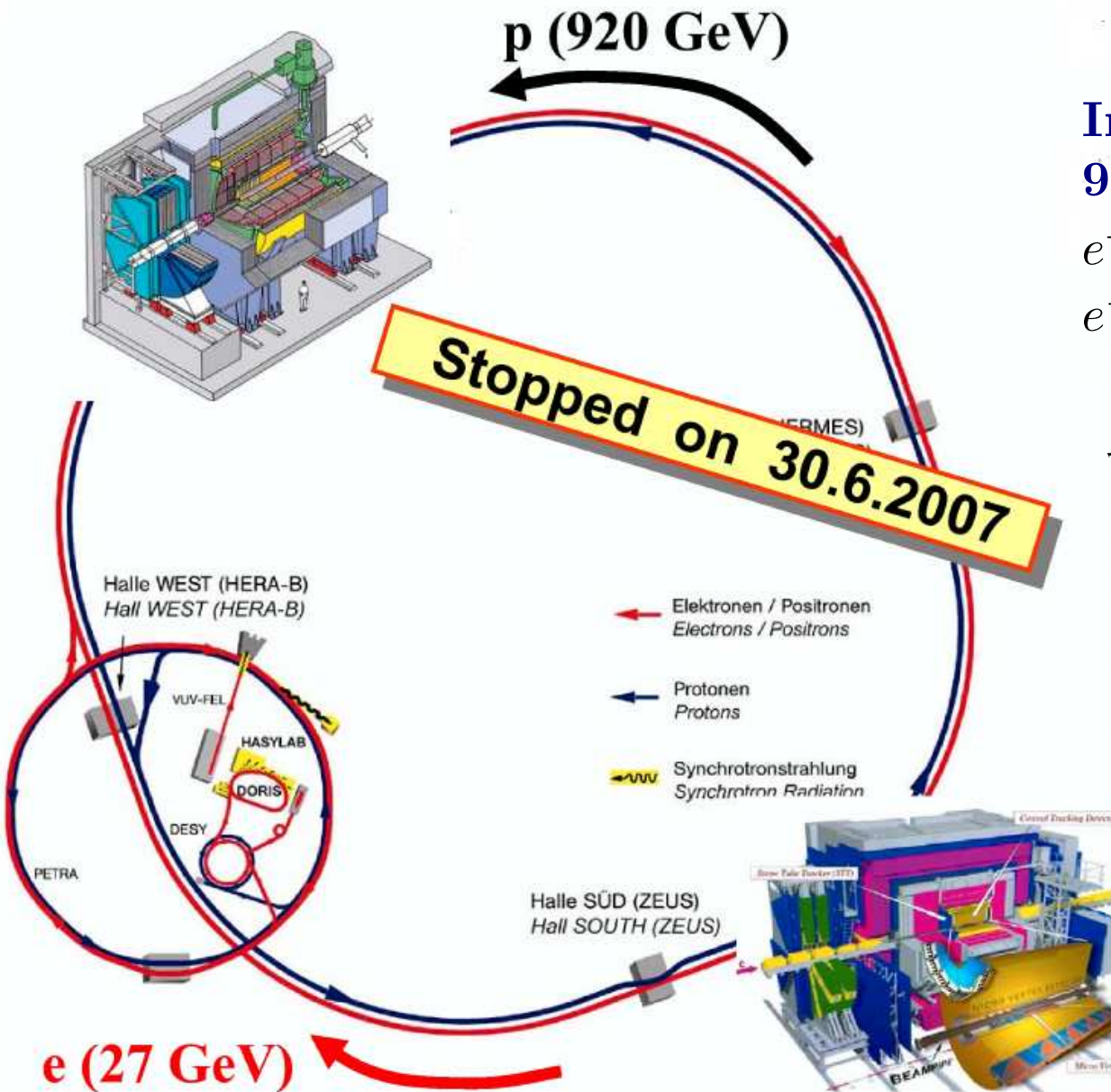
H1 Collaboration
HERA at DESY



CLAS12 Workshop

Genova - 24-28th of Feb. 2009

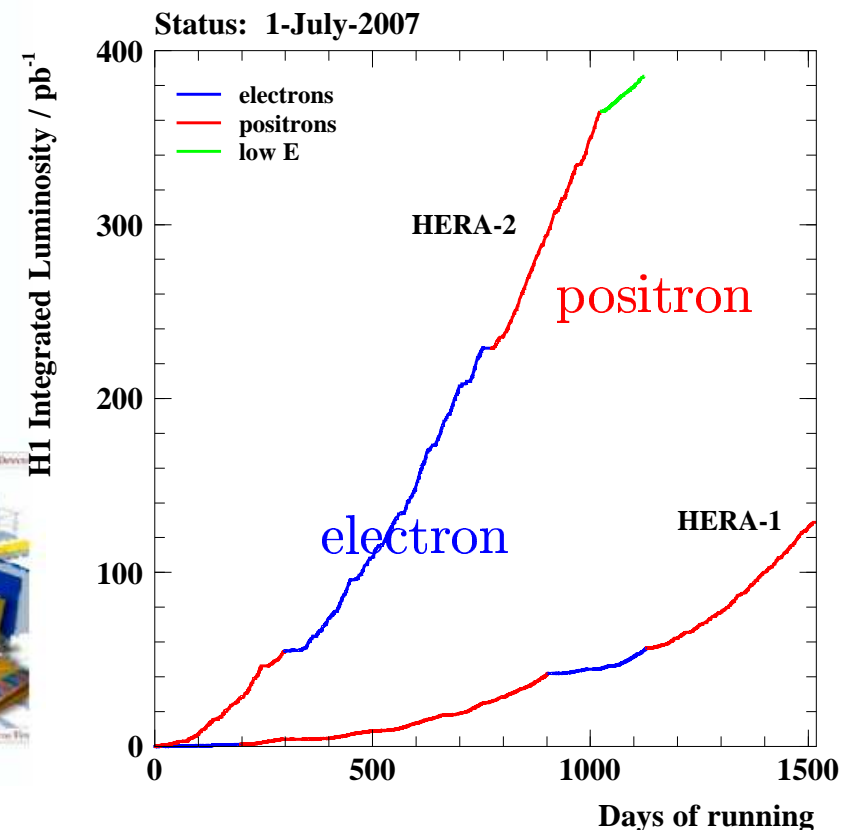
HERA - $e - p$ collider at DESY



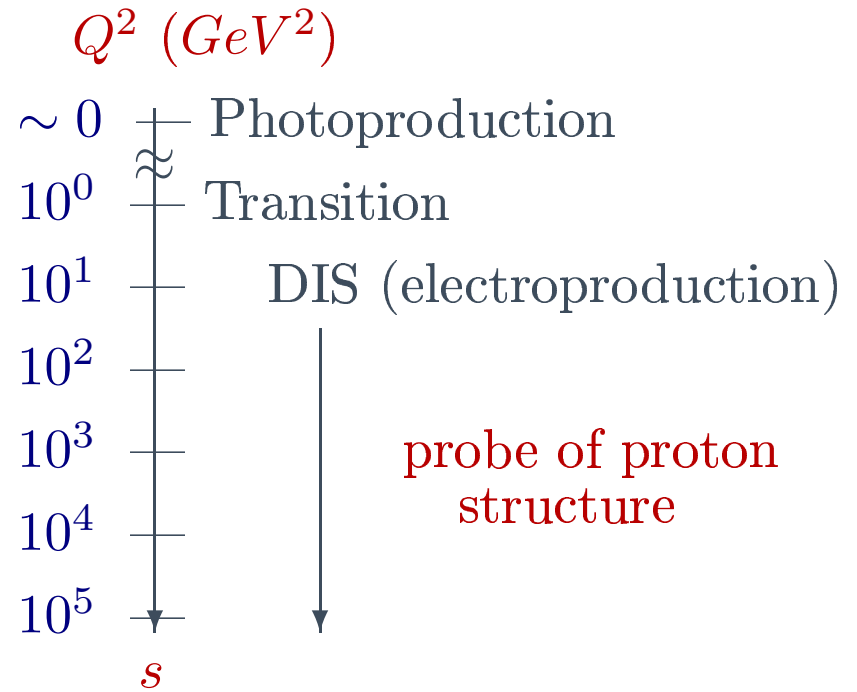
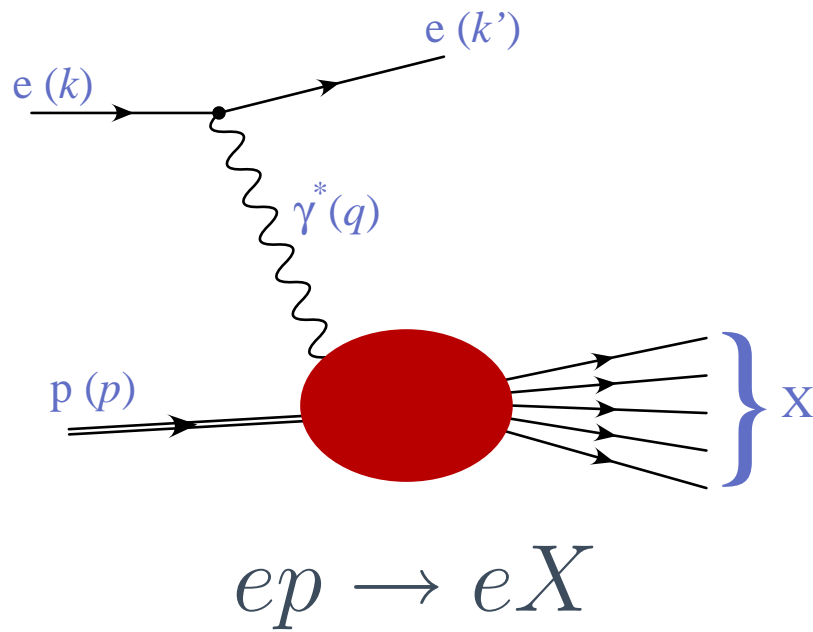
Integrated luminosity
96-00 + 03-07 (high energy)

$$e^+p : \sim 300 \text{ pb}^{-1}$$

$$e^-p : \sim 185 \text{ pb}^{-1}$$



$e - p$ Interactions



- Kinematic Variables

$Q^2 = -q^2 = -(k - k')^2$ squared 4-momentum transfer

$x = Q^2 / (2p \cdot q)$ Bjorken- x

$y = p \cdot q / (p \cdot e)$ Inelasticity

$W^2 = (p + q)^2$ $\gamma^* - p$ system energy

$$Q^2 = x y s$$

H1 detector

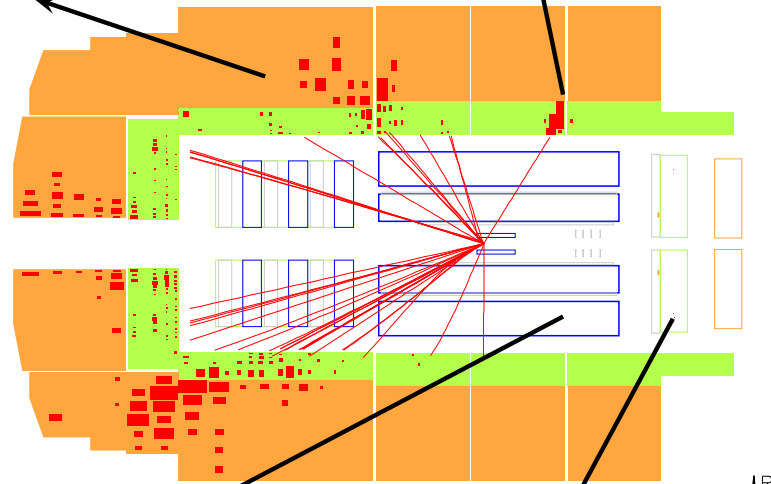


Run 170677 Event 152772 Class: 2 4 8 9 15 16 17 18 20 22

LAr Calorimeter
em+had

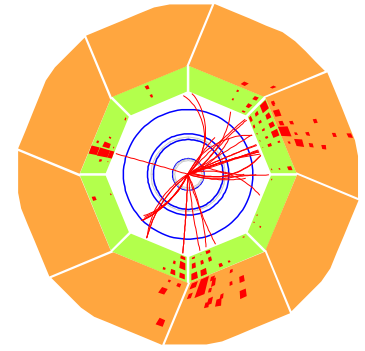
Scattered electron
High Q^2

$e \rightarrow$



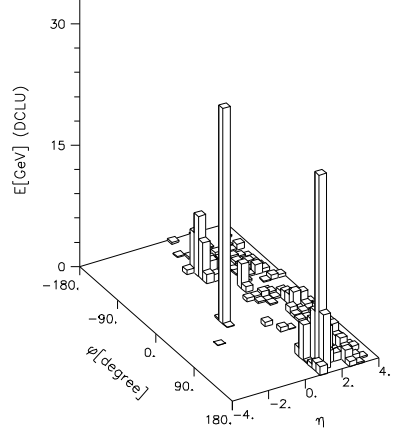
Tracker
B field 1.15 T

Backward Calo
Low Q^2 electron



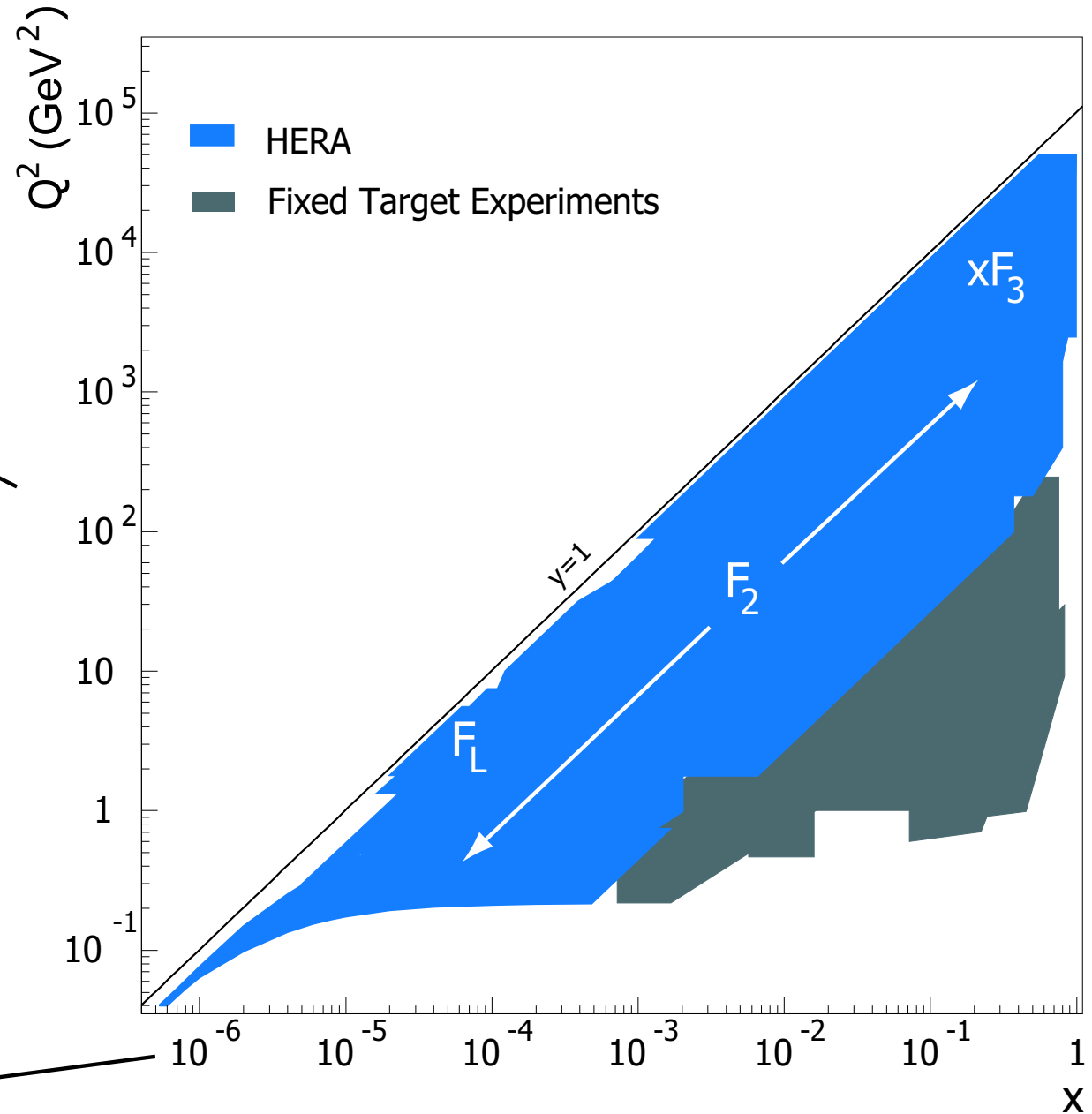
x₁ y₁

\leftarrow p



Kinematic range

5 orders of magnitude in Q^2

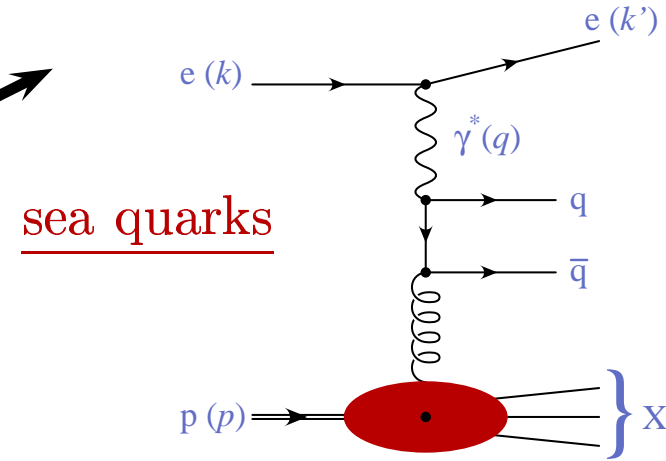
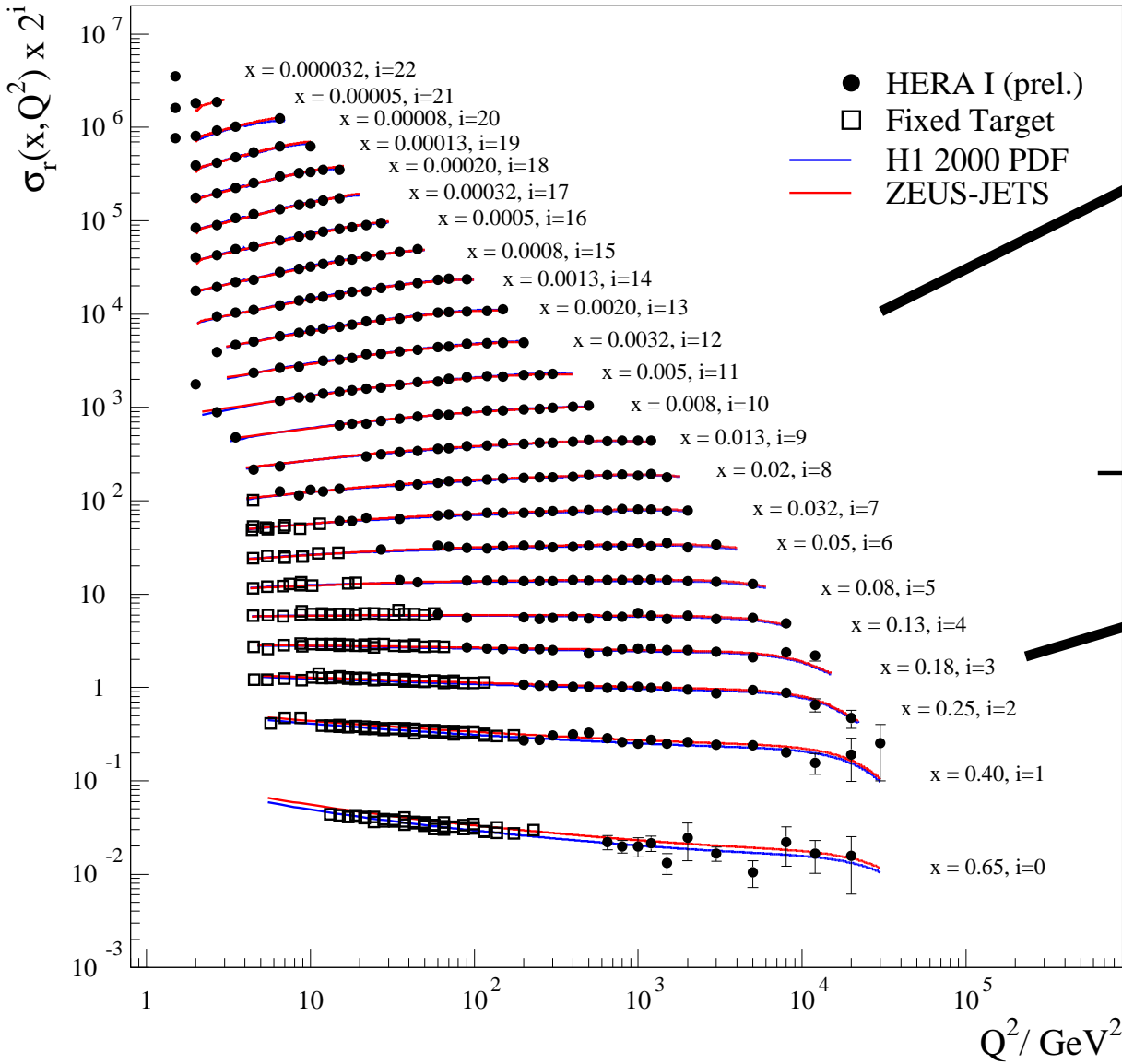


5 orders of magnitude in x

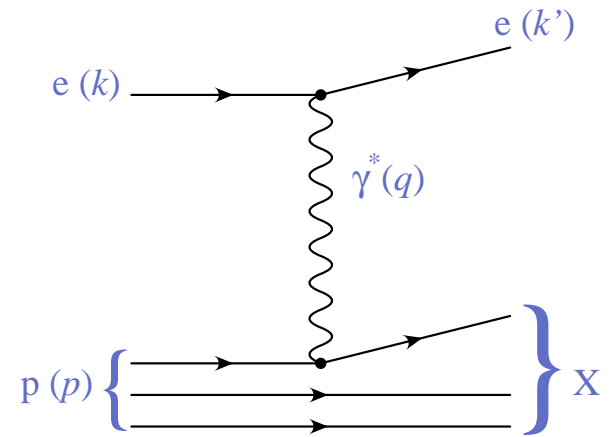
F_2 Measurements

HERA I e^+p Neutral Current Scattering - H1 and ZEUS

Scaling Violation: at small x



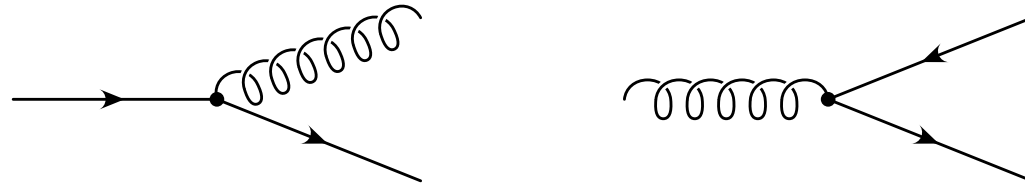
Scaling: at $x \simeq 0.2$
valence quarks



HERA Structure Functions Working Group

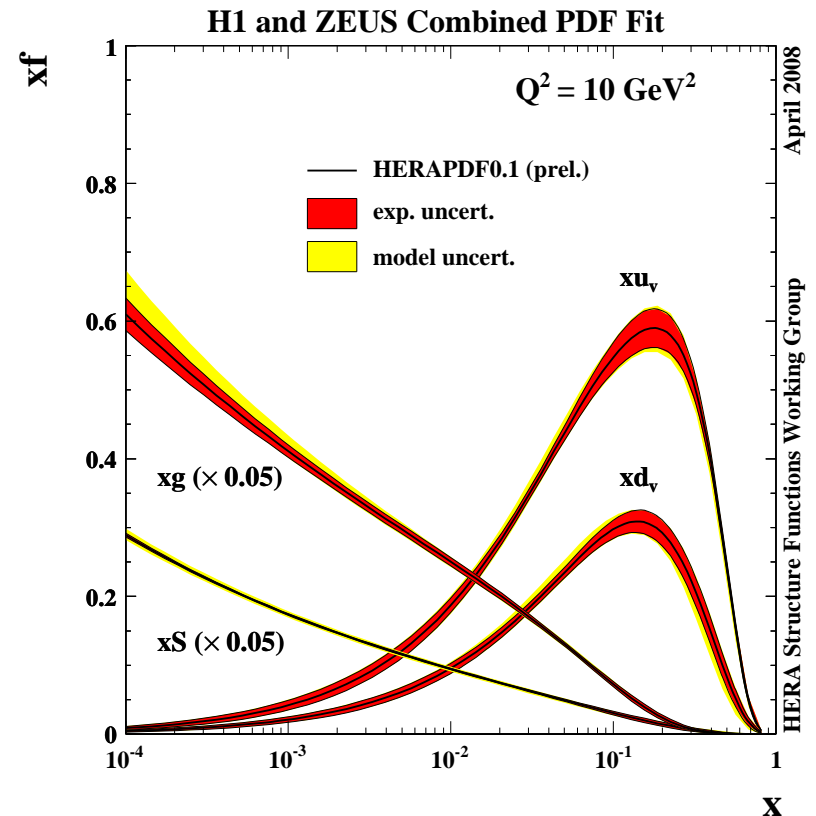
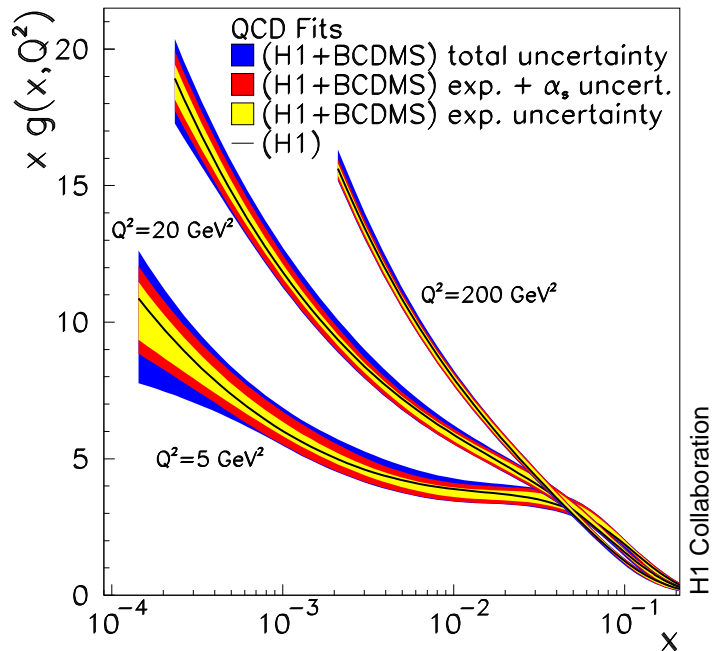
QCD: DGLAP equation

QCD predicts the evolution of F_2 in Q^2



$$\frac{dq(x, Q^2)}{d\log Q^2} \sim \alpha_s \int_x^1 (q(x', Q^2) P_{qq} + g(x', Q^2) P_{qg}) dx'$$

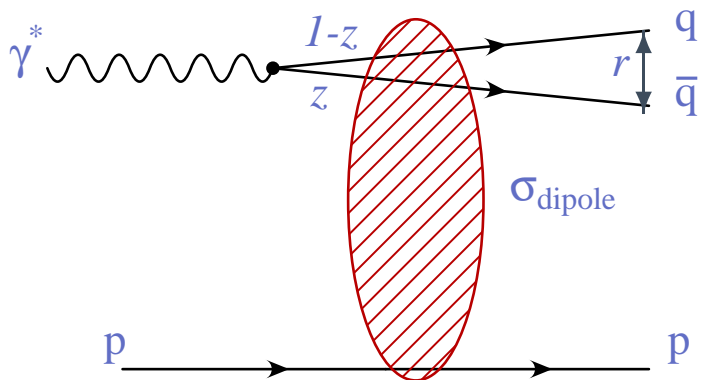
- allows the Gluon density extraction
- steep rise as Q^2 increases and x decreases



Vector Meson and DVCS

Two approaches

Colour Dipole



In the proton rest frame:

- γ^* fluctuates in $q\bar{q} + q\bar{q}g + \dots$

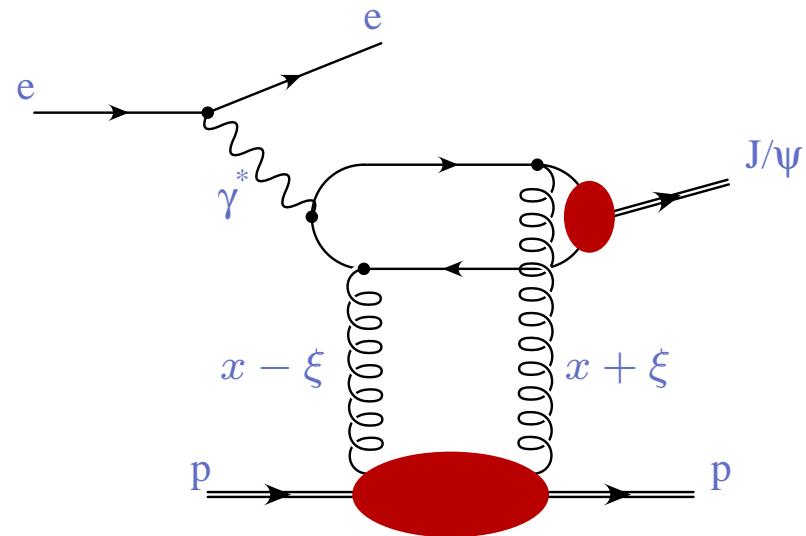
$$\sigma = \int dr^2 \psi^{in}(r, z, Q^2) \sigma_d^2 \psi^{out}(r, z, Q^2)$$

- ψ^{in} calculable

- σ_d is modelised (e.g. two gluons)

- integrated over trans. $q\bar{q}$ separation r

QCD in Breit frame



- "exact" QCD calculation possible

- $\int GPD(x, \xi, Q^2) dx$

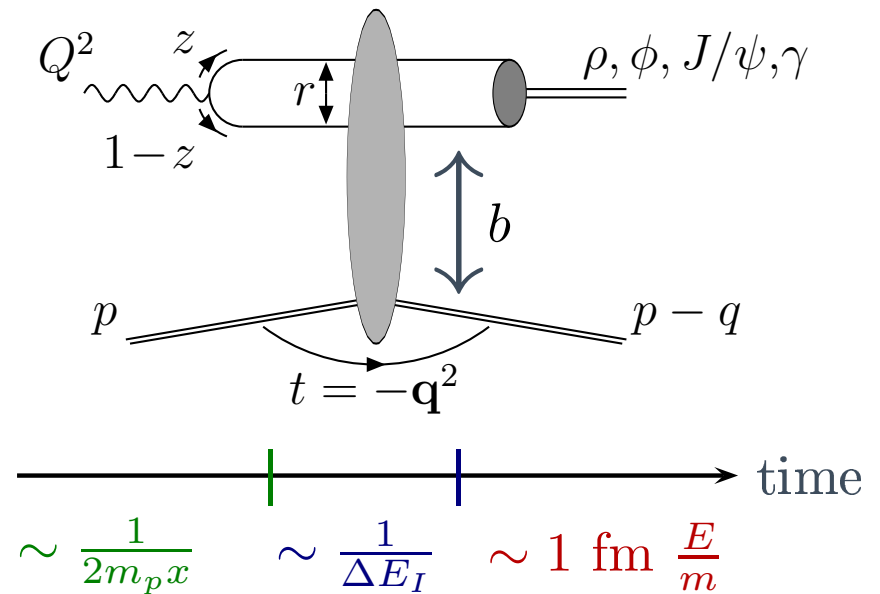
- J/Ψ wave function

- $GPDs(x, \xi, t; \mu)$ build from the PDFs with a skewing effect and a t dependence

Vector meson production in Colour Dipole approach

- at large energy, for \mathcal{A}_L (large Q^2 or heavy quarks):

1. γ fluctuates in $q\bar{q}$ dipole:
QED γ wave function Ψ_γ
2. dipole-proton interaction:
universal $\sigma_{dip}(r, z, b)$
3. $q\bar{q}$ recombination into VM



- The scanning radius r is expected to decrease with increasing Q^2 or M_V

\Rightarrow **universal scale:** $\mu^2 = z(1-z)(Q^2 + M_V^2)$

- for \mathcal{A}_L (large Q^2) or heavy quarks: $z \simeq 1/2 \Rightarrow \mu^2 \simeq (Q^2 + M_V^2)/4$

- for light quarks, \mathcal{A}_T : contrib. from end points $z = 0, 1 \Rightarrow \mu^2$ can be small even for large $Q^2 \Rightarrow$ **soft contributions**

Q^2 , W , t and M_Y expected dependences

Q^2 dependence

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

\Rightarrow Naive $R = \sigma_L/\sigma_T \propto Q^2/M_V^2$ modified.

W dependence

- $\sigma \sim W^\delta \sim |x g(x, \mu^2)| \Rightarrow$ hard W dependence: signature of a hard scale

$\Rightarrow \delta = 4(\alpha(t) - 1) = 4(\alpha(0) + \alpha't - 1)$ larger than soft

\Rightarrow Hard scale: $\delta, \alpha(0)$: universal with $\frac{Q^2 + M_X^2}{4}$ for σ_L and delayed for σ_T

t dependence

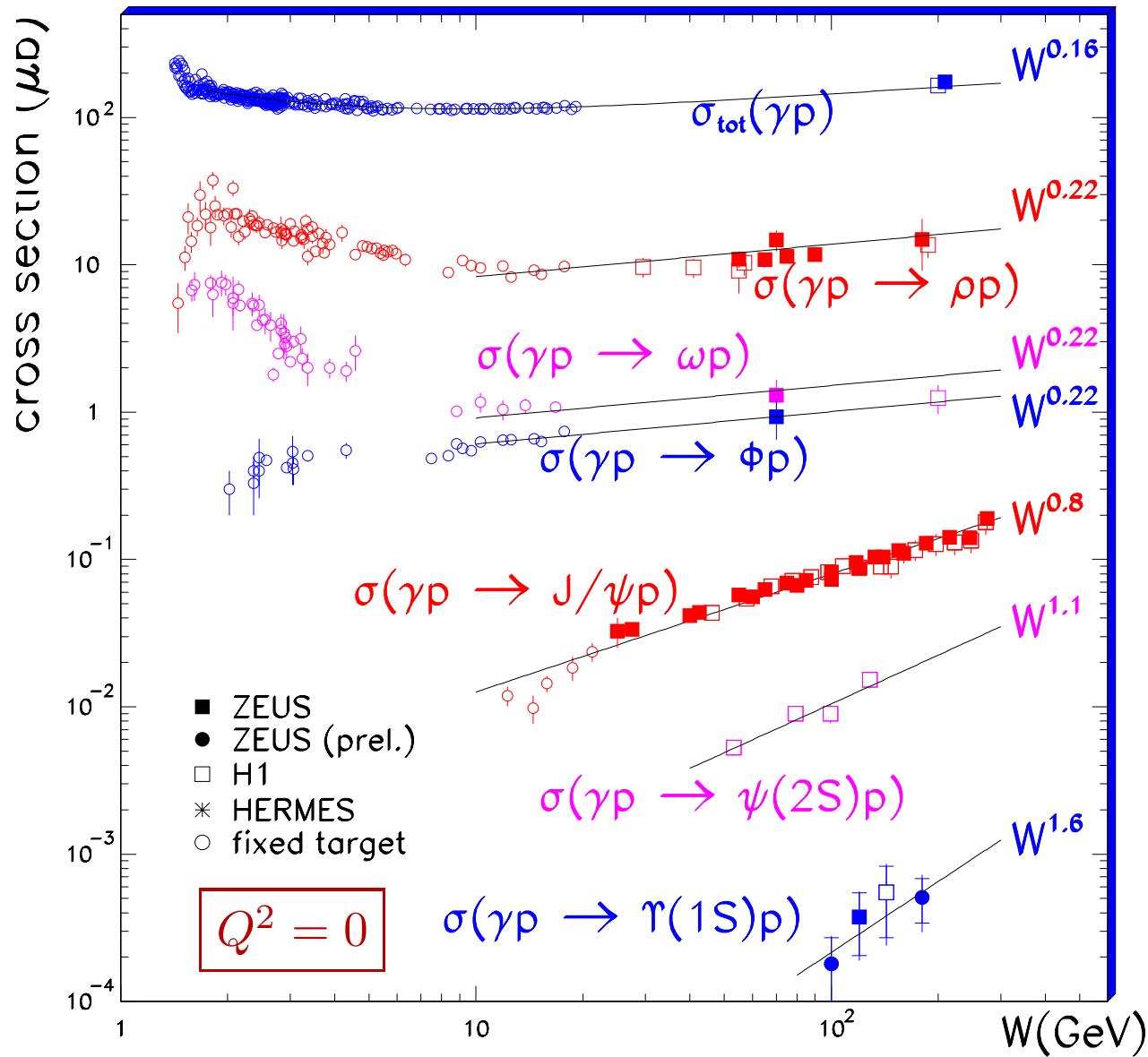
- $d\sigma/dt \sim e^{-b|t|}$ $b = b_{dip} \oplus b_{exch} \oplus b_Y$

\Rightarrow Hard scale: b : universal with $\frac{Q^2 + M_X^2}{4}$ with $b_T > b_L$

M_Y dependence

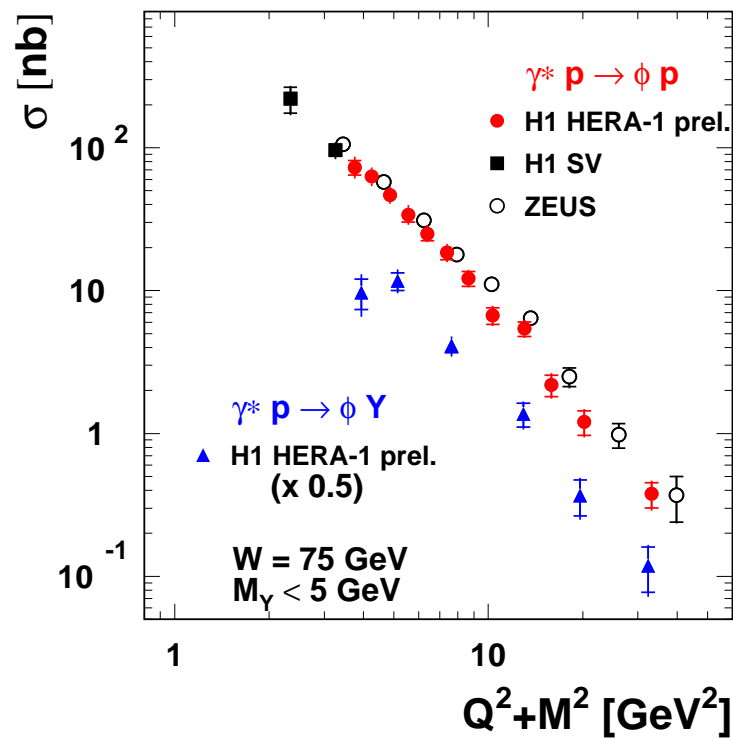
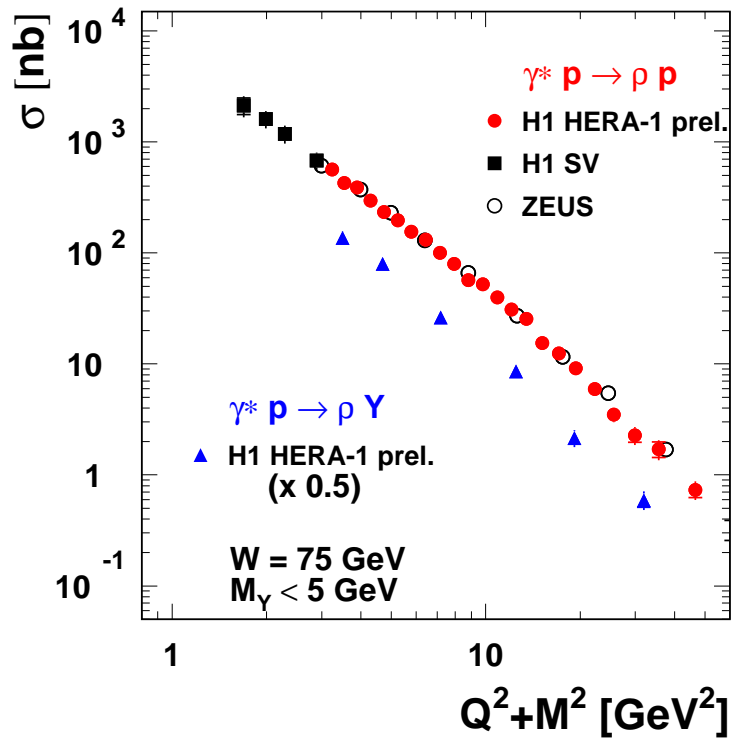
- elastic- proton dissociation universality for Q^2 , W and helicity amplitudes.

Soft to hard transition: mass

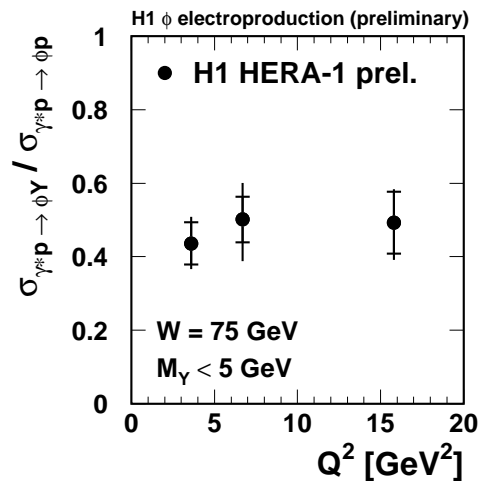
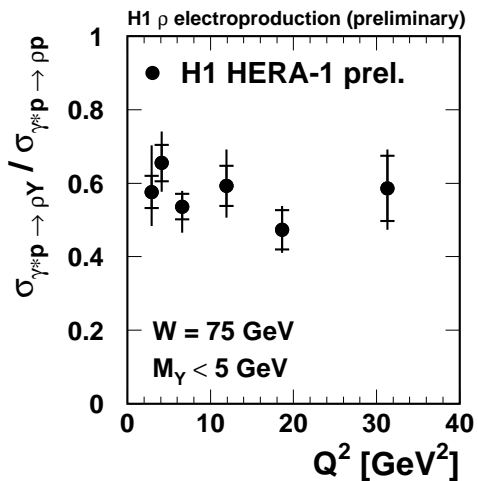


- Low mass ($\rho, \phi, \omega; M_V^2 \simeq 1 \text{ GeV}^2$): no pert. scale
 → weak energy dep. (soft regime)
- High mass ($J/\psi, \psi$): pert. scale
 → strong energy dep. (hard regime)
- Large mass (Υ) important skewing effect

Light VM Cross-sections versus Q^2

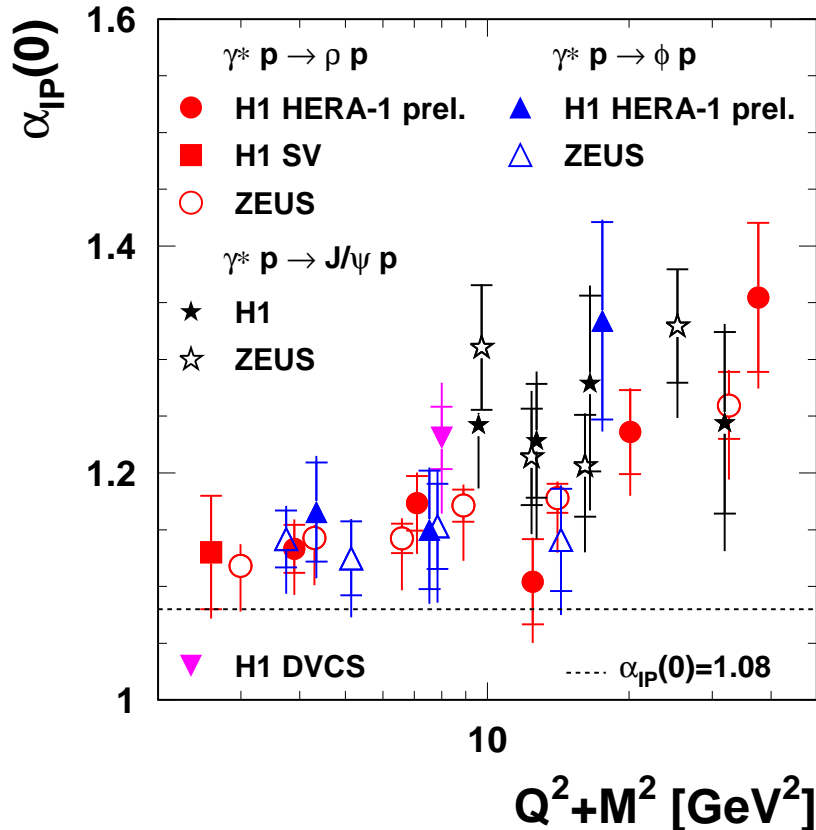
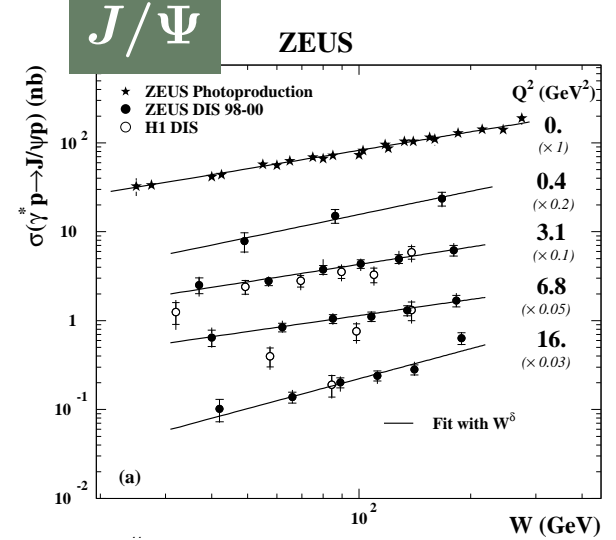
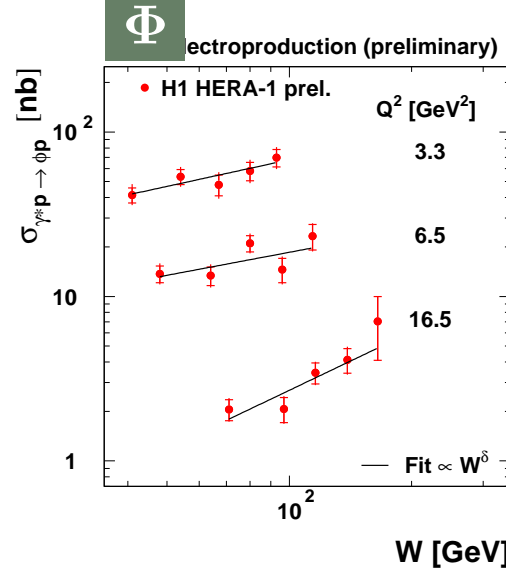
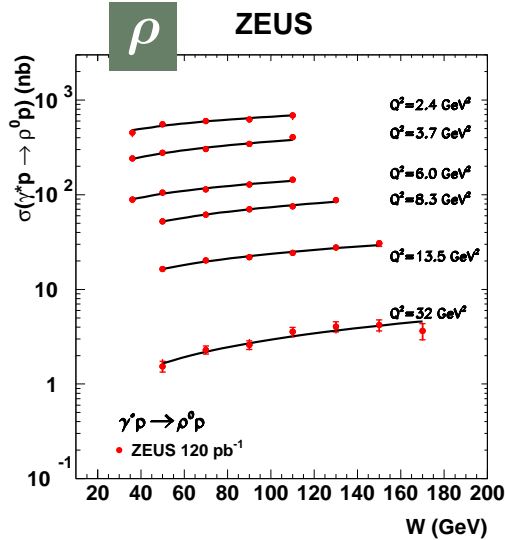


- High precision for elastic cross-sections; First ϕ p-diss. cross-section



- p.diss/el: no Q^2 dep.
i.e. vertex factorisation

W dependences



$$\alpha_P(0) = 1 + \delta/4 + \alpha'_P / \langle |t| \rangle$$

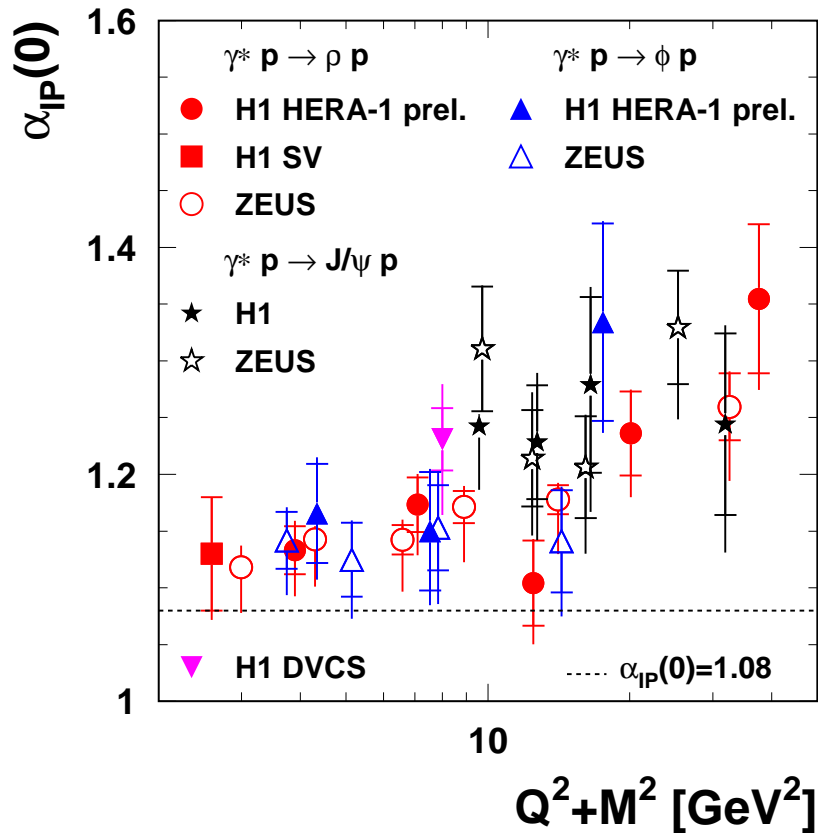
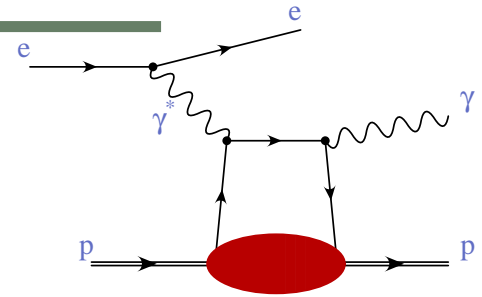
$$\alpha'_P = 0 - 0.25 \text{ GeV}^{-2}$$

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

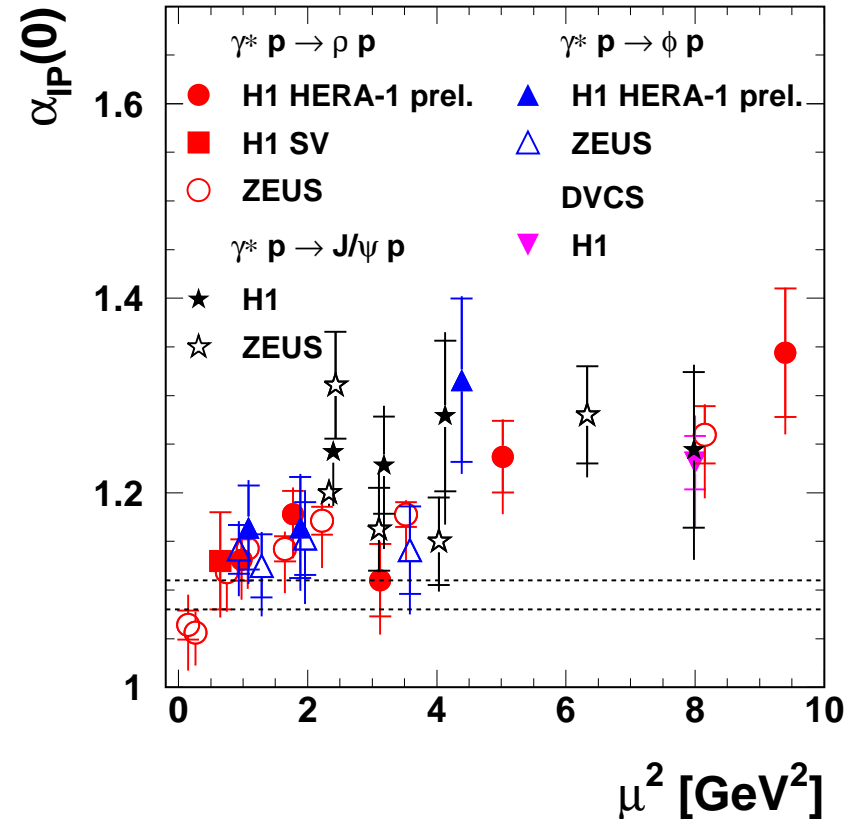
⇒ Transition from soft to hard regime with $Q^2 + M^2$ but soft contrib. up to 20 GeV² (σ_T ?)

Note on the scale

DVCS is like DIS, the photon (at LO) interacts directly with a resolved quark.



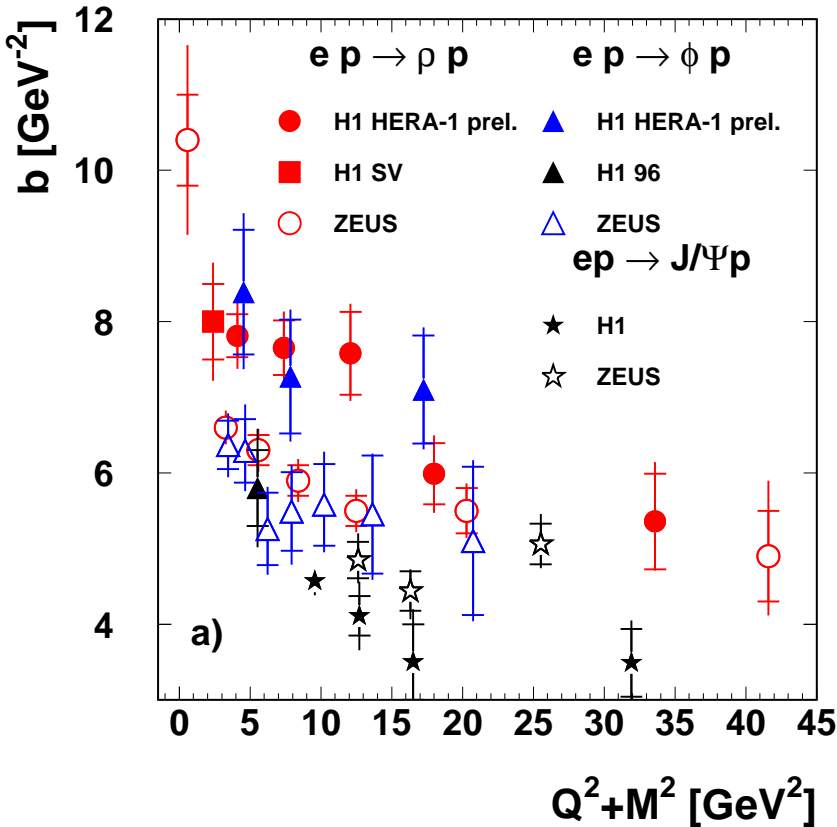
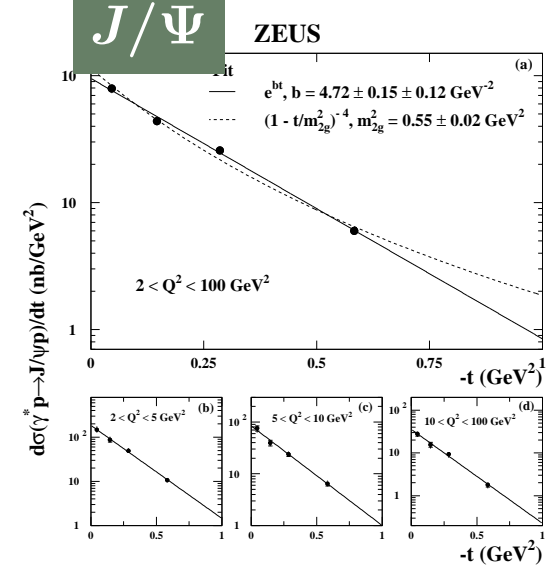
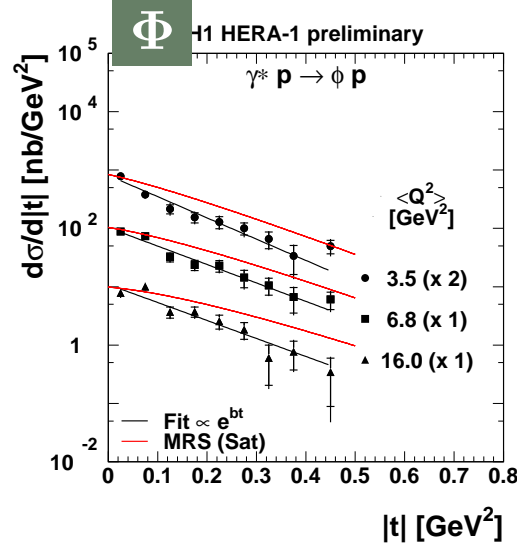
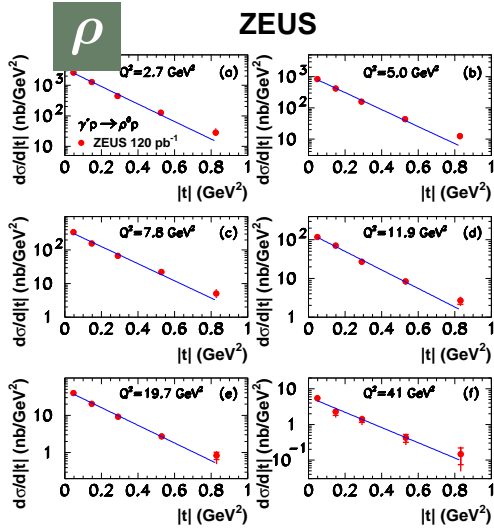
for all: $\mu^2 = Q^2 + M_X^2$



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

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

t dependences

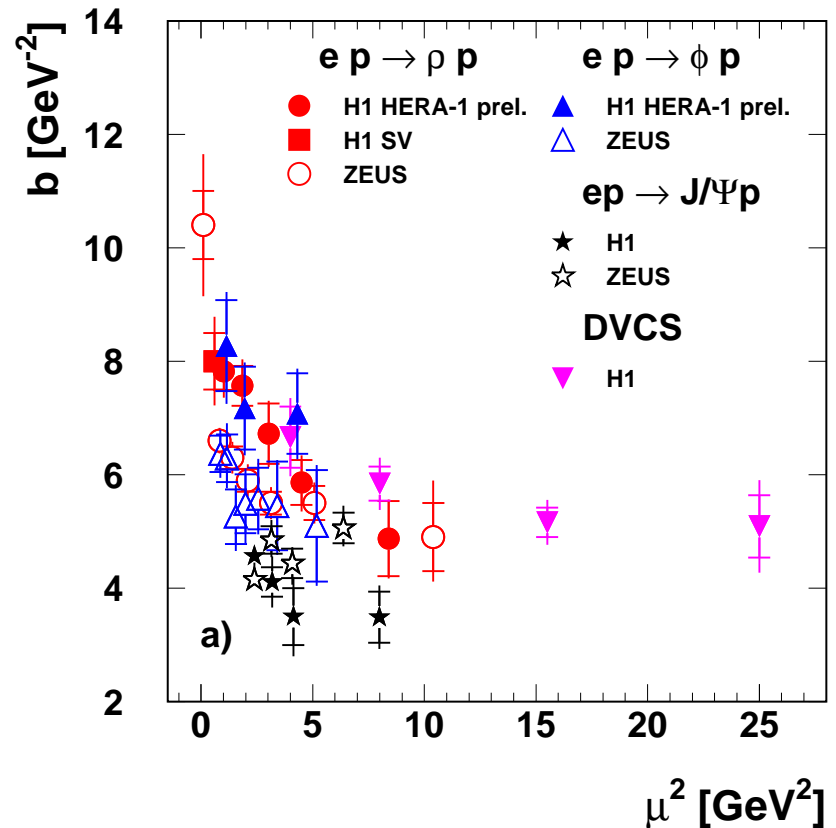
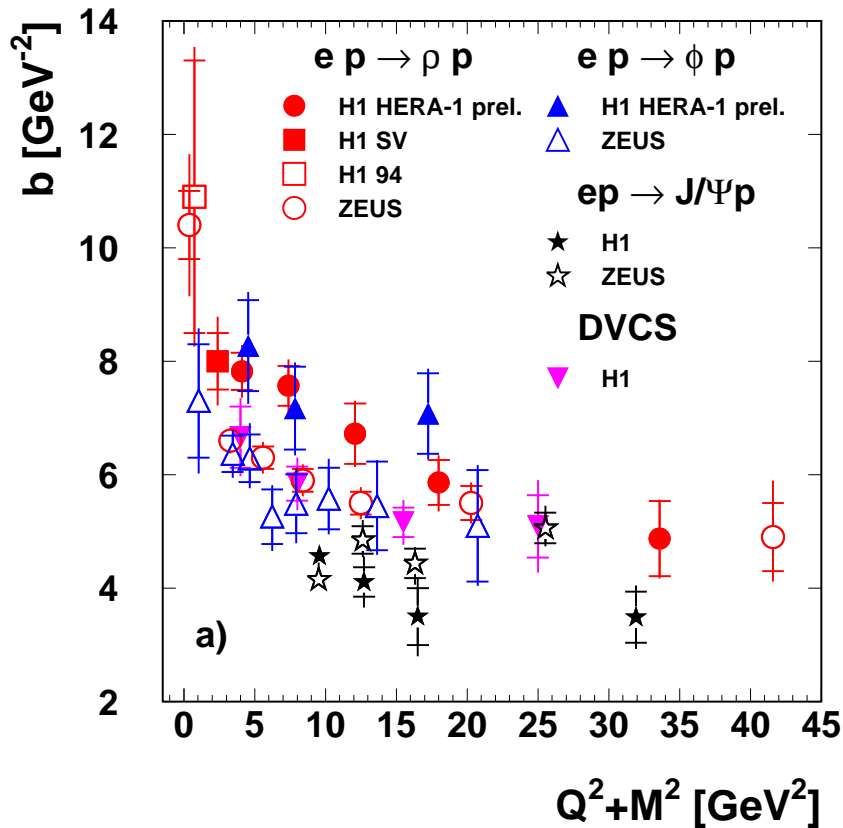


fit of $e^{-b|t|}$

- t slope hardening with $Q^2 + M^2$ for all VM and DVCS

⇒ Transition from soft to hard regime with $Q^2 + M^2$ effect of VM WF ?

Note on the scale



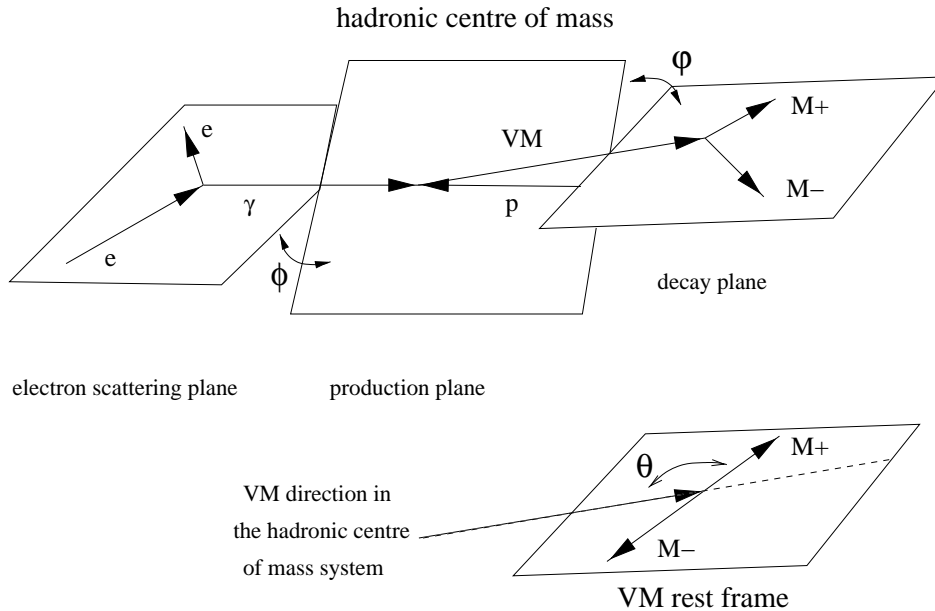
for all: $\mu^2 = Q^2 + M_X^2$

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

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

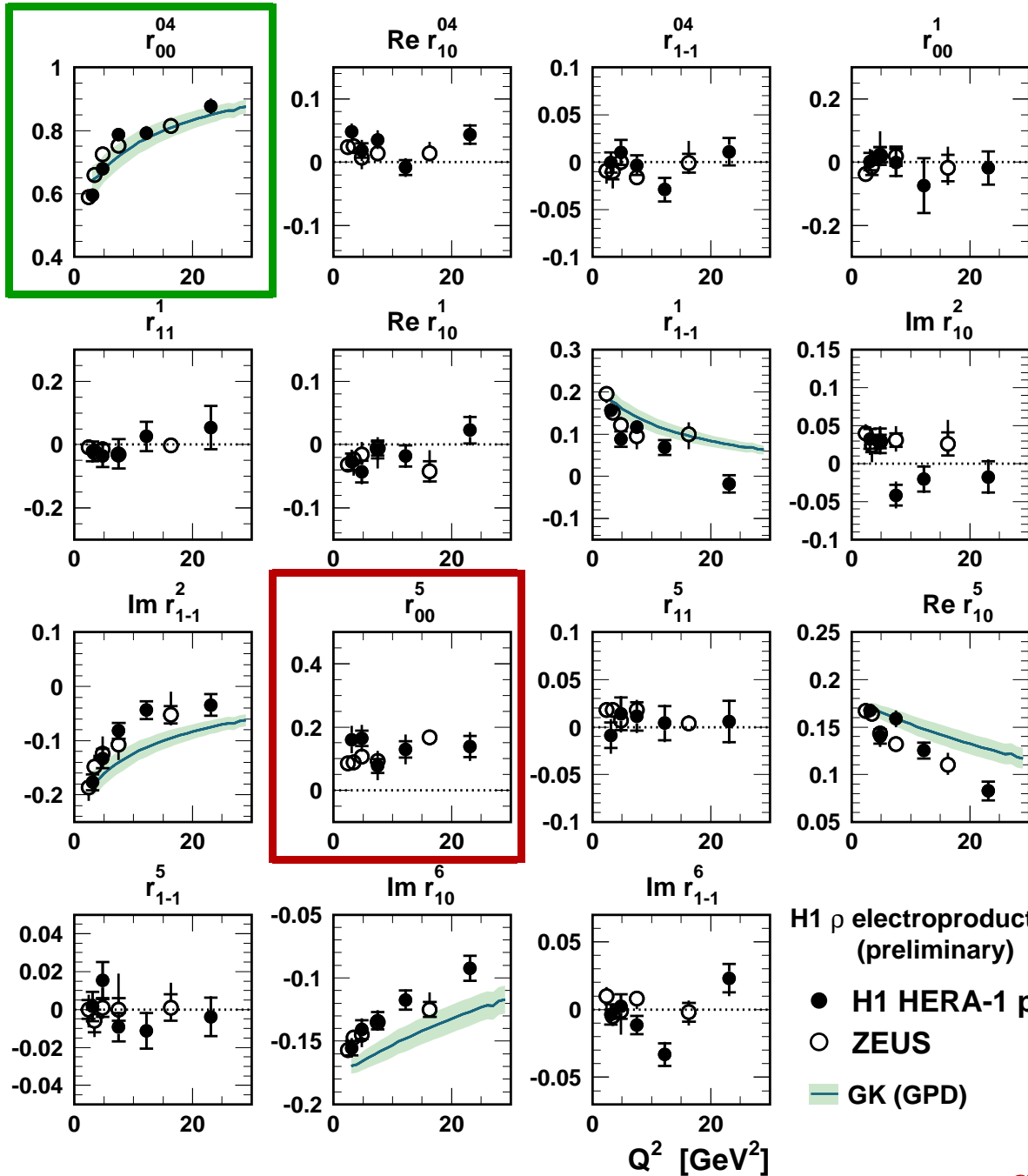
$T_{10} : \gamma_L \rightarrow \rho_T$

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

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

- SCHC violation (single flip $\propto \sqrt{|t|}$, double $\propto |t|$)
- pQCD Hierarchy ($|t| < Q^2$): $|T_{00}| > |T_{11}| > |T_{01}| > |T_{10}| > |T_{1-1}|$

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 Goloskokov-Kroll
 (GPD) model
- r_{00}^5 violates SCHC (flip)
- Other SDME $\simeq 0$

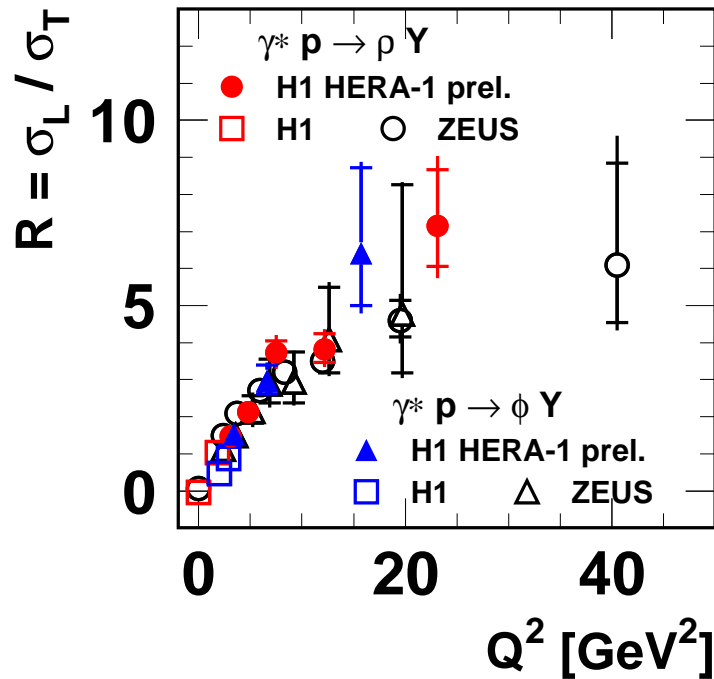
H1 ρ electroproduction
 (preliminary)

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

Polarisation - $R = \sigma_L / \sigma_T$

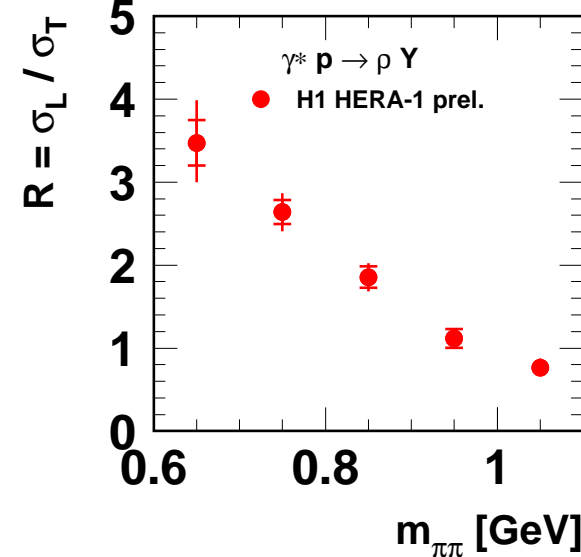
$$R_{SCHC} = \frac{1}{\epsilon} \frac{r_{00}^{04}}{1 - \epsilon r_{00}^{04}} = \frac{|T_{00}|^2}{|T_{11}|^2}$$

H1 ρ and ϕ electroproduction (preliminary)

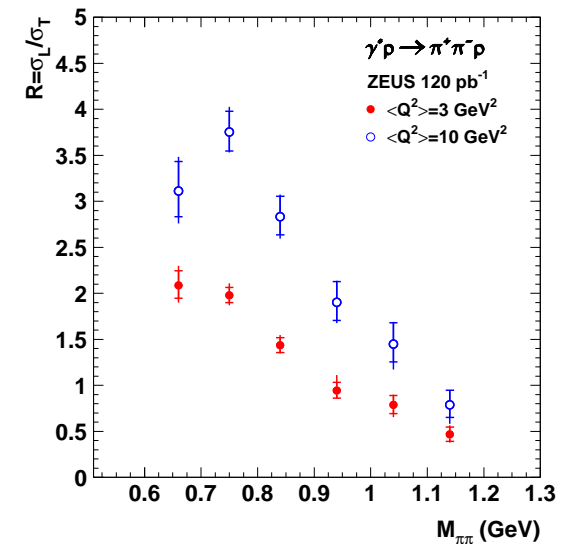


- Naive $R \propto Q^2 / M^2$ - modified at high Q^2
- Similar R for ϕ and ρ
- Strong invariant mass dependence in ρ case

H1 ρ electroproduction (preliminary)

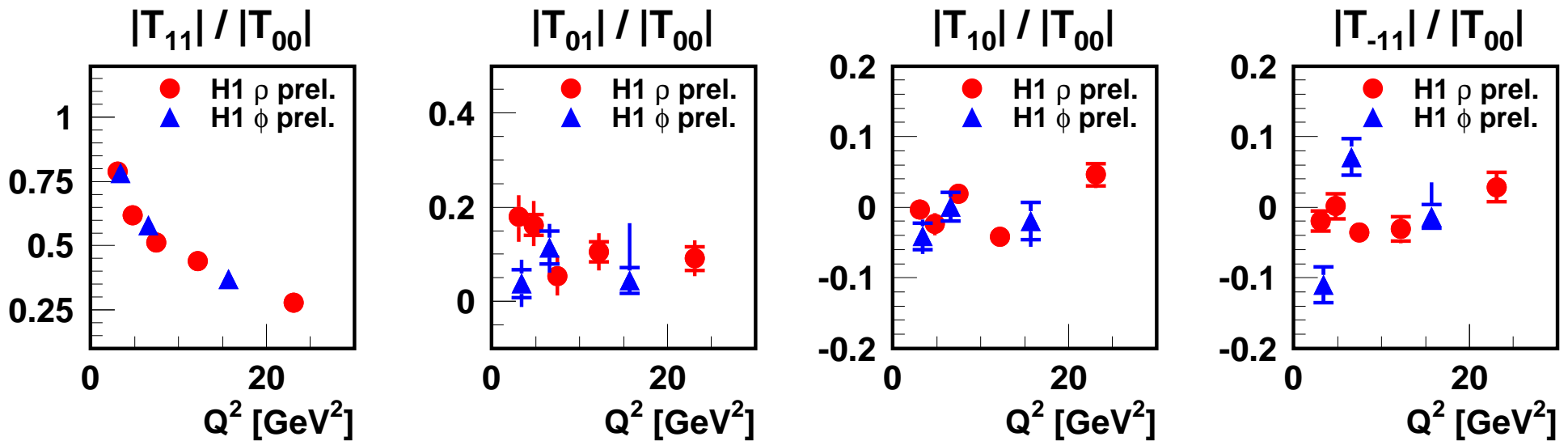


ZEUS



Polarisation - Amplitude ratios vs. Q^2

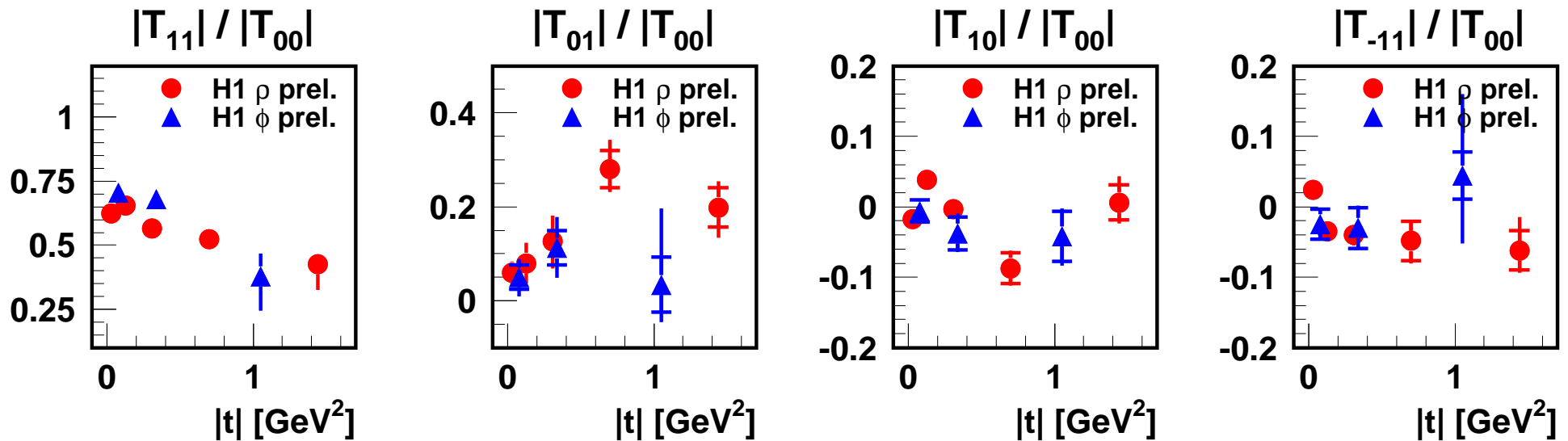
- pQCD :
- $|T_{11}|/|T_{00}| \sim \frac{M}{Q} \frac{1+\gamma}{\gamma}$
 - $|T_{10}|/|T_{00}| \sim -\frac{M}{Q^2} \frac{\sqrt{|t|}}{\gamma} \frac{\sqrt{2}}{\gamma}$
 - $|T_{01}|/|T_{00}| \sim \frac{\sqrt{|t|}}{Q} \frac{1}{\sqrt{2}\gamma}$
- γ : gluon anomalous dim.



- $|T_{11}|/|T_{00}|$ 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:
- $|T_{11}|/|T_{00}| \sim \frac{M}{Q} \frac{1+\gamma}{\gamma}$
 - $|T_{10}|/|T_{00}| \sim -\frac{M}{Q^2} \frac{\sqrt{|t|}}{\gamma} \frac{\sqrt{2}}{\gamma}$
 - $|T_{01}|/|T_{00}| \sim \frac{\sqrt{|t|}}{Q} \frac{1}{\sqrt{2}\gamma}$
- γ : gluon anomalous dim.

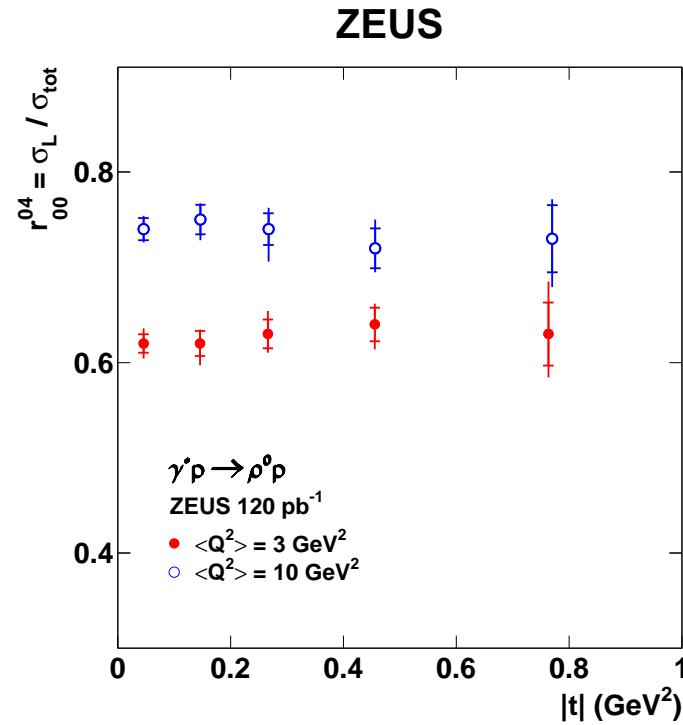
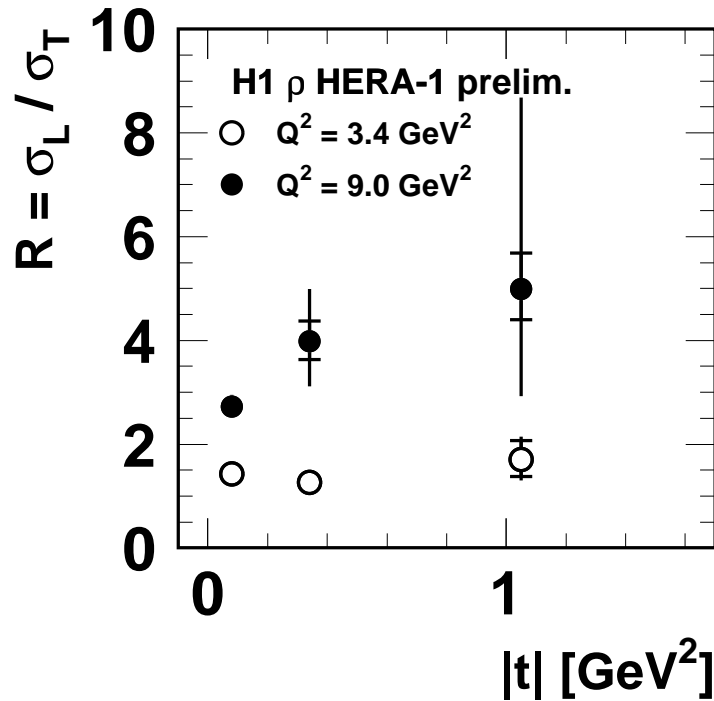


- $|T_{11}|/|T_{00}|$ decreases with $|t|$
- $|T_{01}|/|T_{00}|$ increases with $|t| \leftrightarrow$ SCHC violation increases with $|t|$
- $|T_{10}|/|T_{00}|$ and $|T_{-11}|/|T_{00}|$ are small but some $|t|$ dependence
- $|T_{11}|/|T_{00}|$ decrease partially compensated by $|T_{01}|/|T_{00}|$ increase

$\Rightarrow \sigma_L/\sigma_T$ is the result of partial compensations

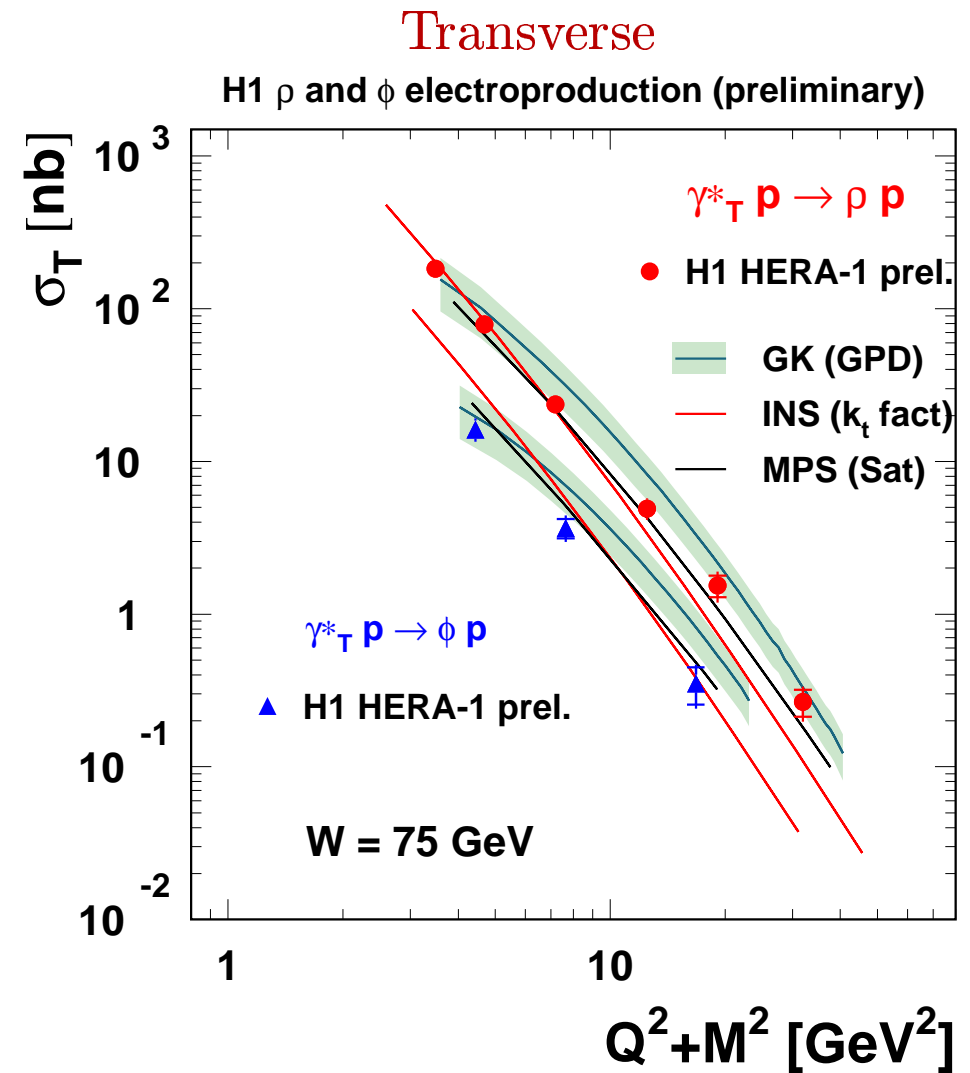
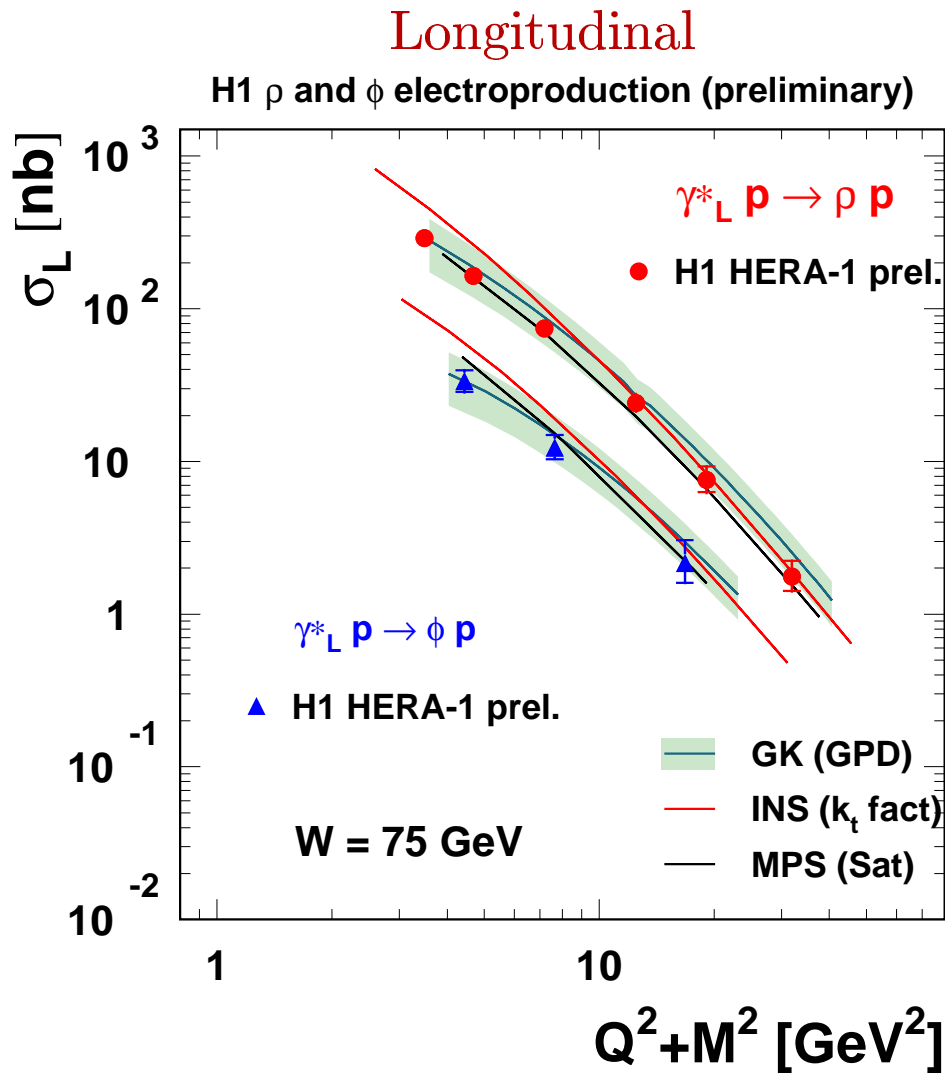
Polarisation - $R = \sigma_L / \sigma_T$ versus t

$$R_{SCHC+T_{01}} = \frac{|T_{00}|^2}{|T_{11}+T_{01}|^2}$$



- H1: R depends on t for large $Q^2 \Rightarrow b_L < b_T$!!! (σ_L more pert. than σ_T)
- Not seen by ZEUS
- due to different ρ' background treatment

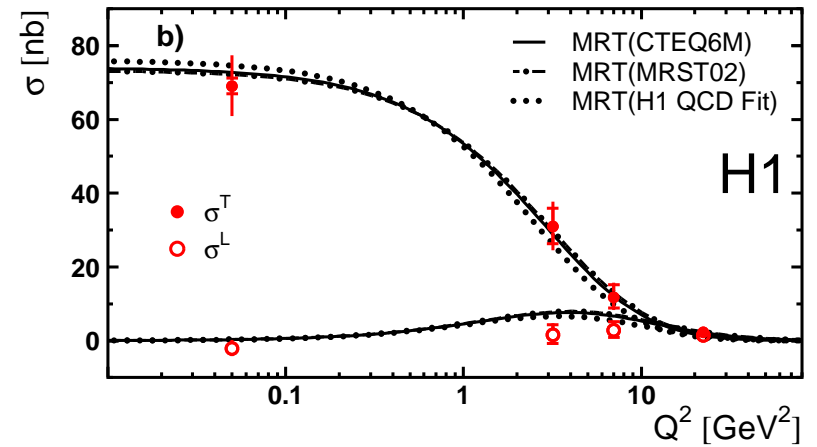
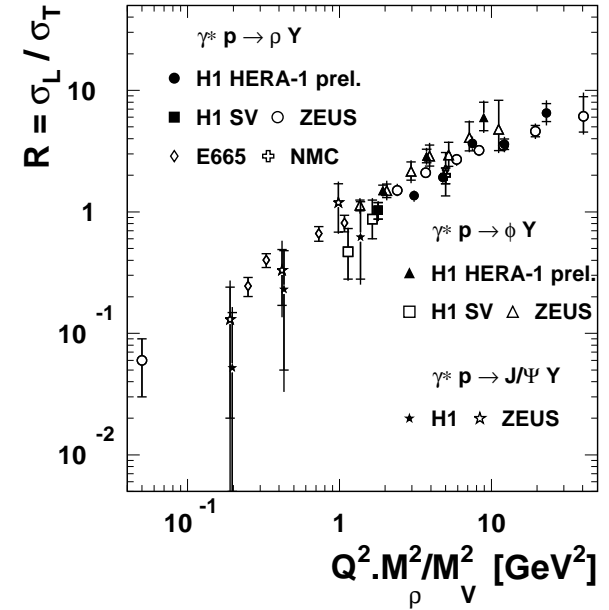
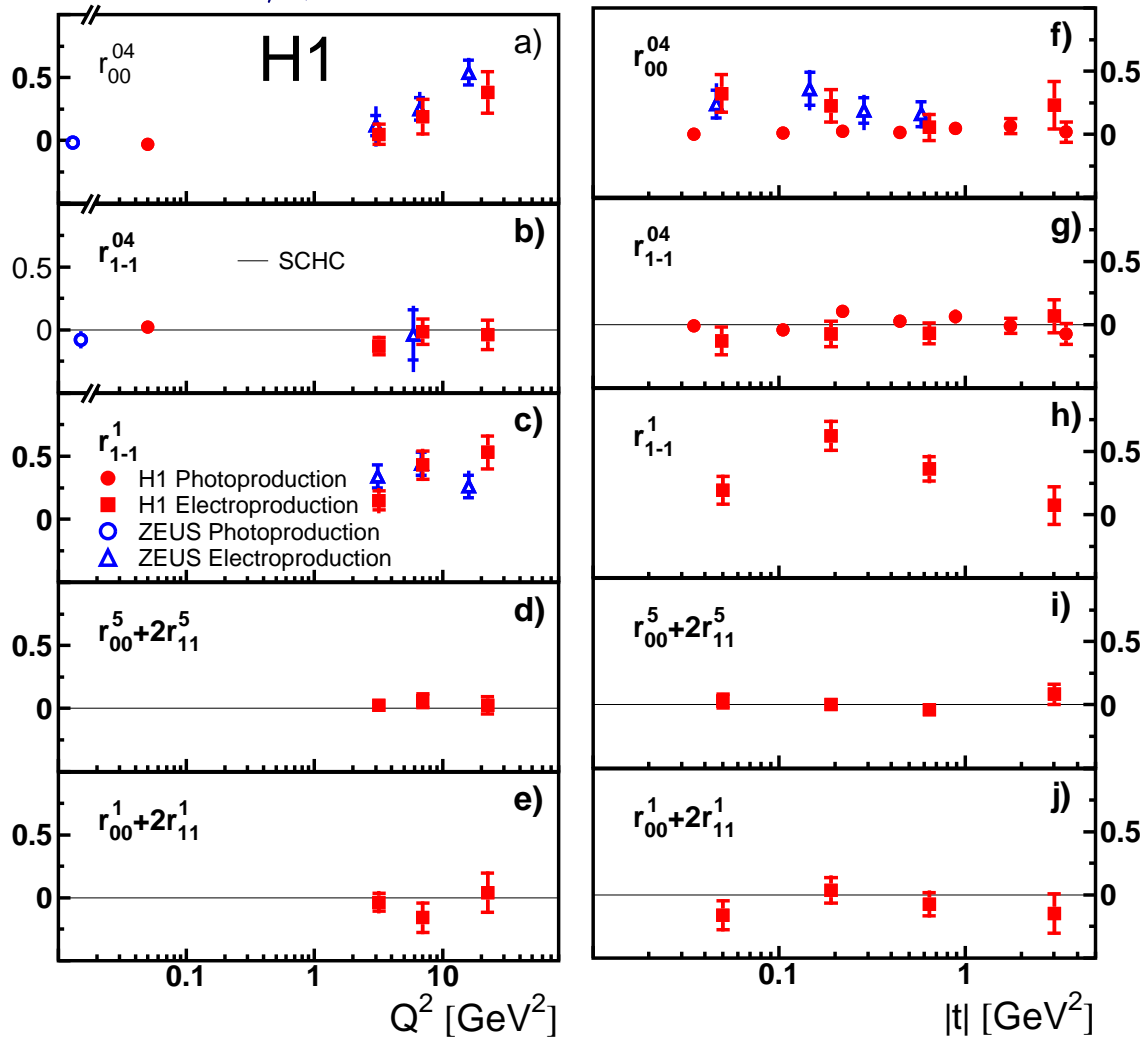
ρ and ϕ Polarisation - Cross-sections



- Different $Q^2 + M^2$ dependences of σ_L and σ_T ($\sigma_L = 0$ at $Q^2 = 0$)
- Best description of σ_L by GK (GPD) model; σ_T not described

J/ψ Polarisation

J/ψ SDME vs Q^2 and t :



- J/ψ SDME compatible with SCHC: non-relativistic WF
- Common behaviour of R for all VM vs. $Q^2 M_\rho^2 / M_{VM}^2$
- J/ψ mostly transverse

DVCS: QCD interpretation

- correct Q^2 dependence of the propagator and of b in the cross section:

$$S = \sqrt{\frac{\sigma_{DVCS} Q^4 b(Q^2)}{(1 + \rho^2)}}$$

- **skewing** factor: around 2

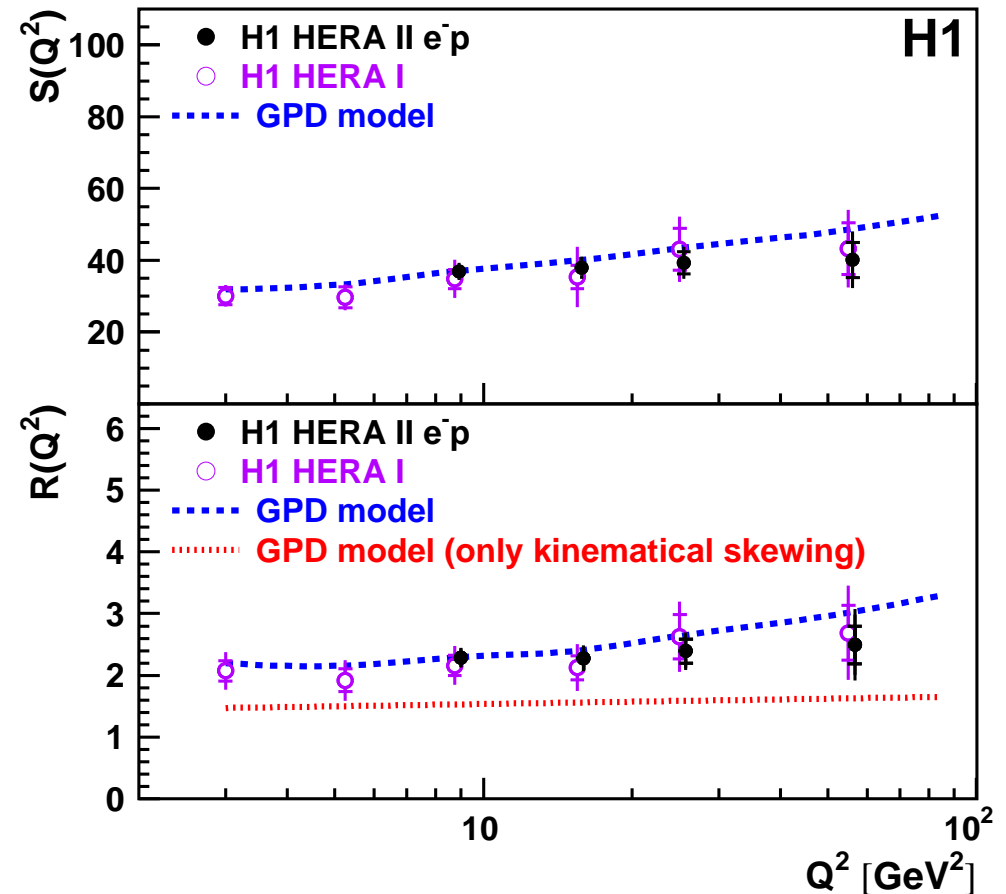
$$R = \frac{\text{Im} A(\gamma^* p \rightarrow \gamma p)}{\text{Im} A(\gamma^* p \rightarrow \gamma^* p)}$$

$$= \frac{4 \sqrt{\pi} \sigma_{DVCS} b(Q^2)}{\sigma_T(\gamma^* p \rightarrow X) \sqrt{(1 + \rho^2)}}$$

$-\sigma_T(\gamma^* p \rightarrow X)$ taken from QCD analysis of inclusive DIS H1 measurement.

⇒ important skewing factor

⇒ Q^2 evolution close to the one of DIS (pure DGLAP)

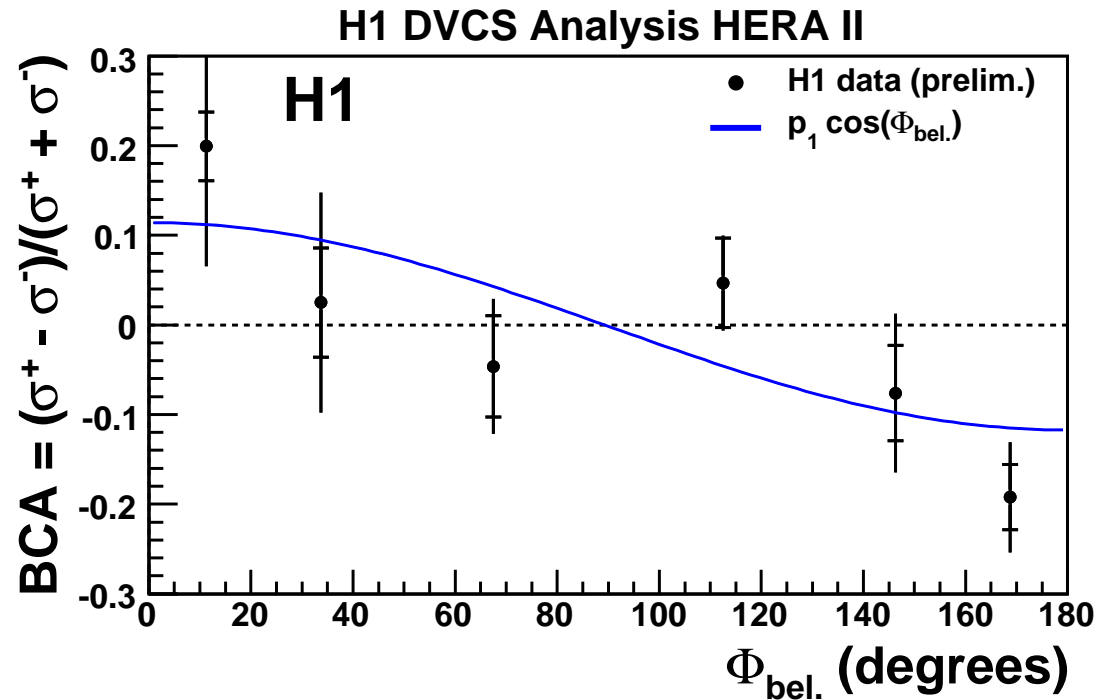


Beam Charge Asymmetry

New H1 measurement based on 291 pb^{-1} of HERA II data (e^+ and e^-).

- First DVCS BCA measured at HERA.

$$BCA \equiv \frac{\sigma(e^+p) - \sigma(e^-p)}{\sigma(e^+p) + \sigma(e^-p)} \sim p_1 \cos(\Phi)$$



$0.05 < |t| < 1 \text{ GeV}^2$ - before deconvolution by the ϕ resolution.

Conclusions

High energy HERA data provide a **large variety of measurements**:

- $\rho, \phi, J/\psi, \Upsilon, \gamma$
- large kinematic domain in Q^2, W, t
- cross sections, helicity amplitudes, p-diss/el, BCA

Rich field for **QCD understanding**:

- precision in the **soft to hard** transition: W dep., t dep.
- effective **QCD scales**, and L/T separation
- many models: GPD, BFKL, dipole, saturation,...
with semi-qualitative understanding
but many quantitative description still lacking

Back-up Slides

VM theory: Dipole approach and k_T factorisation

Dipole approach - Saturation :

Shown here: C.Marquet, R.Peschanski, G.Soyez
[hep-ph/0702171]

- $\sigma_{q\bar{q}-p}$ extracted from fits to inclusive data (F_2) with geometric scaling.
- Fits may include VM data as well (see later) and QCD evolution at high Q^2 .

k_T factorisation - BFKL pomeron:

Shown here: I.Ivanov, N.Nikolaev, A.Savin
[hep-ph/0501034]

- Conjugate approach to dipole one in " k_T space".
- $\sigma_{q\bar{q}-p}$ computed from k_T -unintegrated gluon pdf $\mathcal{F}(x, \vec{\kappa})$:

$$\sigma_{q\bar{q}-p} = 4\pi/3 \int d^2\vec{\kappa}/\kappa^4 \mathcal{F}(x, \vec{\kappa}) \alpha_s(\mu^2) [1 - \exp(i\vec{\kappa}\vec{r})]$$

N.B: for small dipole,

$$\sigma_{q\bar{q}-p} \simeq \pi^2/3 r^2 \alpha_s(\mu^2) G(x, \mu^2) \quad \text{with } \mu^2 = A/(z(1-z)Q^2 + m_q^2) ; A = 9 - 10$$

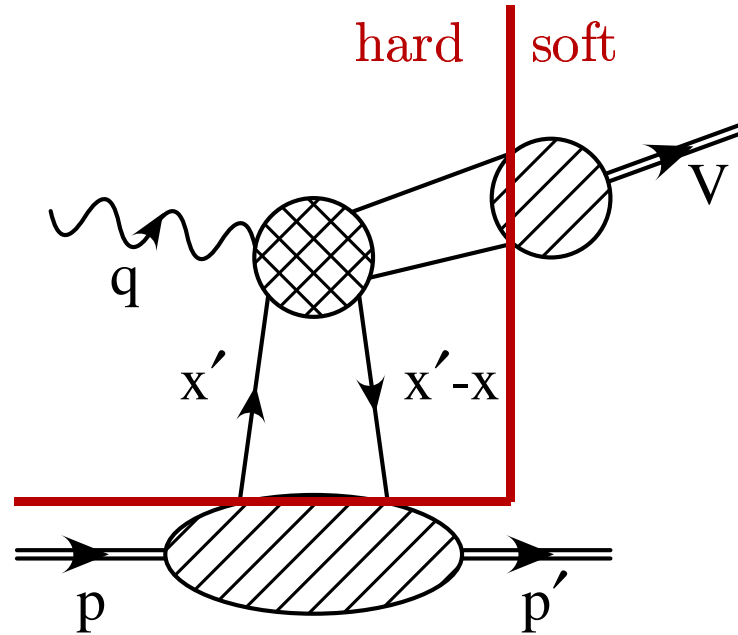
$$\longrightarrow \sigma_T \propto (Q^2 + M_V^2)^{-4} [\alpha_s(\mu^2) G(x, \mu^2)]^2$$

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

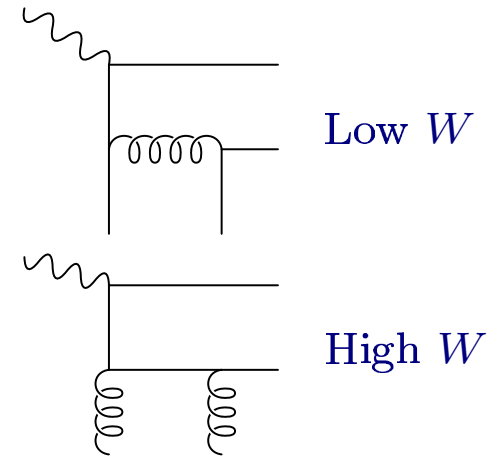
VM theory: Collinear factorisation

QCD factorisation theorem valid for leading power of Q in DIS:

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



Typical LO diagrams for H_{ij} :



$$\mathcal{A}_{\gamma^{(*)} p \rightarrow V p} = \sum_{i,j} \int_0^1 dz \int dx' f_{i/p}(x', x' - x, t, \mu) H_{ij}(Q^2 x'/x, Q^2, z, \mu) \Psi_j^V(z, \mu)$$

where $f_{i/p}$: non-forward PDF ($x' \neq x' - x$, t dependant) \rightarrow GPD's

H_{ij} : hard scattering m.a. ; Ψ_j^V : VM wave fct

Theorem is **proven** for γ_L ; extended/assumed for γ_T in many models

Shown here: S.Goloskokov and P.Kroll

[hep-ph/07083569]

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:

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

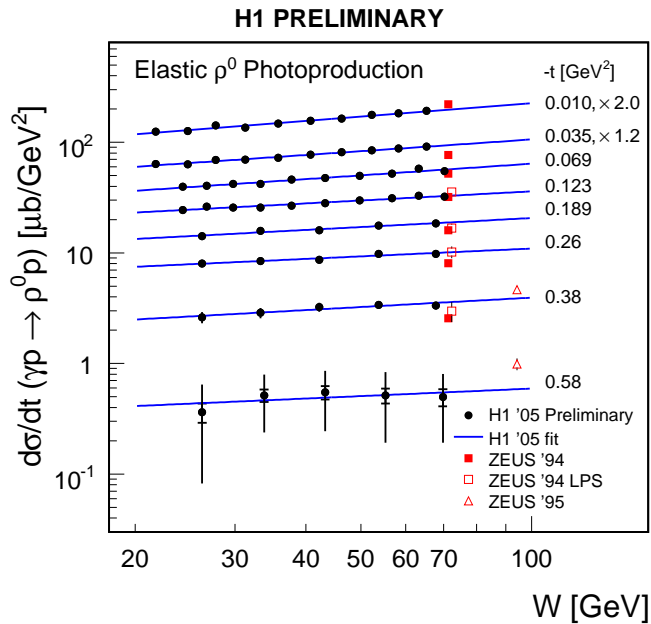
$$\begin{aligned}
 \alpha &= |T_{11}|/|T_{00}| \\
 \beta &= |T_{01}|/|T_{00}| \\
 \delta &= |T_{10}|/|T_{00}| \\
 \eta &= |T_{-11}|/|T_{00}|
 \end{aligned}$$

$$\begin{aligned}
 B &= \frac{1}{N_T + \varepsilon N_L} = \frac{R}{1 + \varepsilon R} \\
 N_T &= \alpha^2 + \beta^2 + \eta^2 \\
 N_L &= 1 + 2\delta^2
 \end{aligned}$$

Shrinkage : α'_{IP} measurements

H1 ρ photoproduction measurements:

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

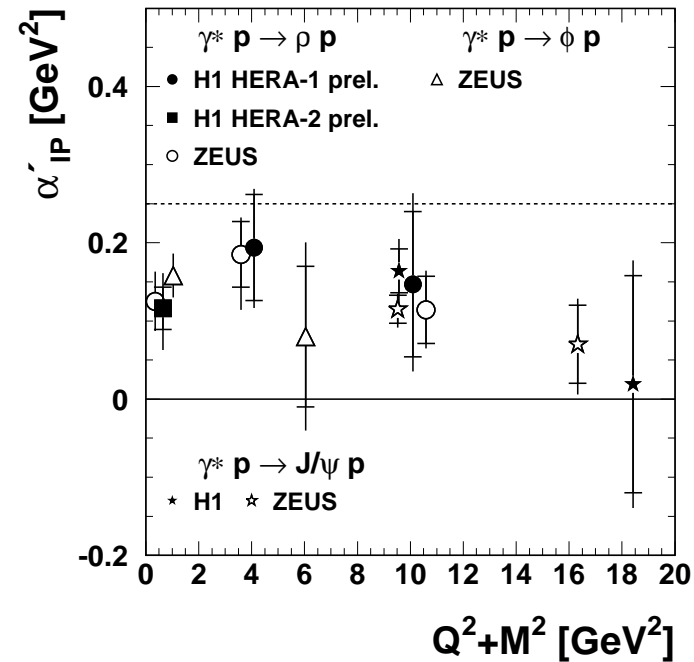
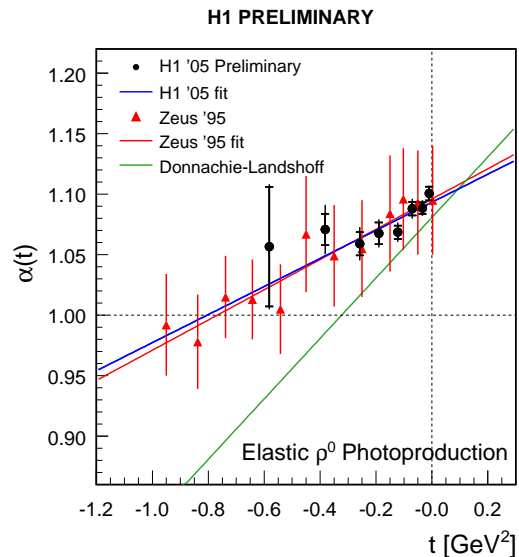


1. Study W depend. in bins of t :

$$\rightarrow \text{Fit: } W^\delta \rightarrow \alpha_P(t) = 1 + \delta/4$$

2. Study $\alpha_P(t)$ trajectories:

$$\rightarrow \text{Fit: } \alpha_P(t) = \alpha_P(0) + \alpha'_{IP} t$$



\Rightarrow For all VM, α'_{IP} smaller than 0.25 (DL, $p\bar{p}$)

(cf BFKL, multiple IP exchange)

Rho mass

ZEUS

