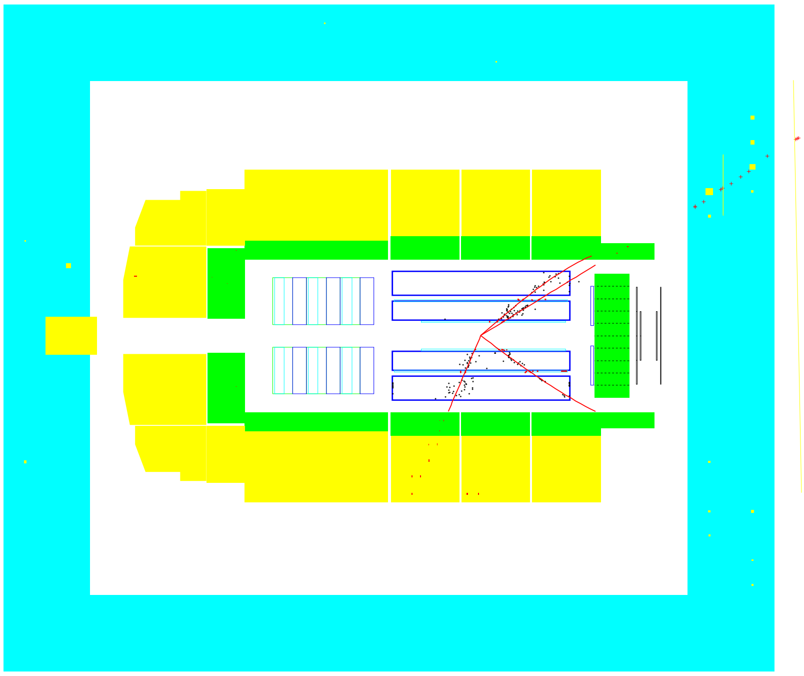
5th Workshop on QCD, Villefranche-sur-Mer, Januar 3-7 2000

HERA Results on Elastic Hadronic and Sub-Hadronic Diffraction

Gerhard Knies

DESY, Hamburg



Introduction

The HERA switchboard for hadronic - subhadronic scales

Experimental Results
The t-, W-, (t,W)-, and Q^2- dependences

Conclusions

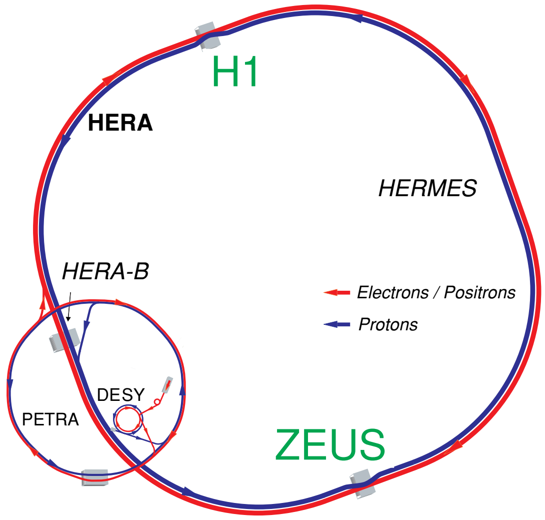
The HERA ep Collider at DESY, Hamburg

H E R A

$$e^{\pm} \quad \Longrightarrow \quad \Longleftarrow \quad p$$

27.5 GeV **820 – 920 GeV**

$$\sqrt{s} = 300 - 320 \text{ GeV}$$



1992-1994

e^-p at $\sqrt{s} = 300$ GeV

$0.8 pb^{-1}$

1994-1997

e^+p at $\sqrt{s} = 300$ GeV

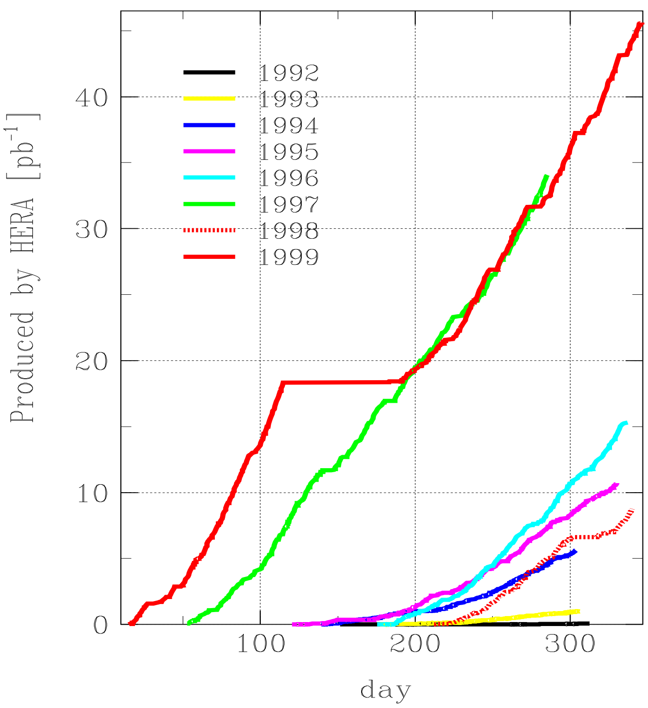
$37 - 48 pb^{-1}$

1998-1999

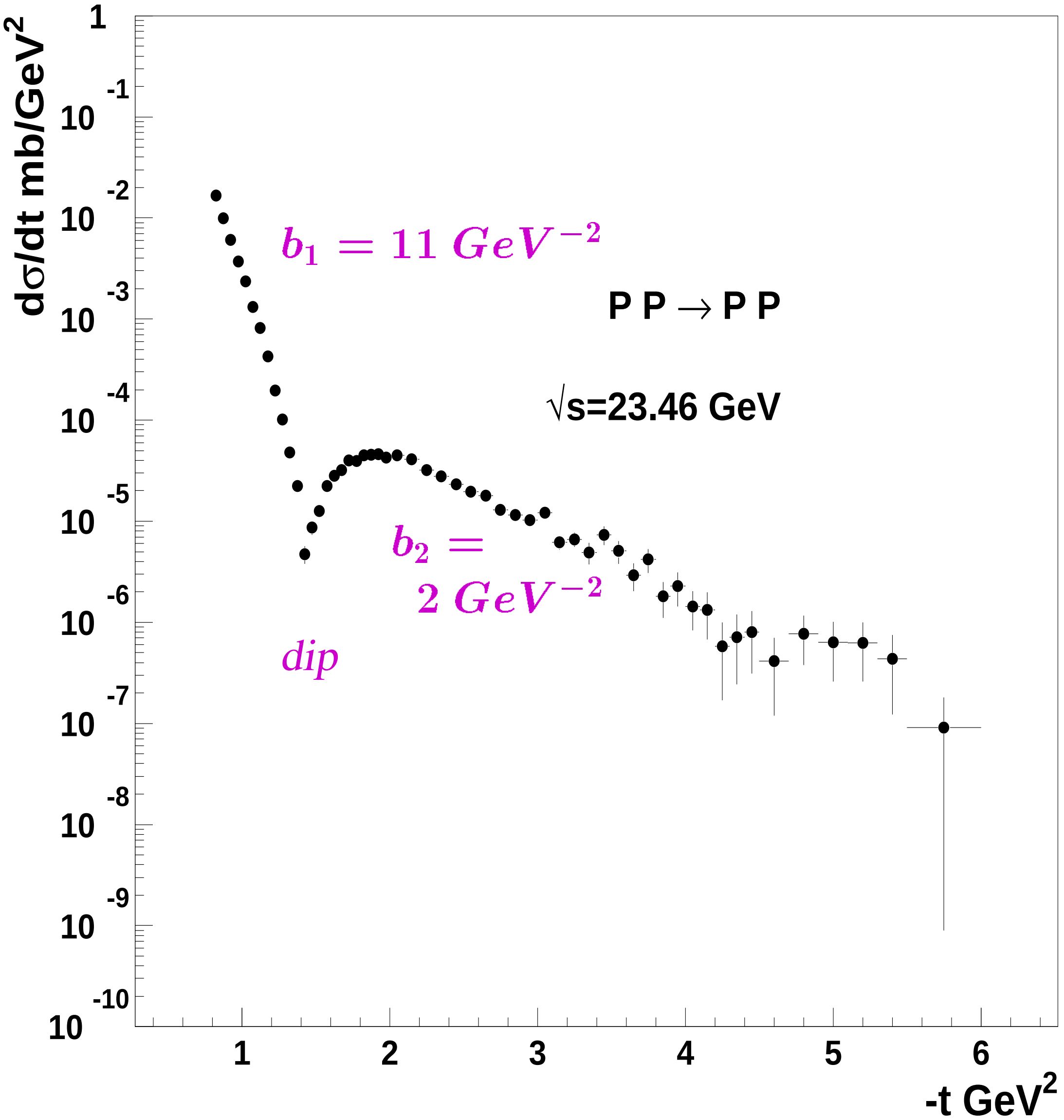
$e^{\pm}p$ at $\sqrt{s} = 320$ GeV

$53 pb^{-1}$

Integrated Luminosity

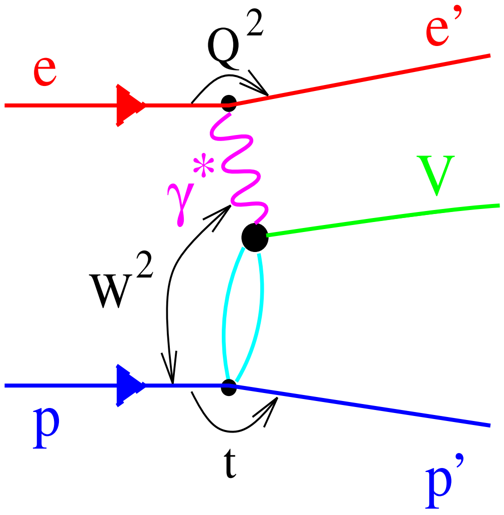


Diffractive elastic scattering $p\,p \;\rightarrow\; p\,p$



- **slopes b_1, b_2, and dip as expected in optical model**
- **slope at small $-t$ reveals size of reaction: $b_1 \propto 2 \star R_H^2$**
- **also at large $-t$, $\sim 5\ GeV^2$, proton can stay intact, i.e. acts "coherent", is not resolved and smashed into pieces**
- **geometry of reaction important for diffraction**

HERA switchboard
for hadronic/ sub-hadronic diffraction



Switch:	Range:
Q^2	$\sim 0 < Q^2 <\sim 100\ GeV^2$
M_V	$\rho^\circ,\ \omega,\ \phi,\ \rho',\ J/\Psi,\ \Psi',\ \Upsilon$
(P/N)	proton intact / break-up

$\sim 0 < |t| < 10\ \ GeV^2$

$20 < W_{\gamma p} < 285\ GeV$

$$\frac{d\sigma}{dt} = \sigma_0'\, e^{b\,t} \left(\frac{W}{W_0}\right)^{\epsilon}$$

$$b = b_0 + 4\,\alpha'_{I\!P}\, ln\frac{W}{W_0}$$

with slope $b \propto R_1^2 + R_2^2$

With $Q^2,\ M_V,\ P/N$ it is possible to move from one diffractive channel to another, within one experiment.

$R^2 \sim 5\ GeV^{-2}$ for "normal" hadron size vertex:

- *Proton $P \to P$*
- $\gamma \to V$ *with* $Q^2 \leq\sim 1 GeV^2$, *and* $V = \rho, \omega, \phi$

with $R^2 \ll 5\ GeV^{-2}$ for "sub" hadron size vertex:

- *Proton$_{out}$ break-up, dissociated,*
- $\gamma \to V$ *with* $Q^2 \gg 1 GeV^2$, *and/or(?)* $V = J/\psi, \Upsilon$

Convention: $N_H (N_S) = \#$ *of "normal" ("sub") hadron size vertices* $(N_H + N_S = 2)$.

What can be measured in elastic VM production?

Mass of V $=: \quad \rho^\circ,\ \omega,\ \phi,\ (\rho'),\ J/\Psi,\ (\Psi'),\ \Upsilon$

Photon virtuality Q^2

Production Angle and Energy

$$d\sigma/dt\,(W,\ t,\ Q^2)\ =\ \sigma_0'\, e^{b\,t}\,(W/W_0)^{\epsilon}$$

$$b(Q^2, M_V, P/N, W)\ =\ b_0\ +\ 4\,\alpha_{I\!P}'\, ln(W/W_0)$$

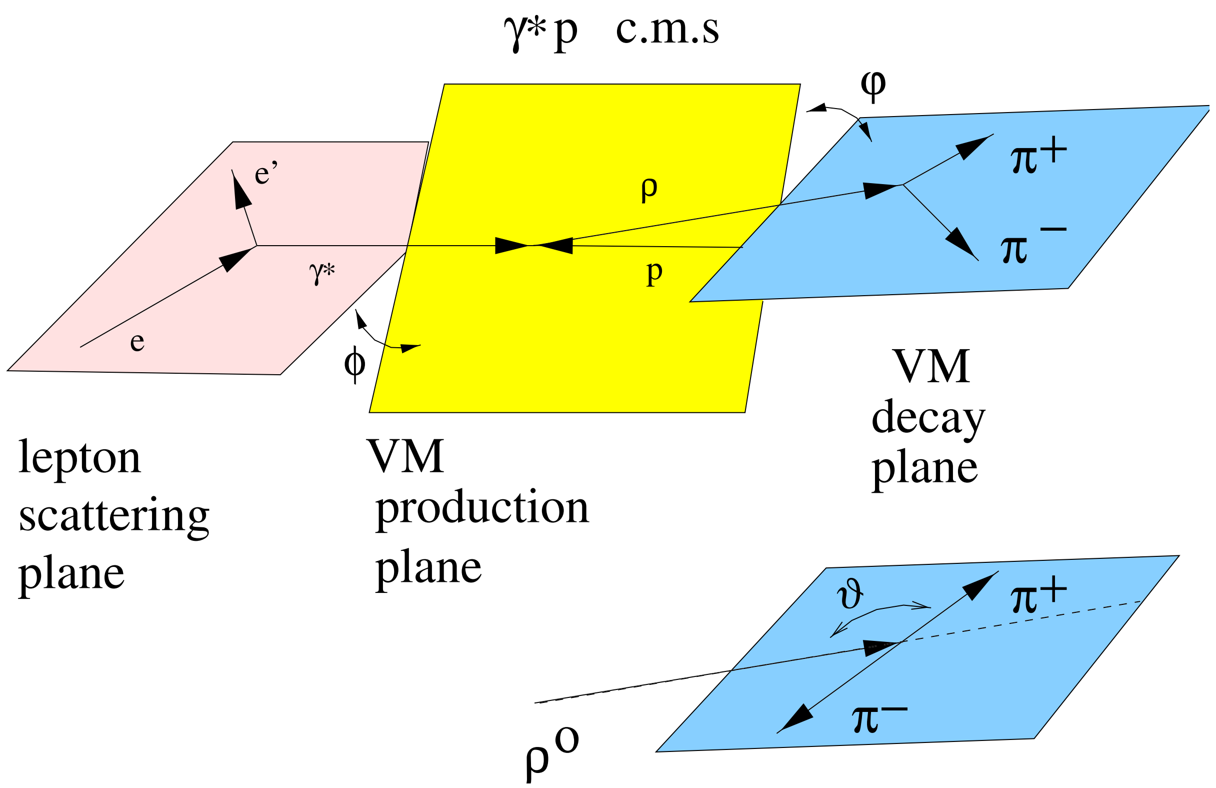
$$\epsilon(Q^2, M_V) = 4\,(\alpha_{I\!P}(0; M_V, Q^2) - 1)$$

$\rightarrow$ Regge trajectory $\alpha_{I\!P}(t)\ =\ \alpha_{I\!P}(0)\ +\ \alpha_{I\!P}'\,t$

$$\sigma_0'(M_V, Q^2, P/N) \propto (M_V^2 + Q^2)^{-n}$$

Decay angular distribution

$W(\cos\vartheta, \varphi, \phi;\ W, t, Q^2)$, (Helicity Frame)



$\Rightarrow\ \sigma_L/\sigma_T$, **SCHC** (s - channel helicity conservation)

HERA hadronic & sub-hadronic diffractive channels

The various diffractive channels can be classified along their number of ''normal'' hadron sized vertices, N_H:

- $N_H = 2$ ($N_S = 0$, no short distance vertex, no pQCD) signature: b $\propto 2 \star R_H^2 \sim 10\ GeV^{-2}$. E.g.:
  - ▷ $\gamma p \rightarrow \rho p,\ \omega p,\ \phi\, p(?)$
- $N_H = 1$ ($N_S = 1$, 1 short distance vertex, pQCD) signature: b $\propto 1 \star R_H^2 \sim 5\ GeV^{-2}$. E.g.:
  - ▷ $\gamma^* p \rightarrow \rho p,\ \omega p,\ \phi\, p(?)$
  - ▷ $\gamma p \rightarrow J/\Psi$
  - ▷ $\gamma p \rightarrow \rho N$
- $N_H = 0$ ($N_S = 2$, 2 short distance vertices, pQCD) signature: b $\propto 0 \star R_H^2 \sim 1\ GeV^{-2}$. E.g.:
  - ▷ e.g. $\gamma(\gamma^*)p \rightarrow J/\psi N$
  - ▷ e.g. $\gamma^* p \rightarrow \rho N$

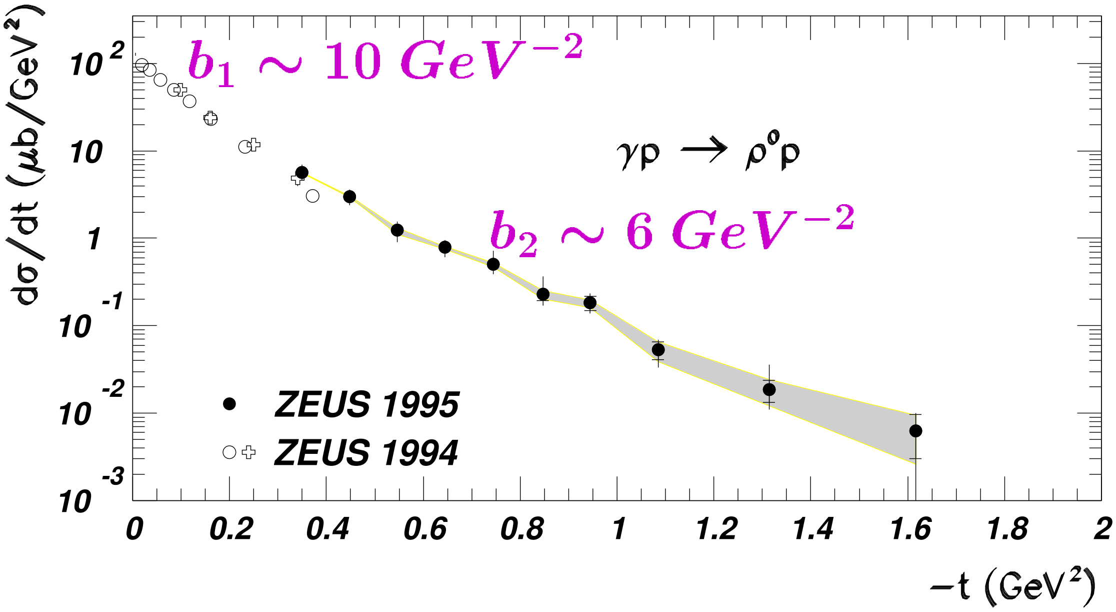
Short distance is the precondition for validity of pQCD.

If a diffractive process includes a short distance diffraction $\rightarrow$ at small $-t$: $b \ll 10\ GeV^{-2}$

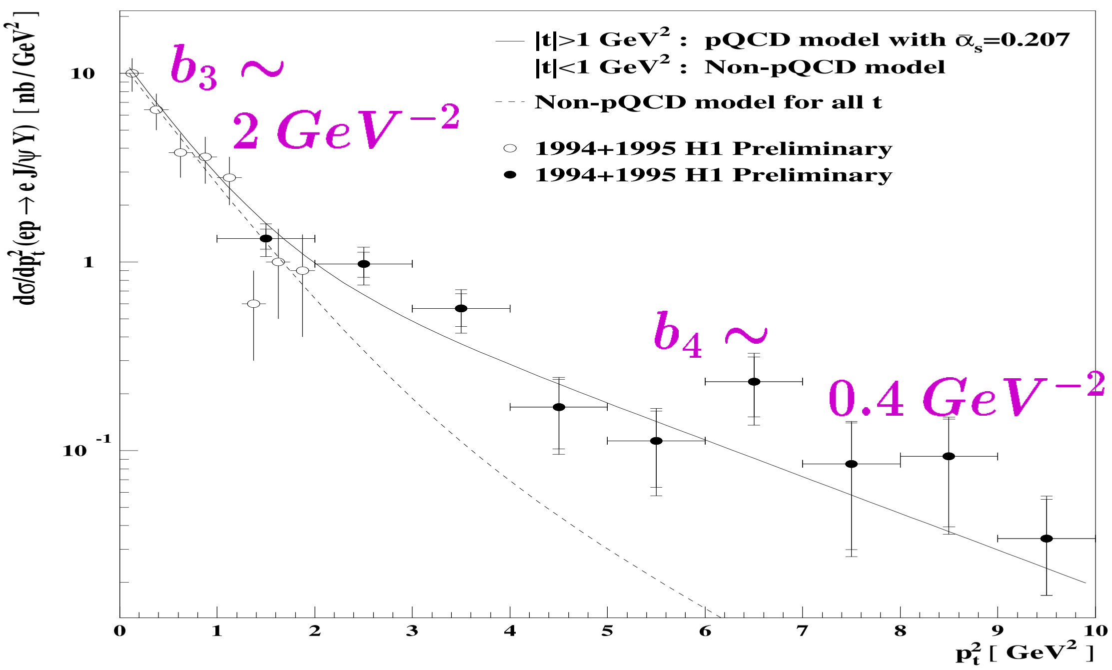
What do the data say ?

Examples for t - Distributions

$\gamma p \to \rho p$, elastic, proton intact

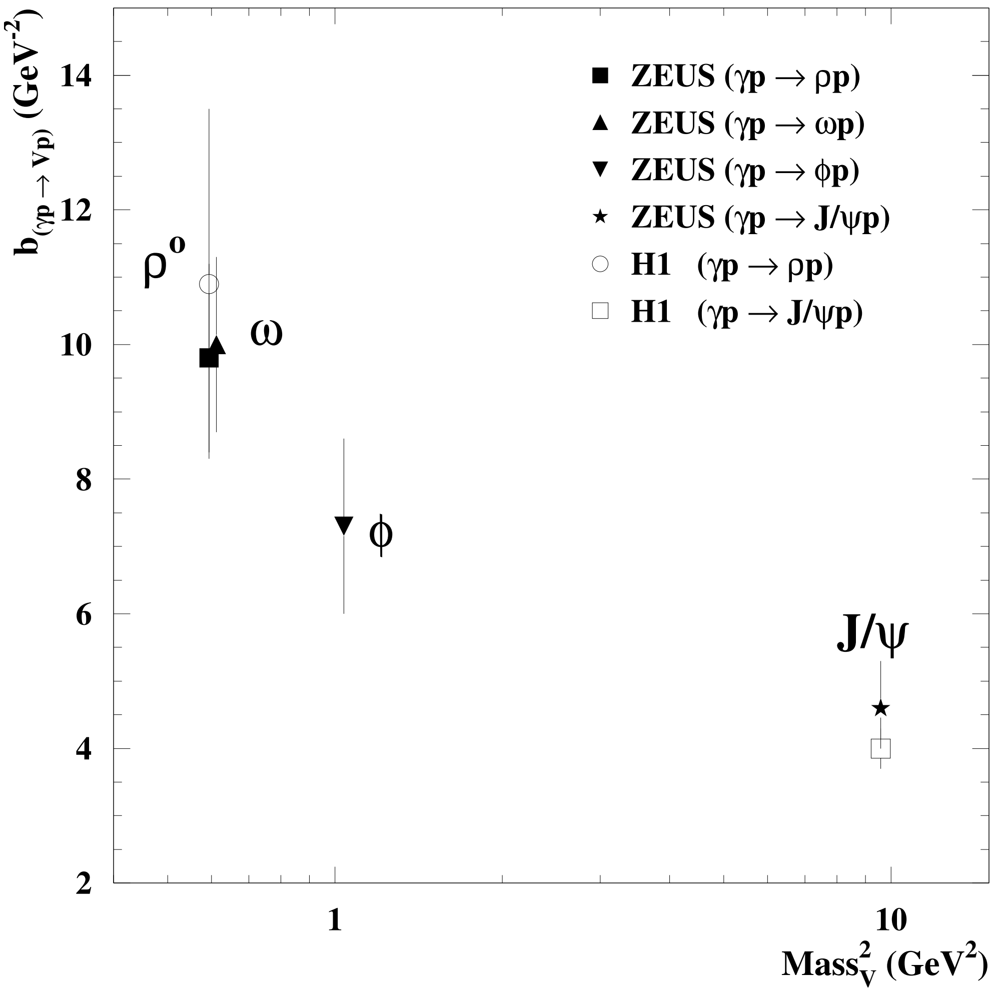


$\gamma p \to J/\Psi N$, proton break-up



M_V Switch on $e^{b\,t}$

Photoproduction of Vector Mesons
Slopes from fits of $d\sigma/dt \sim e^{b\,t}$



$$b \propto R_p^2 + R_V^2 \qquad R_p^2 \sim 5GeV^{-2}$$

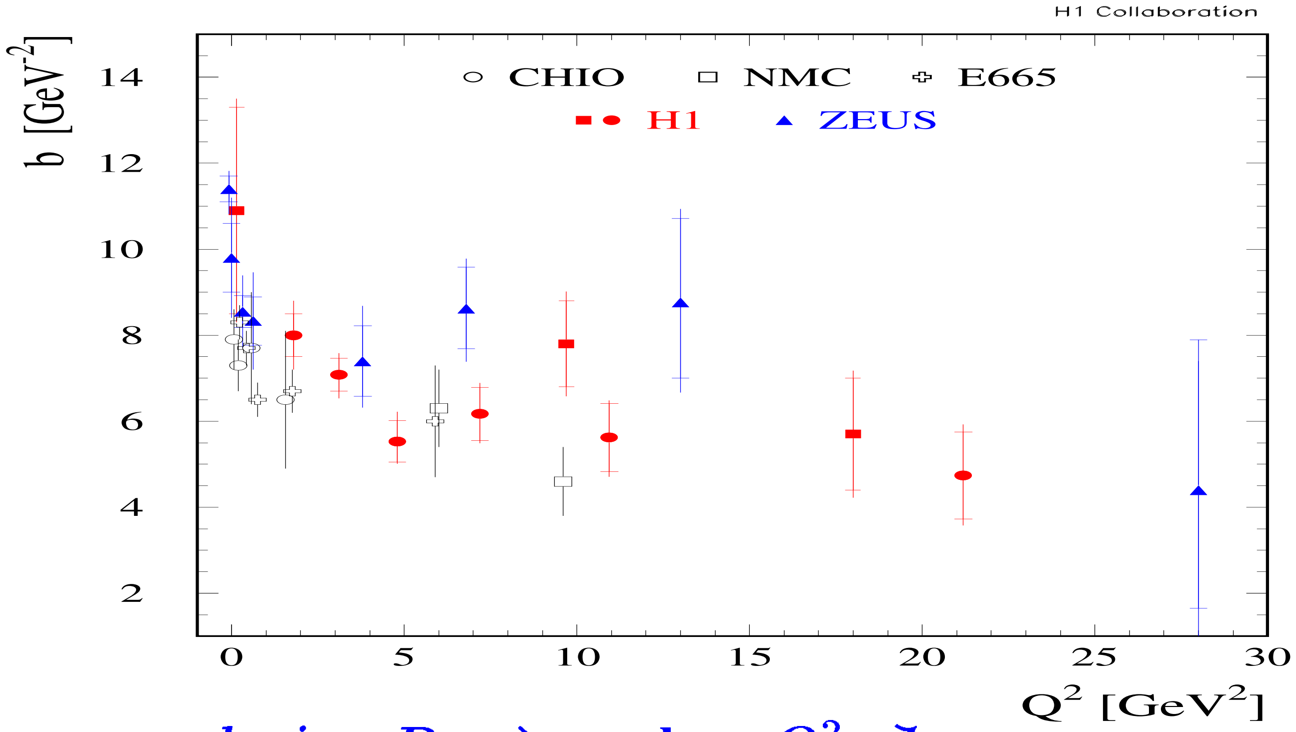
$$b \sim 10 \to 5 \;:\; R_V^2 \to \sim 1 \;\text{ when } M_V^2 \sim 0.5 \to 10\; GeV^{-2}$$

$$\Rightarrow R_{J/\Psi} << R_{Proton}$$

J/Ψ small enough to allow for pQCD !

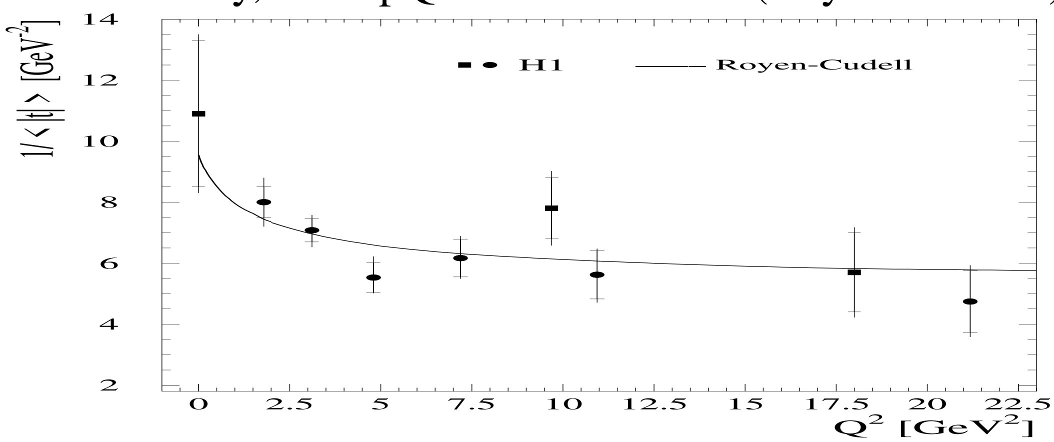
Q^2 Knob on $e^{b\,t}$

$\gamma p \to \rho p$: Q^2 dependence of the slope b



b, *i.e.* $R_{q\bar{q}} \searrow$ **when** $Q^2 \nearrow$

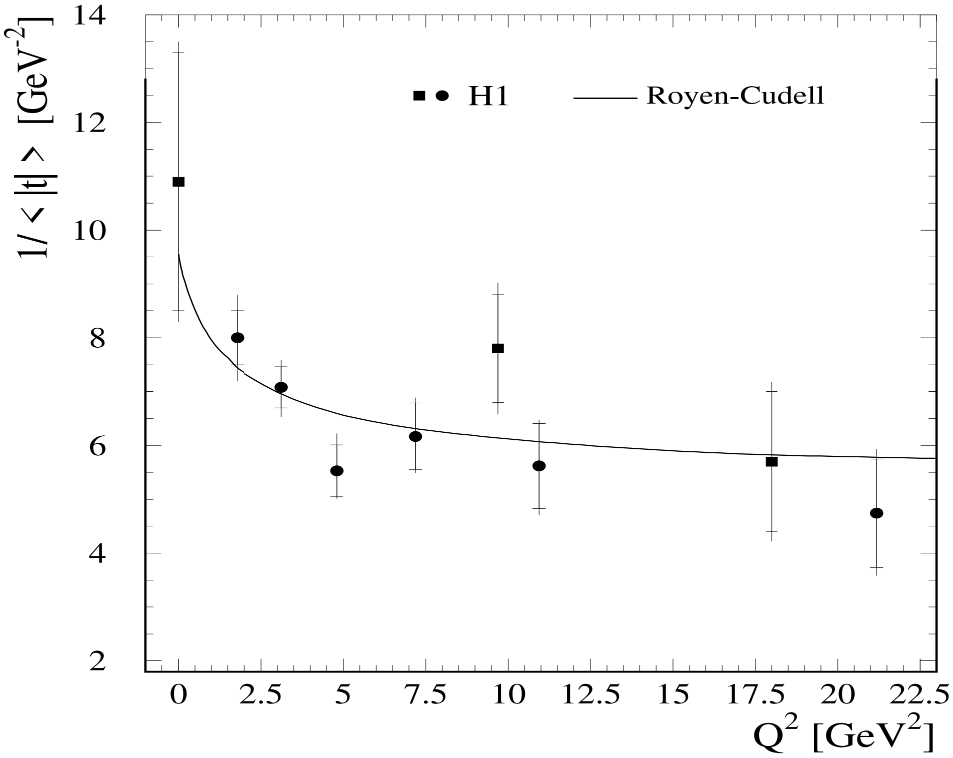
H1 data only, with pQCD based model (Royen - Cudell)



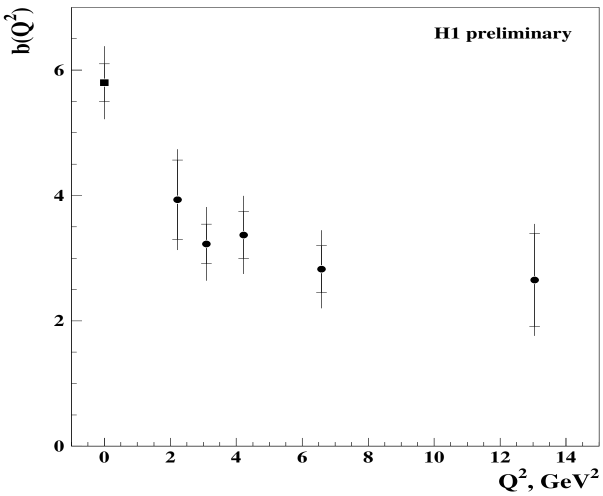
When Q^2 from $0 \to\ 25\ GeV^2,\ b:\ 10 \to 5 GeV^2$
$R^2(\gamma \to \rho) \to \sim 1 GeV^2$

Q^2 Knob and P/N Switch on $e^{b\,t}$

$\gamma p \to \rho p$, intact



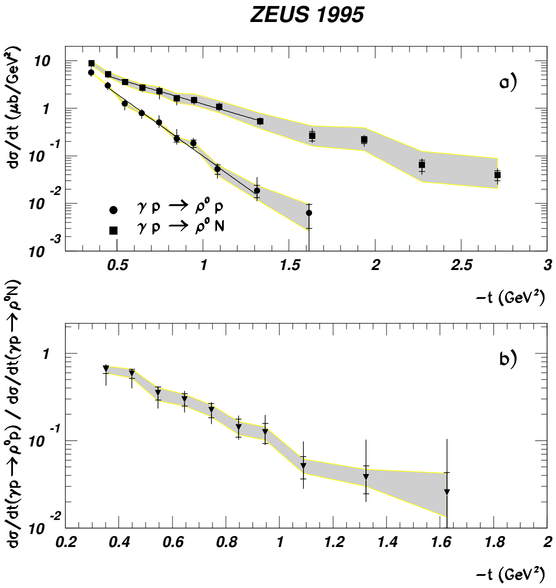
$\gamma p \to \rho N$, break-up



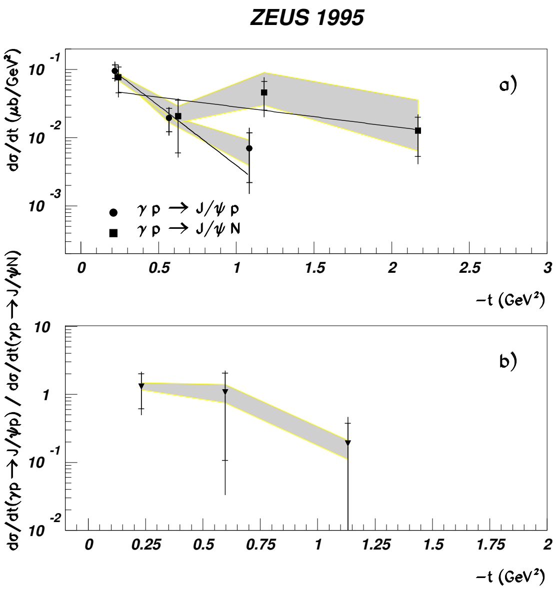
Proton intact $\to$ break-up: $\Delta b = 3 - 4 GeV^2$
$R^2\ (P \to N)\ \searrow$ independent of Q^2

P/N Switch: Proton intact $\rightarrow$ break-up on $e^{b\,t}$

$$\gamma + P \rightarrow \rho \; + \; P/N$$



$$\gamma + p \rightarrow J/\Psi \; + \; P/N$$



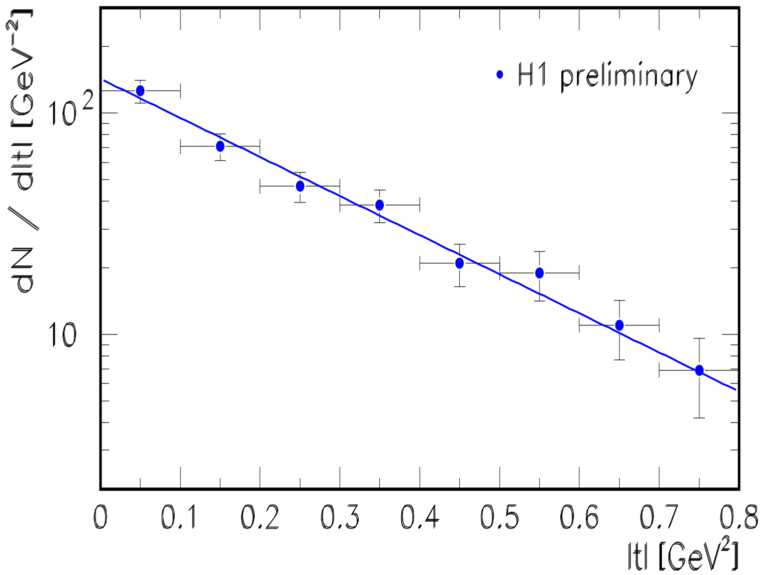
$\Delta b \;\sim\; 3.5$ when P breaks up

$$R^2(P \rightarrow N) \ll R^2(P \rightarrow P)$$

irrespective of *hadronic/sub-hadronic* size of V (ρ, $\Psi . \Phi$)

Switch to: big M_V, big Q^2, break-up: effect on $e^{b\,t}$

$$\gamma + P \rightarrow J/\Psi \ + \ P$$



proton intact *(elastic)*

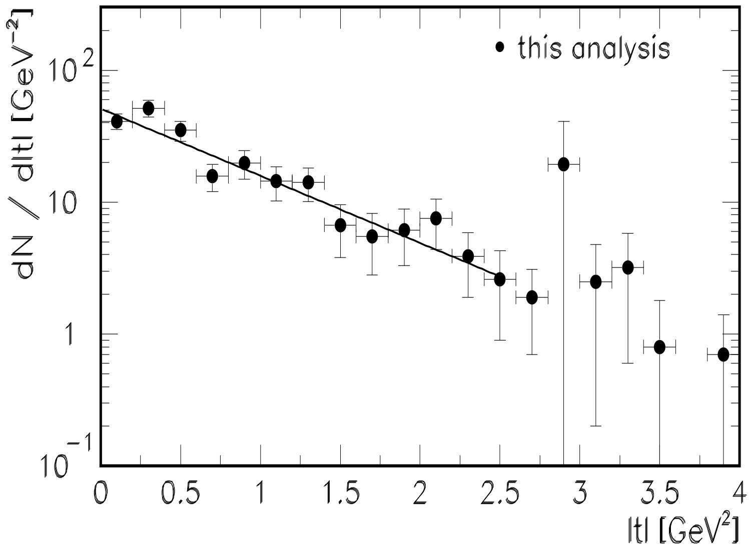
$$b_{el} = 4.2 \pm 0.2 \pm 0.6 \, GeV^{-2}$$

$$= 4.1 \pm 0.3 \pm 0.4 \, GeV^{-2}$$

in electroproduction

$$\langle Q^2 \rangle = 8 GeV^2$$

$$\gamma + p \rightarrow J/\Psi \ + \ N$$



proton break-up *(disso)*

$$b_{pd} = 1.3 \pm 0.1 \pm 0.2 \, GeV^{-2}$$

$\Delta b \ \sim \ 3$ *when P breaks up*

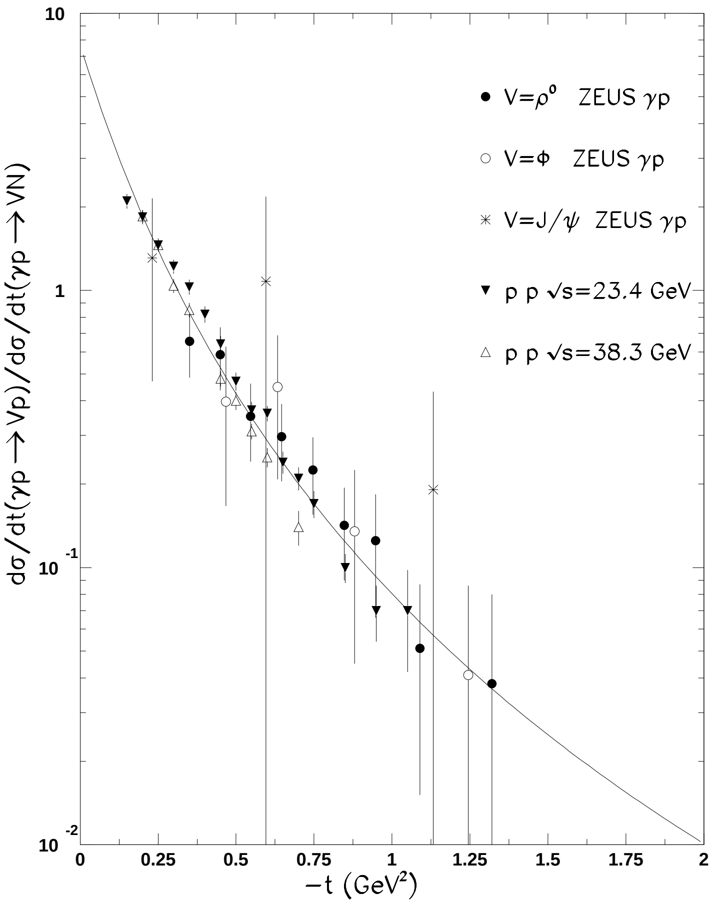
irrespective of hadronic/sub-hadronic size of V (ρ/Ψ)

$\Delta b \ \sim \ 0$ *when* $Q^2 \, from \; 0 \; to \; 8 \; GeV^2$

and M_V^2 *large enough*

P/N Switch on slope b

Ratio of $d\sigma/dt\ \frac{P(\gamma)+P\rightarrow P(V)+P}{P(\gamma)+P\rightarrow P(V)+N}\ \sim\ e^{\Delta b\, t}$



$$\Delta b\ = b_{P-intact} - b_{P-break-up} \propto\ 4GeV^{-2}$$

Reduction Δb **corresponds to** $\sim 1R_p^2$

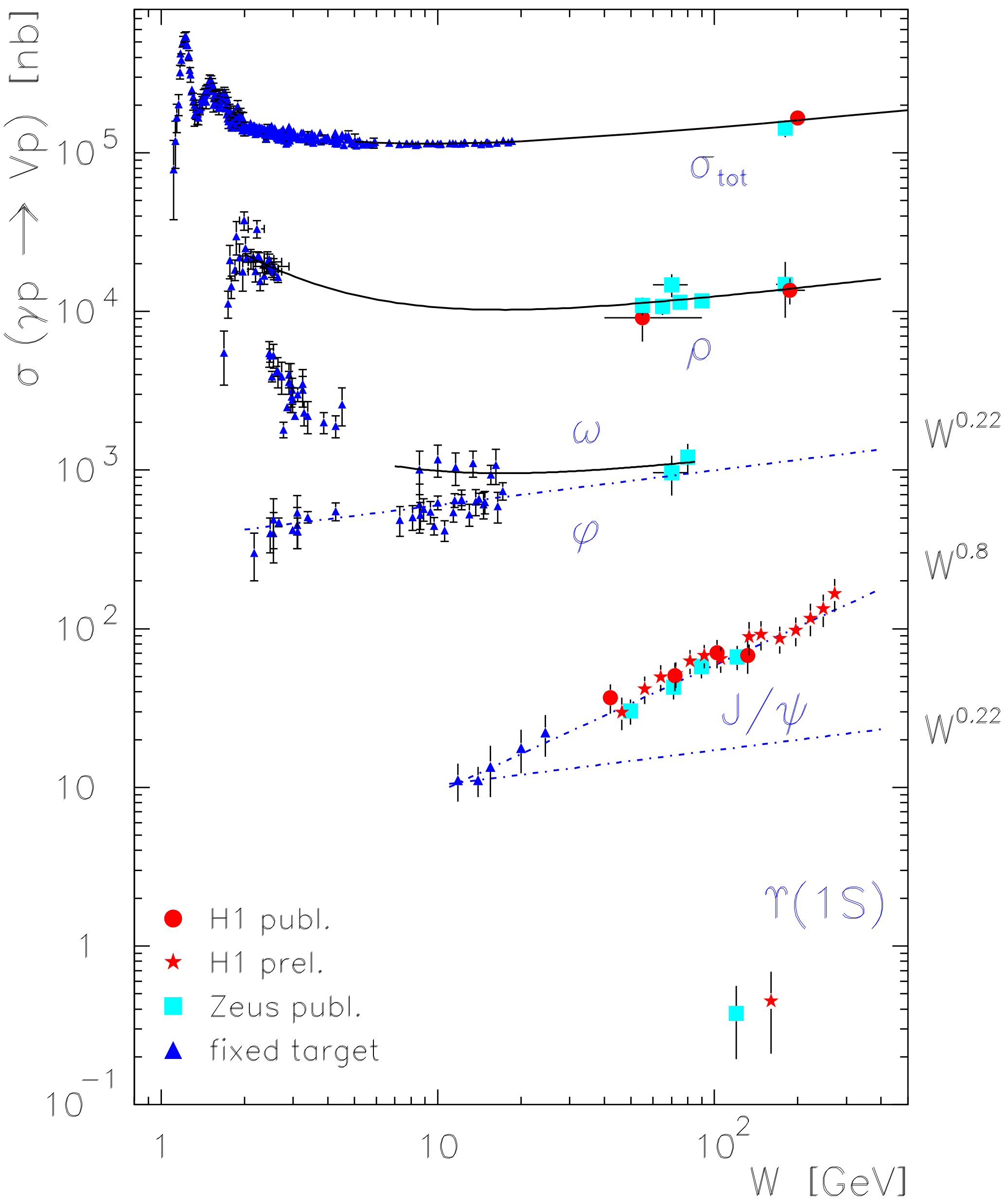
$$\Rightarrow R^2_{P-break-up} \sim 1GeV^{-2}$$

curve = el. mag. dipole proton form factor $F_P^2 = D/(0.47-t)^4$

An exponential form describes the ratio better.

In break-up diffractive reactions
the proton interacts at a subhadronic scale.

M_V Switch on W^{δ} $\gamma\, p \;\rightarrow\; V\, p$

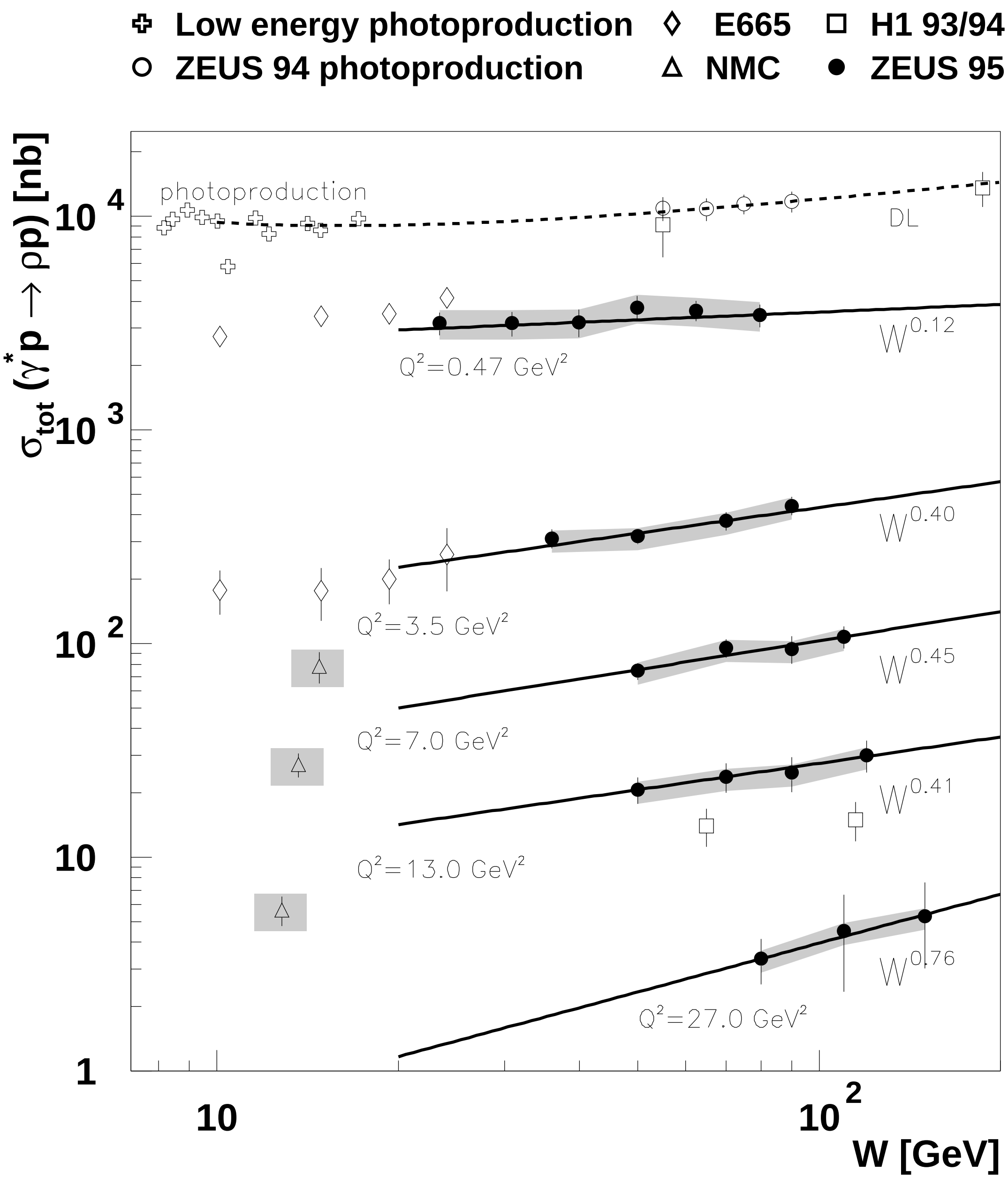


Optical Theorem $\Rightarrow\;\; \sigma^2_{tot} \;\sim\; d\sigma/dt(t=0) \;\;\sim W^{4\epsilon}$

$\boldsymbol{\sigma_{\gamma p \rightarrow\, Vp}} \;\sim\; \boldsymbol{W^{\delta}},\; \boldsymbol{\delta} \leq 4\epsilon,$ ($<$ in case of shrinkage)

- When M_V^2 from $\leq 1 \rightarrow 10\; GeV^2$: δ from (soft) $0.22 \rightarrow\; 0.85$
- $\phi,\;\; J/\Psi$ no Reggeon contribution, purely diffractive

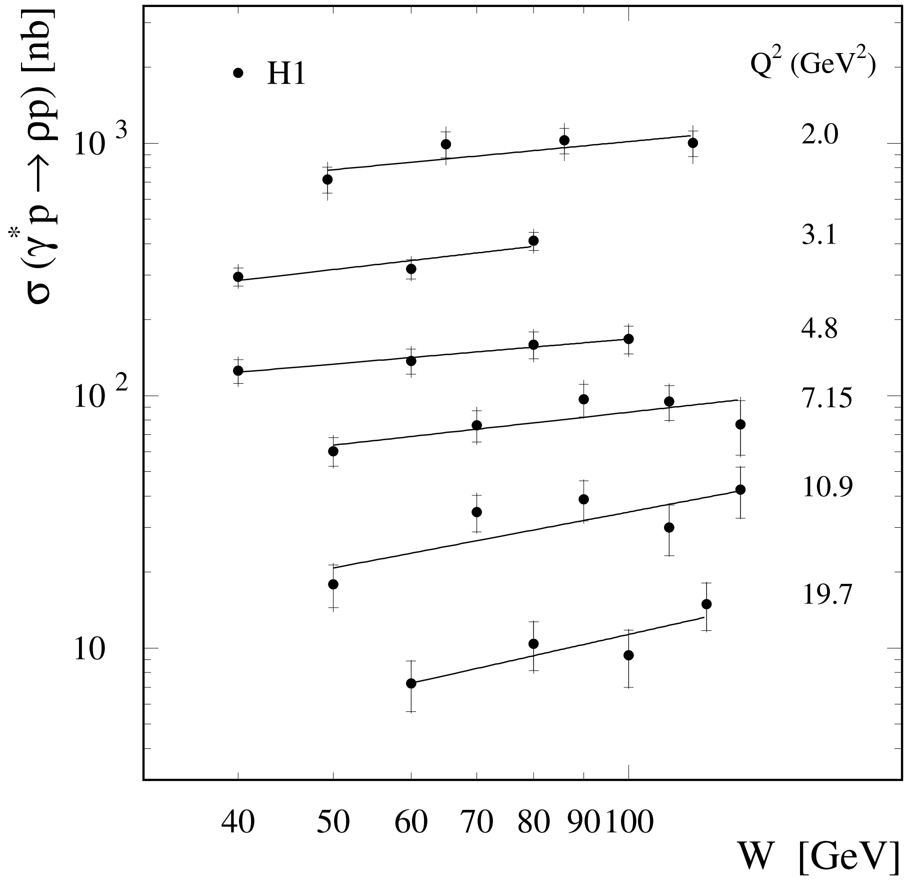
Q^2-Knob on W^{δ} – $\gamma^* p \rightarrow \rho^\circ p$

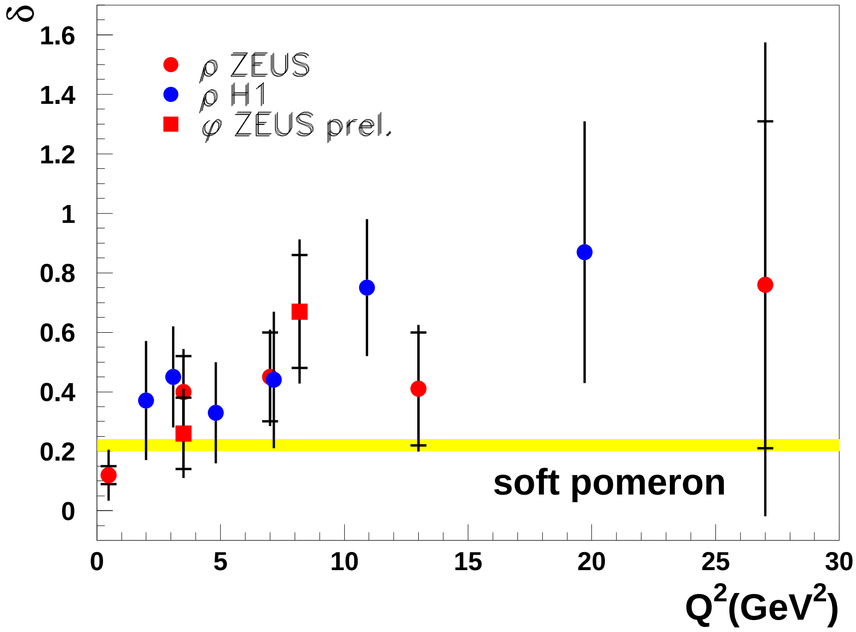


Fits to $\sigma(\gamma^* p \rightarrow \rho^\circ p) = W^{\delta}$

Zeus data: When $Q^2 \nearrow$: $\delta \nearrow$

Q^2-Knob on W^δ – $\gamma^* p \to \rho^\circ p$

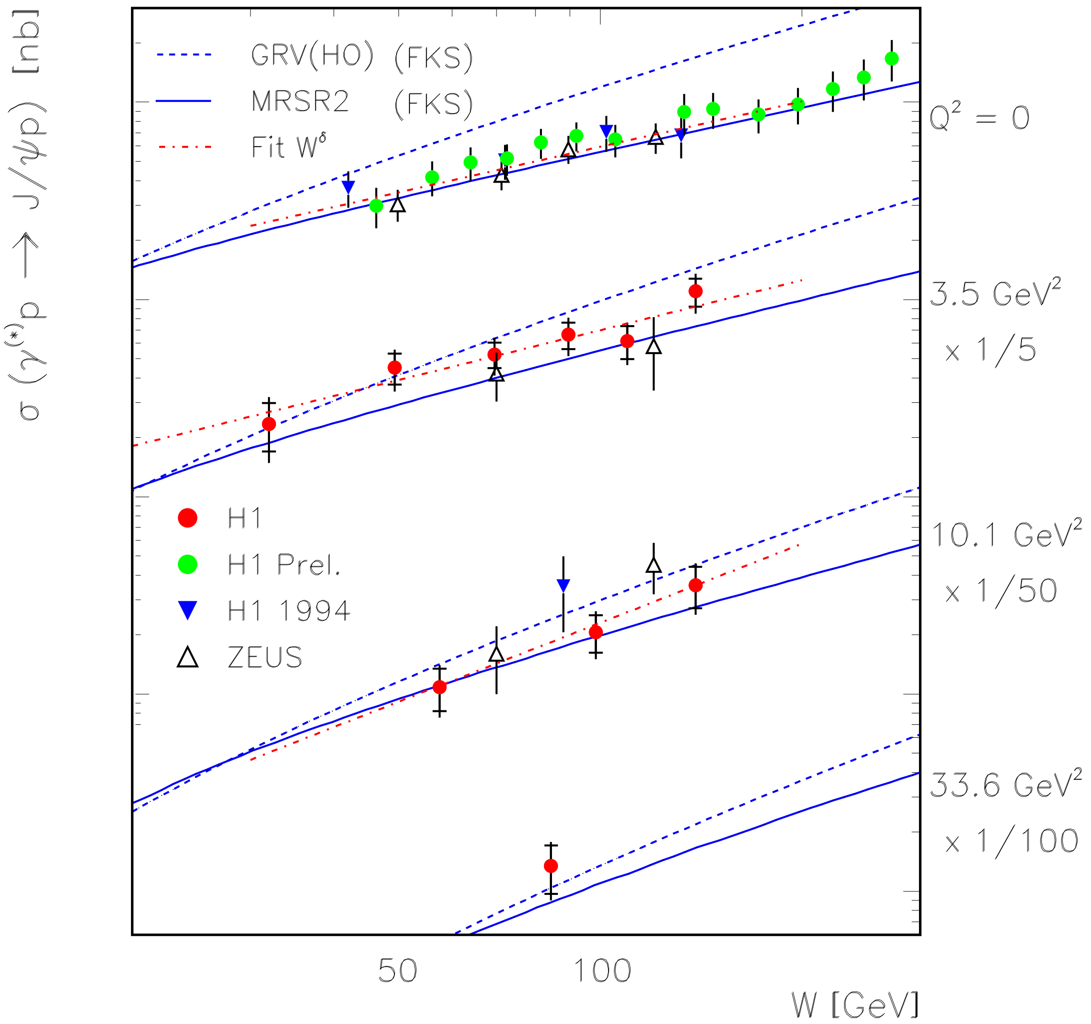




Data: when $Q^2 \nearrow$: $\delta \nearrow$

Q^2 Knob on W^{δ} at large M_V

$$\gamma^{(*)}\, p \;\rightarrow\; J/\Psi\, p$$



$\delta \sim 0.9$, independent of Q^2, when $Q^2 <\sim M_V^2$

Q^2, M_V^2 : the larger one wins ?

Model curves exhibit sensitivity to different parameterisations of the gluon density in the proton

Optical Theorem in DIS and $\gamma^* p \rightarrow V p$

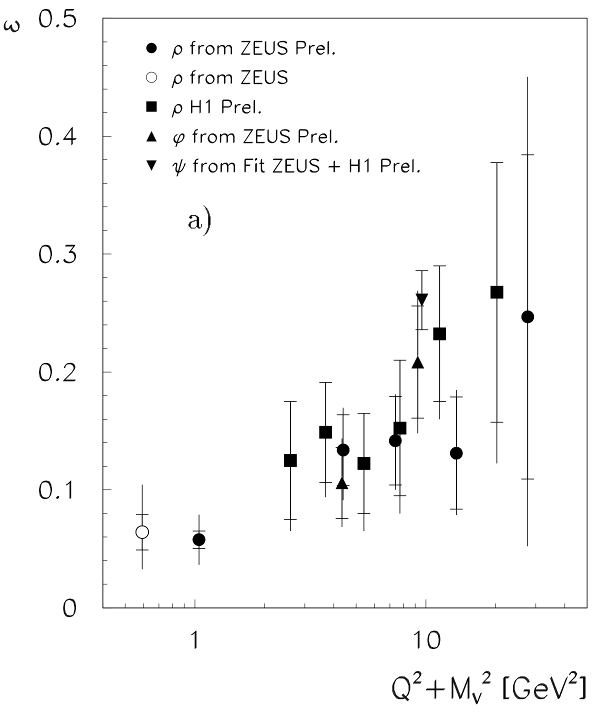
The increase of $\sigma_{\gamma^* p \rightarrow V p}$ as W^{δ}
is related to
Increase of DIS cross sections with decreasing x $F_2^p \sim x^{-\lambda}$

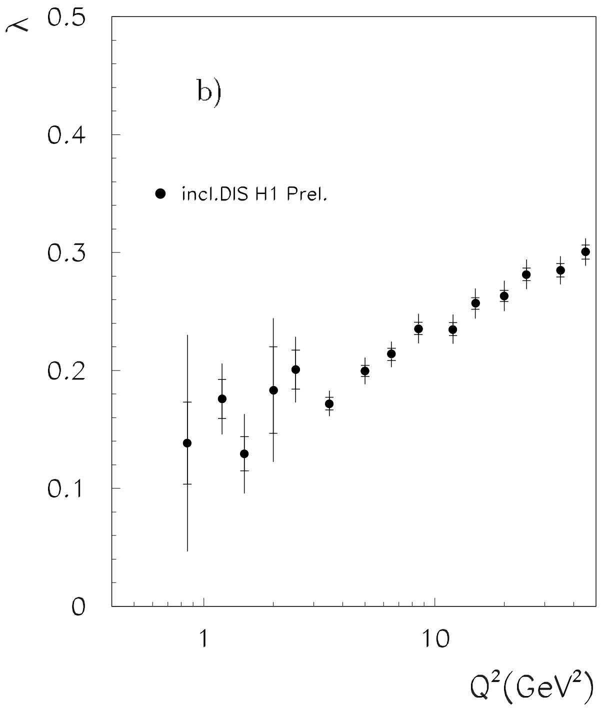
At fixed Q^2 and small x, using the relation $x W^2 \approx Q^2$,
one can write

$$\sigma^2_{\gamma^* p}(Q^2, W) \sim (F_2^p(Q^2, x))^2 \sim x^{-2\lambda} \sim W^{4\lambda}$$
$$\sim d\sigma/dt(Q^2, W,\ t = 0, \gamma^* p \rightarrow V p) \sim W^{(\delta = 4\epsilon)}$$
$$\sim \sigma_{\gamma^* p \rightarrow V p}\ \textit{(if shrinkage small)}$$

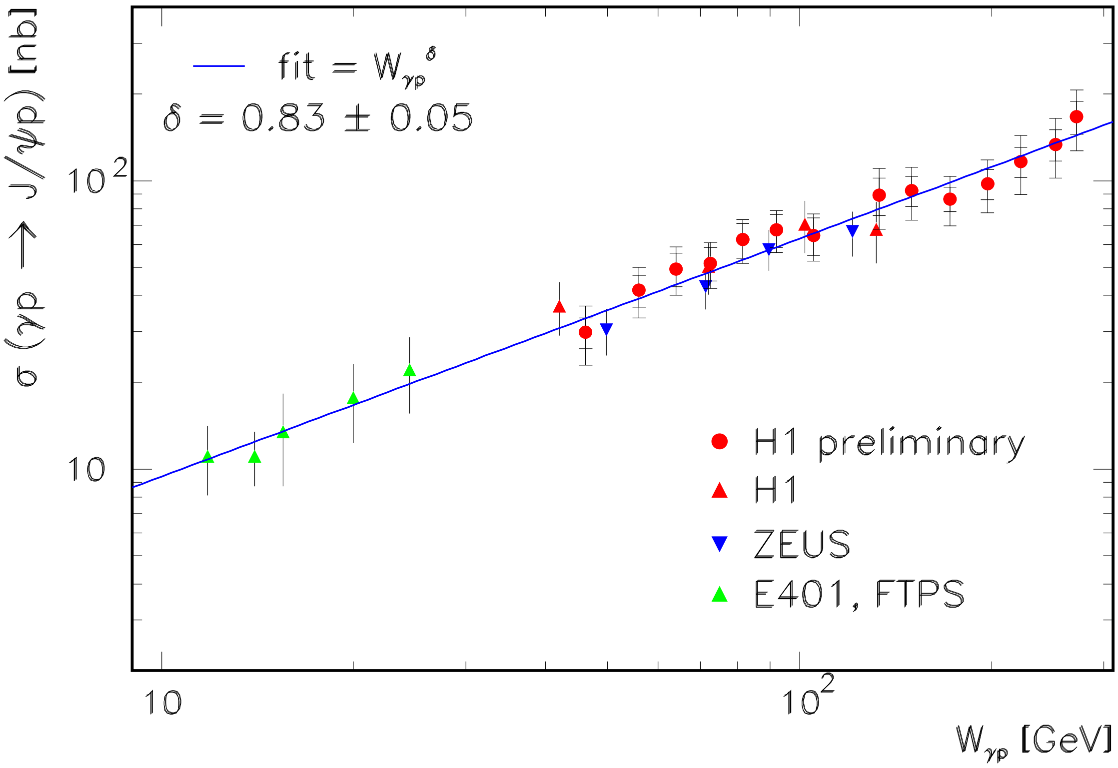
Thus, *increase of F_2^p with decreasing x*
and *increase of $\sigma_{\gamma^* p \rightarrow V p}$ with increasing W*
have to have a common origin: *the Gluon density in the proton*

ϵ (δ) and λ have similar $Q^2(+M_V^2)$ dependences

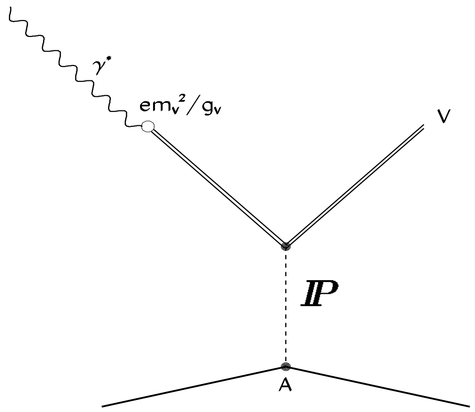




W^{δ} of $\gamma\, p \;\rightarrow\; J/\Psi\, p$ on soft and/or hard $I\!P$



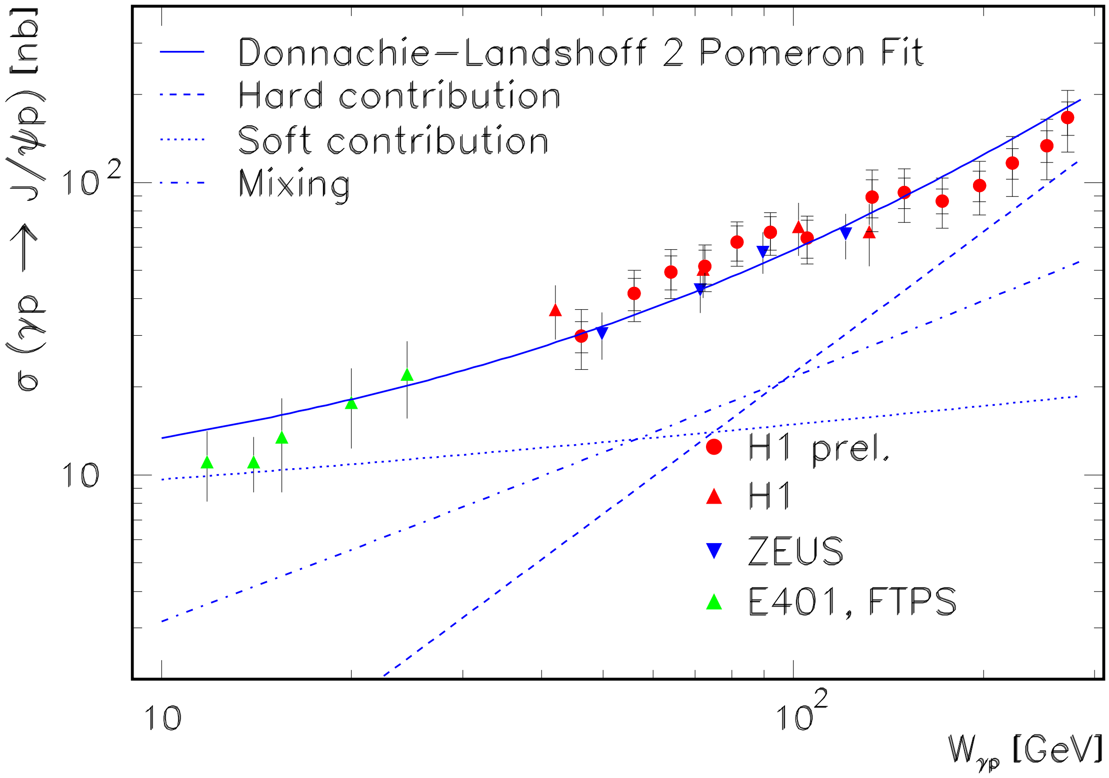
Light Vector Meson photoproduction described via "Soft Pomeron" exchange



But: J/Ψ data steeper than "soft expectation"

$\Longrightarrow$ *D + L try 2 Pomerons: (soft + hard)^2*

W^{δ} of $\gamma\, p \;\rightarrow\; J/\Psi\, p$ on soft and/or hard $I\!\!P$

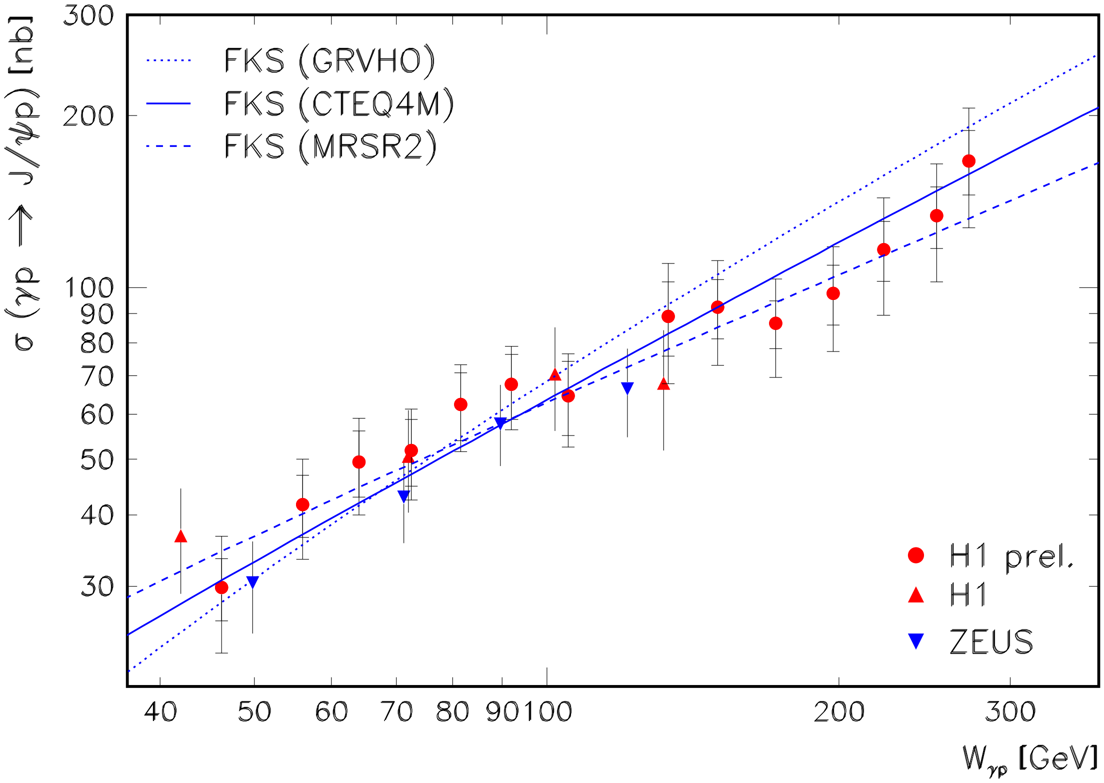


D+L: $(I\!\!P_{soft} + I\!\!P_{hard})^2$

1 universal soft ($\alpha_{soft}(0) - 1 = \epsilon_1 = 0.0808$) and 1 universal hard ($\epsilon_0 = 0.418$) "Pomeron" (Glueball ?), from fits to $\sigma_{tot}(had, had)$ and to $\sigma_{tot}(\gamma^* p)$

2 universal Pomeron fit: $(a \star W^{4\epsilon_1} + b \star W^{4\epsilon_0})$
not better than single exponential $(c \star W^{\delta})$

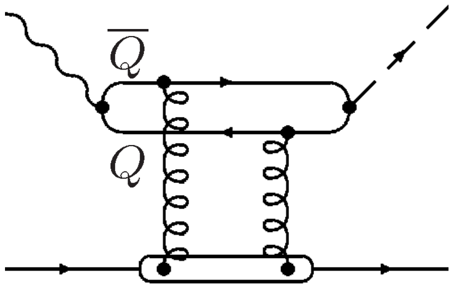
W^{δ} of $\gamma\, p \;\rightarrow\; J/\Psi\, p$ on soft and/or hard $I\!P$



The heavy c quark provides a hard scale $\Longrightarrow$

pQCD Approach:

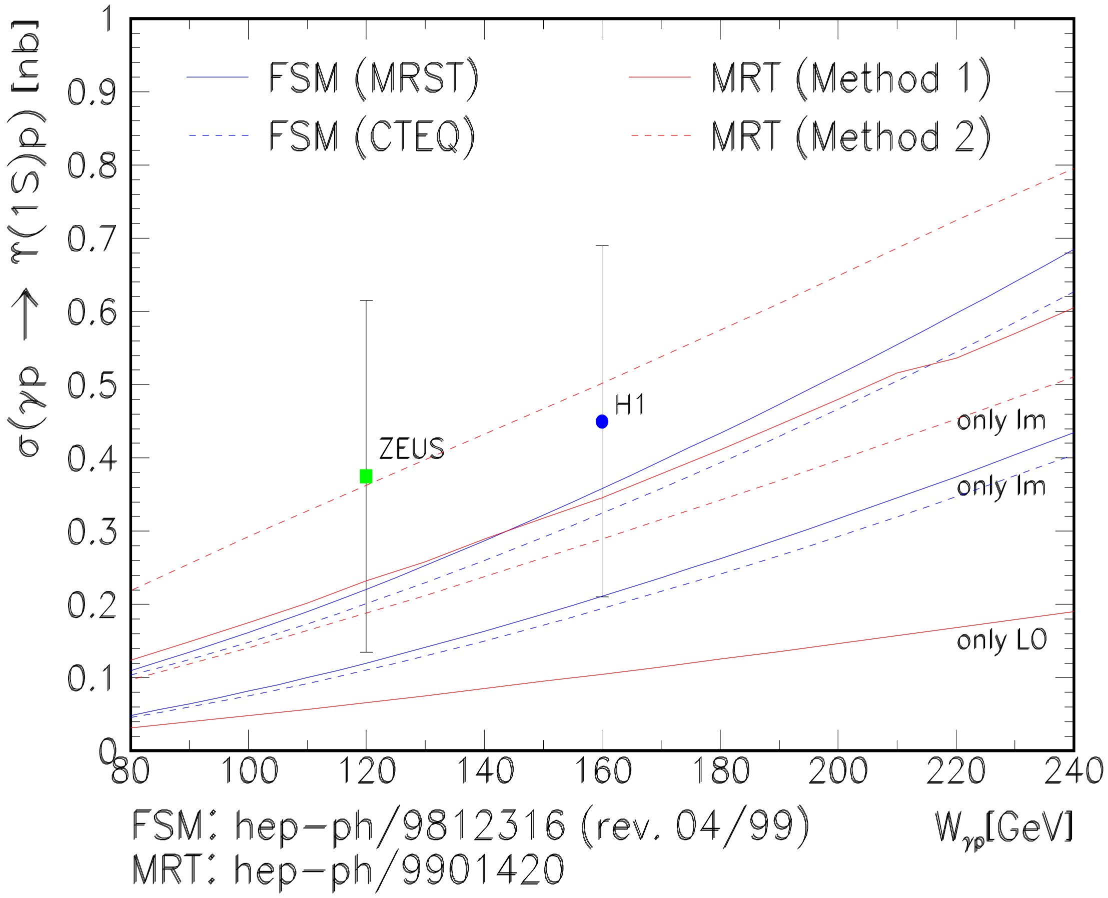
Factorization (timescales !)



1. Photon fluctuates into $Q\bar{Q}$
   α_{EM}, M_Q
2. $Q\bar{Q}$ scatters off proton
   $\int_x [x\, g(x, Q^2)]^2$ gluon density
3. $Q\bar{Q}$ forms a bound state
   J/Ψ wave function

Good description of data
Sensitivity to parameterisation of gluon density in proton

Elastic $\gamma\, p \;\rightarrow\; \Upsilon\, p$



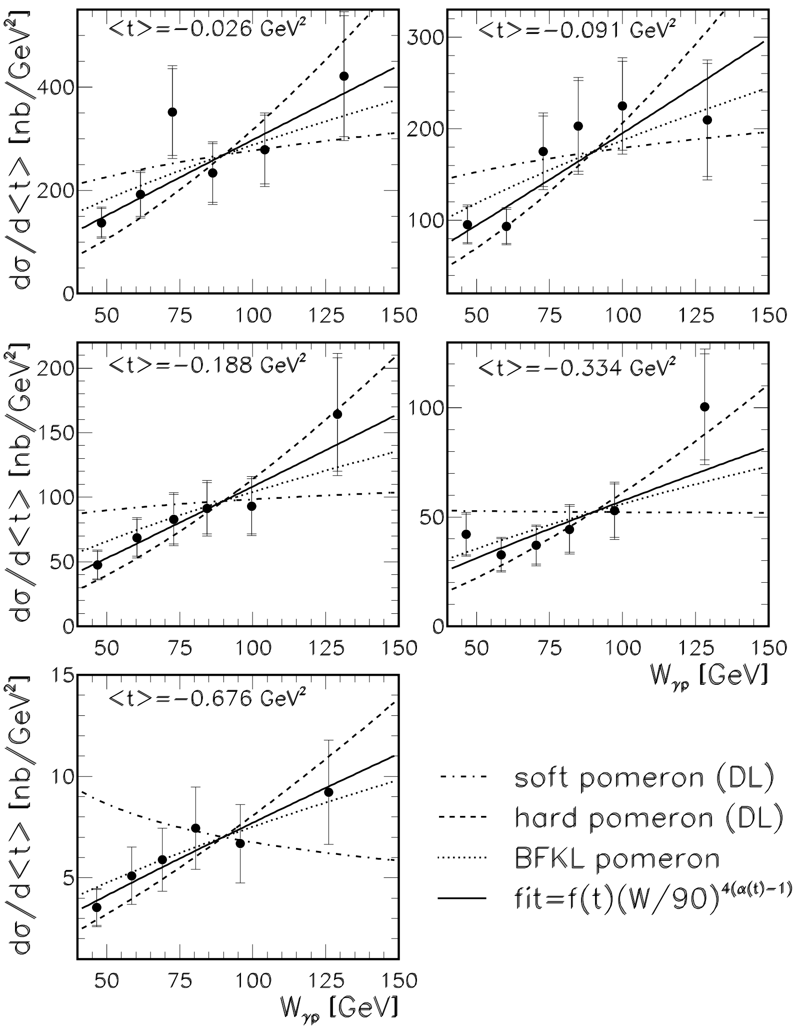
ZEUS (green), and H1 (blue) preliminary

pQCD calculations include "skewed" gluon distributions and real parts for the amplitude

Shrinkage in sub-hadronic diffraction ?

H1 data. $\gamma\, p \;\rightarrow\; J/\Psi\, p$

W dependence in bins of |t|

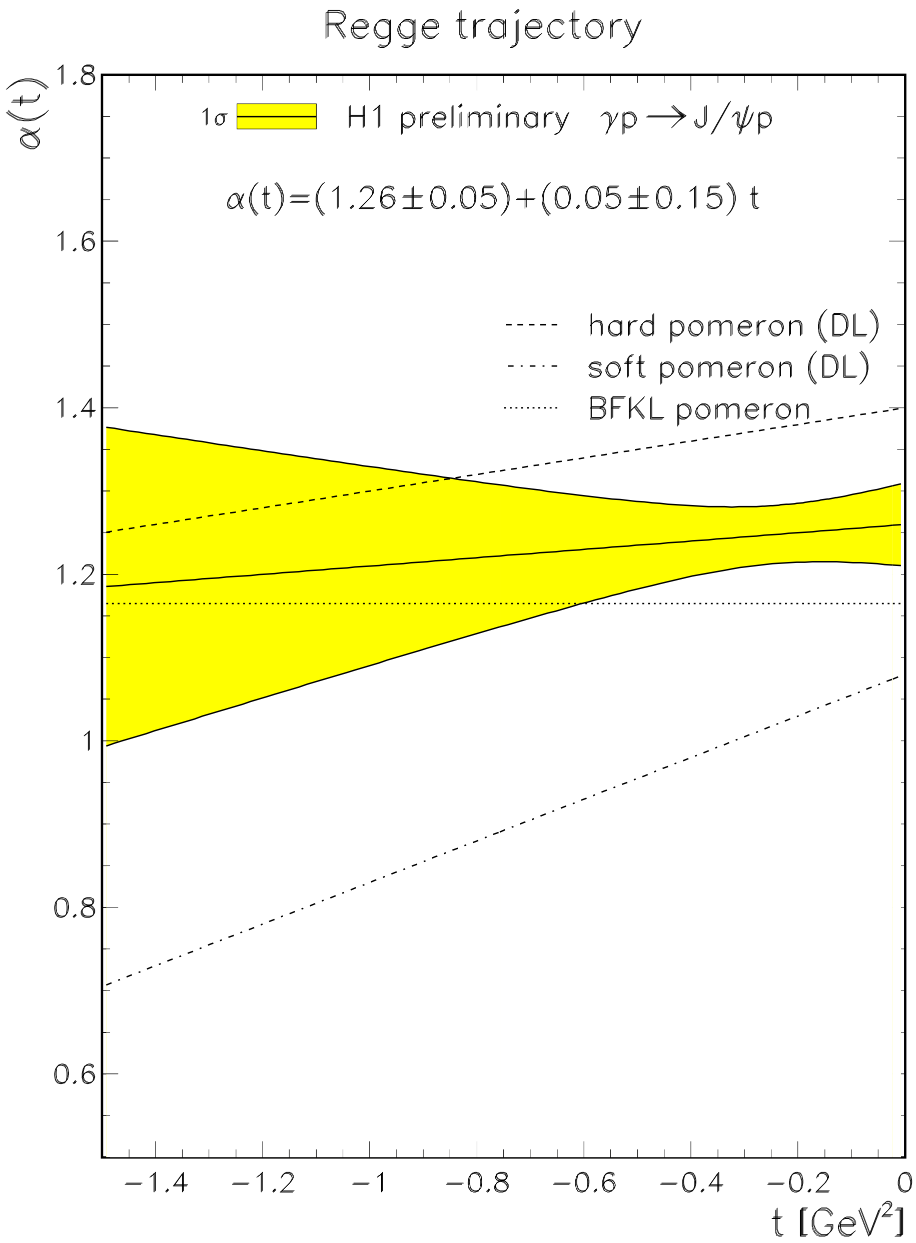


- **Intercept ($\alpha(0) = 1.0808$) and shrinkage ($\alpha' = 0.25$) of soft Pomeron yield σ falling with W when $t < -0.4GeV^2$, in clear contradiction to data**
- **Fit of 5 t-bins to $d\sigma/dt \;\sim\; W^{4\,(\alpha(t)-1)}$ yields $\alpha(t)$ for J/Ψ:**

Shrinkage in sub-hadronic Diffraction?

$\gamma\, p \;\rightarrow\; J/\Psi\, p$

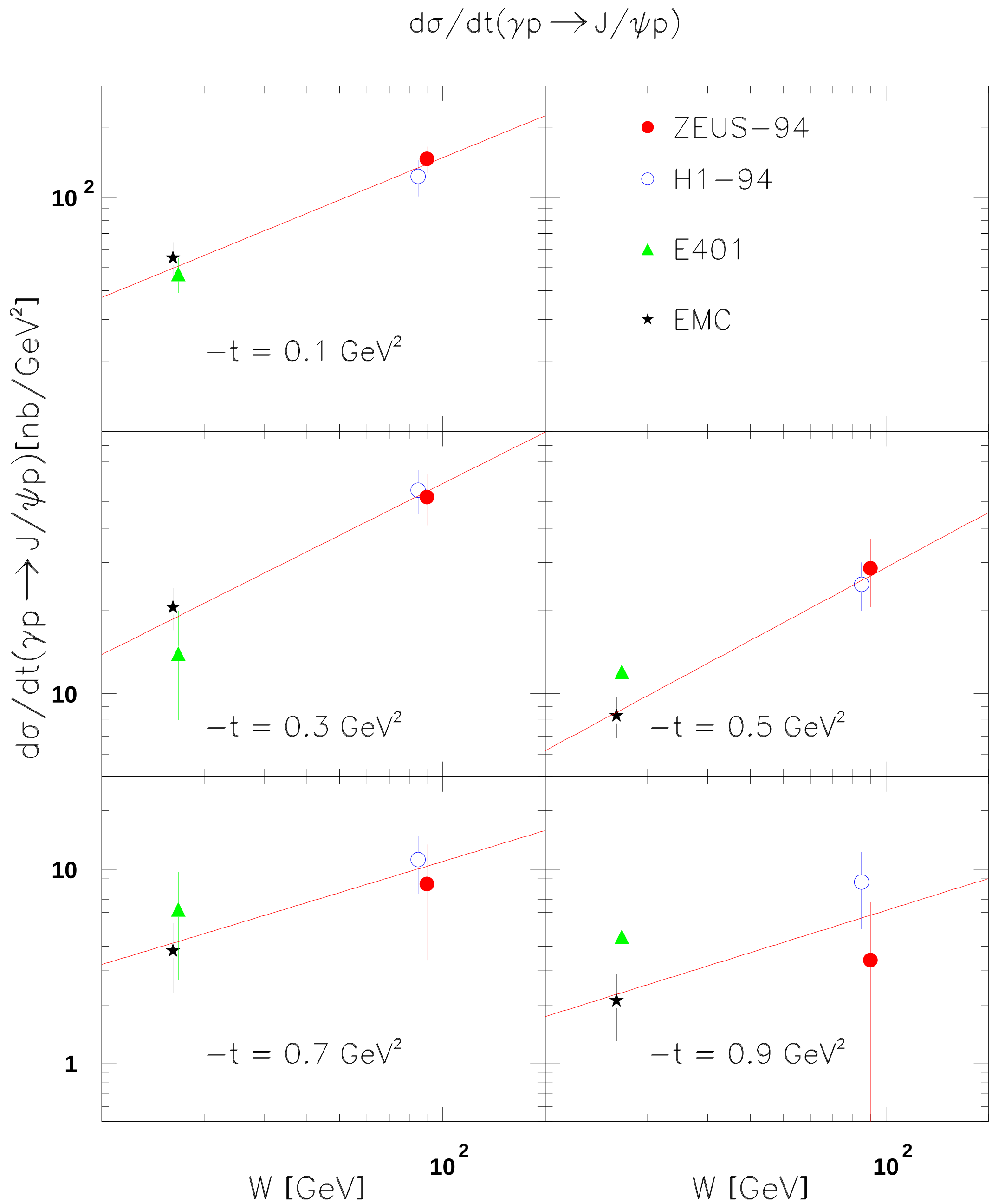
H1 data. **Fit** $\alpha(t) \;=\; \alpha(0) \;+\; \alpha'\, t$



- *soft pomeron incompatible with data*
- *exchange without shrinkage compatible with data*
- *BFKL prediction for intercept compatible with data*
- *DL-type (soft + hard)^2 pomeron poor but not excluded*

Correlated W - t dependence: Shrinkage ?

Zeus, H1, E401 and EMC data on $\gamma\, p \;\rightarrow\; J/\Psi\, p$



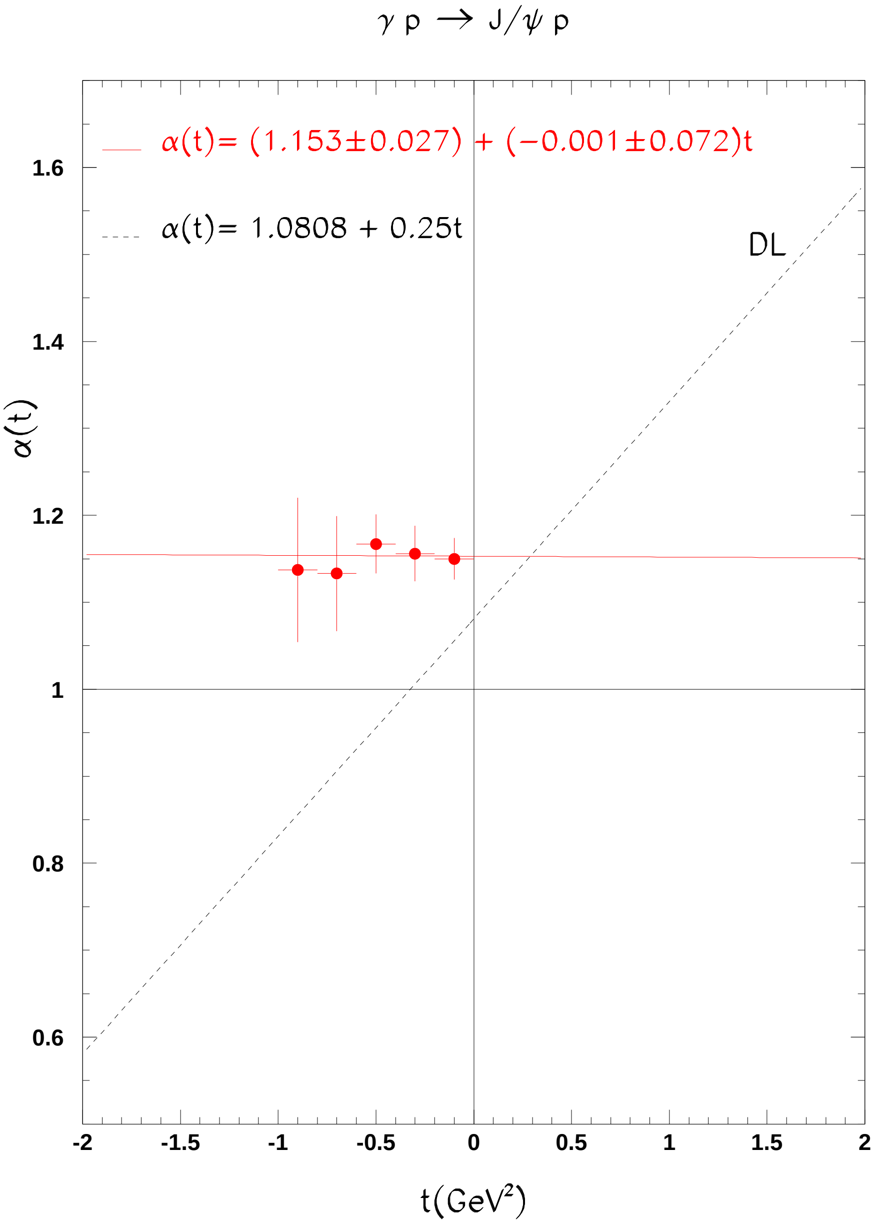
In each t-bin, determine $\alpha(t)$ via $d\sigma/dt \;\sim\; W^{4\,(\alpha(t)-1)}$ *from W dependence.*

Determine $\alpha(t)$ for ρ, Φ, J/Ψ

Shrinkage in sub- hadronic Diffraction?

HERA + fixed target data: $\gamma p \rightarrow J/\Psi\, p$

Fit $\alpha(t) = \alpha(0) + \alpha' t$



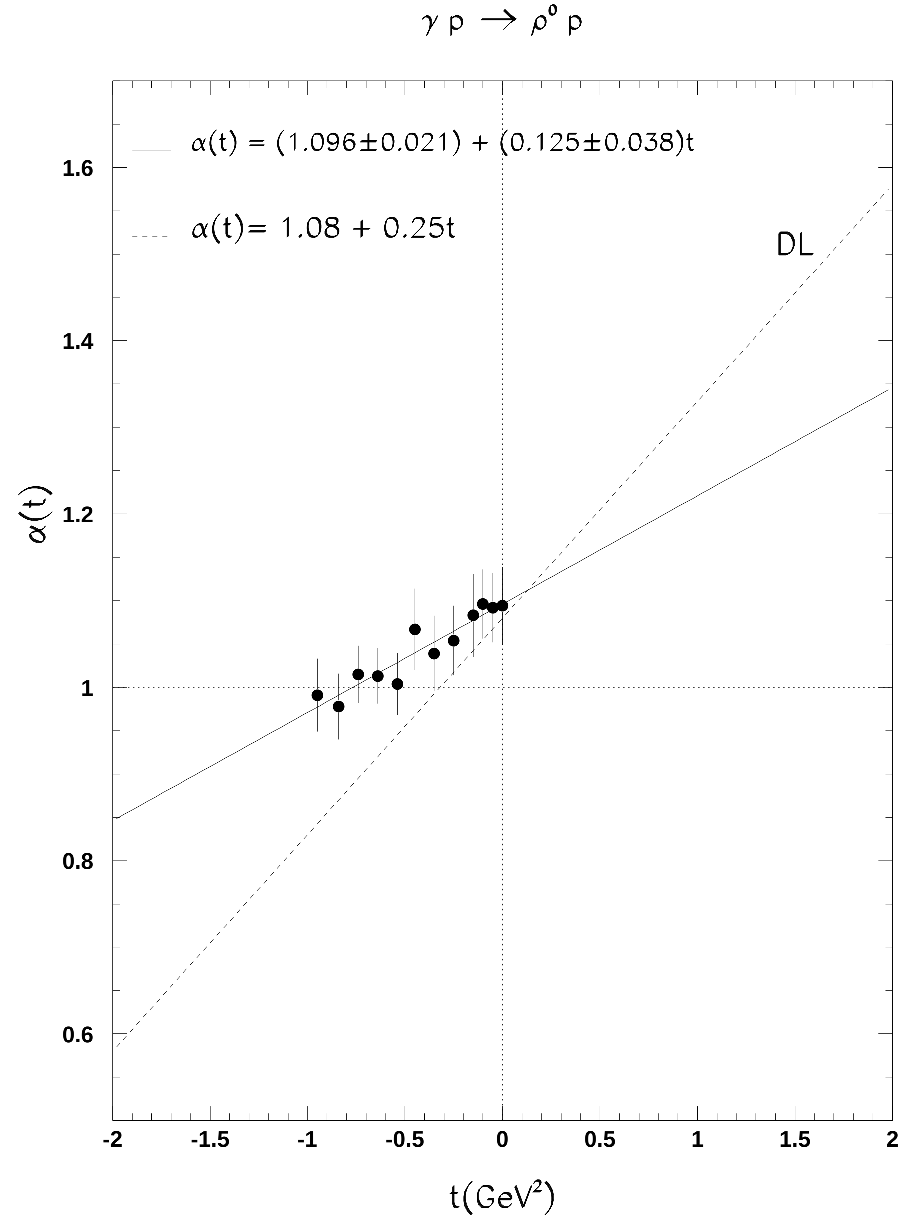
J/Ψ : Soft Pomeron trajectory fails

- intercept is higher
- shrinkage is smaller, compatibel with absent

Shrinkage in hadronic Diffraction?

HERA + fixed target data: $\gamma p \rightarrow \rho p$

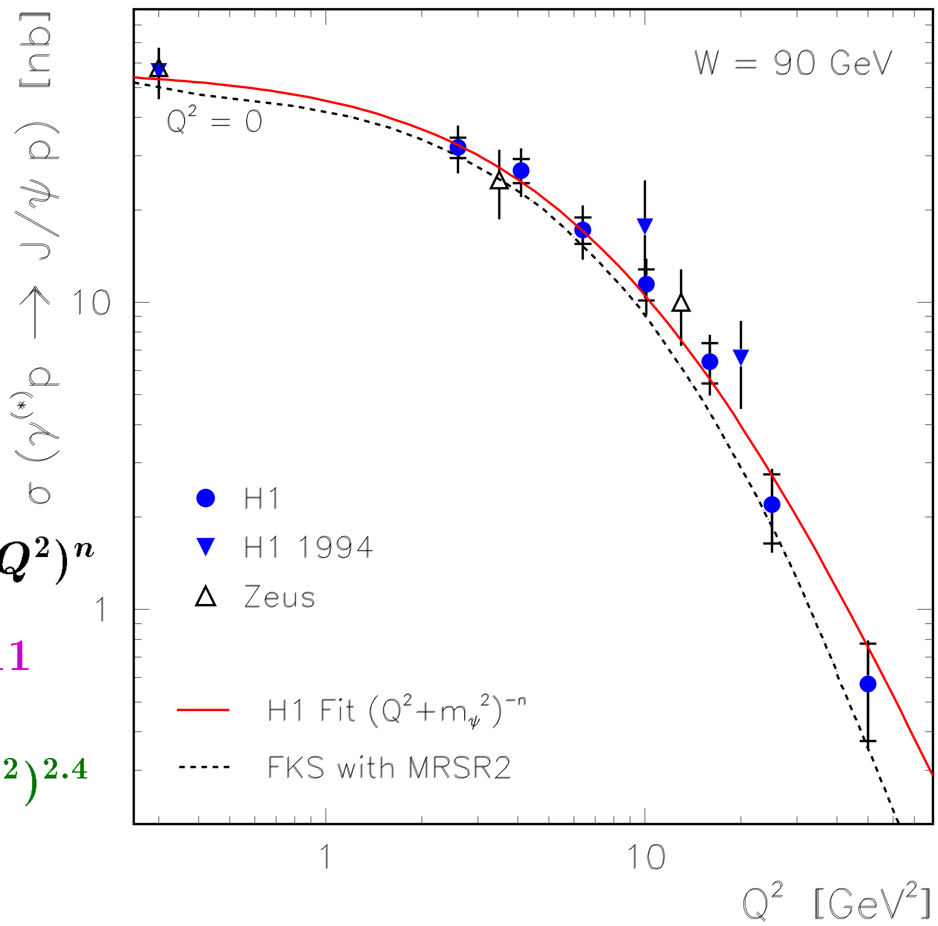
Fit $\alpha(t) = \alpha(0) + \alpha' t$



$\gamma \rightarrow \rho$: Pomeron trajectory not universal

- **shrinkage is signifikant**
- **shrinkage is smaller than for soft Pomeron from ($pp \rightarrow pp$)**

M_V Switch on $(Q^2)^n$



***J/Ψ*:**

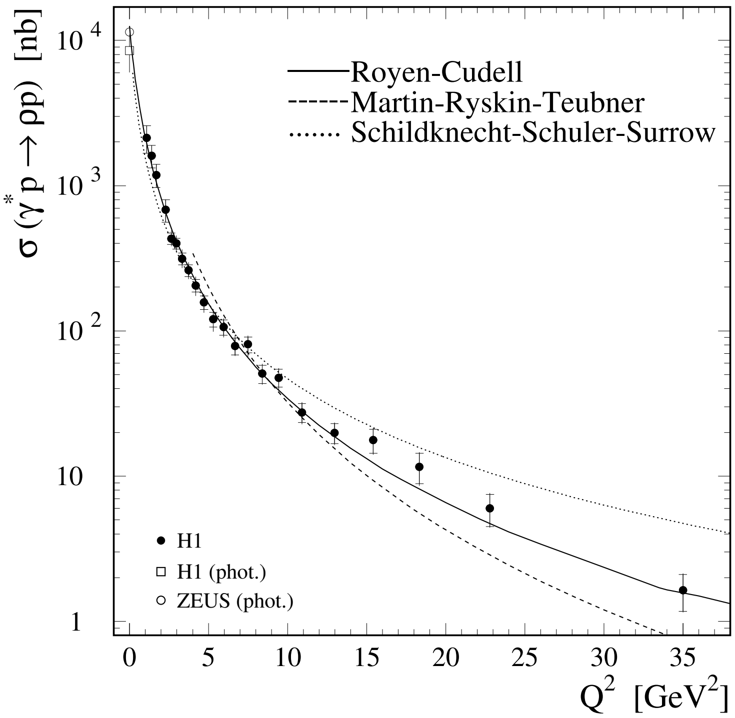
Fit to

$$\sigma \sim 1/(M_V^2 + Q^2)^n$$

$$n = 2.38 \pm 0.11$$

pQCD:

$$\sigma \sim \alpha_s^2(Q^2)/(Q^2)^{2.4}$$



***ρ°*:**

Fit (not shown) to

$$\sigma \sim 1/(M_V^2 + Q^2)^n$$

$$n = 2.24 \pm 0.09$$

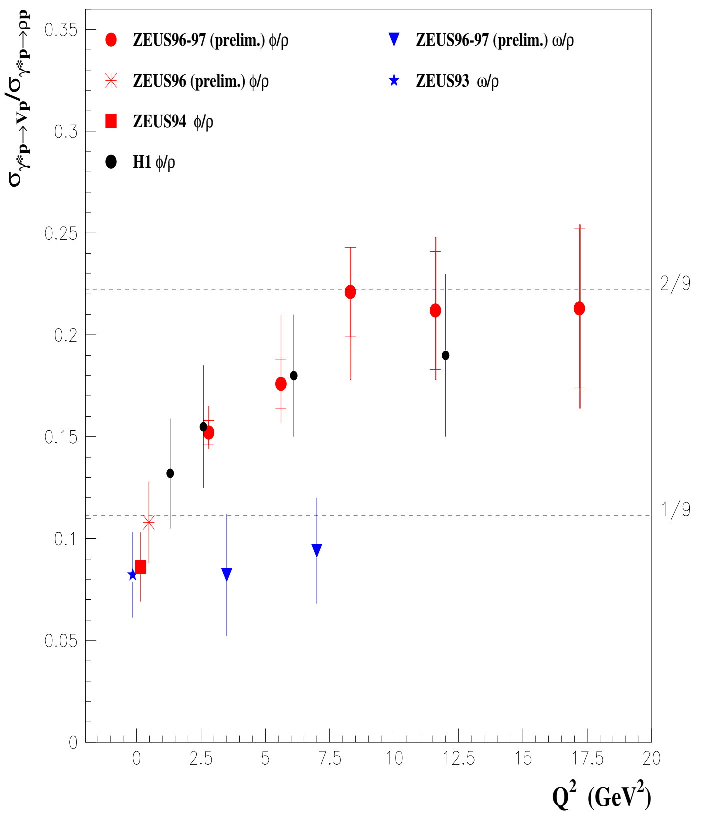
$n(\rho) = n(J/\Psi)$

within errors,

pole positions

quite different

Q^2 Knob on $\sigma(V)$ / $\sigma(\rho)$



Φ

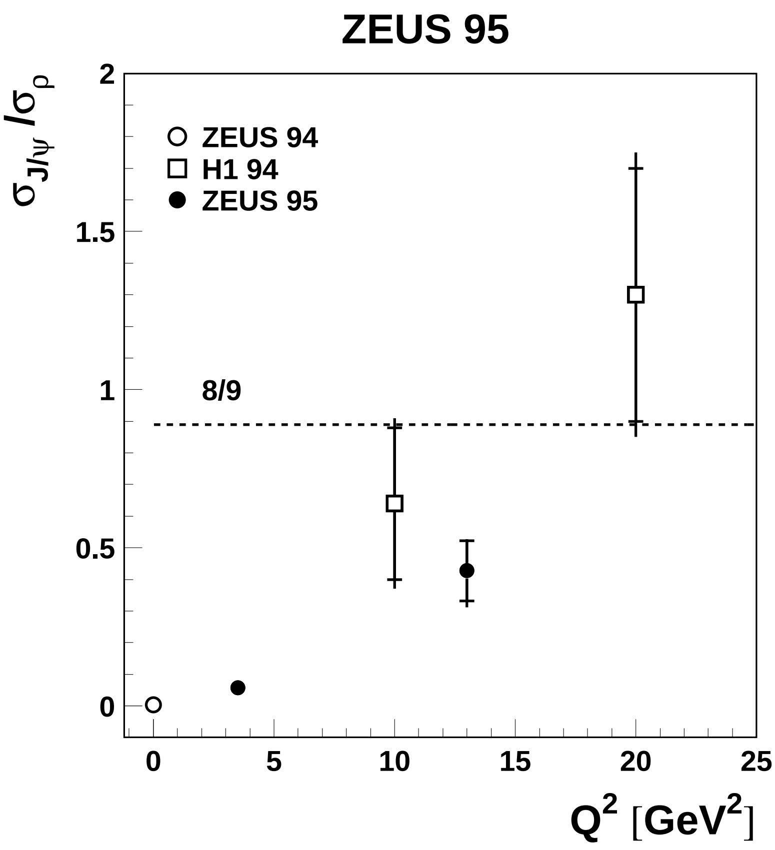
ω

Flavour dependent limit

for ω and Φ
$Q^2 \sim 10\ GeV^2$

SU(4) prediction,
from el.magn. coupling

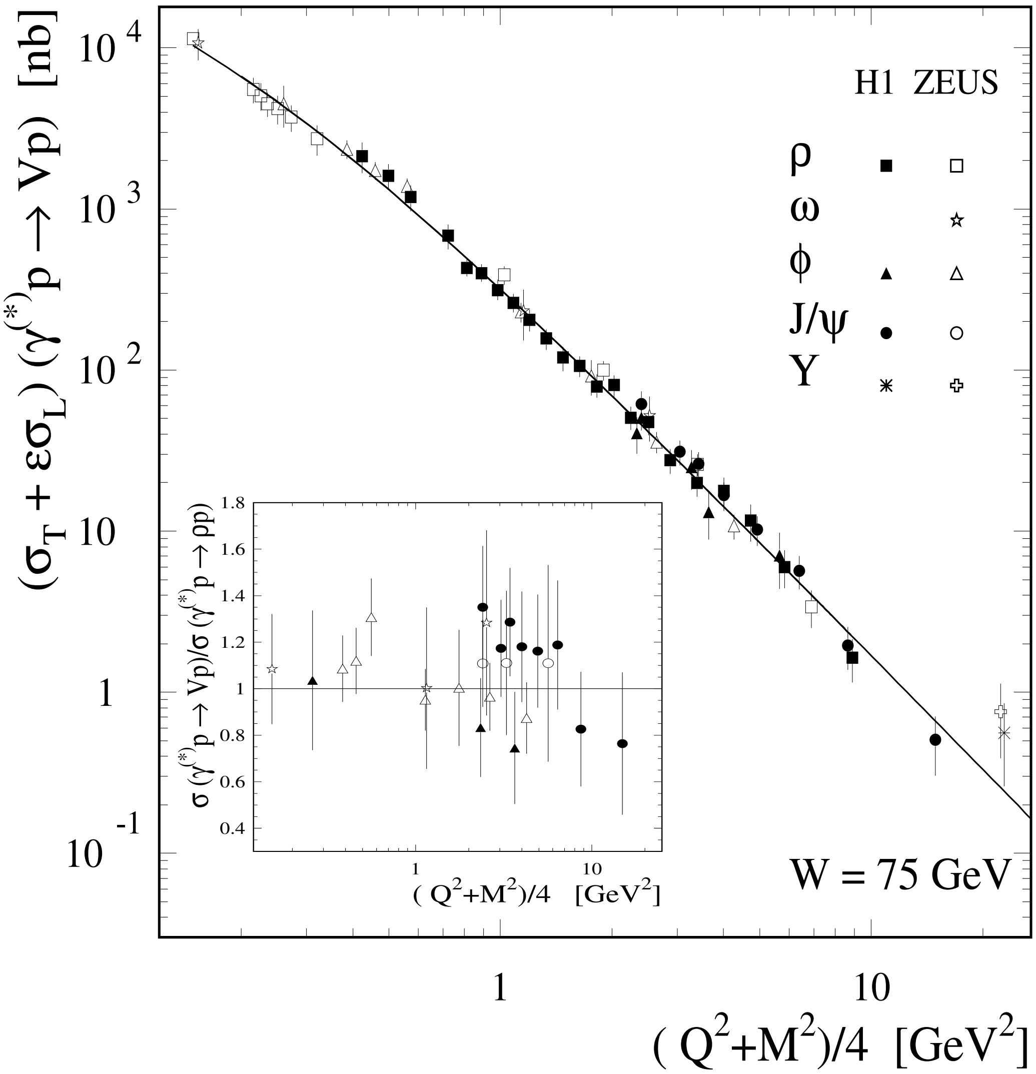
ρ° : ω : ϕ : J/Ψ
9 : 1 : 2 : 8



J/Ψ

for J/Ψ
$Q^2 \sim 20\ GeV^2$

V and Q^2 Universality of $\sigma(\gamma^* p \rightarrow V p)$?



SU(4) prediction, $\rho^\circ : \omega : \phi : J/\Psi$

from el.magn. coupling $9 : 1 : 2 : 8$

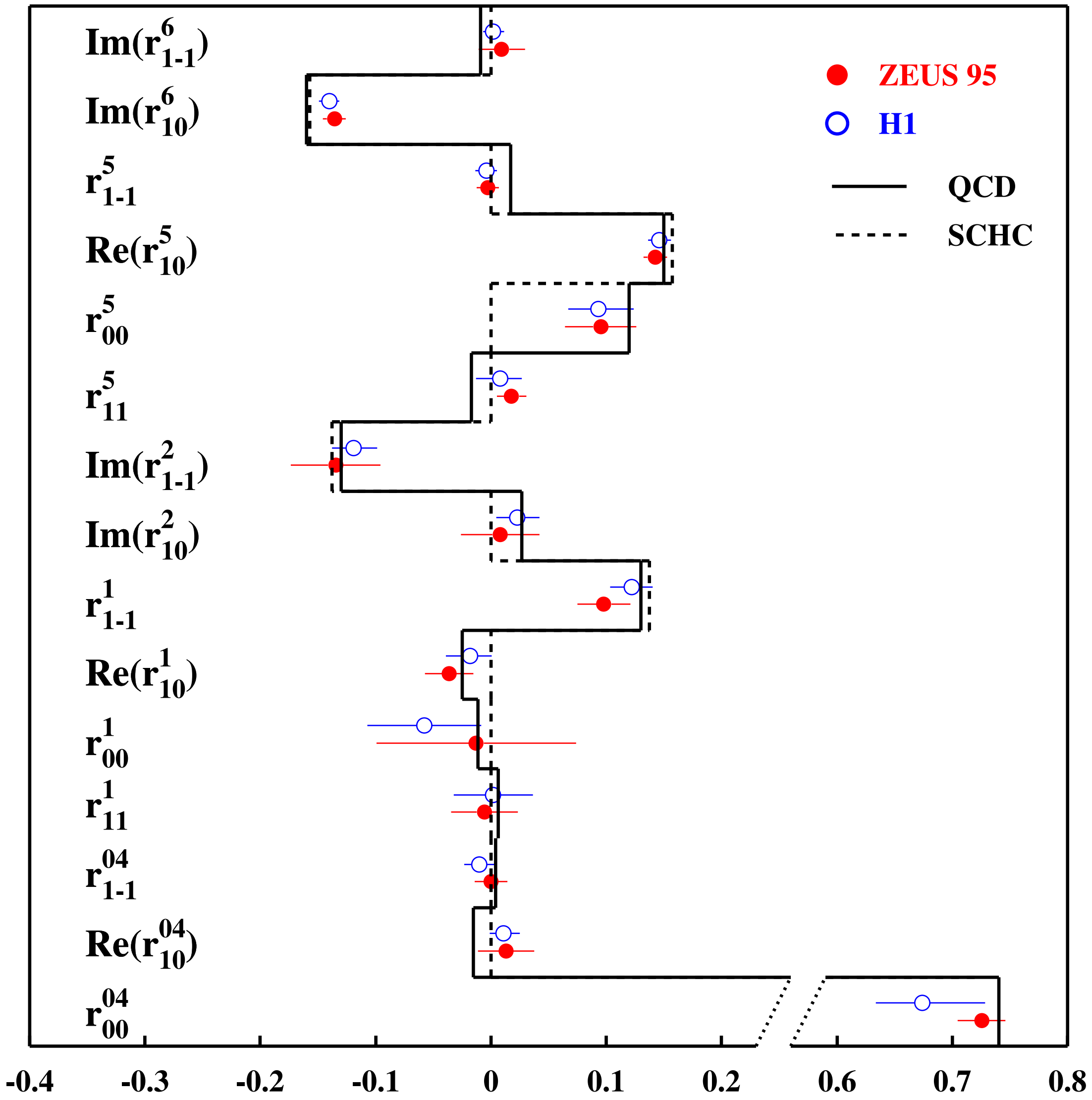
Fit $\sigma = a(Q^2 + M_V^2 + c^2)^n$

$c^2 = 0.11 \pm 0.03\ GeV^{-2}, \ \rightarrow c^2 \ll M_\rho^2, \ n = -2.37 \pm 0.10$

Extrapolated to W = 75 GeV as W^δ, with $\delta(M_V, Q^2)$ as from data

ρ, ω, ϕ, J/Ψ behave universally when distance to respective pole M_V^2 and quark el. charges are regarded,
Υ is high by factor 2, when extrapolated down with $W^{1.7}$.

Spin density matrix elements $\gamma^* p \to \rho^\circ p$



SCHC violated in combination r^5_{00}

Excellent agreement between H1 and ZEUS

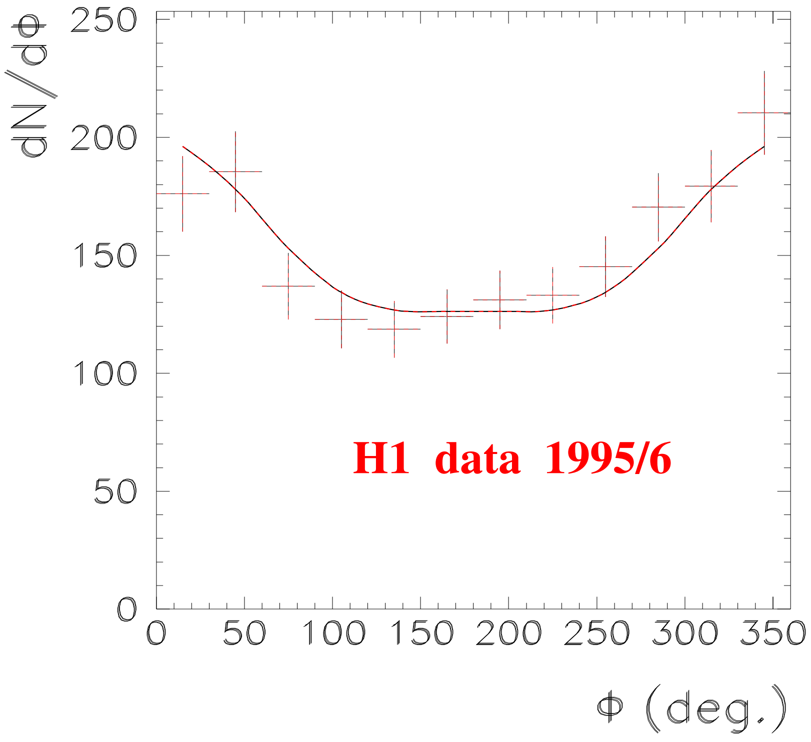
H1 : $1 < Q^2 < 60\ GeV^2$, ZEUS : $3 < Q^2 < 30\ GeV^2$

pQCD model (Ivanov, Kirschner) describes data well

SCHC in $\gamma^* p \to \rho^\circ p$

$$W(\phi) \propto 1 - \epsilon \cos 2\phi(2r^1_{11} + r^1_{00}) + \sqrt{2\epsilon(1+\epsilon)} \cos\phi(2r^5_{11} + r^5_{00})$$

(integrated over $\cos\theta, \varphi$)



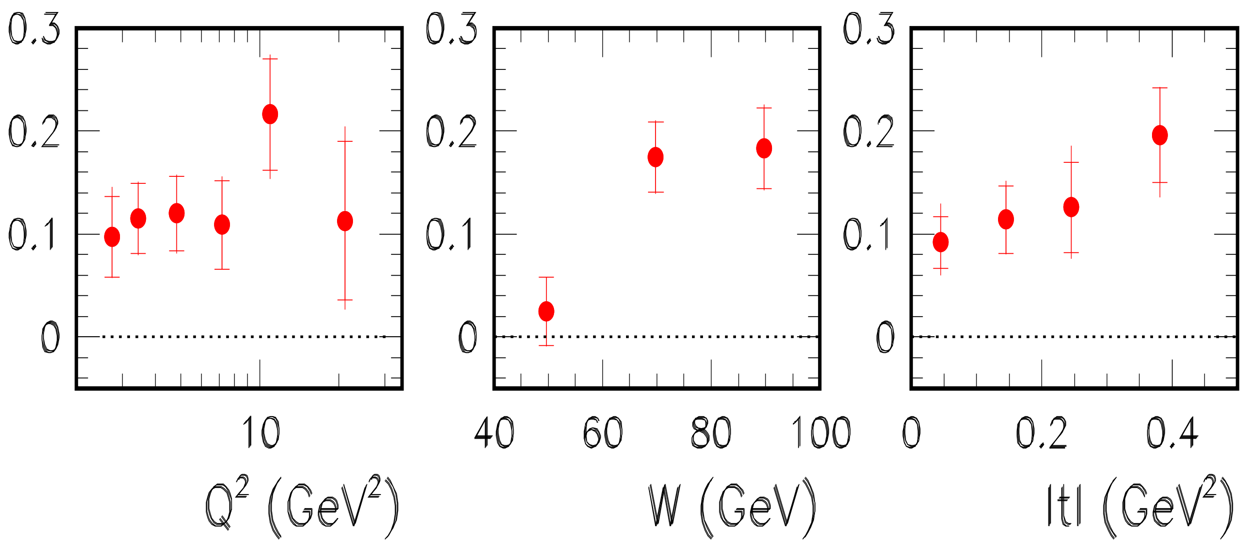
SCHC: expect uniform ϕ distribution

$$r^5_{00} \sim \frac{\sqrt{2}\,R}{1+\epsilon R}\,\frac{|T_{01}|}{|T_{11}|}$$

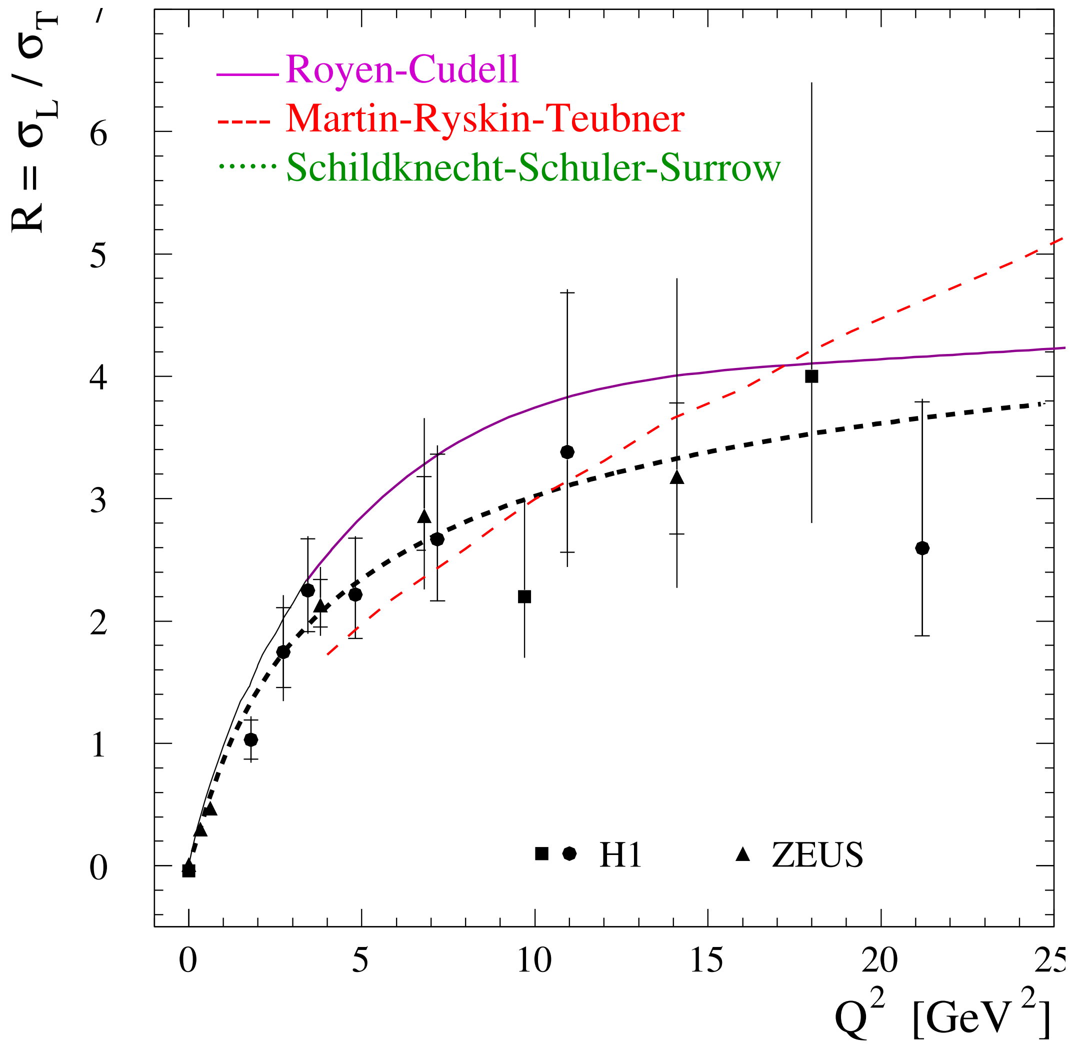
$$\simeq 8 \pm 3\%$$

T_{01}: Amplitude for a transverse photon to produce a longitudinal ρ°

$$(2r^5_{11} + r^5_{00})$$



Q^2 Knob on σ_L/σ_T in $\gamma^* p \to \rho^\circ p$



SCHC violation effect $\sim$ 8%

influence on R : $2 - 3\%$

Assuming SCHC,

$$R = \sigma_L/\sigma_T = \frac{1}{\epsilon}\frac{r_{00}^{04}}{(1-r_{00}^{04})}$$

r_{00}^{04} **: probability to produce longitudinal ρ°,**

from either transverse or longitudinal γ^*

Dependence of R on Q^2 can be described by pQCD and GVDM

"My" Summary on Elastic Hadronic & Sub-hadronic Diffraction

1. HERA provides a switchboard for selecting different channels of elastic (and inelastic) diffraction:
   - tunable size - hadronic/sub-hadronic - scattering particles, on the IN side (Q^2), and on the OUT side ($M_V, P/N$).
   - channels with/without Reggeon admixtures
2. t - dependence: slope b at small t shows a clear correlation of the transverse size of the diffractive process with
   N_h, the number of "normal" hadron-size vertices:
   $N_h = 2$: b $>$ 8, $N_h = 1$: 6 $> b >$ 4, $N_h = 0$: b $\sim 1 GeV^{-2}$
3. $W_{\gamma p}$ dependences:
   2 W^δ classes: $\delta \sim 0.2$ $(N_h = 2)$, $\delta \sim 0.8$ $(N_h = 1)$.
   ($N_h = 0$ not yet measured.)
4. $W - t$ correlation:
   No shrinkage is observed in $(\gamma p \rightarrow J/\Psi p)$, an $N_h = 1$ reaction.
5. phenomenological pomeron soft only: no way. (soft + hard)^2 exchange not favored.
6. pQCD calculations for $N_h = 1$ reactions can reproduce t- and W-dependences.
7. Linkage of W dependence of $F_2^P(Q^2, W)$ to $\sigma_{tot}(\gamma^* p \rightarrow Vp)$ of quasi-elastic channels by "Optical Theorem for $\gamma^* p$" is confirmed.
8. $Q^2 dependence$: $\gamma^* p \rightarrow Vp$ x-sections pretty "universal" in the variable $(Q^2 + M_V^2)$, when $SU4$ couplings are regarded. (Υ?)
9. VM helicity properties and the σ_L/σ_T ratio at large Q^2 can be accomodated by pQCD, including a small departure from SCHC.

”My” Summary on
Elastic Hadronic & Sub-hadronic Diffraction

Hera is a unique laboratory
to study soft and hard diffraction
of free and of virtual particles.

Outlook:

data on the new elastic diffractive channel of
Deep Virtual Compton Scattering

$$\gamma^* p \rightarrow \gamma\, p$$

are coming up.