Results on the proton structure from HERA

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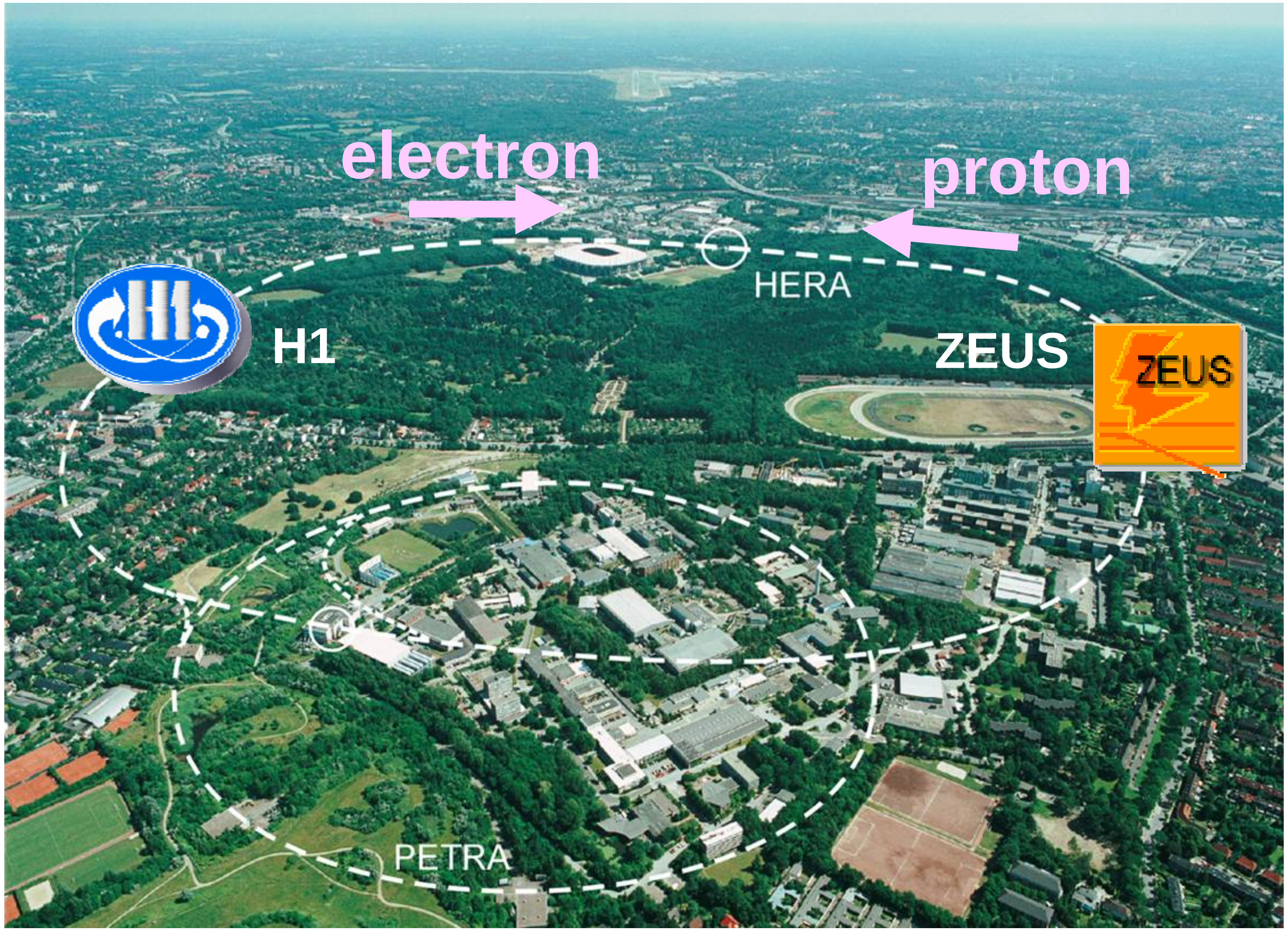
Introduction

HERA physics

Proton structure

The world only e-p collider: HERA



A unique collider at
DESY, Hamburg

Circumference:
6.3 km

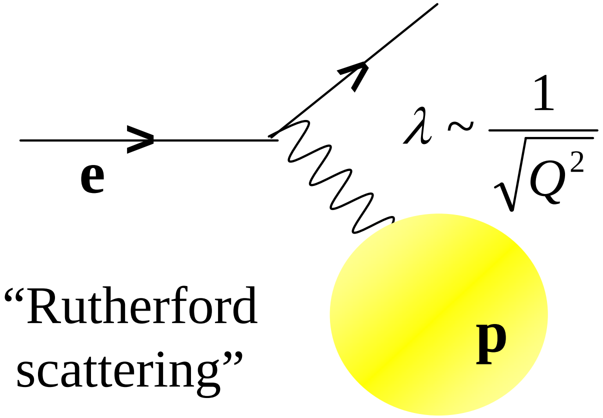
Operated
since 1992 to 2007

2 collider experiments:
H1 & ZEUS

- proton 920 GeV
- electron/positron 27.5 GeV

→ center of mass energy $\sqrt{s} = 318\text{GeV}$

HERA looks into the proton



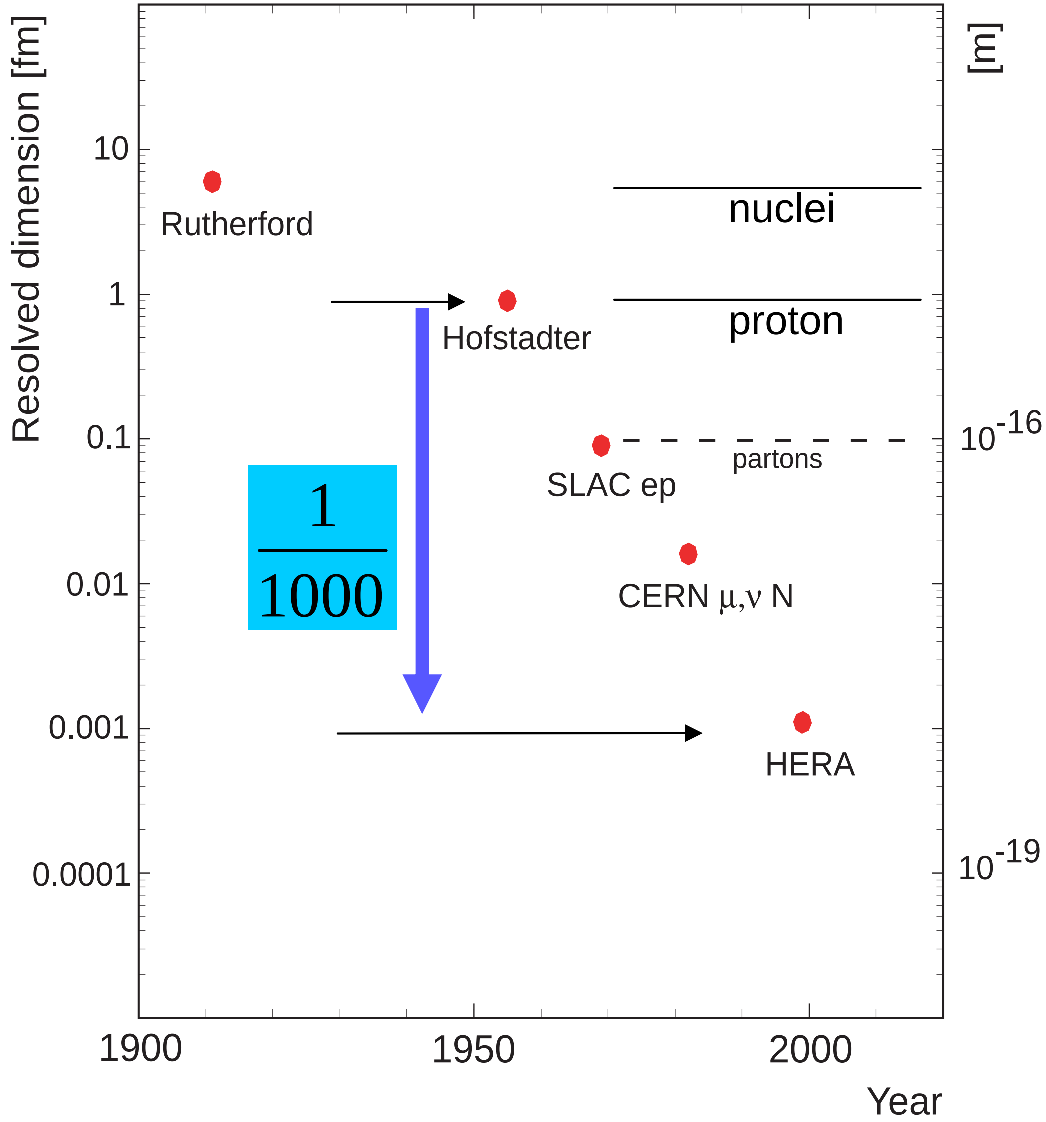
"Rutherford scattering"

Resolution @ HERA

$$\sqrt{s} = 318\text{GeV} \rightarrow s \sim 10^5\,\text{GeV}^2$$

$$\lambda_{\min} \sim \frac{1}{\sqrt{Q^2_{\max}}} \sim 10^{-18}\,m$$

HERA can have a resolution of 1/1000 of proton size.



Proton has a structure

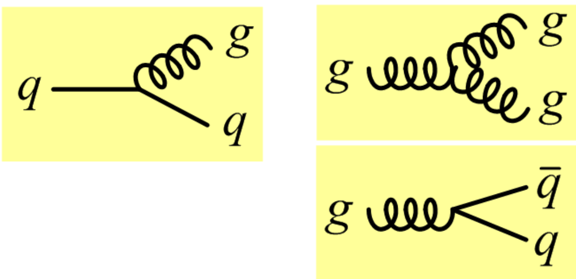
Proton has its subcomponents: **partons**

- Naive parton model

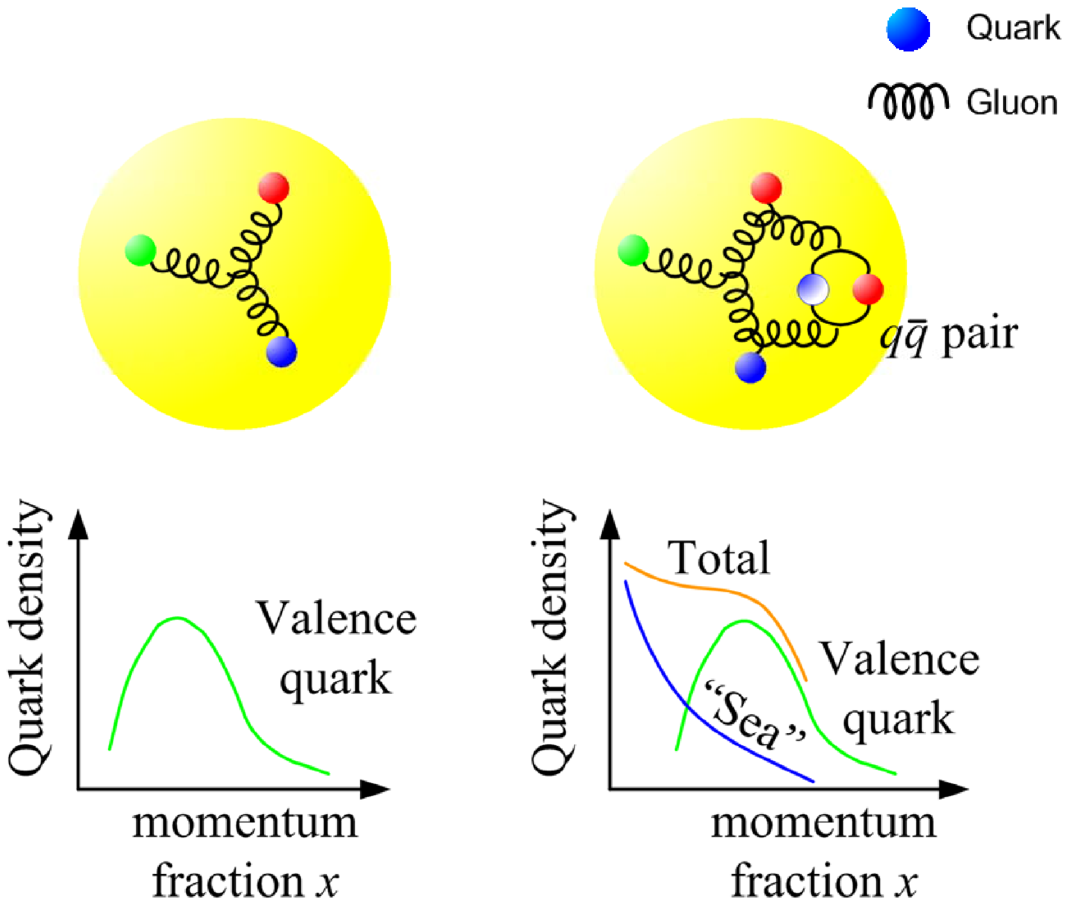
  u u d quarks: **'valence'** quarks
- QCD

  quark emits gluon.

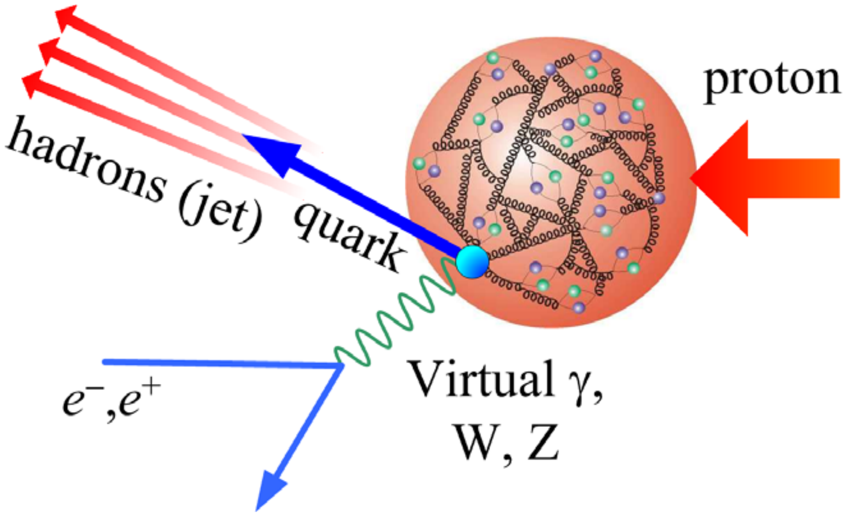
  gluon splits to qq or gg.



→ Many quarks with lower momentum: **'Sea'** quarks



HERA looks into the proton



ep collision

→ scattering of electron and a quark.

It reflects the proton structure.

Cross section of ep scattering

= Cross section of eq scattering $\otimes$ proton structure

Details come later, but;

F_2 : structure function ∝ total charge-squared weighted number of quarks in the proton

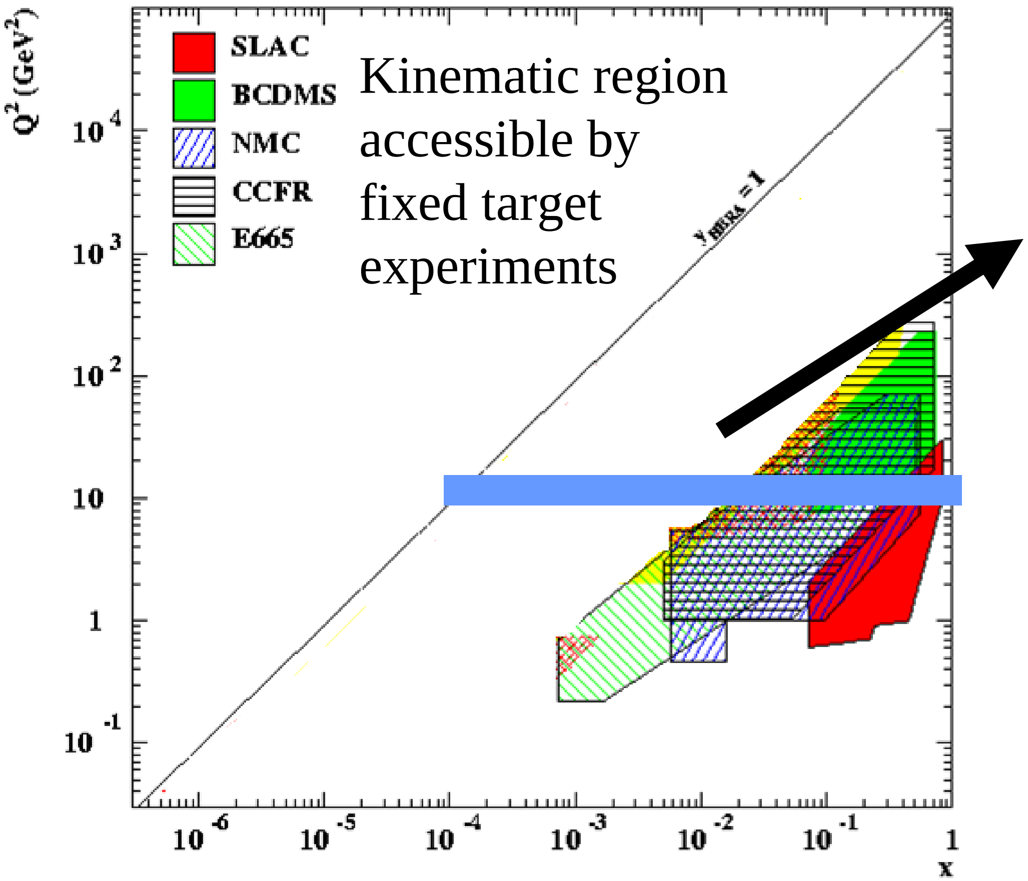
Q^2 : momentum transfer → resolution

x : momentum fraction of a parton to the proton

Before HERA

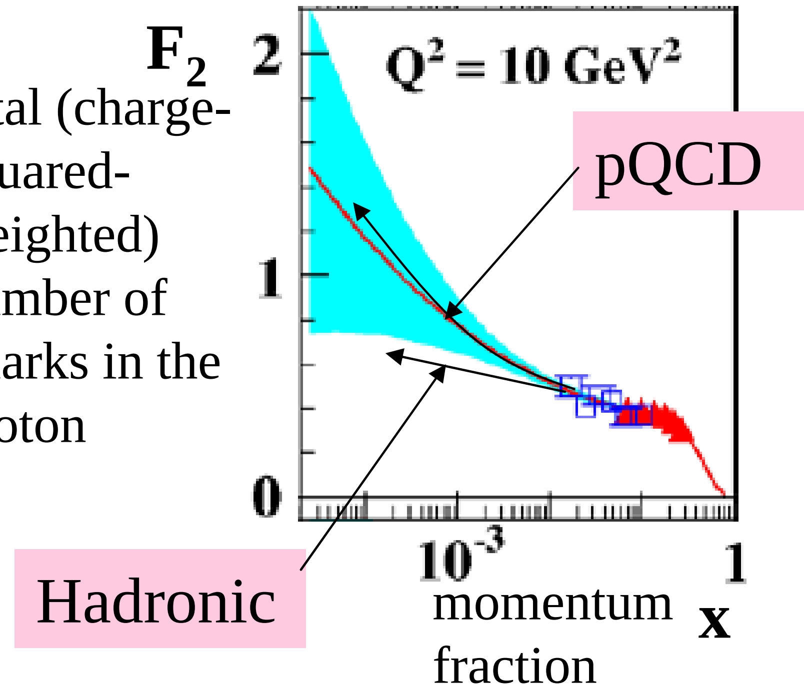
Fixed target experiments only.

- It was unclear how to describe the proton structure at low-x.
  - perturbative QCD: quarks are asymptotically free.
  - hadronic view : partons are confined in the proton



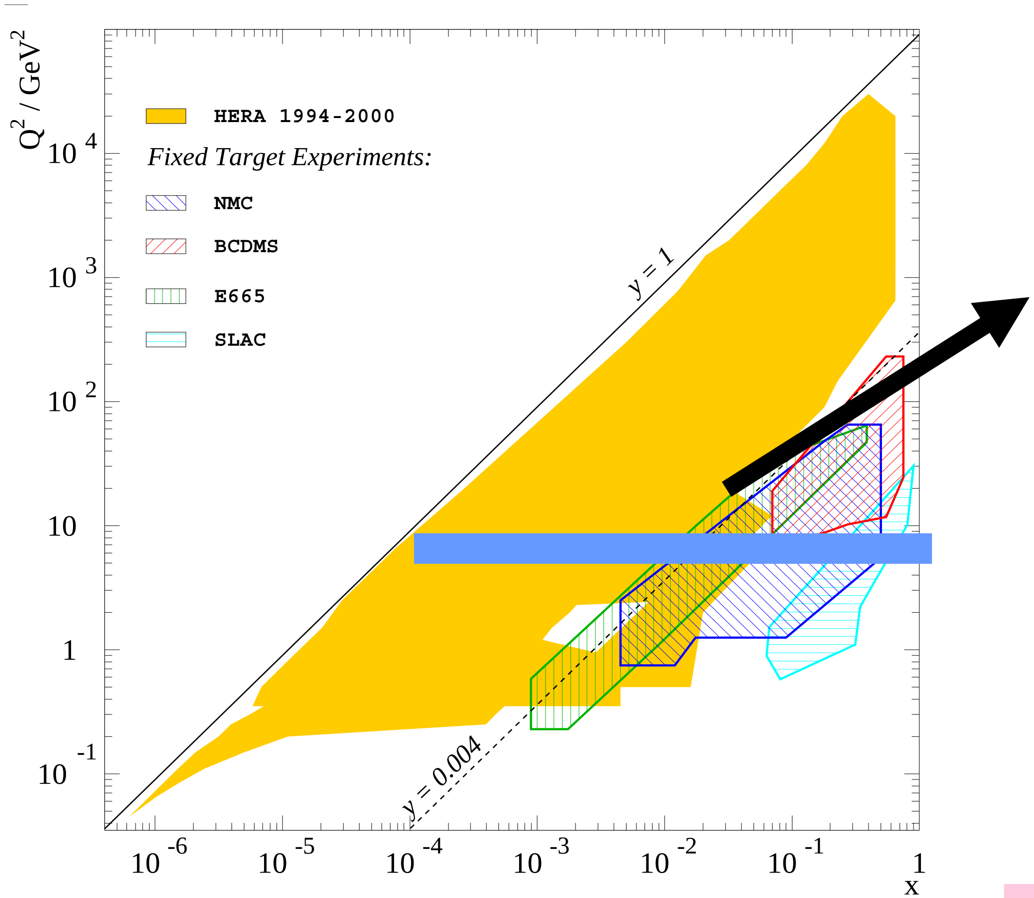
momentum (x) distribution of quarks at a certain resolution (Q^2=10GeV^2)

total (charge-squared-weighted) number of quarks in the proton

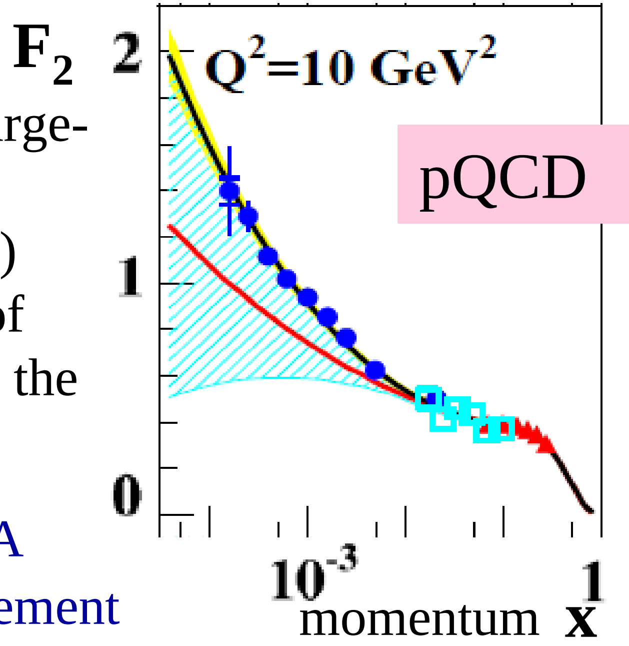


HERA opened the new kinematic region

- HERA has expanded accessible kinematic region largely.
  - 2 orders in both x and Q^2



With HERA data …



total (charge-squared-weighted) number of quarks in the proton

• HERA measurement

momentum x fraction

steep rise at low x

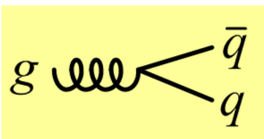
→ pQCD descriptions is verified.

Plenty of Gluon and Sea quarks

- Steep rise of F_2 at low x.
- higher Q^2 = finer resolution

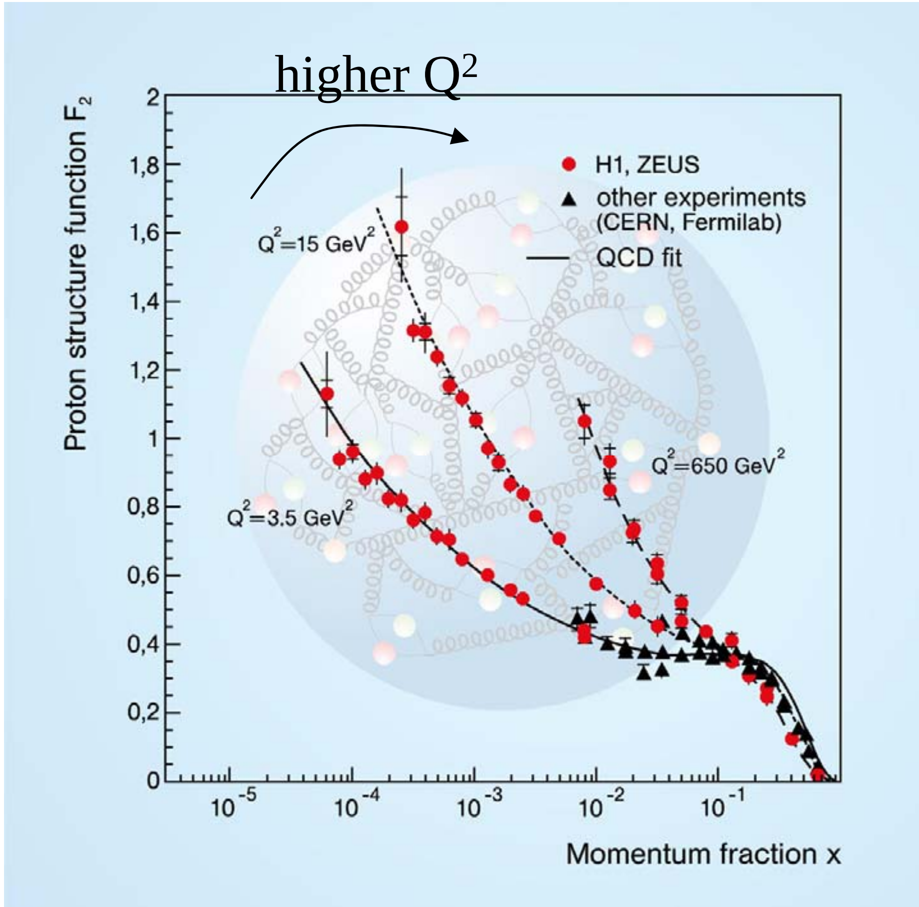
  → more low-momentum quarks are 'visible'

  i.e. Sea quarks
- Sea quarks are generated by gluon.



Abundant Sea quarks

⇔ Abundant gluons



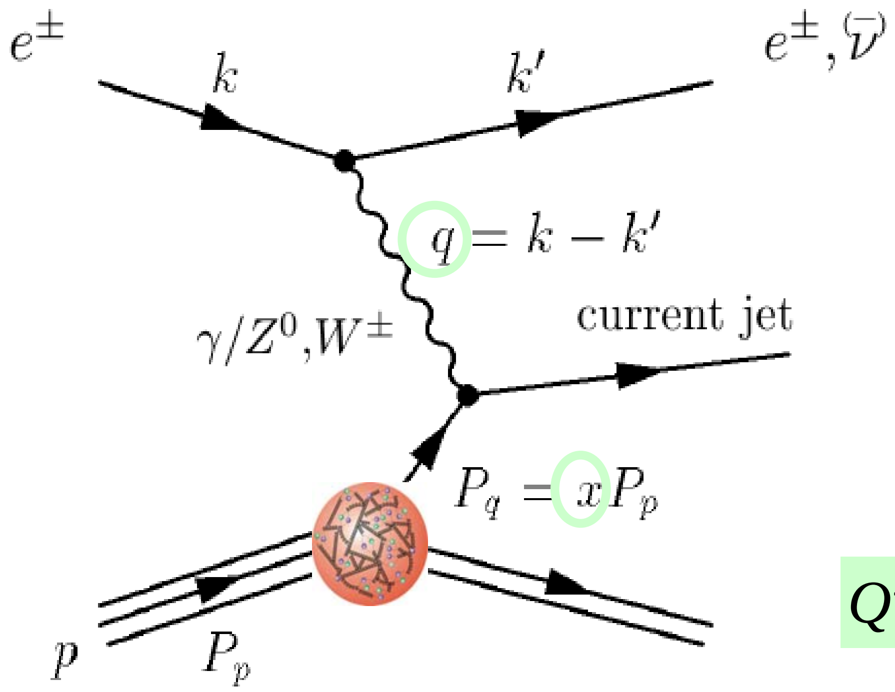
Gluon and Sea quarks' physics is started by HERA.

Introduction

HERA physics

Proton structure

Deep Inelastic Scattering (DIS)



- Kinematic variables to describe DIS

  Q^2: Virtuality

  → probing power

  x : Bjorken scaling variable

  → momentum fraction of struck quark

  y : Inelasticity

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

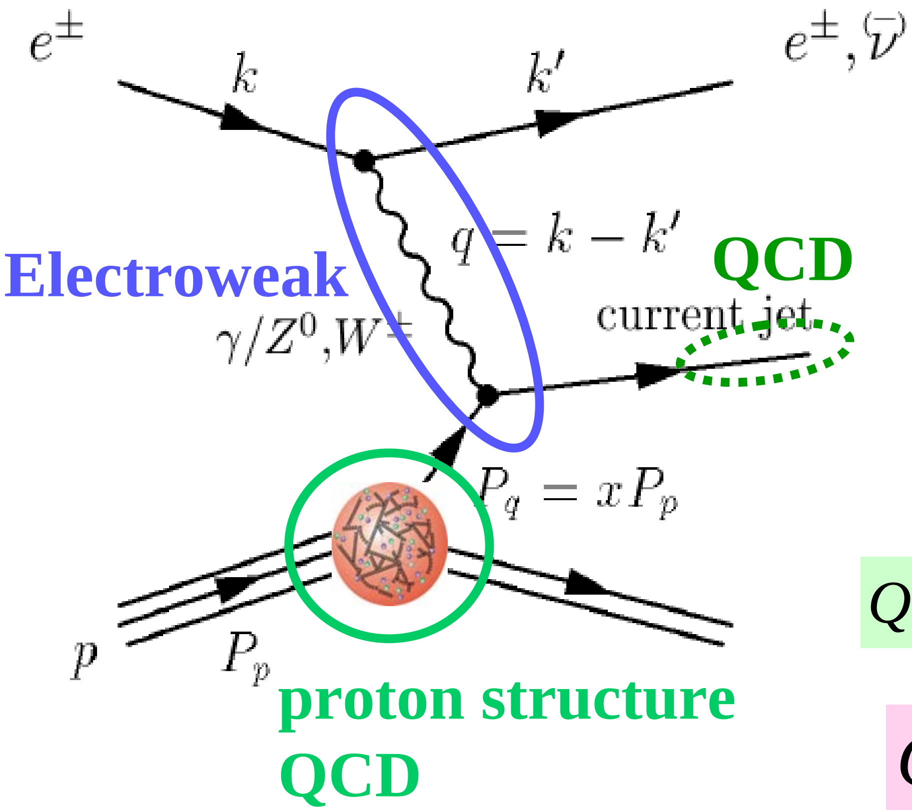
$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot k}$$

$$Q^2 = sxy$$

$\sqrt{s}$ = center of mass energy

Deep Inelastic Scattering (DIS)



- Kinematic variables to describe DIS

  Q^2: Virtuality

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  x : Bjorken scaling variable

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$$Q^2 = -q^2 = -(k - k')^2 \qquad x = \frac{Q^2}{2p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k}$$

$$Q^2 = sxy$$

$\sqrt{s}$ = center of mass energy

- DIS is a convolution of **electroweak (EW)** physics and the **proton structure.**
  - Good prove to the proton structure
  - Sensitive to EW physics from space-like view.
- Hadronic final state is also sensitive to QCD. (not covered in this talk)

DIS in the detectors

Neutral current (NC) process

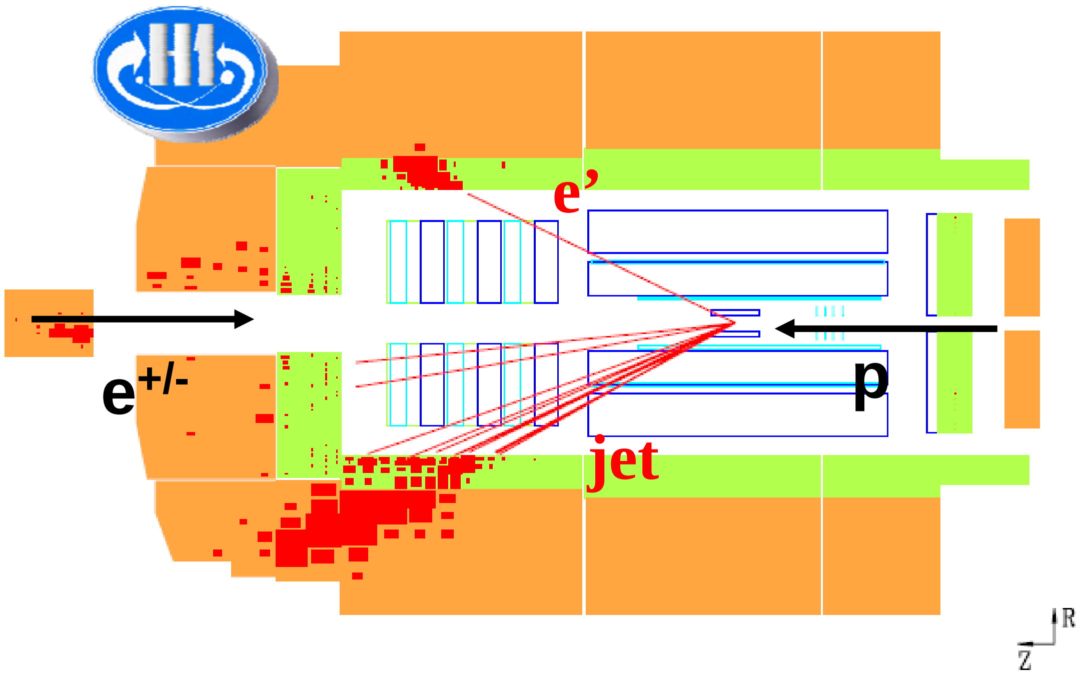
γ/Z^0 exchange

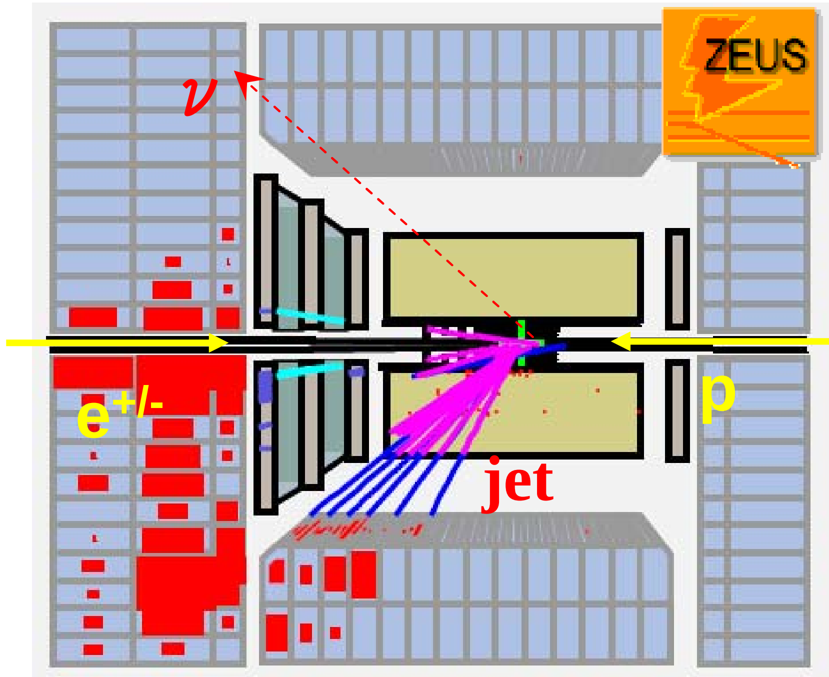
ep→e'X

Charged current (CC) process

W^{+-} exchange

ep→ν X





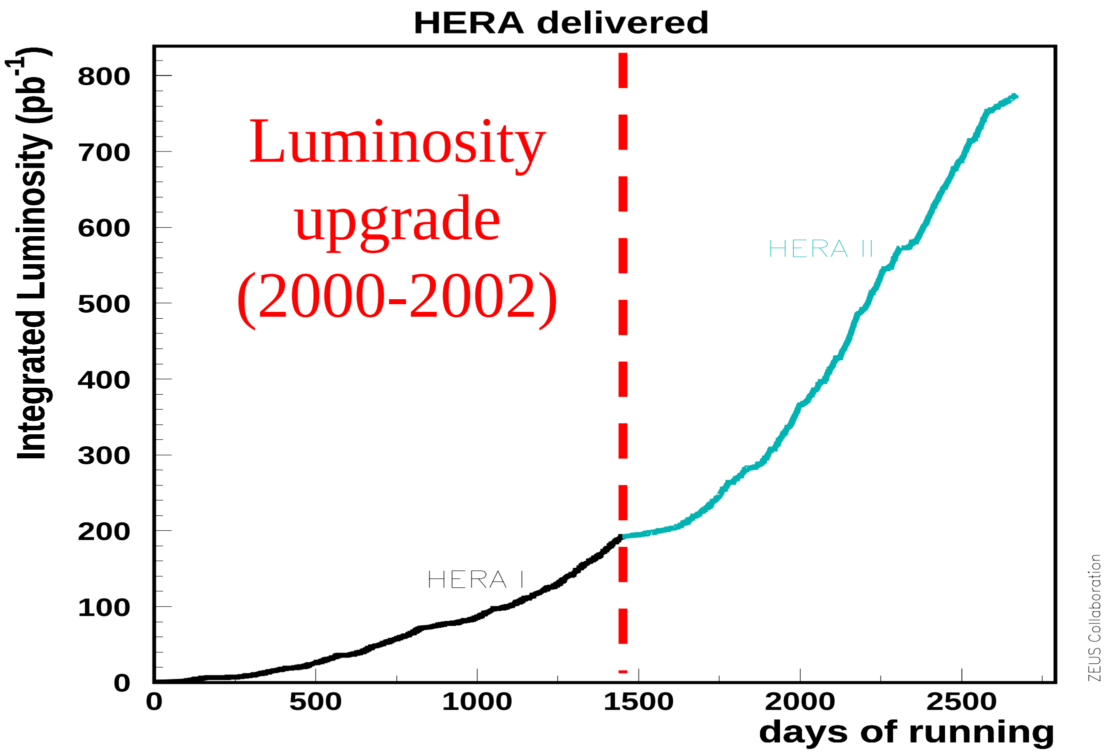
- Kinematic variables are reconstructed by two of measured variables;

  (energy / angle) of (scattered electron / jet (~ struck quark))

History of HERA

- 1992-2000: HERA-I
  (started with E_p=820GeV, until 1997)
  - measurements go down to low-Q^2

→ Make full use of large kinematic region.
$1.5GeV^2<Q^2<30000GeV^2$



- 2002-2007: HERA-II
  - High luminosity to collect high-Q^2 data. (high-Q^2 ↔ Weak boson exchange)
  - lepton beams are polarized.

→ Increased sensitivity to EW.

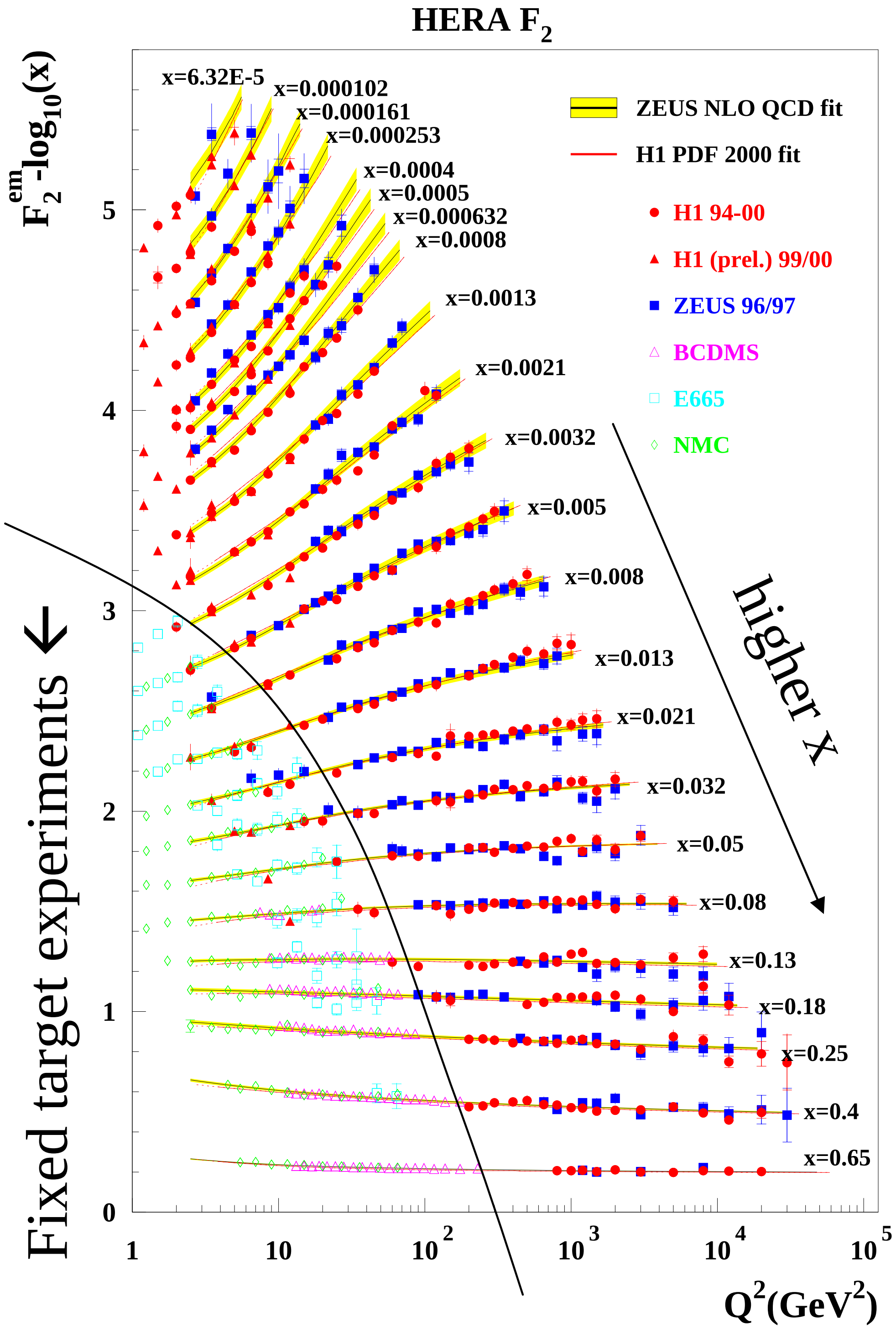
Some of results will be shown in next slides.

F_2 measurement

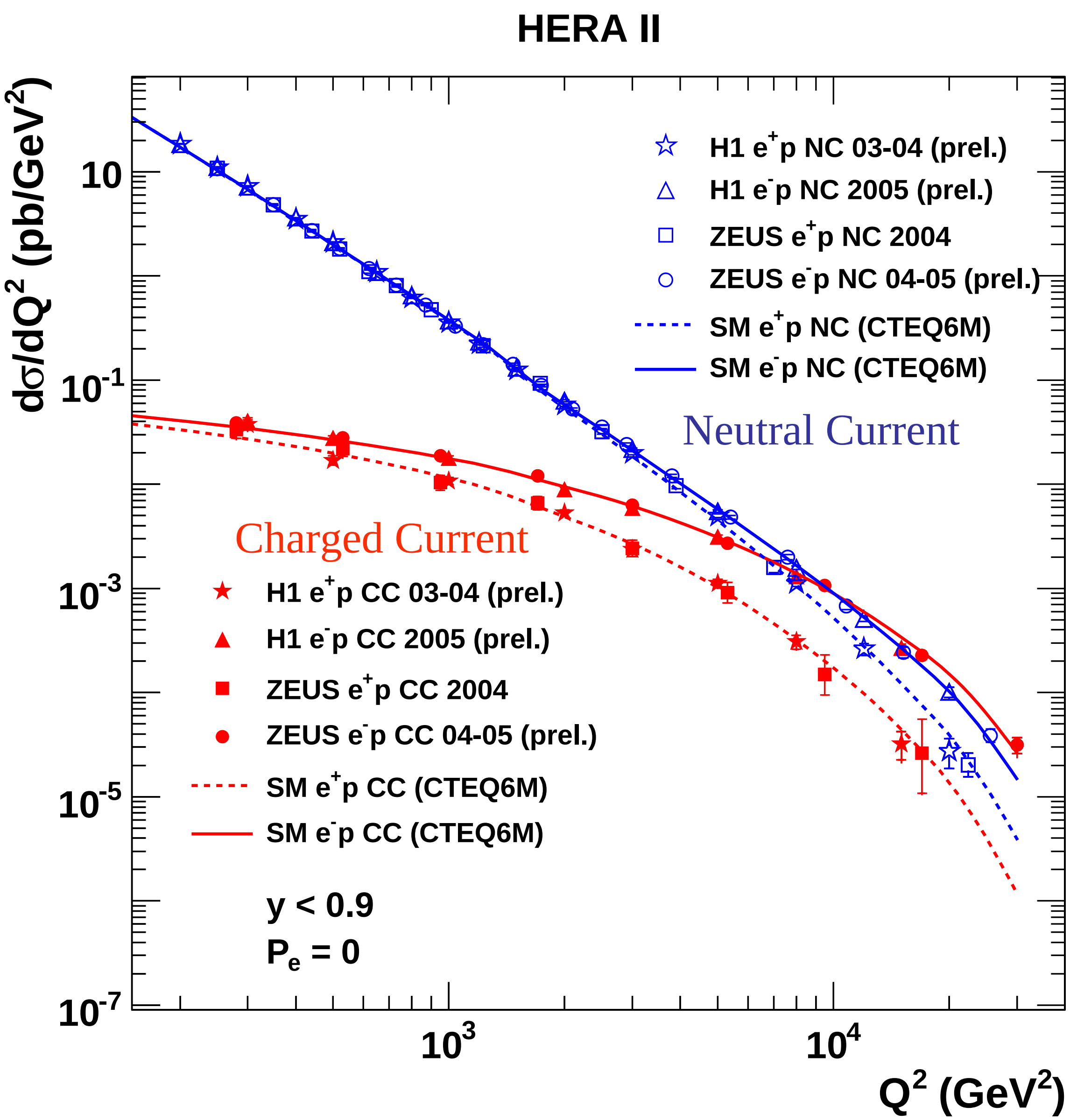
- F_2 is measured over 4 orders of magnitude in (x, Q^2).

  low x
  → strong dependence on Q^2
  "scaling violation"

  more $g \to \bar{q}q$ is visible.



EW unification (NC/CC cross sections)



$$\frac{d\sigma}{dQ^2} \propto \left(\frac{1}{Q^2 + M_{\text{boson}}^2} \right)^2$$

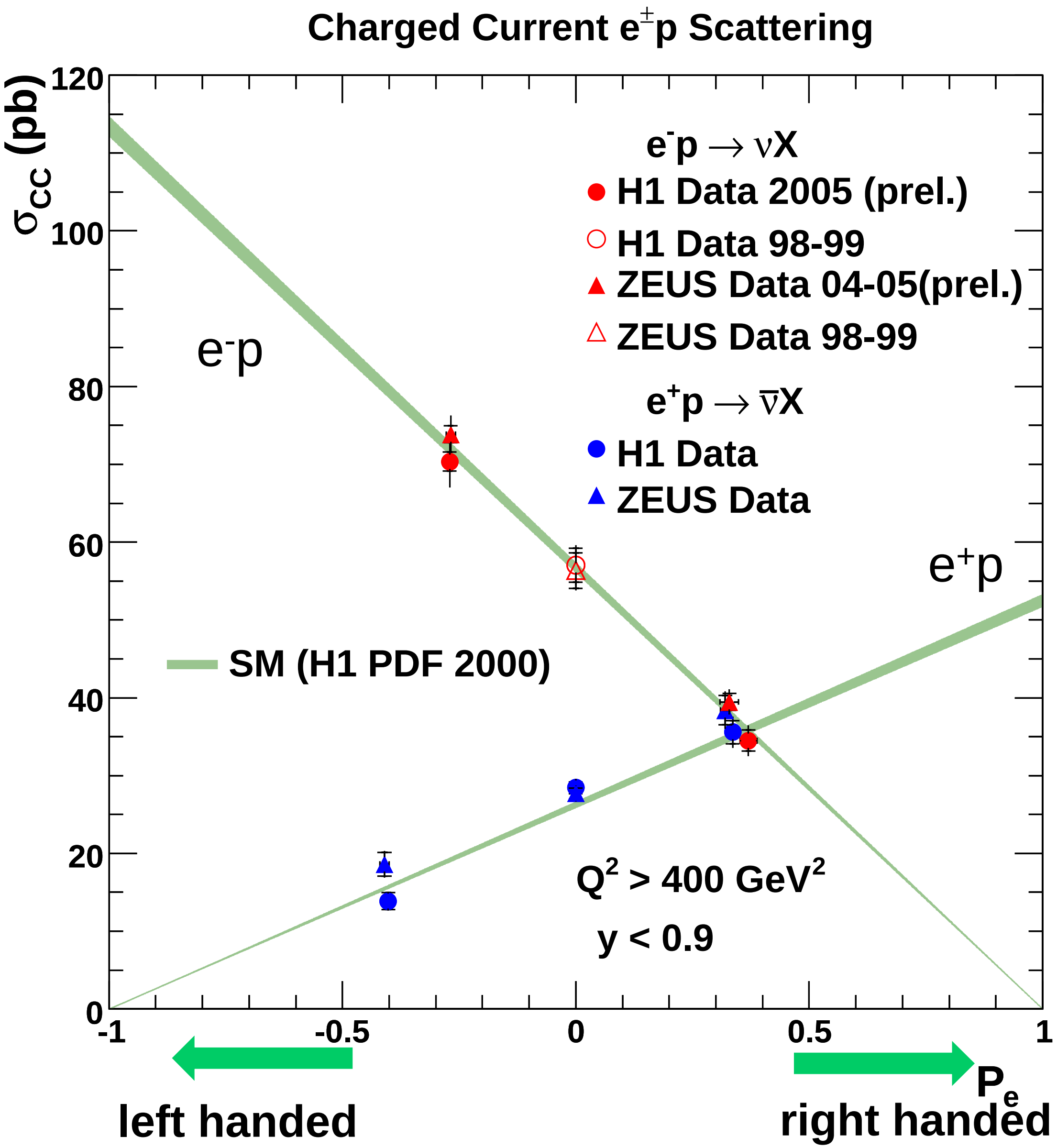
Weak bosons are heavy.

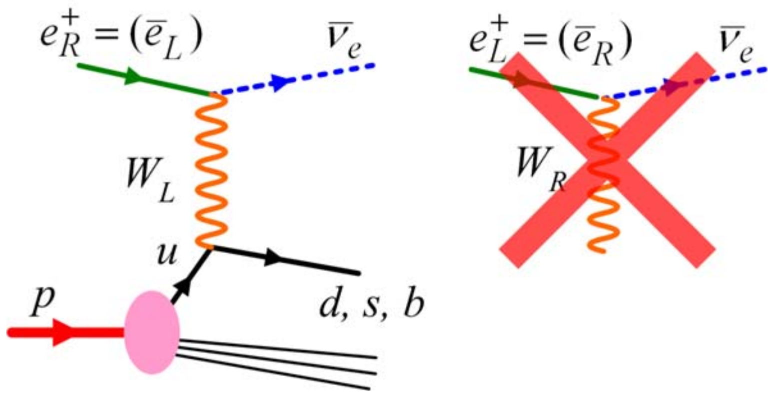
→ σ_{weak} is small

- low Q^2
  - NC: γ-exchange
  - CC: W-exchange
  - ➔ σ(NC) >> σ(CC)
- high Q^2
  - NC: γ/Z
  - CC: W-exchange
  - ➔ σ(NC) ~ σ(CC)

Electroweak unification

Polarized CC cross sections





Weak process
= No right-handed current
CC is purely weak process
→ linear dependence on polarization.

Introduction

HERA physics

Proton structure

Parton Distribution Function (PDFs)

- Parton distribution functions are used to describe the proton structure.

$$q(x,Q^2) \quad \bar{q}(x,Q^2) \quad g(x,Q^2)$$

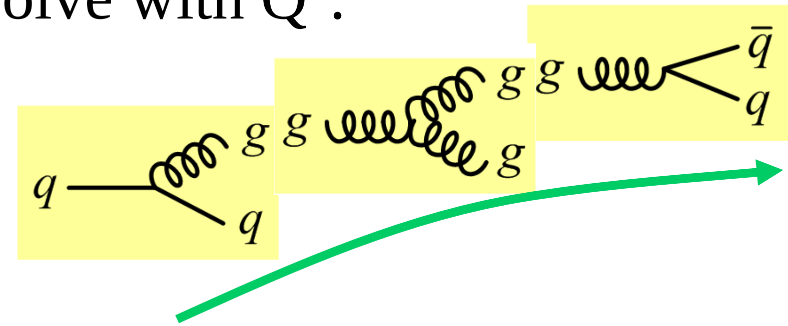
  – Valence quarks:

  $u_{\text{Val}}(x,Q^2) = u(x,Q^2) - u_{\text{Sea}}(x,Q^2)$, same for d quark

  – Sea quarks:

  $u_{\text{Sea}}(x,Q^2) = \bar{u}(x,Q^2) = s(x,Q^2) = \bar{s}(x,Q^2)$ … etc.

- PDFs evolve with Q^2.



Larger Q^2 allows to see more quarks.

- The Q^2 evolution is described by **DGLAP equation**, based on pQCD.

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

Structure functions

- DIS cross sections can be written with structure functions.

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4} Y_+ \left[F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2) \mp \frac{Y_-}{Y_+} xF_3(x,Q^2) \right] \quad Y_{\pm} = 1 \pm (1-y^2)$$

cross section with point-like particle

Structure functions: they reflect momentum distribution of partons in the proton.

Structure functions are sensitive to PDFs.

- F_2 : total number of quarks

$$F_2 = \sum A_q x(q + \bar{q})$$

- F_L : longitudinal structure function ⟶ gluon

  only sizable at high-y → Details will come up later

- xF_3 : parity violation term

$$xF_3 = \sum B_q x(q - \bar{q}) \longrightarrow \text{Valence quarks}$$

Extraction of PDFs

$q(x, Q^2)$
$g(x, Q^2)$

- Q^2 evolution of PDFs can be predicted by perturbative QCD, i.e. by DGLAP equation.
- x-dependence of PDFs can be extracted from fits to measured cross sections.

PDFs@ Q_0^2 ← Input

↓ Evolution in Q^2 : DGLAP@NLO

PDFs@ Q^2

↓

Fit to measured cross sections @ Q^2

PDFs are parameterized @ $Q_0^2 = 7\text{GeV}^2$ @ZEUS

$$x f(x) = A x^b (1-x)^c (1+dx)$$ for $xu_v,\ xd_v,\ xS,\ xg,\ x\Delta(= x\bar{d} - x\bar{u})$

A: Normalization, *b*: Low x, *c*: High x, *d*: smoothing for middle x

Constraints from momentum and number sum rule, etc.

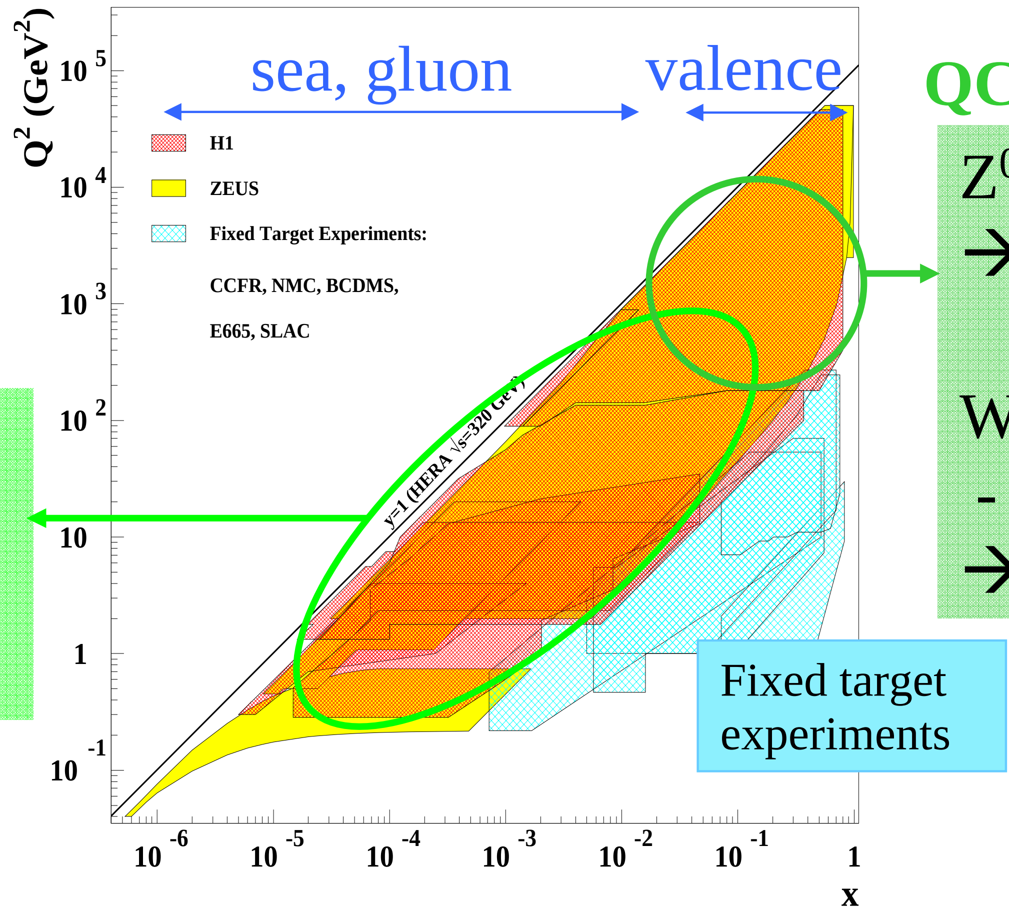
→ 11 free parameters

PDF extraction at HERA

A **single experiment** can determine PDFs.

Jets cross sections → gluon

γ exchange
→ sea
scaling violation
→ gluon

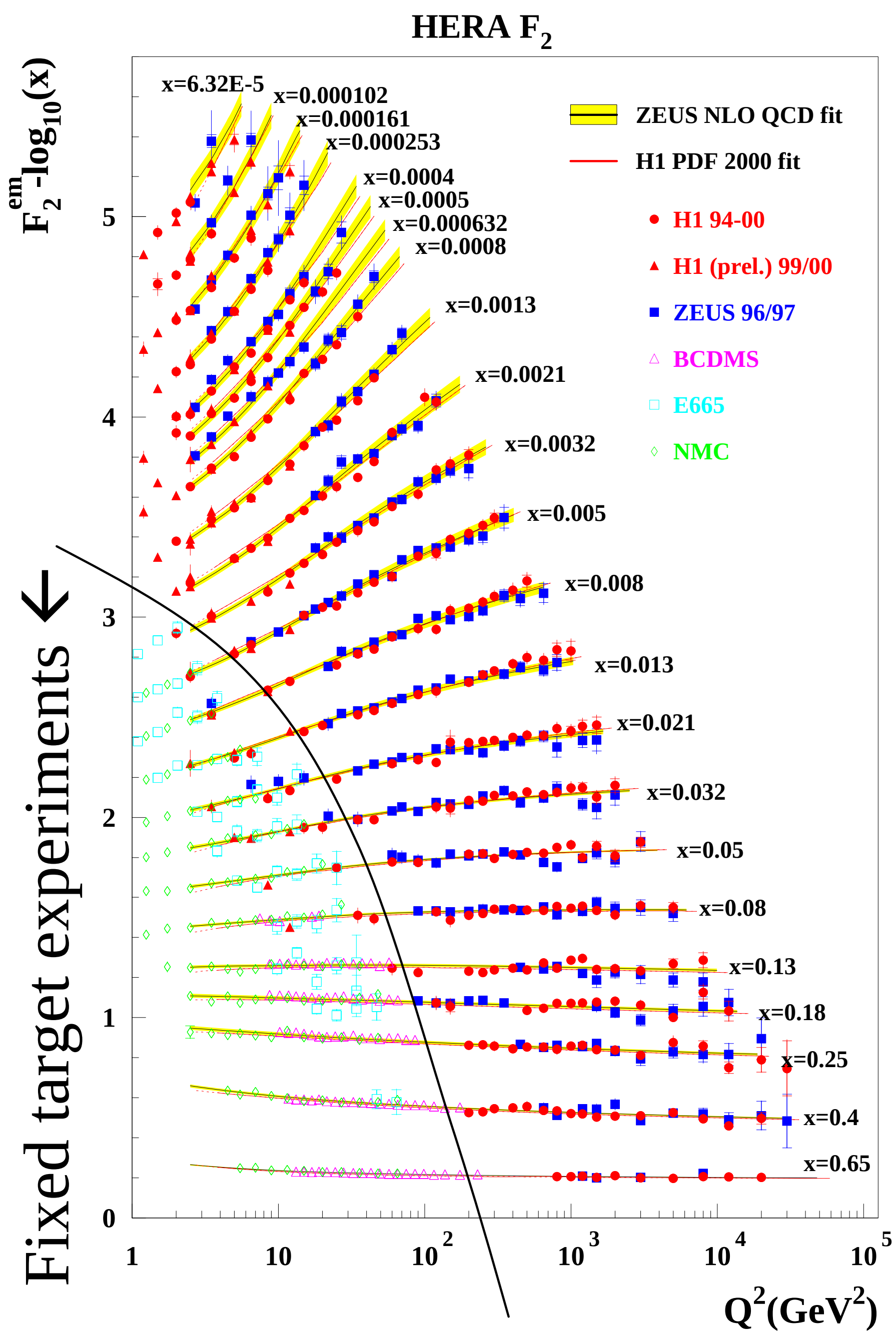


QCD + EW physics

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

- Pure proton target→ Free from target correction, nuclear effect.
- Single experiment→ systematic uncertainties are well understood.

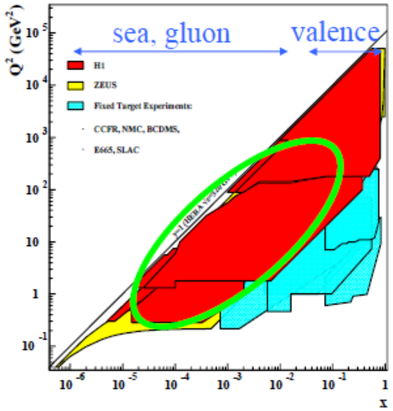
NC cross sections for PDF extraction



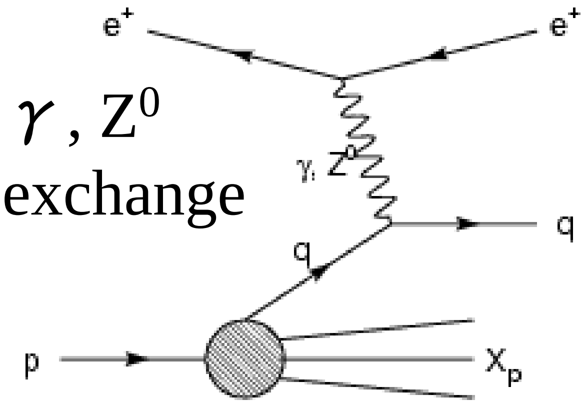
Large kinematic coverage

$3 < Q^2 < 30000$ GeV^2

$6\times10^{-5} < x < 0.6$



γ, Z^0 exchange



$$F_2 \propto \sum x(q+\bar{q})$$

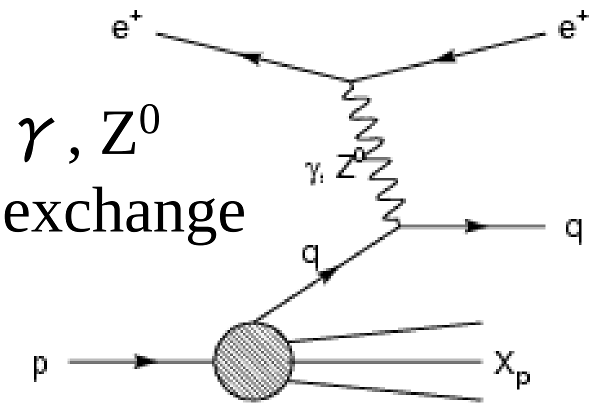
Sea + valence quark

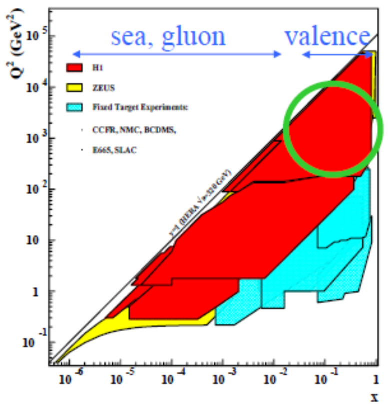
scaling violation of F_2

$$\frac{\partial F_2}{\partial \ln Q^2} \propto xg \qquad \text{gluon}$$

NC cross sections @ high-Q^2

γ, Z^0 exchange





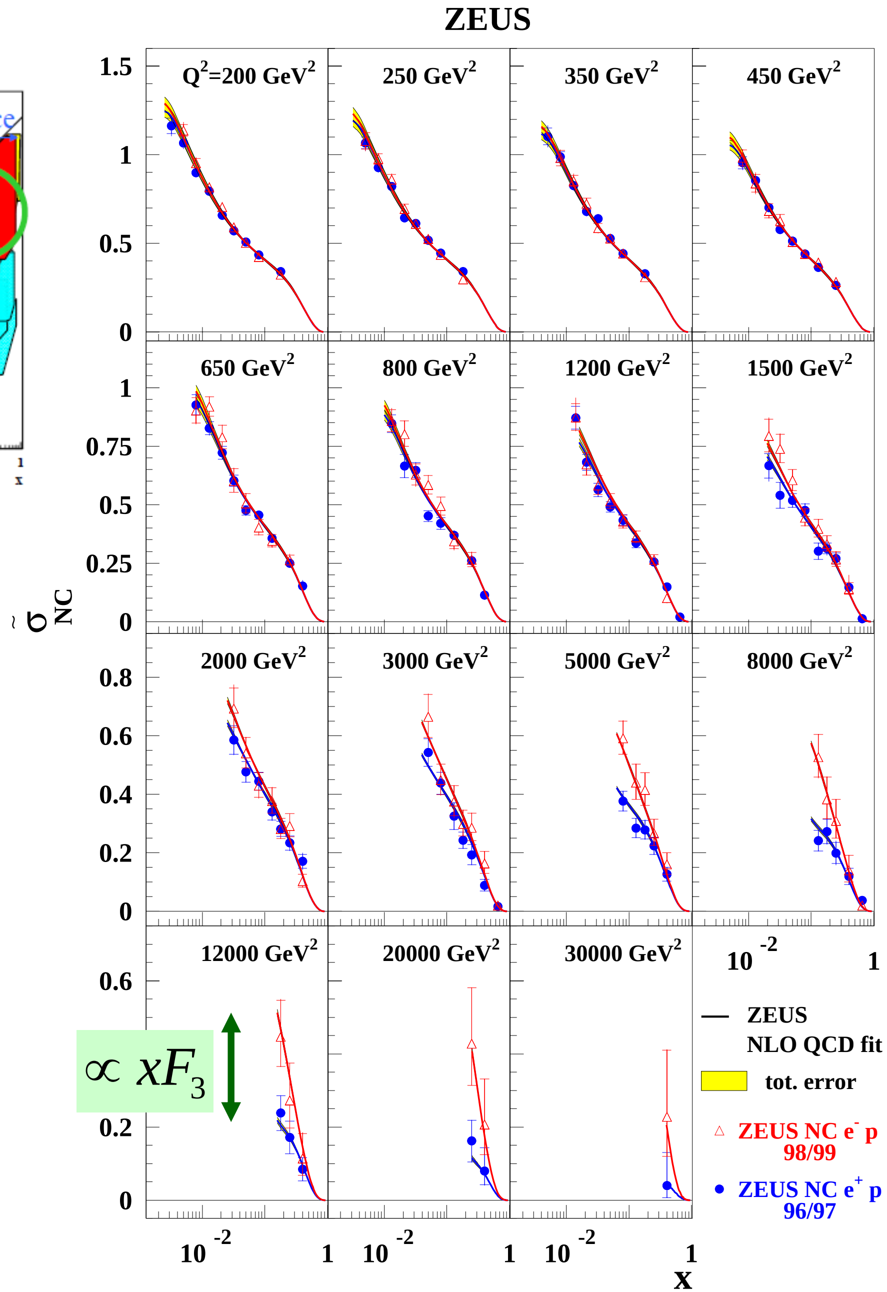
- At high Q^2, weak current (Z^0) introduces parity violation.

$$\tilde{\sigma}(e^{\pm} p) = F_2(x, Q^2) \mp \frac{Y_-}{Y_+} xF_3(x, Q^2)$$

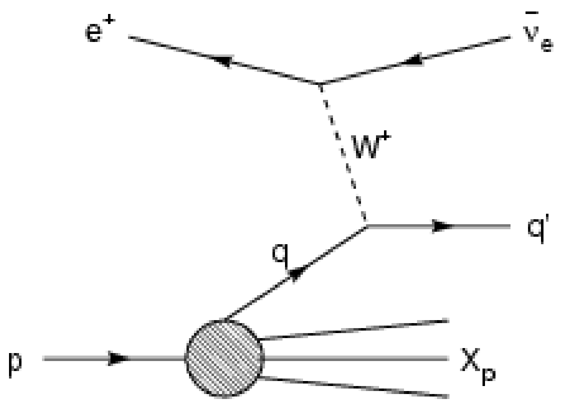
$$\tilde{\sigma}(e^- p) - \tilde{\sigma}(e^+ p)$$

$$\longrightarrow xF_3 \propto \sum x(q - \bar{q})$$

valence quark

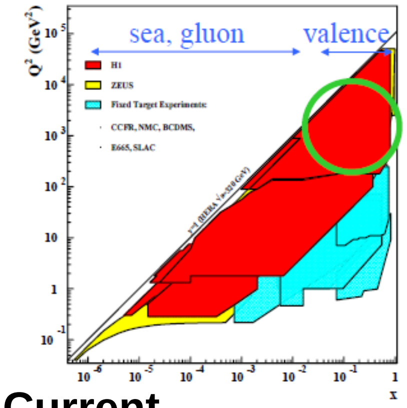


CC cross sections for PDF extraction



$$e^+ q^{(-)} \rightarrow \bar{\nu} q^{(+)}$$

$$e^- q^{(+)} \rightarrow \nu q^{(-)}$$



CC is charge selective interaction.

- positron-induced

  → negative-charged partons

$$\tilde{\sigma}(e^+ p) \propto [(\bar{u} + \bar{c}) + (1-y)^2 (d + s)]$$

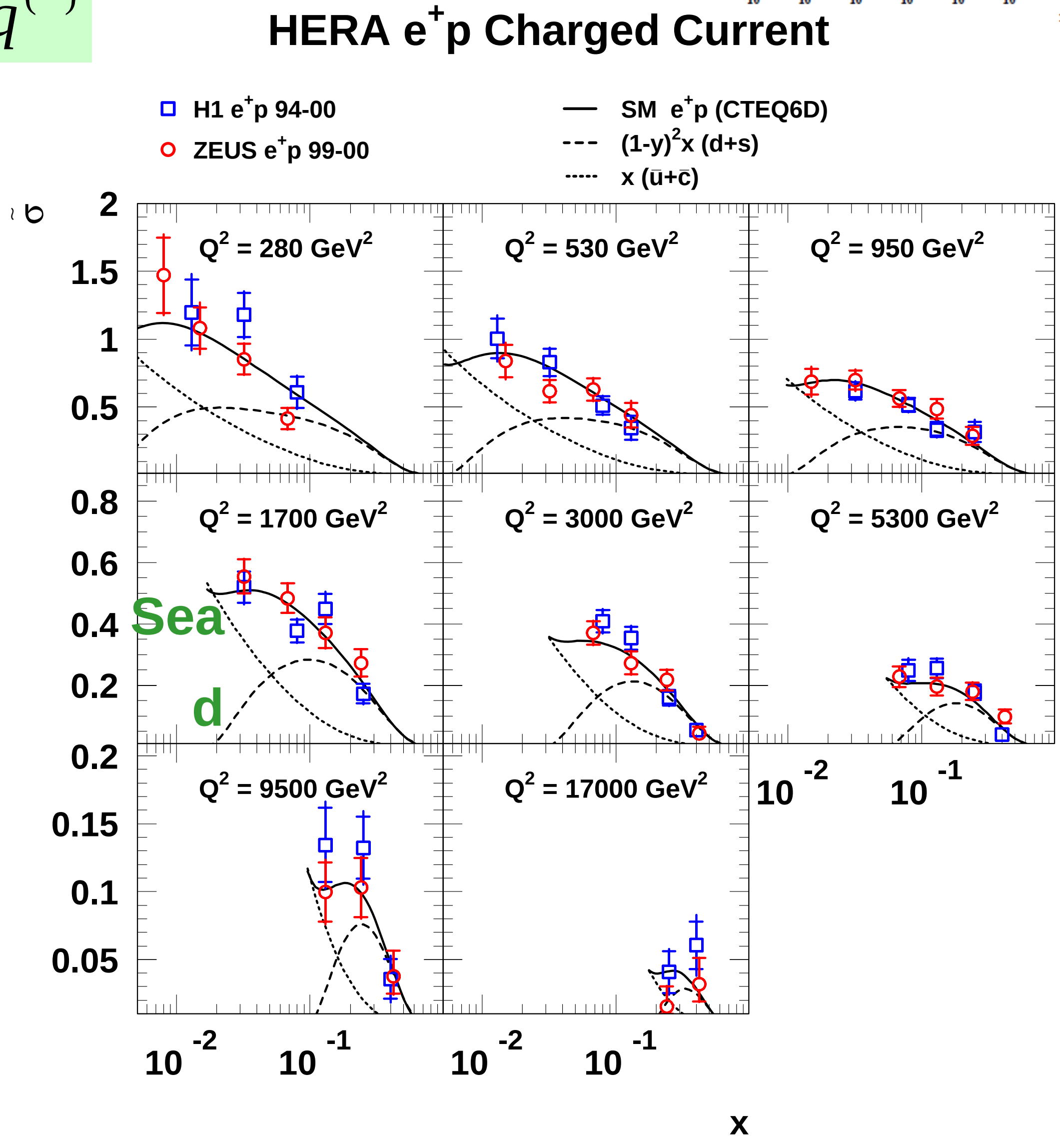
d quark

- electron-induced

  → positive-charged partons

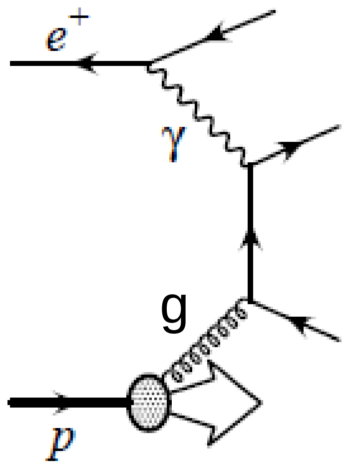
$$\tilde{\sigma}(e^- p) \propto [(u + c) + (1-y)^2 (\bar{d} + \bar{s})]$$

u quark



Jet Cross sections for PDF extractions

Directly sensitive
to gluon density



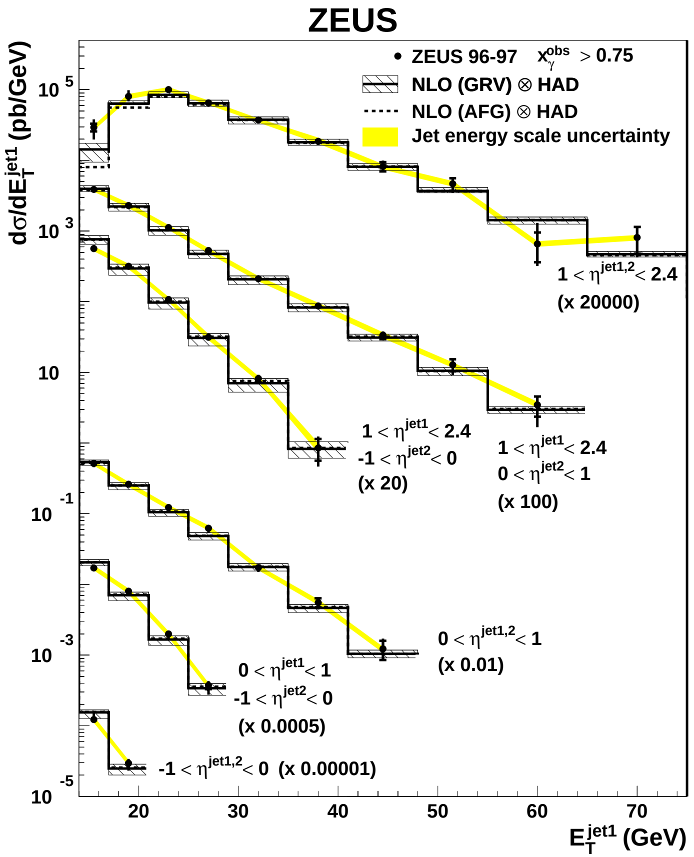
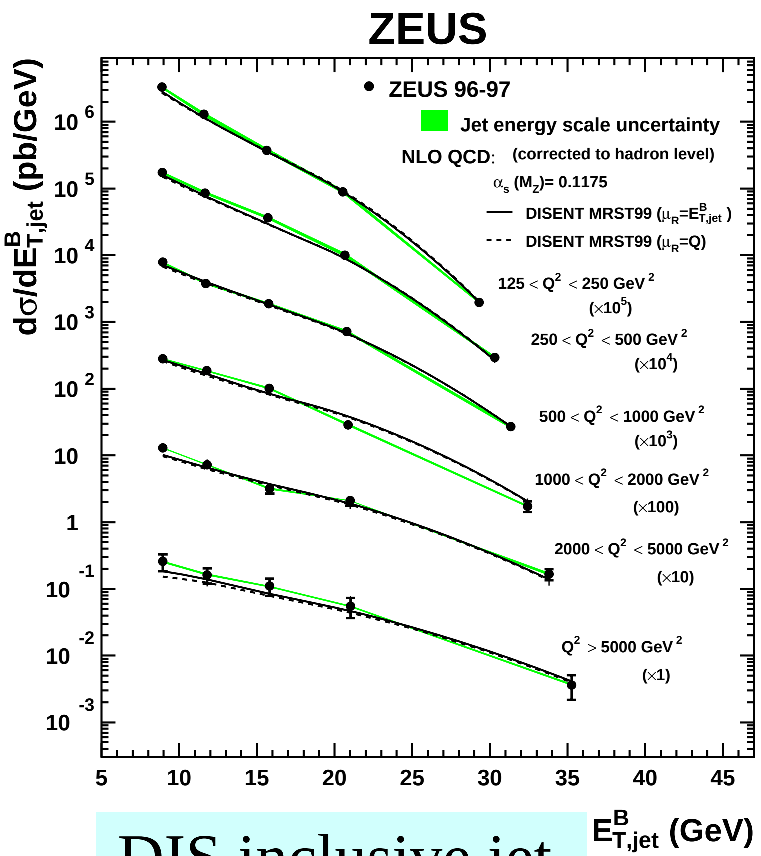


Photo-production (Q^2~0) dijets



DIS inclusive jet

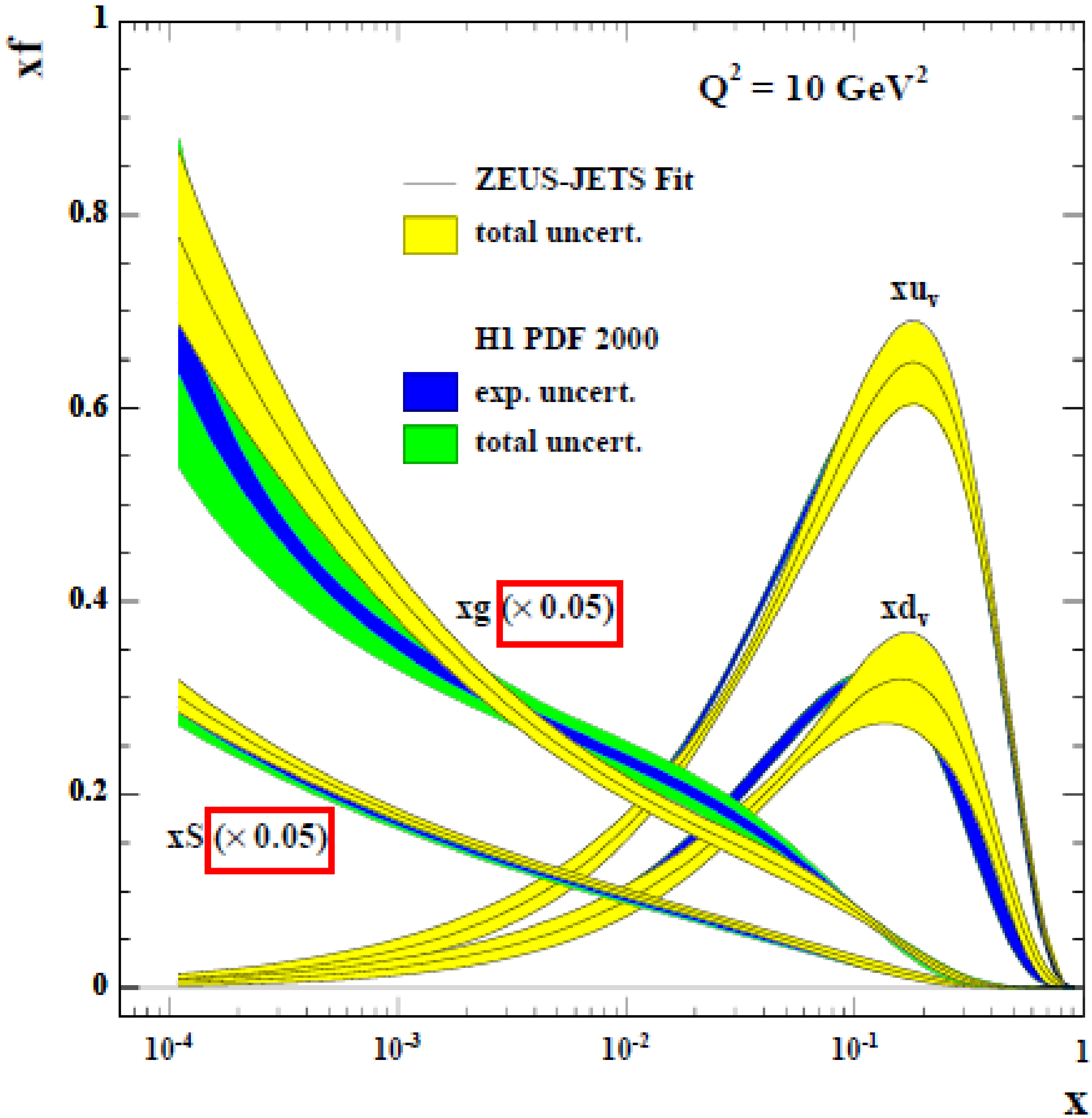
PDFs from HERA

All 547 data points (ZEUS) are fitted simultaneously.

→ PDF extraction.

- Strong rise of gluon PDF at low x.
- Sea quarks are also many.

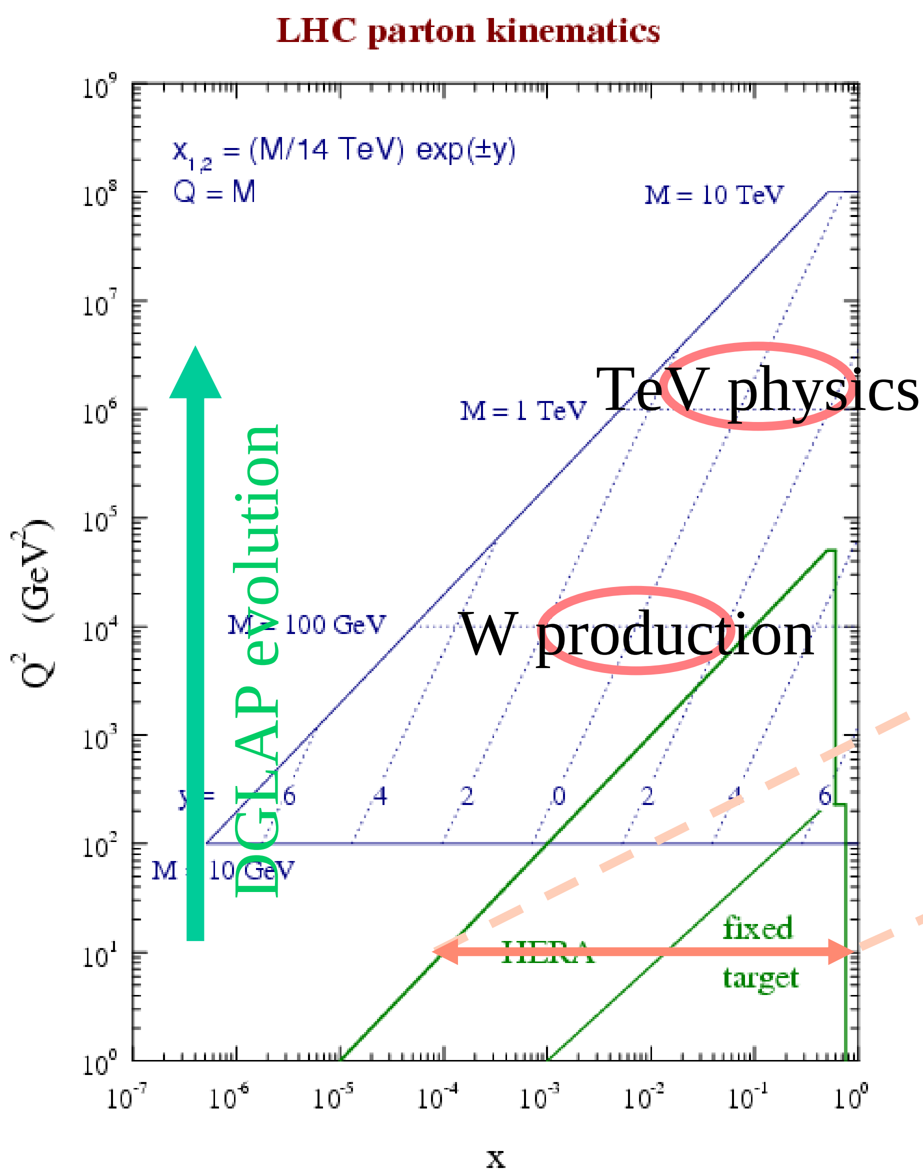
(Note: in the plot they are 1/20)

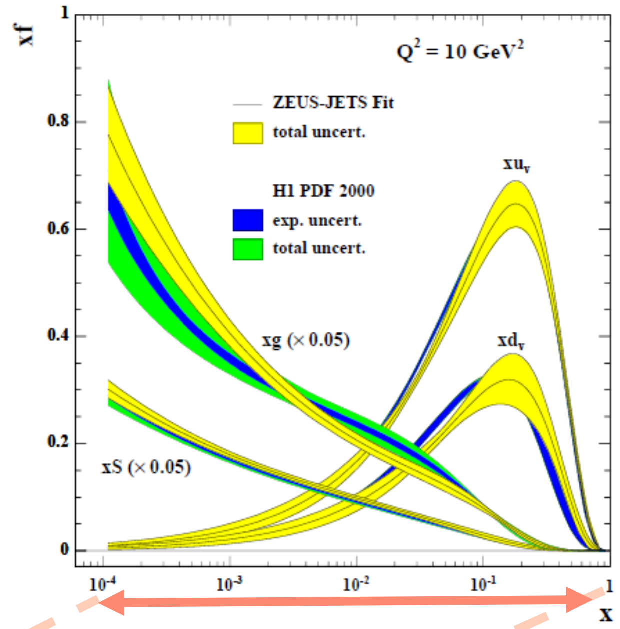


H1/ZEUS difference

- data set (H1 does not have jets, but results from fixed target exp.)
- parameterization
- systematic uncertainty

Why is PDF extraction at HERA important?





- LHC: proton-proton collision
  → Definitely needs PDFs.
- Main physics of LHC are at the x range which HERA covers.

We can improve our understanding further

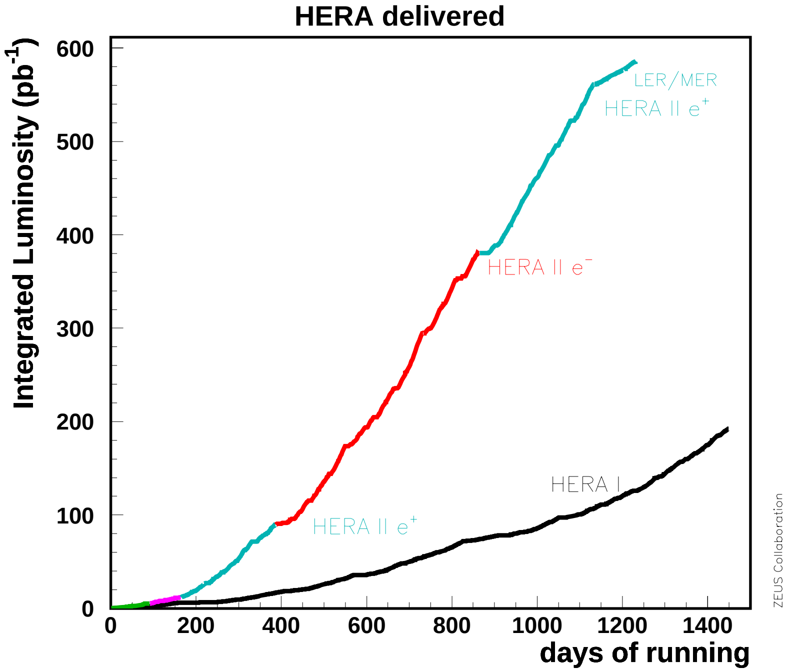
Other (and/or more) measurements

- NC/CC
  - More statistics with polarized beam.
- Heavy Flavour production
  - Large statistics with the updated detector in HERA-II.
- F_L
  - First direct measurement at the end of HERA.

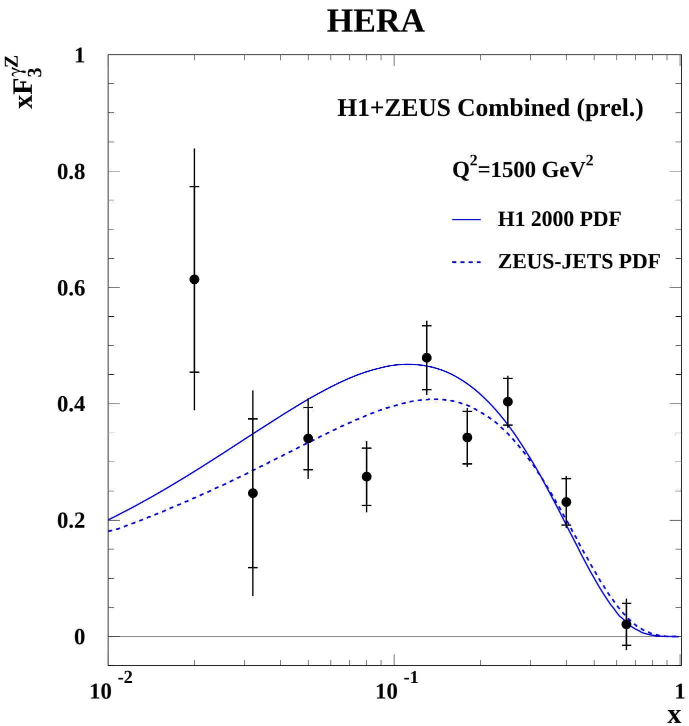
Understanding of systematic uncertainties of measured cross section in HERA-I

- Combining cross sections from the H1 and ZEUS experiments.

NC/CC cross sections with more statistics



	HERA-I	HERA-II
e^-p	$20pb^{-1}$	$180pb^{-1}$
e^+p	$100pb^{-1}$	$170pb^{-1}$



- Increase of electron data

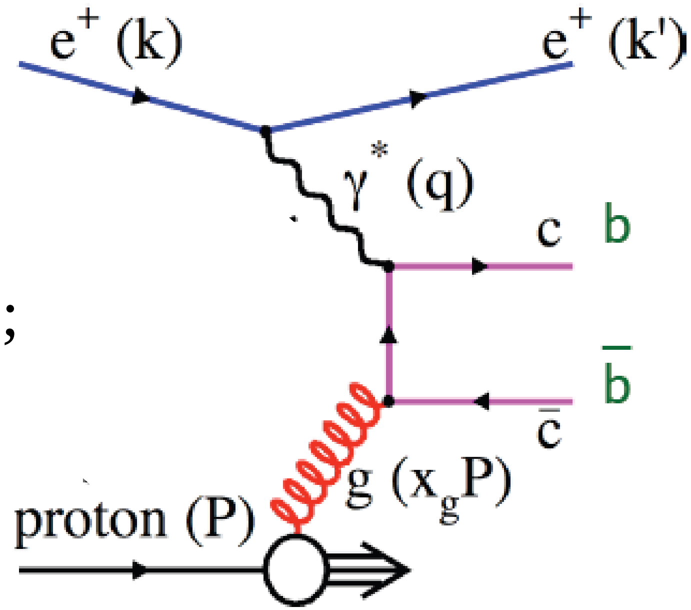
  NC → More sensitivity to xF_3

  i.e. valence quarks (u+d)

- Increase of positron data

  CC → More sensitivity to d quark

Heavy Flavour production



- Dominant process of heavy quark production:
  Boson-Gluon-Fusion (BGF)
- Two schemes to treat heavy quarks in pQCD;
  - massive scheme (FFN)

    appropriate for $Q^2 \sim M_q^2$

    Heavy quarks are produced via BGF.

    → Sensitive to gluon PDFs
  - massless scheme (ZMVFN)

    appropriate for $Q^2 >> M_q^2$

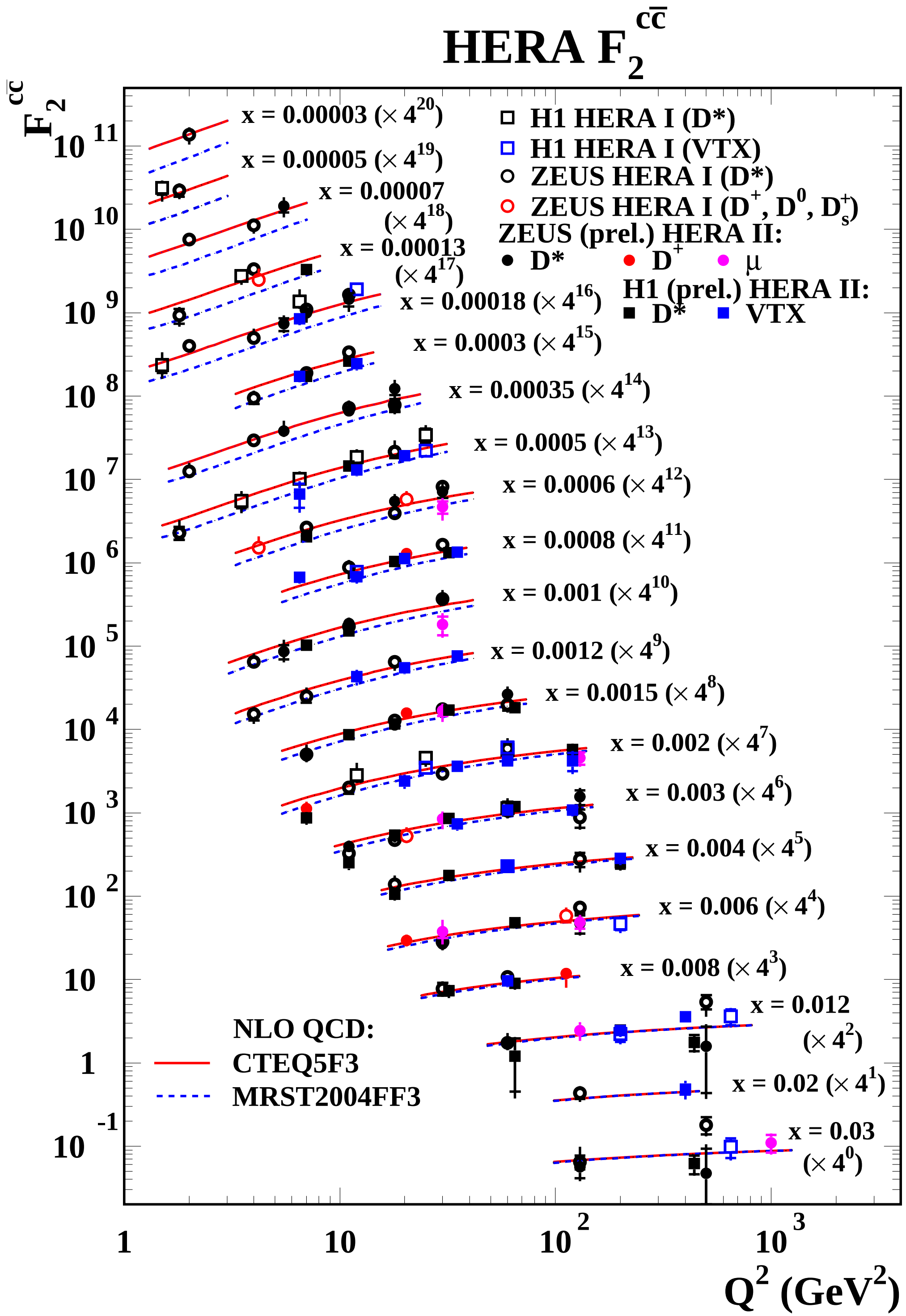
    Heavy quarks are massless and exist in the proton if Q^2 is above the mass threshold.

    → Intrinsic heavy quarks' PDFs
- Cross check for current pQCD description for the proton.

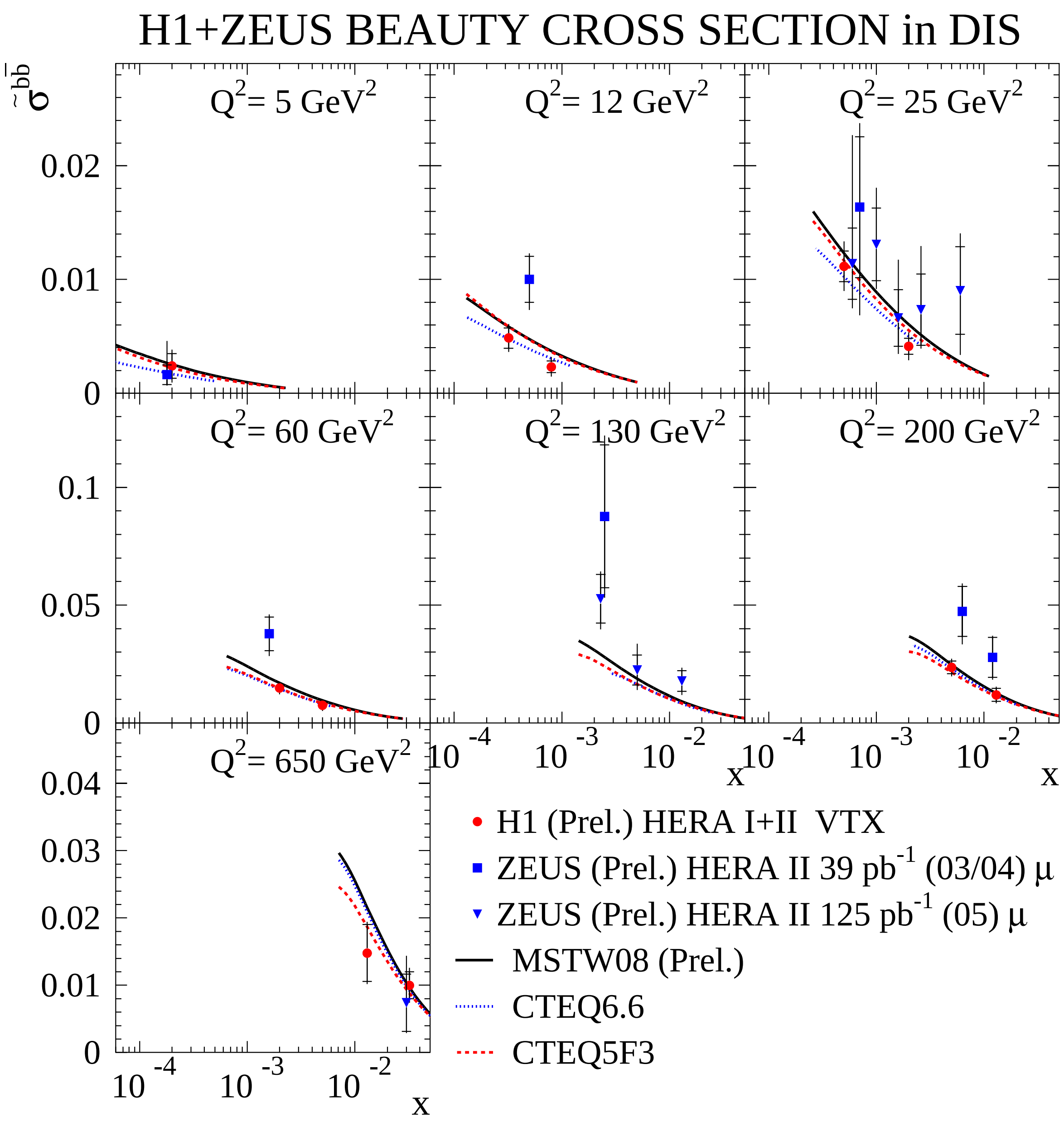
F_2^{cc}

- F_2^{cc} is extracted for large kinematic region.
  - different methods
    - D mesons by slow pions
    - Impact parameter tagging
  - different data sets, theory

  → In good agreement
- Scaling violation is seen.
- Well described by NLO-QCD.



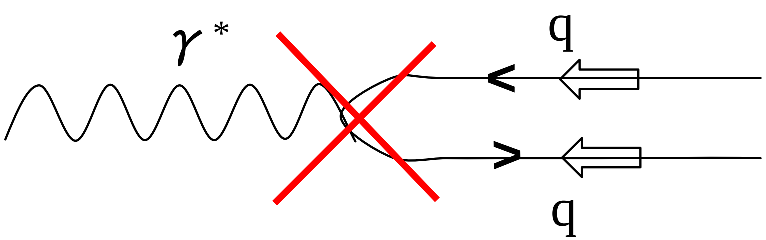
F_2^{bb}



- First measurement of F_2^{bb} at HERA.
- Different methods
  - H1: Impact parameter tagging
  - ZEUS: μ +jet
- More data to come

Longitudinal structure function: F_L

- Proportional to longitudinal photon interacting with proton.
- In naive QPM, proton has co-linear spin ½ quarks only.



Longitudinal photon cannot interact with a quark → $F_L = 0$

- gluon emission in the proton → $F_L \neq 0$

  i.e. F_L directly reflects gluon dynamics in the proton.

gluon PDF

In pQCD: $$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2 + 8 \sum_q e_q^2 \left(1 - \frac{x}{z} \right) z g(z) \right]$$

Measurement of F_L is good test for the current understanding of proton structure and QCD.

F_L @ HERA

$F_L \Leftrightarrow$ gluon ➔ Probably HERA is the best place to measure F_L.

- Why had F_L not been measured before the end of HERA?

  Ans. Technical difficulties

  – Needs cross section measurements with different beam energies.

  – Needs to tag scattered electrons with lowest energies as possible.

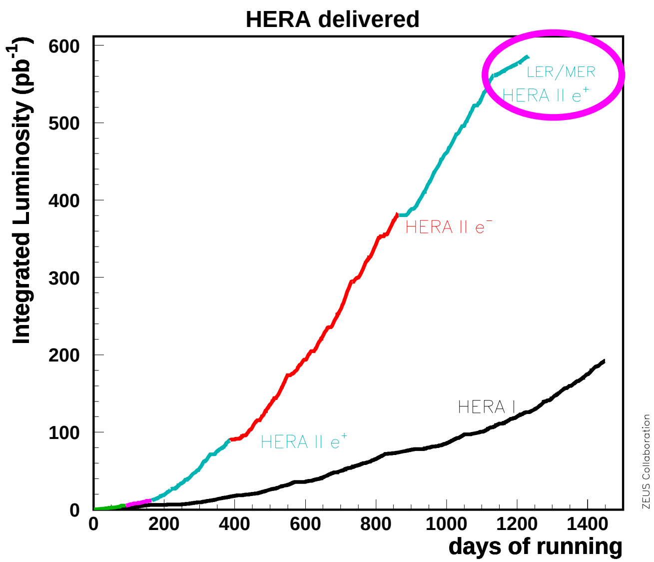
- The last 4 months of HERA operation were dedicated to F_L measurement.

  → Operation with lowered proton beam energy.

  E_p= 460 GeV : 14 pb^{-1}

  E_p= 575 GeV : 8 pb^{-1}

  Successfully done!



F_L measurement

- Cross section is combination of F_2 and F_L.

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

- **F_L** ← Comparison of $\tilde{\sigma}$ at the same (x, Q^2) but different y

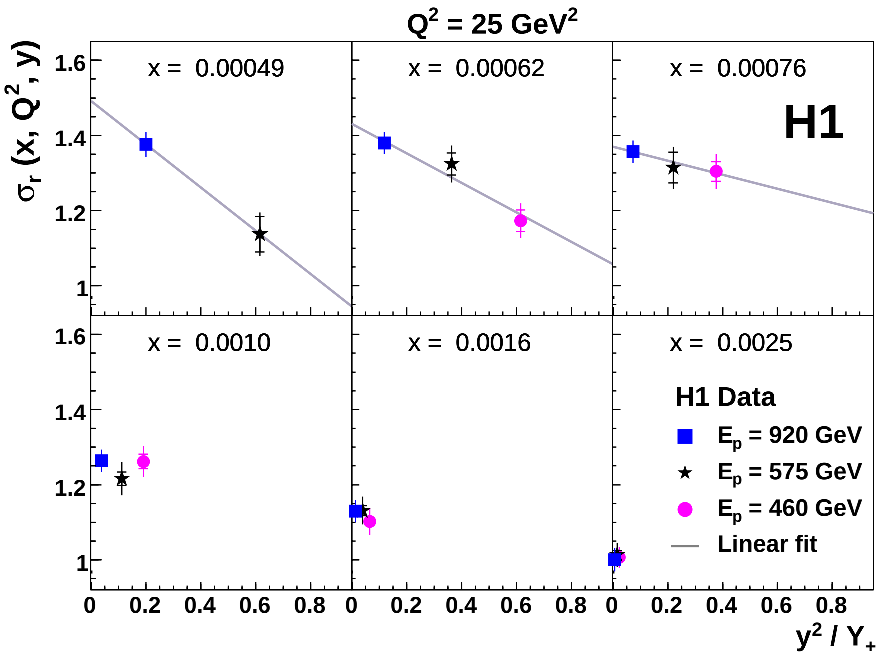
$$Q^2 = sxy$$

→ different beam energy

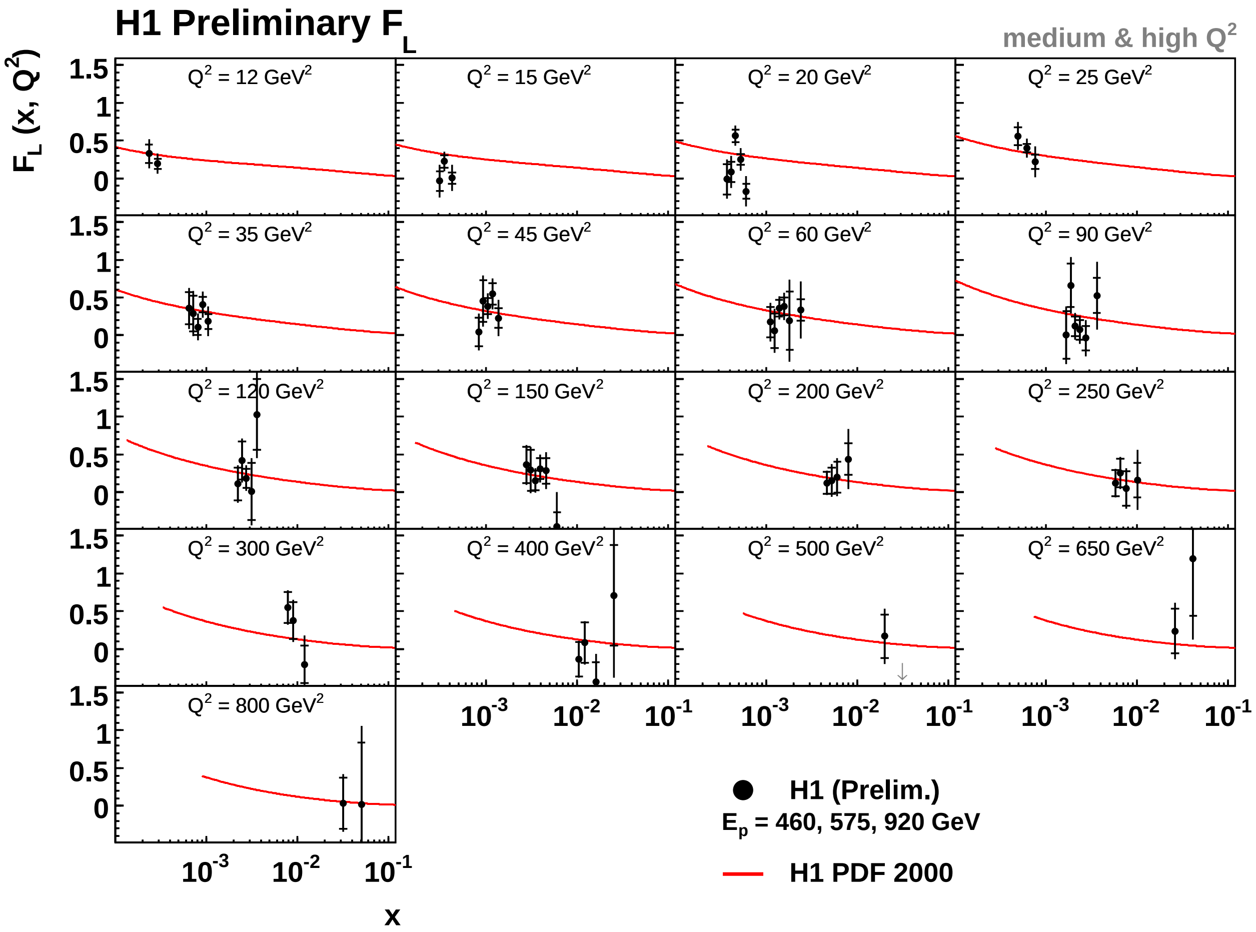
Sizable only at high-y ⇔ Low energy of scattered electron.

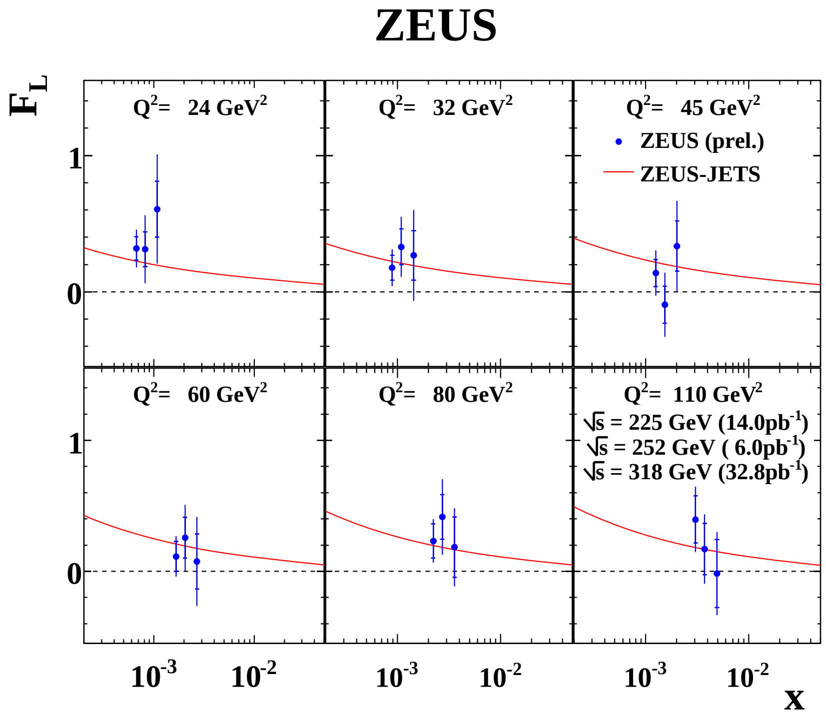
- Linear fit on cross sections at each (x, Q^2) bin.

→ slope = F_L



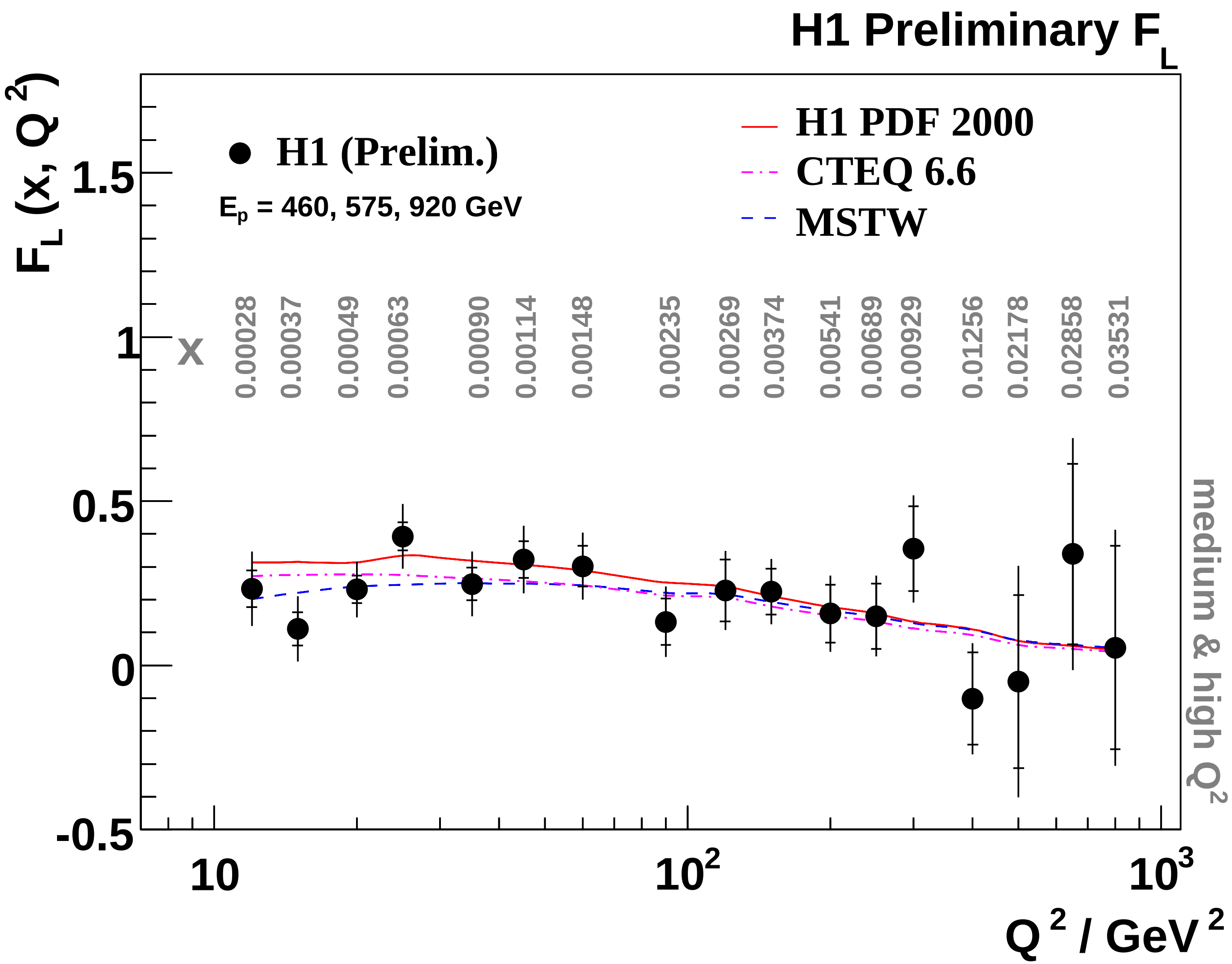
F_L from two experiments





- The first F_L measurement at low x.
- The measured F_L is consistent with pQCD description.

x-averaged F_L



- Again, consistent with pQCD prediction.

Combining H1 and ZEUS cross sections

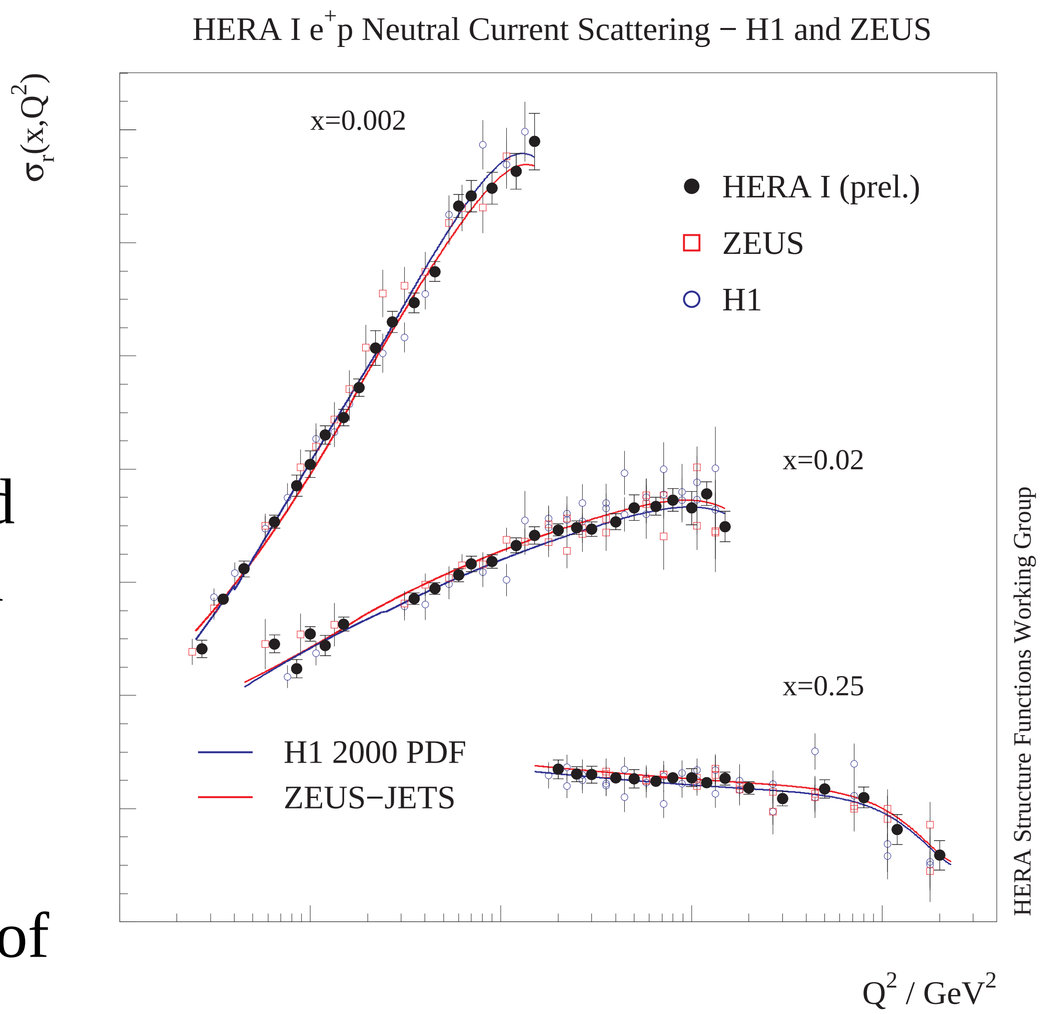
All HERA-I inclusive DIS cross sections from H1 and ZEUS are combined by averaging.

- Averaged each data point by simultaneous χ^2 fit.
  - Assumption:

    H1 and ZEUS measure the same cross sections.
  - taking account of correlated systematics within/between experiments.

  ➔ Cross calibration

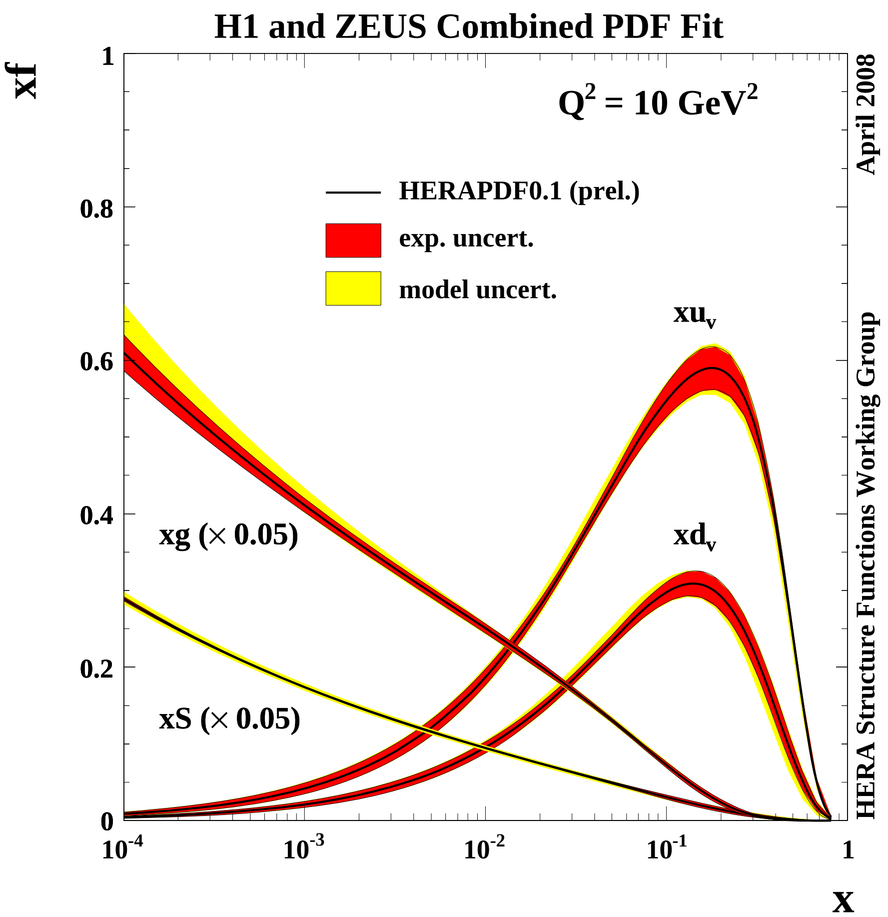
    Reduction of sys. errors.
- It is also an consistency check of two experiments.



Uncertainty gets improved by more than sqrt(2).

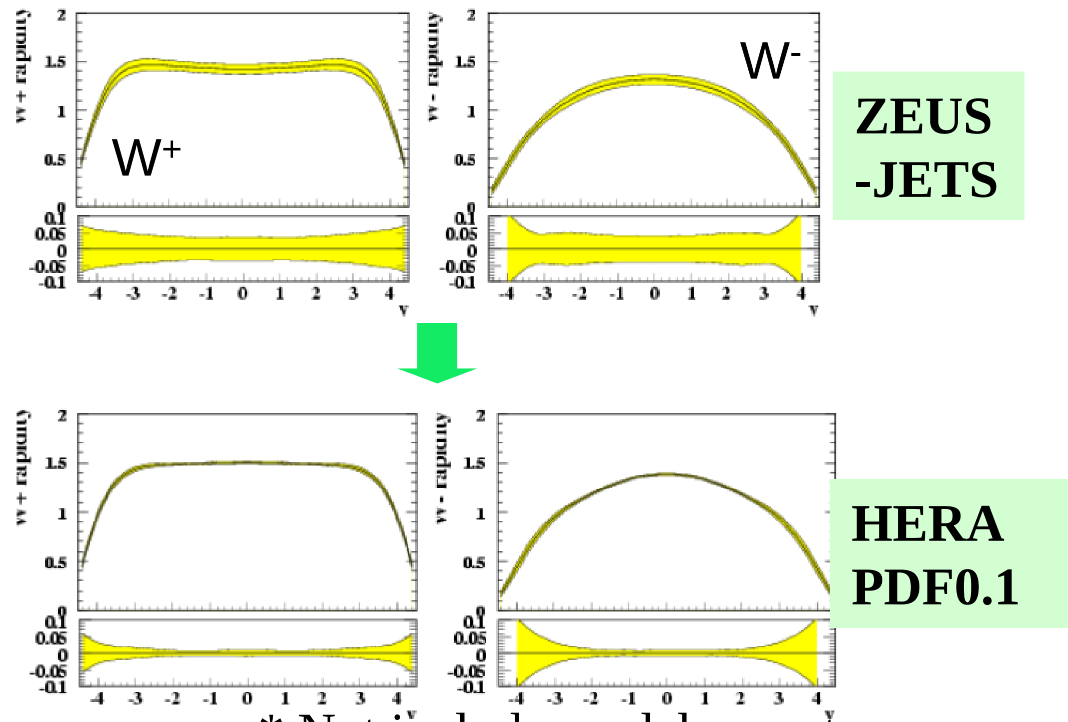
PDFs from combined cross sections

- QCD-Fit on combined cross section.
  - Good constraint on PDFs.



W rapidity @ LHC

A. M. Cooper-Sarker



* Not include model uncert.

- HERA PDFs have strong impact on W/Z physics at LHC.
- Combination is done only for HERA-I. → HERA-II will come.

Summary

- During its operation over 15 years, HERA provided plenty of physics through electron-proton collision.
  - Not only the proton structure, but Electroweak and QCD physics.

- Proton structure has been vigorously investigated at HERA.

  We have precise understanding of the proton structure.
  - Steep rise of gluons and Sea quarks at low-x
  - Good description by pQCD

  → Good input to LHC!

- Still, many results from HERA will come up.

  → We can improve our understanding of the proton structure.

Backup

W_R boson

Extrapolation to $P_e = \pm 1$ → limits on RH σ_{CC}

$\sigma_{CC}(e^-p)$ [pb] extrapolated to P_e = +1	
H1 (prel.)	$-0.9 \pm 2.9_{stat} \pm 1.9_{syst} \pm 2.9_{pol}$
ZEUS (prel.)	$0.8 \pm 3.1_{stat} \pm 5.0_{syst+pol}$

$\sigma_{CC}(e^+p)$ [pb] extrapolated to P_e = -1	
H1 (pub.)	$-3.9 \pm 2.3_{stat} \pm 0.7_{syst} \pm 0.8_{pol}$
ZEUS (pub.)	$7.4 \pm 3.9_{stat} \pm 1.2_{syst+pol}$

95% CL on heavy W_R boson

- M_{WR}>208GeV (H1, e+p)
- M_{WR}>186GeV (H1, e-p)
- M_{WR}>180GeV (ZEUS, e-p)

assuming g_L=g_R and ν_R is light

Chi2 definition for averaging

Fit for data points (554 of them)

And j systematic uncertainties

$$\chi_e^2(\{\mu\},\{r\}) = \sum_{i=1}^{N} \left(\frac{m_i^e - \mu_i - \sum_{j=1}^{Ke} \beta_{ji}^e r_j^e}{\sigma_i^e} \right)^2 + \sum_{j=1}^{Ke} \left(r_j^e\right)^2$$

m_i^e = measured cross section in bin i by exp e

μ_i^e = true cross section in bin i

σ_i^e = statistical uncertainty in bin i by exp e

β_{ji}^e = correlated syst. unc. in bin i by exp e

$s_i, r_j \sim N(0,1)$

α_s measurement