Diffraction at HERA
(on behalf of H1 and ZEUS)

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May 26, 2009

CIPANP'09, San Diego

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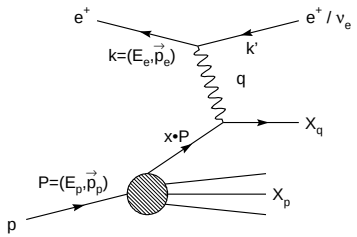
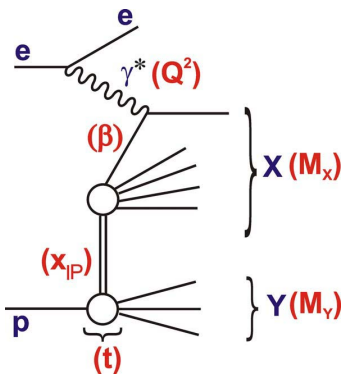
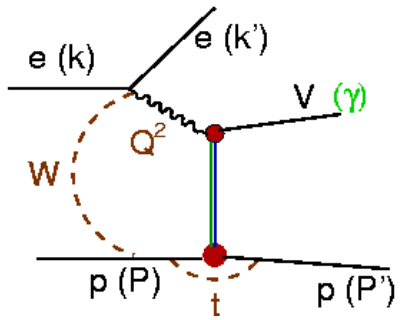






HERA

HERA - *ep* collider (1991-2007),
HERA-I in $\leq$ 2000, afterwards: HERA-II
located at DESY, Hamburg
$E_e = 27.5 GeV$
$E_p =$ different:

820 GeV ($\sqrt{s} = 300$), 95p-97p : 42 pb^{-1}
920 GeV ($\sqrt{s} = 320$), 98e-07p : 455 pb^{-1}
575 GeV ($\sqrt{s} = 252$), 07p : 11 pb^{-1}
460 GeV ($\sqrt{s} = 225$), 07p : 6 pb^{-1}

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

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

ep collisions: Inclusive DIS - study structure of the proton

$e(k) + p(P) \rightarrow l_e(k')X$:

$s = (k + P)^2$, ep system energy

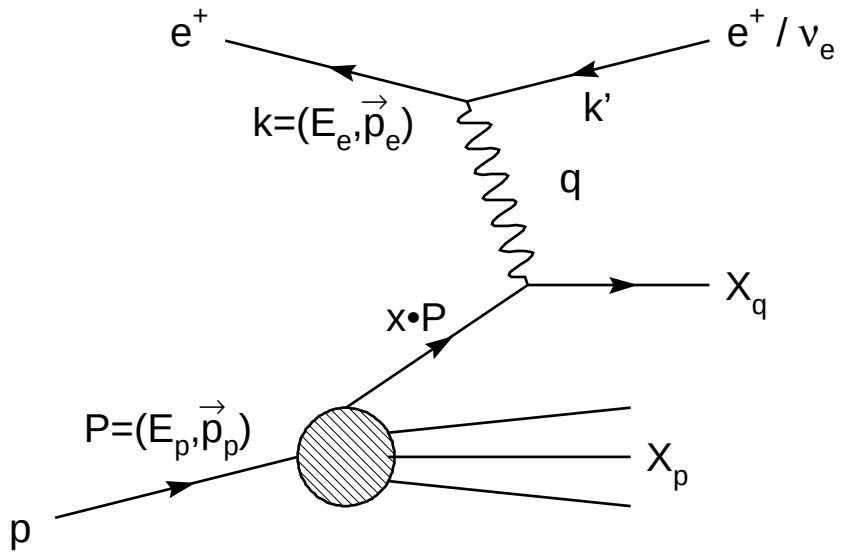
$Q^2 = -q^2$, virtuality of the photon

$Q^2 > 1$ GeV^2 - DIS

$Q^2 \approx 0$ - PHP

$x = \frac{Q^2}{2pq}$, momentum fraction of the struck parton

$y = \frac{qP}{kP}$, inelasticity



$$\frac{d^2\sigma^{ep}(x,Q^2)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ [F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)]$$

where F_2, F_L - proton structure functions and $Y_+ = 1 + (1-y)^2$

measure so called reduced x-section: $\sigma_r(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$,

$F_2(x,Q^2)$ - measures contributions of quarks, $dF_2/dlnQ^2$ - gluons

$F_L(x,Q^2) \sim \alpha_s x g(x,Q^2)$ - directly sensitive to gluons

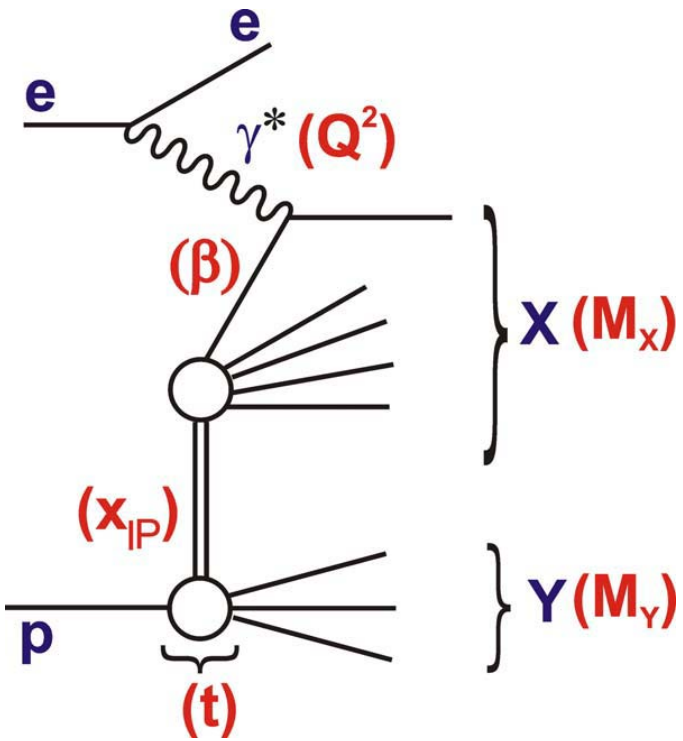
ep collisions: Inclusive Diffraction (ep→ eXY)

Additional variables:

$|t|$ = squared 4-momentum transfer at proton vertex

x_{IP} = fractional momentum loss of proton (momentum fraction IP/p)

β = x/x_{IP} (momentum fraction q/IP)

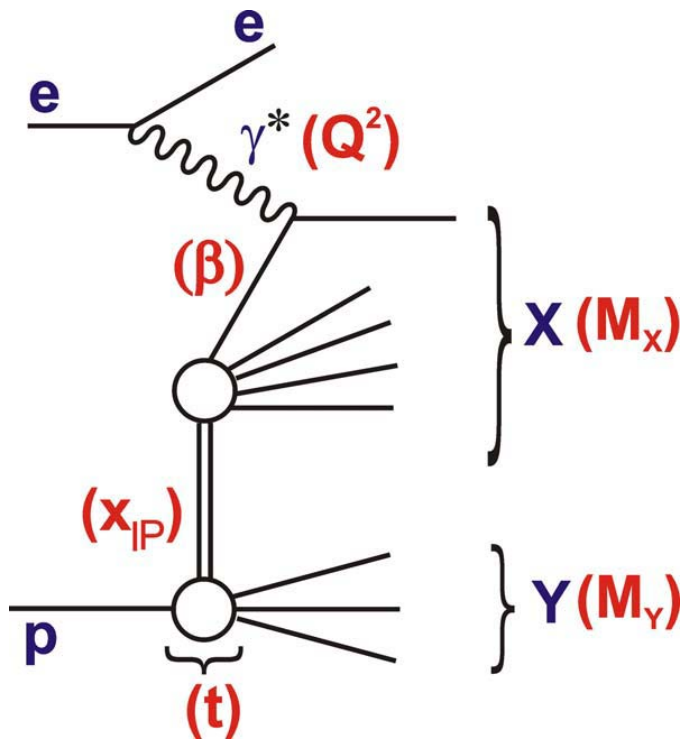


reduced diffractive x-section:

$\sigma_r^{D(3)}(x, Q^2) = F_2^{D(3)}(x, Q^2) - \frac{y^2}{Y_+} F_L^{D(3)}(x, Q^2)$,

similar meaning of F_2^D, F_L^D to inclusive structure functions F_2 and F_L.

ep collisions: Diffraction (in general ep→ eXY)



...and also:

M_X = invariant mass of diffractively produced system

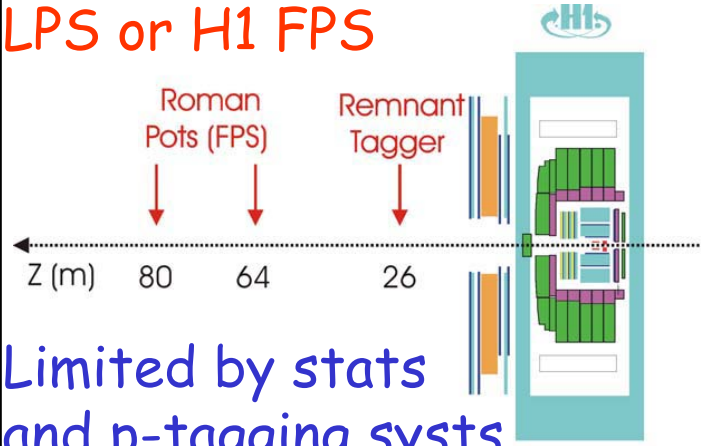
M_Y = invariant mass of proton remnant system

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

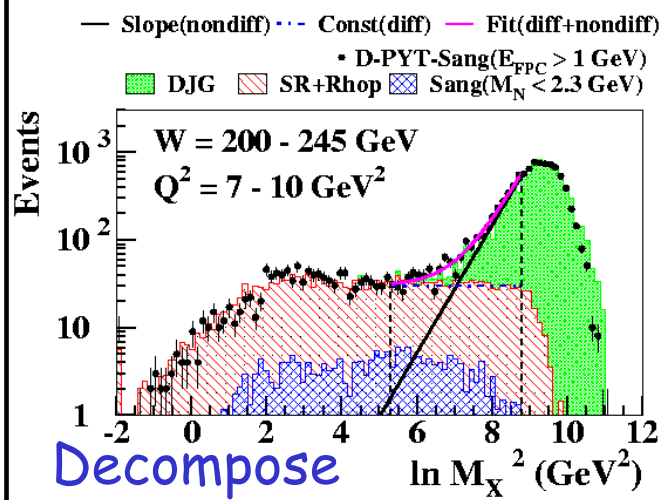
$M_Y > m_p$ - proton dissociates,
→ the background to be understood and disantangled.

Signatures and Selection Methods

Scattered proton in ZEUS LPS or H1 FPS



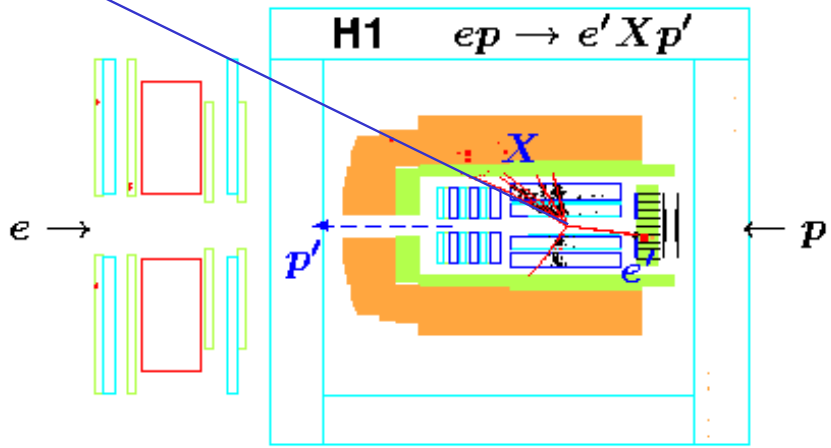
Limited by stats and p-tagging systs



Decompose inclusive ln(Mx) distn

`Large Rapidity Gap' adjacent to outgoing (untagged) proton

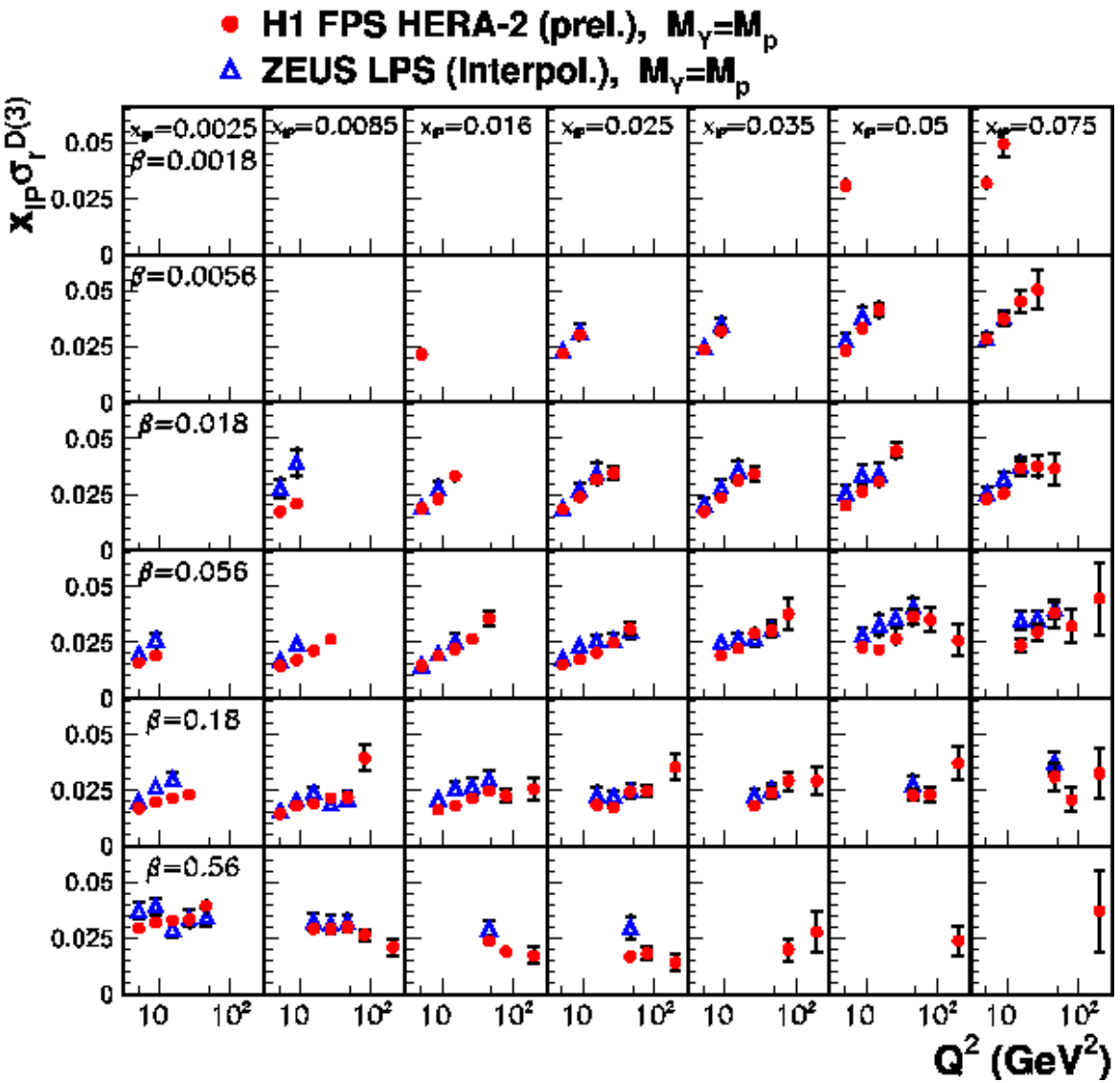
η_{max}

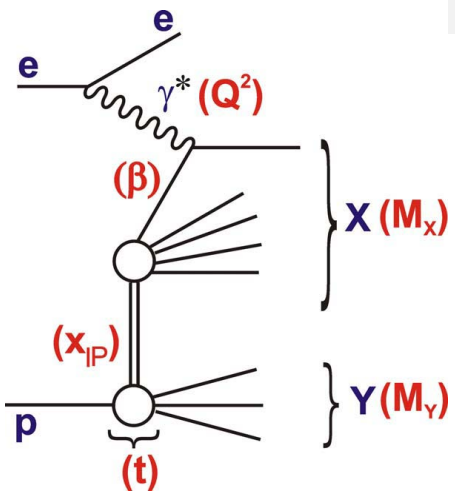


Limited by p-diss systs

The methods have very different systematics!

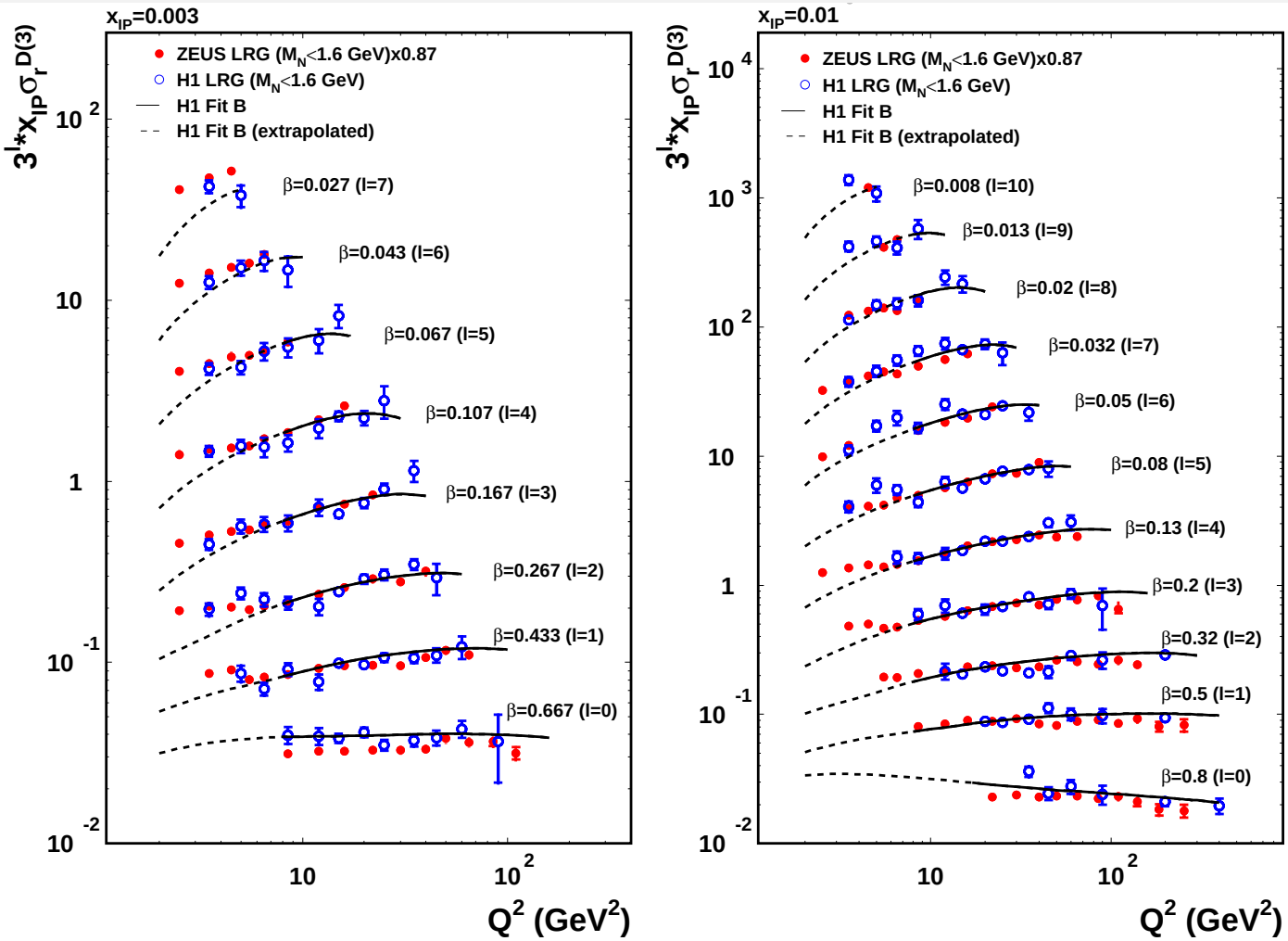
Reduced x-section measurement: LPS - Leading prot





- H1 HERA-II data (156 pb^{-1}) improve stats by factor of 20 and reach higher Q^2
- Fair agreement (combined norm uncertainty ~10%)

Reduced x-section measurement: LRG - Large Rapidity Gap



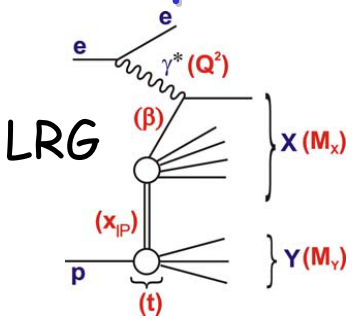
Final ZEUS LRG data (62 pb^{-1}) reach new level of statistical precision

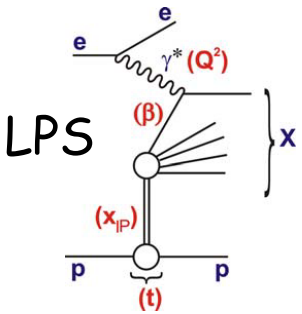
... Overall 13% H1-ZEUS difference within normalis^n errors

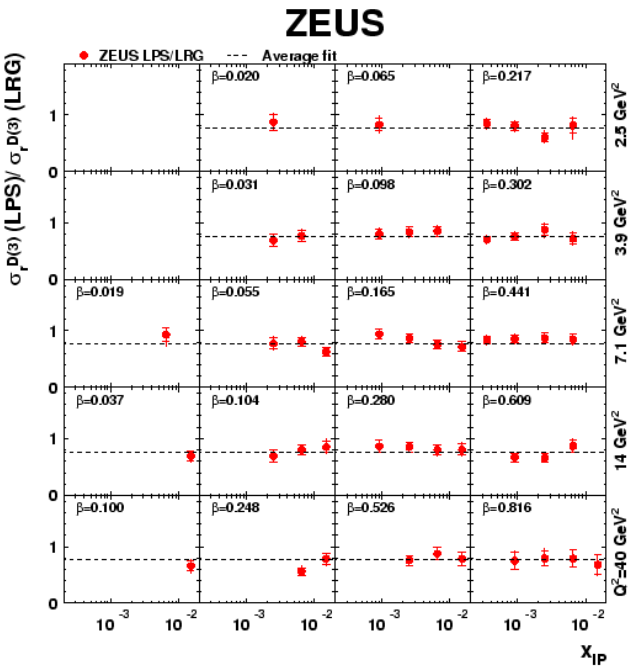
... Good shape agreement in most of phase space (high, low β?)

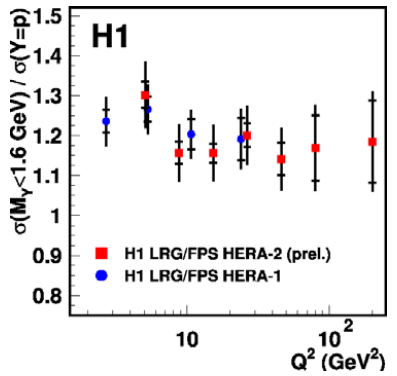
Reduced x-section measurement: LPS - LRG, comparison

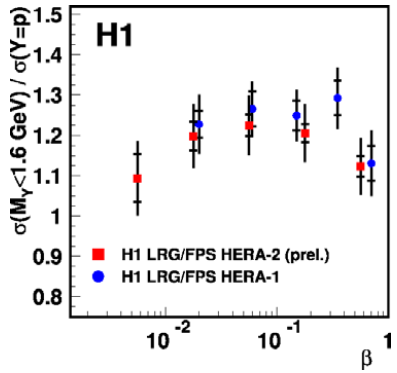
Comparisons between Methods

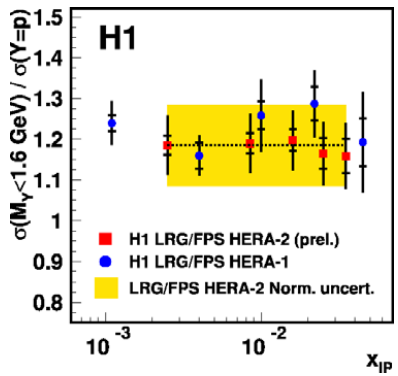












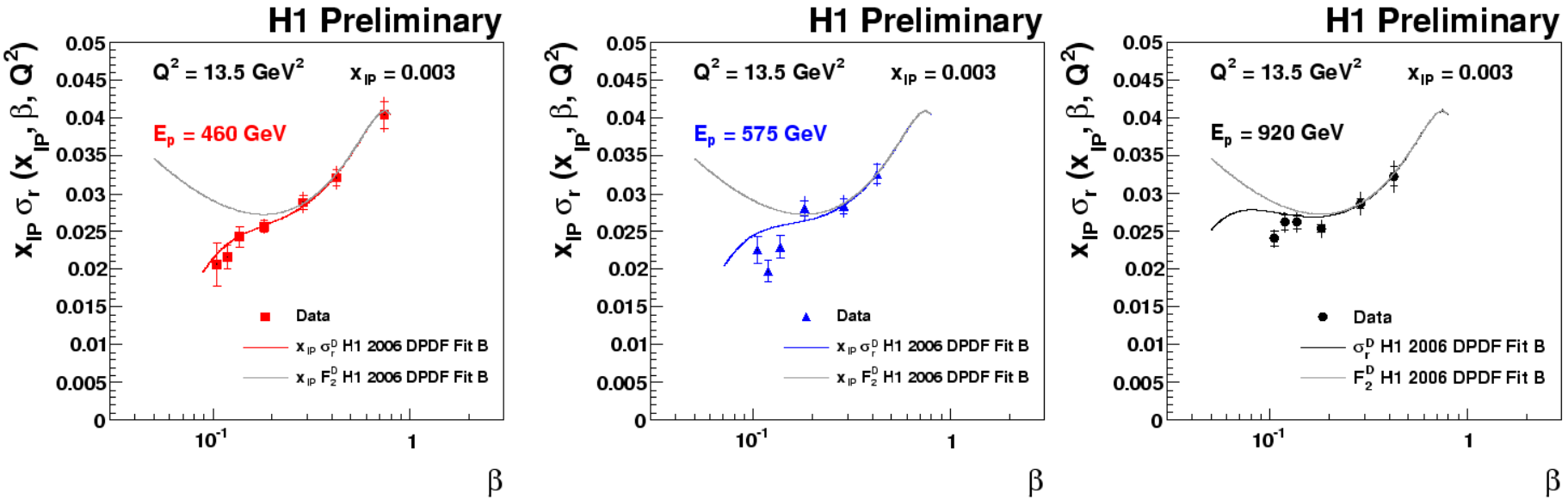
LRG selections contain typically 20% p diss
No significant dependence on any variable
Similar compatibility with Mx method
… **well controlled, precise measurements**

First F_L^D Measurement

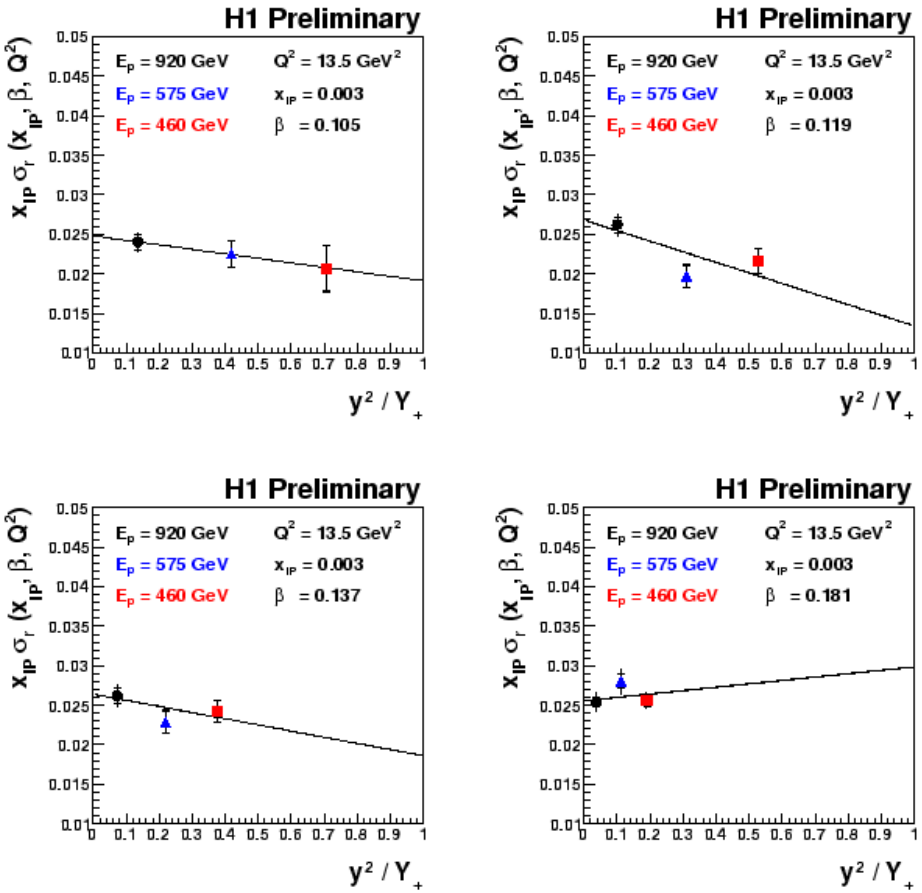
A new test of gluon density (including low scales) …

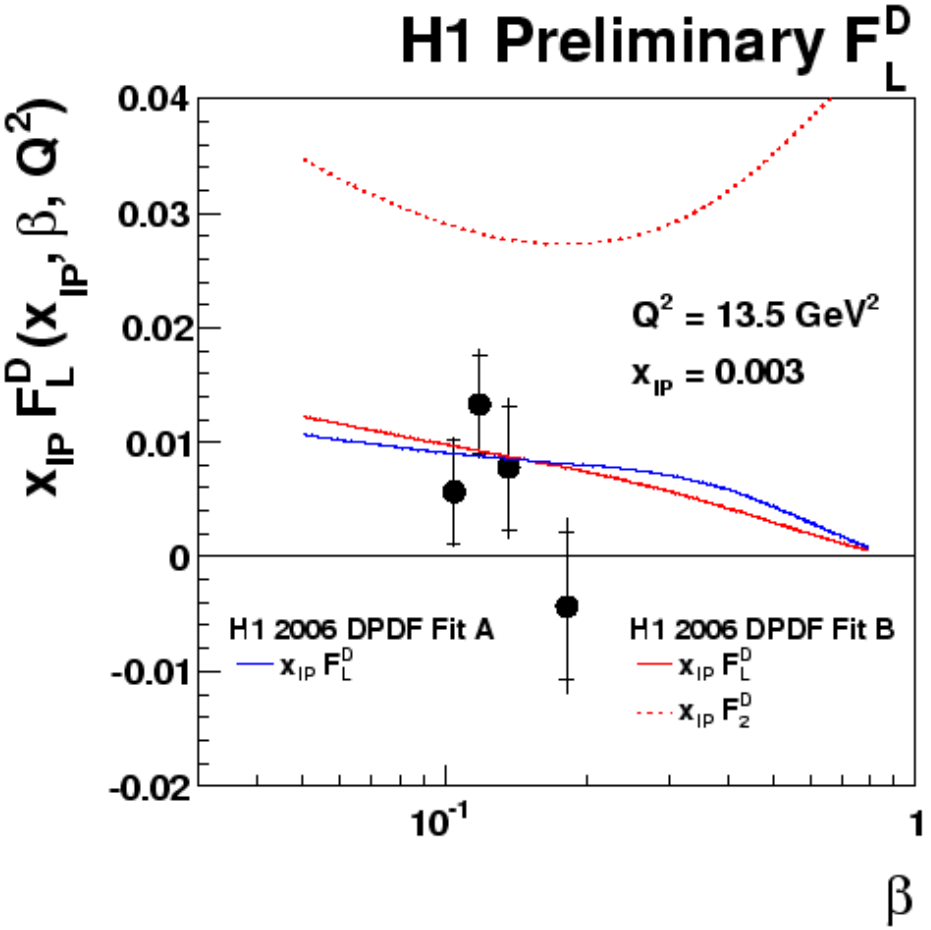
$$\sigma_r^{D(3)}(\beta, Q^2, x_{IP}) = F_2^{D(3)} - \frac{y^2}{Y_+} F_L^{D(3)} \qquad F_L^{D(3)} \sim \alpha_S \; xg(x)$$

… sensitivity to F_L^D @ highest y (lowest β at fixed x_{IP}, Q^2)
… varying beam energy changes y at fixed β, x_{IP}, Q^2

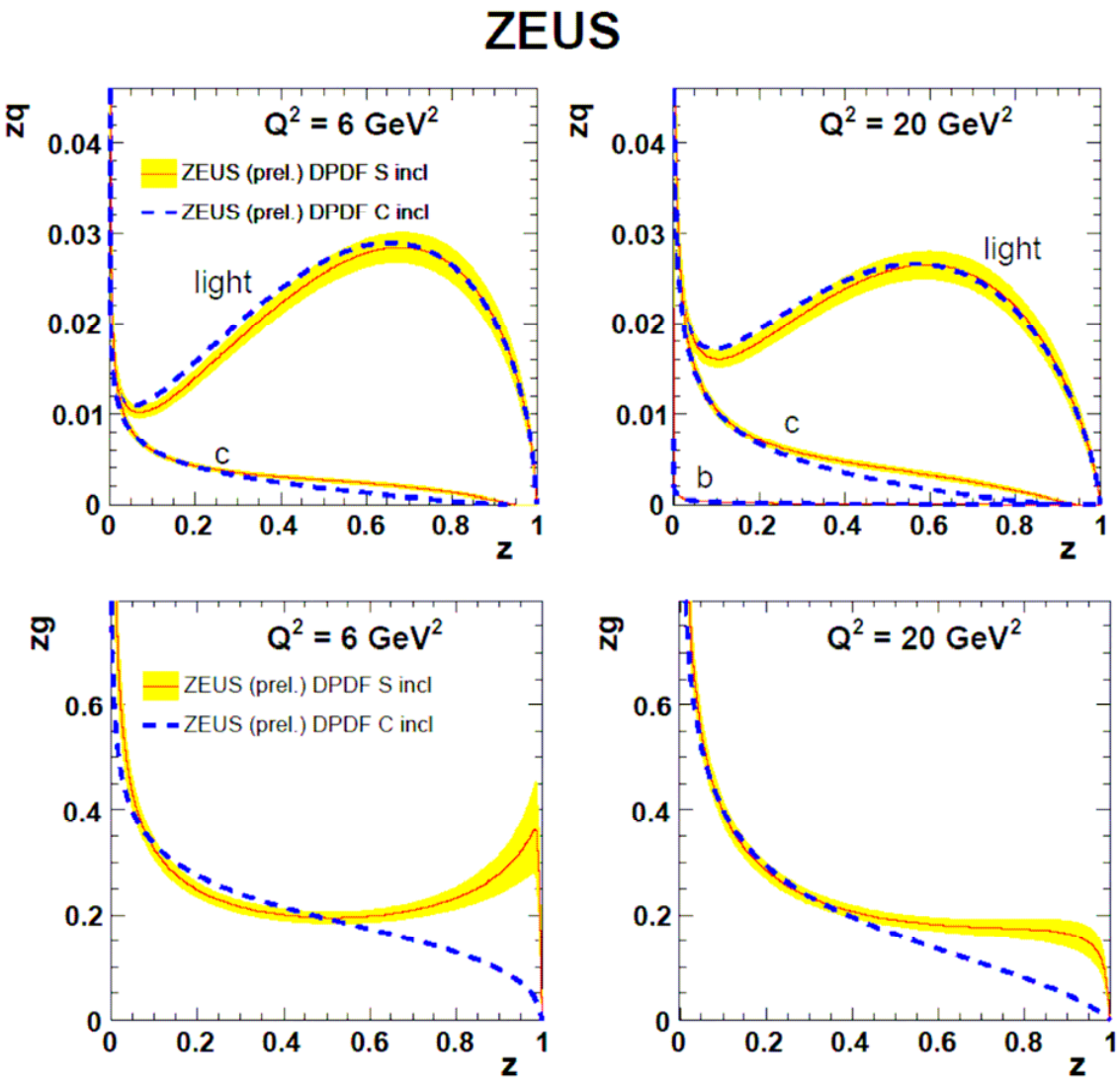


From reduced x-section to F_L^D





QCD fits to New ZEUS LRG data



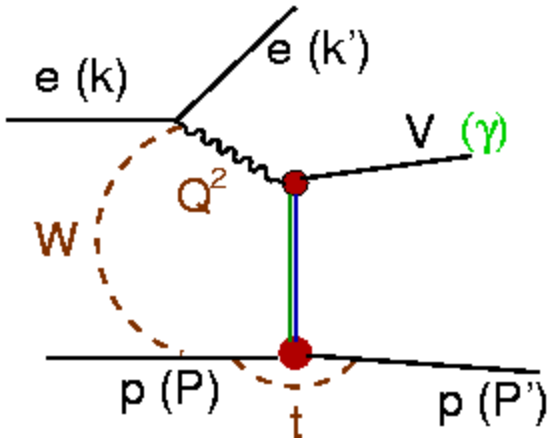
F_2^D measures quarks
$dF_2^D/dlogQ^2$ - gluons

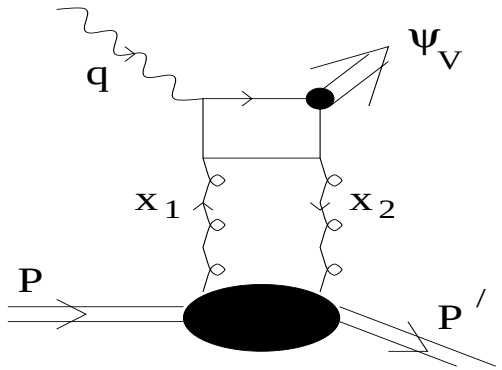
z = incoming momentum fraction of parton ($=\beta$ for quarks, $>\beta$ for gluons)

two schemes:

DPDF S - "Standard" scheme (flexible gluons)
DPDF C - "Constant" scheme (stiff gluons)

An important subset of diffractive reactions - Exclusive Diffraction





Exclusive process kinematics.

Diffractive system:

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

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

M_V^2 - vector meson mass squared,

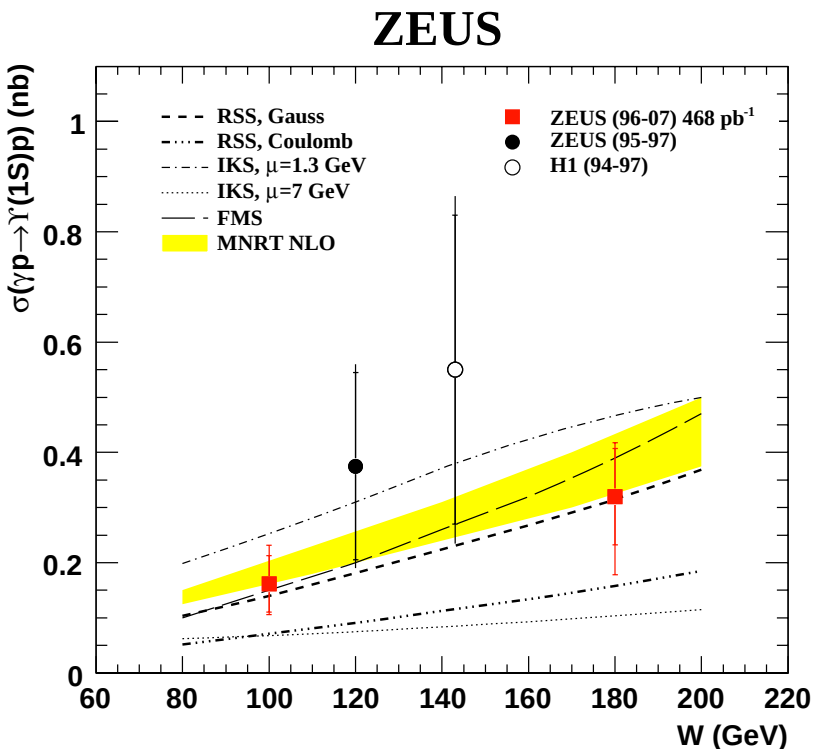
In pQCD sensitive to gluons in the proton via:
W - invariant mass of the γp system,
gluon longitudinal momentum in the proton
$W^2 = 2E_p(E - p_z)_V$, $E_p = 920\ GeV$.

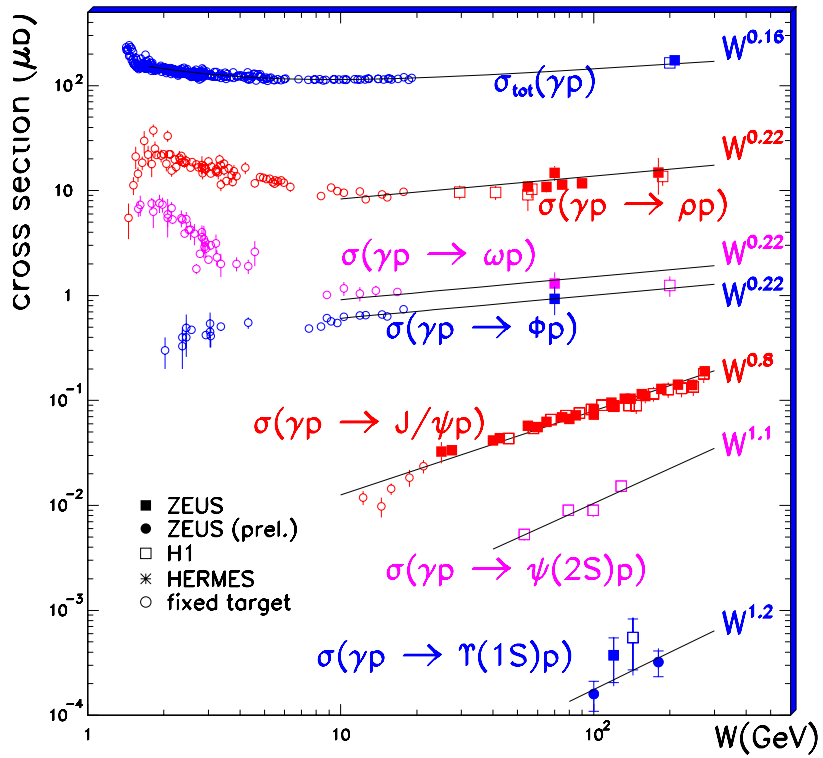
$|t|$ - 4-momentum transfer at the proton vertex,
$|t| = |P' - P|^2 \approx p_{TV}^2$ (approx. true, if $p_{Te}^2 \lesssim 1$ GeV^2).
The cross section $\frac{d\sigma}{dt} \sim e^{-b|t|}$, b -
transverse distribution of the gluons in the proton,

pQCD: 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)



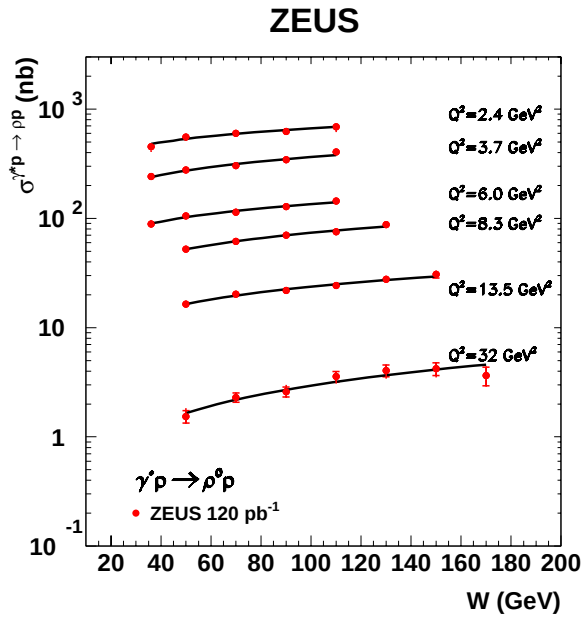


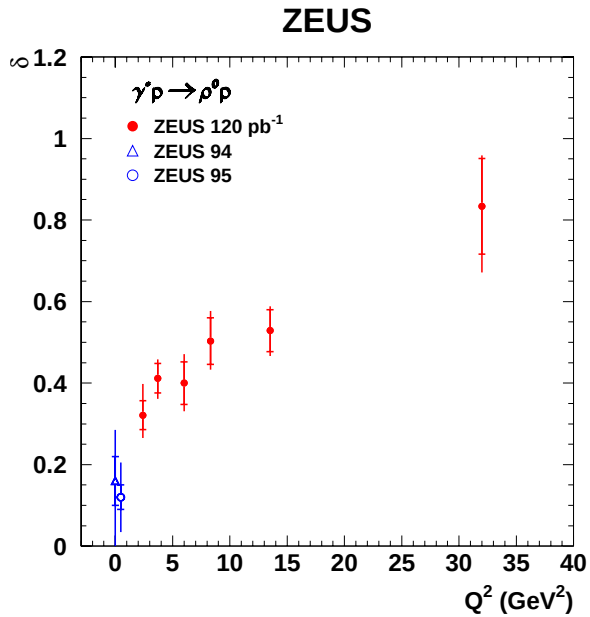
$\sigma \sim W^{\delta}$, δ rises with M_V^2 from "soft" ($\delta = 0.22$) to "hard" ($\delta \approx 1.0$)

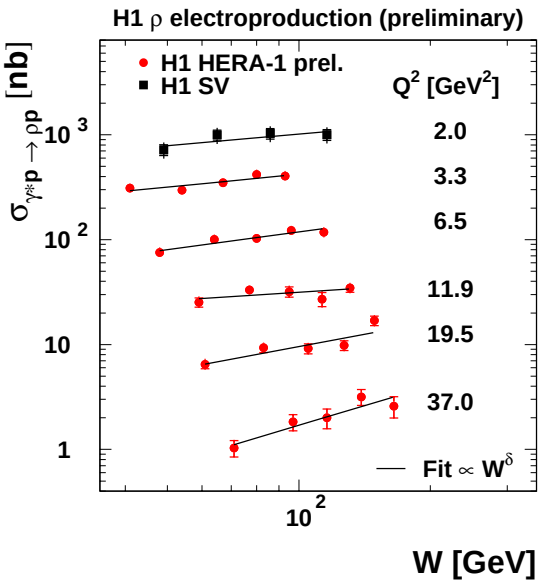
- all: not only Q^2 (DIS), but also mass M_V sets the scale of the interaction
- Y: sensitive to vector meson wave function: seems to prefer Gauss to Coulomb,
- Y: sensitive to hard scale value: NRQCD NLO scale is between $1.3 < \mu < 7$ GeV,
- Y: pQCD models W-slope: FMS LO (δ=1.7), other NLO give value $\delta \approx$1.2

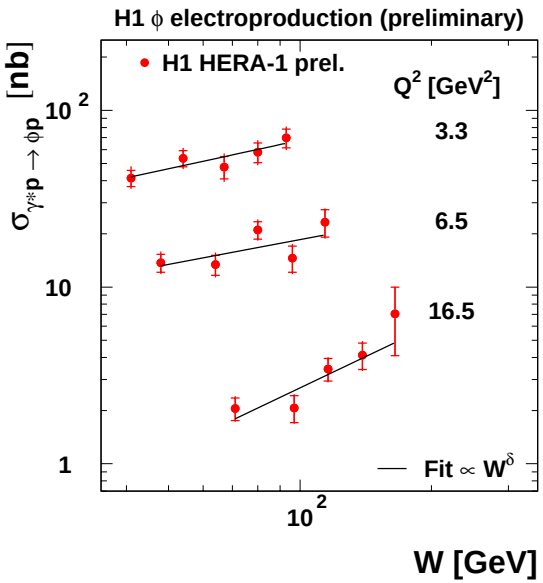
W-dependence, (light VM: ρ, ϕ)

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









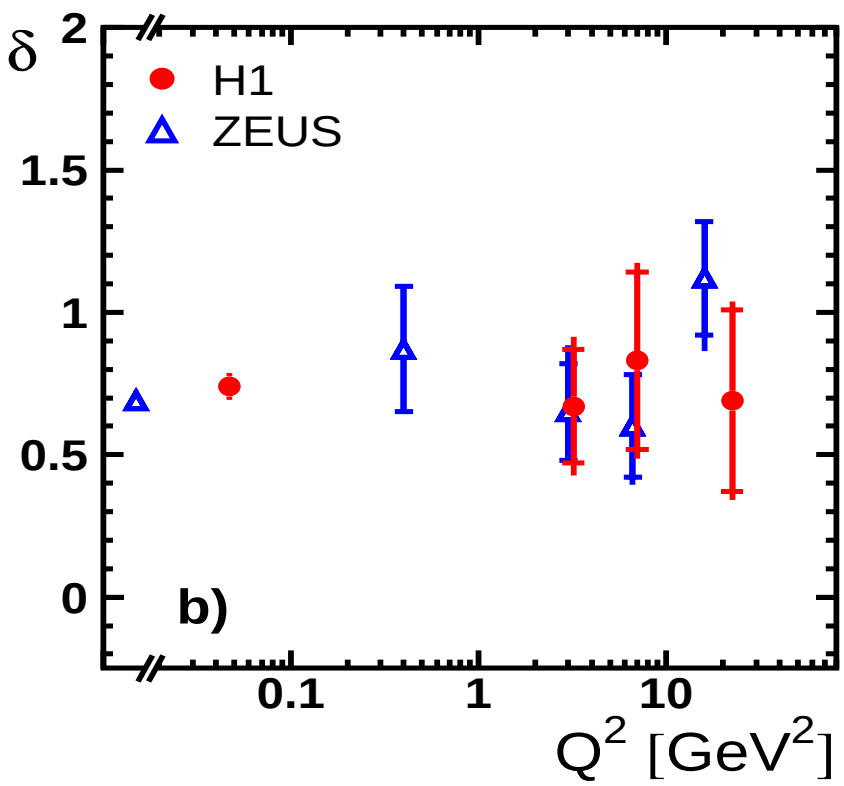
light Vector Mesons

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

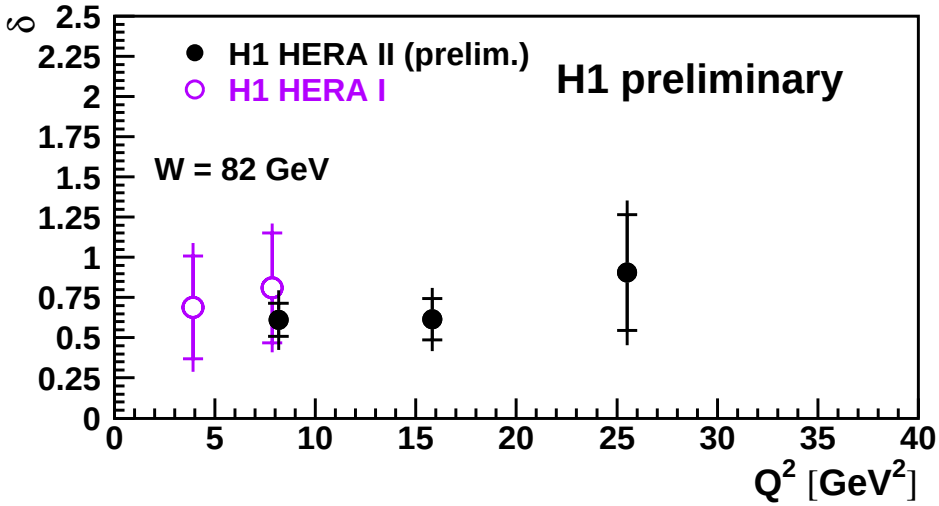
W-dependence

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

heavy VM: J/ψ



DVCS

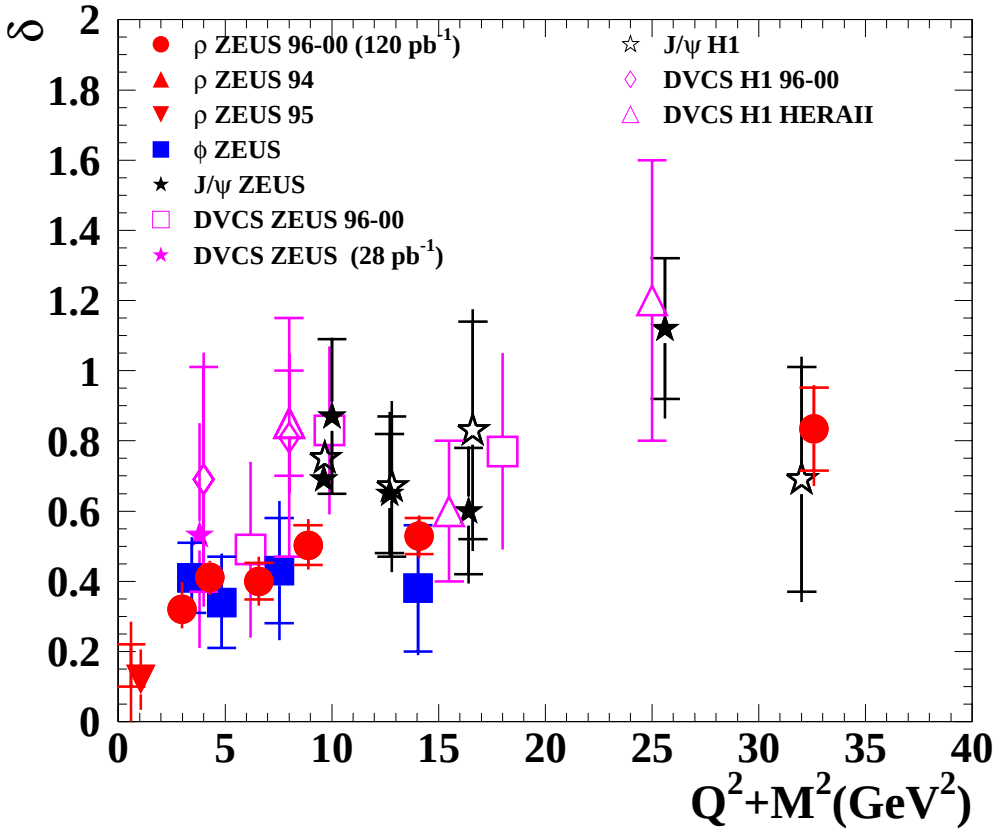


J/ψ and DVCS,

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

W-dependence summary

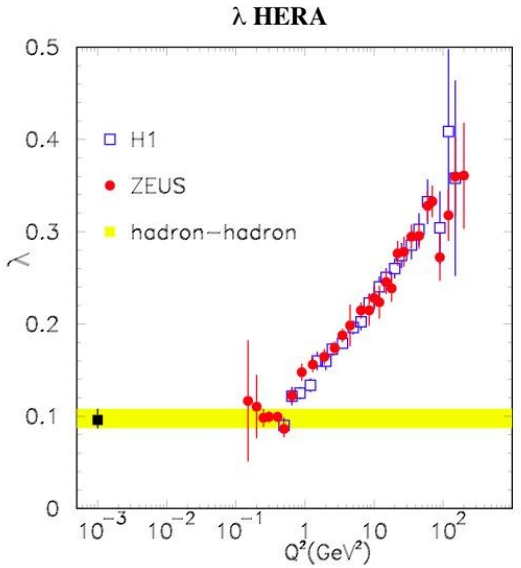
PHP+DIS



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

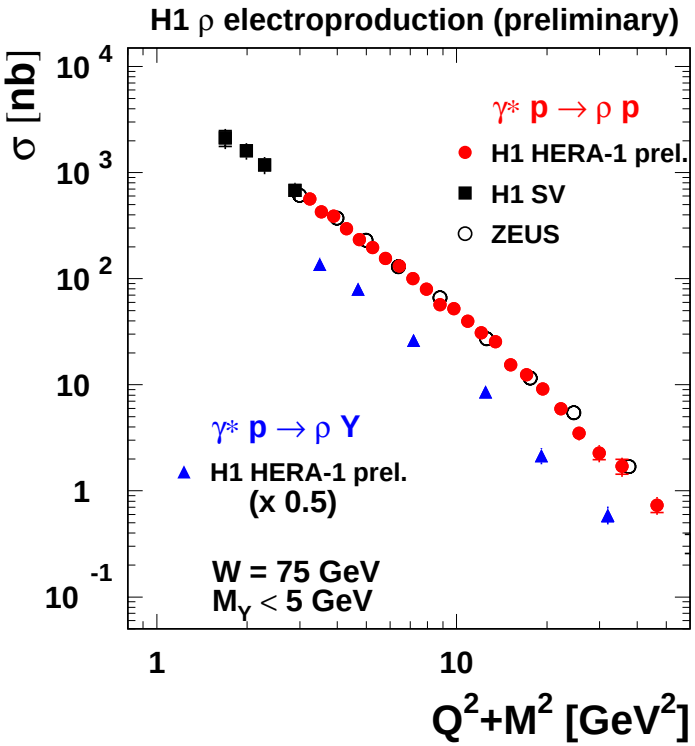
consistent within pQCD

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

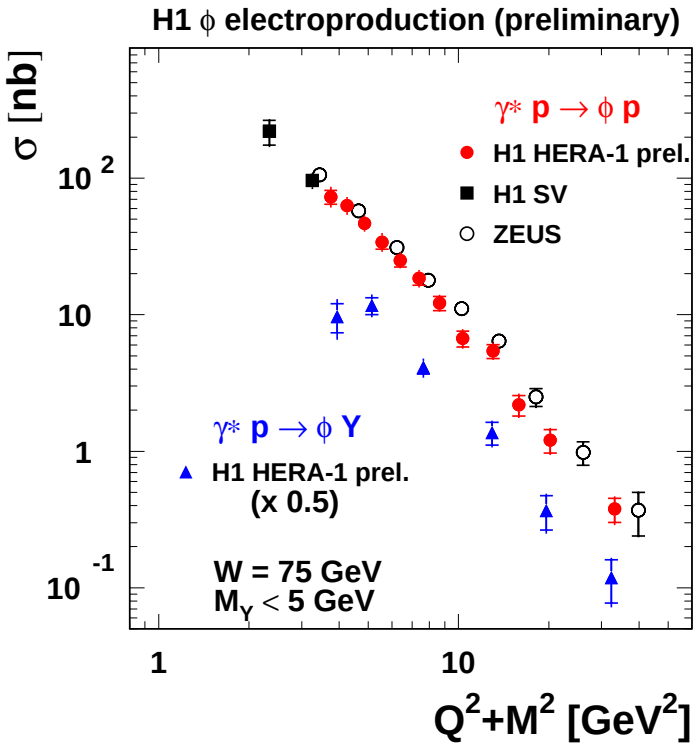


Q^2-dependence, $\sigma \sim (Q^2 + M_V^2)^{-n}$

ρ^0, $m_\rho^2 = 0.5$ GeV^2



ϕ^0, $m_\phi^2 = 1.0$ GeV^2

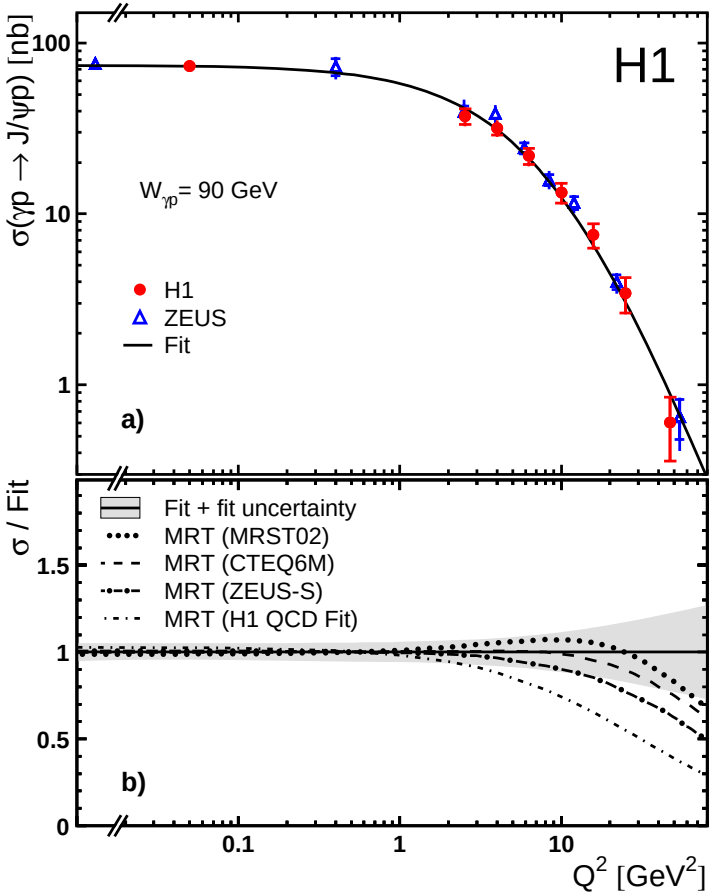


H1/ZEUS: perfect agreement

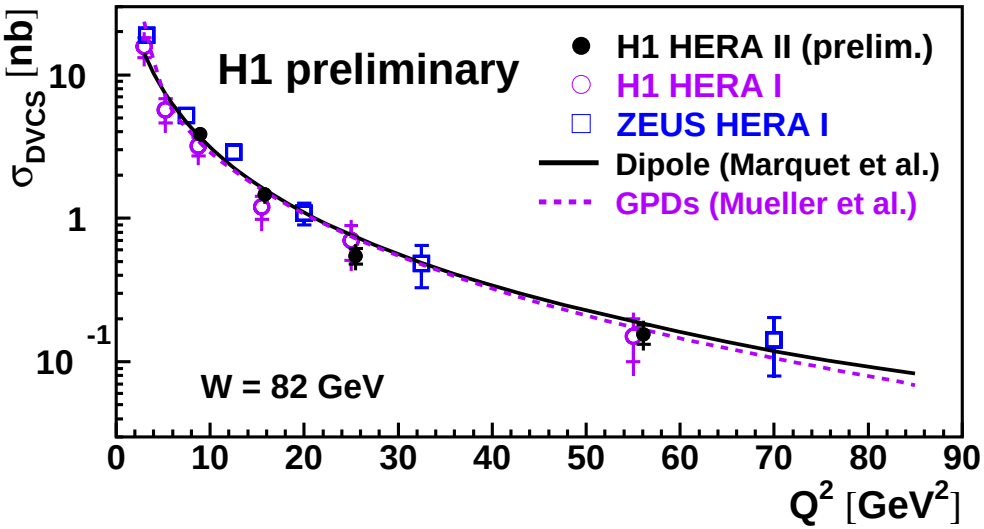
- $Q^2 \geq 0$ GeV^2, n$\approx$2.00$\pm$0.01, $\chi^2/ndf \sim 10$
- $Q^2 \geq 10$ GeV^2, n$\approx$2.50$\pm$0.02, $\chi^2/ndf \sim 1.5$

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

$|t|$-dependence

$\frac{d\sigma}{dt} \sim e^{-b|t|}$

b - sensitive to the transverse size of the interaction region

Geometric picture - transverse size:

$b = b_V + b_p$

transverse size:

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

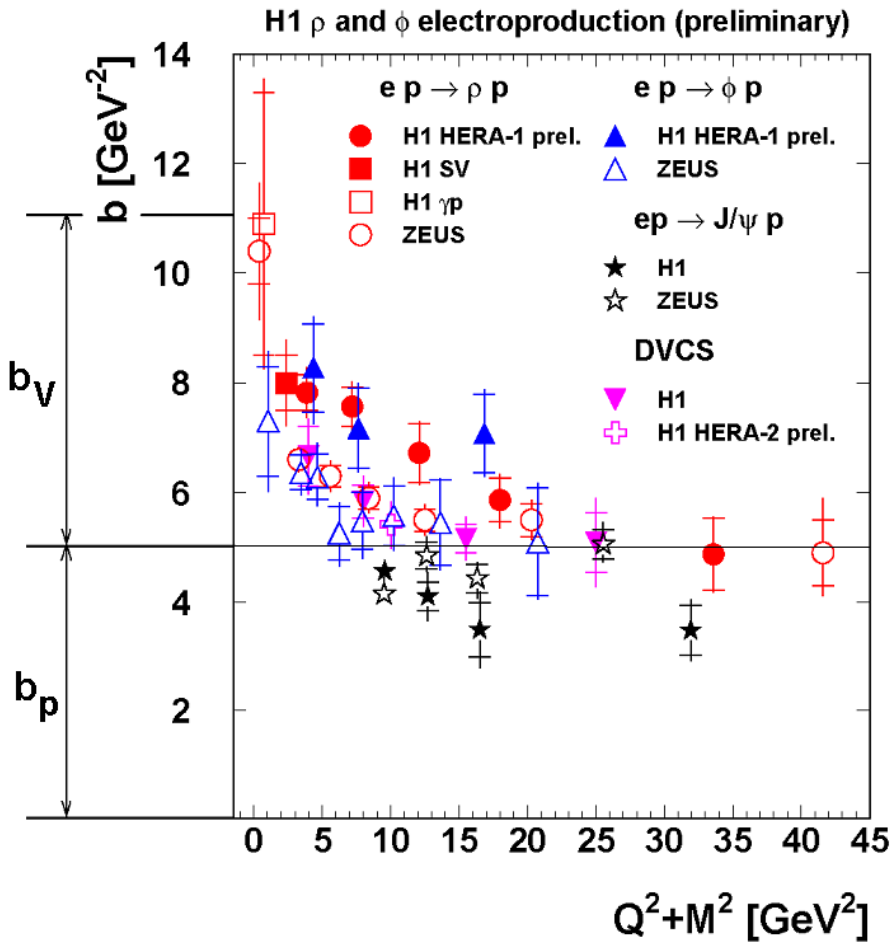
Target: $b_p \approx 5\ \text{GeV}^{-2}$

b_p can be interpreted as

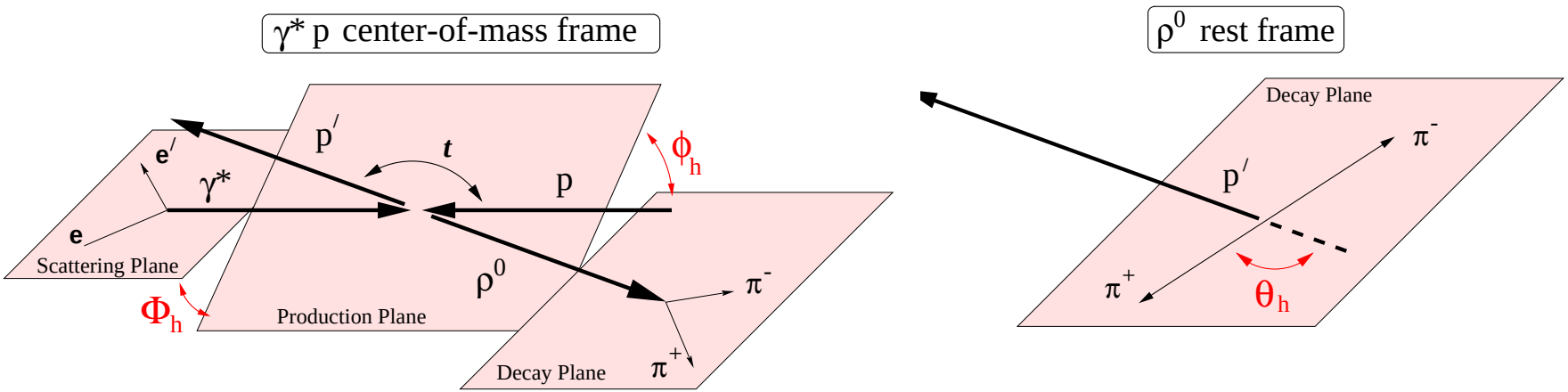
$r_{gluons} \approx 0.5$ fm

charge radius of the proton

$r_{em} \approx 0.8$ fm



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



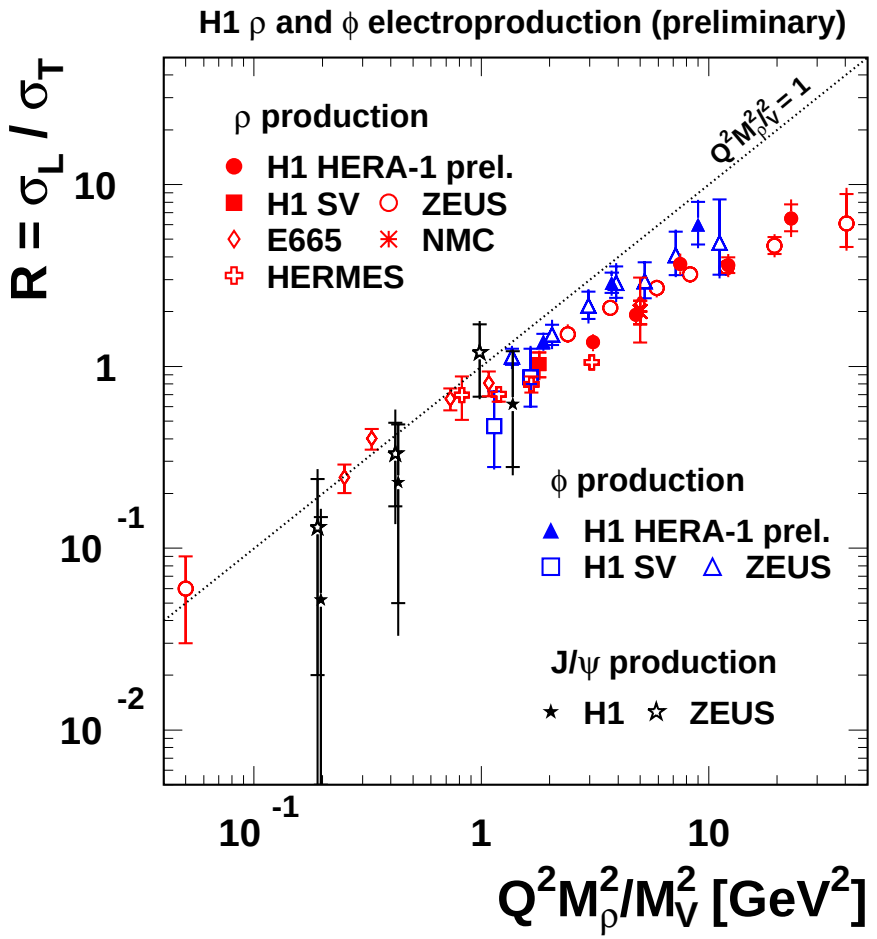
- Study angular distributions: 3 angles (θ_h, ϕ_h, Φ_h)
- 15 combinationof spin-density matrix elements, r_{ij}^{kl}
- s-channel helicity conservation SCHC
  - $\gamma_T^* \rightarrow \rho_T$
  - $\gamma_L^* \rightarrow \rho_L$
- if SCHC holds $\rightarrow R = \sigma_L/\sigma_T = r_{00}^{04}/\epsilon(1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

$R = \sigma_L/\sigma_T$

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

γ_L - only small size configurations
γ_T - both, small and large, size configurations

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



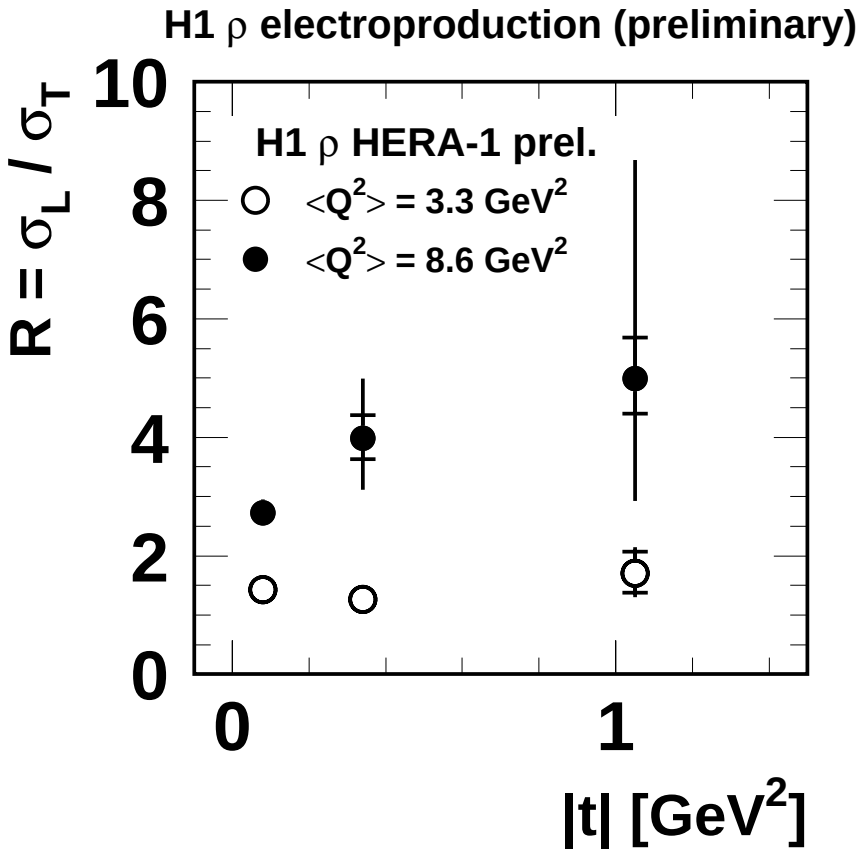
$R = \sigma_L/\sigma_T$

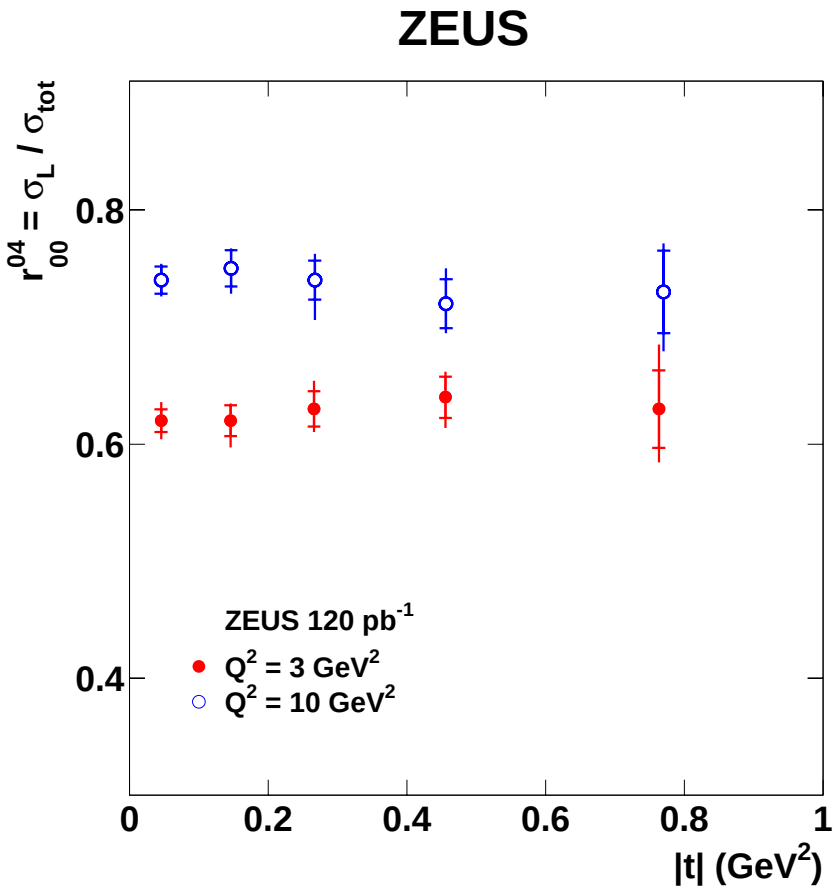
and R does not depend significantly on $|t|$!!

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

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

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





Summary

- HERA provides large amount of unique data
- large choice of hard scales allows pQCD treatment of Diffraction reactions
- first results on diffractive structure functions F_2^D and F_L^D from inclusive diffractive cross section measurement presented
  - three different methods (LPS, LRG, Mx) from two experiments (H1 and ZEUS) are in good agreement with each other
  - diffractive PDFs are well constrained in Diffractive DIS
  - detailed understanding of the hard Diffractive PHP is needed (see Backup slides)
- exclusive diffraction:
  - Vector Meson mass, M_V^2, provides a hard scale of the interaction
  - an effective scale, $Q^2_{eff} = Q^2 + M_V^2$, looks like a good option for consistent representation of exclusive Vector Meson production kinematics,
  - W-slope, δ, rises with Q^2_{eff}
  - $|t|$-distribution slope, b, levels off at $b \sim 5 GeV^{-2}$ at high Q^2_{eff}
  - Q^2-distributions consistent with pQCD,
  - the ratio, σ_L/σ_T, increases with Q^2/M_V^2,
    - does not depend on W and $|t|$,
    - requires precise understanding of all mechanisms which produce transversity $\gamma_T^* = \rho_T$
- good progress in HERA data analysis and understanding of Diffraction within pQCD

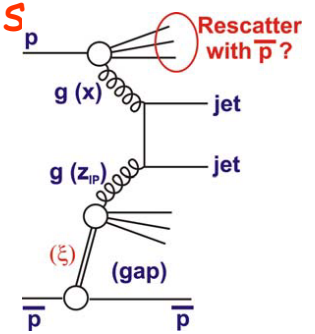
Backup slides

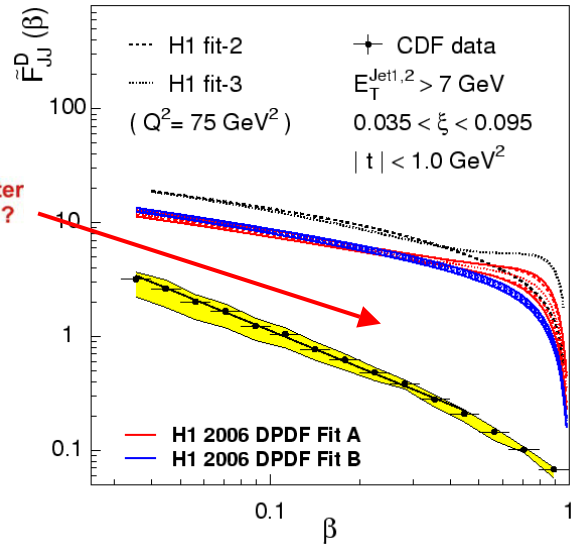
Diffractive dijets in PHP, 1/3

slides from P.Newmann, Photon'09

.. meanwhile in pp(bar) ...

Tevatron effective DPDFs from dijets show strong factorisation breaking compared with HERA DPDFs ...
`gap survival' factor $S^2 \sim 0.1$



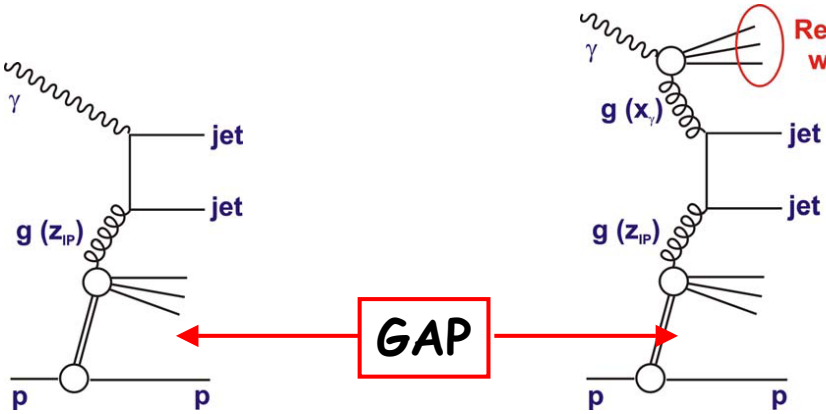


... explained by rescattering / absorption

... **photoproduction jets as the perfect control experiment?...**

"Direct" photon ($x_\gamma \to 1$)

"$S^2 = 1$"



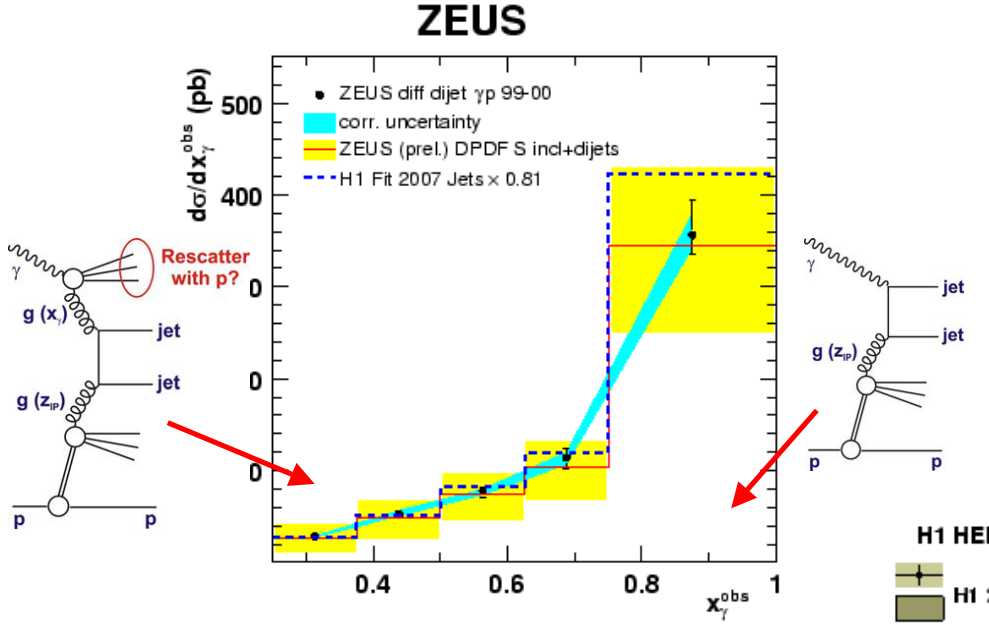
"Resolved" photon ($x_\gamma < 1$)

"$S^2 \sim 0.34$" (KKMR)

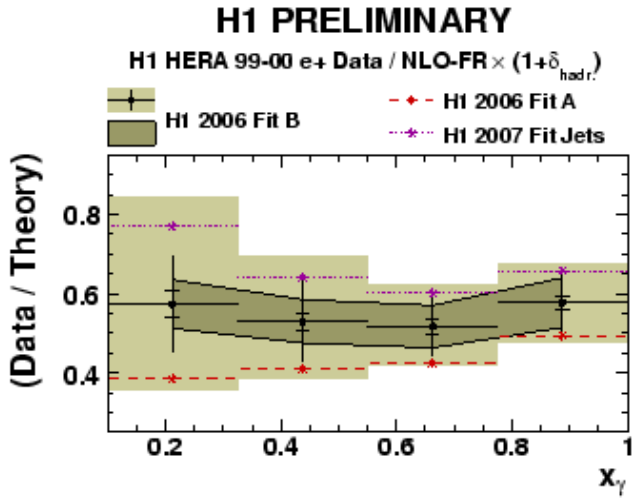
Diffractive dijets in PHP, 2/3

slides from P.Newmann, Photon'09

X-Section Differential in x_γ



$$x_\gamma = \frac{\sum_{jets}(E - p_z)}{\sum_{HFS}(E - p_z)}$$



- Similar quality of descriptions of high / low x_γ regions!
- H1: $E_t^{jet1} > 5$ GeV

... suppression by factor ~2

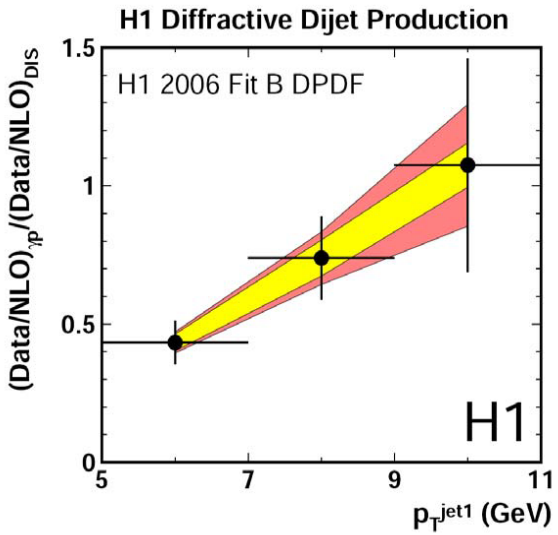
-ZEUS: $E_t^{jet1} > 7.5$ GeV

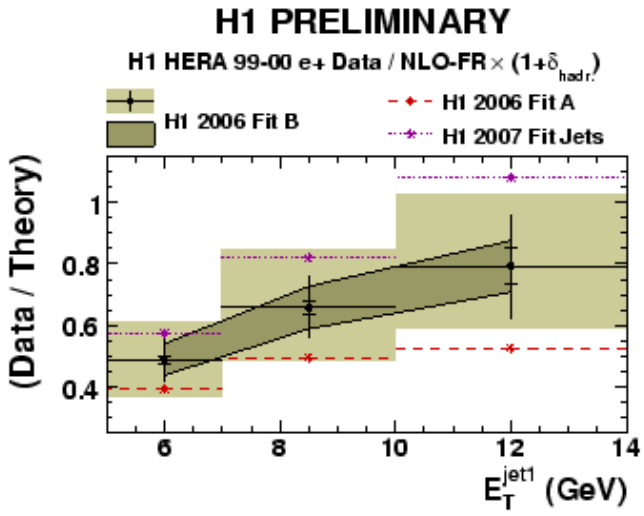
-... little or no suppression ...

Diffractive dijets in PHP, 3/3

slides from P.Newmann, Photon'09

Cross Section Differential in E_T





- Suggestions of harder Et dependence in data than NLO theory … thus of E_t dependent gap survival probability

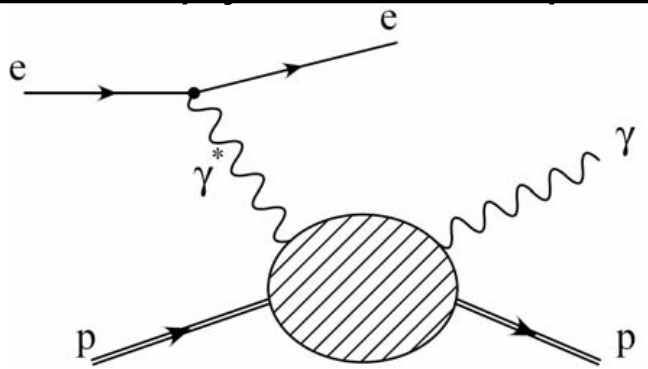
- For highest E_t^{jet1}, survival probability compatible with unity (c.f. previous ZEUS results)

- Could rescattering effects for photon depend on Et, not x_γ?

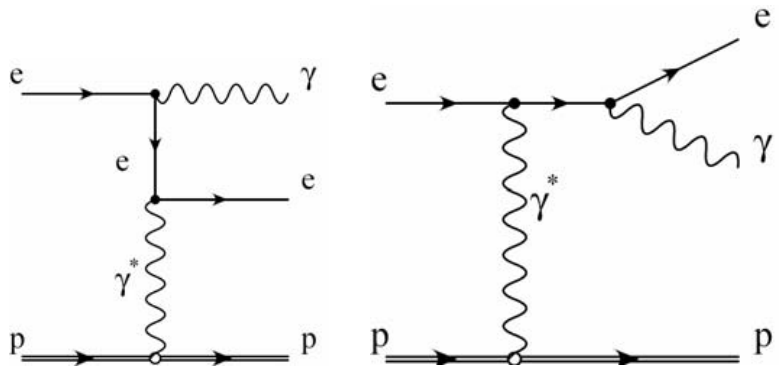
DVCS: Beam Charge Asymmetry, 1/2

H1-prelim-09-014

DVCS – Deeply Virtual Compton Scattering



BH – Bethe-Heitler



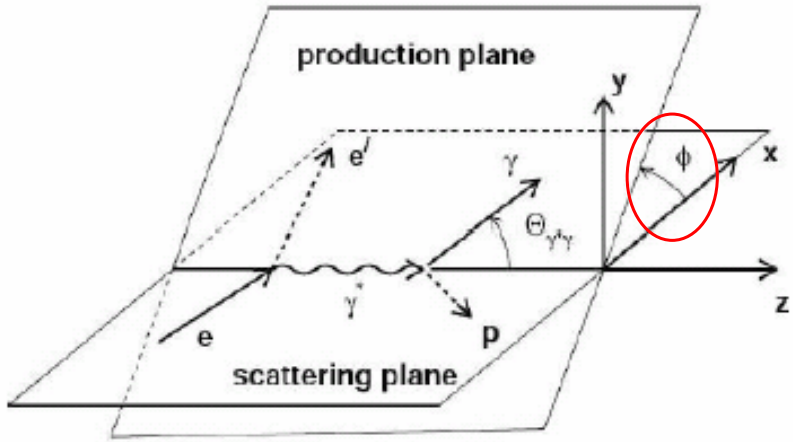
$$d\sigma = d\sigma^{BH} + d\sigma^{DVCS} \pm Interferen\,ce.Term.$$

+ for beam lepton charge (+)

- for beam lepton charge (-)

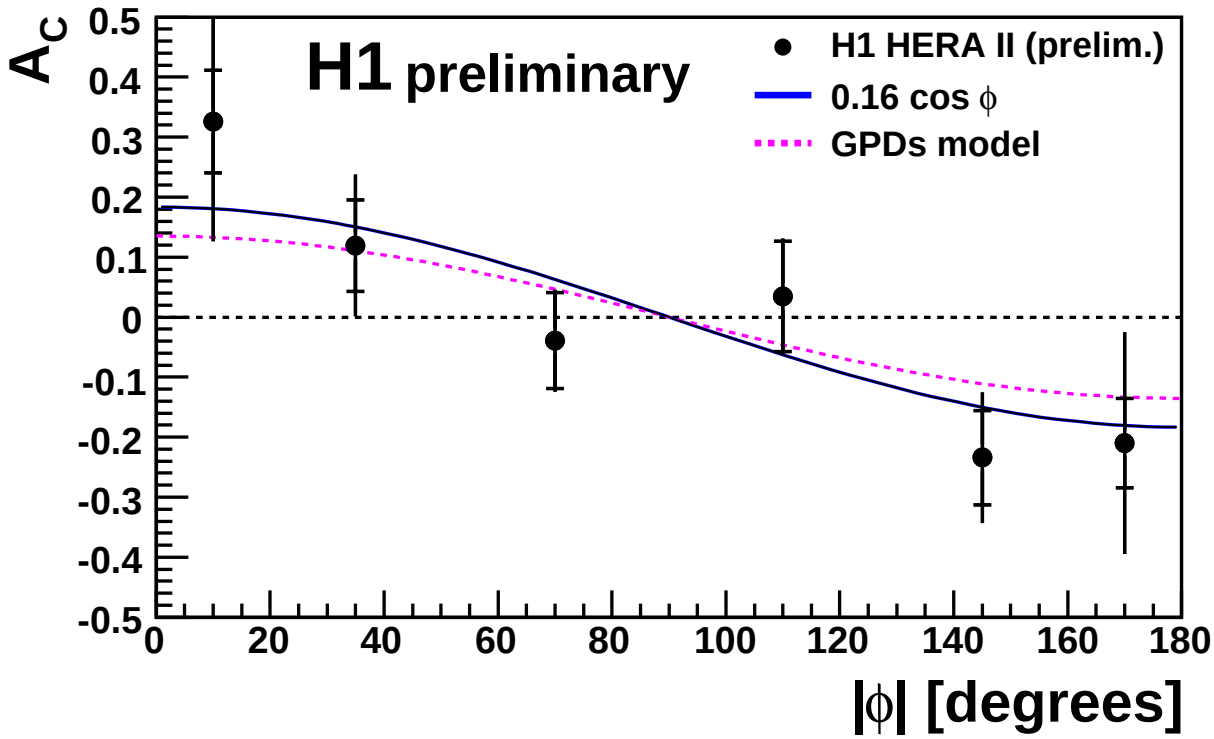
$$\sigma^{+} - \sigma^{-} \sim \mathrm{Re}(Interference.Term)$$

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



DVCS: Beam Charge Asymmetry, 2/2

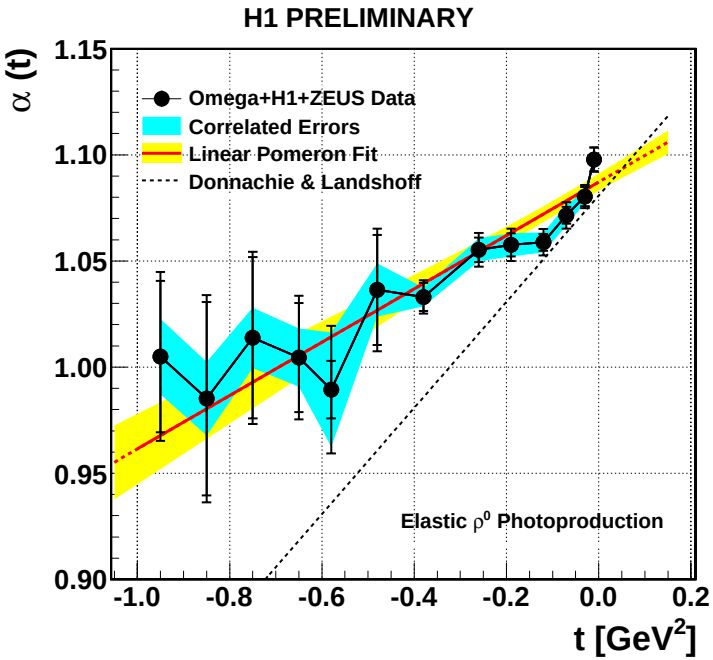
H1-prelim-09-014



Effective Pomeron trajectory, 1/3

slides from S.Kananov, Photon'09

Effective Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' \cdot t$

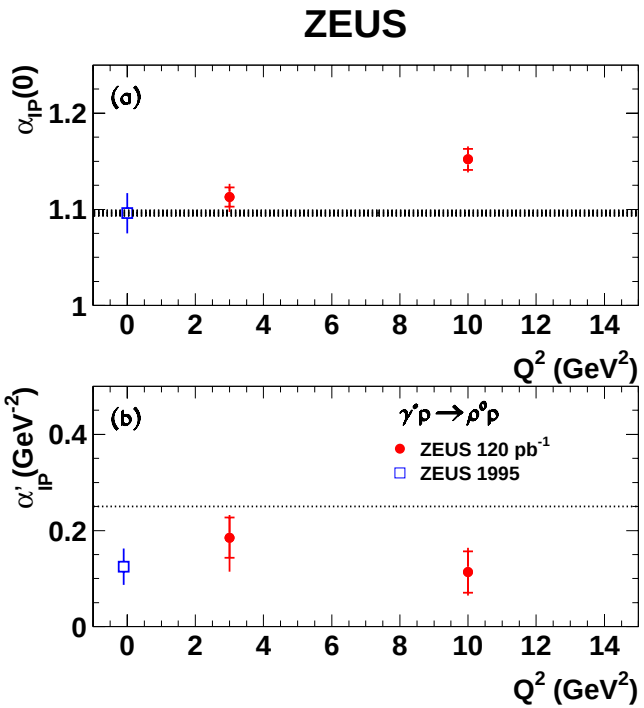


- **Global fit: ρ^o Photoproduction, (Omega, H1, ZEUS)**
  $(1.0871 \pm 0.0026 \pm 0.003) + (0.126 \pm 0.013 \pm 0.012)\ GeV^{-2} \cdot t$
- **H1:** $(1.093 \pm 0.003^{+0.008}_{-0.007}) + (0.116 \pm 0.027^{+0.038}_{-0.046})\ GeV^2 \cdot t$
- **ZEUS:** $(1.096 \pm 0.021) + (0.125 \pm 0.038)\ GeV^{-2} \cdot t$

Effective Pomeron trajectory, 2/3

slides from S.Kananov, Photon'09

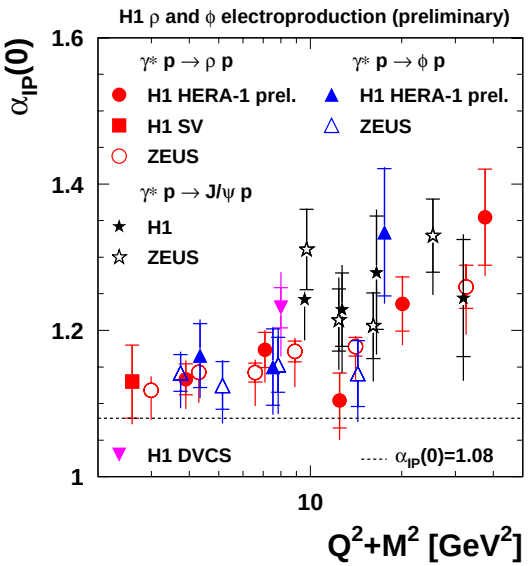
Effective Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' \cdot t$

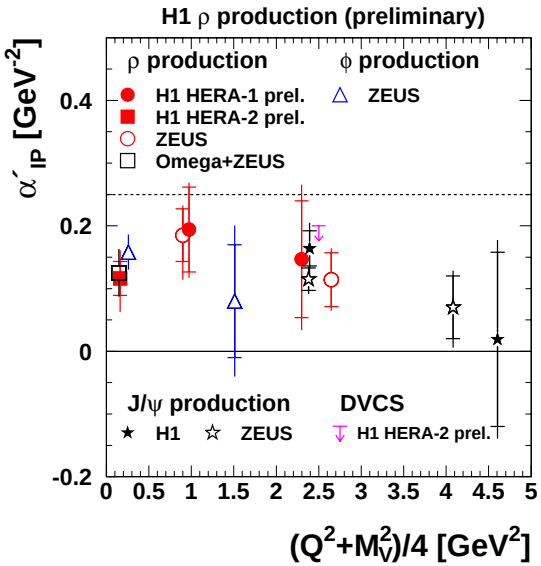


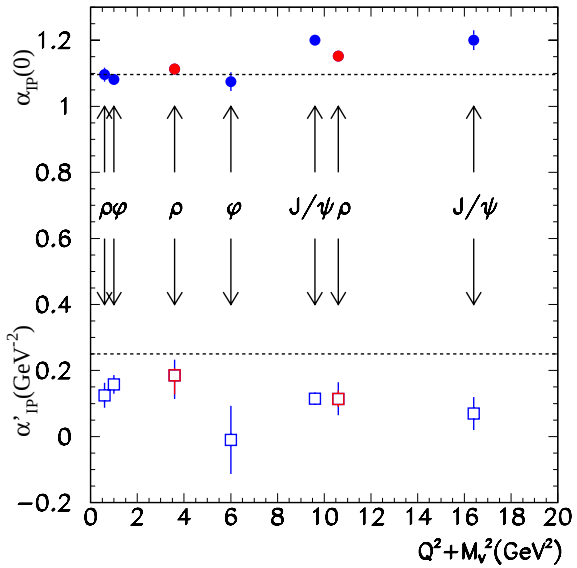
ZEUS, ρ^o electroproduction: $\alpha(0)$ and α' as a function of Q^2

Effective Pomeron trajectory, 3/3

slides from S.Kananov, Photon'09



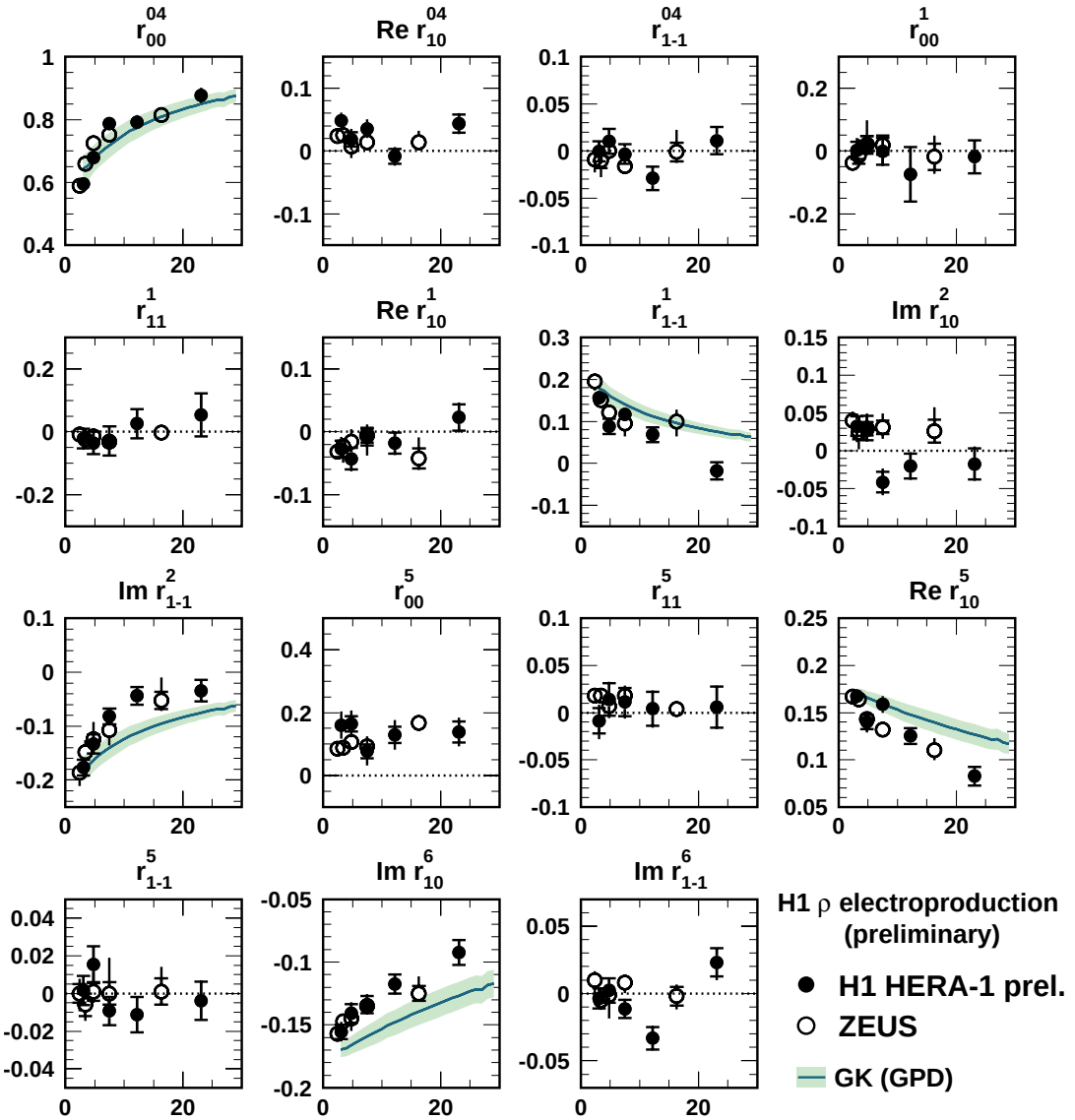




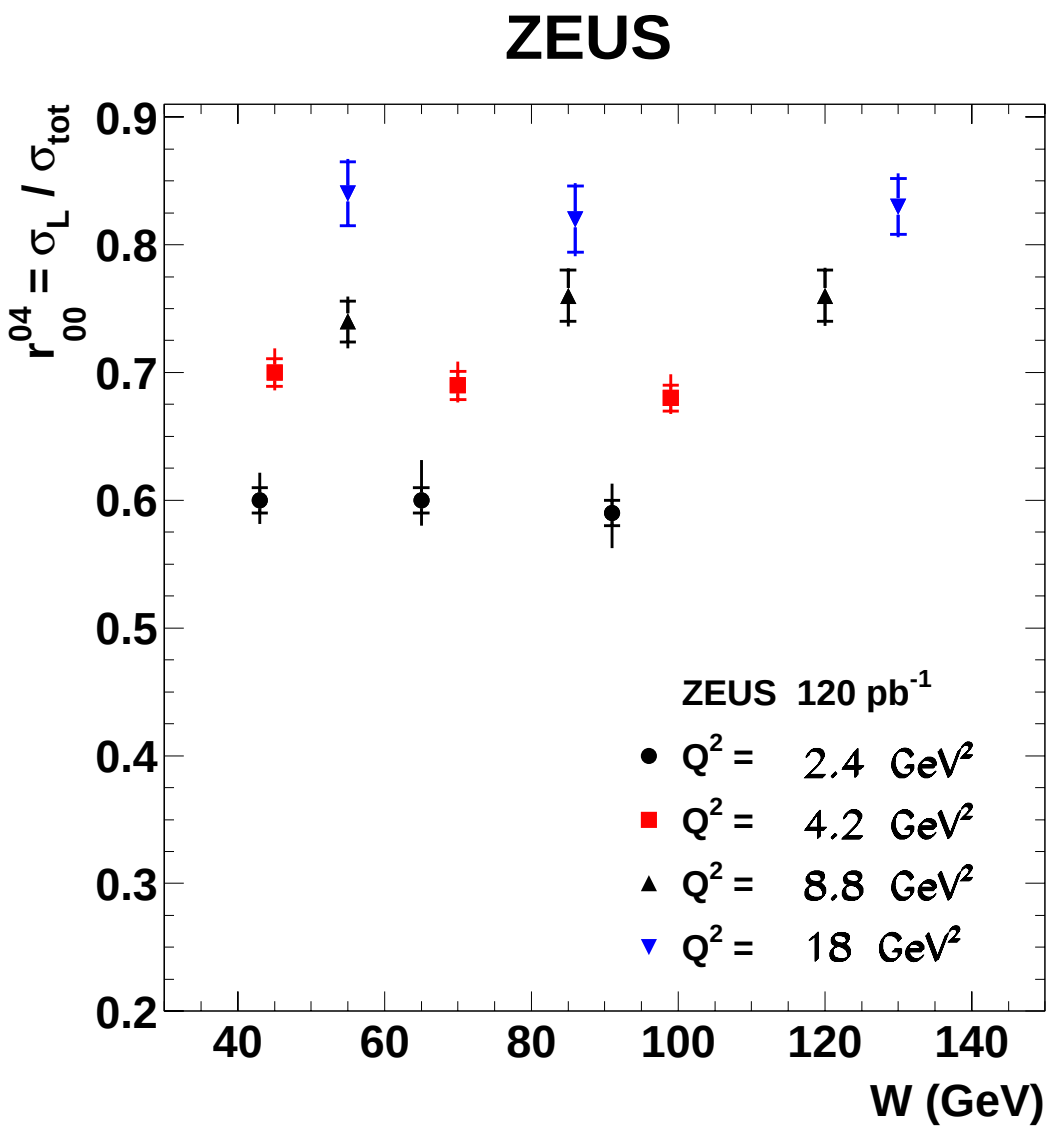
Helicity angles study, $R = \sigma_L/\sigma_T$

- **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,** $\gamma^*_T \longrightarrow \rho_L$
- **if SCHC holds** $\longrightarrow R = \sigma_L/\sigma_T = r^{04}_{00}/\epsilon(1 - r^{04}_{00})$
- **if not** $\longrightarrow r^{04}_{00} \longrightarrow r^{04}_{00} - \Delta^2$, $\Delta \propto r^5_{00}/\sqrt{2r^{04}_{00}}$
- **R(SCHC) - R(SCHNC)** $\sim$ **3 %**

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



$R = \sigma_L / \sigma_T$ does not depend on W



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