Vector meson production and DVCS
(on behalf of H1 and ZEUS)

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DESY

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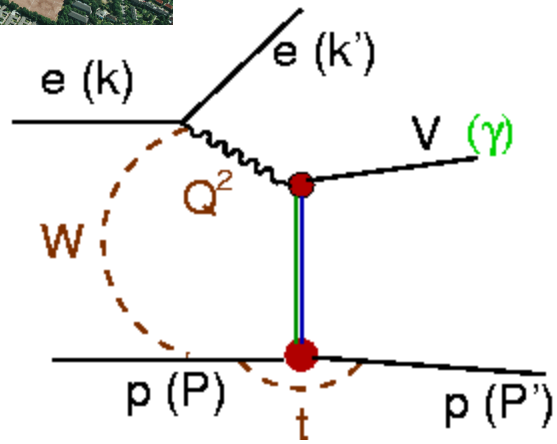
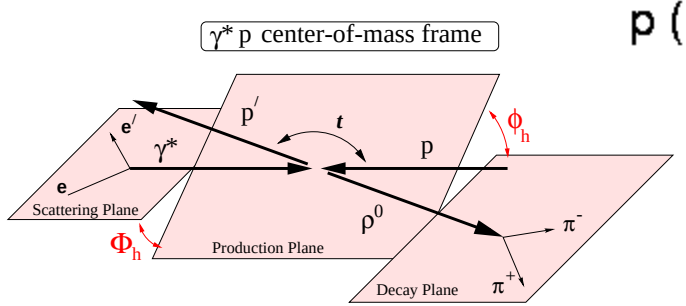
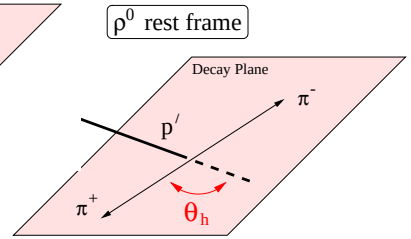
1. Introduction
   - HERA accelerator
   - Exclusive diffraction
2. Measurement results
   - W-dependence
   - Q^2-dependence
   - $|t|$-dependence
   - Helicity angles study (ρ/ϕ)
   - Beam Charge Asymmetry (DVCS)
   - High $|t|$ measurements
3. Summary and Outlook
4. Backup







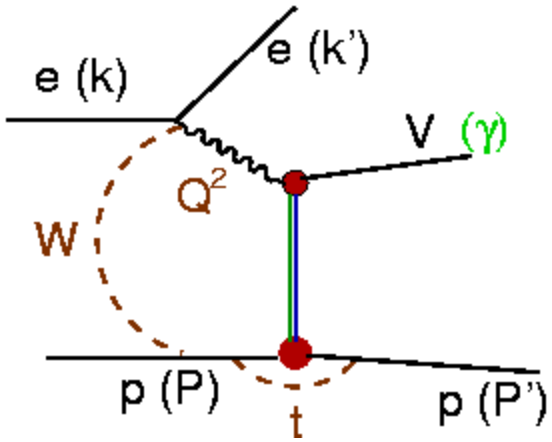
HERA

HERA - *ep* collider (1991-2007),
HERA-I in $\leq$ 2000, afterwards: HERA-II
located at DESY, Hamburg
$E_e = 27.5$ GeV
$E_p = 820$ GeV (95p-97p): 42 pb^{-1}
920 GeV (98e-07p): 455 pb^{-1}

H1 and ZEUS: colliding beams experiments with similar physics analysis program.

luminosity collected: $\approx 0.5 fb^{-1}$ per experiment

Exclusive diffraction



Exclusive process kinematics.

Diffractive system:

- vector mesons ($J^{PC} = 1^{--}$, $\rho, \phi, J/\psi, \Upsilon$)
- photon (DVCS)

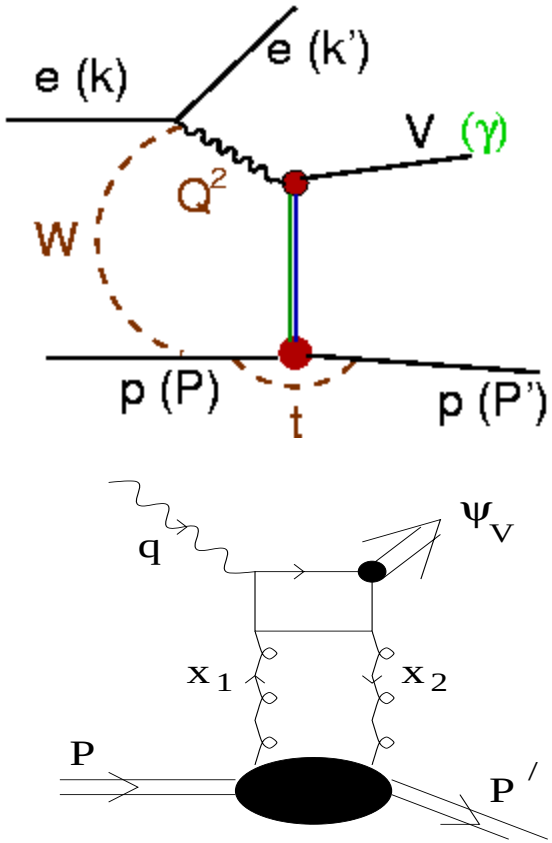
Kinematics: $\mathbf{M_V^2}, \mathbf{Q^2}, \mathbf{W}, \mathbf{|t|}$

Q^2 - photon virtuality,
M_V^2 - vector meson mass squared,

W - invariant mass of the γp system,
$W^2 = 2E_p(E - p_z)_V$, $E_p = 920\ GeV$.

$|t|$ - 4-momentum transfer at the proton vertex,
$|t| = |P' - P|^2 \approx p_{TV}^2$ (approx. true, if $p_{Te}^2 \lesssim 1$ GeV^2).

Exclusive diffraction



Exclusive process kinematics and pQCD representation

Diffractive system:

- vector mesons ($J^{PC} = 1^{--}$, $\rho, \phi, J/\psi, \Upsilon$)
- photon (DVCS)

Kinematics: $\mathbf{M_V^2}, \mathbf{Q^2}, \mathbf{W}, \mathbf{|t|}$

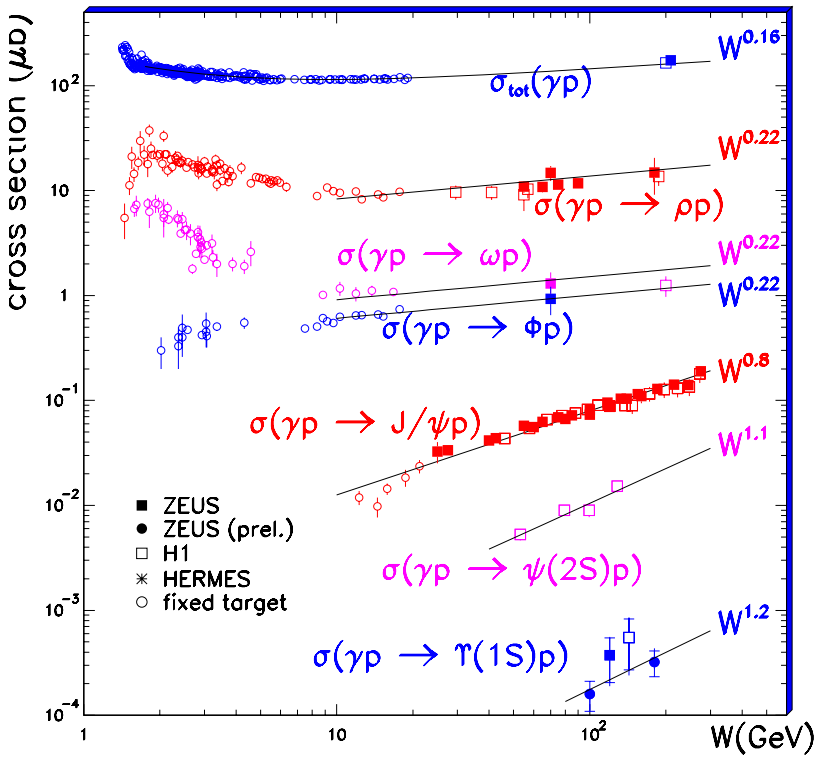
In pQCD sensitive to gluons in the proton via:
W - gluon **longitudinal momentum** in the proton
W $\sim 1/x$, in general $x_1 \neq x_2$ (skewed gluons)

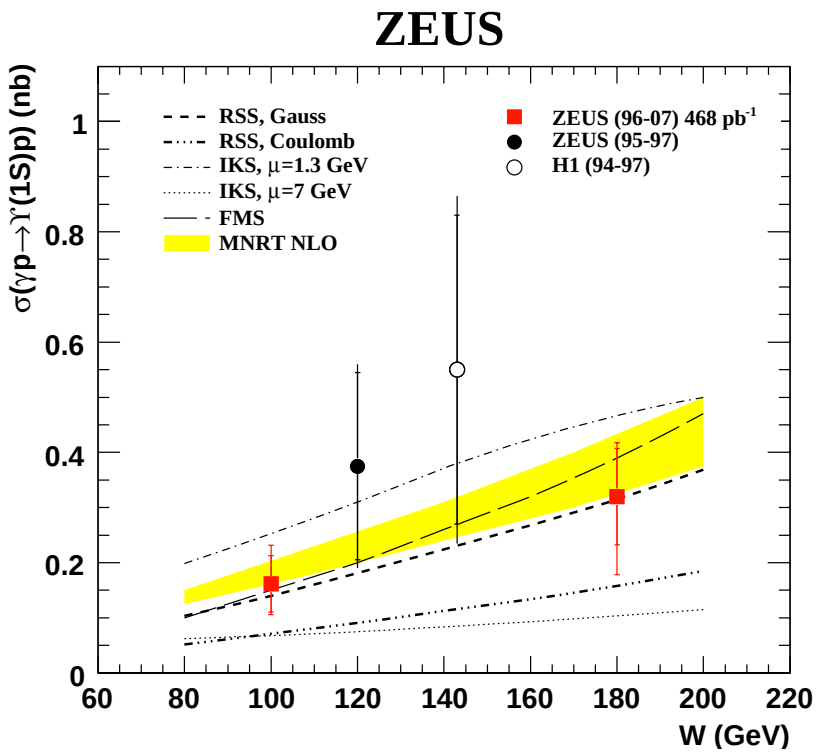
The cross section $\frac{d\sigma}{dt} \sim e^{-b|t|}$,
b - **transverse distribution** of the gluons in the proton,

M_V^2 and Q^2 - set the scale at which the W and $|t|$ are probed.

W-dependence

PHP ($Q^2 \approx 0$ GeV^2)





$\sigma \sim W^{\delta}$, δ rises with M_V^2 from "soft" ($\delta = 0.22$) to "hard" ($\delta \approx 1.0$)

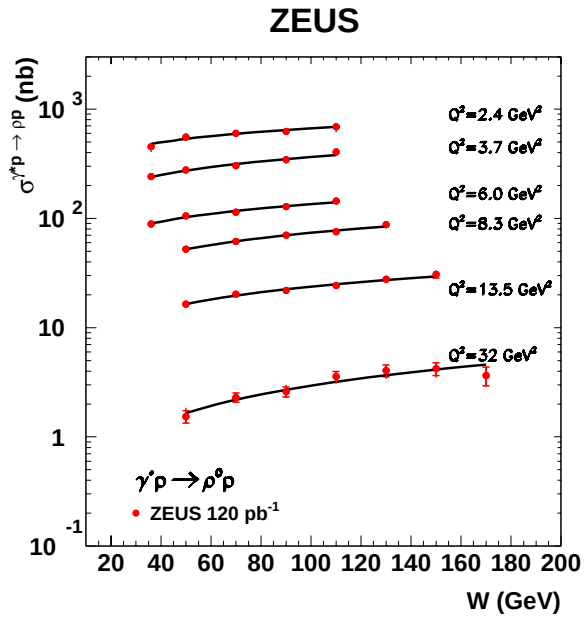
mass M_V sets the scale of the interaction

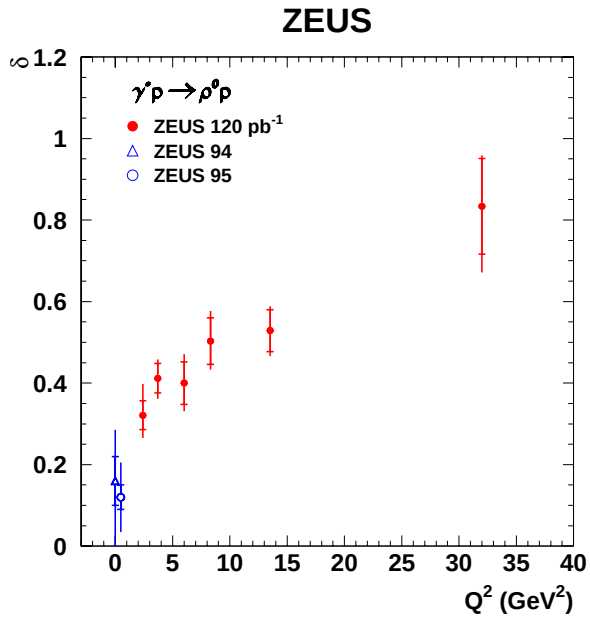
new measurement of Υ meson ($M_V = 9.46$ GeV), $\delta = 1.2 \pm 0.8$

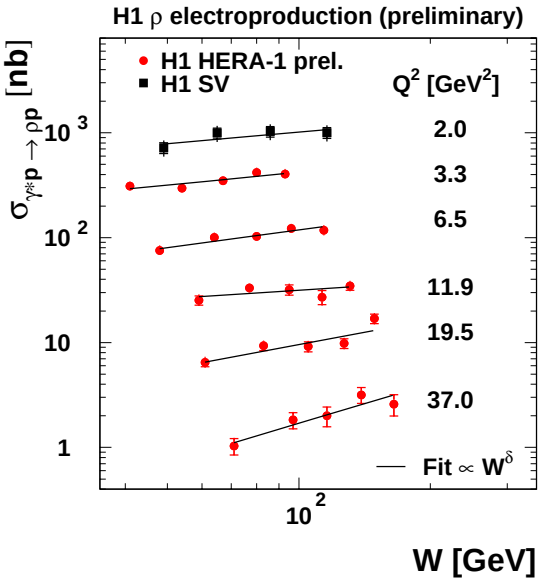
- Y: sensitive to vector meson wave function: seems to prefer Gauss to Coulomb,
- Y: sensitive to hard scale value: NRQCD NLO scale is between $1.3 < \mu < 7$ GeV,
- Y: pQCD models W-slope: FMS LO (δ=1.7), other NLO give value $\delta \approx$1.2

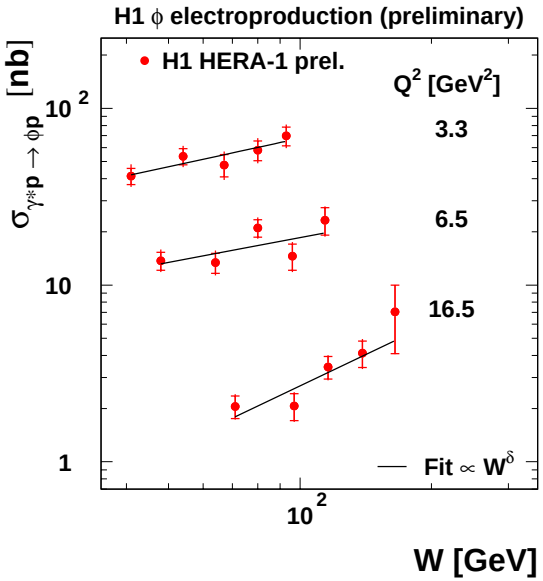
W-dependence, (light VM: ρ, ϕ)

DIS ($Q^2 > 1$ GeV^2)









light Vector Mesons

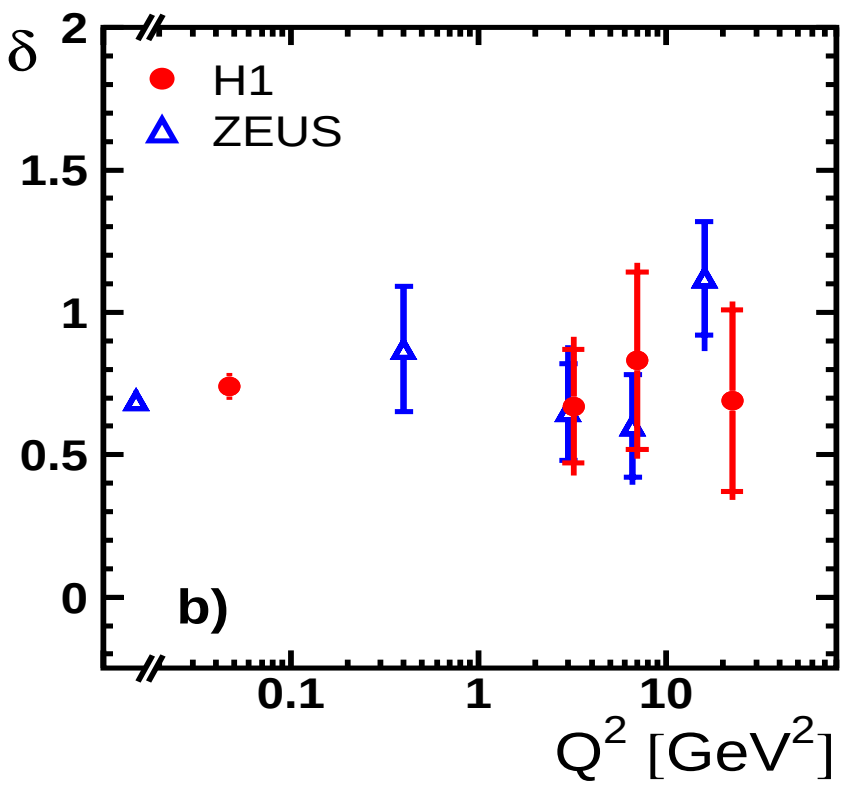
$\sigma \sim W^\delta$,
δ rises with Q^2
from "soft" to "hard"

similar for ρ and ϕ mesons

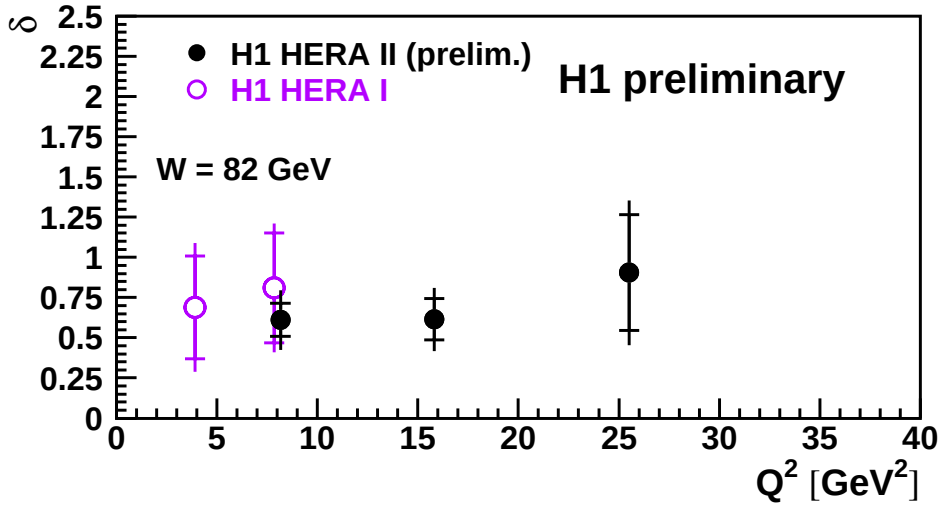
W-dependence

DIS ($Q^2 > 1$ GeV^2)

heavy VM: J/ψ



DVCS

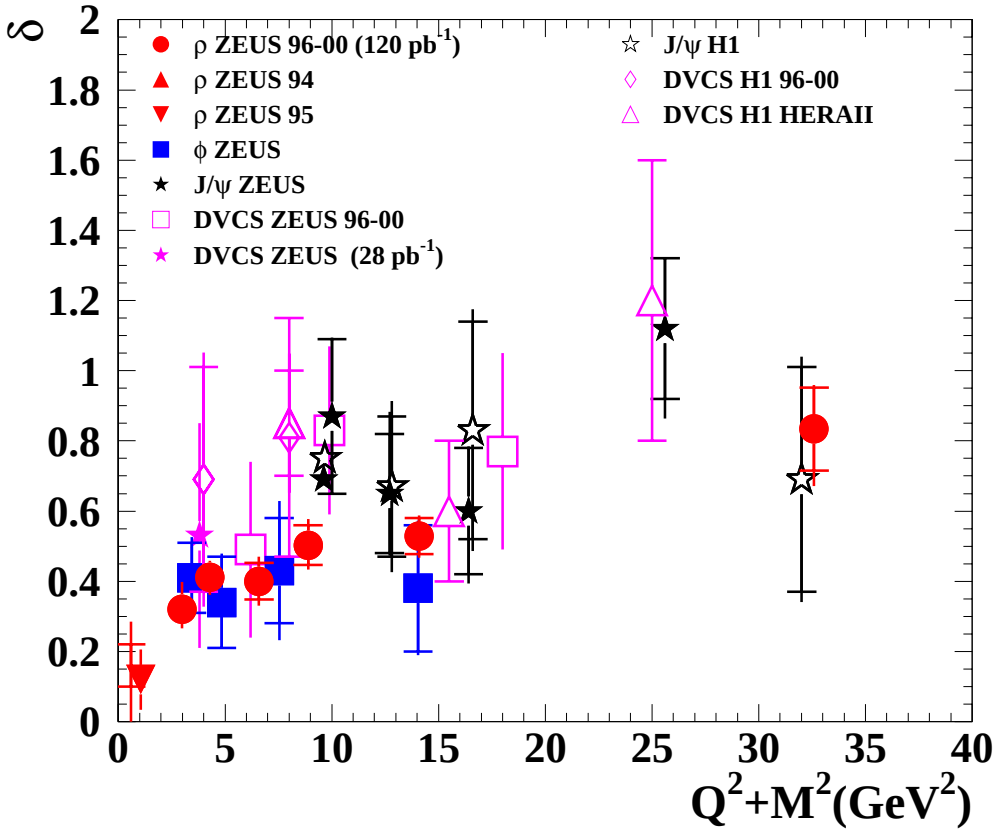


J/ψ and DVCS,

$\sigma \sim W^{\delta}$,
δ - flat with Q^2
the process is already "hard"

W-dependence summary

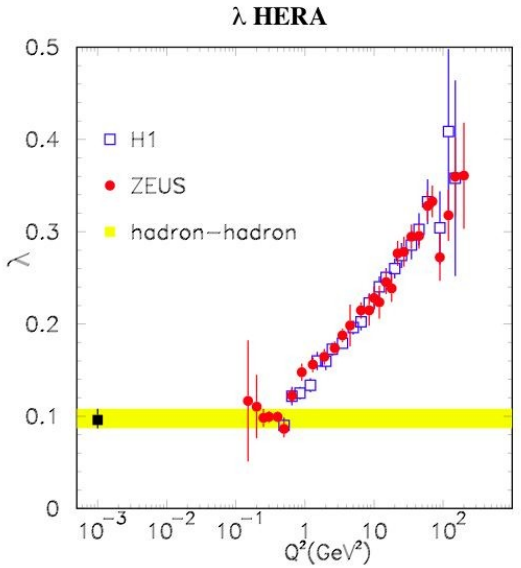
PHP+DIS



$\sigma \sim W^{\delta}$,
δ rises with $Q^2_{eff} = Q^2 + M_V^2$

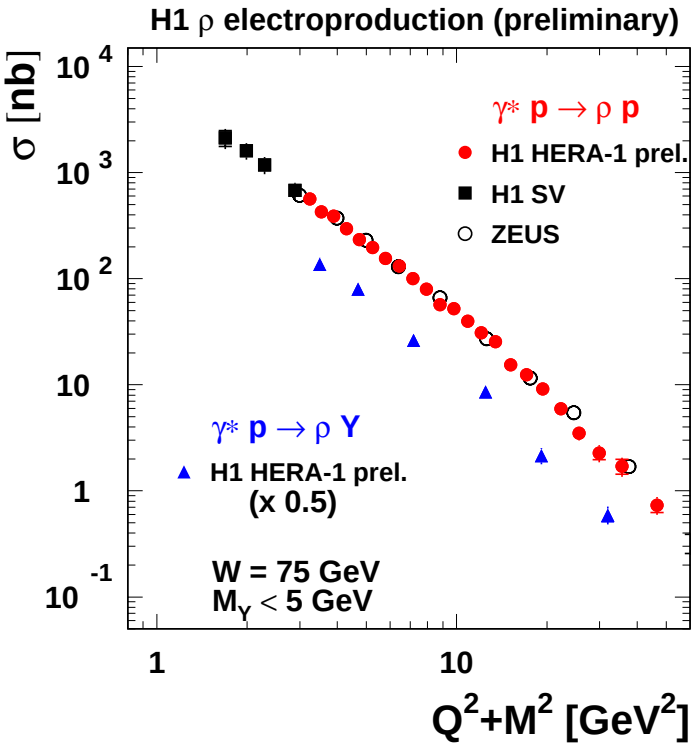
consistent within pQCD

- experiment gives $\sigma \sim W^{\delta}$
- two gluon exchange: $\sigma \sim \alpha_s |xg(x, Q^2)|^2$
- at low x: $F_2(x, Q^2) \sim xg(x, Q^2) \sim x^{-\lambda(Q^2)}$ and $W^2 \sim 1/x$
- so, $\delta \sim 4\lambda(Q^2)$

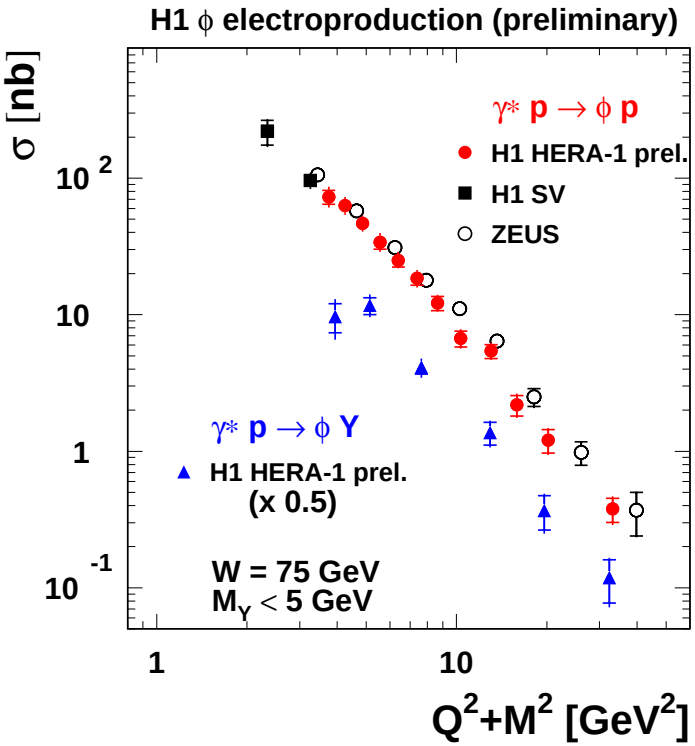


Q^2-dependence, $\sigma \sim (Q^2 + M_V^2)^{-n}$

ρ^0, $m_\rho^2 = 0.5$ GeV^2



ϕ^0, $m_\phi^2 = 1.0$ GeV^2

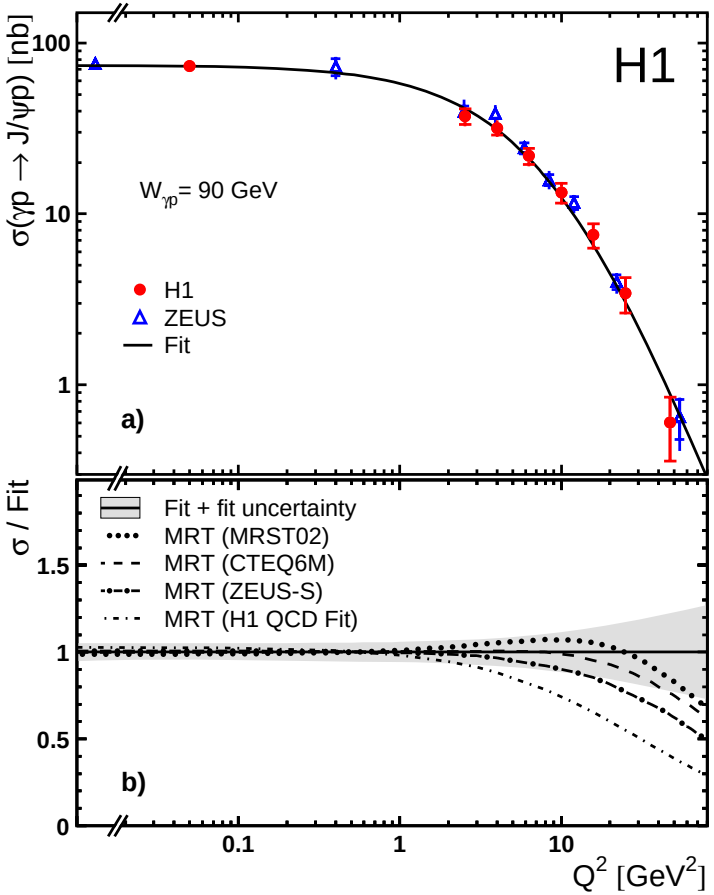


H1/ZEUS: very good agreement

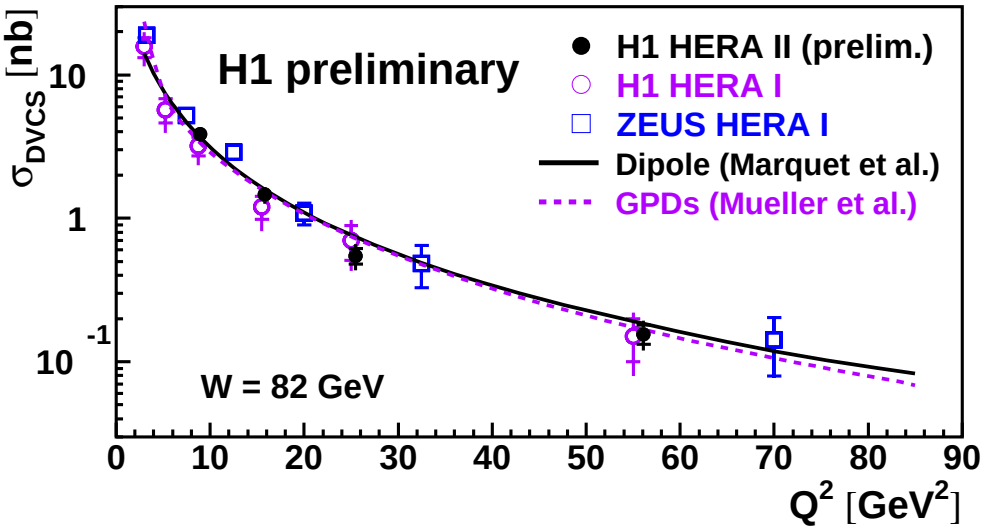
- $Q^2 \geq 0$ GeV^2, n$\approx$2.00$\pm$0.01, $\chi^2/ndf \sim 10$ (n $\neq$ const)
- $Q^2 \geq 10$ GeV^2, n$\approx$2.50$\pm$0.02, $\chi^2/ndf \sim 1.5$

Q^2-dependence, $\sigma \sim (Q^2 + M_V^2)^{-n}$

J/ψ



DVCS



H1/ZEUS: perfect agreement

- J/ψ n=2.49±0.08
- *DVCS* n=1.54±0.06

measurements agree well with pQCD calculations

$|t|$-dependence

$\frac{d\sigma}{dt} \sim e^{-b|t|}$, $|t|$ <2 GeV^2

b - sensitive to the transverse size of the interaction region

Geometric picture - transverse size:

$b = b_V + b_p$

transverse size:

Vector Meson: $b_V \sim \frac{1}{Q^2+M_V^2}$

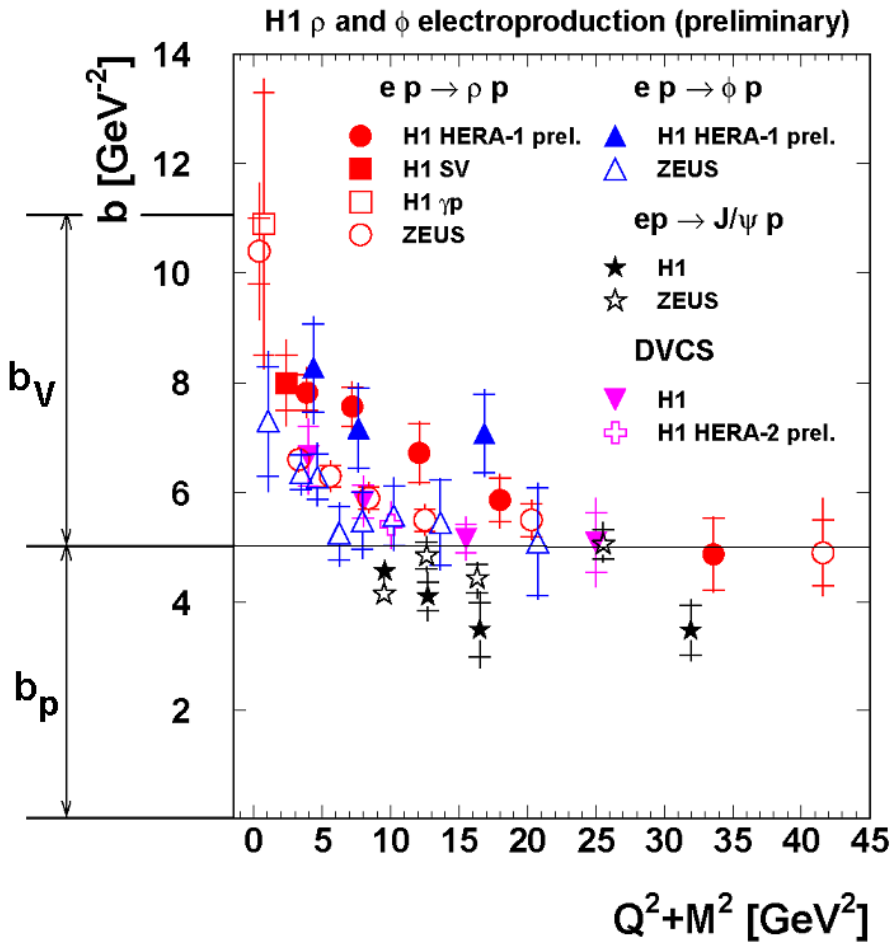
Target: $b_p \approx 5$ GeV^{-2}

b_p can be interpreted as

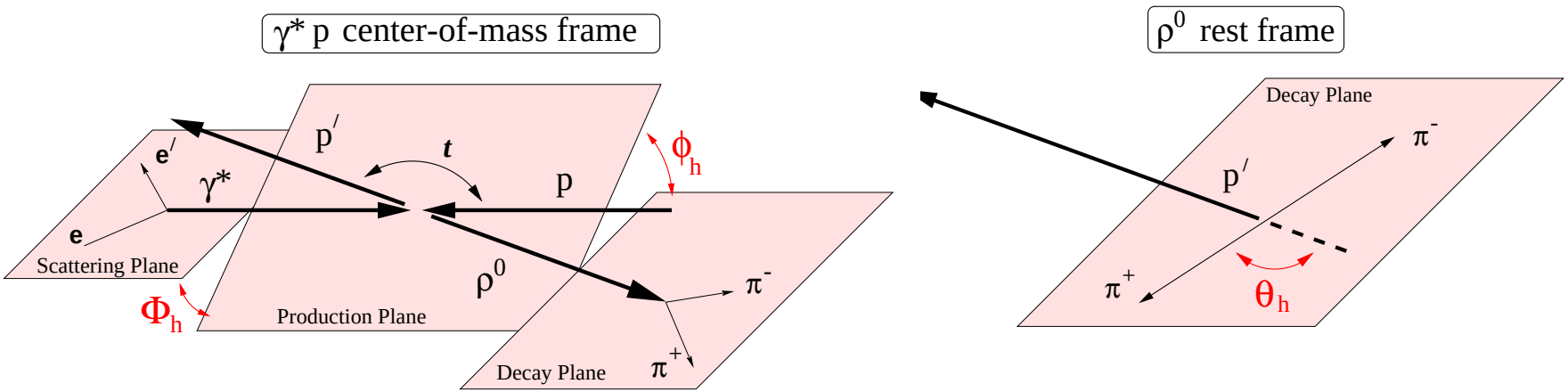
$r_{gluons} \approx 0.5$ fm

charge radius of the proton

$r_{em} \approx 0.8$ fm



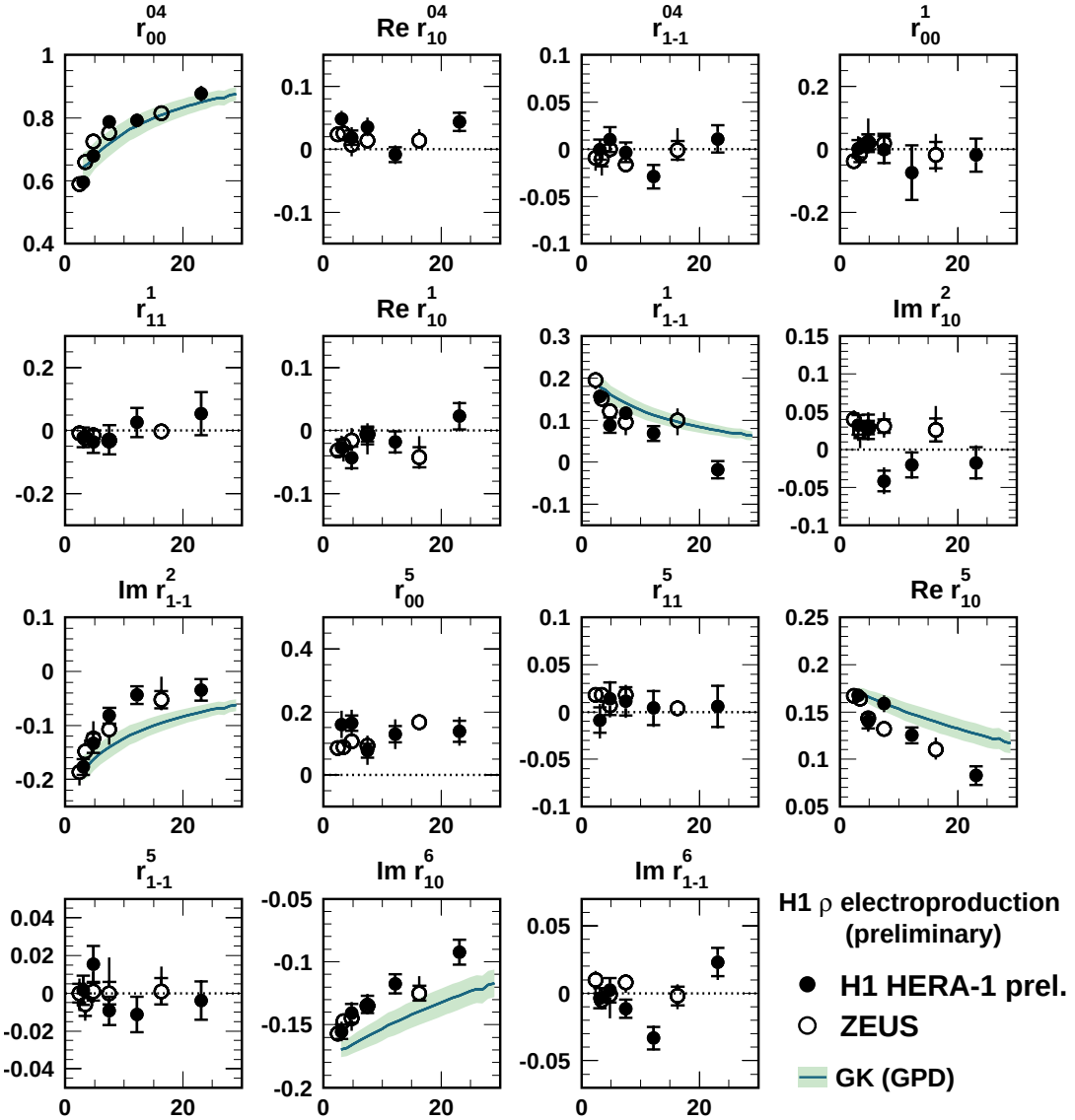
Helicity angles analysis, $R = \sigma_L/\sigma_T$



- Study angular distributions: 3 angles (θ_h, ϕ_h, Φ_h)
- 15 combination of spin-density matrix elements, r_{ij}^{kl}
- s-channel helicity conservation SCHC
  - $\gamma_T^* \longrightarrow \rho_T$
  - $\gamma_L^* \longrightarrow \rho_L$
- if SCHC holds $\longrightarrow R = \sigma_L/\sigma_T = r_{00}^{04}/\epsilon(1 - r_{00}^{04})$
- equivalent to fitting $cos\theta_h$: $\frac{d\sigma}{dcos\theta_h} \sim 1 - r_{00}^{04} + (3r_{00}^{04} - 1)cos^2\theta_h$

Helicity angles study, $R = \sigma_L/\sigma_T$

- 5 elements are non-zero in pQCD (GPD) calculations
  - $r_{00}^{04} \rightarrow R = \sigma_L/\sigma_T$
- other 10 are supposed to be zero due to SCHC
- (but) r_{00}^{5} is not zero
  stands for a single spin-flip, can be interpreted in pQCD due gluon exchange (which are spin-1 particles)

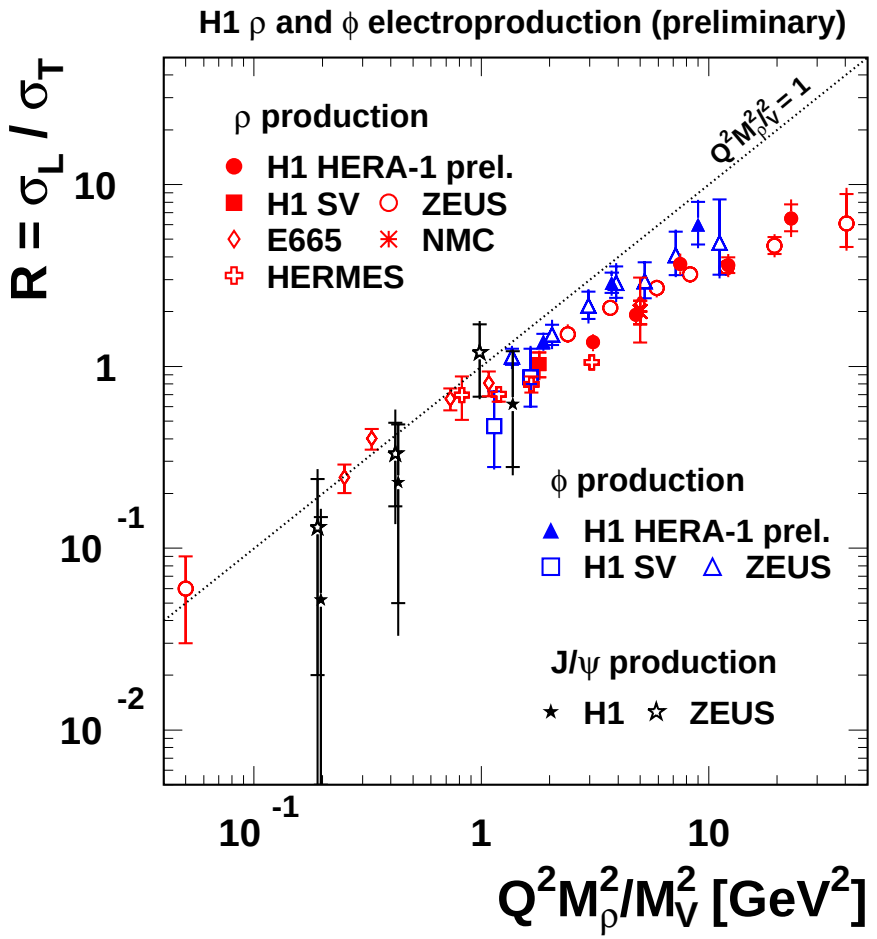


$R = \sigma_L/\sigma_T = f(Q^2/M_V^2)$

$R = \xi(Q^2/M_V^2)^k$
$\xi = 0.74 \pm 0.04$
$k = 0.56 \pm 0.03$
(fit to ZEUS only)

$\sigma_L(\gamma_L)$ - only small size configurations
$\sigma_T(\gamma_T)$ -both, small and large, size configurations

naive interpretation:
small size configurations dominate at higher $\frac{Q^2}{M_V^2}$



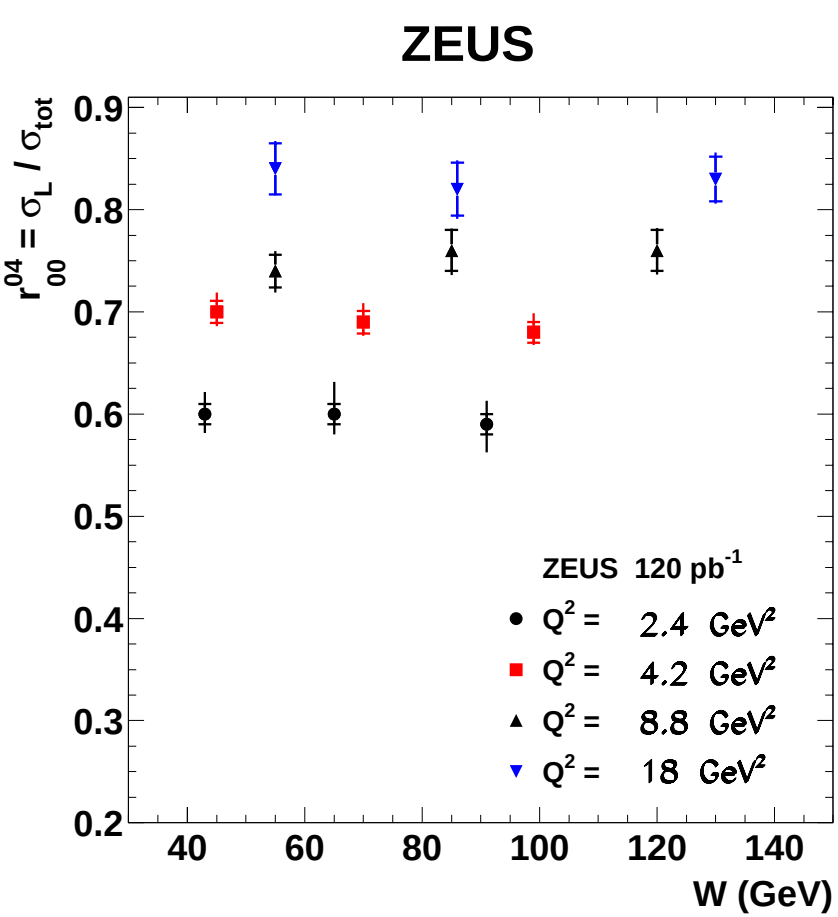
$R = \sigma_L/\sigma_T = f(|t|)$, =f(W)

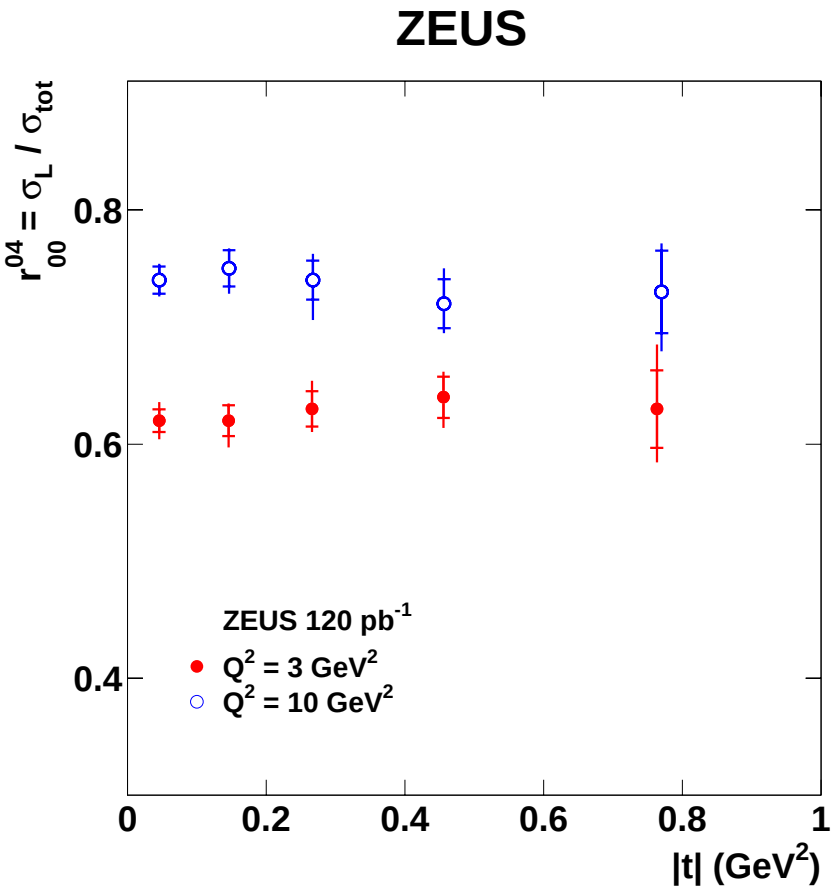
and R does not depend on W and $|t|$!!

$|t|$-distributions are most sensitive to differences in interaction 'size'

$\longrightarrow$ conclusion "small size configurations dominate at high Q^2/M_V^2" not quite correct

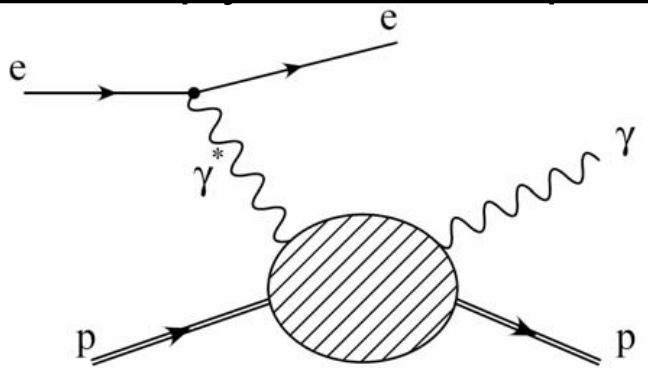
$\longrightarrow$ one must better understand all mechanisms of "transversity" in V_T



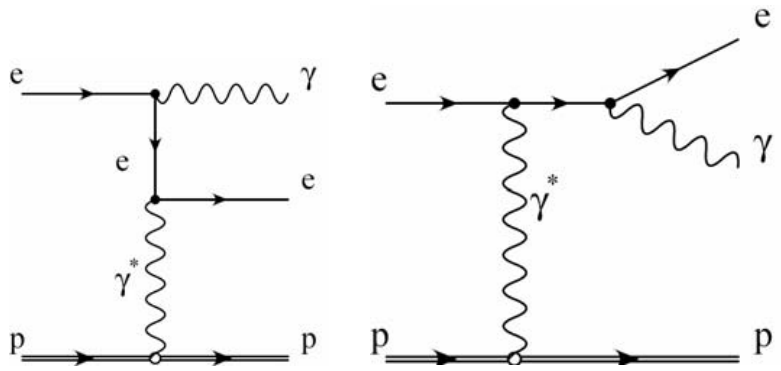


DVCS: Beam Charge Asymmetry, 1/2

DVCS – Deeply Virtual Compton Scattering



BH – Bethe-Heitler



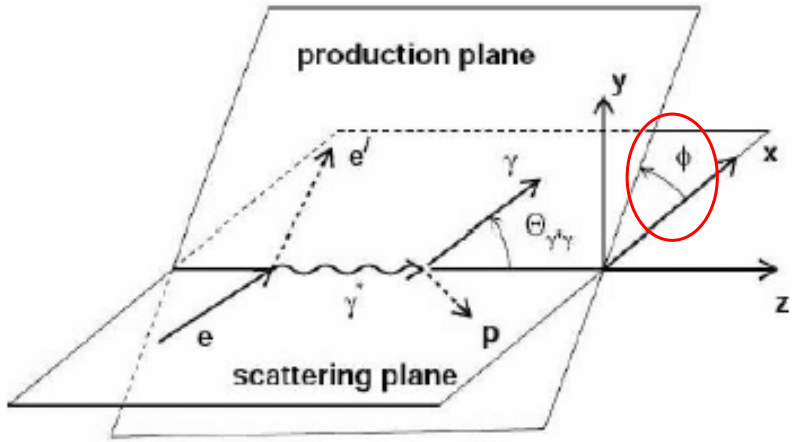
$$d\sigma = d\sigma^{BH} + d\sigma^{DVCS} \pm Interferen\,ce.Term.$$

+ for beam lepton charge (+)

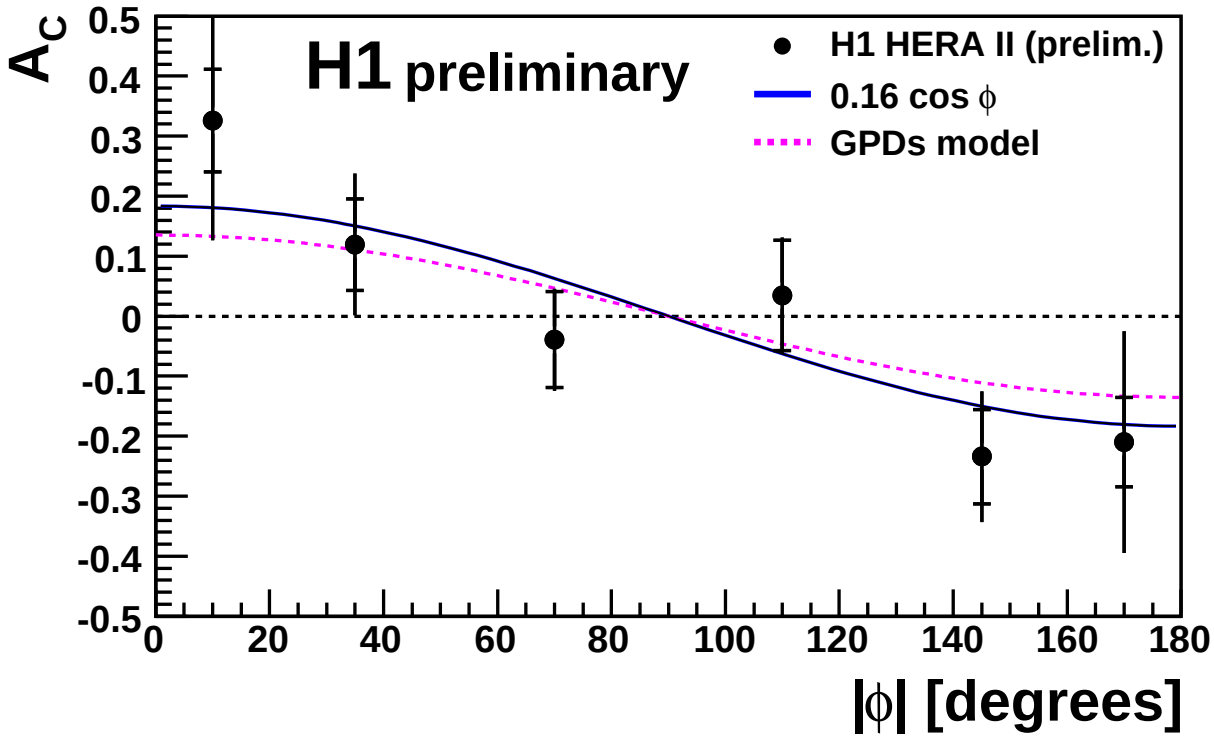
- for beam lepton charge (-)

$$\sigma^{+} - \sigma^{-} \sim \mathrm{Re}(Interference.Term)$$

$$BCA = \frac{\sigma^{+} - \sigma^{-}}{\sigma^{+} + \sigma^{-}} = p_1 * \cos(\phi) + \ldots \,, \; p_1 \sim GPD$$

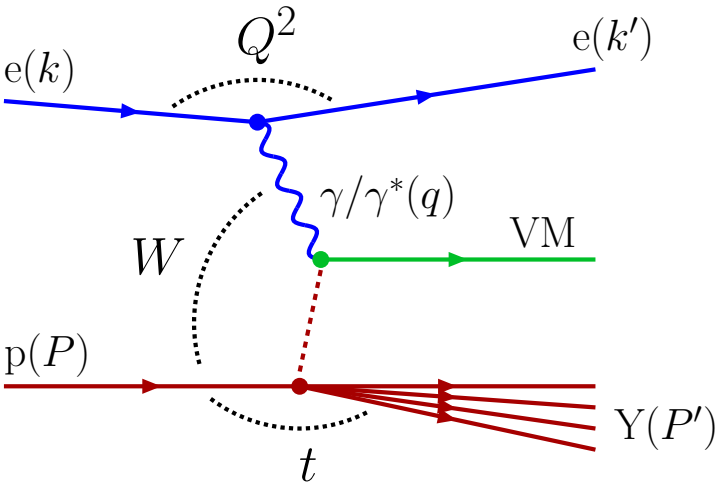


DVCS: Beam Charge Asymmetry, 2/2



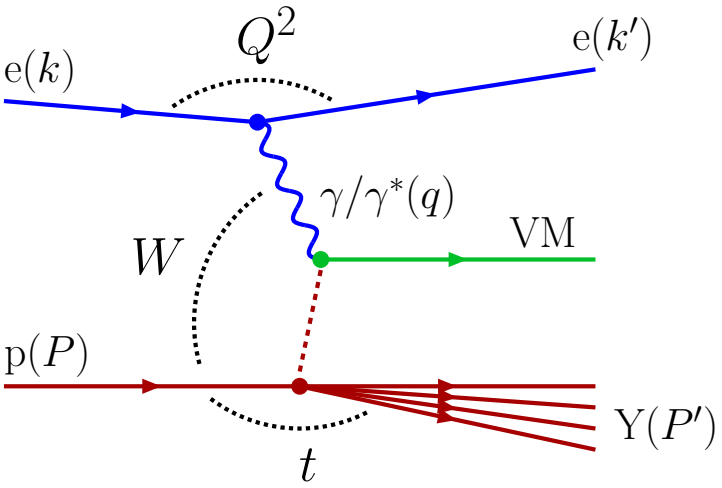
predictions based on GPDs describe the data well

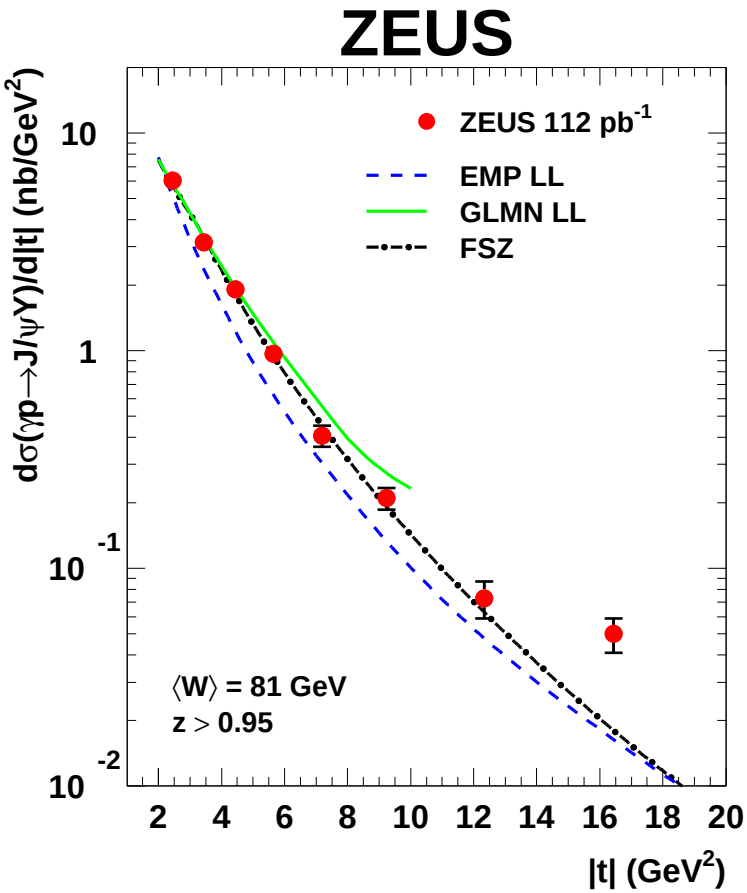
$|t| > 2$ GeV $^{-2}$, reaction with proton dissociation



- also an "exclusive" process
- hard scale is given by high $|t|$
- good test playground for BFKL and DGLAP

$|t|$ dependence is no longer an exponential



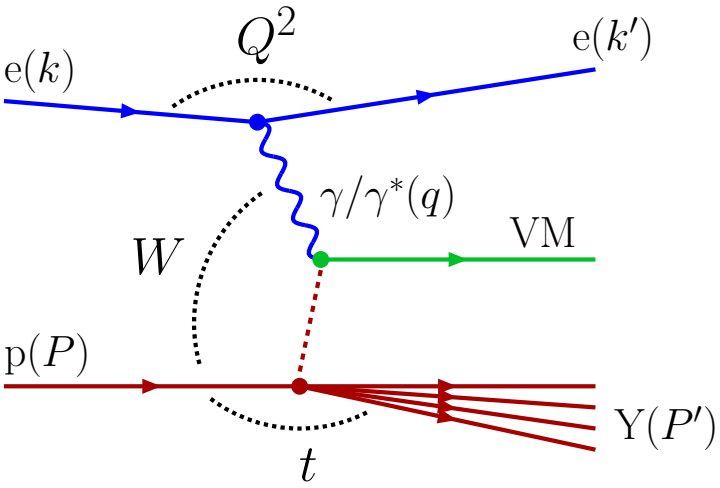


$\frac{d\sigma}{d|t|} \sim t^n$

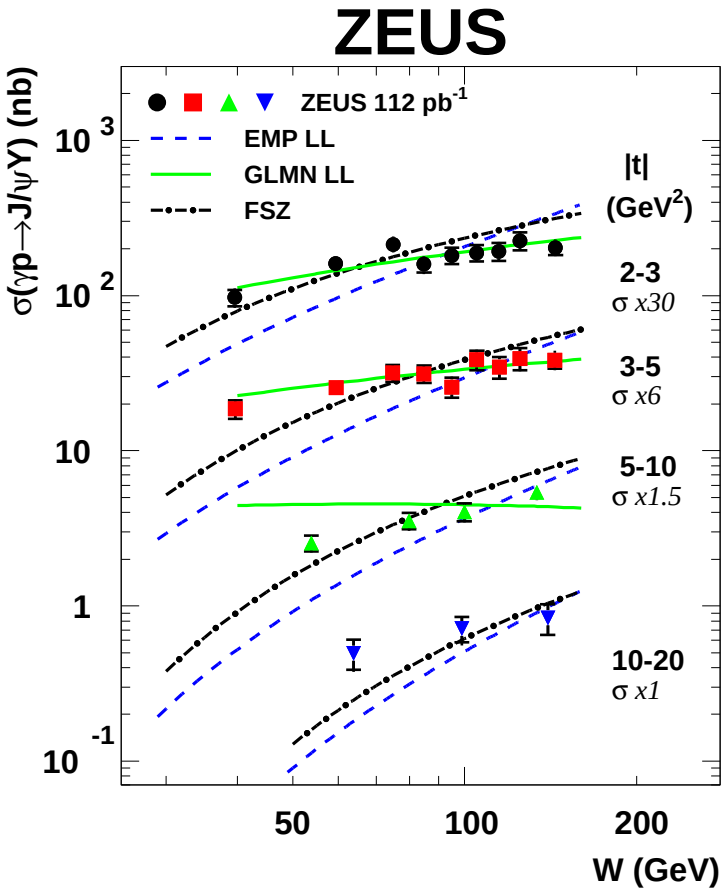
- n = -1.9 ± 0.1, $2 < |t| < 4$ GeV^{-2}
- n = -3.0 ± 0.1, $4 < |t| < 16$ GeV^{-2}

- EMP LL - BFKL (E.Gotsman, E.Levin, U. Maor, E. Naftali)
- GLMN LL - DGLAP (R.Enberg, L. Motyka, G. Poludniowski)
- FSZ - (L. Frankfurt, M.Strikman, M. Zhalov)

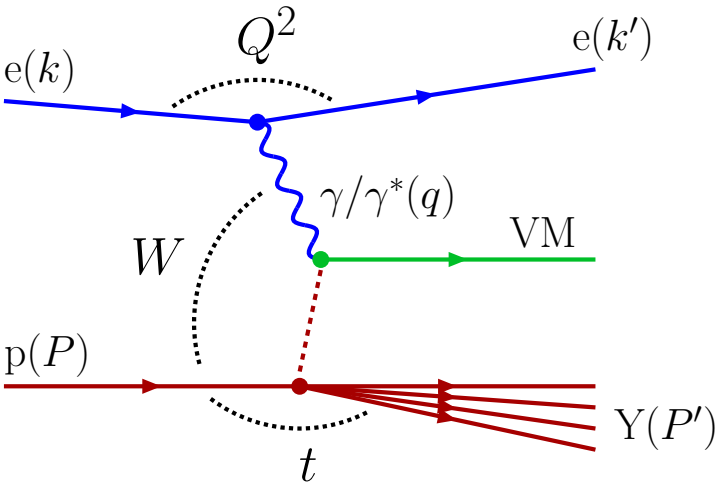
W-dependence very sensitive to models

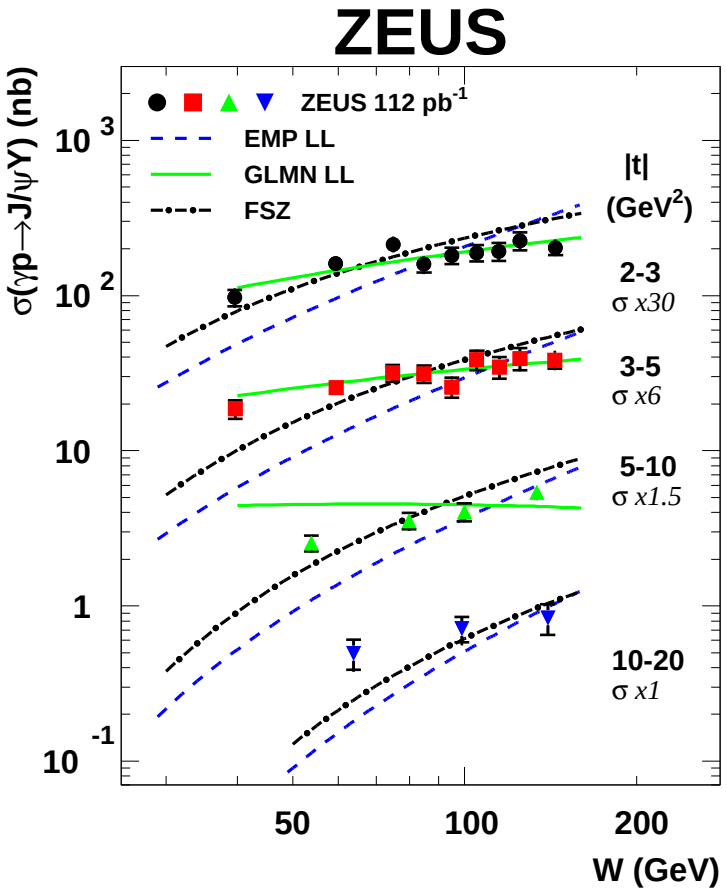


none of the models describe the data



W-dependence very sensitive to models



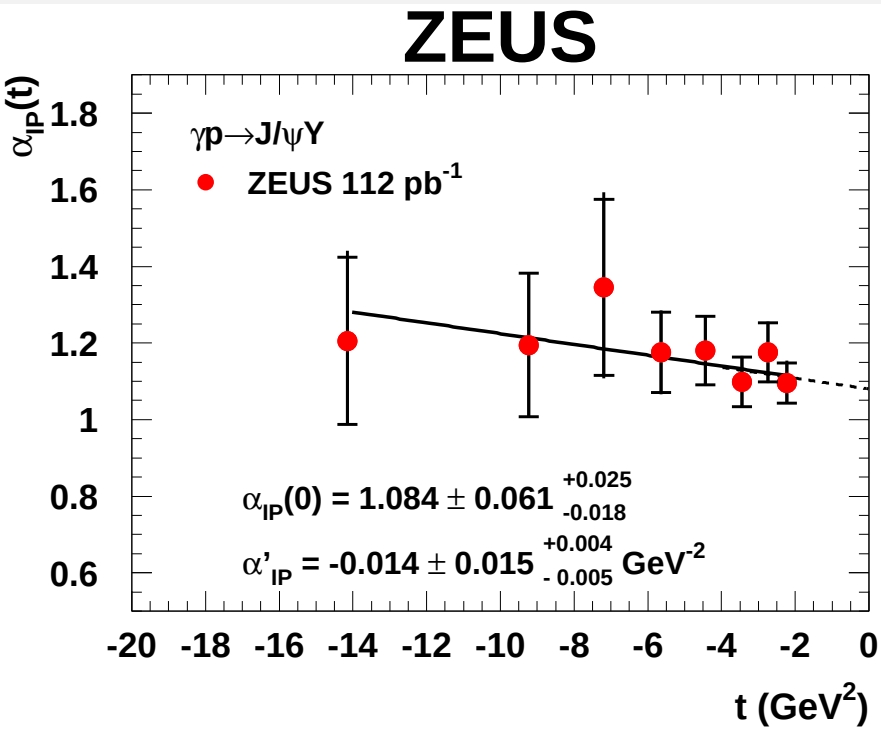


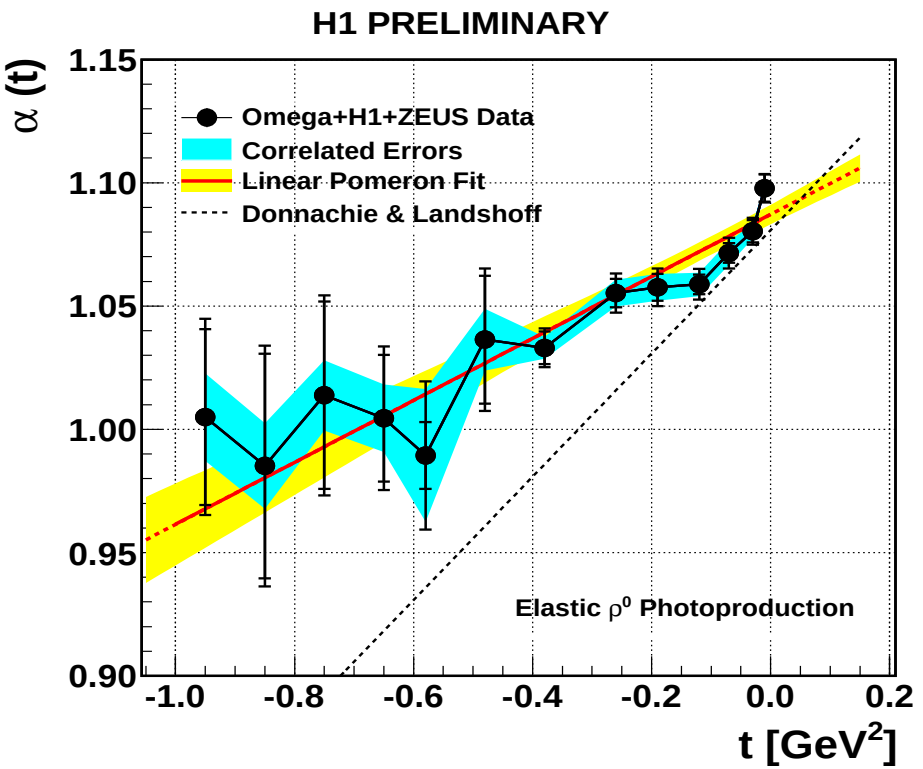
interpret in terms of Pomeron trajectory,

$\frac{d\sigma}{d|t|} \sim \frac{W}{W_0}^{4(\alpha(t)-1)}$

- $\delta = 4(\alpha(t) - 1)$
- $\alpha(t) = \alpha_0 + \alpha' t$

Effective Pomeron trajectory





Heavy VM (J/ψ), high $|t|$ (p.diss.)

- $\alpha(0) = 1.084 \pm 0.031^{+0.025}_{0.018}$
- $\alpha' = -0.014 \pm 0.007^{+0.004}_{-0.005}$ GeV^{-2}

Light VM (ρ), low $|t|$ (elastic)

- $\alpha(0) = 1.087 \pm 0.003 \pm 0.003$
- $\alpha' = 0.126 \pm 0.013 \pm 0.012$ GeV^{-2}

differ from Donnachie-Landschof (DL):

- $\alpha(t) = 1.08 \pm 0.25t$

Summary

- HERA provides large amount of unique data
  - production of various particle types in differing kinematic regions
  - can study an interplay of different scales in one experiment
- lots of new measurements
  - W, $|t|$, Q^2, M_V^2 - follow pQCD model predictions
  - ...but not exactly
- still to be better understood:
  - the ratio, $R = \sigma_L/\sigma_T$, requires precise understanding of mechanisms which produce transversity $\gamma_T^* = \rho_T$
  - new measurements of diffractive reactions at high $|t|$,
    - pQCD models are not able to describe all features of the data
  - effective $\mathbb{P}$omeron trajectory is different from DL "soft" $\mathbb{P}$omeron and exibits a non linear behaviour

Backup slides

ZEUS:

- Exclusive Photoproduction of Upsilon Mesons at HERA
  DESY-09-036 (March 2009)
- Leading Proton Production in Deep Inelastic Scattering at HERA
  DESY-08-176 (December 2008)
- Deep Inelastic Scattering with Leading Protons or Large Rapidity Gaps at HERA
  DESY-08-175 (December 2008)
- A Measurement of the Q^2, W and t Dependences of Deeply Virtual Compton Scattering at HERA
  DESY-08-132 (December 2008)
- Deep inelastic inclusive and diffractive scattering at Q^2 values from 25 to 320 GeV^2 with the ZEUS forward plug calorimeter
  DESY-08-011 (February 2008)
- Diffractive photoproduction of dijets in ep collisions at HERA
  DESY-07-161 (September 2007)
- Dijet production in diffractive deep inelastic scattering at HERA
  DESY-07-126 (August 2007)
- Exclusive ρ^0 production in deep inelastic scattering at HERA
  DESY-07-118 (August 2007)
- Diffractive photoproduction of Dstar(2010) at HERA
  DESY-07-039 (March 2007)

H1:

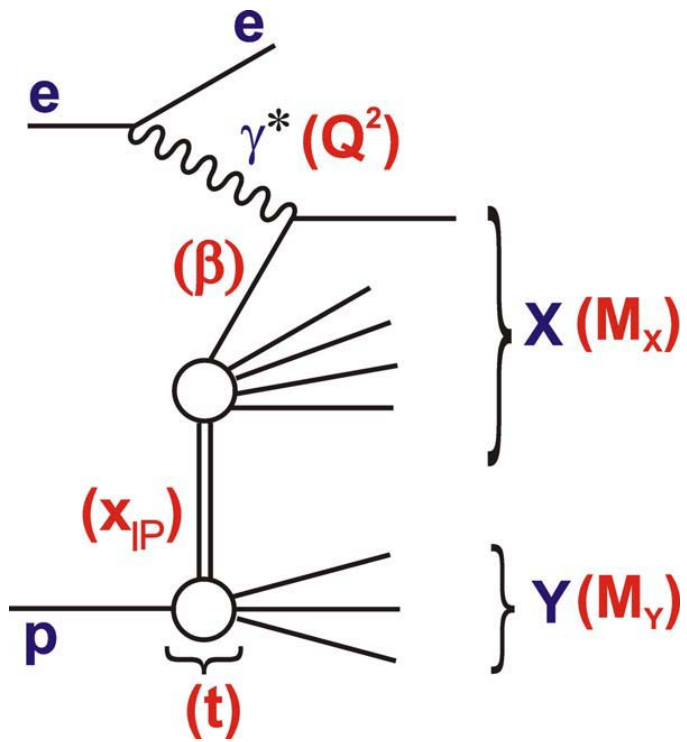
- Inclusive Photoproduction of ρ^0, K^{*0} and ϕ Mesons at HERA
  DESY-08-172
- Measurement of Deeply Virtual Compton Scattering and its t-dependence at HERA
  DESY-07-142
- Dijet Cross Sections and Parton Densities in Diffractive DIS at HERA
  DESY-07-115
- Tests of QCD Factorisation in the Diffractive Production of Dijets in Deep-Inelastic Scattering and Photoproduction at HERA
  DESY-07-018
- Diffractive Open Charm Production in Deep-Inelastic Scattering and Photoproduction at HERA
  DESY-06-164
- Measurement and QCD Analysis of the Diffractive Deep-Inelastic Scattering Cross Section at HERA
  DESY-06-049
- Diffractive Deep-Inelastic Scattering with a Leading Proton at HERA
  DESY-06-048

ep collisions: Diffraction (in general ep→ eXY)

...and also:

M_X = invariant mass of diffractively produced system

M_Y = invariant mass of proton remnant system



$M_Y = m_p$ - proton stays intact,
need special detector setup to detect protons
→ H1 FPS, ZEUS LPS

$M_Y > m_p$ - proton dissociates,
→ the background to be understood and disantangled.

Helicity angles study, $R = \sigma_L/\sigma_T$

- **s-channel helicity conservation (SCHC)**
- **natural parity exchange ($P = (-1)^J$) in the t-channel (NPE)**
- **5 non-zero spin-density matrix elements**
- **15 parameters fit to total angular distribution**
- r^5_{00} **deviates from zero !**
- $r^5_{00} = 0.095 \pm 0.019 \pm 0.024$ **(ZEUS) and** $r^5_{00} = 0.093 \pm 0.024^{+0.19}_{-0.10}$ **(H1)**
- $r^5_{00} \sim$ **single-flip amplitude,** $\gamma^*_T \to \rho_L$
- **if SCHC holds** $\to R = \sigma_L/\sigma_T = r^{04}_{00}/\epsilon(1 - r^{04}_{00})$
- **if not** $\to r^{04}_{00} \to r^{04}_{00} - \Delta^2$, $\Delta \propto r^5_{00}/\sqrt{2r^{04}_{00}}$
- **R(SCHC) - R(SCHNC)** $\sim$ **3 %**

t-slope with ZEUS LPS DVCS