Vector meson production at HERA

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(on behalf of the H1 and ZEUS collaborations)

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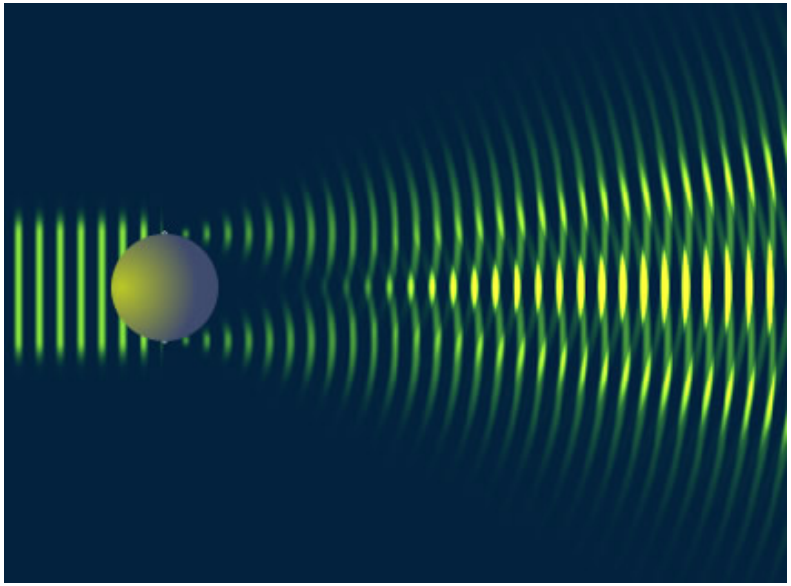
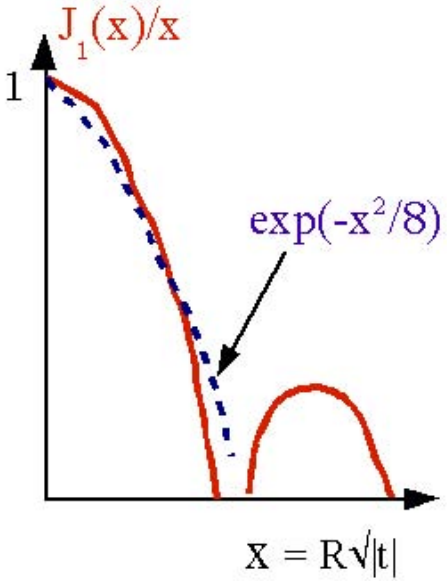
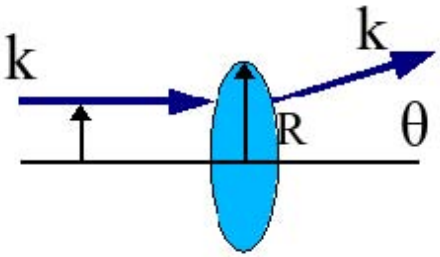
Outlook

- Introduction
  - H1 and ZEUS detectors
  - Kinematics
- Theory of exclusive photo- and electroproduction of Vector Mesons and Deeply Virtual Compton Scattering (DVCS)
- Overview of H1/ZEUS experimental results:
  - W dependence
  - Q^2 dependence
  - t dependence
  - Beam Charge Asymmetry in DVCS
- Effective Pomeron Trajectory
- Summary

Diffraction of Light



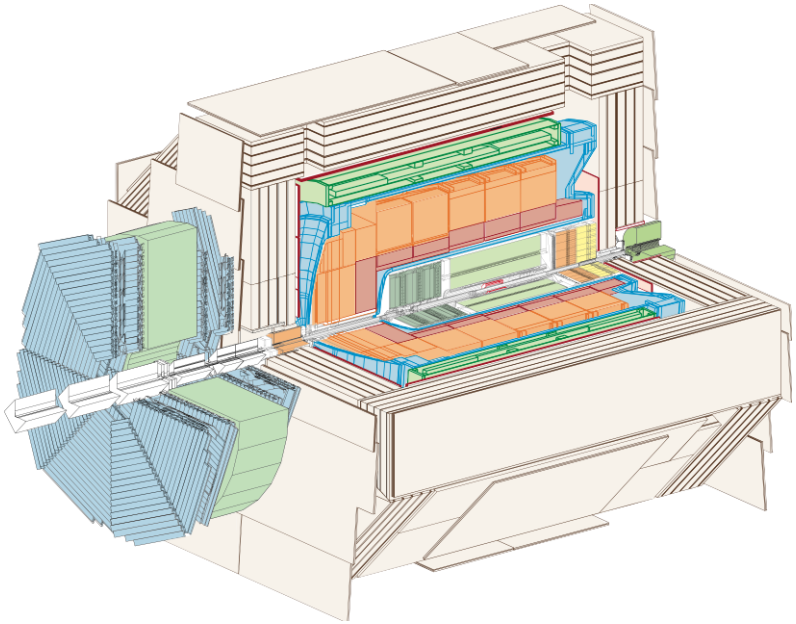


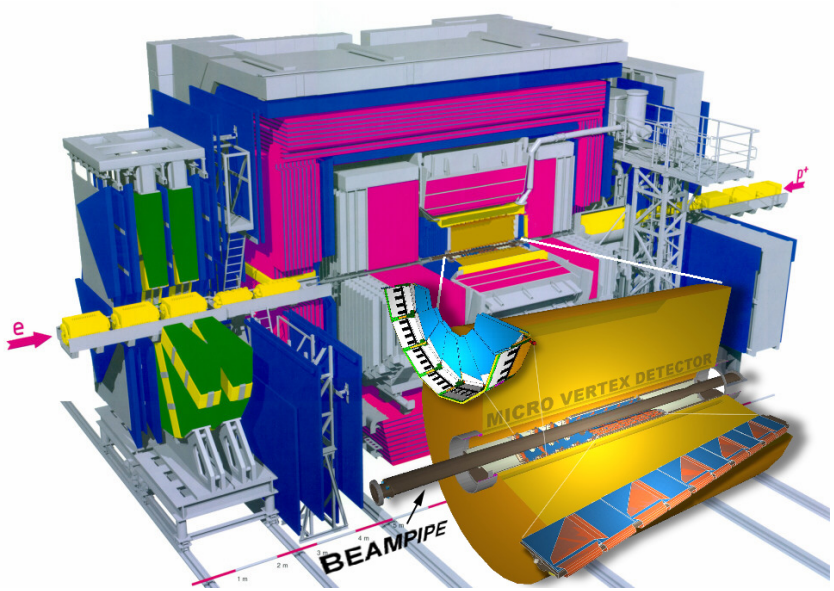


Light Scattering in Fraunhofer approximation ($\lambda \sim 1/k << R$)

- $|t| = 4k^2 sin^2(\theta/2)$
- $d\sigma/dt \sim e^{-b|t|}$ (first diffractive peak approximated from Bessel function)
- $b = (R/2)^2 \rightarrow$ transverse size of the target

H1 and ZEUS Detectors at HERA *ep* Collider in DESY (Hamburg)



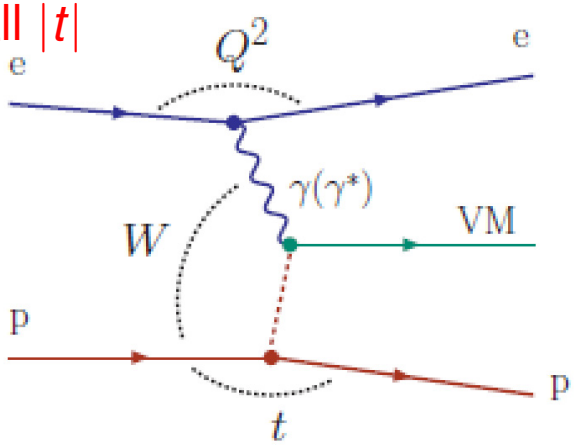


- detectors optimised for asymmetric HERA beams
- equipped with microvertex, central/forward trackers, EMC/Hadron CAL instrumented Iron Yoke, Muon detectors, (very) forward/backward detectors in the tunnel for proton/neutron tagging and lumi measurement
- HERA II: ZEUS $\rightarrow$ MVD, H1 $\rightarrow$ fast track trigger

- HERA operated in years 1992-2007 in e^+p and e^-p modes
- $E_e = 27.5$ GeV, $E_p = 820 - 920$ GeV, $E_{CMS} = 300 - 318$ GeV
- collected $\int L \sim 500$ pb^{-1} per experiment

Production of Vector Mesons in *ep* Scattering and DVCS process

exclusive (elastic)
small $|t|$



VM - Vector Meson : $\rho, \omega, \phi, J/\psi, \psi', \Upsilon$ (or real γ for **DVCS**)

Kinematics:
$Q^2 = -q^2 = -(k - k')^2$ - photon virtuality
$W = \sqrt{(q + P)^2}$ - c.m. energy of the $\gamma^* p$ system
$t = (P - P')^2$ - 4-momentum transfer squared at the proton vertex
M_{VM} - mass of the produced Vector Meson

$\rightarrow$ VM at HERA: transition from the soft to the hard regime
$\rightarrow$ access to different scales of :
$M^2_{VM} \in (0 \div 10)\ GeV$, $Q^2 \in (0 \div 100)$ GeV^2, $W \in (20 \div 300)$ GeV, $|t| \in (0 \div 30)$ GeV^2

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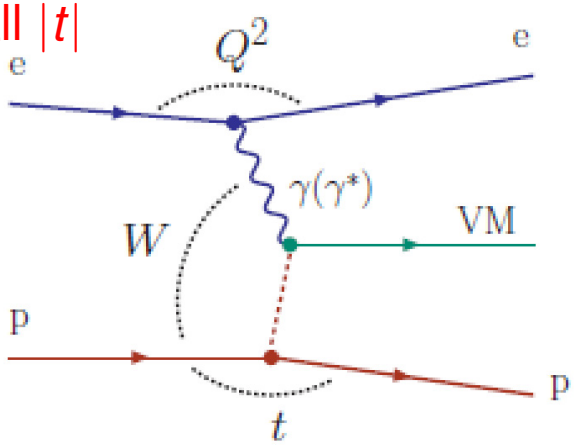
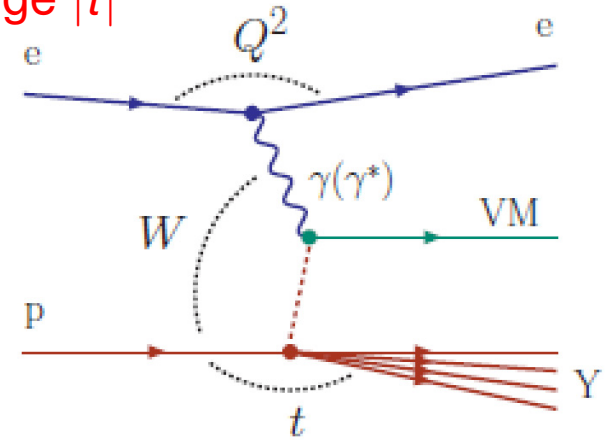


proton dissociative
large $|t|$



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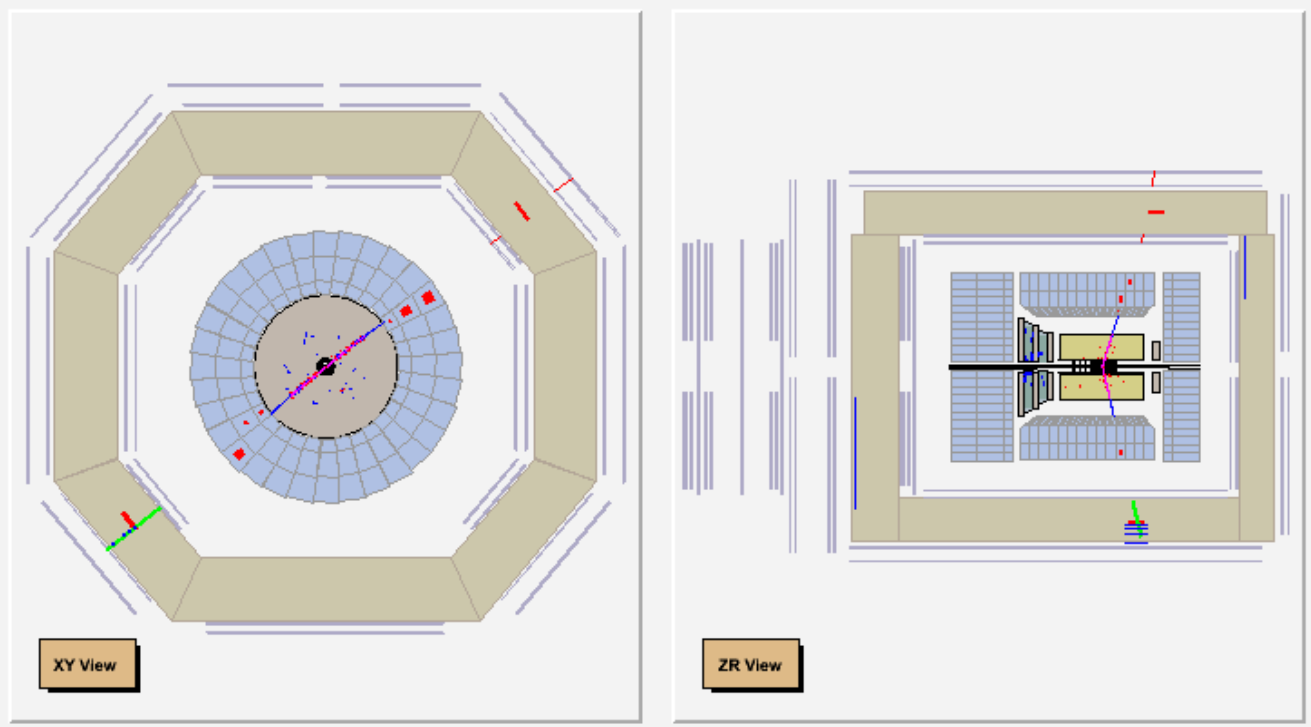
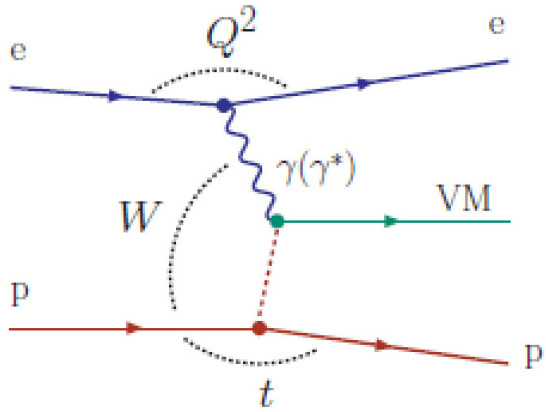
Example of Final State Topology for $ep \to \Upsilon p$, $\Upsilon \to \mu^+\mu^-$





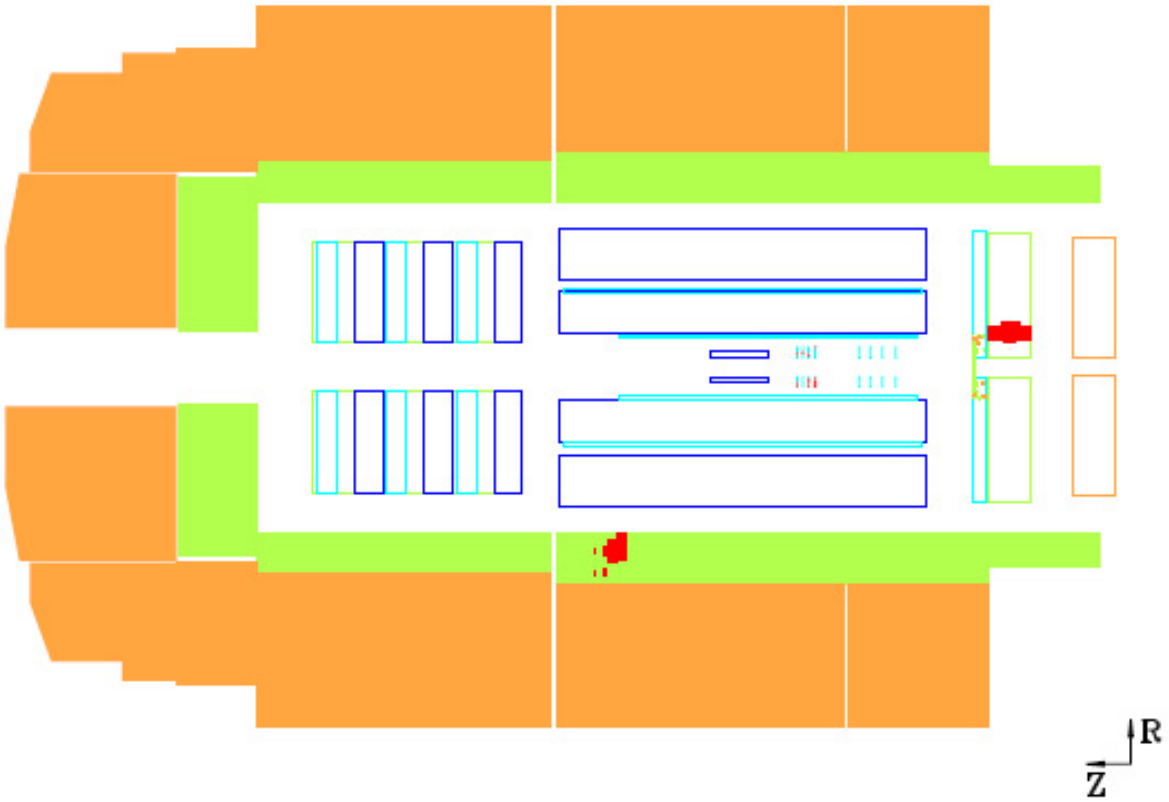
Exclusive process, reaction mediated by exchange of colourless object;
proton stays intact.

VM are detected in the two-body decay channel ($\pi^+\pi^-, e^+e^-, \mu^+\mu^-, \ldots$)
very clean final state topology:

Photoproduction ($Q^2 < 1$ GeV^2): two charged particles and nothing else
Electroproduction ($Q^2 > 1$ GeV^2): scattered electron also visible in the detector

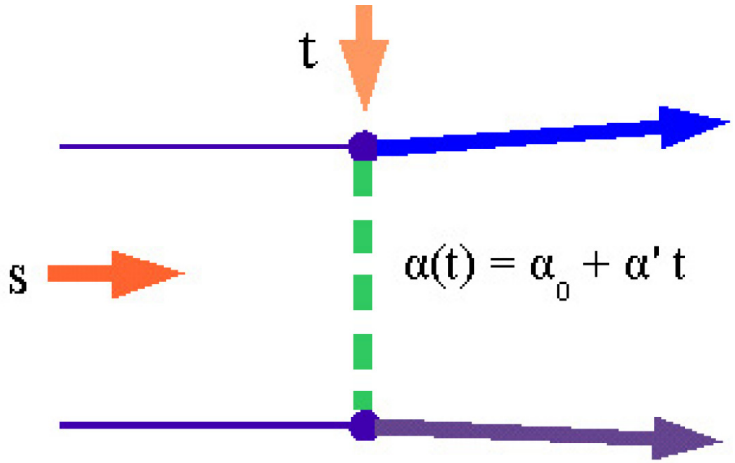
THIS EXAMPLE: NOTE THE OPENING ANGLE OF THE DECAY PRODUCTS

Example of Final State Topology for DVCS ($ep \to ep\gamma$)



DVCS are identified by scattered electron and isolated photon
very clean final state topology:
no energy deposits not associated with electron or photon

Regge Theory and Vector Dominance Model (soft interactions)

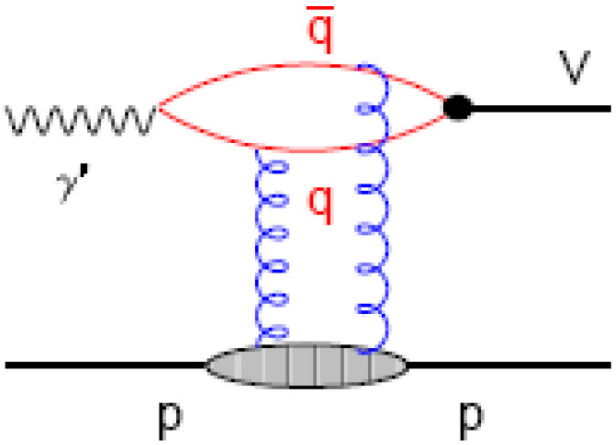


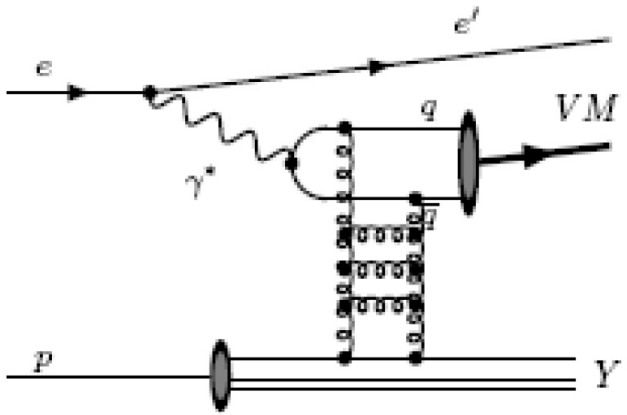
- photon fluctuates into Vector Meson V (which carries the same quantum numbers): $\gamma p \rightarrow Vp$
- Vector Meson scatters off the incoming proton: $Vp \rightarrow Vp$

Regge Theory and VDM (soft interactions) (cont.)

- Predictions:
  $\frac{d\sigma}{d|t|} \propto e^{-b|t|}(W^2/W_0^2)^{2(\alpha(0)-1)}$
- Experimental observations:
  - $\alpha(t) = \alpha(0) + \alpha' t$
  - $\alpha(0) \approx 1.1$, $\alpha' \approx 0.25$
    (Donnachie, Landshoff parametrisation - DL)
  - $b(W) = b_0 + 4\alpha' ln(W/W_0)$, $b_0 \approx 10$ GeV^{-2}
    (shrinkage of the diffractive peak)
  - weak energy dependence of the total production cross section:
    $\sigma \propto W^{\delta}$, $\delta \approx 0.22$

Perturbative QCD models (hard interactions)



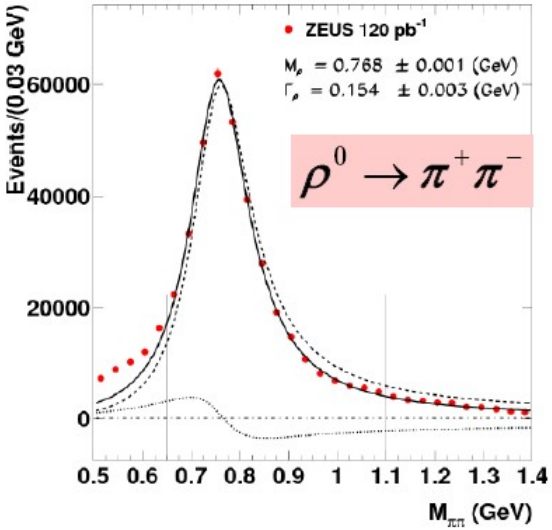


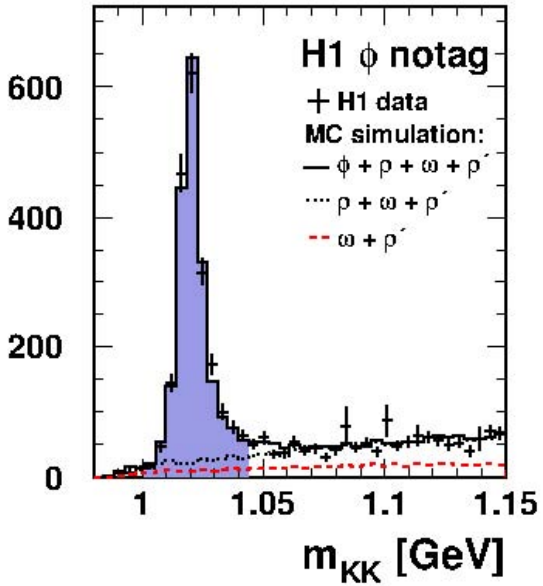
- photon fluctuates into the $q\bar{q}$ state
- the $q\bar{q}$ pair (dipole) scatter off the proton
- the $q\bar{q}$ pair forms a vector meson (on mass shell)
- length of the fluctuation $(\gamma^* \to q\bar{q})$: $\lambda = \frac{2E_\gamma}{M^2_{q\bar{q}}+Q^2} > 1$ fm
- hard scale $\mu^2 \simeq z(1-z)(Q^2 + M^2_{VM})$, z - fraction of γ^* energy transfered to q if $z \neq \frac{1}{2} \to$ skewness from Generalized Parton Distributions (GPD)

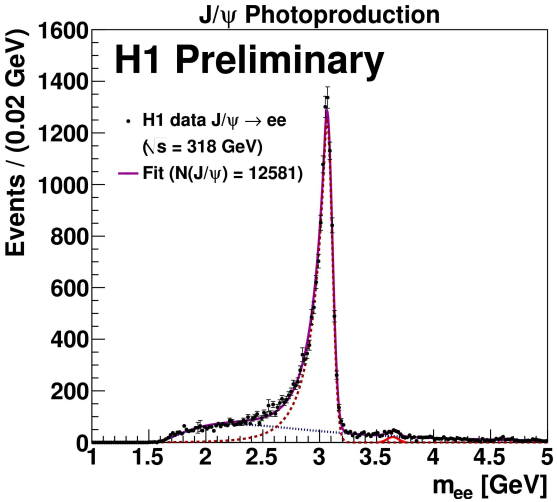
Perturbative QCD models (hard interactions) (cont.)

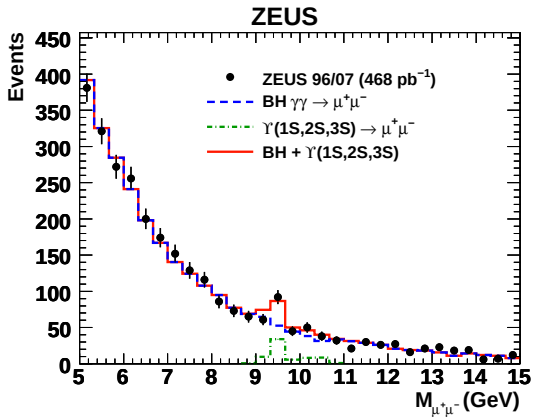
- Predictions:
  - $\sigma \sim \frac{\alpha_s^2(Q)}{Q^6}|xG(x,Q^2)|^2$, $x \sim Q^2/W^2$
    where $G(x,Q^2)$ is the gluon density in the proton
    (NB.: at HERA $10^{-2} > x > 10^{-4} \rightarrow$ small x phenomenon)
  - fast increase of the total cross section
    with the γp c.m. energy W
  - universal exponential $|t|$ dependence:
    $\frac{d\sigma}{d|t|} = e^{-b|t|}$, $b = 4 \div 5$ GeV^{-2}, $\alpha' \rightarrow 0$

Example of reconstructed Vector Mesons in H1 and ZEUS detectors

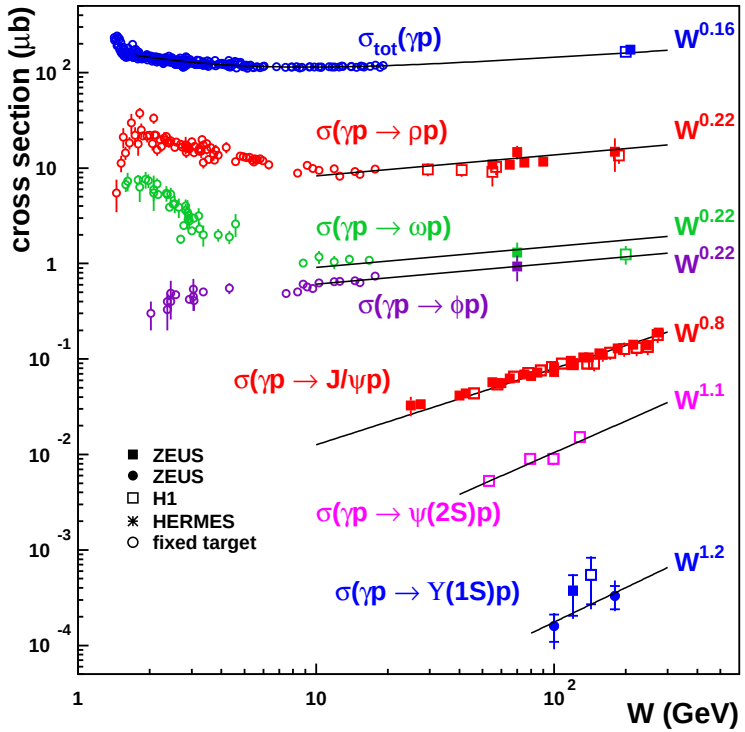






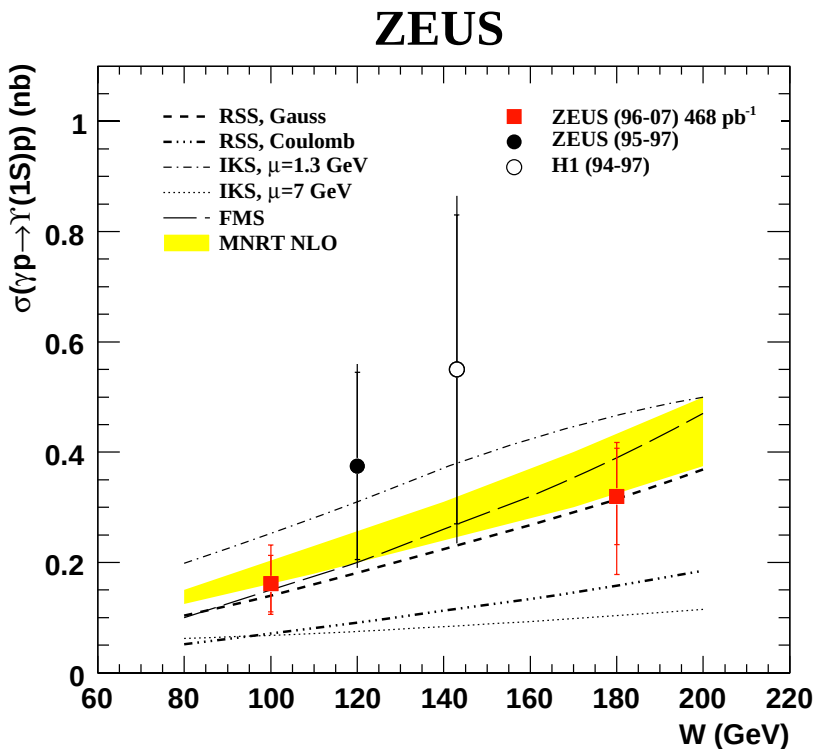


W-dependence of the VM exclusive cross section for PHP: $\sigma(\gamma p \to Vp)$



- total cross sections σ_{VM} for VM photoproduction spans over 6 orders of magnitude ! (for higher VM masses $\longrightarrow$ smaller transverse size of $q\bar{q}$ $\longrightarrow$ "color screening")
- σ_{VM} rises with γp c.m. energy W as W^{δ} (expected from the gluon behaviour in the proton $\longrightarrow$ probing small x)
- power δ rises with M_V^2 from "soft" ($\delta \approx 0.22$) to "hard" ($\delta \approx 1.2$) processes

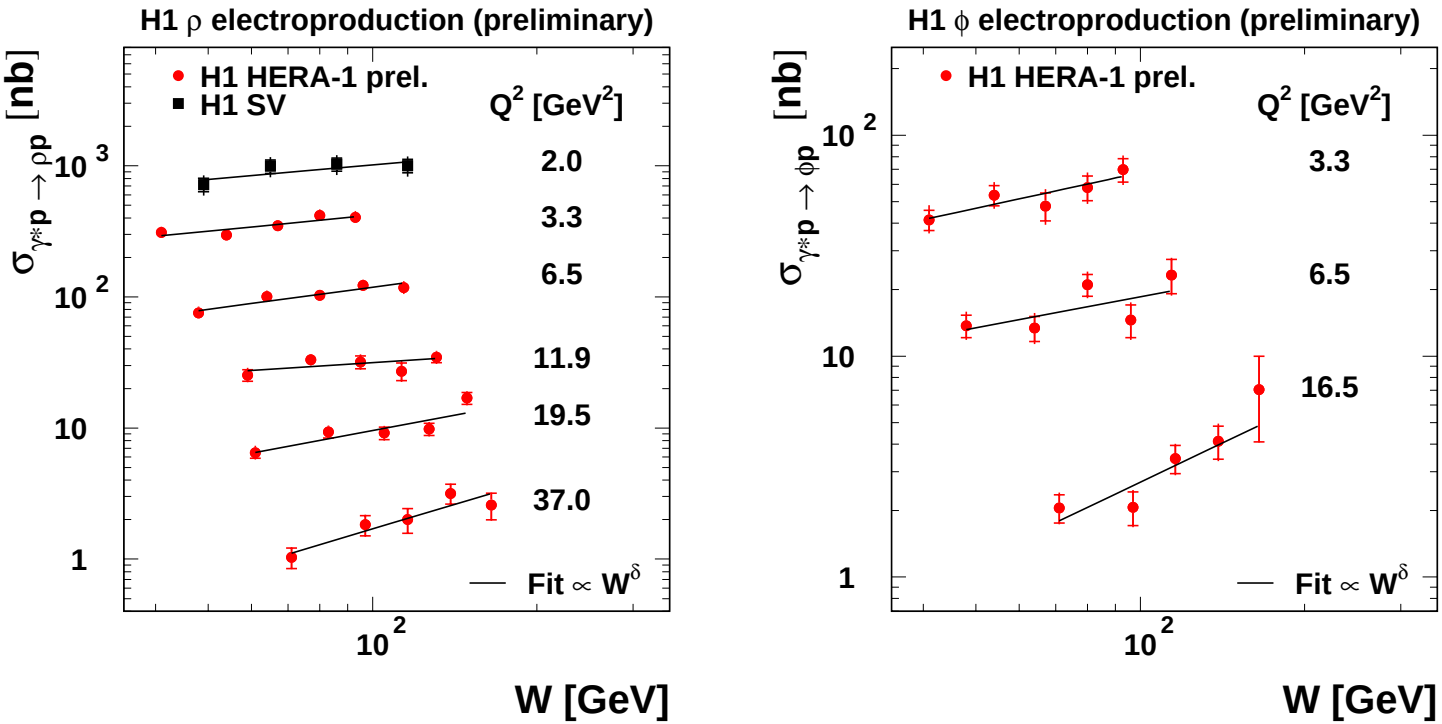
Upsilon exclusive cross section for PHP: $\sigma(\gamma p \to \Upsilon p)$



ZEUS measurement of Υ meson: $\delta = 1.2 \pm 0.8$ (Phys. Lett. **B 680**, 4 (2009))

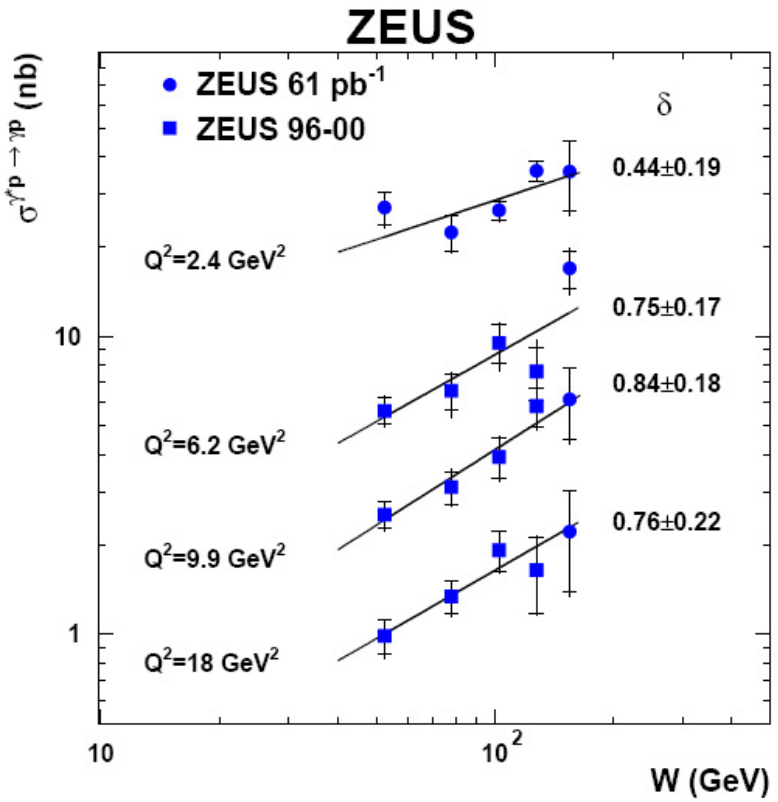
- Υ: sensitive to vector meson wave function: seems to prefer Gauss to Coulomb,
- Υ: sensitive to hard scale value: NRQCD NLO scale is between $1.3 < \mu < 7$ GeV,
- Υ: pQCD models *W*-slope: FMS LO (δ=1.7), other NLO give value $\delta \approx 1.2$

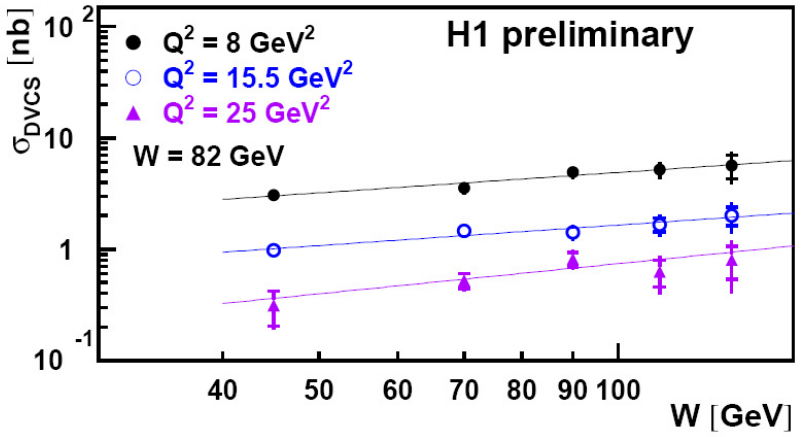
Exclusive cross section for electroproduction: $\sigma(\gamma p \to \rho/\phi\, p)$

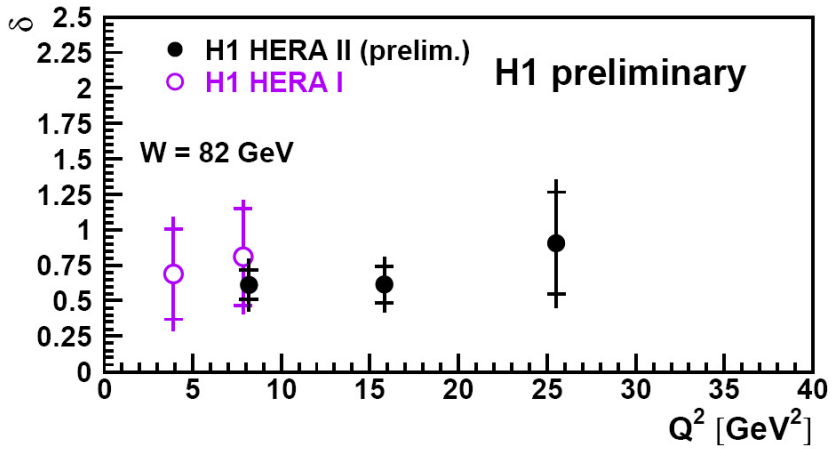


- electroproduction of ρ and ϕ mesons measured by H1: $Q^2 > 0$ GeV^2, σ_{VM} for different Q^2 bins
- similar behaviour: $\sigma \sim W^{\delta}$
- now steeper dependence for higher Q^2
- relevant hard scale related to M_{VM}^2 and Q^2

Exclusive cross section for DVCS: $\sigma(\gamma^* p \to \gamma p)$

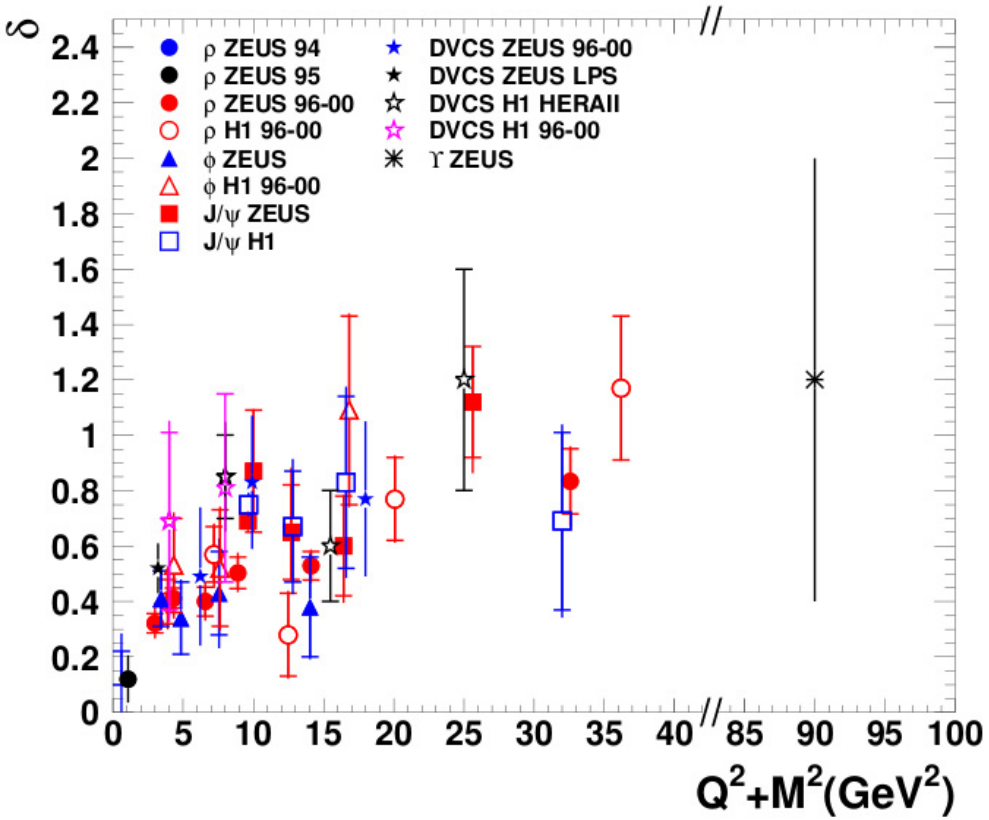


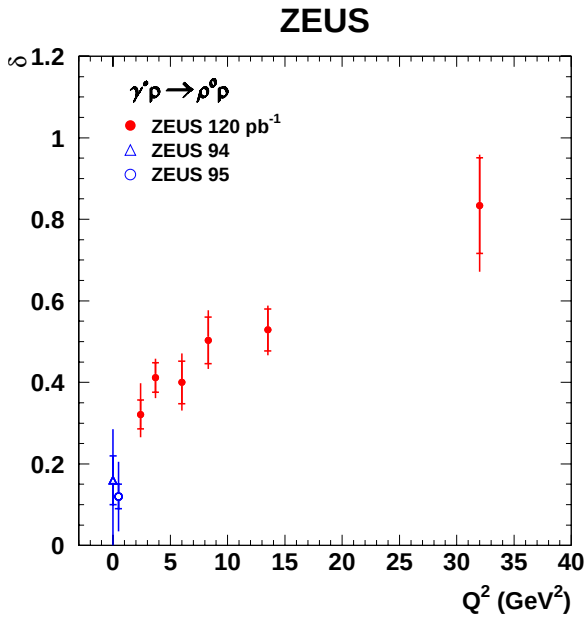




- $\sigma_{DVCS} \sim W^{\delta}$
- no δ dependence on Q^2
- $< \delta >= 0.63$ (H1), $< \delta >= 0.52$ (ZEUS)

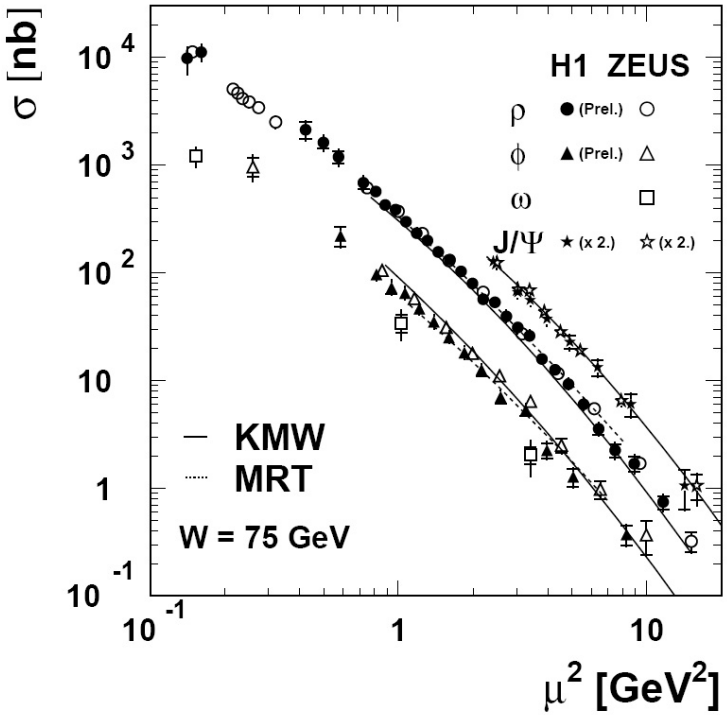
δ dependence as a function of $Q^2 + M^2_{VM}$





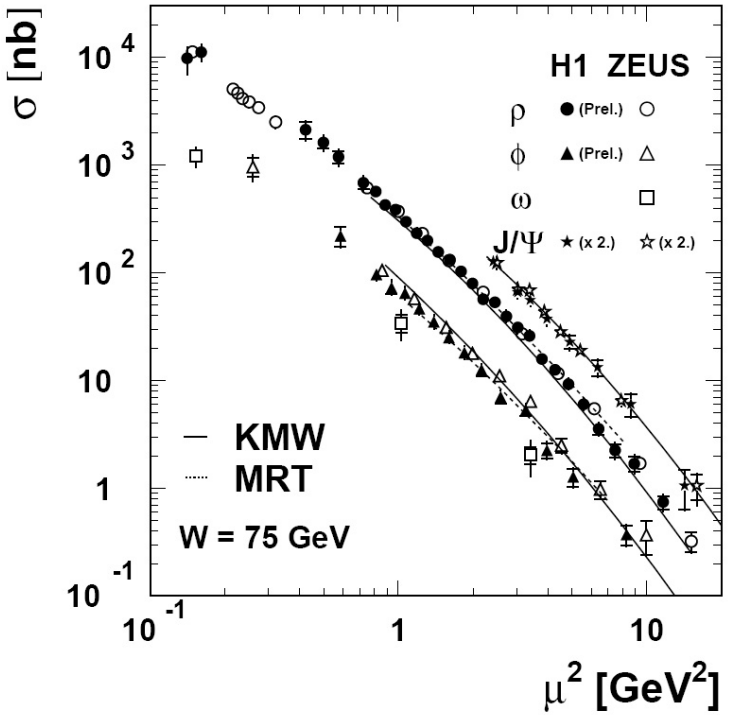
- photo- and electroproduction of light and heavy VM and DVCS
- for VM process becomes harder as the scale $Q^2 + M^2_{VM}$ grows
- DVCS hard from $Q^2 \to 0$

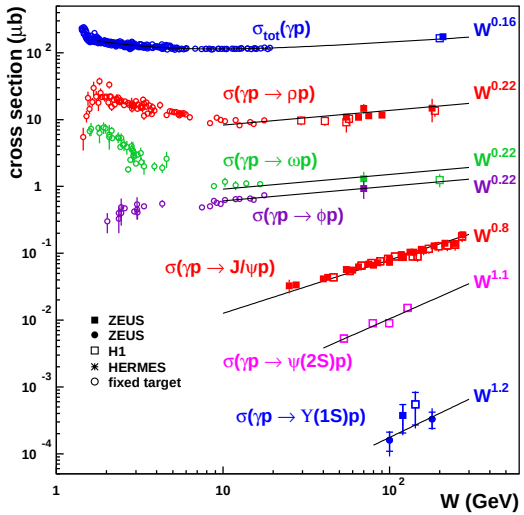
σ_{VM} dependence as a function of $\mu = Q^2 + M_{VM}^2$



- σ_{VM} for photo- and electroproduction of light and heavy VM
- **perfect agreement between H1 and ZEUS !**
- universal dependency as a function of the scale parameter $\mu^2 = Q^2 + M_{VM}^2$
  $\sigma_{VM} \sim (Q^2 + M_{VM}^2)^{-n}$, $n \approx 2.5$ ($n \approx 1.5$ for DVCS)
- remaining differences can be attributed to the charge composition of the VMs
  $\rho : \omega : \phi : J/\psi = 9 : 1 : 2 : 8$

σ_{VM} dependence as a function of $\mu = Q^2 + M_{VM}^2$





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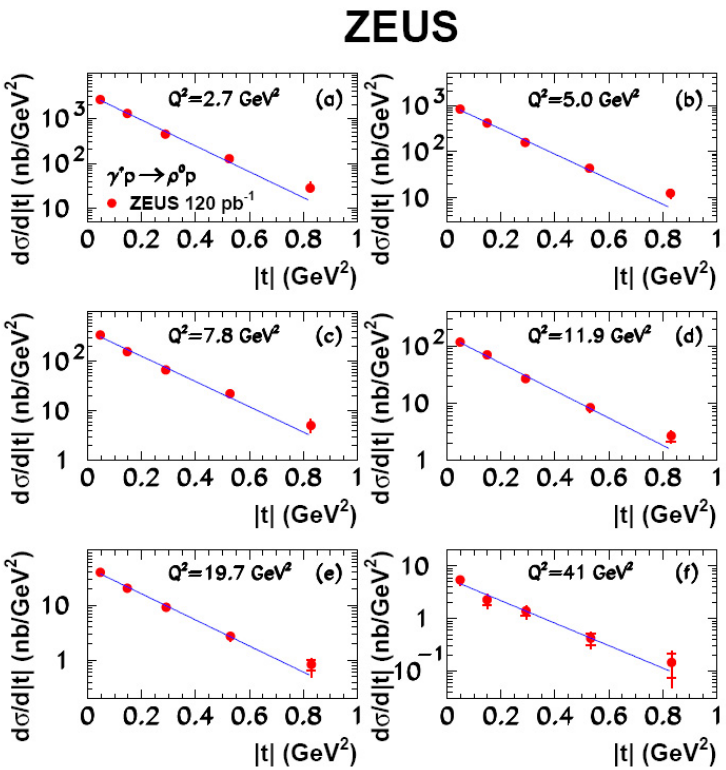
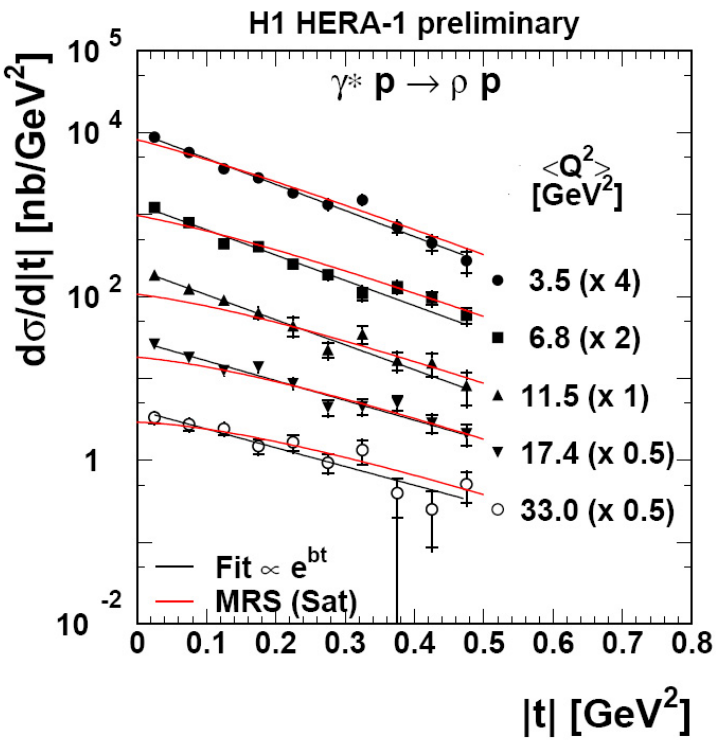
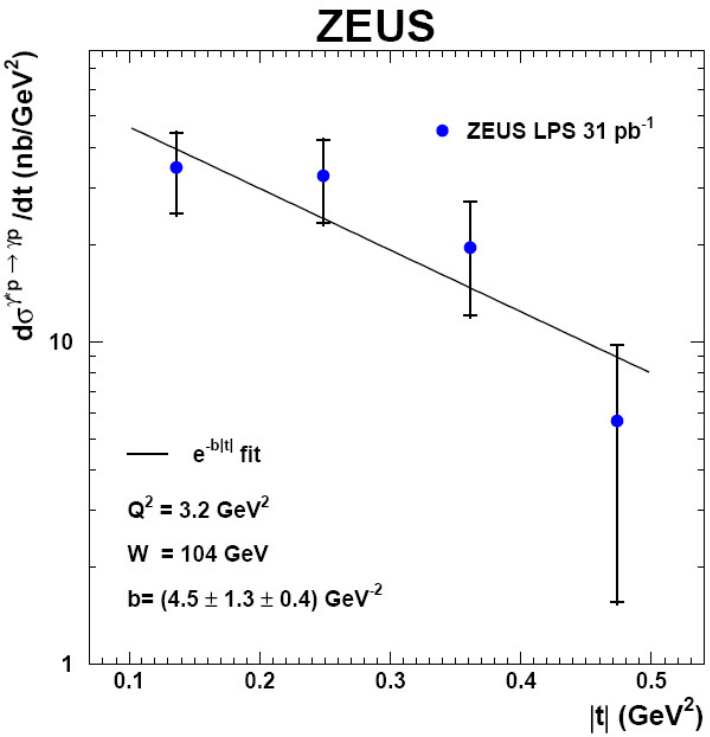
$d\sigma/d|t|$ dependence for exclusive ρ production





- $d\sigma/d|t| \sim e^{-b|t|}$ for different bins of Q^2
- slope b decreases as a function of Q^2 from ≈ 10 to ≈ 5 GeV^{-2} ("shrinkage" of diffractive peak)

$d\sigma/d|t|$ dependence for DVCS



- direct measurement of the t variable from Leading Proton Spectrometer (LPS) !
- $d\sigma/d|t| \sim e^{-b|t|}$
- $b \approx 4.5$ GeV^{-2} already for small Q^2

Overview of t-dependence for Vector Mesons and DVCS

$$\frac{d\sigma}{d|t|} \propto \exp(-b|t|)$$

Geometric picture - transverse size:

$b \approx (R_p^2 + R_{VM}^2)/4$

$b = b_{VM} + b_p$

Vector Meson tr. size:

$b_{VM} \sim \frac{1}{Q^2 + M_{VM}^2}$

Target (proton) tr. size:

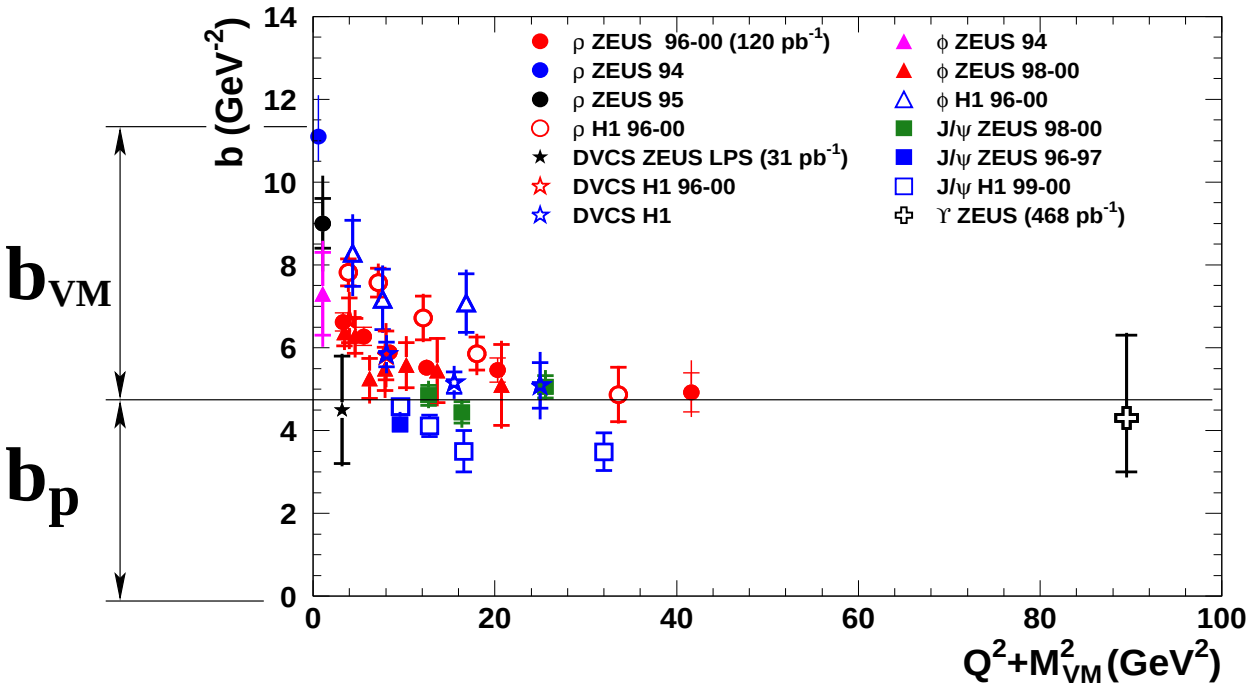
$b_p \approx 5 GeV^{-2}$

can be interpreted as

$r_{gluons} \approx 0.6$ fm

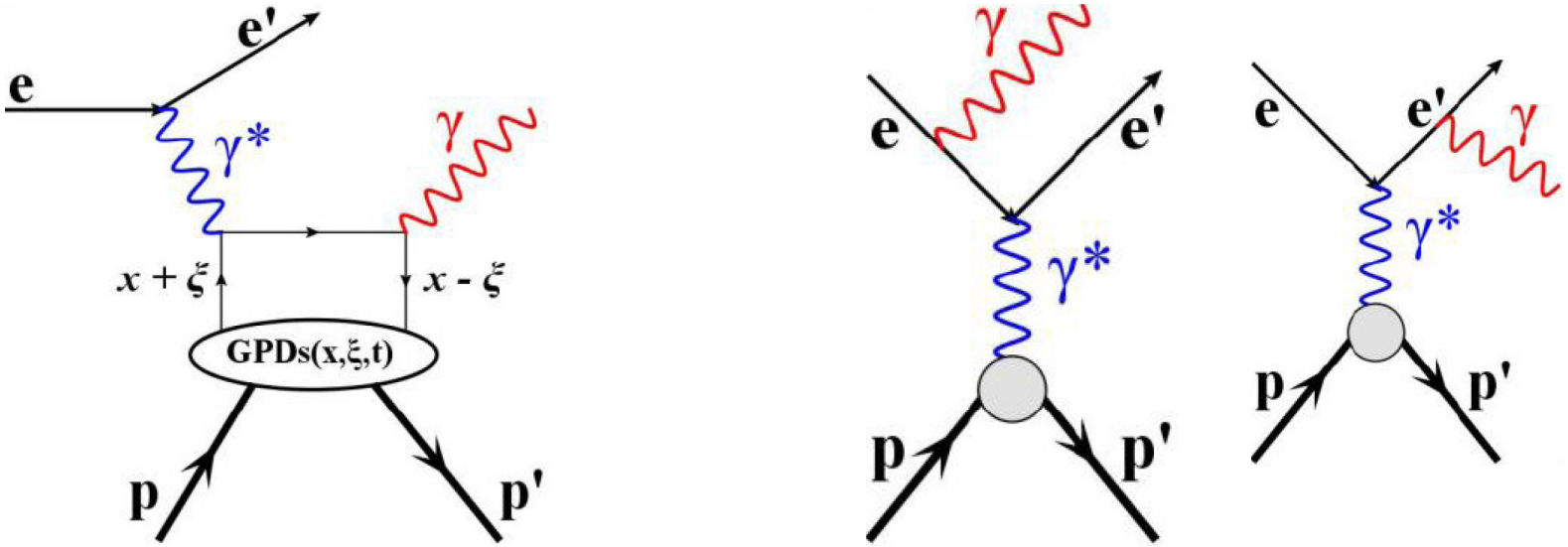
(NB.: charge radius of the proton

$r_{em} \approx 0.8$ fm)



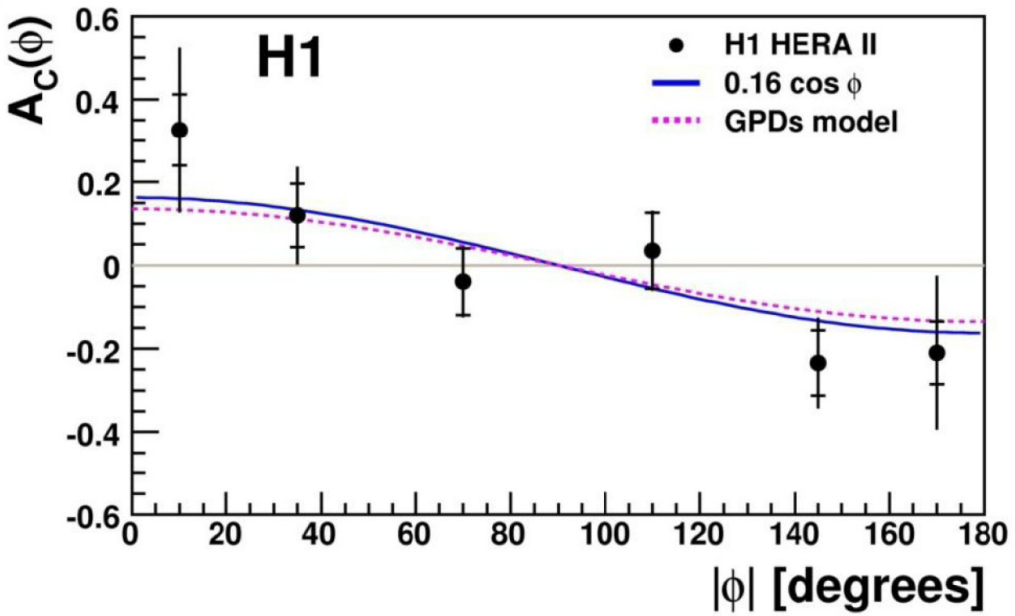
The t-slope, **b**, decreases with the scale $Q^2 + M_V^2$

Beam charge asymmetry in DVCS



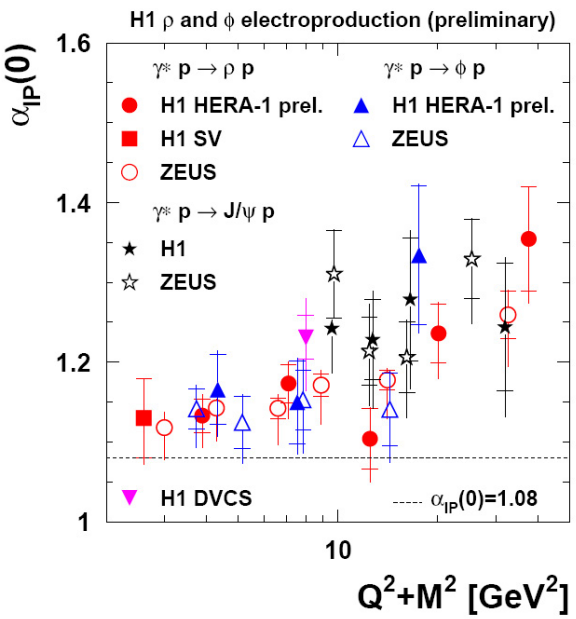
- **DVCS** allows to probe the **GPD (Generalised Parton Distributions)**
- **sensitive to the correlations between partons** which carry the longitudinal ($x_{1,2} = x \pm \xi$) and transverse (t) momentum at given Q^2
- DVCS and ISR or FSR (Bethe-Heitler) have the same initial and final state
- The QCD-QED interference term change the sign with lepton beam charge: $\sigma = \sigma_{DVCS} + \sigma_{BH} \pm \sigma_{interf}$.

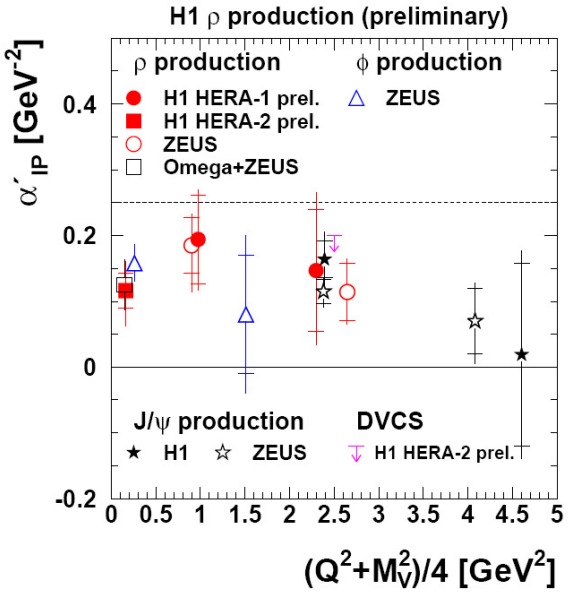
Beam charge asymmetry in DVCS (cont.)

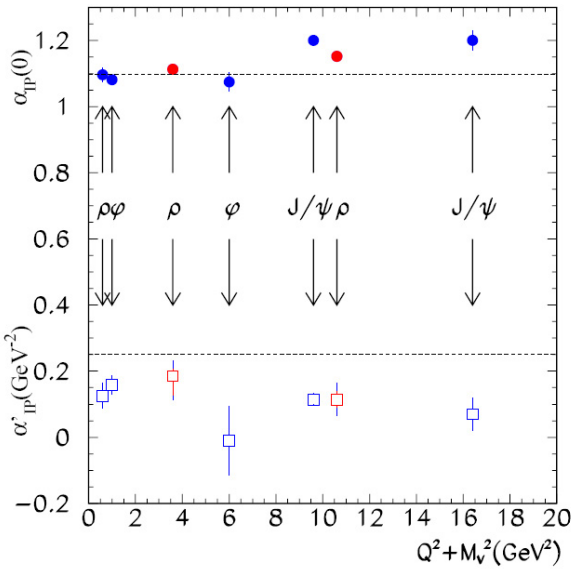


- $A_{BC} = \frac{d\sigma^+/d\phi - d\sigma^-/d\phi}{d\sigma^+/d\phi + d\sigma^-/d\phi} = p_1 cos(\phi) + (...)$, $p_1 = 0.16 \pm 0.04(stat.) \pm 0.06(syst.)$
- ϕ - angle between two planes:
  (incoming-outgoing lepton) and (γ^*-outgoing proton)
- GPDs based model in agreement with data (H1: Phys. Lett. **B 681** (2009), 391)

Transition from “soft” to “hard” physics







- effective Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' t$
- $\alpha(0)$: energy dependence of the total xsec: $\sigma_{tot} = W^{\delta} = W^{2(\alpha(0)-1)}$
  δ: 0.2 $\nearrow$ 1.2
- α': shrinkage of the diffractive peak: $\frac{d\sigma}{d|t|} = e^{-b|t|}$, $b(W) = b_0 + 4\alpha' ln(W/W_0)$
  b: 10 $\searrow$ 5 GeV^{-2}, α': 0.25 $\searrow$ 0.1 GeV^{-2}
- **larger intercept and smaller slope then observed in soft hadron-hadron physics**
  (horizontal lines: DL parameters)

Summary and Conclusions

- Cross section for VM and DVCS rise with energy in the presence of hard scale like Q^2 or M_{VM}^2
- The slope of the t-dependence of the cross section decreases with $Q^2 + M_{VM}^2$ and levels off at $b \approx 5$ GeV^{-2}
- visible transition from soft to hard regime
- Evidence of "hard Pomeron": the effective Pomeron trajectory has larger intercept and smaller slope then anticipated from soft interactions
- All observed features are compatible with models based on perturbative QCD for hard diffraction
  (for heavy VM bigger experimental precision needed to discriminate between various theoretical models)

Thank You For Your Attention