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Exclusive diffractive processes at HERA
(Vector Mesons and DVCS)

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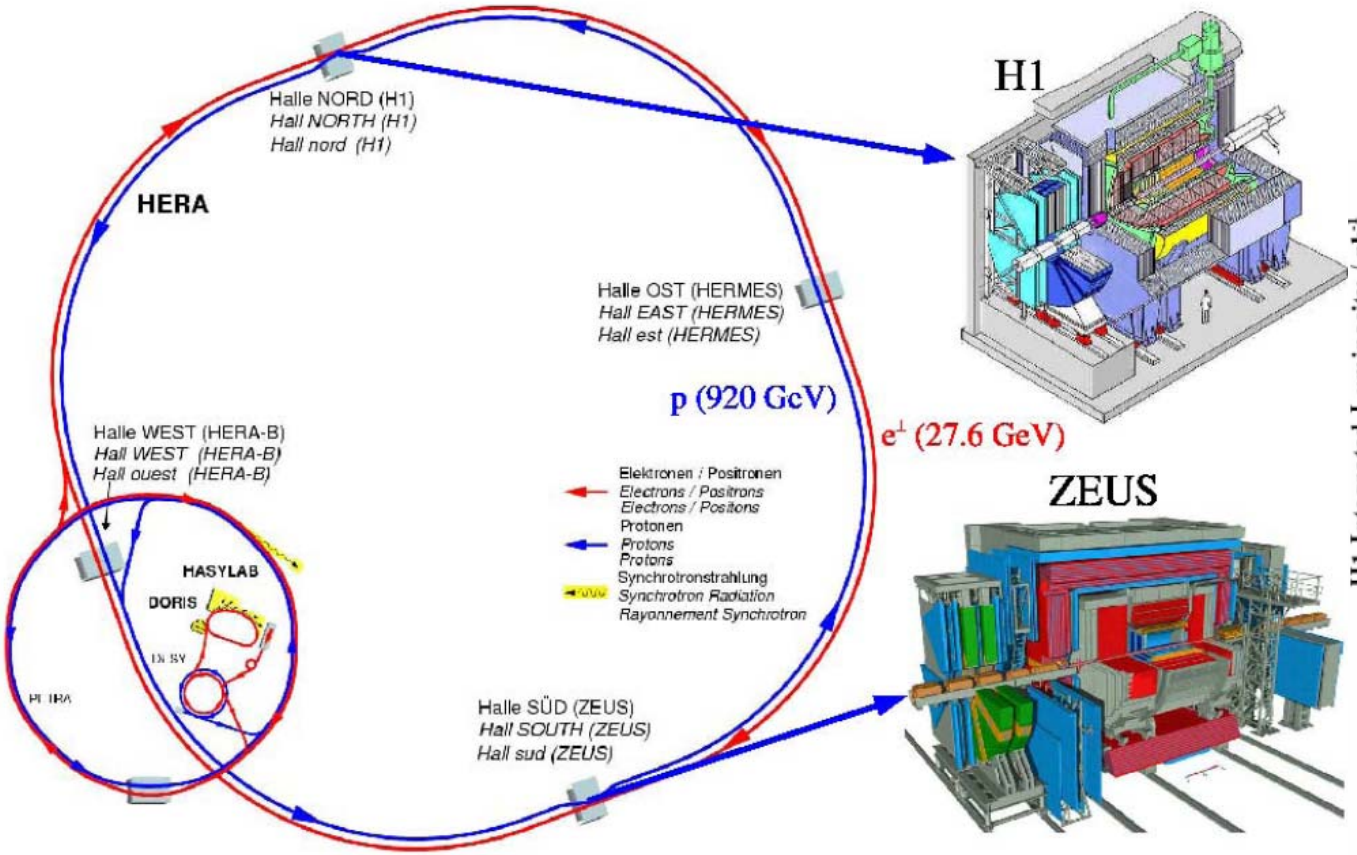
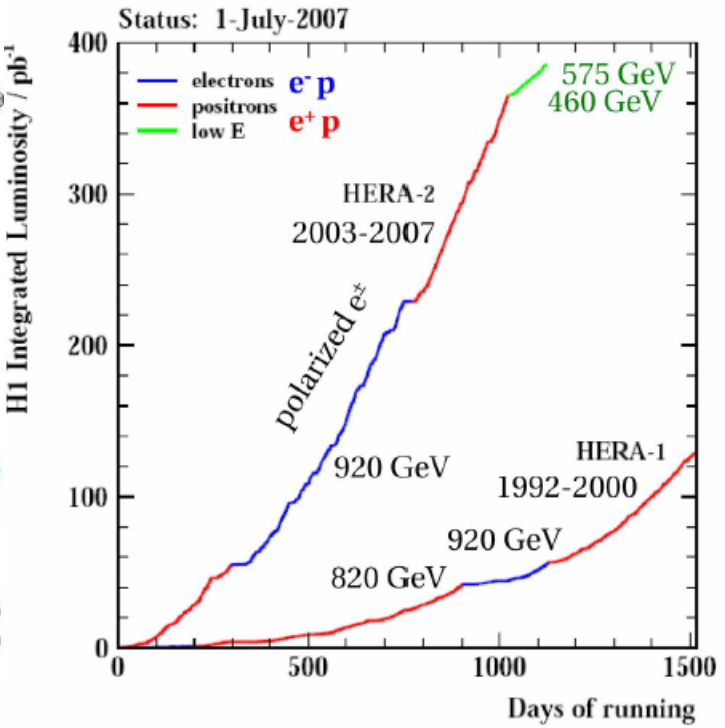
On behalf of the H1 and ZEUS Collaborations

HERA

The world's only electron/positron-proton collider at DESY, Hamburg
E_e = 27.6 GeV E_p = 920 GeV (also 820, 460 and 575 GeV)
(total centre-of-mass energy of collision up to $\sqrt{s} \approx 320$ GeV)

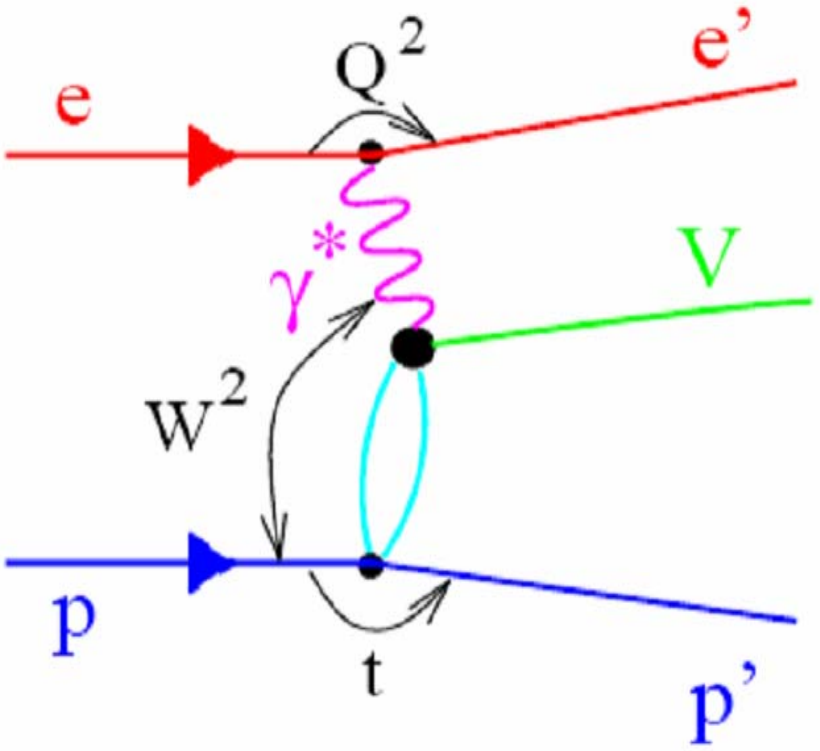




Two collider experiments: H1 and ZEUS

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)

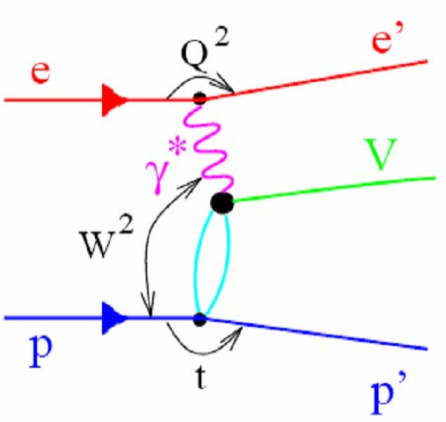
- $Q^2=-(e-e')^2$ - photon virtuality:
  $Q^2 \sim 0$ → 'photoproduction'
  $Q^2 > 0$ → Deep Inelastic Scattering (DIS)

- W - γ^*p center of mass energy

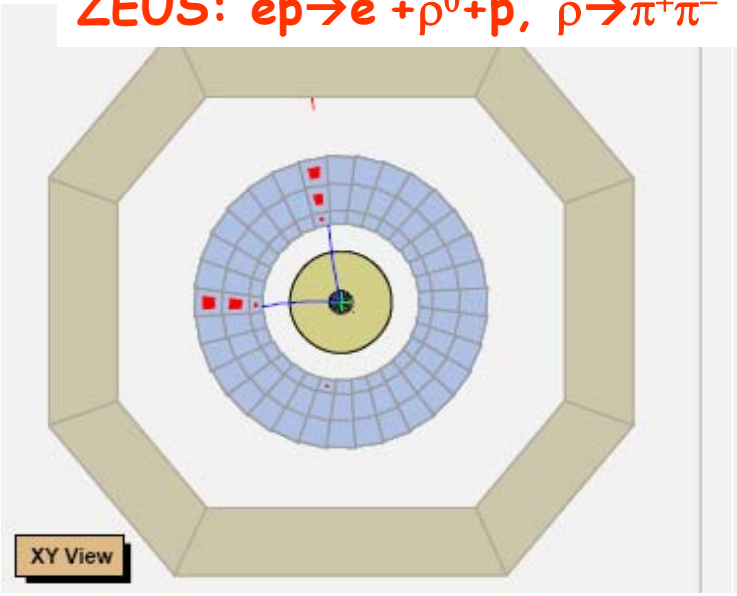
- $t=(p-p')^2$ -momentum transfer squared at the proton vertex

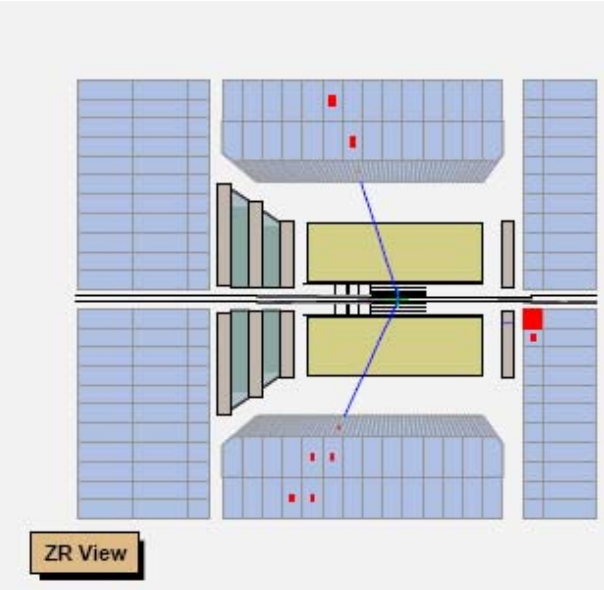
Introduction

Exclusive Vector meson production – clean experimental signatures



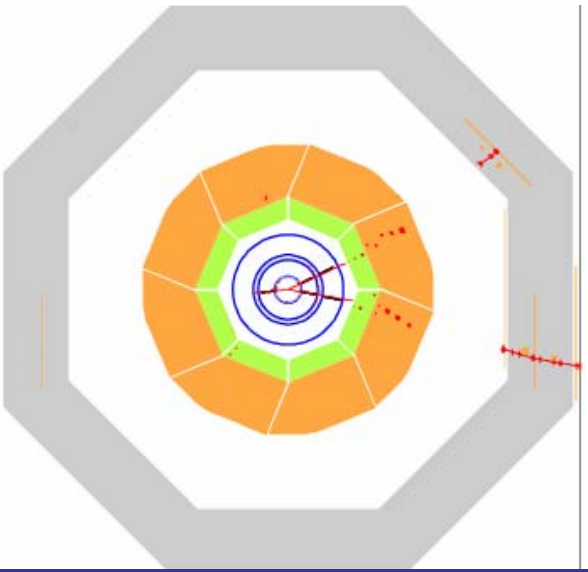
ZEUS: $ep \to e' + \rho^0 + p$, $\rho \to \pi^+\pi^-$

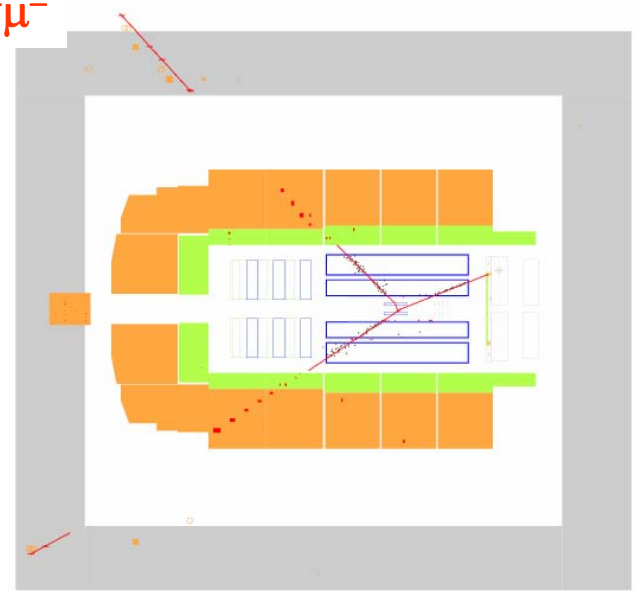




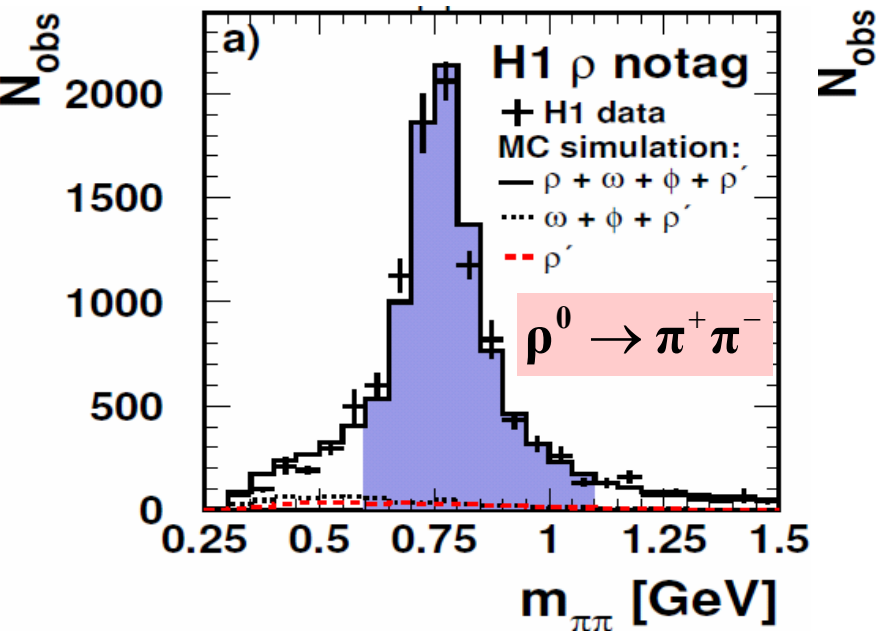
- scattered $e^{\pm}$ reconstructed in e/m calorimeters (DIS) or undetected (photoproduction)
- scattered p undetected
- decay products of VM
- nothing else in the central detector

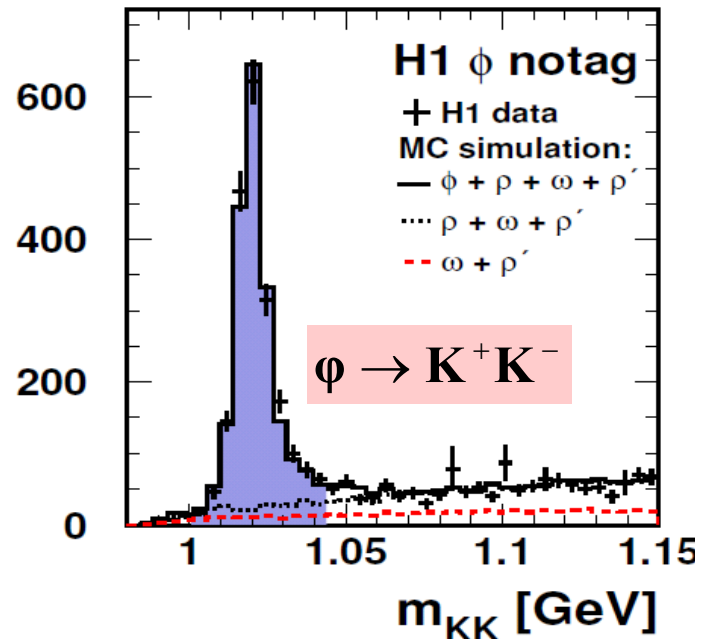
H1: $ep \to e' + J/\Psi + p$, $J/\Psi \to \mu^+\mu^-$

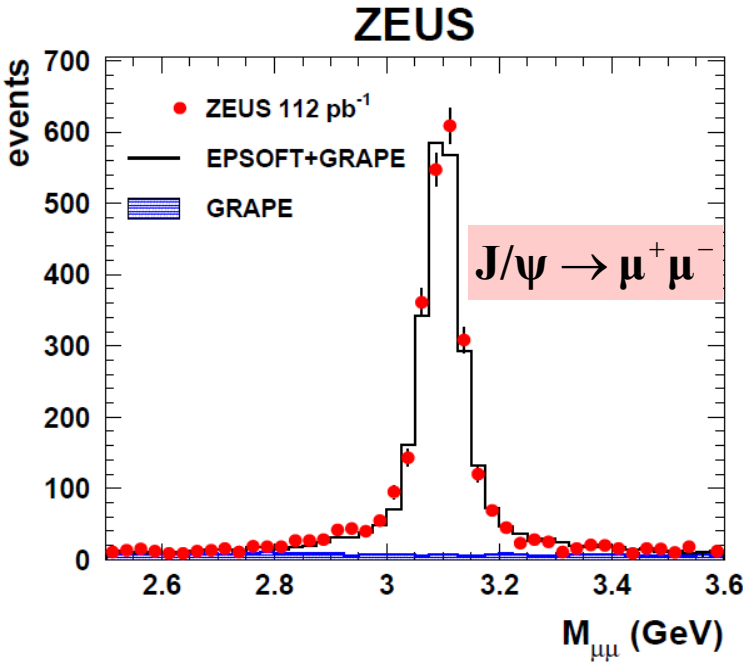


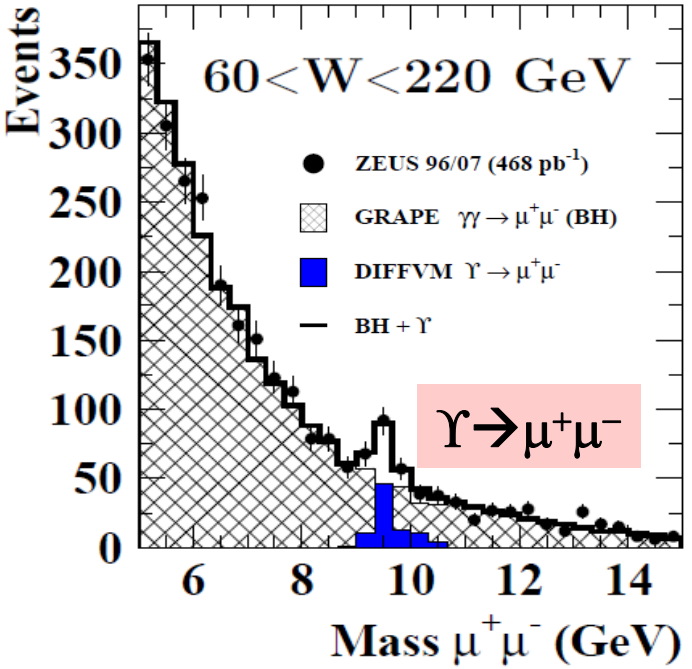


Vector Mesons mass distributions



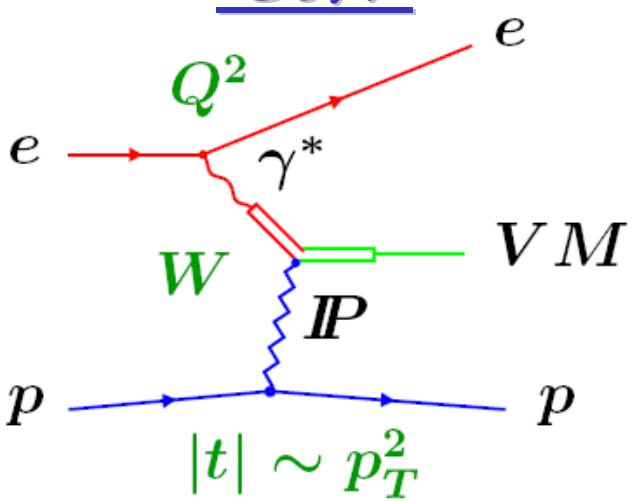






Introduction

"Soft"



Regge theory and VDM model

$\sigma \propto W^{\delta}$ -Weak energy dependence, δ~0.2

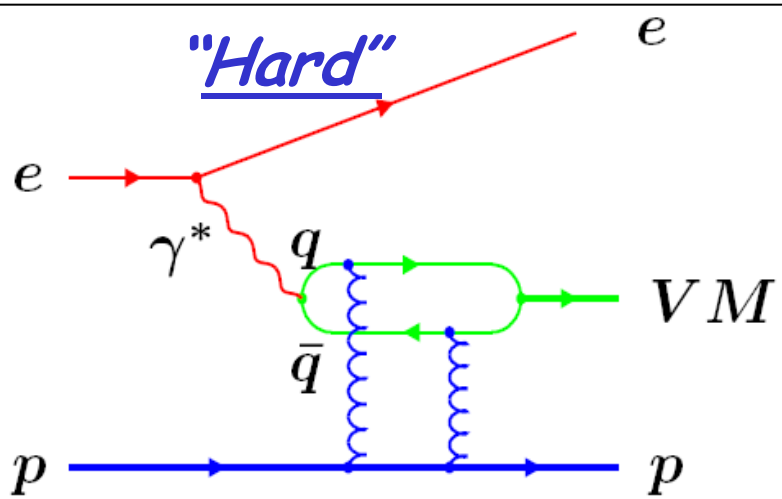
$\delta = 4(\alpha_{IP}(t) - 1)$ $\alpha_{IP}(t)=1.08+0.25 \cdot t$ (DL)

$\frac{d\sigma}{dt} \propto e^{-bt}$ -Shrinkage of diffractive peak

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

(*b* is related to the size of interaction)

"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

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

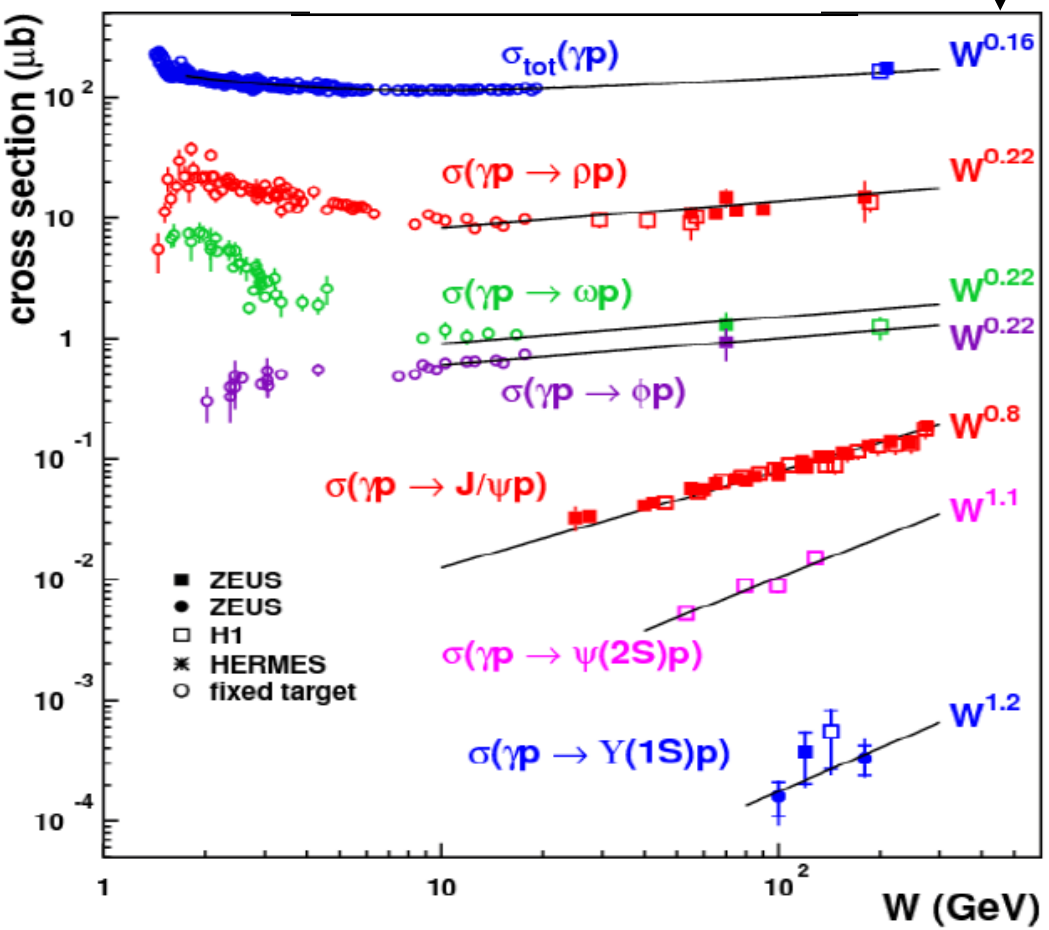
Increasing *W* corresponds to going to small *x* $W^2 \propto \frac{1}{x}$

- Expect δ to increase from 'soft' (~0.2) to 'hard' (~0.8)
- Expect b to decrease from 'soft' (~10 GeV^{-2}) to 'hard' (~4÷5 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 $\sigma(W) \propto W^{\delta}$

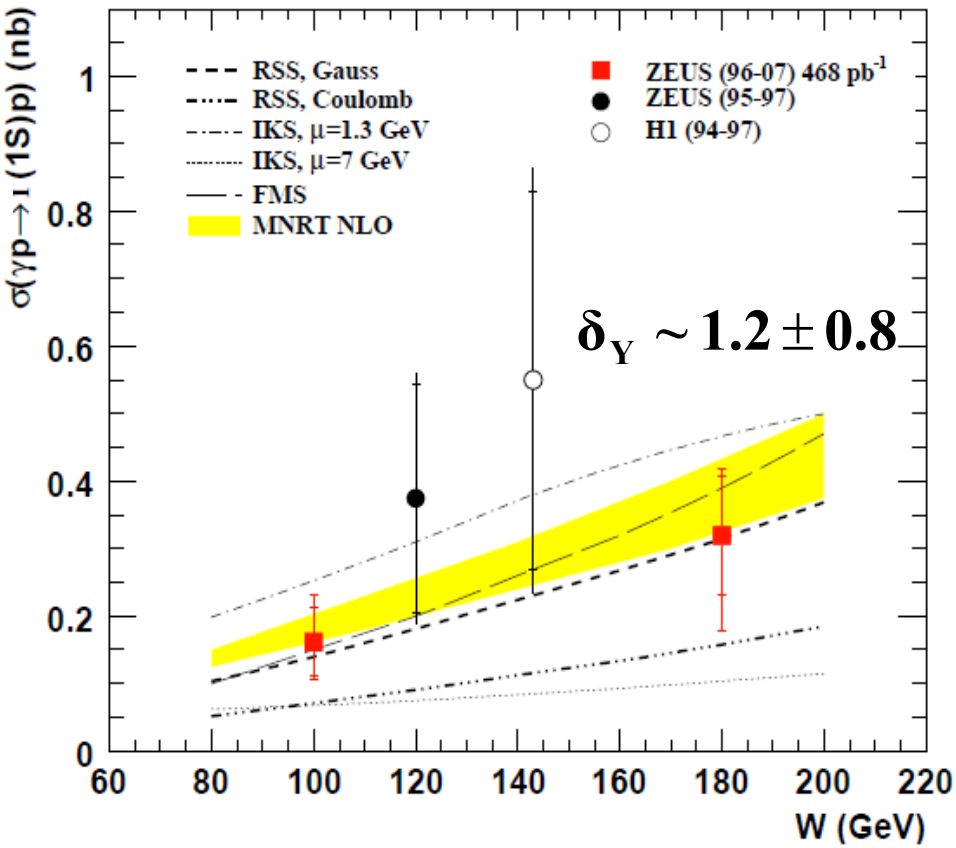


VM mass sets hard scale of interaction

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

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

ZEUS DESY-09-036



- 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

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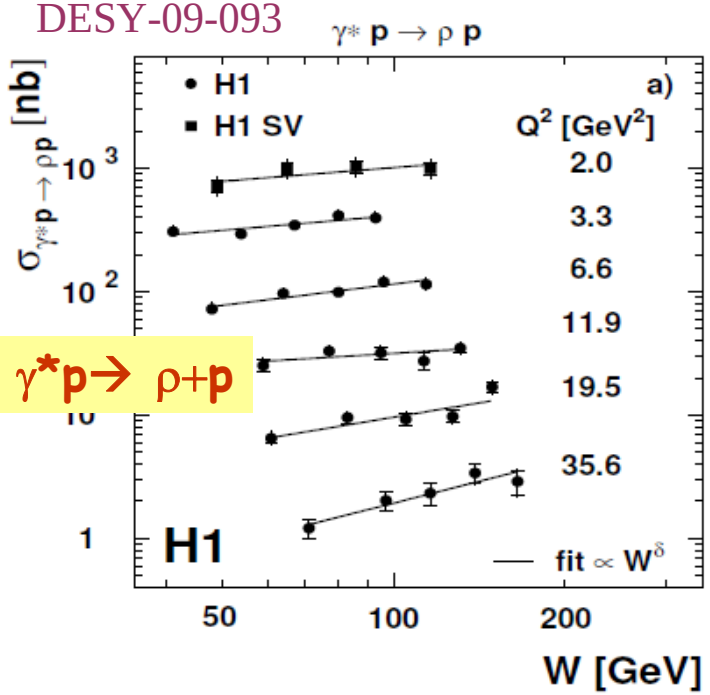
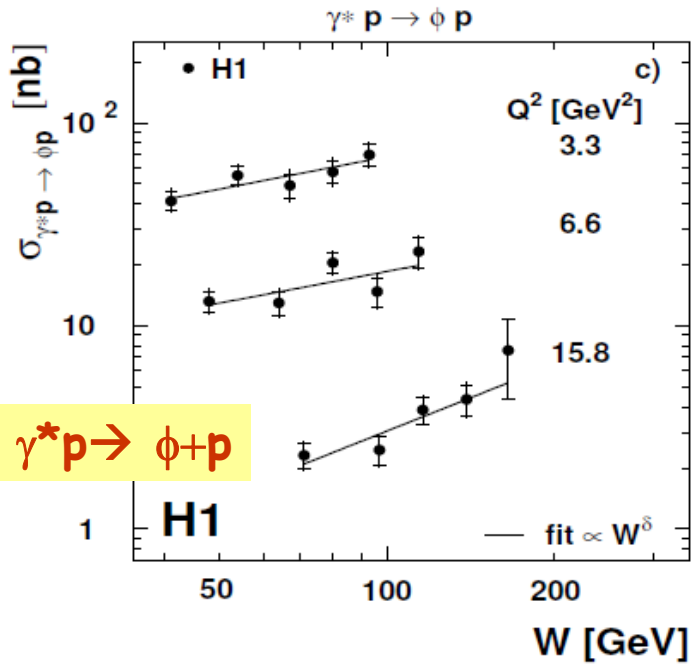
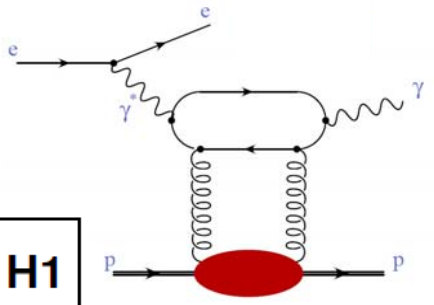


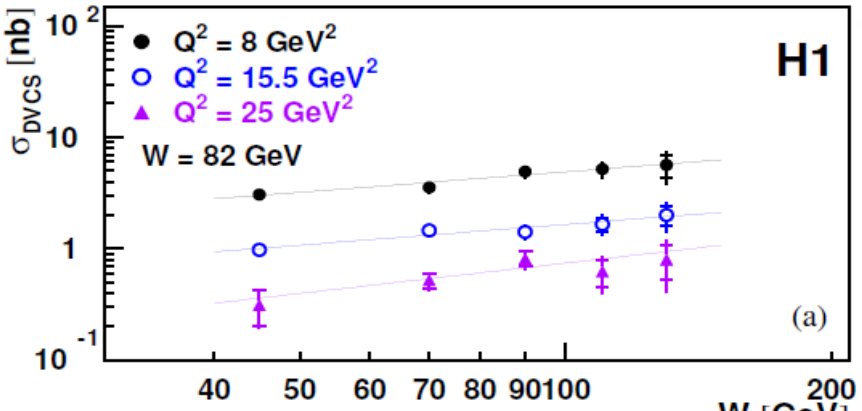
γ*p→ ρ+p



γ*p→ ϕ+p

DVCS (elastic scattering of virtual photon off a proton)





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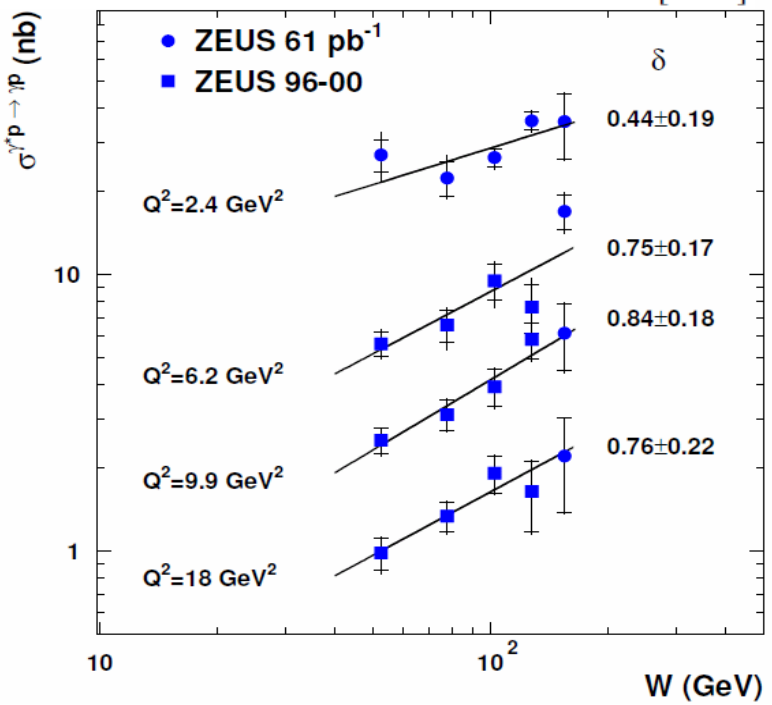
γ*p→ γ+p (DVCS)



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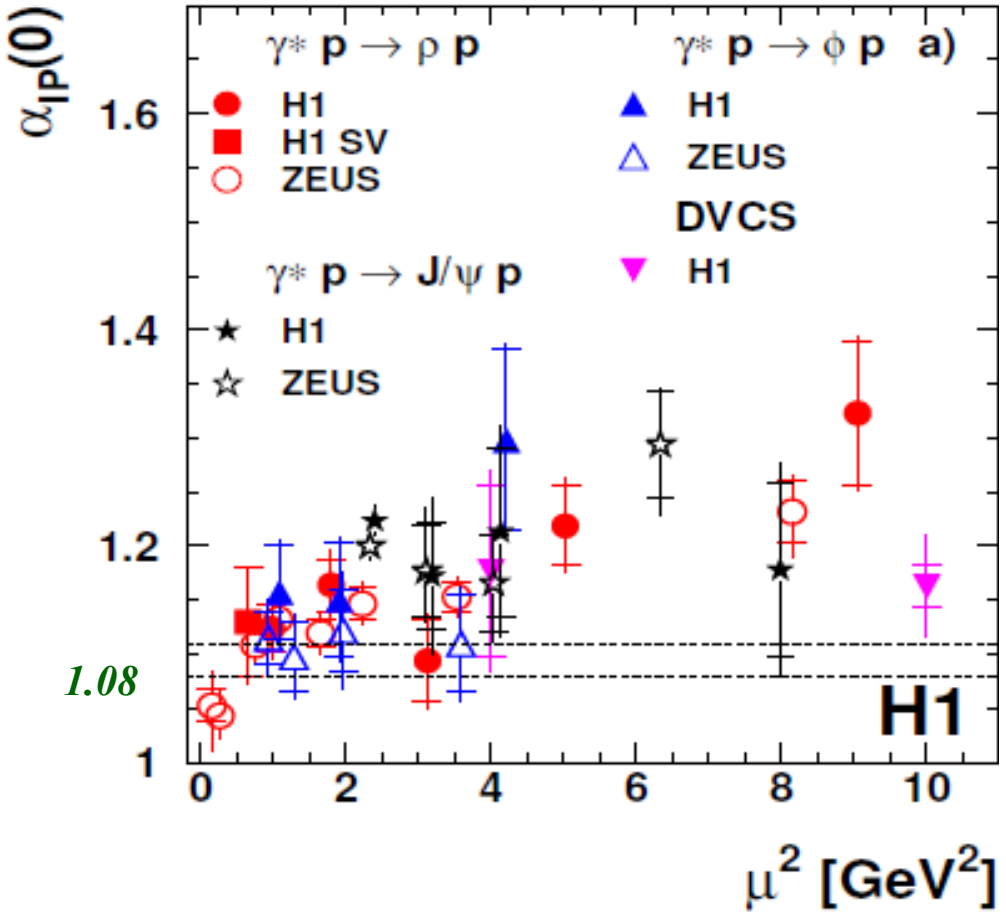
summary: W-dependence



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

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

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

$$\mu^2\ [\mathrm{GeV}^2] = \left(Q^2 + M_V^2\right)/4$$

$$\left(Q^2 \text{ for DVCS}\right)$$

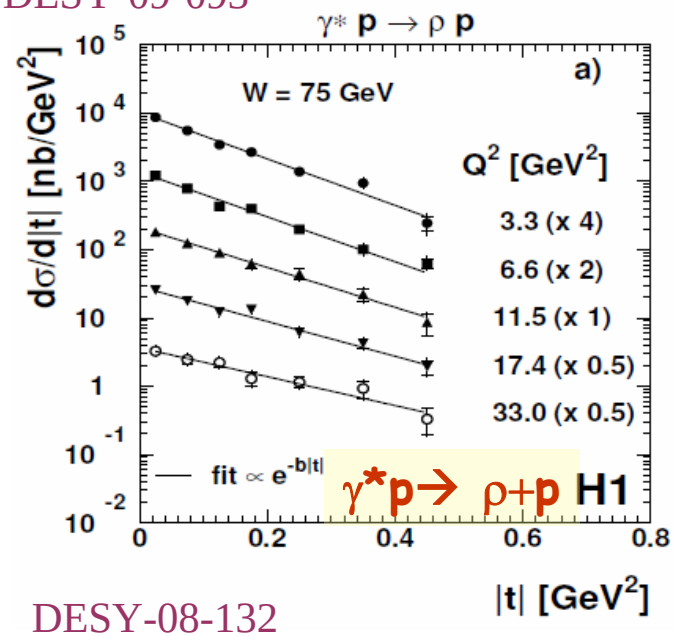
- similar behavior for DVCS and all VMs : common hardening of $\alpha_{IP}(0)$ with μ^2

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

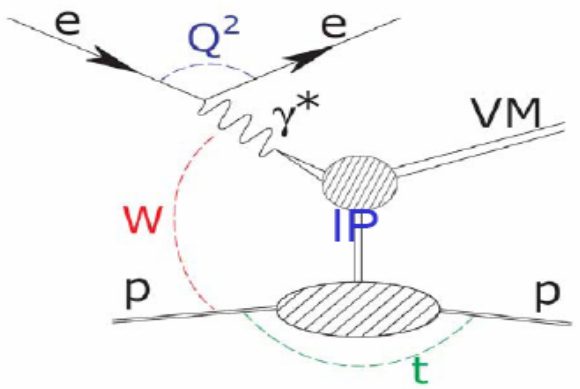
- DVCS shows a 'hard' behavior: steep rise even at lowest Q^2, no significance Q^2 dependence (may suggest that the most sensitive part to soft scale is the VM wave function)

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
  ➔ large dipole for light VM at low Q^2

➔ Transition from soft to hard regime with μ^2

- ***b*** for DVCS - no W dependence

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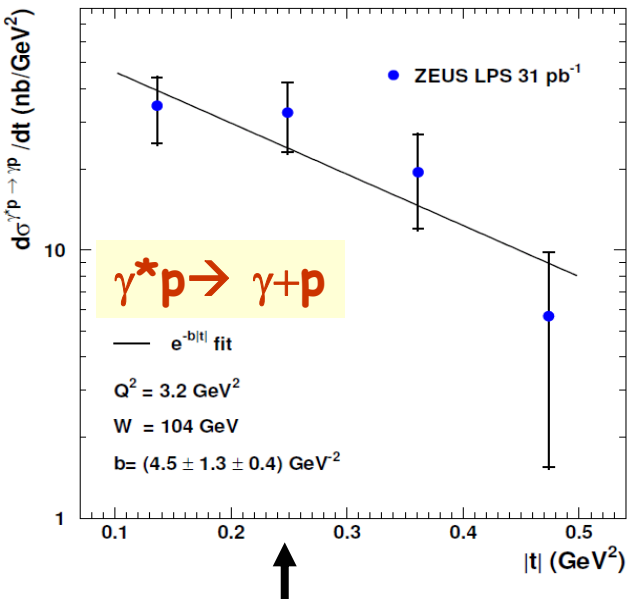

(direct t measurement using Leading Proton Spectrometer)

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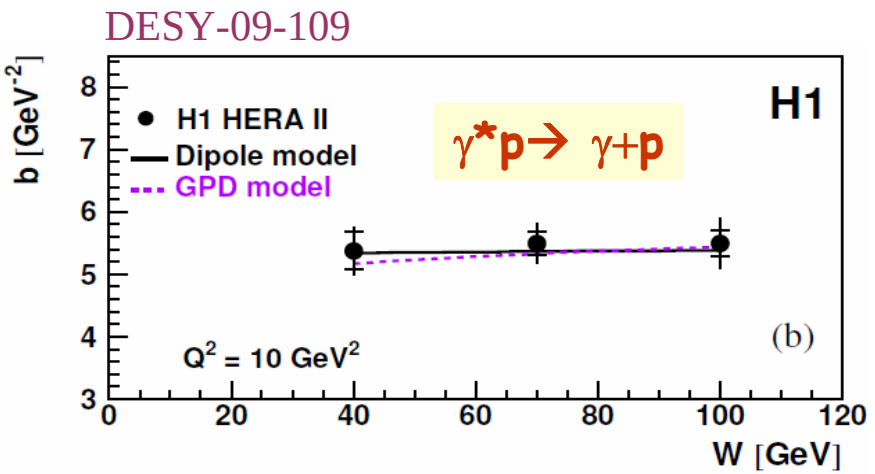
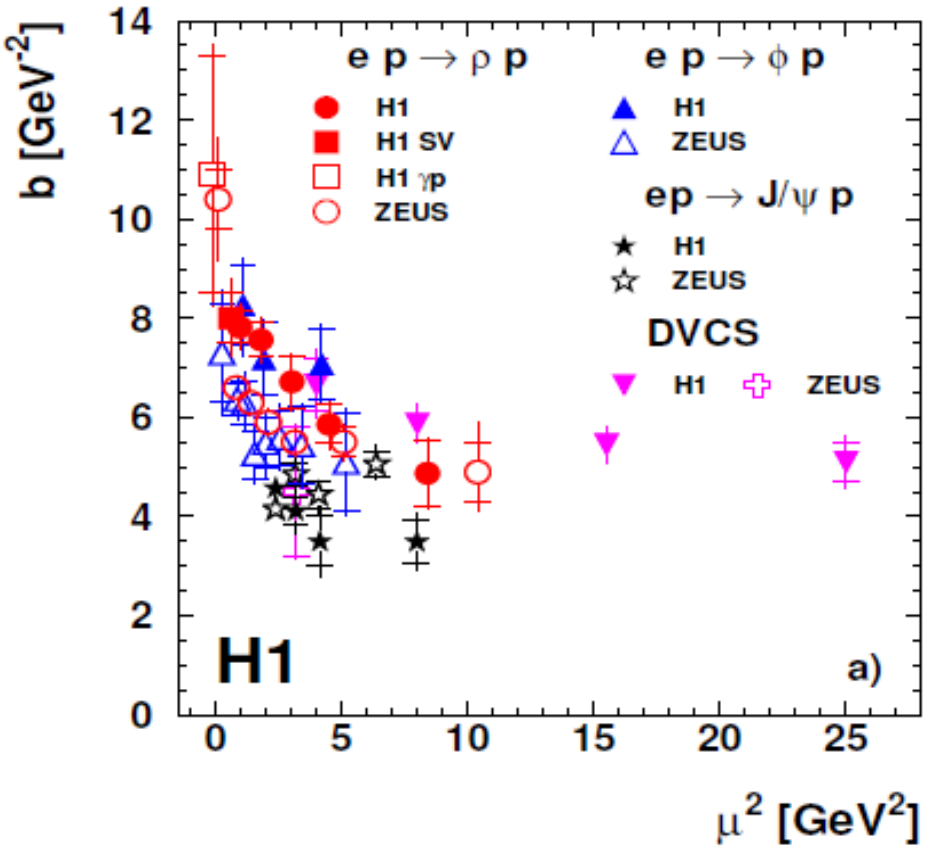


summary: t-dependence



$= \left(Q^2 + M_V^2\right)/4$ (Q^2 for DVCS)

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

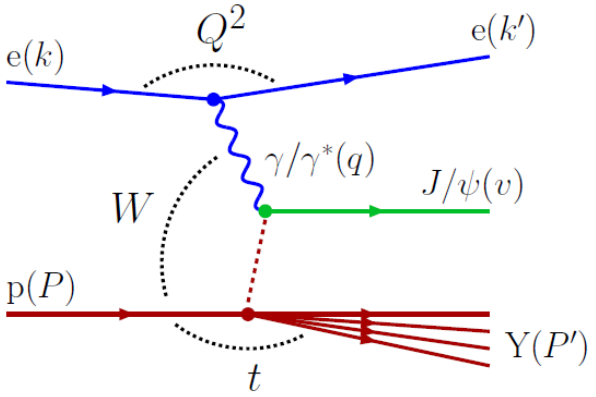
- ***b* decreases with μ^2 from ~10 GeV^{-2} (soft) to ~5 GeV^{-2} (hard process)**

➔ size of scattered VM getting smaller with scale

- for DVCS, b=5.41±0.14±0.31 GeV^{-2} at Q^2=10 GeV^2 (H1)

➔ Average transverse extension of sea quarks and gluons in proton $\sqrt{\langle r^2_T \rangle}$= 0.64±0.02 fm

J/ψ photoproduction at high |t|



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

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

n=-1.9±0.1, 2<|t|<4 GeV²
n=-3.0±0.1, 4<|t|<16 GeV²

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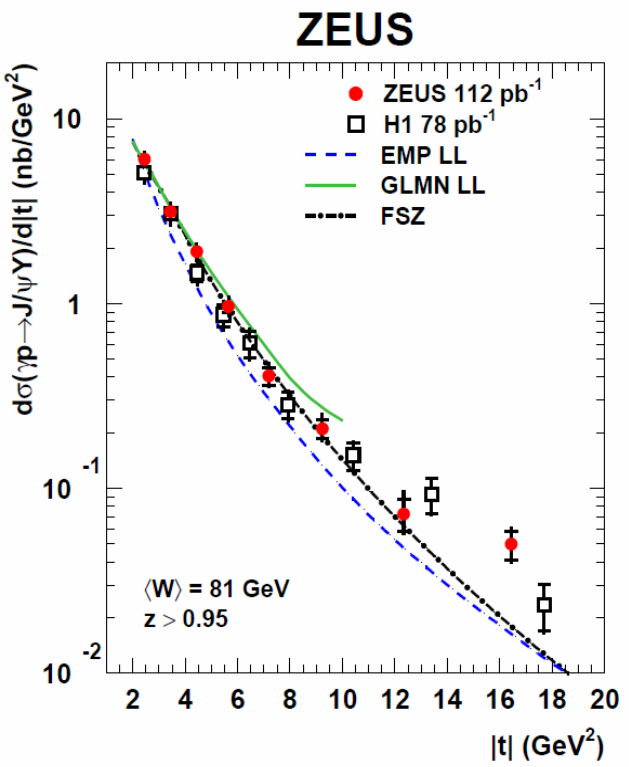
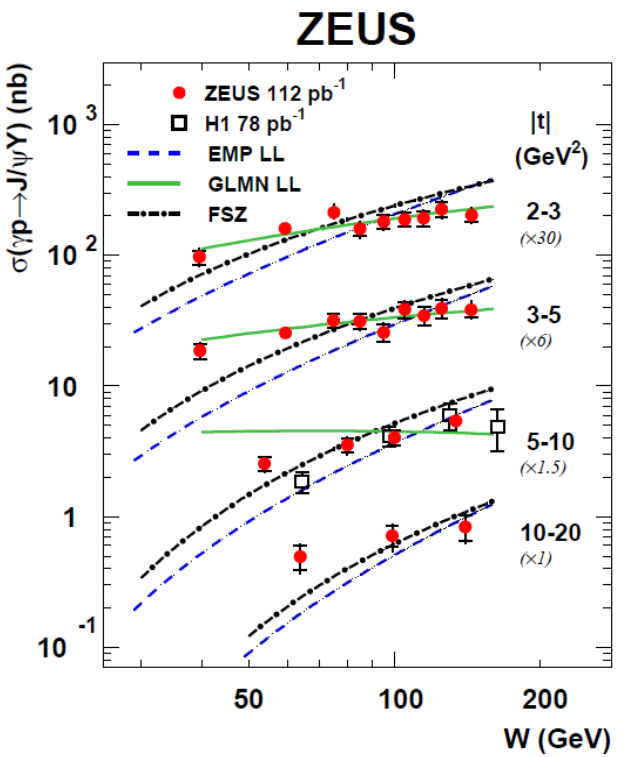




- σ vs W in t ranges: data rise with W for all t
- EMP *(BFKL)* below data
- GLMN *(DGLAP)* fails at |t|>5GeV²
- FSZ *(W dependence of σ depends on the gluon distribution):* describes data up to |t|=12 GeV²
- None of the models describes the data over the full t-range

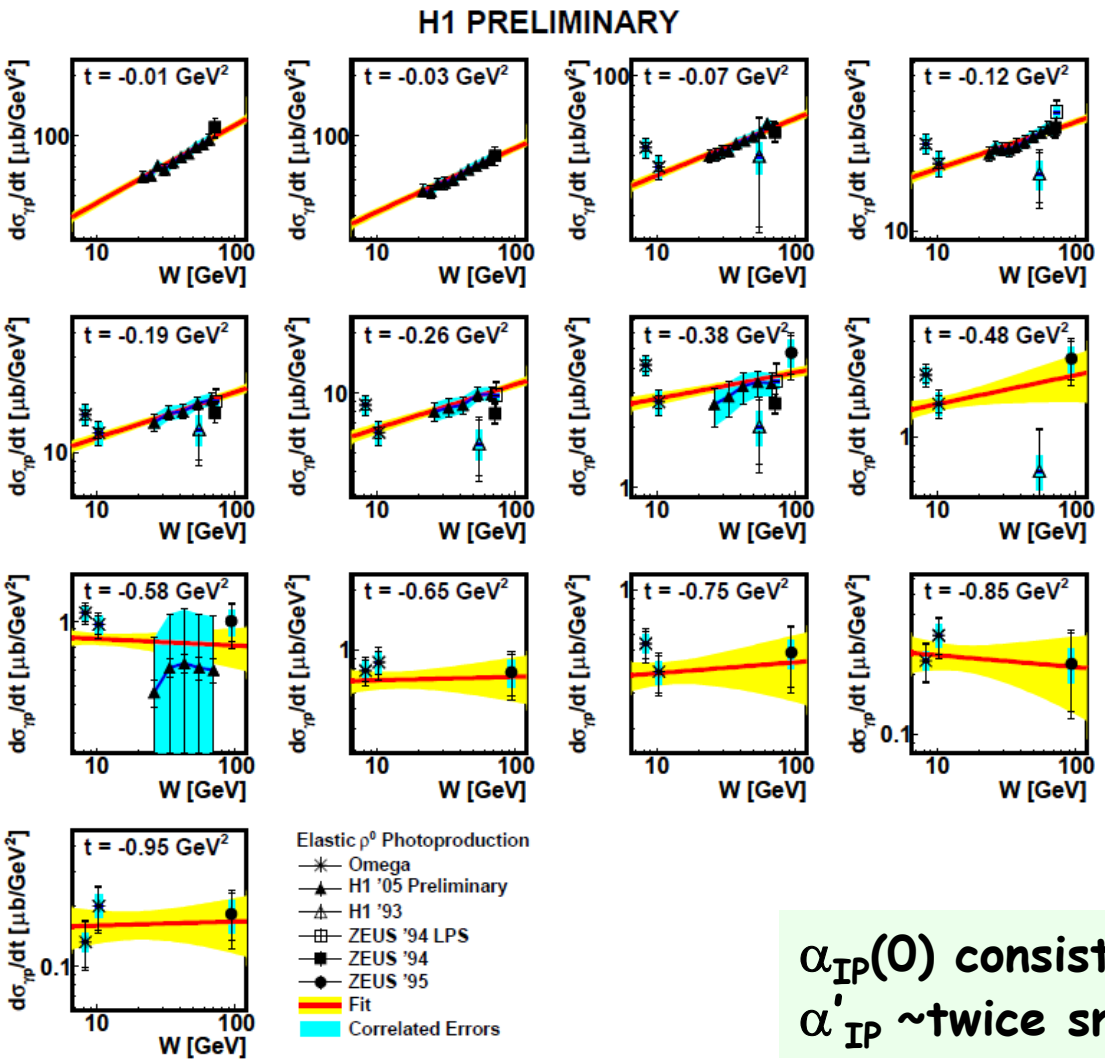
Pomeron trajectory from elastic ρ- photoproduction

H1prelim-09-016

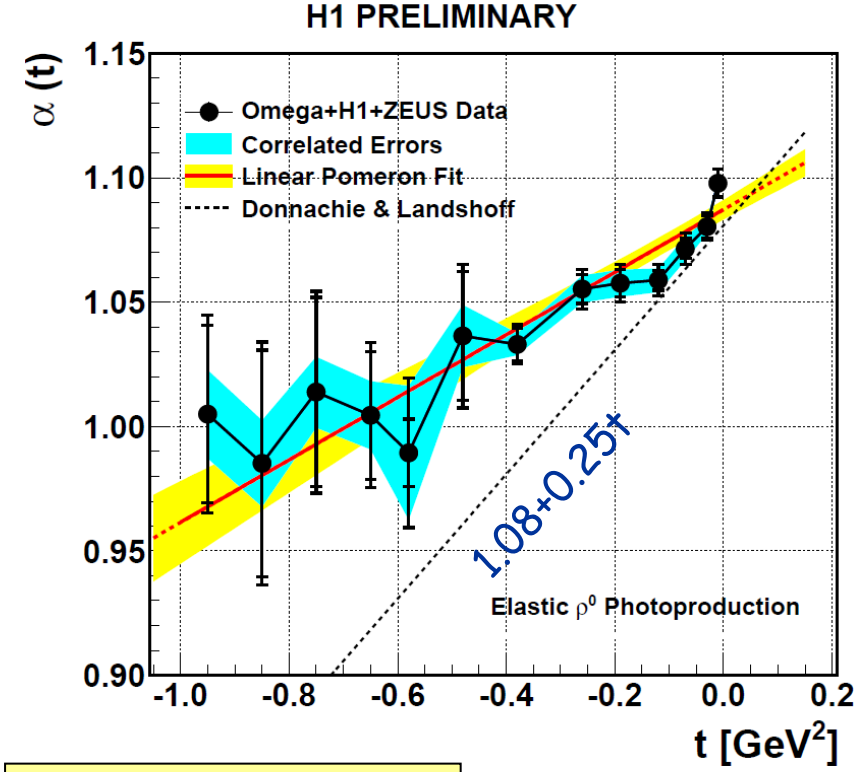
$\gamma p \rightarrow \rho^0 p$: energy dependence of elastic ρ^0-photoproduction at fixed t related to the Pomeron trajectory :

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

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



Result of the fit



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

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

α_{IP}' =0.126 ±0.013(stat)±0.012(sys) GeV^{-2}

$\alpha_{IP}(0)$ consistent with 1.08 from soft $\bar{p}p$ scattering;

α'_{IP} ~twice smaller than 0.25 GeV^{-2}

Summary of α'_{IP} measurements

study W dependence in bins of t

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

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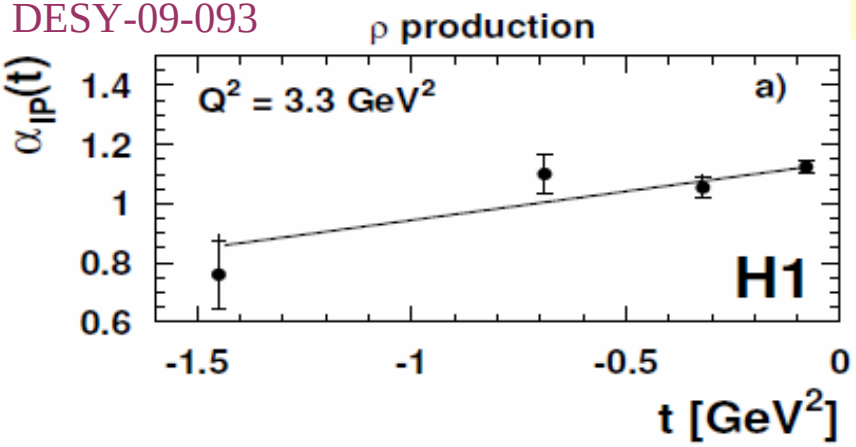

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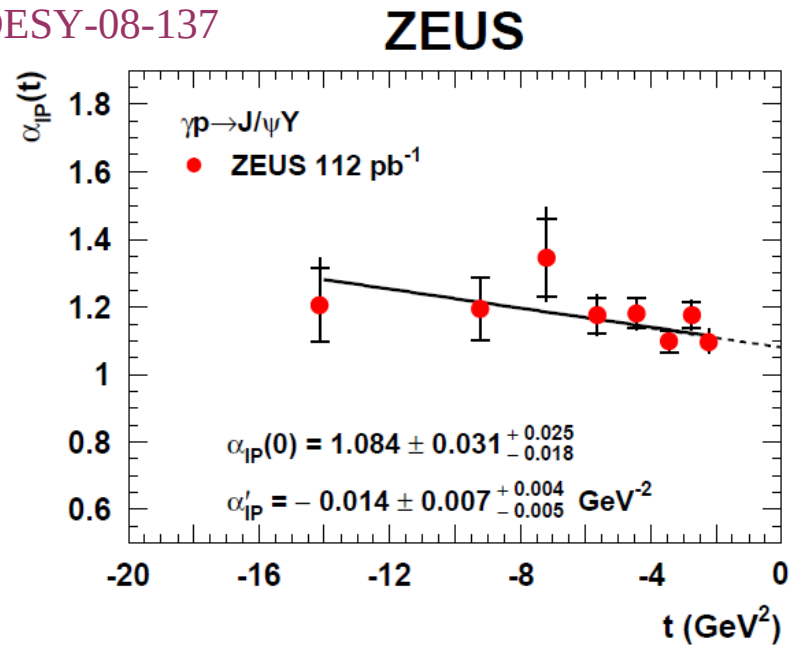
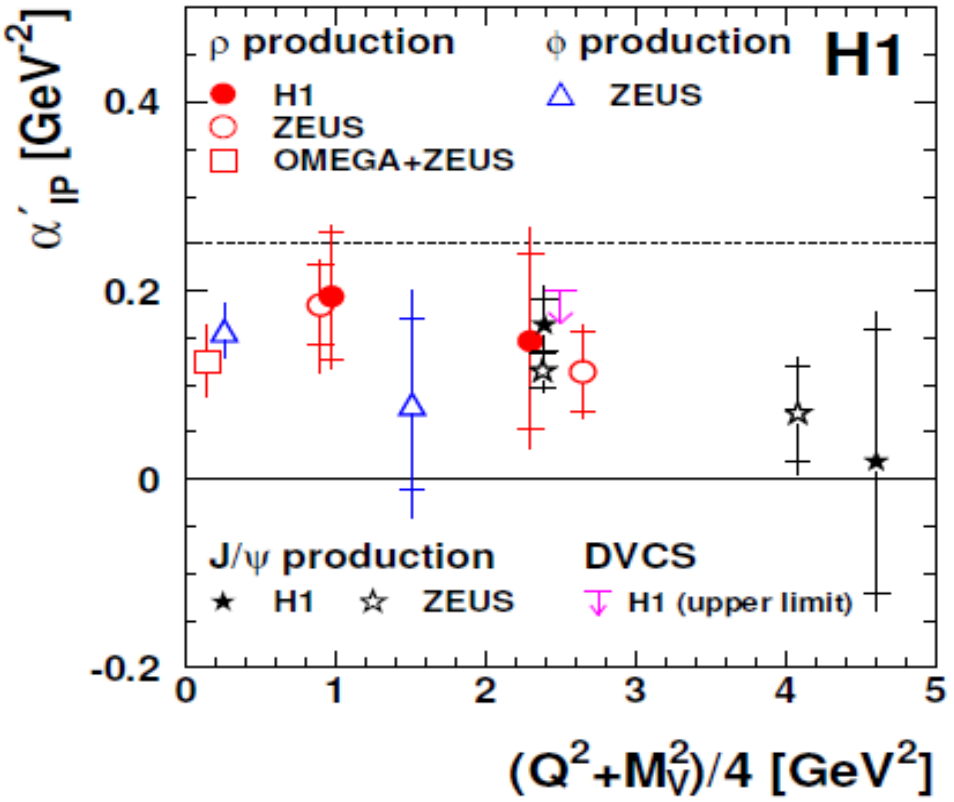
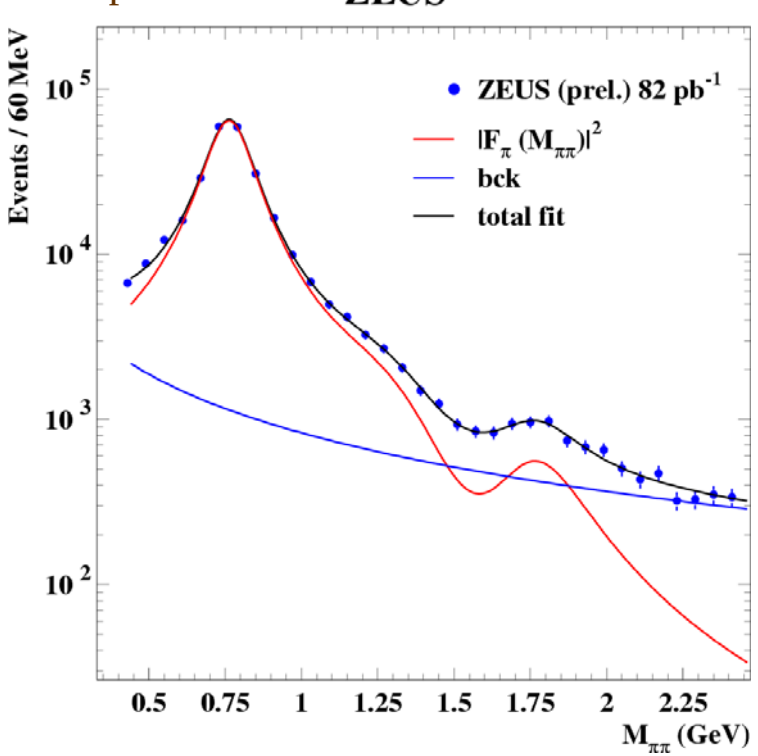




➔For all VM and DVCS α'_{IP} smaller then 0.25

Two pion diffractive electroproduction

ZEUS-prel-10-012



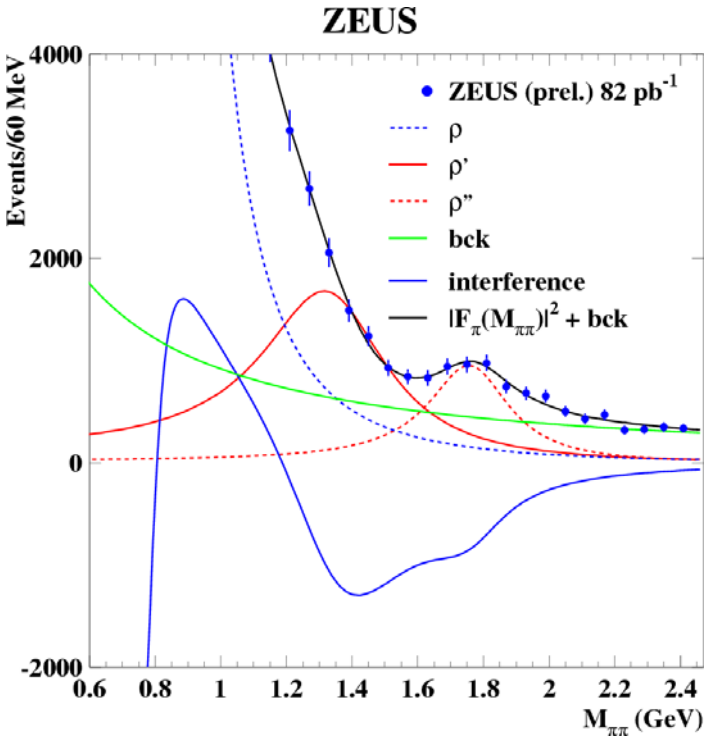
Measure two pion mass distribution $0.4<M_{\pi\pi}<2.4$ GeV in DIS ($2<Q^2<80$ GeV^2)

Fit with 3 resonances: ρ, ρ', ρ''

- $\frac{dN(M_{\pi\pi})}{dM_{\pi\pi}} = N\left[|F_\pi(M_{\pi\pi})|^2 + \frac{B}{M^n_{\pi\pi}}\right]$
- $F_\pi(M_{\pi\pi}) = \frac{BW(\rho)+\beta BW(\rho')+\gamma BW(\rho'')}{1+\beta+\gamma}$ -formfactor

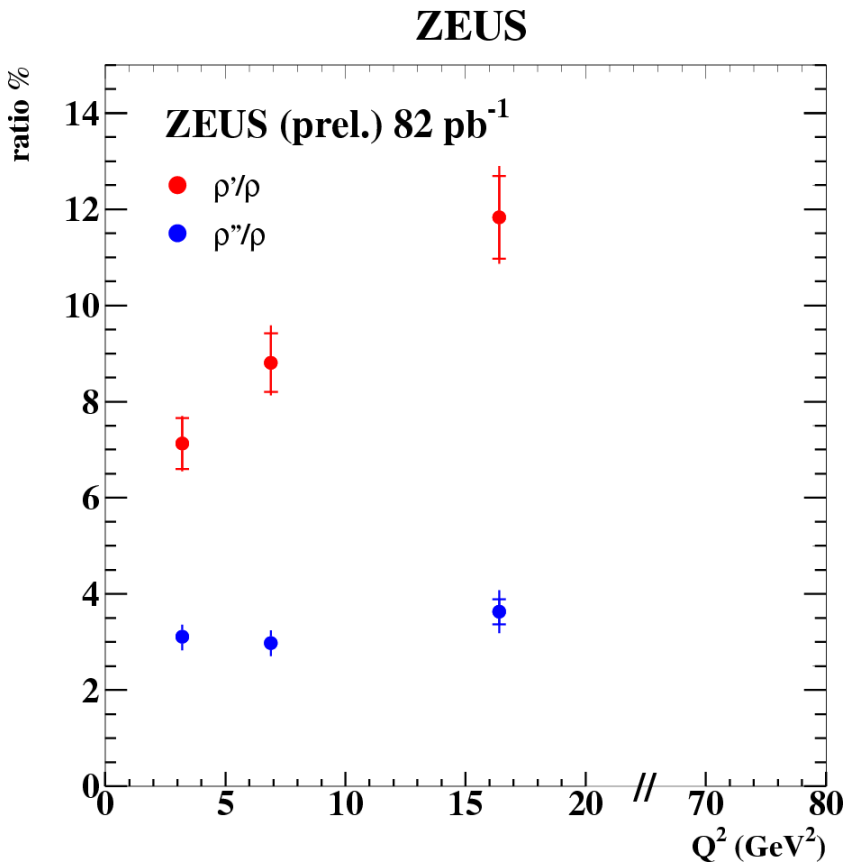
11 parameter fit: N – total normal.factor; B,n-background, M,Γ-masses and widths of ρ,ρ',ρ''; β, γ – relative amplitudes

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 ρ′/ρ, ρ″/ρ

ZEUS-prel-10-012



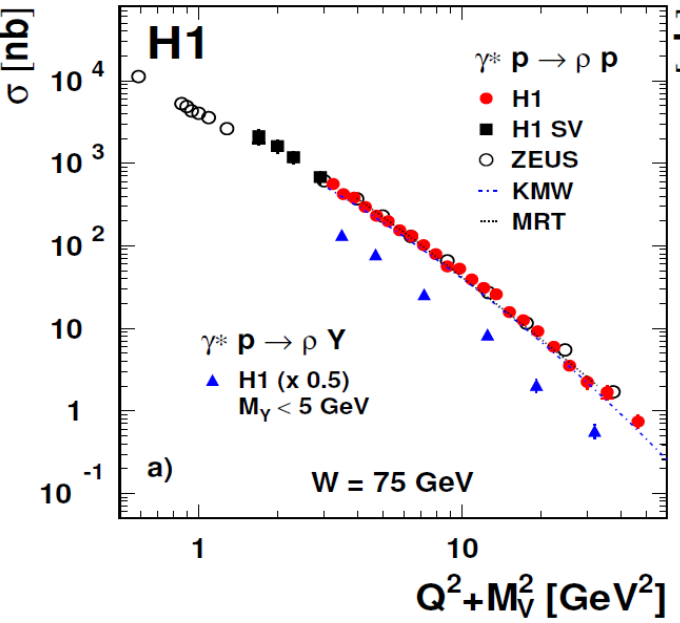
ρ′/ρ – increases with Q^2

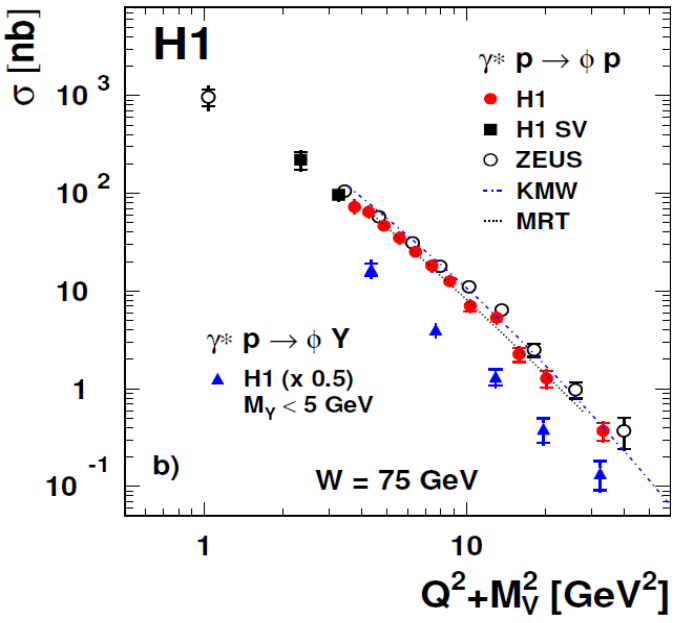
→ consistent with pQCD expectation

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

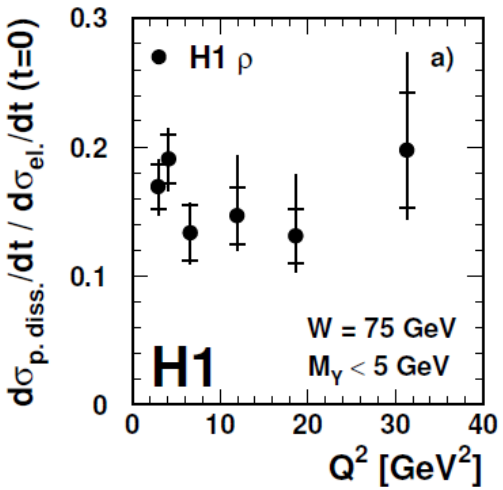


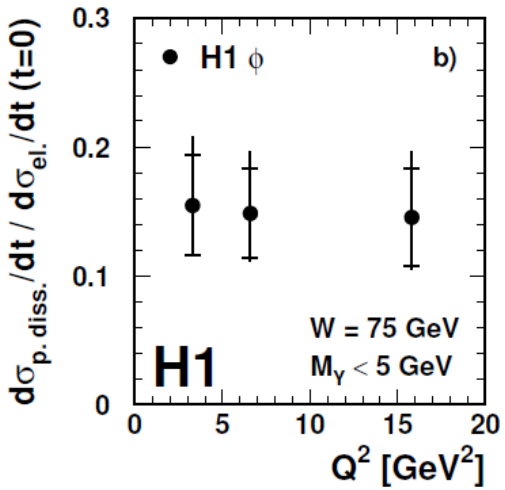


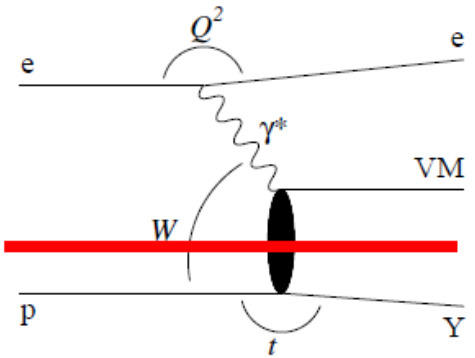
DESY-09-093

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







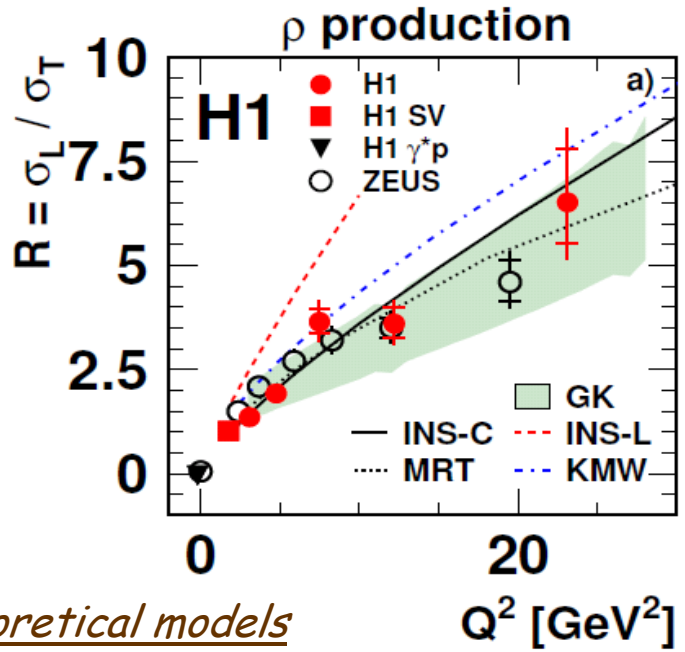
→no Q^2 dependence: support vertex factorization

Elastic ρ-electroproduction: polarised cross sections σ_L, σ_T

QCD expectation: $R=\sigma_L/\sigma_T \sim Q^2/M^2$ ➔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)



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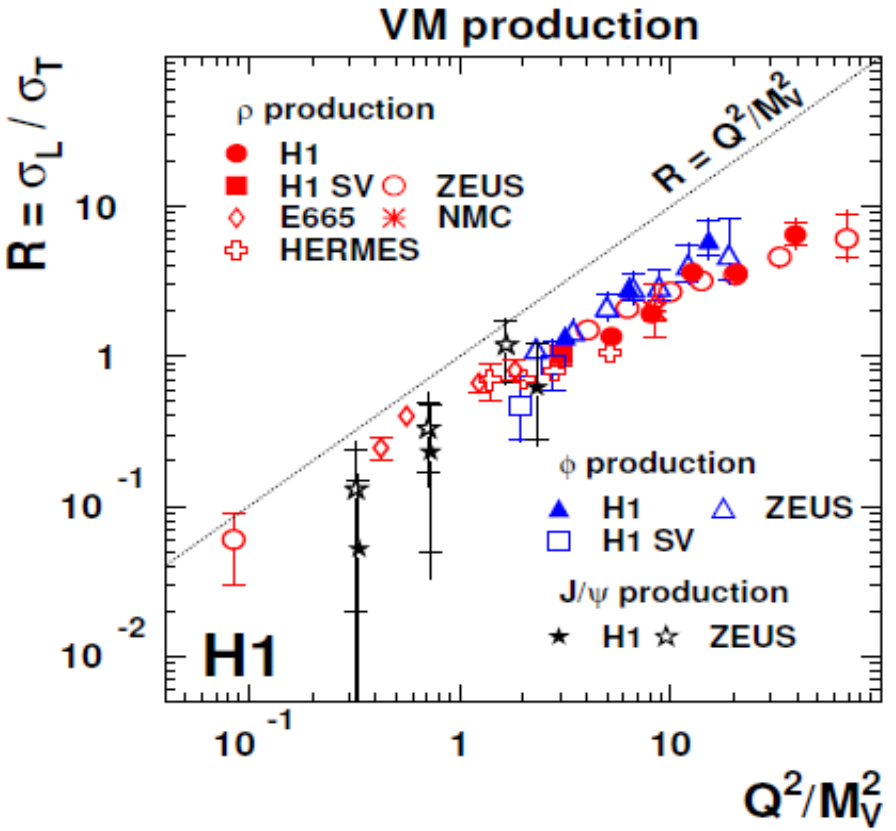

Theoretical models

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 ρ,ϕ,J/Ψ over the full Q^2/M^2 range
- scaling for all VM with Q^2/M^2
- damping at large Q^2

Elastic ρ,ϕ- electroproduction: polarised cross sections σ_L, σ_T

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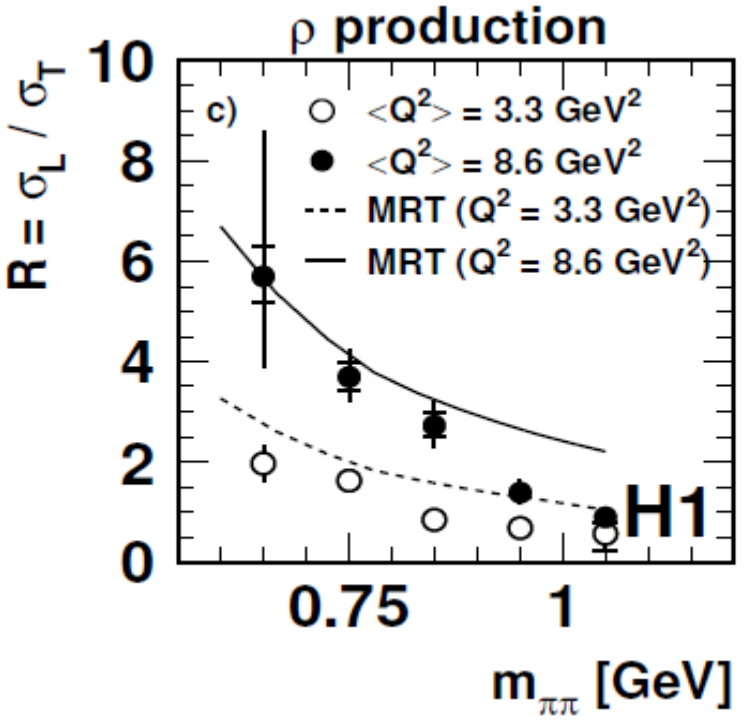
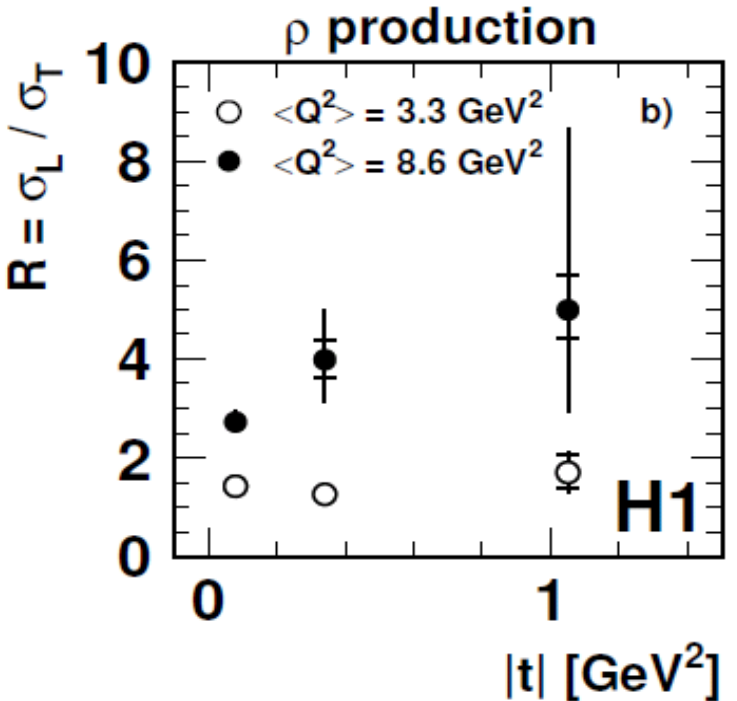




- Strong invariant mass dependence for ρ-meson
- expect from $R \sim (Q^2/M^2)$ behavior, where M is a dipion mass

(cf Martin,Ryskin,Teubner calculations)

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

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

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

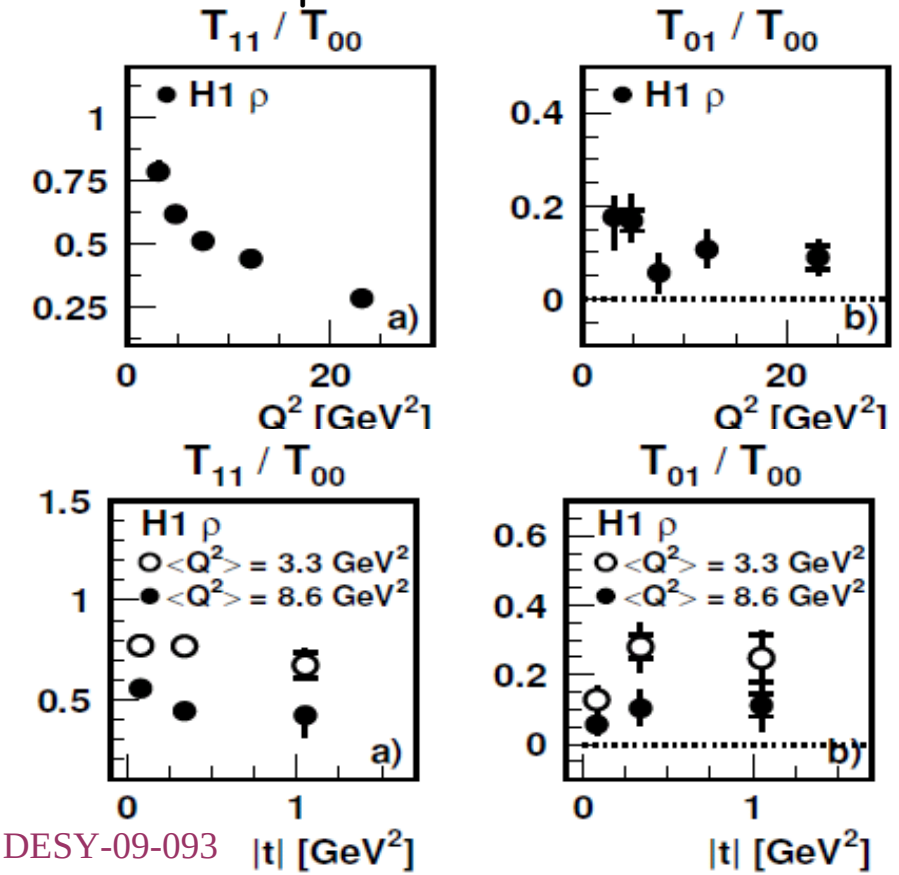
- expect smaller dipole in σ_L at higher Q^2 →harder QCD regime reached
- large dipoles present in σ_L at lower scales

ρ: helicity amplitude ratios vs Q^2 and t

Extract 15 Spin Density Matrix Elements r^{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} : $\gamma_L \to \rho_L$; T_{11}: $\gamma_T \to \rho_T$ **Single flip**: T_{01}: $\gamma_T \to \rho_L$; T_{10}: $\gamma_L \to \rho_T$
Double flip: T_{1-1}: $\gamma_T \to \rho_T$

- **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→ helicity flip between photon and meson is possible



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- $|T_{11}|/|T_{00}|$ decreases with Q^2
  → σ_L/σ_T increases with Q^2
  decreases with t
  → 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 $|T_{-11}|/|T_{00}|$ are small

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

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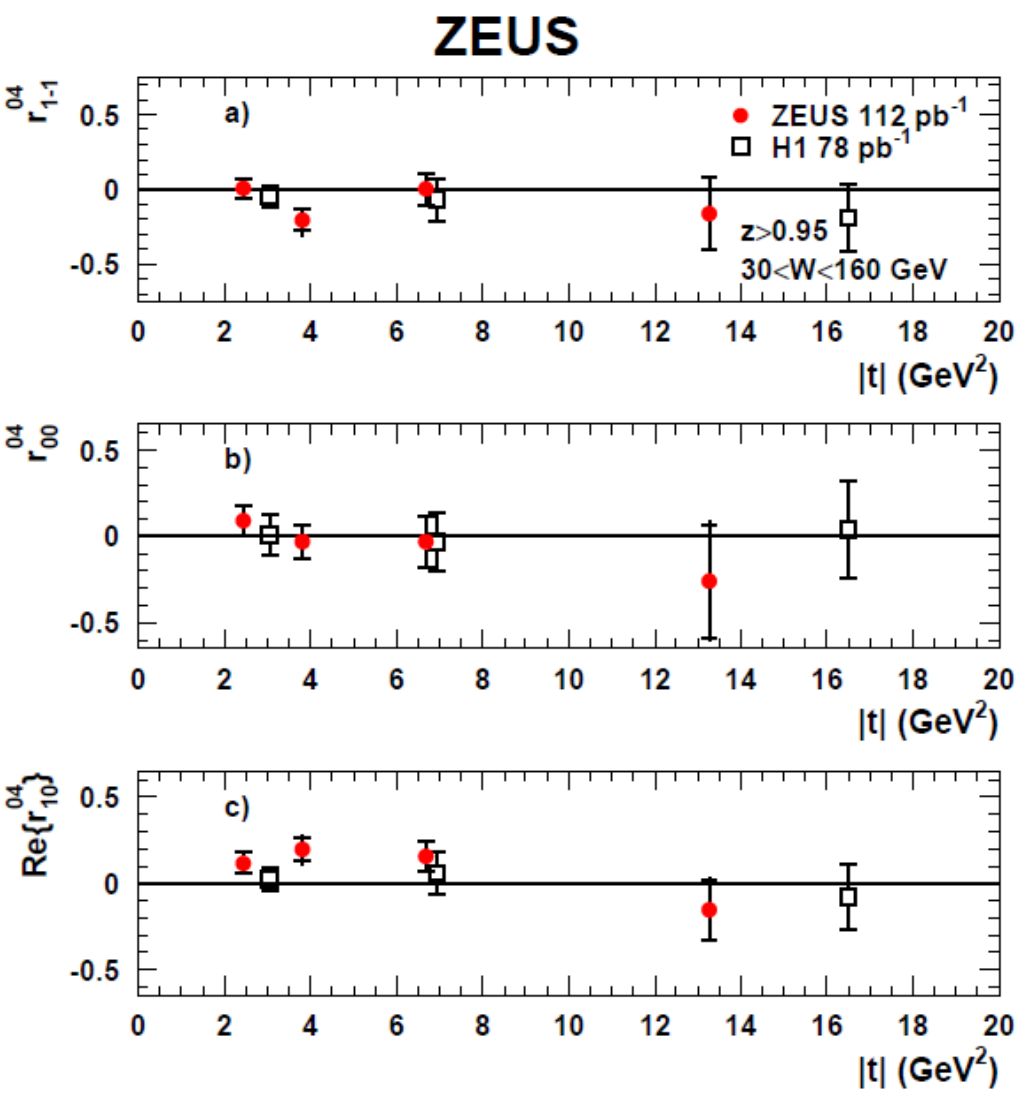
Helicity spin density matrix elements as a function of t



- SDME r^{ij}_{kl} extracted from fit to the decay angular distributions

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

- r^{04}_{00} represents the probability that J/Ψ has 0 helicity
  ➔compatible with 0, as expected for in SCHC

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

DVCS: Beam Charge Asymmetry (BCA)

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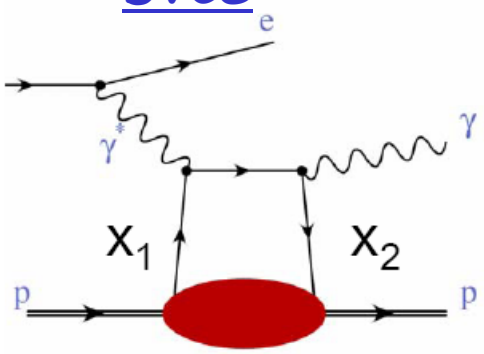
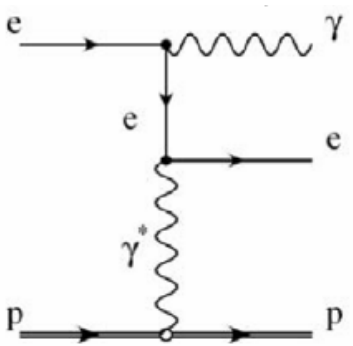
DVCS

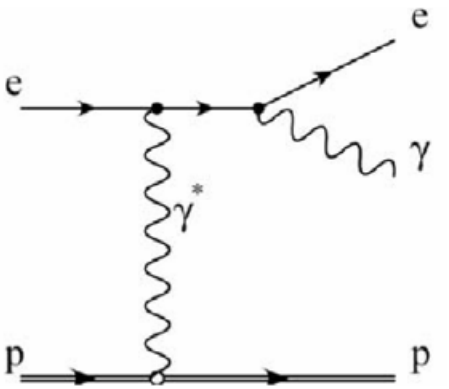


DVCS gives access to Generalized (skewed) Parton Distributions (GPD), which describe the correlations between two partons (x_1,x_2) which differ by longitudinal ($x_1 \neq x_2$) and transverse (t) momentum at given Q^2

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



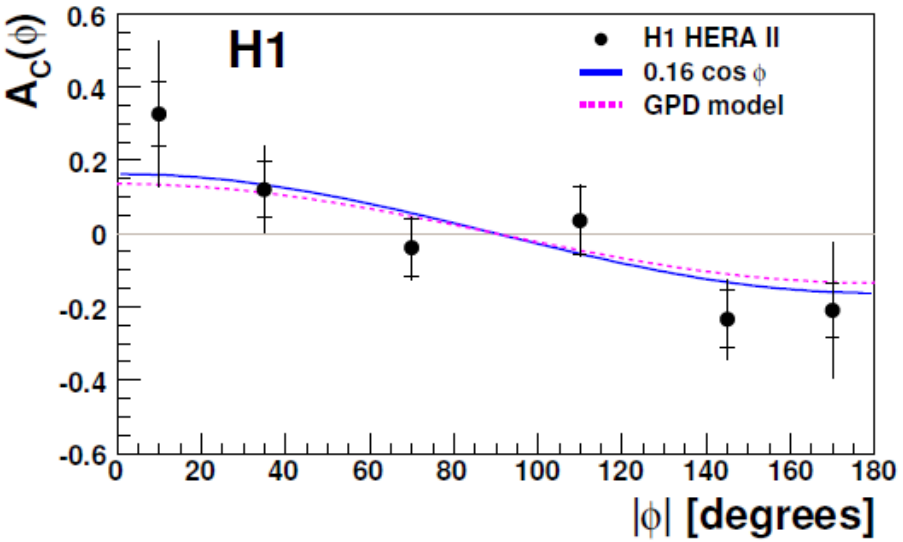
BH

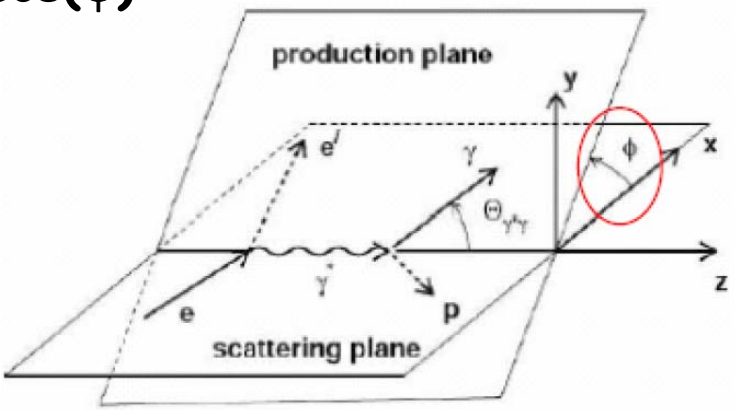


$|A|^2=|A_{DVCS}|^2+|A_{BH}|^2+|A_I|^2$ ← interference term

Beam Charge Asymmetry: $A_C(\varphi)=\dfrac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto \mathrm{Re}(A_{DVCS})\cdot\cos(\varphi)$

Related to GPD





$\rho=\mathrm{Re}\,A_{DVCS}/\mathrm{Im}\,A_{DVCS}=0.20\pm0.05\pm0.08$

GPDs based model compatible with data

Conclusions

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

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

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

$$\mathrm{Re}\, r^{04}_{10} = \frac{1}{1+\varepsilon R}\mathrm{Re}\left[\frac{1}{2N_T}\left(T_{11}T^{\dagger}_{01}+T_{1-1}T^{\dagger}_{0-1}\right)+\frac{\varepsilon \bar{R}}{N_L}T_{10}T^{\dagger}_{00}\right]$$

$$R = \frac{N_L}{N_T}, \quad N_L = |T_{00}|^2+|T_{10}|^2+|T_{-10}|^2$$

$$N_T = \frac{1}{2}\left[|T_{11}|^2+|T_{-1-1}|^2+|T_{01}|^2+|T_{0-1}|^2+|T_{-11}|^2+|T_{1-1}|^2\right]$$

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