

*Exclusive diffractive processes at
HERA
(Vector Mesons and DVCS)*

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On behalf of the H1 and ZEUS Collaborations

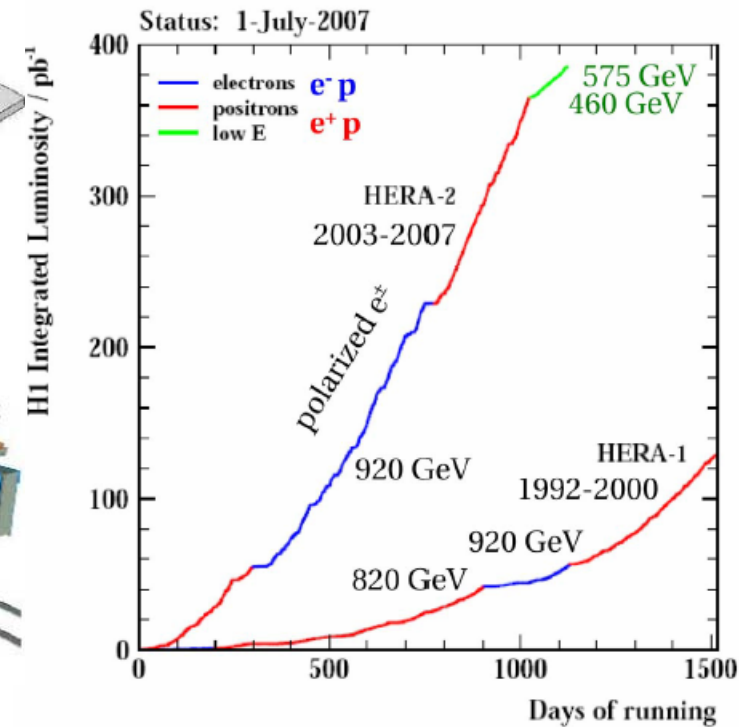
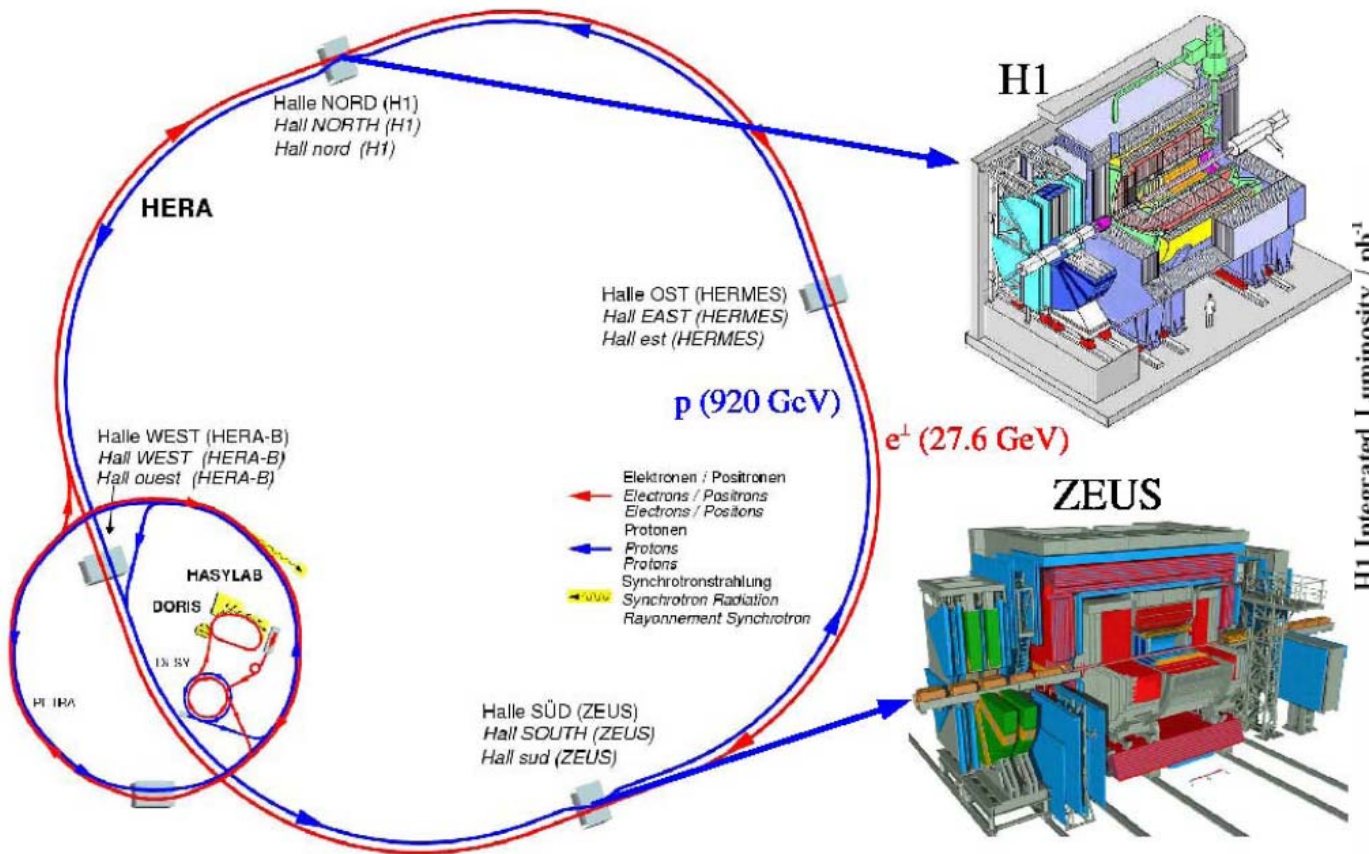


HERA

The world's only electron/positron-proton collider at DESY, Hamburg

$E_e = 27.6 \text{ GeV}$ $E_p = 920 \text{ GeV}$ (also 820, 460 and 575 GeV)

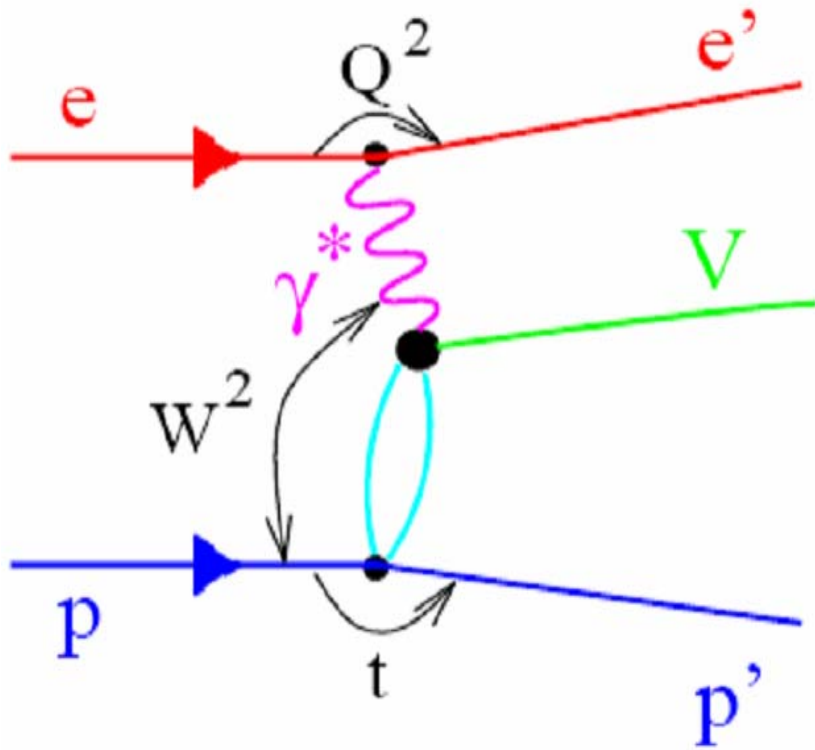
(total centre-of-mass energy of collision up to $\sqrt{s} \approx 320 \text{ GeV}$)



Two collider experiments: H1 and ZEUS

HERA-1: 1992 - 2000
 HERA-2: 2003 - 2007
 total lumi: 0.5 fb^{-1} per experiment

Introduction

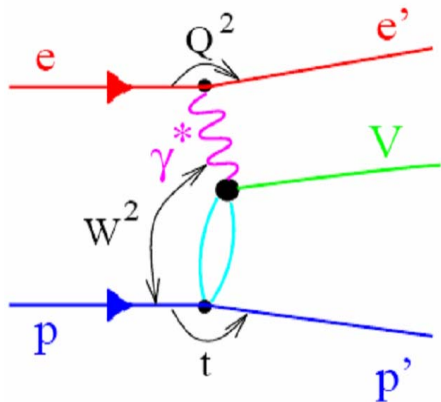


$$V=(\rho, \omega, \phi, J/\psi, \Upsilon, \gamma)$$

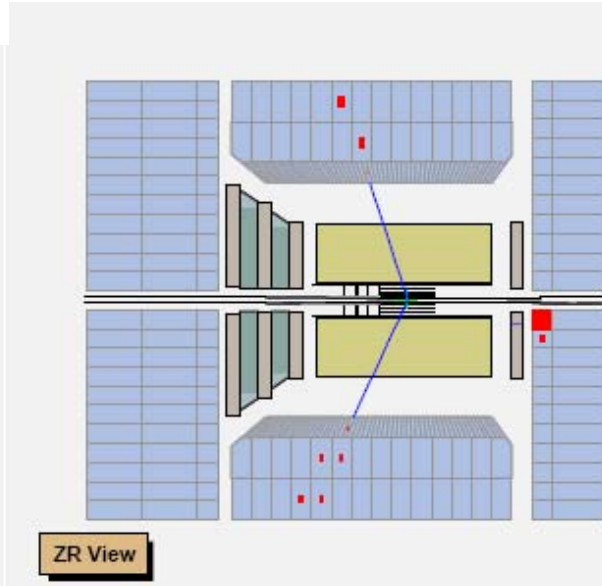
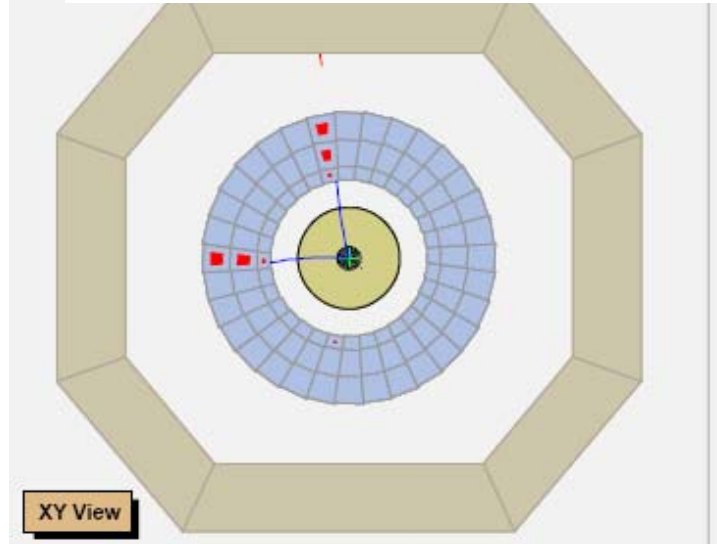
- no quantum numbers exchanged in the interaction
- the proton stays intact (or dissociates)
- $Q^2=-(e-e')^2$ - photon virtuality:
 - $Q^2 \sim 0 \rightarrow$ 'photoproduction'
 - $Q^2 > 0 \rightarrow$ Deep Inelastic Scattering (DIS)
- W - γ^*p center of mass energy
- $t=(p-p')^2$ - momentum transfer squared at the proton vertex

Introduction

Exclusive Vector meson production - clean experimental signatures

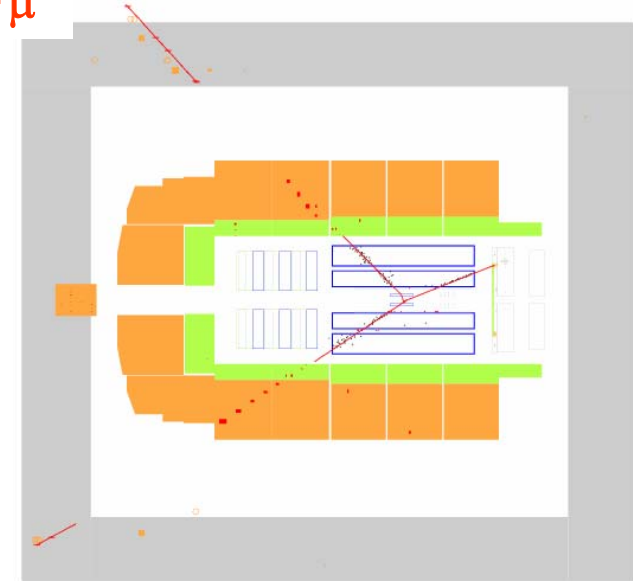
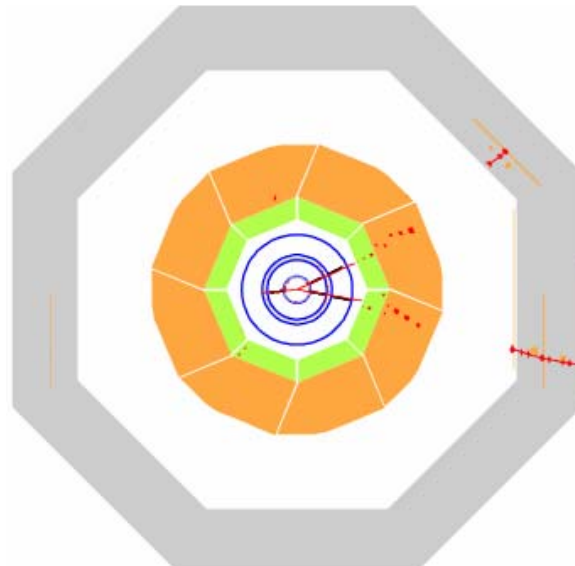


ZEUS: $ep \rightarrow e' + \rho^0 + p$, $\rho \rightarrow \pi^+ \pi^-$

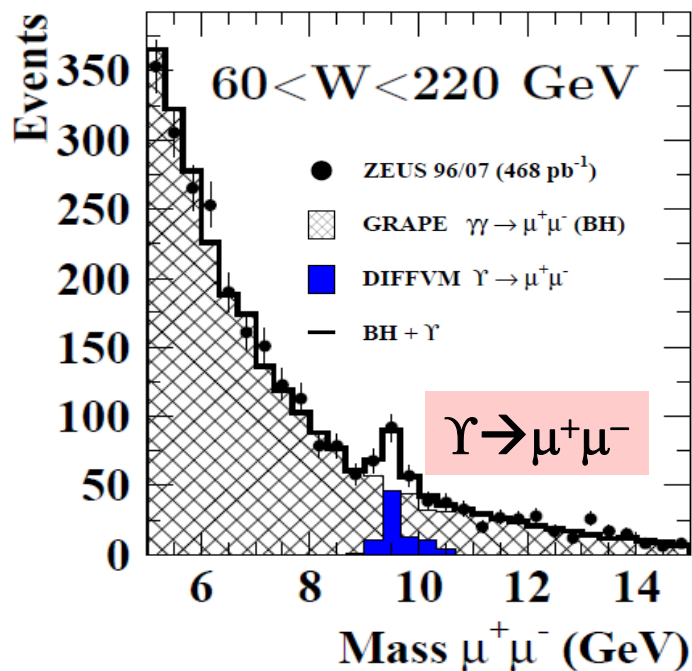
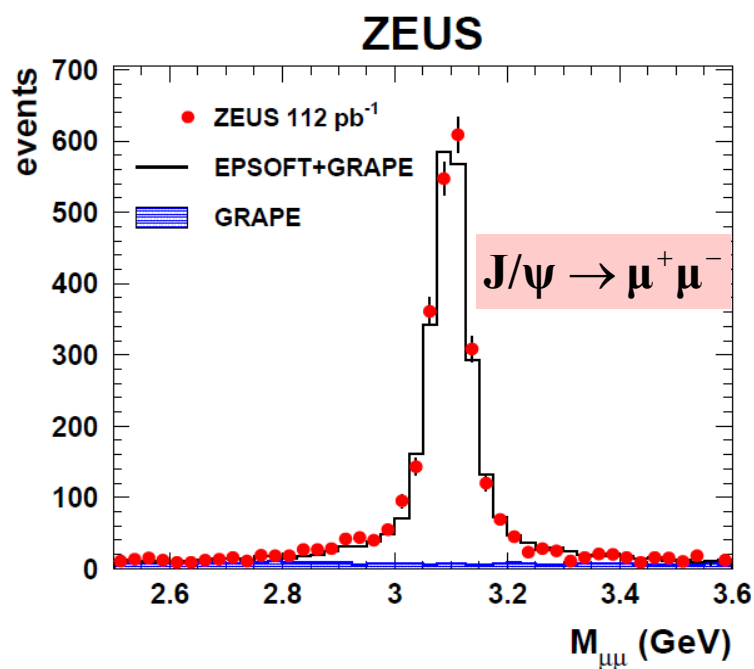
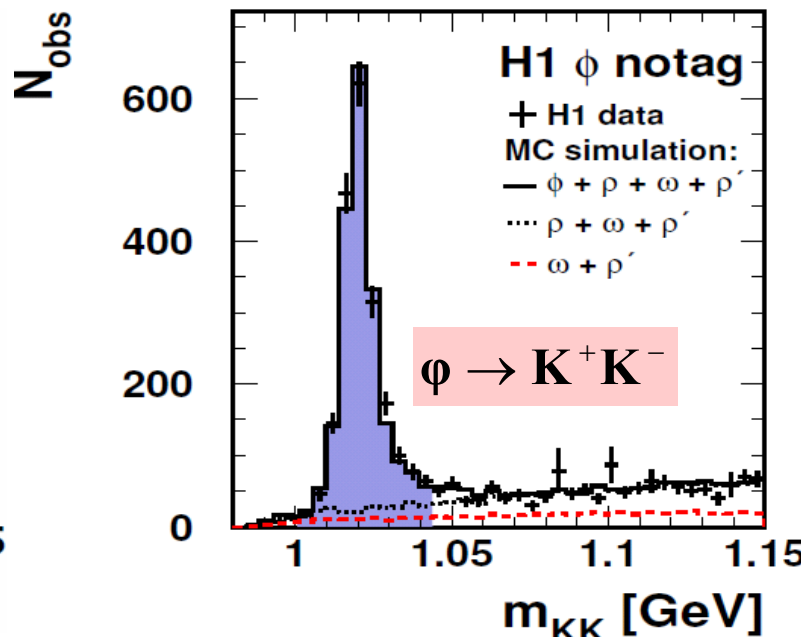
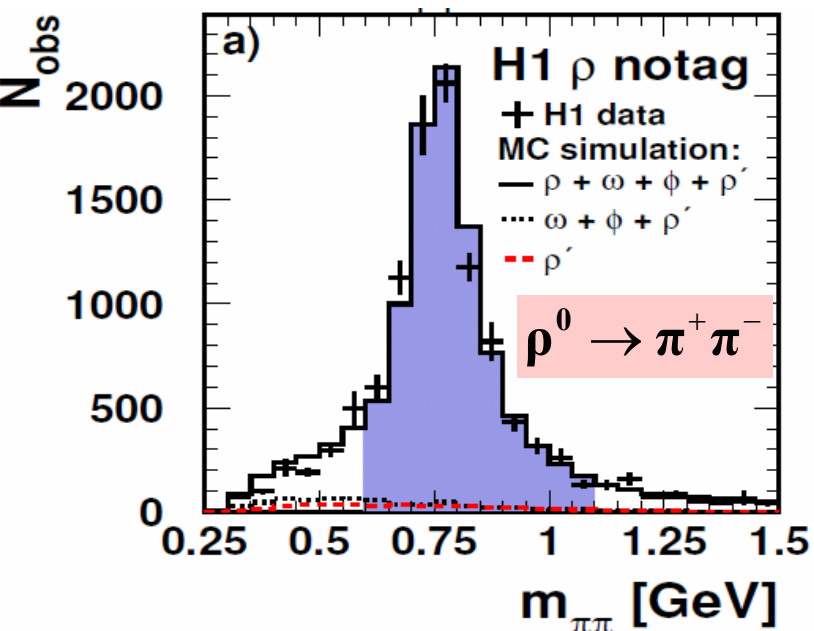


- scattered e^\pm reconstructed in e/m calorimeters (DIS) or undetected (photoproduction)
- scattered p undetected
- decay products of VM
- nothing else in the central detector

H1: $ep \rightarrow e' + J/\Psi + p$, $J/\Psi \rightarrow \mu^+ \mu^-$



Vector Mesons mass distributions



Introduction

Regge theory and VDM model

-Weak energy dependence, $\delta \sim 0.2$

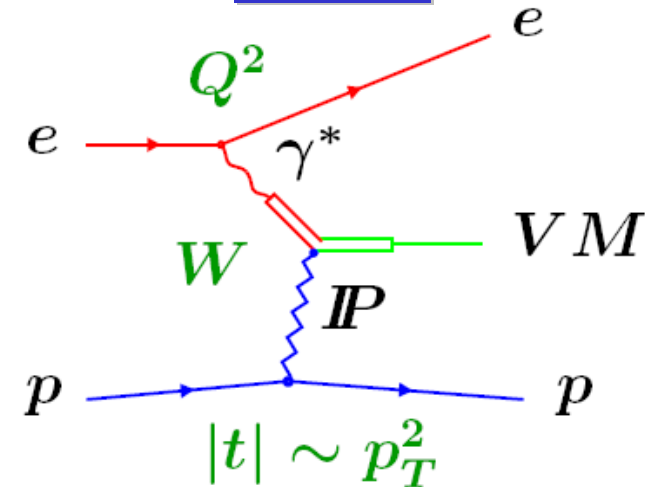
$$\delta = 4(\alpha_{IP}(t) - 1) \quad \alpha_{IP}(t) = 1.08 + 0.25 \cdot t \text{ (DL)}$$

-Shrinkage of diffractive peak

$$b(W) = b_0 + 4\alpha' \ln(W/W_0); \quad b_0 \sim 10 \text{ GeV}^{-2}$$

(b is related to the size of interaction)

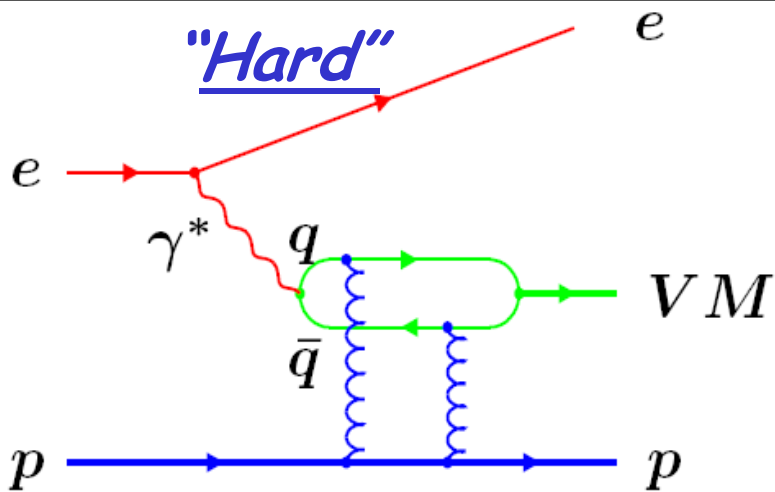
"Soft"



$$\sigma \propto W^\delta$$

$$\frac{d\sigma}{dt} \propto e^{-bt}$$

"Hard"



in presence of hard scale: Q^2, M_{VM} or t
pQCD description (exchange of ≥ 2 gluons)

-Fast increase of cross section with energy due to gluon density in proton

$$\sigma \sim |x g(x, Q^2)|^2$$

Increasing W corresponds to going to small x $W^2 \propto \frac{1}{x}$

- Expect δ to increase from 'soft' (~ 0.2) to 'hard' (~ 0.8)
- Expect b to decrease from 'soft' ($\sim 10 \text{ GeV}^{-2}$) to 'hard' ($\sim 4 \div 5 \text{ GeV}^{-2}$)

With HERA data it is possible to investigate the transition from "soft" to "hard" pomeron exchange processes with increasing of Q^2, M_{VM} or t .

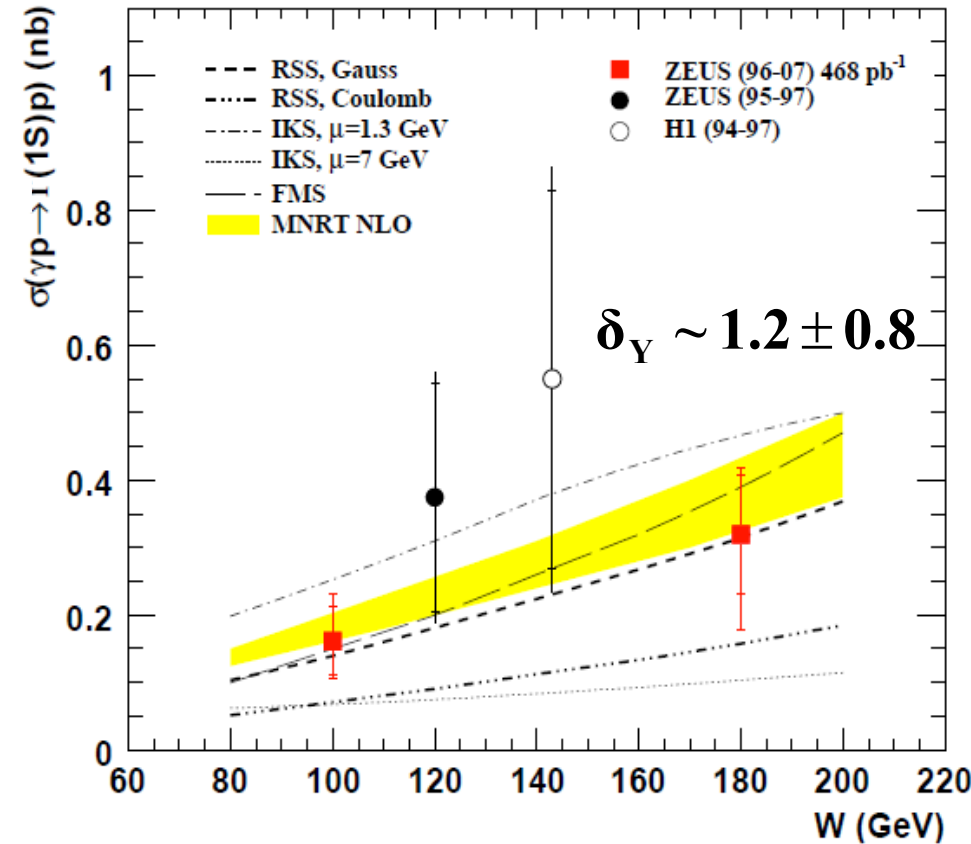
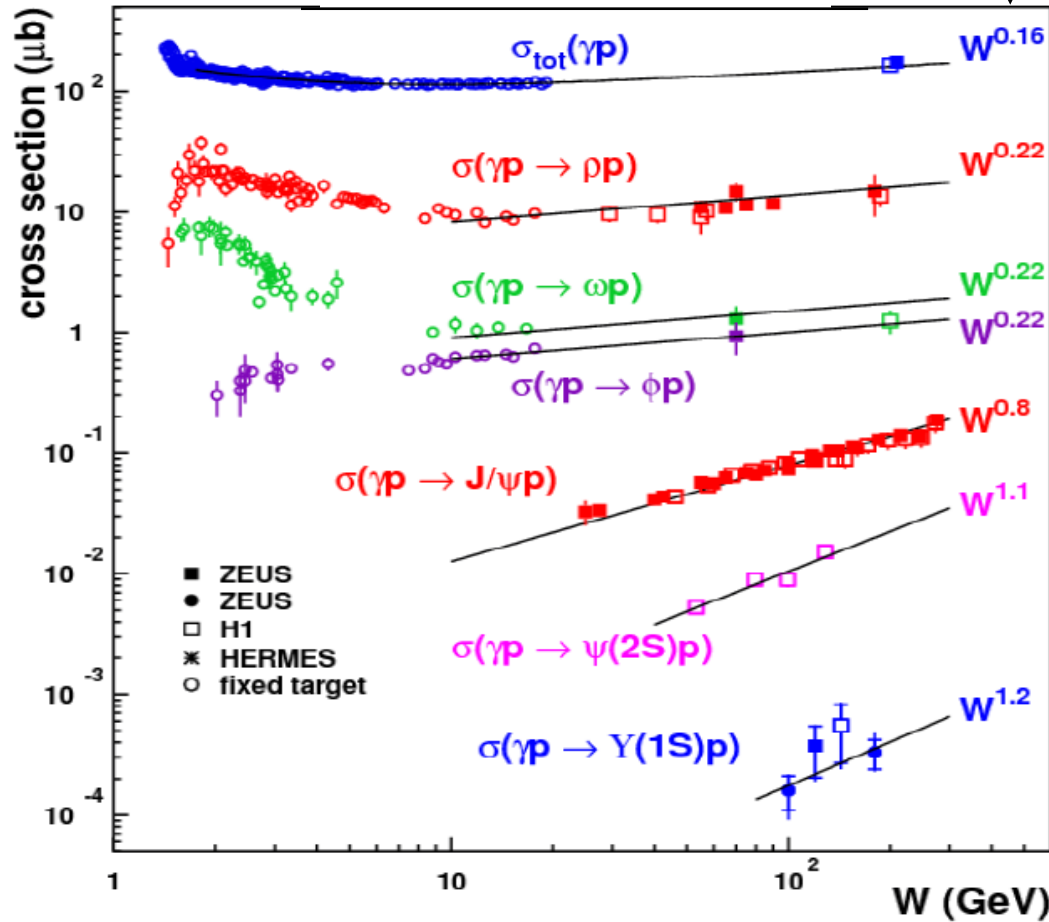
Elastic photoproduction of Vector mesons $\gamma p \rightarrow VM+p$ ($V=\rho,\phi,\omega,J/\Psi, \Upsilon$)

W dependence $\sigma(W) \propto W^\delta$

$\gamma p \rightarrow \Upsilon + p$ ($M_\Upsilon = 9.46 \text{ GeV}$)

ZEUS

DESY-09-036



VM mass sets hard scale of interaction

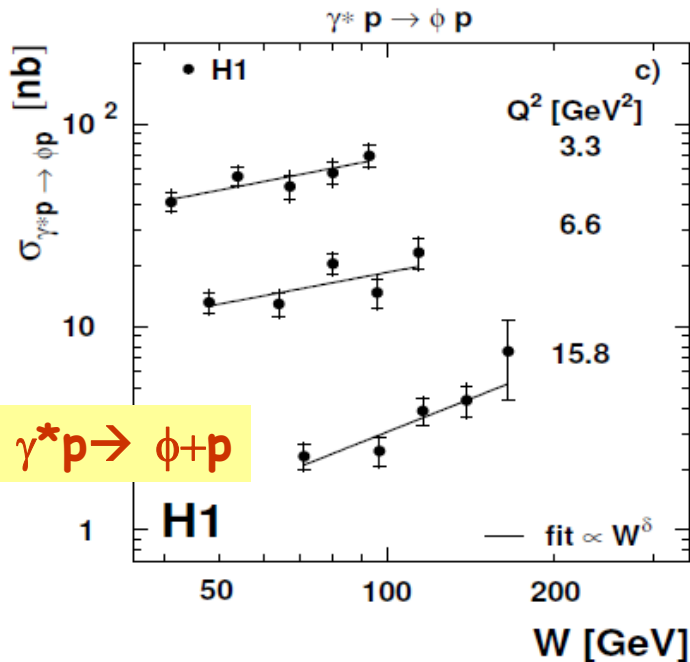
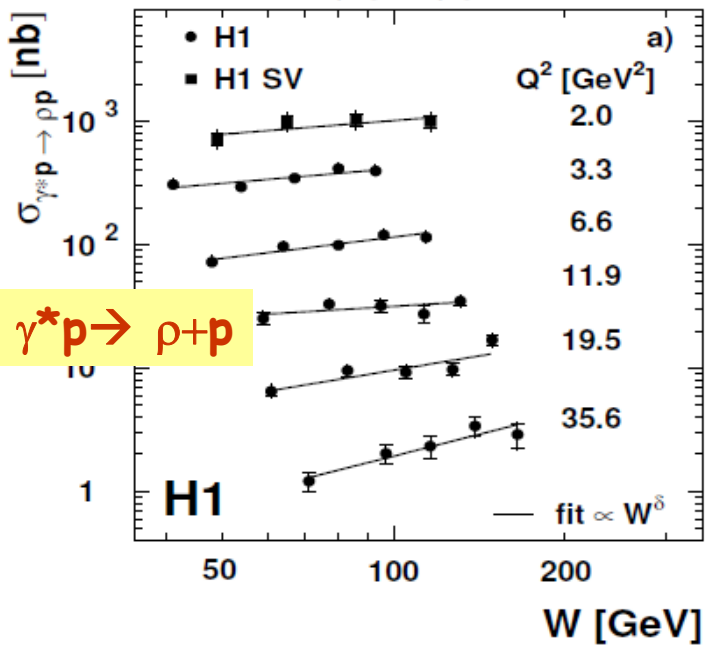
Process becomes hard (steeper W dependence) as M_{VM} becomes larger ($J/\Psi, \Upsilon$)

- different QCD models consistent with the data
- sensitive to VM wave function: Gaussian-like light-cone WF favoured by the data

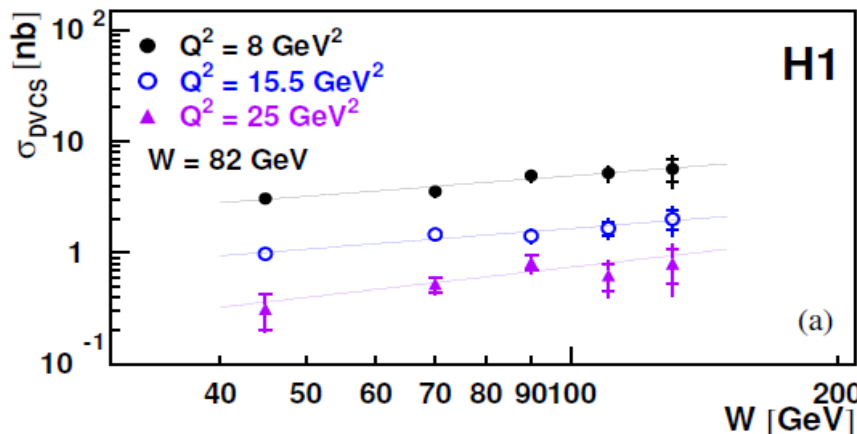
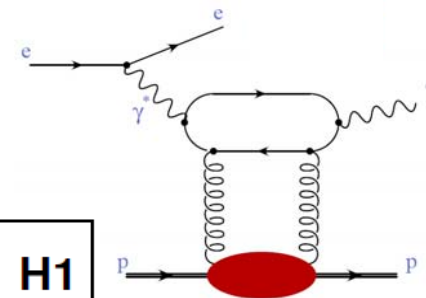
ρ, ϕ -electroproduction and DVCS: W dependences

DESY-09-093

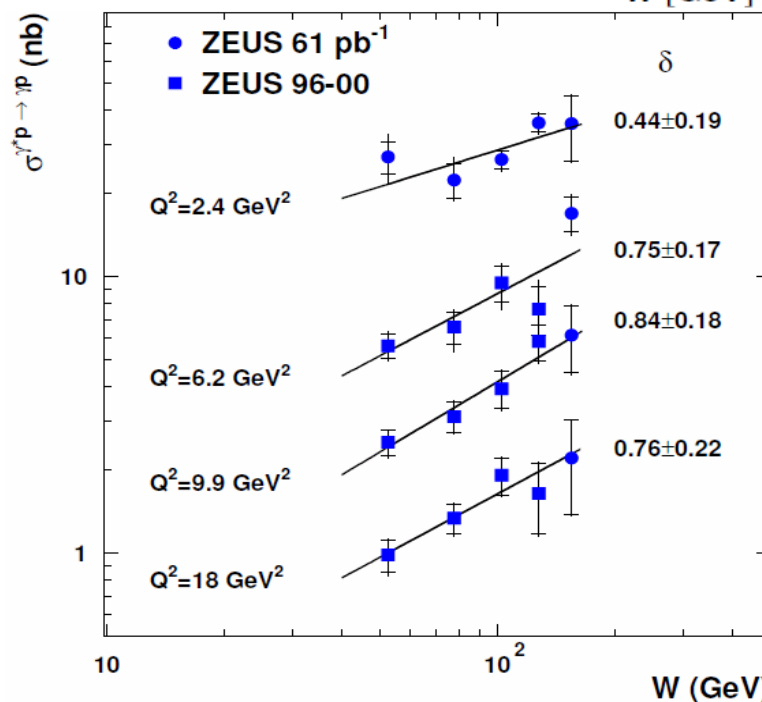
$\gamma^* p \rightarrow \rho p$



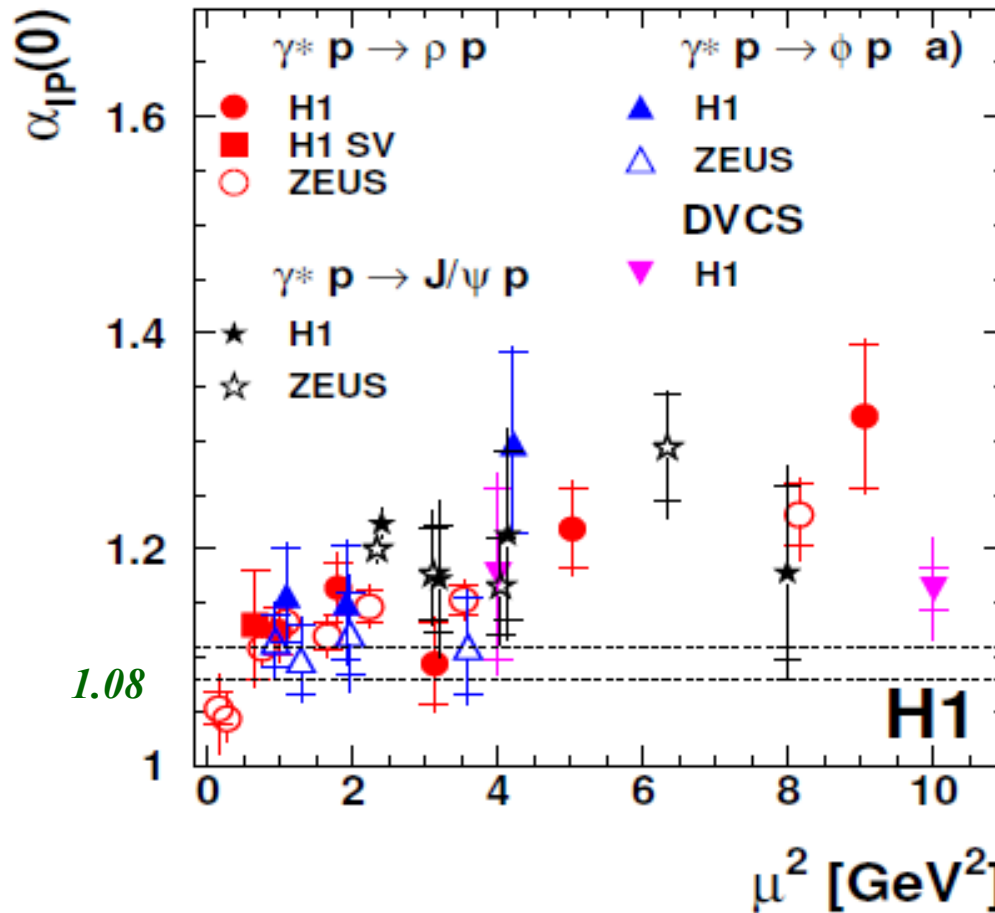
DVCS (elastic scattering of virtual photon off a proton)



DESY-09-109



summary: W -dependence



$$\sigma(W) \propto W^\delta$$

$$\delta(t) = 4(\alpha_{IP}(t) - 1)$$

$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP}t \quad - \text{effective}$$

Pomeron trajectory

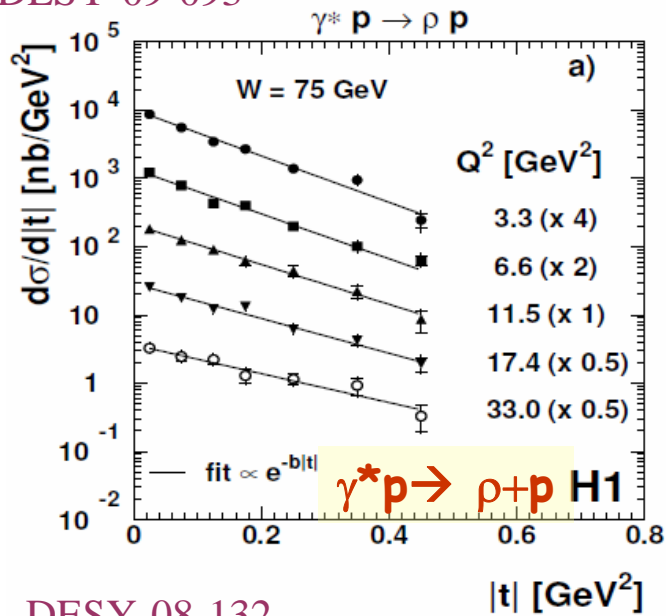
- similar behavior for DVCS and all VMs : common hardening of $\alpha_{IP}(0)$ with μ^2

→ Transition from soft to hard regime with increasing of hard scale

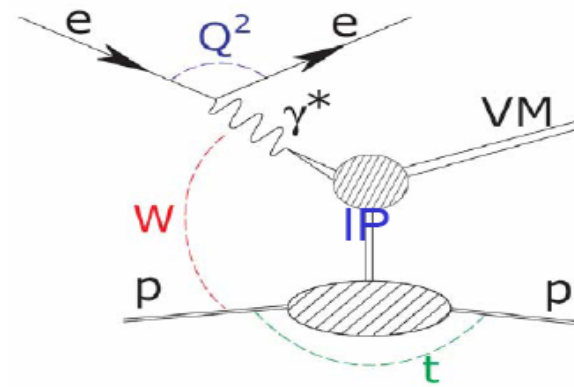
- DVCS shows a 'hard' behavior: steep rise even at lowest Q^2 , no significance Q^2 dependence (may suggest that the most sensitive part to soft scale is the VM wave function)

ρ, ϕ -electroproduction: t -dependence

DESY-09-093



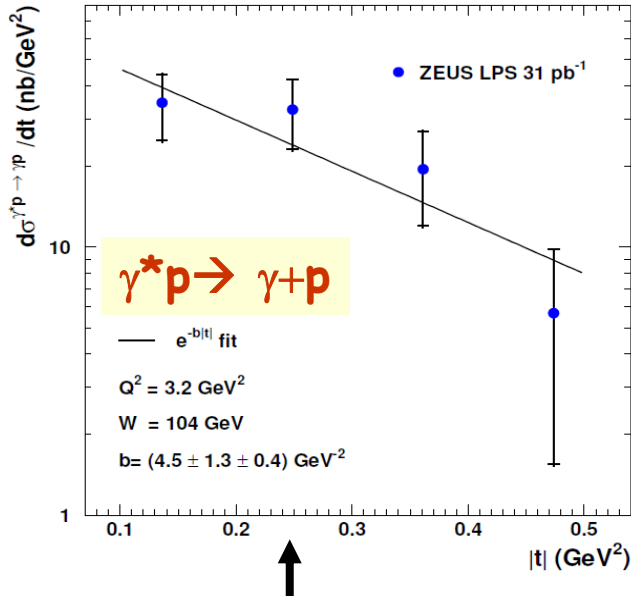
$$\frac{d\sigma}{d|t|} \propto e^{-b|t|}$$



b characterize the size of interaction

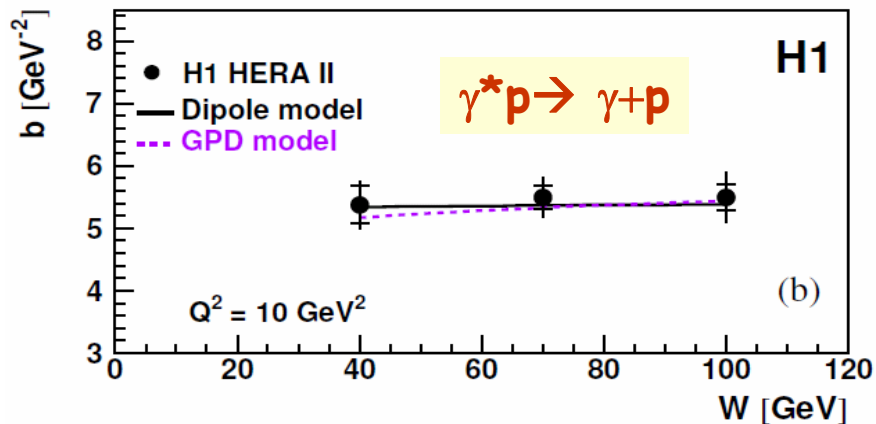
- b for ρ and ϕ decreases with increasing scale
 \rightarrow large dipole for light VM at low Q^2
 \rightarrow Transition from soft to hard regime with μ^2
- b for DVCS - no W dependence

DESY-08-132

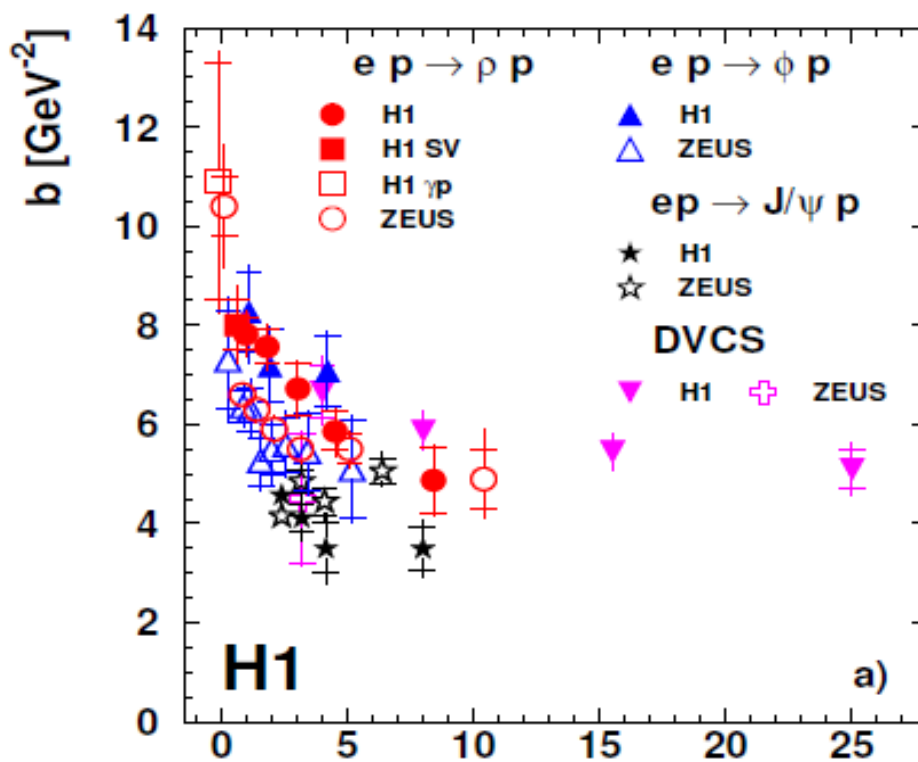


(direct t measurement using Leading Proton Spectrometer)

DESY-09-109



summary: t -dependence



$$\mu^2 [\text{GeV}^2] = \begin{cases} (Q^2 + M_V^2)/4 \\ Q^2 \text{ for DVCS} \end{cases}$$

Similar behavior of slope with μ^2 scale for $\rho, \phi, J/\psi, \text{DVCS}$

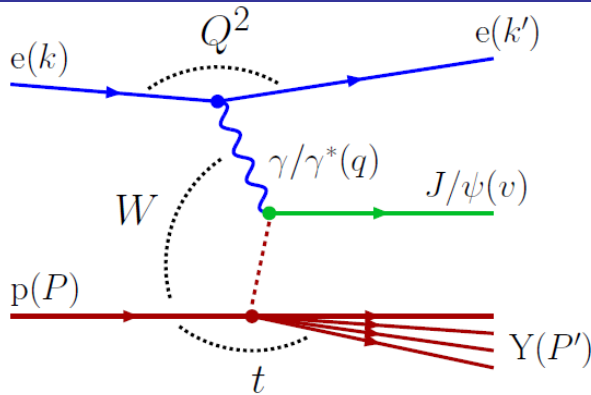
- b decreases with μ^2 from $\sim 10 \text{ GeV}^{-2}$ (soft) to $\sim 5 \text{ GeV}^{-2}$ (hard process)
- size of scattered VM getting smaller with scale

• for DVCS, $b = 5.41 \pm 0.14 \pm 0.31 \text{ GeV}^{-2}$ at $Q^2 = 10 \text{ GeV}^2$ (H1)

→ Average transverse extension of sea quarks and gluons in proton $\sqrt{\langle r_{\perp}^2 \rangle} = 0.64 \pm 0.02 \text{ fm}$

J/ψ photoproduction at high |t|

DESY-09-137

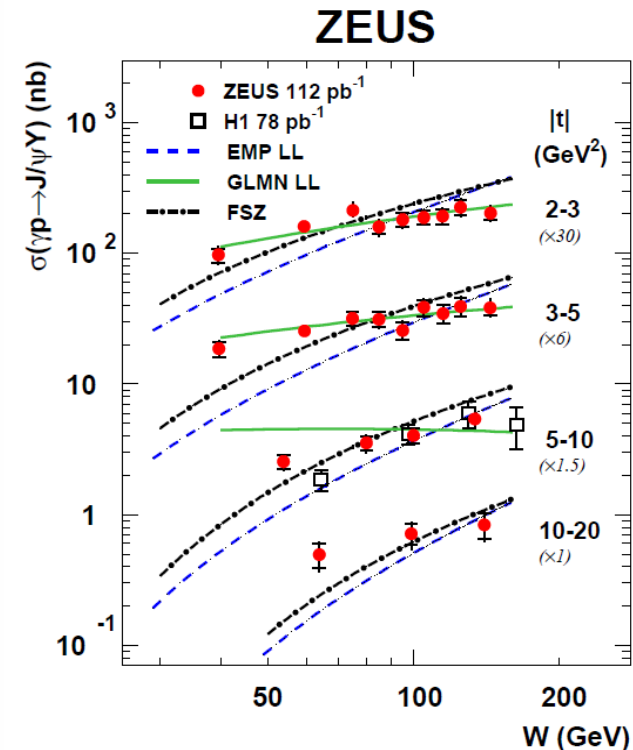
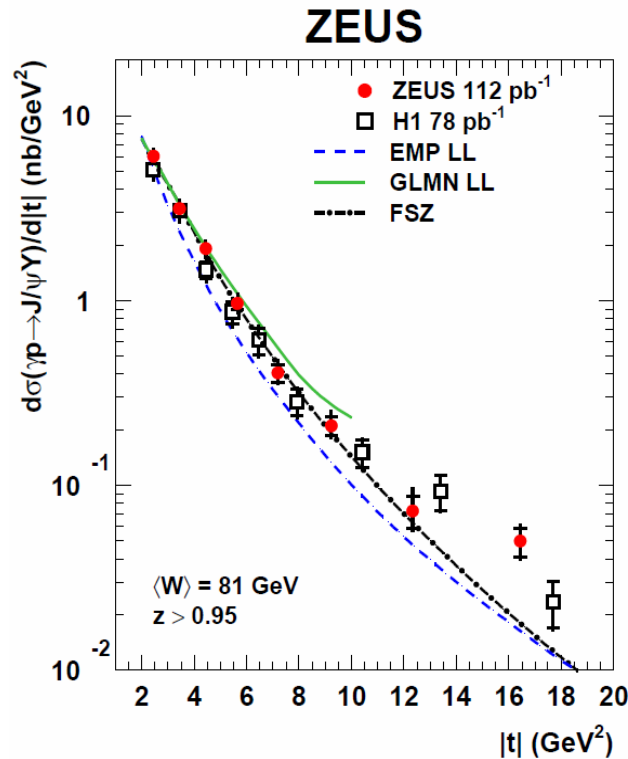


- Two hard scales: $M_{J/\psi}$ and t
- At $|t| \gg M_{J/\psi}^2$, BFKL should be favoured
- t -dependence no longer exponential

$$\frac{d\sigma}{d|t|} \propto t^n$$

$$n = -1.9 \pm 0.1, \quad 2 < |t| < 4 \text{ GeV}^2$$

$$n = -3.0 \pm 0.1, \quad 4 < |t| < 16 \text{ GeV}^2$$



- σ vs W in t ranges: data rise with W for all t
- EMP (BFKL) below data
- GLMN (DGLAP) fails at $|t| > 5 \text{ GeV}^2$
- FSZ (W dependence of σ depends on the gluon distribution): describes data up to $|t| = 12 \text{ GeV}^2$
- None of the models describes the data over the full t -range

Pomeron trajectory from elastic ρ^0 -photoproduction

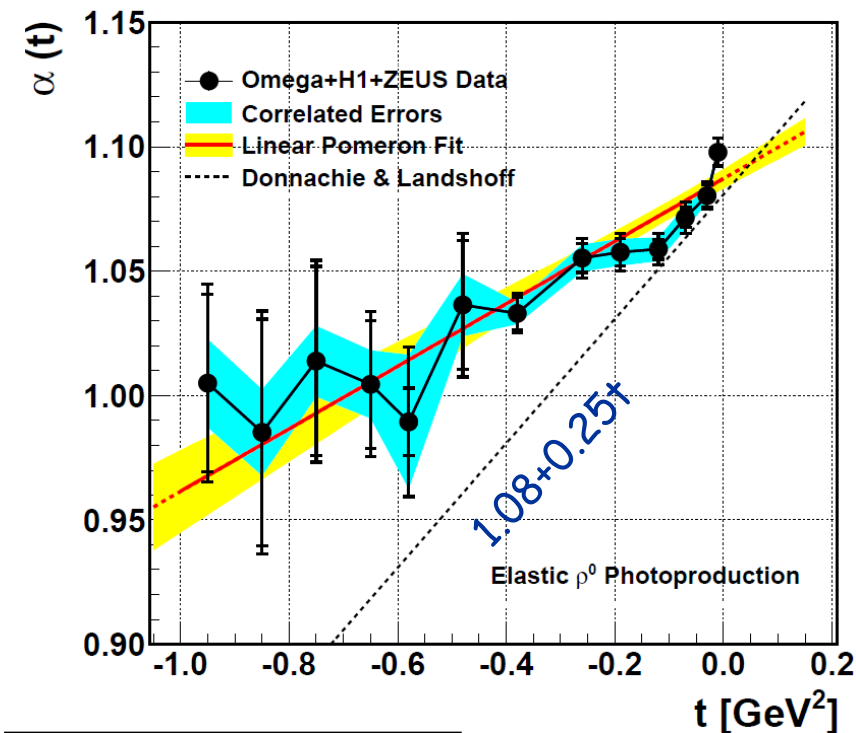
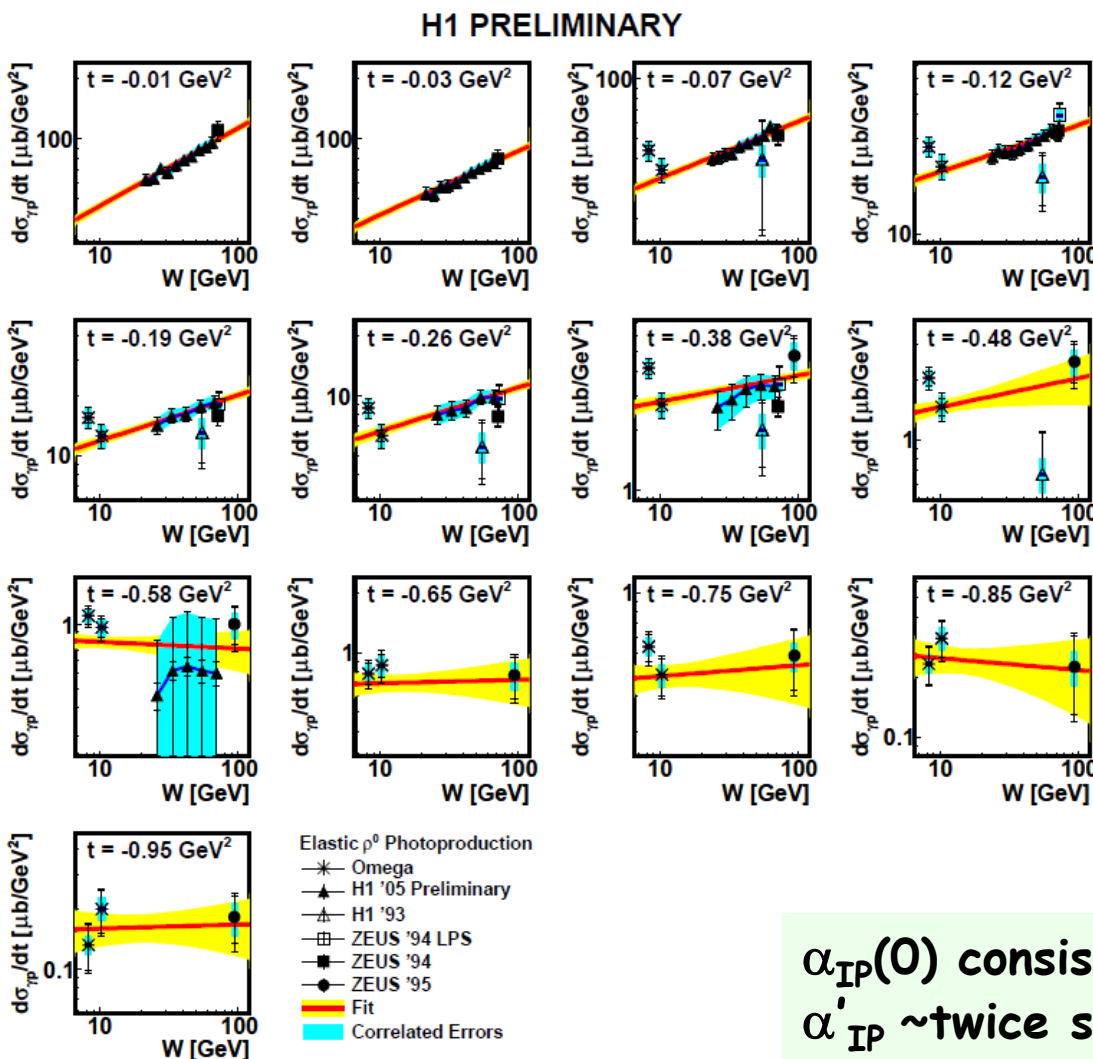
H1prelim-09-016

$\gamma p \rightarrow \rho^0 p$: energy dependence of elastic ρ^0 -photoproduction at fixed t related to the Pomeron trajectory :

Pomeron trajectory $\alpha_{IP}(t)$ from the global fit to H1, ZEUS and Omega data

$$\frac{d\sigma_{\gamma p}(W)}{dt} \propto \left(\frac{W}{W_0} \right)^{4(\alpha_{IP}(t)-1)}$$

Result of the fit
H1 PRELIMINARY



$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha'_{IP} \cdot t$$

$$\alpha_{IP}(0) = 1.0871 \pm 0.0026(\text{stat}) \pm 0.0030(\text{sys})$$

$$\alpha'_{IP} = 0.126 \pm 0.013(\text{stat}) \pm 0.012(\text{sys}) \text{ GeV}^{-2}$$

$\alpha_{IP}(0)$ consistent with 1.08 from soft $p\bar{p}$ scattering;
 $\alpha'_{IP} \sim$ twice smaller than 0.25 GeV^{-2}

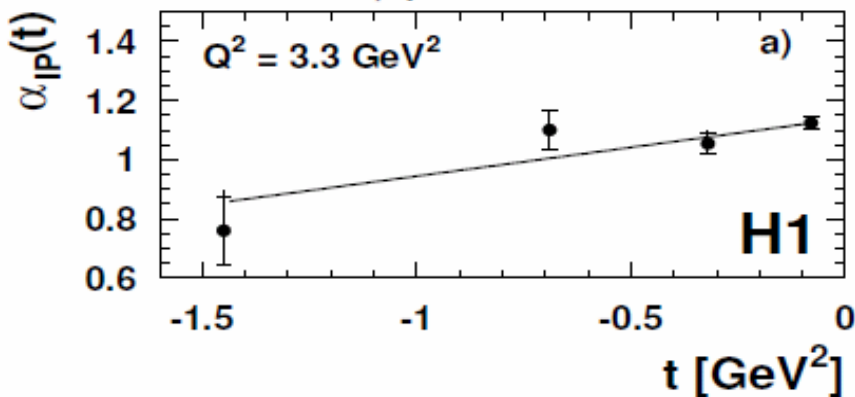
Summary of α'_{IP} measurements

study W dependence in bins of t

$$\frac{d\sigma}{dt}(W) \propto e^{bt} = e^{b_0 t} W^{4(\alpha'_{IP}(t)-1)}; \mathbf{b} = \mathbf{b}_0 + 4\alpha' \ln(W/W_0)$$

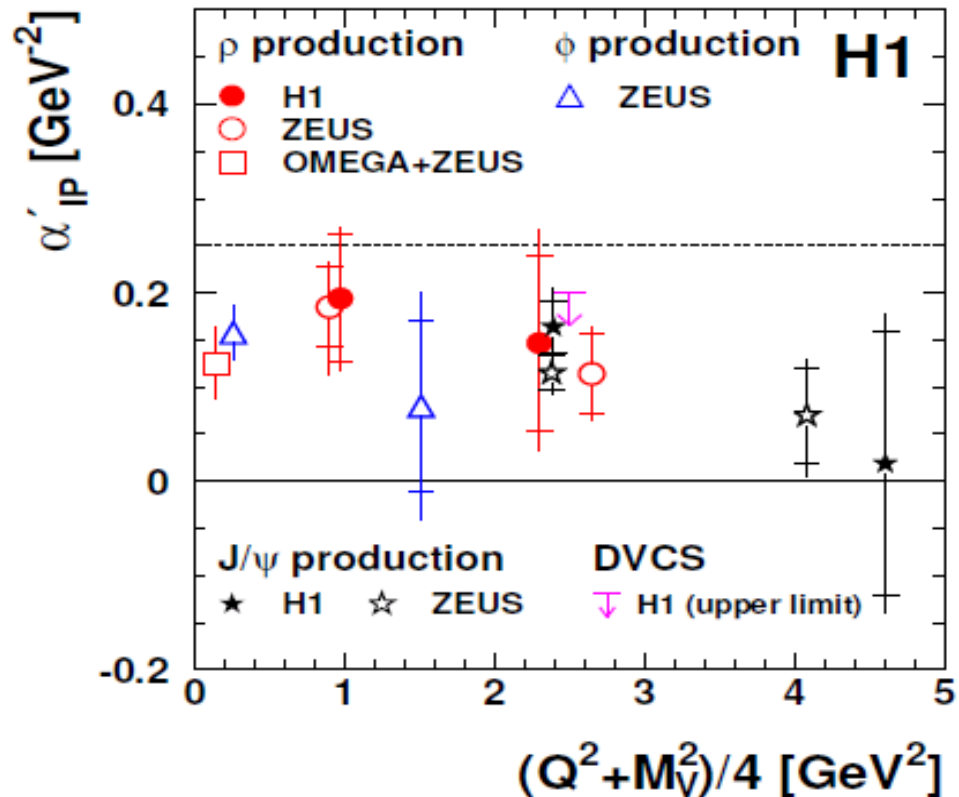
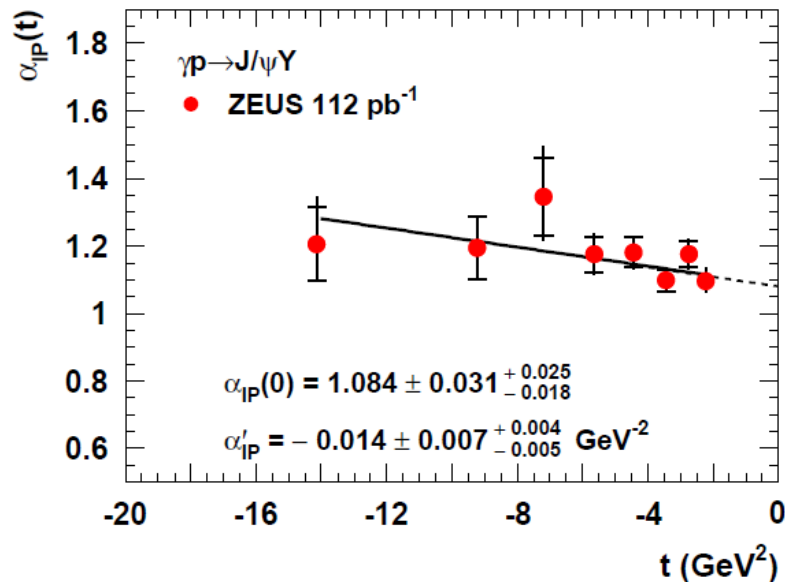
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ρ production



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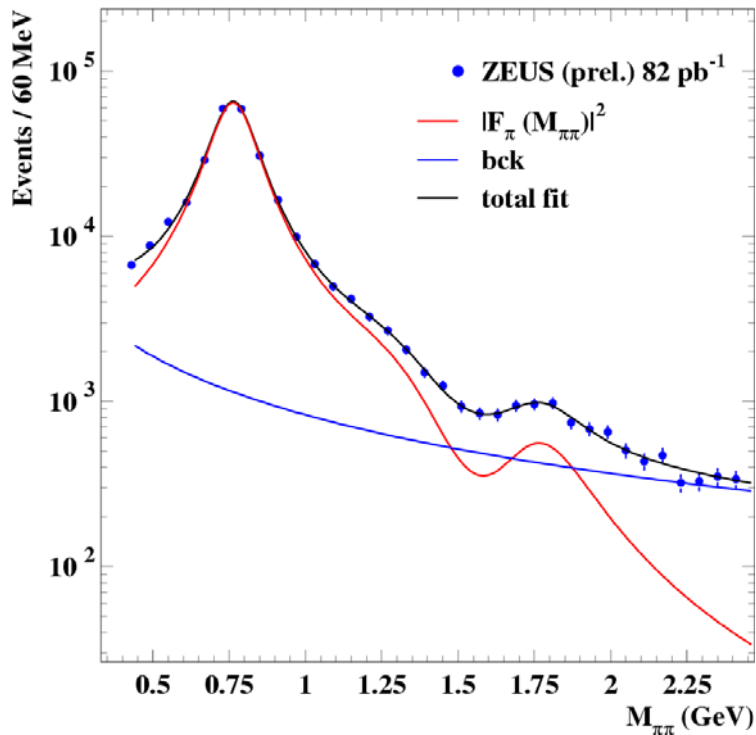
ZEUS



→ For all VM and DVCS α'_{IP} smaller than 0.25

Two pion diffractive electroproduction

ZEUS-prel-10-012 ZEUS



Measure two pion mass distribution $0.4 < M_{\pi\pi} < 2.4 \text{ GeV}$ in DIS ($2 < Q^2 < 80 \text{ GeV}^2$)

Fit with 3 resonances: ρ, ρ', ρ''

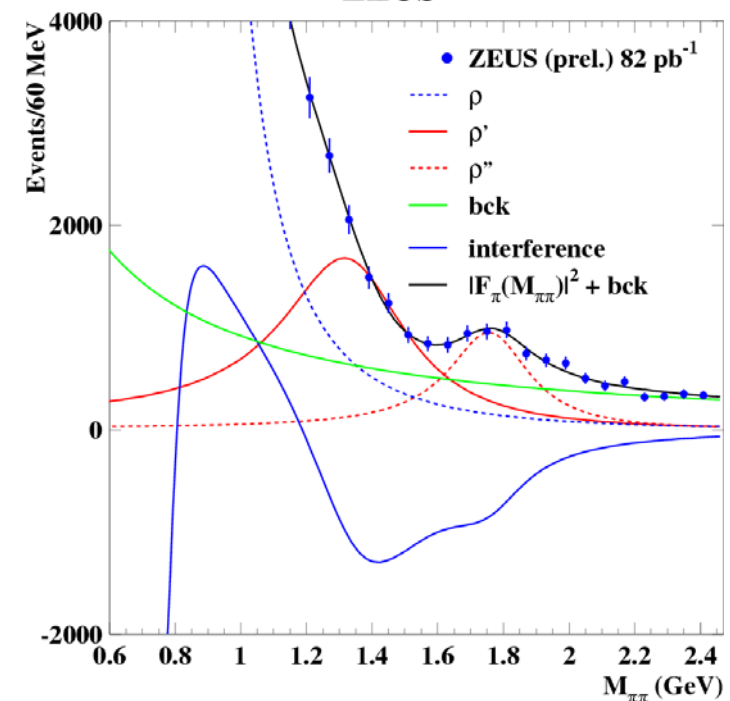
$$\bullet \frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} = N \left[|F_{\pi}(M_{\pi\pi})|^2 + \frac{B}{M_{\pi\pi}^n} \right]$$

$$\bullet F_{\pi}(M_{\pi\pi}) = \frac{BW(\rho) + \beta BW(\rho') + \gamma BW(\rho'')}{1 + \beta + \gamma} \quad \text{-formfactor}$$

11 parameter fit: N - total normal.factor; B,n-background, M, Γ -masses and widths of ρ, ρ', ρ'' ; β, γ - relative amplitudes

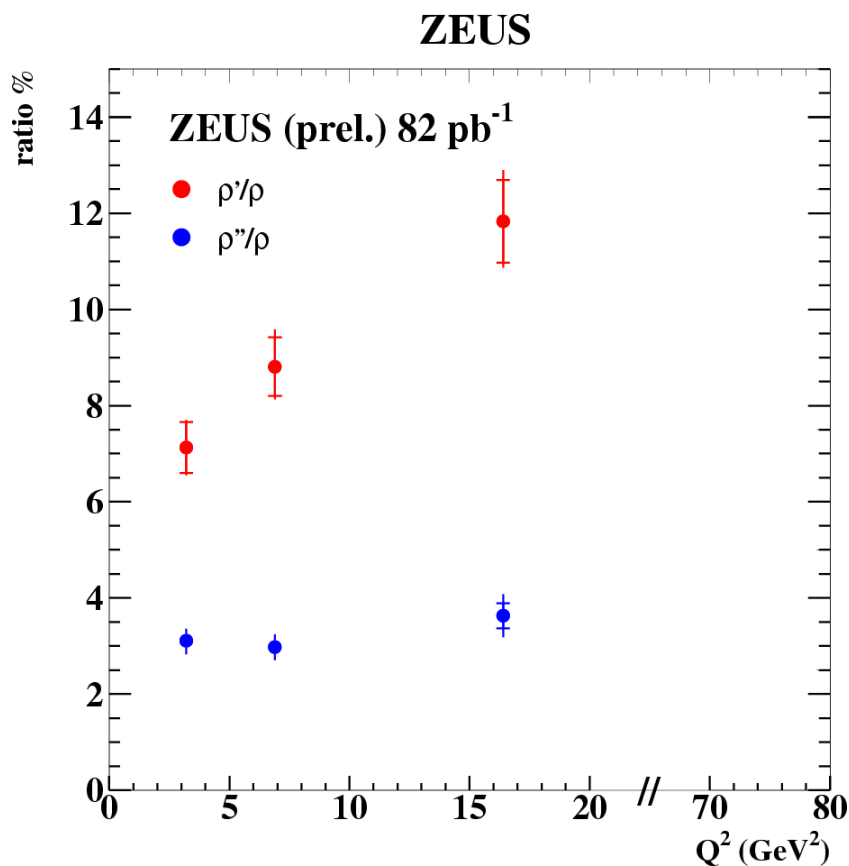
ZEUS

| Parameter | ZEUS (prel.) | PDG |
|--------------------|---------------------------------|-------------------|
| M_{ρ} (GeV) | $772 \pm 2^{+2}_{-1}$ | 775.49 ± 0.34 |
| Γ_{ρ} | $155 \pm 5 \pm 2$ | 149.4 ± 1.0 |
| β | $-0.27 \pm 0.02 \pm 0.02$ | |
| $M_{\rho'}$ (GeV) | $1360 \pm 20^{+20}_{-30}$ | 1465 ± 25 |
| $\Gamma_{\rho'}$ | $460 \pm 30^{+40}_{-45}$ | 400 ± 60 |
| γ | $0.10 \pm 0.02^{+0.02}_{-0.01}$ | |
| $M_{\rho''}$ (GeV) | $1770 \pm 20^{+15}_{-20}$ | 1720 ± 20 |
| $\Gamma_{\rho''}$ | $310 \pm 30^{+25}_{-35}$ | 250 ± 100 |



ρ, ρ', ρ'' electroproduction: Q^2 dependence of relative rates $\rho'/\rho, \rho''/\rho$

ZEUS-prel-10-012



ρ'/ρ - increases with Q^2

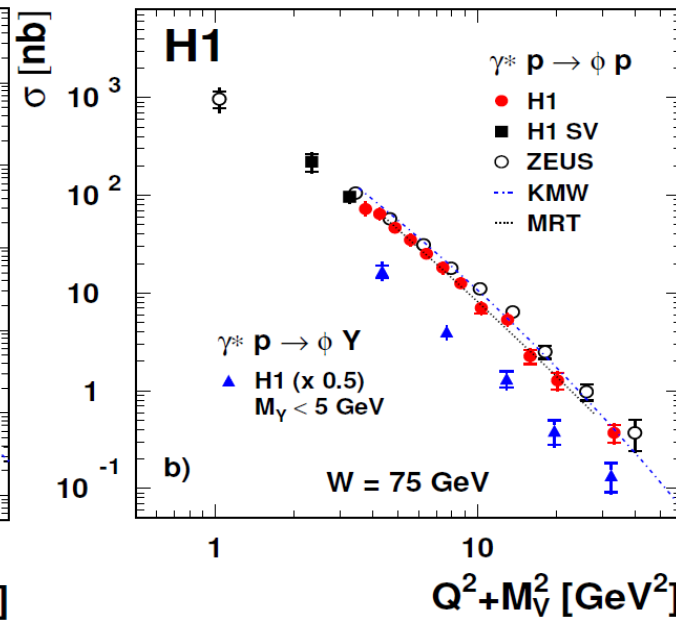
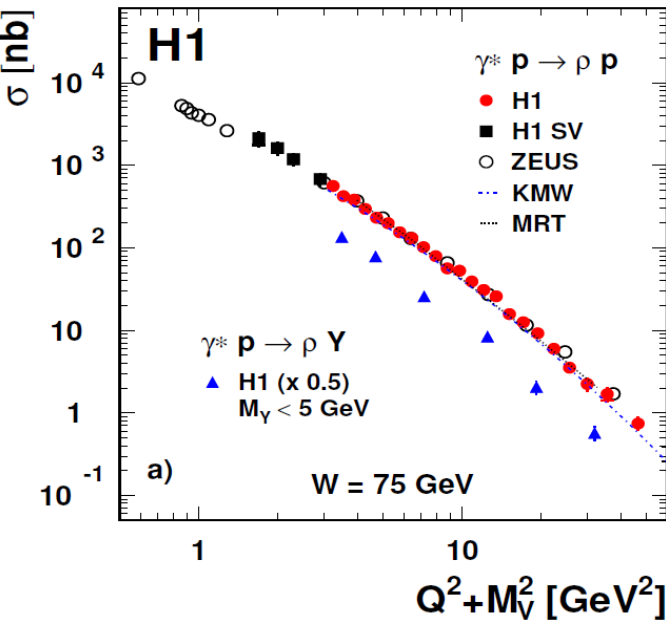
→ consistent with pQCD expectation

Martin,Ryskin,Teubner Phys.Rev.D56, 3007 (97)

ρ''/ρ - constant with Q^2

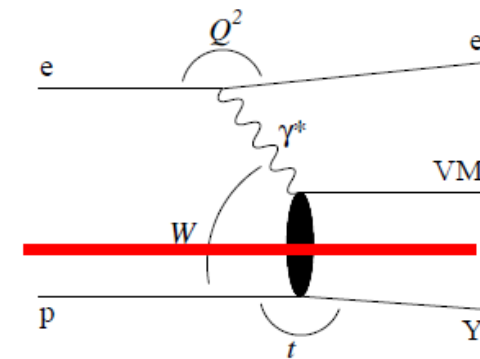
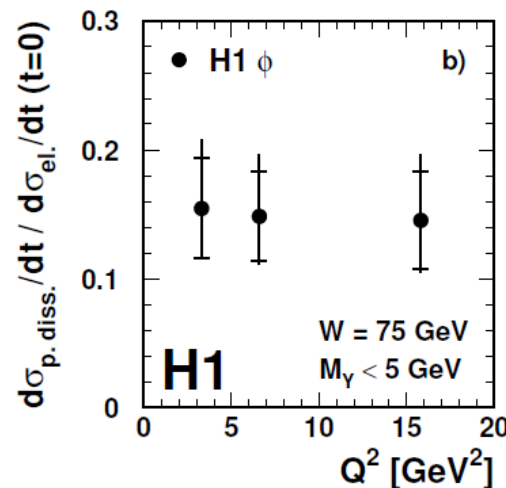
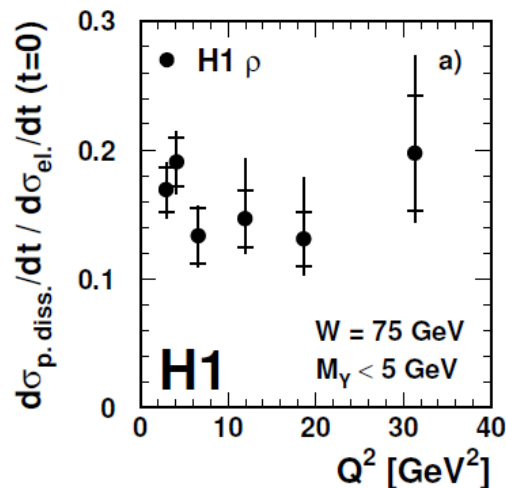
Elastic and p-diss. ρ, ϕ -mesons in DIS: Q^2 dependence

DESY-09-093



- high precision for elastic ρ, ϕ cross sections
- good agreement between H1/ZEUS
- Steep decrease of σ with increasing $Q^2 + M^2$
- similar for p-dissociation

Ratio $\sigma_{p\text{-diss}}/\sigma_{el} \rightarrow$ test of vertex ('Regge') factorisation



\rightarrow no Q^2 dependence: support vertex factorization

Elastic ρ -electroproduction: polarised cross sections σ_L, σ_T

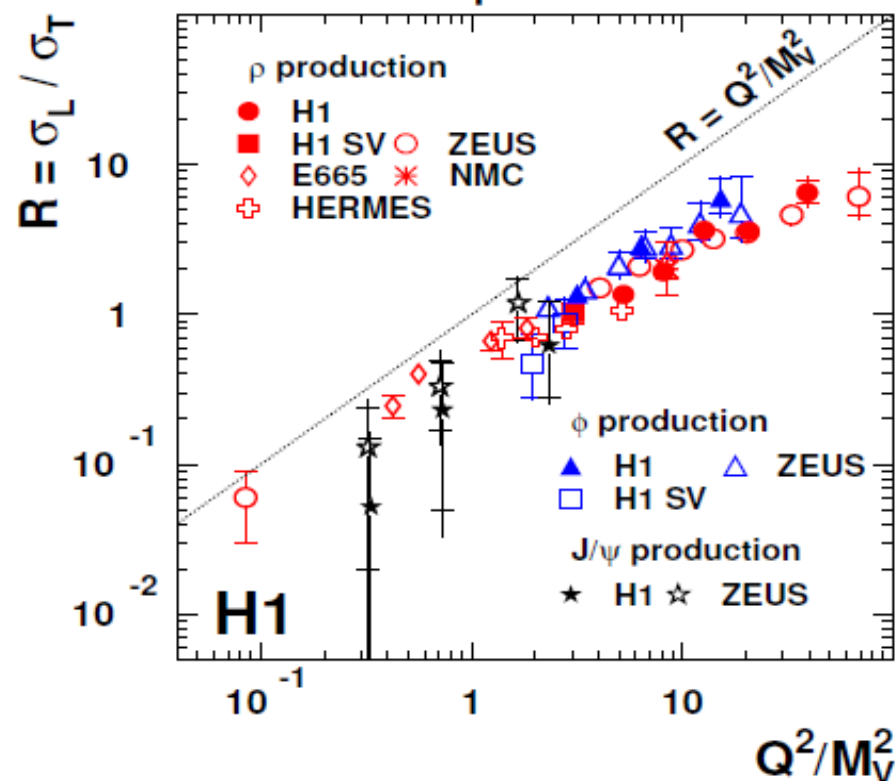
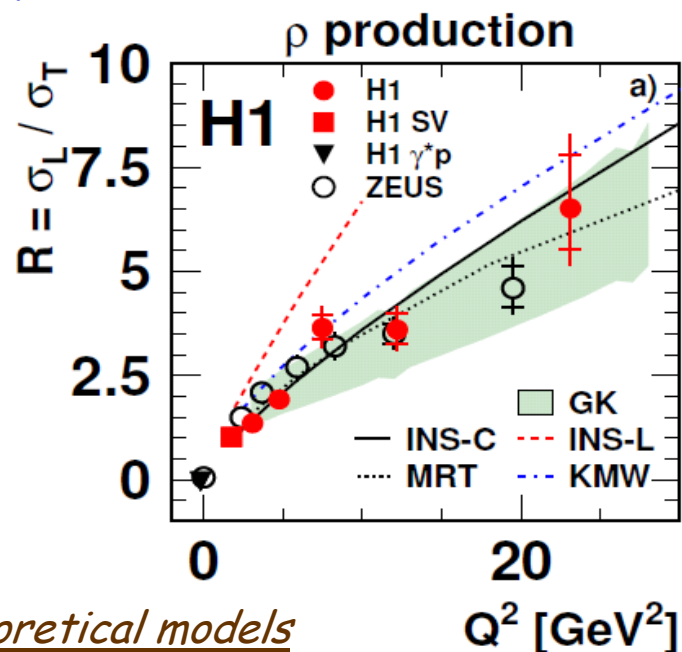
QCD expectation: $R = \sigma_L / \sigma_T \sim Q^2 / M^2 \rightarrow$ as the scale gets harder σ_L dominates

$\sigma_L(\gamma_L^*)$ -small spatial configuration (large k_T)

$\sigma_T(\gamma_T^*)$ -large spatial configuration (small k_T)

DESY-09-093

VM production



Theoretical models

Dipole –saturation:

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

Dipole - k_T factorisation:

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

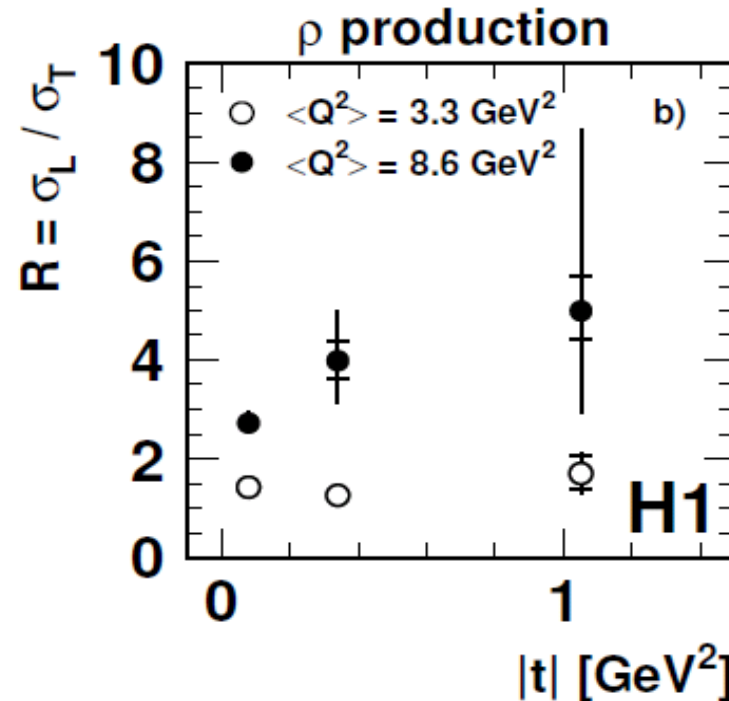
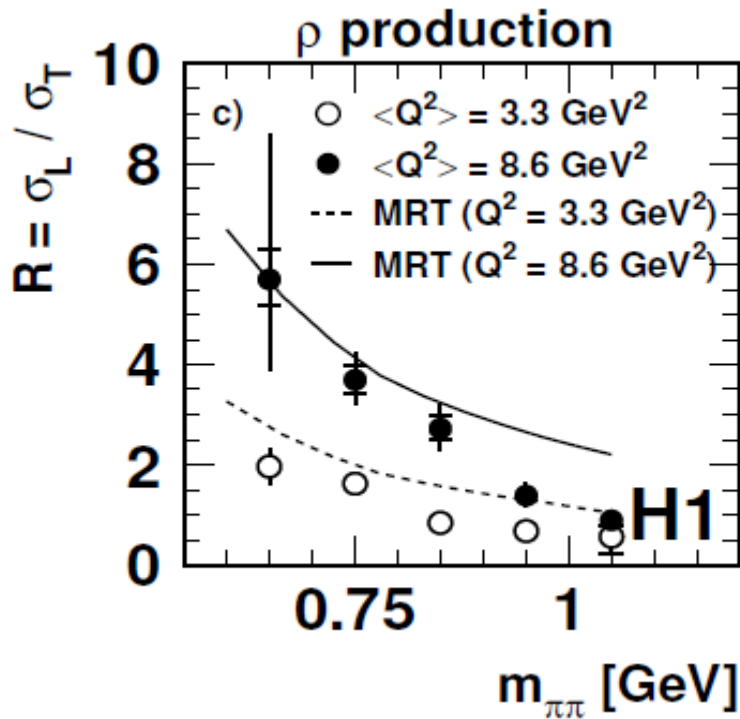
Collinear – GPD:

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

Parton-hadron duality:

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

- common behaviour for $\rho, \phi, J/\Psi$ over the full Q^2/M^2 range
- scaling for all VM with Q^2/M^2
- damping at large Q^2



$$R(t) = \sigma_L / \sigma_T \propto e^{-(b_L - b_T)|t|}$$

indication for $b_L - b_T < 0$ (1.5σ) at $Q^2 > 5 \text{ GeV}^2$

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

- expect smaller dipole in σ_L at higher Q^2
→ harder QCD regime reached
- large dipoles present in σ_L at lower scales

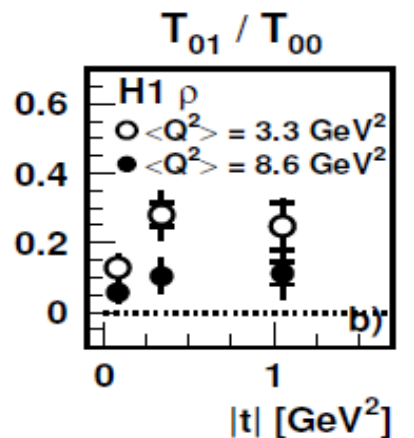
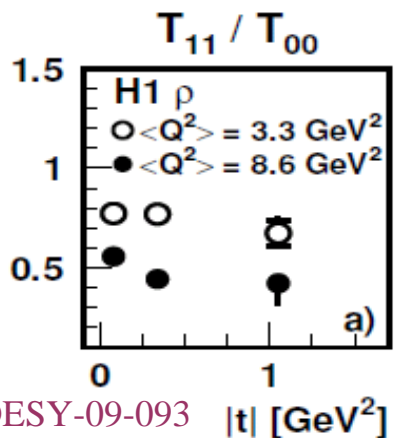
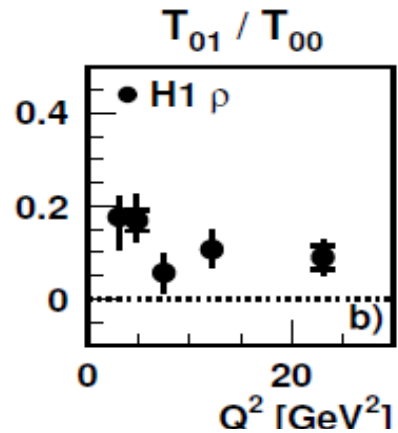
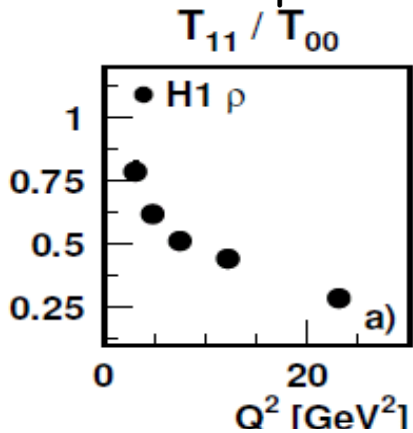
- Strong invariant mass dependence for ρ -meson
- expect from $R \sim (Q^2/M^2)$ behavior, where M is a dipion mass (cf Martin, Ryskin, Teubner calculations)

ρ : helicity amplitude ratios vs Q^2 and t

Extract 15 Spin Density Matrix Elements $\rho_{ij_{kl}}$ from fit to the decay angular distributions; determine ratios of helicity amplitudes $T_{\lambda_{VM}\lambda_{\gamma}}$ from SDMEs.

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):** the VM retains the γ^* helicity $T_{01}=T_{10}=T_{1-1}=0$
- pQCD models: SCHC violation:** the angular momentum of $q\bar{q}$ can be modified through the transfer of transverse momentum carried by gluons \rightarrow helicity flip between photon and meson is possible



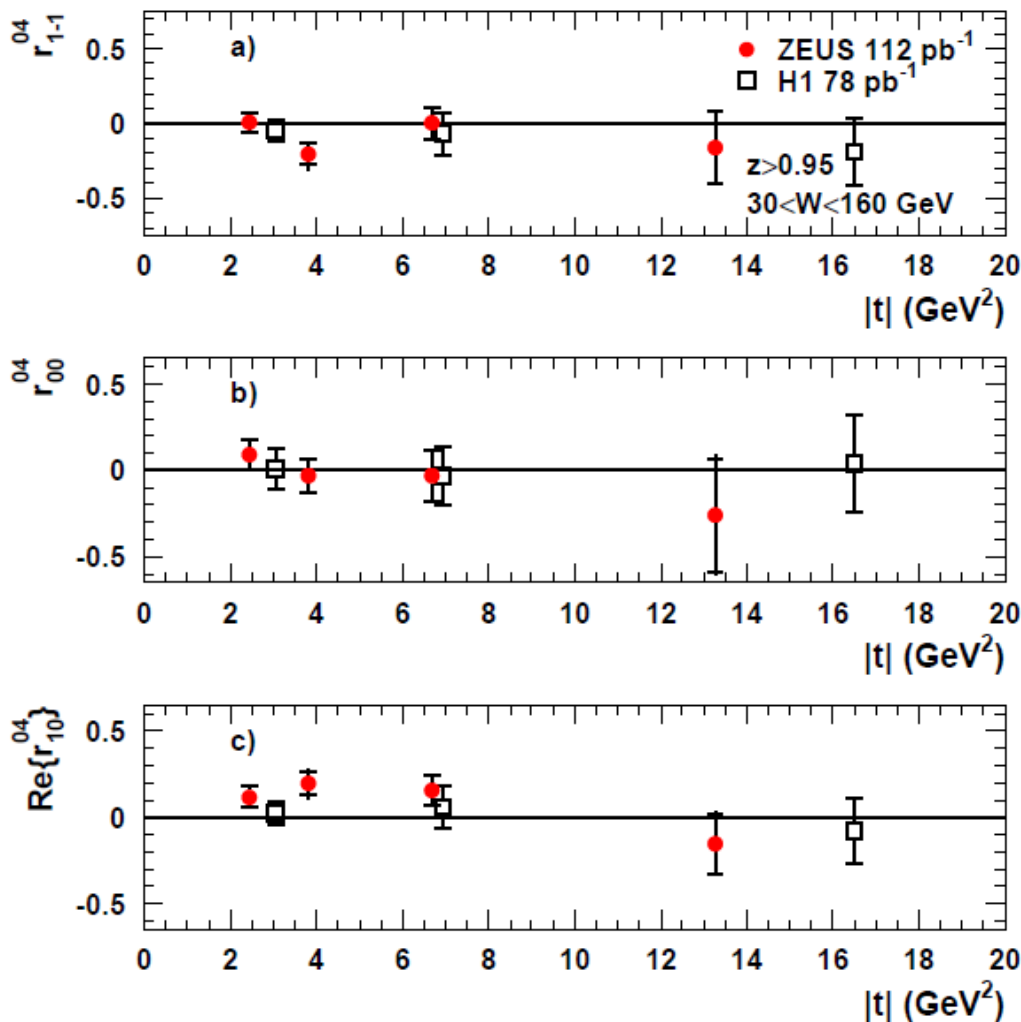
- $|T_{11}|/|T_{00}|$ decreases with Q^2
 $\rightarrow \sigma_L/\sigma_T$ increases with Q^2
decreases with t
 \rightarrow related to $b_L - b_T < 0$
- $|T_{01}|/|T_{00}| > 0$, increases with t
SCHC violation increases with t

$|T_{10}|/|T_{00}|$ and $|T_{1-1}|/|T_{00}|$ are small

Hierarchy $|T_{00}| > |T_{11}| > |T_{01}| > |T_{10}| > |T_{1-1}|$ is observed

Helicity spin density matrix elements as a function of t

ZEUS



- SDME $r_{ij_{kl}}$ extracted from fit to the decay angular distributions

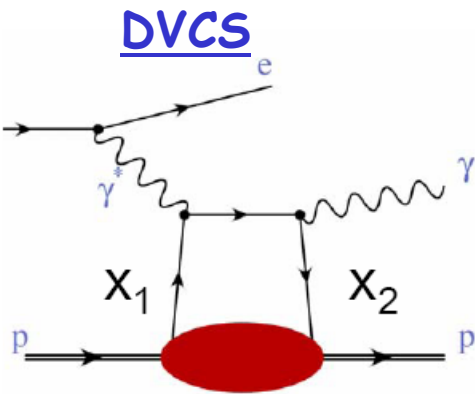
- r_{1-1}^{04} is related to interference between non-flip and double-flip amplitude
 \rightarrow compatible with 0, as expected for in SCHC: (J/ψ) retains the helicity of photon

- r_{00}^{04} represents the probability that J/ψ has 0 helicity
 \rightarrow compatible with 0, as expected for in SCHC

- $\text{Re}(r_{10}^{04})$ is proportional to the single flip amplitude
 r_{10}^{04} not compatible with 0 at $|t| < 10 \text{ GeV}^2$

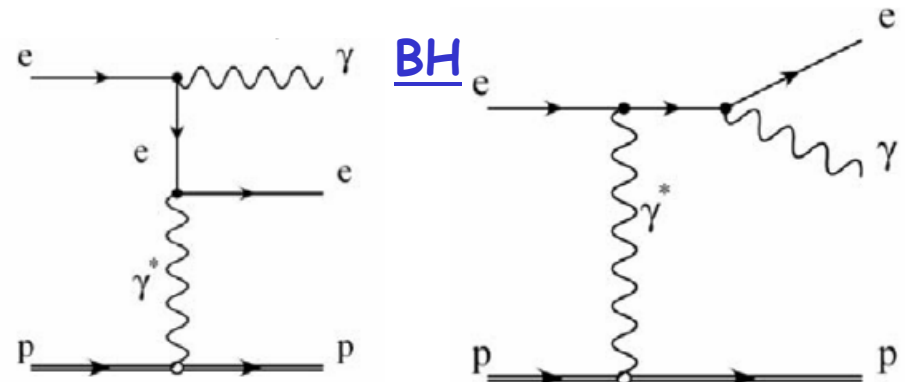
DVCS: Beam Charge Asymmetry (BCA)

DESY-09-109



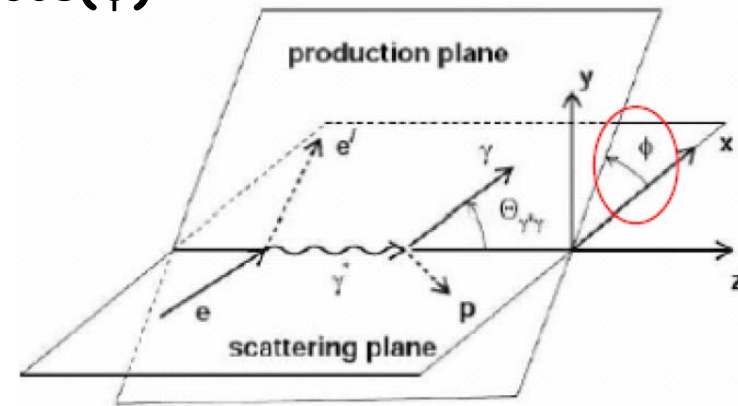
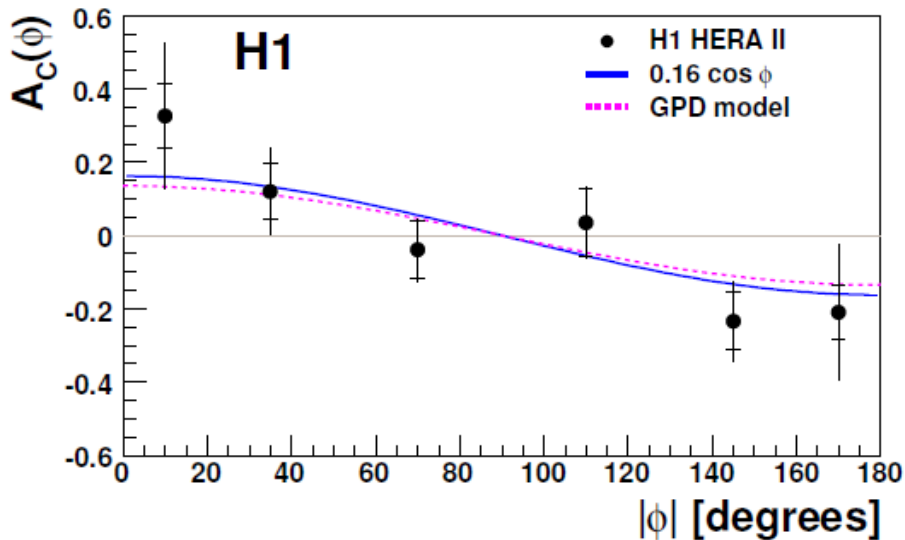
DVCS gives access to Generalized (skewed) Parton Distributions (GPD), which describe the correlations between two partons (x_1, x_2) which differ by longitudinal ($x_1 \neq x_2$) and transverse (t) momentum at given Q^2

Interference between DVCS (QCD) and Bethe-Heitler (QED) processes



$$|A|^2 = |A_{DVCS}|^2 + |A_{BH}|^2 + |A_I|^2 \leftarrow \text{interference term}$$

Beam Charge Asymmetry: $A_C(\phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto \text{Re}(A_{DVCS}) \cdot \cos(\phi)$
 Related to GPD



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

GPDs based model compatible with data

Many new high statistics measurements of exclusive Vector Mesons and DVCS at HERA

- The measurements allow us to study the transition from the soft to hard regime.
- Perturbative QCD expectations are in general compatible with the data. The different models describe main features, but differ in details.
- The measurements provide new insight into the proton structure with a high sensitivity to gluon density, skewing effects and GPDs.

Definition of the matrix elements in terms of helicity amplitudes

$$r_{00}^{04} = \frac{1}{1 + \varepsilon R} \left[\frac{1}{2N_T} (|T_{01}|^2 + |T_{0-1}|^2) + \frac{\varepsilon R}{N_L} |T_{00}|^2 \right]$$

$$r_{1-1}^{04} = \frac{1}{1 + \varepsilon R} \left[\frac{1}{2N_T} (T_{11}T_{-11}^\dagger + T_{1-1}T_{-1-1}^\dagger) + \frac{\varepsilon R}{N_L} T_{10}T_{-10}^\dagger \right]$$

$$\text{Re } r_{10}^{04} = \frac{1}{1 + \varepsilon R} \text{Re} \left[\frac{1}{2N_T} (T_{11}T_{01}^\dagger + T_{1-1}T_{0-1}^\dagger) + \frac{\varepsilon R}{N_L} T_{10}T_{00}^\dagger \right]$$

$$R = \frac{N_L}{N_T}, \quad \begin{aligned} N_L &= |T_{00}|^2 + |T_{10}|^2 + |T_{-10}|^2 \\ N_T &= \frac{1}{2} [|T_{11}|^2 + |T_{-1-1}|^2 + |T_{01}|^2 + |T_{0-1}|^2 + |T_{-11}|^2 + |T_{1-1}|^2] \end{aligned}$$

$e^+e^- \rightarrow \pi^+\pi^-$ and photoproduction $\pi^+\pi^-$

