Review of Vector Mesons and DVCS

Xth Blois Workshop on Elastic and Diffractive Scattering

Uta Stösslein (DESY Hamburg)

Hanasaari, Helsinki, Finland, June 23rd - 27th, 2003

Outline

- **Motivation**

- **Vector Mesons** $\gamma p \rightarrow VM\ p\ (Y)$, $\gamma^* p \rightarrow VM\ p$
  - elastic photo- and electroproduction
  - scale and universality tests
  - dissociative photo- and electroproduction
  - helicity studies

- **Deeply Virtual Compton Scattering** $\gamma^* p \rightarrow \gamma\ p$
  - cross sections
  - asymmetries

- **Conclusions**

Motivation

confinement of color: the most important open problem in QCD

→ still not possible to calculate bulk of hadronic processes by first principle if the reactions are *soft , i.e. distances and strong coupling are large:* σ_{tot}, $\sigma_{elastic}$ and σ_{diffr}

→ at large distances confinement changes radically the pQCD radiation pattern

→ in high energy hadronic scattering **hard diffraction** deliver class of events where an initial hadron may stay **confined → hope to learn about fundamental properties of binding forces**

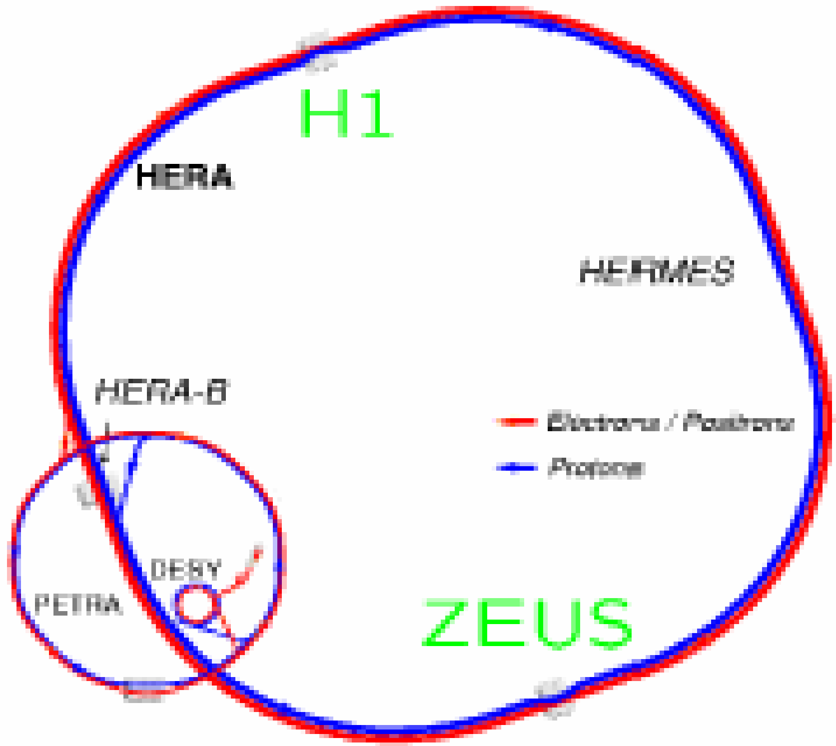
strategy

→ study the structure of hadronic interactions and identify here kinematic ranges where pQCD dominates: **transition soft→hard**

→ explore asymptotic behavior of high energy interactions

→ measure new non-perturbative structure of hadrons (GPDs)

HERA Experiments @ DESY



H1, ZEUS:

$e^{\pm} \Rightarrow \Leftarrow p$

27.5 GeV   920 GeV

$\sqrt{s} = 320$ GeV

→ **high parton densities!**

HERMES:

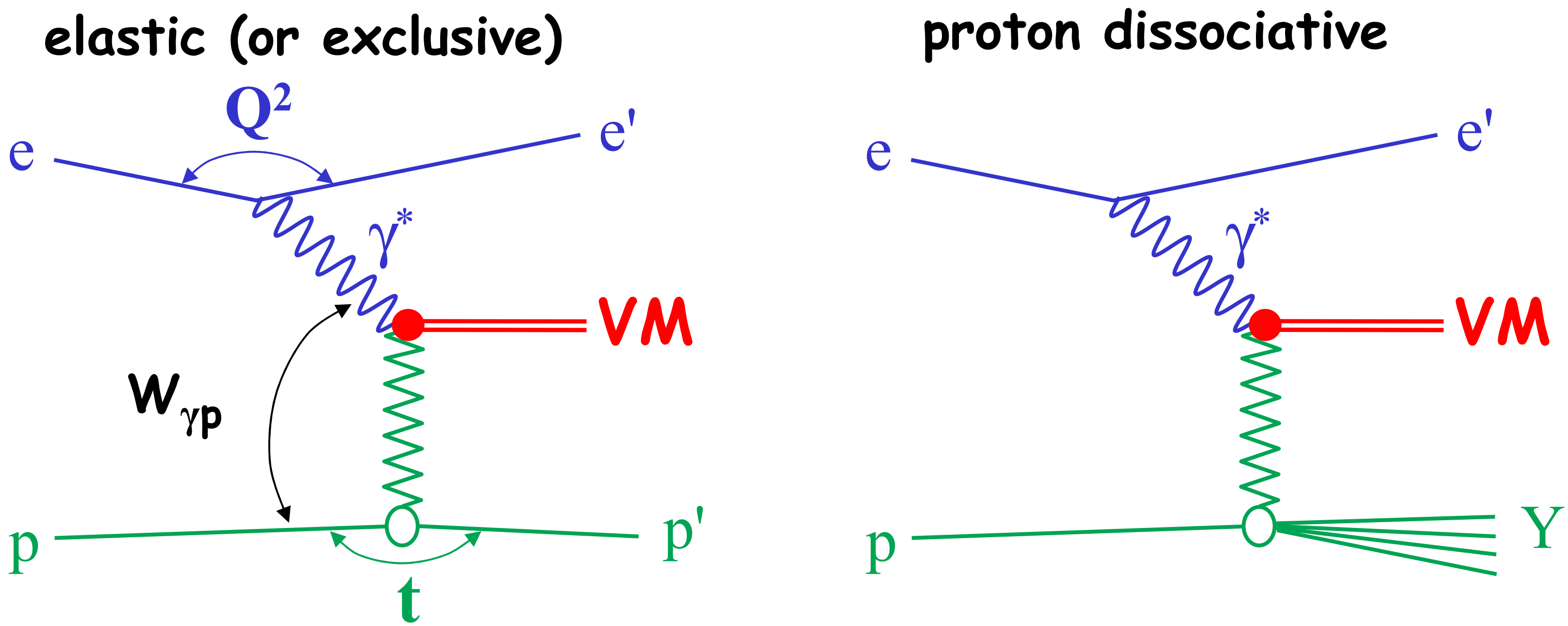
long. pol $e^{\pm}$ on internal gas target: H, D, He, N, Ne, Kr

$\sqrt{s} = 7.5$ GeV

→ **spin and A dep. quantities**

➔ **powerful probes of QCD**

Diffractive Vector Meson Production at HERA



Experimentally: very clean processes in wide kinematic range

Q^2	γ^* virtuality	$0 < Q^2 < 100\ (20)\ \mathrm{GeV}^2$
$W_{\gamma p}$	c.m. energy of γ^*p system	$20\ (4) < W_{\gamma p} < 300\ (7)$ GeV
t	4-mom. transfer squared at p-vertex	$0 < \|t\| < 20\ (1)\ \mathrm{GeV}^2$
VM	Vector Meson	$\rho^0, \omega, \varphi, J/\psi, \psi', \Upsilon$

→**simultaneous control of <u>different scales</u>: Q^2, $|t|$, M^2_{VM}**

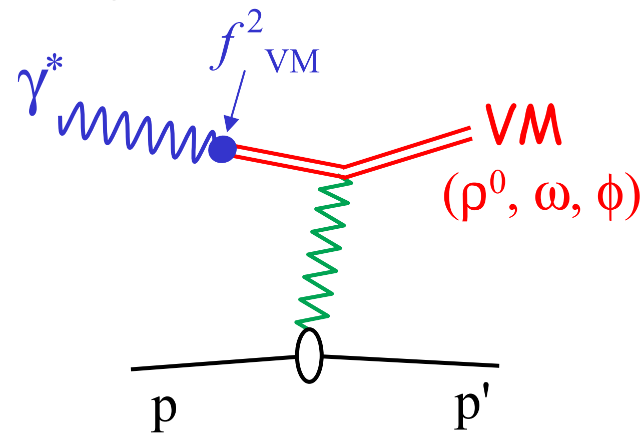
Models for Diffractive VM Production

VDM:

1. photon (γ*) fluctuates into VM
   ➔ VM retains γ* helicity (SCHC)

2. VM scatters off the incoming proton

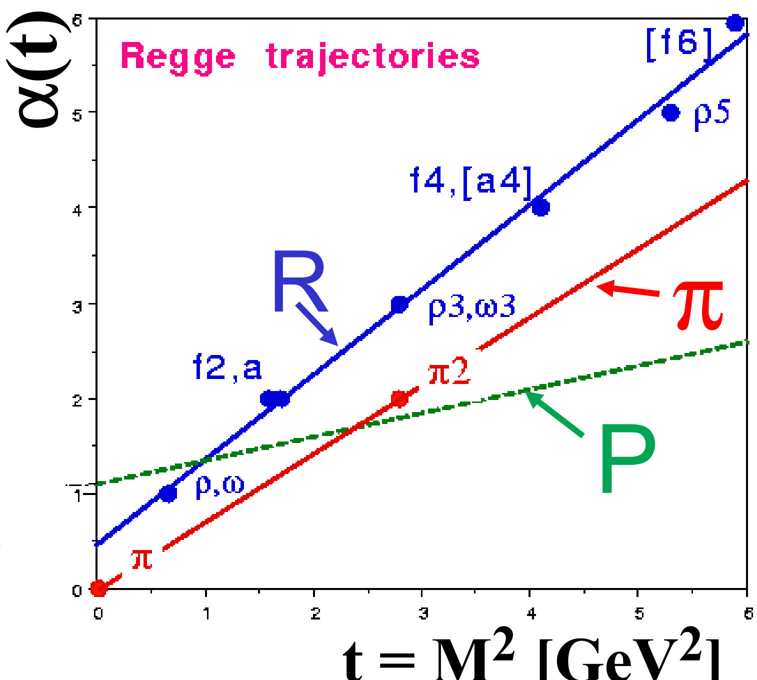
→ elastic photoproduction ($Q^2 \sim 0$) of light Vector Mesons (VM) is a soft process



+

Regge model (soft diffraction):
analytic theory of hadronic scattering described by the exchange of collective states: linear trajectories in the spin-energy (α-t) plane,

$$\alpha_j(t) = \alpha_j(0) + \alpha'_j \cdot t \qquad (j = \pi, P, R)$$



Regge Theory and Experimental Observations

in diffractive scattering (soft process):

$\sigma \propto s^{2(\alpha_P(0)-1)}$

- **weak energy dependence** of cross sect. : $\sigma \propto s^{\sim 0.2}$
- **very small scattering angles** ⇒ exponential dep. : $d\sigma/d|t| \propto e^{-b(W)\cdot|t|}$
- **b slope increases with W** ⇒ shrinkage: $b(W) = b_0 + 4\alpha'_P \cdot \ln(W)$

→ successfully parameterized by **Regge trajectories**, $\alpha_j(t) = \alpha_j(0) + \alpha'_j \cdot t$

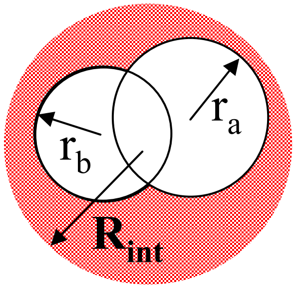
→ soft Pomeron exchange: $\alpha_P(t) = 1.08 + 0.25 \cdot t$ (Donnachie-Landshoff)

$\alpha_P(0)$ **= 1 + ε=** "intercept", determines the **energy dependence** of σ^{tot} ($\propto \sigma^{\alpha_P(0)-1=\varepsilon}$) and σ^{el}, σ^{diffr} ($\propto s^{2\varepsilon}$)

α'_P = "slope", determines the growth with energy of the **transverse size of the interaction** (⇒ color radiation cloud) and reflects the strength of binding forces

⇒ **characterizes the confinement forces in QCD**

$b \sim R_{int}^2$

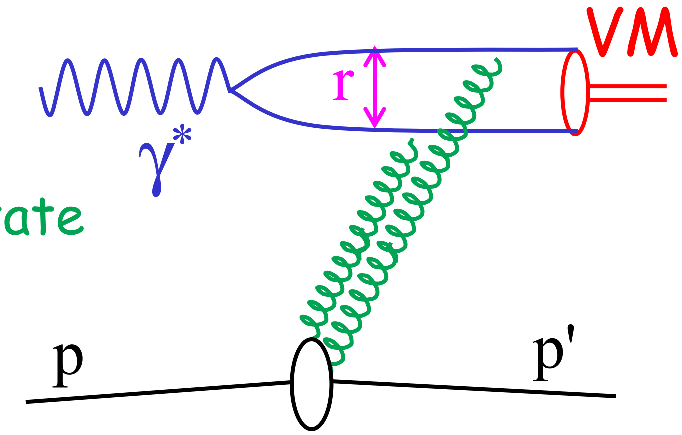


access to α'_P only in diffraction

Models for Hard VM Production

In the presence of a **hard scale** $\Rightarrow$ perturbative QCD applicable
<u>In the target frame</u>, VM production is a 3-step process:

1. $\gamma^* \rightarrow q\bar{q}$ oscillation
2. $q\bar{q}$ scatters off the proton by two-gluon exchange (at lowest order) in colour singlet state
3. VM is formed after the interaction



If **dipole size** $r = 1/[z(1-z)Q^2 + m_q^2]^{\frac{1}{2}}$ is **small**
(large m_q or γ^*_L at high Q^2) $\Rightarrow$ **qq pair resolves gluons**

Elastic VM at Hard Scale: pQCD Predictions

1. **fast rise with energy, $W^{2(\alpha_P(<t>)-1)}$:**

Gluon from F_2 scaling violations

$$\sigma_L \propto \alpha_s^2 (Q_{eff}^2) / Q^6 \cdot [xg(x, Q_{eff}^2)]^2 \approx [x^{-0.2}]^2 \approx W^{0.8}$$

(use $x \approx Q^2/W^2$ at small x)

→ fast increase of σ_L with W^2

→ Q^2 dependence slower than $1/Q^6$

2. **universality of t-dependence: $\sim e^{-b_{2g}|t|}$**

→ $b_{2g} \sim 4 - 5$ GeV^{-2} independent of W $\Rightarrow \alpha'_P = 0$ in 2 gluon approx.

→ BFKL LLA: $\alpha'_P \leq 0.1$ GeV^{-2} $\Rightarrow$ weak dep. of b on W only

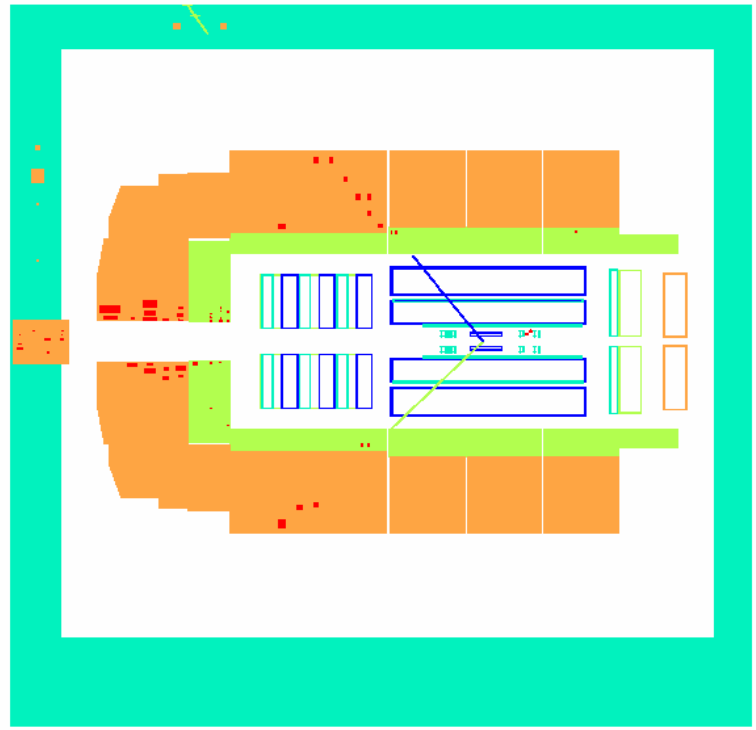
3. **approximate restoration of flavor independence at large Q^2**

$\rho^0 : \omega : \varphi : J/\psi = 9 : 1\ (\cdot 0.8) : 2\ (\cdot 1.2) : 8\ (\cdot 3.4)$

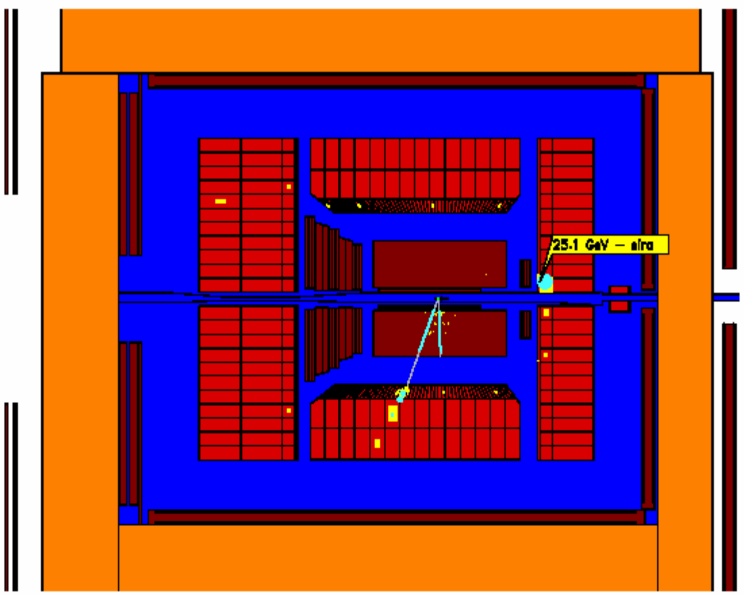
→confront models with data

Experimental Signatures

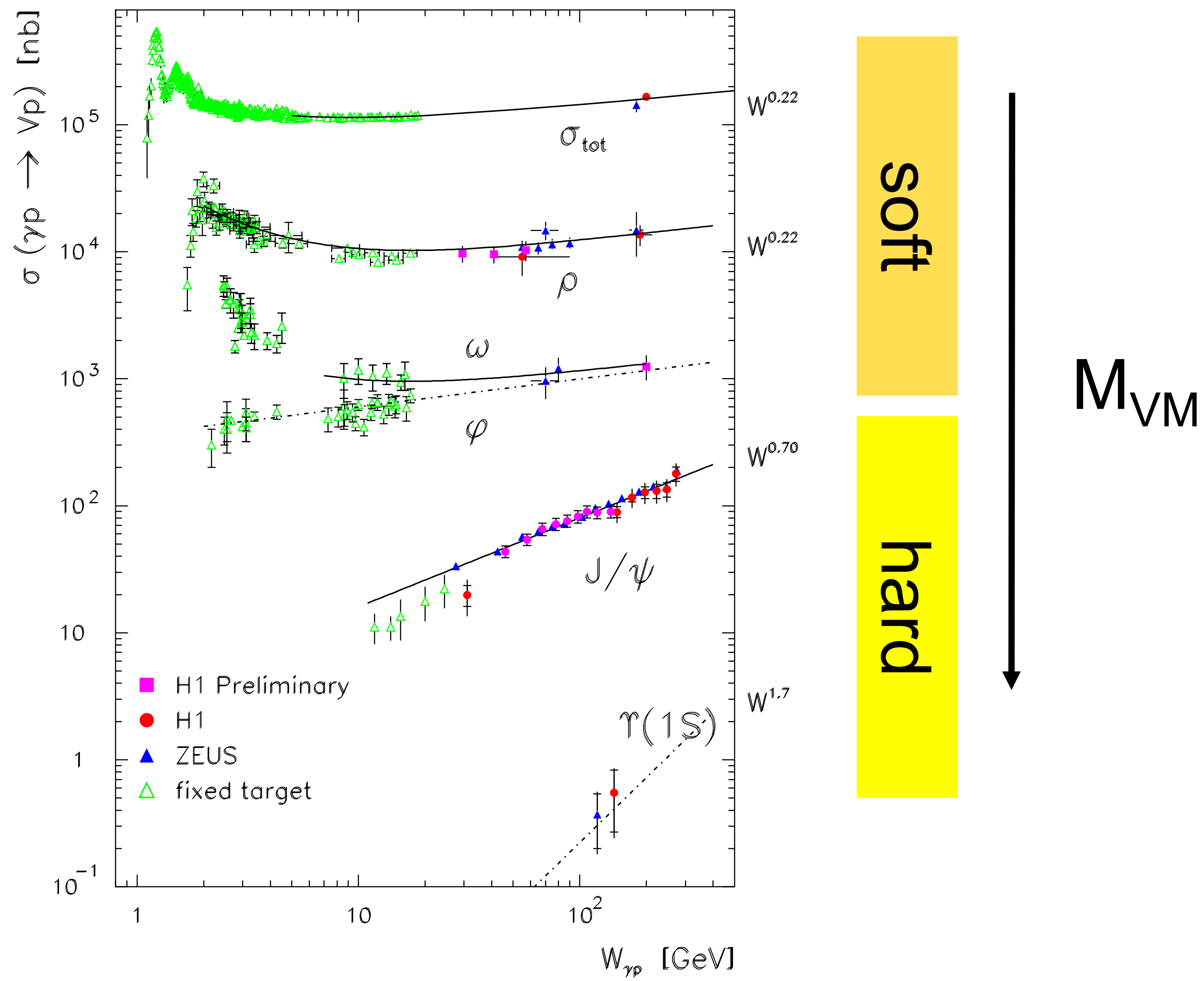
H1 DETECTOR: $\gamma p \rightarrow J/\psi Y$ event



ZEUS DETECTOR: $\gamma^* p \rightarrow \rho^0 p$ event



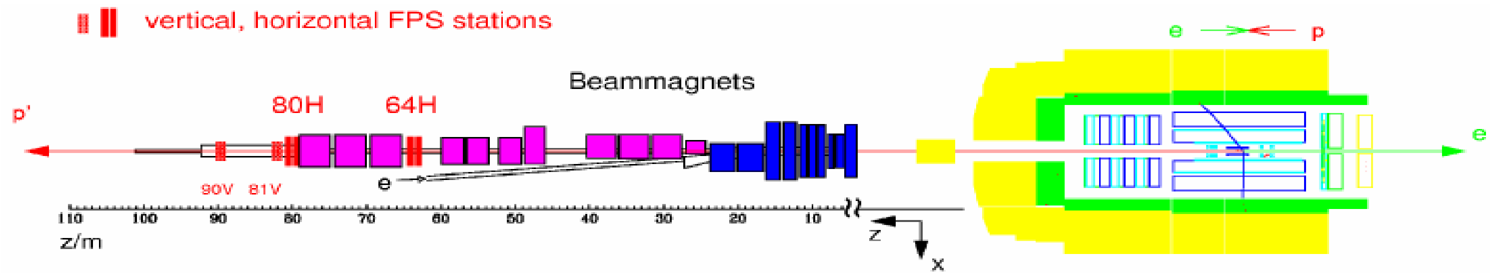
Elastic VM in photoproduction (Q^2 = 0, |t| ≈ 0)

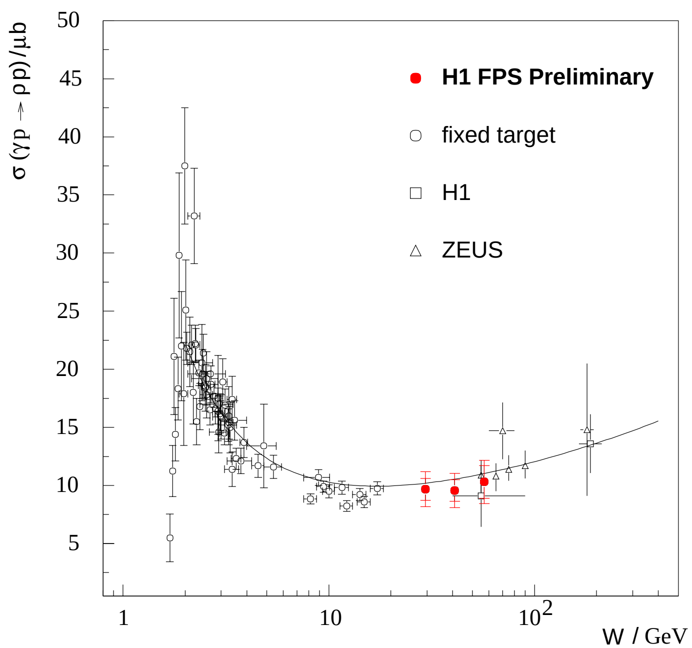


⇒ **change of regime with mass of VM at Q^2 = 0**

Elastic ρ^o Mesons in γp

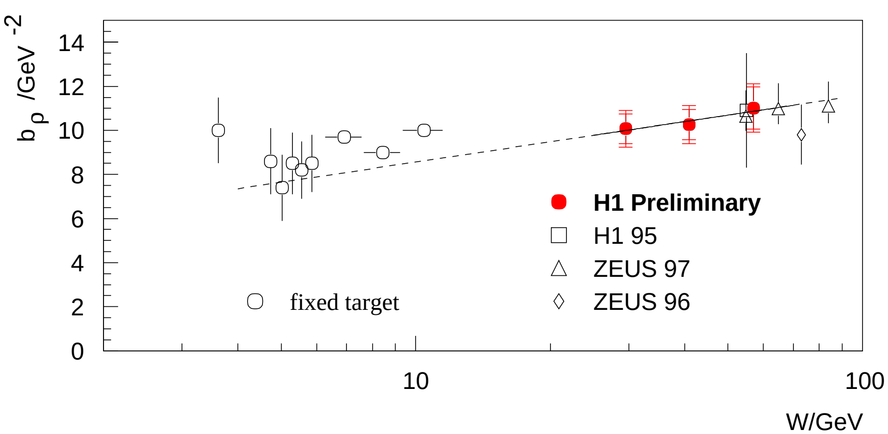
p measured in forward proton spectrometer





fit $\sigma \propto W^{0.22}$

fit $d\sigma/dt \propto e^{bt}$



$b_\rho \propto \ln W$

➔ according to Regge model

Elastic J/ψ Mesons in γp

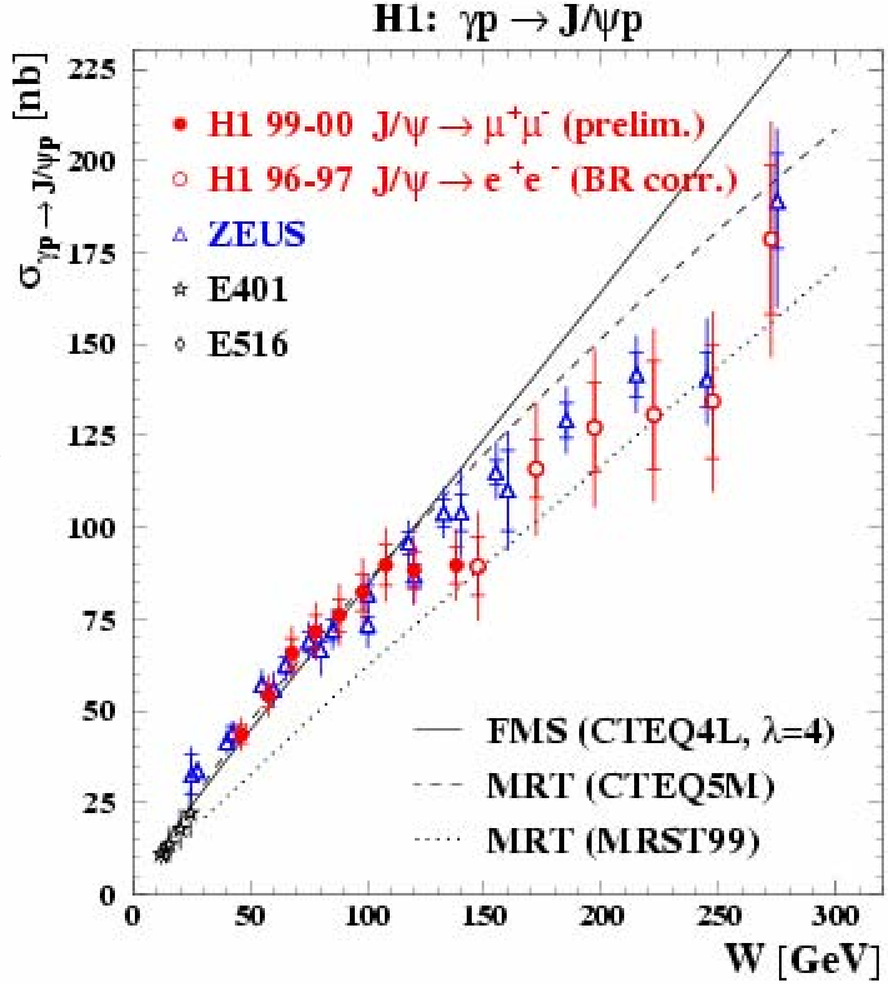
fast rise with W^δ
ZEUS : $\delta = 0.69 \pm 0.02(stat)$
$\pm 0.03(sys)$
H1: $\delta = 0.70 \pm 0.08$

pQCD based models reproduce the data with $M_{J/\psi}$ as hard scale

determination of gluon density

$\sigma_L \propto |xG(x,Q^2)|^2$

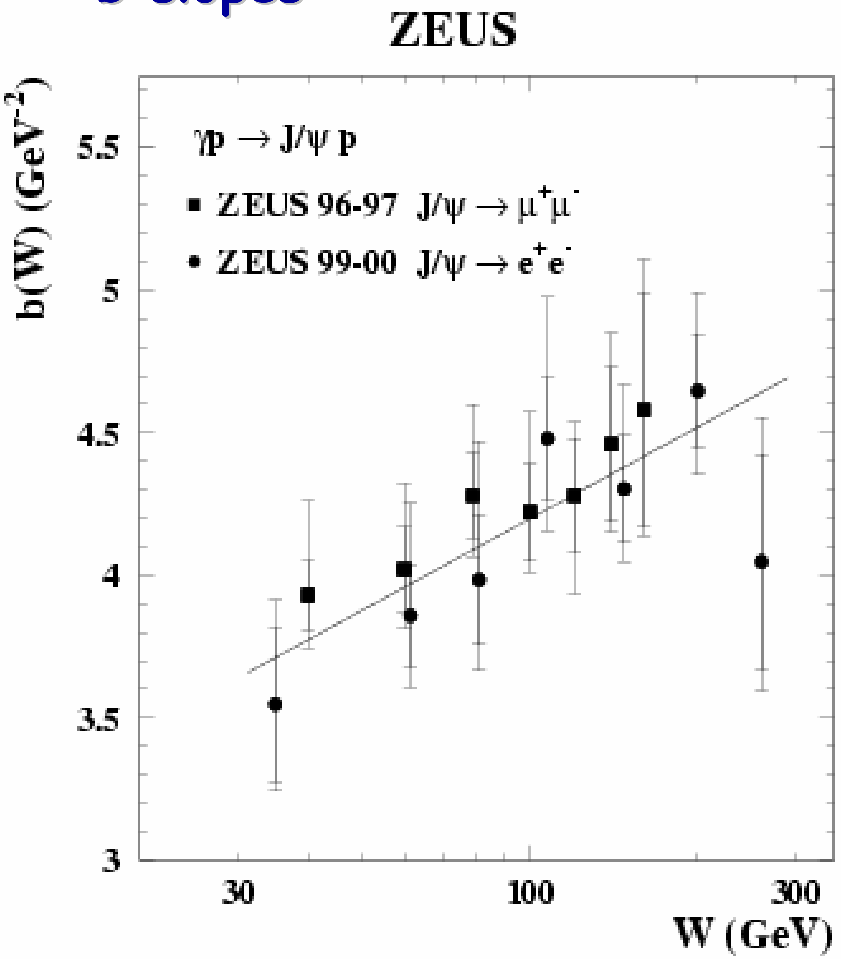
alternatively to DGLAP



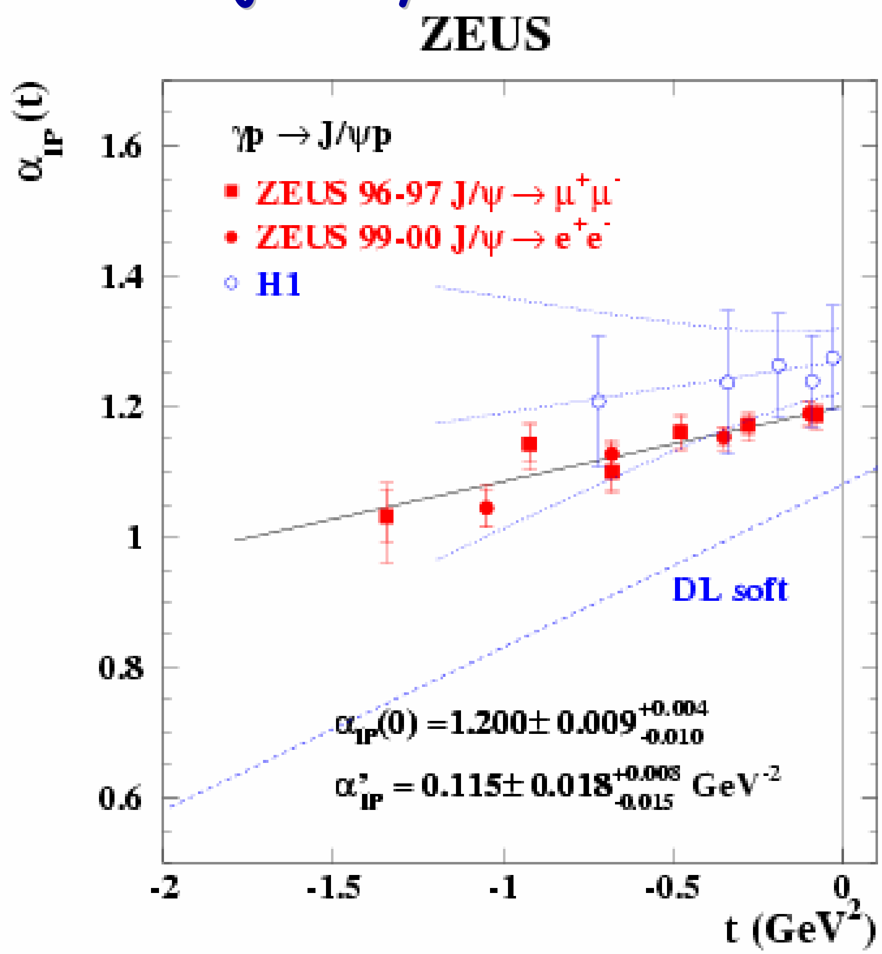
➔ but deconvolution of xg from data still not possible

Elastic J/ψ Mesons in γp

b slopes



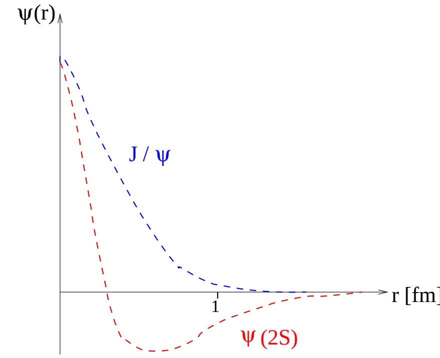
P trajectory



➔ pointlike interaction

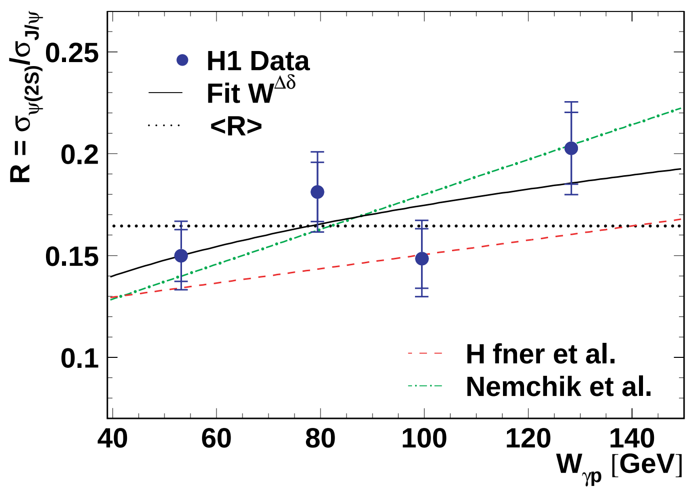
➔ “soft” Pomeron alone excluded

Diffractive ψ(2S) Mesons in γp

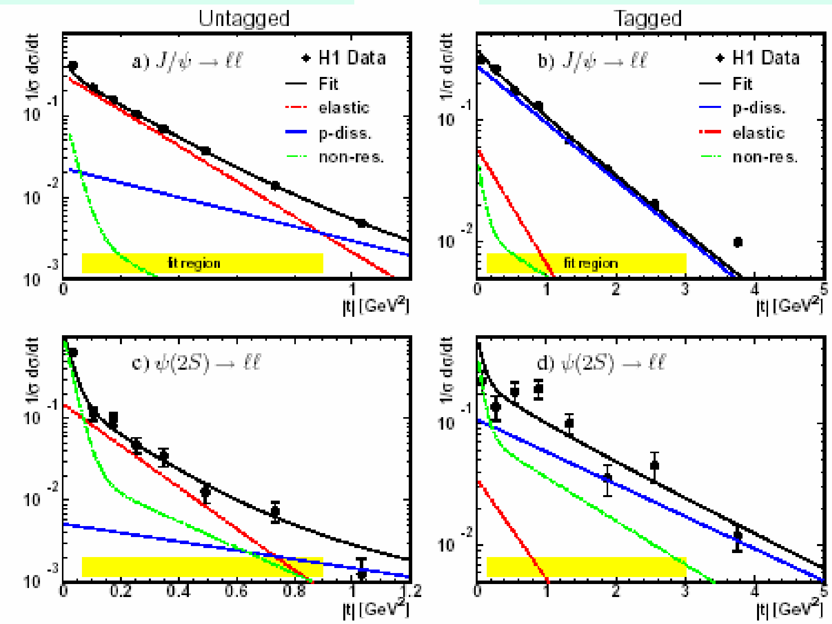


ratio $R = \sigma_{\gamma p \to \psi' p} / \sigma_{\gamma p \to J/\psi p}$ sensitive to radial wave function of charmonium

QCD predicts R ~ 0.17



$d\sigma/dt(\gamma p \to \psi p)$ $d\sigma/dt(\gamma p \to \psi Y)$

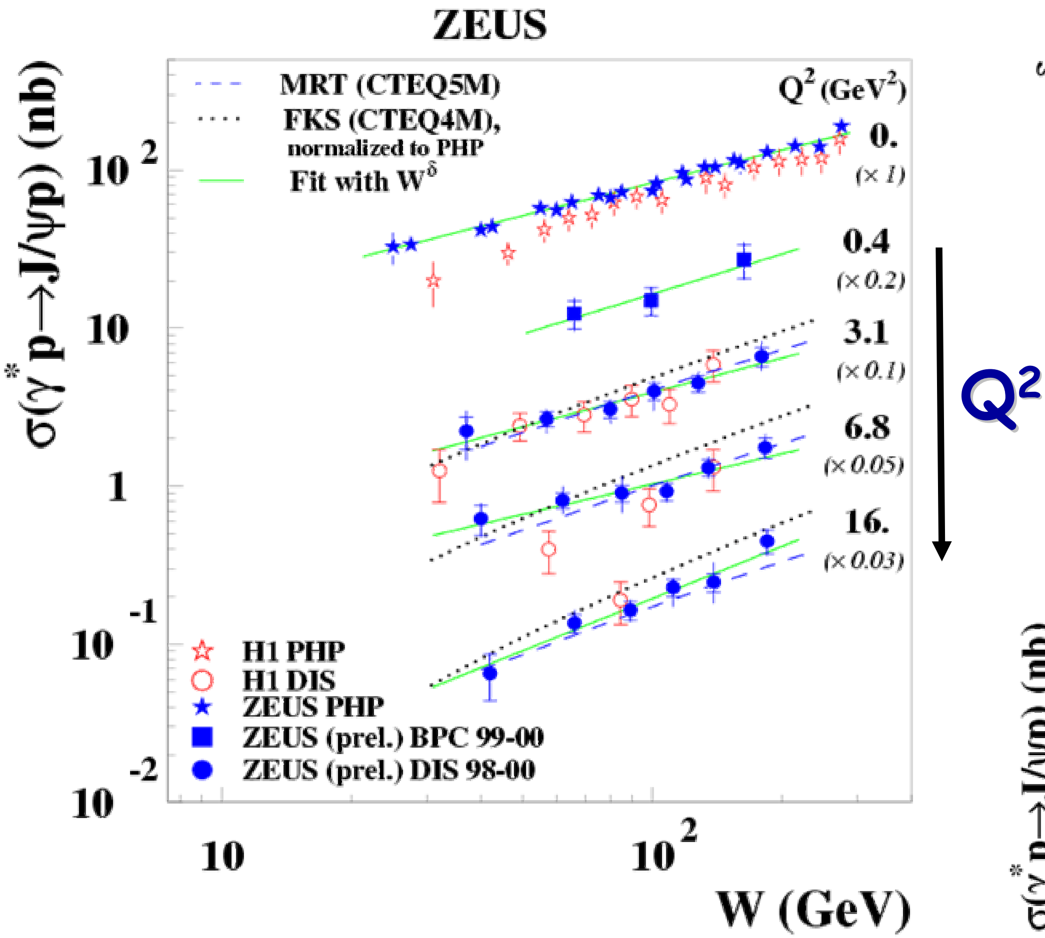


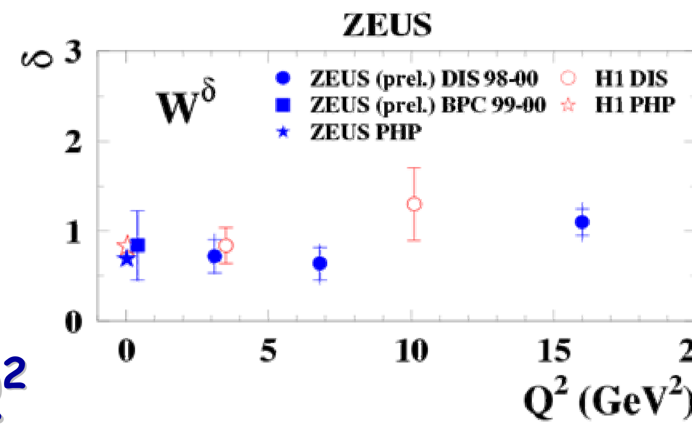
➔ production of ψ(2S) suppressed

➔ energy dependence similar to J/ψ: wave function + QCD o.k.

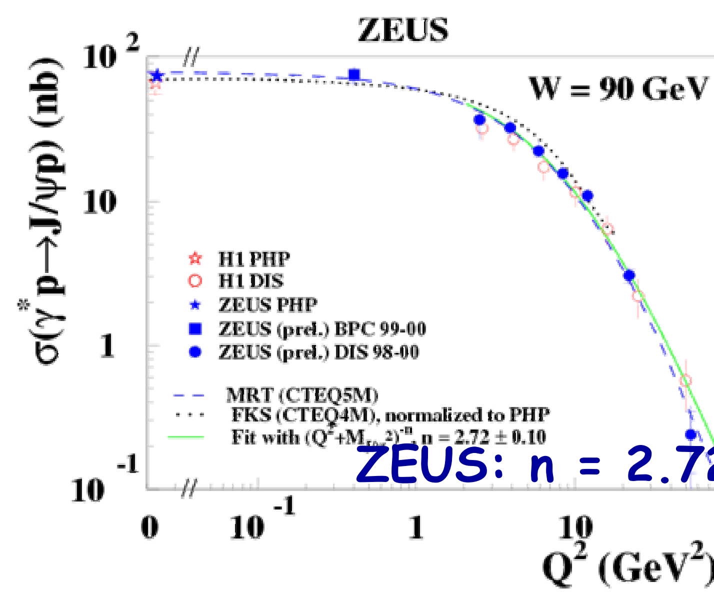
➔ t-dependence of ψ(2S) similar to J/ψ

Elastic J/ψ Electroproduction





→ δ flat in Q² : δ ~ 0.7



ZEUS: n = 2.72±0.10

➔ J/ψ production "hard" process

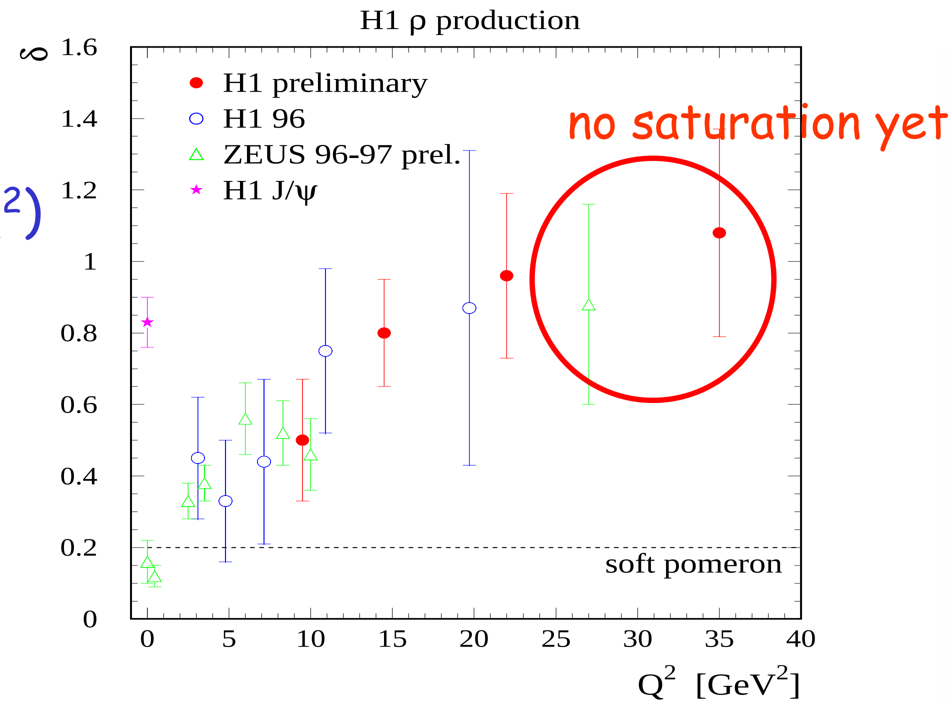
➔ pQCD models using xg ~ o.k.

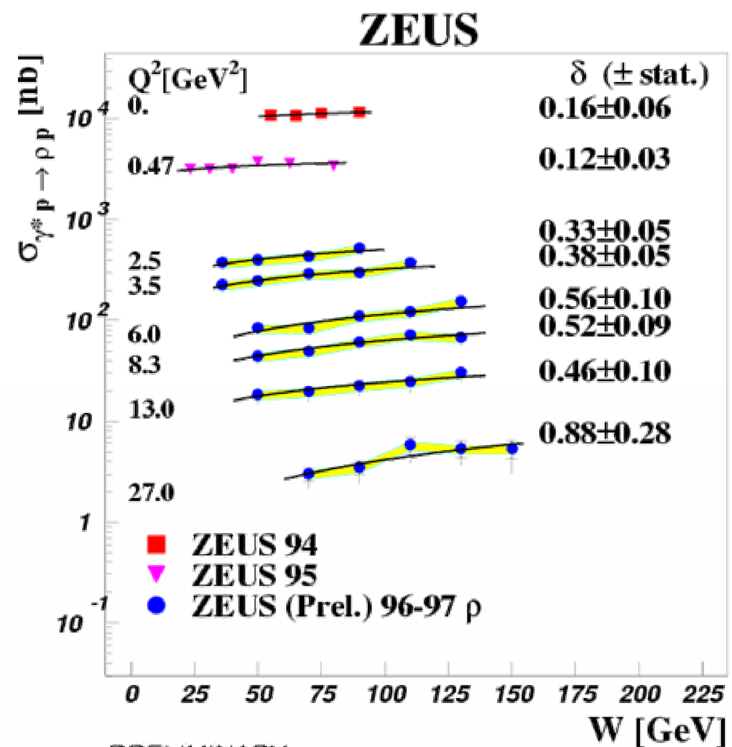
… but new level of prec. of data!

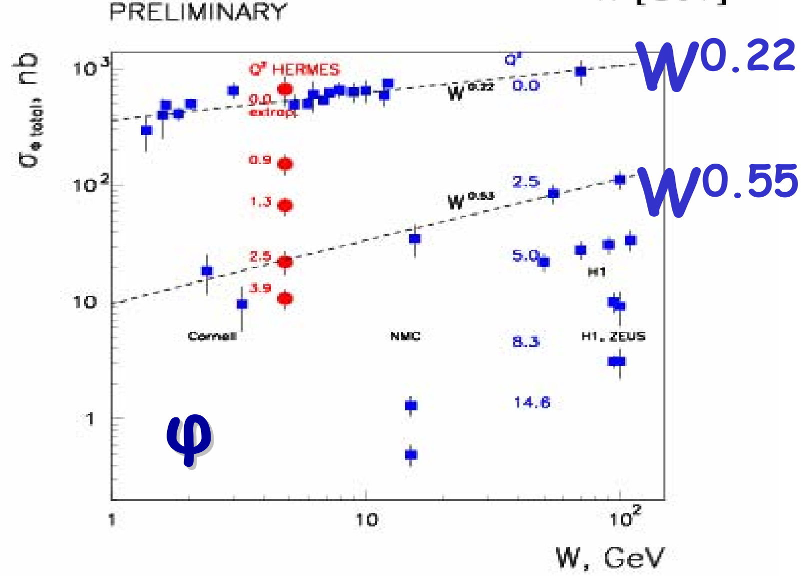
Elastic ρ^o Electroproduction

W dependence : fit $\sigma(W) \propto W^{\delta}$

$\delta(Q^2)$





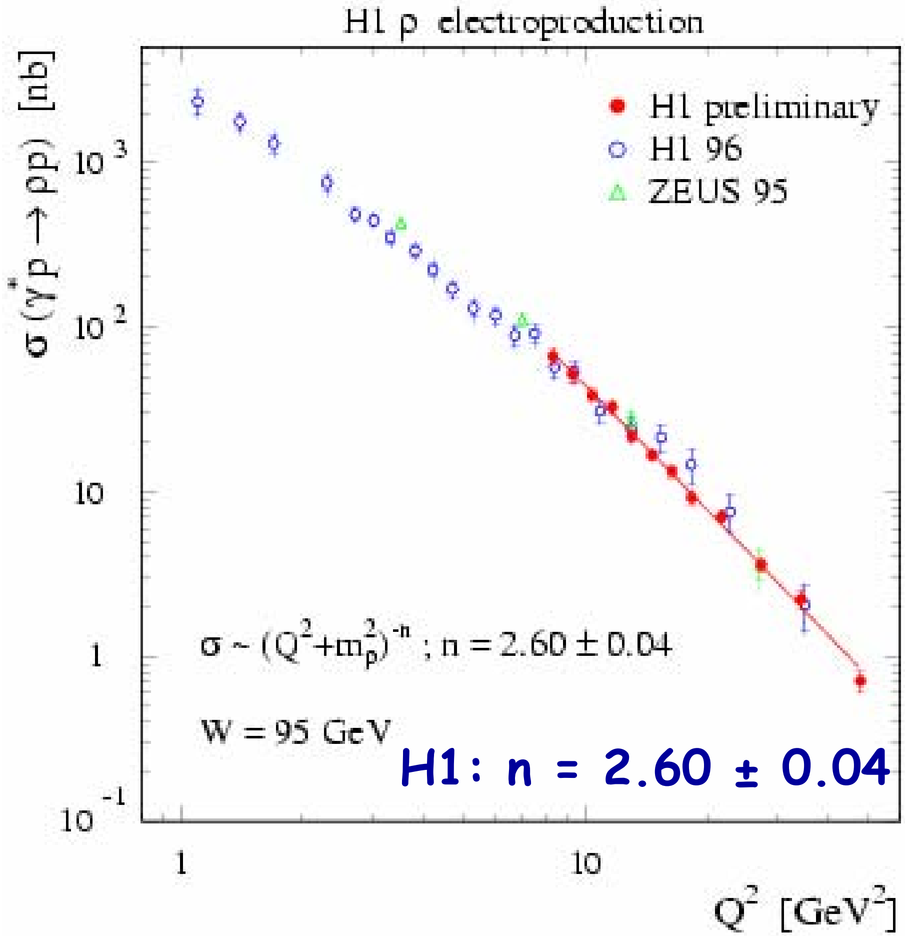


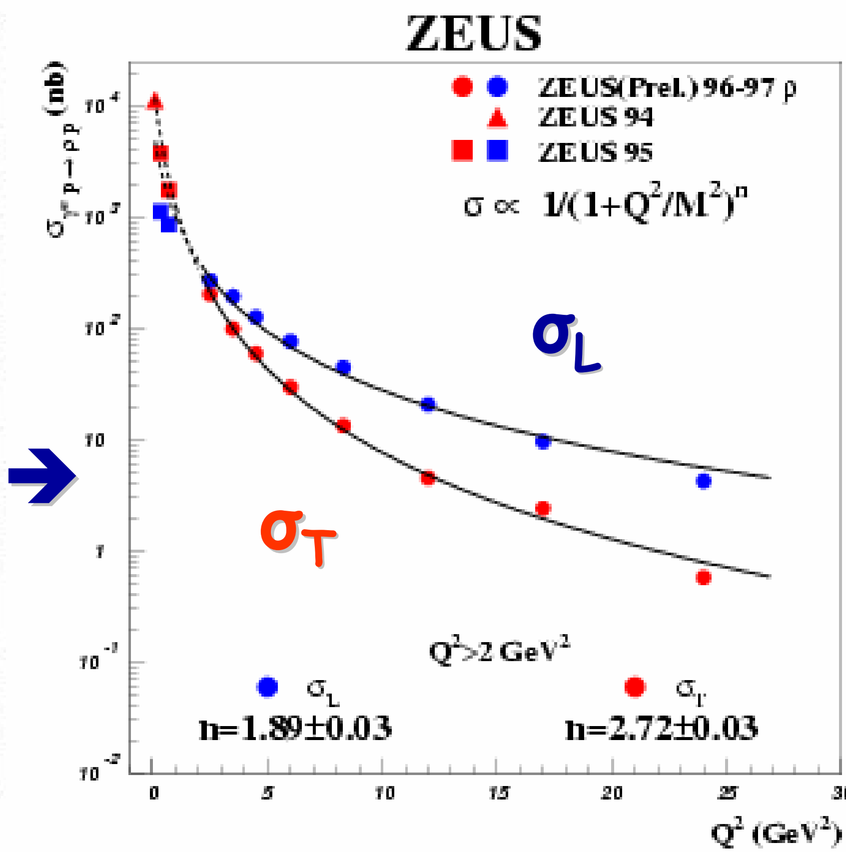
➔ δ increases with Q^2

➔ for ρ: high Q^2 possible hard scale!
… but also for φ?

Elastic ρ^o Electroproduction

Q^2 dependence : fit $\sigma(Q^2) \propto (Q^2 + M_\rho^2)^{-n}$

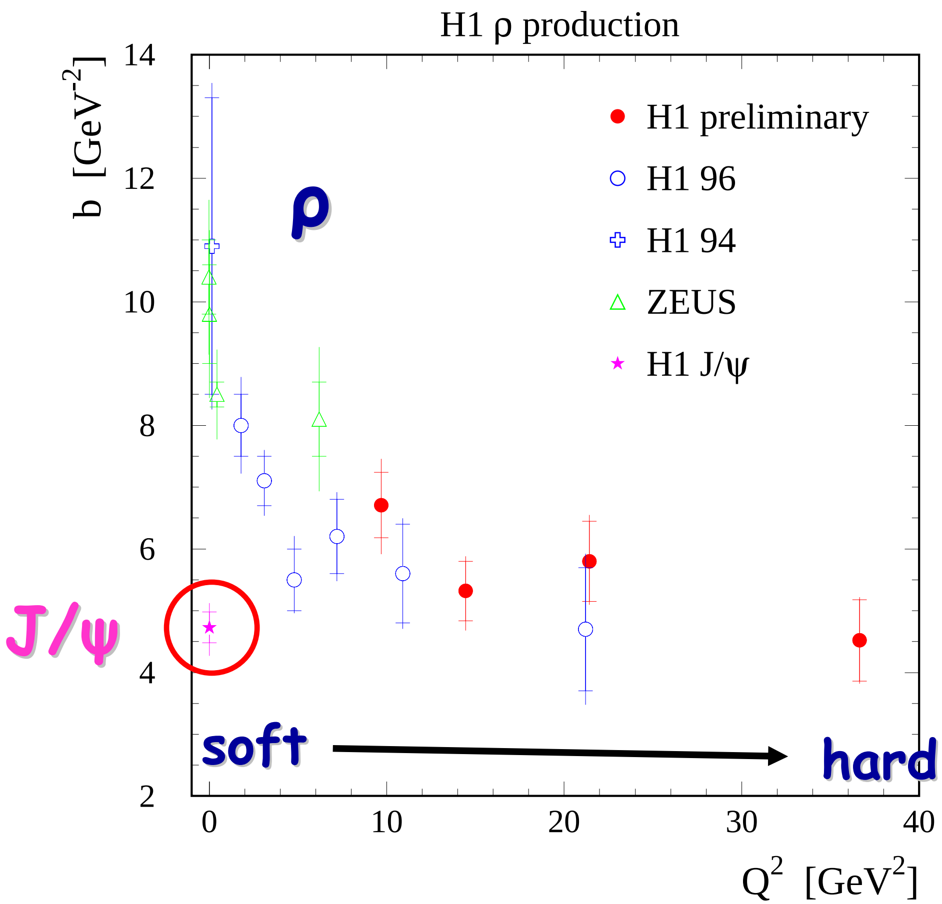


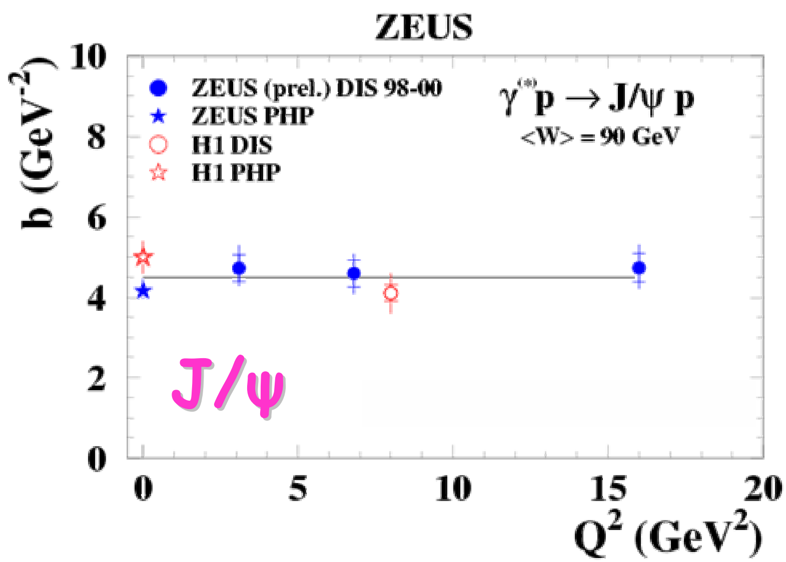


pQCD: $\sigma_L \propto \alpha_s^2 / Q^6 \cdot [xg]^2$

→ steep rise of gluon density expected to weaken $1/Q^6$ dependence

b(Q^2) in Elastic Electroproduction: ρ vs J/ψ





ZEUS: $\langle b \rangle_{J/\psi} = 4.3 \pm 0.2$ GeV^{-2}

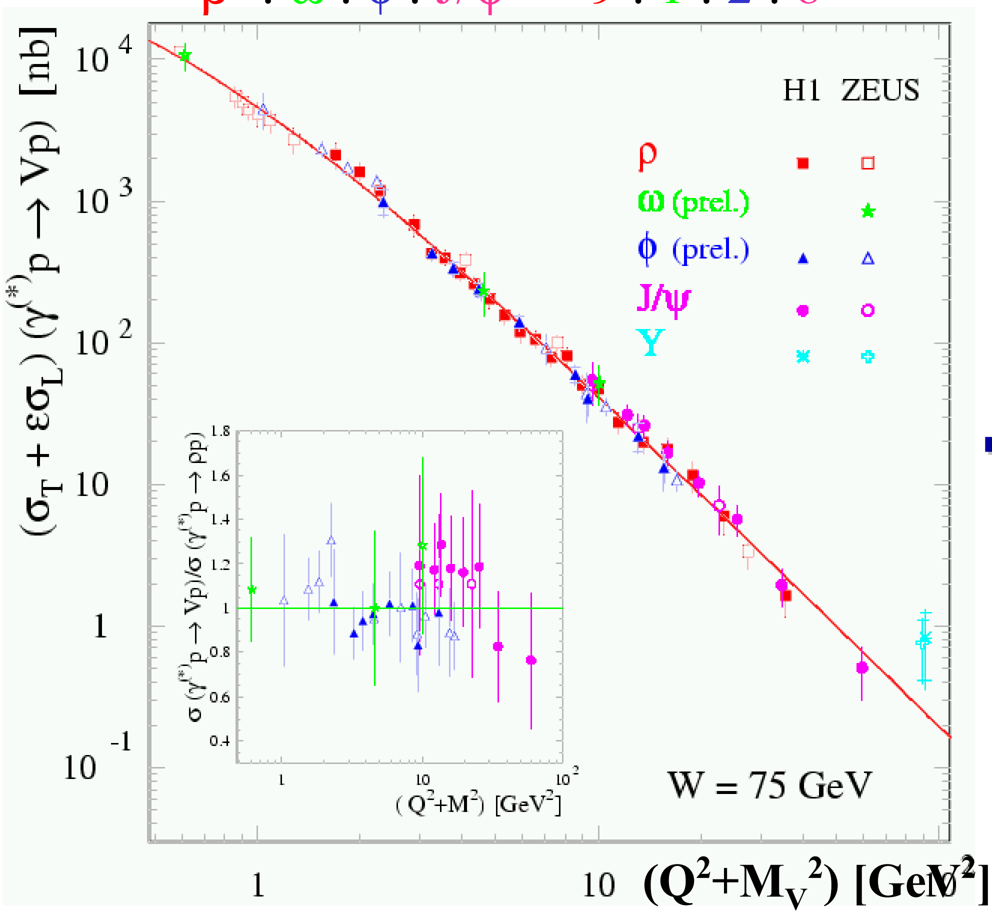
➔ slope b_ρ decreases with Q^2 : $b_\rho \approx b_{J/\psi}$ at high Q^2

➔ universal |t|-dependence if scale (Q^2 or M^2) is large

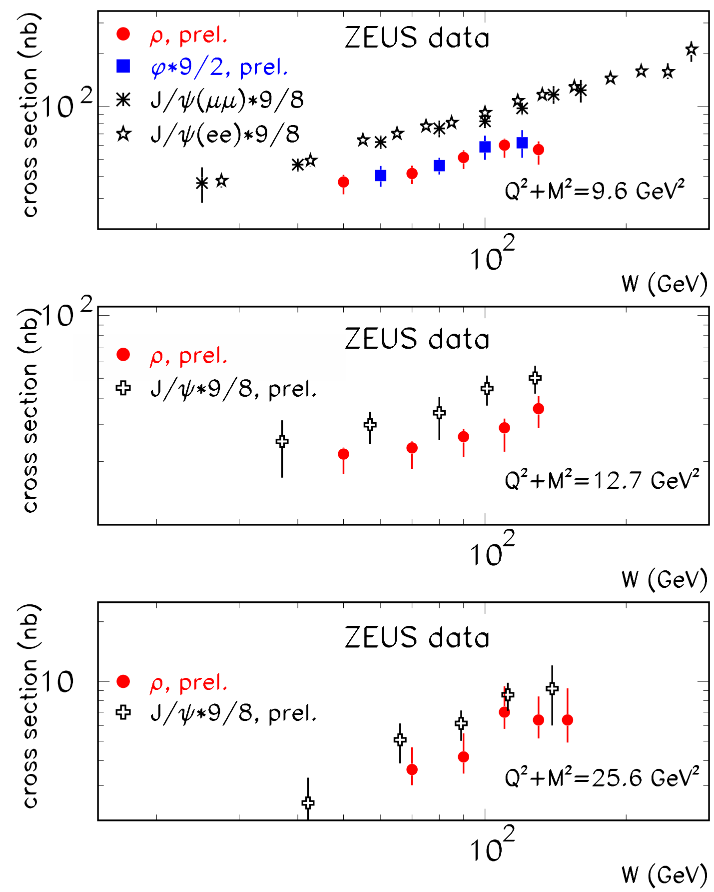
Universality of VM Production?

VM cross-sections scaled by SU(4) factors:

$\rho^0 : \omega : \phi : J/\psi = 9 : 1 : 2 : 8$



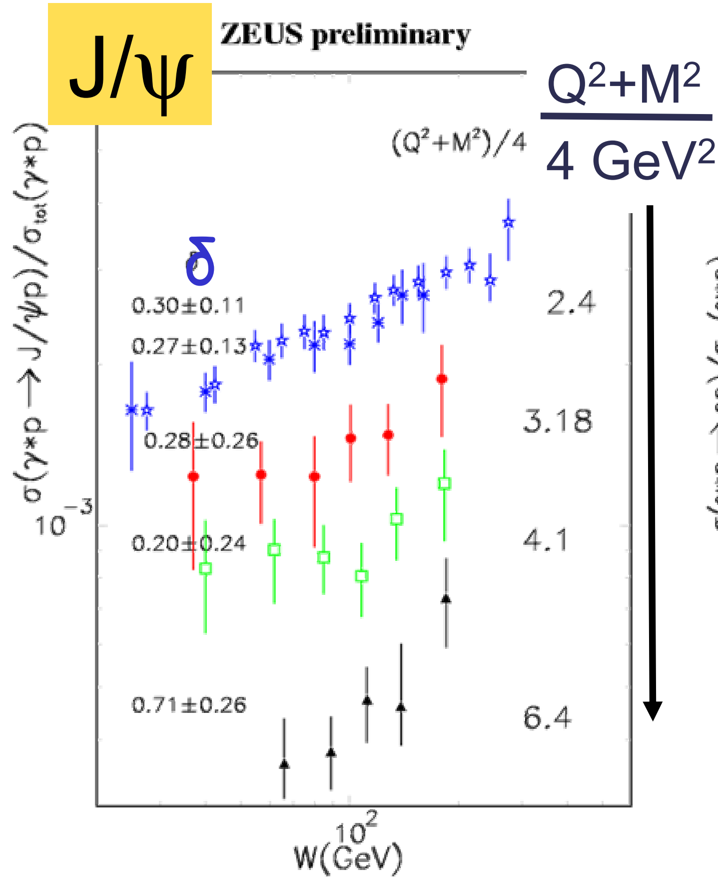
... more precise look

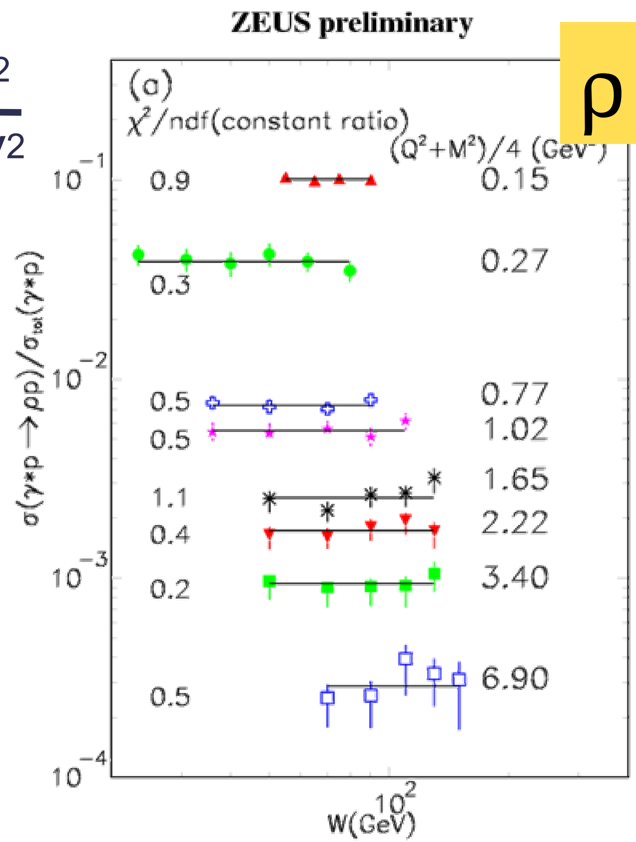


→ no simple universality for VM if $Q^2 + M^2$ is used as scale

→ naïve SU(4) may be altered by VM wave function effects

Universality of VM Production : Ratio σ_{VM}/σ_{tot}





pQCD:

$\sigma_V \propto \alpha_S/Q^6\ |xG(x,Q^2)|^2$

$\sigma_V/\sigma_{tot} \propto W^{2\lambda}/b$

Regge:

$\sigma_V \propto\ W^{4\,(\alpha(0)\,-\,1)}$

$\sigma_V/\sigma_{tot} \propto W^{2\,(\alpha(0)\,-\,1)}\,/b$

➔ **clear W dependence of $\sigma_{J/\psi}/\sigma_{tot}$**

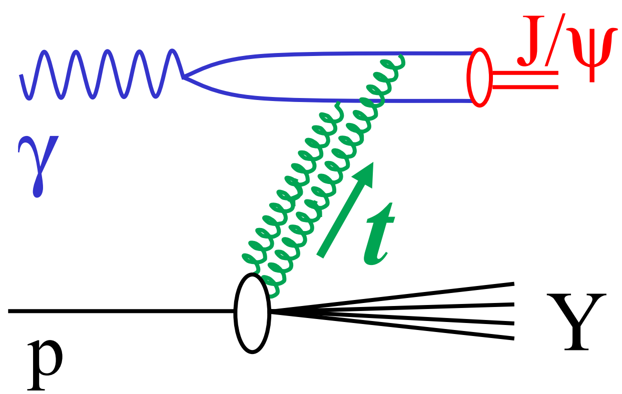
➔ **W independence of σ_ρ/σ_{tot} cannot be explained by pQCD or Regge**

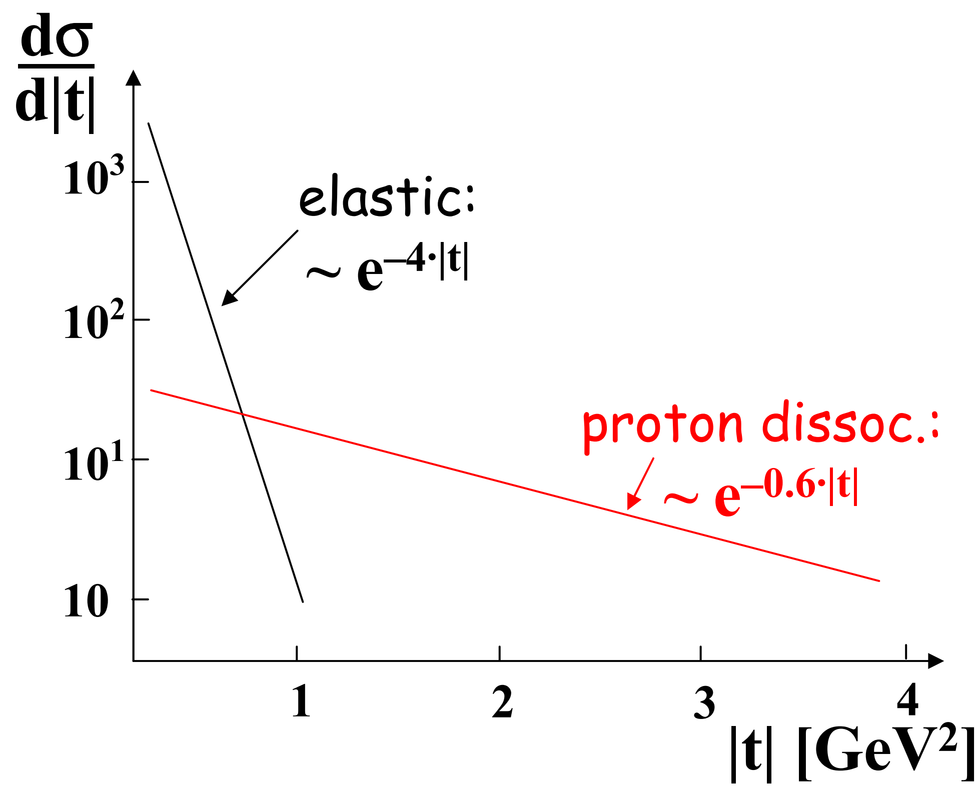
… but pattern similar to inclusive diffraction …?

Proton-Dissociative VM Production in γp : High |t|

high-|t| domain: little explored so far
at high-|t|, proton dissociative production dominates :

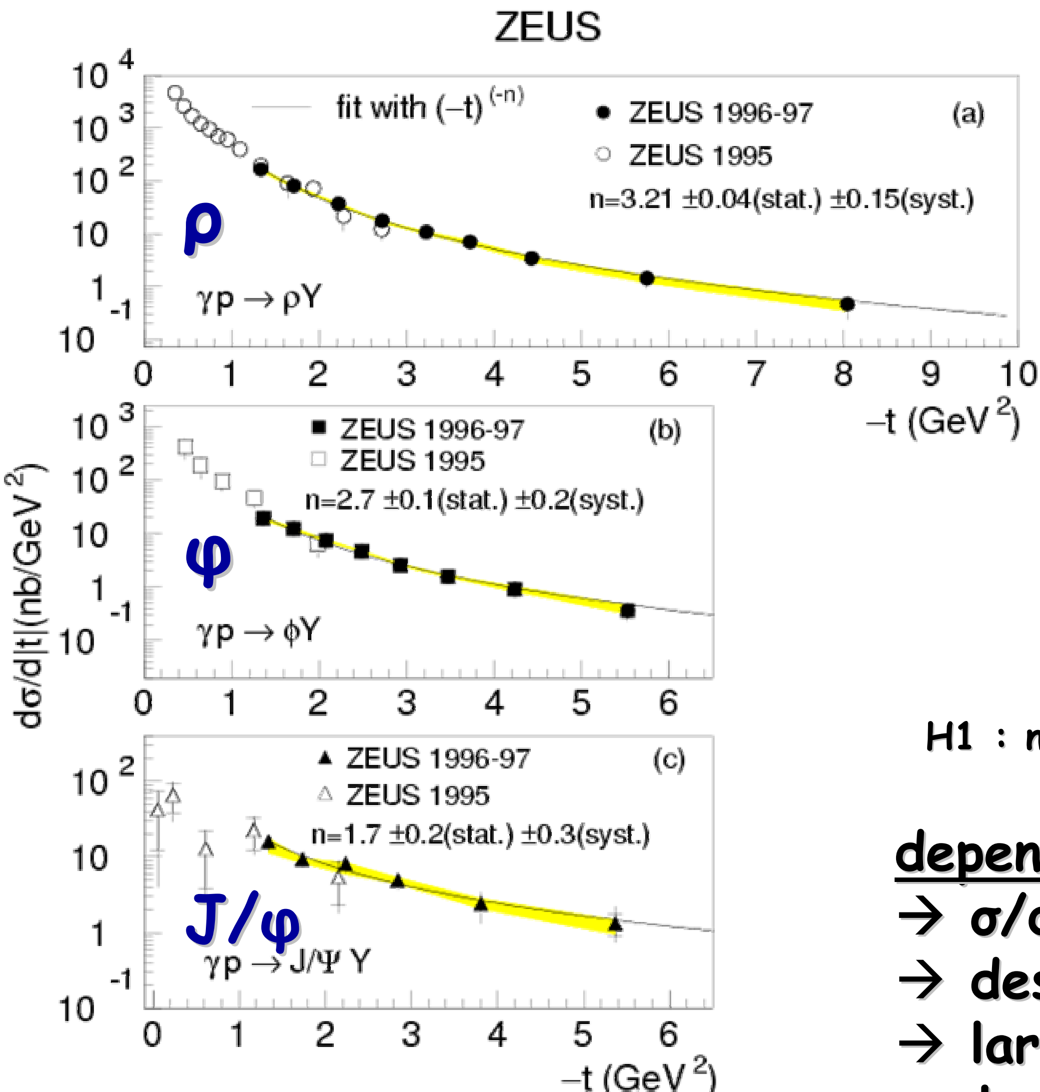
$\gamma^* p \rightarrow J/\psi Y$ at $Q^2 \sim 0$

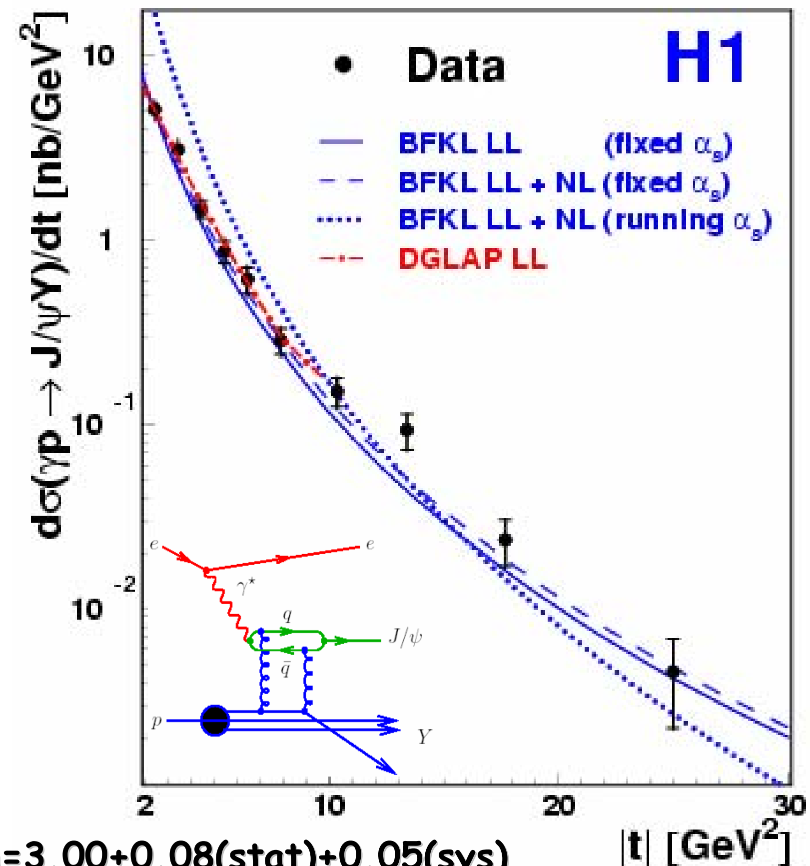




➔ **study proton dissociation to investigate high-|t| dynamics**

VMs at High t





H1 : n=3.00±0.08(stat)±0.05(sys)

→ **power-like behavior**

dependence at large |t|

→ $\sigma/d|t| \sim (t)^{-n}$ (not exponential)

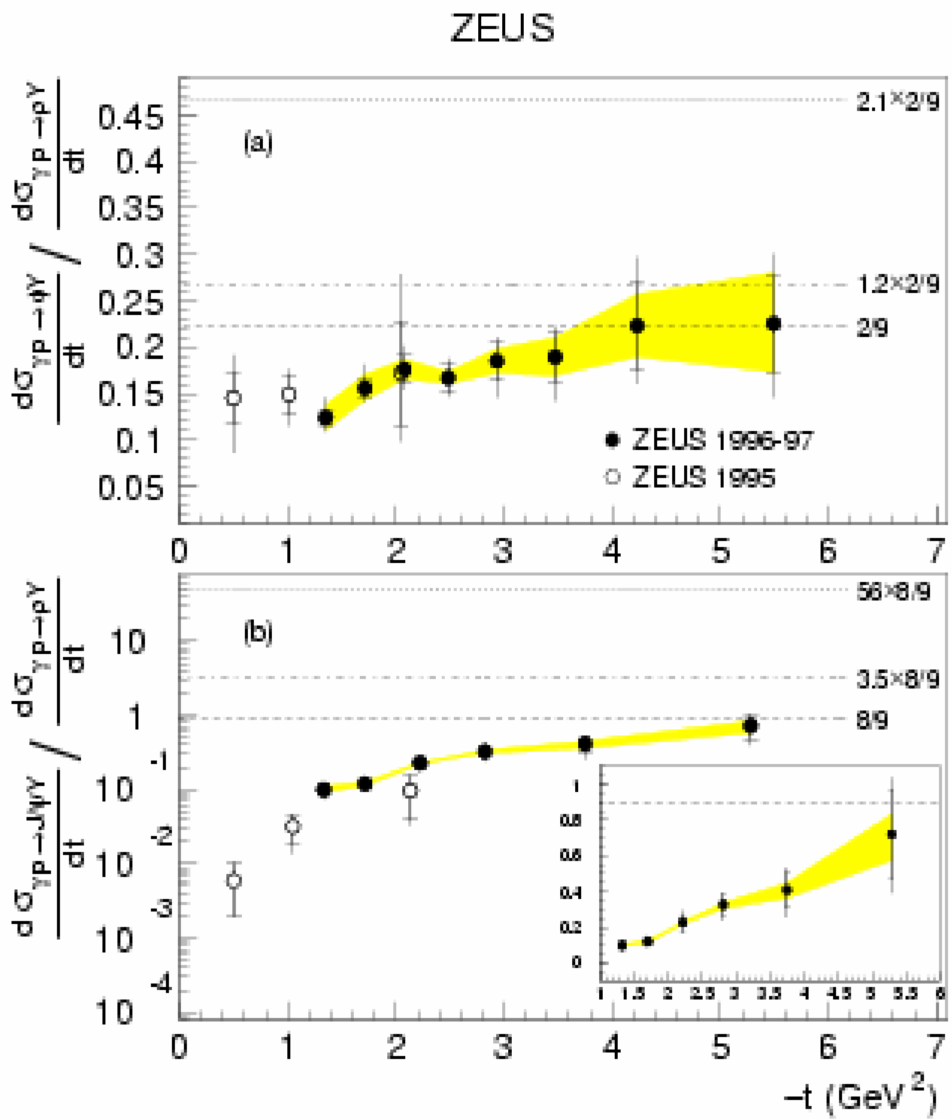
→ described by **BFKL-type behavior**

→ large |t| may provide a hard scale to apply pQCD

VMs at High t : σ_V/σ_ρ and SU(4)

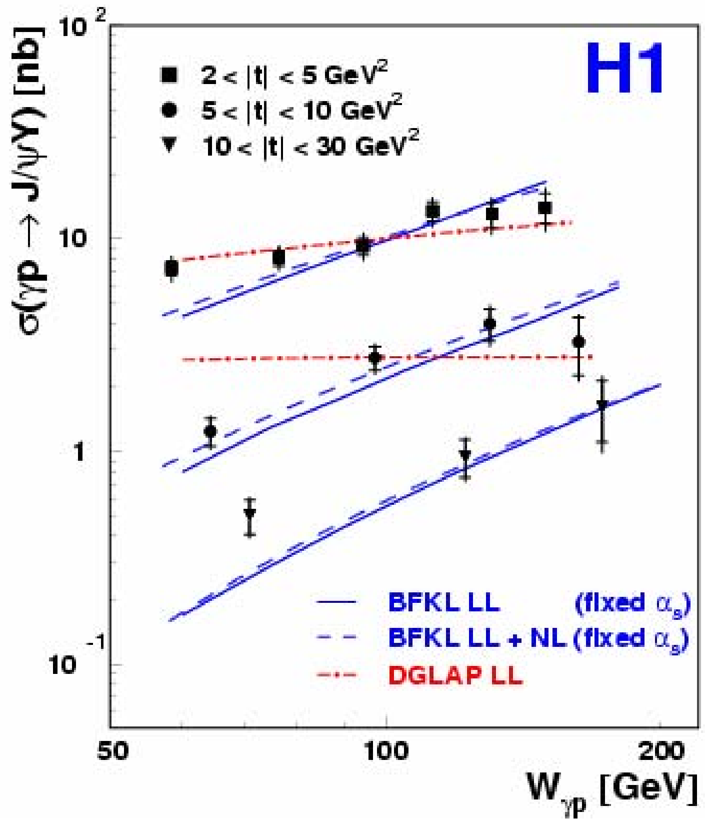
φ

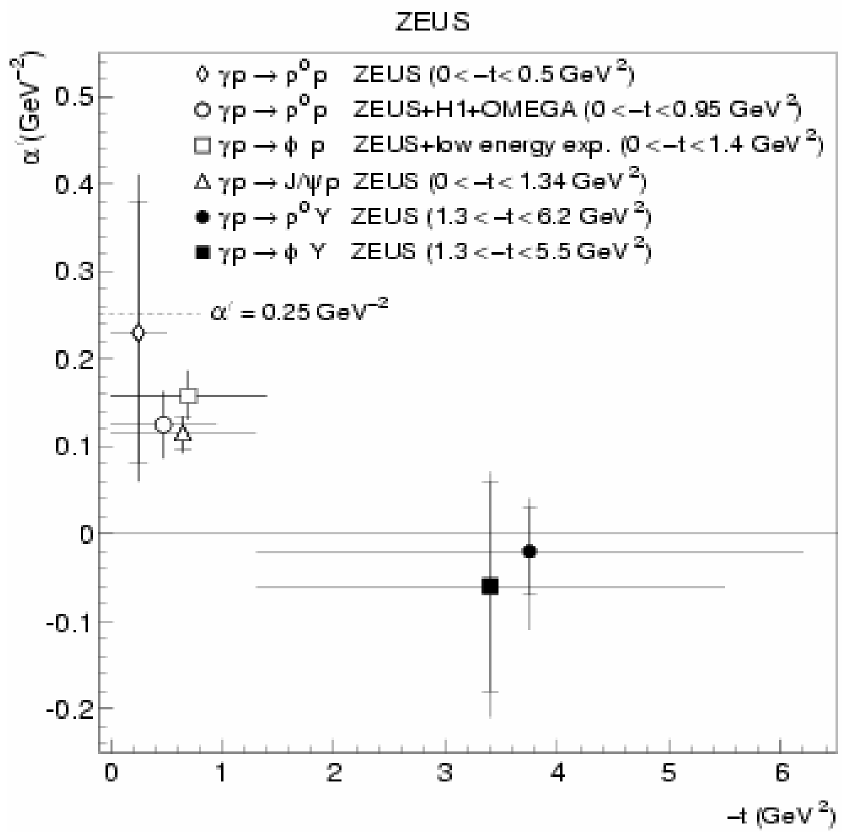
J/φ



➔ indication of flavor independence of VM production at high t?

VMs at High t : t-Dependence of W and α'_P





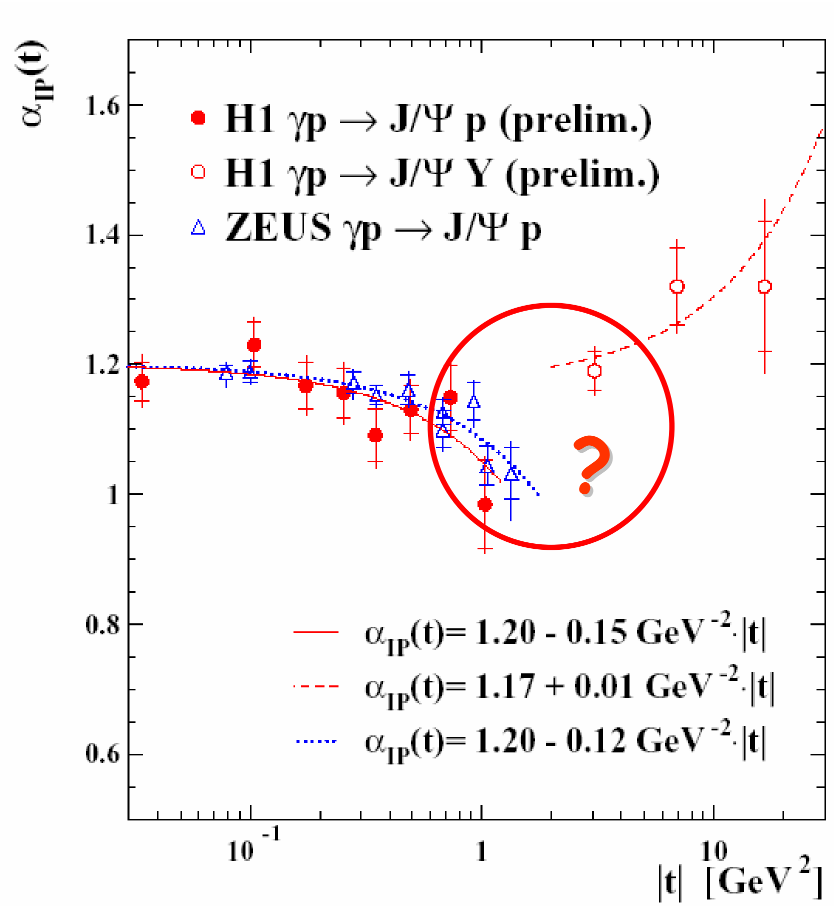
→ W-dependence doesn't change with |t|, described by pQCD

→ t provides a hard scale

→ $\alpha_P(t)$?

Pomeron Trajectory in Dependence of |t|

ZEUS : Pomeron trajectory in $\gamma^* p \rightarrow J/\psi p$ same as in $\gamma p \rightarrow J/\psi p$



$\gamma p \longrightarrow J/\psi p$:

$$\alpha'_{H1} = 0.154 \pm 0.054 \pm 0.023$$
$$\alpha'_{ZEUS} = 0.115 \pm 0.018^{+0.008}_{-0.015}$$
$$\alpha'_{soft} = 0.25$$

$\Rightarrow$ moderate shrinkage seen

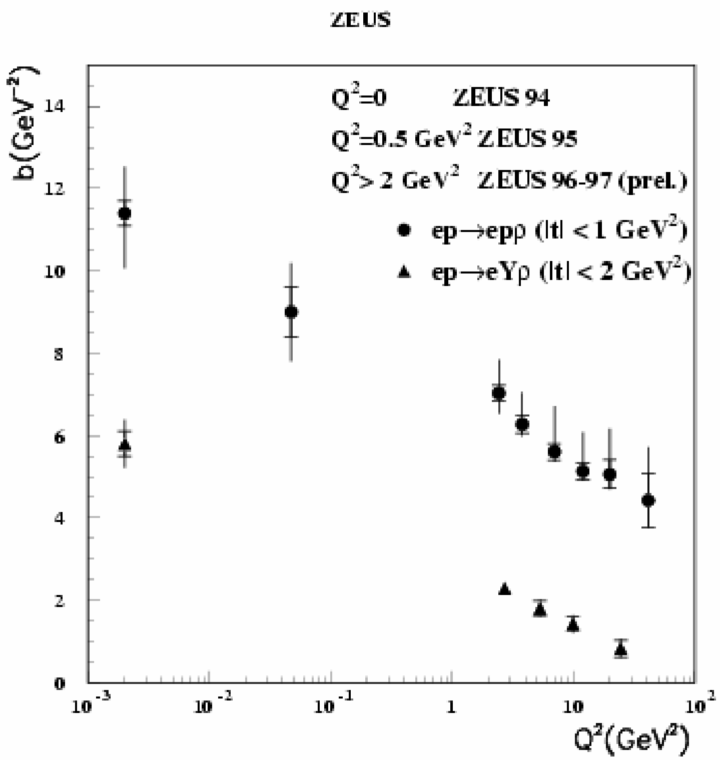
$\gamma p \longrightarrow J/\psi Y$:

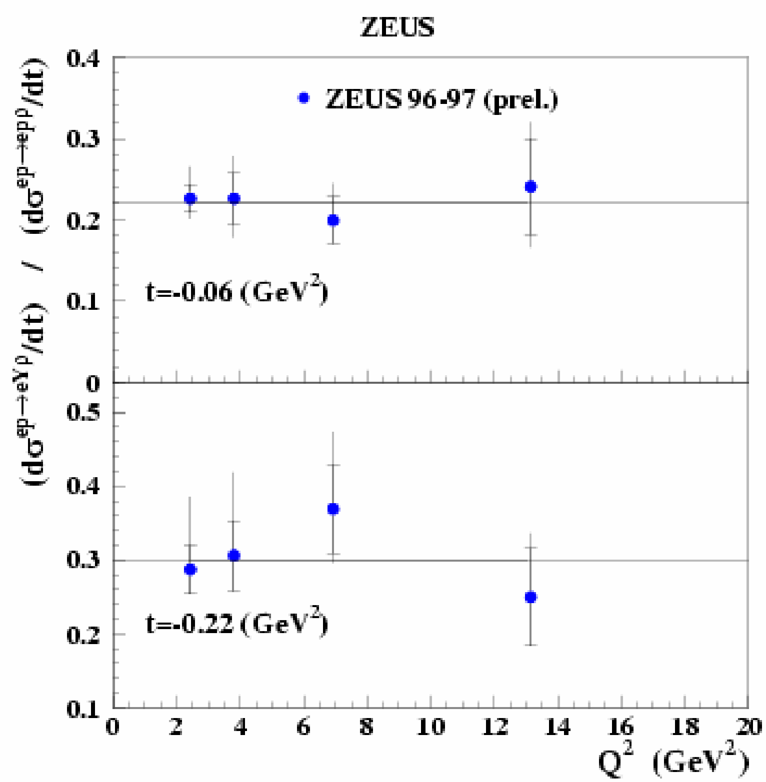
$$\alpha'_{H1} = -0.013 \pm 0.007 \pm 0.007$$

$\Rightarrow$ shrinkage consistent with zero

➔ change of production mechanism? BFKL?

Proton-Dissociative ρ^0 Electroproduction

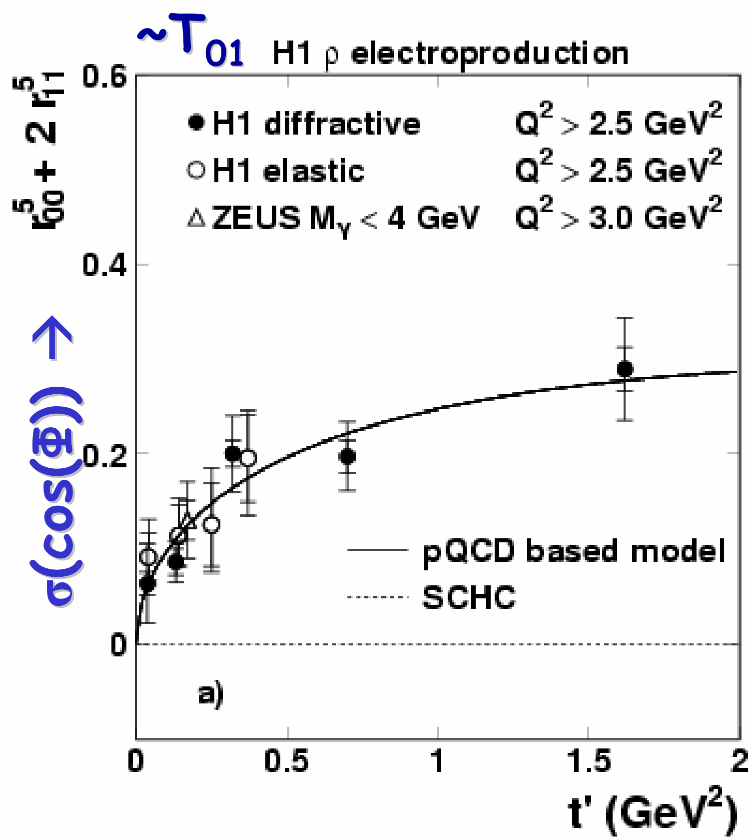


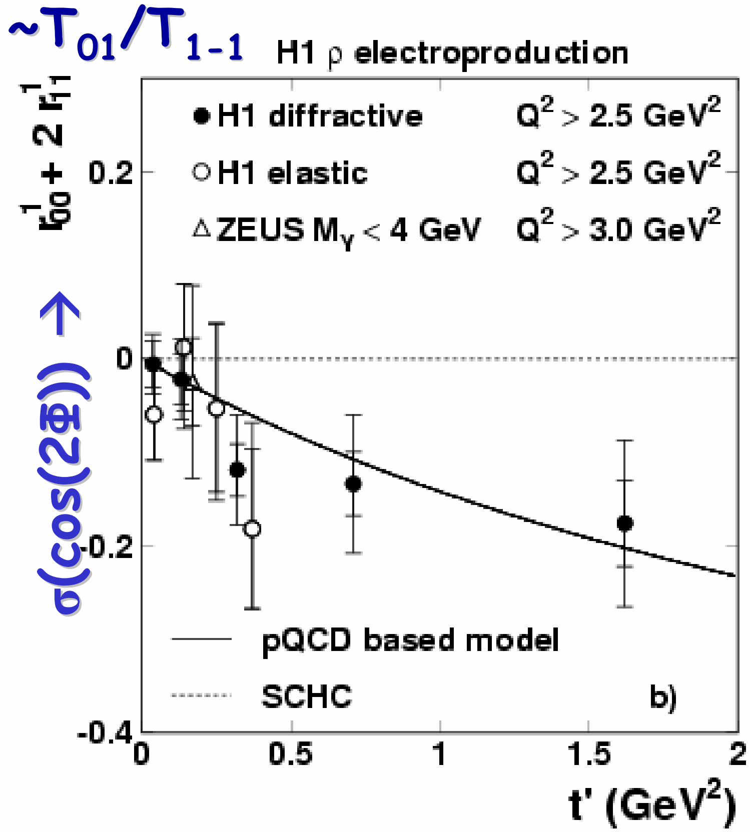


➔ factorization holds at proton vertex at low |t| :
probability of proton disscociation is independent of projectile

Exclusive ρ° in γ*p : Helicity Studies

angular distribution of ρ → ππ decay gives information about helicity amplitudes $T_{\lambda\rho\lambda\gamma}$ via spin-density matrix elements : test SCHC





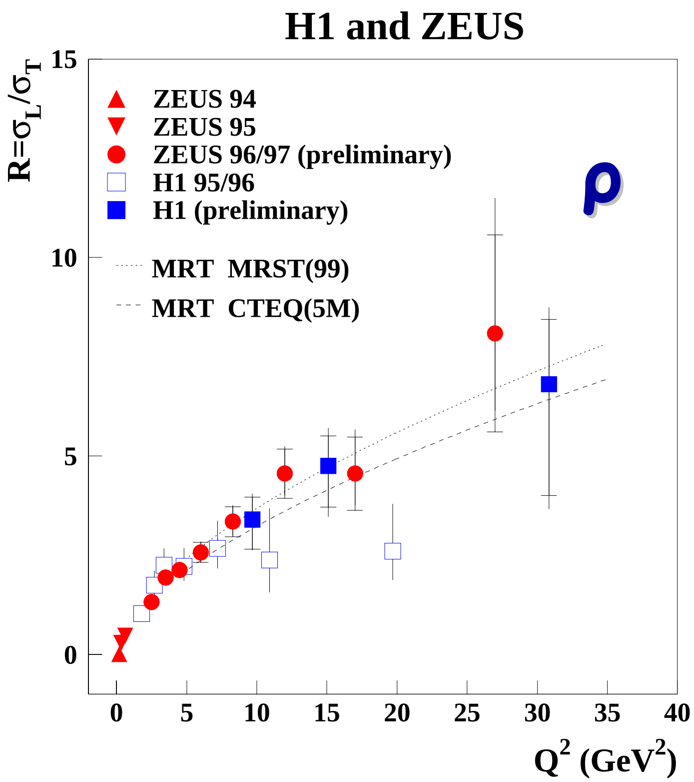
→ **single-flip amplitude significant at high t**

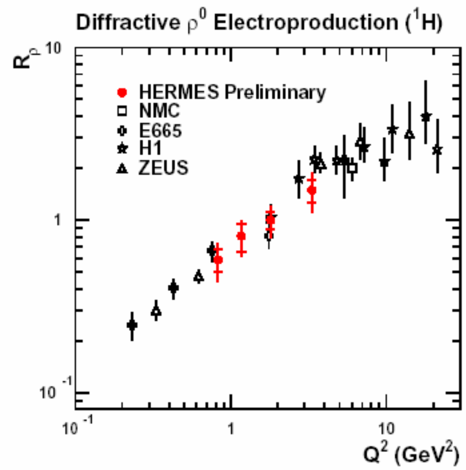
→ **single-flip » double flip amplitude**

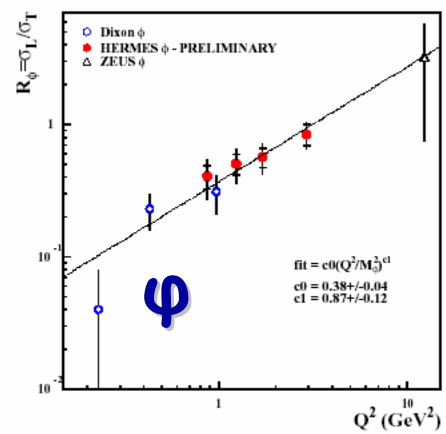
➔ **measurements well described by pQCD model of 2-gluon exchange**

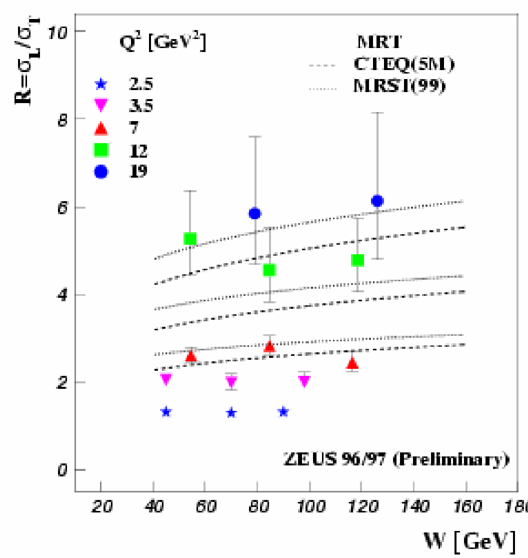
Exclusive ρ^o and φ in γ^*p : $R = \sigma_L/\sigma_T$

assuming SCHC + knowledge of γ^* polarisation: $R = \frac{\sigma_L}{\sigma_T} = \frac{1}{\epsilon}\frac{r_{00}^{04}}{1 - r_{00}^{04}}$





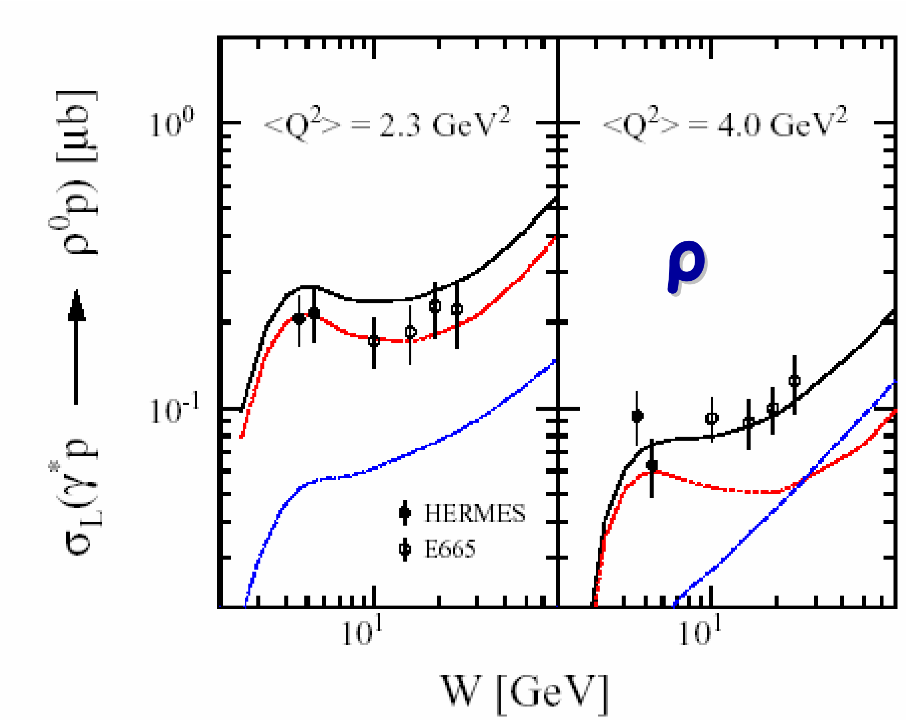


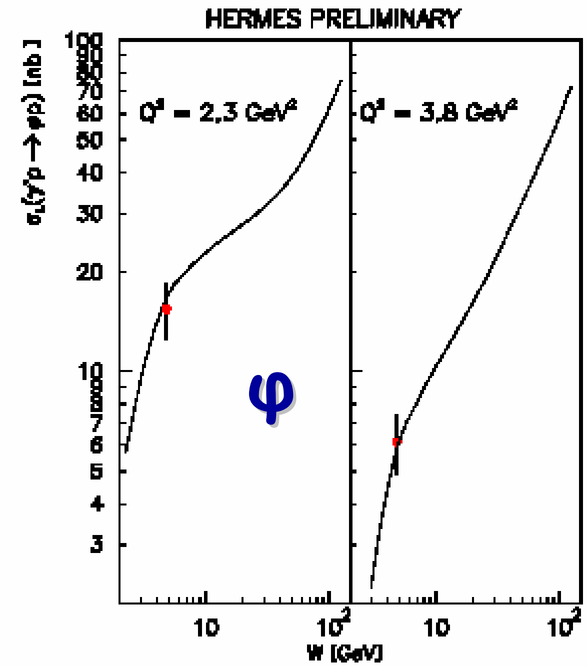


➔ rise of R with Q^2

➔ same W-dependence for σ_L and σ_T

Exclusive ρ° and φ in γ^*p : σ_L

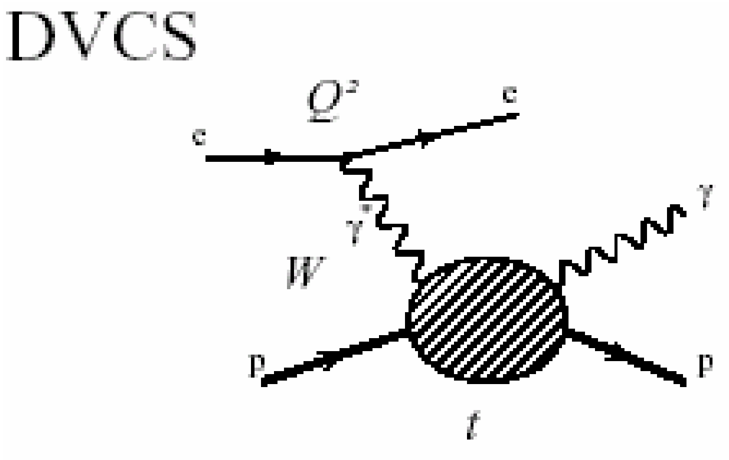


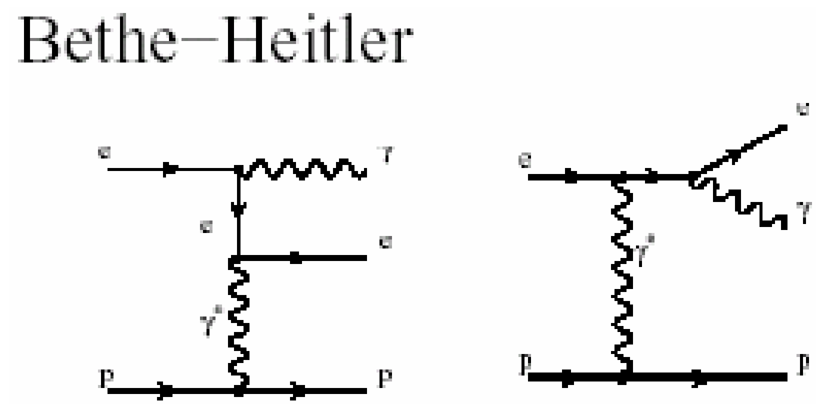


[Guichon, Guidal, Vanderhaegen, Phys. Rev. D 60 (1999), 094017; private communication 2001]

GPD calculations:
- ○ quark exchange mechanism dominates $\sigma_L(\gamma^* p \rightarrow \rho^0 p)$
- ○ 2-gluon exchange mechanism dominates $\sigma_L(\gamma^* p \rightarrow \phi\ p)$

DVCS : Introduction





elastic production of real photon

$d\sigma \propto |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + |\tau^*_{DVCS}\,\tau_{BH}| + |\tau_{DVCS}\,\tau_{BH}^*|$

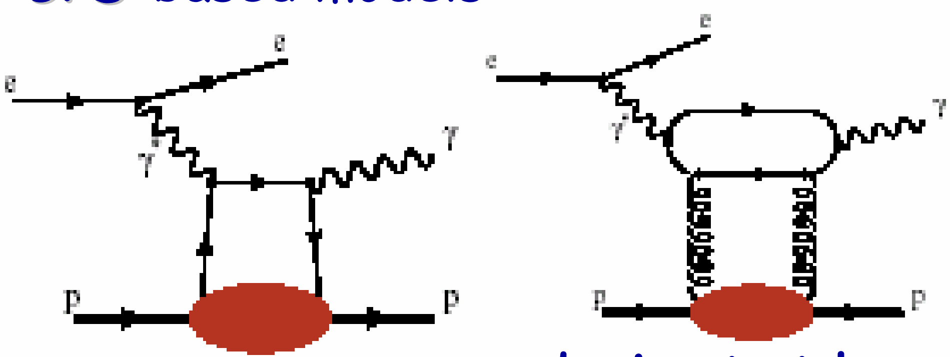
DVCS : QCD process → sensitive to **underlying dynamics**

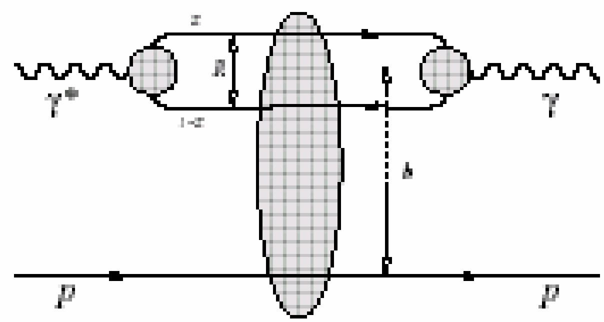
Bethe-Heitler : QED process → background and **interference**

H1,ZEUS : high Q^2, small x ➔ DVCS > BH ➔ DVCS cross section
HERMES : low Q^2, medium x ➔ BH > DVCS ➔ DVCS asymmetries

DVCS : Models

GPD based models





Color Dipole based models

dominant at low x

$$A \sim \int \frac{dx}{x} C\left(\xi / x, Q^2\right) G\left(x, \xi, Q^2\right)$$

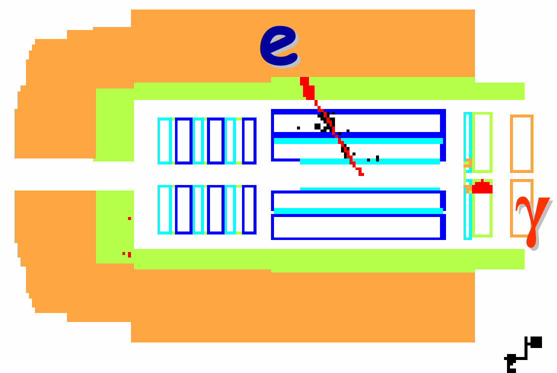
- Frankfurt, Freund and Strikman
- Freund and McDermott

$$A \sim \int \psi_{ini} \sigma_D \psi_{out}$$

- Donnachie and Dosch
- Forshaw, Kerley and Shaw
- McDermott, Frankfurt, Guzey and Strikman

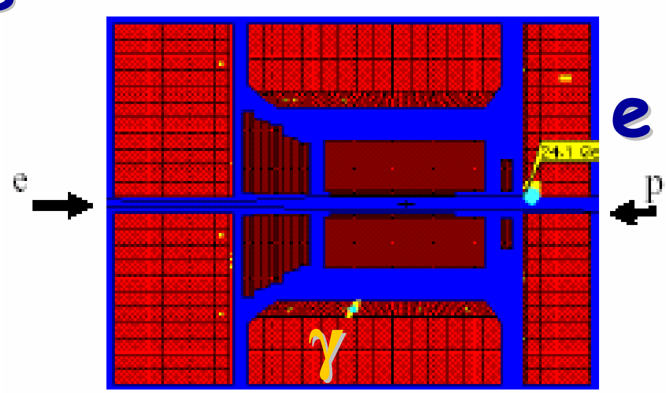
DVCS : Experimental Signatures

BH

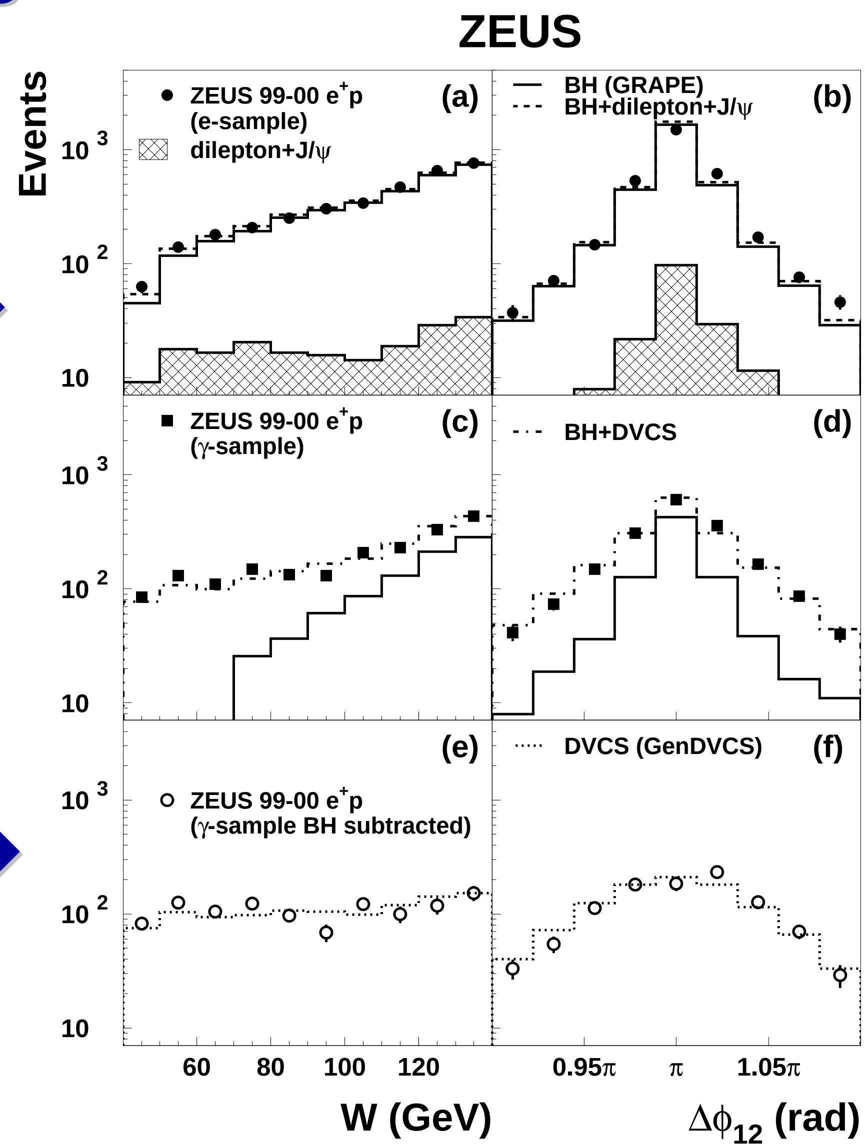


control sample

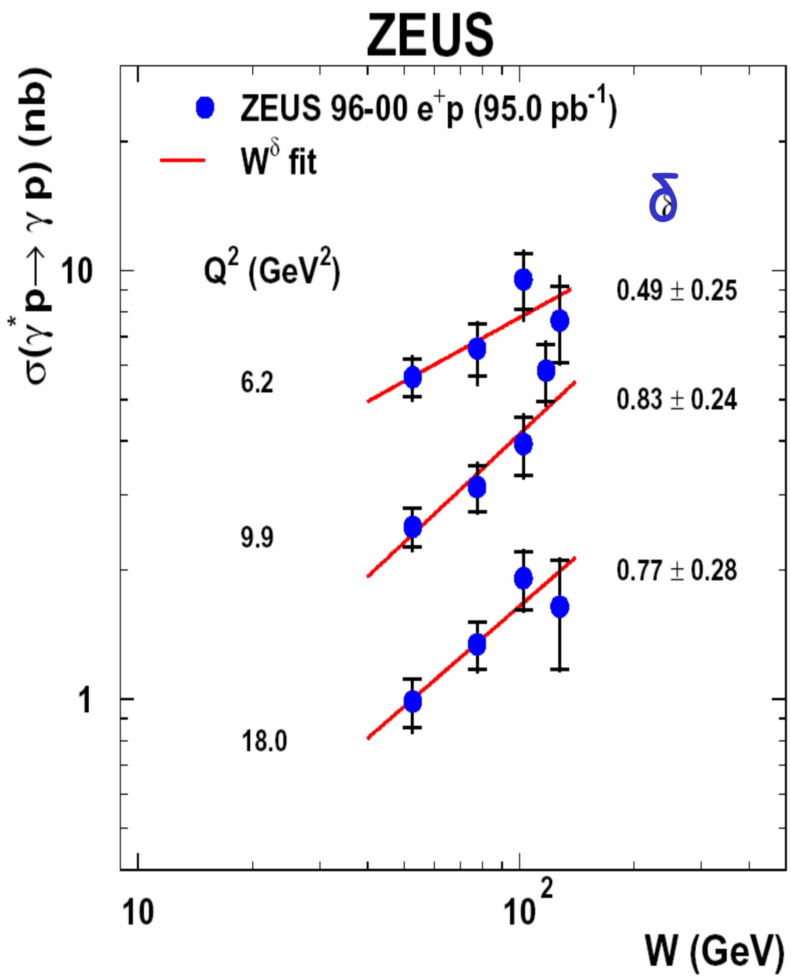
DVCS

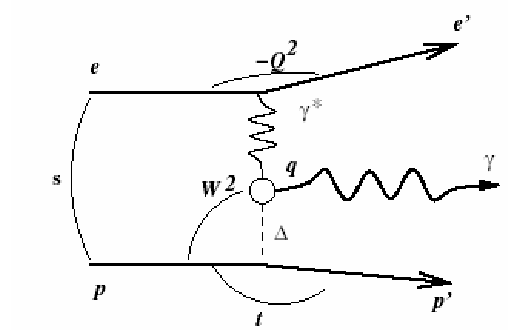


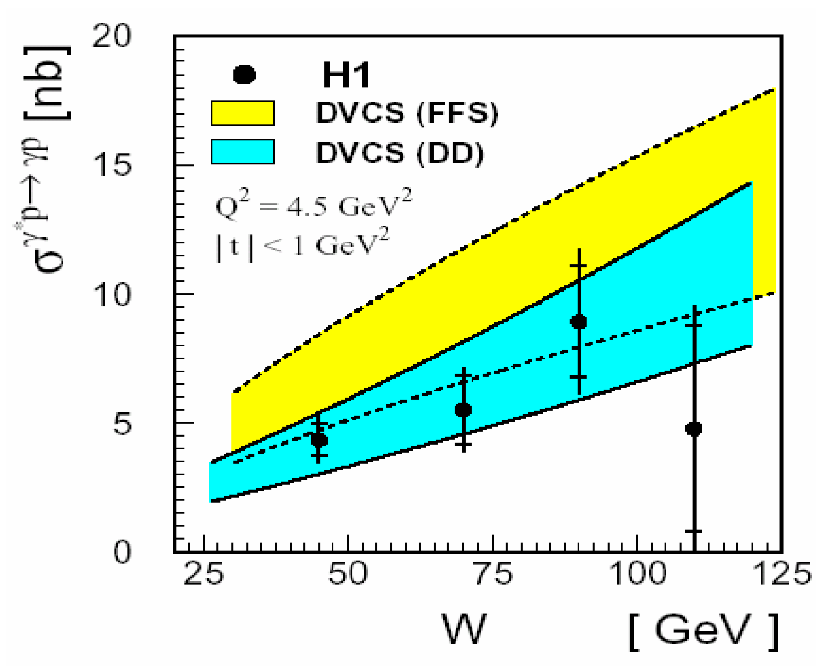
signal sample



DVCS : Cross Section vs W

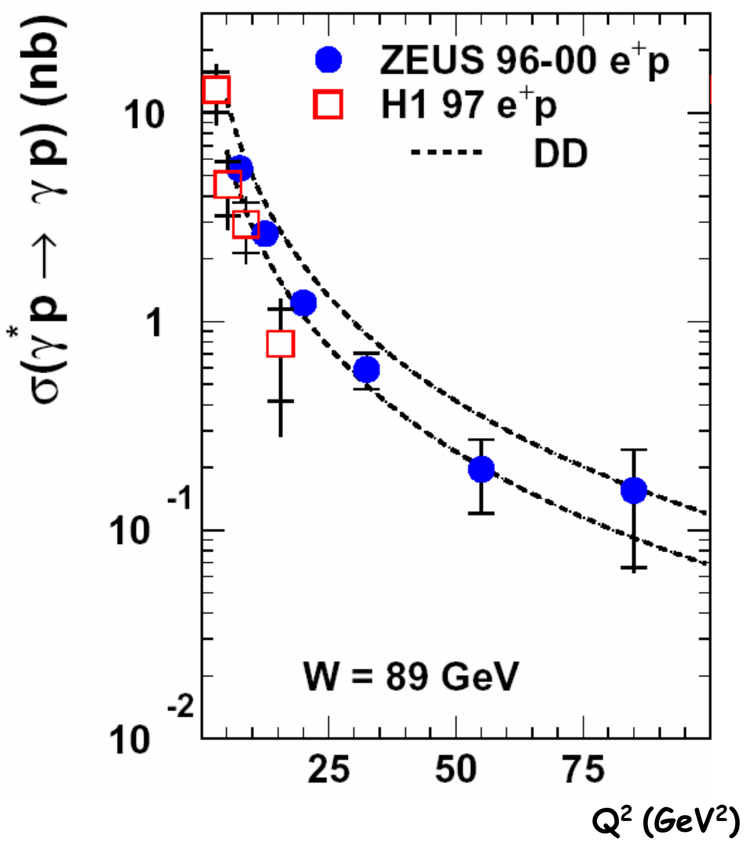


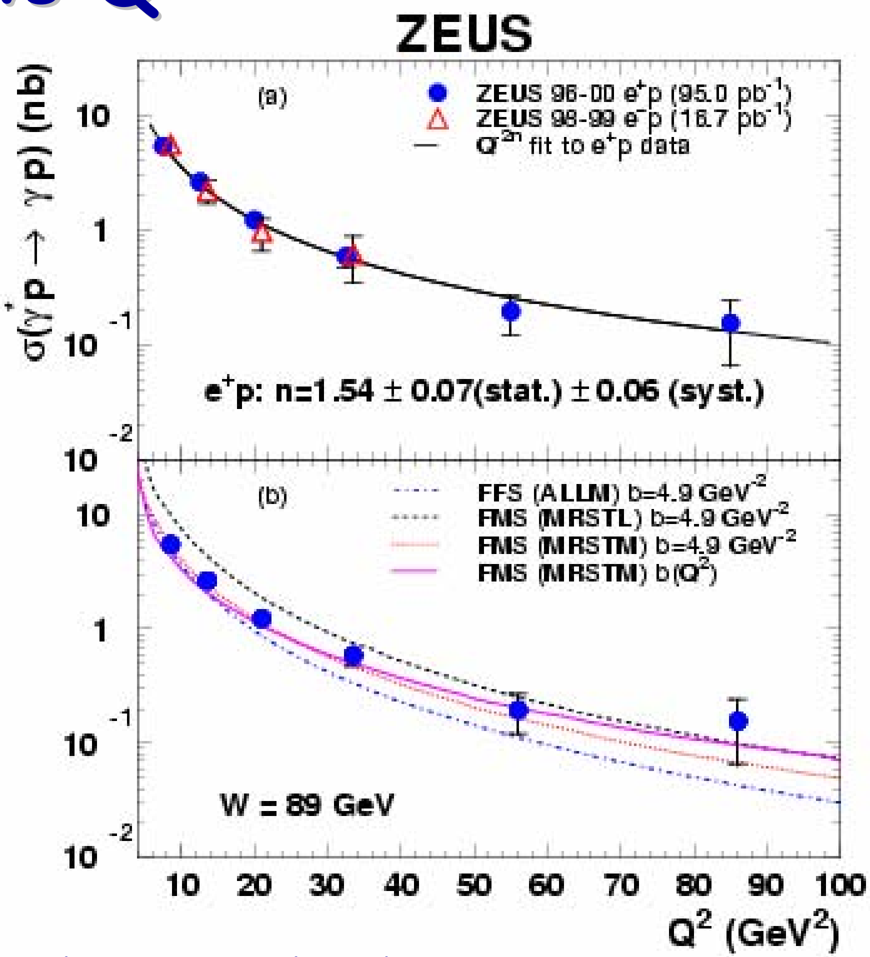




→ W dependence matches $W^{0.7}$ behavior of hard VM production

DVCS : Cross Section vs Q^2



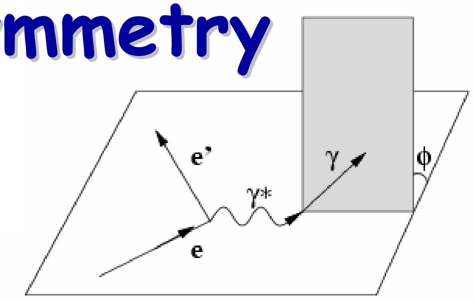


➔ fit Q^{-2n} : n = 1.54 ± 0.07(stat) ± 0.06(sys)

➔ Q^2 dependence well described by GPD or color dipole based models (integrated over experimental t range)

DVCS : Beam Charge and Spin Asymmetry

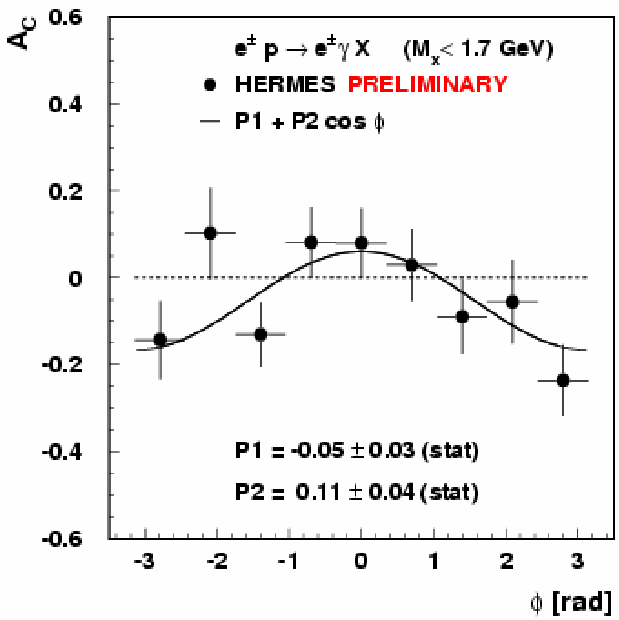
- ➔ explore BH-DVCS interference term
- ➔ BH suppressed in asymmetry measurements
- ➔ BCA and BSA : access to full amplitude



Φ: azimuth between $\gamma\gamma^*$ and e scattering planes

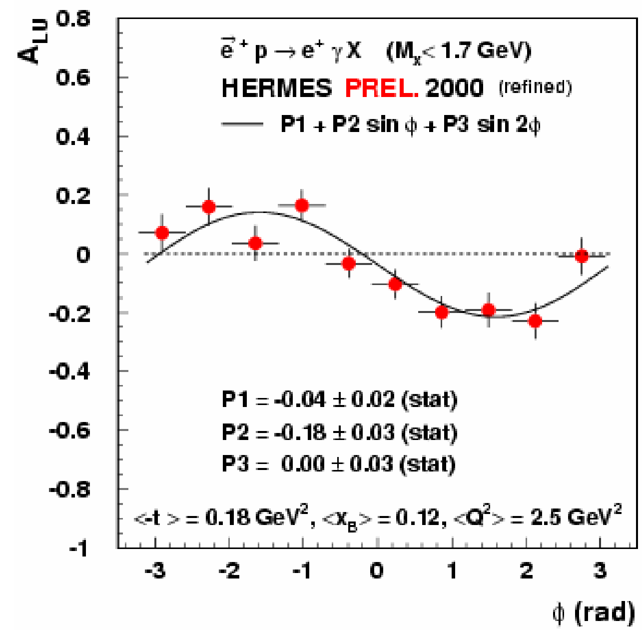
beam charge asymmetry → e^+-e^-

$A_C \sim \mathrm{Re}\,(BH \cdot \mathbf{DVCS^*})\ \mathbf{cos}\ \Phi$

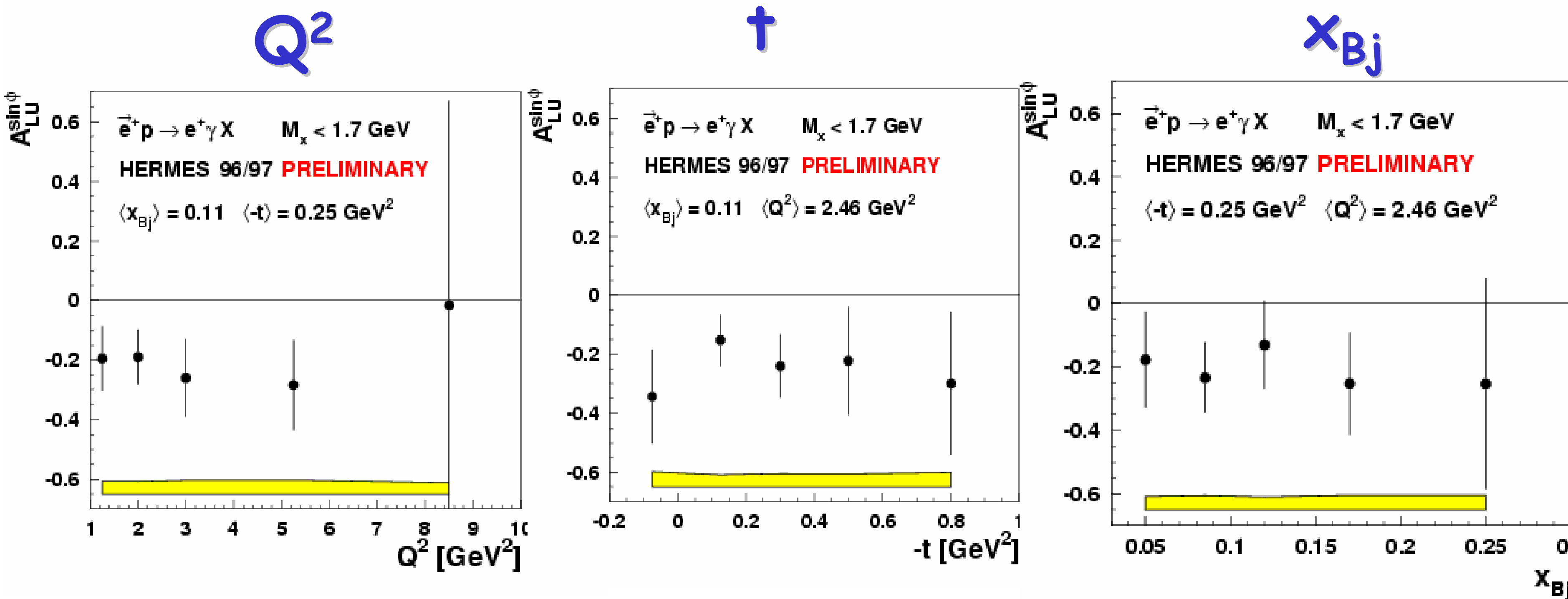


beam spin asymmetry → pol. e beams

$A_{LU} \sim \mathrm{sign}(e) \cdot \mathrm{Im}\,(BH \cdot \mathbf{DVCS^*})\ \mathbf{sin}\ \Phi$

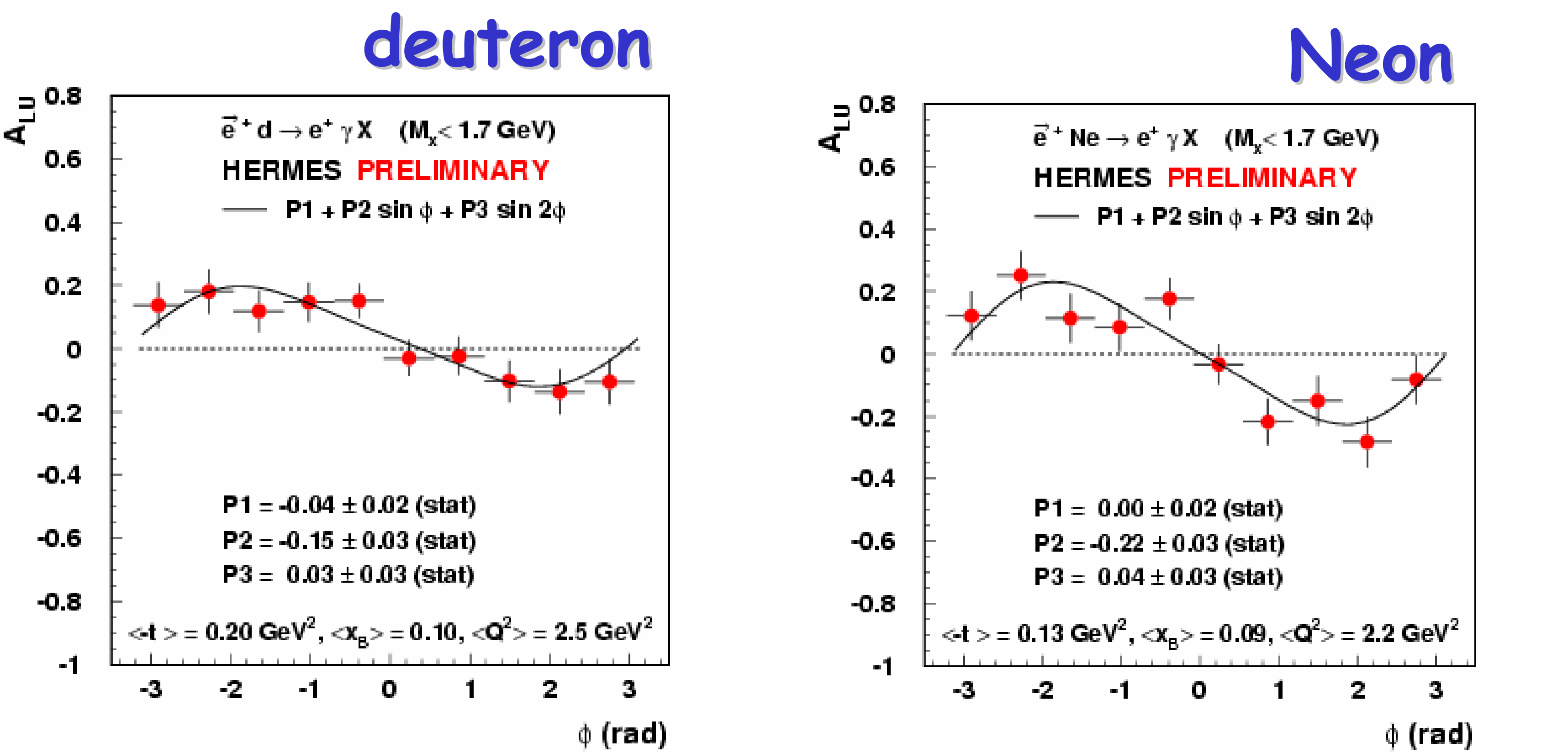


DVCS : Kinematic Dependencies of BSA



- → no significant dependencies on kinematic variables
- → HERMES results limited by t-resolution : recoil detector upgrade (2005-6)

DVCS : Beam Spin Asymmetry for d and Neon



- ➔ sizeable BSA for d and Ne
- ➔ ratio A_{LU}^d/A_{LU}^p = 0.74 ± 0.24
- ➔ needed : disentangle coherent and incoherent contributions

Conclusions

- Experimentally much progress has been achieved with high precision data in large kinematic region
- Theoretically the overall picture looks o.k., but
  - uncertainties still large
  - full NLO calculation are missing
- Scattering subprocess at hard scales understood in terms of pQCD
  ➔ explore **GPDs** = map of the proton wave function
  Can we achieve the same level of understanding here as with F_2^p?
  ... more precise data (polarized and unpolarized) needed...

… and Outlook

For the near future:

- increased statistics of VMs at high Q^2 will help (HERA II)
- H1 and ZEUS with e-beam spin rotators and $e^{\pm}$

  ➔ study DVCS interference effects at the highest scale
- DVCS studies at COMPASS (commissioned in 2001) and HERMES

For the near+X future:

- improve detectors for diffractive measurements (Hermes recoil detector; EIC, HERA III…)