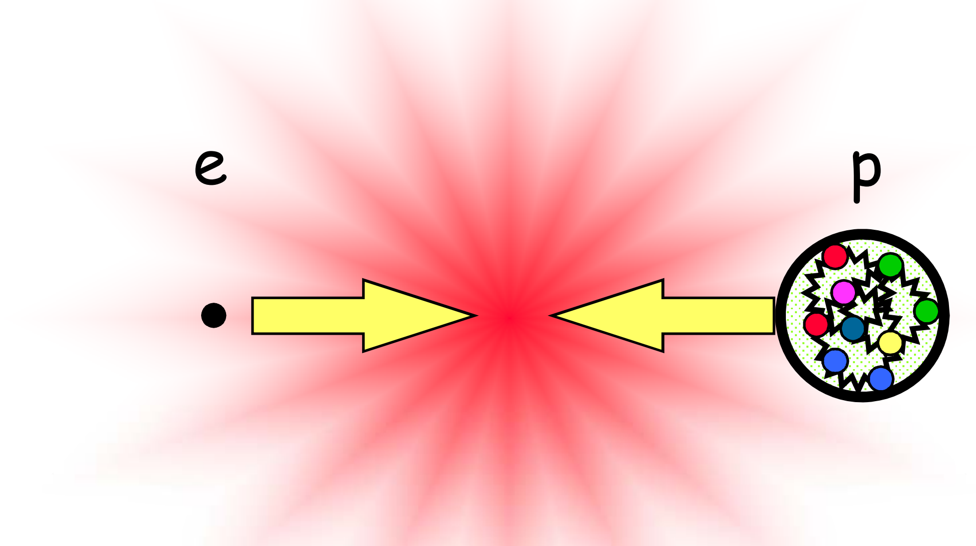
HERA
- Structure of Matter and QCD

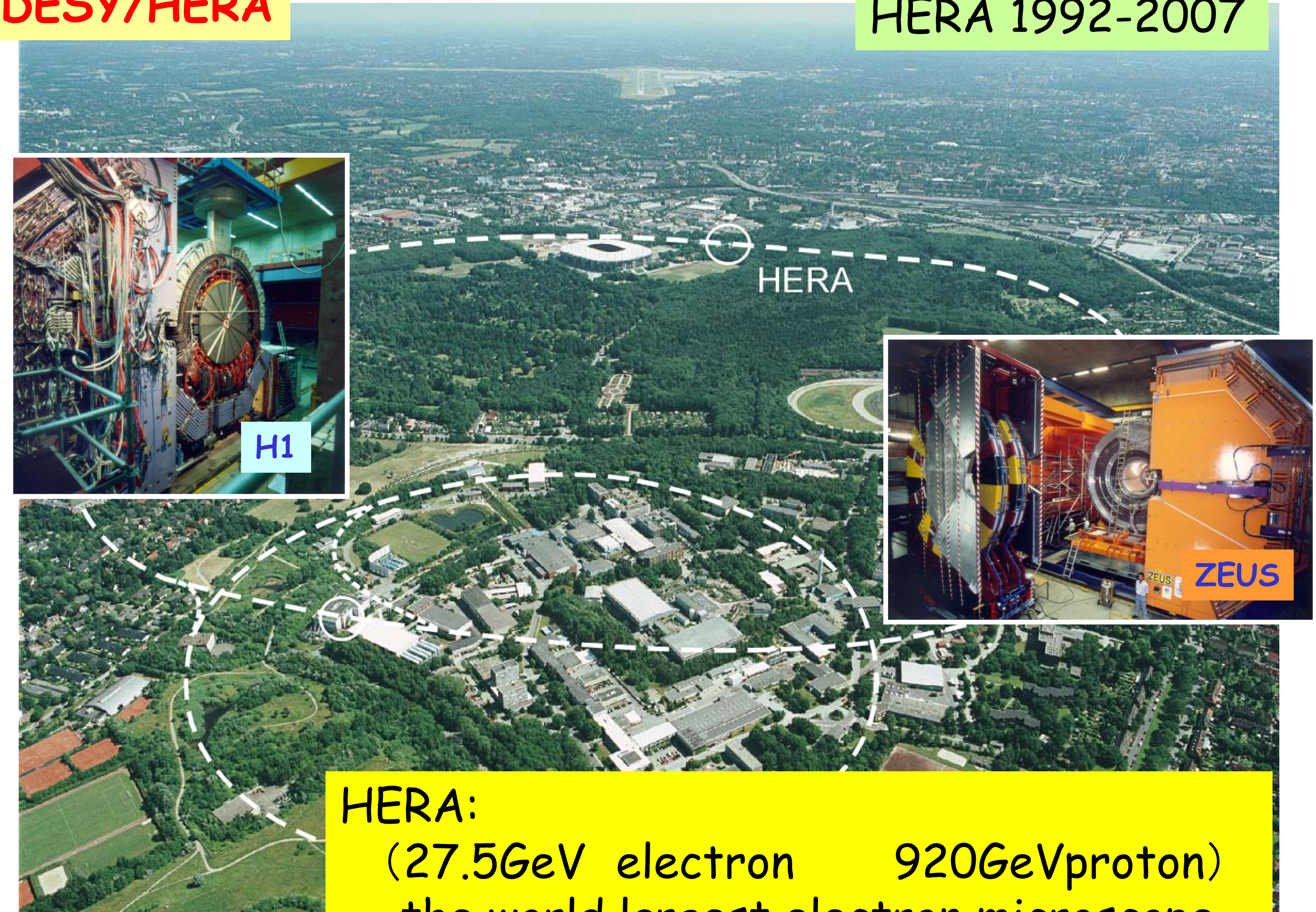


Contents
- 15 year running of HERA and H1/ZEUS
- Electroweak results
- Structure of the proton

Katsuo Tokushuku
(KEK, ZEUS)

DESY/HERA

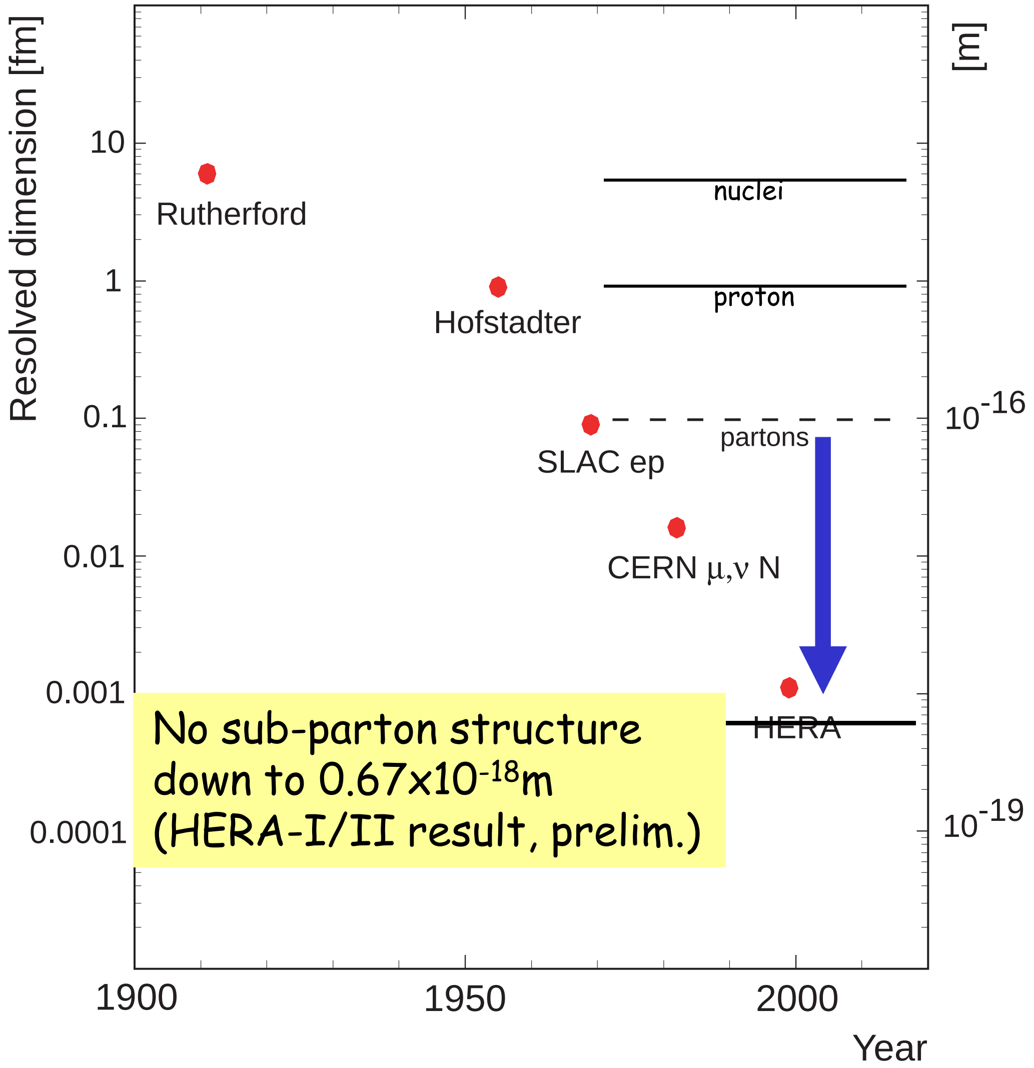
HERA 1992-2007



HERA:
(27.5GeV electron 920GeVproton)
the world largest electron microscope

$$\text{Resolution} \sim (\text{Wavelength})^{-1} \sim \hbar / Q$$

$$Q^2 \equiv (q_i - q_f)^2$$



Progress in accelerator enables us to investigate the smaller structure.

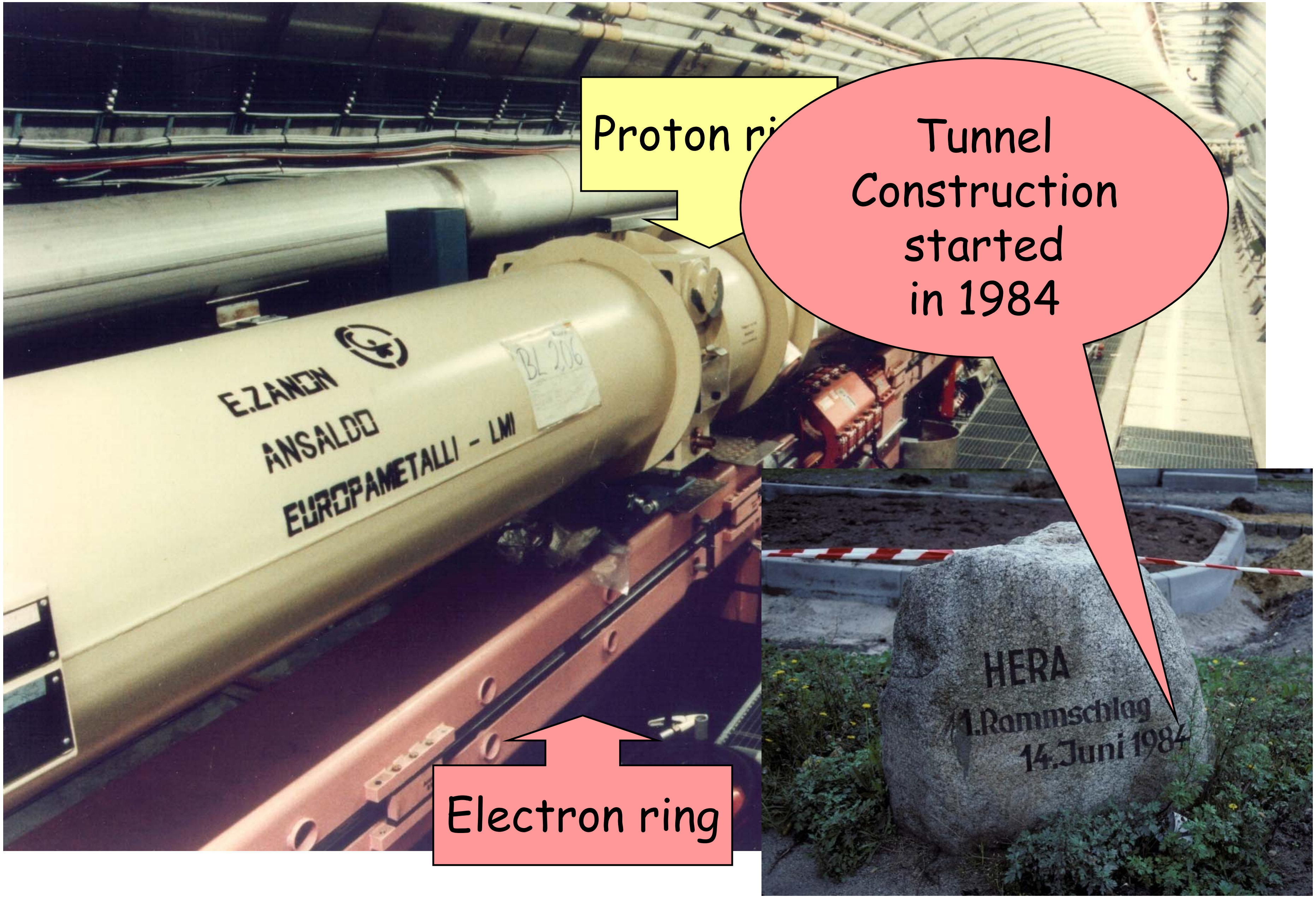
HERA:
(27.5GeV electron(positron) vs. 920 GeV proton)

$Q^2_{max} = s = 4E_eE_p \sim 10000 \text{GeV}^2$

cf. in the rest frame
$s = 2E_eM_p$

In order to obtain the same CMS energy as HERA in a fixed target experiment, it requires 54TeV electron beam.

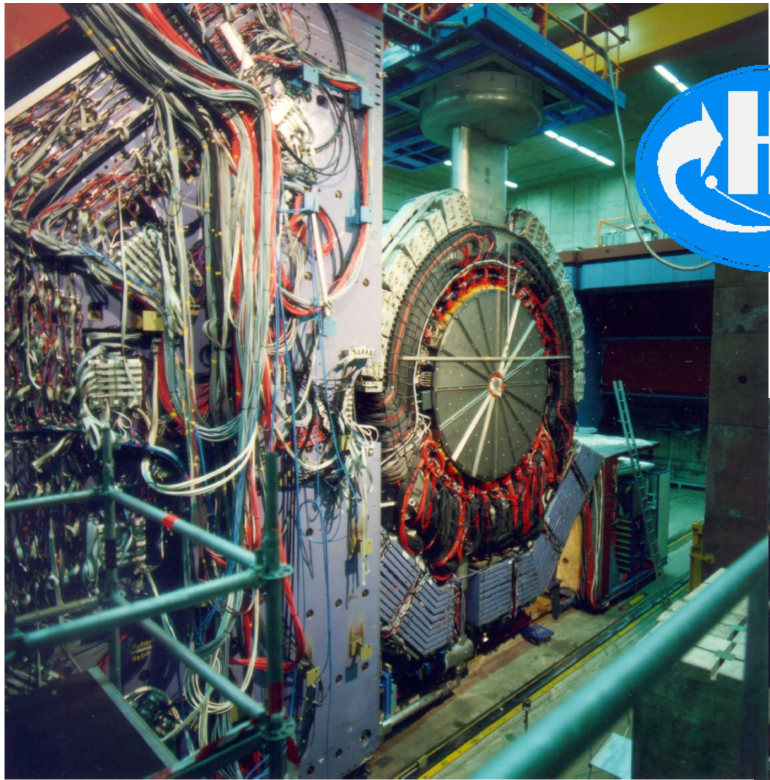
A view of the HERA ring tunnel



Proton ri

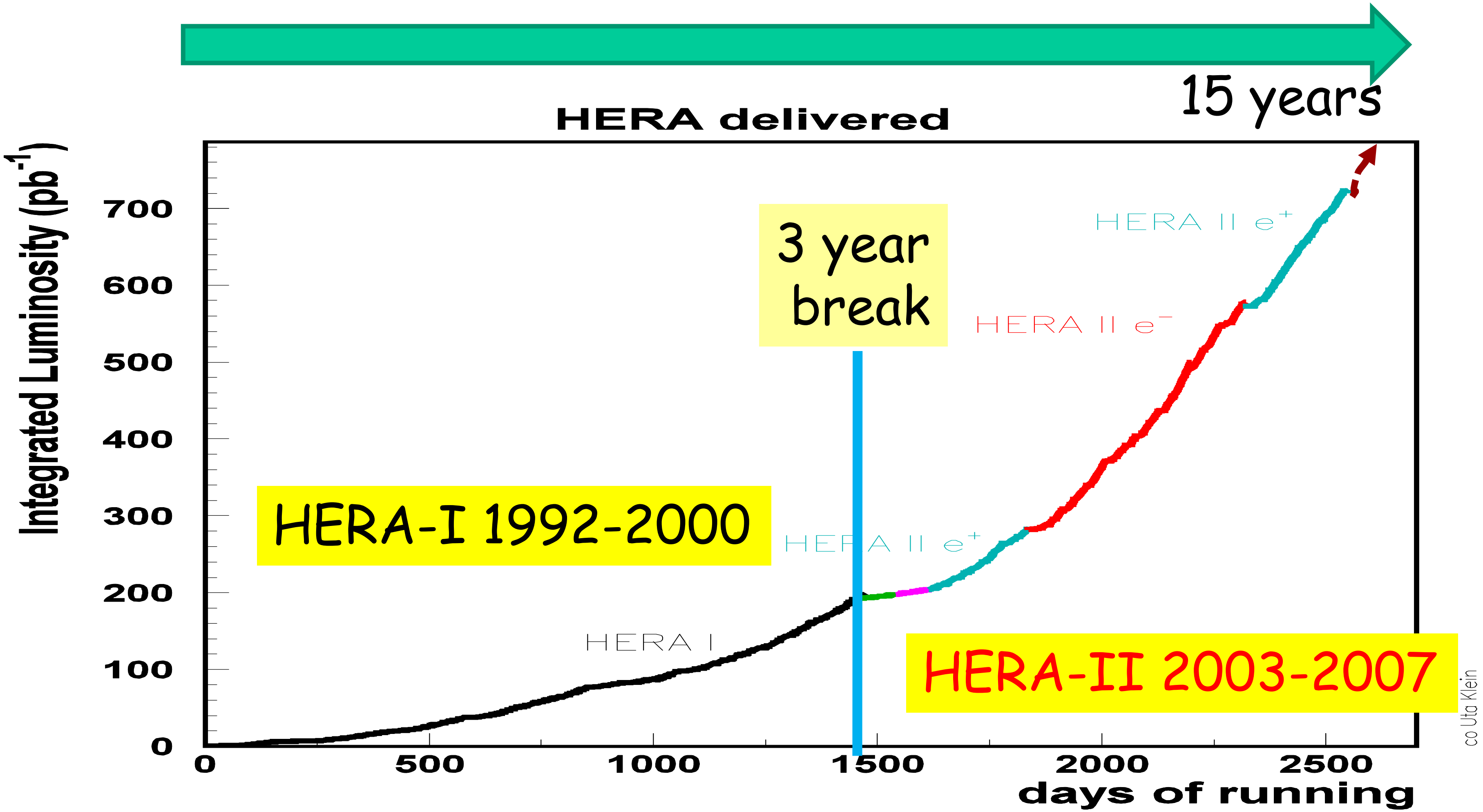
Tunnel Construction started in 1984

Electron ring

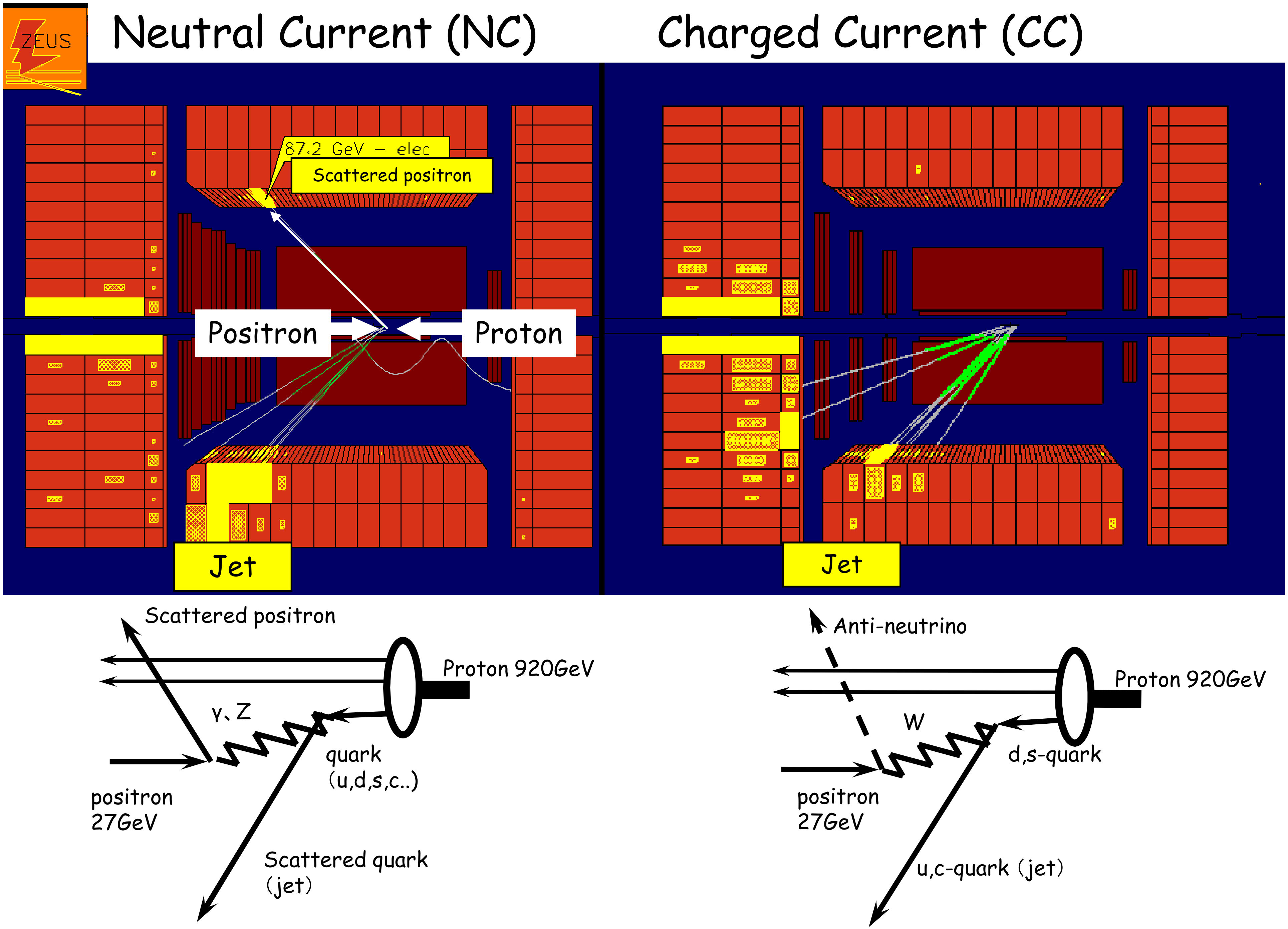


Experiments started in 1992

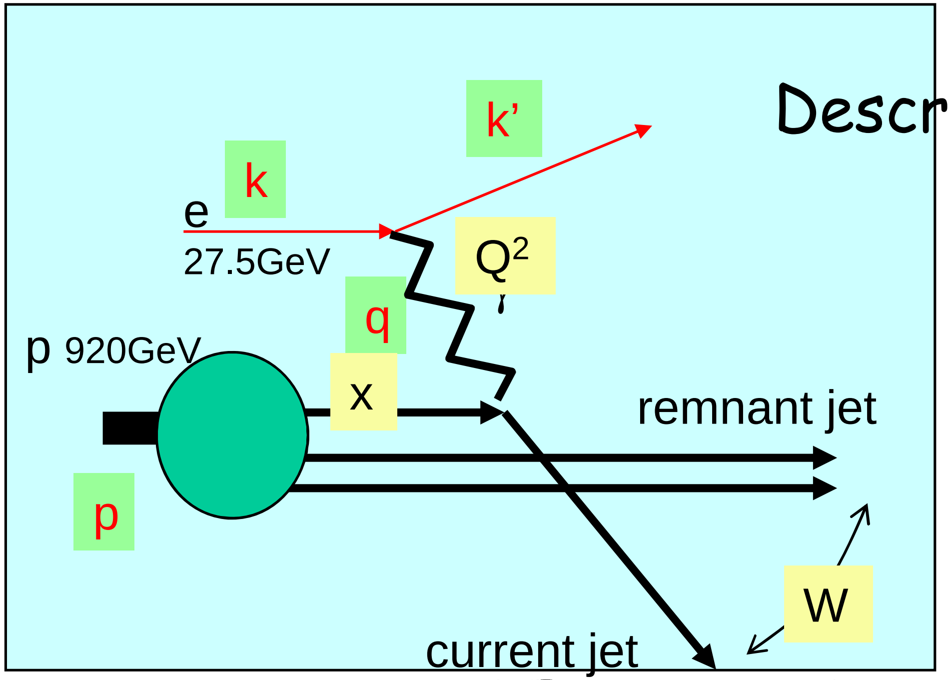
HERA History (1992-2007)



HERA will stop at the end of June in 2007


ZEUS
Neutral Current (NC)
Charged Current (CC)
87.2 GeV – elec
Scattered positron
Positron
Proton
Jet
Jet
Scattered positron
Proton 920GeV
γ, Z
quark
(u,d,s,c..)
positron
27GeV
Scattered quark
(jet)
Anti-neutrino
Proton 920GeV
W
d,s-quark
positron
27GeV
u,c-quark (jet)

Introduction: Deep Inelastic Scattering



Described by 2 kinematic variables

$Q^2 = -q^2$ photon virtuality

$x = Q^2/2p.q$ Bjorken x

$y = p.q/p.k$ Inelasticity

$s = Q^2 xy$

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

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

F_L : Longitudinal Str. Ft. (0 in QPM)

F_3 : Small at $Q^2 \ll M_Z^2$

$$F_2 = \sum_f e^2 x q_f(x, Q^2)$$

$q_f(x, Q^2)$: quark distribution function

pQCD view of F_2

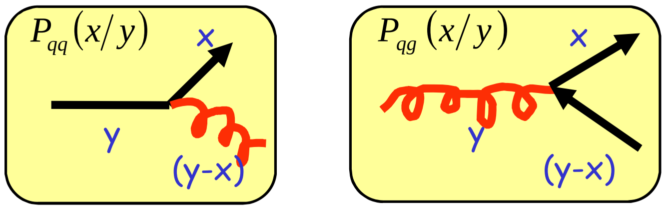
$$F_2 = \sum_f e^2 x q_f(x, Q^2)$$

PDF depends on Q^2

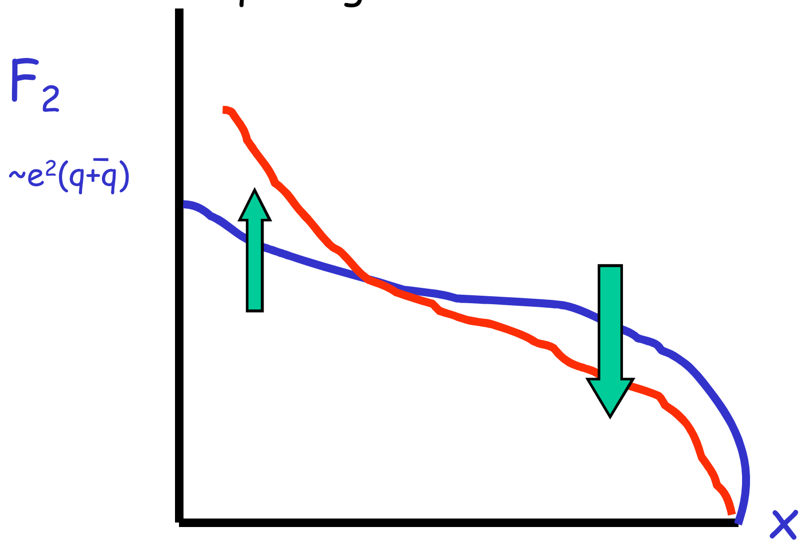
DGLAP evolution (Dokshitzer, Gribov, Lipatov, Altarelli, Parisi)

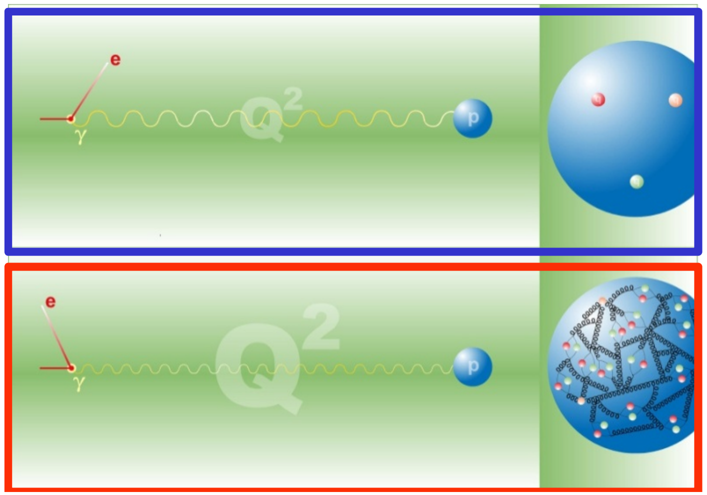
$$\frac{dF_2}{d\ln Q^2} = \propto \sum_q e_q^2 \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} \left[P_{qq}(x/y) \cdot q(y, Q^2) + P_{qg}(x/y) \cdot g(y, Q^2) \right]$$

splitting function (known from pQCD)



$Q^2 \rightarrow$ larger:
high-x q and g are split into
low x q and g.

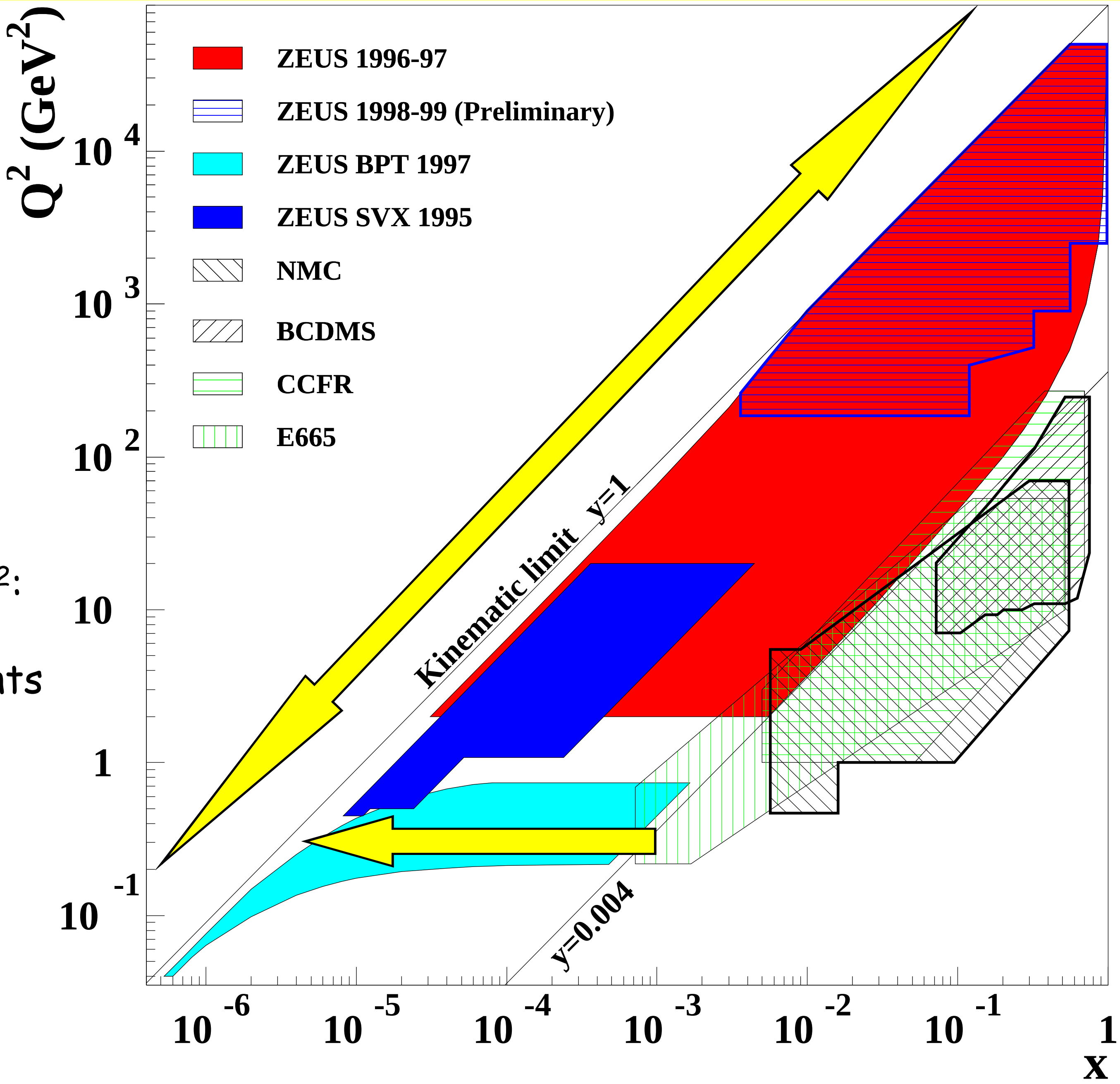




Kinematical region for HERA structure function measurements

- 2 order higher region in Q^2,
- 2 order lower region in x
- Wide ($O(10^6)$) span in Q^2:

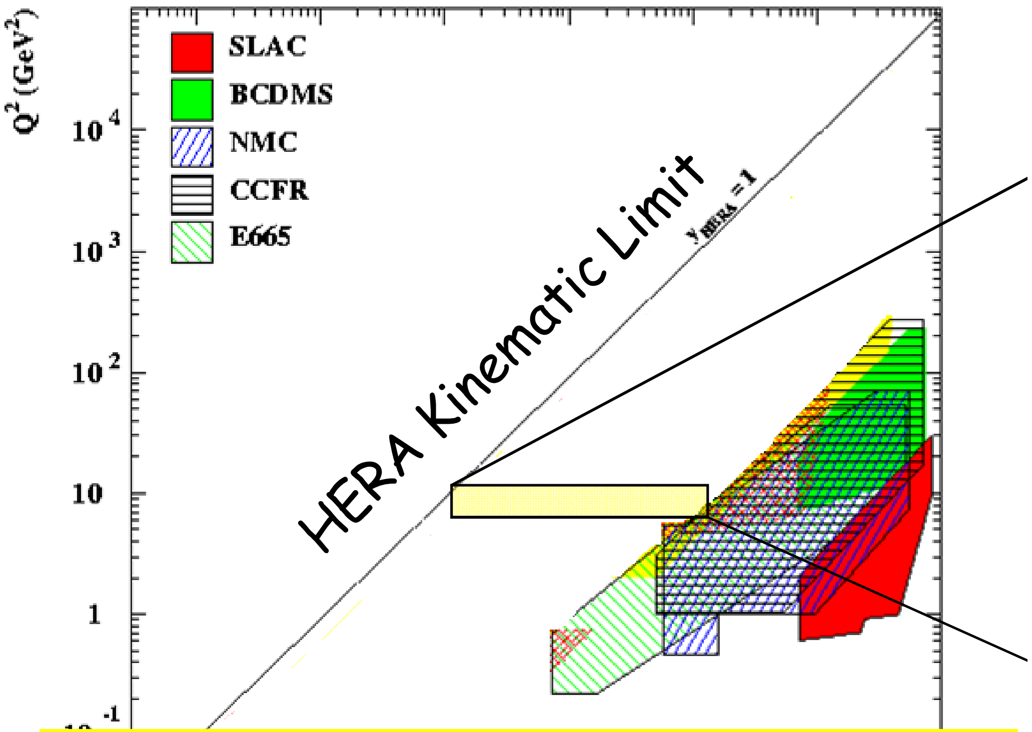
Precise measurements for Q^2 evolution

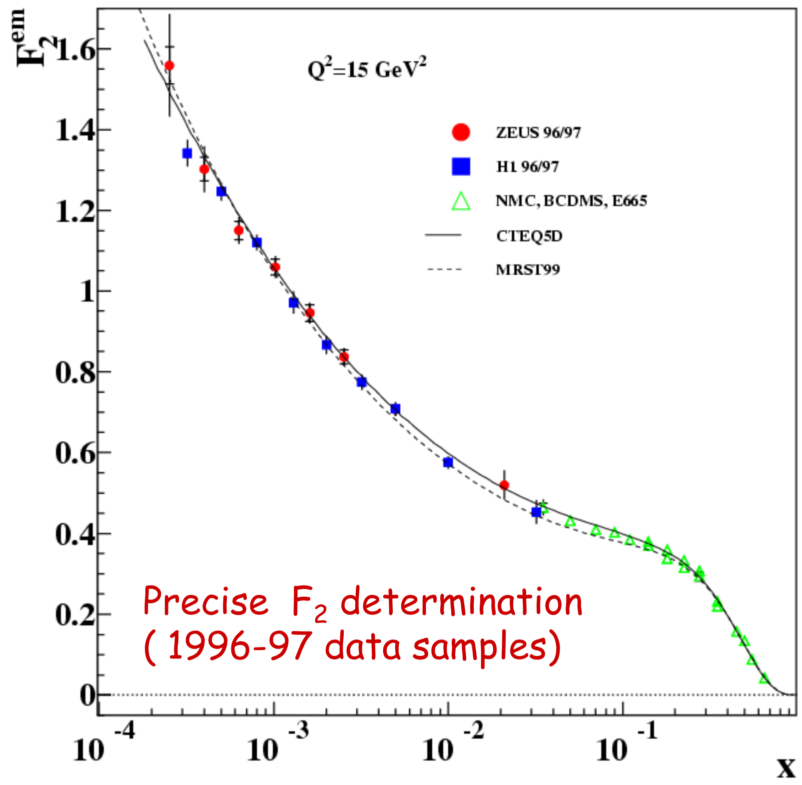


Predictions of F_2

Gluck, Reya and Vogt

"pQCD" : parton evolution





Early HERA data showed rapid increase of F_2 at low x.

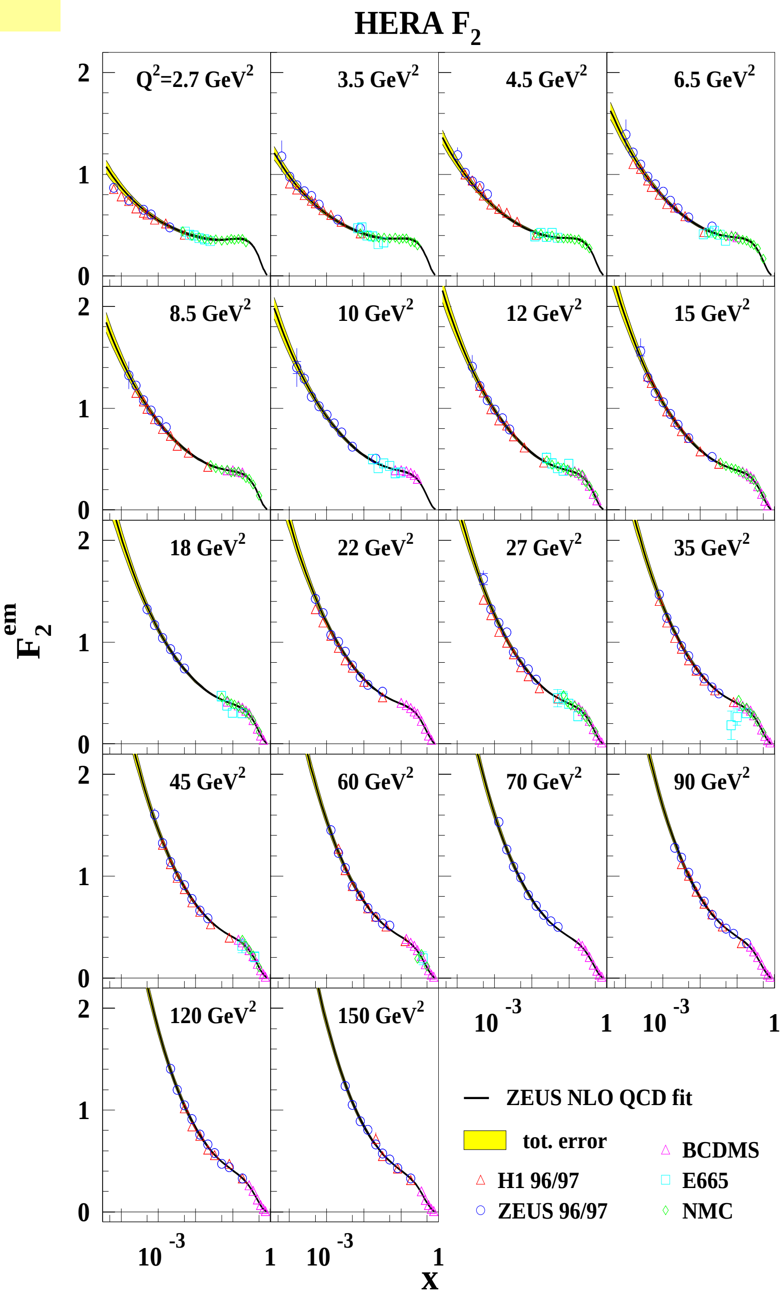
Donnachie & Landshoff

"Hadronic": Regge theory behavior of γp total cross section

Results of F_2 Structure Function

- Strong rise of F_2 as x decreases
  - Soft 'sea' of quarks in the proton
- Slope of rise gets steeper as Q^2 goes up

- Good agreement with fixed-target experiments at middle - high x
  - Sea + valence quarks

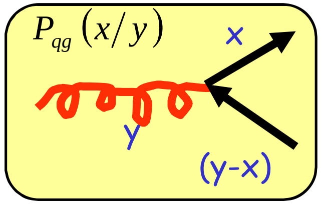


F_2 for fixed x, as a function of Q^2

- At low x, strong scaling violation is seen.

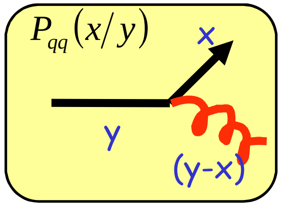
  Large gluon density + $g \to q\bar{q}$ splitting

  $\to F_2$ increases

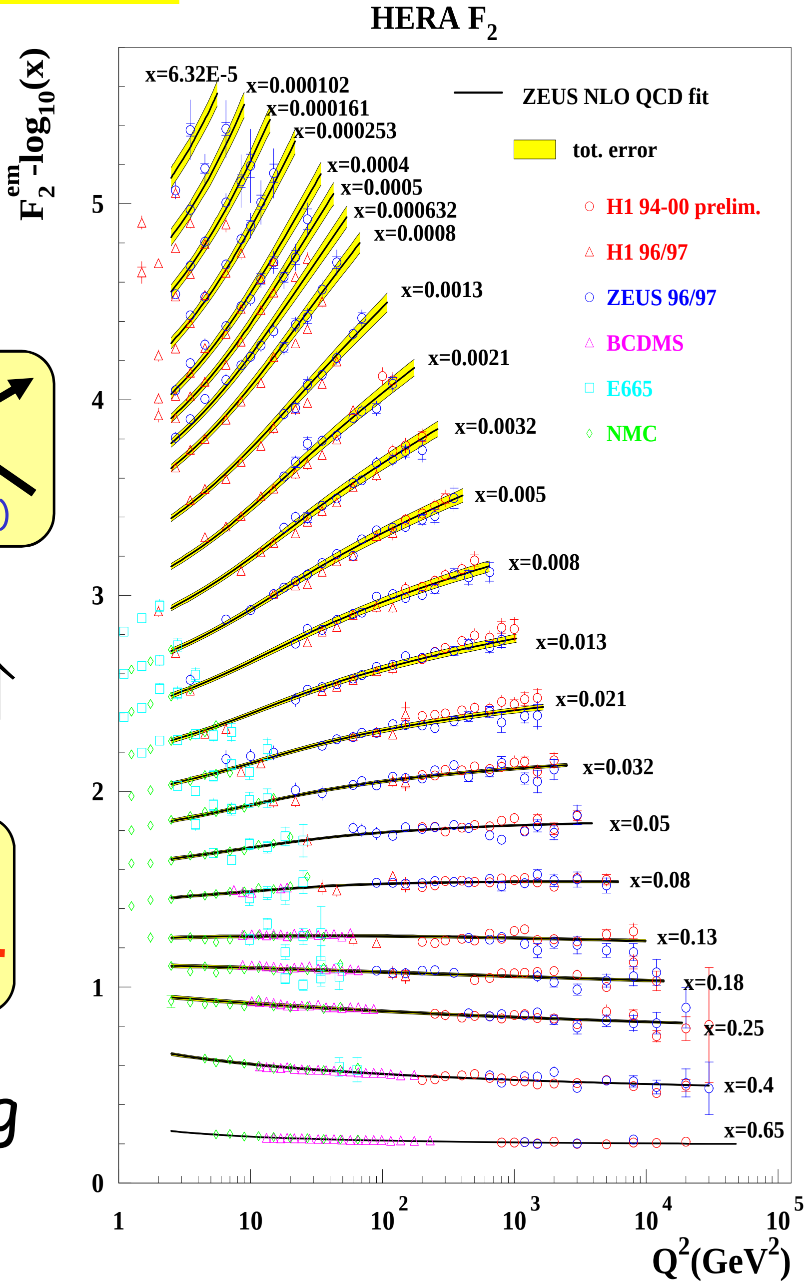


- At $x \sim 0.1$, approximate scaling.
- At higher x, F_2 decreases as $Q^2 \uparrow$

  Quark radiates off gluon: $q \to qg$



- Line = result of QCD fit (comming slides)
  - All data points well described.



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$s=Q^2xy$

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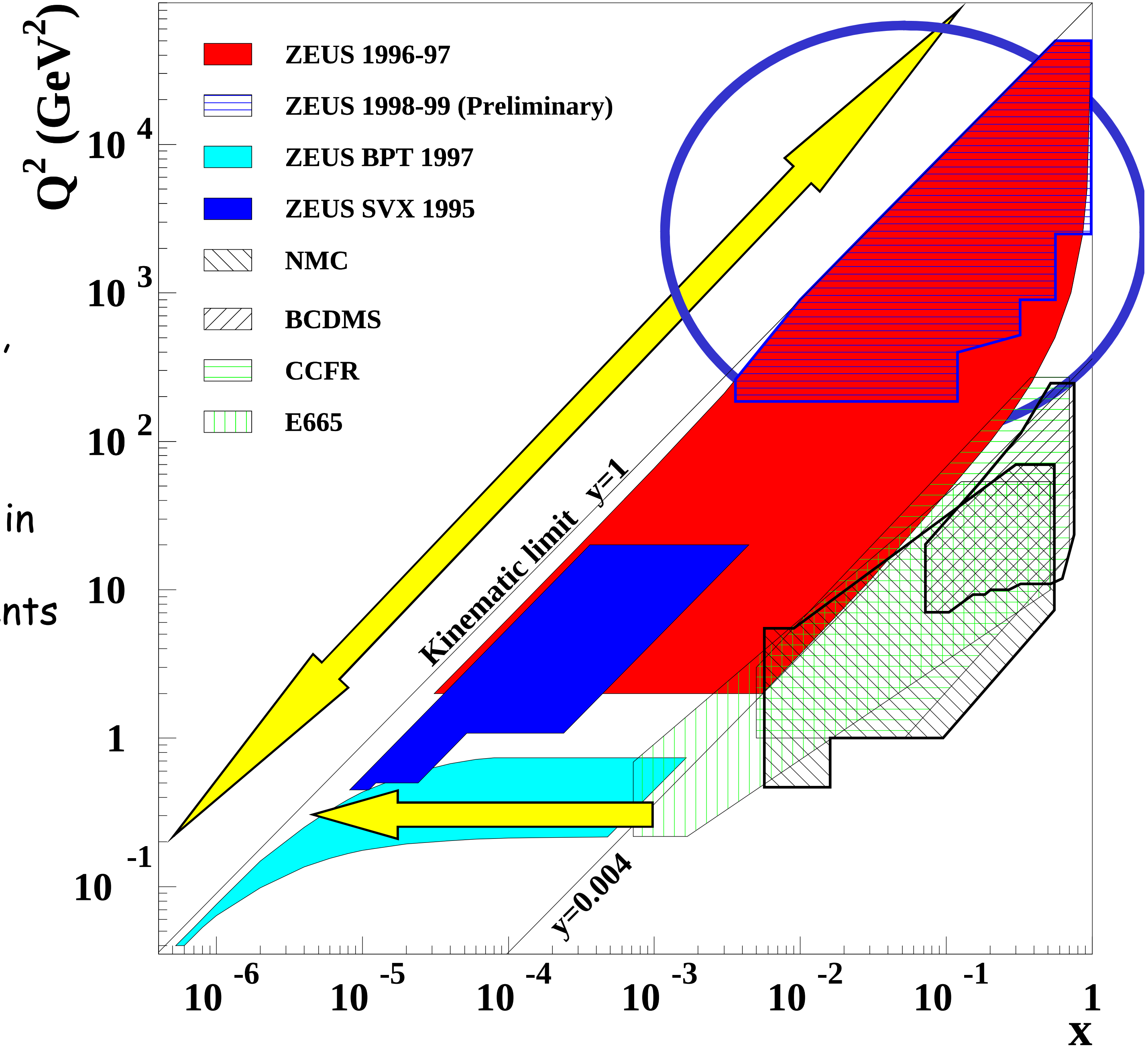
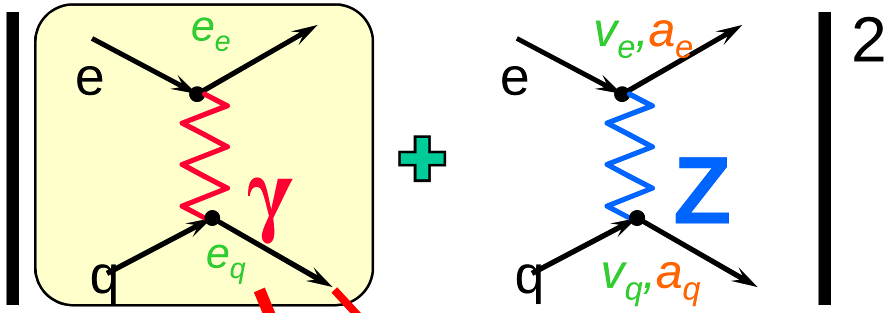
•Wide ($O(10^6)$) span in Q^2:
Precise measurements for Q^2 evolution





In SM, $v_q = I_q^3 - 2e_q \sin^2\theta_W$,

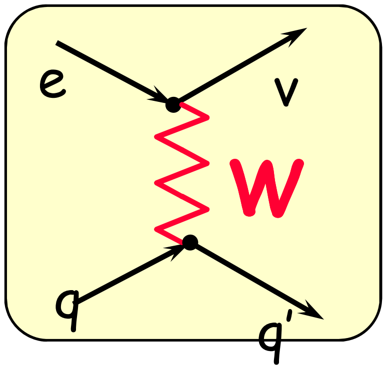
$a_q = I_q^3$

$$P_z = \frac{1}{\sin^2 2\theta_w} \frac{Q^2}{Q^2 + M_Z^2}$$

$$F_2(x,Q^2) = \sum_q \{e_q^2 - 2e_q v_q v_e P_Z + (v_q^2 + a_q^2)(v_e^2 + a_e^2)P_Z^2\}\left[xq(x,Q^2) + x\bar{q}(x,Q^2)\right]$$ parity +

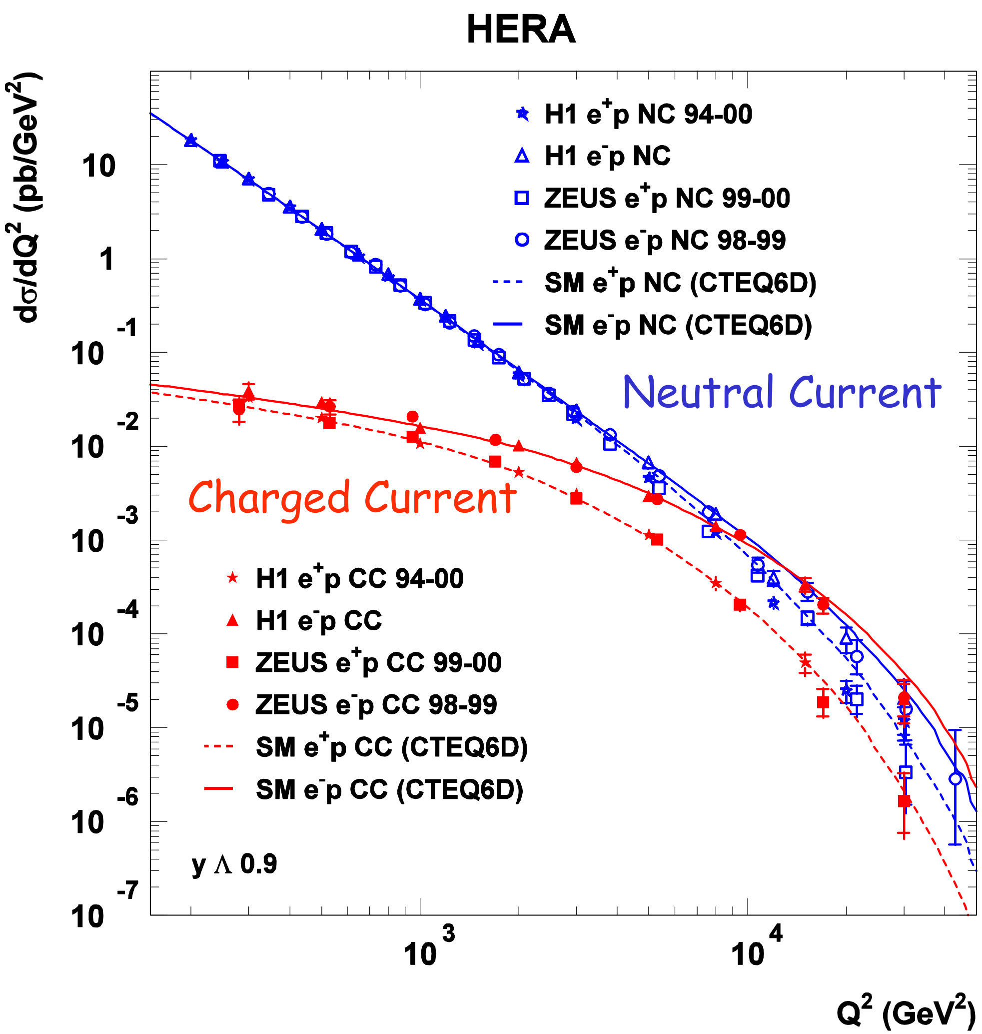
$$xF_3(x,Q^2) = \sum_q \{-2e_q a_q a_e P_Z + 4v_q a_q v_e a_e P_Z^2\}\left[xq(x,Q^2) - x\bar{q}(x,Q^2)\right]$$ parity -

$$\frac{d^2\sigma_{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\{1+(1-y)^2\}F_2 \mp \{1-(1-y)^2\}xF_3\right]$$



$$\frac{d^2\sigma^{CC}_{e^\pm p}}{dxdQ^2} = \frac{G_F}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2\left[\{1+(1-y)^2\}F_2 \mp \{1-(1-y)^2\}xF_3\right]$$

Measurements of NC/CC Cross sections



HERA-I Final Results

At high Q^2 ($Q^2 \sim M_{W,Z}^2$),

$\sigma_{NC} \sim \sigma_{CC}$

$$\frac{d\sigma}{dQ^2} \propto \frac{\alpha'^2}{\left(Q^2 + M_{Exchange}^2\right)^2}$$

$\alpha_{NC} \sim \alpha_{CC}$

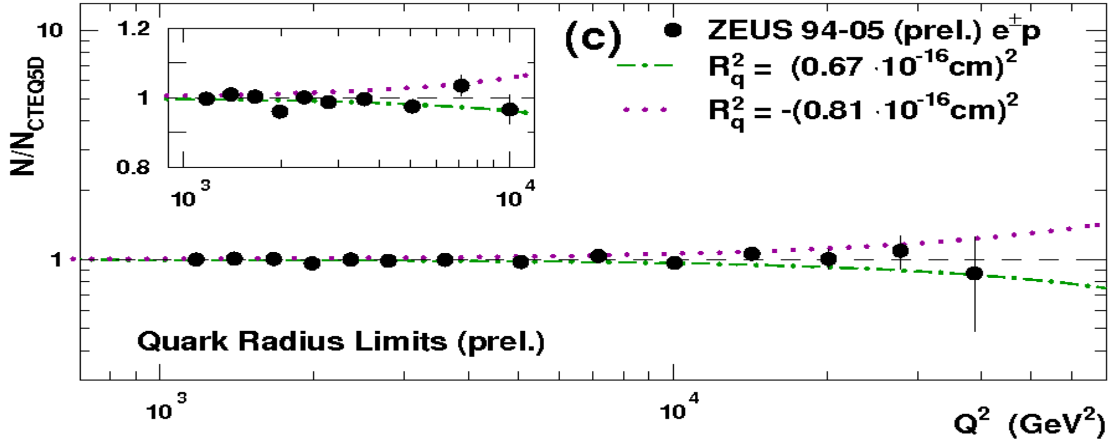
→ Electroweak unification

Good agreement with the SM

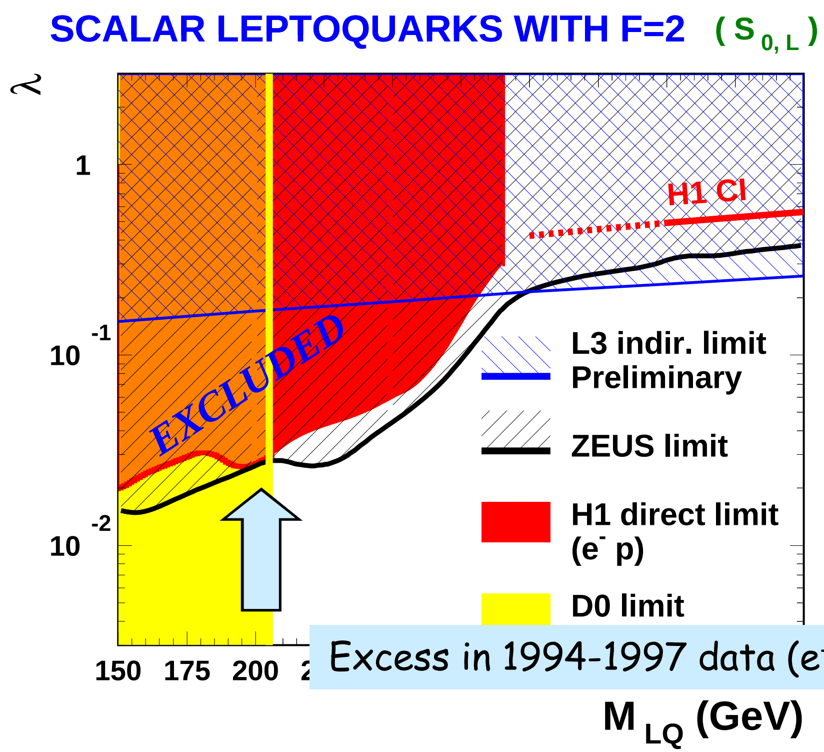
Mw = 80.3 ±2.1(stat)±1.2(syst)±1.0(PDF) GeV (from ZEUS e⁻p data)

- NC(e^+p) < NC(e^-p)
  ← γZ interference
- CC(e^+p)<CC(e^-p)
  ← u,d-quark distribution in the proton

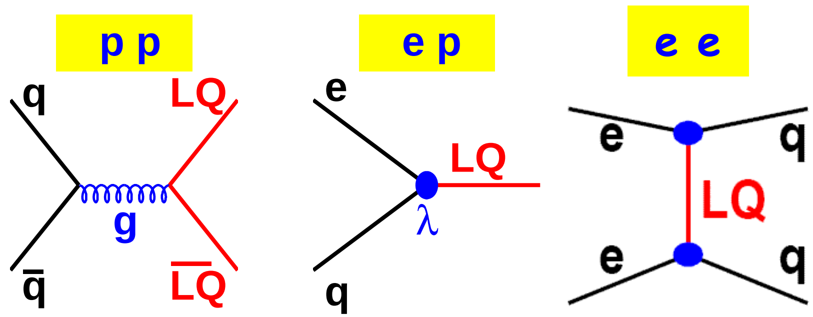
Seaches of BSM



"softer" scattering
If the quark is not point-like



Excess in 1994-1997 data (e^+p)

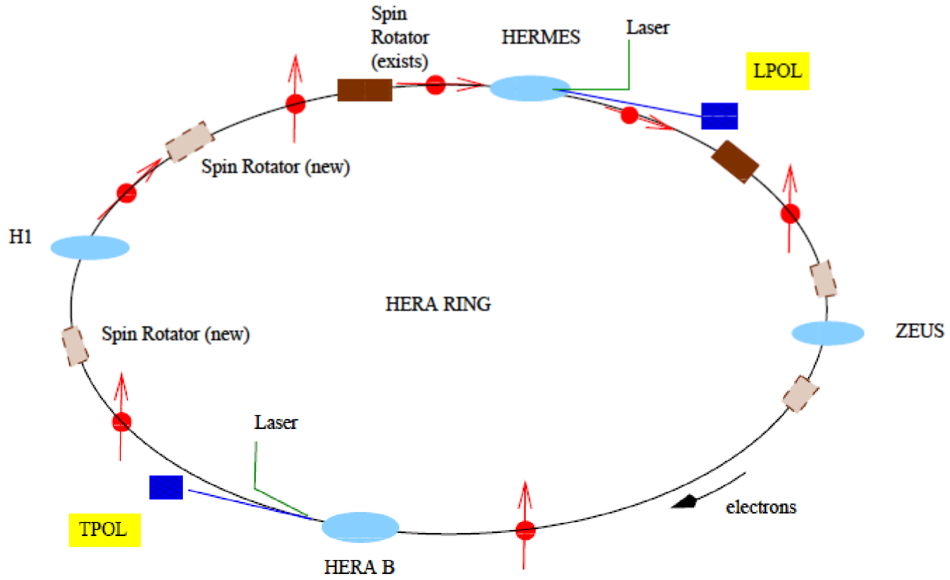


Good agreement with the SM

Quark Radius $< 0.67 \times 10^{-16}$ cm (prelim.)
No signal for Leptoquarks so far

HERA I → II

Longitudinal polarization of lepton beam : → Direct EW sensitivity

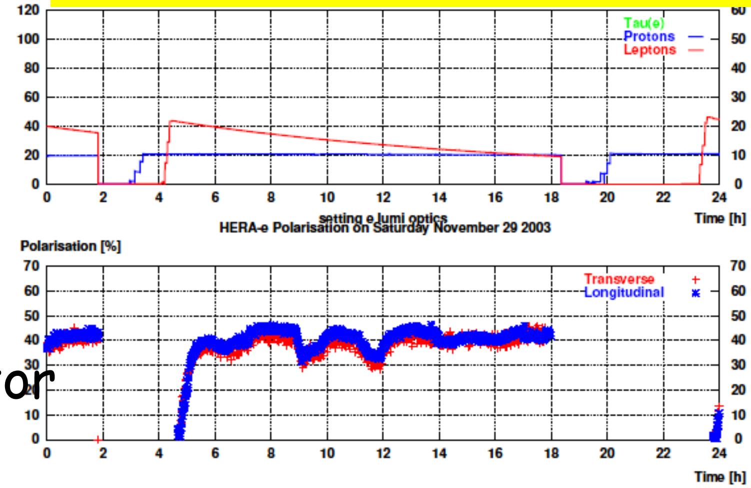


- Sokolov-Ternov effect
→ Lepton beam has transverse polarization

+

- Spin rotator before/after the H1/ZEUS/HERMES

Polarization build-up at HERA

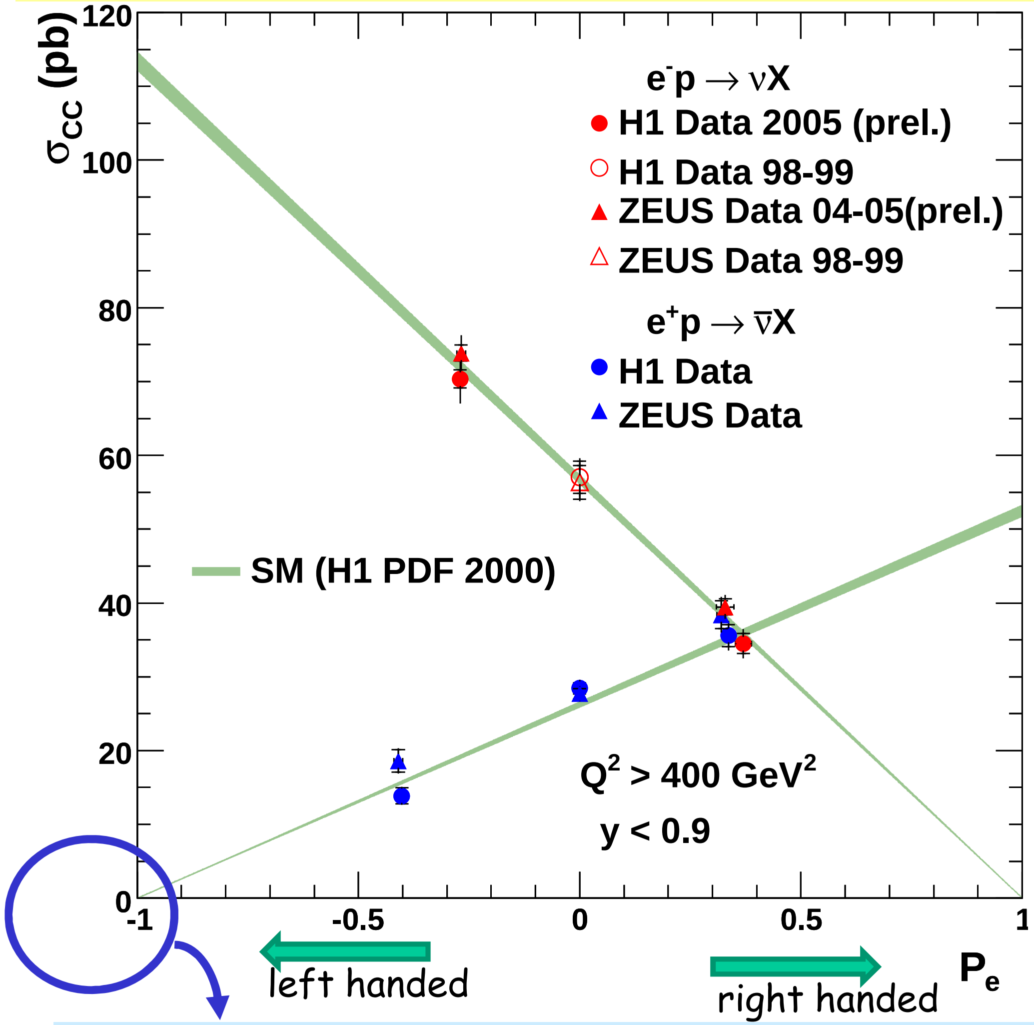


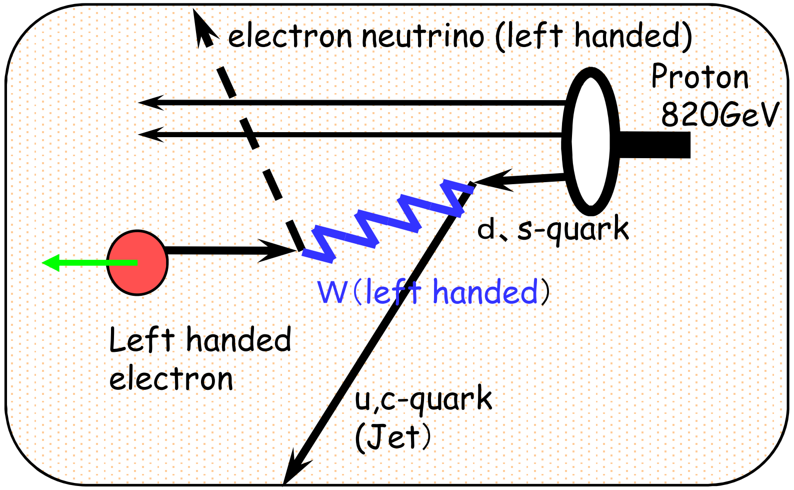
30 ~40% on average

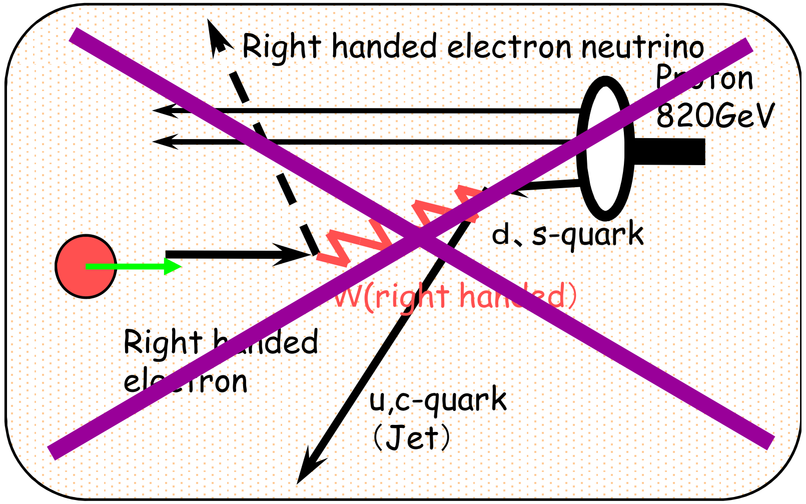
Luminosity Upgrade :
← High-Q^2 requires large luminosity

- Final focusing magnets in the detector

Charged Current Scattering







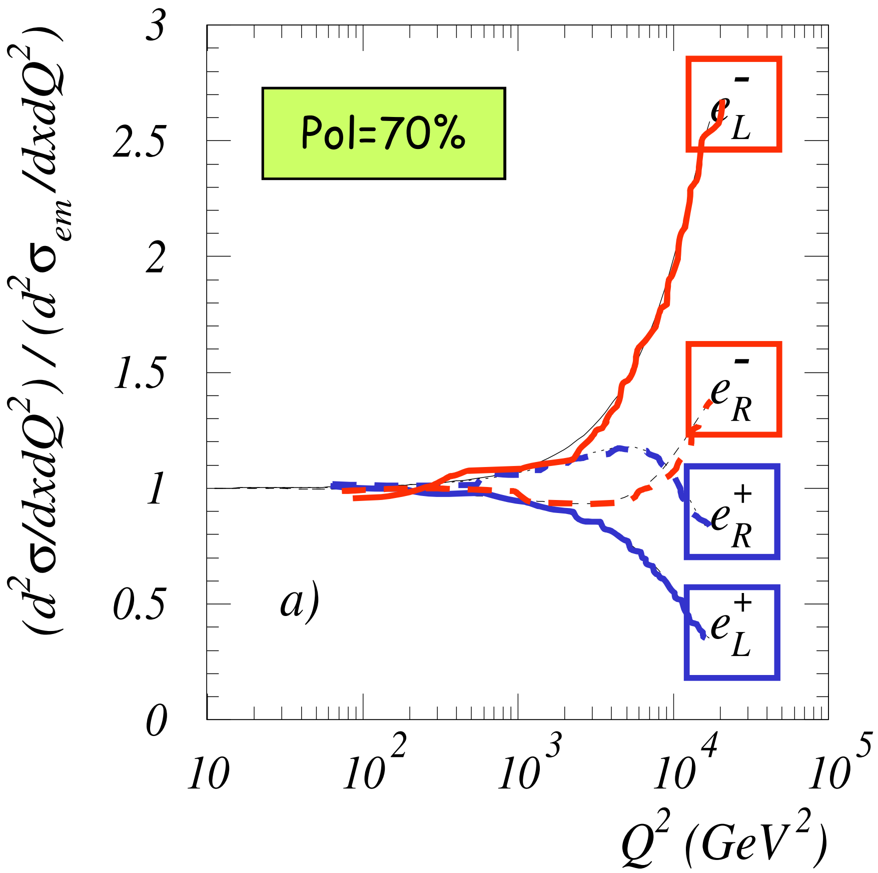
σ_R=0.2±1.8±1.6 pb (H1 and ZEUS combined preliminary result) -> W_R mass limit ~ 200 GeV

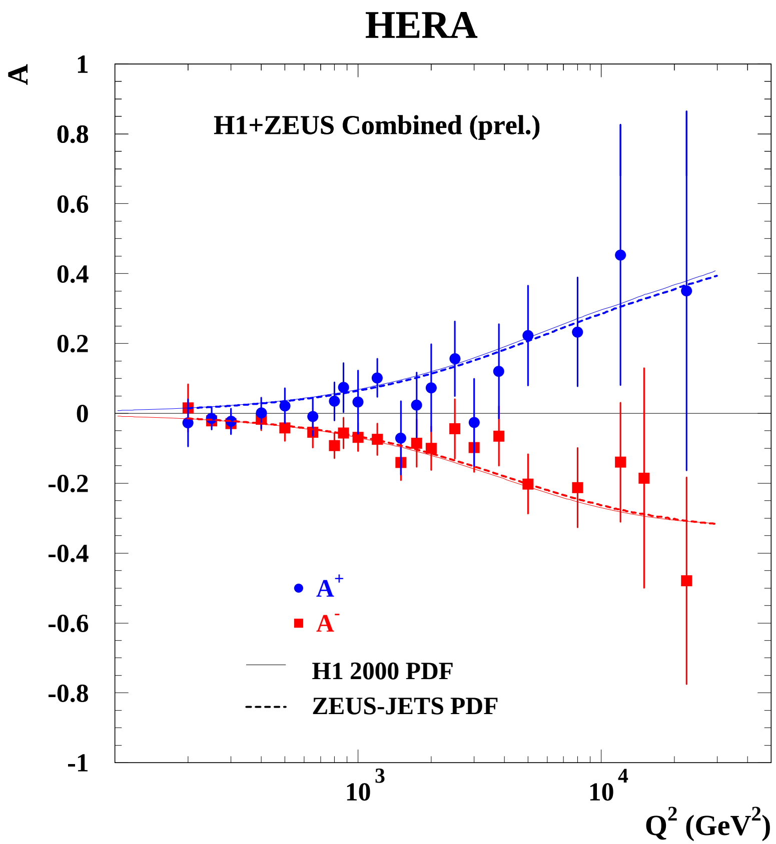
• The first measurement of Left/Right asymmetry in CC in this energy region.

Polarized Neutral Current Cross section

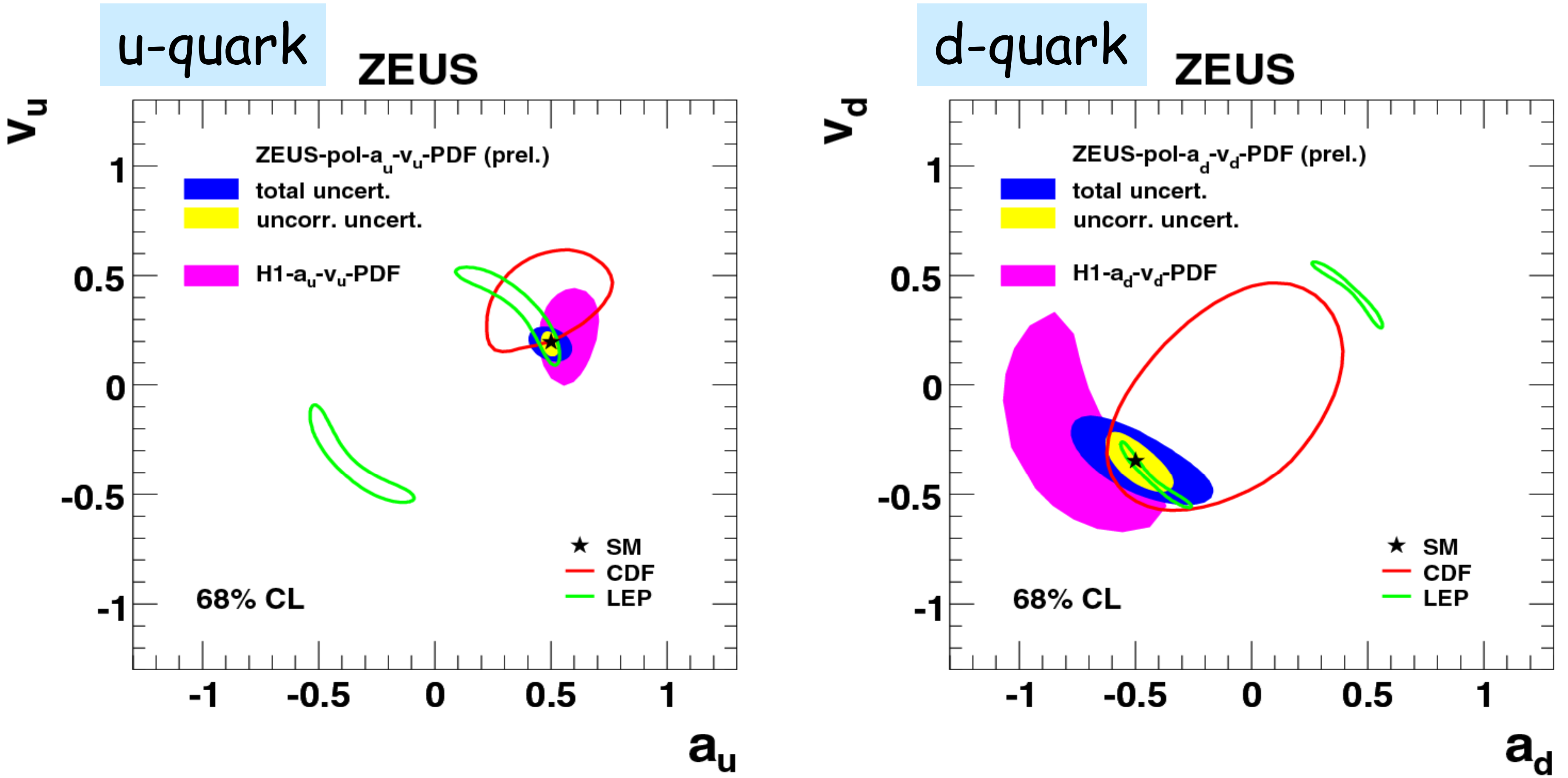
- Very subtle effect from g-Z interference
  -> H1+ZEUS combined results

$$A^{\pm} \equiv \frac{2}{P_R - P_L} \frac{\sigma_R^{e^{\pm}p} - \sigma_L^{e^{\pm}p}}{\sigma_R^{e^{\pm}p} + \sigma_L^{e^{\pm}p}}$$





Measurement of q-Z coupling



- Polarized data improves the vector couplings.
- HERA-II data makes a significant impact on the quark couplings

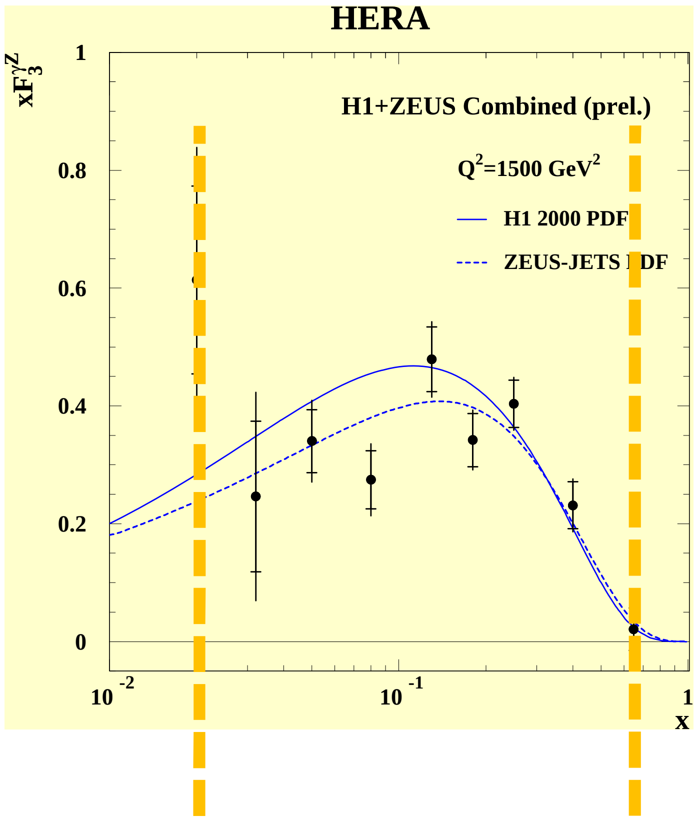
$$\frac{d^2\sigma_{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\{1+(1-y)^2\}F_2 \mp \{1-(1-y)^2\}xF_3\right]$$

$$\sigma_{e^-p} - \sigma_{e^+p} \Rightarrow \quad xF_3^{\gamma Z}(x,Q^2) \equiv xF_3(x,Q^2)/a_e P_Z$$
$$= 2x\sum_q e_q a_q [q - \bar{q}]$$

Quark-charge weighted valence quark distribution

cf. νp: F_3 : valence quark

ep : F_2 : charge-square weighted



$$\int_0^1 xF_3^{\gamma Z}\frac{dx}{x} = \int_0^1 \{\frac{2}{3}u_v + \frac{1}{3}d_v\}dx = \frac{5}{3}$$

$$\int_{0.02}^{0.65} xF_3^{\gamma Z}\frac{dx}{x} = 1.21 \pm 0.09 \pm 0.08$$

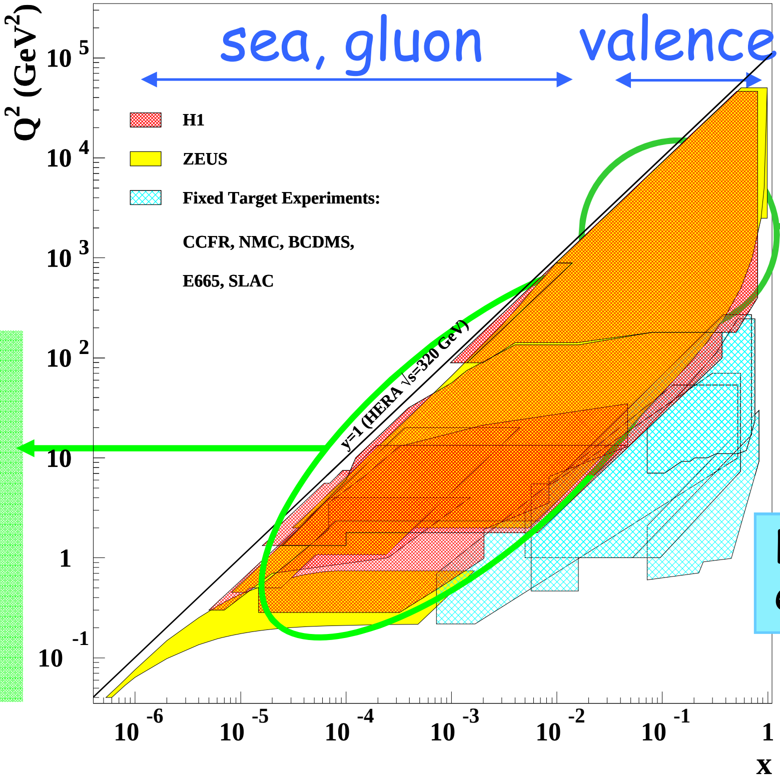
consistent with QCD fit : 1.06 ± 0.02

PDF determination from HERA

A fit (almost) exclusively with HERA data

Jets cross sections
→ gluon

γexchange
→ sea
scaling violation
→ gluon



QCD + EW physics

Z^0 exchange
→ • sea + valence
• valence only
$W^{\pm}$ exchange
→ u or d quark

Fixed target experiments

Standard fits (a la CTEQ, MRST…) use data from various (fixed-target and collider) experiments. Why HERA only fits?

- Single Experiment: Well known systematic uncertainties including correlation.
- Proton Only: No nuclear effects.
- High Q^2: No Higher twist

Still we need following information from the other experiments:
•Strange quark information
•Ubar-dbar asymmetry

from HERA

QCD + EW physics

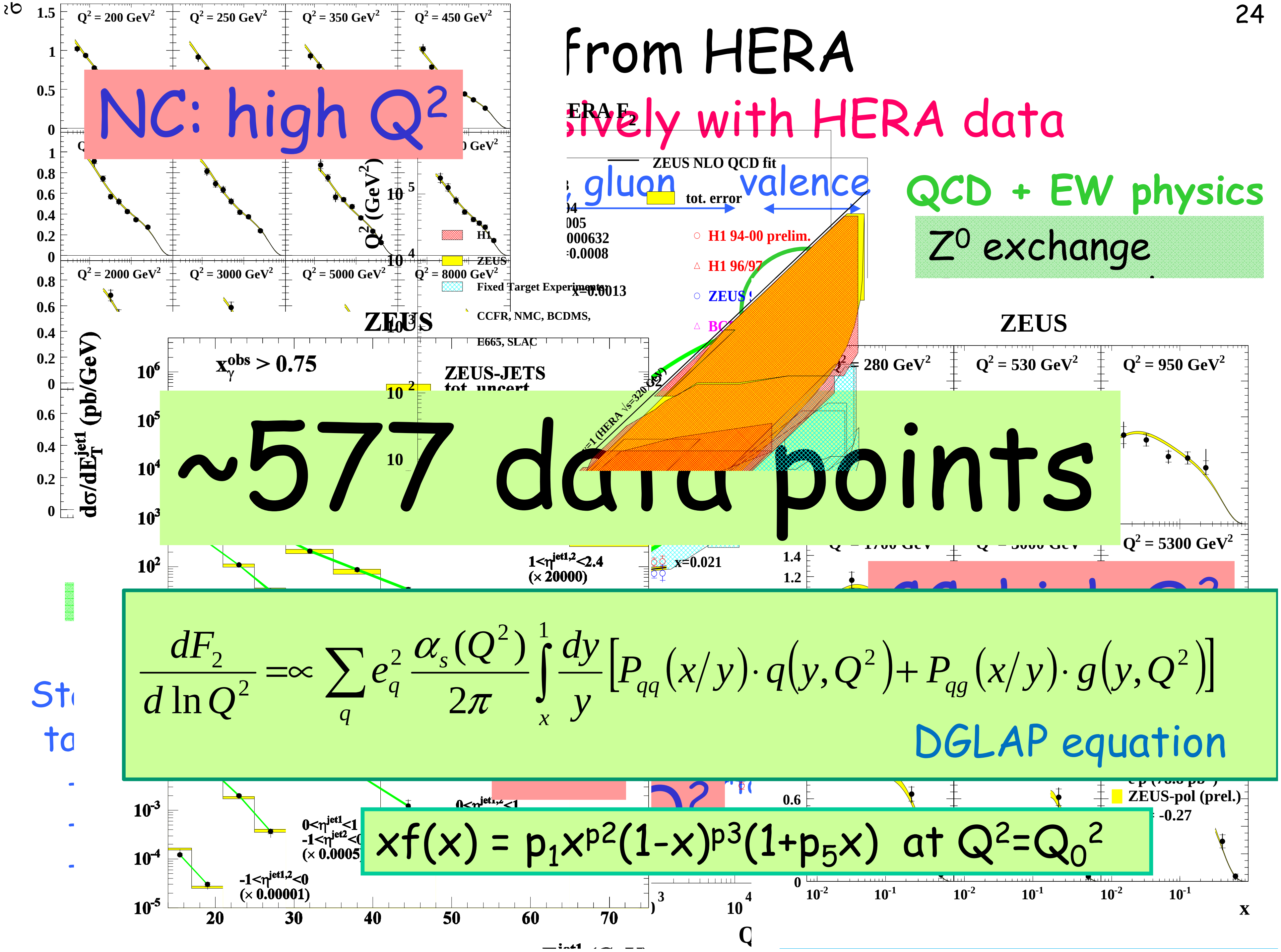
Z^0 exchange

NC: high Q^2

gluon

valence

~577 data points

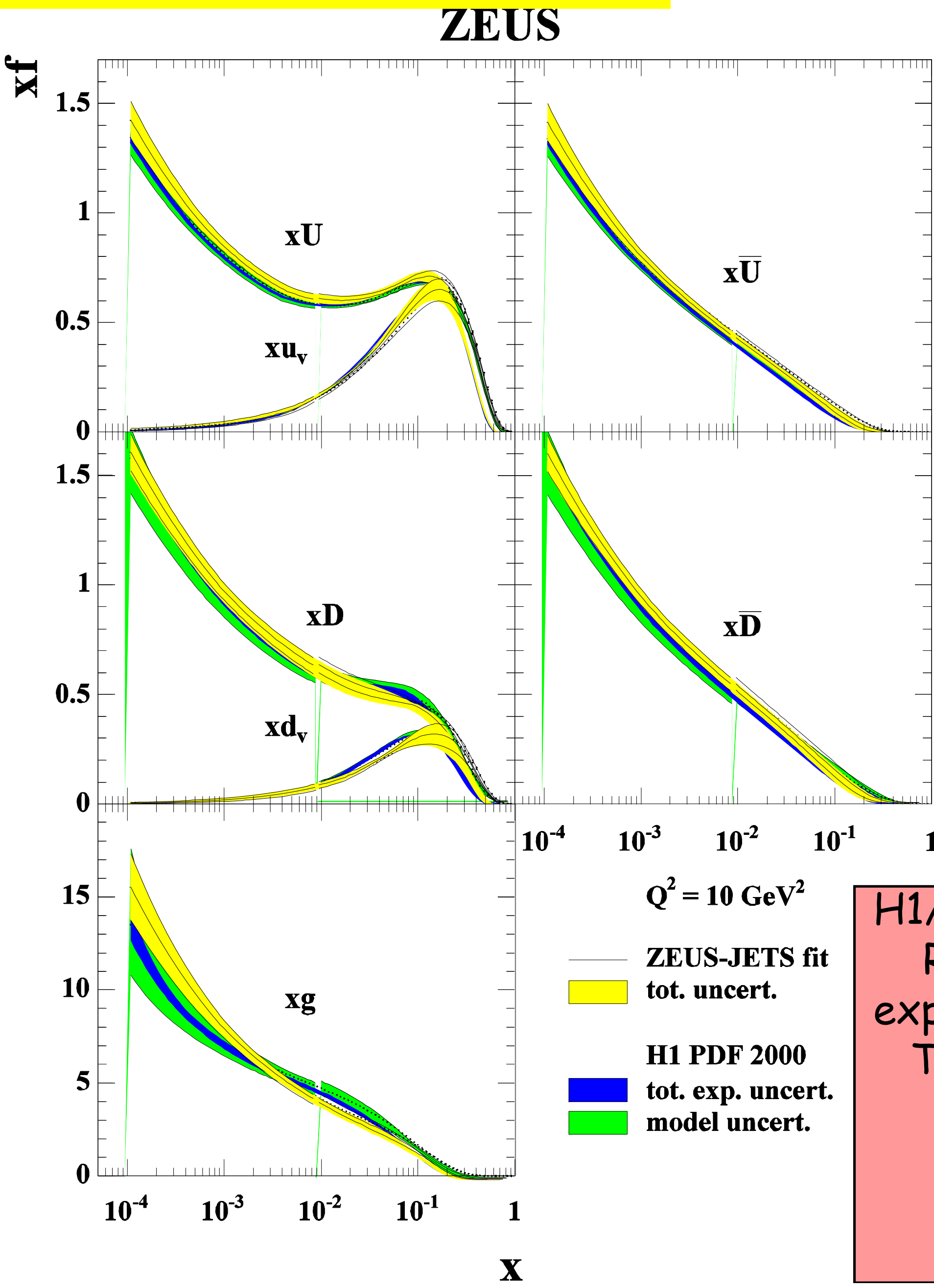


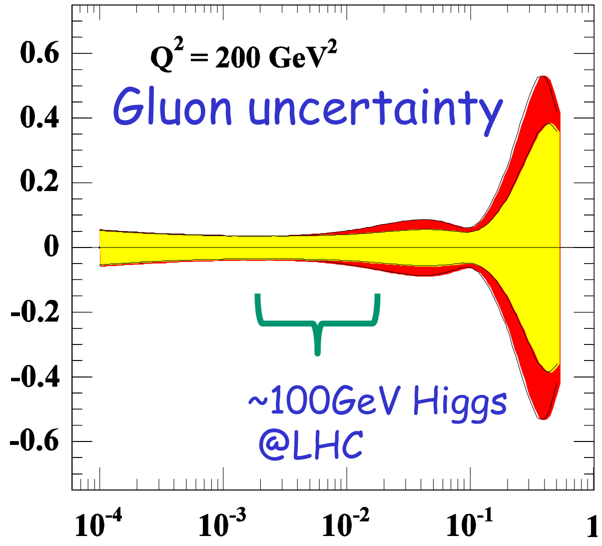
$$\frac{dF_2}{d\ln Q^2} = \propto \sum_q e_q^2 \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}(x/y)\cdot q(y,Q^2) + P_{qg}(x/y)\cdot g(y,Q^2)\right]$$

DGLAP equation

$xf(x) = p_1 x^{p2}(1-x)^{p3}(1+p_5 x)$ at $Q^2=Q_0^2$

PDFs obtained from the fits





- As seen in the F_2 rise at low-x, many sea quarks.
- Gluons are dominant at low-x
- Gluon density is determined at ~ 5% level, in the "LHC-Higgs" region.

H1/ZEUS comparison:

Reasonable agreement between the experiment

The main difference comes from

- Initial Parameter
- Handling of sys. errors
- Selection of low energy experiments

Simultaneous extraction of α_s and PDF

- Scaling violation:

$$\partial F_2/\partial \ln Q^2 \sim \alpha_s \bullet xg(x,Q^2)$$

Data at low x allow disentangling correlation of α_s and xg

- α_s-free fit gives:

H1+fixed target:

$$\alpha_s = 0.1150 \pm 0.0017(\text{exp})^{+0.0009}_{-0.0005}(\text{model})$$

(additionally ±0.0005 from renormalization scale)

ZEUS+fixed target:

$$\alpha_s = 0.1166 \pm 0.0049(\text{exp}) \pm 0.0018(\text{model})$$

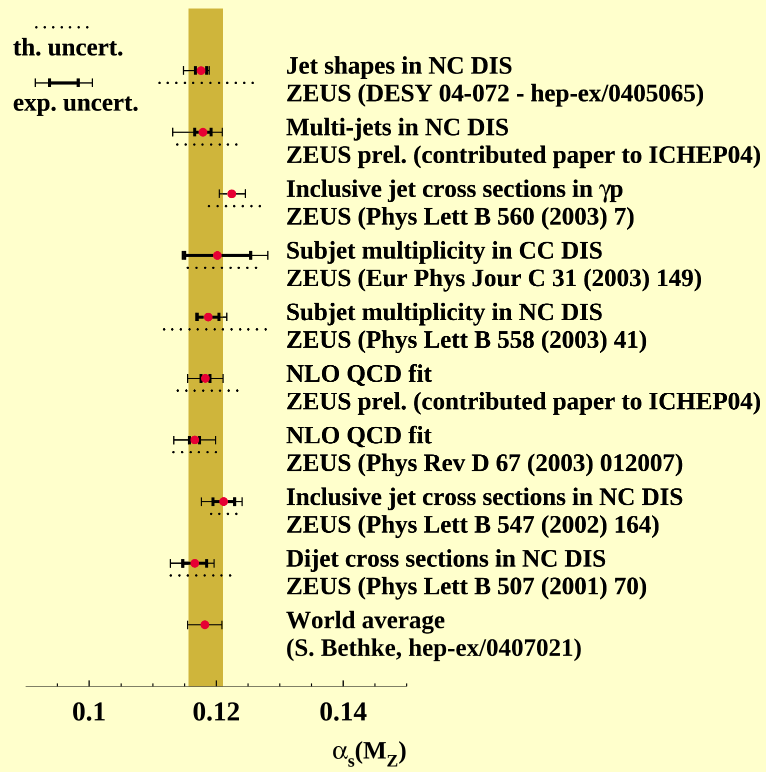
(additionally ±0.0004 from renormalization scale)

ZEUS only:

$$\alpha_s = 0.1183 \pm 0.0028(\text{exp}) \pm 0.0018(\text{model})$$

(additionally ±0.0004 from renormalization scale)

Difference in exp. error mainly from the treatment of systematic error and normalization of data points in the fitting procedure and error propagation.



Various α_s measurements at HERA. : All consistent

-> Universality of QCD

Summary

- HERA and ZEUS/H1 experiments
  - Collider = x100 extended region in Q^2 and x.

- High- Q^2 NC and CC: electroweak effects
  - NC: effect of Z exchange (q-Z coupling, valence quark)
  - CC: flavor-specific (sees positive and negative quarks differently)
  - Measurements with the polarized electron beam are more sensitive to the EM parameters.

- F_2 measurement and PDF determination
  - Very steep rise of sea and gluon at low x.
  - pQCD (DGLAP) gives a fairly good description of the data for Q^2= 1 ~ 10000 GeV^2
  - Proton PDF is determined with HERA data. Gluon distribution is well constrained.