Physics Results from HERA

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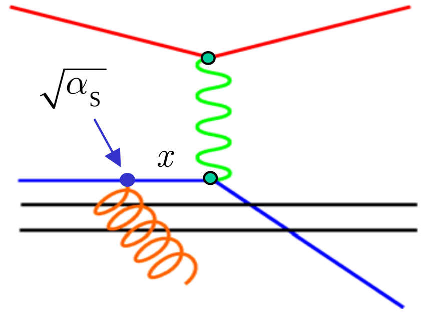
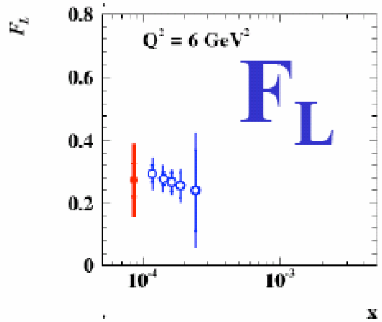
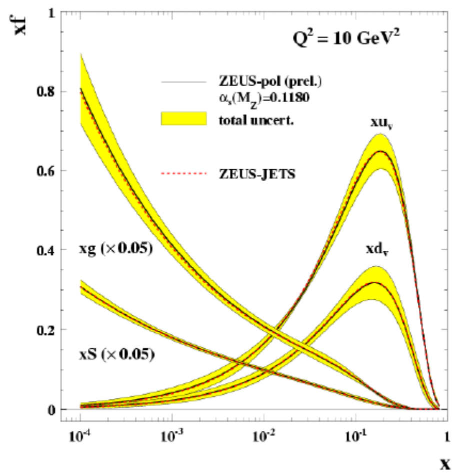
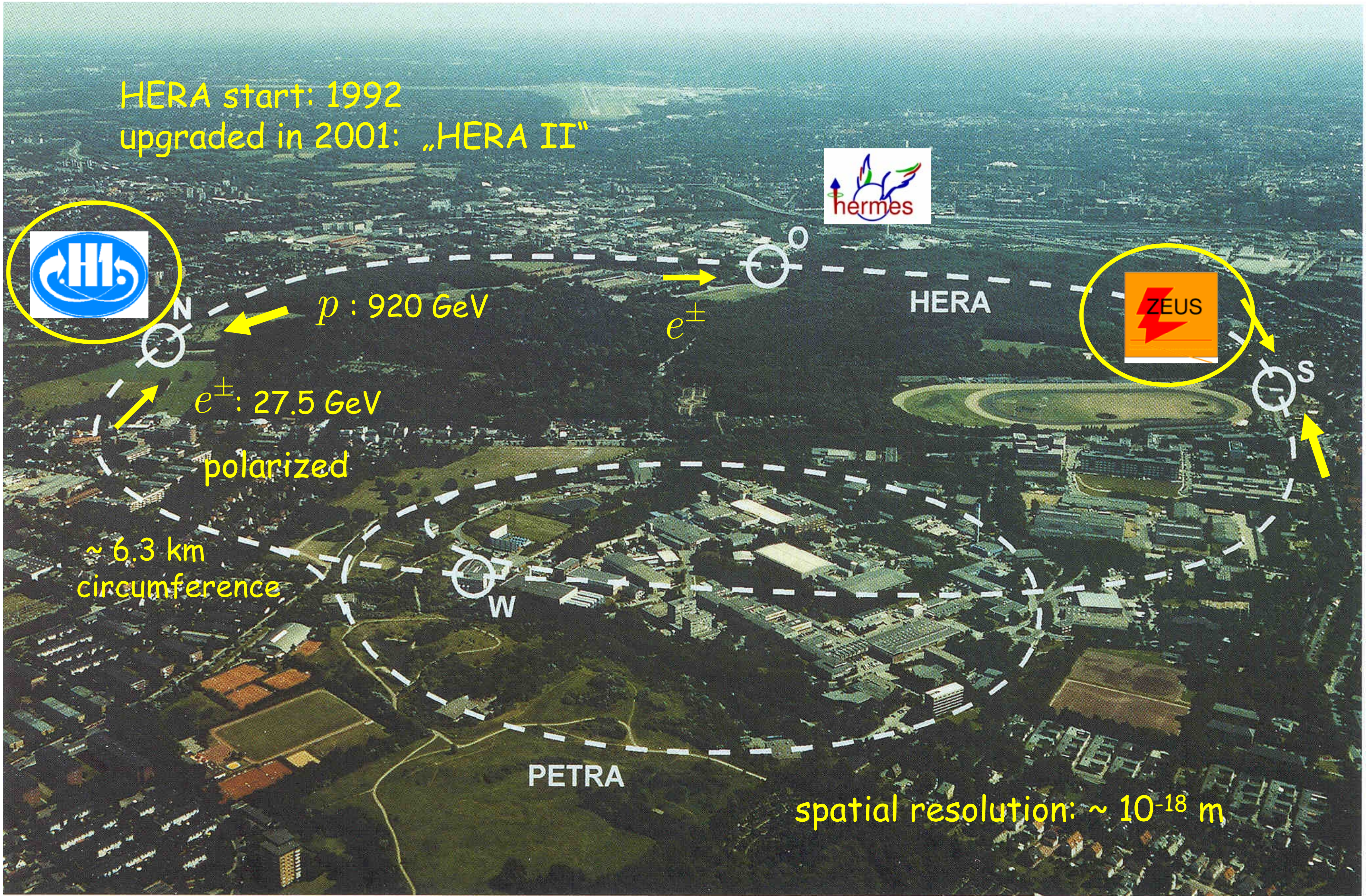


- Introduction to HERA: the QCD-machine
- Recent Results from Inclusive Scattering
- Diffraction at HERA
- Partonic Structure of Diffractive Exchange
- The last 3 Months
- Summary and Conclusions

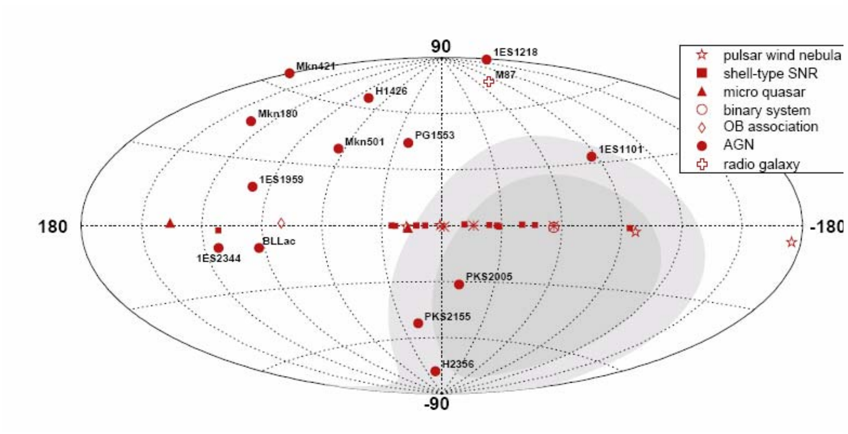




HERA – the world's largest electron microscope
(Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)



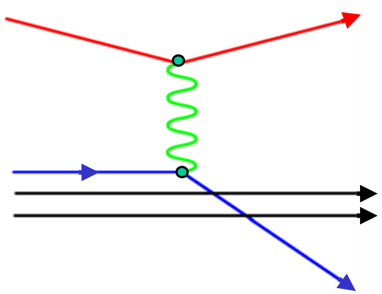
HERA and VHE γ-rays



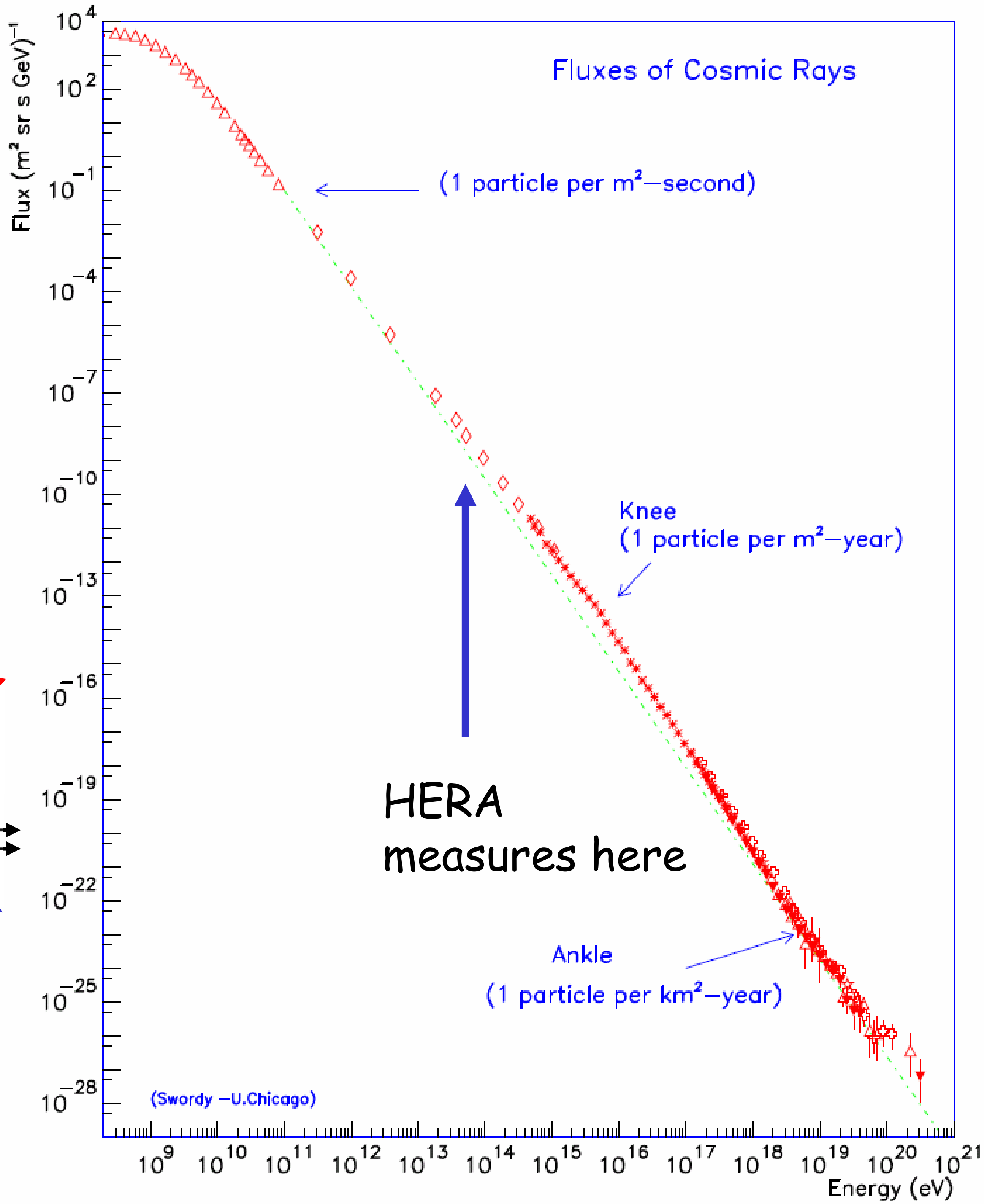
HERA is a collider:

$$E_e = 27.5\,\mathrm{GeV}$$

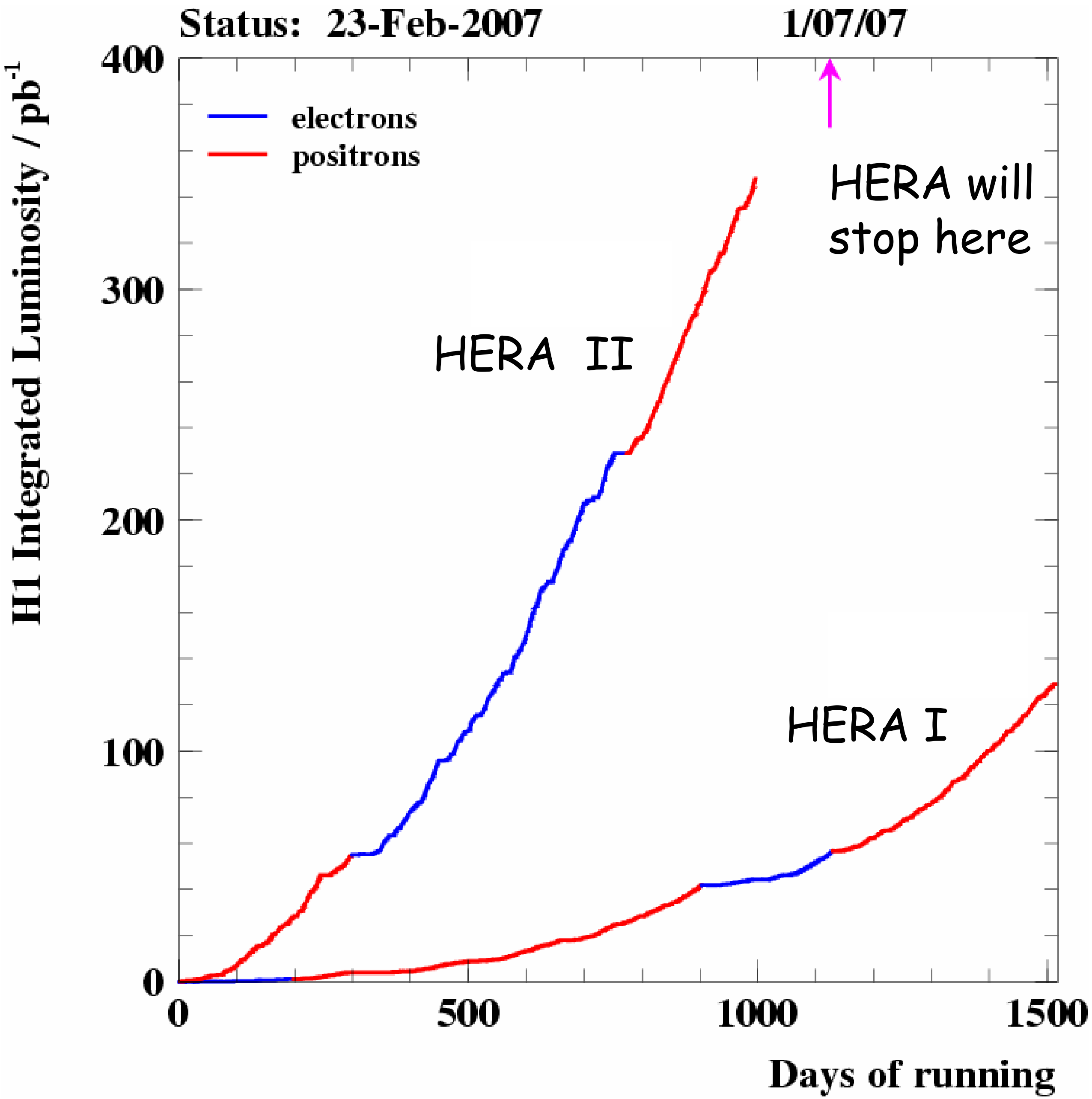
$$E_p = 920\,\mathrm{GeV}$$



→ 50 TeV photon beam on a stationary proton target



HERA Luminosity



HERA I: 1992-2000

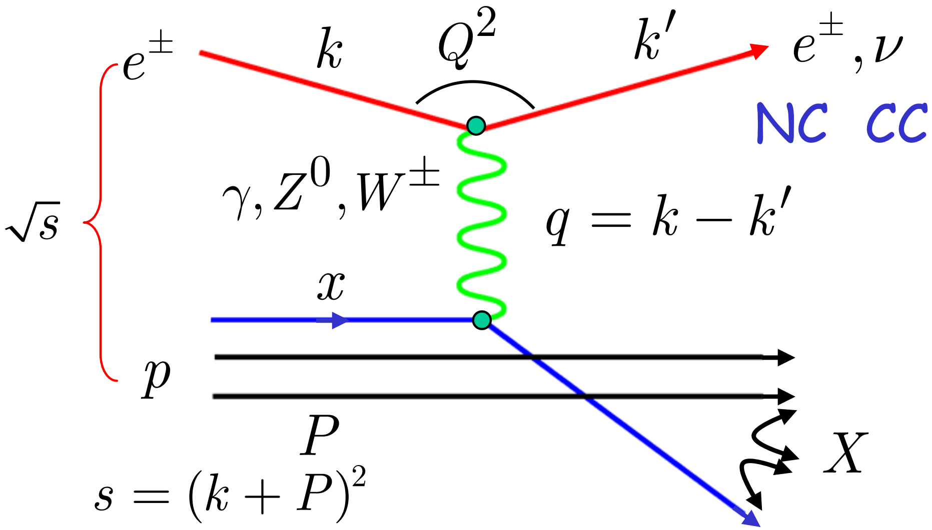
HERA II upgrade:

- luminosity
- longitudinal polarization of the lepton beams (spin rotator pairs around the interaction regions)

$$\langle P_e \rangle \sim 30 - 40\%$$

- running efficiently from 2003 onwards
- massive upgardes also for the detectors

Deep Inelastic Scattering (DIS)



$$s = (k+P)^2$$

$$Q^2 = -(k-k')^2 = -q^2$$

$$W^2 = M_X^2 = (q+P)^2$$

$$x = \frac{Q^2}{2\,P\cdot q}$$ fraction of the proton momentum carried by the charged parton

$$y = \frac{P\cdot q}{P\cdot k}$$ fraction of the electron energy carried by the virtual photon („inelasticity")

$$\boxed{Q^2 = sxy}$$ fixed s: 2 indep. variables

DIS :

electron scatters off a charged constituent (parton) of the proton (= elastic scattering)

$$\frac{d^2\sigma(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3 \right]$$

$$Y_\pm = 1 \pm (1-y)^2$$

"reduced cross section" σ_r (bracketed term)

γ exchange only:

$$F_2(x) = \sum_{i=u,d} e_i^2 x q_i(x)$$

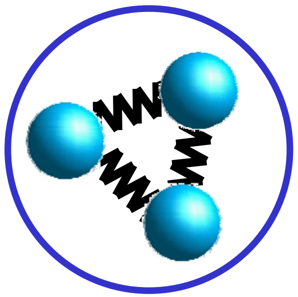
parton densities $xf_i(x)$ (pdf)

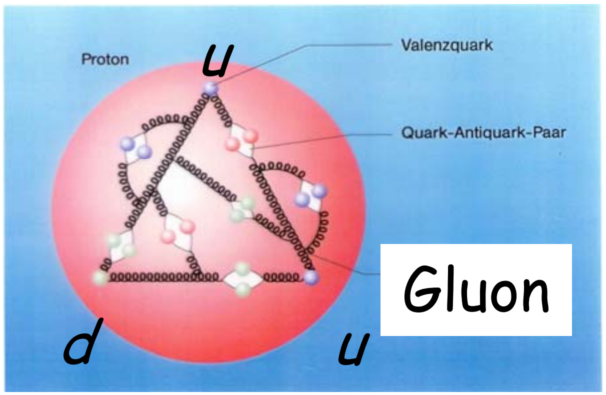
$W^\pm$ exchange only:

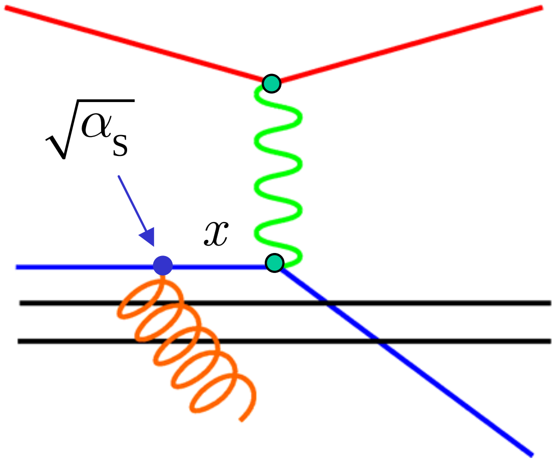
$$e^- p: \quad F_2(x) \sim xq_u(x)$$

$$e^+ p: \quad F_2(x) \sim (1-y)^2 xq_d(x)$$

Quantum Chromodynamics (QCD)







Basic ingredients of QCD:

1. Asymptotic freedom :

$\alpha_s \to 0$ at short distances

→ perturbative QCD (pQCD)

2. Factorization :

„hard" scale Q^2

$$\sigma = \sum_i \sigma_{\gamma^* i}(Q^2) \otimes x f_i(x)$$

non-perturbative part

3. Evolution (calculable in pQCD) :

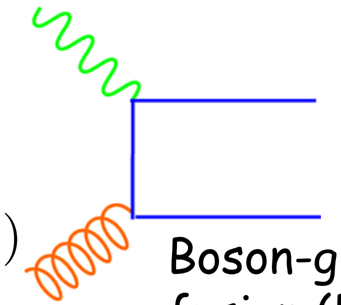
Parton densities become functions of Q^2

$xq_i(x) \to xq_i(x,Q^2)$ quarks

$x\bar{q}_i(x,Q^2)$ antiquarks

\+ gluons

$g(x,Q^2)$



Boson-gluon fusion (BGF)

Kinematic Regime of HERA

- large reach in x
- large reach in Q^2

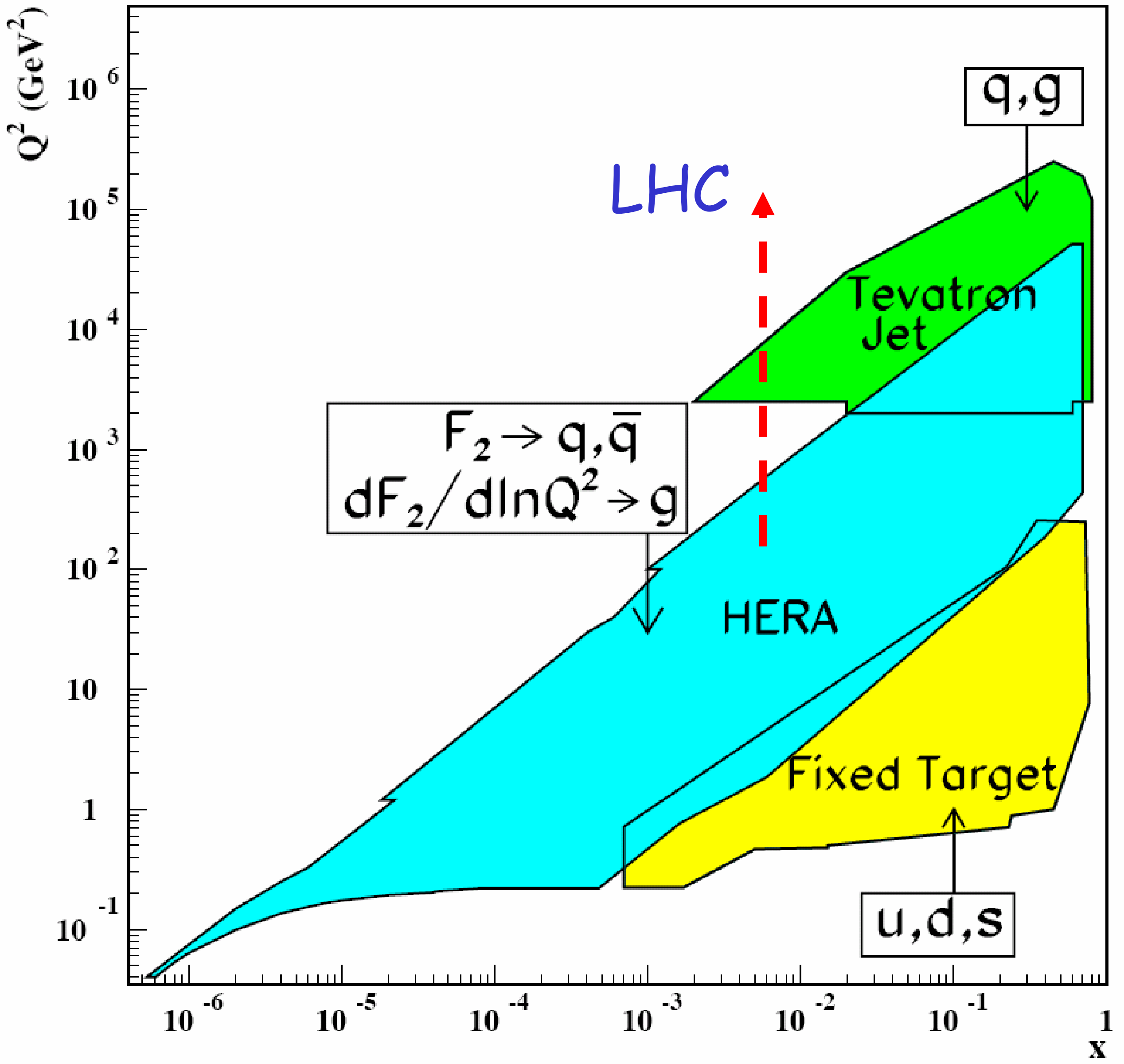
"Inclusive" scattering
(integrate over all
hadronic final states X)

→ pdf's of quarks from F_2

→ pdf of gluon from Q^2 variation of F_2 (e.g. DGLAP evolution)

New: $P_e = \frac{N_R - N_L}{N_R + N_L}$

longitudinal polarization



QCD Analysis of F_2 data (low and high Q^2)

Very precise measurements of F_2 provided by ZEUS and H1

Clear scaling violation observed, violation is driven by gluon emission

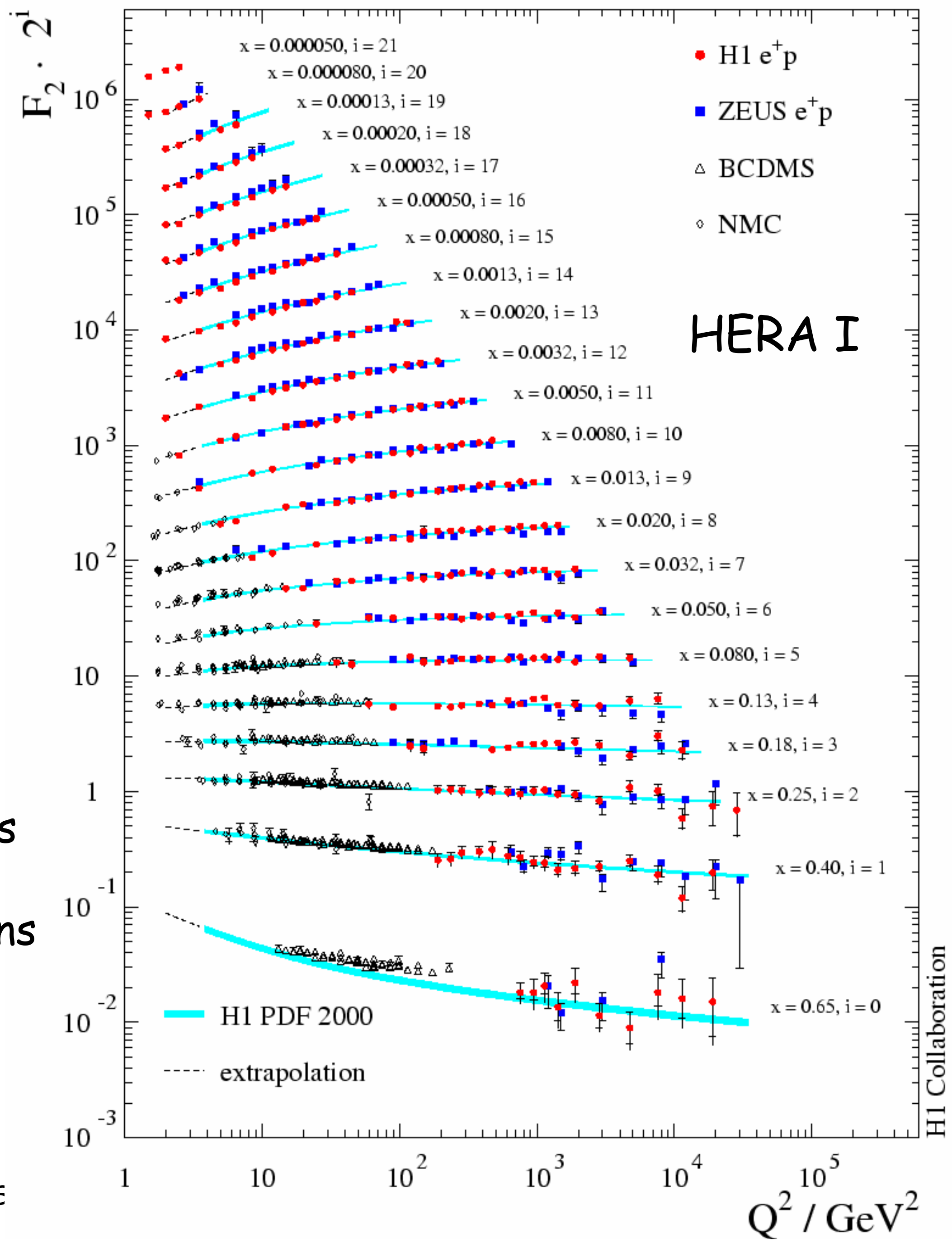
Describing this data in a QCD fit gives access to the parton densities within the proton

- Parameterize parton densities, typically

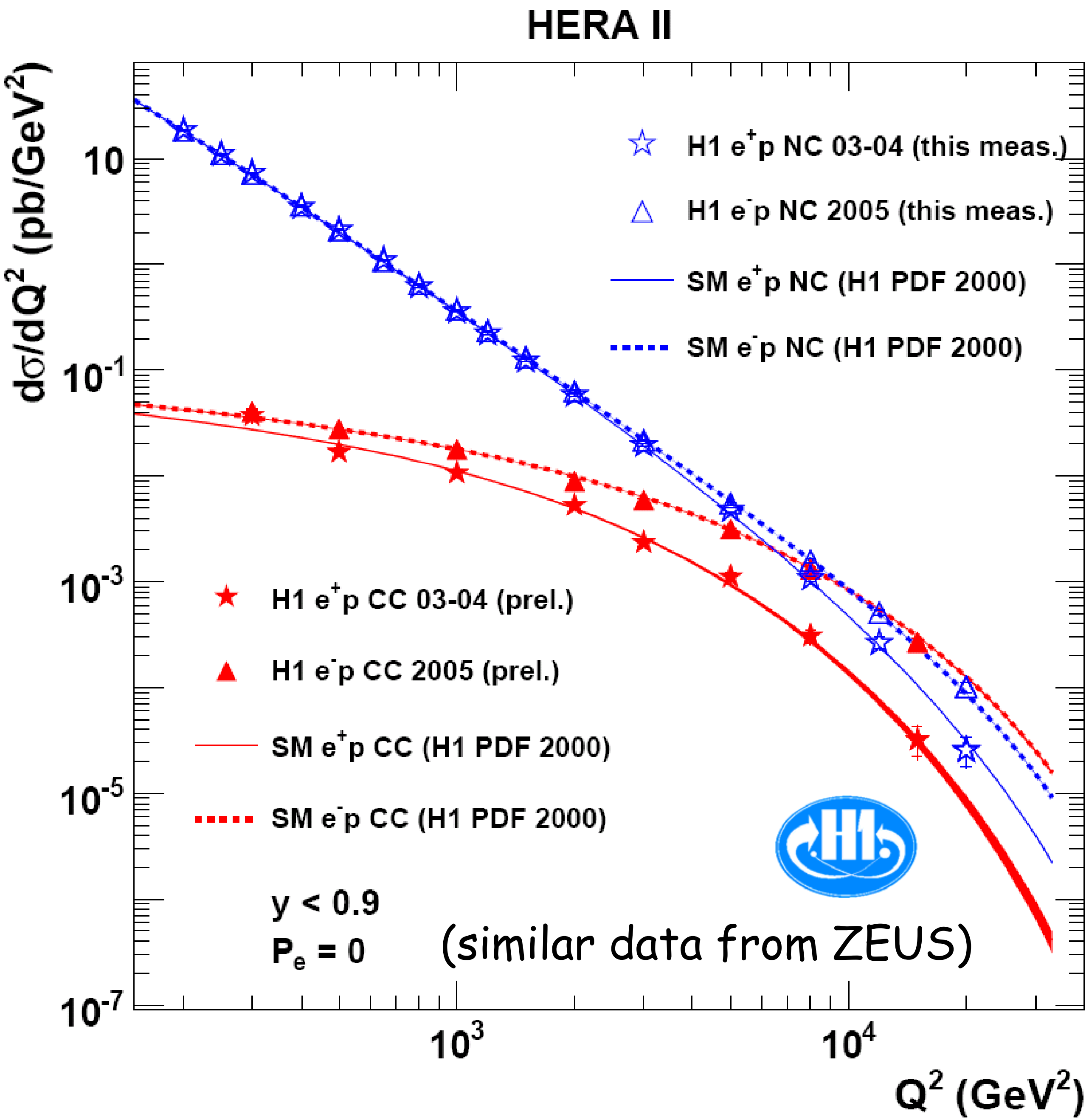
$$xf(x,Q_0) = Ax^B(1-x)^C\left[1 + D\sqrt{x} + Ex\right]$$

- Fit data to obtain the various parameters (e.g. H1 uses 16 including α_s), evolution in Q^2, e.g. using DGLAP equations

Data are very well described by QCD



Electroweak Unification at High Q^2 (NC & CC)



combine data from both polarization states (unpolarized cross sections)

$$\sigma_{NC} \gg \sigma_{CC}$$

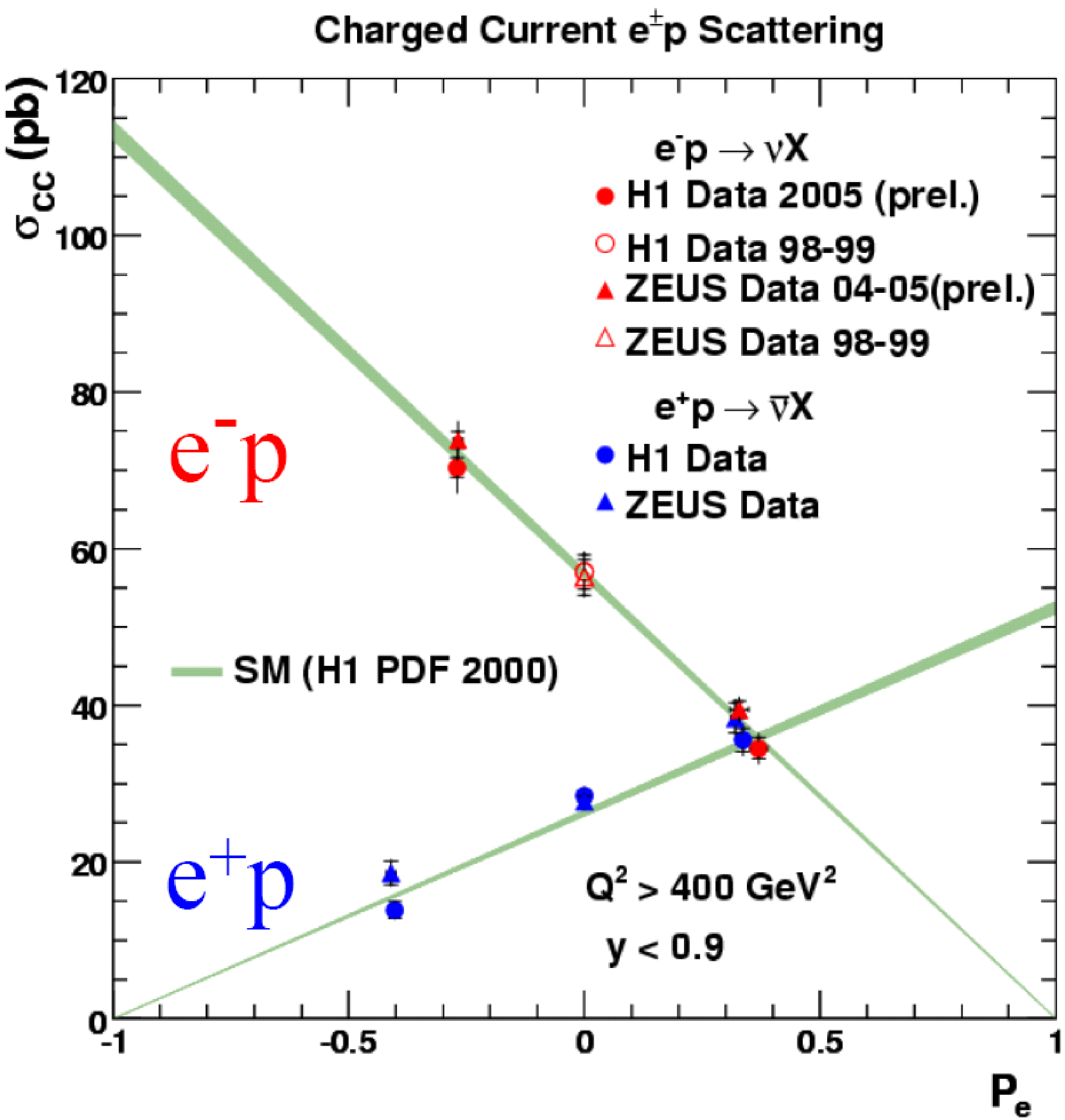
for $Q^2 \ll M_Z^2$

(photon exchange dominates)

$$Q^2 \geq M_Z^2 : \quad \sigma_{CC} \sim \sigma_{NC}$$

manifest electroweak unification

Recent results from High Q² Reactions (CC)



Total CC cross section with longitudinally polarized electrons and positrons

$$\sigma_{cc}^{e^{\pm}p}(P_e) =$$

$$(1 \pm P_e)\sigma_{cc}^{e^{\pm}p}(P_e = 0)$$

- linear dependence on P_e firmly established
- extrapolations to $P_e = \mp 1$ consistent with zero
  → no right-handed weak currents
- $e^- : M_{W_R} > 208\,\text{GeV}$

  $e^+ : M_{W_R} > 186\,\text{GeV}$

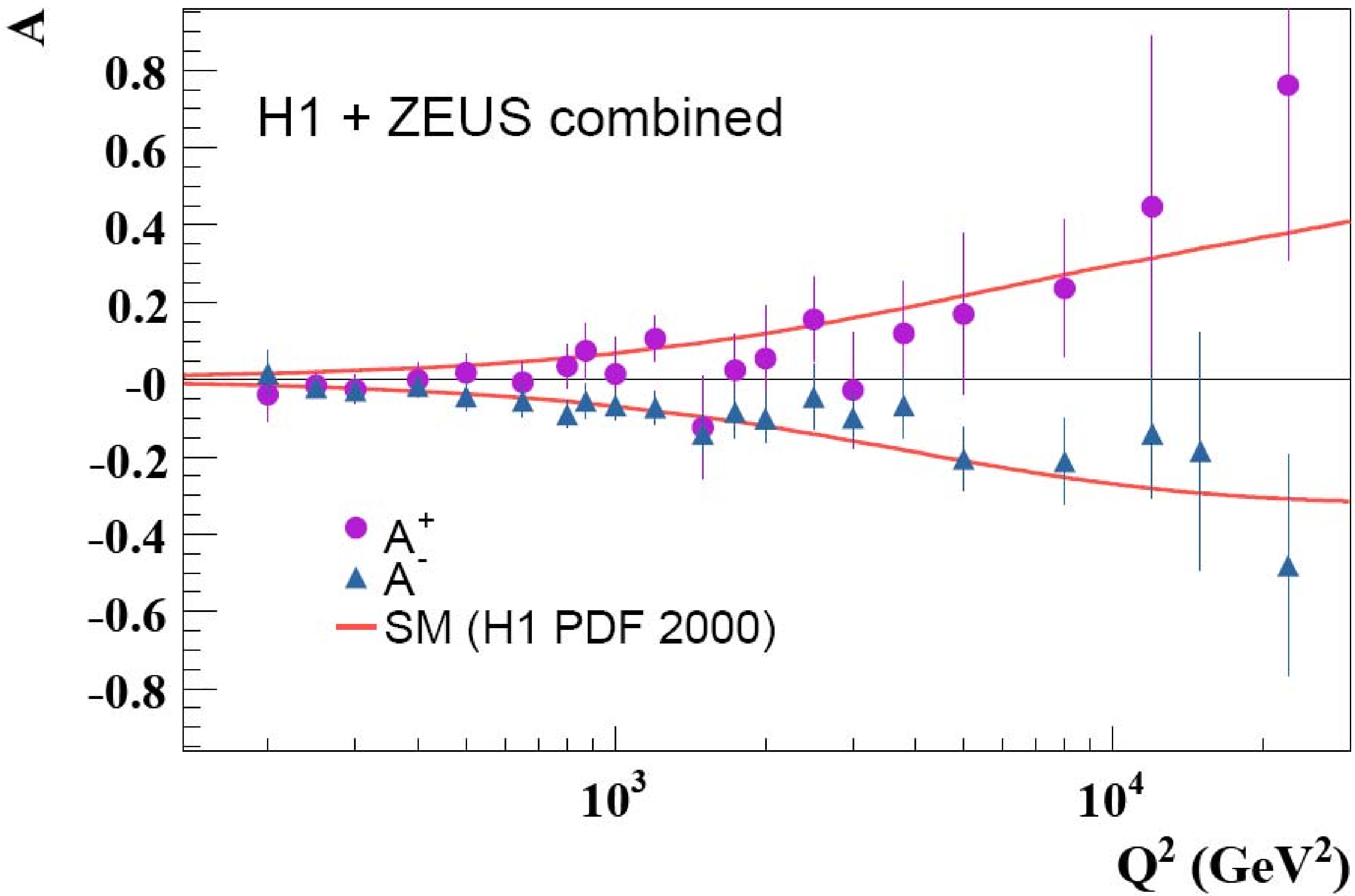
  $95\%\,C.L.$

Recent results from High Q^2 Reactions (NC)

Polarization asymmetry:

$$P_e = \frac{N_R - N_L}{N_R + N_L} \qquad P_R : P_e > 0 \qquad P_L : P_e < 0$$

$$A^{\pm} = \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \cdot \frac{2}{P_R - P_L}$$



$$\sigma^{\pm} \equiv \sigma_{NC}^{e^{\pm}p}$$

$$\delta A = A^{+} - A^{-}$$

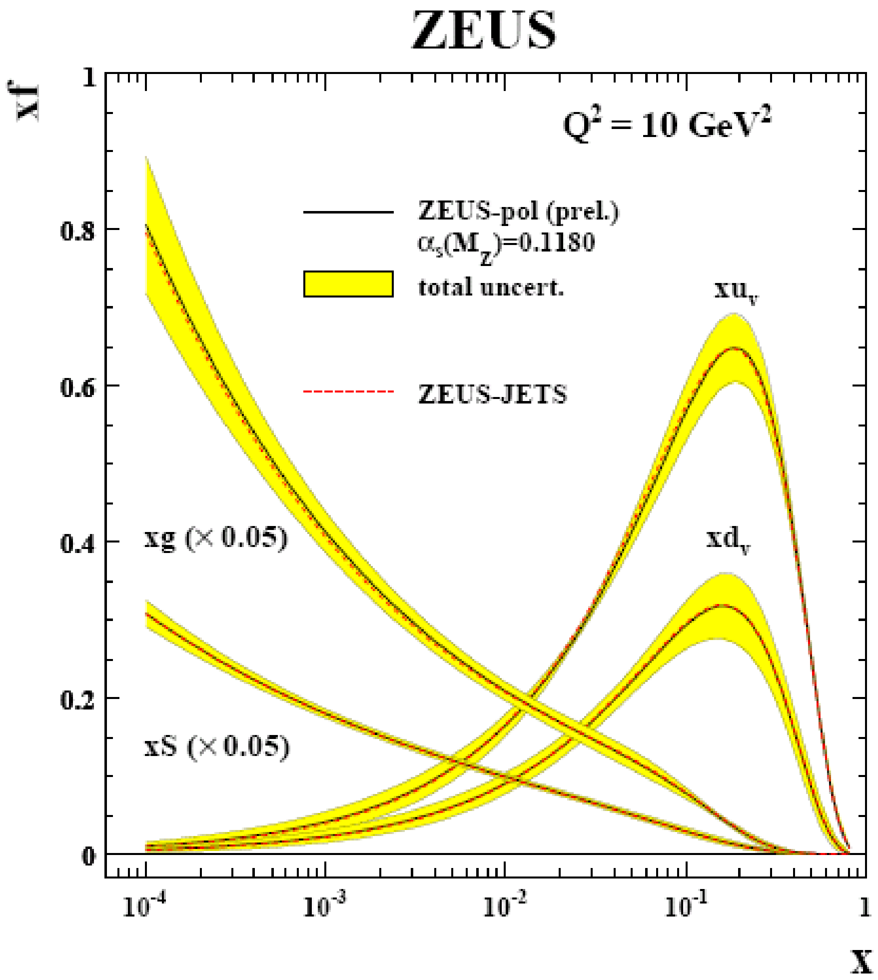
test for $\delta A = 0$:

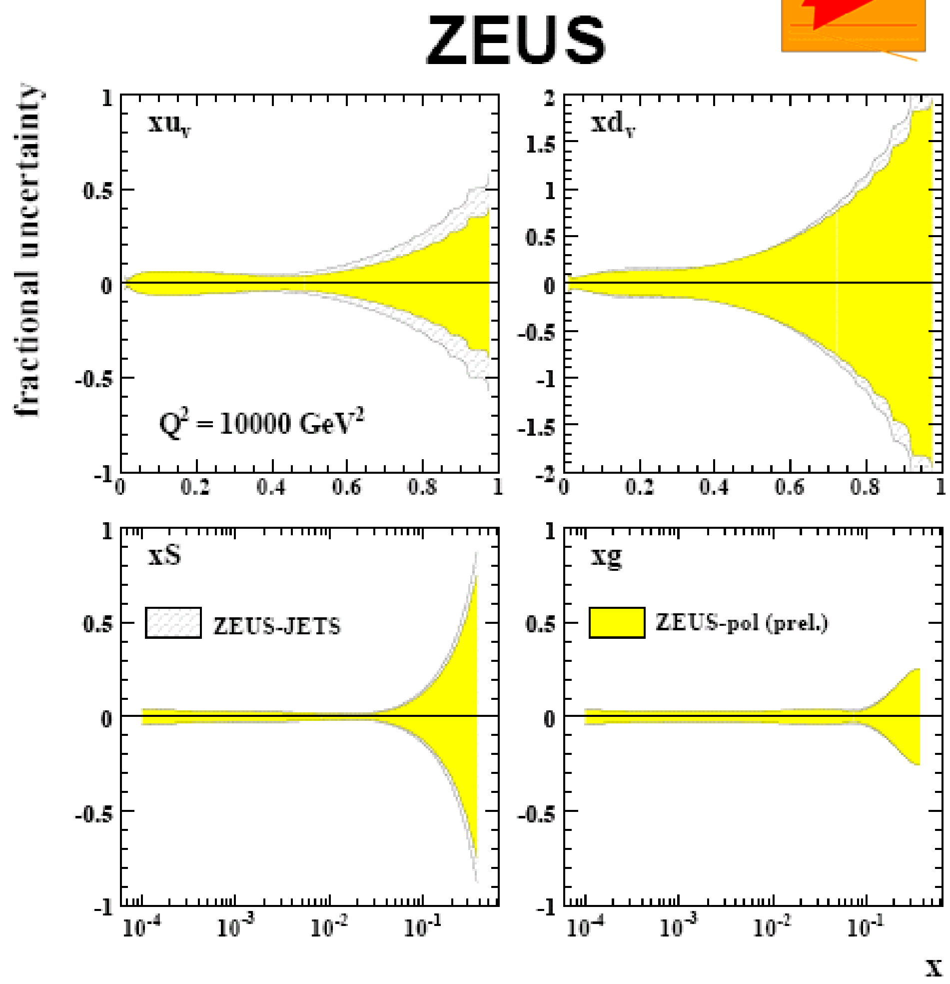
$$\chi^2 / ndf = 4.0$$

(prob $< 3 \times 10^{-3}$)

Parity violation in NC established @10^{-18} m

Uncertainties of the Parton Distribution Functions

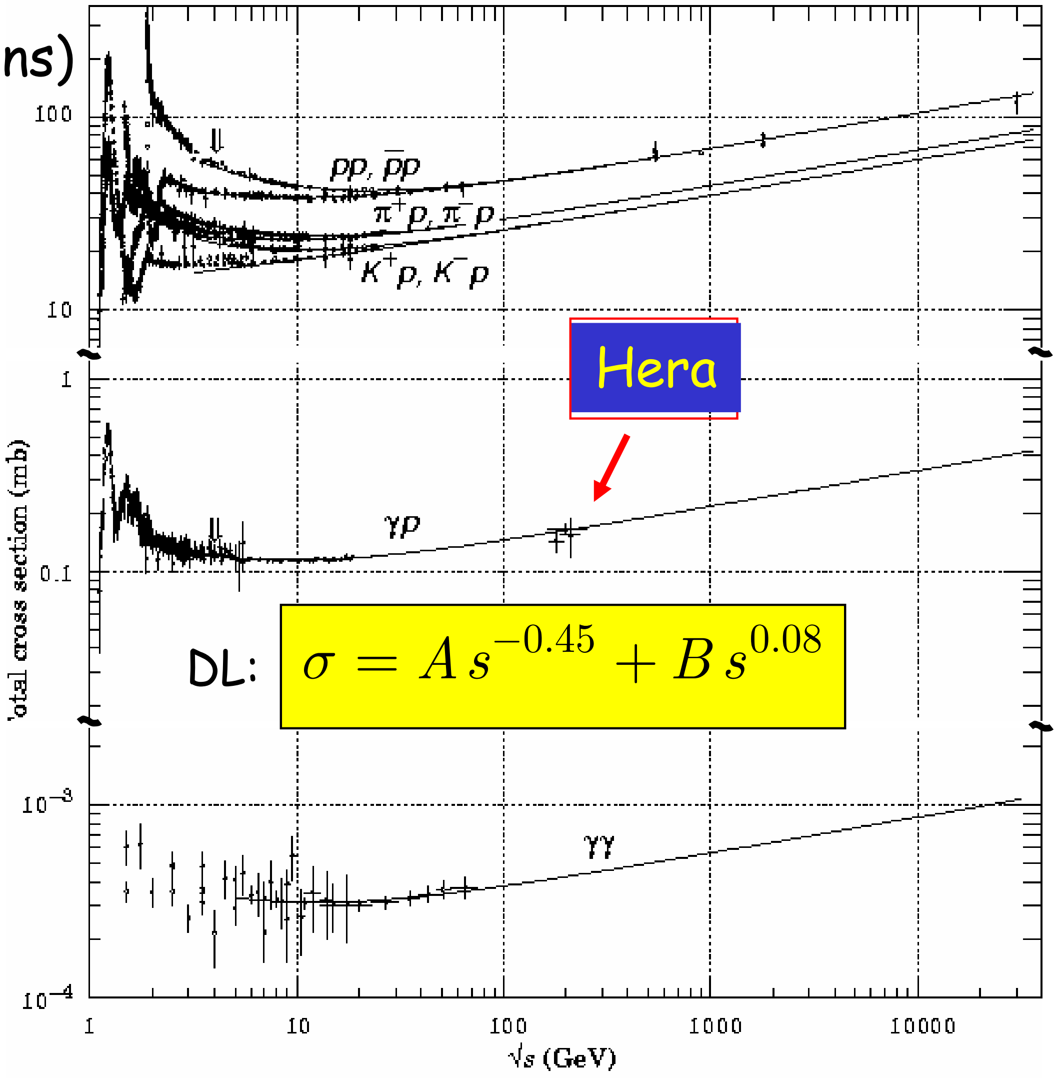




- Combined EW and QCD fit, including also data from inclusive (di) jets
- pdf's are supposed to be "universal", test these ideas in more detail: → diffraction

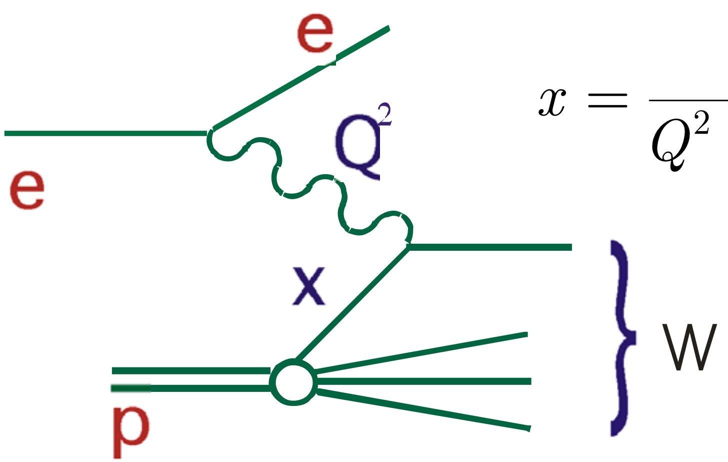
Diffraction: a short Introduction

- All total cross sections involving strongly interacting particles (hadrons) show approximate constancy, more precisely: a universal slow rise towards high energy
- „constant“ cross sections arise from Diffractive Phenomena
- Regge theory: trajectory in the t-channel
  vacuum QNE = „Pomeron“
- QCD: colorless exchange
  Gluons, quarks in a color singlet ?

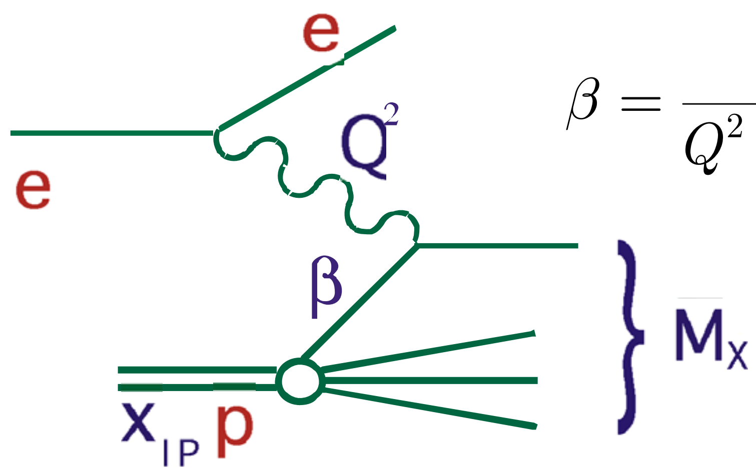


What is diffraction in the partonic language ?

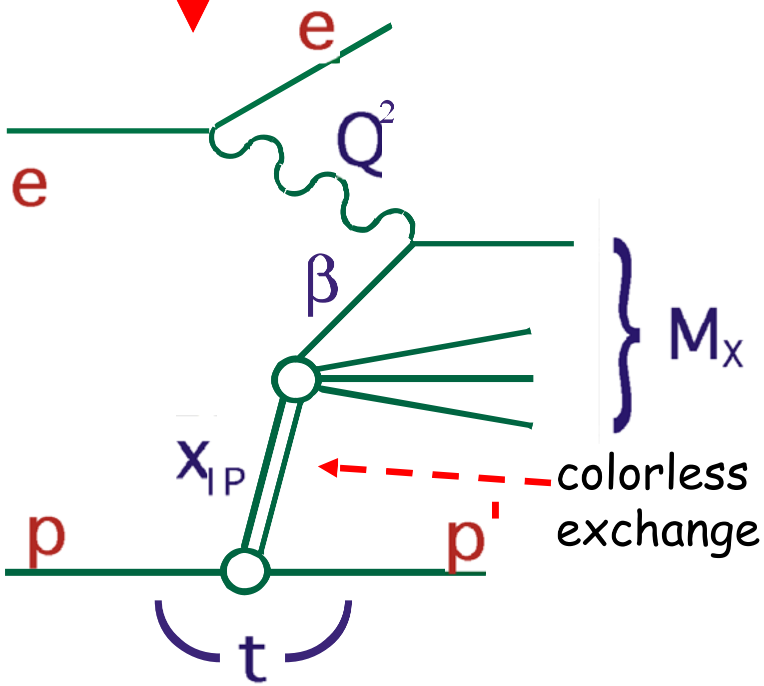
From Inclusive Scattering to Diffraction: Kinematics



$$x = \frac{Q^2}{Q^2 + W^2}$$



$$\beta = \frac{Q^2}{Q^2 + M_X^2}$$



$$x_{\mathbf{P}} = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

x (DIS) $\Leftrightarrow$ β (Diff. DIS)

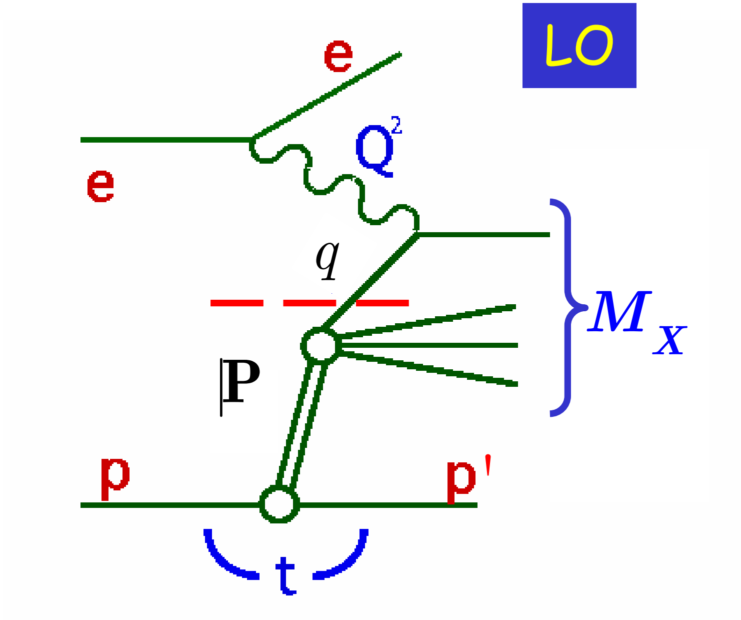
momentum fraction of color singlet exchange relative to the proton

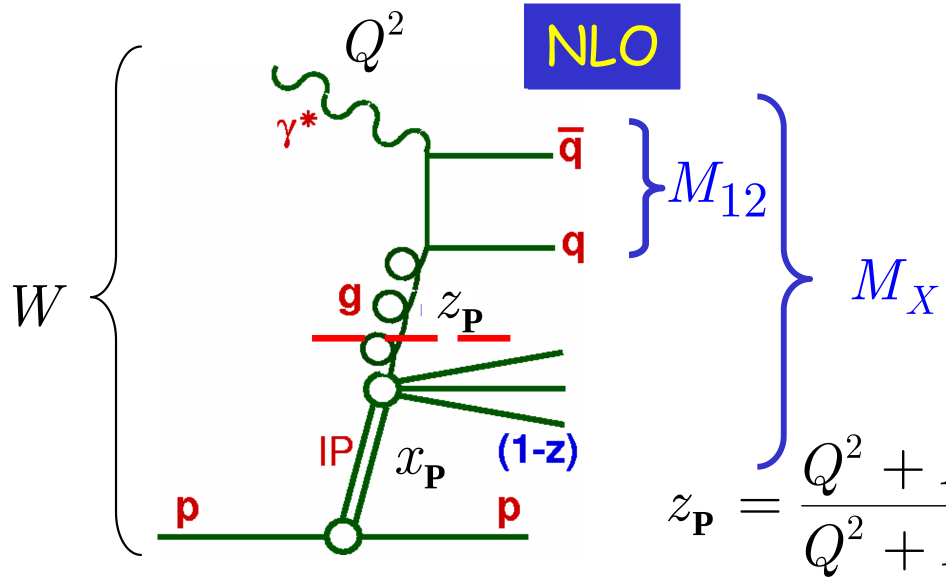
$$\beta = \frac{Q^2}{Q^2 + M_X^2} = x \,/\, x_{\mathbf{P}}$$

momentum fraction of charged constituent of the diffractive exch., participating in the hard scattering

$t = (p - p')^2$ (momentum transfer)^2 at proton vertex

Factorization: the General Idea





$$z_{\mathbf{P}} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$

measure $F_2^D(\beta, Q^2)$:

↓

quarks dominate

measure $\frac{d\sigma}{dz_{\mathrm{P}}}(\text{di-jets/charm})$:

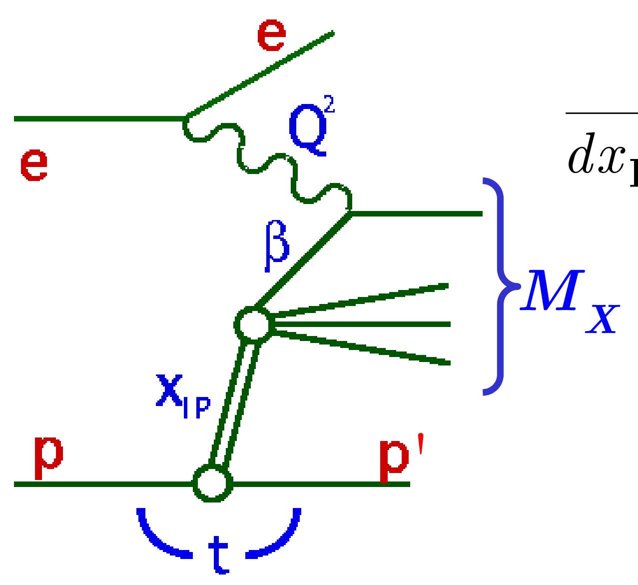
↓

gluon dominates

below the red line:
universal diffractive parton densities, identical for all processes

Test of factorization: measure pdf's in one process, use in another process for the prediction and compare to the data

Diffractive Cross Sections and QCD Factorization



$$\frac{d^4\sigma}{dx_{\mathbf{P}}\,dt\,d\beta\,dQ^2} = \frac{2\pi\alpha^2}{\beta Q^4}\left(1+(1-y)^2\right)\sigma_r^{D(4)}(x_{\mathbf{P}},\beta,t,Q^2)$$

$$\sigma_r^{D(4)} = F_2^{D(4)} - \frac{y^2}{1+(1-y)^2}F_L^{D(4)}$$

($F_L^{D(4)}$ can be neglected at low y)

(QCD) Factorization for diffractive scattering (Collins et al.):

$$\frac{d^2\sigma^{\gamma^* p\to p' X}(x,Q^2,x_{\mathbf{P}},t)}{dx_{\mathbf{P}}\,dt} = \sum_i \int_x^{x_{\mathbf{P}}} d\xi\, f_i^D(\xi,Q^2,x_{\mathbf{P}},t)\,\hat{\sigma}^{\gamma^* i}(\xi,Q^2)$$

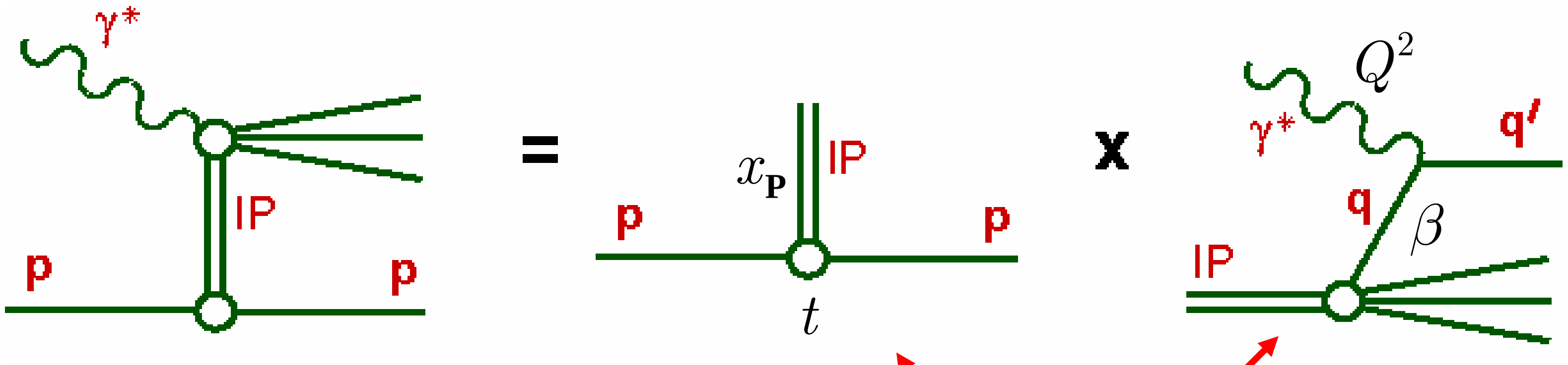
$f_i^D(\xi,Q^2,x_{\mathbf{P}},t)$ diffractive PDF's of flavor i in the proton, for fixed $x_{\mathbf{P}},t$ (evolves in Q^2 according to DGLAP)

$\hat{\sigma}^{\gamma^* i}(\xi,Q^2)$ universal, hard scattering cross section, calculable in pQCD

Regge Factorization

Additional assumption (no proof):

Regge factorization, the „Resolved Pomeron“ (Ingelman-Schlein-Model)



$$F_2^D(x_{\mathbf{P}}, t, \beta, Q^2) = f_{\mathbf{P}/p}(x_{\mathbf{P}}, t)\, F_2^{\mathbf{P}}(\beta, Q^2)$$

$$f_{\mathbf{P}/p}(x_{\mathbf{P}}, t) \sim 1 / x_{\mathbf{P}}$$

Pomeron flux factor

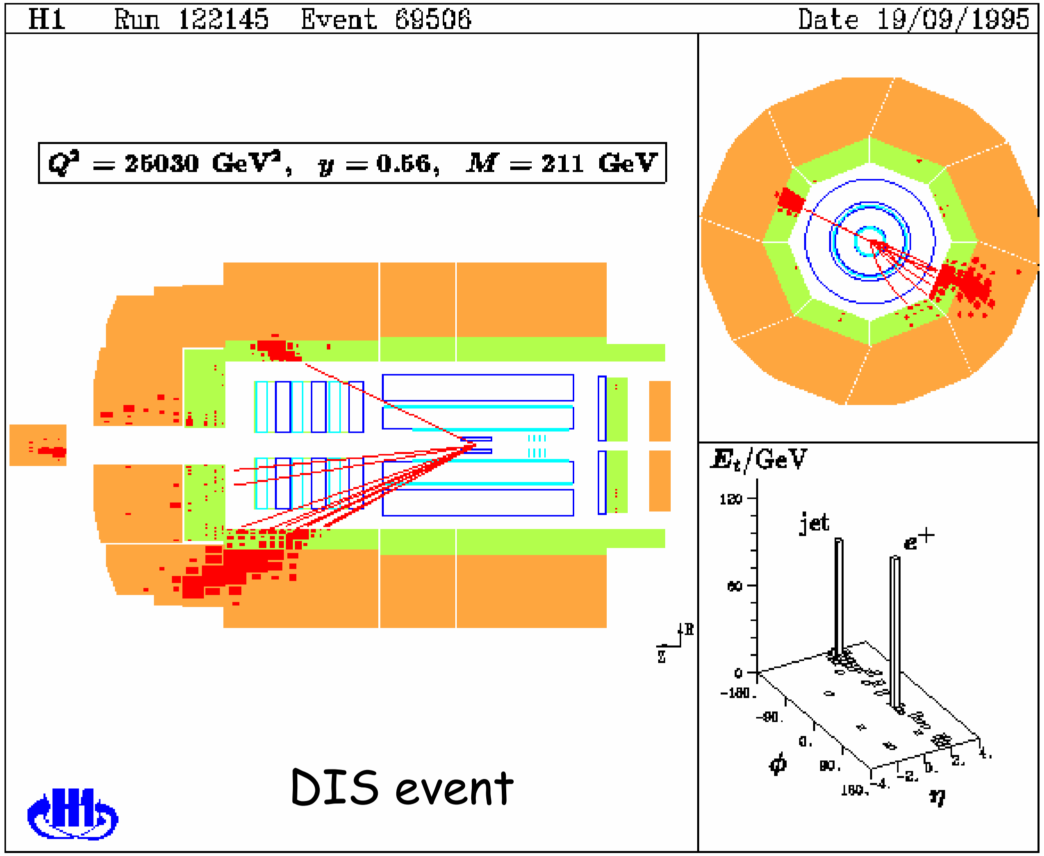
- shape of diffr. PDF's independent of $x_{\mathbf{P}}, t$
- normalization of F_2^D controlled by Pomeron flux

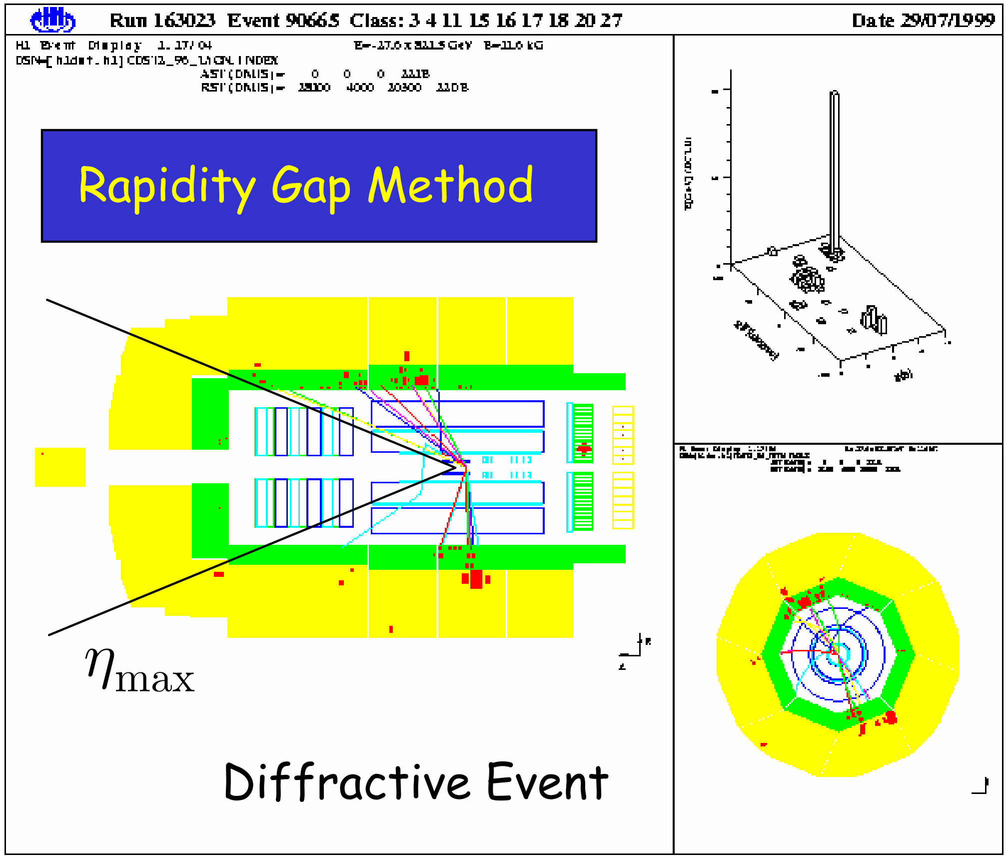
Integration over t (usually unobserved):

$$\sigma_r^{D(3)} = F_2^{D(3)} = \int dt F_2^{D(4)}$$

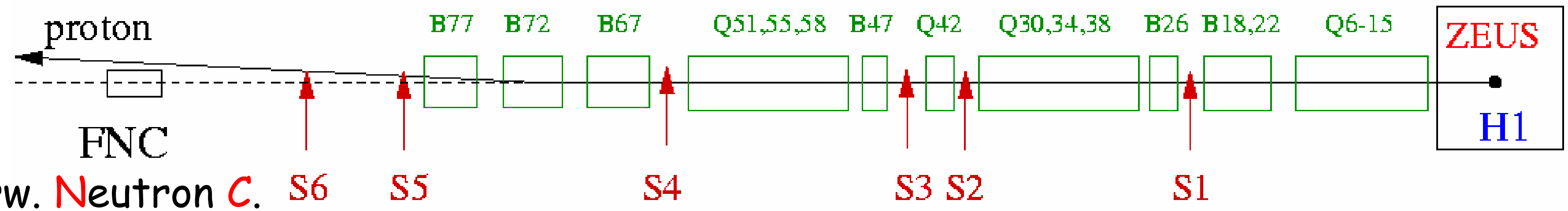
Experimental Techniques

Selection of diffractive events: 3 methods





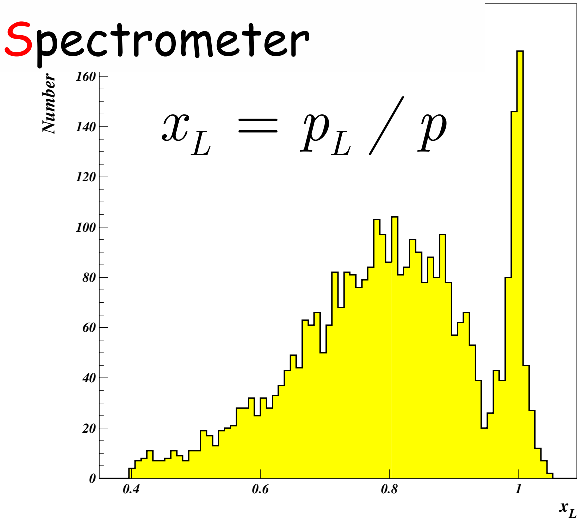
Experimental Techniques (cont.)



Forw. Neutron C.

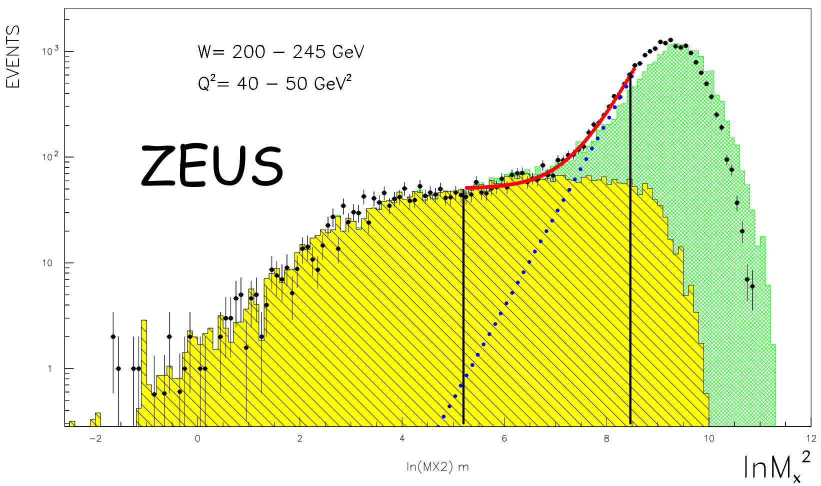
FPS Forw. Pr. Spect. LPS Leading Proton Spectrometer

LPS Method Measuring the scattered proton



proton scattered at small angles,
measured in LPS, get longitudinal and transverse
momentum components

M_X Method



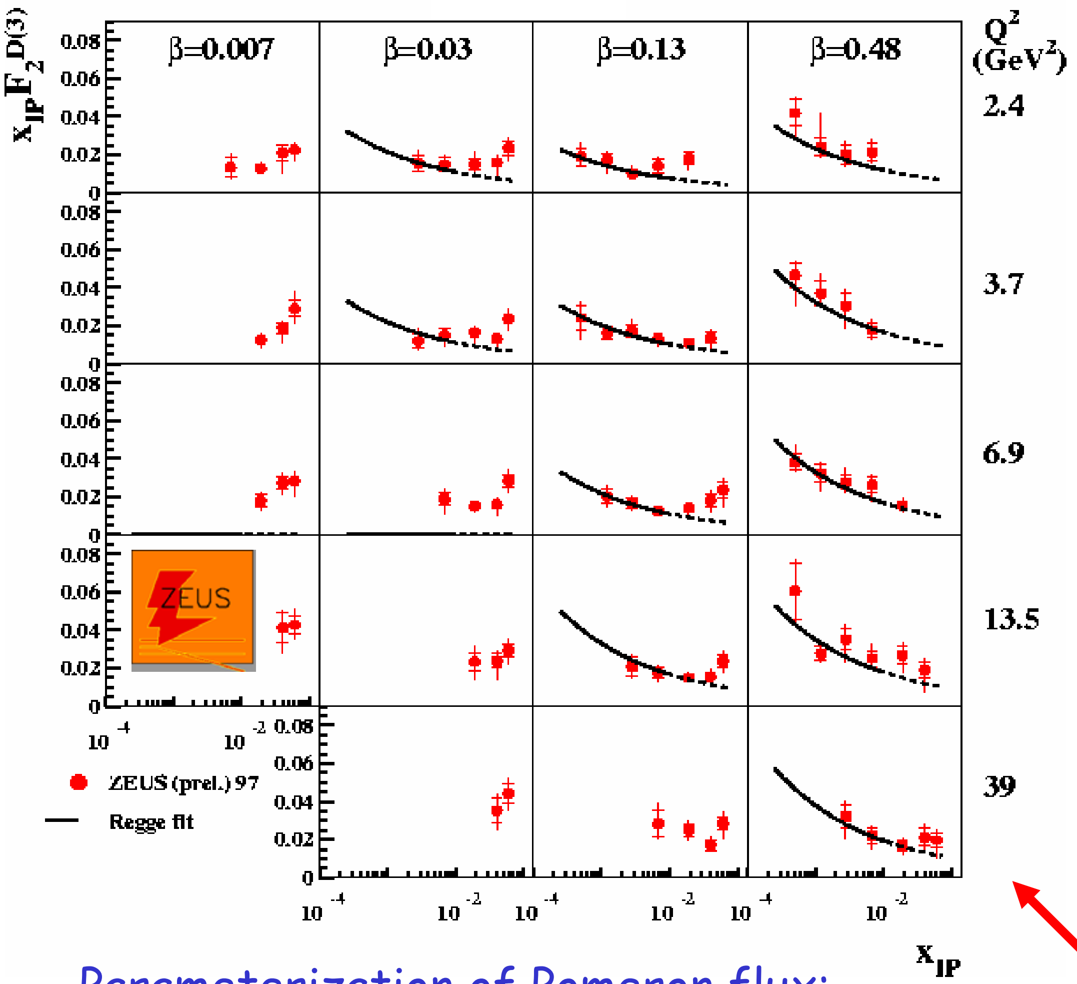
QCD radiation suppressed
between struck quark and proton
remnant ➔ rapidity gap

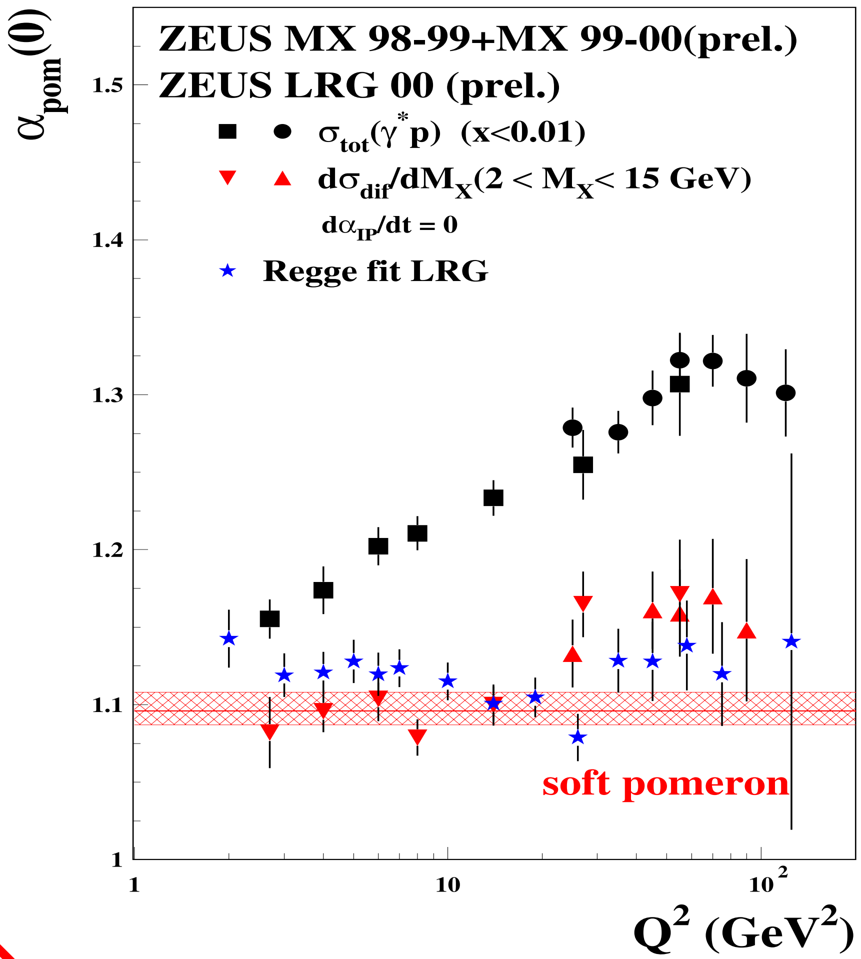
fit to non-diff mass distribution:

$$\frac{dN}{d\ln M_X^2} = D + Ce^{B\ln M_X^2}$$

Experimental Test of Regge Factorization

Example: ZEUS LPS data





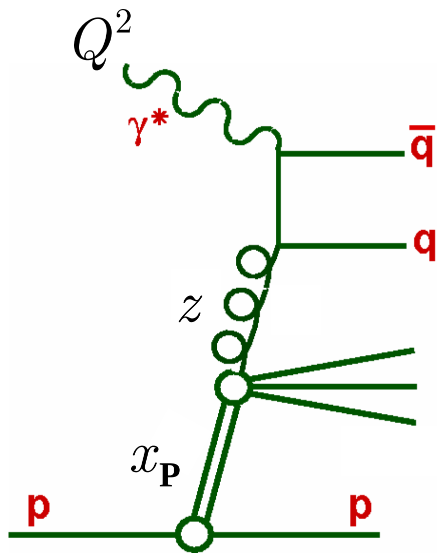
Parameterization of Pomeron flux:

$$f_{\mathbf{P}/p}(x_{\mathbf{P}}) \sim \frac{1}{(x_{\mathbf{P}})^{2\alpha_{\mathbf{P}}(0)-1}}$$

data support Regge factorization

Pomeron is not universal,
varies with Q², $\alpha_{\mathbf{P}}(\mathrm{DIS}) \neq \alpha_{\mathbf{P}}(\mathrm{DDIS})$

Partonic Structure of Diffraction: (NLO DGLAP fits)



- ansatz for the partonic structure:

$$\Sigma = \sum_{i=\text{light}} e_i^2 (zq(z,Q^2) + z\overline{q}(z,Q^2)); \qquad G = g(z,Q^2)$$

$$u = d = s = \overline{u} = \overline{d} = \overline{s}$$

$$zf_i(z,Q_0^2) = A_i z^{B_i}(1-z)^{C_i} \qquad Q_0^2 = 2.5\ \text{GeV}^2$$

- Charm/bottom via boson gluon fusion

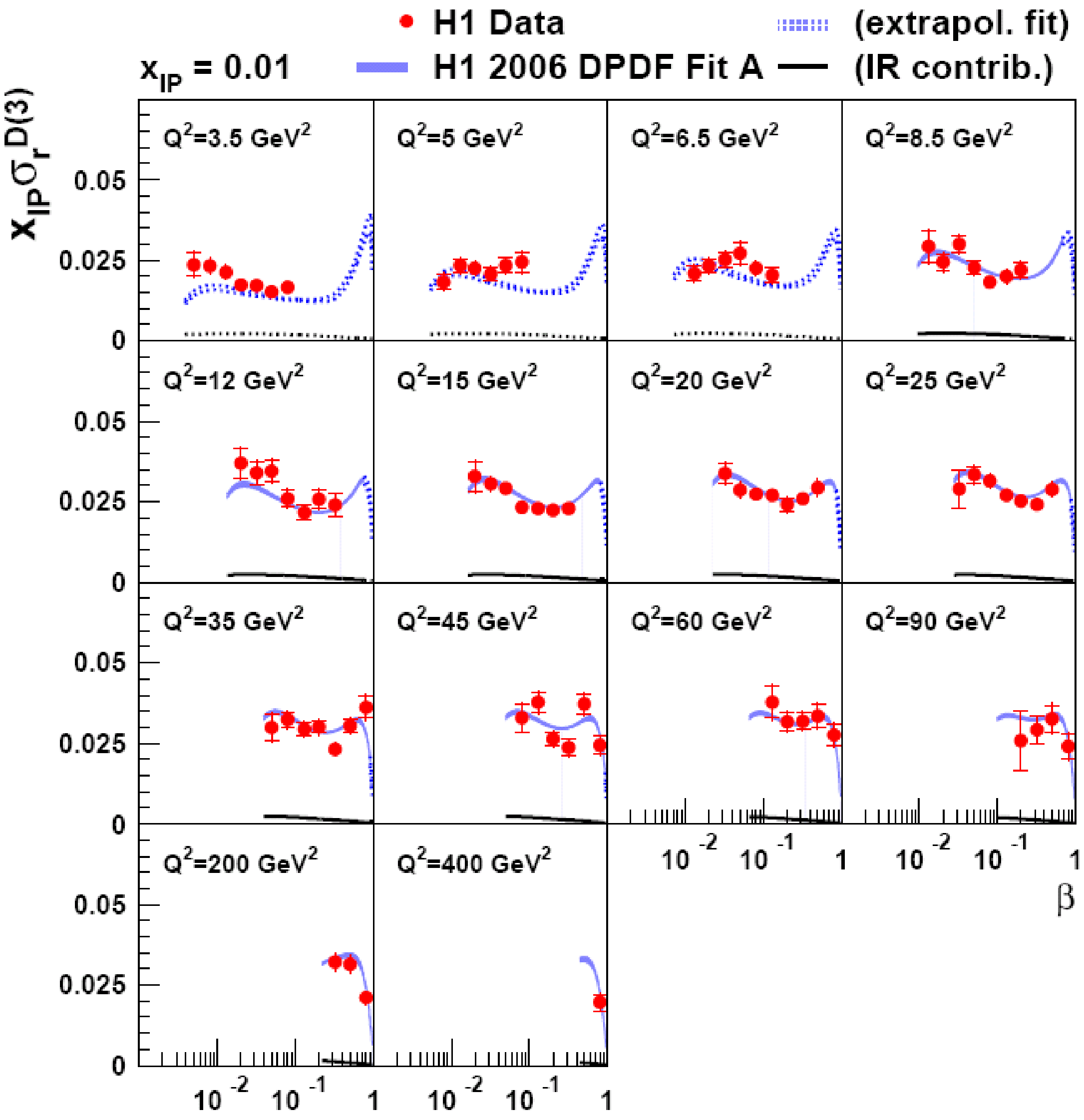
$$\Lambda = 399 \pm 37\,\text{MeV},$$

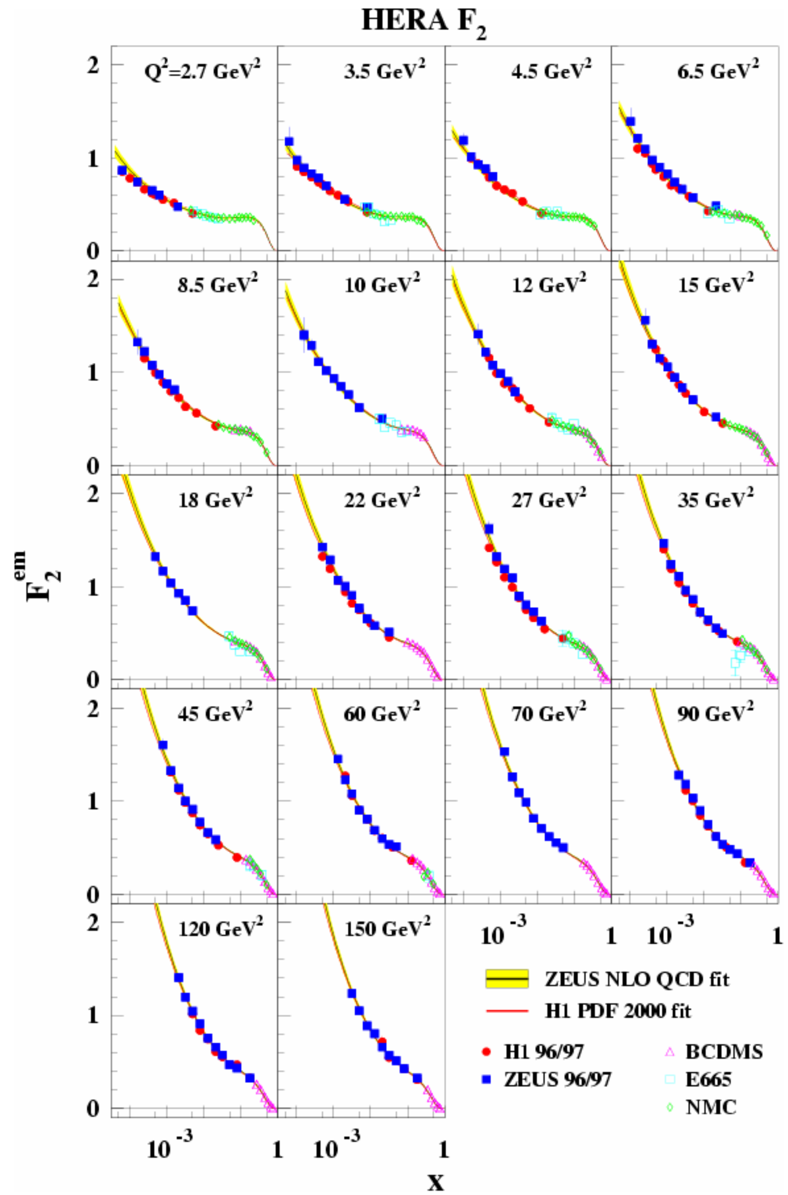
$$m_c = 1.4 \pm 0.2\,\text{GeV},\ m_b = 4.5 \pm 0.5\,\text{GeV}$$

- F_L^D via QCD relation
- for large $x_{\mathbf{P}}$ and small β the data demand an additional subleading Reggeon (meson exchange)
- NLO DGLAP fit for singlet and gluon contributions to $\sigma_r^{D(3)}(\beta, Q^2, x_{\mathbf{P}})$

$$8.5\,\text{GeV}^2 < Q^2 < 80\,\text{GeV}^2$$ → Diffractive pdf's: DPDF

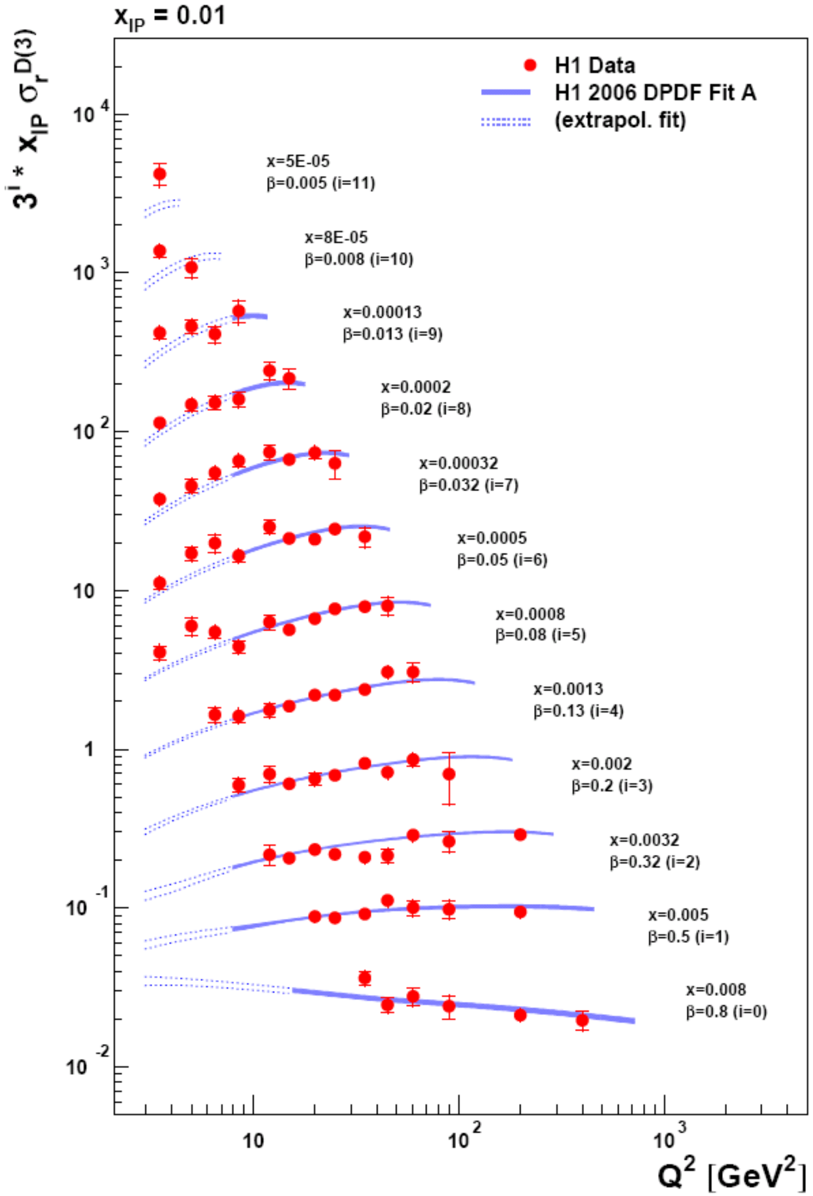
Diffractive vs Inclusive DIS: x-depend. β (Diff. DIS) $\Leftrightarrow$ x (DIS)





weak dependence on β , similar to the photon (few partons ?)

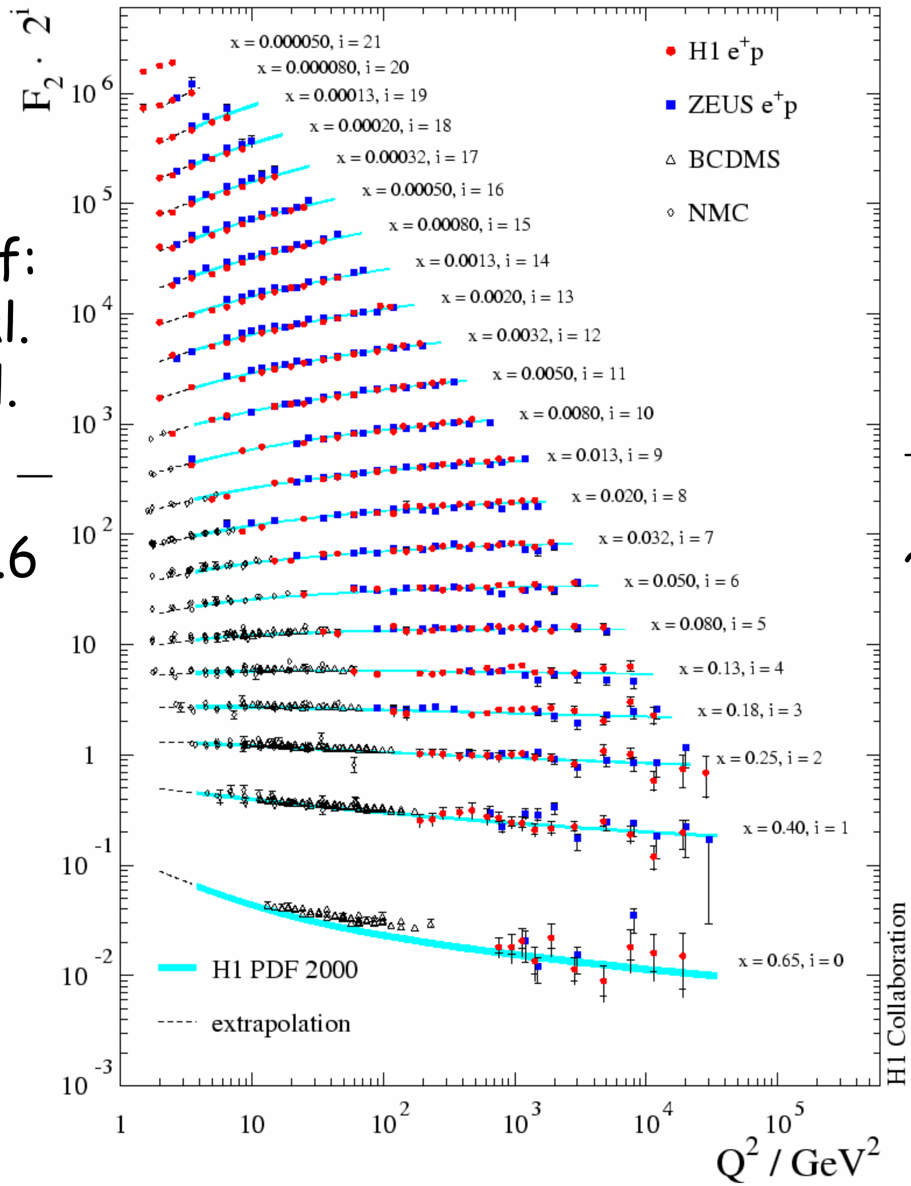
Diffractive vs Inclusive DIS (cont.): Q^2 dependence



diff:
scal.
viol.

+ ↔ −

~ 0.6



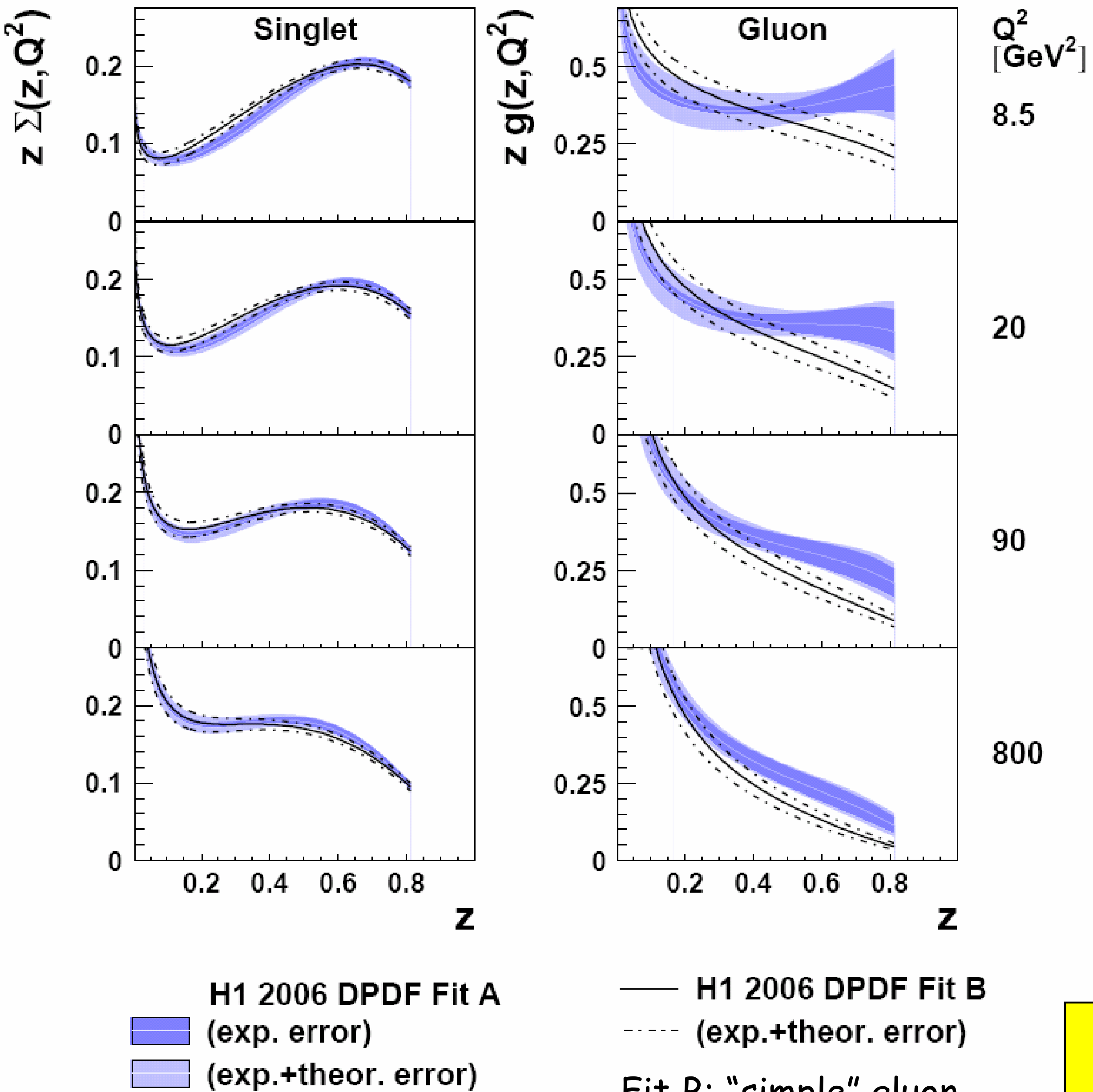
incl:
scal.
viol.

+ ↔ −

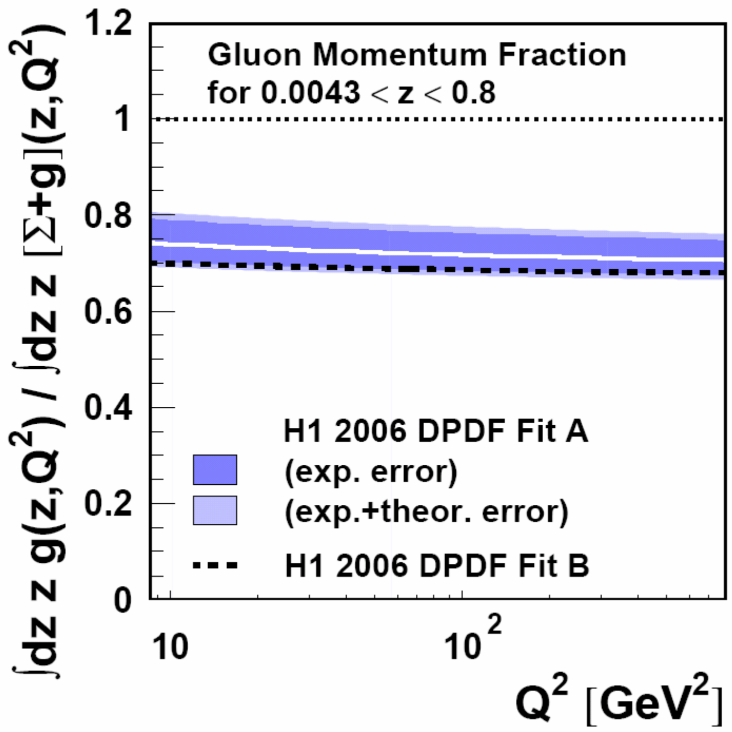
~ 0.12

Positive scaling violations up to large β : gluon-dominated

Partonic Structure of Diffraction from the Inclusive Data



Fit B: "simple" gluon

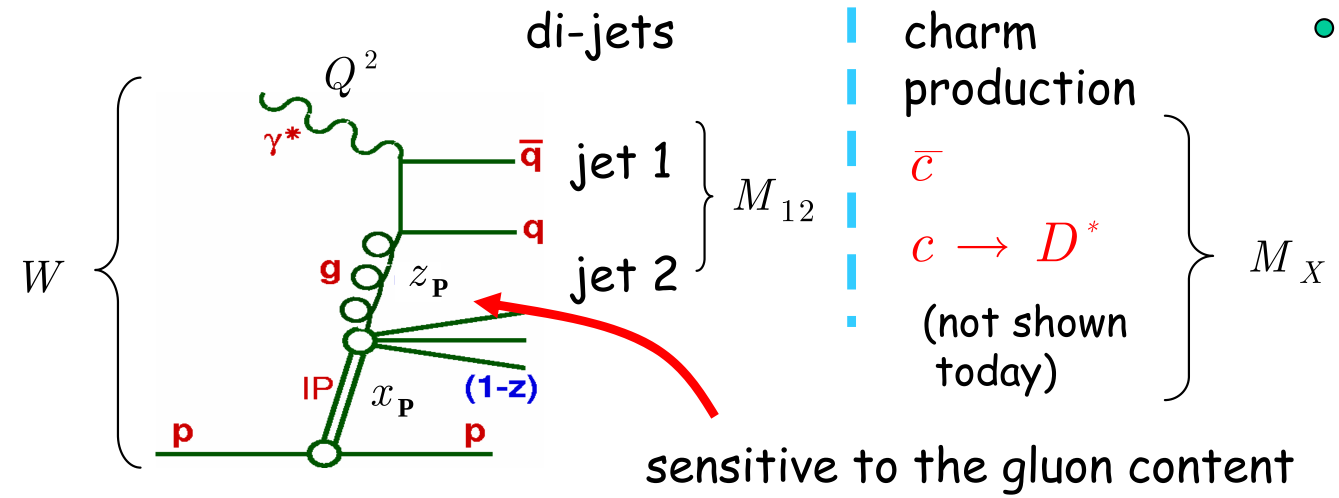


Gluon momentum fraction:

$$(70 \pm 5)\%$$

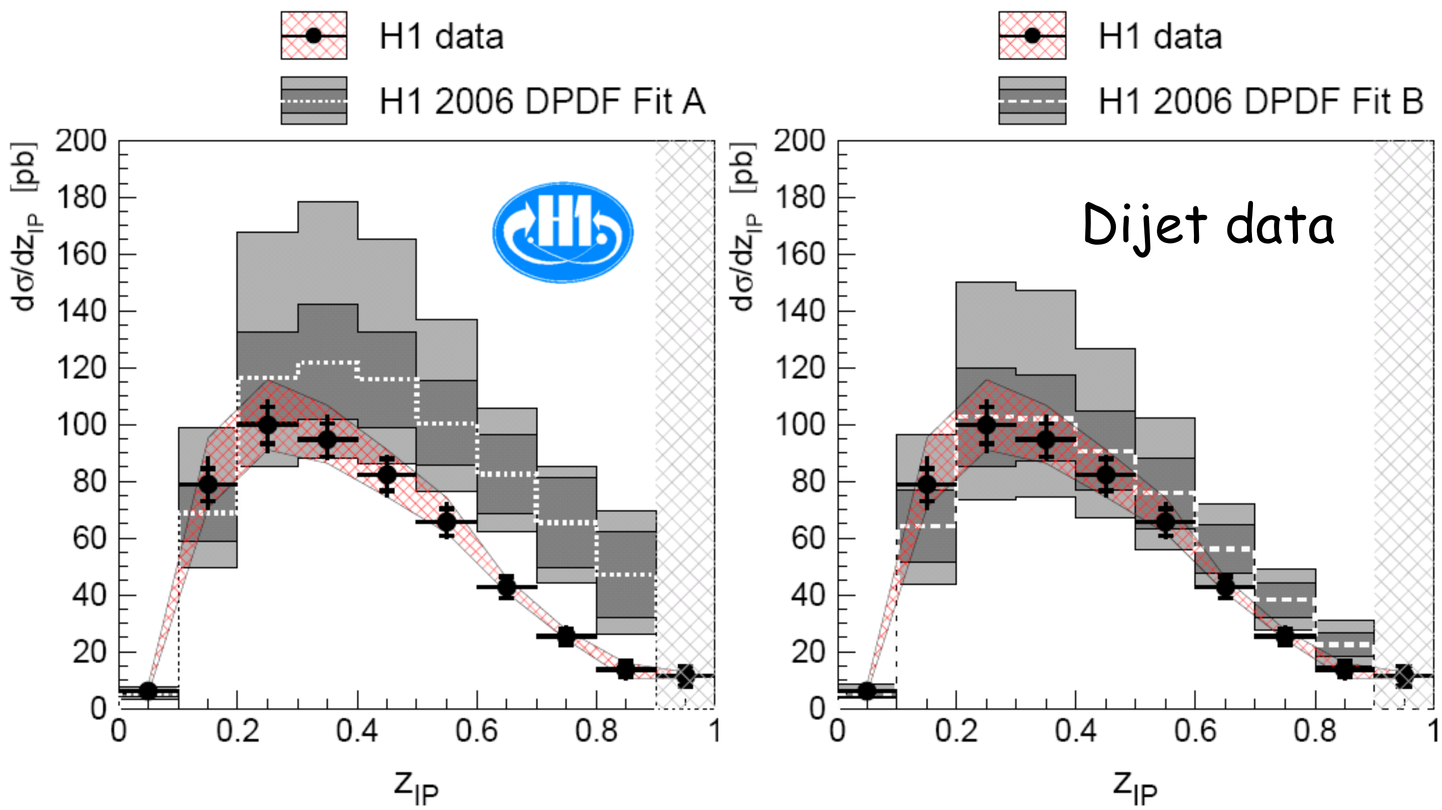
Diffraction is gluon-dominated

Test of QCD Factorization using DPDF's



- measure z_P directly from identified jets (k_T algo.), or using the identified D*

$$z_P = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$



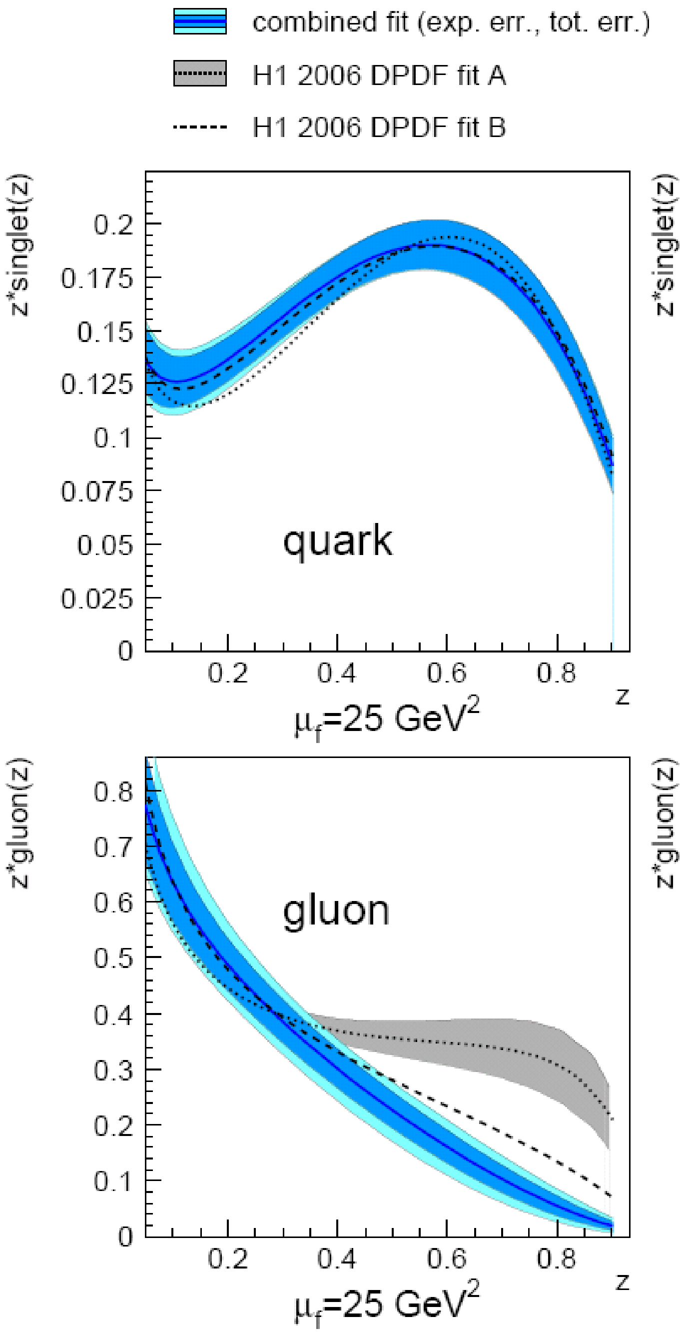
Uncertainties of prediction:

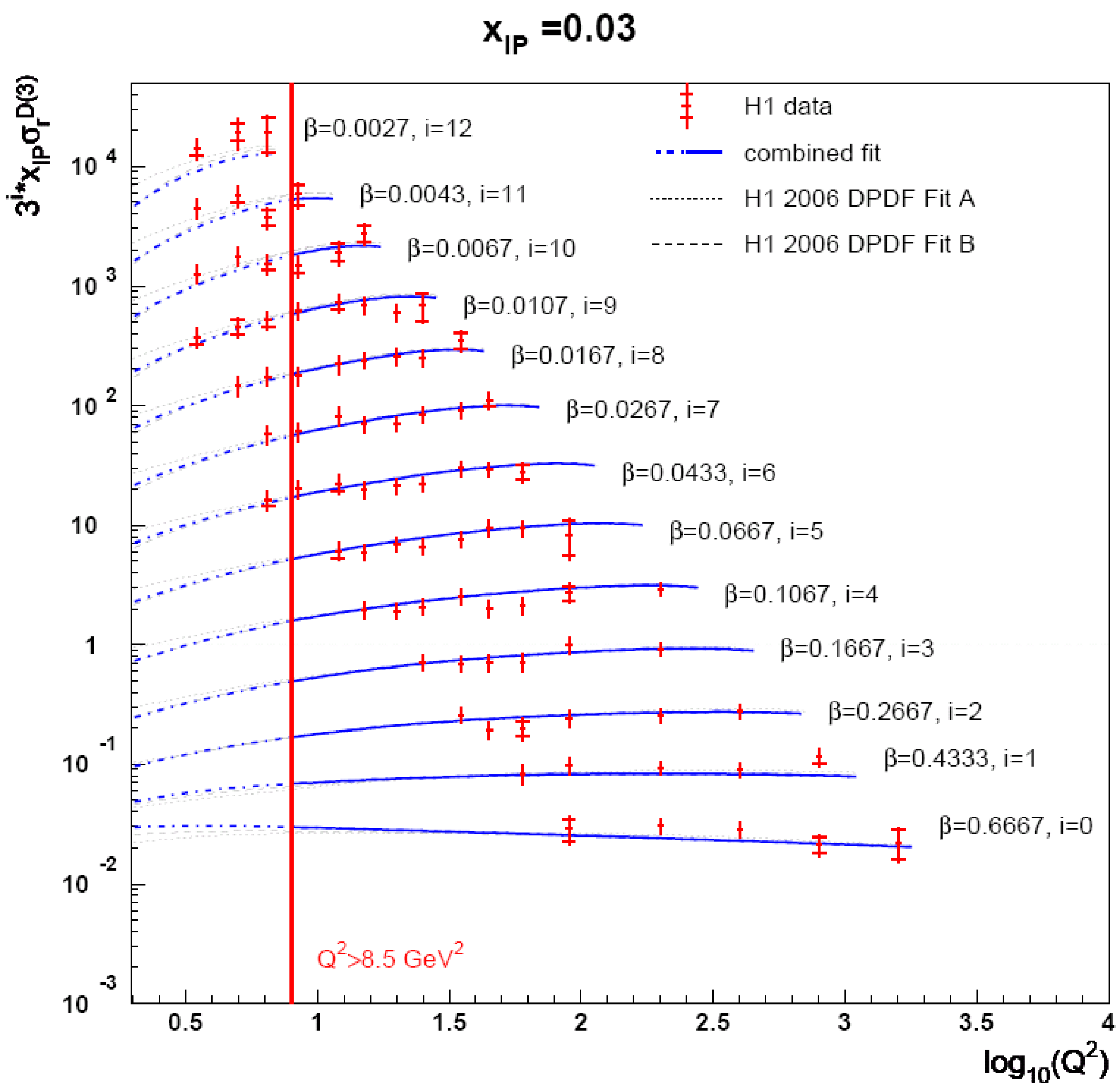
DPDF's (dark) ⊕ renorm. scale (light)

Fit B ("simple" gluon) preferred

(Charm well described, not shown)

Combined Fit (Inclusive & Dijet Data)





Dijets well described (Charm still OK!), hardly any difference in desciption of inclusive data

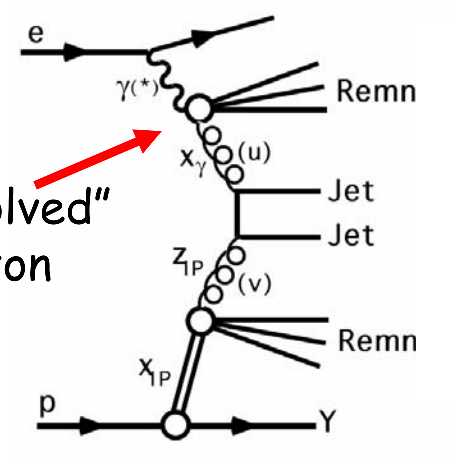
Further Test: Di-Jets in Diffractive Photoproduction

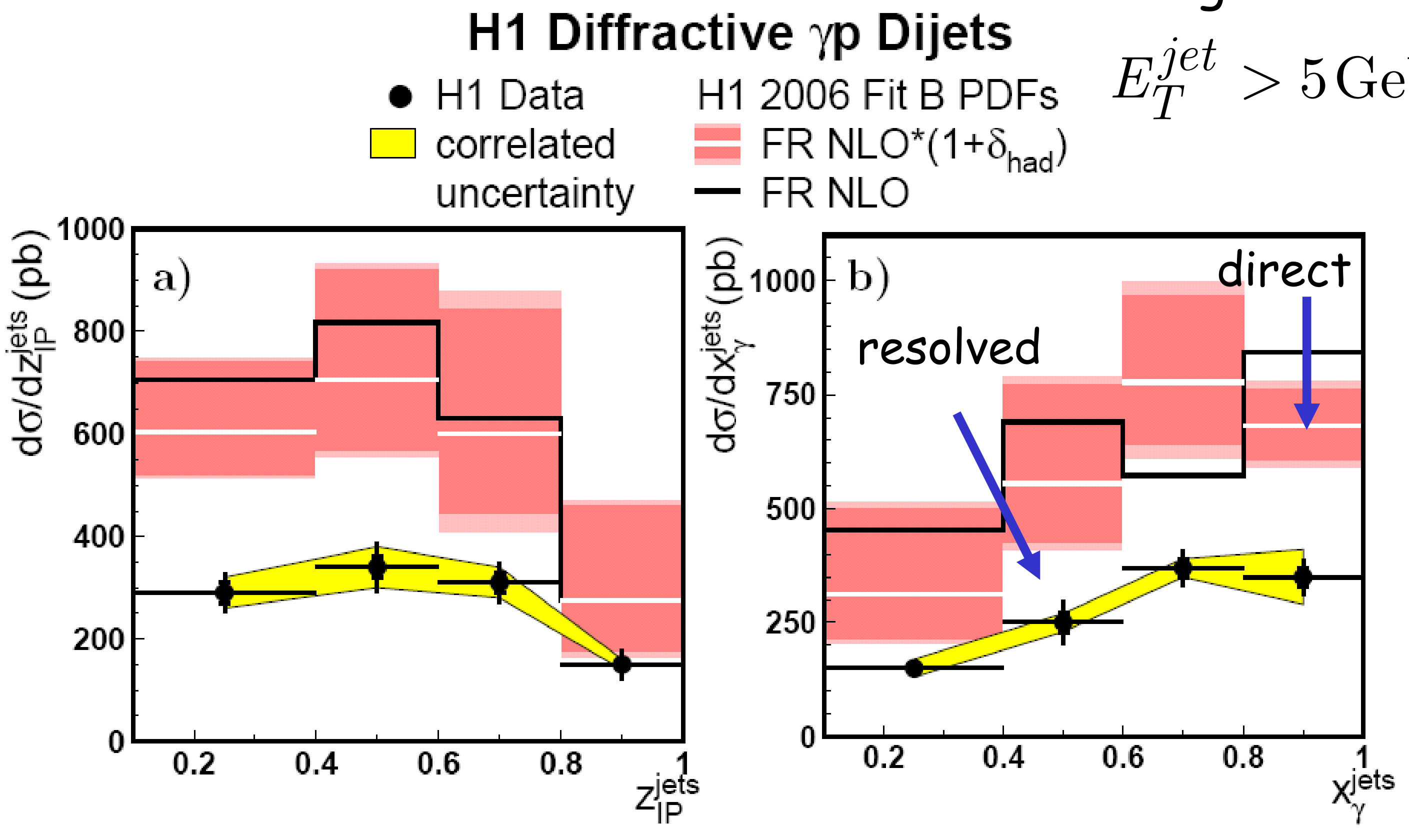
➡ low virtuality photons at HERA are „hadrons"

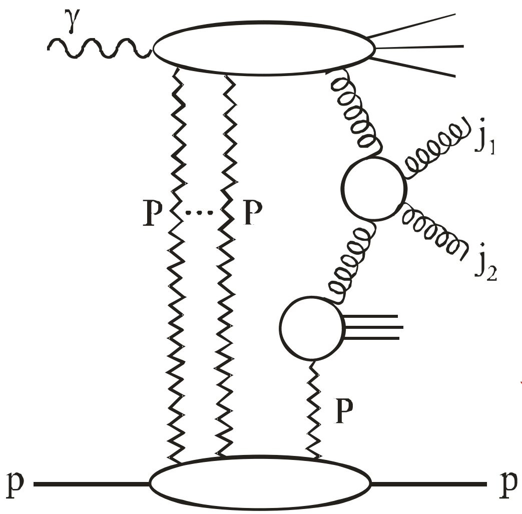
"large" scale:

$$E_T^{jet} > 5\,\mathrm{GeV}$$

"resolved" photon







- large violation of naïve scaling observed (charm OK!)
- factorization breaking occurs in resolved and direct processes

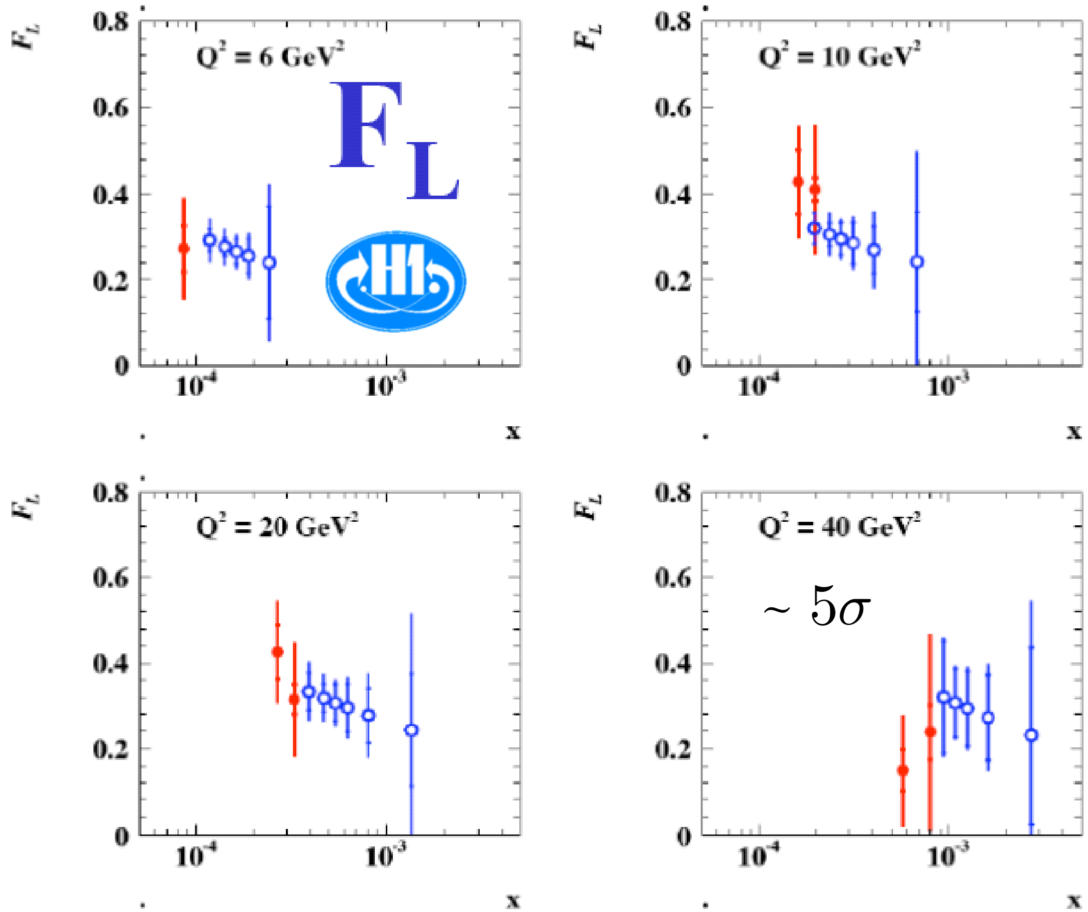
absoptive corrections (Khose et al.) should disappear when $x_\gamma \rightarrow 1$

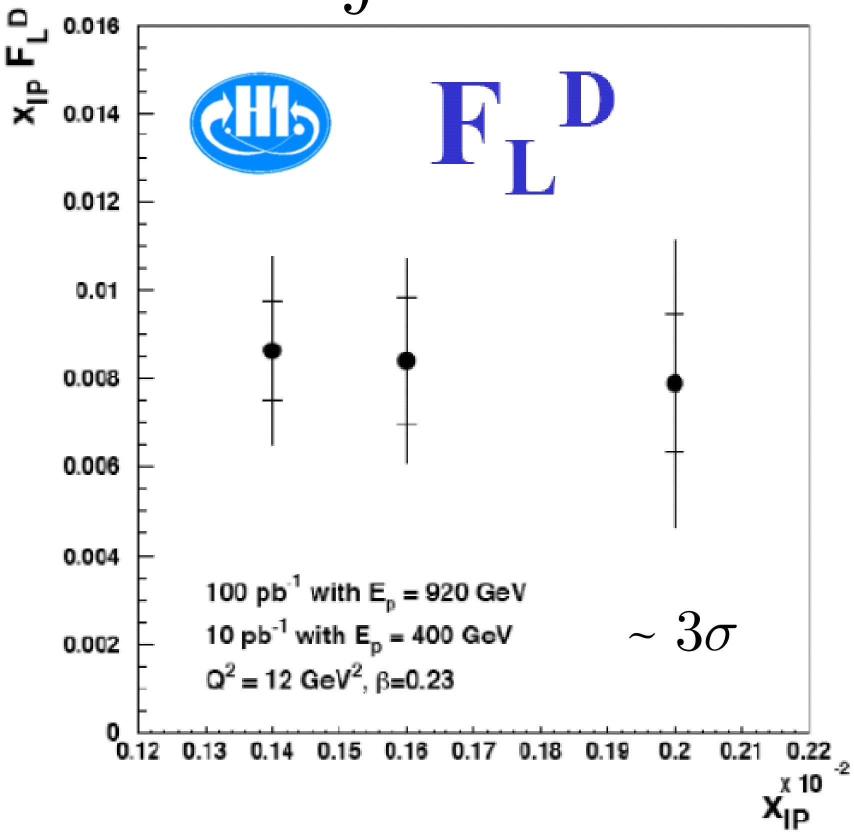
HERA: The last 3 Months

$F_L(x,Q^2)$ = direct measure of $g(x,Q^2)$: need 2 different cms energies

$$\frac{d^2\sigma(ep)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[F_2 - \frac{y^2}{Y_+} F_L\right] \qquad (\ Q^2 = sxy\ ) \qquad \text{run with } E_p = 460\,\mathrm{GeV}$$

$$\int L dt = 10\,\mathrm{pb}^{-1}$$





ZEUS will have similar precision

Summary and Conclusions

- HERA provides an equivalent of a 50 TeV photon beam.
  -> nice laboratory for UHE γ-rays (-> Cosmic Ray Community)
- Beautiful textbook measurements from HERA with and without polarized $e^{\pm}$ beams. Electroweak model and QCD are verified with high precision. DGLAP works over many orders of magnitude in Q^2 (good news for LHC)
- Diffraction, contributing a large part of the cross section in soft hadronic interactions, is also a substantial part of hard scattering at HERA. QCD models based on colorless gluon exchange work nicely.
- Strong experimental evidence for gluonic structure of diffractive exchange NLO QCD fit to diffractive data: gluons dominate (~70%).
- QCD factorization verified at HERA in diffractive DIS (di-jets, charm). Photoproduction of di-jets breaks factorization, but charm is OK!
- The HERA program will come to an end by July 2007, last three months devoted to F_L measurements (@lower proton energy) as a direct measure of the gluon in DIS and DDIS (-> LHC Community)

BACKup

Further Tests of QCD Factorization in Diffraction

One step further: use dpdf's to predict di-jets at the Tevatron

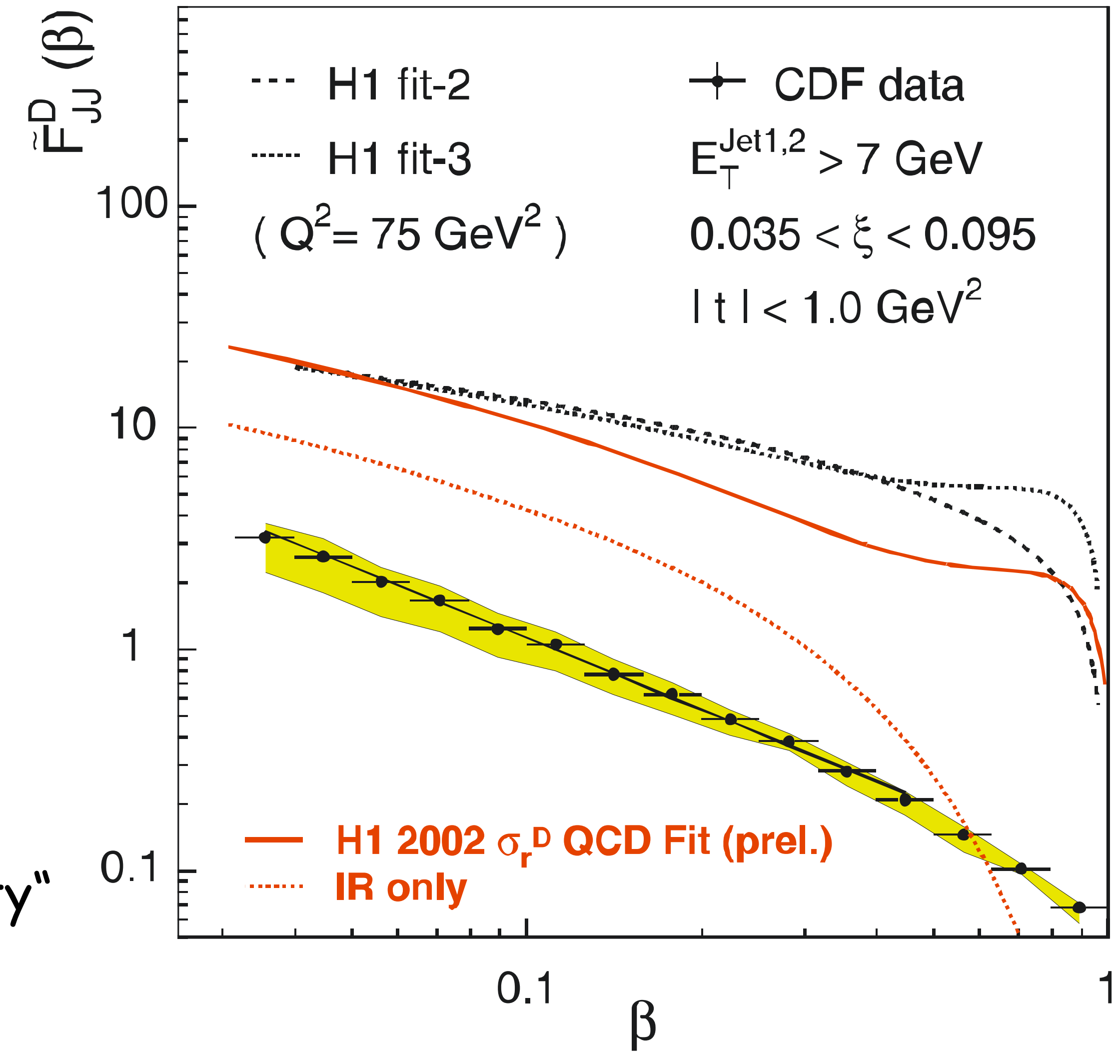
Observe serious breakdown of factorization:

Prediction from HERA an order of magnitude too large

Generally for Tevatron:

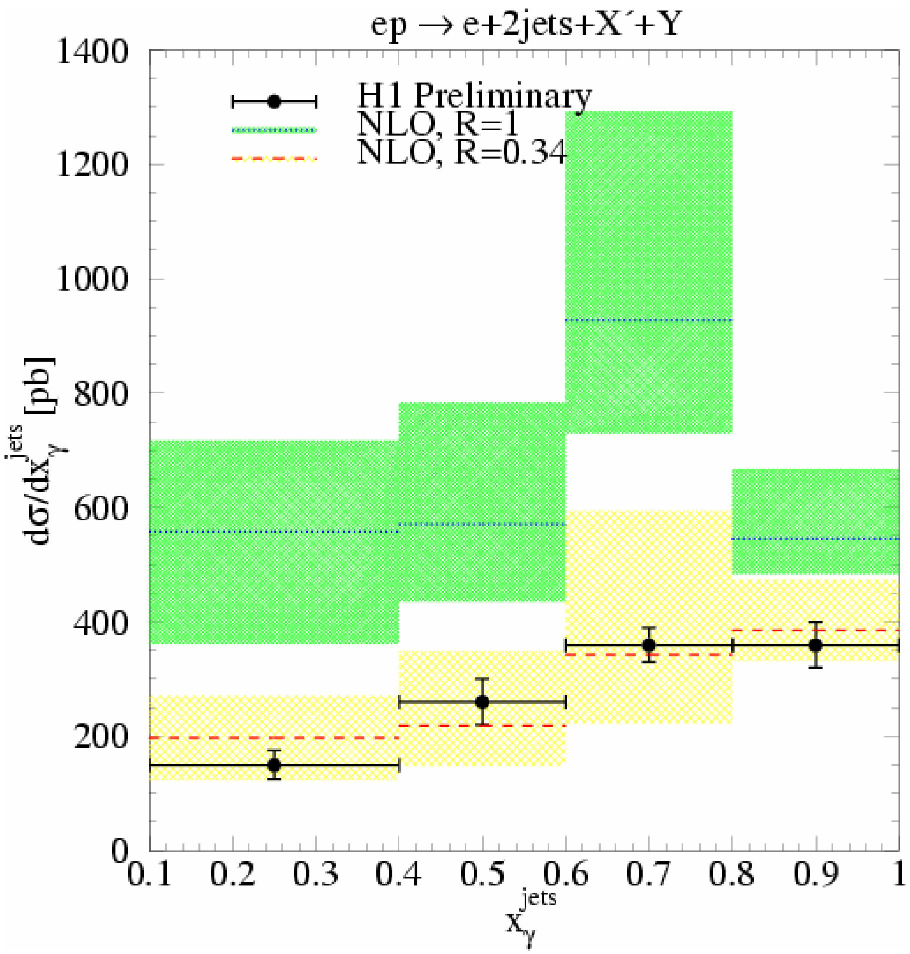
Also other diffractive processes only of order 1 %

Possible reason: additional hadron in the initial state, rescattering, reduction of „gap survival probability"
(Kaidalov, Khoze et al.)

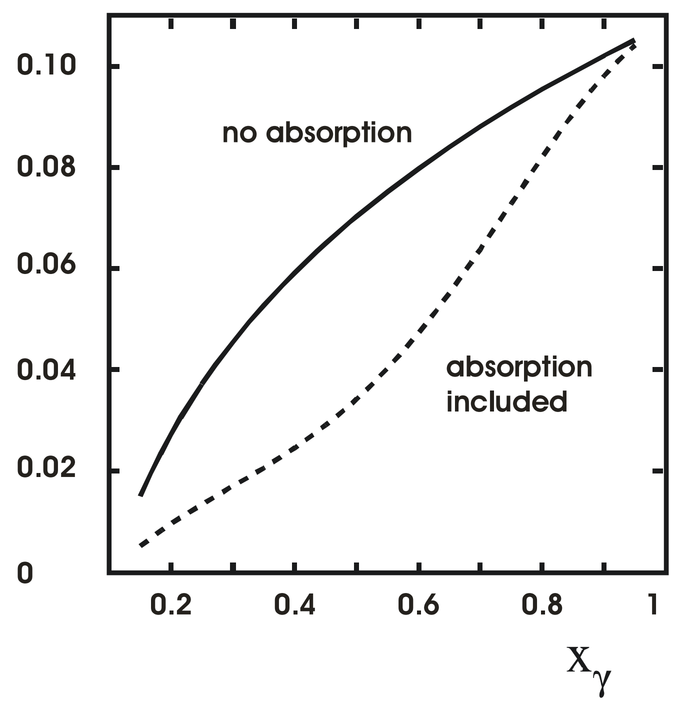


Factorization Tests in Diffractive Photoproduction (cont.)

NLO calculation by Klasen & Kramer (2004)
resolved photon contributions:



Ratio diffractive/inclusive dijet photoproduction



factor ~ 3 reduction seems to match with the data

(absorption correction suggested by Kaidalov, Khoze et al., 2003)