Vector meson production at HERA

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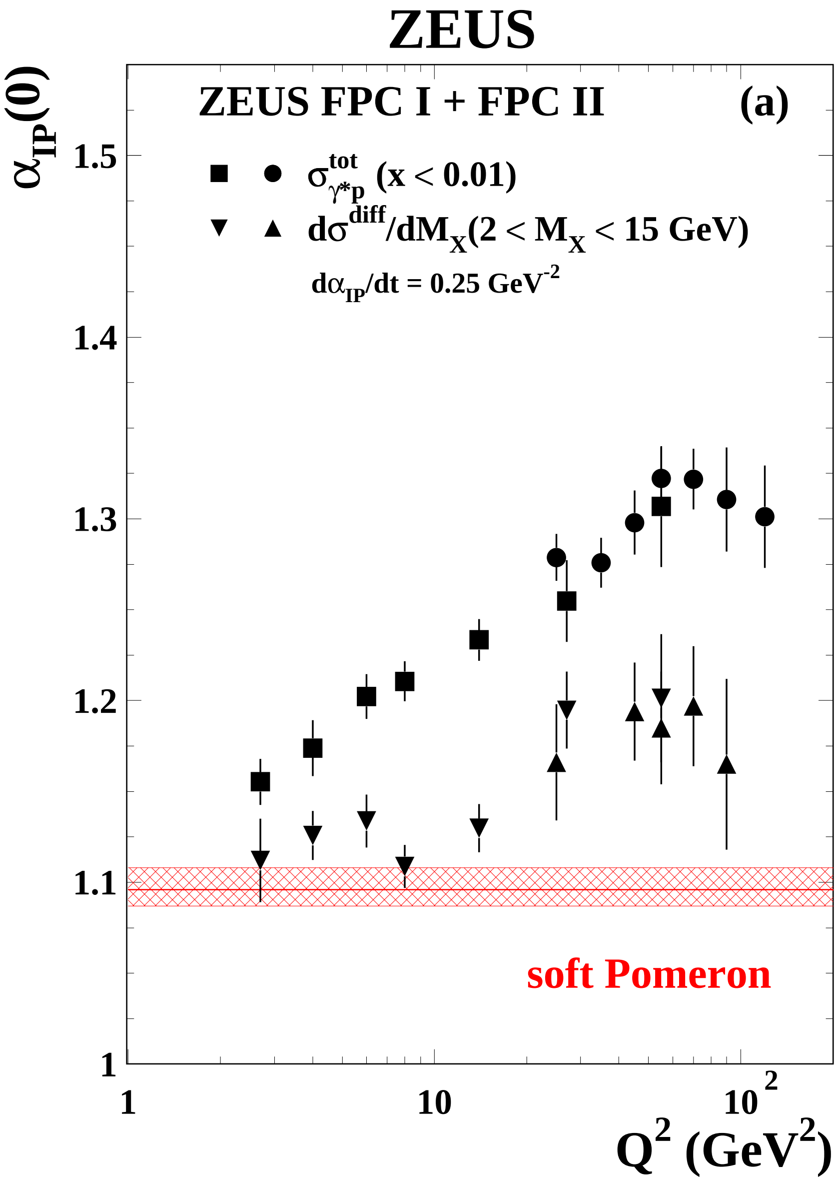
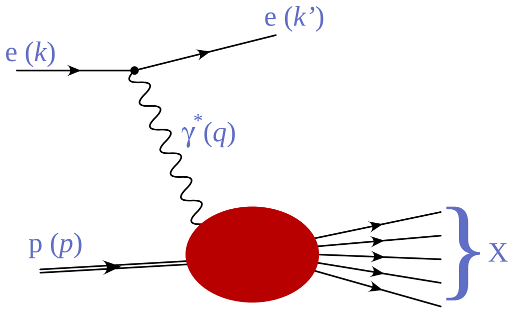
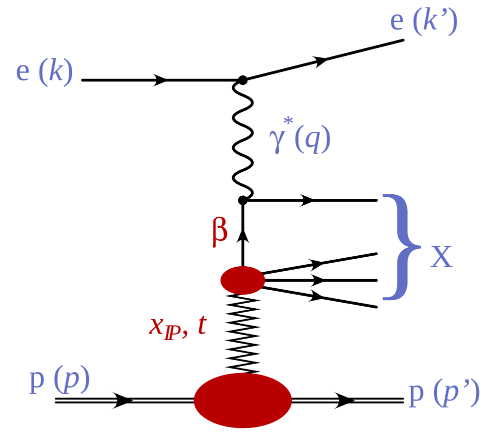
On behalf of H1 and ZEUS

From inclusive to exclusive diffraction





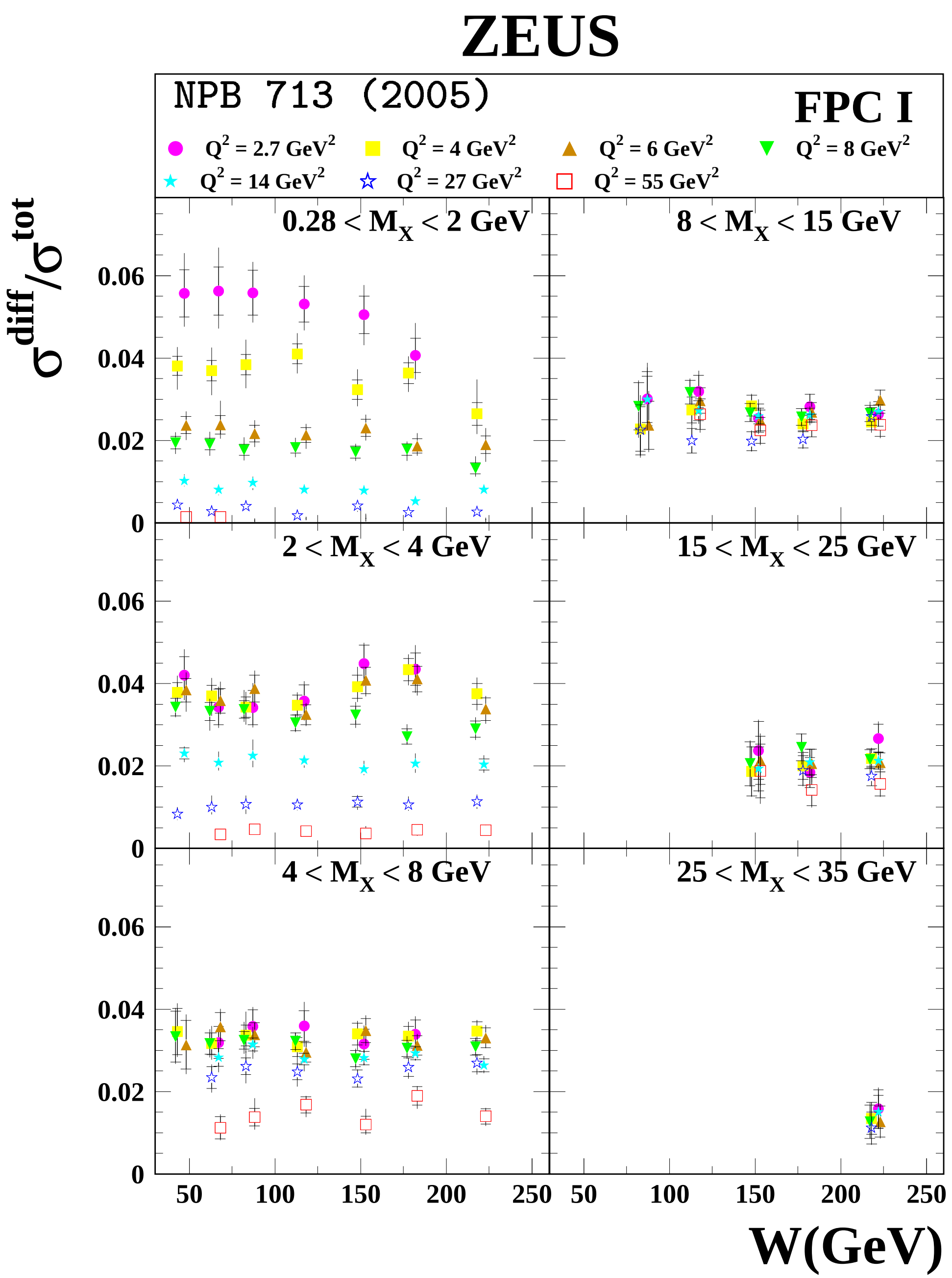


- Diffraction keeps an important soft contribution up to high Q^2

- But J/Ψ or DVCS are well described by pQCD.

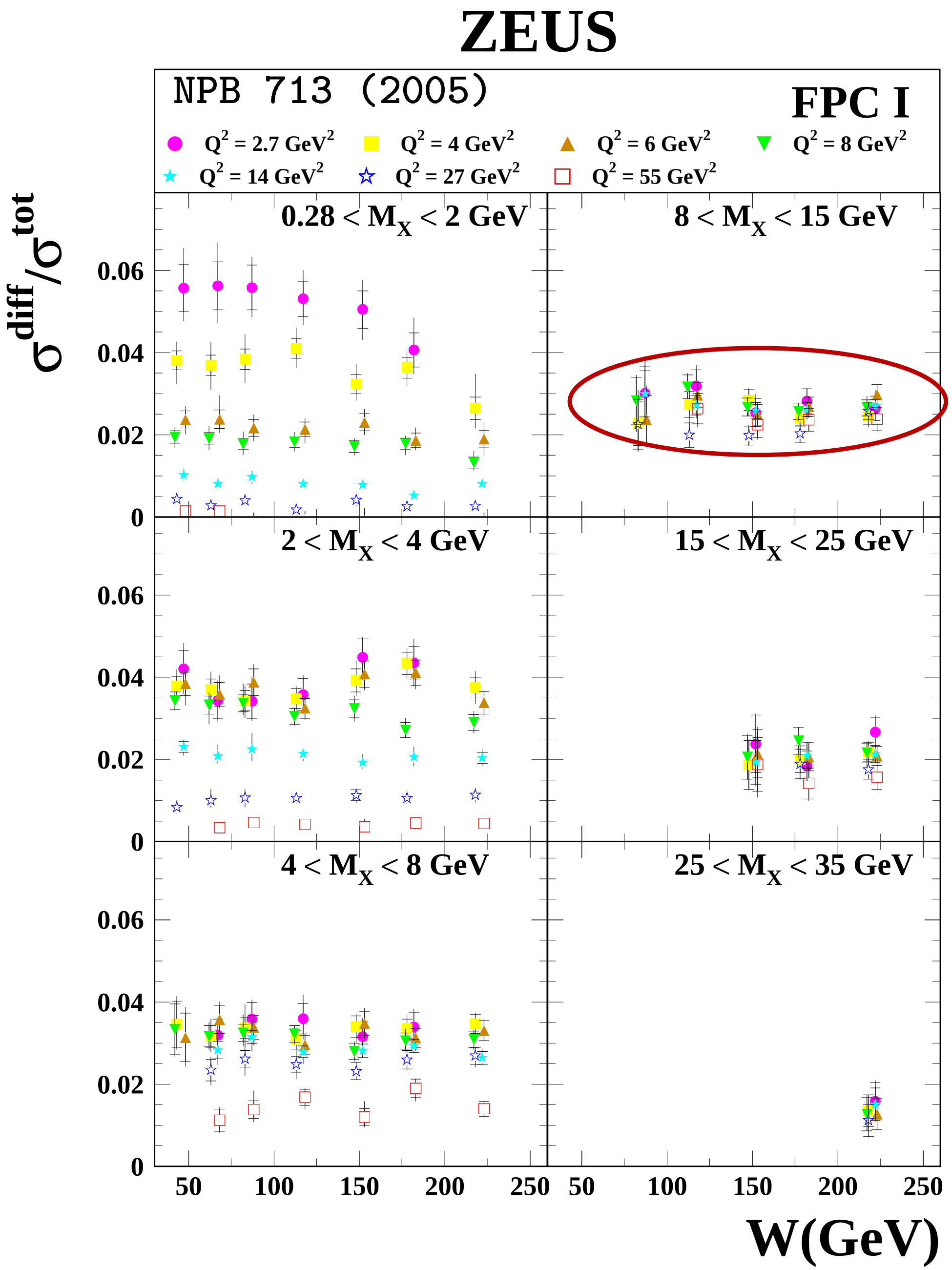
$\Rightarrow$ How to link inclusive and exclusive diffraction?

Ratio of Diffractive to inclusive cross-sections



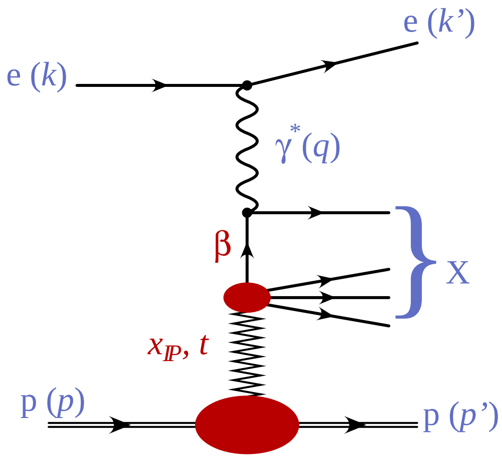
$W^2 \simeq Q^2/x$ $\beta \simeq Q^2/(Q^2 + M_X^2)$

Ratio of Diffractive to inclusive cross-sections



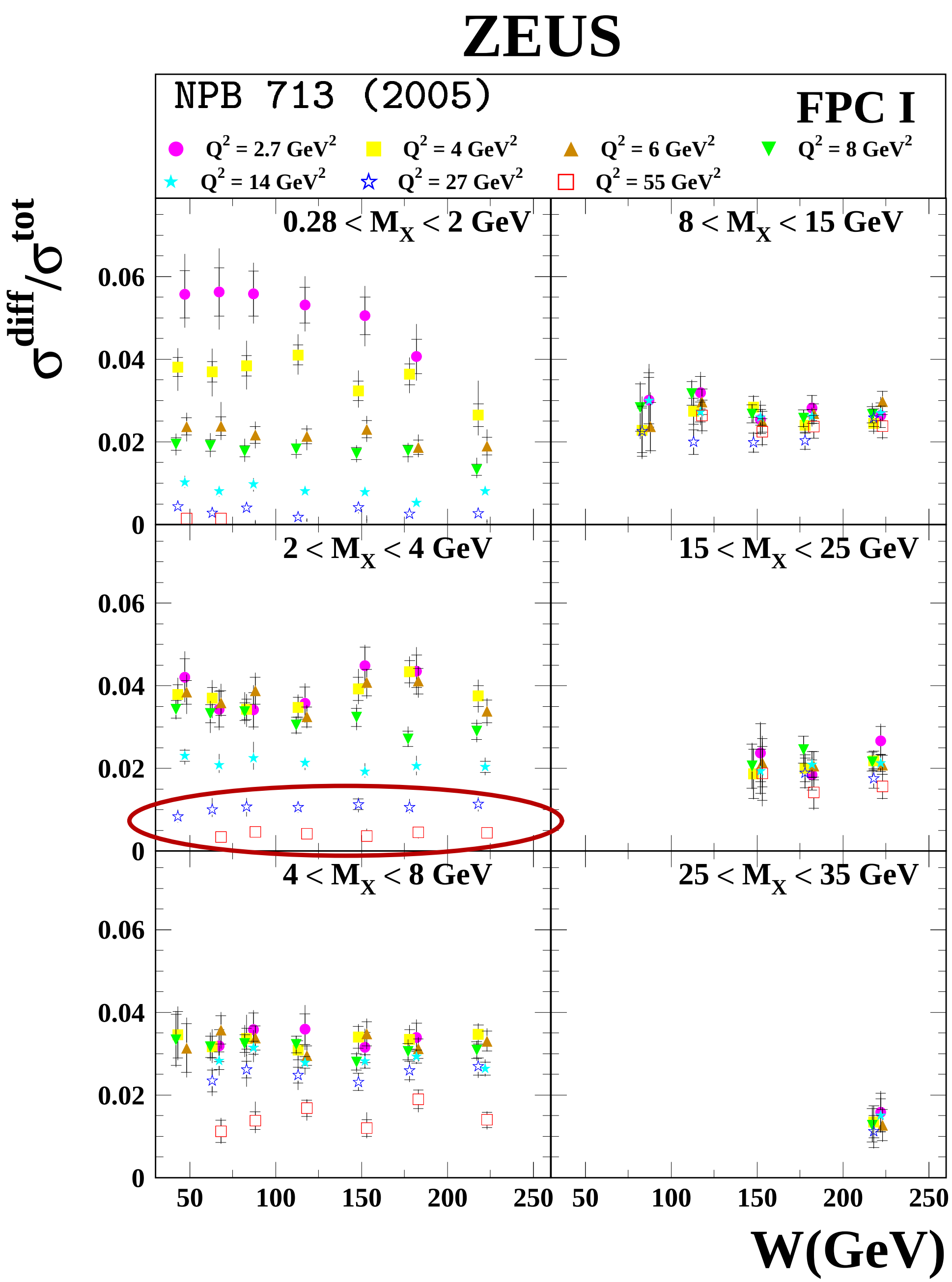
- $M_X > 8$ GeV:
  - → same W dependence as σ_{tot}
  - → no Q^2 dependence
  - → same DGLAP evolution
  - → γ^* sees: 1 parton that can radiate

no distinction between DIS and DDIS!



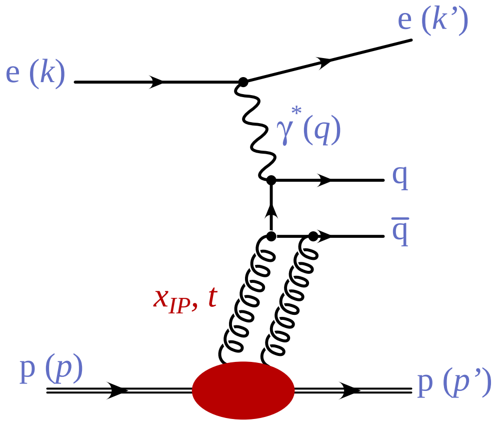
$W^2 \simeq Q^2/x$ $\qquad\qquad$ $\beta \simeq Q^2/(Q^2 + M_X^2)$

Ratio of Diffractive to inclusive cross-sections



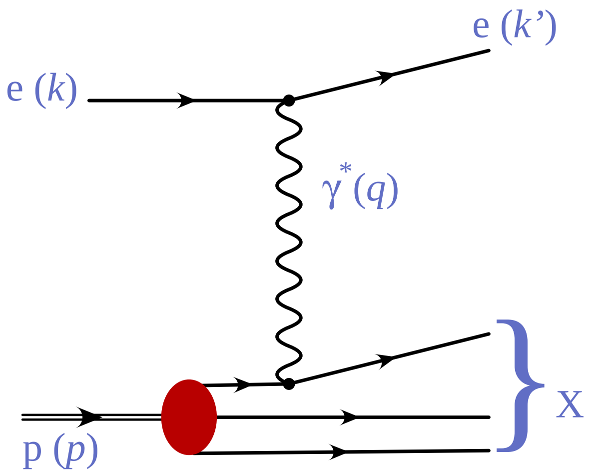
- If $M_X \searrow, \beta \nearrow$ ➜ γ^*: more and more of the exchanged object (2 g)
- large β: $M_X \ll Q^2$
  - ➜ contribution of Vector Meson
  - ➜ no g radiation allowed
  - ➜ "closed" gluon object

should increase with W but does not!



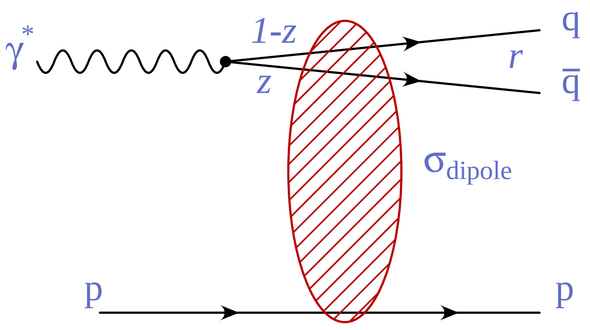
$W^2 \simeq Q^2/x$ $\qquad$ $\beta \simeq Q^2/(Q^2+M_X^2)$

What scale should we use ?



DIS: direct $\gamma - q$ interaction

$\Rightarrow$ scale: $\mu^2 = Q^2$



DDIS: hadron-hadron interaction $\Rightarrow \gamma \rightarrow q\bar{q}$

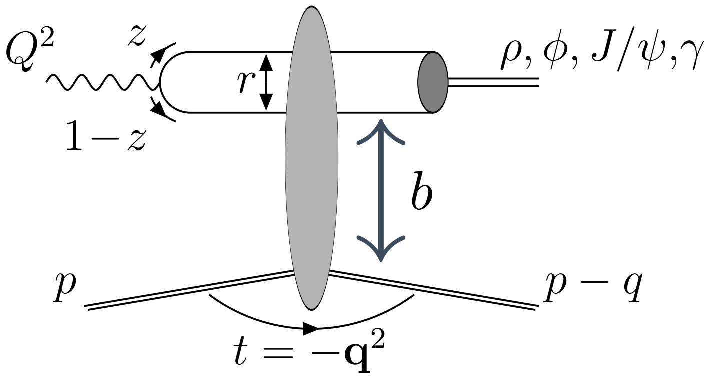
$$\mu^2 \simeq \frac{Q^2 + M_X^2}{4}$$

$\Rightarrow$ We should not compare directly DIS en DDIS at using the same scale

when M_X^2 of DDIS is large, μ^2 gets closer to the scale used for DIS in previous plot $\Rightarrow$ beter agreement.

Vector meson production: QCD factorisation

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 scaning radius r is expected to decreases 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

W, t and M_Y dependences

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 $\frac{Q^2+M_X^2}{4}$**

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t dependence

- $\mathrm{d}\sigma/\mathrm{d}t \sim e^{-b|t|}$

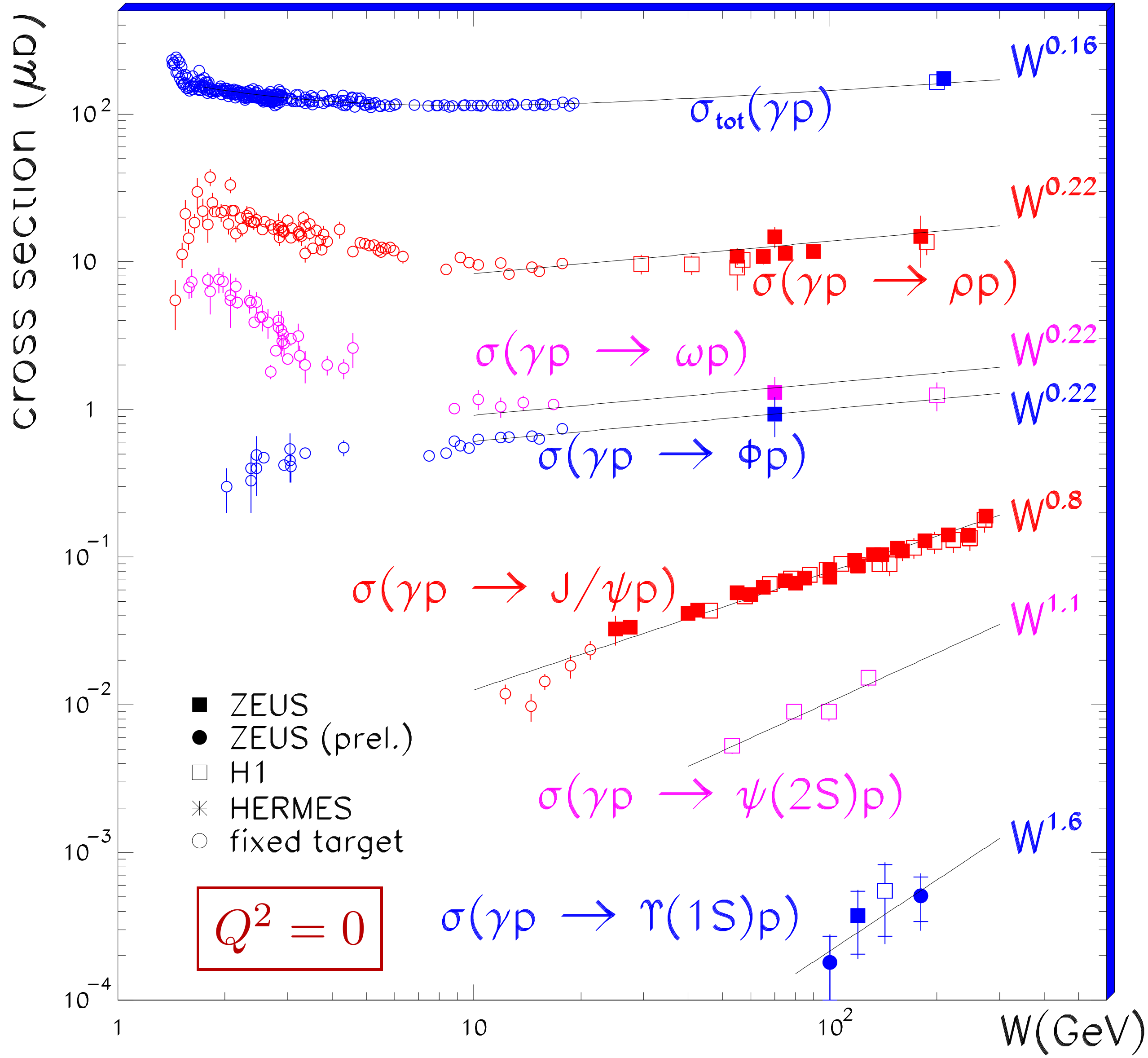
$b = b_{dip} \oplus b_{exch} \oplus b_Y$

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

M_Y dependence

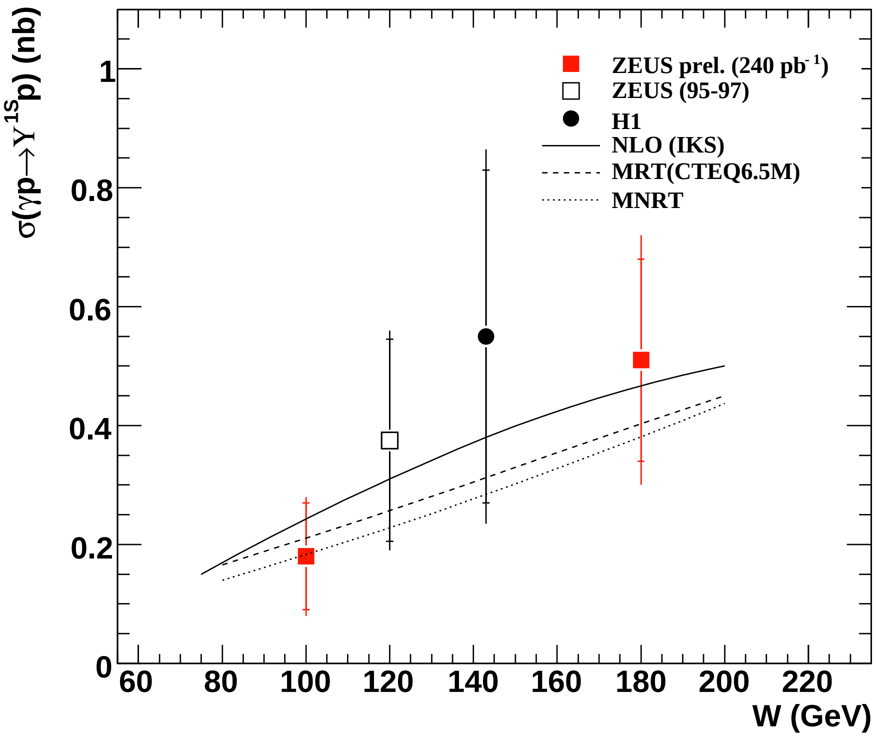
- elastic- proton dissociation universality for Q^2, W and helicity amplitudes.

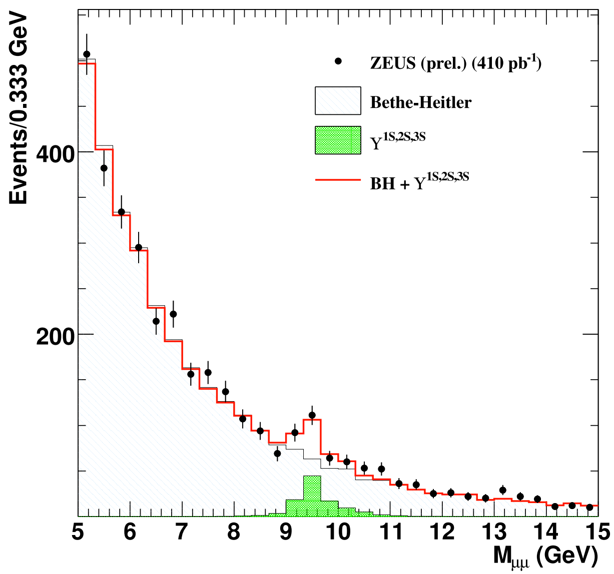
Soft to hard transition: mass



- Low mass (ρ, ϕ, ω; $M_V^2 \simeq 1$ GeV^2): no pert. scale $\rightarrow$weak energy dep. (soft regime)
- High mass (J/ψ, υ): pert. scale $\rightarrow$strong energy dep. (hard regime)
- Large mass (Υ) important skewing effect

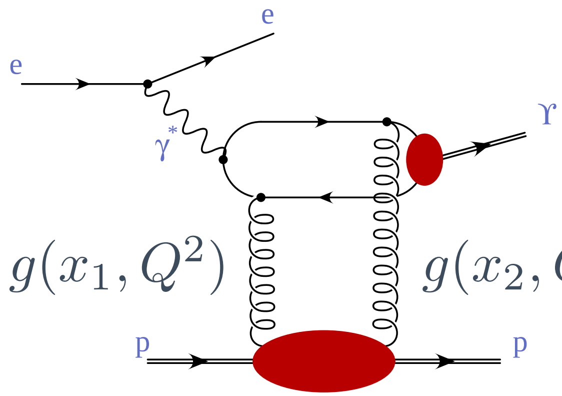
Upsilon





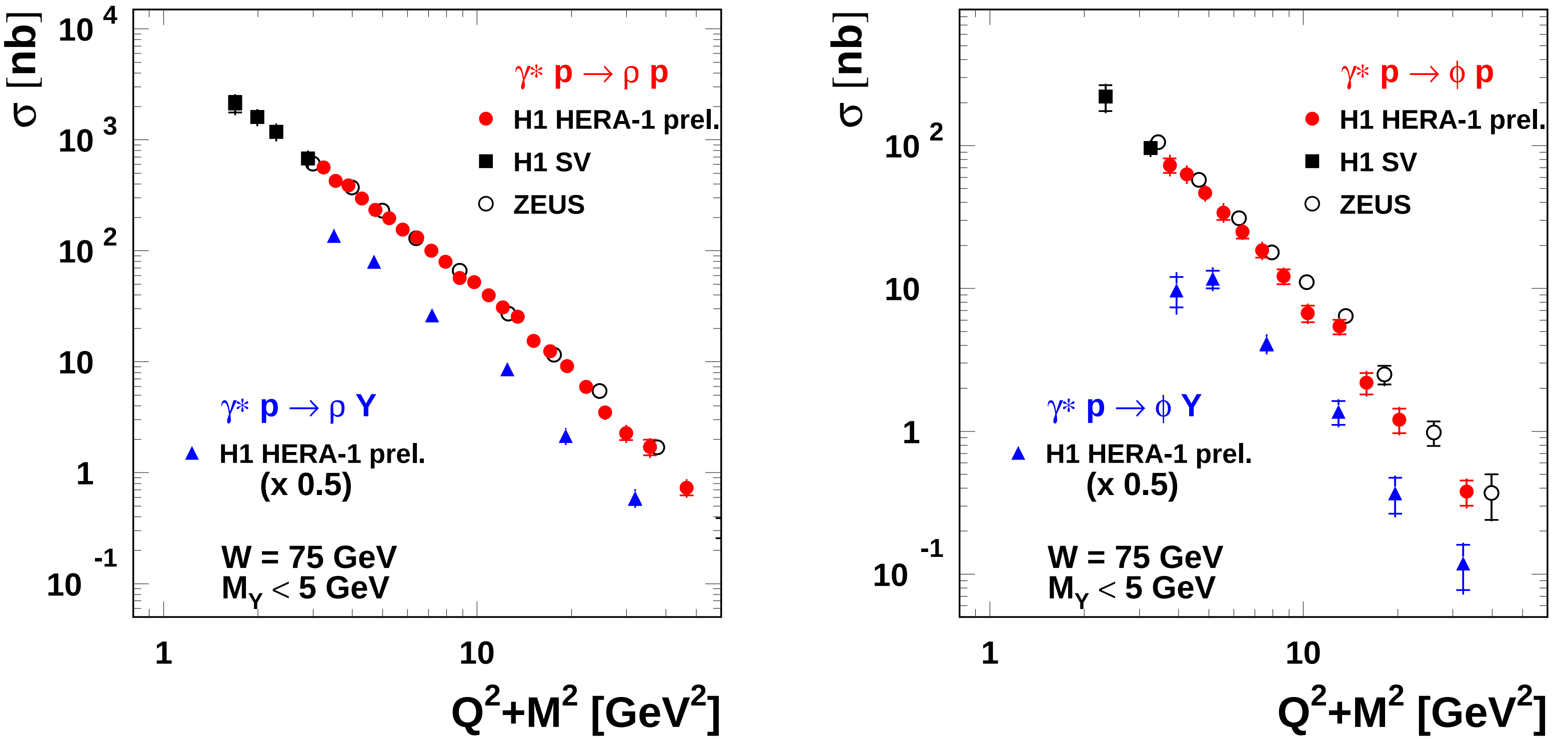
ZEUS (HERA I+II): 104 ± 21 events candidates

In agreement with NLO predictions including skewing and real part of the amplitude

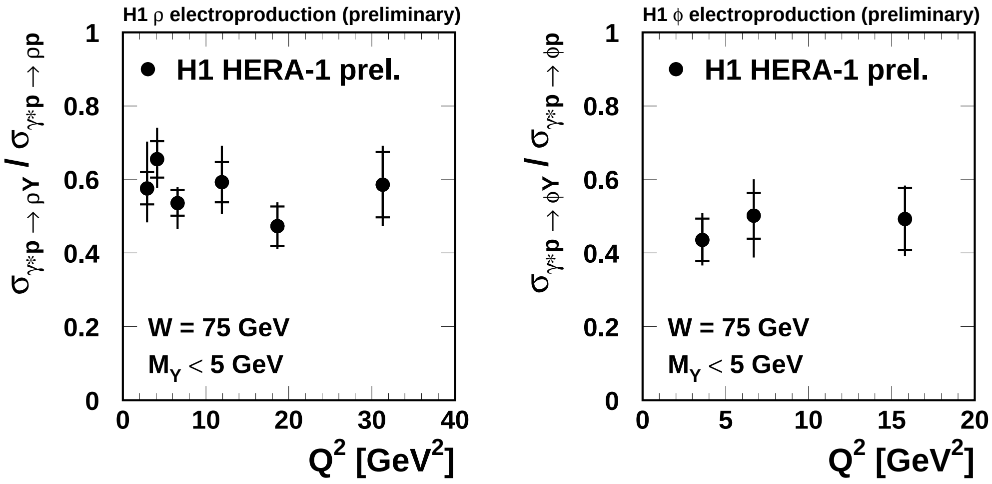


$g(x_1, Q^2)$ $g(x_2, Q^2)$ $x_1 \neq x_2$

Light VM Cross-sections versus Q^2

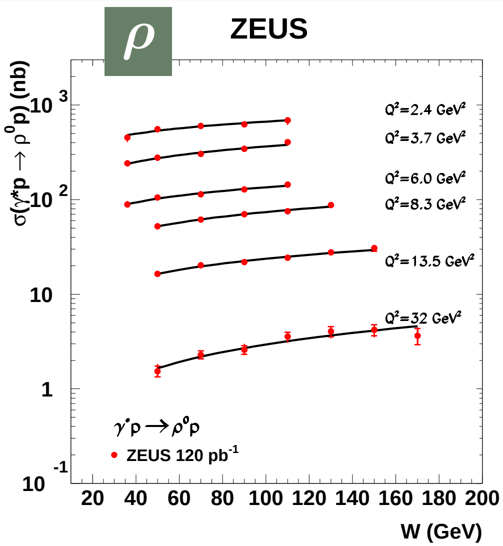


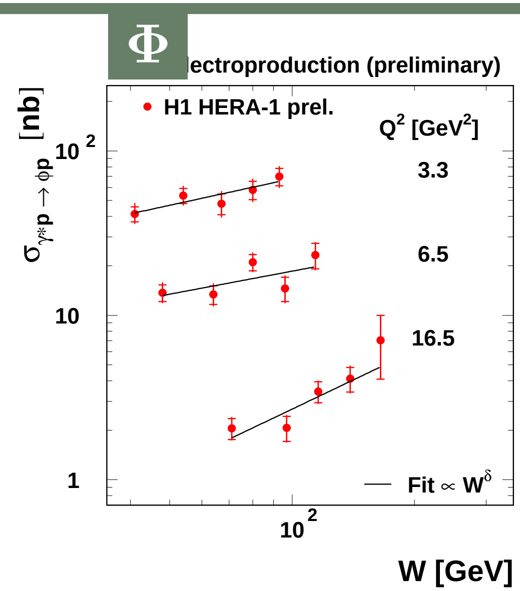
- High precision for elastic cross-sections; First ϕ p-diss. cross-section

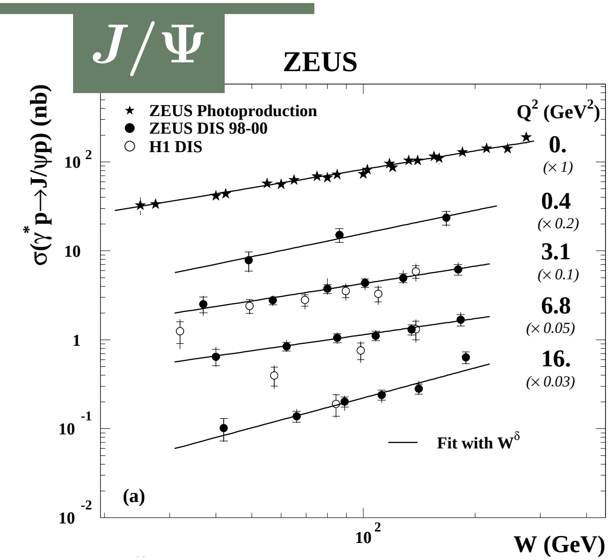


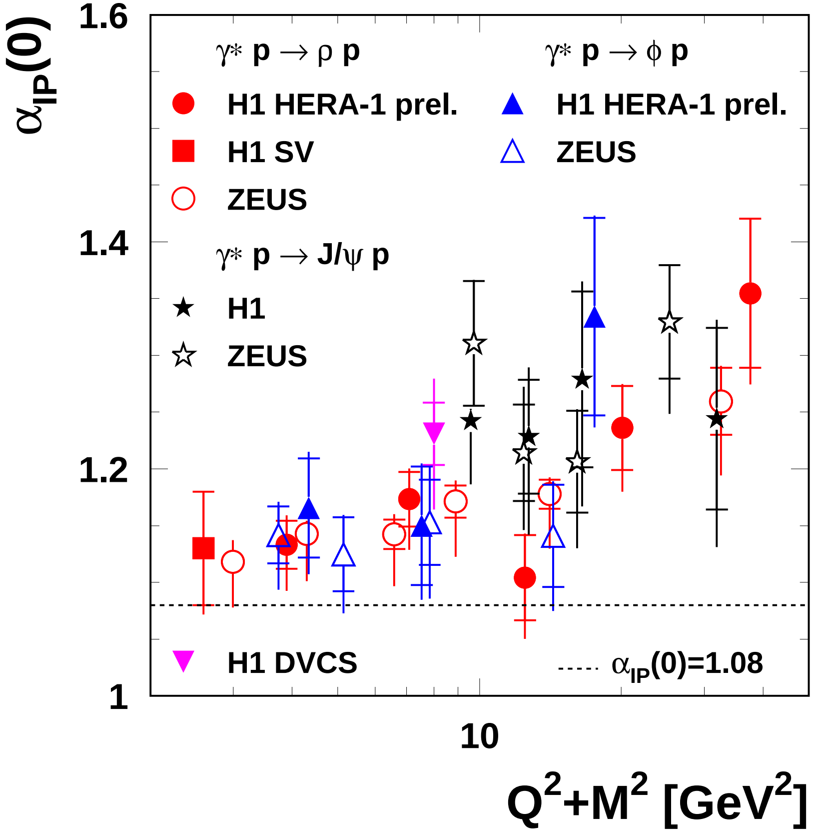
- p.diss/el: no Q^2 dep.
  i.e. vertex factorisation

W dependences









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

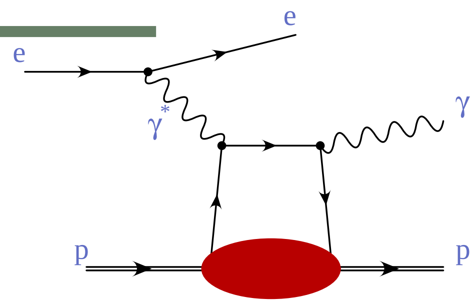
$$\alpha'_{I\!P} = 0 - 0.25\ \mathrm{GeV}^{-2}$$

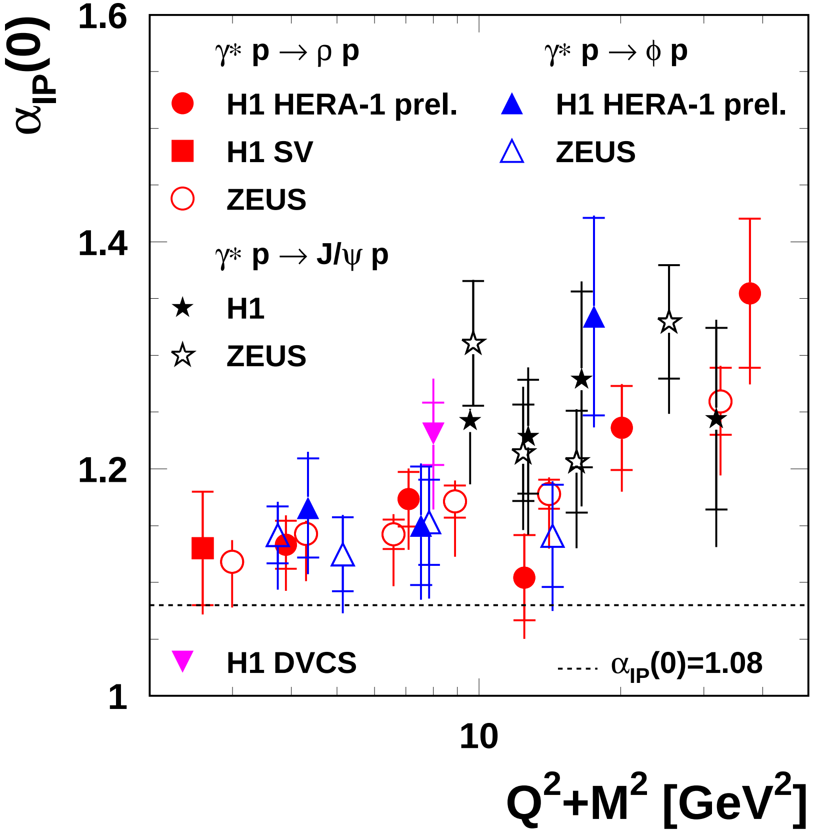
- Common hardening of $\alpha_{I\!P}(0)$ with $Q^2 + M^2$ for all VM and DVCS

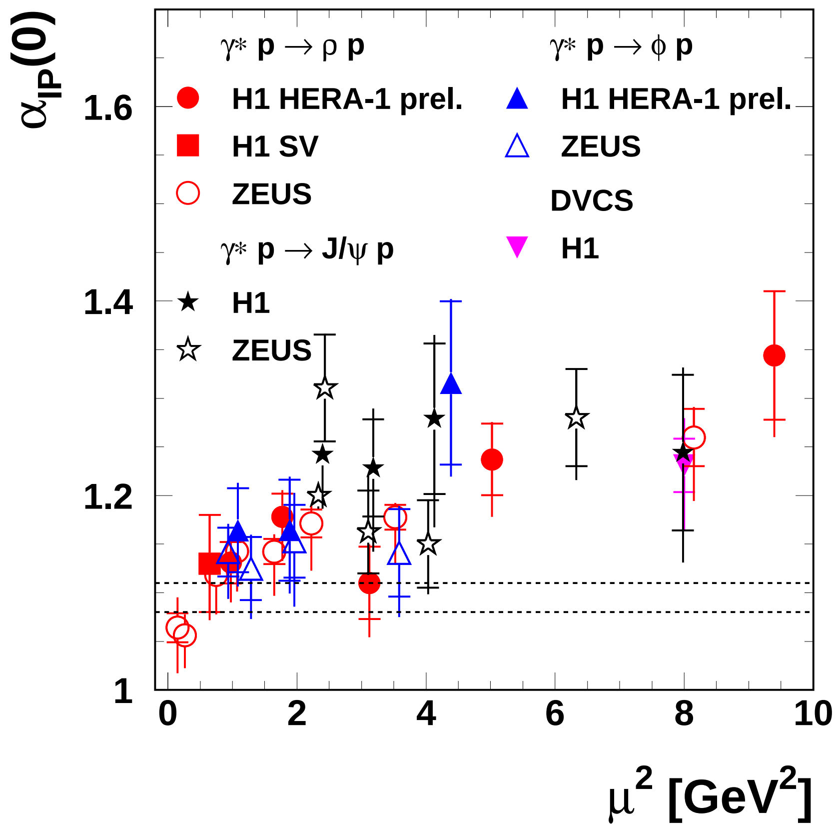
$\Rightarrow$ Transition from soft to hard regime with $Q^2 + M^2$

Note on the scale

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





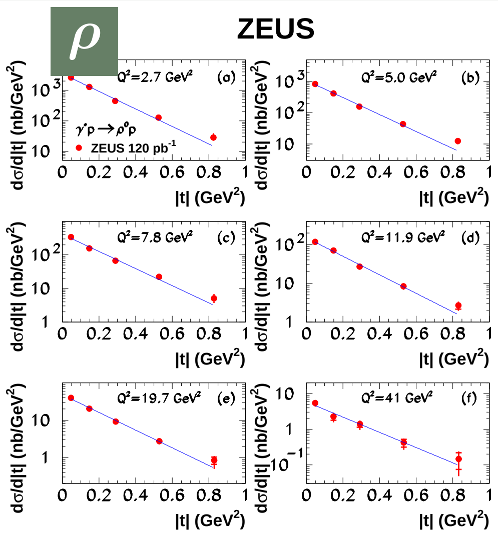


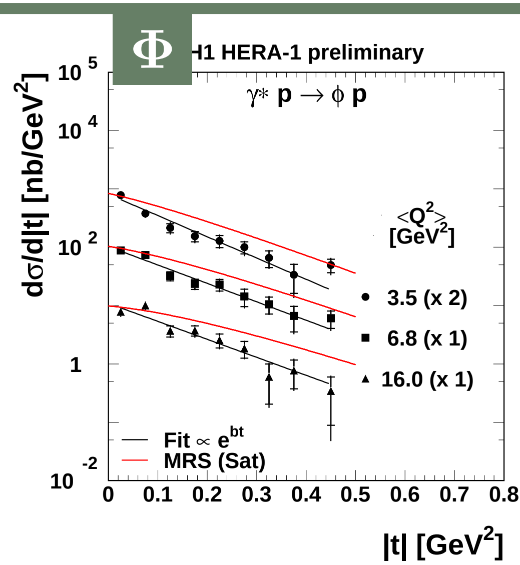
for all: $\mu^2 = Q^2 + M_X^2$

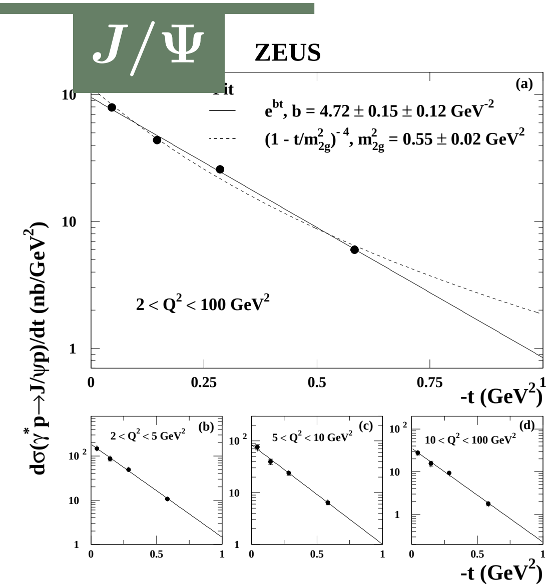
for VM: $\mu^2 = \frac{Q^2+M_X^2}{4}$

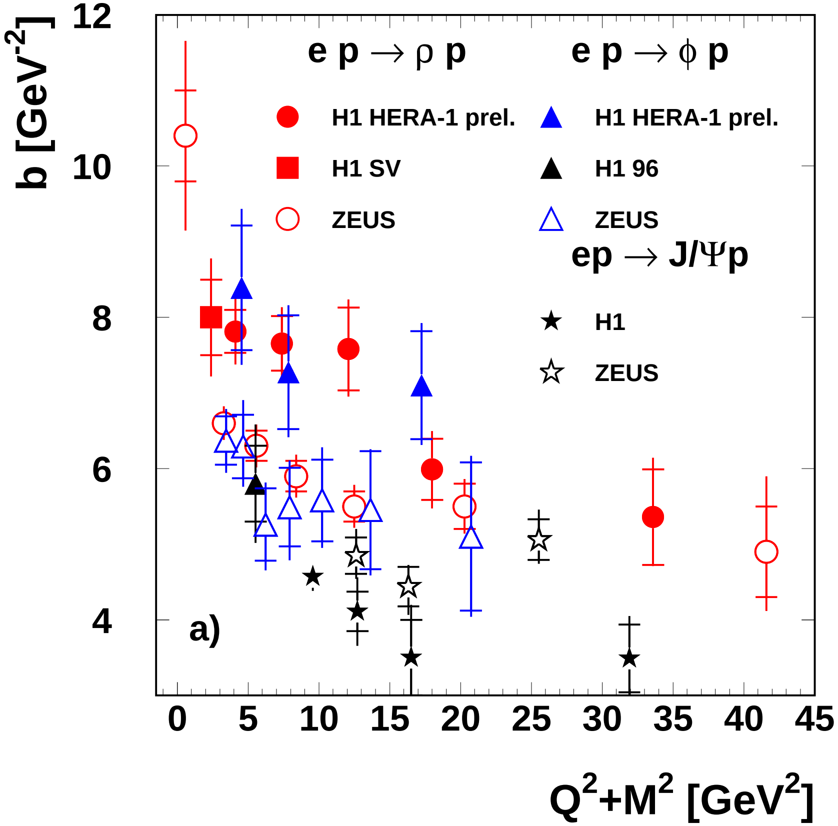
for DVCS : $\mu^2 = Q^2$

t dependences







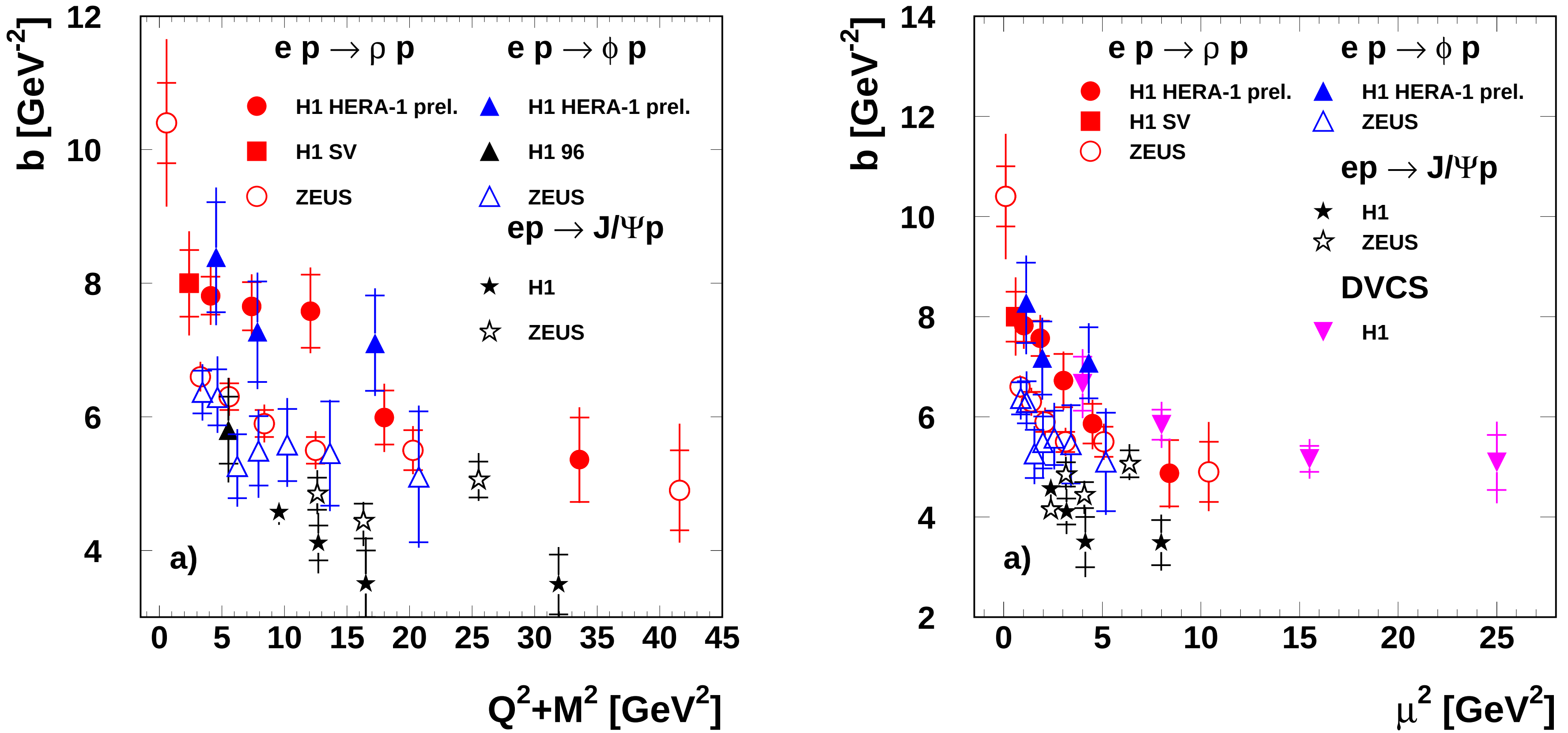


fit of $e^{-b|t|}$

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

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

Note on the scale



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

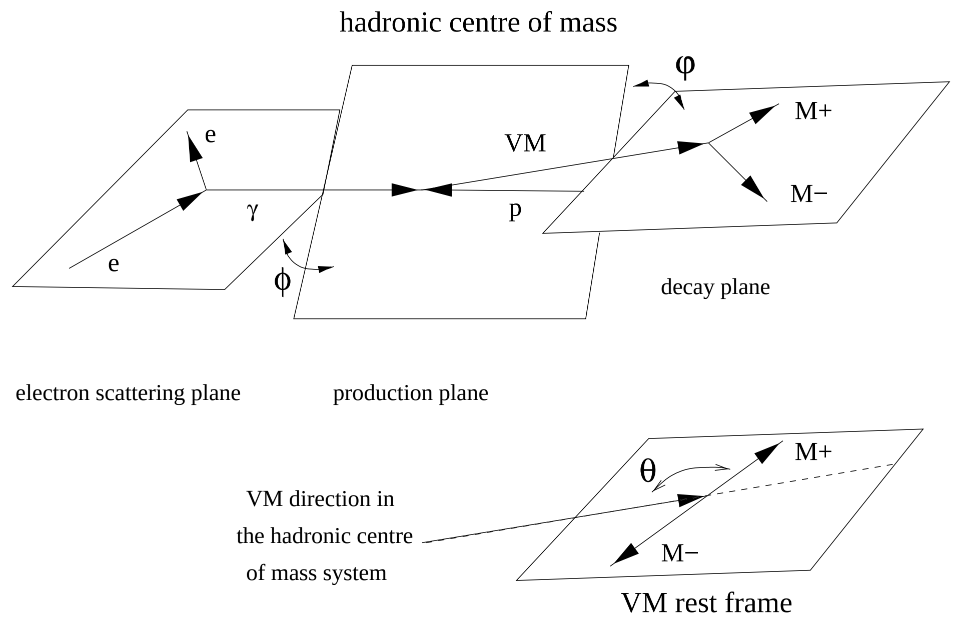
for VM: $\mu^2 = \frac{Q^2+M_X^2}{4}$

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

SPIN DENSITY MATRIX ELEMENTS

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

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

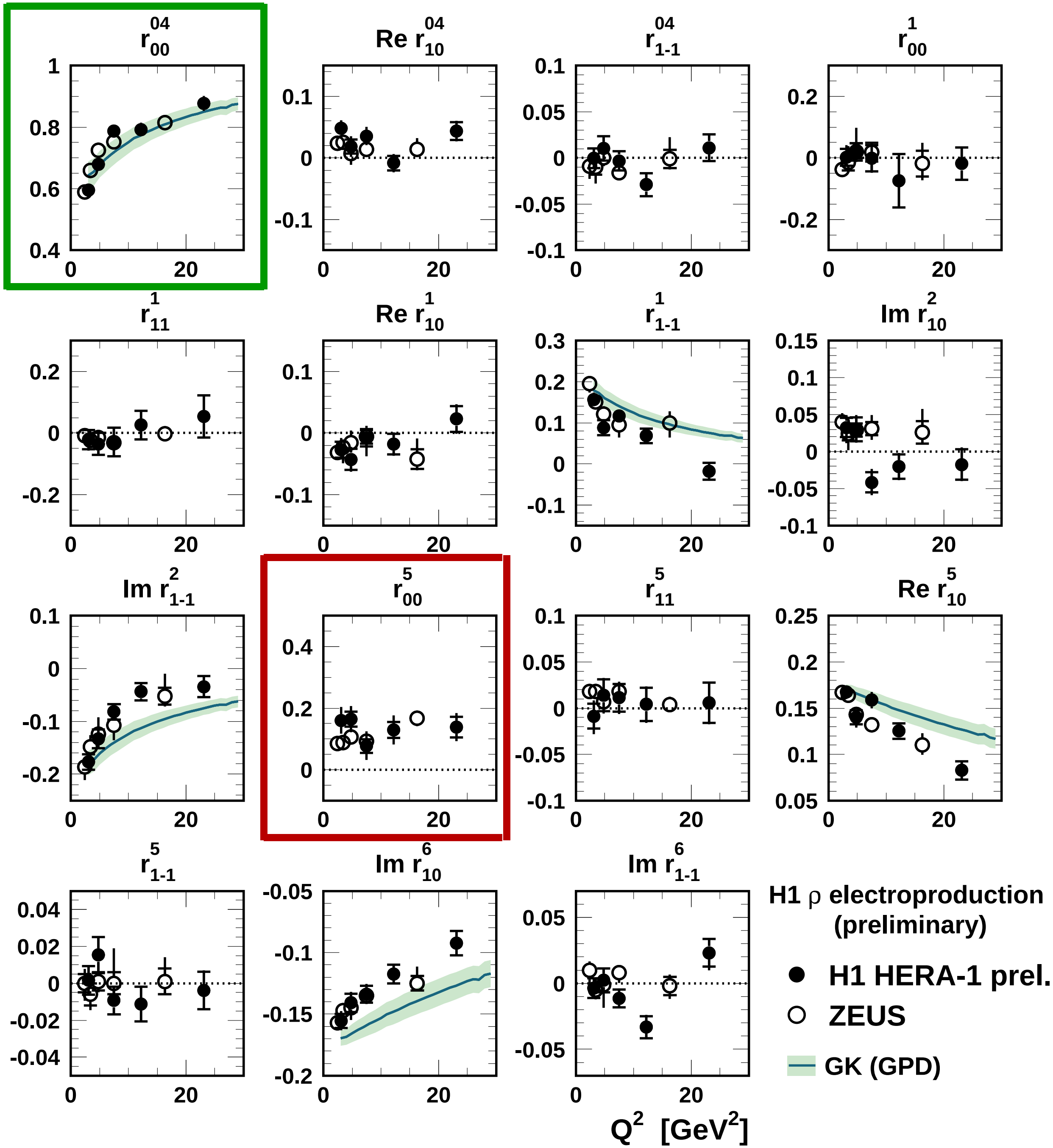


No helicity flip:	$T_{00} : \gamma_L \longrightarrow \rho_L$
	$T_{11} : \gamma_T \longrightarrow \rho_T$
Single flip:	$T_{01} : \gamma_T \longrightarrow \rho_L$
	$T_{10} : \gamma_L \longrightarrow \rho_T$
Double flip:	$T_{1-1} : \gamma_T \longrightarrow \rho_T$

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^{04}_{00} increases with Q^2

$\leftrightarrow$ similar effects for r^{1}_{1-1}, Im r^{2}_{1-1}, Re r^{5}_{10} and Im r^{6}_{10} (in SCHC)

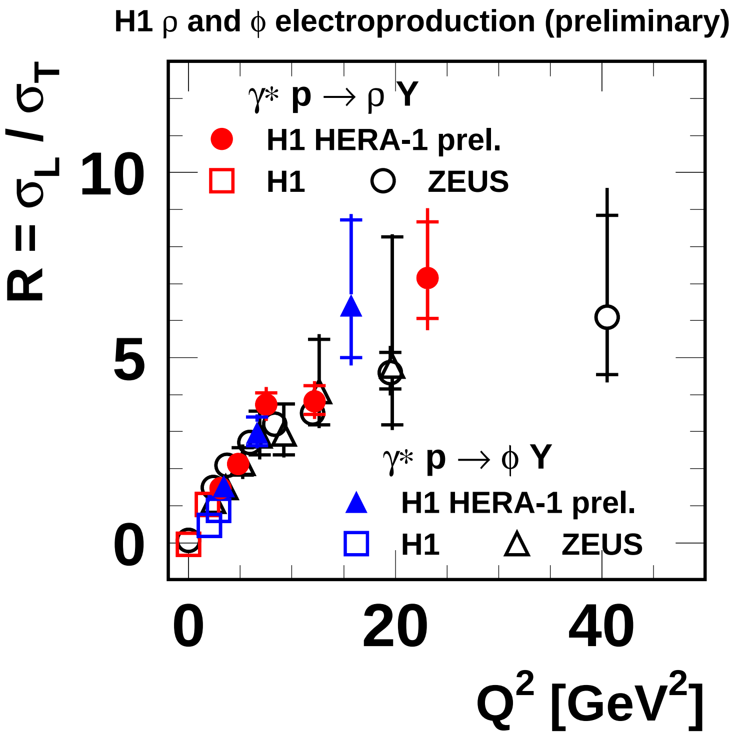
$\leftrightarrow$ Fair description by Goloskokov-Kroll (GPD) model

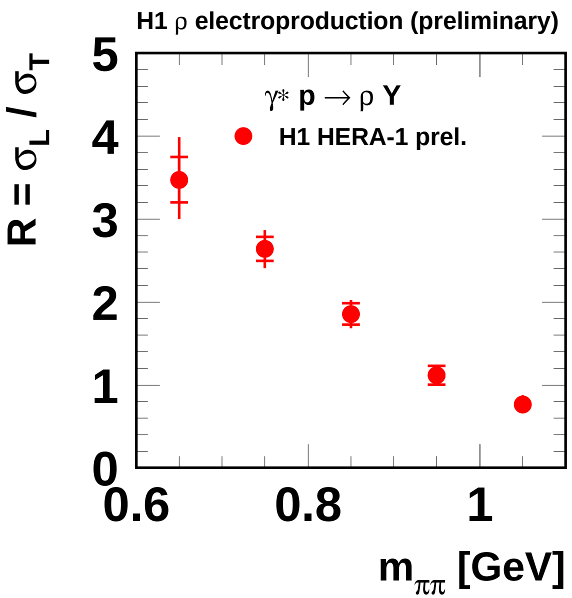
- r^{5}_{00} violates SCHC (flip)

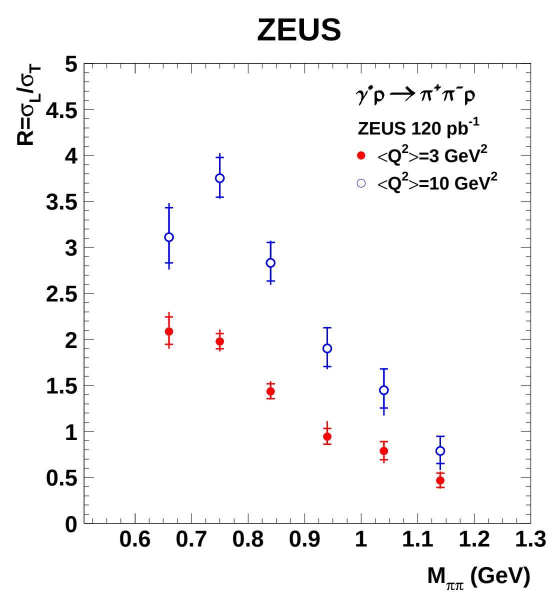
- Other SDME $\simeq 0$

Polarisation - $R = \sigma_L/\sigma_T$

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







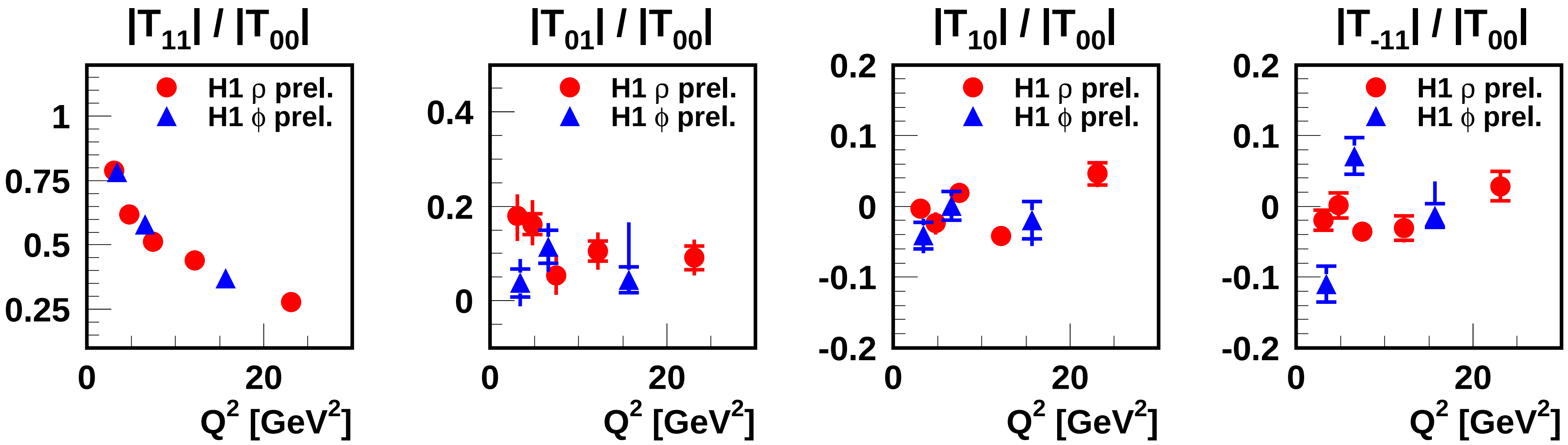
- Naive $R \propto Q^2/M^2$ - modified at high Q^2
- Similar R for ϕ and ρ
- Strong invariant mass dependence in ρ case

Polarisation - Amplitude ratios vs. Q^2

pQCD :

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

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

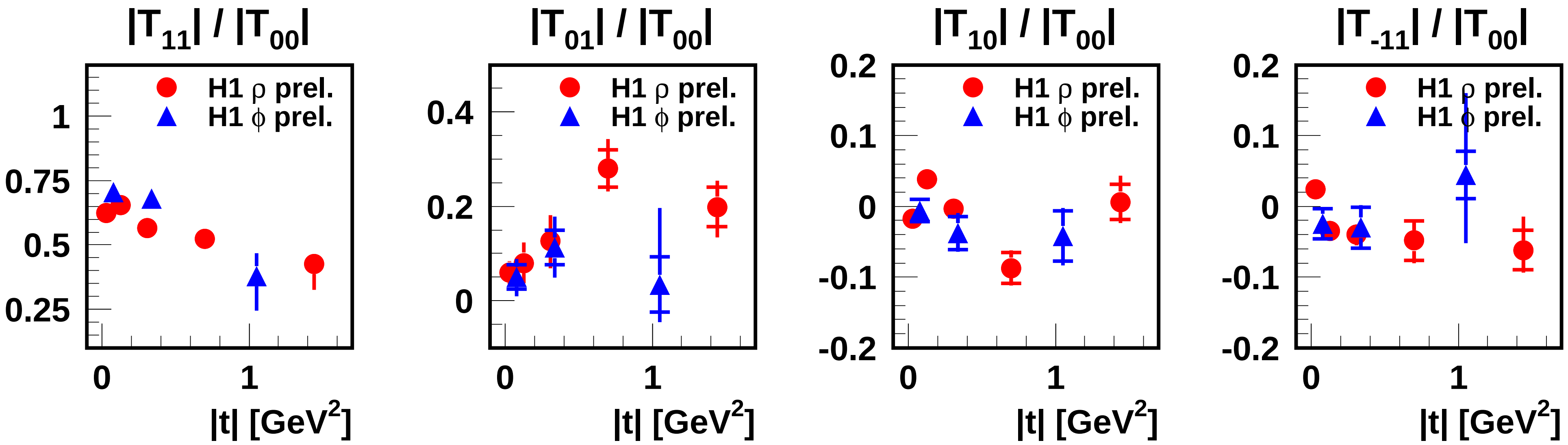
$\Rightarrow |T_{00}| > |T_{11}| > |T_{01}| > |T_{10}|, |T_{-11}| \leftrightarrow$ hierarchy observed

Polarisation - Amplitude ratios vs. $|t|$

pQCD:

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

γ : gluon anomalous dim.

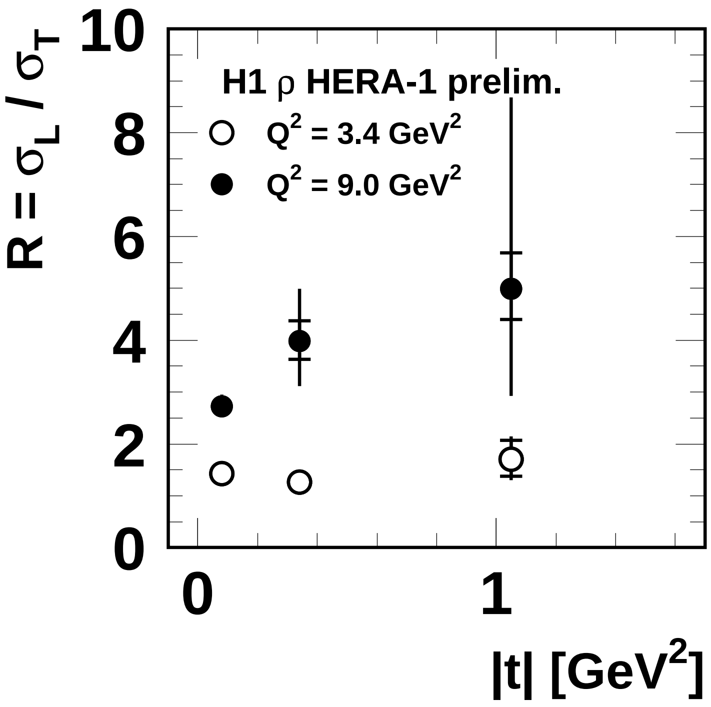


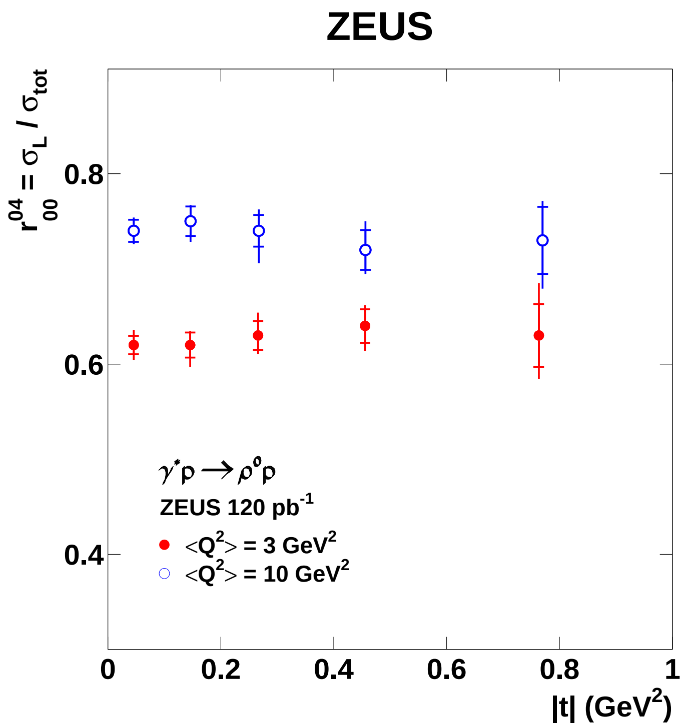
- $|T_{11}|/|T_{00}|$ decreases with $|t|$
- $|T_{01}|/|T_{00}|$ increases with $|t| \leftrightarrow$ SCHC violation increases with $|t|$
- $|T_{10}|/|T_{00}|$ and $|T_{-11}|/|T_{00}|$ are small but some $|t|$dependence
- $|T_{11}|/|T_{00}|$ decrease partialy acompensated by $|T_{01}|/|T_{00}|$ increase

$\Rightarrow$ σ_L/σ_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: $\boldsymbol{R}$ depends on $\boldsymbol{t}$ for large $\boldsymbol{Q^2}$ $\Rightarrow \boldsymbol{b_L < b_T}$!!! ($\boldsymbol{\sigma_L}$ more pert. than $\boldsymbol{\sigma_T}$)
- Not seen by ZEUS
- due to different $\boldsymbol{\rho'}$ background treatement

Conclusions

Important progresses in precision of VM measurements and understanding of underlaying dynamics.

- $\rho, \phi, J/\psi, \Upsilon, \gamma$
- in Q^2, W, t, helicity amplitudes, p-diss/el
- precision in the soft to hard transition: scales, and L/T separation
- many models: GPD, BFKL, dipole, saturation,...
  with semi-qualitative understanding
  but many quantitative desription still lacking

Back-up Slides

Polarisation - Retrieving Amplitude ratios

Assume purely imaginary amplitudes $\longrightarrow$ phase $= \pm 1$!

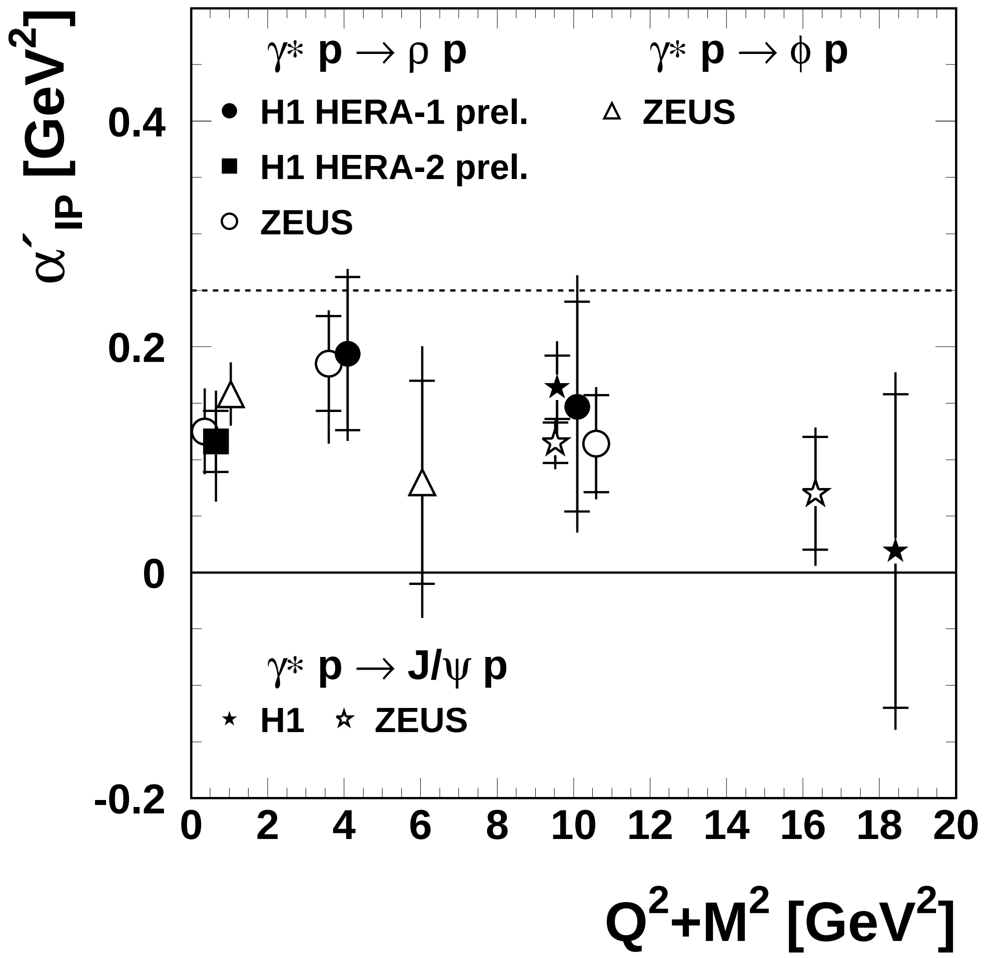
$\longrightarrow$ Extract $|T_{11}|/|T_{00}|$, $|T_{01}|/|T_{00}|$, $|T_{10}|/|T_{00}|$ and $|T_{-11}|/|T_{00}|$ from fit to the 15 SDMEs:

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

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

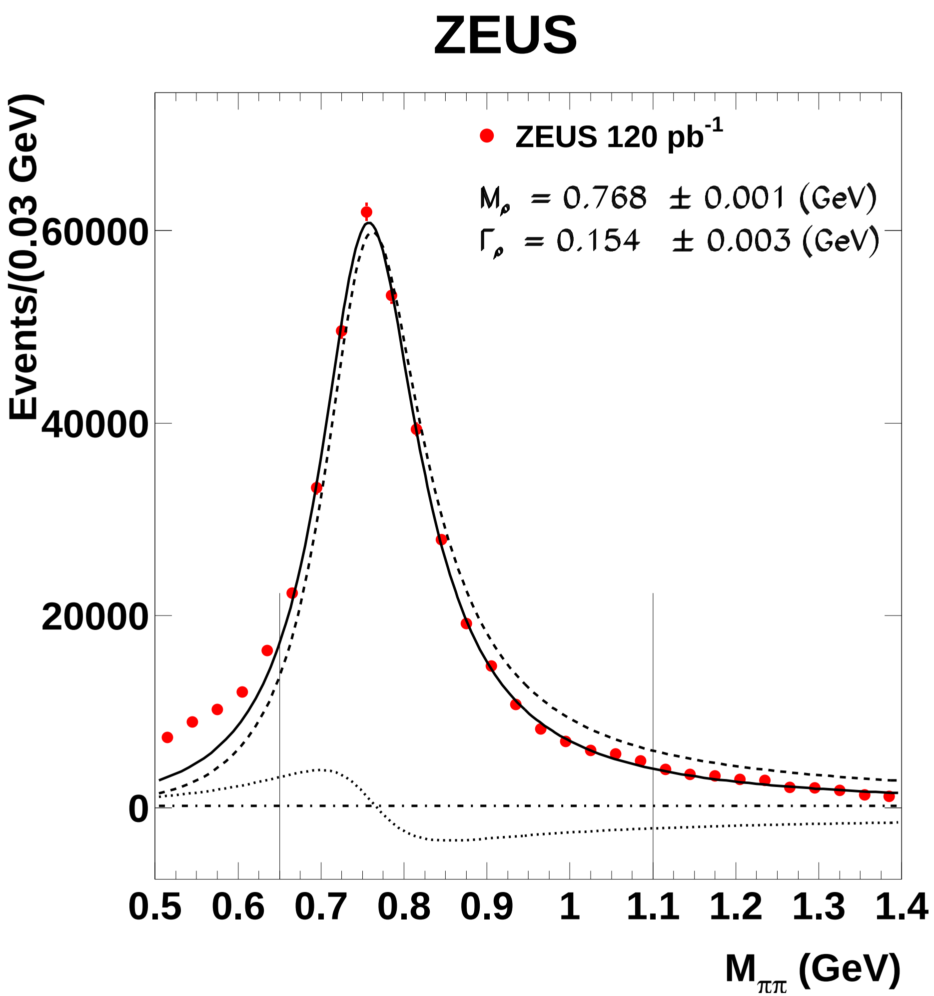
$$
\begin{aligned}
B &= \frac{1}{N_T + \varepsilon N_L} = \frac{R}{1 + \varepsilon R} \\
N_T &= \alpha^2 + \beta^2 + \eta^2 \\
N_L &= 1 + 2\delta^2
\end{aligned}
$$

α'



γ* p → ρ p
H1 HERA-1 prel.
H1 HERA-2 prel.
ZEUS
γ* p → φ p
ZEUS
γ* p → J/ψ p
H1
ZEUS
α´ IP [GeV2]
Q2+M2 [GeV2]
0.4
0.2
0
-0.2
0
2
4
6
8
10
12
14
16
18
20

Rho mass



ZEUS
ZEUS 120 pb-1
Mρ = 0.768 ± 0.001 (GeV)
Γρ = 0.154 ± 0.003 (GeV)
Events/(0.03 GeV)
60000
40000
20000
0
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4
Mππ (GeV)