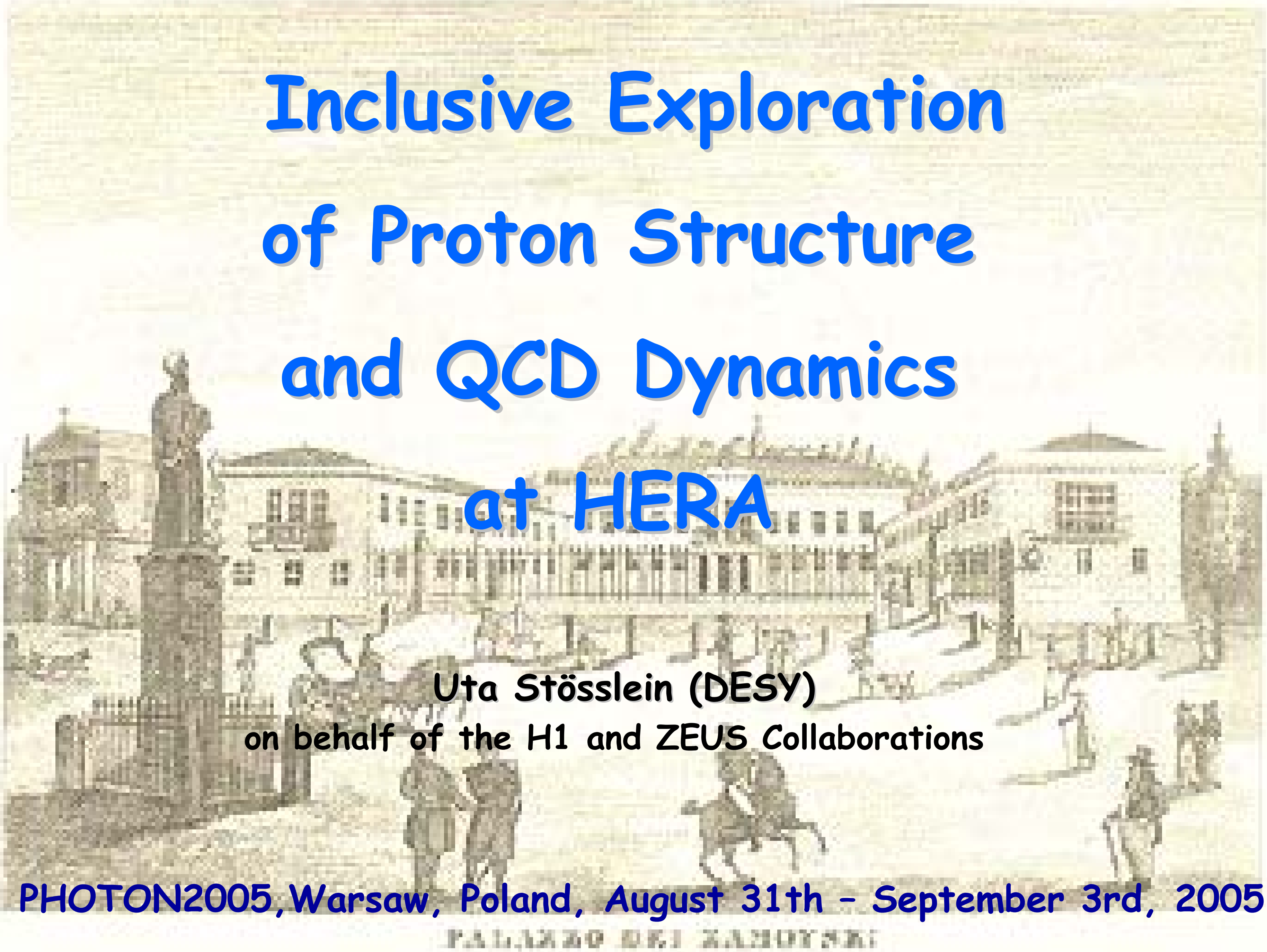
# Inclusive Exploration of Proton Structure and QCD Dynamics at HERA

Uta Stösslein (DESY)
on behalf of the H1 and ZEUS Collaborations

PHOTON2005,Warsaw, Poland, August 31th – September 3rd, 2005

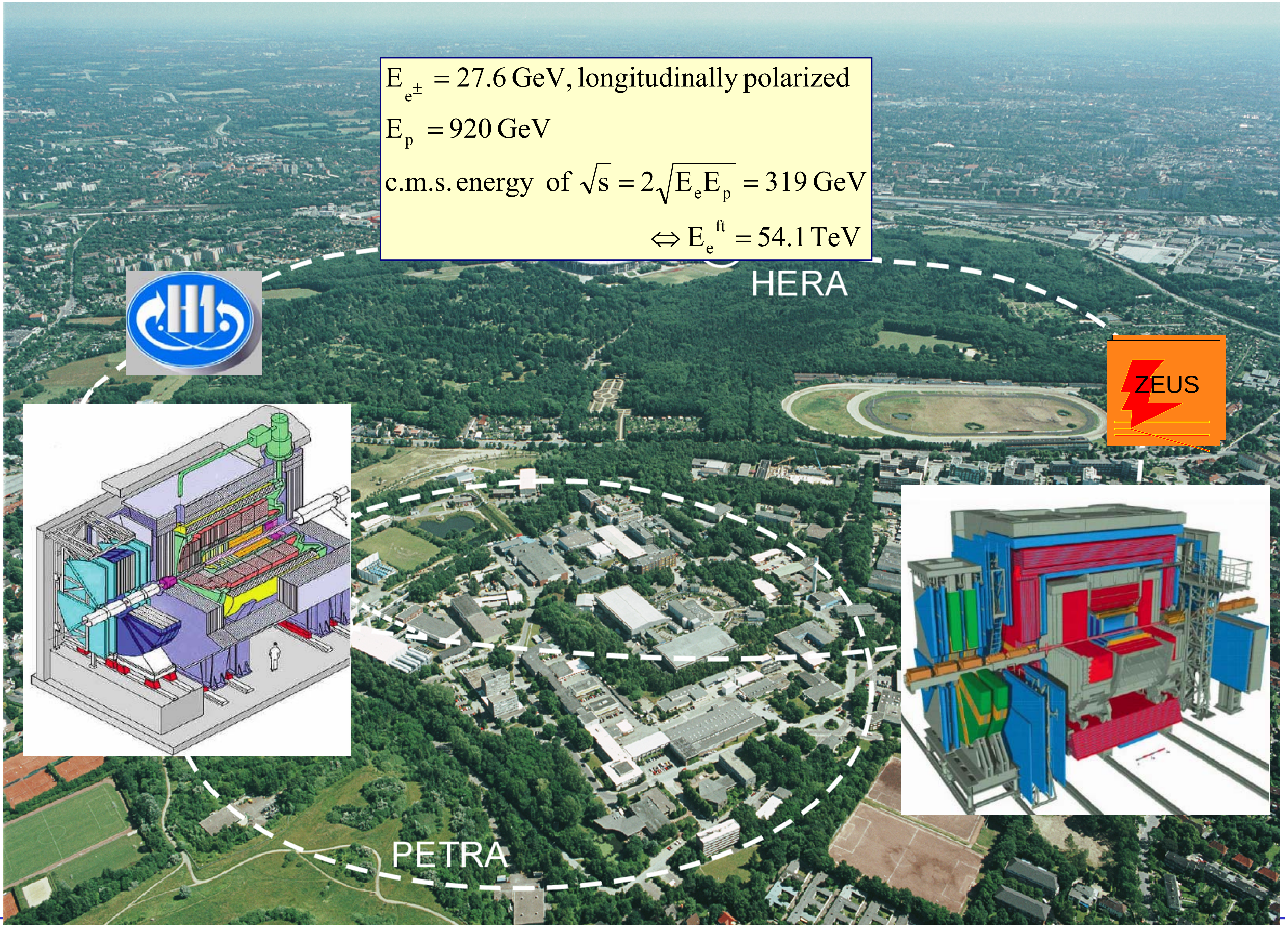


$E_{e^\pm} = 27.6\,\text{GeV}$, longitudinally polarized

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

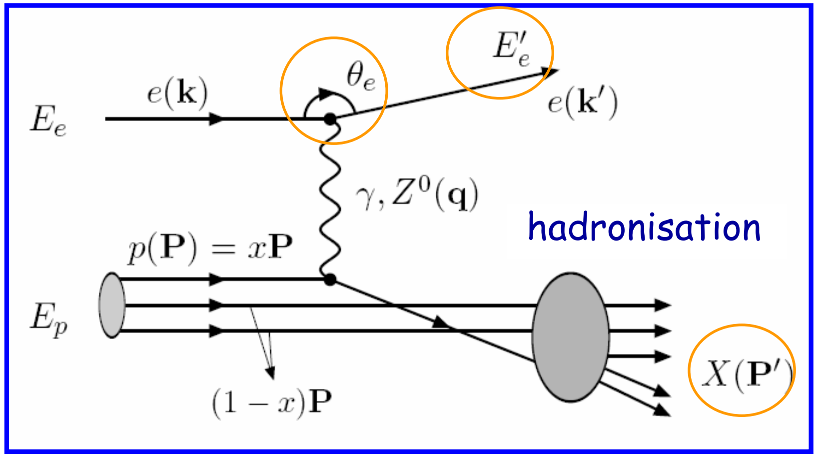
c.m.s. energy of $\sqrt{s} = 2\sqrt{E_e E_p} = 319\,\text{GeV}$

$\Leftrightarrow E_e^{ft} = 54.1\,\text{TeV}$



# Deep inelastic scattering kinematics

## Neutral Current (NC) interactions




At HERA :

NC : kinematics over-constrained ($E_e$,$\theta_e$ and/or $E_{jet}$,$\theta_{jet}$)

CC : ν escapes detection kinematics from $E_{jet}$,$\theta_{jet}$

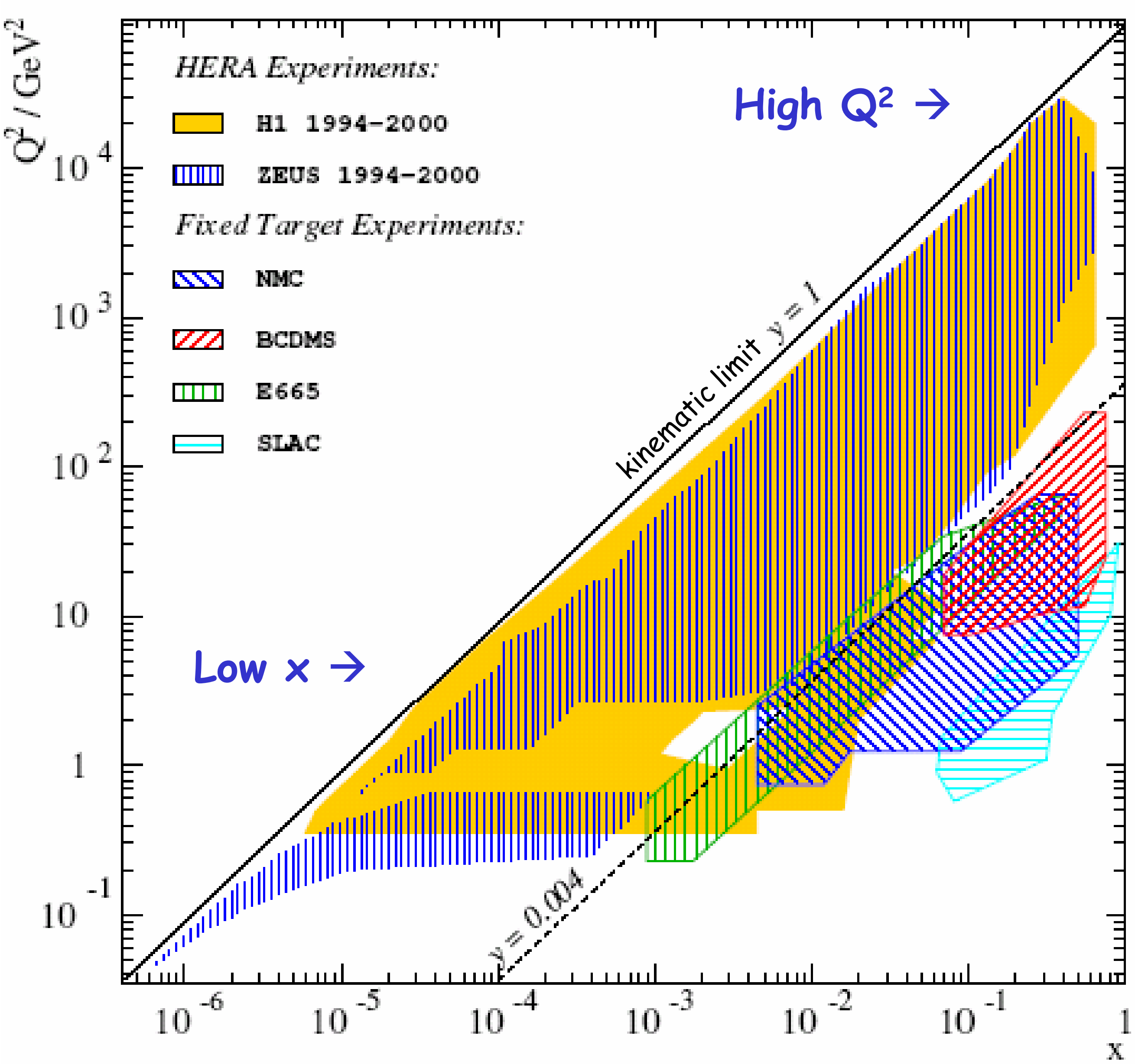
$Q^2 = -q^2$ : resolving power of the exchanged boson ~$1/\sqrt{Q^2}$

➔ 'DIS' : $Q^2 \gg M^2_{proton}$

➔ snapshot of proton structure

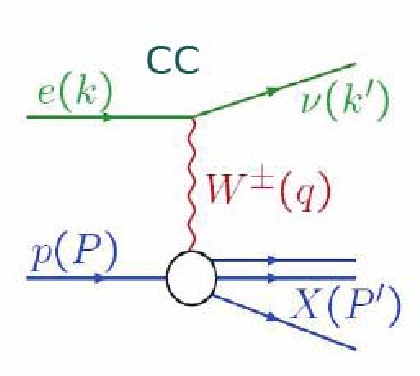
$x = Q^2/2Pq$ : fraction of proton momentum carried by struck quark (Bjorken '68)

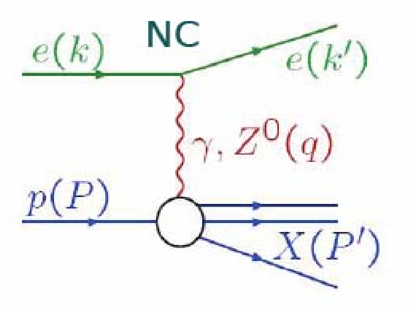
$y = Pq/Pk$ : fraction of lepton momentum carried by the exchange (inelasticity)




$Q^2 = sxy \rightarrow$ *high*

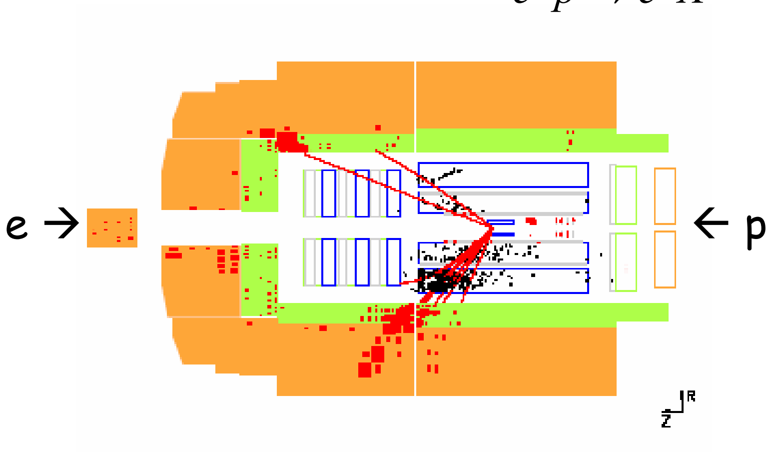
$x = Q^2/sy \rightarrow$ *low*



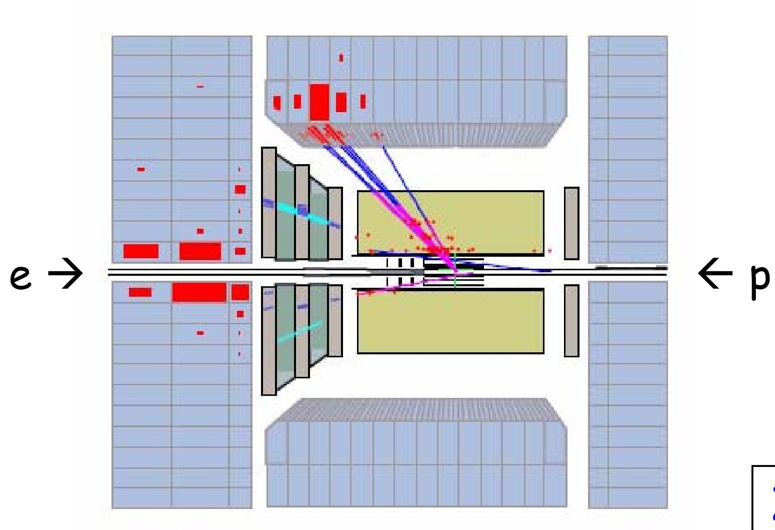



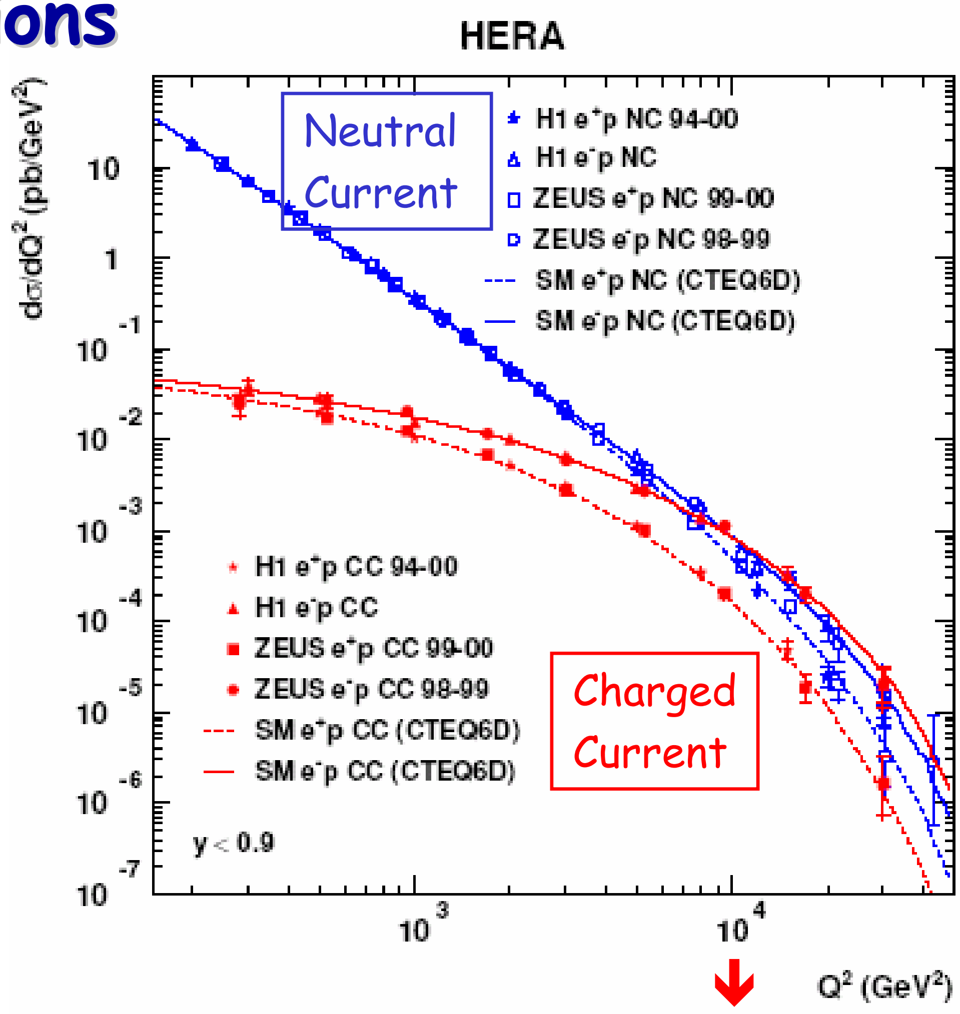
# NC and CC cross sections

Neutral current $e^+ p \rightarrow e^+ X$




Charged current $e^+ p \rightarrow \bar{\nu} X$




$$\sigma_{NC}^{\pm} \approx \sigma_{CC}^{\pm} \leftrightarrow Q^2 \approx M_Z^2 \approx 10^4 \, \mathrm{GeV}^2$$

**ZEUS (H1) r ≤ 0.85 (1.0) $10^{-18}$ m → quarks are point-like down to proton radius/1000**

# DIS structure functions

**NC**

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\,\phi^{\pm}_{NC}\,(1+\Delta^{\pm,weak}_{NC}),$$

with $\phi^{\pm}_{NC} = Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L,$

$$[F_2, F_2^{\gamma Z}, F_2^Z] = x\sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2]\{q+\bar{q}\}$$

$$[xF_3^{\gamma Z}, xF_3^Z] = 2x\sum_q [e_q a_q, v_q a_q]\{q-\bar{q}\} = 2x\sum_{q=u,d}[e_q a_q, v_q a_q] q_v$$

## PDFs

below bottom threshold

$$xU = x(u+c)$$
$$x\overline{U} = x(\bar{u}+\bar{c})$$
$$xD = x(d+s)$$
$$x\overline{D} = x(\bar{d}+\bar{s})$$

valence quarks

$$xu_v = x\,(U-\overline{U})$$
$$xd_v = x\,(D-\overline{D})$$

**CC**

$$\frac{d^2\sigma^{\pm}_{CC}}{dx\, dQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2 \phi^{\pm}_{CC}\,(1+\Delta^{\pm,weak}_{CC})$$

with $\phi^{\pm}_{CC} = \frac{1}{2}(Y_+W_2^{\pm} \mp Y_- xW_3^{\pm} - y^2 W_L^{\pm}),$

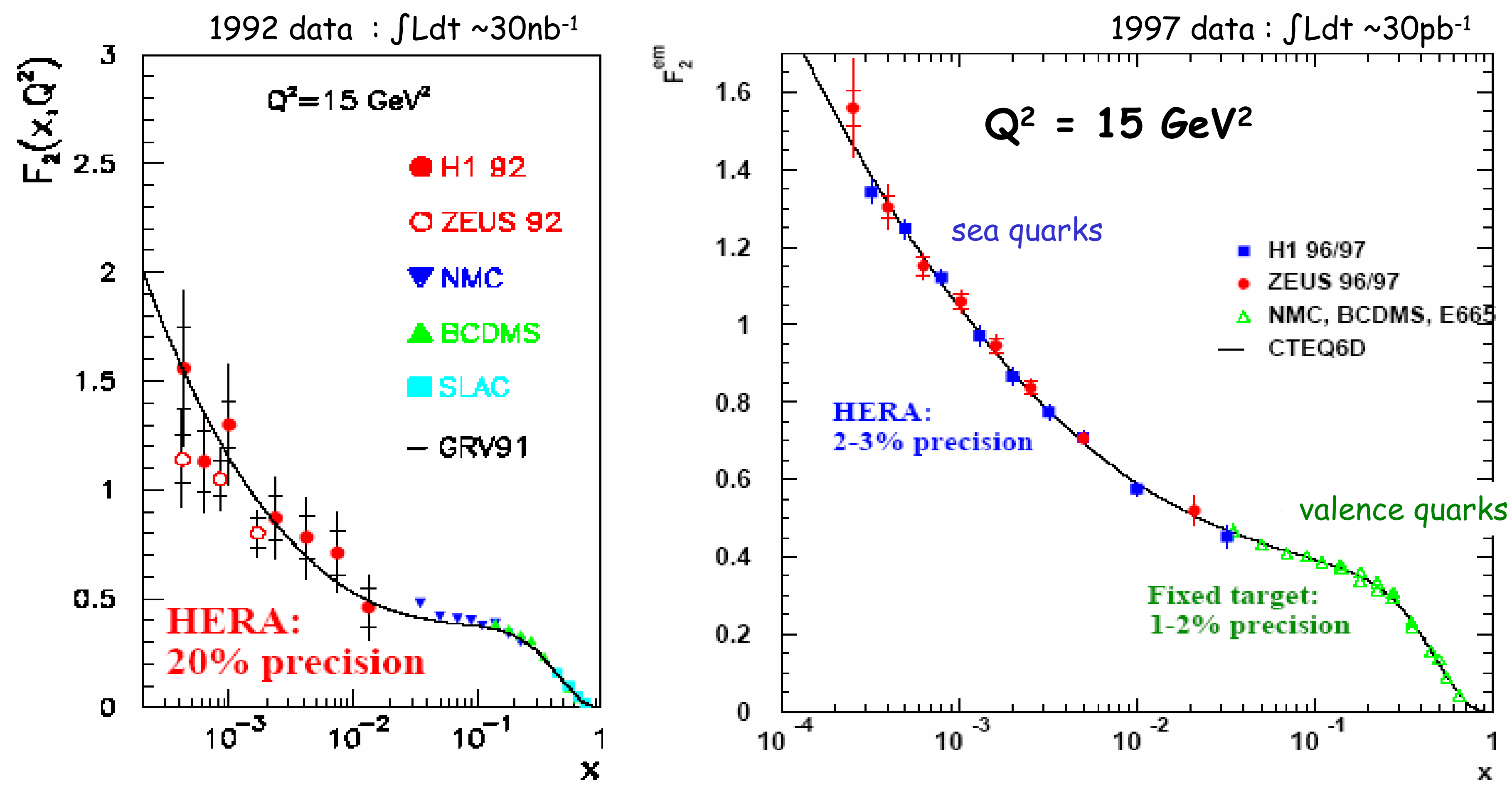
$$W_2^+ = x(\overline{U}+D),\quad xW_3^+ = x(D-\overline{U})$$

$$W_2^- = x(U+\overline{D}),\quad xW_3^- = x(U-\overline{D})$$

$$\phi^+_{CC} = x\overline{U} + (1-y)^2 xD,\qquad \phi^-_{CC} = xU + (1-y)^2 x\overline{D}$$

# What HERA DIS data taught us on $F_2^{em}$

$$F_2 = \frac{4}{9}x(U+\overline{U}) + \frac{1}{9}x\left(D+\overline{D}\right)$$




e.m. structure of the proton known to few % in a large area of x and $Q^2$

# PDFs

at low x

$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)\,xg(x,Q^2)$$

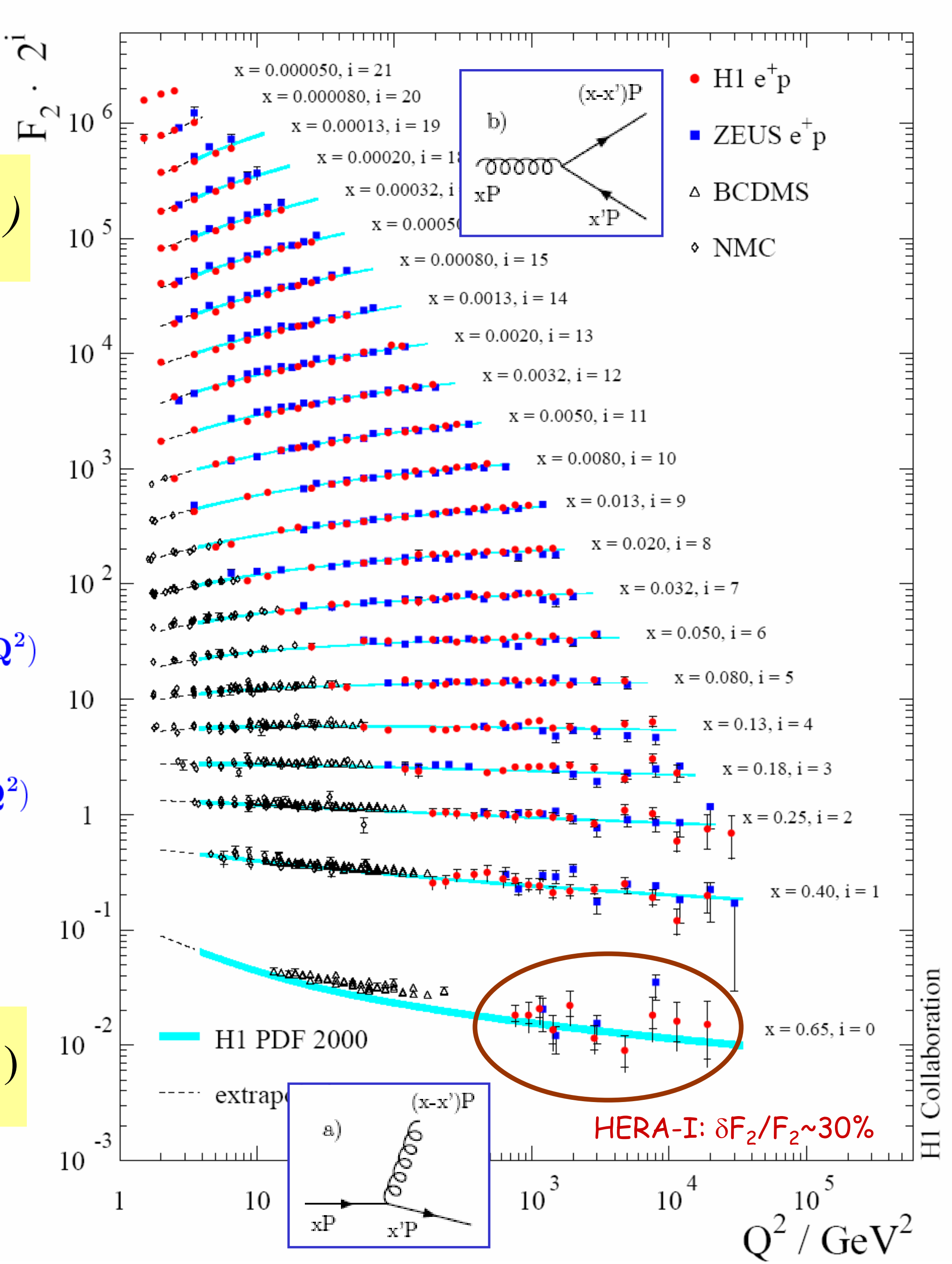
*x* dependence of *q(x,Q²)* determined by fit to *eN* data, *Q²* dependence determined by **DGLAP** equations:

$$\frac{\partial \mathbf{q_i(x,Q^2)}}{\partial \log \mathbf{Q^2}} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{\mathbf{dy}}{\mathbf{y}}\Big\{\mathbf{P_{q_iq_j}(y,\alpha_S)\, q_j(\frac{x}{y},Q^2)} + \mathbf{P_{q_ig}(y,\alpha_S)\, g(\frac{x}{y},Q^2)}\Big\}$$

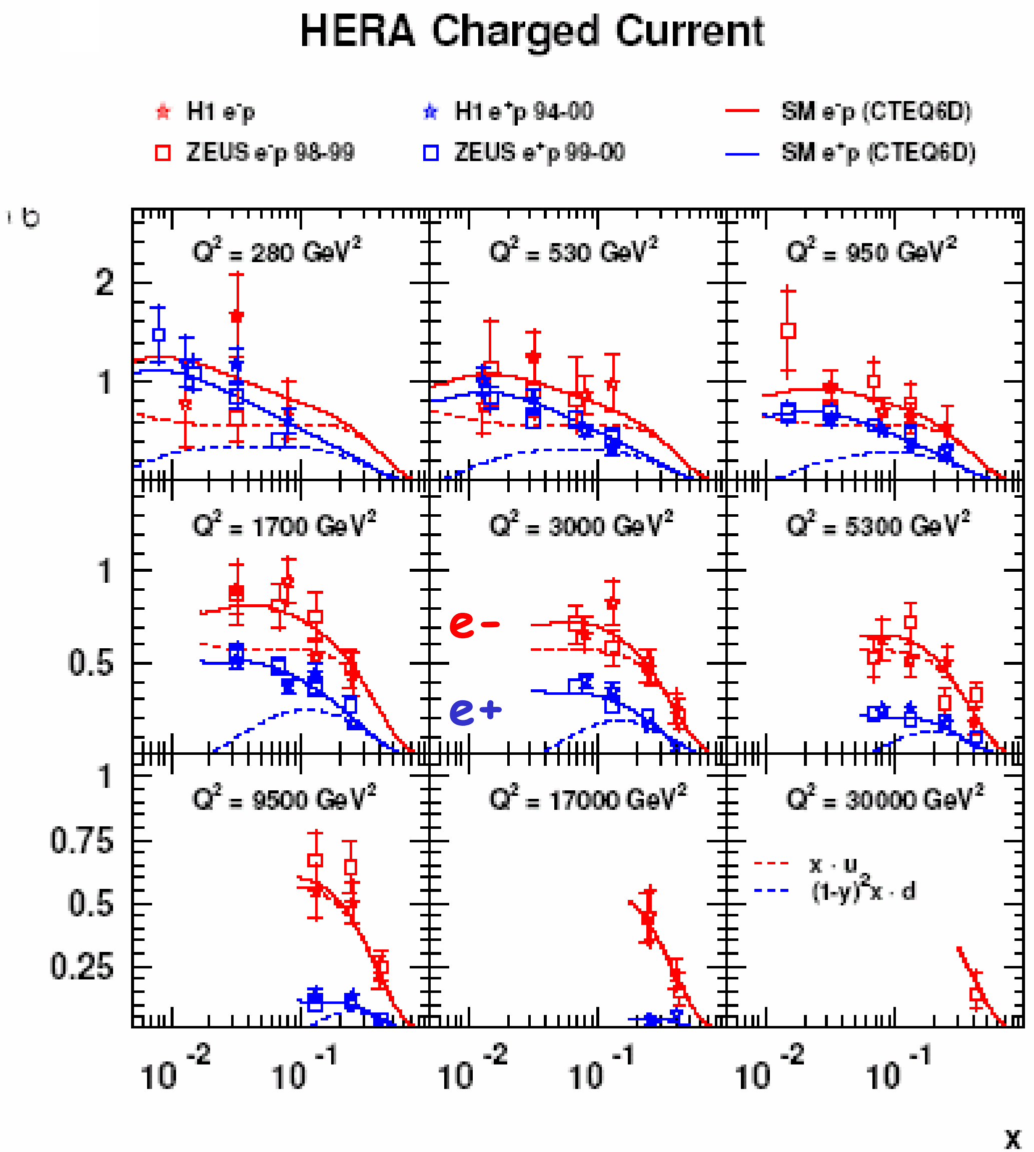
$$\frac{\partial \mathbf{g(x,Q^2)}}{\partial \log \mathbf{Q^2}} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{\mathbf{dy}}{\mathbf{y}}\Big\{\mathbf{P_{gq_j}(y,\alpha_S)\, q_j(\frac{x}{y},Q^2)} + \mathbf{P_{gg}(y,\alpha_S)\, g(\frac{x}{y},Q^2)}\Big\}$$

at high x

$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)\,q(x,Q^2)$$



# Reduced charged current cross sections




--- $\sigma(e^-p) \sim x\,(u+c) + (1-y^2)\,x\,(\bar{d}+\bar{s})$

--- $\sigma(e^+p) \sim x\,(\bar{u}+\bar{c}) + (1-y^2)\,x\,(d+s)$

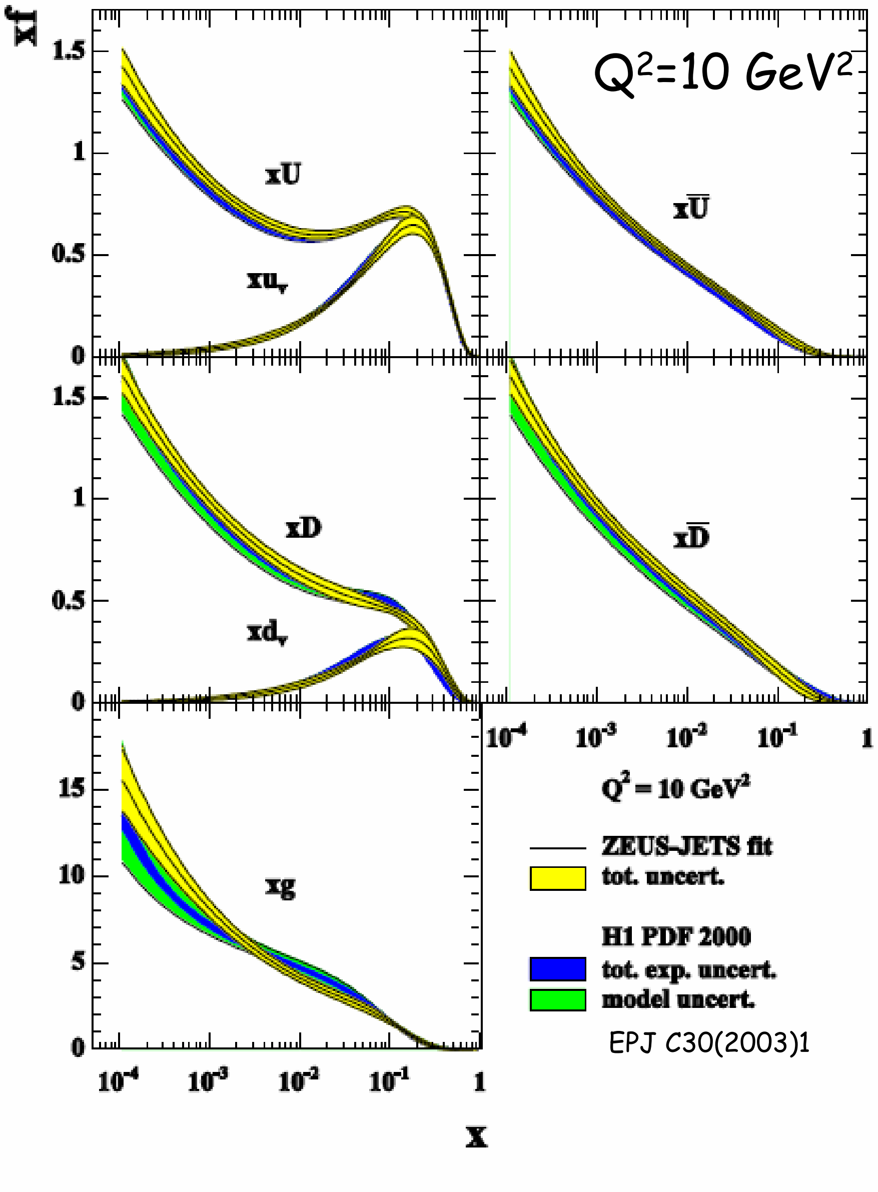
HERA can disentangle parton distributions

at large $Q^2$ and large $x > 0.01$ within *single* experiments, independently of nuclear

corrections and free of higher twists and isospin assumptions

(measure *d* of the proton directly)

# Unfolding PDFs using CC and NC cross sections




E.g. **ZEUS NLO QCD fit** [EPJC42(2005)1]

| |
|---|
| all HERA-I ZEUS incl. NC/CC $e^+/e^-$ (94-00) |
| ZEUS inclusive jets in DIS (96-97) |
| ZEUS dijets in photoproduction (96-97) new |

Parameterisation:

| PDF | Param. at $Q_0^2$ =7 GeV$^2$ |
|---|---|
| u-val. ($xu_v$) | $A_{uv}\, x^{b_{uv}}\, (1-x)^{c_{uv}}\, (1+d_{uv}x)$ |
| d-val. ($xd_v$) | $A_{dv}\, x^{b_{dv}}\, (1-x)^{c_{dv}}\, (1+d_{dv}x)$ |
| total sea (xS) | $A_S\, x^{b_S}\, (1-x)^{c_S}$ |
| gluon (xg) | $A_g\, x^{b_g}\, (1-x)^{c_g}\, (1+d_g x)$ |
| dbar-ubar ($x\Delta$) | $A_\Delta\, x^{b_\Delta}\, (1-x)^{c_\Delta}$ |

Constraints:

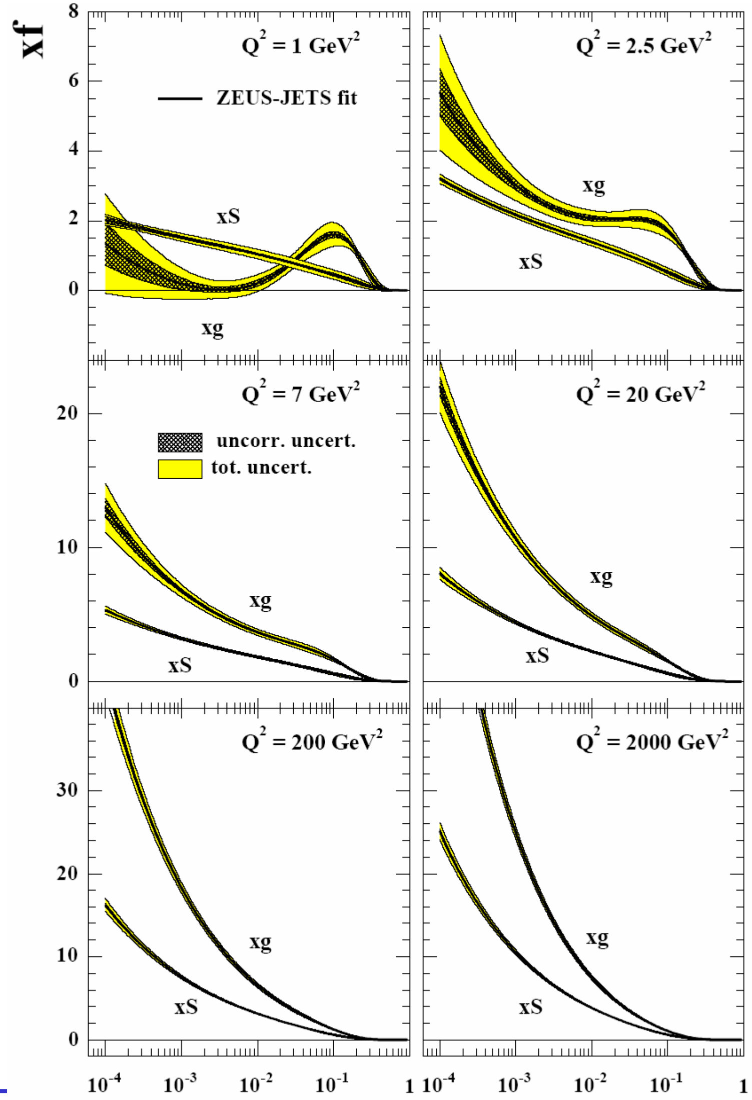
- momentum and quark number sum rules
- low-x behaviour of $u_v$ and $d_v$ set equal
- $\Delta$ set consistent with Gottfried sum and DY

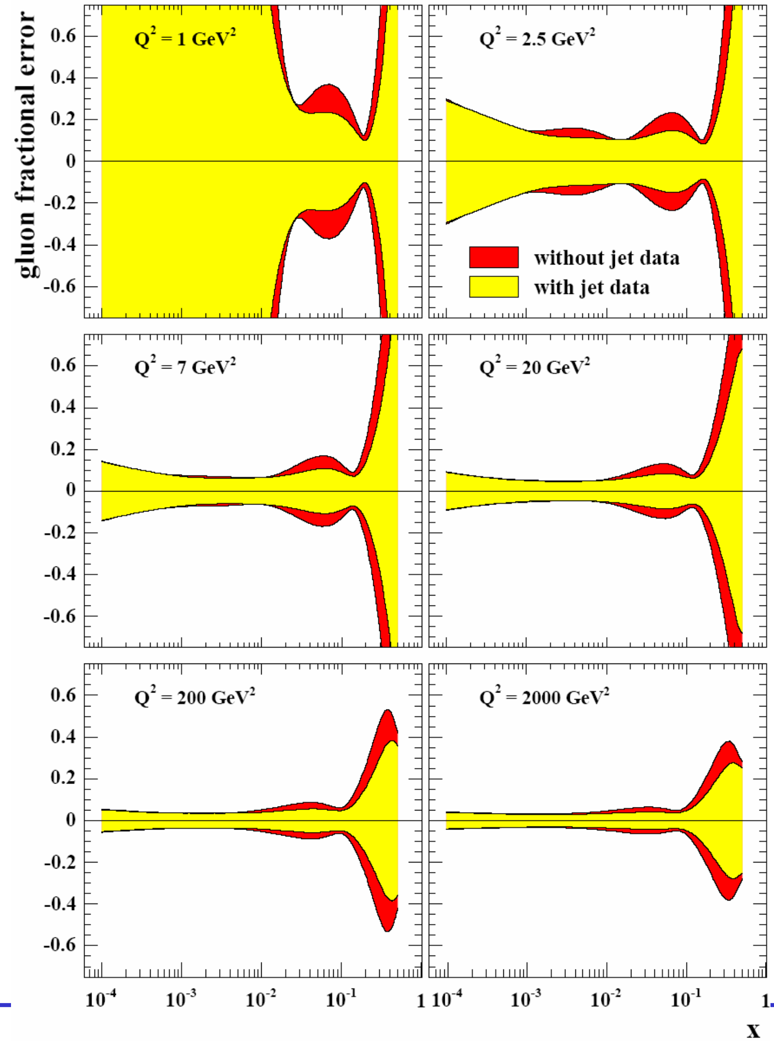
➧ 11 free parameters in total

- heavy quarks treated in variable flavour number scheme of Thorne and Roberts
- uncertainties evaluated using Offset Method

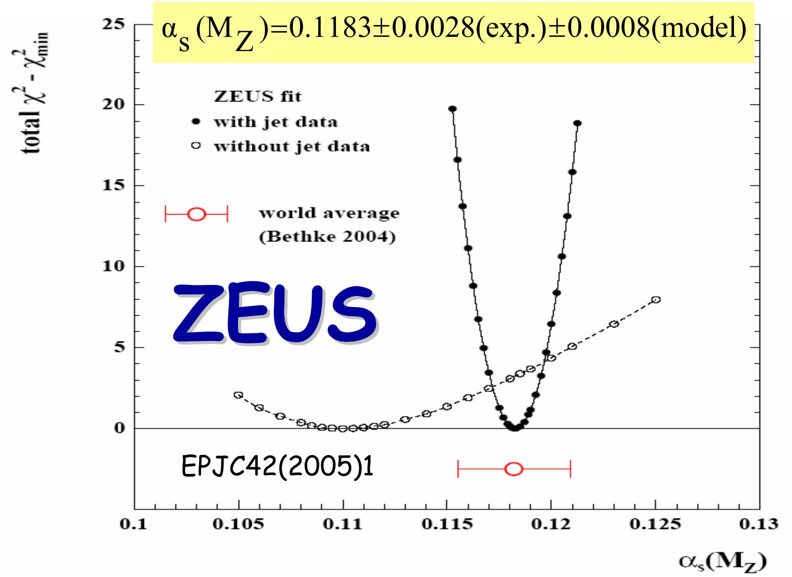
# Sea quarks and gluon

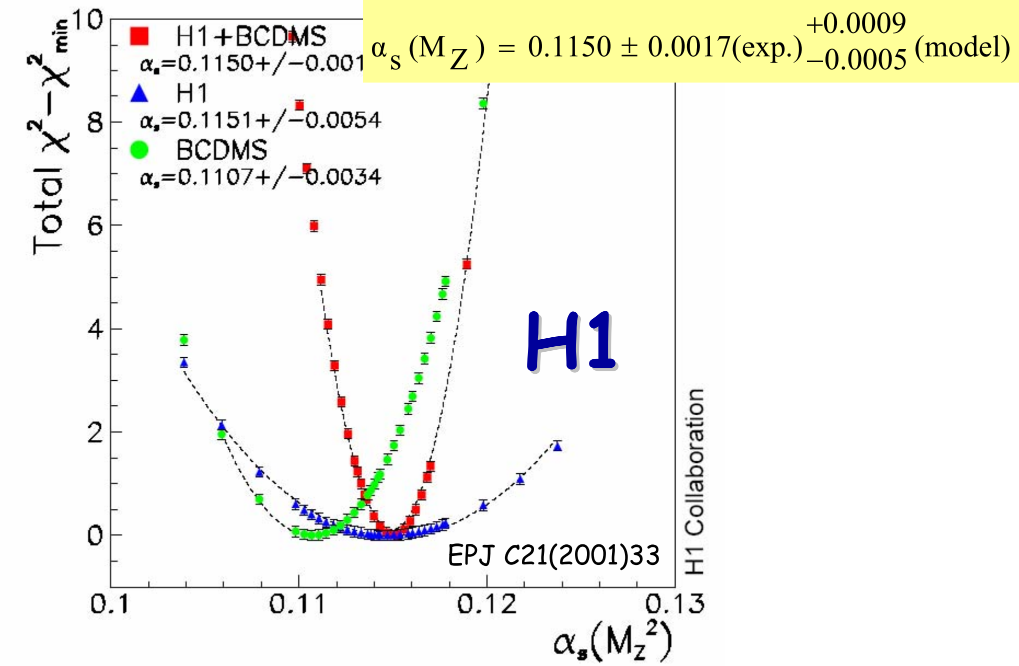
ZEUS inclusive NC+CC & jets ➔ improved precision for gluon at medium x



# The strong coupling $\alpha_S$ from NLO QCD fits




- strong improvement observed from using ep jet data
- experimental uncertainties in the range of 2%
- both $\alpha_S$ values have an additional 'scale' uncertainty of 0.005 (4.3%) which reflects an *ad hoc* approach to cover beyond NLO effects

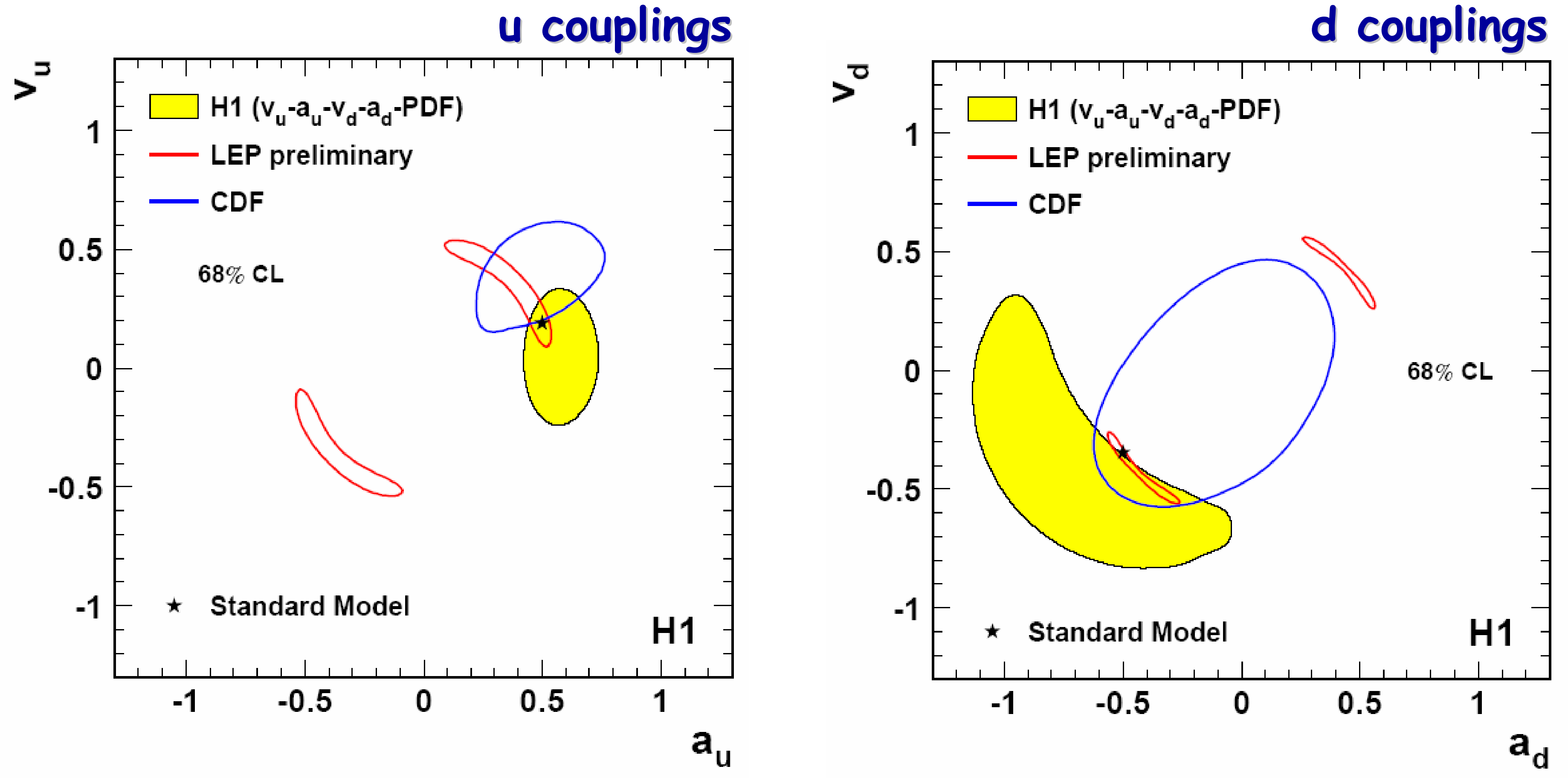
➔ precision of HERA data call for NNLO QCD analyses

➔ NNLO calculation now available, thanks S.Moch,J.A.M. Vermaseren,A.Vogt [hep-ph/0403192 & 0404111]

➔ deuterons at HERA would disentangle nonsinglet – singlet evolution and further reduce $\alpha_S$ error significantly

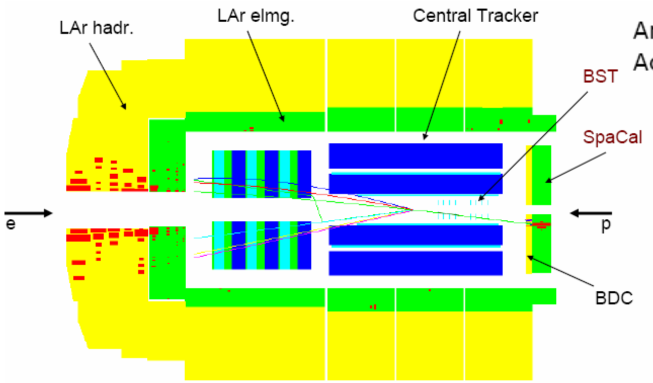
# New: Determination of light quark couplings to Z boson from LEP, CDF and H1

HERA has entered "new", electroweak, territory in QCD&electroweak SM analysis (H1 hep-ex/0507080)




➔HERA data fix sign of high precision LEP results

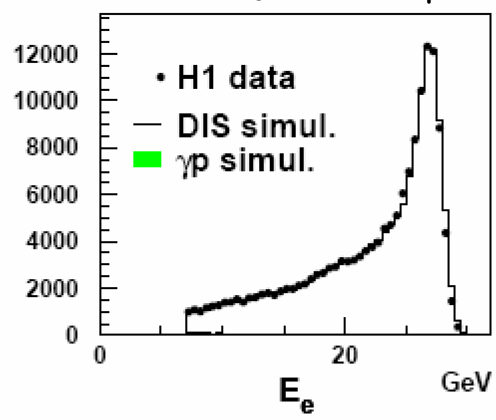
# NC DIS at low $Q^2$ and low x




Angular resolution ~0.1 mrad
Acceptance: $161.5^0 < \Theta < 176.5^0$

Energy resolution $=7.5\%/E^{1/2} \oplus 2\%$
Acceptance: $153^0 < \Theta < 177^0$

99/00 data : $\int Ldt \sim 3.3 pb^{-1}$




## rise of F2 towards low x

F2 used to fit x-dependences in $Q^2$ bins for x<0.01 and W>12 GeV:

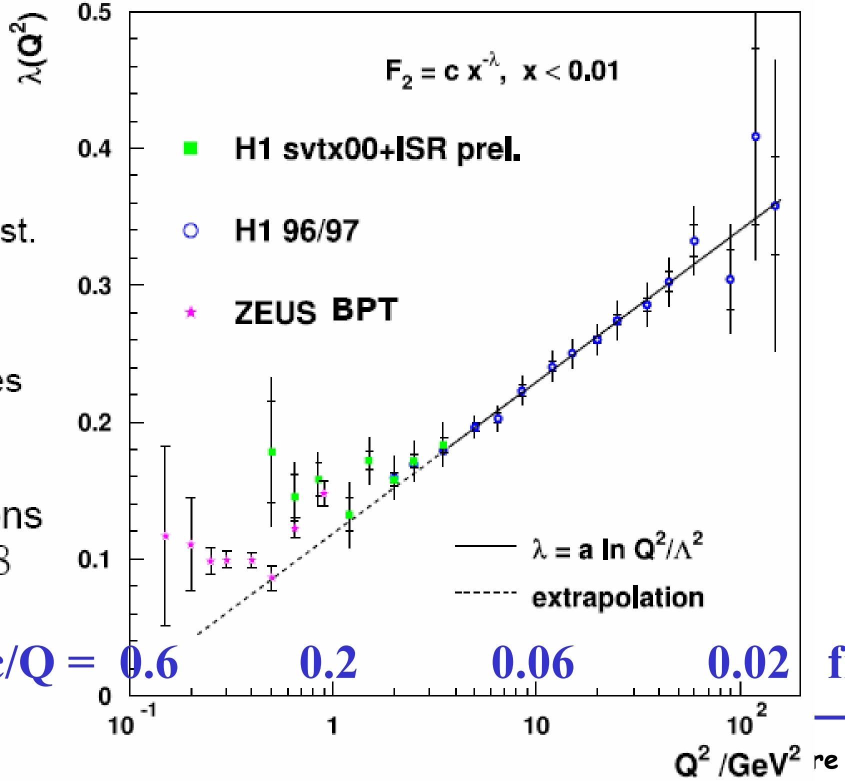
$$F_2 = c(Q^2) \cdot x^{-\lambda(Q^2)}$$

$\lambda \sim \ln(Q^2/\Lambda^2)$ and $c(Q^2)$~const.

for $Q^2 > 3.5\,\mathrm{GeV}^2$

Around $Q^2 = 1\,\mathrm{GeV}^2$ $\lambda$ deviates from log-dependence

From soft hadronic interactions it is expected that $\lambda \to 0.08$ for $Q^2 \to 0$

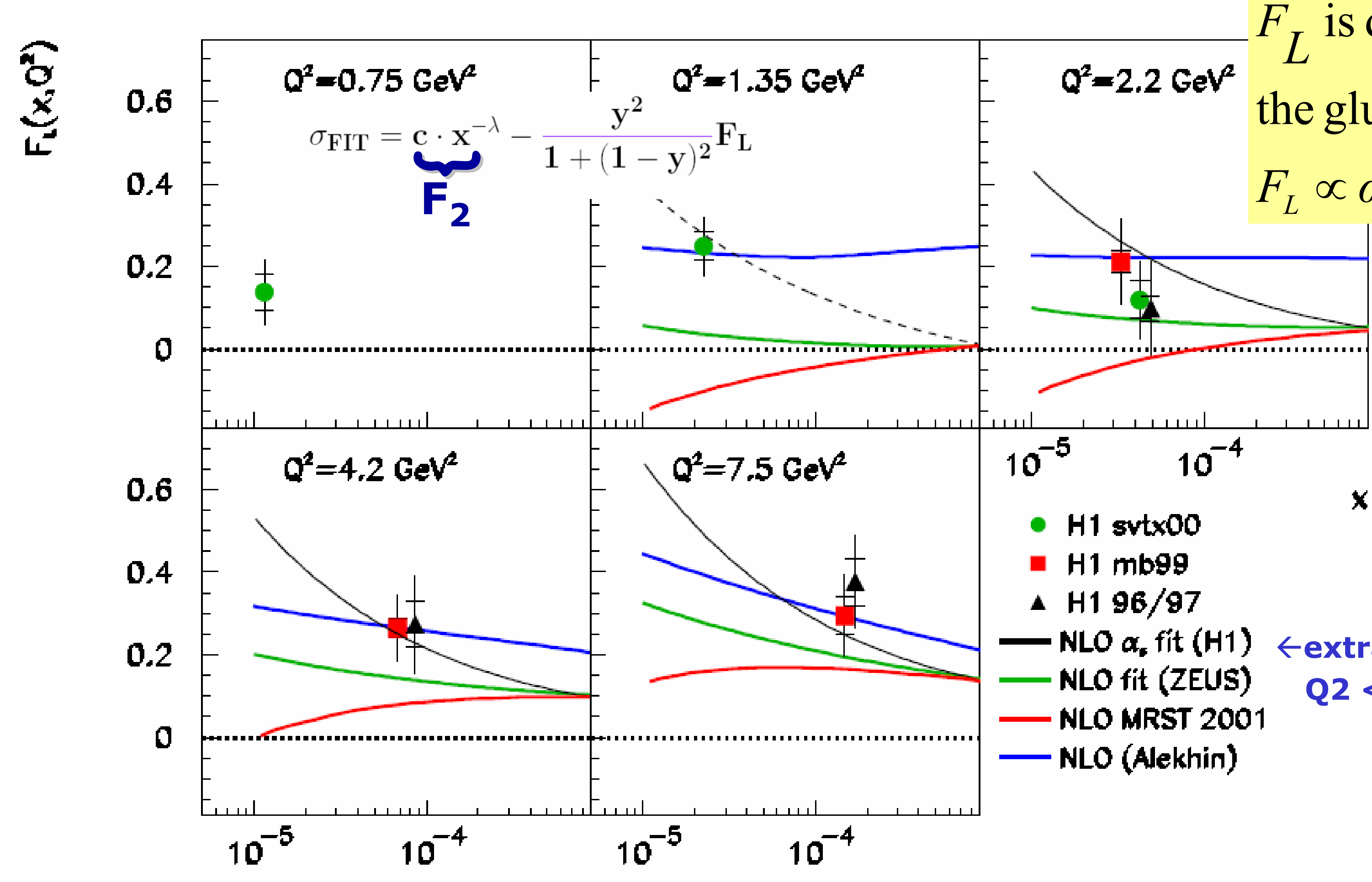



re

$F_2 \propto x^{-\lambda}$ at small x
→ rise of the parton densities

At x<0.01, a color dipole of variable size steered by 1/Q interacts with the proton

# $F_L$ from reduced inclusive DIS cross section




$F_L$ is directly sensitive to the gluon in the proton

$F_L \propto \alpha_s(Q^2) g(x,Q^2)$

**$F_L > 0$**

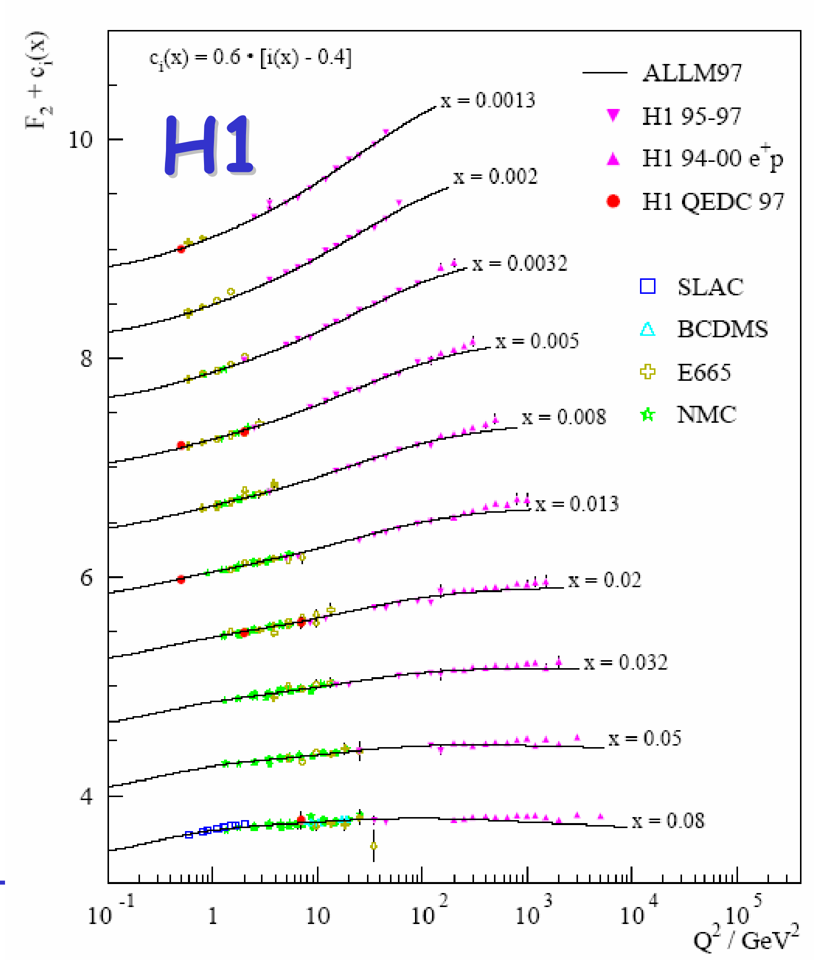
But H1 determination of $F_L$ has two limitations:

- small x & $F_L$ extraction needs assumptions on $F_2$
- x-dependence of $F_L$ can not be determined

➔ Precision $F_L$ measurement requires low-Ep running!

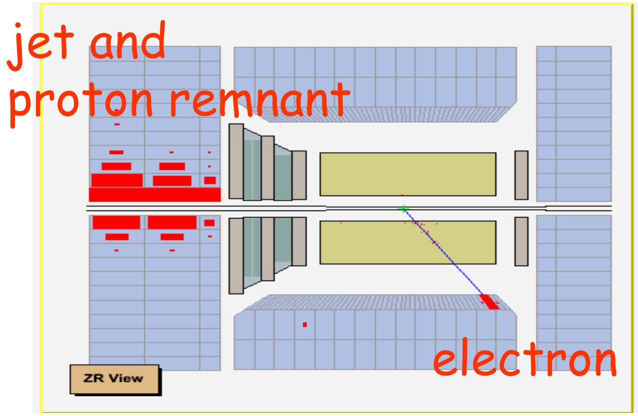
# New NC measurements

$F_2$ at medium x (FT region)
using inelastic QEDC events
Q2 : 0.5 … 7 GeV$^2$
x : 0.001 … 0.01

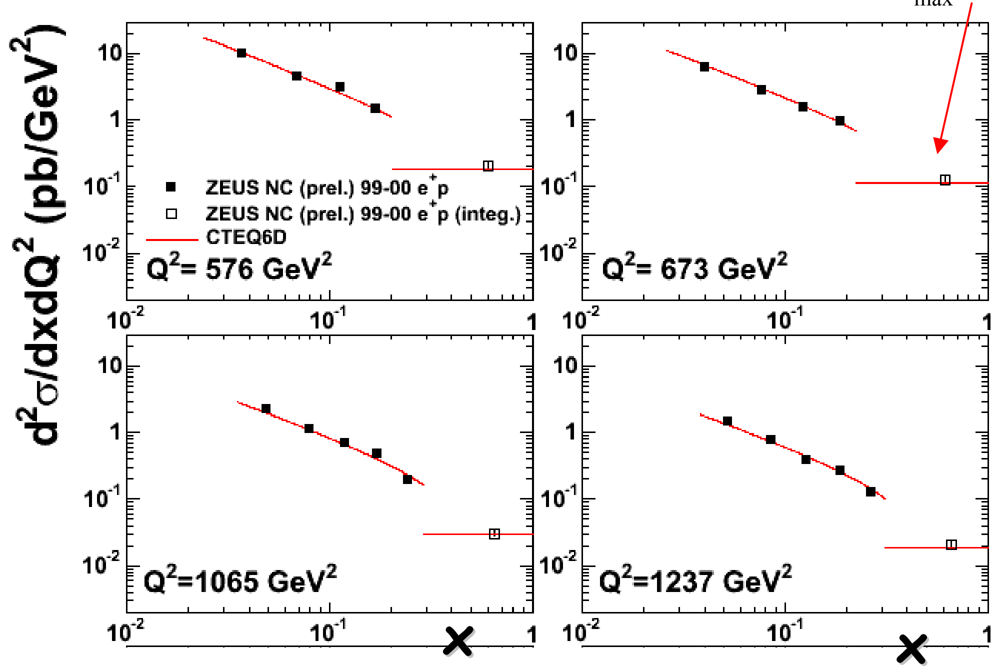



$d^2\sigma/dxdQ^2$ at high x using an improved reconstruction method
$Q^2$ : 576 … 5253 GeV$^2$
x : 0.02 … 1

ZEUS

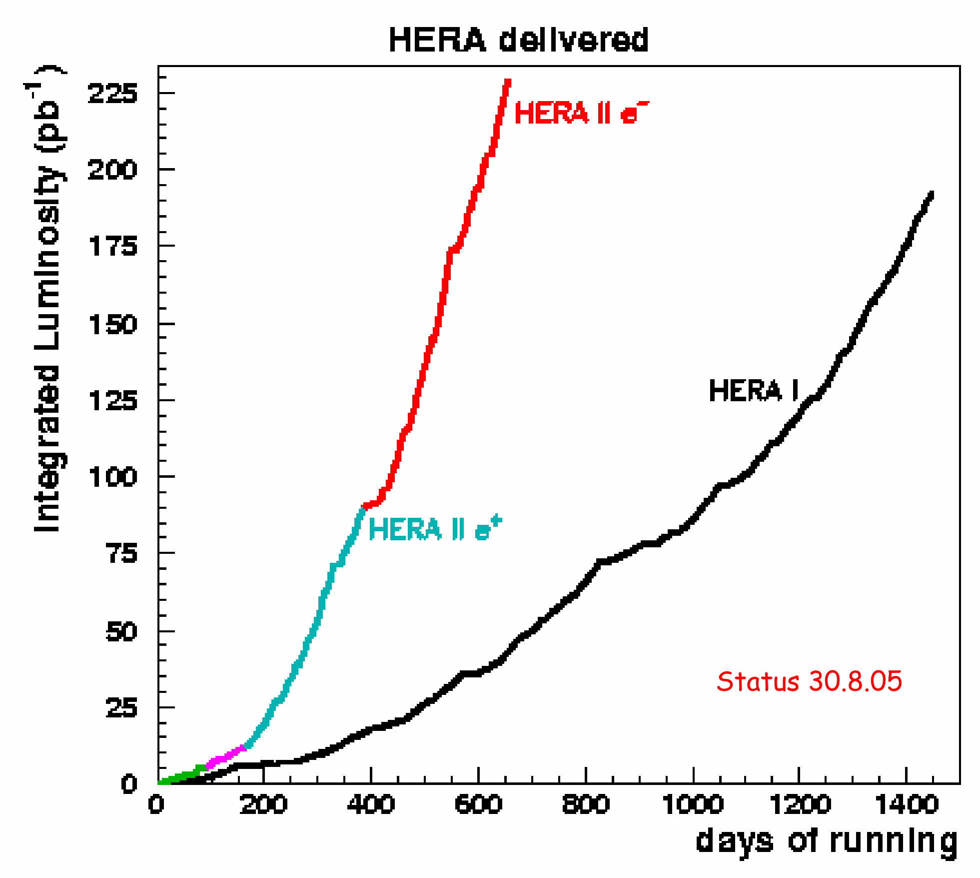



$$\frac{\int_{x_{\max}}^{1} dx \frac{d^2\sigma}{dxdQ^2}}{1 - x_{\max}}$$



# Luminosity development at HERA

**I: 92-00** (unpolarized e)
**II: 03-07** (polarized e)




HERAI: H1 and ZEUS took about 130$pb^{-1}$ with HV on including 16 $pb^{-1}$ e- data

HERAII "luminosity upgrade"

- 2003/2004: positrons H1, ZEUS ~50 $pb^{-1}$
- 2005: electrons: so far 85 $pb^{-1}$ (H1)
  103 $pb^{-1}$ (ZEUS)
- 2007: scheduled end of HERA

# First measurement of $\sigma^{\pm}_{CC}(\lambda)$

low y : $q_v$ high y : q-qbar

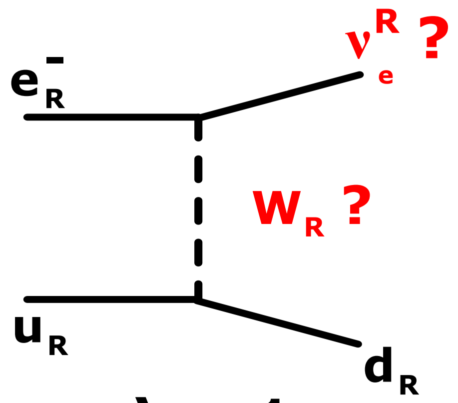
$$\sigma^{\pm}_{CC} = \frac{2\pi\alpha^2}{xQ^4}\kappa_W^2\,(Q^2)\,\frac{1\pm\lambda}{2}\left(Y_+W_2^{\pm} \mp Y_- xW_3^{\pm}\right)$$

with $Y_+ = 2 - 2y + y^2/(1+R)$

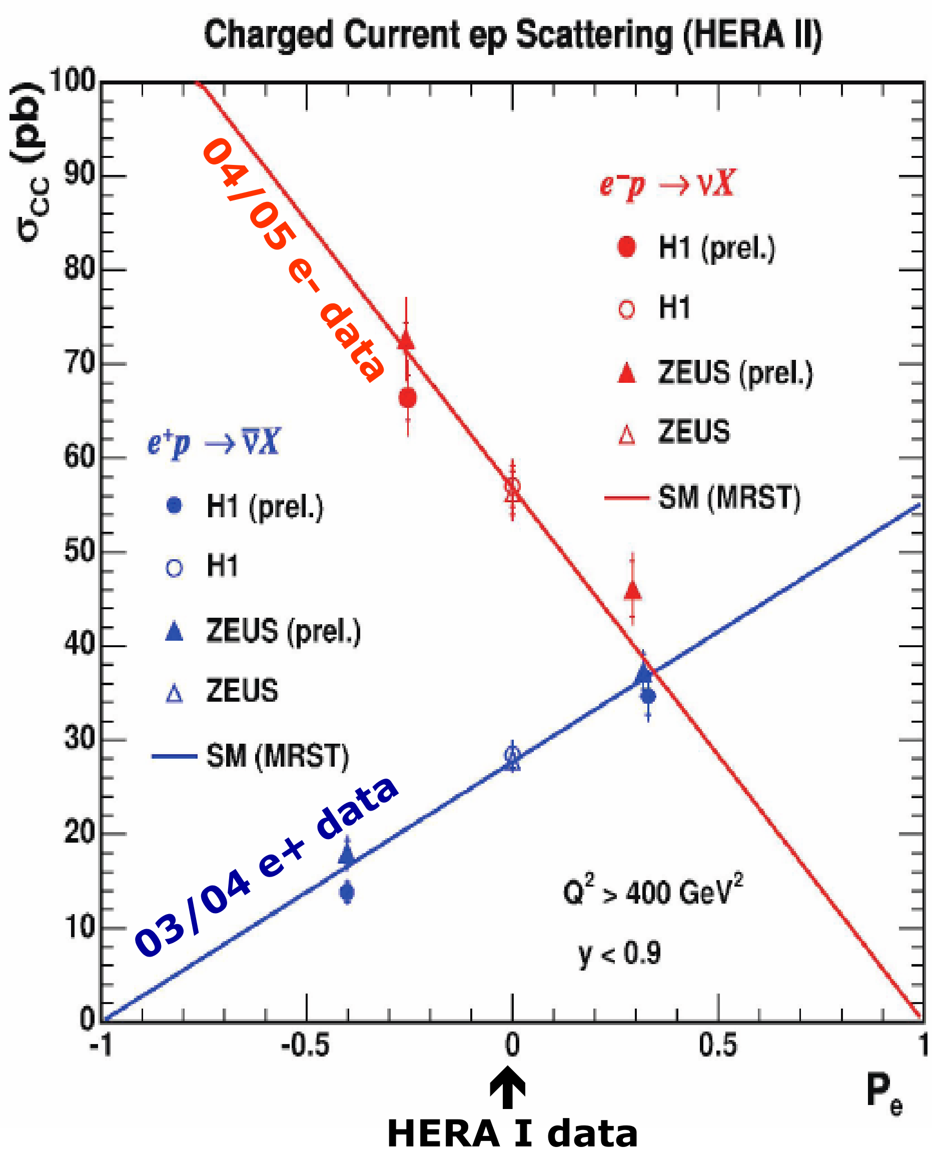
$Y_- = 1 - (1-y)^2$

$$\kappa_W = \frac{Q^2}{Q^2+M_W^2}\,\frac{1}{4\sin^2\theta_W} \approx 1 \quad \text{for } Q^2 \gg M_W^2$$

➔ *textbook* measurement !




$\lambda = +1$



# Summary and outlook

- First round of measurements and QCD analyses of NC and CC DIS HERA I data is essentially finished.

- HERA can determine full PDF set with controlled systematic employing new techniques and theoretical developments
  + inclusion of ep jet data
  + new experimental techniques
  + combined EW and QCD analysis
  + inclusion of new polarized HERA II data

HERA data have a great potential but to reach a next level of precision in PDFs and $\alpha_S$ is a serious challenge (data, analysis, NNLO…).

# Back Ups

# First Polarized $e^+$ @H1+ZEUS in 2003