Structure Function Measurements at HERA

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for the H1 and ZEUS Collaborations

Sino-German Workshop on

Frontiers in QCD

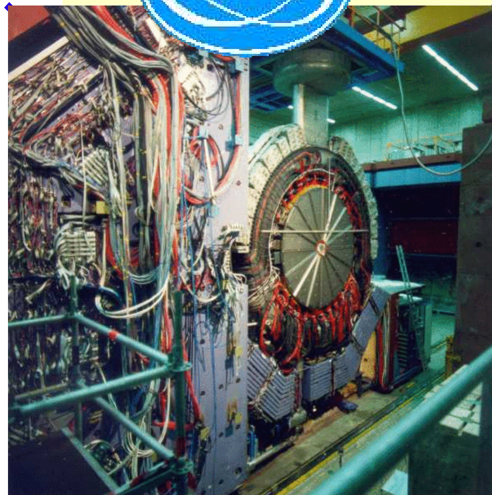
21.9.2006

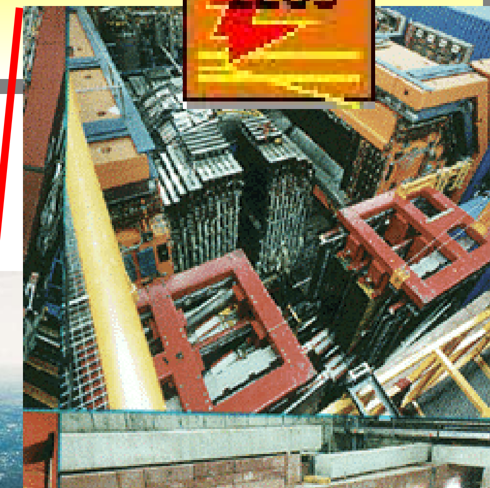
- Introduction
- Structure function measurements
- Structure function fits: parton densities and α_s
- Summary and outlook

Introduction

- Introduction
  - HERA
  - The ZEUS and H1 Detectors
  - Kinematics
- Structure Function Measurements
- Structure Function Fits
- Summary and Outlook

HERA



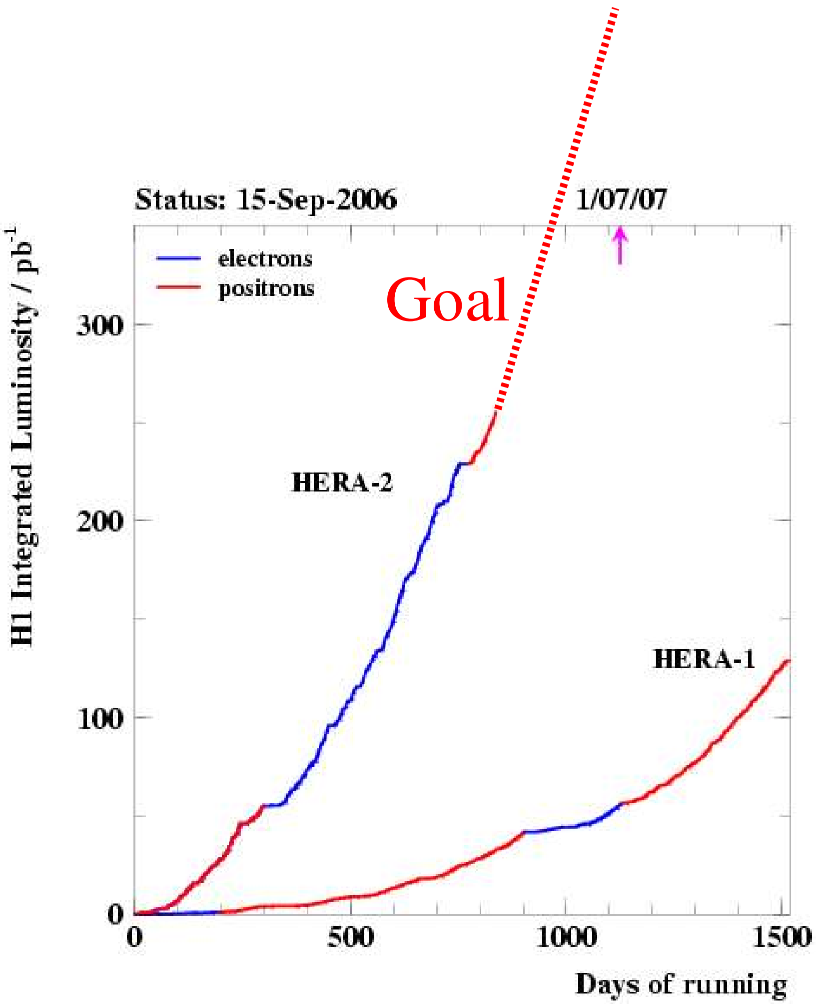


27.5GeV electrons/positrons on 920GeV protons $\rightarrow \sqrt{s} = 318$GeV
2 Collider experiments: H1 und ZEUS
HERA-I: 16pb^{-1} e^-p, 120pb^{-1} e^+p
HERA-II: ca. 500pb^{-1}, ca. 40% polarisation

Status of HERA-II

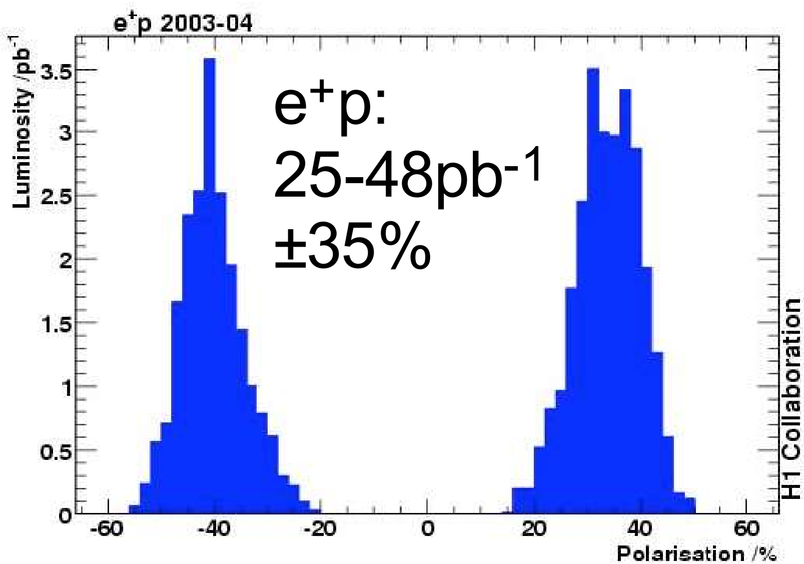
- HERA-I: 1992-2000:
  16pb^{-1} e^{-}p, 120pb^{-1} e^{+}p
- Upgrade 2001-2002,
  slow startup
- HERA-II: 2003 - July 2007
  up to now:
  ~175pb^{-1} e^{-}p, 105pb^{-1} e^{+}p
- e+ running will continue for 6 more months, then 3 months low energy run

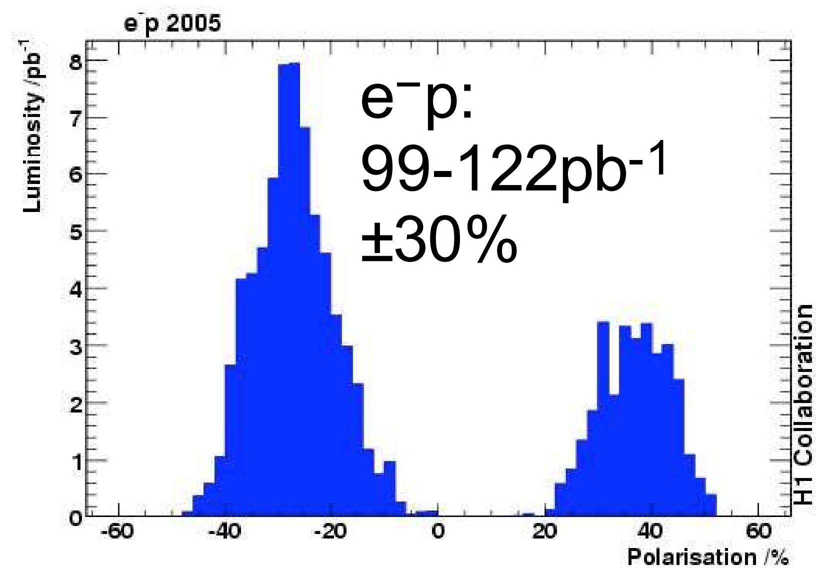
HERA: Integrated Luminosity



Lepton Polarization at HERA-II

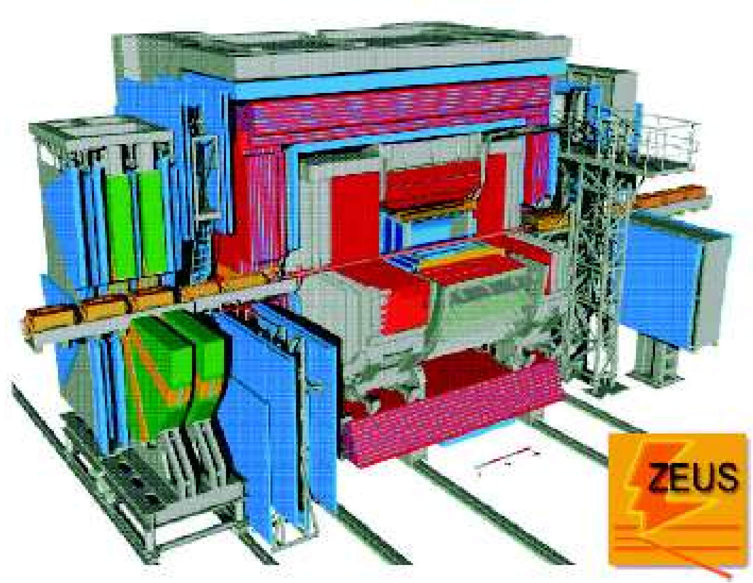
- New HERA-II feature:
  Use spin rotators to produce longitudinal polarization in experiments
- Allows to measure polarization dependence of high-Q^2 processes:
  - Charged currents: limits on right-handed currents
  - Neutral current: γZ interference

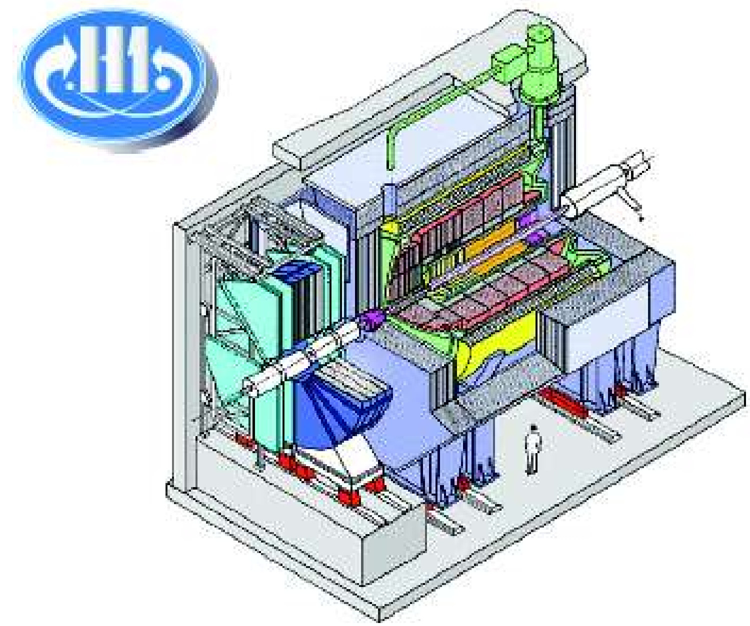




ZEUS and H1

- Omni-purpose detectors:
  silicon tracking, drift chambers, calorimeter, muon system





Uranium-Scintillator calorimeter:
em: $\sigma(E)/E = 18\%/\sqrt{E}$
had: $\sigma(E)/E = 35\%/\sqrt{E}$

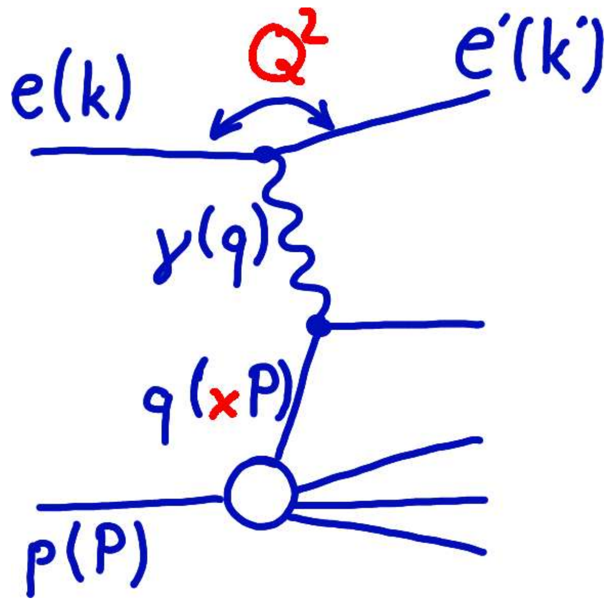
Fine-grained LAr calorimeter:
em: $\sigma(E)/E = 12\%/\sqrt{E} \oplus 1\%$
had: $\sigma(E)/E = 55\%/\sqrt{E} \oplus 1\%$

Backward lead-scintillator calo:
em: $\sigma(E)/E = 7\%/\sqrt{E} \oplus 1\%$

Kinematics

Quark Parton Model: „Scattering on asymptotically free quarks“

- Photon momentum $q=k'-k$
- Squared center-of-mass energy $s=(k+P)^2 \approx 2k \cdot P$
- Virtuality $Q^2 = -q^2$
- Quark momentum $x \cdot P$:
  Bjorken-$x = Q^2/(2q \cdot P)$
- Inelasticity $y = q \cdot P / k \cdot P$
  (E_γ / E_e in proton rest system)
- „Master formula“: $Q^2 = x \cdot y \cdot s$
  => only 2 independent variables, normally x und Q^2



Kinematics can be reconstructed from electron or hadronic final state alone => over constrained!

Structure Functions, Parton Densities

- Hadron tensor is expressed in terms of structure functions F_1, F_2, F_3
  Resulting ep cross section
  (F_3 is parity violating, vanishes for pure γ exchange):

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{xQ^4}\left((1-y)\tilde{F}_2 + y^2 x\tilde{F}_1 \mp \left(y - \frac{y^2}{2}\right) x\tilde{F}_3\right)$$

- Contributions from γ, Z^0 exchange and γZ interference:

$$\begin{aligned}\tilde{F}_2 &= F_2 + \quad k(-v_\mathrm{e} \mp P a_e) x F_2^{\gamma Z} + \quad k^2(v_e^2 + a_e^2 \pm P v_e a_e) x F_2^Z \\ x\tilde{F}_3 &= \qquad\quad k(-a_\mathrm{e} \mp P v_e) x F_3^{\gamma Z} + \quad k^2(2 v_e a_e \pm P(v_e^2 + a_e^2)) x F_3^Z\end{aligned}$$

- Structure functions are calculated from parton densities:

$$F_2 = x \sum_q e_\mathrm{q}^2 \, (q + \bar{q})$$

- Parton densities depend on x and Q^2,
  they can be evolved in Q^2 using the DGLAP equations

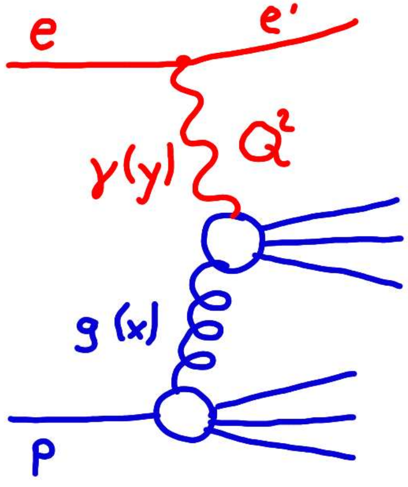
Kinematic Plane

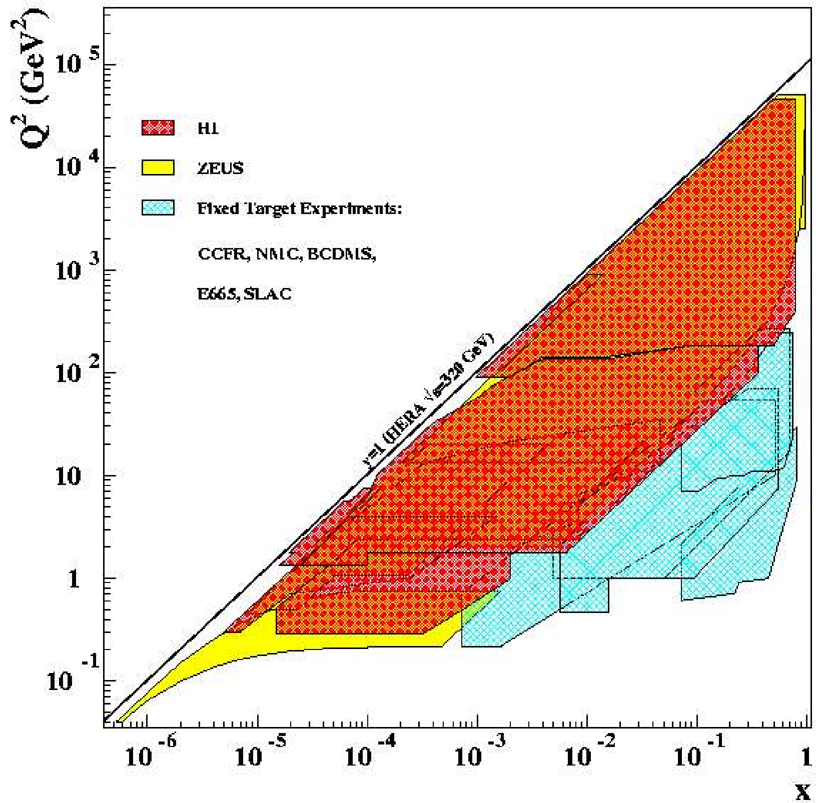
HERA covers more than 5 orders of magnitude in x und Q^2

- Opens region at very low x => high parton densities
- Tests evolution of parton densities over a wide Q^2 region

$Q^2 = x \cdot y \cdot s$

=> Usable y range determines kinematically accessible range

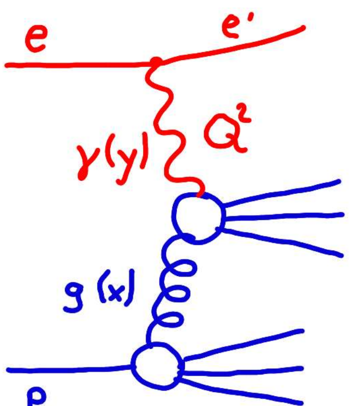


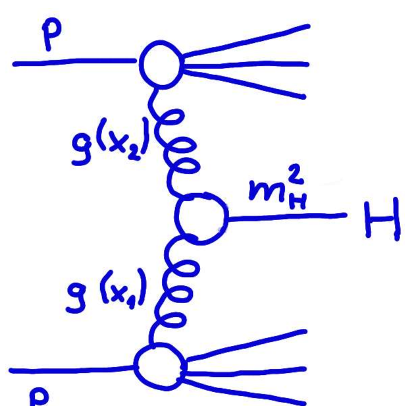


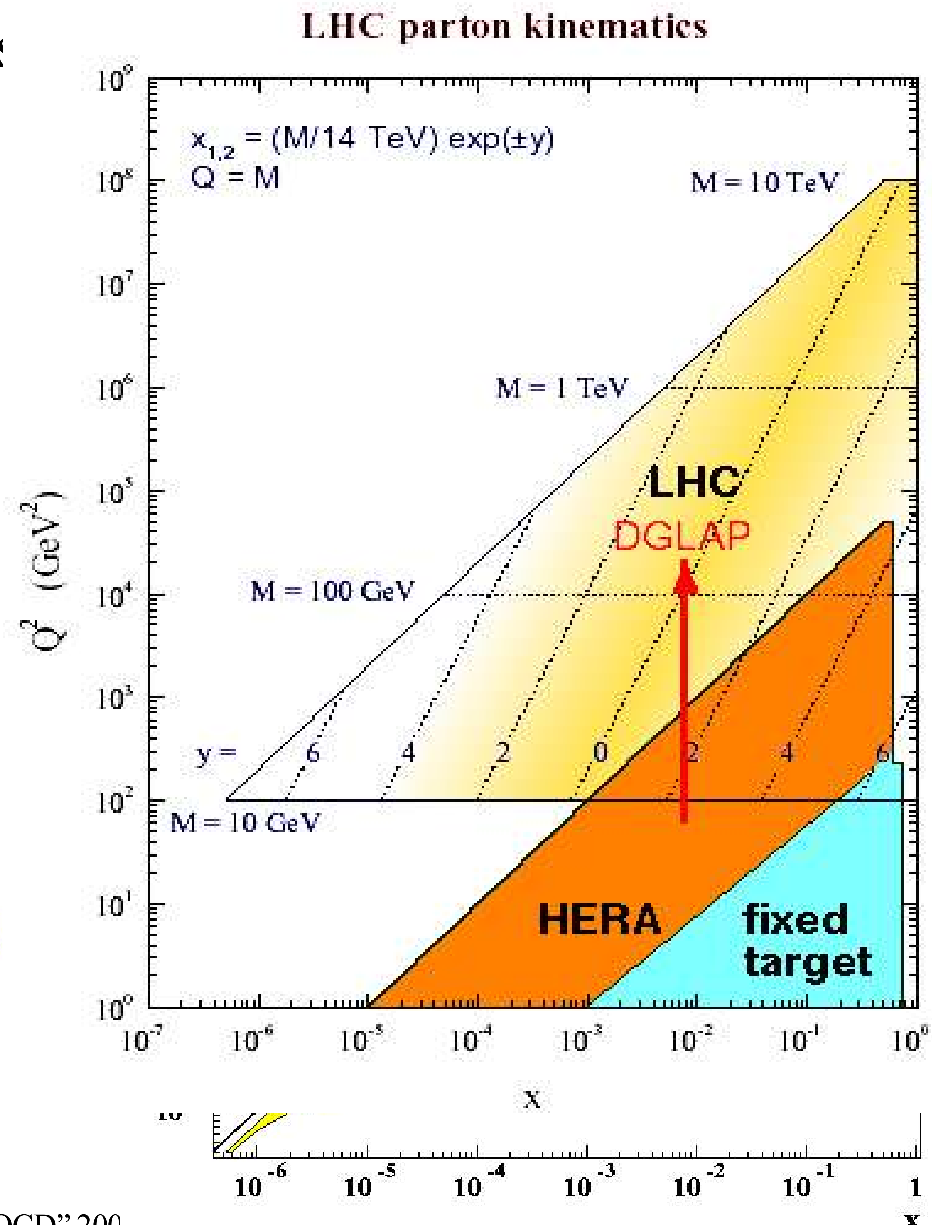
HERA and LHC

HERA results essential for predictions of LHC processes

- Gluon density
- Quark density at large x
  => Discovery potential!
  Needs high Luminosity:
  HERA-II!







Structure Function Measurements

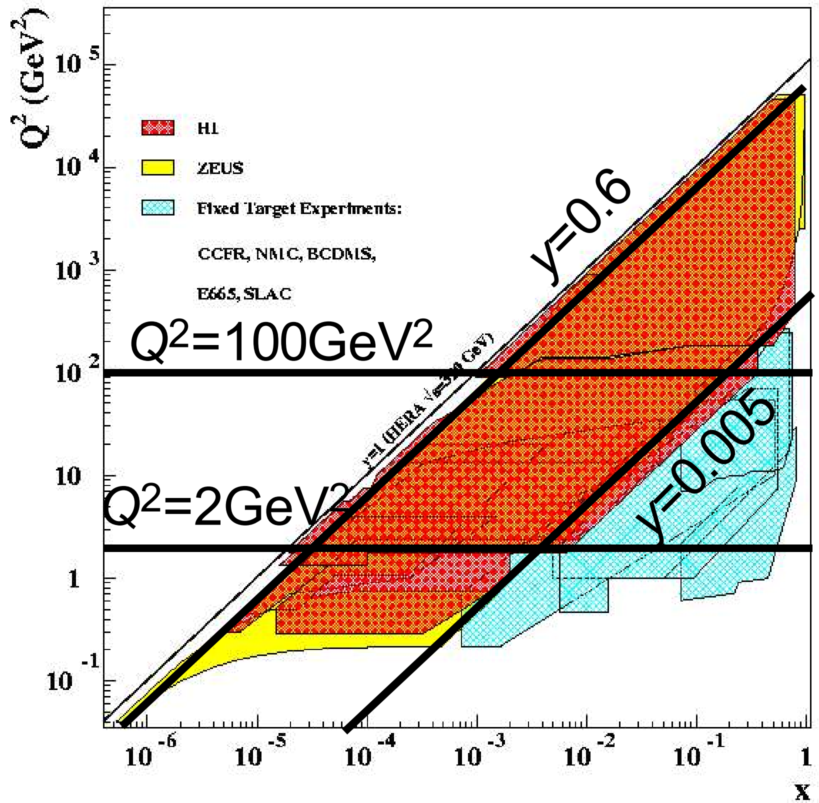
- Introduction
- Structure Function Measurements
  - F_2 in the bulk data
  - F_2 in corners of phase space
  - F_1 / F_L measurements
  - F_3 measurements
  - Flavour-exclusive measurements: $F_2^{c\bar{c}}$,$F_2^{b\bar{b}}$
  - Charged current measurements
- Structure Function Fits
- Summary and Outlook

The Bulk Data: F_2

- Large part of phase: F_2 dominates cross section

$$\frac{\mathrm{d}^2\sigma^{\pm}_{\mathrm{NC}}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}\left(Y_+F_2 \mp Y_-F_3 - y^2F_\mathrm{L}\right) \qquad Y_\pm = 1 \pm (1-y)^2$$

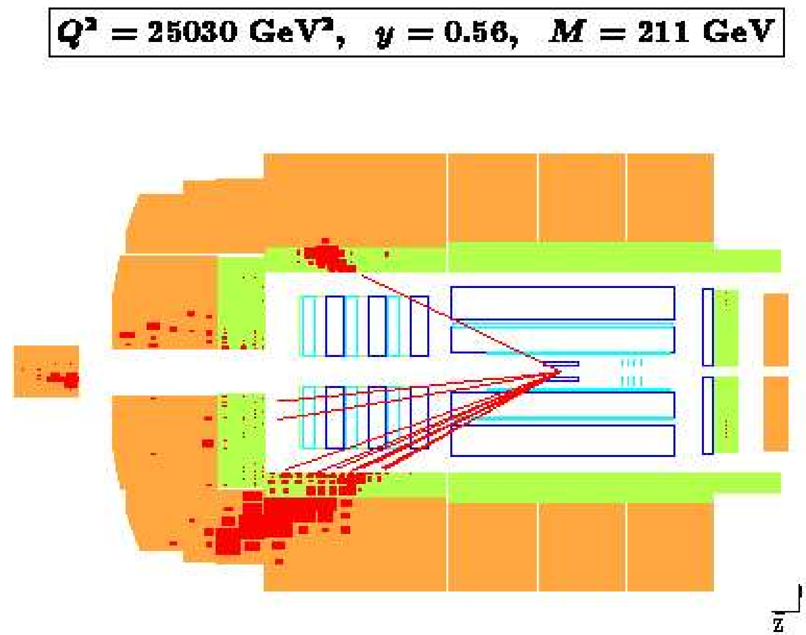
- Bulk data:
  - $0.005 < y < 0.6$:
    Electron well measured
  - $Q2 > 2$ GeV^2:
    Electron in main detector
    ($Q2 < 100$ GeV^2: rear calorimeter)



- $F_\mathrm{L}, xF_3 << F_2$

$$F_2 = x\sum_q e_\mathrm{q}^2(q+\bar{q})$$

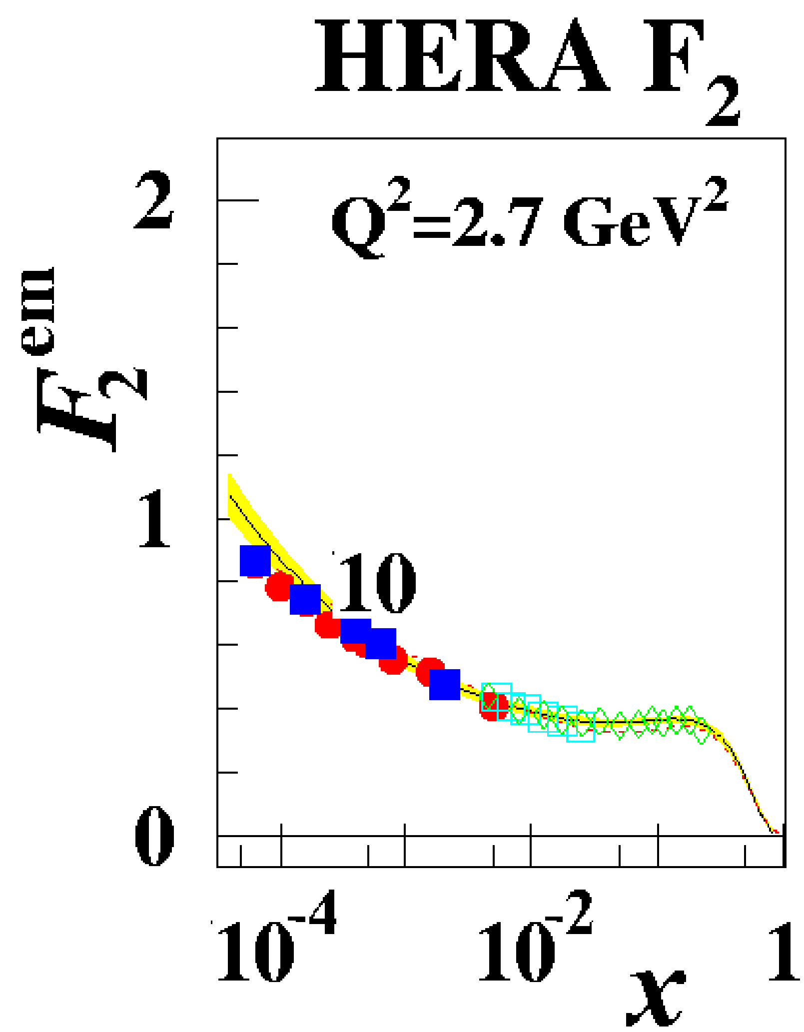
Typical DIS Events



A low-Q^2 event in ZEUS:
electron in rear calorimeter

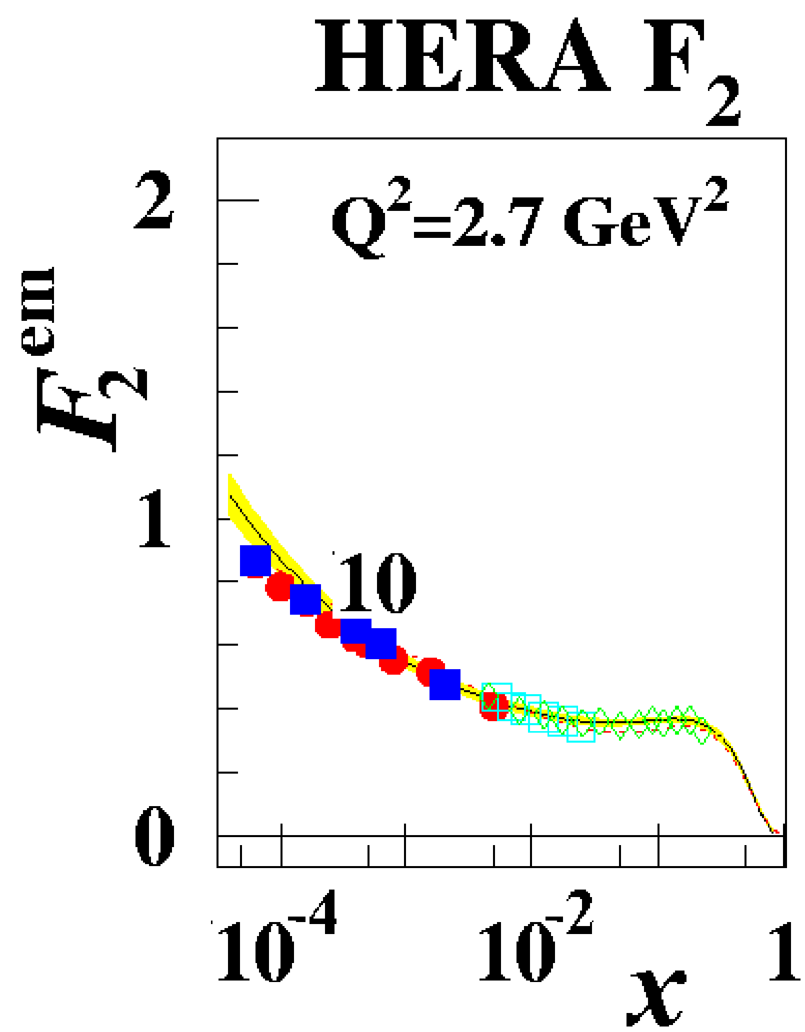
A high-Q^2 event in H1:
electron in central calorimeter

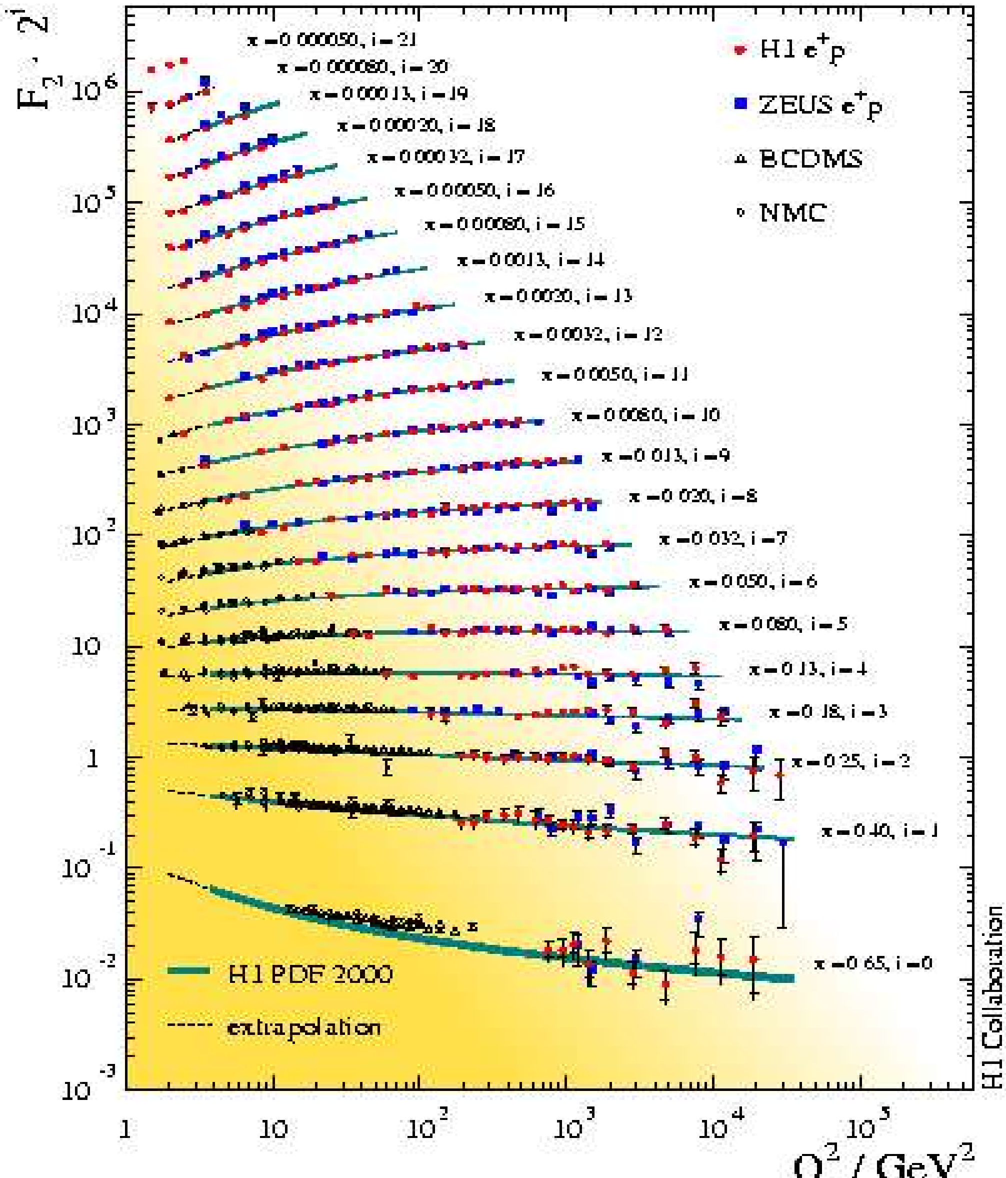
Measurement of F_2



- Precise data of high quality: Error 2-5% of $2.7<Q^2<120$GeV
- Foundation for precise parton density fits and determination of α_s
- Excellent description by NLO-QCD-fit: Test of QCD!

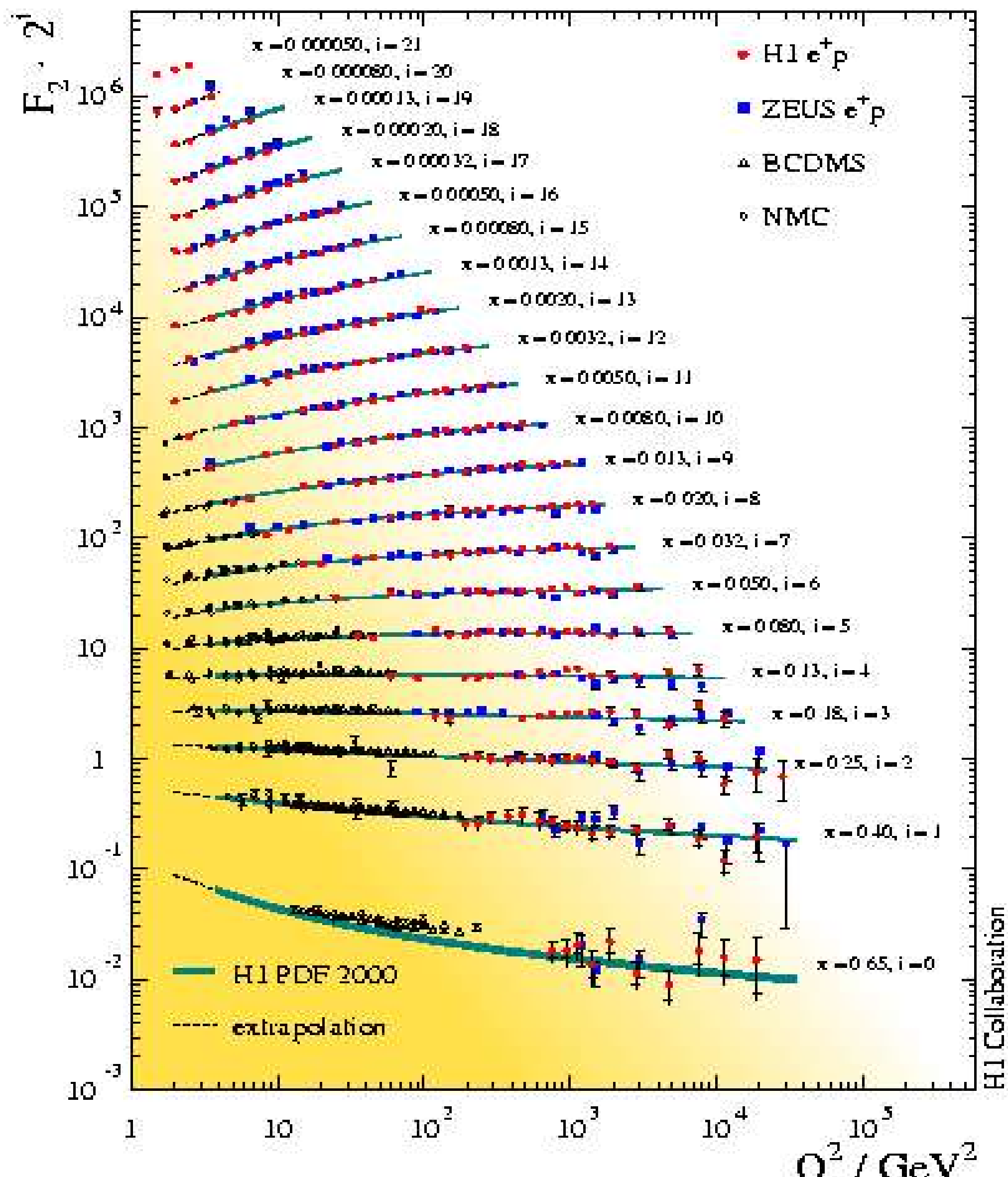
Measurement of F_2





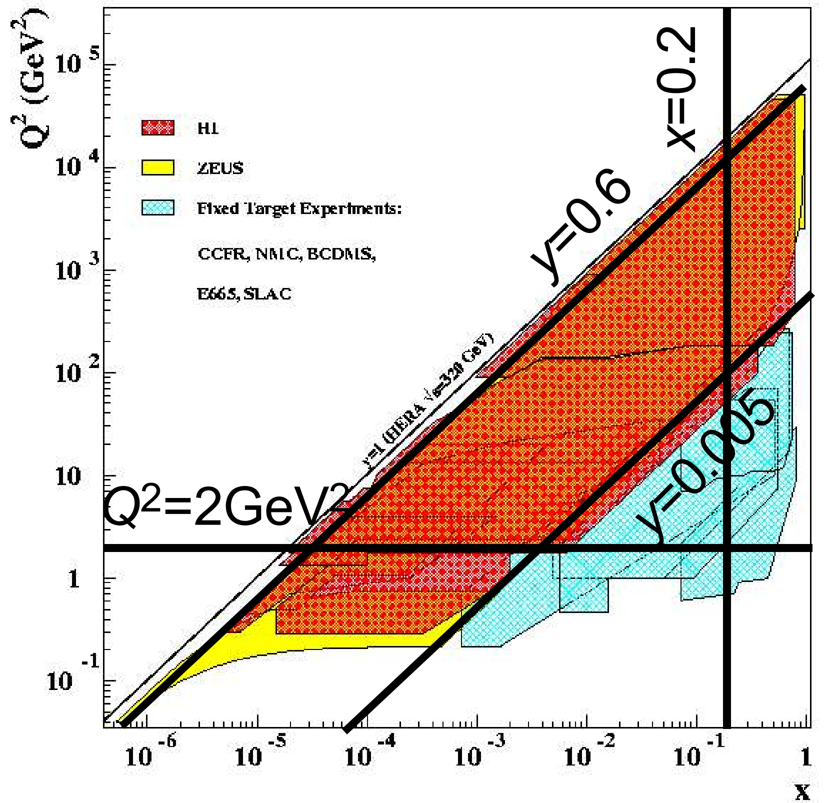
Overview over F_2

- Kinematic region:
  - 4 decades in x: $0.000065<x<0.65$
  - Q^2 up to $30000\,\mathrm{GeV}^2$
- HERA-I data completely analysed
- HERA-II: 3 times (e+) to 10 times (e⁻) more data => better accuracy at small x, large Q^2



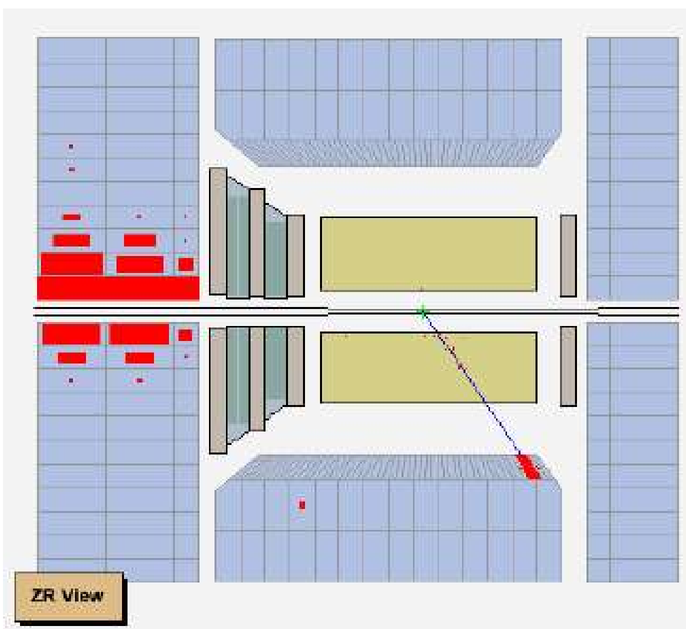
F_2 in Corners of Phase Space

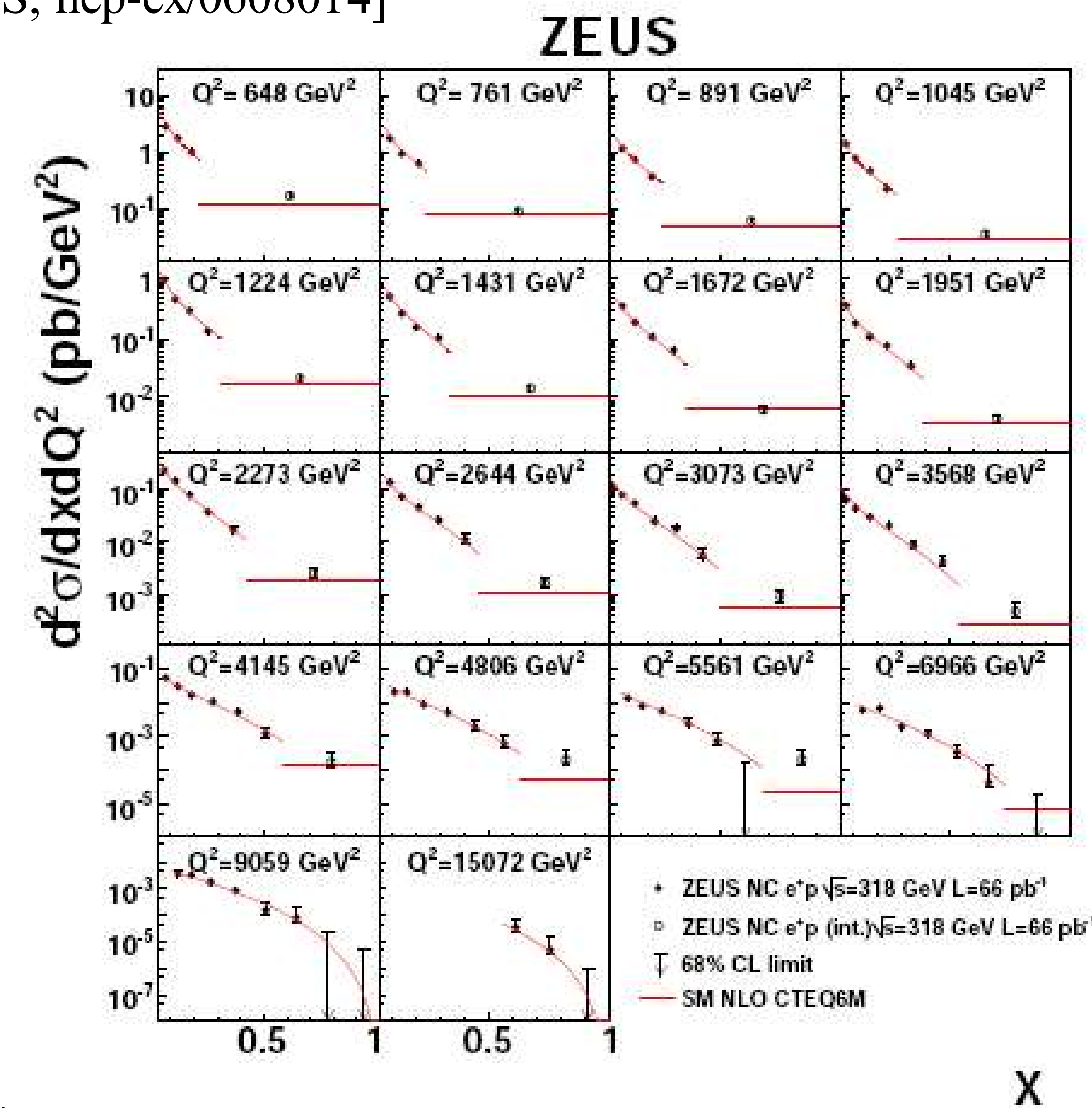
- Very high $x > 0.2$: Hadronic final state very close to beam pipe
- Very low $Q^2 < 2\text{GeV}^2$: Electron escapes main detector
  - Events with QED radiation
  - Special beam pipe calorimeter (ZEUS)
  - Shifted vertex runs: vertex shifted by 70cm
- Very high y>0.6 at moderate Q^2: Small electron energy => large background



ZEUS: High *x* Analysis

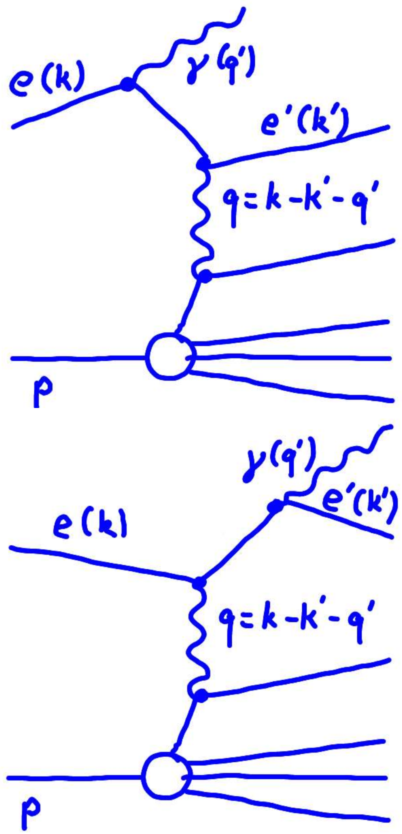
- High x: Hadronic final state very close to forward beam pipe
  New ZEUS analysis [ZEUS, hep-ex/0608014]
- Data agree with SM expectation, but are on the high side

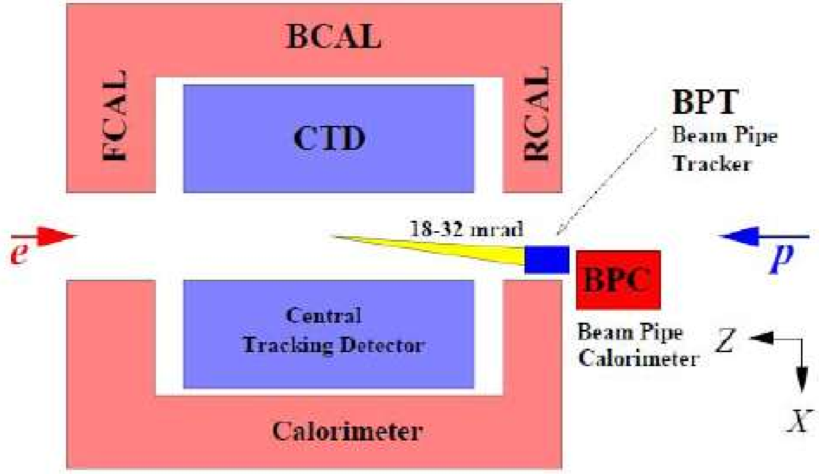


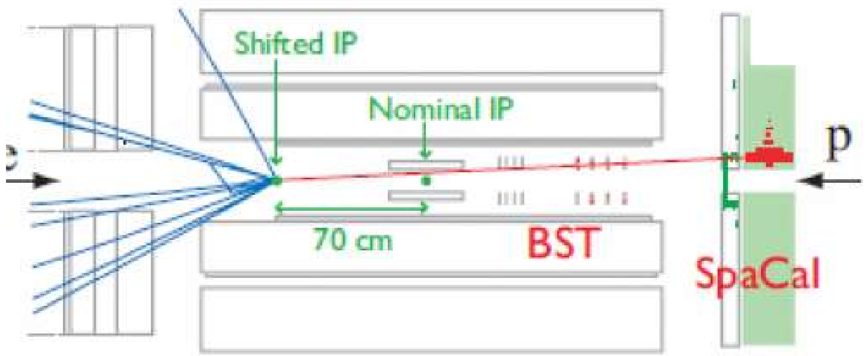


Accessing Low Q^2

- Radiative events: Momentum of exchanged photon reduced by QED radiation
- ZEUS: BeamPipe Calorimeter BPC plus BeamPipe Tracker BPT
- H1: Backward Silicon Tracker BST + data from shifted vertex runs

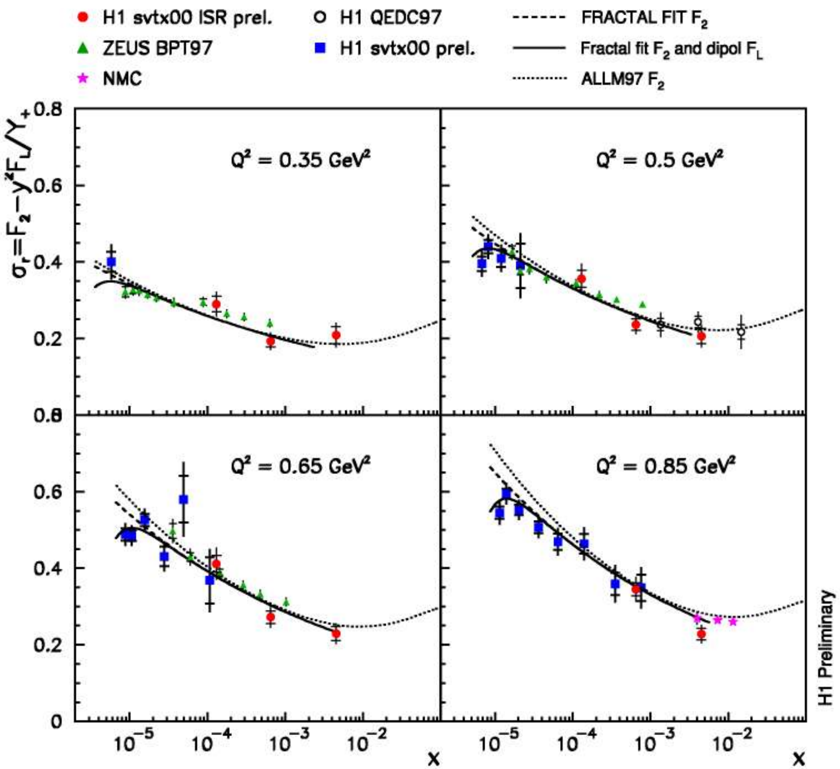


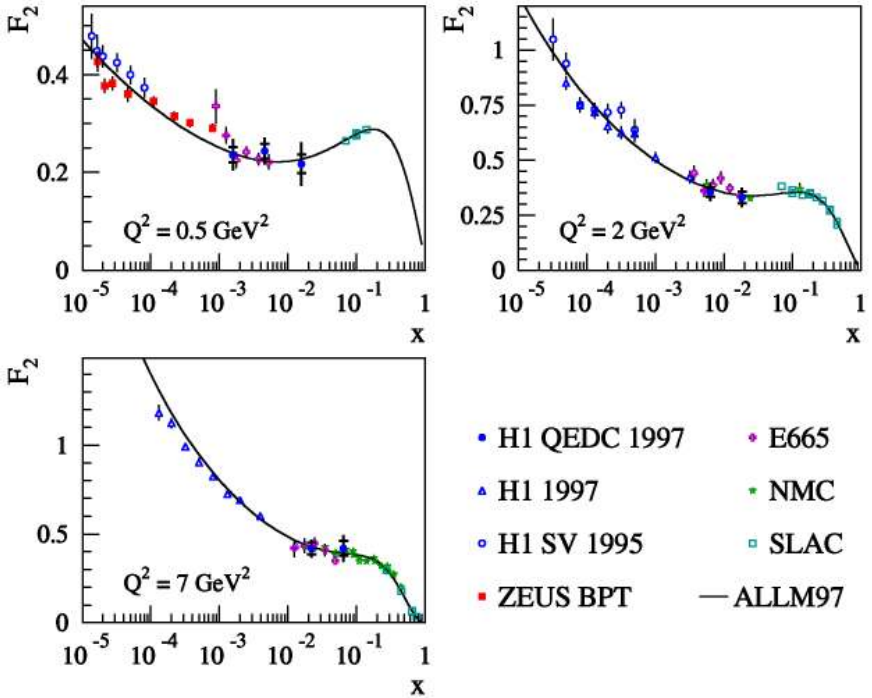




Result of Low-Q^2 Measurements

- Overlap with fixed target data (E665, NMC, SLAC): consistent results
- Data agree with parametrization ALLM97 [Abramowitz & Levi, hep-ph/9712415]





HERA Data: ZEUS, PL B487(2000)53; H1, PL B598(2004)159; H1, EPJ C21(2001) 33; H1prelim-04-042.

Measuring F_1/F_L

- Callan-Gross-Relation: $F_\mathrm{L} = F_2 - 2xF_1 = 0$
  valid in naive Quark-Parton-Model (QPM)

- QCD predicts nonzero F_L

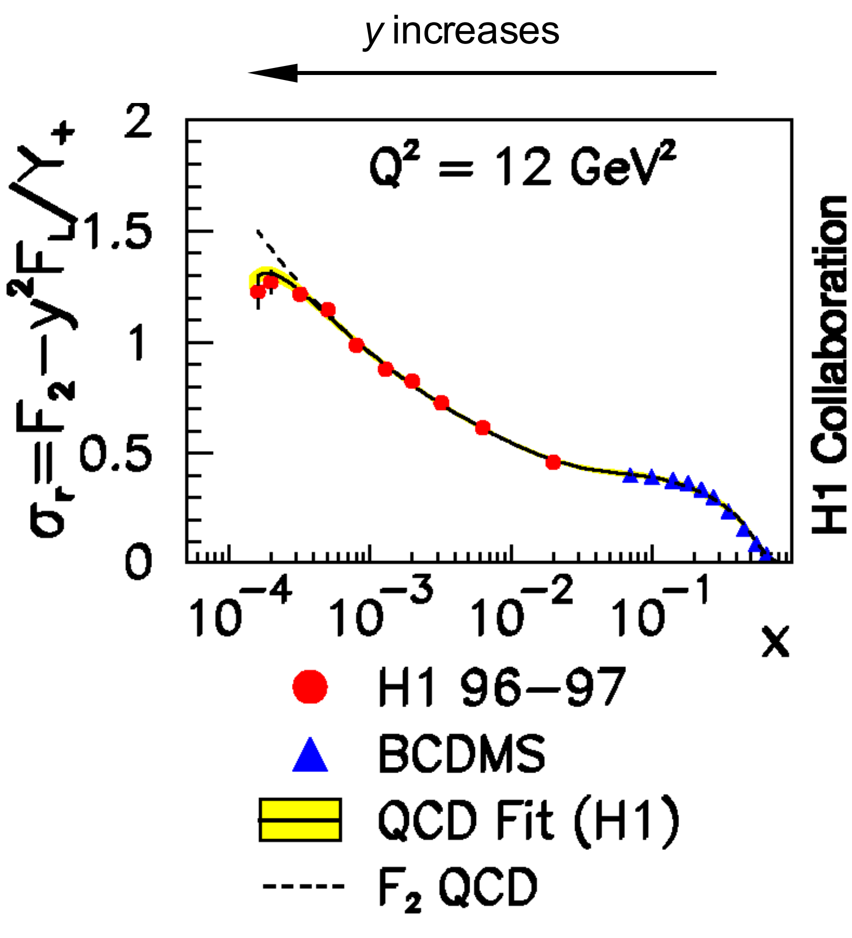
- True F_L measurement needs cross section measurements at same x, Q^2, but different y => Vary beam energies!
  => Planned for last 3 months of HERA-II data taking (next summer)

- Other method: Measure , $$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \underbrace{\left(F_2 - \frac{y^2}{Y_+} F_\mathrm{L} \right)}_{\sigma_\mathrm{r}}$$
  evolve F_2 from at fixed x from low Q^2 = low y to high y
  => difference between F_2 and σ_r gives F_L

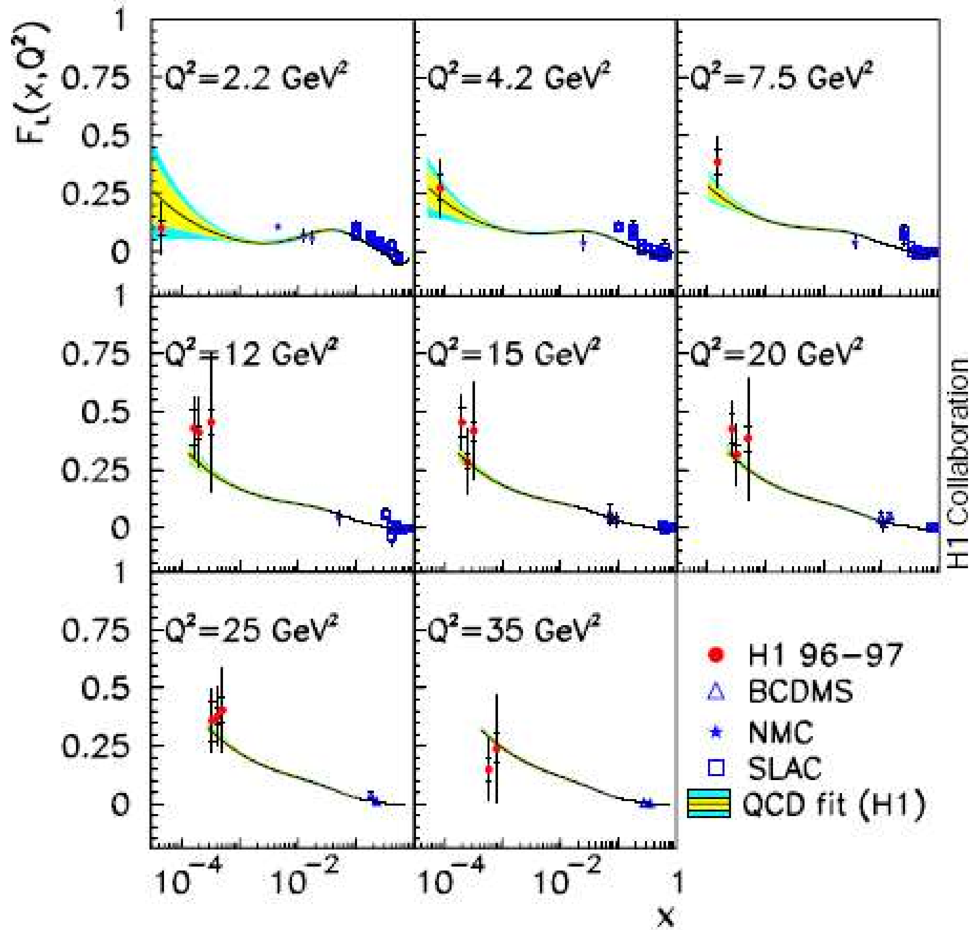
- High y => low electron energy => high background
  needs excellent understanding of photoproduction background

F_L Determination

- F_L results in agreement with QCD expectations
- True measurement next summer



H1, EPJ **C21**(2001)33



F_3

- Remember:

$$\frac{d^2\sigma^{\pm}_{\mathrm{NC}}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_{\mathrm{L}}\right) \qquad Y_\pm = 1 \pm (1-y)^2$$

- F_3 enters with different sign for e^-p and e^+p scattering: measured from difference of e^-p and e^+p cross sections => needs high accuracy data with both lepton charges!
- F_3 dominated by γZ interference, measures difference of quark and antiquark densities: valence quarks

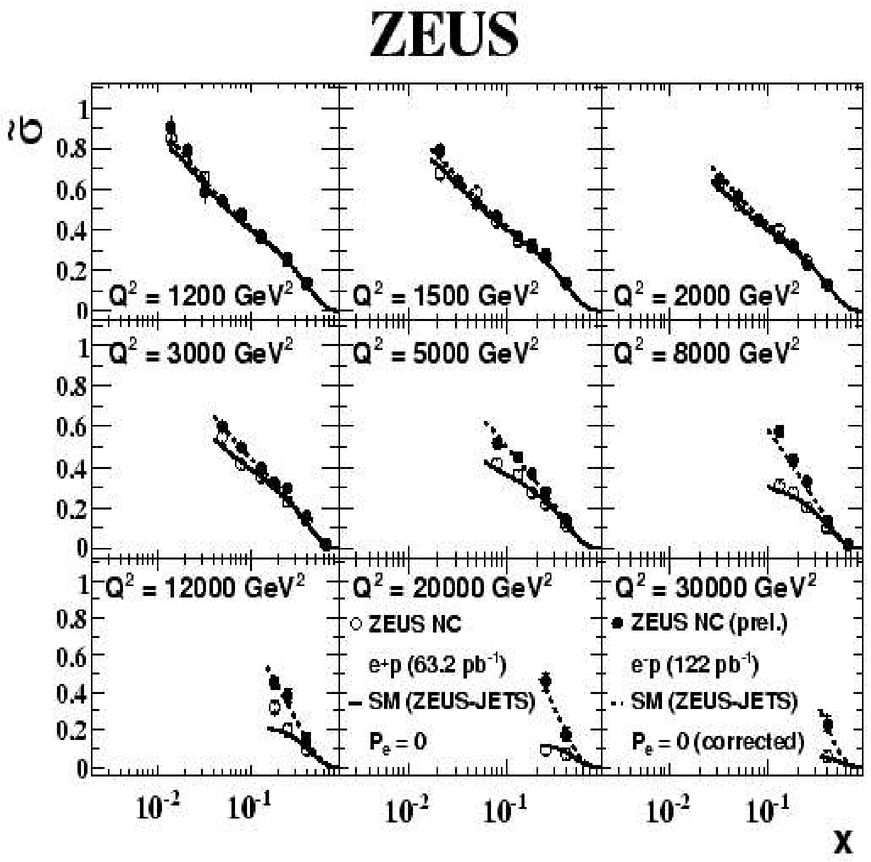
$$x\tilde{F}_3 = k(-a_e)xF_3^{\gamma Z} + k^2(2v_e a_e)xF_3^Z$$

$$xF_3^{\gamma Z} = 2x\sum_q (e_q a_q)(q-\bar{q}) = 2x(2u_v + d_v)$$

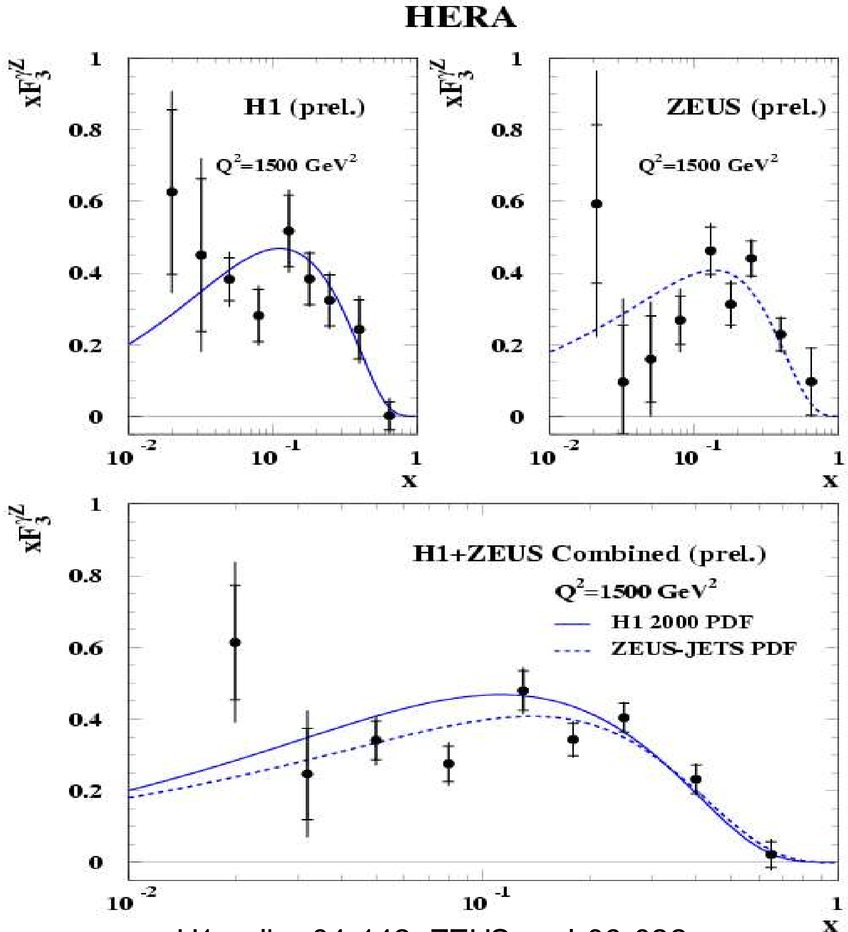
- **Dominated by u quark contribution**: larger charge and 2 u quarks

Measurements of F_3

- ZEUS and H1 have measured F_3, using latest HERA-II $e^{-}p$ data
- First combined H1/ZEUS measurement => overall 478.8pb^{-1}
- Measurement of u valence quark density



ZEUS-prel-06-001



H1prelim-04-142, ZEUS-prel-06-022

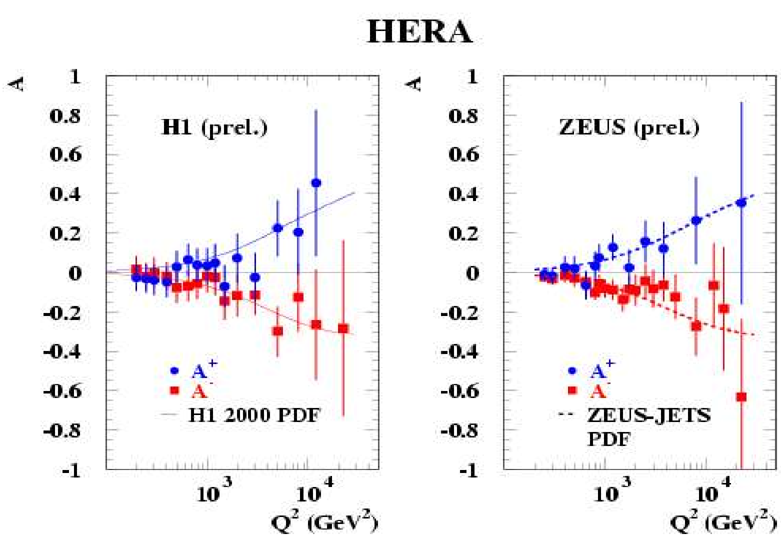
Polarized NC Measurements

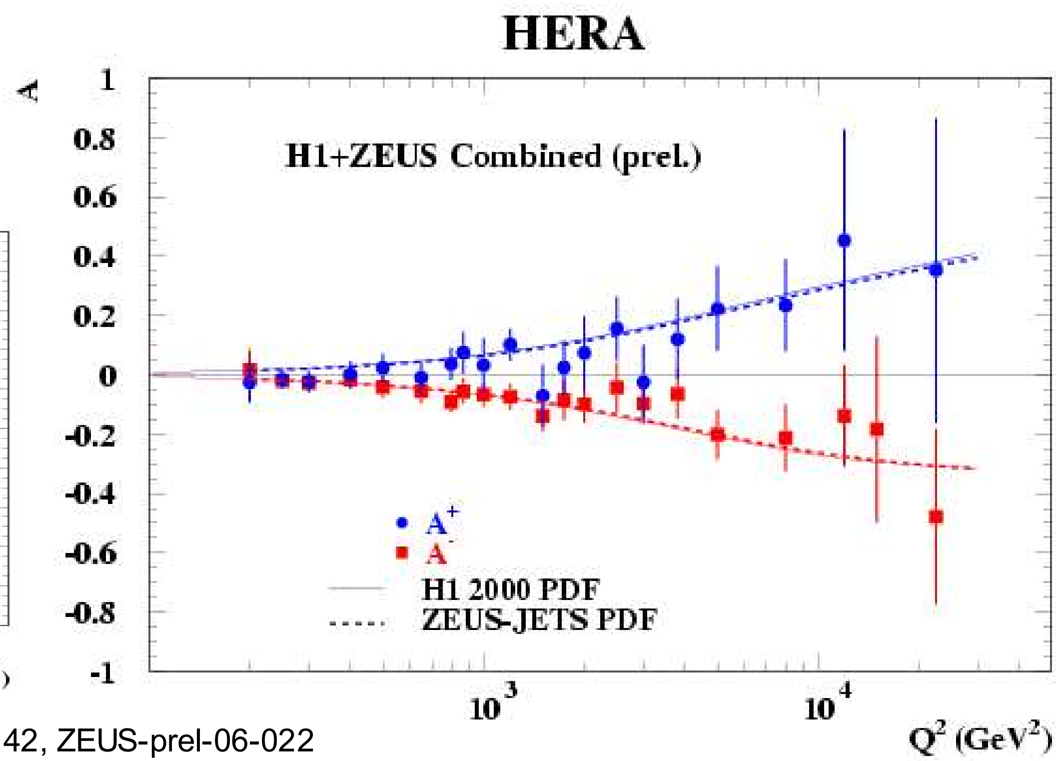
- F_2 and F_3 contain polarization dependent terms from γZ interference and Z exchange:

$$
\begin{aligned}
\tilde{F}_2 &= F_2 + \quad k(-v_e \mp P a_e) x F_2^{\gamma Z} + \quad k^2(v_e^2 + a_e^2 \pm P v_e a_e) x F_2^Z \\
x\tilde{F}_3 &= \qquad\quad k(-a_e \mp P v_e) x F_3^{\gamma Z} + \quad k^2(2 v_e a_e \pm P(v_e^2 + a_e^2)) x F_3^Z
\end{aligned}
$$

- Measure asymmetry between cross sections for left- and righthanded electron positron-proton cross sections:

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

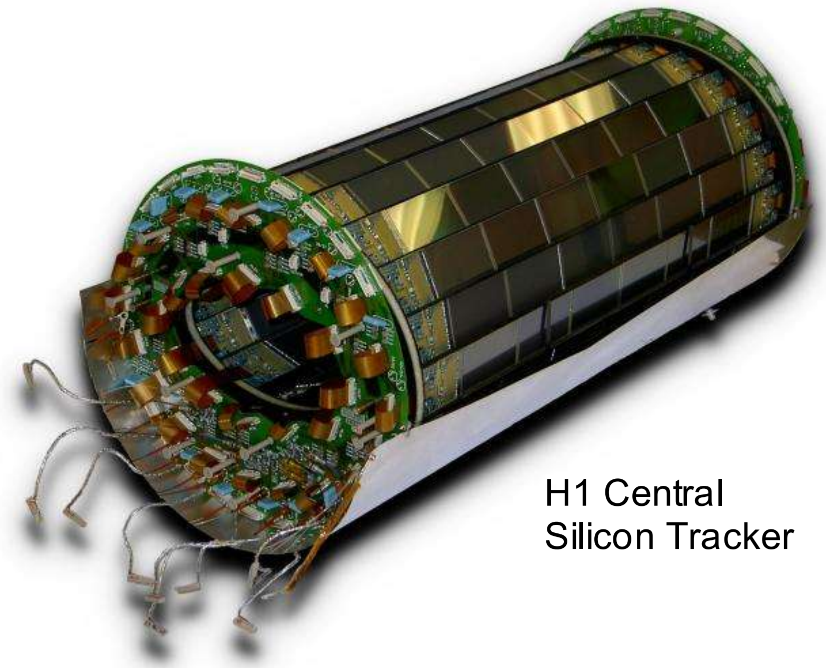




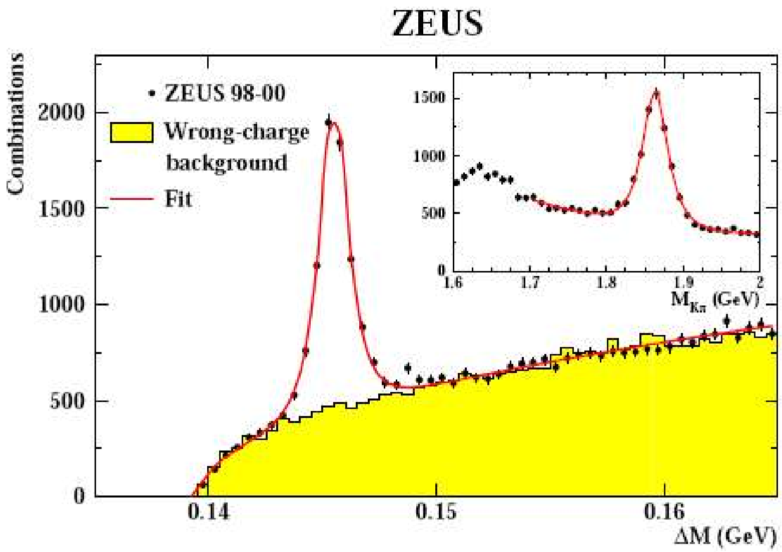
H1prelim-04-142, ZEUS-prel-06-022

Flavour-Exclusive Measurements

- Define structure functions $F_2^{c\bar{c}}$, $F_2^{b\bar{b}}$ for charm and beauty production
- Charm tagging: D* or lifetime tag; beauty: lifetime tag

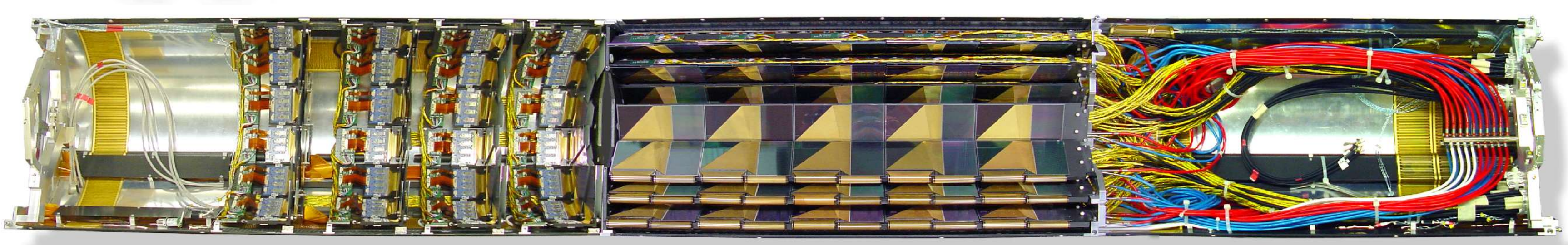


H1 Central
Silicon Tracker



ZEUS, PR **D69** (2004) 012004.

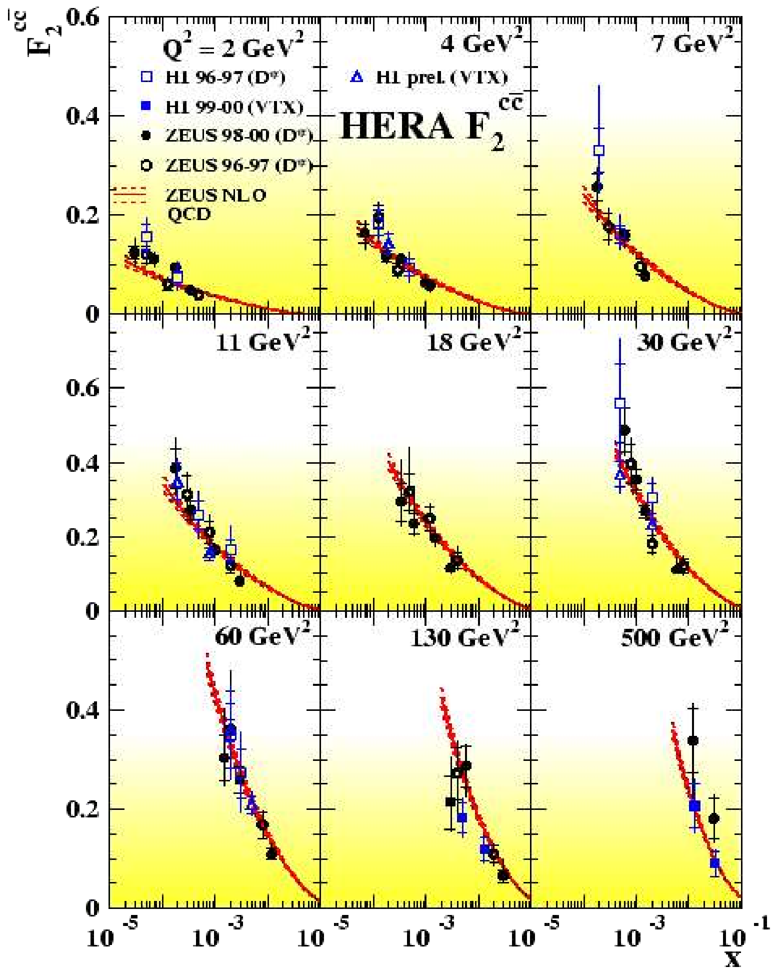
$D^* \rightarrow (K\pi)\,\pi_s$

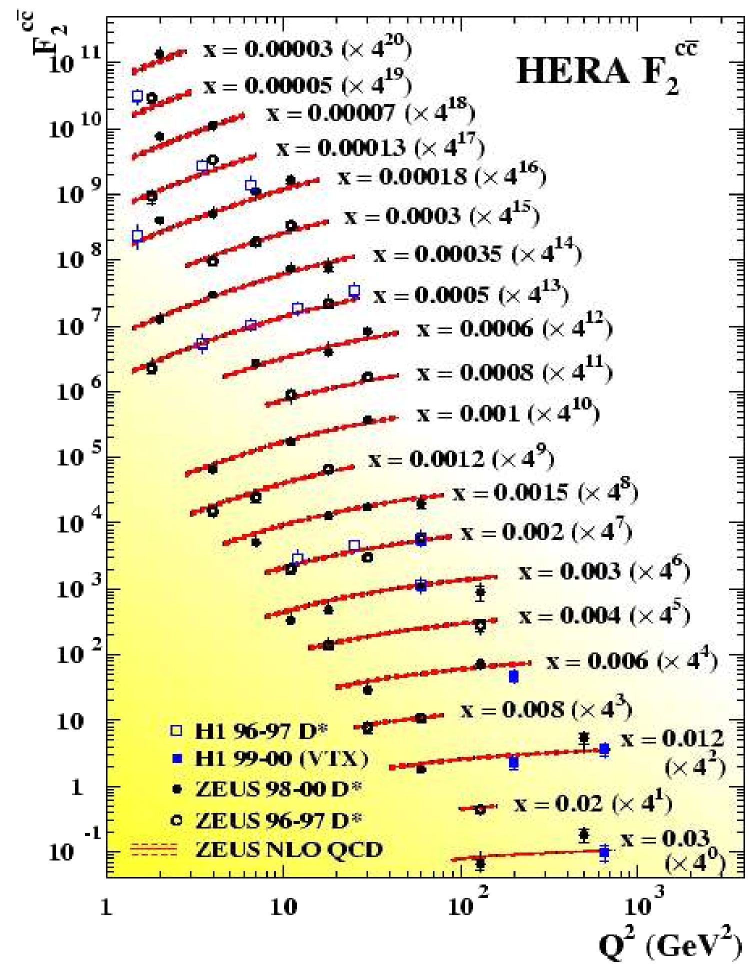


ZEUS BOTTOM MICRO VERTEX DETECTOR

Charm Contribution

- Charm well described by NLO QCD; at low Q^2: slight deviations
- Precise enough to constrain the gluon, but: theory uncertainties!

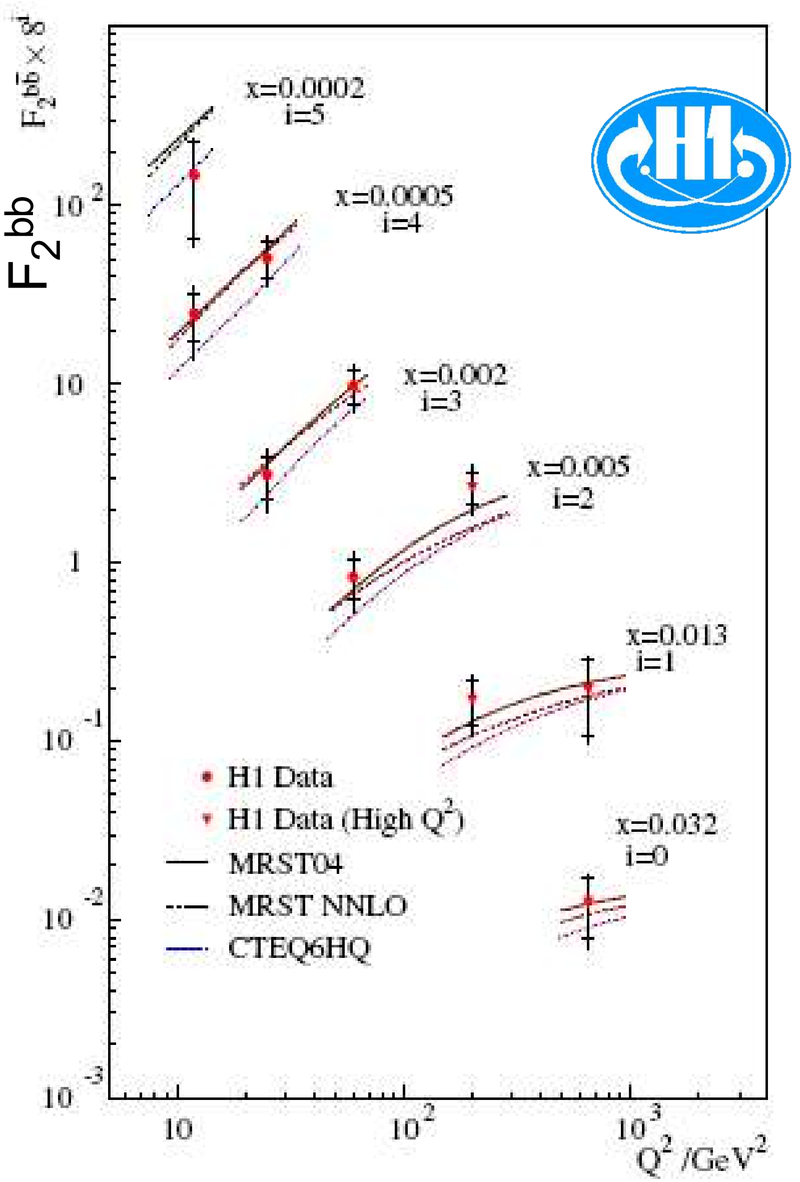




ZEUS, PR **D69**(2000)012004. H1, EPJ **C40** (2005) 349. H1, EPJ **C45** (2006) 23.

Beauty Contribution

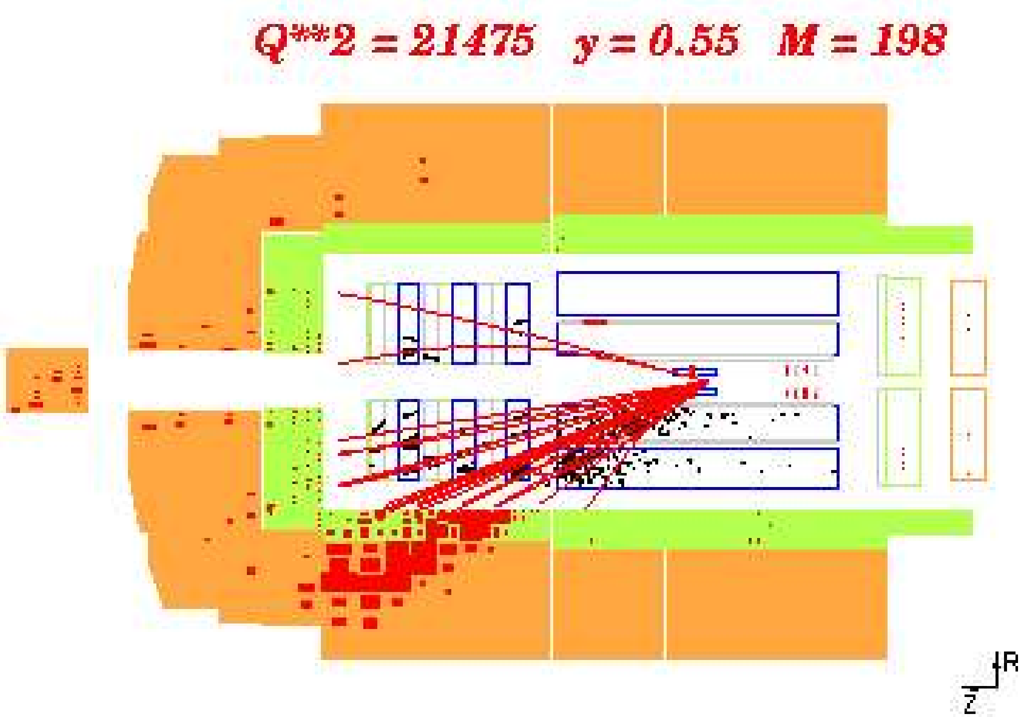
- H1 uses lifetime tagging to extract charm and beauty contribution to F_2 in one measurement
- Reasonably well described by NLO QCD
- NNLO calculations available! [Thorne hep-ph/0506251].
- More data to come from HERA-II

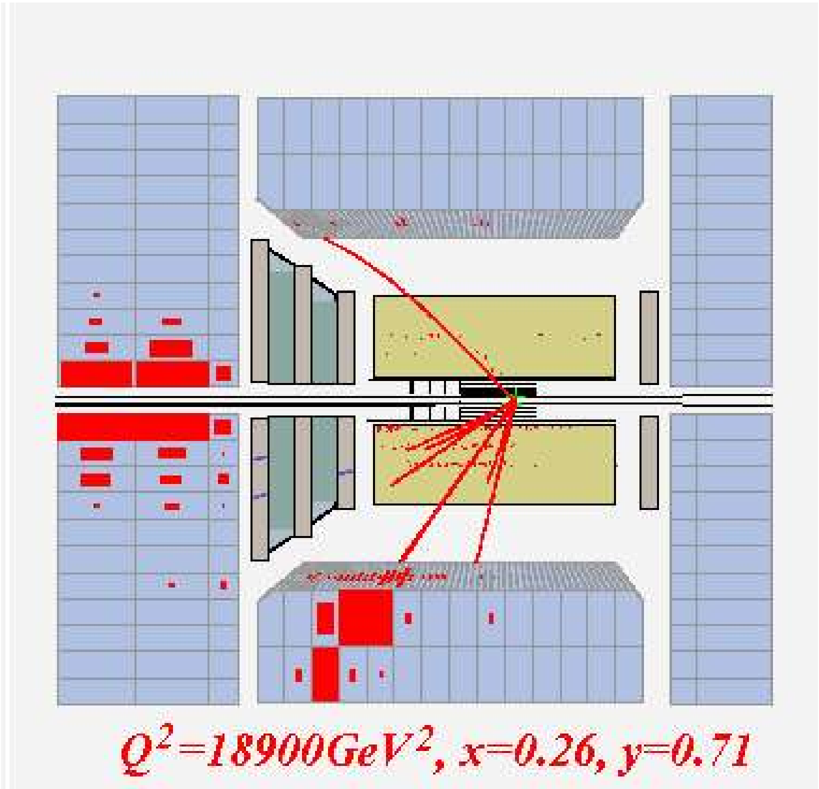


H1, EPJ **C40** (2005) 349. H1, EPJ **C45** (2006) 23.

Charge Current Interactions

- Neutrino escapes the detector
  => reconstruct event from hadronic final state
  => need excellent energy and spatial resolution

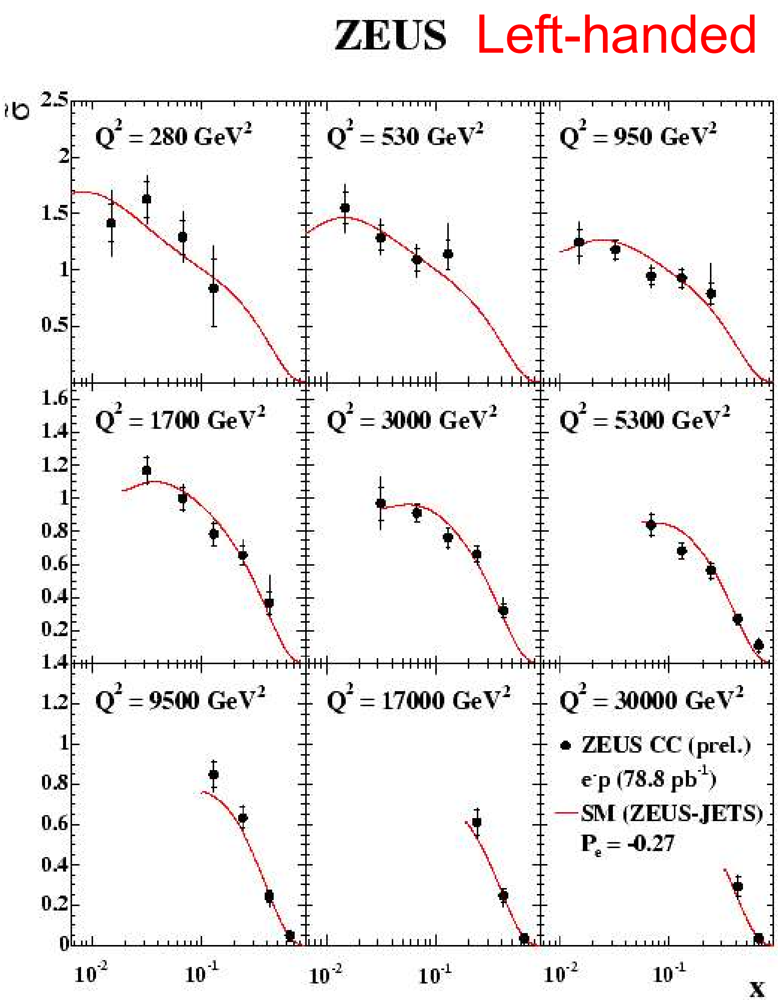


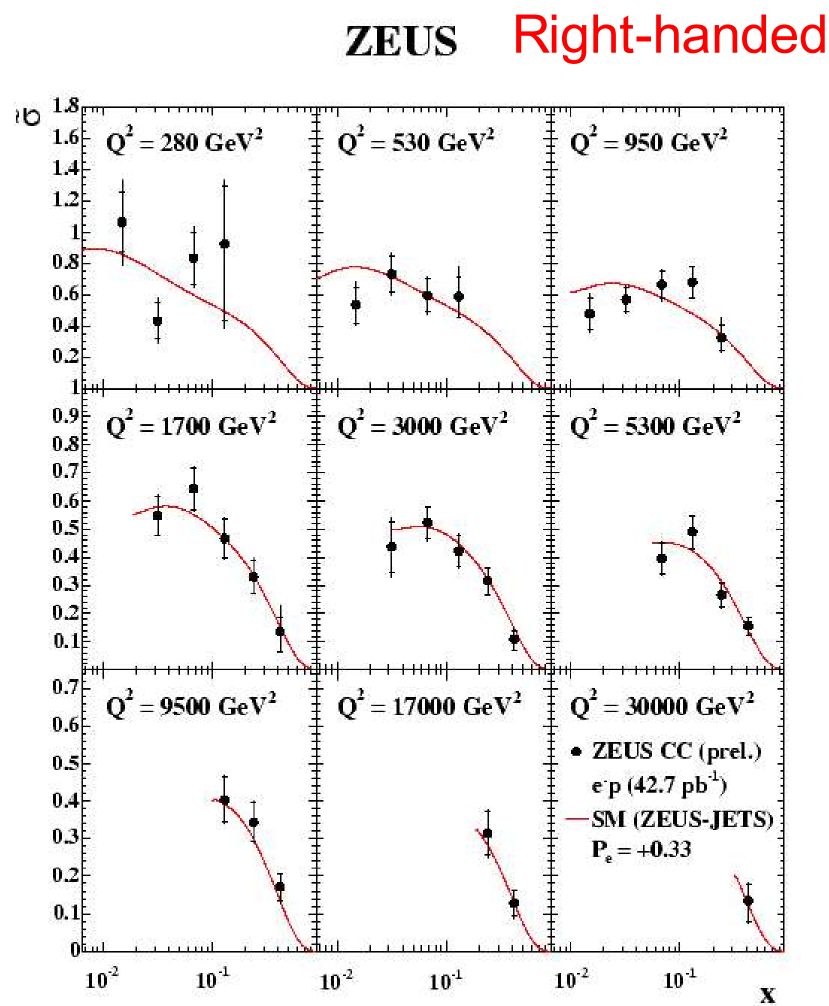


Double Differential Cross Sections

- Reduced cross section: $$\frac{d^2\sigma_{CC}(e^-p)}{dx\,dQ^2} = \frac{G_F^2}{4\pi x}\underbrace{(1-P_e)\left(Y_+ F_2^{CC} + Y_- xF_3^{CC}\right)}_{\tilde{\sigma}_r}$$

HERA-II Data

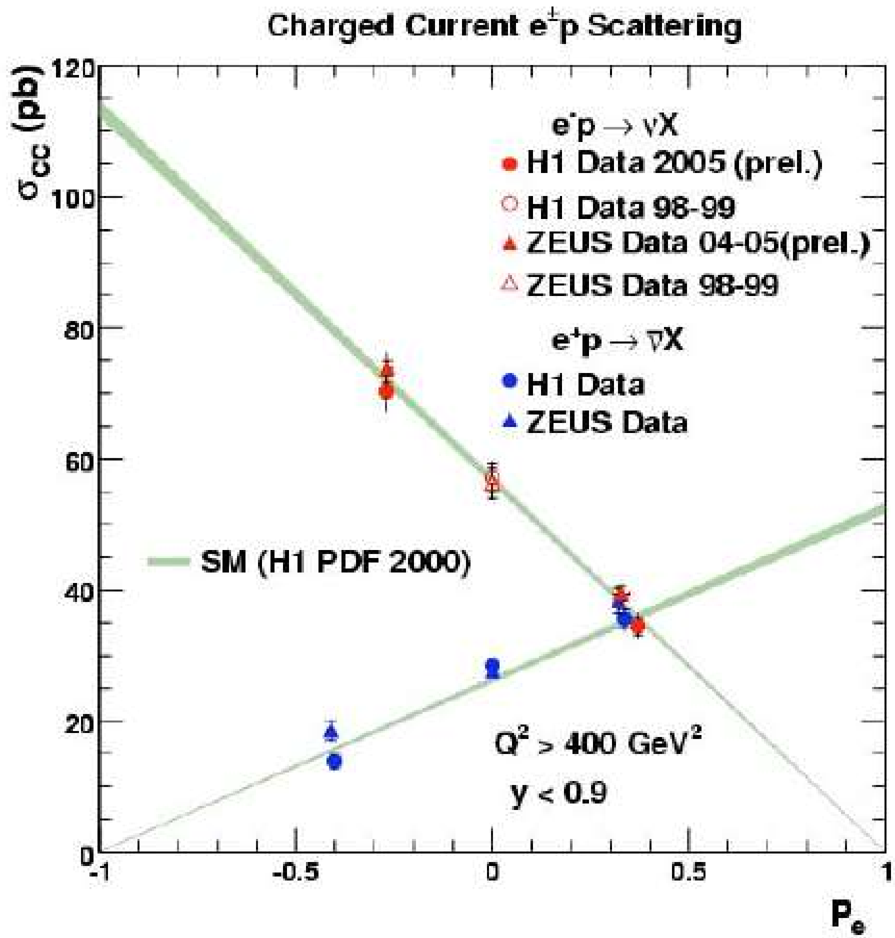


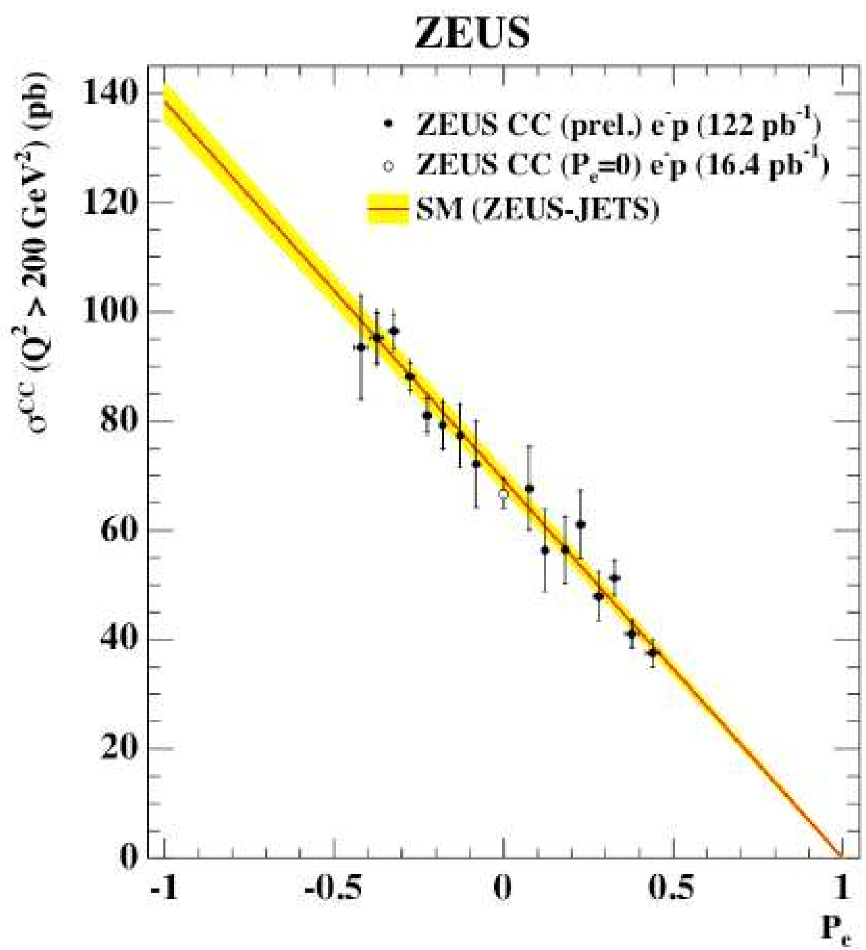


ZEUS-prel-06-002

Probing the Helicity Structure

- Integrated CC cross section proportional to $(1 \pm P_e)$:
  A textbook plot!

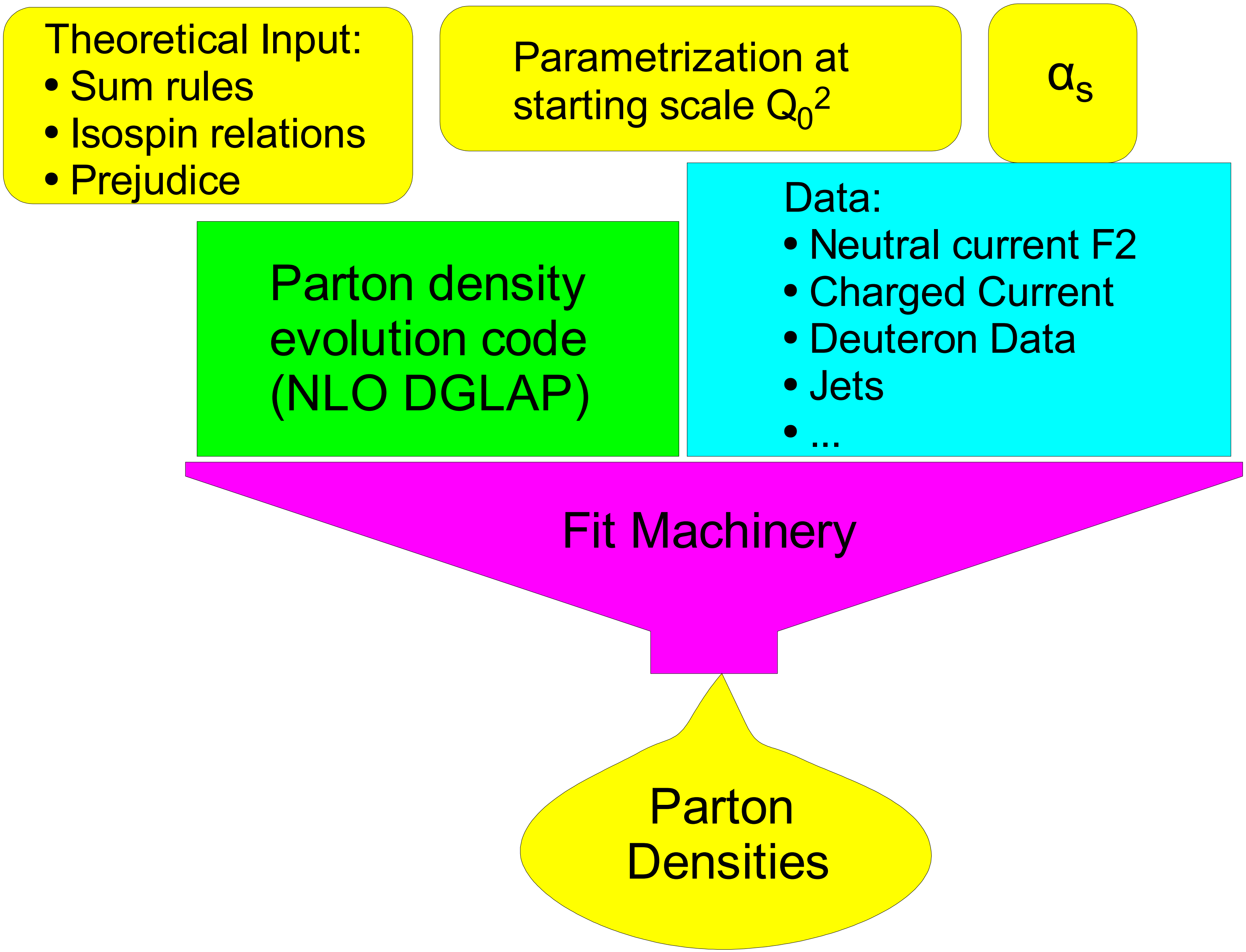




Structure Function Fits

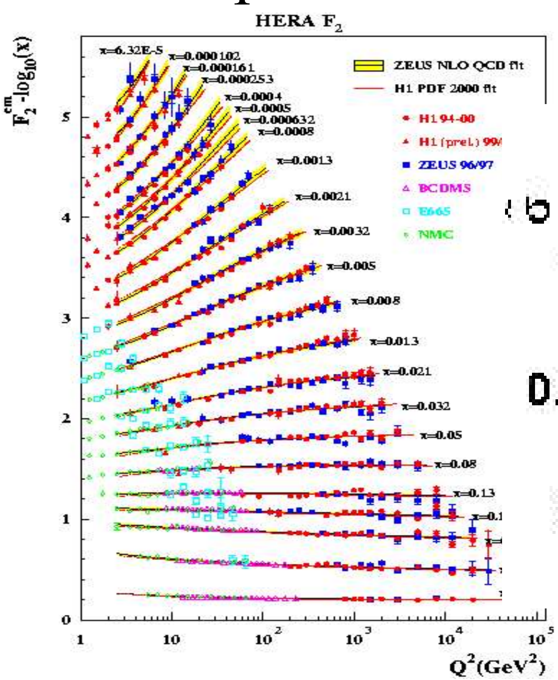
- Introduction
- Structure Function Measurements
- Structure Function Fits
  - Extraction of Parton Densities
  - Extraction of α_s
- Summary and Outlook

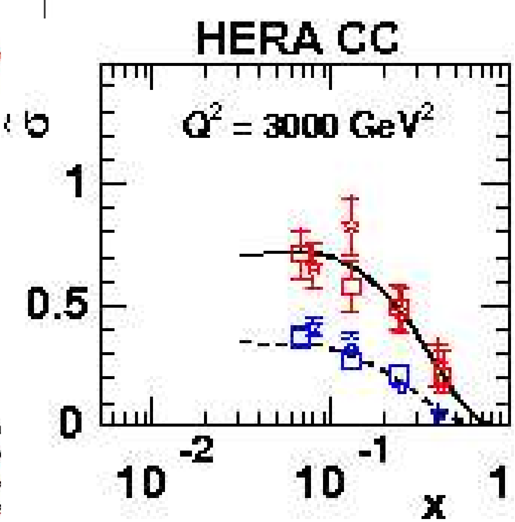
Fitting Parton Densities

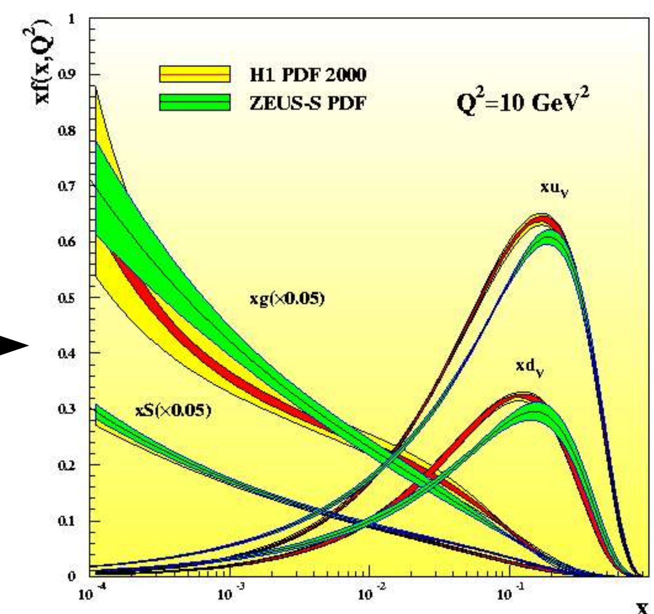


Extraction of Parton Densities

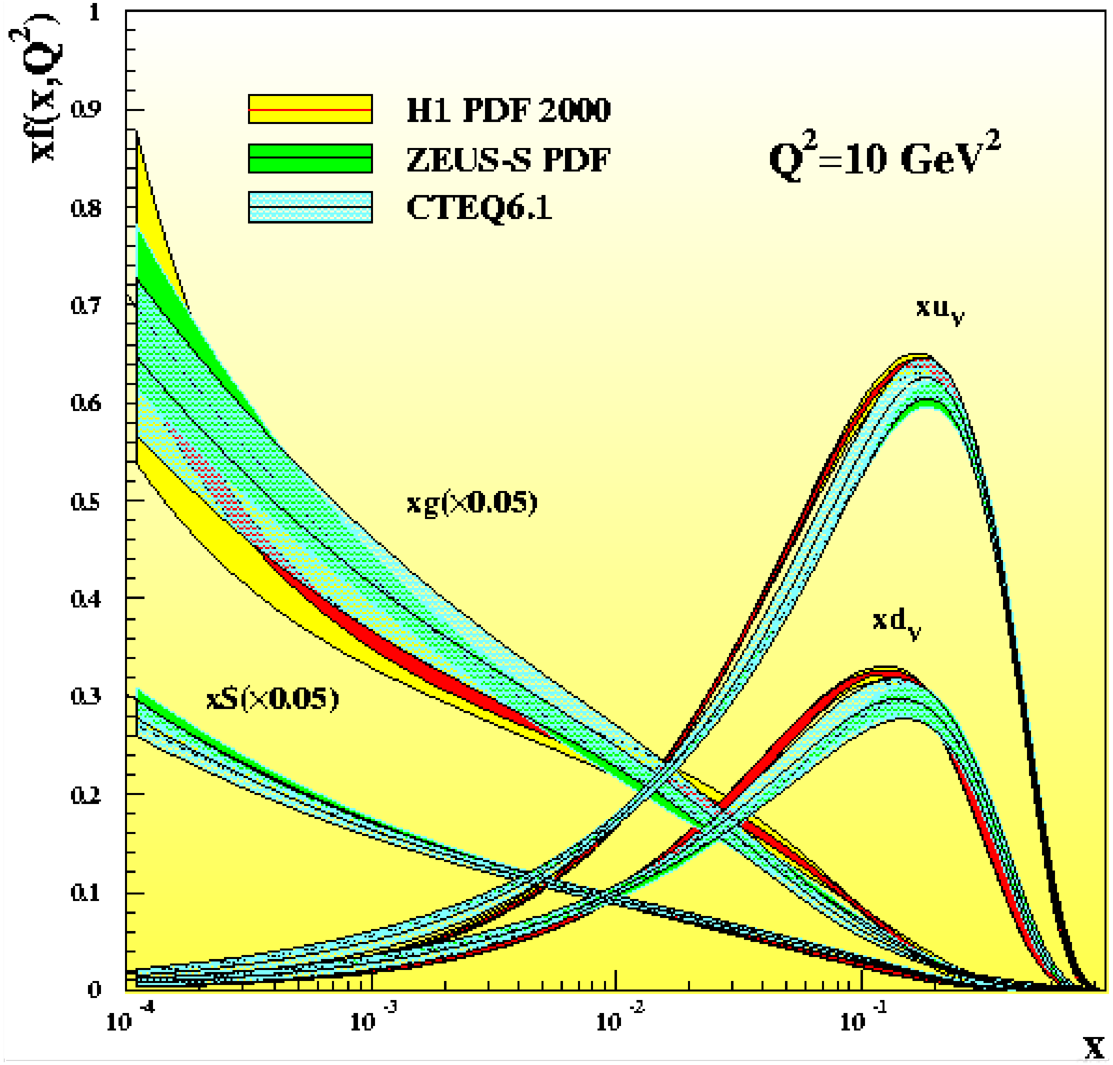
- Analyses by H1 [EPJ C30(2003)1] and ZEUS [PR D67(2003)012007]:
  - Use F_2 data from own experiment
  - Plus CC data (constraints on u, d at high x)
  - Plus fixed target data (ZEUS only)
- Similar results, but significant differences: are the parametrizations general enough?







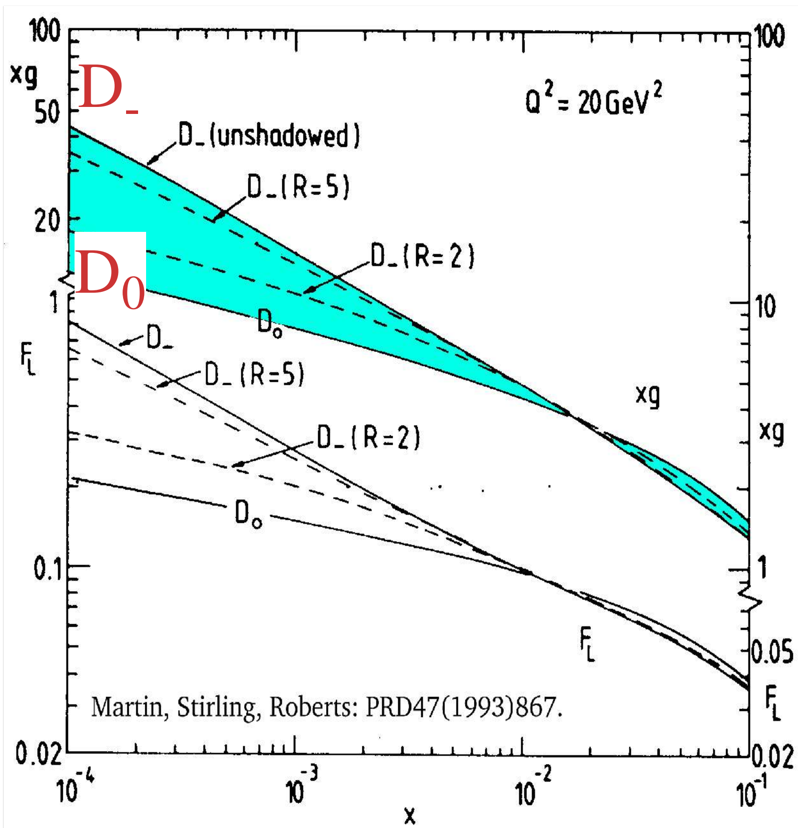
Parton Densities

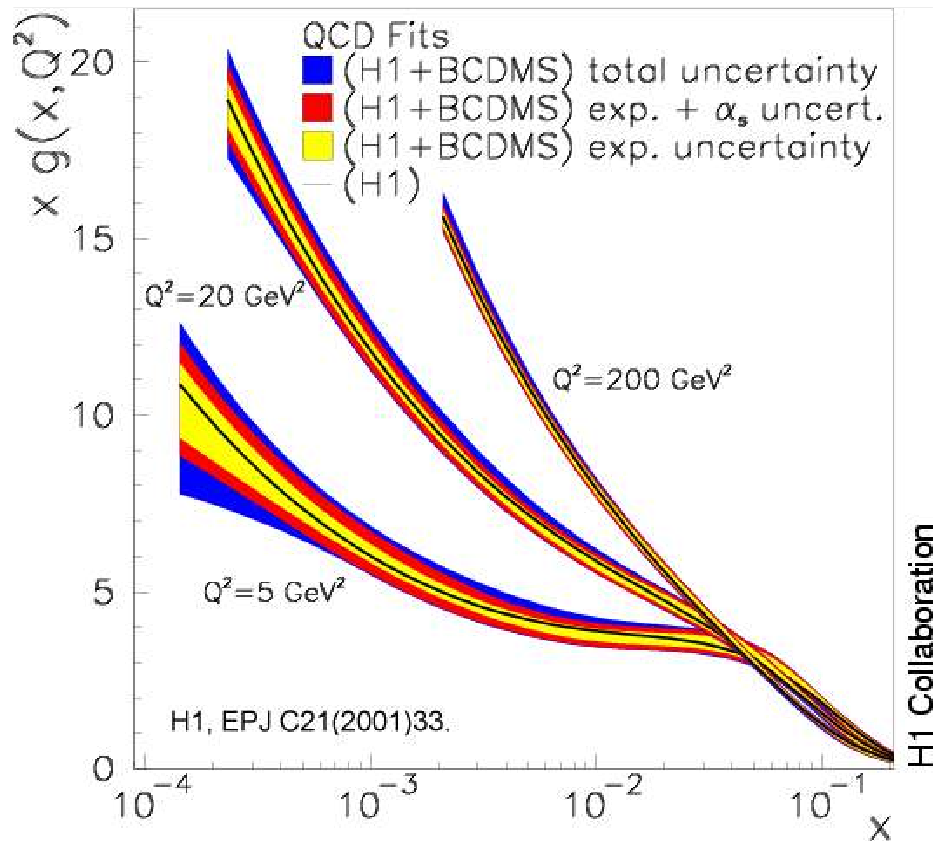


- Qualitative Agreement H1-ZEUS
- Differences due to different methods and data sets

Note: sea quark density *S* and gluon density *g* scaled down by faktor 20!

Gluon Densities before/after HERA



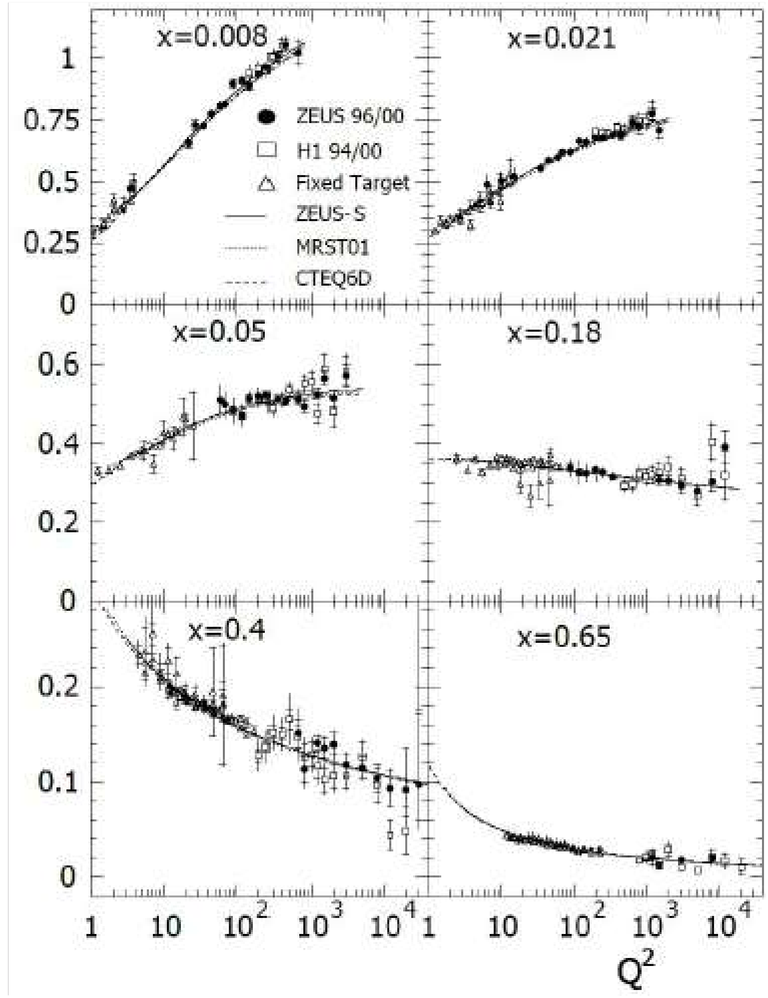


1993: Uncertainty factor 3 at $x=2\cdot10^{-4}$, $Q^2=20\mathrm{GeV}^2$ (theoretical estimate only!)

2001: ±5% uncertainty, based on measurement!

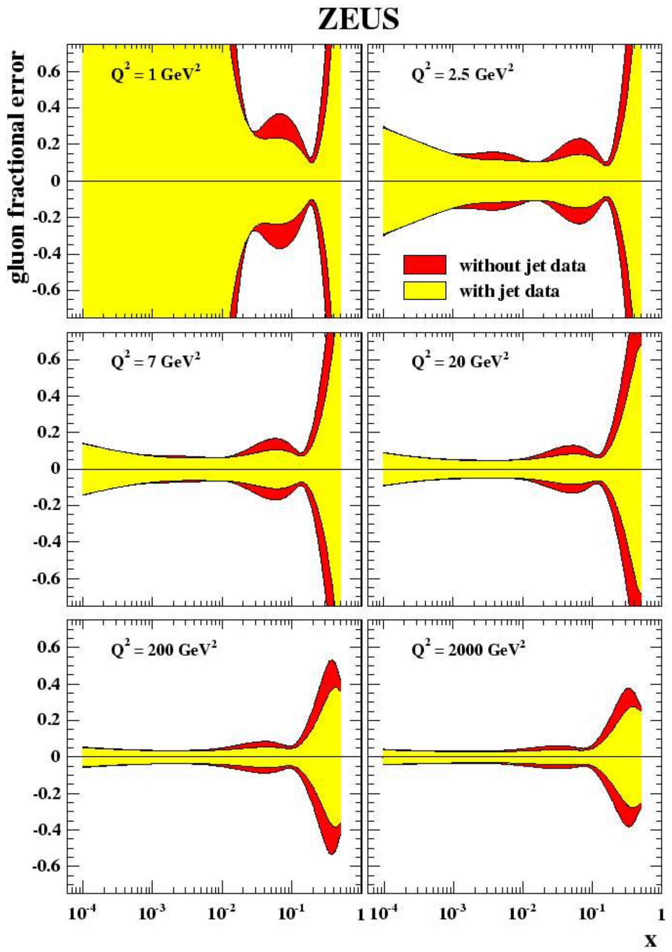
A Success for DGLAP

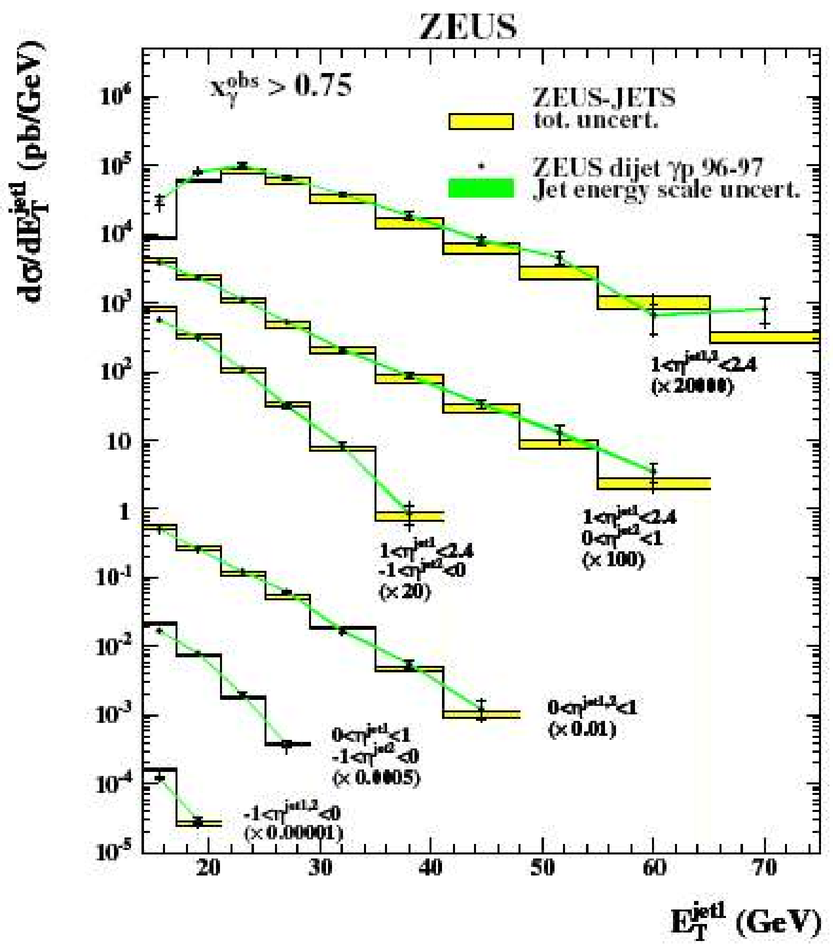
- Together with fixed target data: Test of scaling violations over 4 orders of magnitude in Q^2 at fixed x
- NLO-QCD fits based on DGLAP-evolution describe data very well
- No obvious deviations from "Standard Model of Parton Densities"



Adding Jet Data

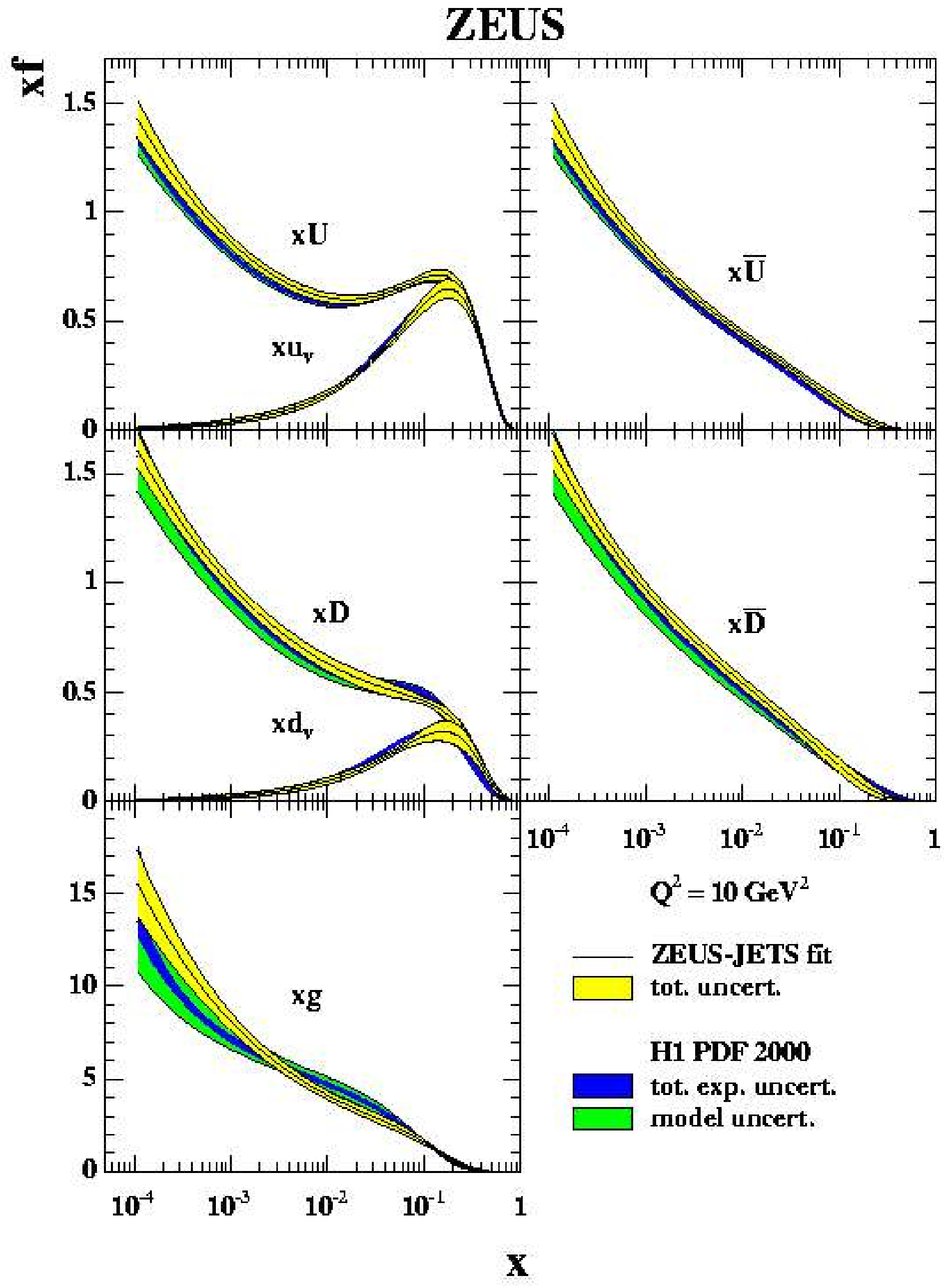
- New ZEUS analysis [EPJ **C42**(2005)1]:
- Add DIS and γp dijet data (direct photoproduction): adds to knowledge of gluon density at large *x*





ZEUS-Jets vs. H1-2000

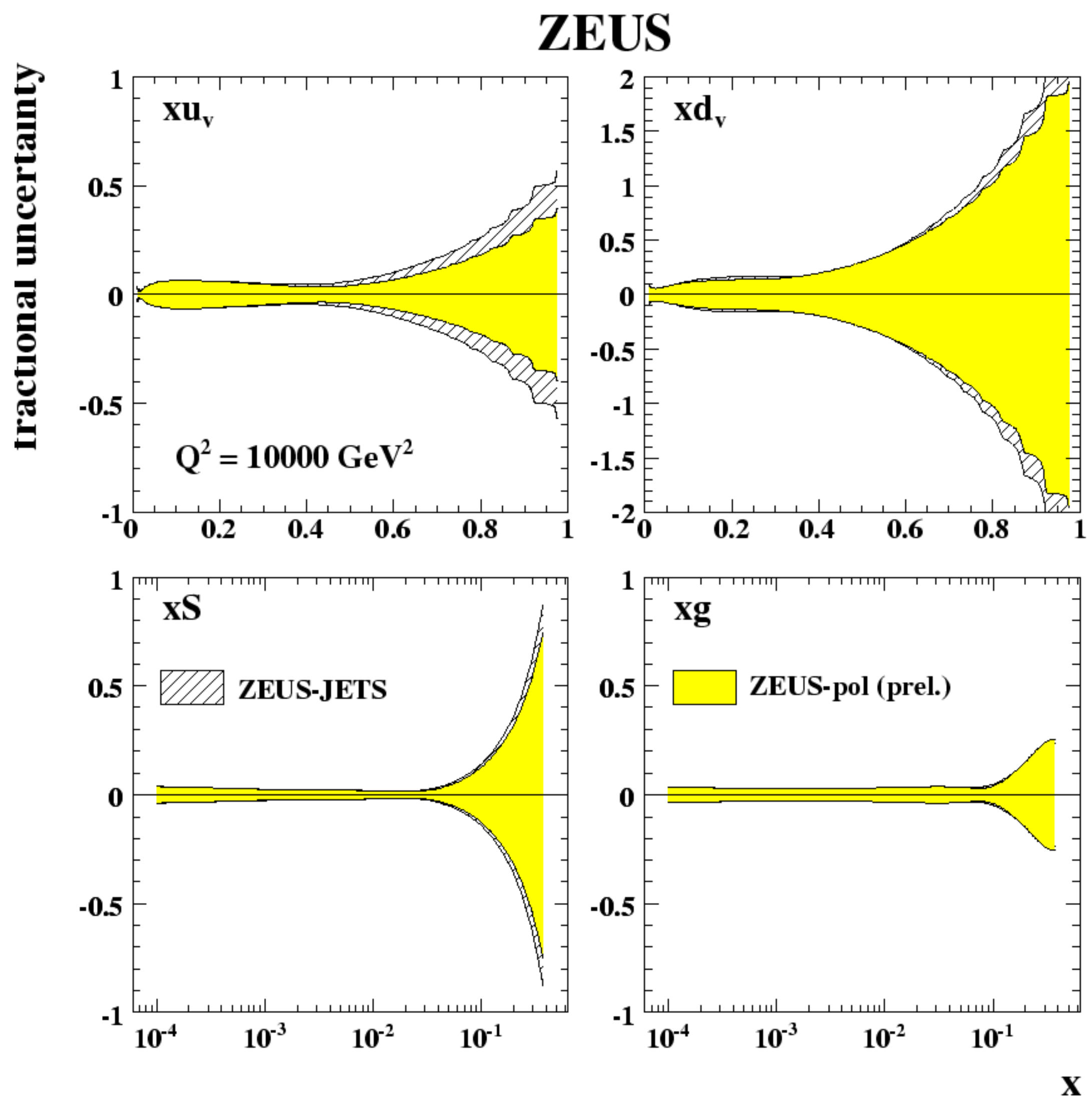
- After inclusion of Jets data by ZEUS, H1 and ZEUS pdf fits agree well
- Still differences for gluon



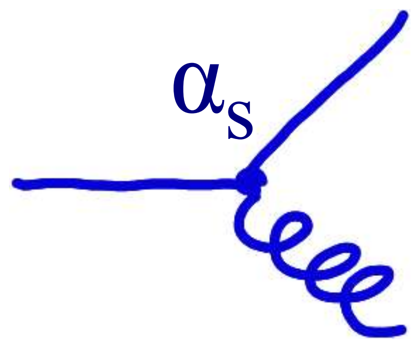
Using Polarized Data

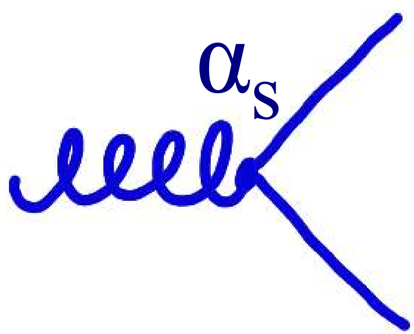
- Preliminary ZEUS result (ZEUS-prel-006-03):
- Polarized HERA-II data improves valence quark uncertainty at large *x*
- Central values unchanged compared to ZEUS-Jets fit

Q^2=10000GeV^2



Extraction of α_s





Scaling violations:

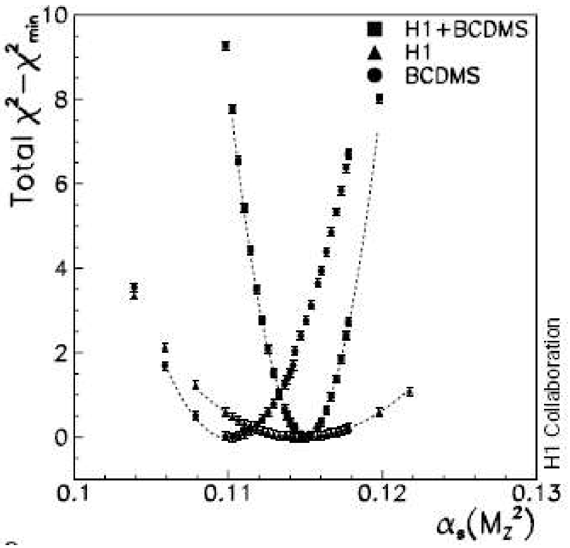
- Proportional to α_s and gluon density
- At large x: Gluon radiation off quarks dominates, $\partial F_2/\partial \ln Q^2$ allows measurement of α_s
- *Gluon Splitting* damps scaling violations from gluon radiation
  => Reliable determination of α_s from DIS needs very good understanding of gluon densities over a wide x range

α_s from Structure Function Fits

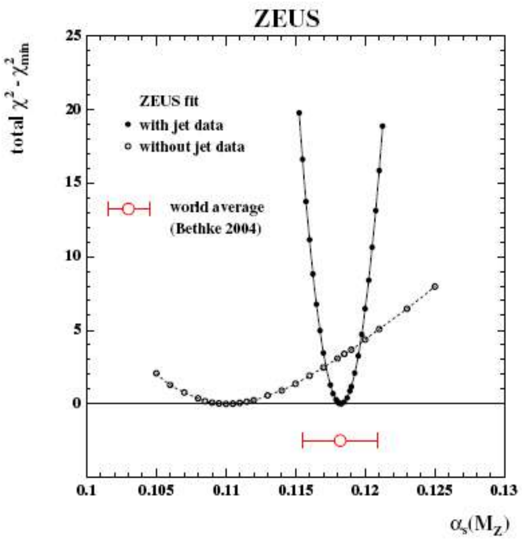
- H1: Combine with fixed target data (BCDMS) to pin down scaling violations at large/medium x (disentangle gluon density and α_s)
  => $\alpha_s(M_Z)=0.1150\pm0.0017\,{}^{+0.0009}_{-0.0005}$
  exp. *model*

- ZEUS: Jet data make external input unnecessary
  => $\alpha_s(M_Z)=0.1183\pm0.0007\pm0.0022\pm0.0016\pm0.0008$
  uncorr. *corr.* *norm.* *model*

- *Theory uncertainty:* ±0.005 (**dominates**)



H1, EPC **C21** (2001) 33.



ZEUS, EPJ **C42**(2005)1

Summary and Outlook

- Introduction
- Structure Function Measurements
- Structure Function Fits
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Summary

- HERA-II is running well, producing lots of new data:
  - 10-fold increase of e^-p data set
  - polarized ep scattering data
- High-precision F2 data over a large range of x and Q^2
- Polarized Charged Current Data test helicity structure of W exchange
- F3 measurements become significant:
  Combination of ZEUS and H1 data has started
- Flavour-exclusive measurements for charm and beauty available
- Polarization effects in Neutral Current data become visible
- α_s measurements compatible and competitive with world average, profit from understanding of gluon at high x

Outlook

- More data coming in: 3-fold increase of e^+p data set possible
- Data analysis of final e^-p data set to come
- Low energy run in summer 2007: a real F_L measurement
- Parton density determination can still be improved:
  - NNLO evolution
  - Improved data and theory: include charm and beauty data in fits

HERA data analysis will deliver interesting results for many years!