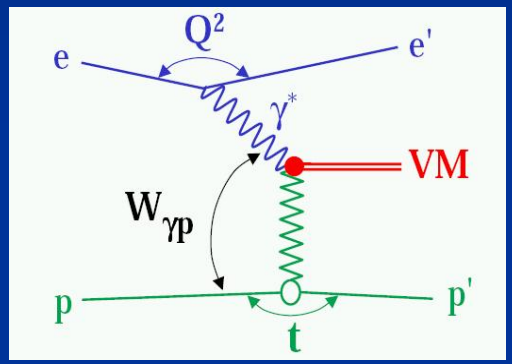
Vector Meson Production and DVCS from H1 at HERA

K.Hiller, DESY - for the H1 Collaboration

- Introduction
- ρ and J/ψ in Photo & Electroproduction
  - W- dependence
  - t – dependence
  - effective Regge trajectories
  - Q^2 – dependence
  - helicity studies
- Deeply Virtual Compton Scattering (DVCS)
- Conclusions

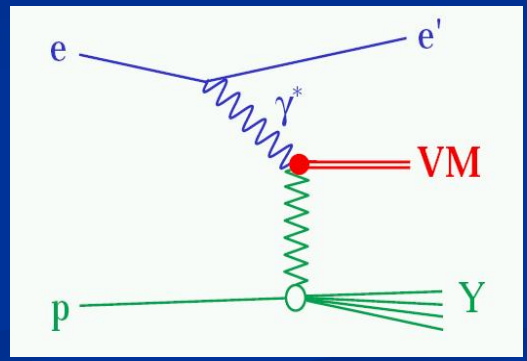
Introduction - Vector Mesons at HERA (1)

Vector mesons have $J^{PC} = 1^{--}$ as photon
→ no quantum number exchange necessary
→ mainly produced in diffractive processes



Elastic process,
dominates at low |t|

Proton-dissociation,
mainly at high |t|

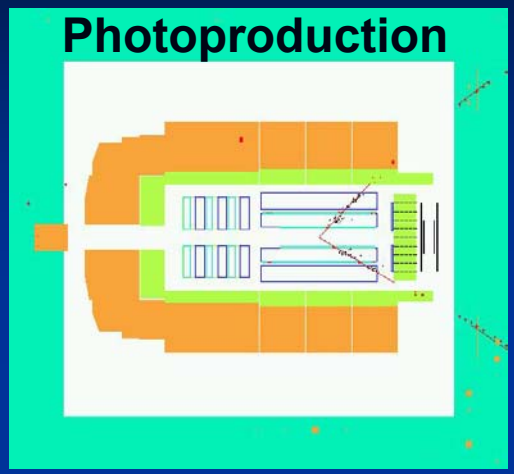


HERA collides e-p
at energies of
27 GeV – 920 GeV

Q^2	γ^* virtuality	$0 < Q^2 < 100$ GeV^2
$W_{\gamma p}$	energy of the γ^*p system	$20 < W_{\gamma p} < 200$ GeV
t	4-momentum tansfer at p-vertex	$0 < \|t\| < 30$ GeV^2
VM	Vector mesons	$\rho, \omega, \phi, J/\psi, \psi', \Upsilon$

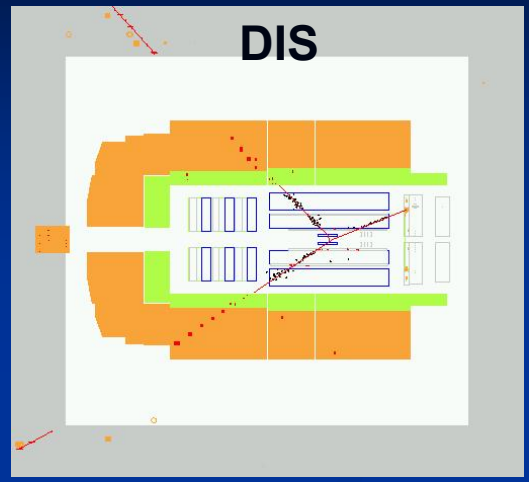
Large diffractive cross sections & wide kinematic range
→ HERA is a good place for VM studies

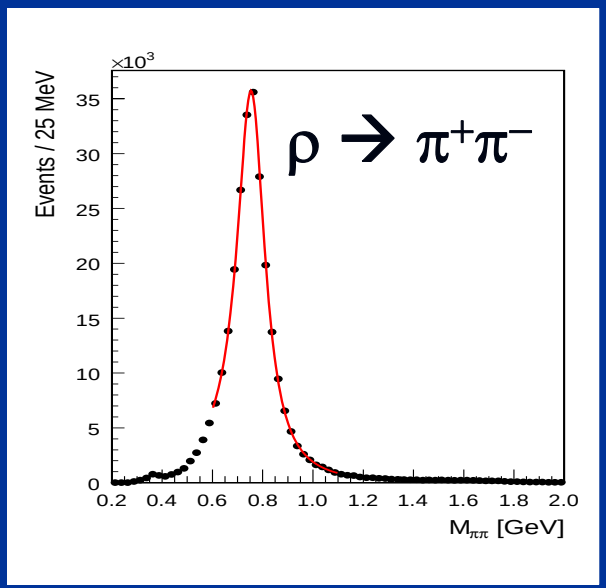
Introduction – Signatures (2)

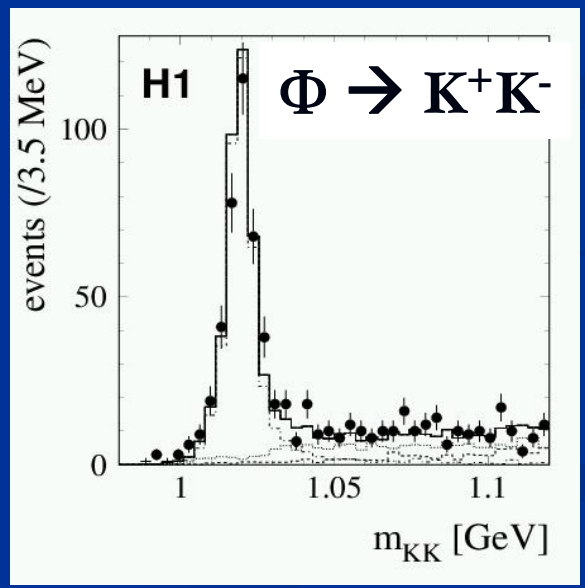


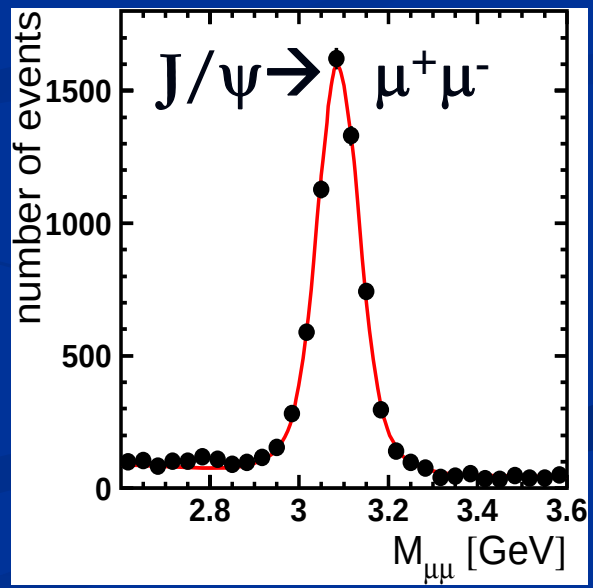
Mainly elastic and p-dissociative processes , 2/3 track topologies

Clean samples with less backgrounds





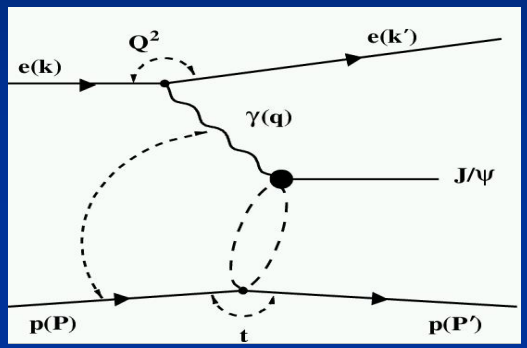




Introduction – Theoretical Concepts (3)

Regge Model

soft processes by Pomeron exchange

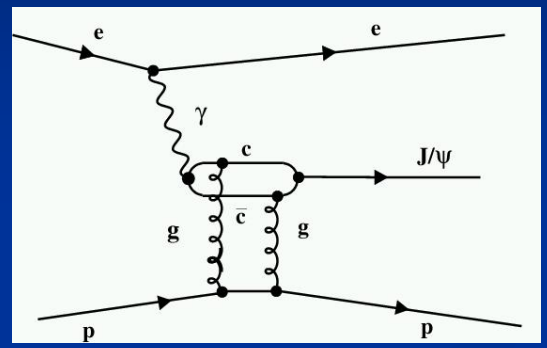


$\alpha_P(t) = \alpha_0 + \alpha' t$,
$\alpha_0 = 1.08$, $\alpha' = 0.25 GeV^{-2}$

- slow increasing total cross section
  $\sigma(W) = W^{\delta}$, $\delta = 4(\alpha_0 - 1 - \alpha'/b)$
- t-dependence $\sigma(t) = \exp(-bt)$
  with shrinkage $b = b_0 + 4\alpha' \ln(W/W_0)$
- s-channel helicity conservation (SCHC)

pQCD Models

hard processes by 2-gluons/ladder exchange

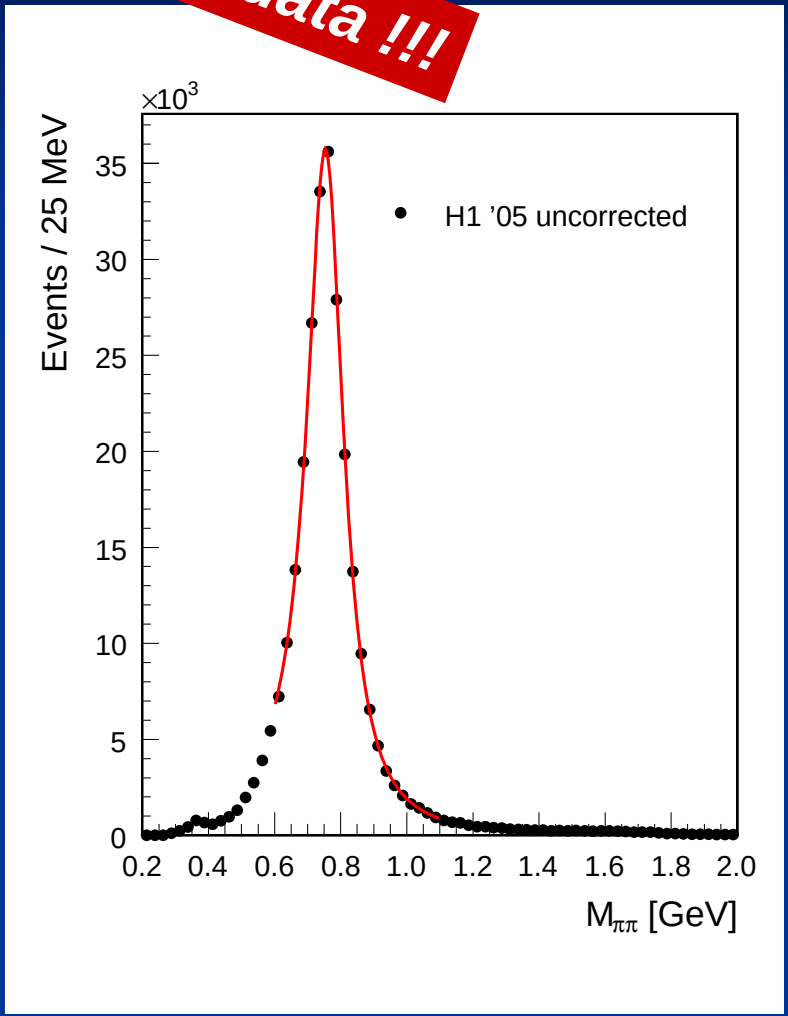


Leading order:
$\sigma \sim [x\, g(x,Q^2)]^2$

- steeper W-dependecnce according to gluon density at low x
- universal slope $d\sigma/dt \sim |t|^{-n}$, without shrinkage
- violation of SCHC

ρ Photoproduction (1)

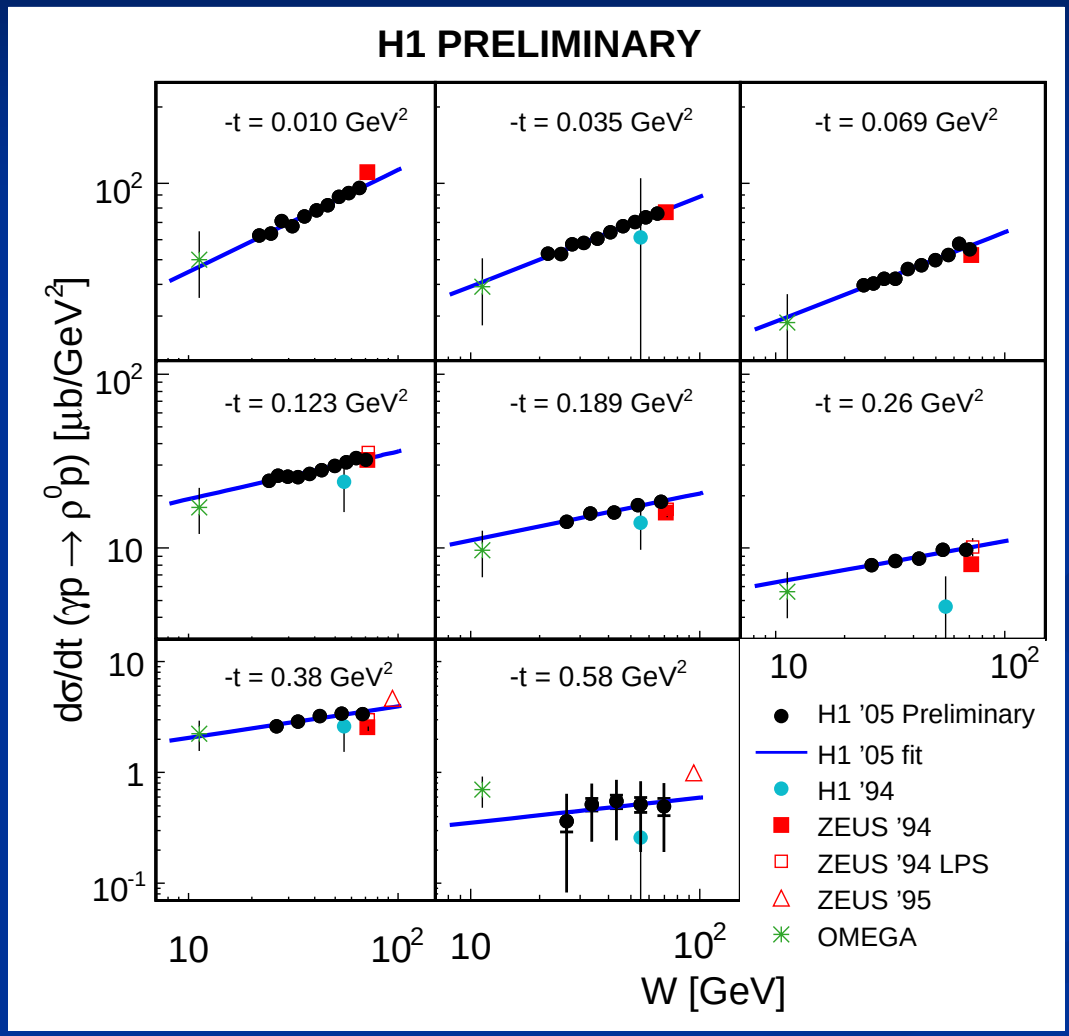
New 2005 data !!!



- Motivation:
  replace 1993 ρ data … 358 events
- 2005 data:
  Fast Track Trigger , 2+3 prong events
  $L = 570\ nb^{-1}$, ~ 240.000 ρ candidates
- kinematic range :
  $Q^2 < 4\ GeV^2$, $\langle Q^2 \rangle \sim 0.01\ GeV^2$
  $20 < W < 90\ GeV$
  $|t| < 3\ GeV^2$
- Backgrounds: ρ', ω, ϕ < 2 %
- separation of elastic and p-dissociative processes using forward detectors

ρ Photoproduction (2)

Large ρ statistics allows 2-dimensional analysis in "W-t-bins"



Fit W-dependence in each t-bin:

$$\sigma \sim (W/W_0)^{4[\alpha - 1]}$$

→ $\alpha(t)$

H1 fit in good agreement with measurements of ZEUS and OMEGA

First $\alpha(t)$ measurement in a single experiment

ρ Photoproduction (3)

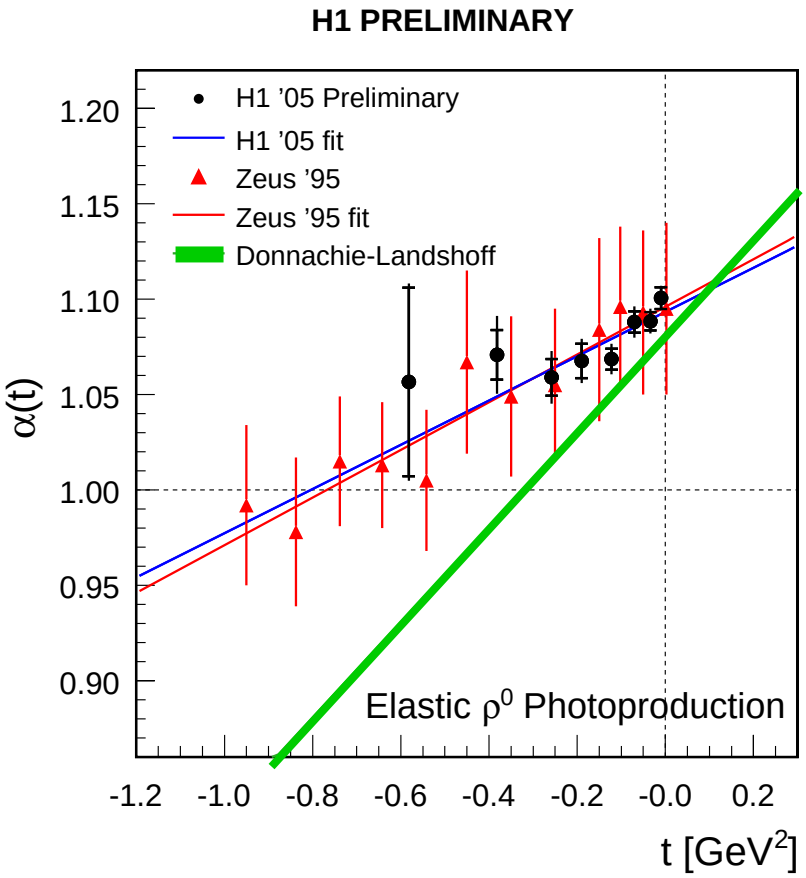
Fitting α in t-bins by a linear trajectory:

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

$\alpha_0 = 1.093 \pm 0.003 \pm 0.008/0.007$
$\alpha' = (0.116 \pm 0.027 \pm 0.036/0.046)\ \mathrm{GeV}^{-2}$

Note: "ZEUS values" combine ZEUS & H1 &OMEGA

α' differs significantly from classical value α' = 0.25 GeV^{-2}



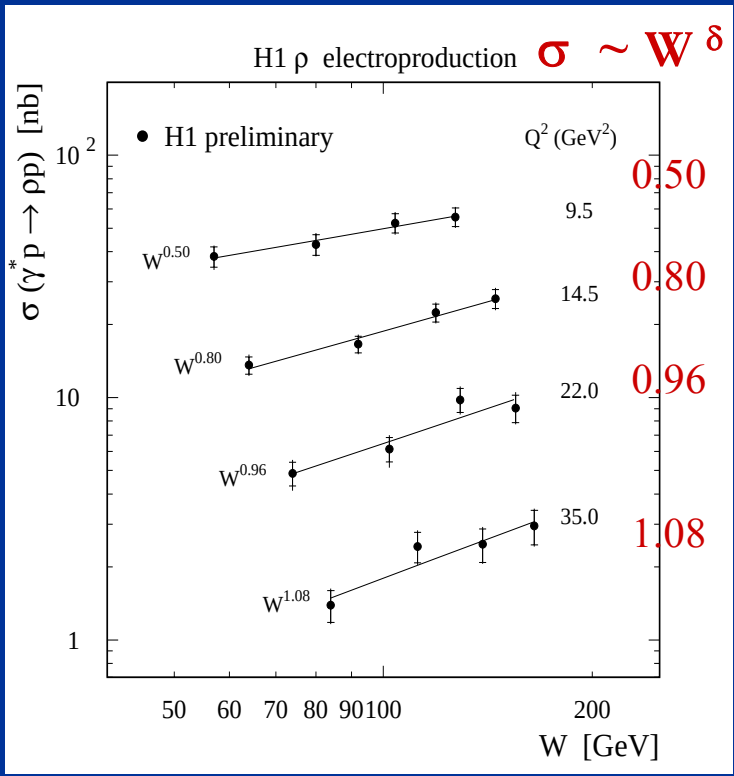
ρ Electroproduction (1)

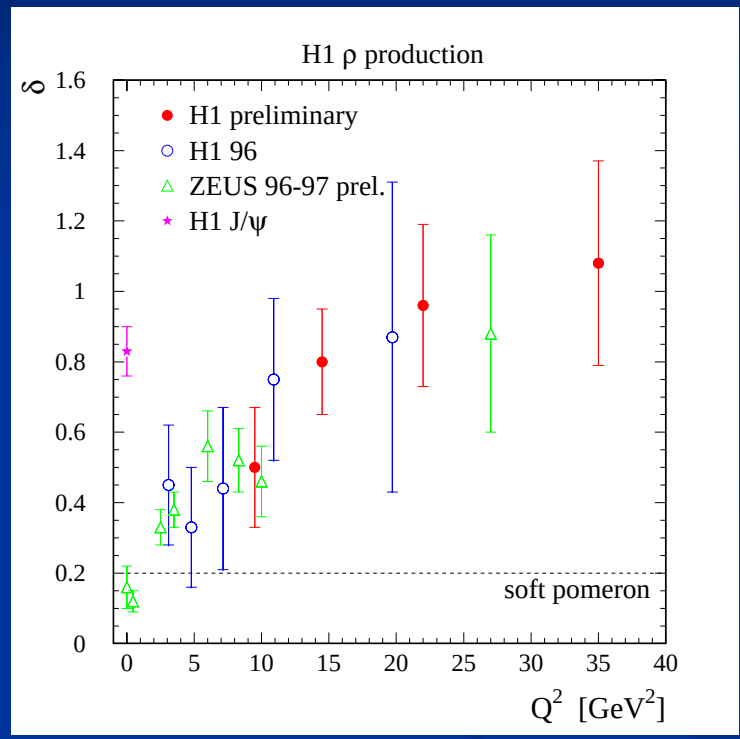
What happens at larger "photon masses" ?

2000 data, L = 42 pb^{-1}

$8 < Q^2 < 60$ GeV^2

$40 < W < 180$ GeV, $|t| < 0.5$ GeV^2



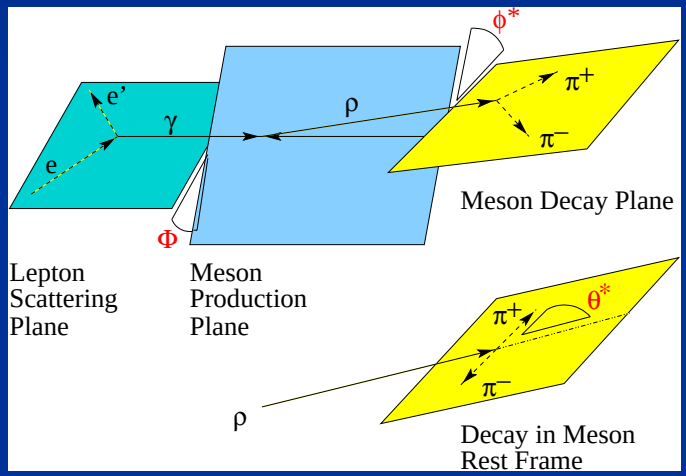


W-dependence steeper at large Q^2
$\delta(W)$ reflect soft → hard transition

ρ Electroproduction (2)

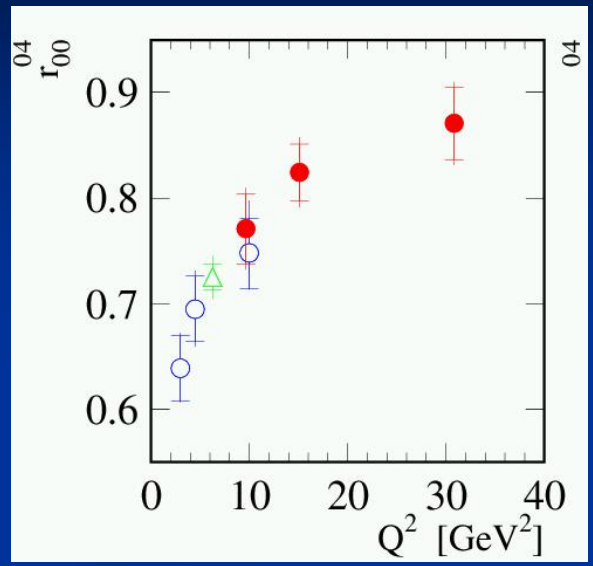
What is the virtual photon polarization ?

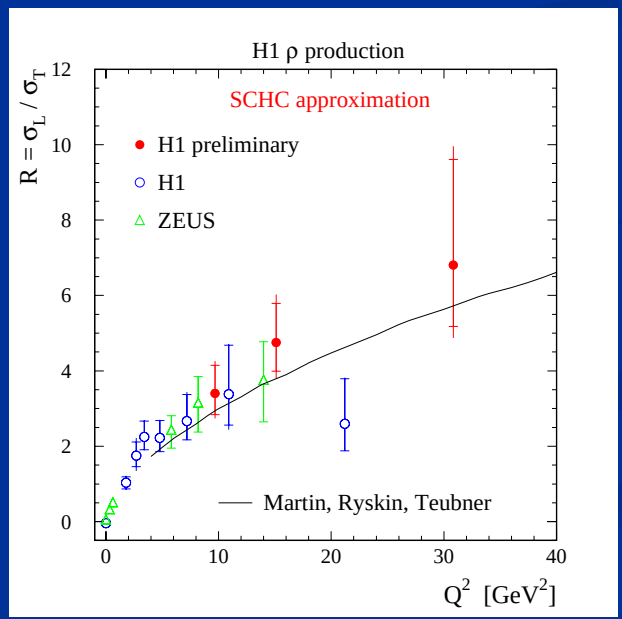
Using 4 production & decay angles
to determine spin density matrix element



ρ polar decay angle:

$d\sigma/d\cos\theta^* \propto 1 - r_{00}^{04} + (3r_{00}^{04}-1)\cos^2\Theta^*$





$R = \sigma_L/\sigma_T = r_{00}^{04} / \varepsilon\,(1-r_{00}^{04})$
$(\varepsilon \sim 1, \text{SCHC})$

Matrix elements based on
no/single/double flip amplitudes:
$M_{++}, M_{--} / M_{+0}, M_{-0} / M_{+-}, M_{-+}$
describe angular spectra

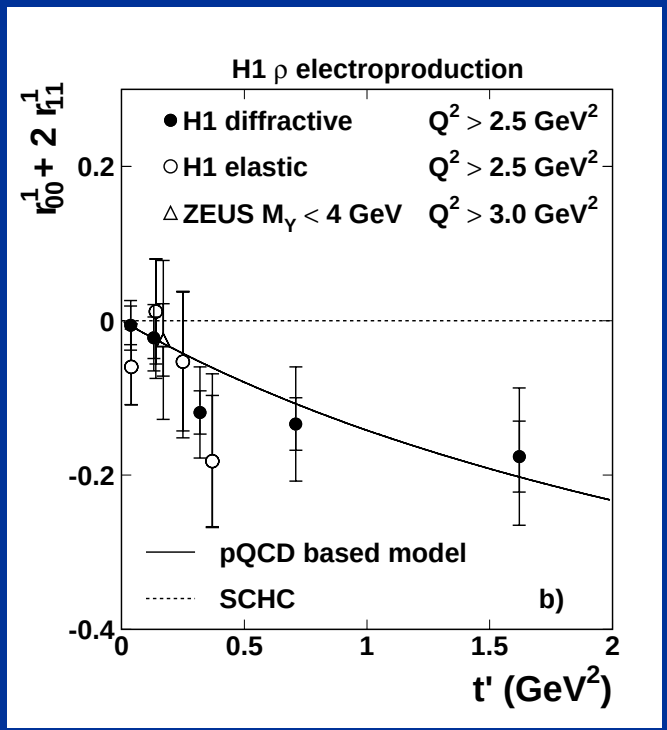
At larger Q^2 longitudinal photon dominates

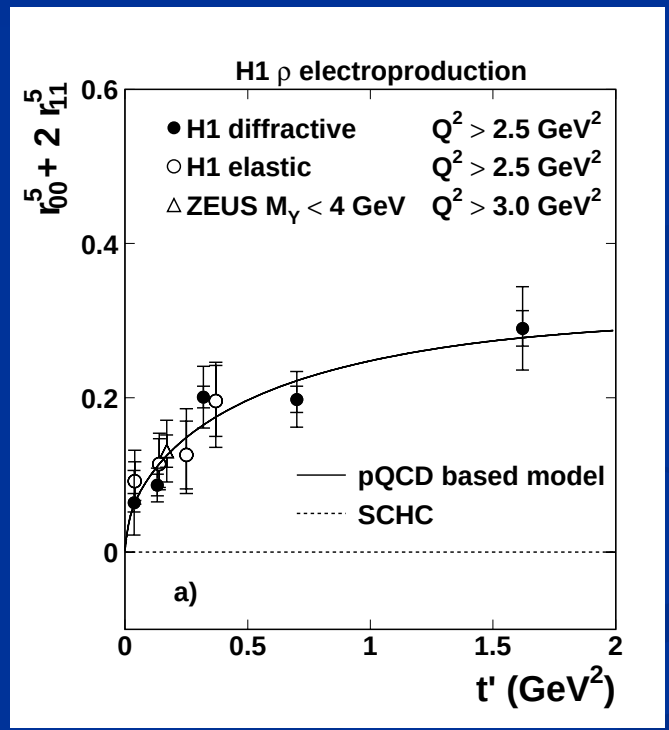
pQCD model works

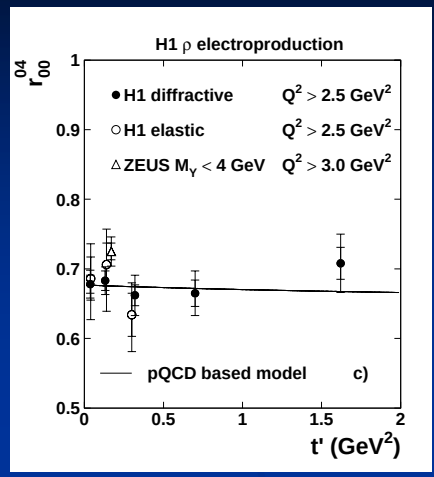
ρ Electroproduction (3)

Is the photon helicity conserved ?
(at large Q^2 $r_{00}^{04} > 0$ consistent with SCHC)

ρ azimuthal production angle:
$d\sigma/d\phi \propto 1 + \sqrt{2\varepsilon(1+\varepsilon)}\ \cos\phi(r_{00}^{5}+2r_{11}^{5}) - \varepsilon \cos 2\phi\ (r_{00}^{1} + 2r_{11}^{1})$







Clear violation of SCHC

Increase with |t| predicted by pQCD model*

*) Ivanov/Kirchner

ρ Photoproduction at large |t| (1)

Published 2006

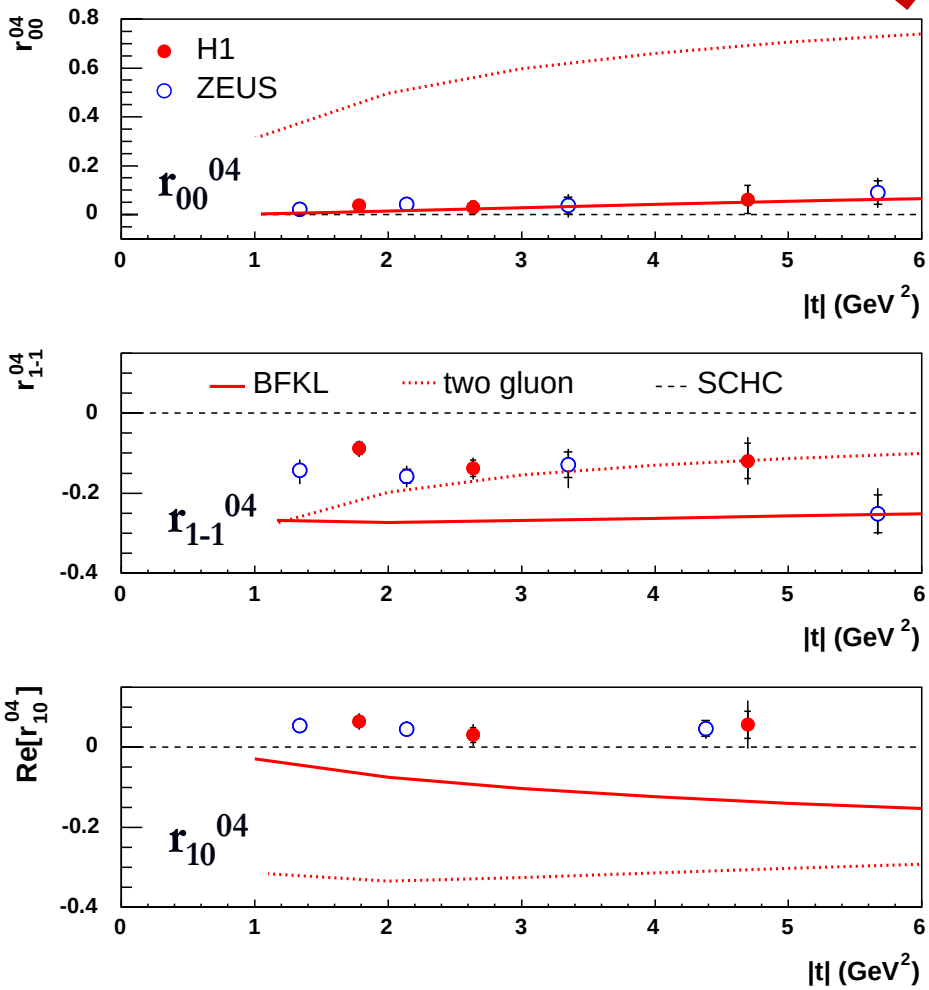
Continues SCHC violation at higher |t| ?

2000 data, $L = 20\ pb^{-1}$

$1.5 < |t| < 10\ GeV^2$

$Q^2 < 0.01\ GeV^2$, $75 < W < 95\ GeV$

Fitting r_{00}^{04}, r_{10}^{04}, r_{1-1}^{04} to $\sigma(\Theta^*, \phi^*)$ in bins of $|t|$

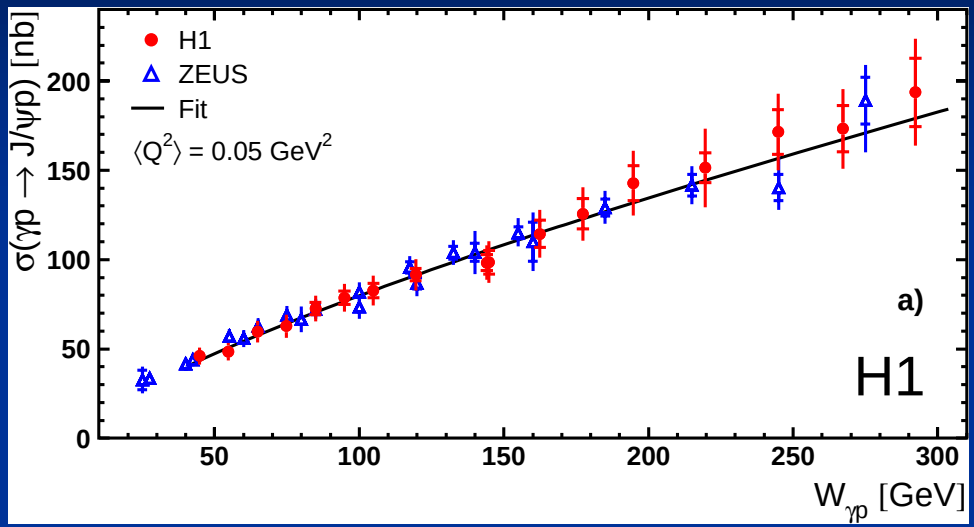


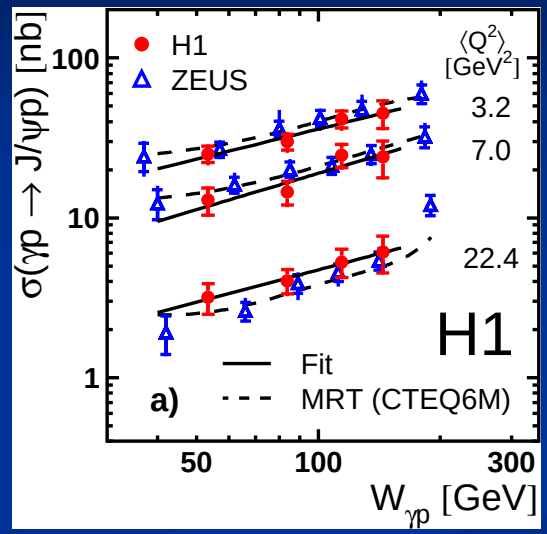
SCHC violation persists

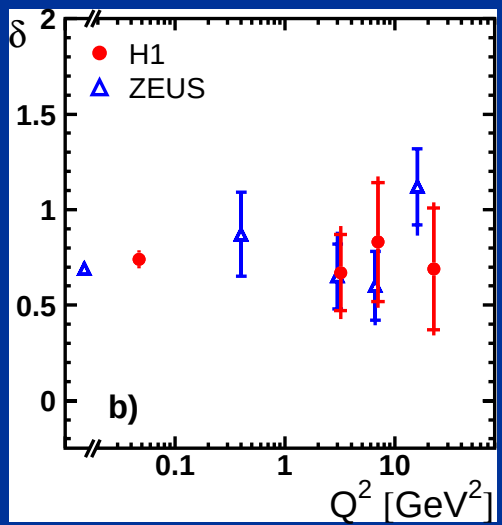
2-gluon and BFKL models clearly inconsistent with data

J/ψ Photo & Electroproduction (1)

Change the mass scale …







1999+2000 data , L=55pb^{-1}
$|t| < 1.2$ GeV^2, $M_Y < 1.6$ GeV
p-diss. background ~ 14%

$\sigma \sim W^{\delta}$, with $\delta \sim 0.75$ at low and high Q^2, J/ψ mass provides a hard scale for pQCD

J/ψ Photo & Electroproduction (2)

Describing W-t dependencies by an "effective" Pomeron trajectory:

$$\sigma \propto \exp(b_0 t)\, W^{\delta}$$

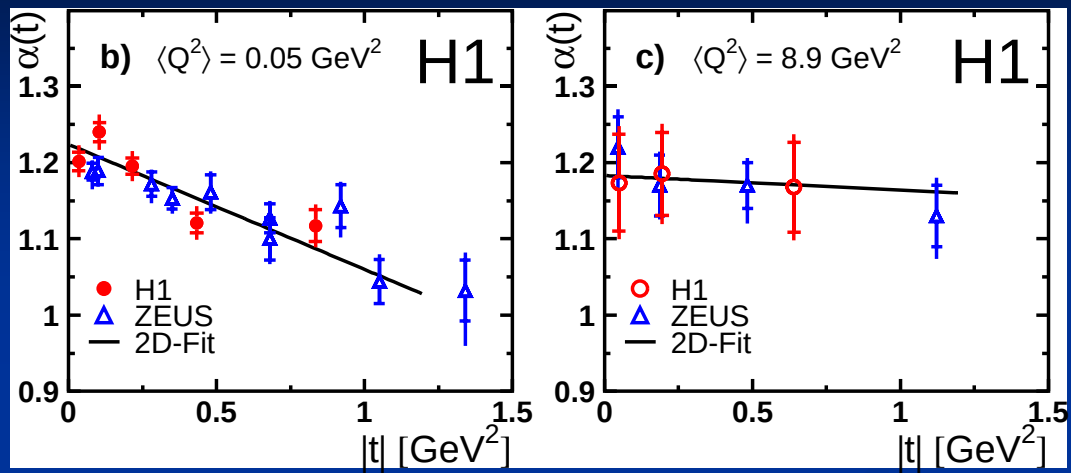
with $\delta = 4(\alpha(t)-1)$,

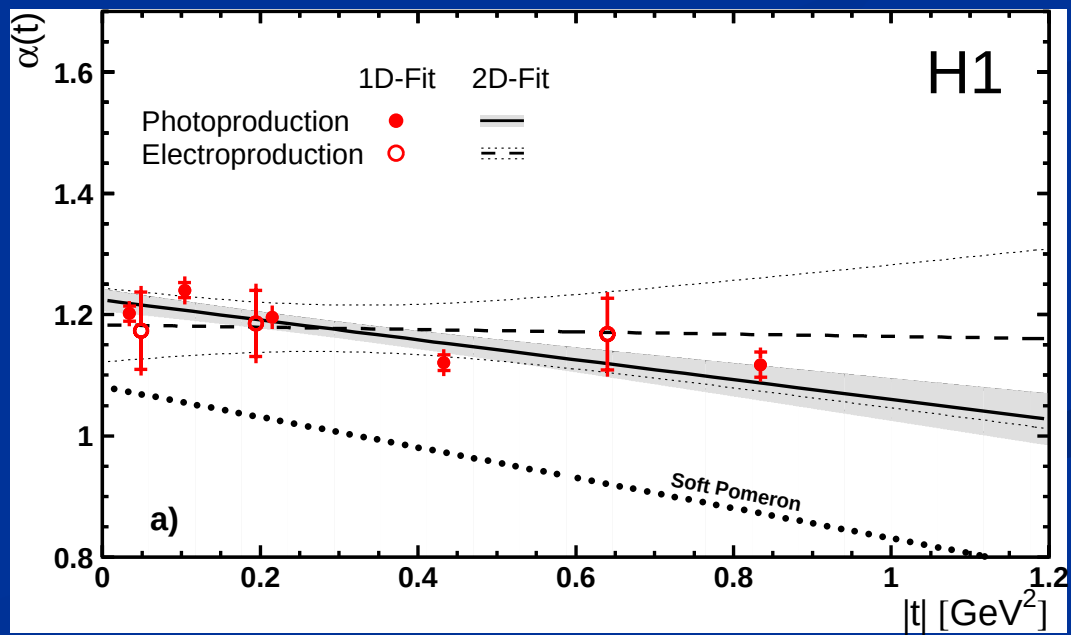
$\alpha(t) = \alpha_0 + \alpha' t$

	$\langle Q^2 \rangle \sim 0$	/	$\langle Q^2 \rangle \sim 9$ GeV^2
α_0	~ 1.22	/	1.18
α'	~ 0.16	/	0.02 GeV^{-2}

trajectories similar (errors !)

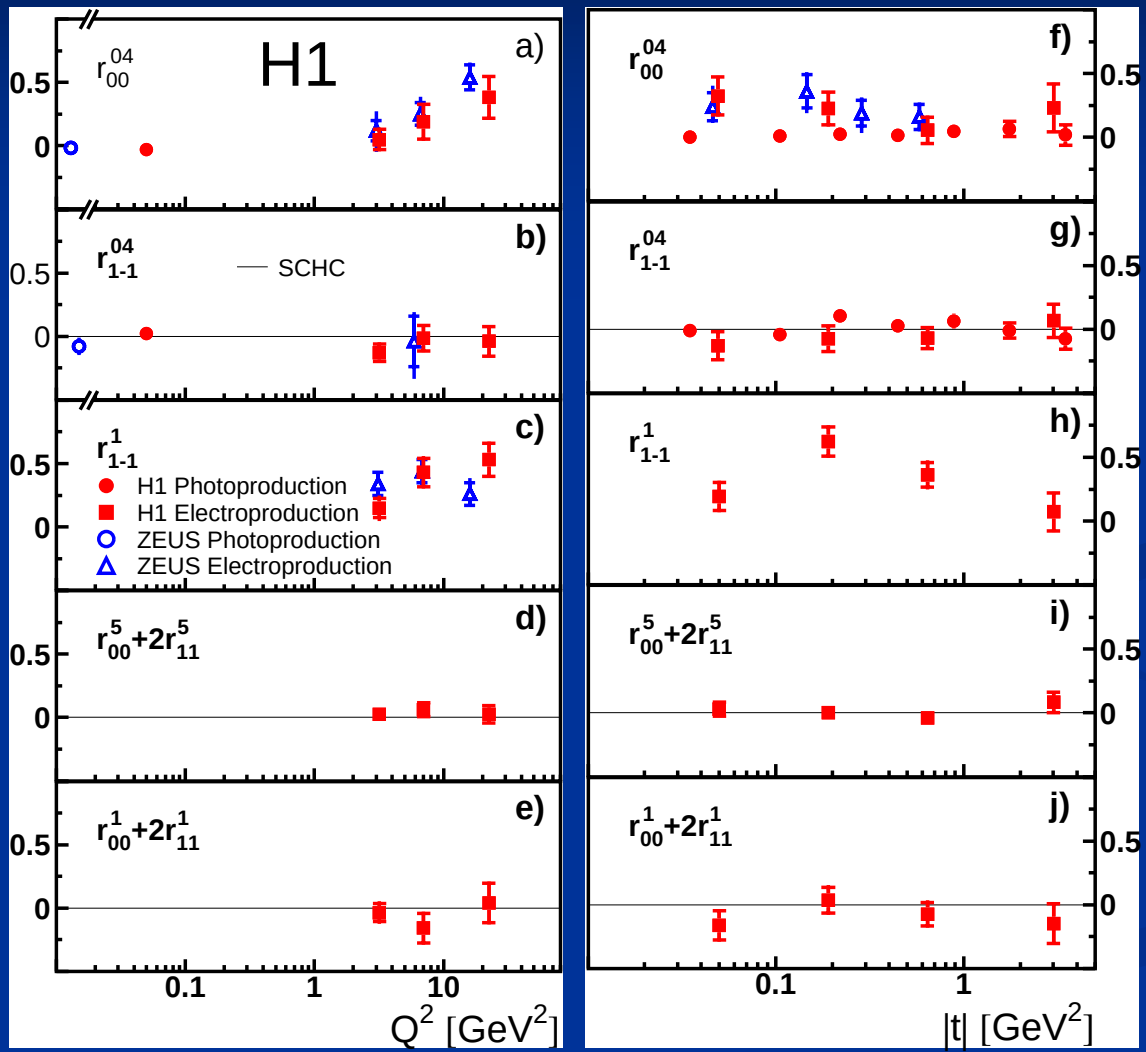
large $\alpha_0 \sim 1.2$ reflects steep W-dependence of hard / perturbative process





J/ψ Photo & Electroproduction (3)

What about helicity conservation ?



$r_{00}^{04} \sim 0$ in photoproduction, but rises with increasing Q^2

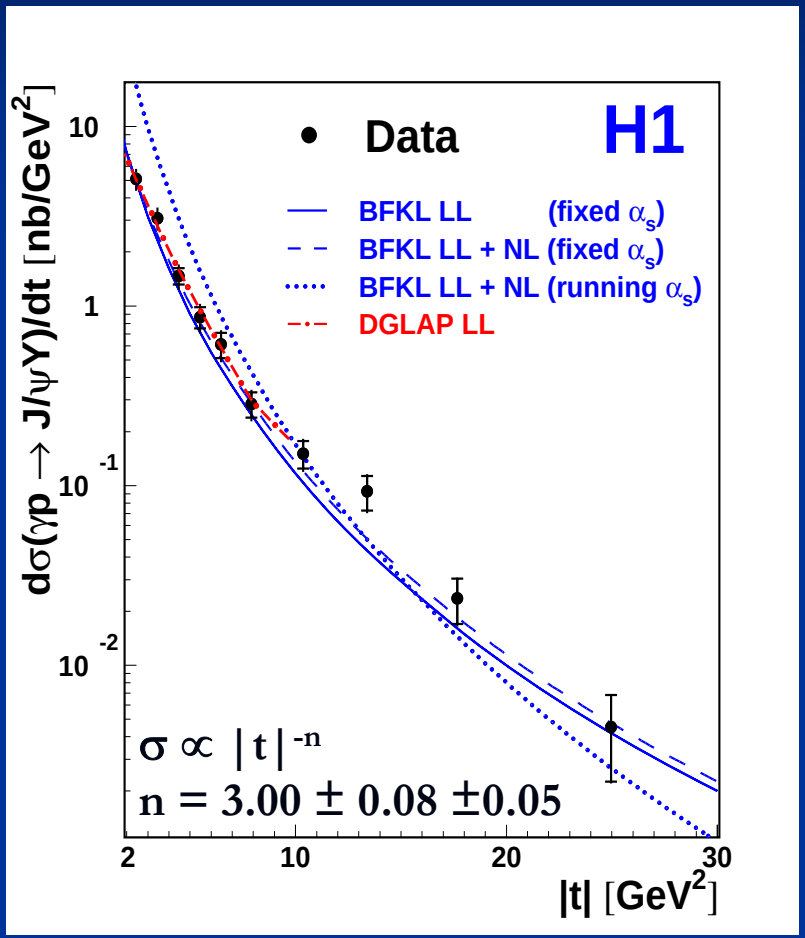
For SCHC:
$r_{1-1}^{1} = (1 - r_{00}^{04})/2$

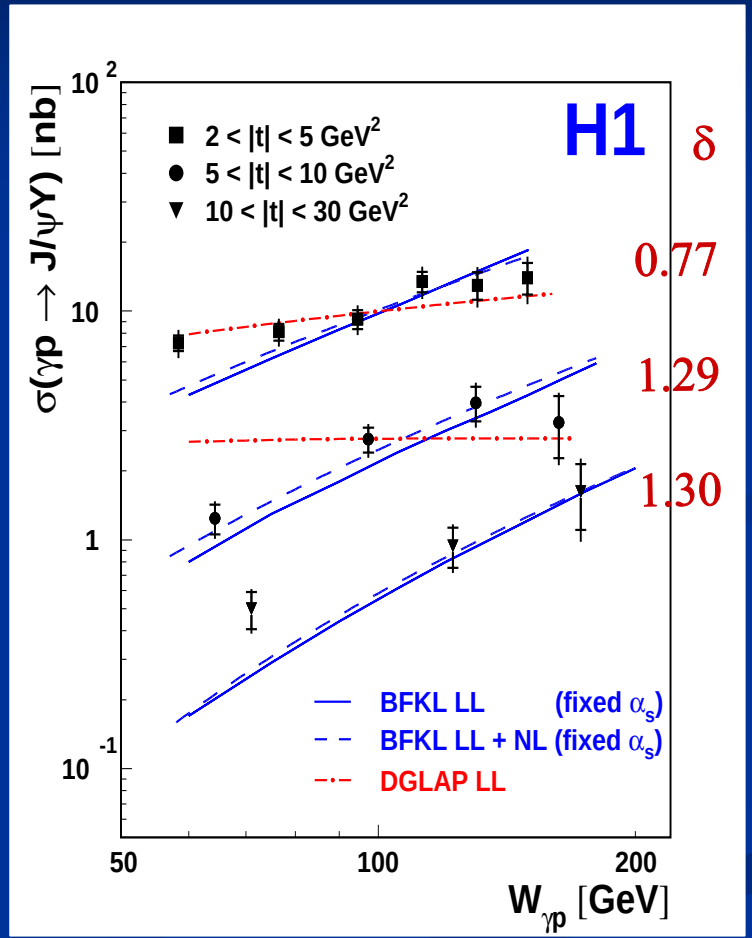
Other spin density matrix elements ~ 0

SCHC works …

J/ψ Photoproduction at large |t| (1)

Extension to higher |t| … $2 < |t| < 30\ \mathrm{GeV}^2$ 1996 – 2000 data, L = 78 pb^{-1}

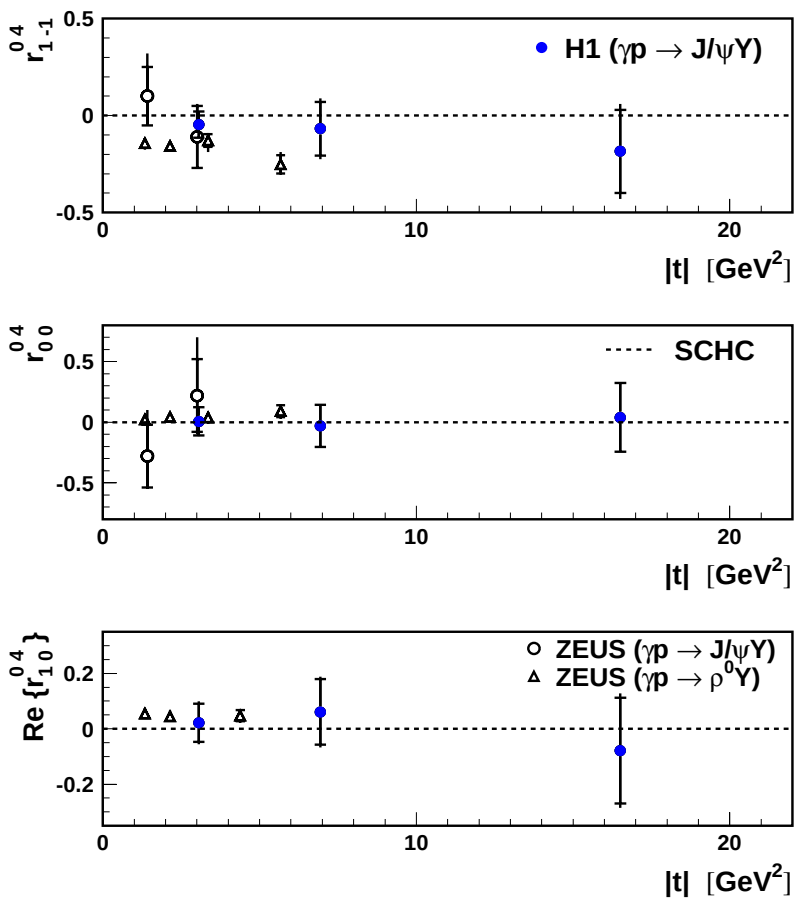




δ ~ 1 confirms large |t| as hard scale,
DGLAP / BFKL work in complementary |t| regions < / > $M_{J/\psi}^2$

J/ψ Photoproduction at large |t| (2)

And helicity conservation …



Untagged photoproduction:
2 angles → 3 matrix elements:

consistent with SCHC:

$r_{00}^{04} = r_{1-1}^{04} = \mathrm{Re}\{r_{10}^{04}\} = 0$
(large errors at highest |t|)

How J/ψ compares to ρ ?

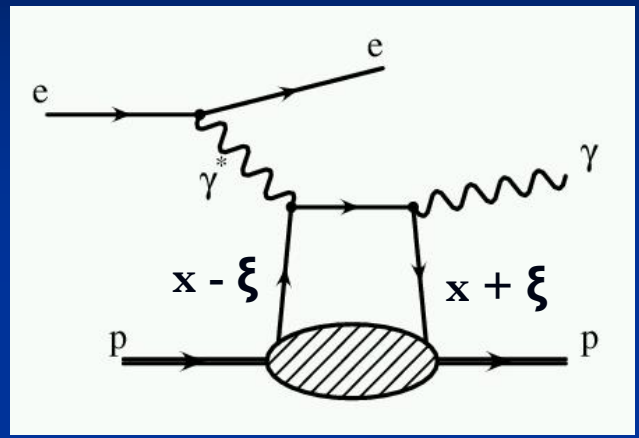
ρ – meson	J/ψ – meson
Low-Q^2, low-$\|t\|$	**Low-Q^2, low-$\|t\|$**
flat W-dependence $\propto W^{0.2}$,	steeper W-dependence $\propto W^1$
exponential $\sigma \sim \exp(-bt)$	✓
$\alpha' \sim 0.1$ GeV^{-2},	✓
no universal Pomeron	✓
High-Q^2, low-$\|t\|$	**High-Q^2, low-$\|t\|$**
steeper W-dependence $\propto W^1$,	✓
"effective" Pomeron $\alpha_0 \sim 1.2$	✓
σ_L dominates at high Q^2	✓
violation of SCHC	SCHC valid
Low-Q^2, high-$\|t\|$:	**Low-Q^2, high-$\|t\|$:**
power law $\sigma \propto \|t\|^{-n}$	✓
violation of SCHC persists	SCHC valid

Deeply Virtual Compton Scattering (1)

What can we learn about parton correlation ?

Ideal process: DVCS e + p → e + p + γ

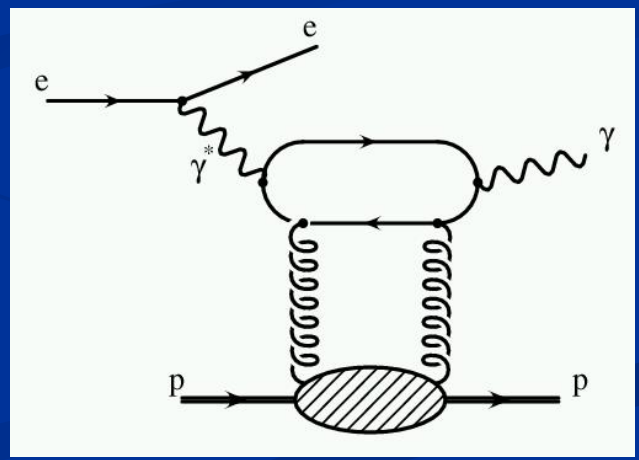
LO



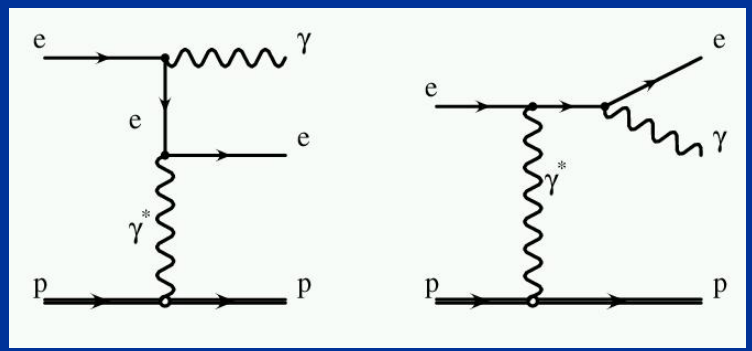
massive γ* needs skewness ξ,
t-dependence for transverse motion

H (x, ξ, t, Q^2)
generalized parton density functions (GPDs)

NLO



- simple process: similar to VM production, but no wave function needed
- Bethe-Heitler background pure el.mag.process, precisely known



DVCS – Theoretical Tools (2)

Generalized PDF Models

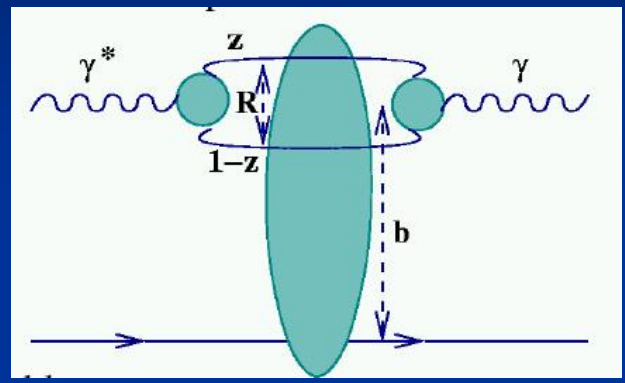
- hard process: use factorized ansatz of hard scattering ME x GPDs
- NLO leading twist calculations * using ansatz for gluon and q-singlet:

$H_g(x, \xi, t, \mu^2) = x\, g(x,\mu^2) \exp(-b|t|)$
$H_q(x, \xi, t, \mu^2) = q(x,\mu^2) \exp(-b|t|)$
with PDFs MRST2001 / CTEQ6

- Q^2 and ξ dependence by evolution

*) Freund, McDermott

Color Dipole Models



- γ^* fluctuates into $q\bar{q}$ pair
- Color dipole interacts with proton
- $q\bar{q}$ pair converts to real γ

$$A = \int d^2R dz\, \Psi_\gamma^{in}\, \sigma_{dipole}\, \Psi_\gamma^{out}$$

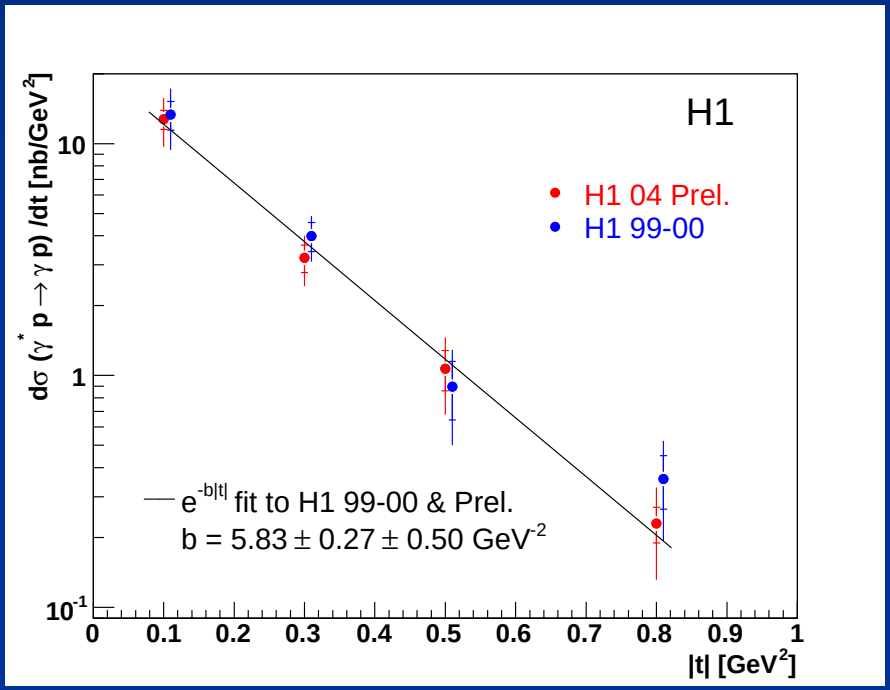
σ_{dipole}: model input

HERA-2 data

DVCS – W & t dependences (3)

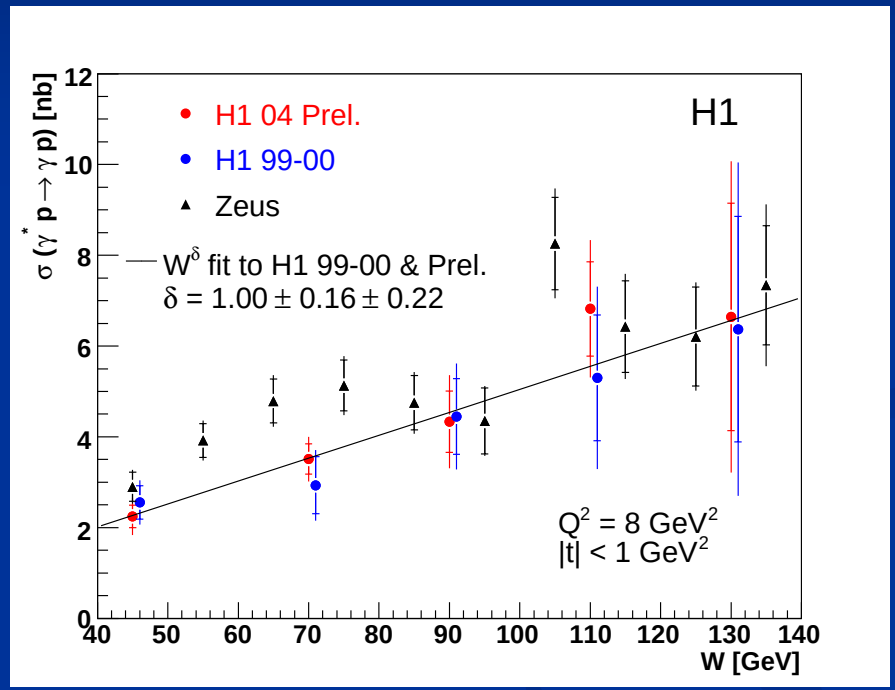
$6.5 < Q^2 < 80\ \text{GeV}^2$, $30 < W < 140\ \text{GeV}$, $|t| < 1\ \text{GeV}^2$

t - dependence



$b \sim 6\ \text{GeV}^{-2}$

W - dependence

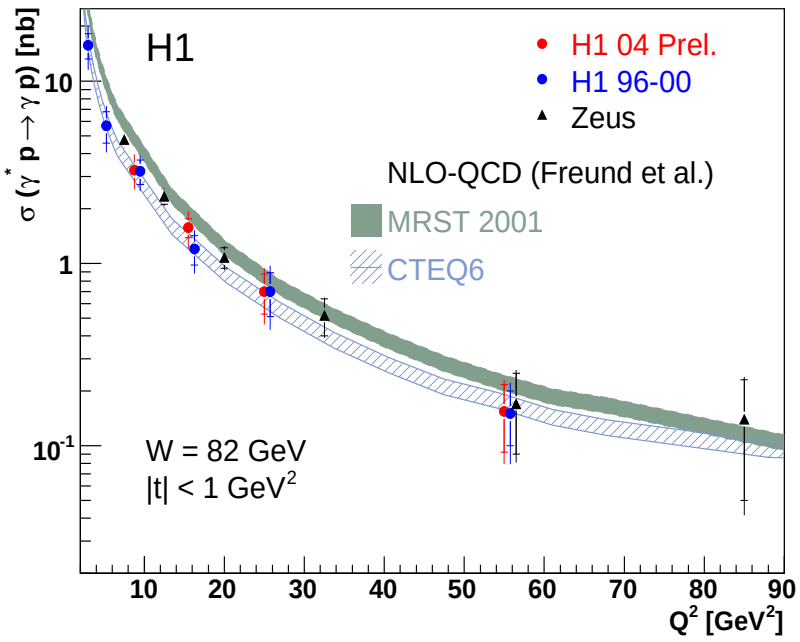


W^δ, with $\delta \sim 1$

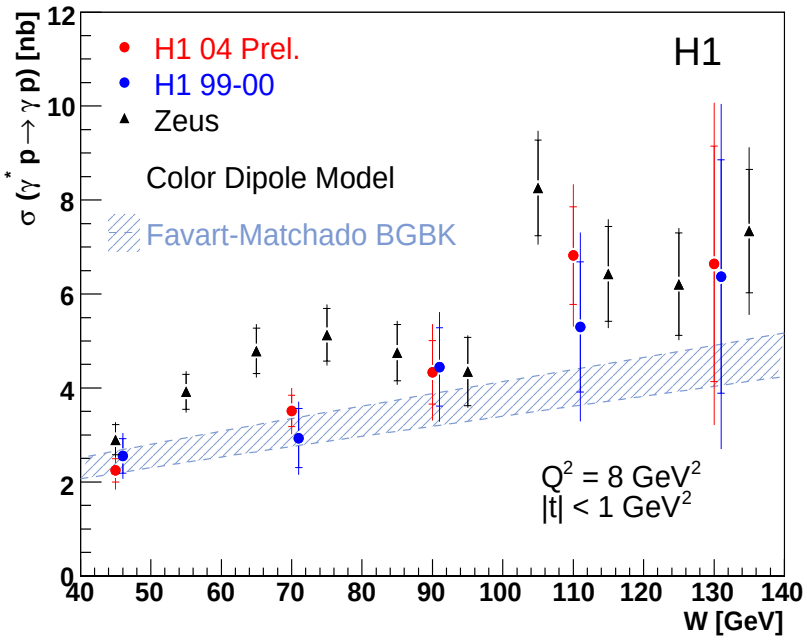
Consistent with H1/HERA-1 data, ZEUS data at low W a bit higher …typical hard process at low |t|

DVCS – Models versus Q^2 / W (4)

GPD - model



Dipole - model



Band for b-range $5.26 < b < 6.4$ GeV^{-2}, no Q^2 dependence of b

Both models reproduce general trend quite well, smaller errors needed for model discrimination

Summary

Vector Mesons

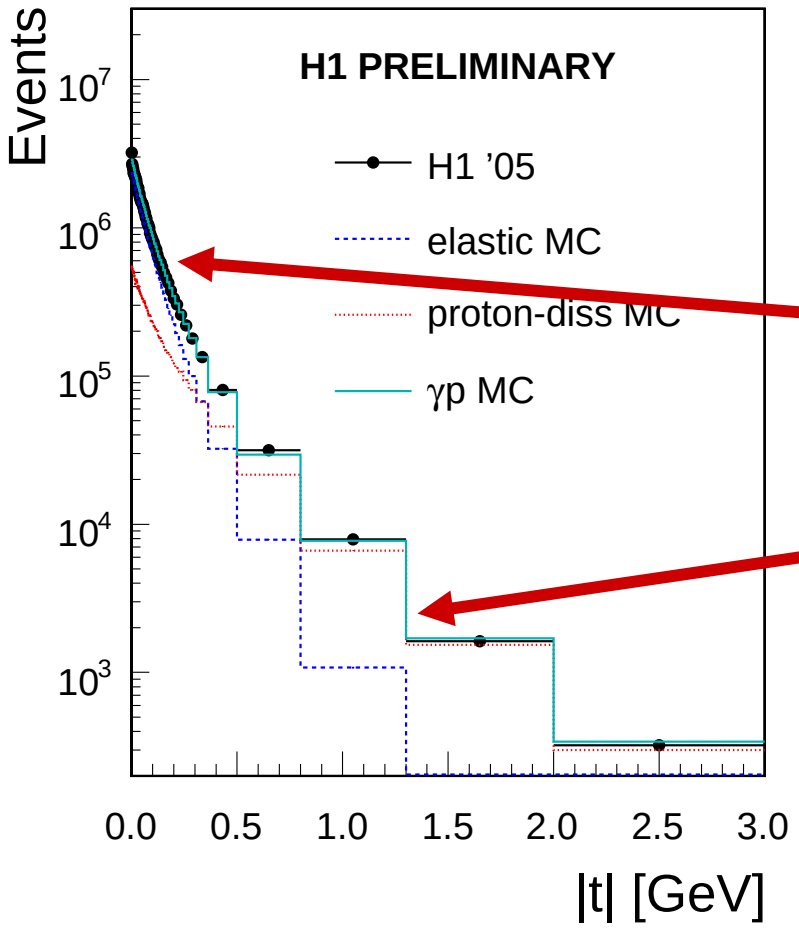
- New high-statistics ρ-measurement at $Q^2 \sim 0$
- New publication of ρ-photoproduction at high $|t|$
- Soft to hard transition visible $\sigma \propto W^{0.2} \rightarrow \sigma \propto W^{1}$
- Regge parametrization alive, but no universal Pomeron
- Violation of SCHC for ρ, not for J/ψ
- pQCD models describe the trend, need improvements in details (… helicity at high $|t|$)

DVCS

- Theoretical interest to extract generalized PDFs
- First HERA-2 measurement performed, confirms HERA-1 data
- Models based on GPDs and color dipoles reproduce trend

Spare slides …

ρ Photoproduction (2)



Data & Monte Carlo

- Generator DIFFVM:
  Pomeron exchange plus VM dominance
- $d\sigma/dM_Y^2 \sim M_Y^{-2(1+\varepsilon)}$ with $\varepsilon = 0.08$
- low-$|t|$: $d\sigma/dt \sim \exp(-b|t|)$
  with $b = 11.4 / 6.5$ GeV^{-2}
  for elastic/p-dissociative
- high-$|t|$: $d\sigma/dt \sim |t|^{-n}$
  with $n = 23 / 8.5$
  for elastic /p-dissocitive

Monte Carlo reproduces well-known features of diffractive vector meson production

ρ Photoproduction at large |t| (2)

What about $d\sigma/d|t|$?

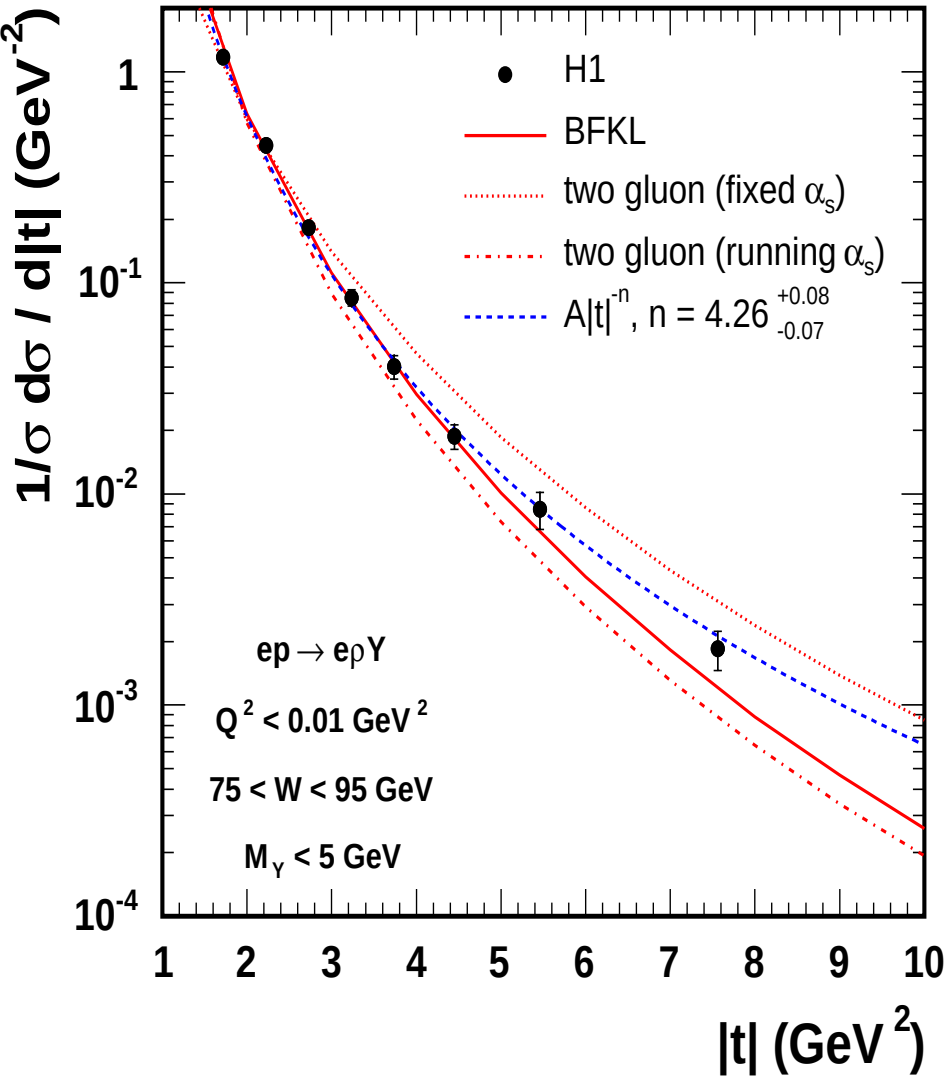
Standard low-$|t|$ exponential fails,

$d\sigma/dt \sim |t|^{-n}$, with $n \sim 4.3$

QCD-Models:
2-gluon model fixed/running as fails

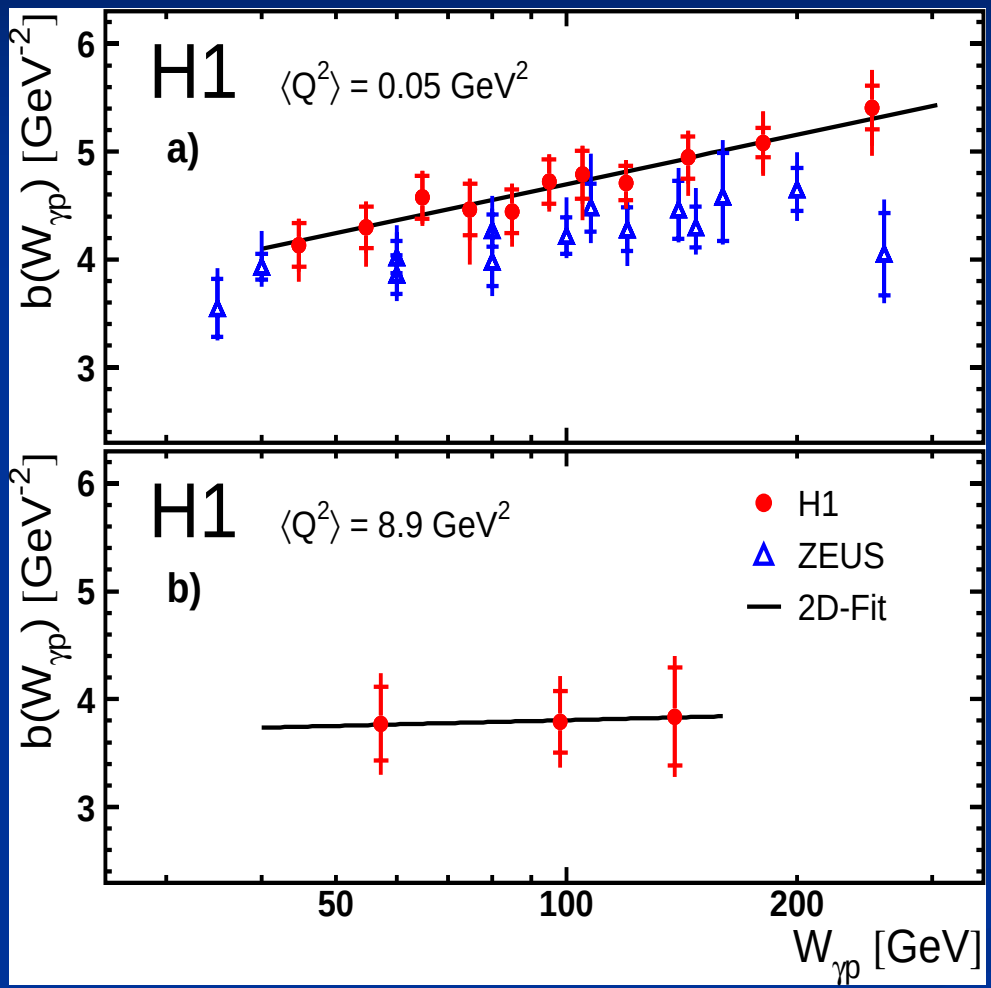
BFKL / gluon ladders better,
but undershoots at highest $|t|$

High |t| range nice for tuning of QCD models



J/ψ Photo & Electroproduction (3)

Slope of the exp(-b|t|) in dependence on W …



$b(W) = b_0 + 4\alpha' \ln(W/W_0)$

Photoproduction

$\alpha' = (0.164 \pm \ldots)\ \mathrm{GeV}^{-2}$

Electroproduction

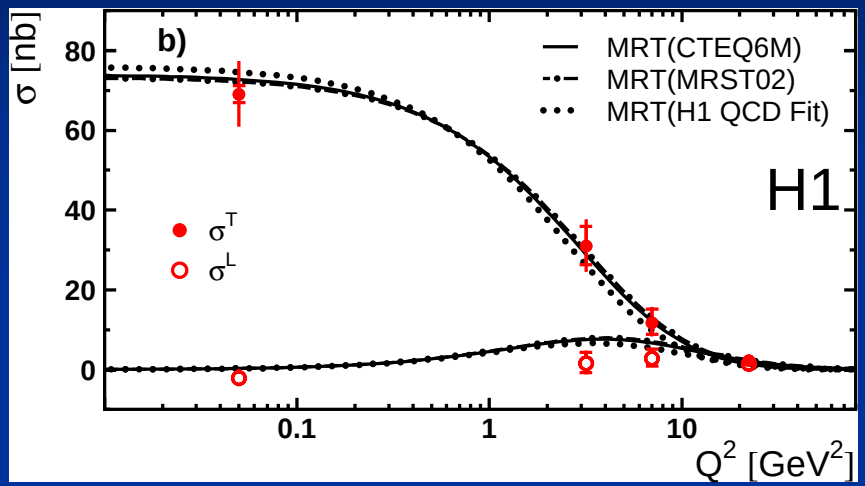
$\alpha' = (0.019 \pm \ldots)\ \mathrm{GeV}^{-2}$

Photoproduction:
b increases with W … shrinkage

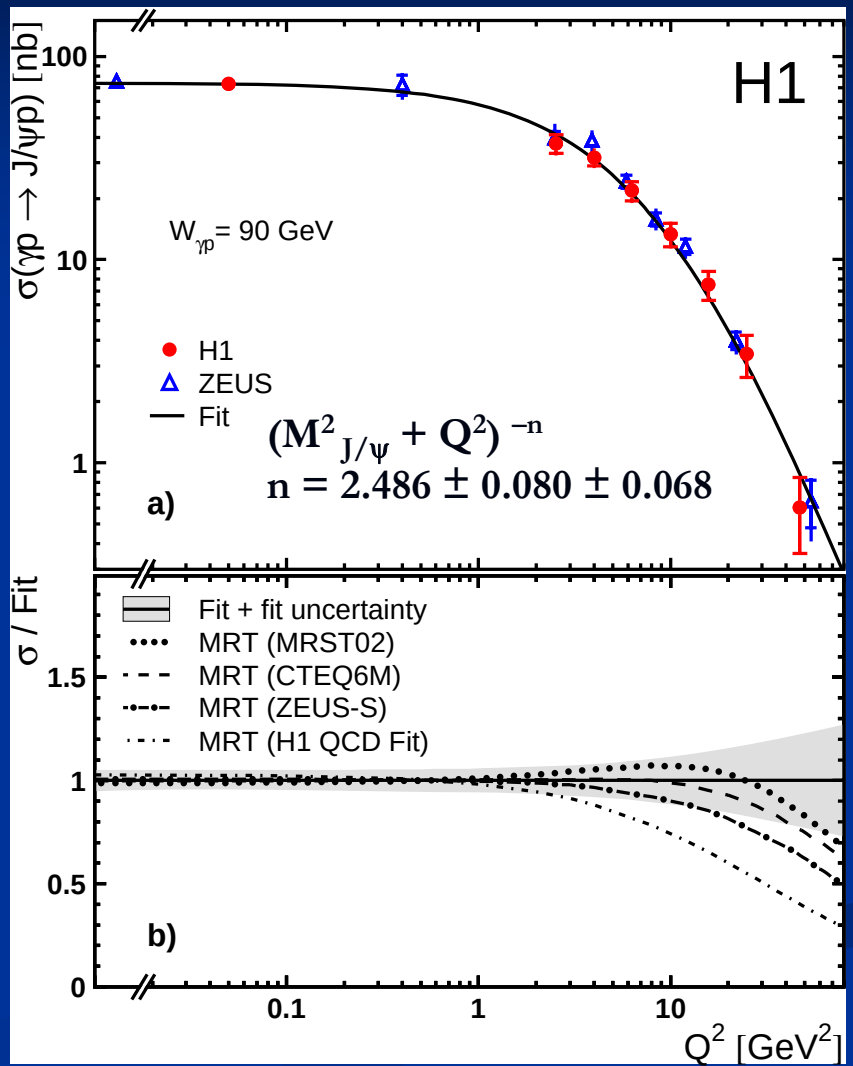
Electroproduction:
b ~ constant

J/ψ Photo & Electroproduction (5)

Use r_{00}^{04} to separate σ_L and σ_T …



$\sigma_{tot} = \sigma_L + \sigma_T$

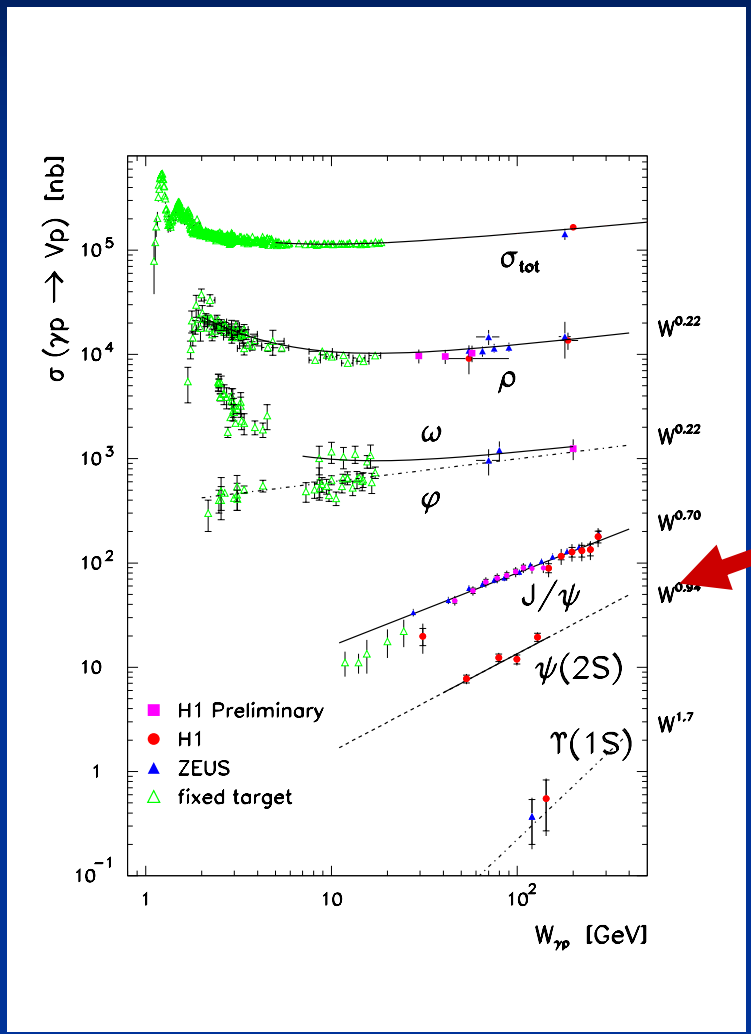


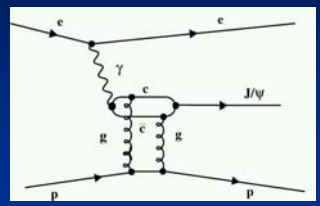
at low Q^2 dominates σ_T, at large Q^2 more σ_L

pQCD predictions*: at large Q^2 sensitive to gluon PDFs

*) Martin, Ryskin, Teubner

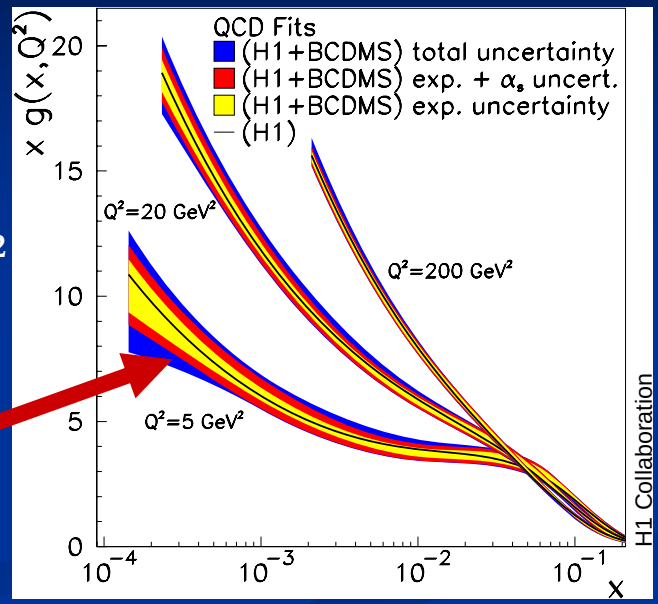
Vector Mesons & pQCD





$\sigma \propto [x\, g(x,Q^2)]^2$

with $x \propto 1/W^2$

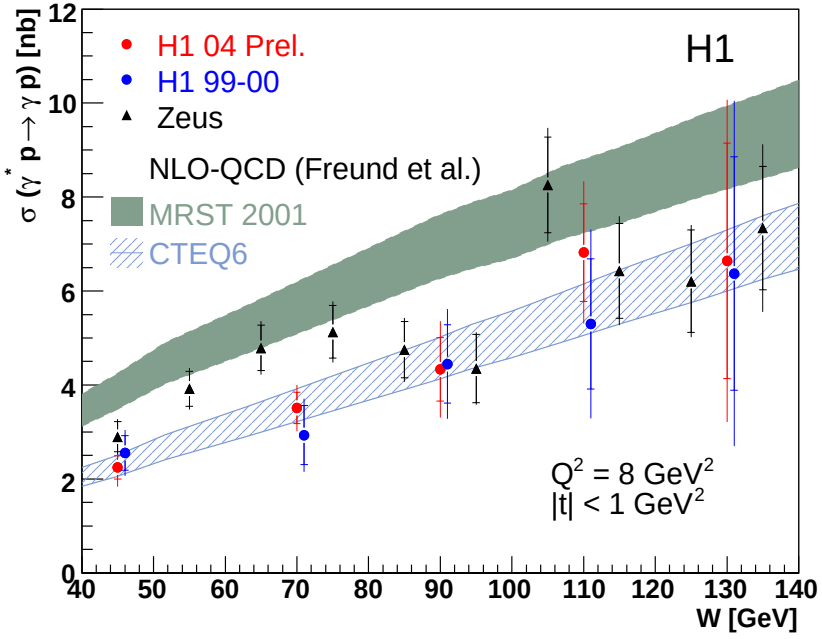


VM production sensitive to $g(x,\mu^2)$

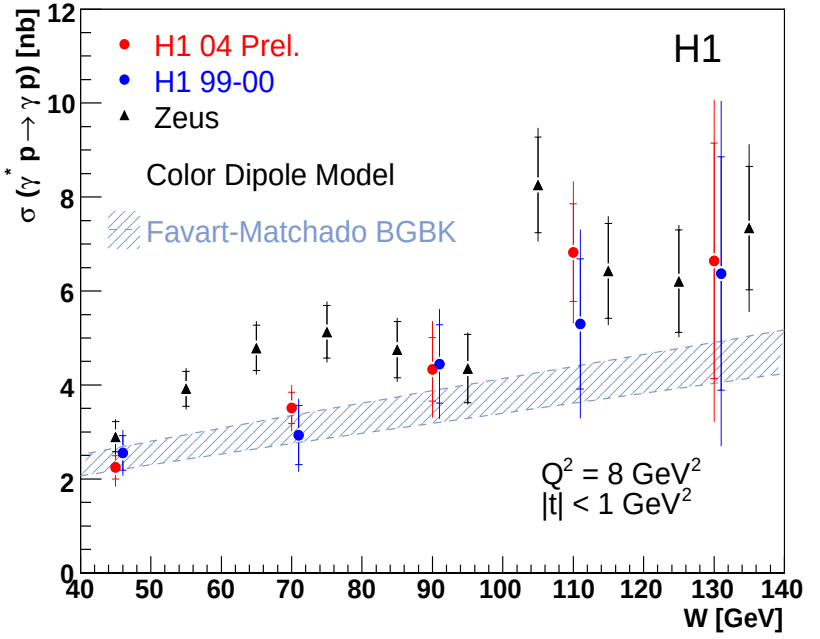
At hard scales, large M_{VM} or Q^2 or $|t|$, pQCD reproduces general features

DVCS – Models versus W (4)

GPD - model



Dipole - model

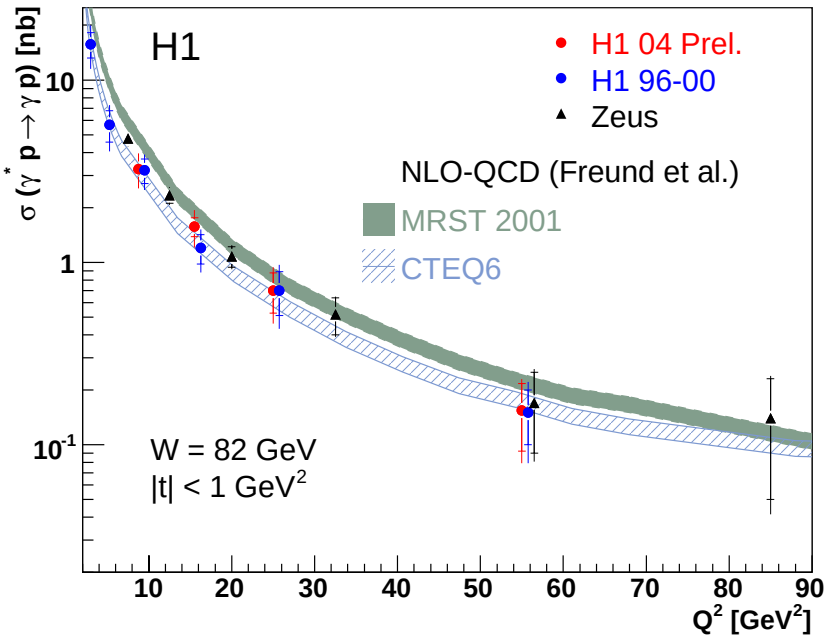


Band for b-range 5.26 < b < 6.4 GeV^{-2}, no Q^2 dependence of b

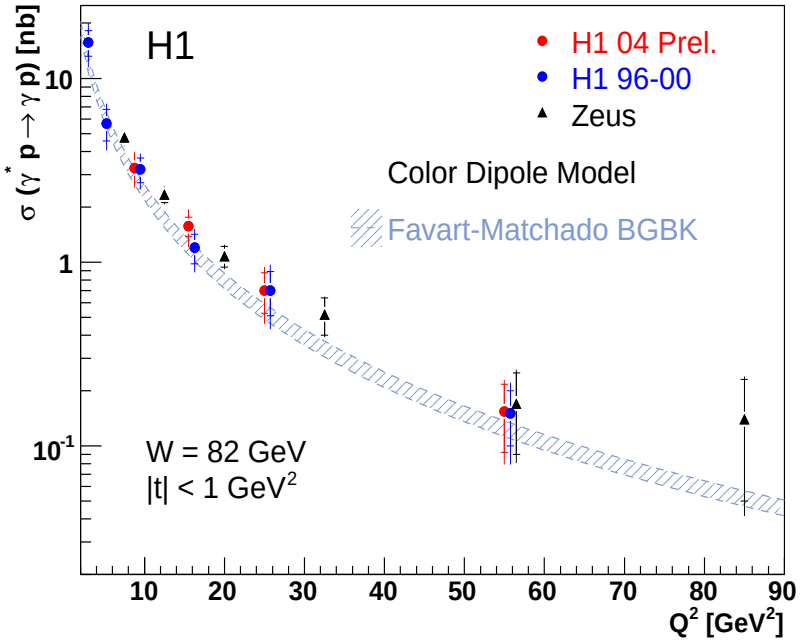
Consistent with H1/HERA-1 data
ZEUS data at low W a bit higher
Both models reproduce trend, MRST2001 ~ 50% off

DVCS – Models versus Q^2 (5)

GPD - model



Dipole - model



Band for b-range $5.26 < b < 6.4$ GeV^{-2}, no Q^2 dependence of b

Again: both models give reasonable predictions, MRST2001 seems to overshoot the data