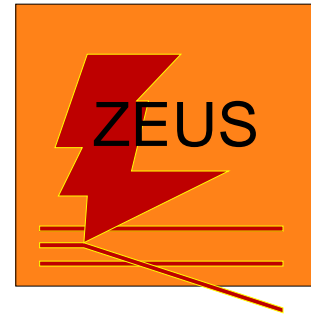


On behalf of H1 and ZEUS Collaborations



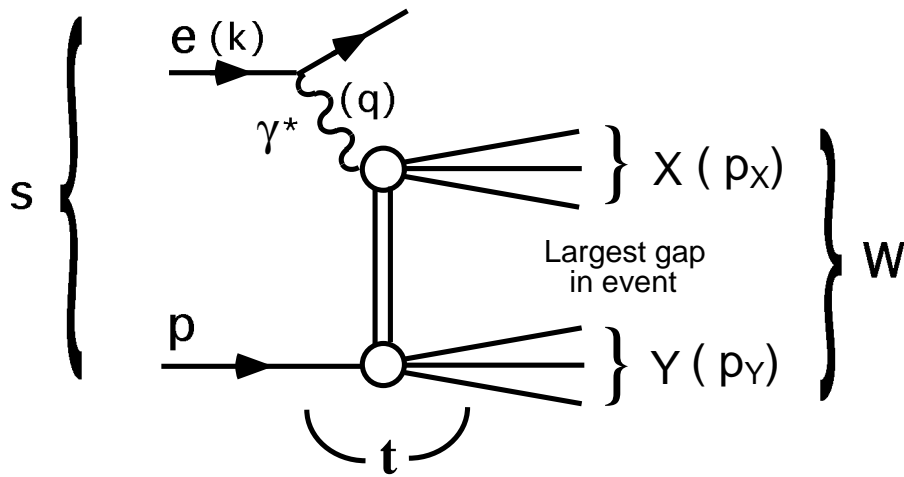
Deeply virtual Compton scattering and vector mesons production at ZEUS and H1 experiments

2nd Workshop on the QCD Structure of the Nucleon

Rome, Italy, 12th-16th June, 2006

Deeply Virtual Compton Scattering

$$e + p \longrightarrow e + \gamma + p$$

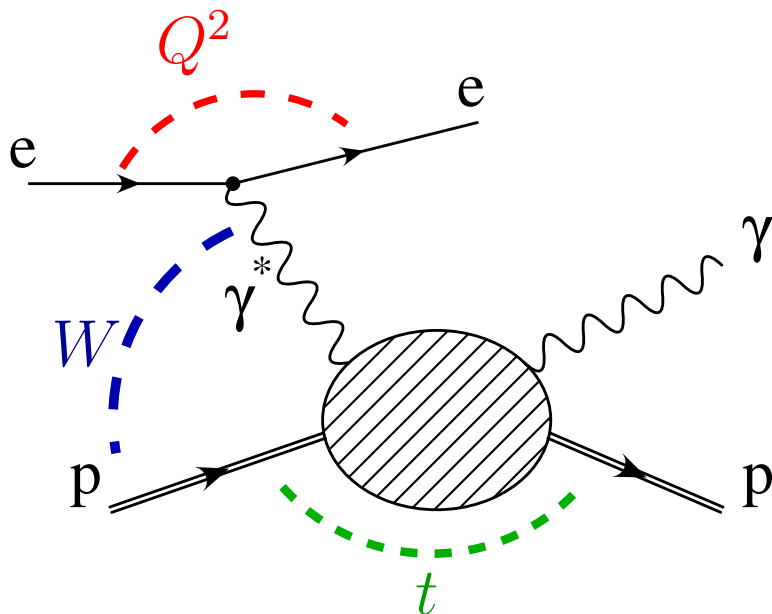


Diffraction: $e + p \rightarrow e + X + Y$

- Factorization theorem:
 - First Diffractive process fully calculable in QCD
- No VM wave function uncertainty
- Access to Generalized Parton Distributions (**GPDs**)

Deeply Virtual Compton Scattering

$$e + p \longrightarrow e + \gamma + p$$



- Factorization theorem:
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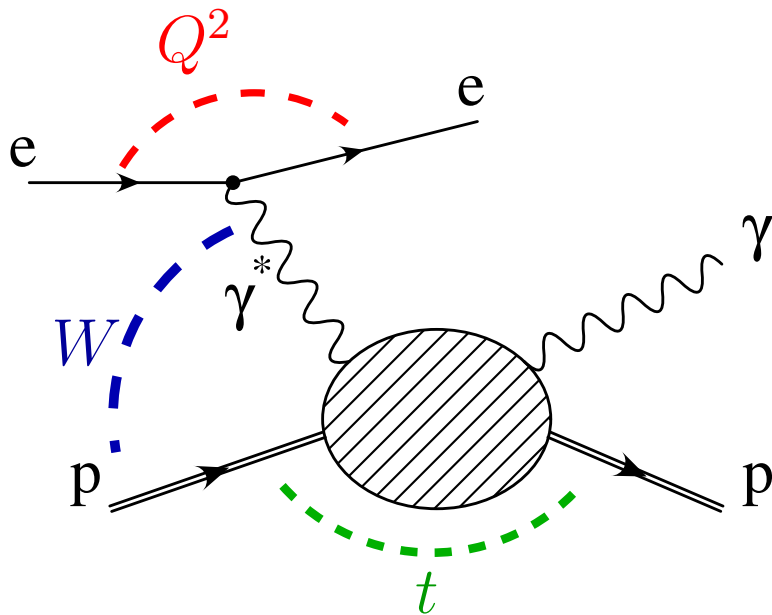
Q^2 : virtuality at which the proton is probed

W : energy in the $\gamma^* p$ center of mass system

t : square of the 4-momentum transfer at the proton vertex

Deeply Virtual Compton Scattering

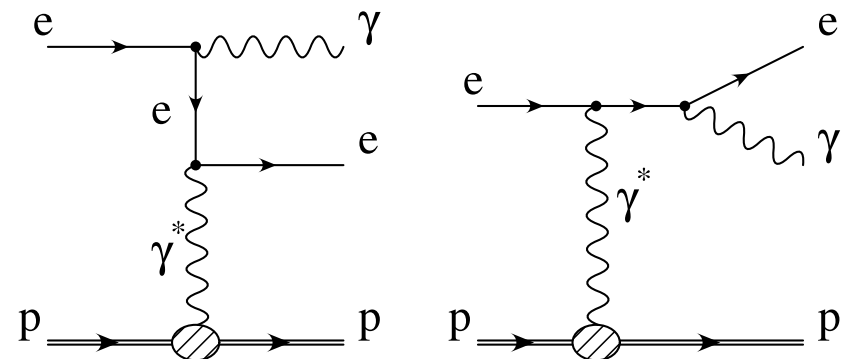
$$e + p \longrightarrow e + \gamma + p$$



- Factorization theorem:
 - First Diffractive process fully calculable in QCD
- No VM wave function uncertainty
- Access to Generalized Parton Distributions (**GPDs**)

- Interference with Bethe-Heitler which is a pure QED process.

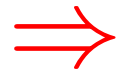
(→ Access to Amplitudes in Asymmetries)



DVCS - QCD predictions

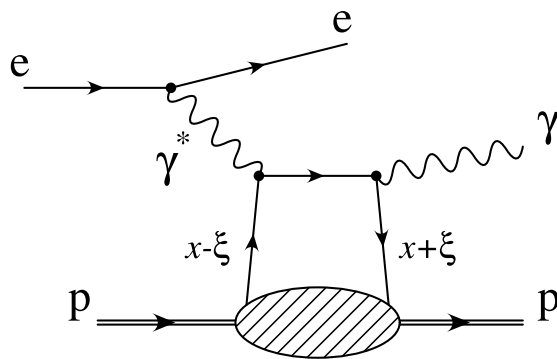
$$Q^2 \gg 1\text{GeV}^2$$

$$-t \ll Q^2$$

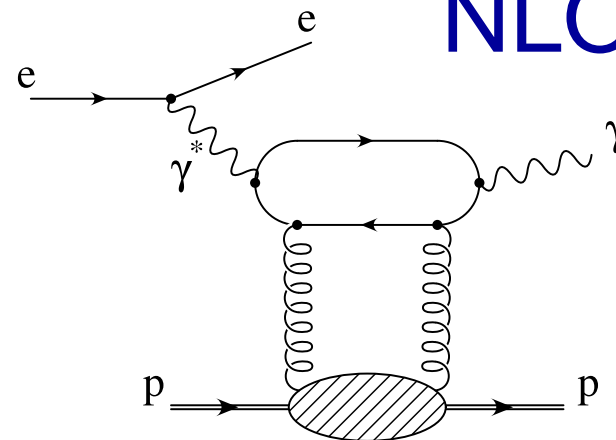


DVCS amplitude factorise in a pQCD calculable hard scattering part and a non-perturbative part describing the internal dynamics of the proton

LO



NLO



ξ - "Skewedness", i.e. momentum difference between emitted and absorbed parton

→ need to use the GPD formalism to describe DVCS

(GPDs encodes info about transverse motion of partons and about their correlations)

DVCS - QCD predictions

4 types of GPD:

	proton helicity conserved	allow proton helicity flip
unpolarized	$H^{q,g}(x, \xi, t; \mu^2)$	$E^{q,g}(x, \xi, t; \mu^2)$
polarized	$\tilde{H}^{q,g}(x, \xi, t; \mu^2)$	$\tilde{E}^{q,g}(x, \xi, t; \mu^2)$

At low x , DVCS is mainly sensitive to $H^g(x, \xi, t; \mu^2)$

NLO leading twist calcl. by A. Freund and M. McDermott
Eur. Phys. J. C23 (2002) 651

DGLAP region ($|x| > \xi$):

$$\begin{array}{l} H^{q,g}(x, \xi, t; \mu^2) \\ \tilde{H}^{q,g}(x, \xi, t; \mu^2) \end{array} \begin{array}{l} \xrightarrow{t \rightarrow 0} \\ \xrightarrow{\xi \rightarrow 0} \end{array} \begin{array}{l} q(x), g(x) \\ \Delta q(x), \Delta g(x) \end{array}$$

ERBL region ($|x| < \xi$):

Simple analytic functions

t dependence:

parametrised as e^{-t}

ξ and Q^2 dependence:

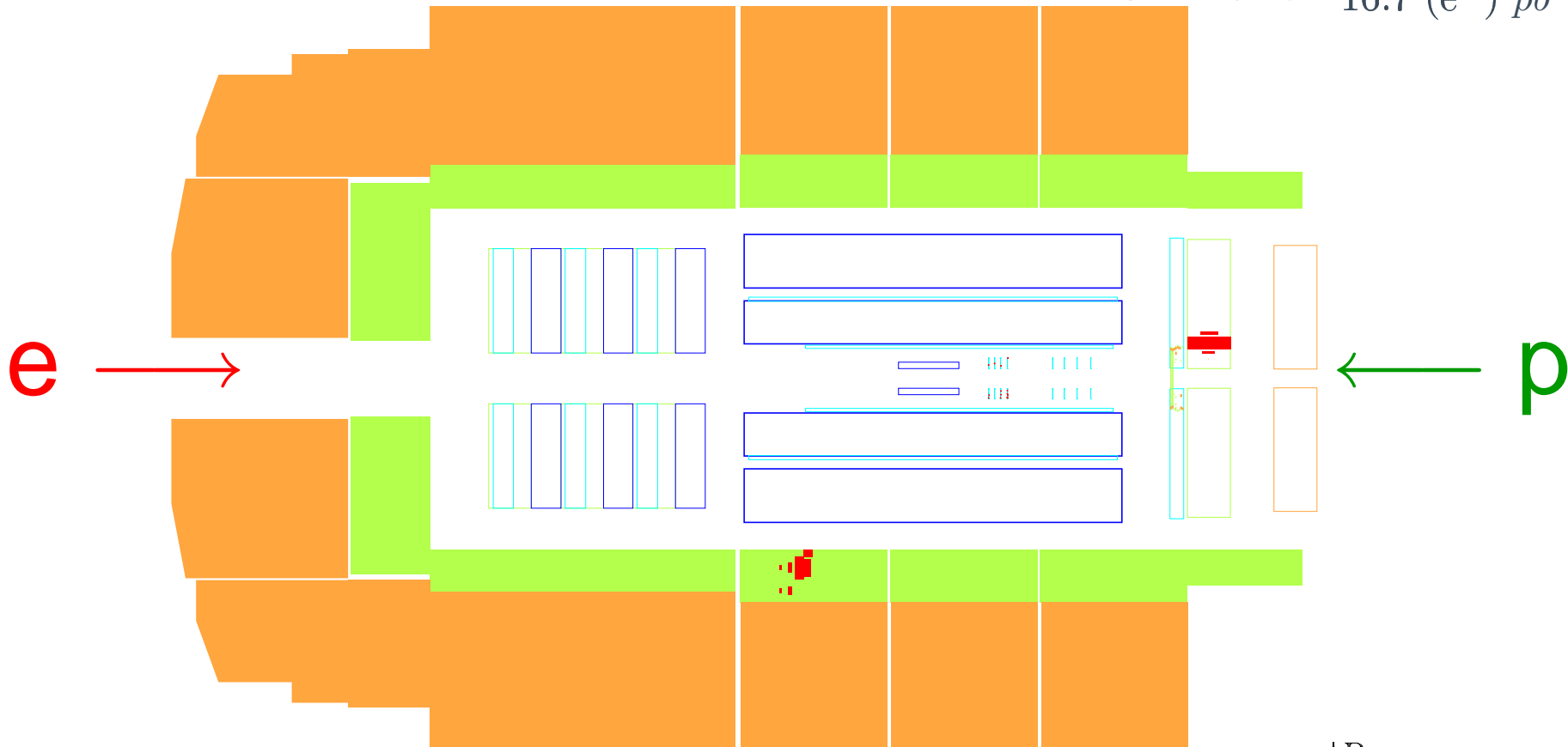
generated dynamically by the evolution equations

DVCS - Data Selection

γ sample

DVCS + Bethe-Heitler

	H1	ZEUS
$E_1 >$	15 GeV	10 GeV
$p_{T_2} >$	1 GeV (2 GeV)	
$E_2 >$		3 GeV
$E_3 <$	0.5 GeV	0.2 GeV
elast.	no track, Fwd	no track
Lumi	46.5 pb^{-1} (e^+)	95 (e^+) pb^{-1}
+ 2004:	39.7 pb^{-1} (e^+)	16.7 (e^-) pb^{-1}

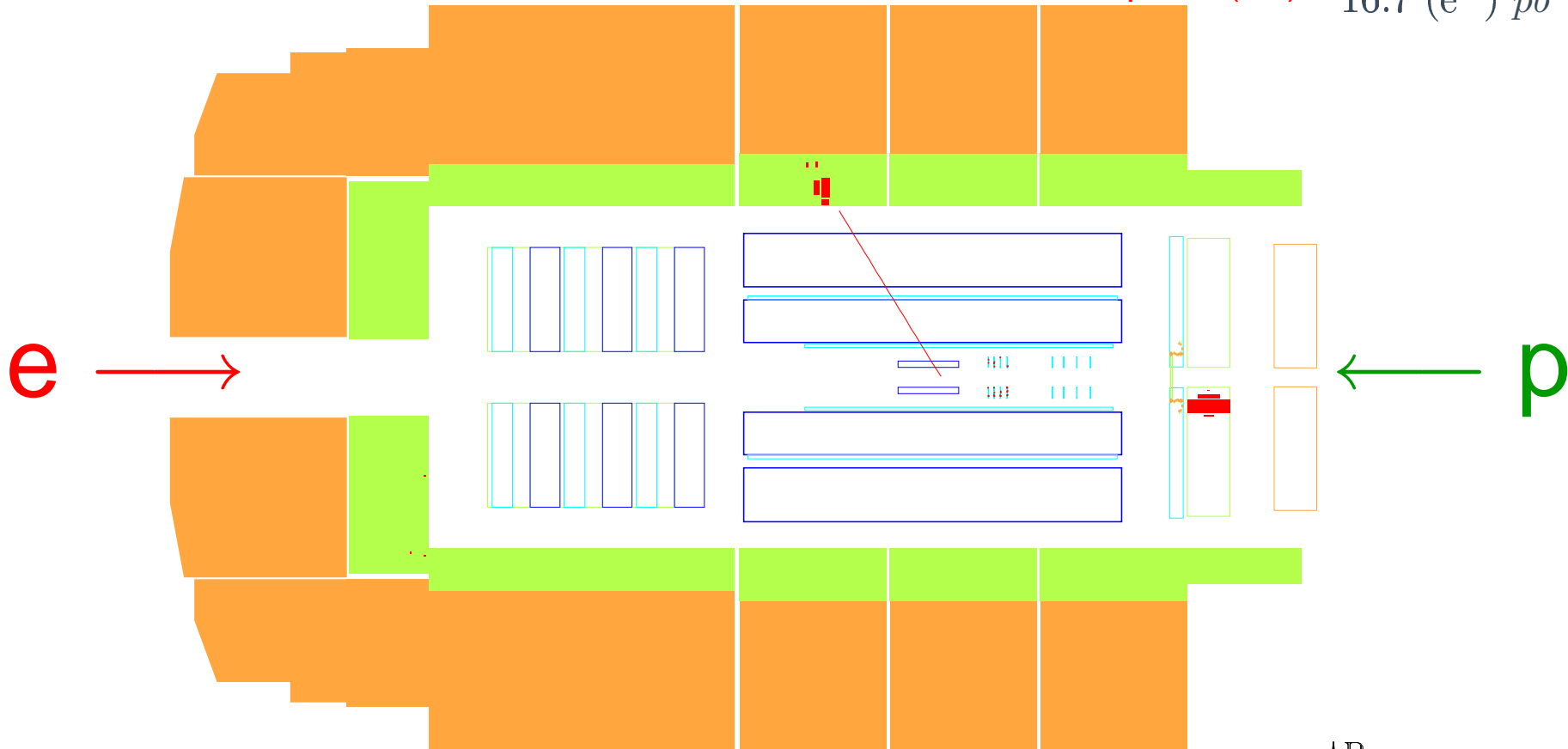


DVCS - Data Selection

Control sample

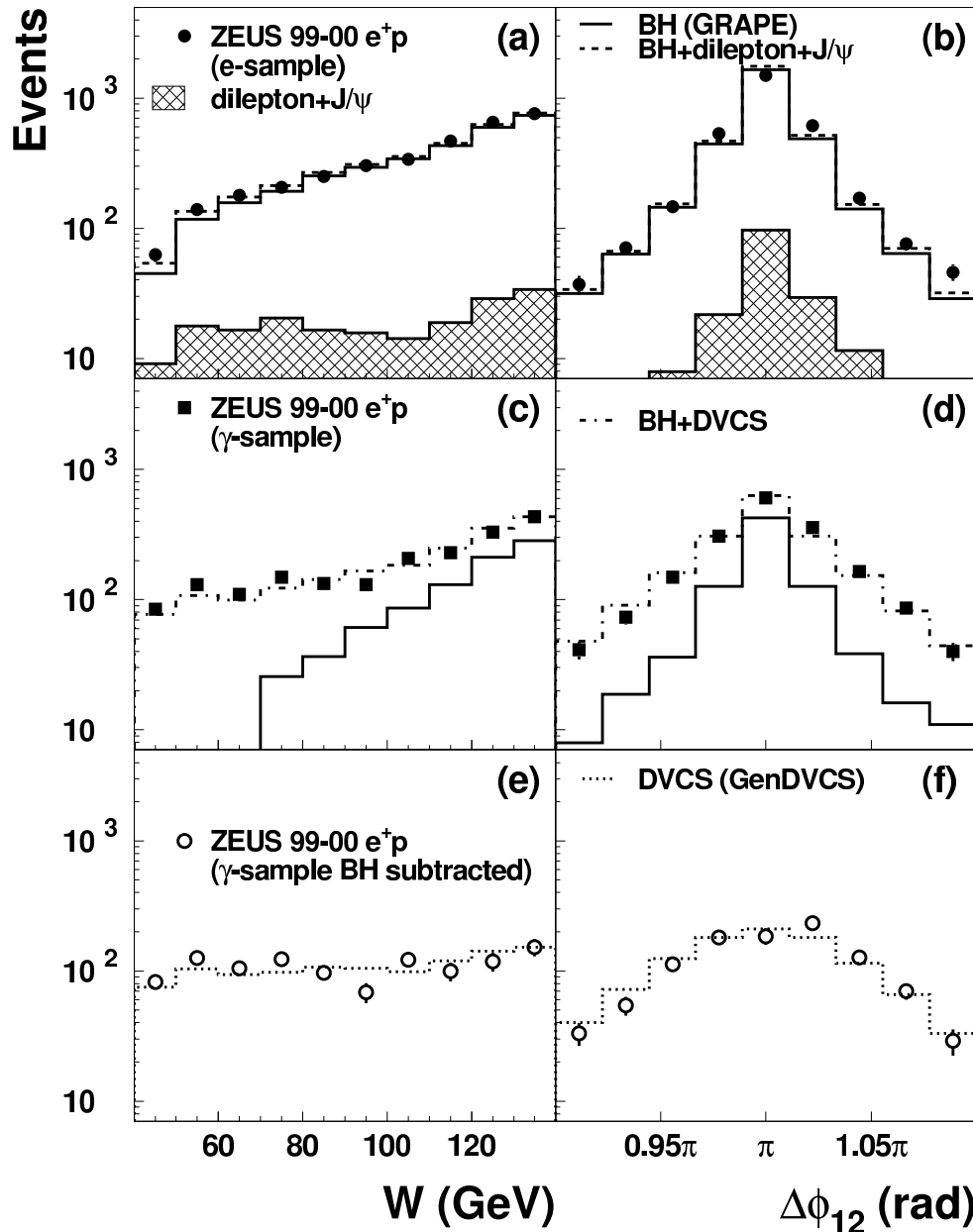
Mainly Bethe-Heitler

	H1	ZEUS
$E_1 >$	15 GeV	10 GeV
$p_{T_2} >$	1 GeV (2 GeV)	
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DVCS - Control Plots

ZEUS



- Control sample:

Well described by MC

→ Detector understood

- γ sample:

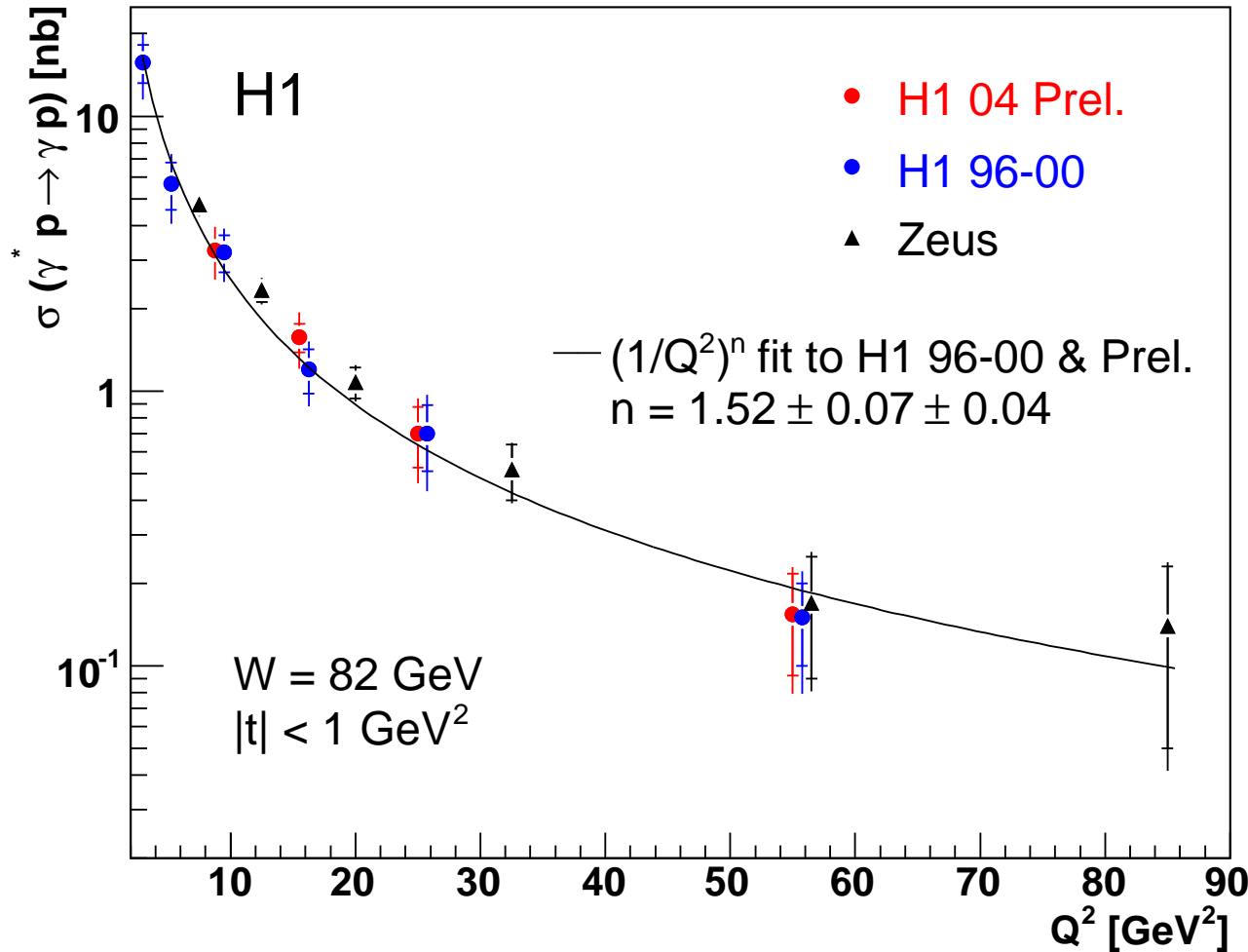
Good description by
BH + DVCS MC

⇒ DVCS cross section:

1. Subtract Bethe-Heitler
($\int d\phi$ Interf. = 0)

2. $\sigma_{ep} \longrightarrow \sigma_{\gamma^*p}$ (/ flux factor)

DVCS - Q^2 dependence

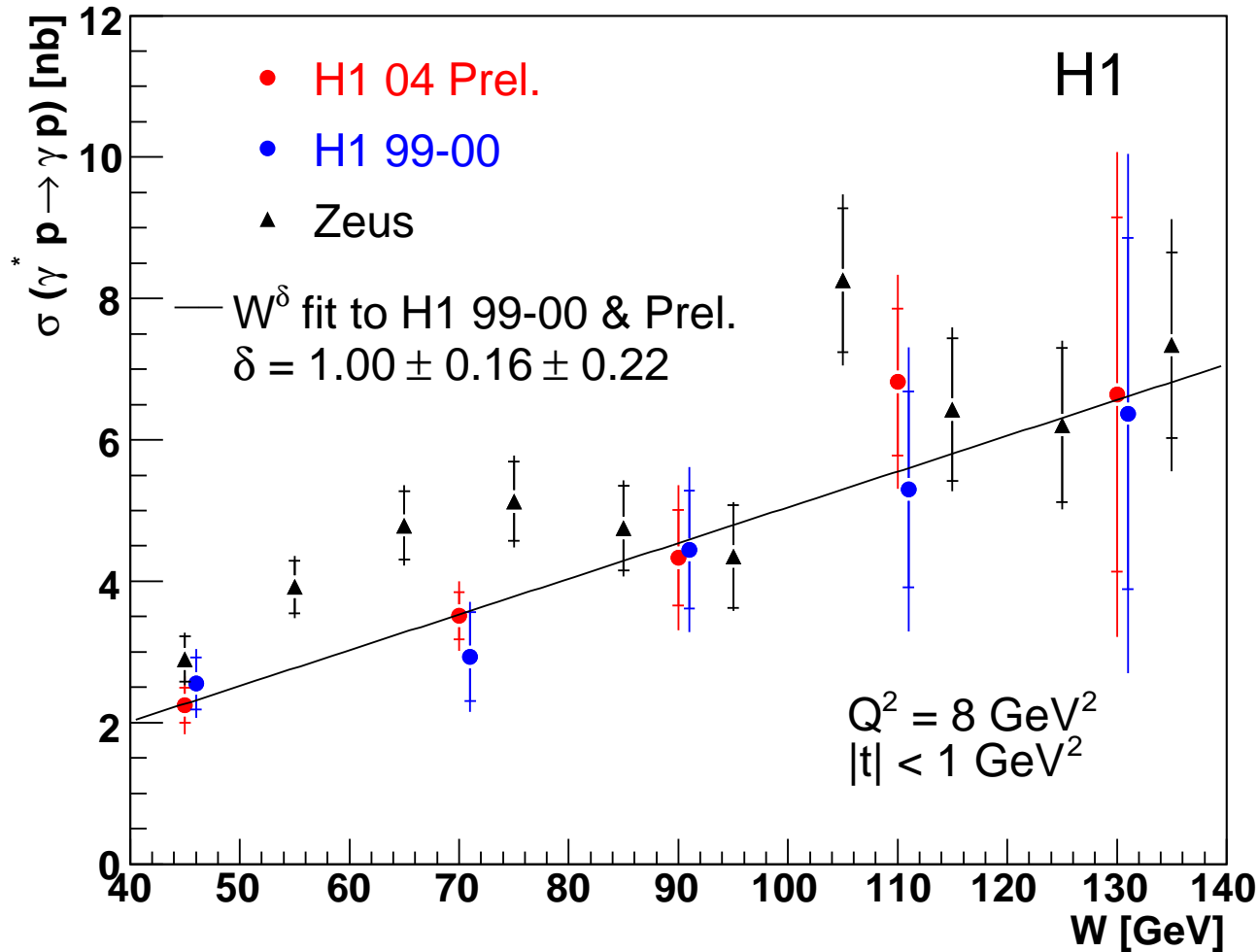


Good agreement
with previous
results

Combined fit to H1 99-00 and H1 2004 data : $\sigma(Q^2) \propto (1/Q^2)^n$

→ statistical error on n parameter decreased

DVCS - W dependence

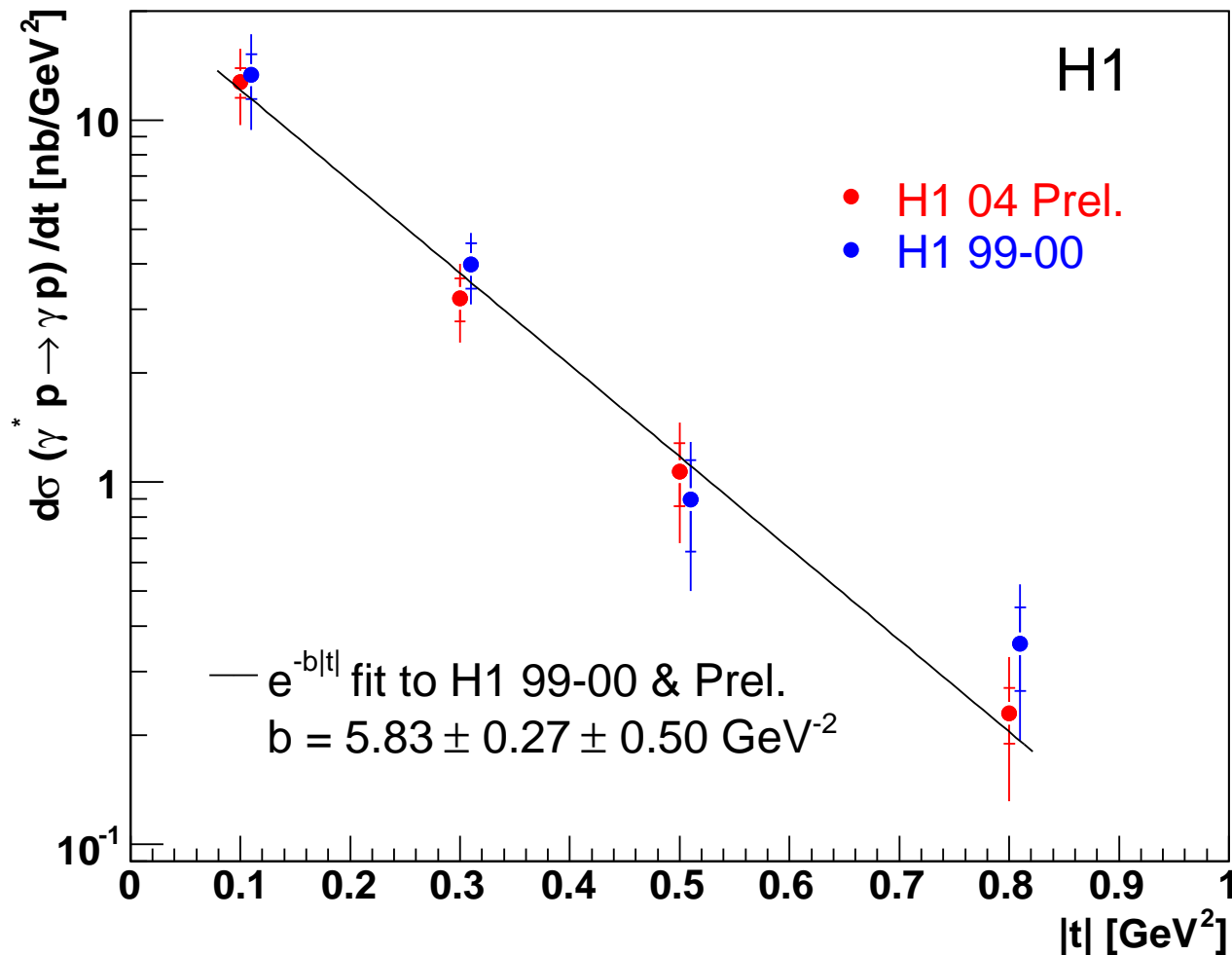


δ value indicates
hard regime

cf. J/ψ production

Combined fit to H1 99-00 and H1 2004 data : $\sigma(W) \propto W^\delta$

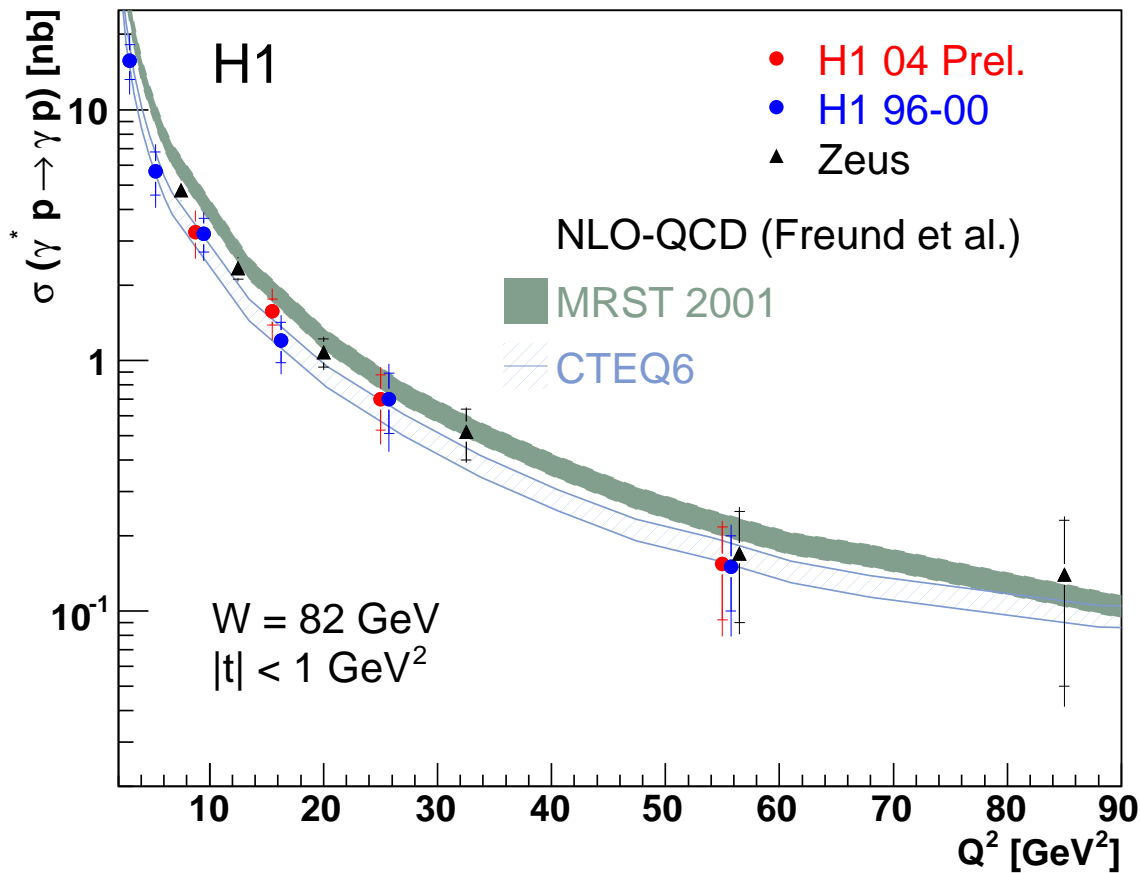
→ statistical error on δ parameter decreased



Combined fit to H1 99-00 and H1 2004 data : $d\sigma/dt \propto \exp(-bt)$

→ statistical error on t slope b decreased

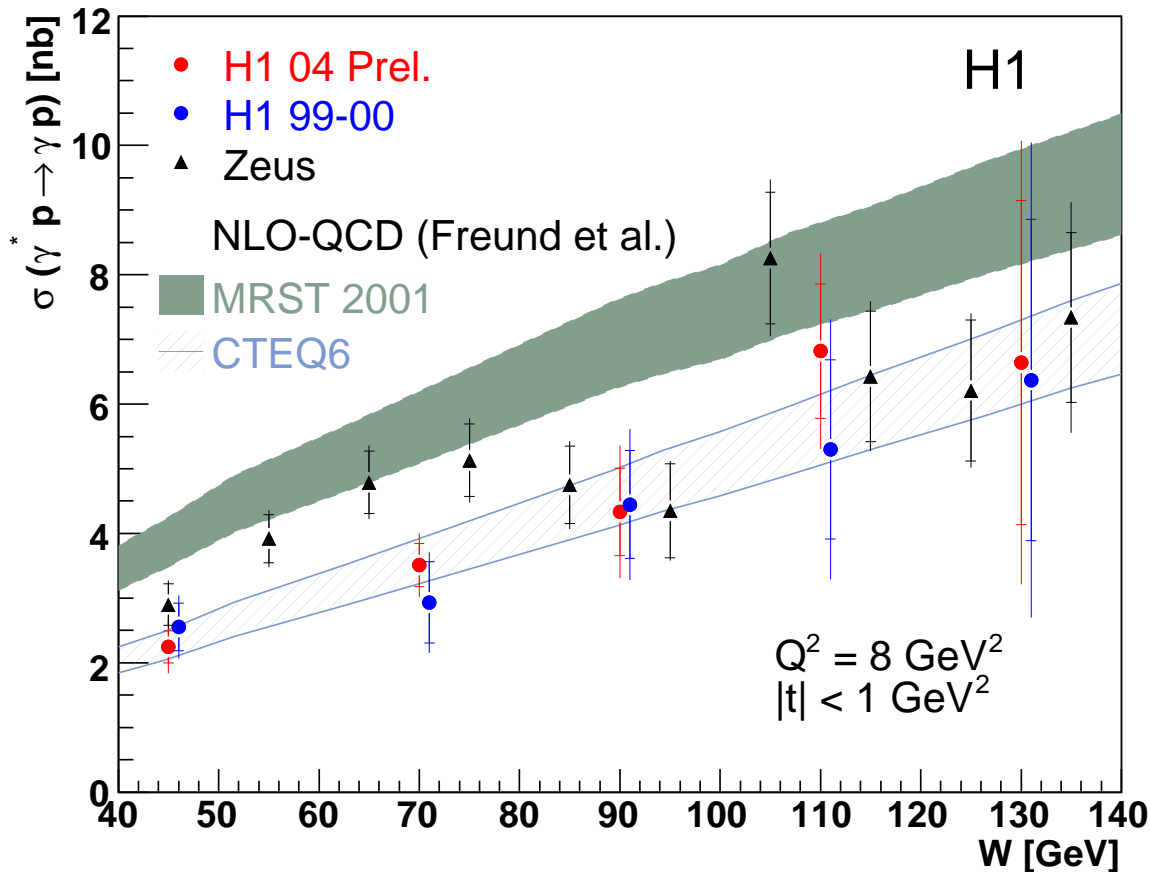
DVCS - Comparison to QCD predictions



Comparison to NLO QCD:

- Band width reduced by b slope measurement
- Good description by NLO QCD calculations.
- Sensitivity to GPDs parametrization
- b kept constant with Q^2
- no need for intrinsic skewing

DVCS - Comparison to QCD predictions

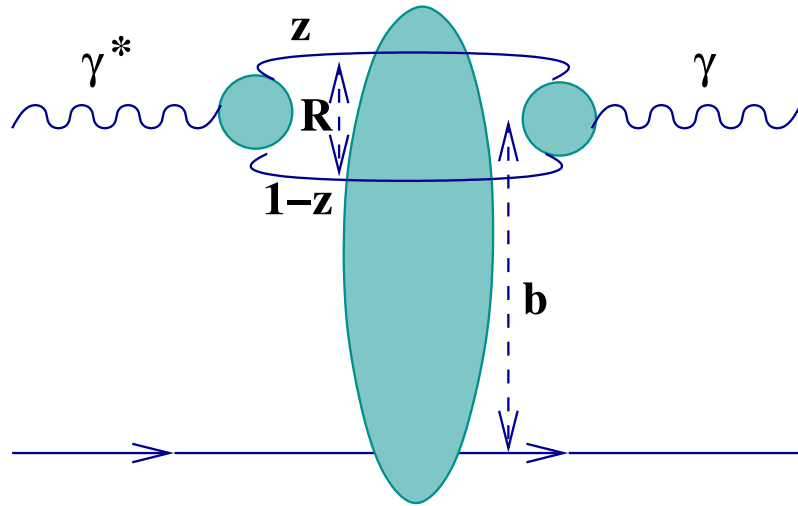


Comparison to NLO QCD:

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DVCS - ... and to Color Dipole Models

In proton rest frame:



- γ^* fluctuates in $q\bar{q} + q\bar{q}g + \dots$

$$\mathcal{A} = \int dR^2 dz \Psi^{in} \sigma_{dipole} \Psi^{out}$$

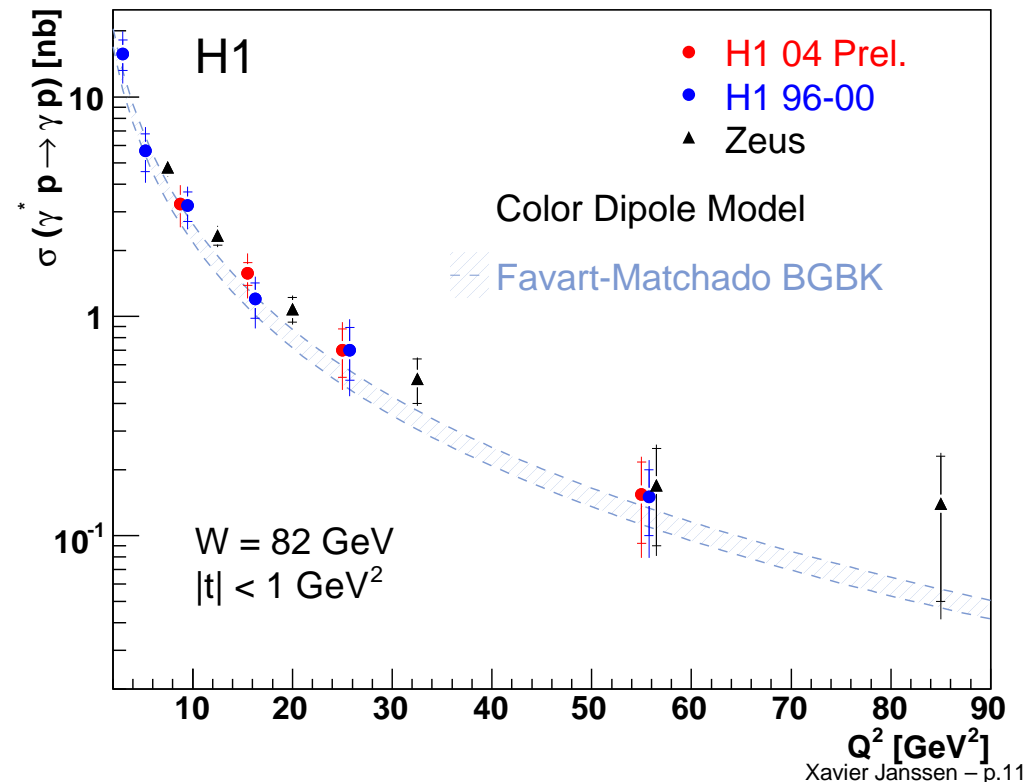
- Ψ^{in} and Ψ^{out} calculable
- σ_{dipole} modeled

Favart-Machado:

GBW Saturation model

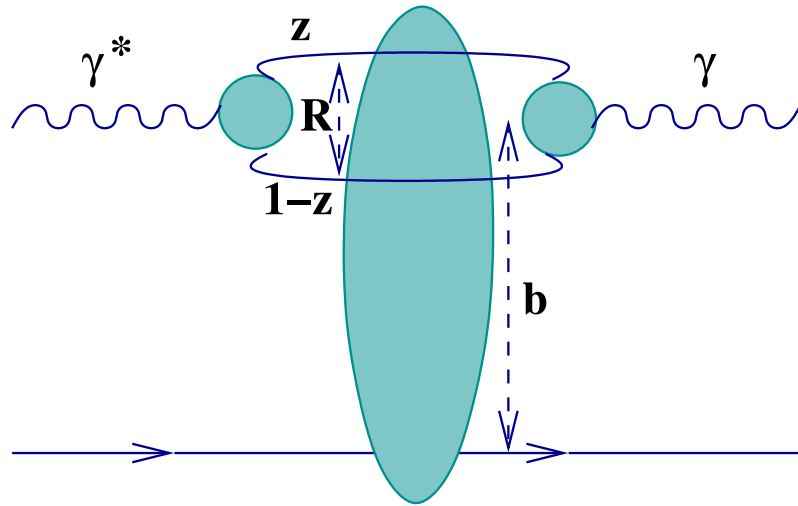
Eur. Phys. J. C29 (2003) 365

→ Describe shape and norm.
when including DGLAP
evolution (BGBK)



DVCS - ... and to Color Dipole Models

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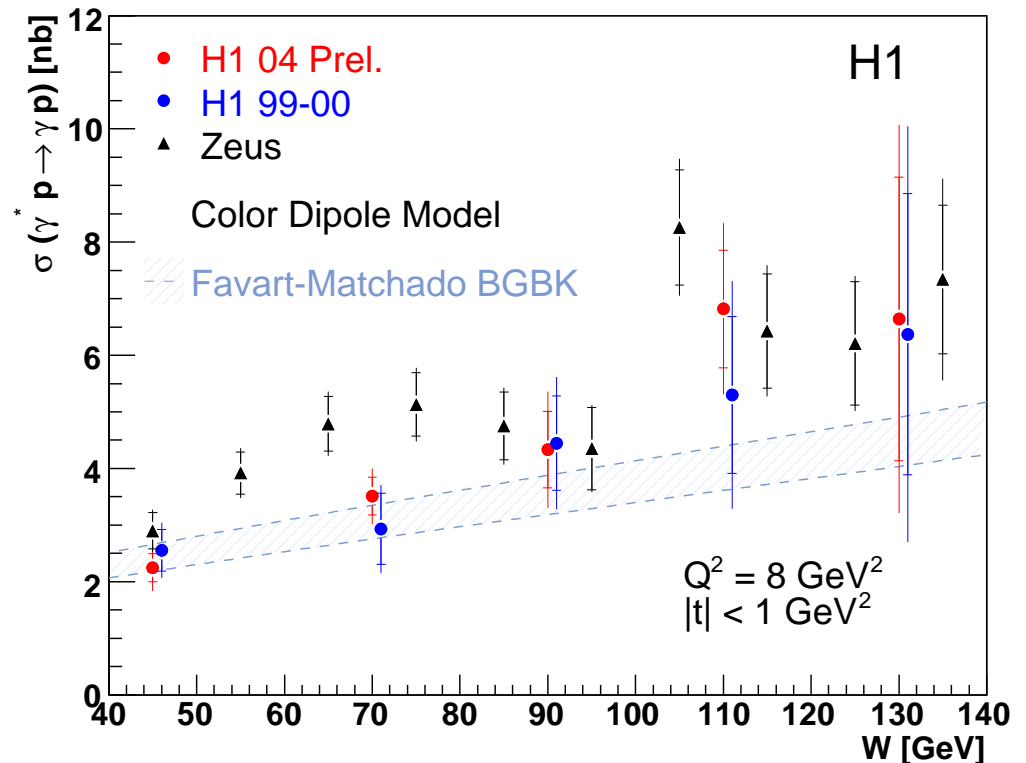
- Ψ^{in} and Ψ^{out} calculable
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Favart-Machado:

GBW Saturation model

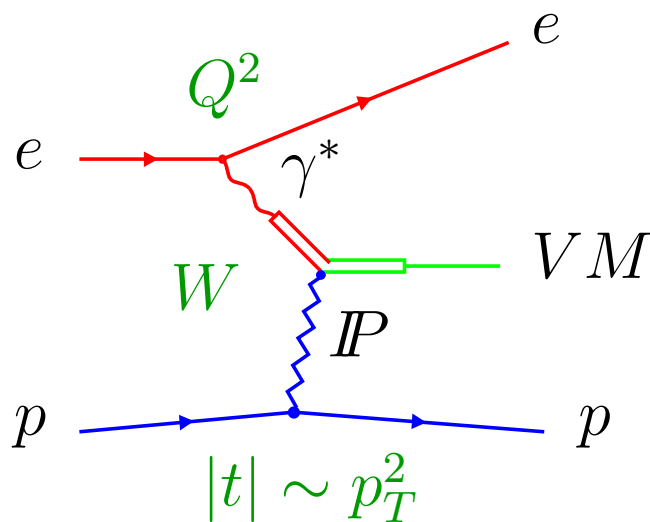
Eur. Phys. J. C29 (2003) 365

→ Describe shape and norm. when including DGLAP evolution (BGBK)



VECTOR MESON PRODUCTION

$$e + p \rightarrow e + VM + p \text{ (or } Y)$$



ρ	$u\bar{u} + d\bar{d}$	771 MeV
ω	$u\bar{u} + d\bar{d}$	782 MeV
ϕ	$s\bar{s}$	1019 MeV
J/ψ	$c\bar{c}$	3097 MeV
$\psi(2S)$	$c\bar{c}$	3686 MeV

Regge Theory

= Soft IP omeron exchange

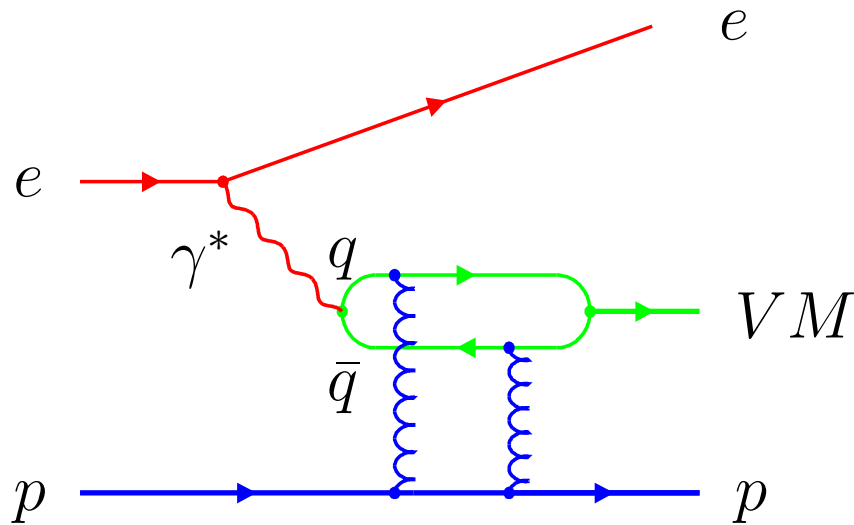
$$\sigma \propto \left(\frac{W}{W_0}\right)^{4(\alpha_{IP}(t)-1)}$$

$$\alpha_{IP}(t) = 1.08 - 0.25|t|$$

Works for light VM

at low Q^2 (and low t)

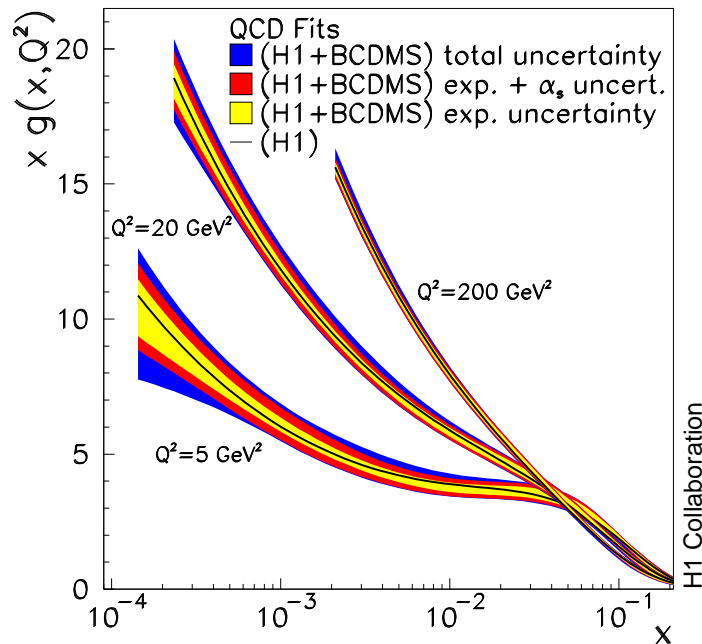
Vector Mesons: Perturbative QCD Models



Assume Factorization

\iff Requires hard scale:
 Q^2, m_q or t

\iff Requires endpoints
cancellation mechanism
to avoid divergence



Exchange of ≥ 2 gluons:

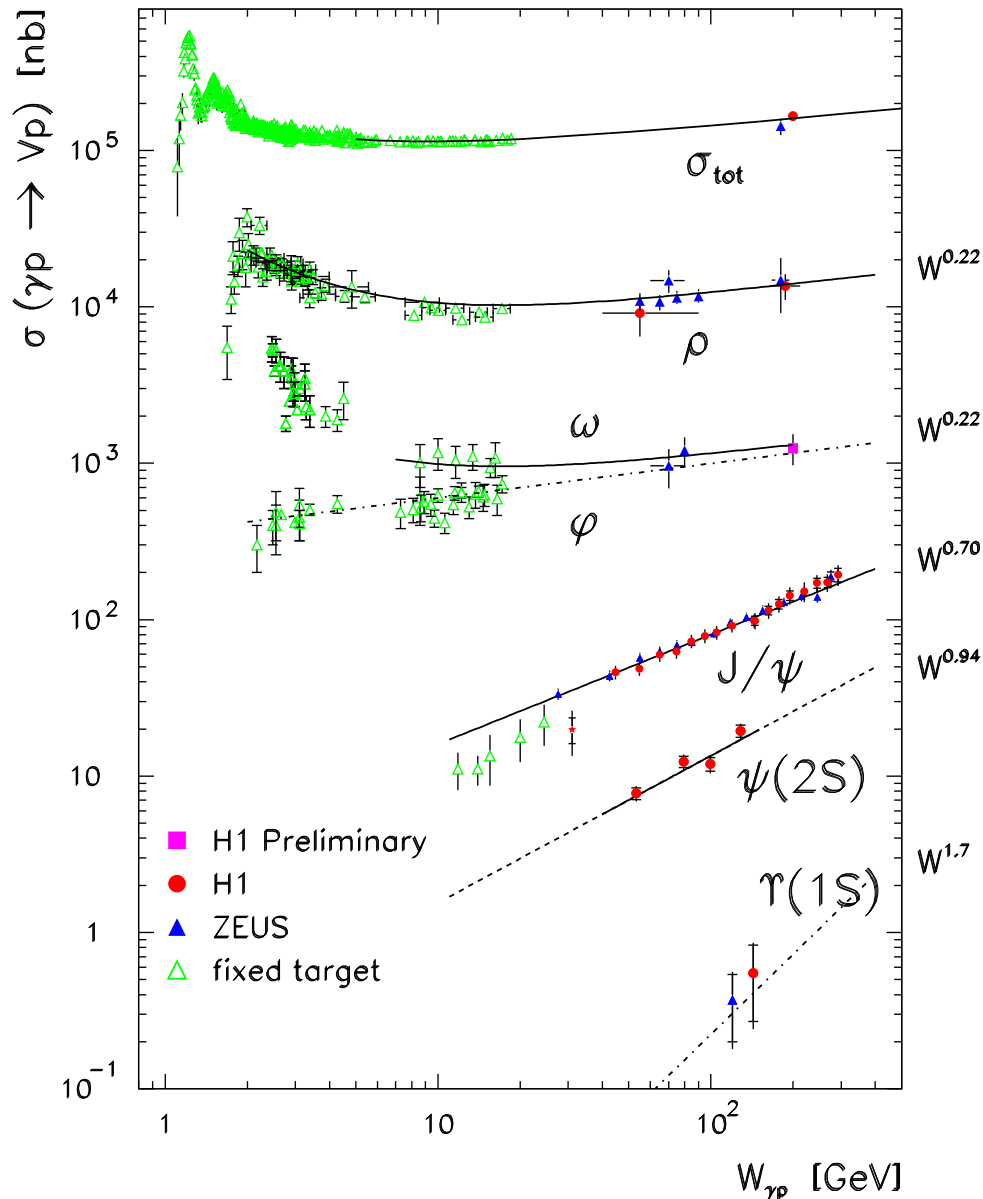
$$\sigma \propto (xG(x, Q^2))^2$$

Steep rise of $xG(x, Q^2)$

No (or little) shrinkage

Vector Mesons : Photoproduction Overview

Photoproduction ($Q^2 = 0 \text{ GeV}^2$)



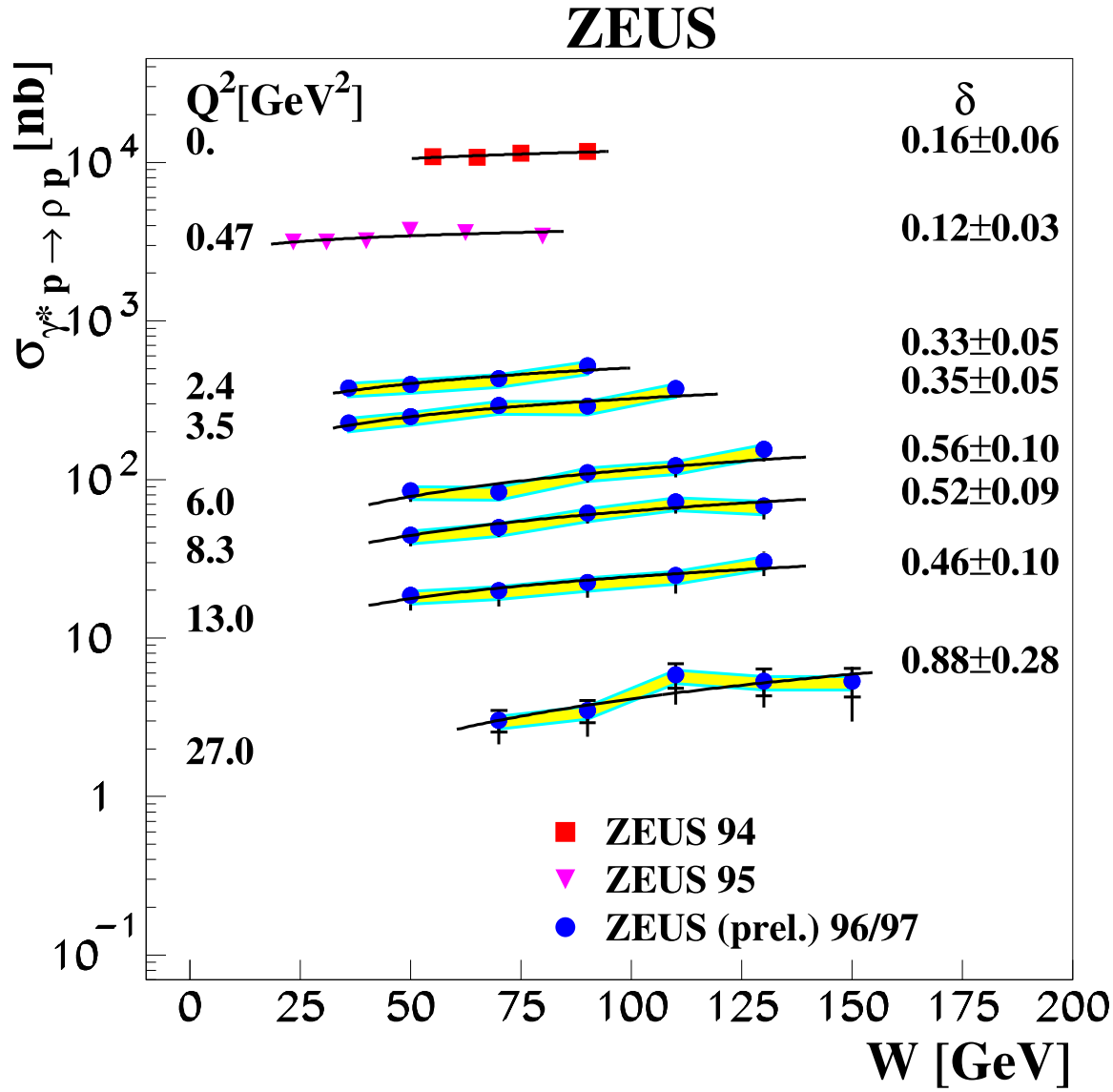
Light vector meson (ρ, ω, ϕ):
Soft energy dependence

J/ψ :

Hard energy dependence

\Rightarrow Quark mass (m_c)
= hard scale

Vector Mesons : Elastic Rho Production



Transition with Q^2 to a hard dependence in W

→ $Q^2 = \text{hard scale}$

- electron not detected:

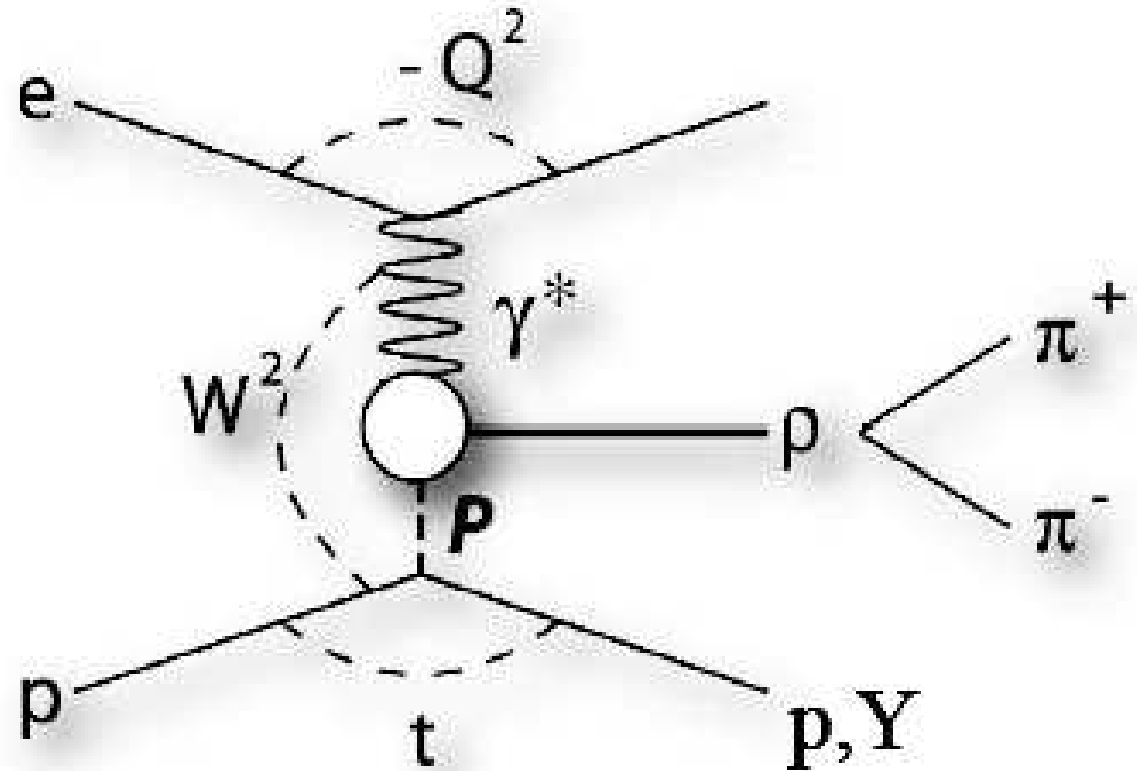
$$Q^2 < 4 \text{ GeV}^2$$

$$\langle Q^2 \rangle = 0.01 \text{ GeV}^2$$

- $W = \sqrt{2E_p(E_\rho - P_{z,\rho})}$

$$20 < W < 90 \text{ GeV}$$

- $t = -P_{t,\rho}^2 \quad |t| < 3 \text{ GeV}^2$



- Previous HERA measurements:

- **H1**: 93 data, 358 events, 20 nb^{-1} \longrightarrow new measurement needed

- **ZEUS**: no level arm in W , combined fit with fix target data

$$\longrightarrow \alpha(t) = (1.096 \pm 0.021) + (0.125 \pm 0.038) t$$

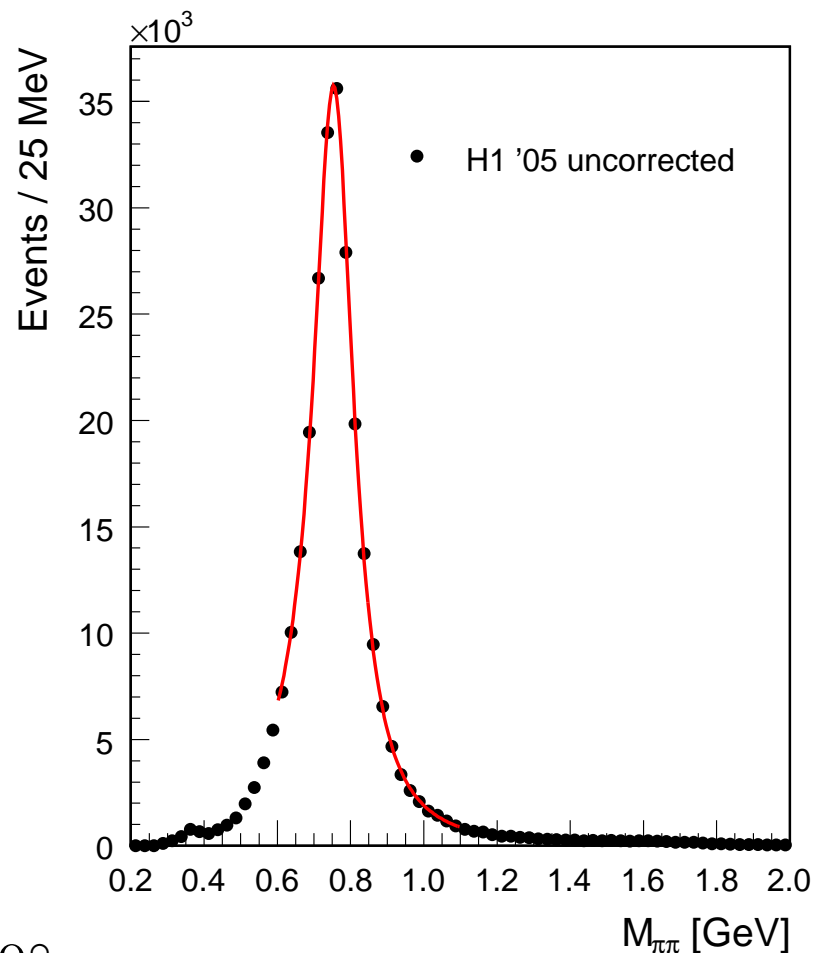


H1 Fast Track Trigger at HERA-II:

- Threshold: $p_t > 100$ MeV
- Selection on nr of tracks, charge
 - 1 Million triggered events in 2005 (570 pb^{-1})

Offline Event Selection:

- Vertex within 25 cm of nominal IP
- 2 tracks, opposite charge
- tracks: $p_t > 200$ MeV, $20^\circ < \theta < 160^\circ$
- No electron detected
- No other particles



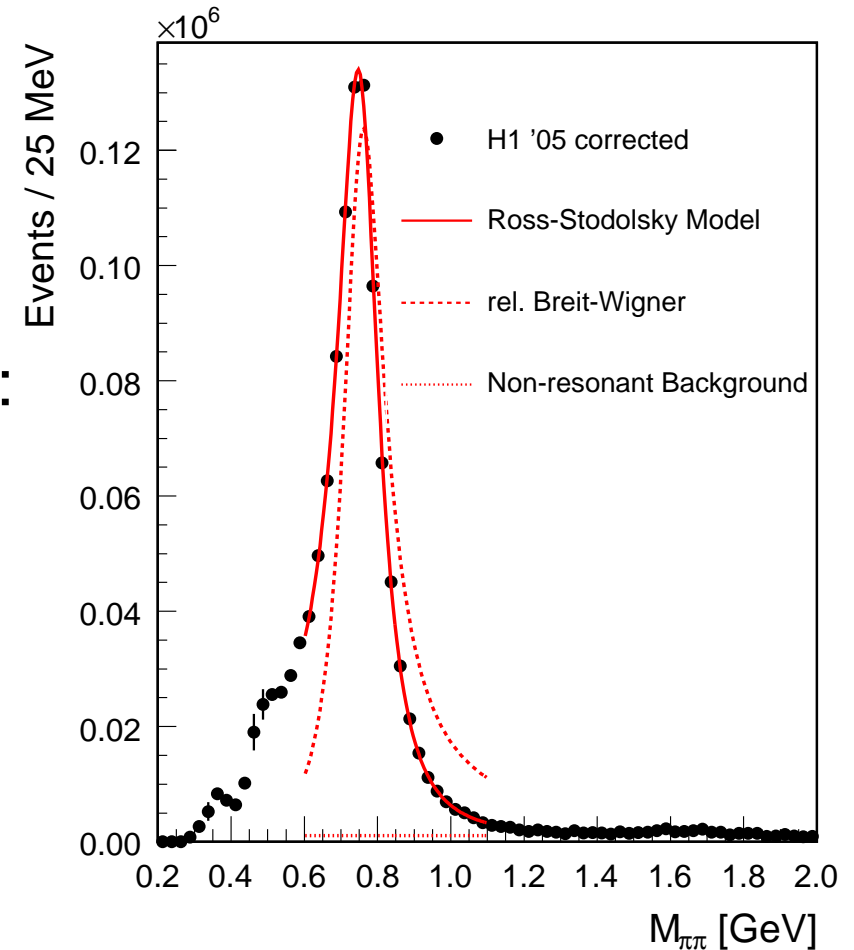
→ 267785 selected ρ^0

→ 12 bins in $|t|$
5-10 bins in W



ρ^0 PhP - Corrected Mass Distribution

- Mass distribution distorted, due to non-resonant $\pi^+\pi^-$ production
- Fit rel. Breit-Wigner, including a skewing factor (Ross-Stodolsky):
 - $m_\rho = 766.4$ MeV (PDG: 768 MeV)
 - $\Gamma_\rho = 145$ MeV (PDG: 150 ± 3 MeV)
- Perform fit in each $W - t$ bin with fixed ρ^0 mass and width to average values above

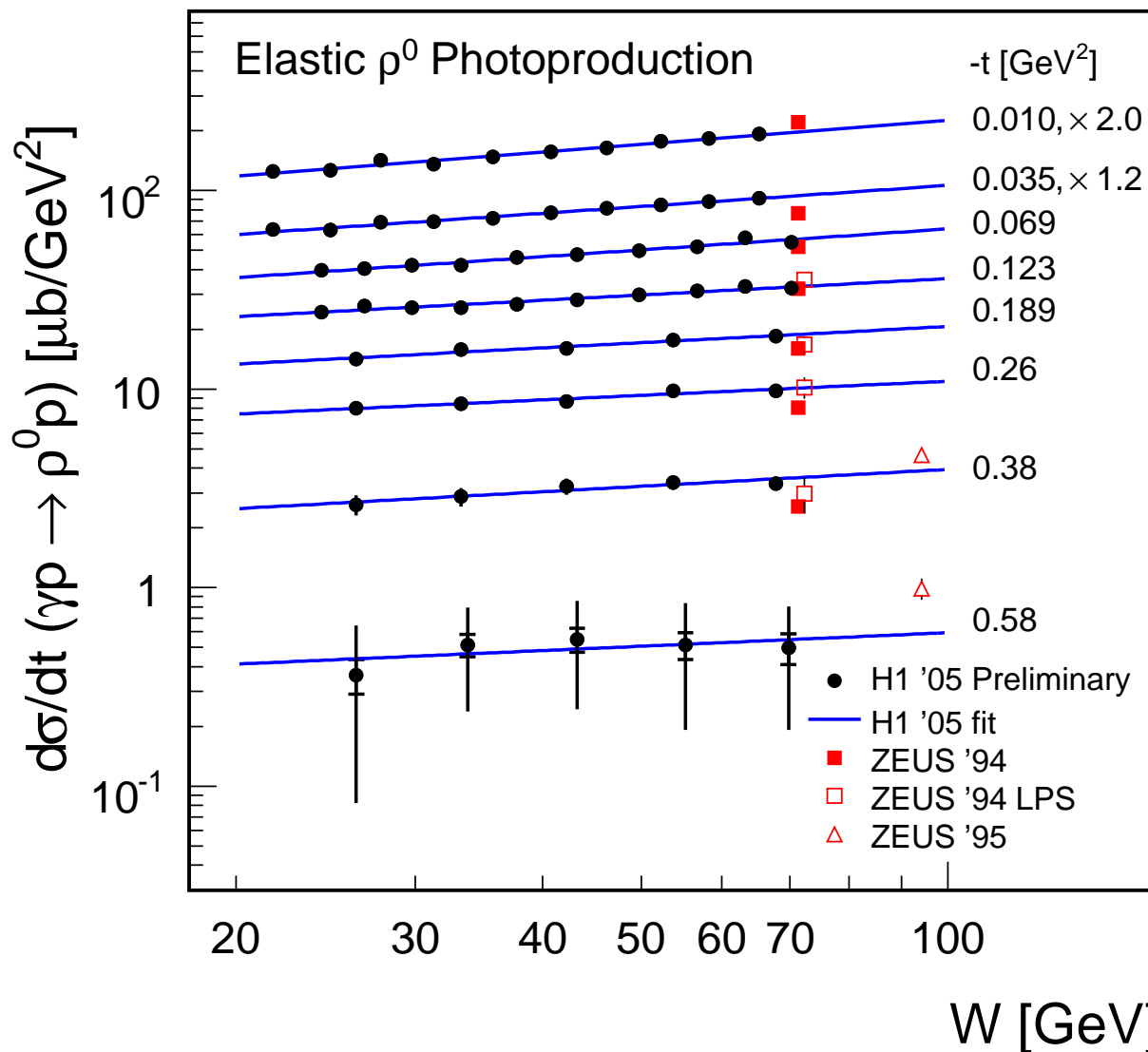


- Obtain number of ρ^0 in each $W - t$ bin (for $2m_\pi < M_{\pi\pi} < m_\rho + 5\Gamma_\rho$)
- Extract σ_{gp} cross sections in each $W - t$ bin



ρ^0 PhP - Elastic Cross Section

H1 PRELIMINARY



Good agreement with previous results from H1, ZEUS and OMEGA (not shown)

Fit to H1 data:

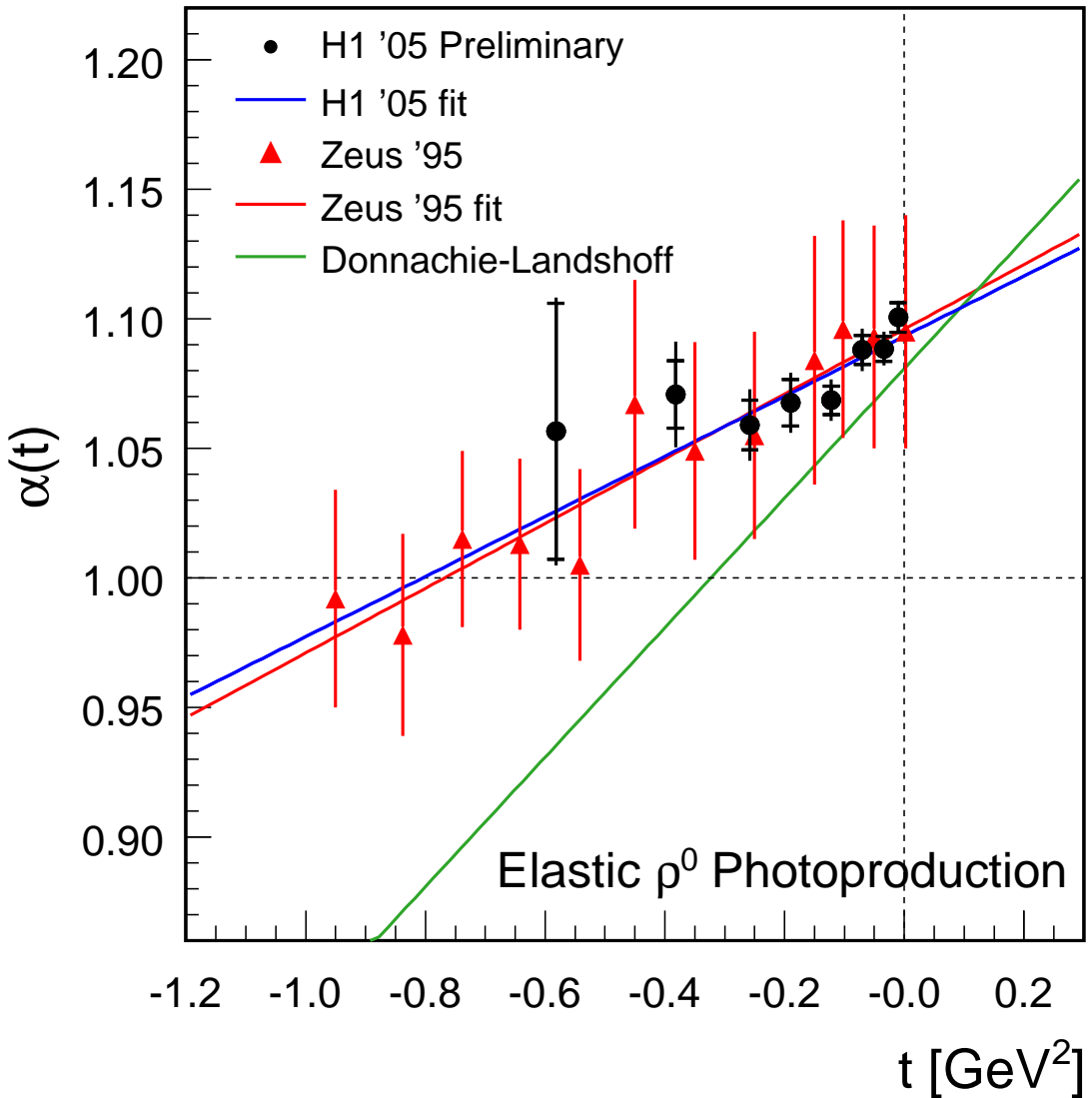
$$\frac{d\sigma}{dt} \propto \frac{W}{W_0}^{4(\alpha(t)-1)}$$

→ Pomeron trajectory



Elastic ρ^0 PhP - Pomeron trajectory

H1 PRELIMINARY



$$\alpha(t) = \alpha_0 + \alpha' t$$

$$\rightarrow \alpha_0 = 1.093 \pm 0.003^{+0.008}_{-0.007}$$
$$\rightarrow \alpha' = 0.116 \pm 0.027^{+0.036}_{-0.046} \text{ GeV}^{-2}$$

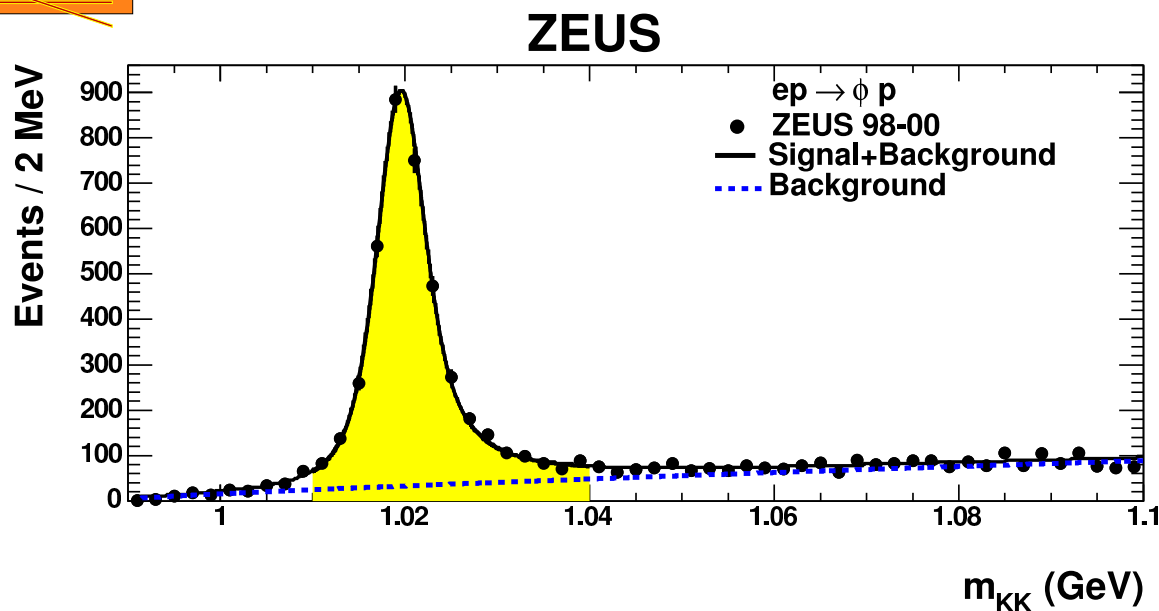
- α' smaller than 0.25 GeV^{-2}
- Good agreement with fit to ZEUS and fix target data:

$$\alpha_0 = 1.096 \pm 0.021$$
$$\alpha' = 0.125 \pm 0.038 \text{ GeV}^{-2}$$



Exclusive ϕ Production in DIS

Nucl. Phys. B 718 (2005) 3-31



98-2000 data:

- $\mathcal{L} = 65.1 \text{ pb}^{-1}$
- Select $\phi \longrightarrow K^+ K^-$
- 3642 events in range
 $1.01 < M_{KK} < 1.04 \text{ GeV}$

Kinematic range:

- $2 < Q^2 < 70 \text{ GeV}^2$
- $35 < W < 145 \text{ GeV}$
($\rightarrow Q^2$ dependent)
- $|t| < 0.6 \text{ GeV}^2$

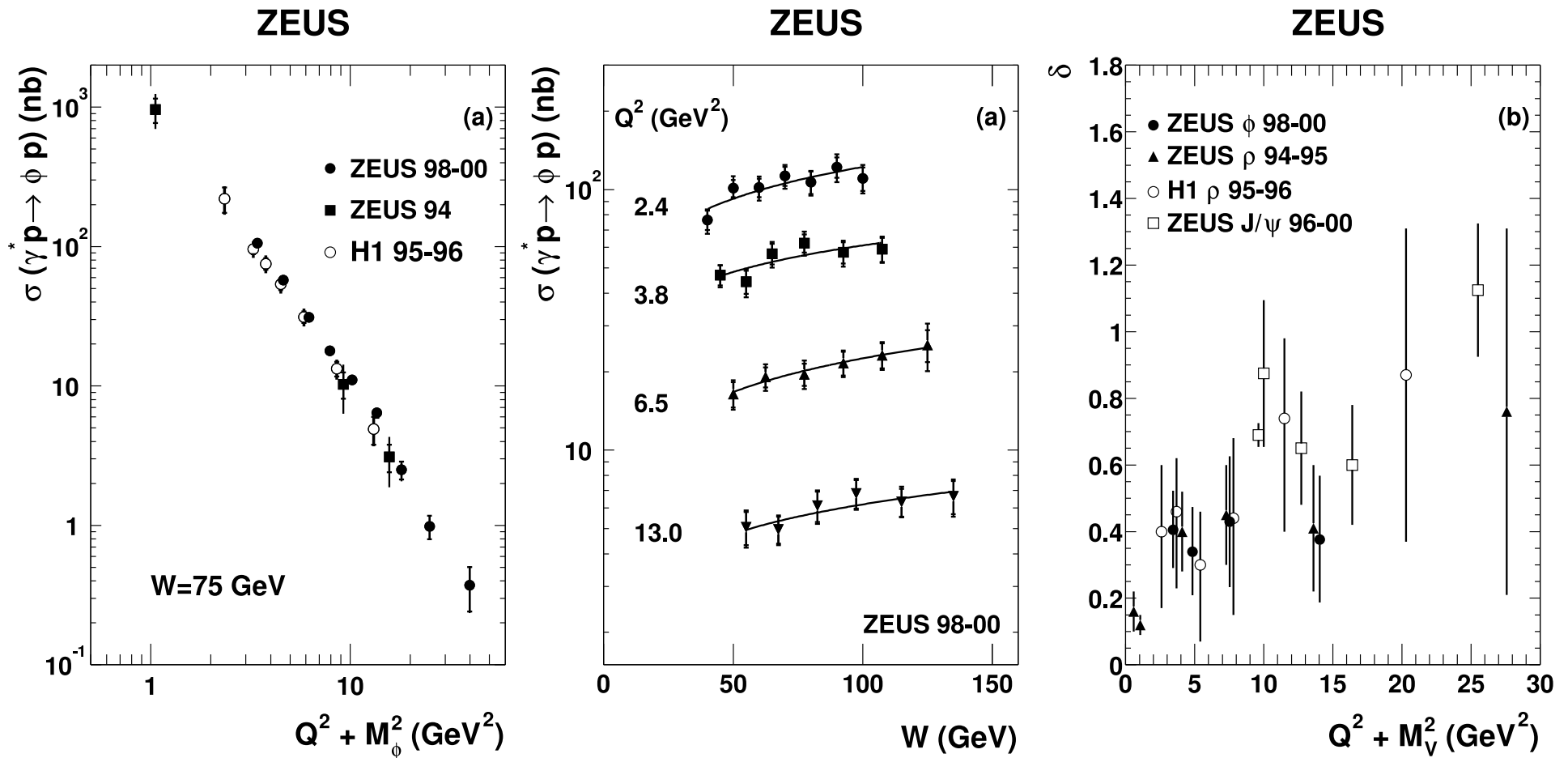
Subtracted backgrounds:

- non-resonant decreasing
from 18 % at $Q^2 = 2.4 \text{ GeV}^2$
to 5 % at $Q^2 = 13 \text{ GeV}^2$
- Proton dissociation: $(7 \pm 0.4^{+4.2}_{-2.8})\%$



ϕ in DIS - Q^2 and W dependence

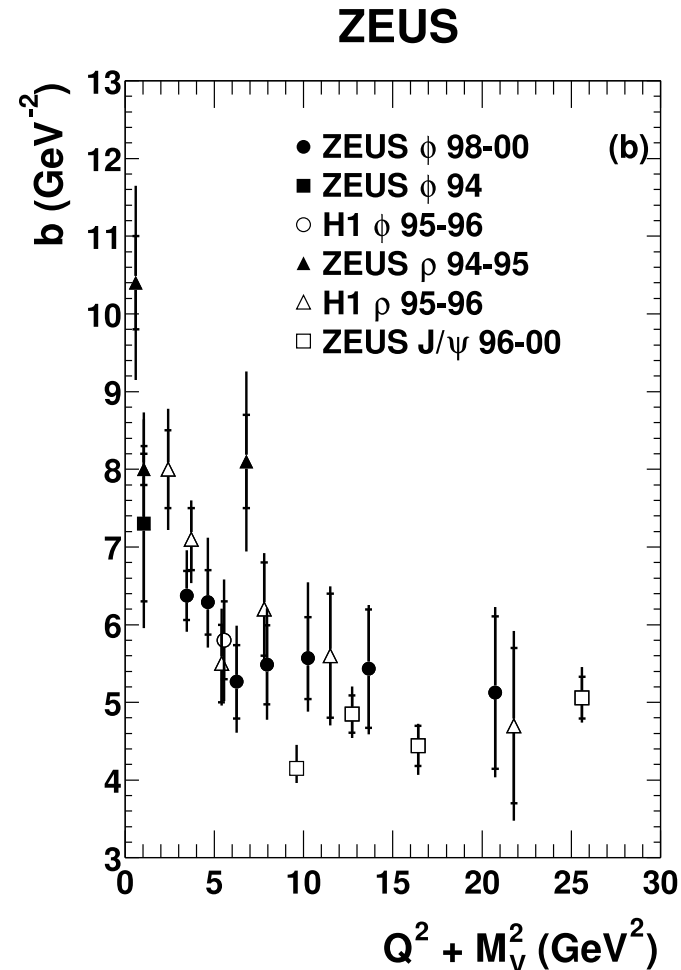
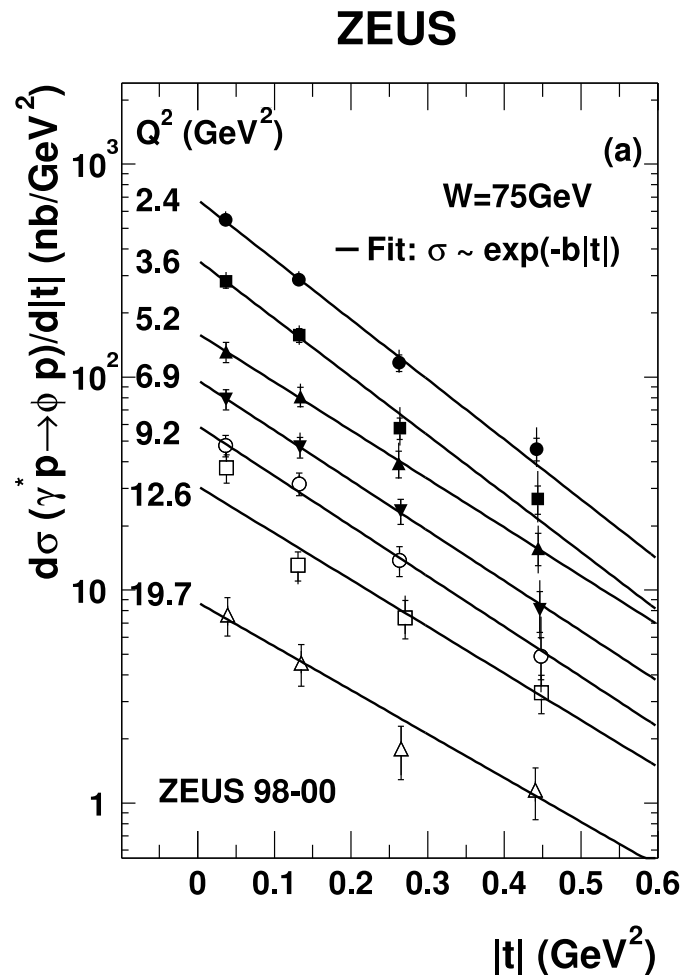
- Fit $\sigma_\phi \propto W^\delta \longrightarrow \delta \sim 0.4 \longrightarrow$ no Q^2 dependence of δ
- rise of δ with $Q^2 + M_{VM}^2$ observed in global VM picture
- ρ, ϕ : transition from soft to hard regime observed

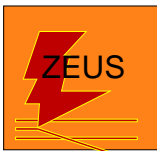




ϕ in DIS - t dependence

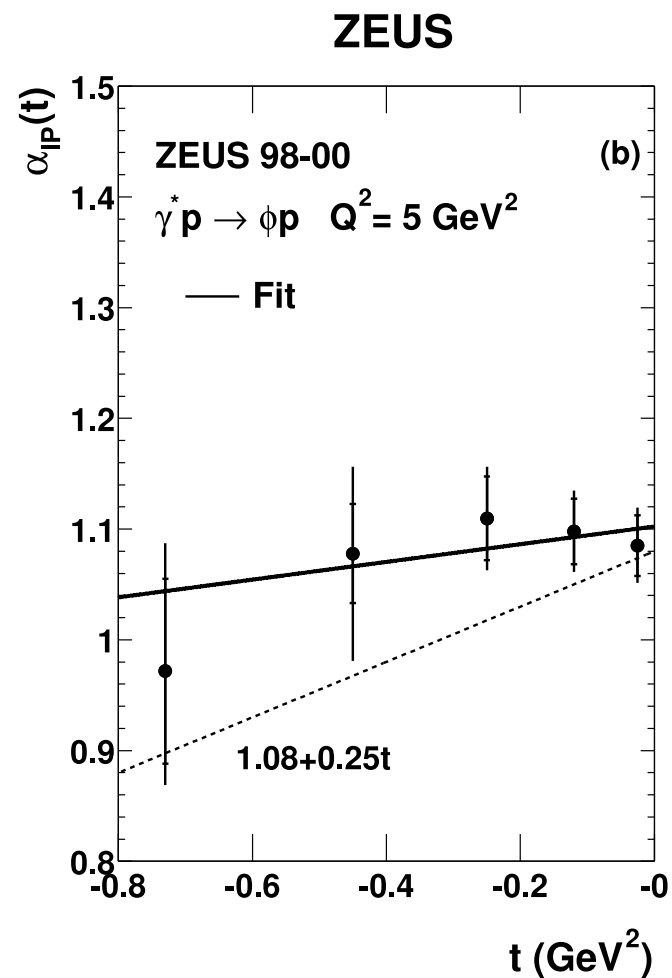
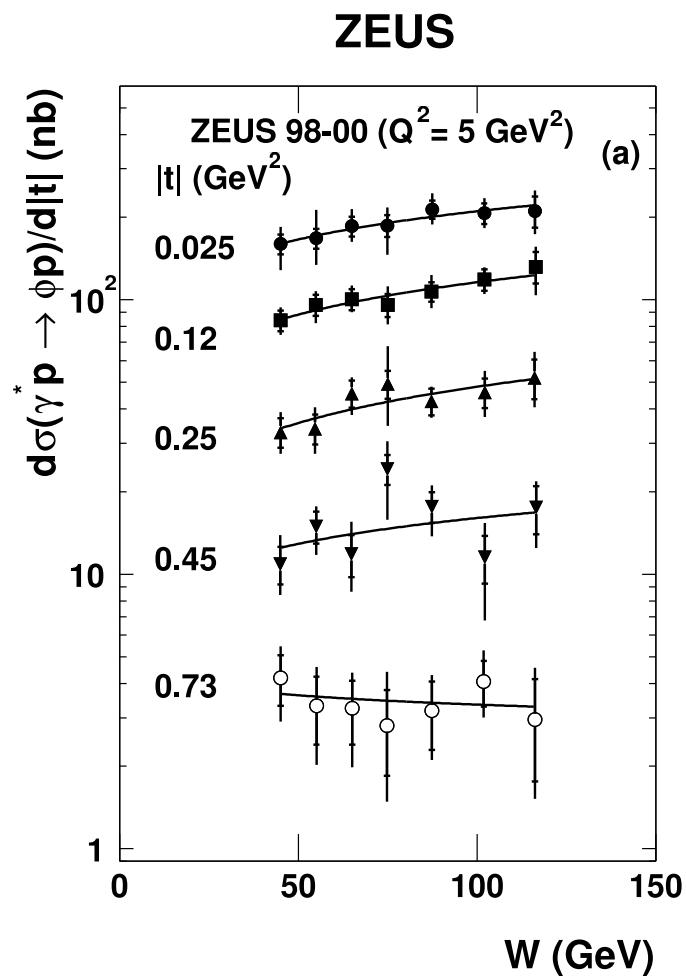
- Fit $d\sigma/dt \propto \exp(-b|t|)$ for $W = 75 \text{ GeV}$
- No Q^2 dependence of b observed within errors
- Data suggest scaling with $Q^2 + M_{VM}^2$ in global VM picture

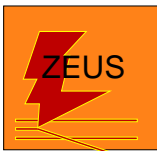




ϕ in DIS - Pomeron trajectory

- Fit $\frac{d\sigma}{dt} \propto \frac{W}{W_0}^{4(\alpha(t)-1)}$
 - $\rightarrow \alpha_0 = 1.10 \pm 0.02$ (stat.) ± 0.2 (syst.)
 - $\rightarrow \alpha' = 0.09 \pm 0.02$ (stat.) ± 0.8 (syst.) GeV^{-2}
- \rightarrow Data compatible with $\alpha' = 0$ (no shrinkage)





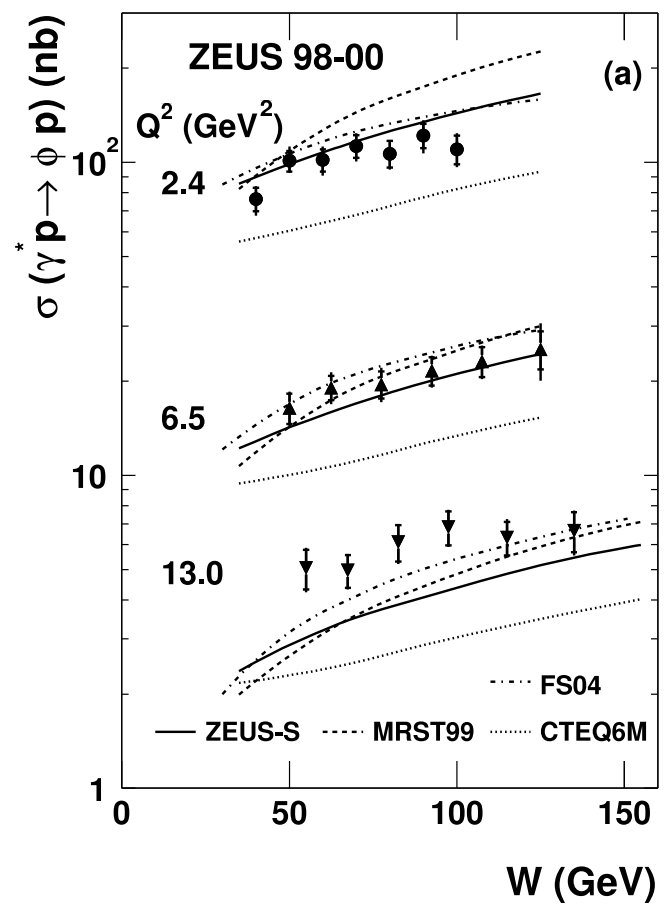
ϕ in DIS - Comparison with pQCD models

- comparison with MRT and FS04 pQCD models
 - different assumptions on gluon densities

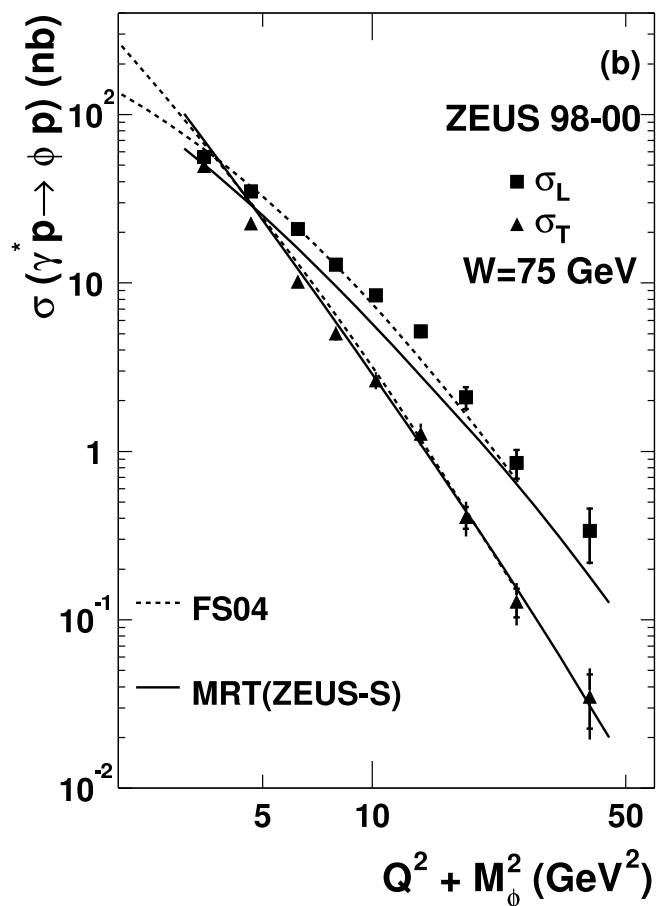
- $\sigma(\gamma p \rightarrow \phi p) = \sigma_T + \epsilon \sigma_L$

JHEP 0412, 052 (2004)
 Phys. Rev. D62, 14022 (2000)

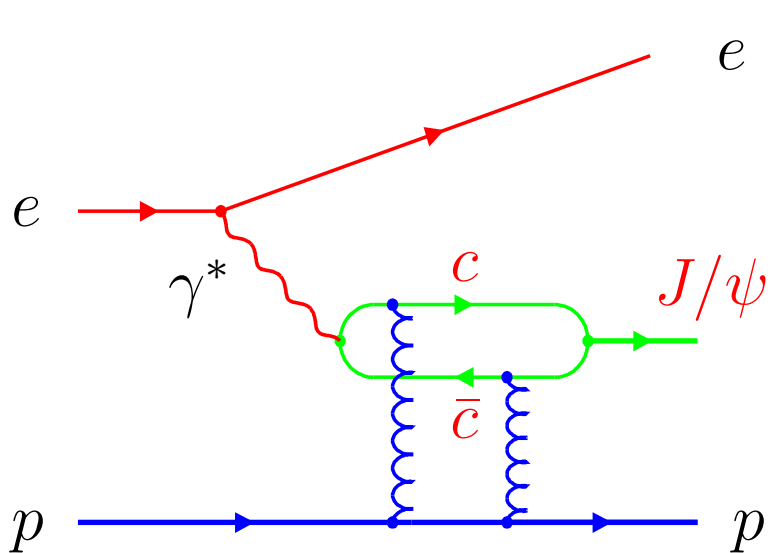
ZEUS



ZEUS



→ models describe qualitatively data; best description by FS04



- Charm q mass as hard scale
 → pQCD valid in photoproduction
- Interplay with second hard scale Q^2 ?
- Sensitivity to GPDs at low x
 → constrain on gluon density ?

Photoproduction $\langle Q^2 \rangle = 0.05 \text{ GeV}^2$

→ $J/\psi \rightarrow \mu^+ \mu^-$ for $40 < W < 160 \text{ GeV}$

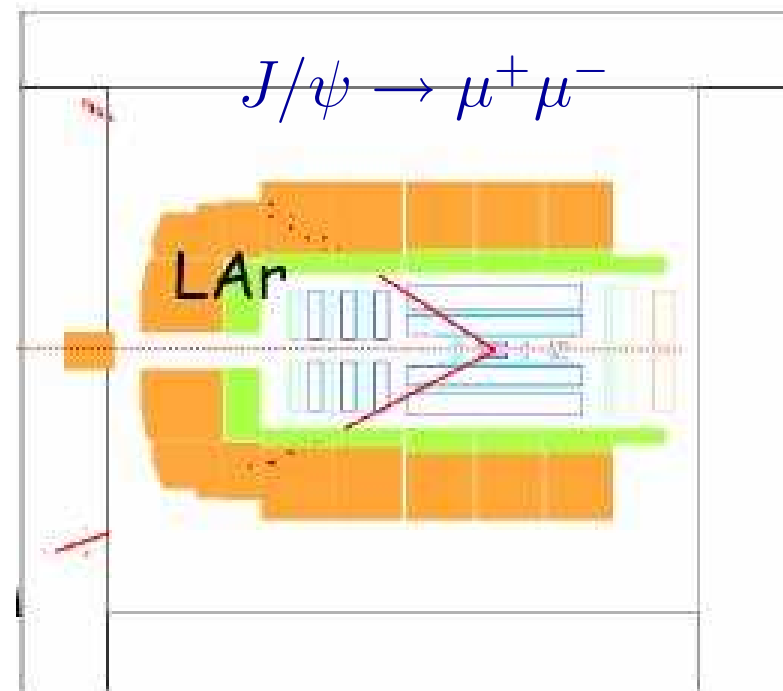
→ **Dedicated** $J/\psi \rightarrow e^+ e^-$ high W analysis

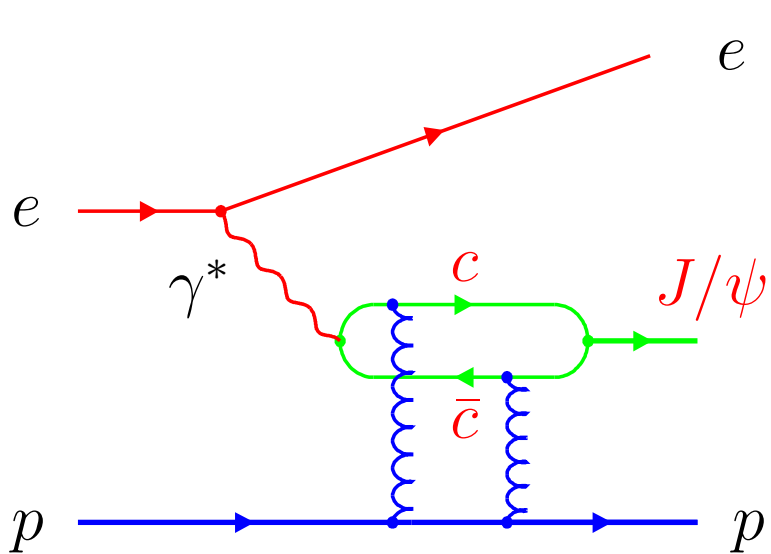
→ $40 < W < 305 \text{ GeV}$

Electroproduction ($J/\psi \rightarrow \mu^+ \mu^-$ Only)

- $2 < Q^2 < 80 \text{ GeV}^2$

- $40 < W < 160 \text{ GeV}$





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 → pQCD valid in photoproduction
- Interplay with second hard scale Q^2 ?
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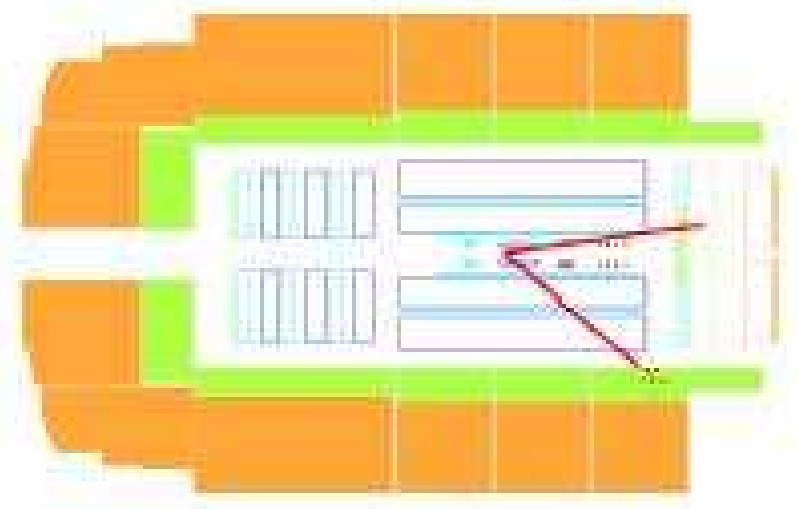
→ $40 < W < 305 \text{ GeV}$

Electroproduction ($J/\psi \rightarrow \mu^+ \mu^-$ Only)

- $2 < Q^2 < 80 \text{ GeV}^2$

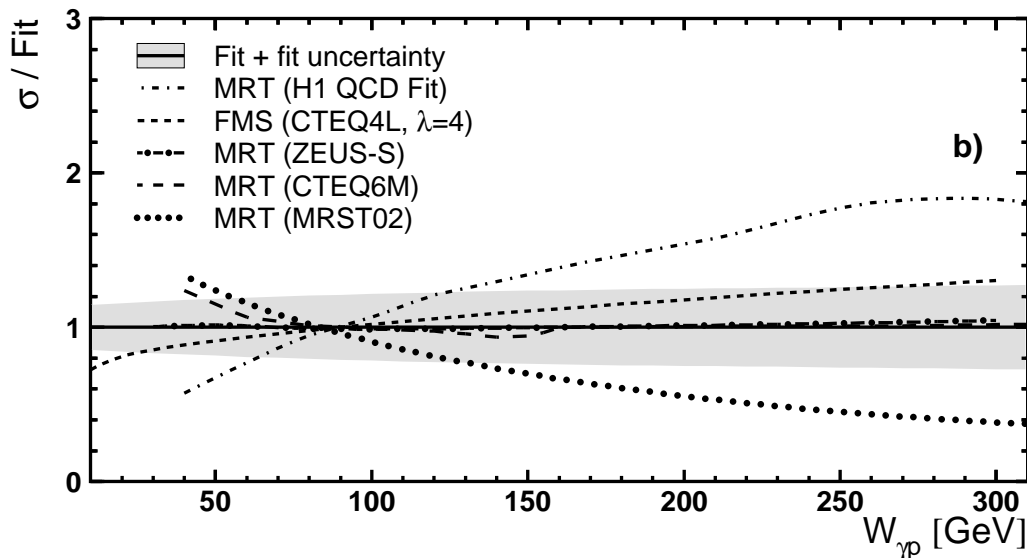
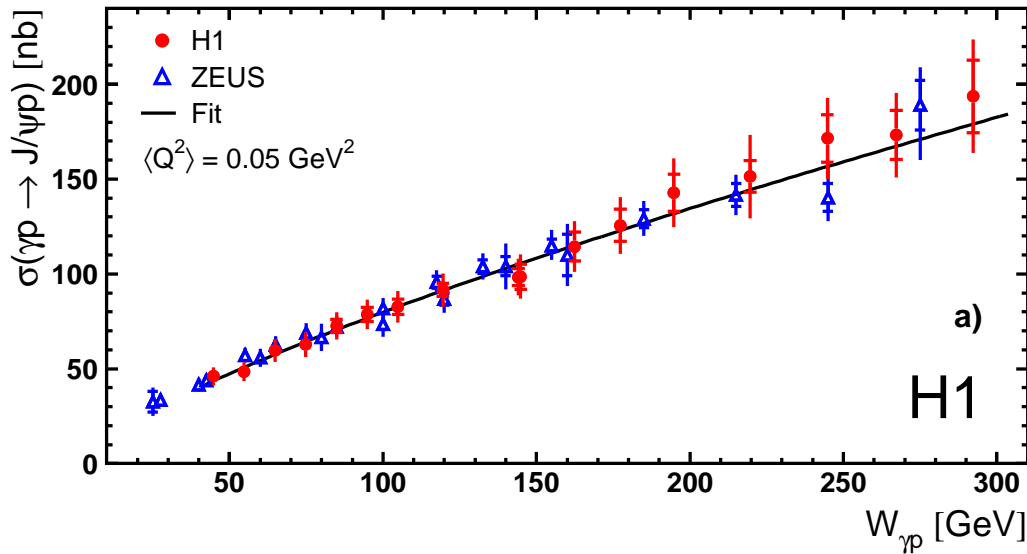
- $40 < W < 160 \text{ GeV}$

$J/\psi \rightarrow e^+ e^-$





Elastic J/ψ - W dependence in PhP



- H1 and ZEUS data agree
- Fit $\sigma \propto W^\delta$ (H1 only):
 $\delta = 0.75 \pm 0.03 \pm 0.03$

Martin, Ryskin, Teubner :

Phys Rev D62 (2000) 014033

$$A = \int_0^{\infty} \frac{dl_T^2}{l_T^4} \alpha_s(l_T^2) f(x, x', l_T^2) \Phi^{L,T}(\dots, l_T^2)$$

$x \neq x' \longrightarrow$ need GPDs

$$f(x = x', l_T^2) = \frac{\partial [(xg(x, q_o^2)T(q_o^2, \mu^2)]}{\partial q_o^2} \Big|_{q_o^2 = l_T^2}$$

+ skewing ansatz

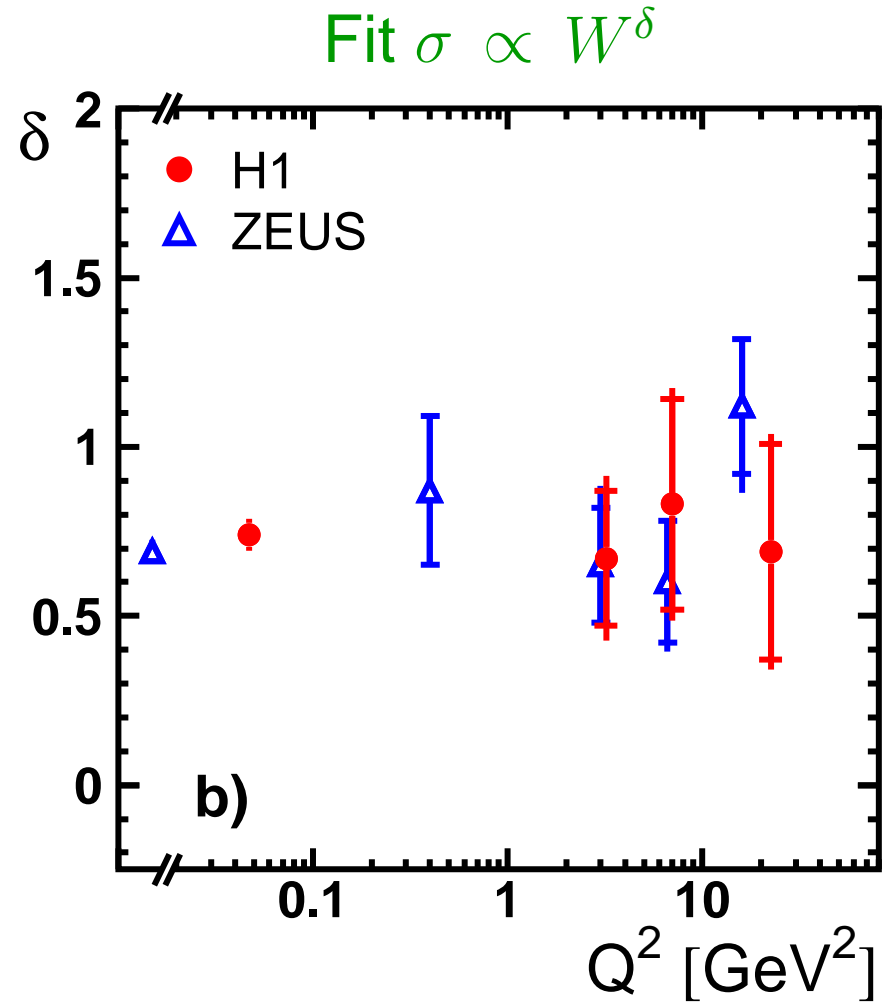
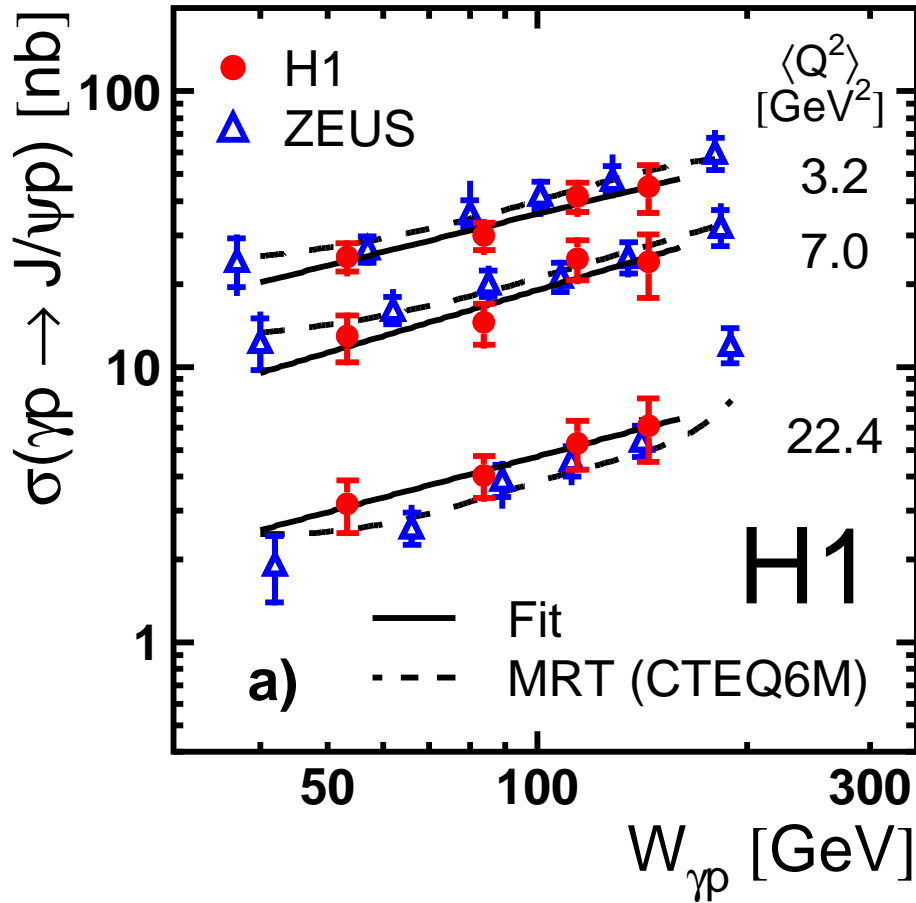
\longrightarrow Sensitivity to gluon at low x (?)

FMS: dipole model \longrightarrow OK

JHEP 0103 (201) 045



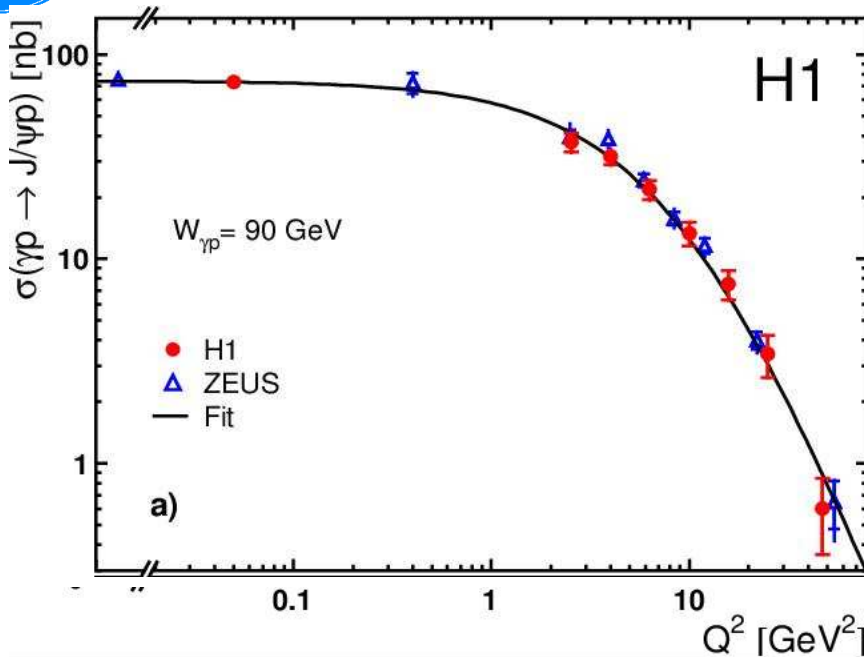
Elastic J/ψ - W dependence in DIS



- No Q^2 dependence of δ within errors
- "Scale" is already hard, set by the charm quark mass



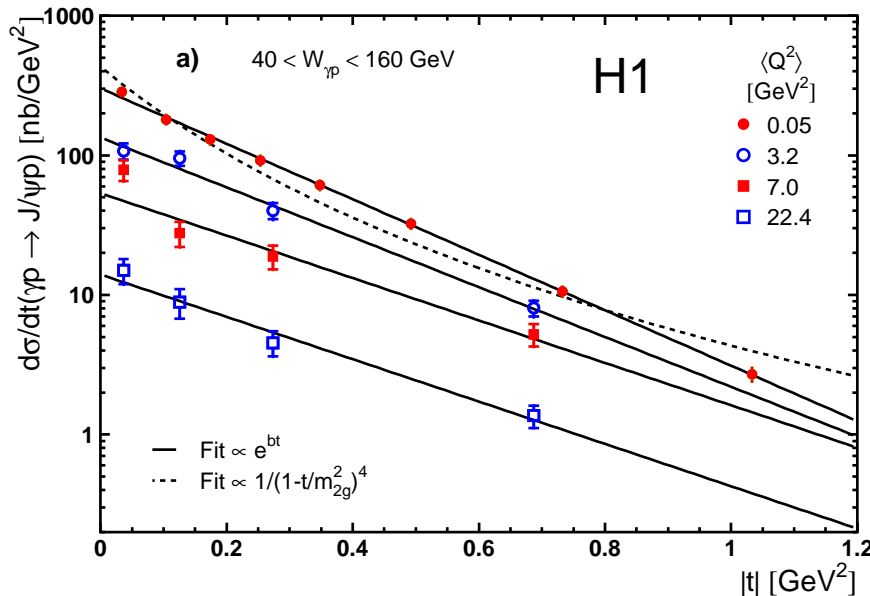
Elastic J/ψ - Q^2 and t dependences



Fit: $\sigma \propto (Q^2 + M_{J/\psi}^2)^{-n}$

$\rightarrow n = 2.486 \pm 0.080 \pm 0.068$

\rightarrow in agreement with ZEUS



Fits: $d\sigma/dt \propto \exp(-b|t|)$

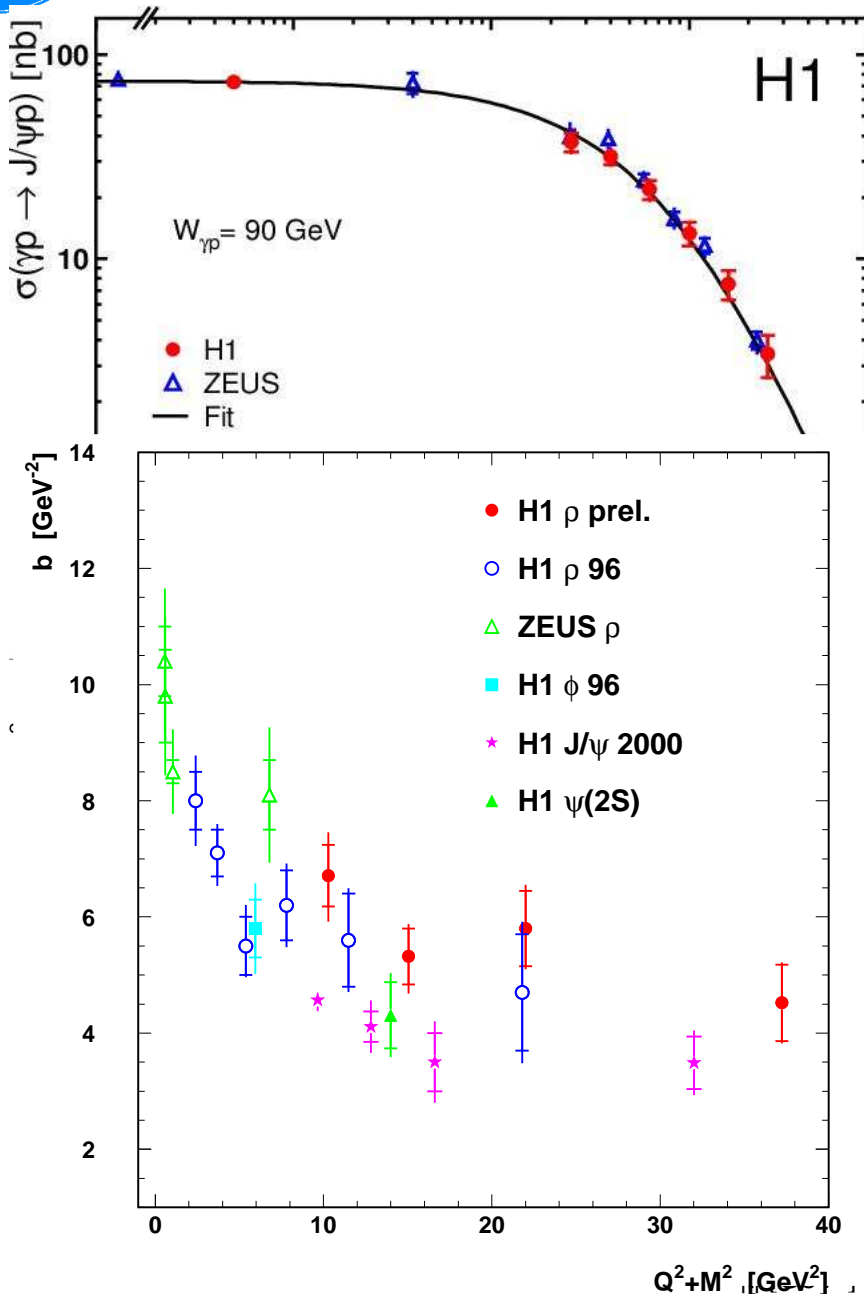
$Q^2 = 0.05 \quad b = 4.57 \pm 0.06^{+.11}_{-.18}$

$Q^2 = 22.4 \quad b = 3.49 \pm 0.45^{+.49}_{-.33}$

\rightarrow no Q^2 dependence within errors



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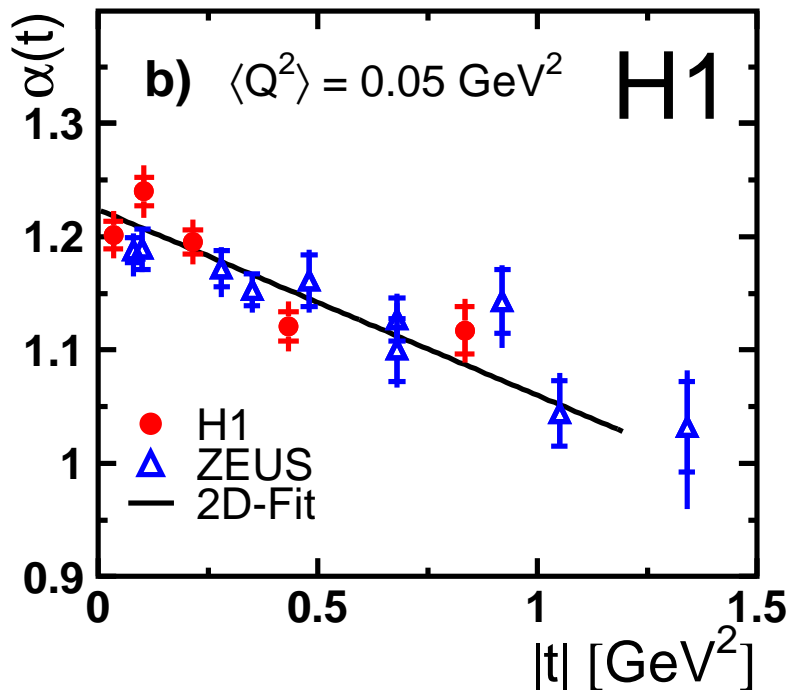
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$Q^2 = 22.4 \quad b = 3.49 \pm 0.45^{+0.49}_{-0.33}$

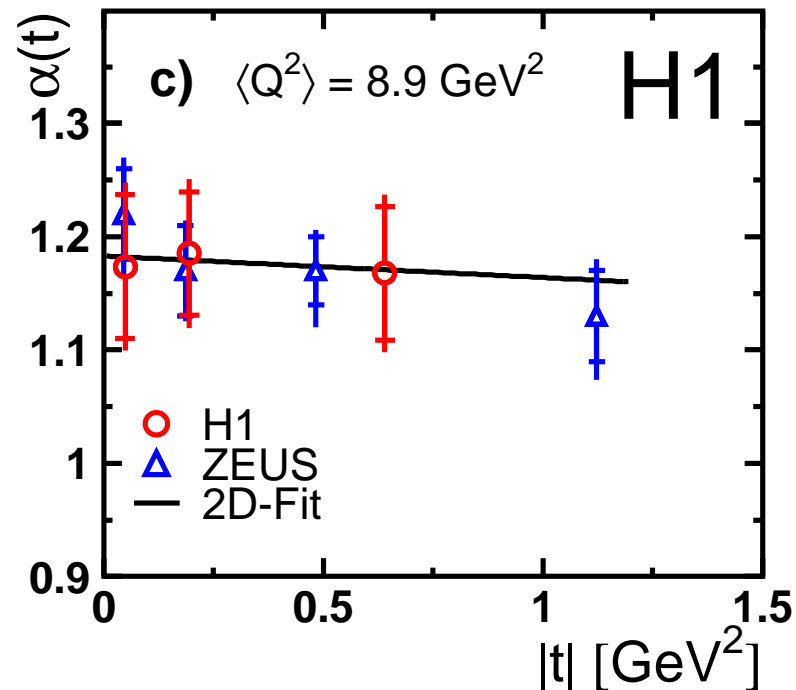
\rightarrow no Q^2 dependence within errors

\rightarrow Universality with $Q^2 + M_{VM}^2$

Photoproduction



Electroproduction



- **PhP:** $\alpha(t) = (1.224 \pm 0.010 \pm 0.012) + (0.164 \pm 0.028 \pm 0.030) \text{ GeV}^{-2} t$

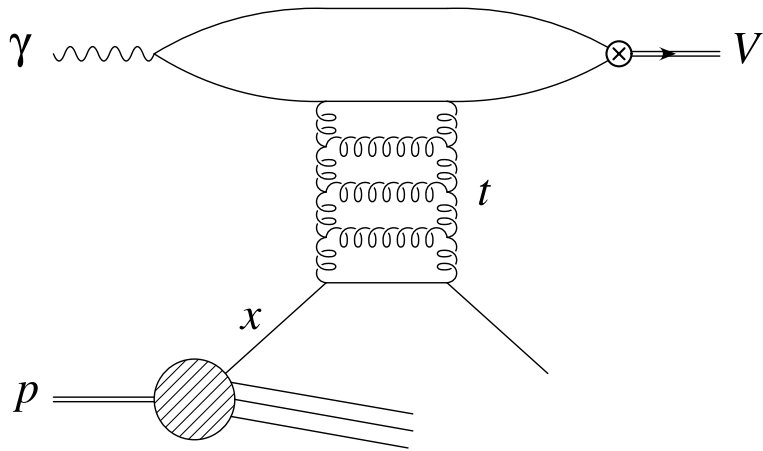
- **DIS:** $\alpha(t) = (1.183 \pm 0.054 \pm 0.030) + (0.019 \pm 0.139 \pm 0.076) \text{ GeV}^{-2} t$

→ Similar trajectories within errors in PhP and DIS

→ **PhP:** $0 \ll \alpha' \ll 0.25 \text{ GeV}^{-2}$

Vector Mesons at Large $|t|$

VM photoproduction at large $|t|$ proposed as test of BFKL



- Need $W^2 > |t| \rightarrow \sum_n \alpha_s^n \ln^n W^2 / |t|$
- BFKL model by Forshaw *et al.*:
 - Free parameters: α_s^{BFKL} , Λ^2
 - Power like t dependence
 - Challenge is to describe both the t dependence and the helicity structure

JHEP 0309 (2003) 008 and JHEP 0312 (2003) 002

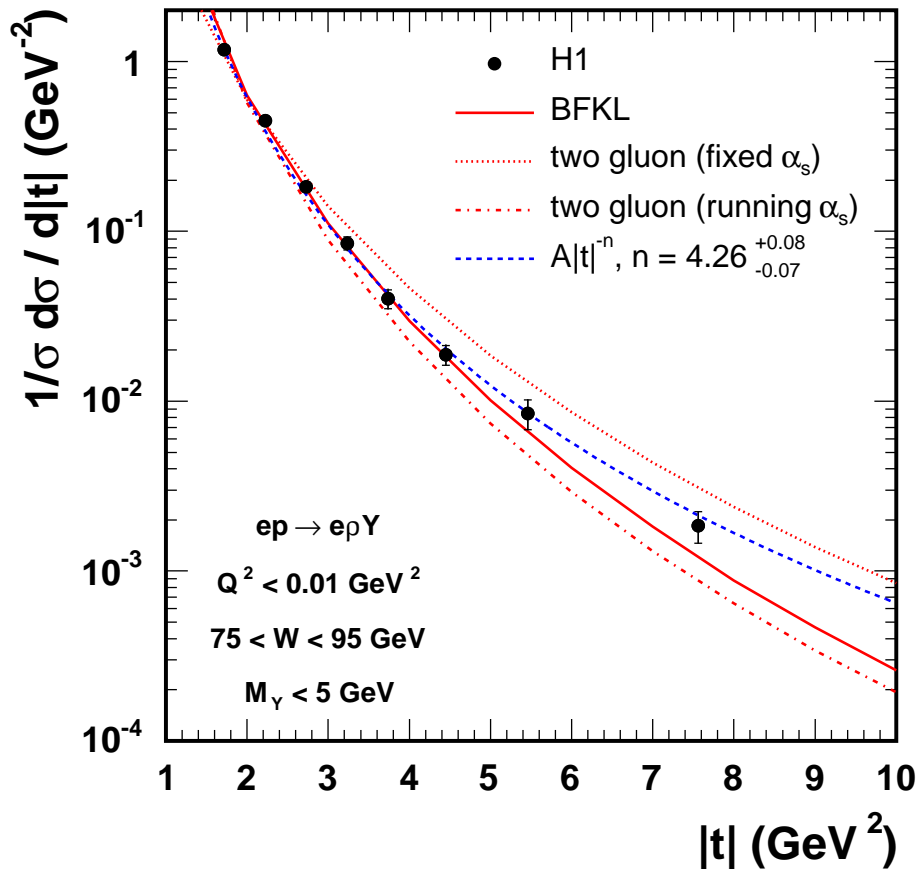
H1: ρ^0 PhP at large $|t|$

- 2000 data: $\mathcal{L} = 20 \text{pb}^{-1}$
 - $75 < W < 95 \text{ GeV}$
 - $1.5 < |t| < 10 \text{ GeV}^2$
 - $M_Y < 5 \text{ GeV}$ (Y=proton remnant)
- Acc by Phys. Lett. B [hep-ex/0603038]

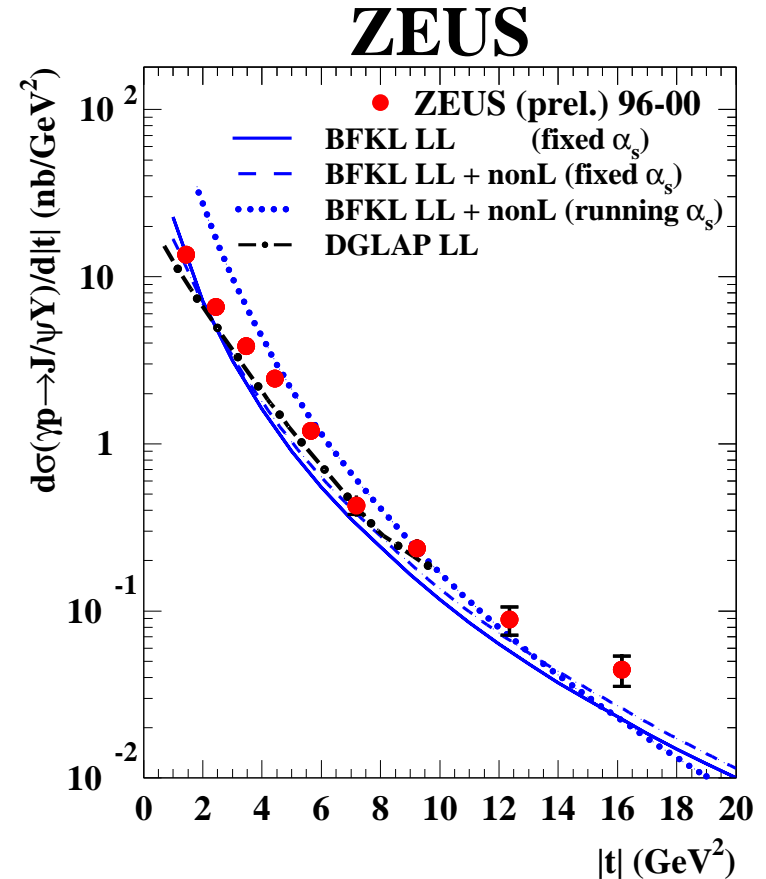
ZEUS: J/ψ PhP at large $|t|$

- 96-2000 data: $\mathcal{L} = 112 \text{pb}^{-1}$
- $50 < W < 150 \text{ GeV}$
- $1 < |t| < 20 \text{ GeV}^2$
- $M_Y < 30 \text{ GeV}$

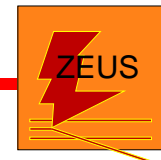
ρ^0 PhP at large $|t|$



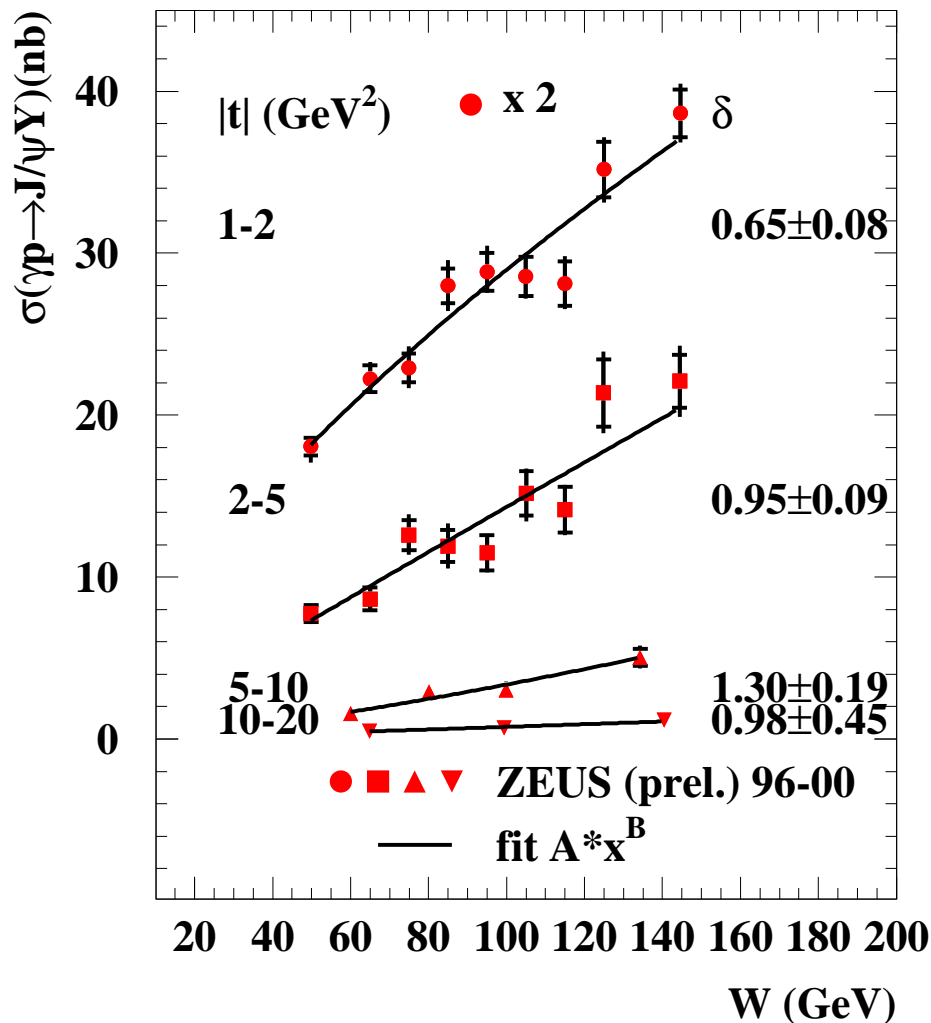
J/ψ PhP at large $|t|$



- Approx. power-like behaviour supported by data
- BFKL predictions (with fixed α_s) describe reasonably the data



ZEUS



J/ψ PhP at large $|t|$

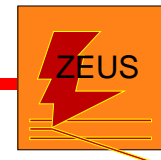
- Fit $\sigma \propto W^\delta$; $\delta = 4(\alpha_P(t) - 1)$

→ δ rise with $|t|$

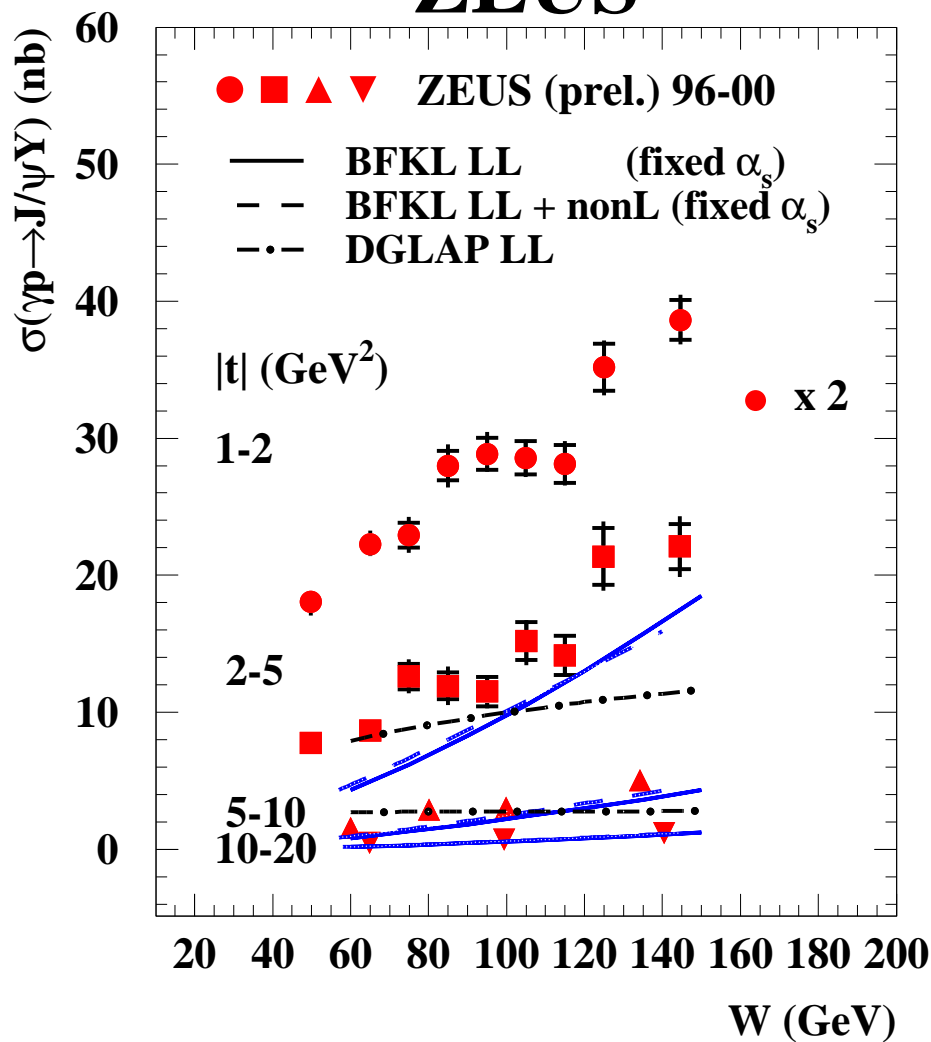
→ effective Pomeron trajectory:

$$\alpha(0) = 1.153 \pm 0.048 \pm 0.039$$

$$\alpha' = -0.020 \pm 0.014 \pm 0.010 \text{ GeV}^{-2}$$



ZEUS



J/ψ PhP at large $|t|$

- Fit $\sigma \propto W^\delta$; $\delta = 4(\alpha_{\mathbb{P}}(t) - 1)$

→ δ rise with $|t|$

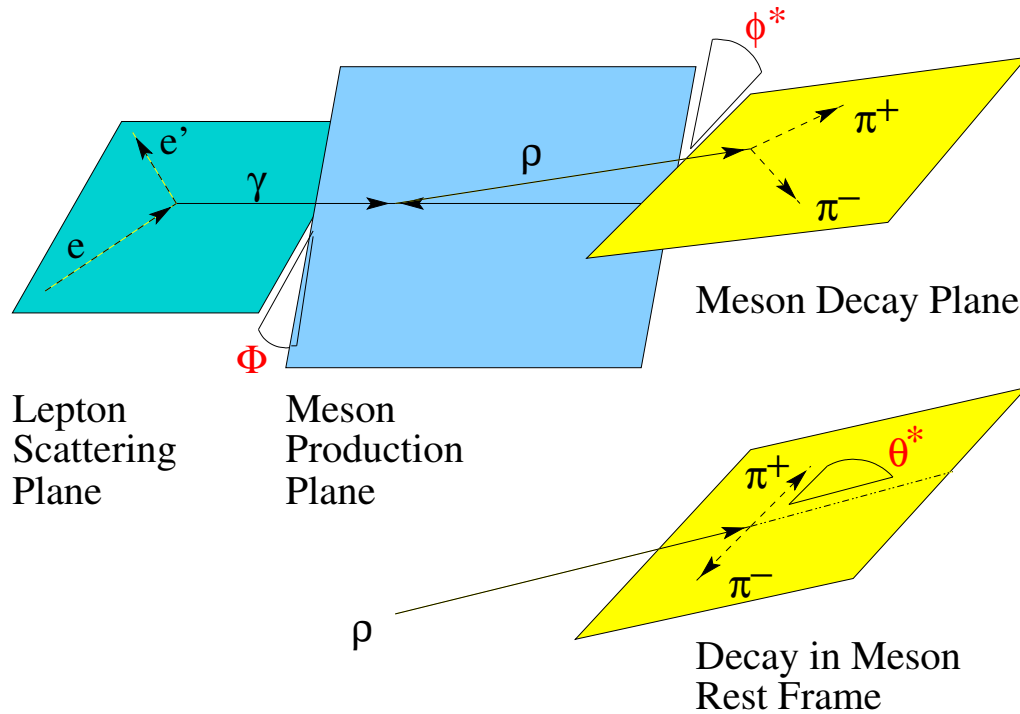
→ effective Pomeron trajectory:

$$\alpha(0) = 1.153 \pm 0.048 \pm 0.039$$

$$\alpha' = -0.020 \pm 0.014 \pm 0.010 \text{ GeV}^{-2}$$

- DGLAP does not describe rise with W
- BFKL reproduces general behaviour of data

VM at Large $|t|$ - Spin Density Matrix Elements



- Production & decay angles
- 15 spin density matrix elements (SDME)

But only 3 accessible in PhP

- SDMEs = bilinear combinations on the helicity amplitudes

$$r_{kl}^{ij} \propto M_{\lambda_{VM}\lambda_\gamma} M_{\lambda'_{VM}\lambda'_\gamma}$$

$$r_{00}^{04} = \frac{|M_{+0}|^2}{|M_{++}|^2 + |M_{+0}|^2 + |M_{+-}|^2}$$

$$r_{10}^{04} = \frac{1}{2} \frac{M_{++}M_{+0}^* - M_{+-}M_{+0}^*}{|M_{++}|^2 + |M_{+0}|^2 + |M_{+-}|^2}$$

$$r_{1-1}^{04} = \frac{1}{2} \frac{M_{++}M_{+-}^* - M_{+-}M_{++}^*}{|M_{++}|^2 + |M_{+0}|^2 + |M_{+-}|^2}$$

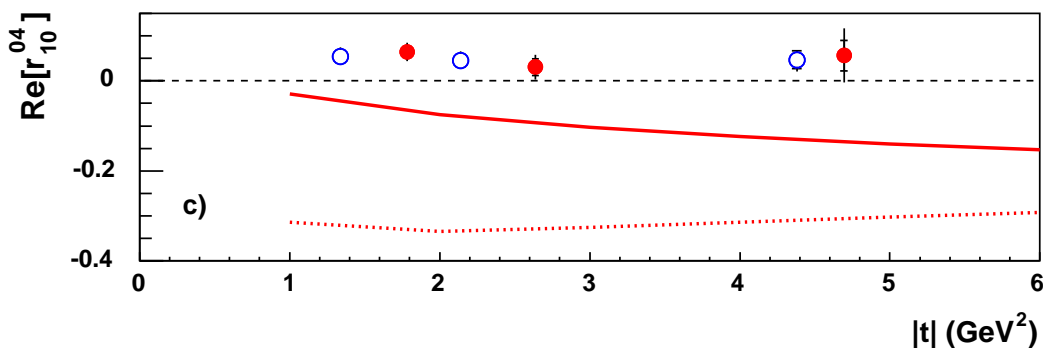
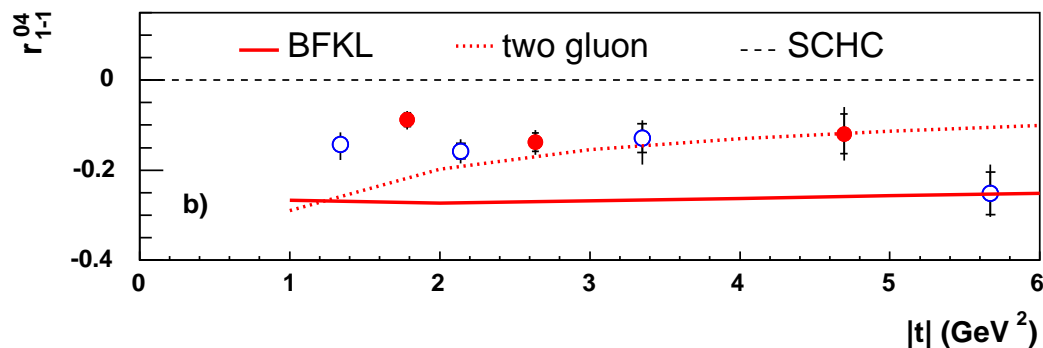
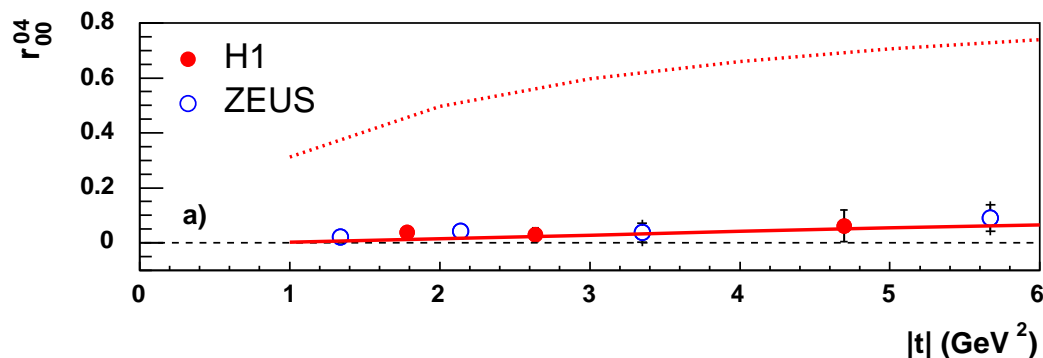
- No helicity flip: M_{++} / M_{--}
- Single flip: M_{+0} / M_{-0}
- Double flip: M_{+-} / M_{-+}

- s-channel helicity conservation (SCHC), i.e. $\lambda_{VM} = \lambda_\gamma$

→ All 3 SDMEs to be zero



VM at Large $|t|$ - Dependence of SDMEs on $|t|$



- Small r_{00}^{04} value ($\sim 5\%$)
→ ρ meson mainly transverse
- Two-gluon model hugely overestimates r_{00}^{04} but BFKL gives a good description
- $r_{1-1}^{04} \ll 0$ → SCHC violation with double flip contribution
- $r_{10}^{04} > 0$ → SCHC violation with single flip contribution
- BFKL model fails to describe r_{10}^{04} (as well as Two-gluon)

CONCLUSION

First HERA-II DVCS cross sections versus Q^2 , W and t :

- H1 preliminary results in agreement with previous results
- t slope measurement \longrightarrow Constraint theory normalisation
- NLO QCD predictions based on GPDs in agreement with data \longrightarrow Sensitivity to different GPD models

Elastic ρ^0 photoproduction using the H1 Fast Track Trigger:

- Pomeron trajectory determined using data within one experiment
- α' significantly smaller than 0.25 GeV^{-2}

Elastic ϕ and J/ψ production:

- ϕ : $\sigma \propto W^\delta$; $\delta \sim 0.4 \longrightarrow$ between soft and hard regime
- J/ψ : $\sigma \propto W^\delta$; $\delta \sim 0.7 \longrightarrow$ charm provide hard scale (at all Q^2)
- High sensitivity of elastic J/ψ to gluon at low x ?

Vector mesons photoproduction at large $|t|$

- W and t dependences are described by pQCD BFKL model
- BFKL model however fails to describe fully the helicity structure