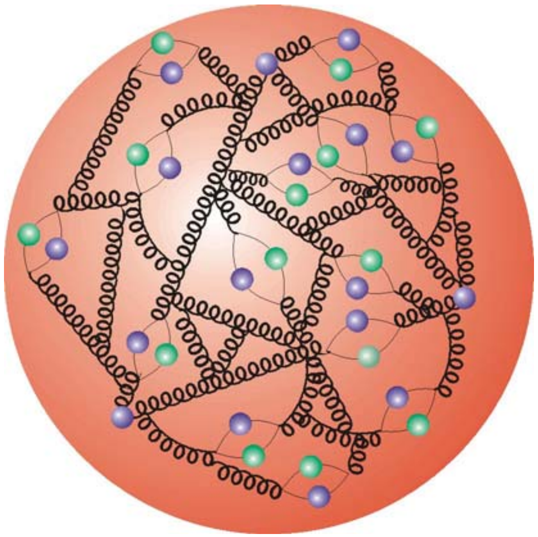
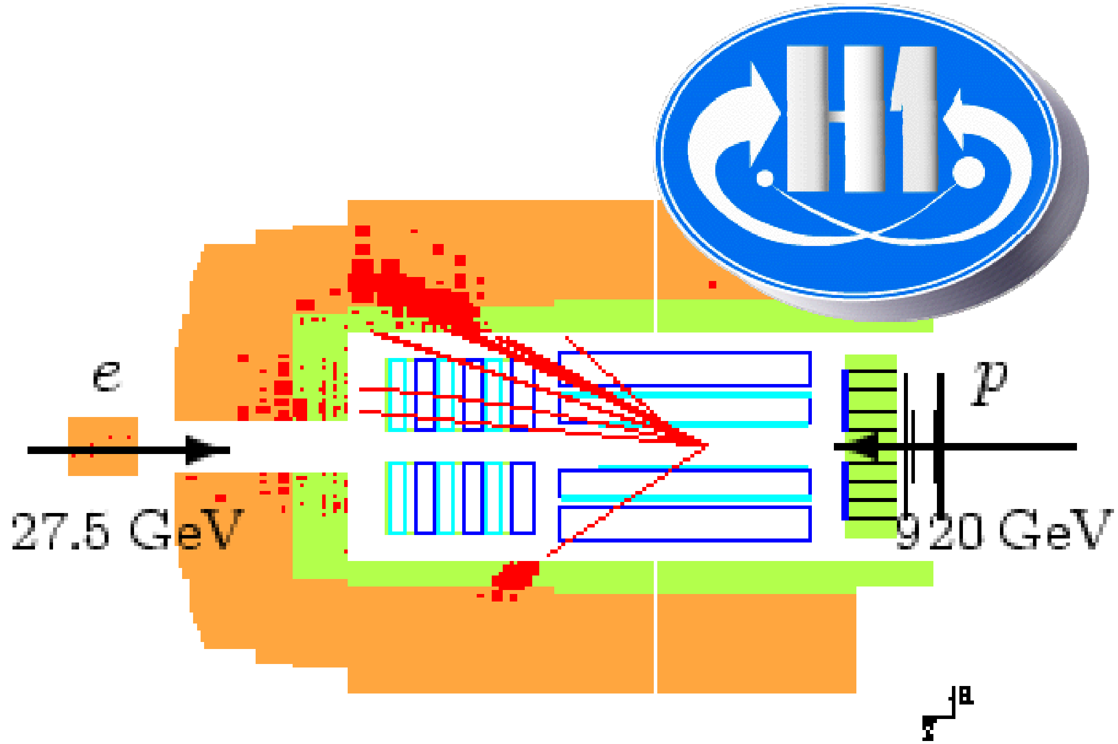
What is a Proton?

P.Newman (Birmingham colloquium 6 / 12 / 06),





Thanks to many H1 and other colleagues, in particular J. Dowell, F. Eisele, E. Eisenhandler, V. Hudgson, I. Kenyon, D. Sankey, P. Thompson, A. Watson, E. Woehrling

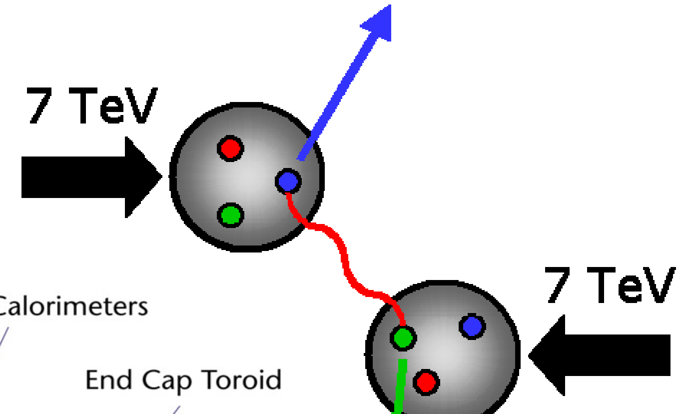
Contents

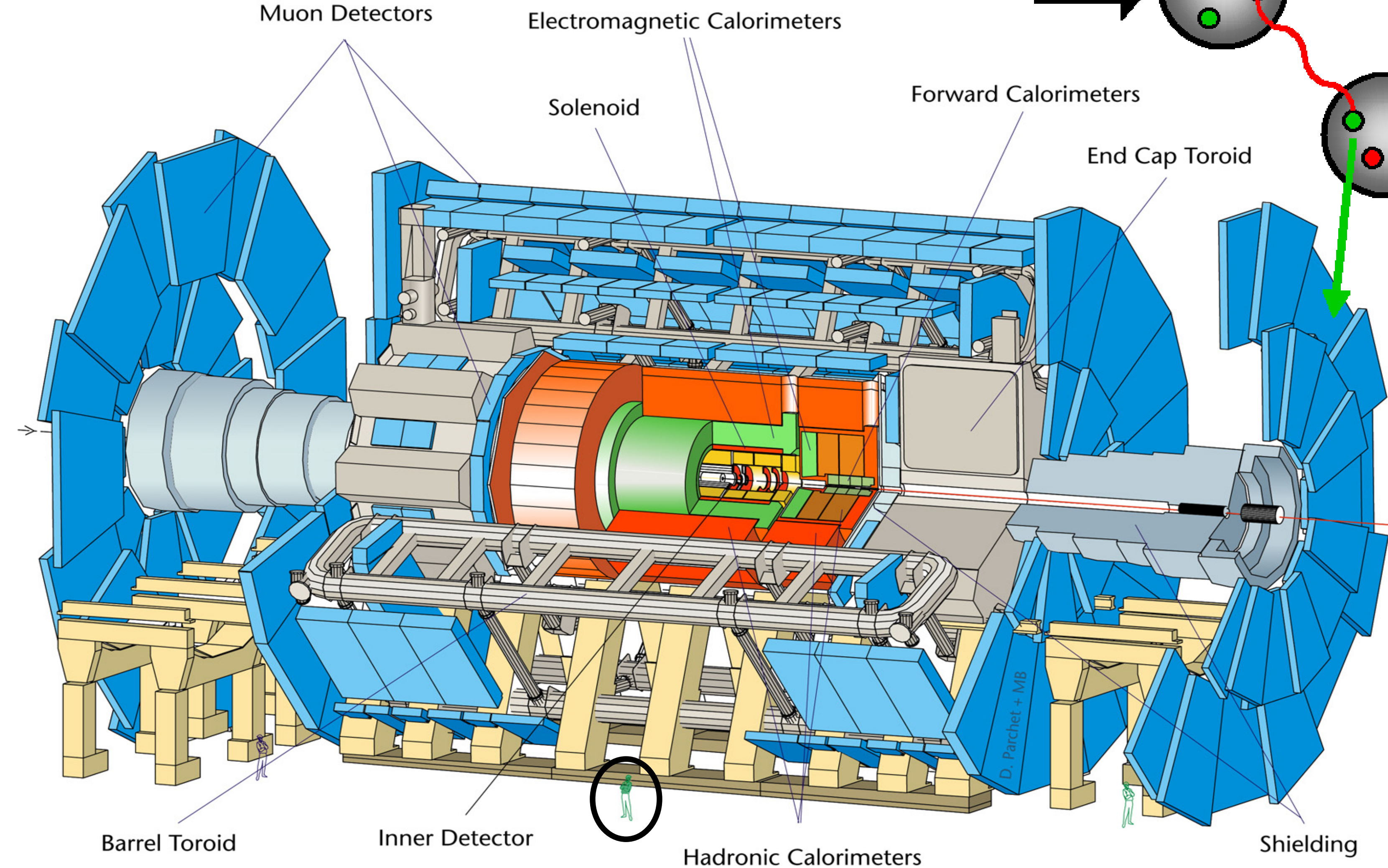
- **From the LHC to HERA**
  - What is a Proton?
  - Why Deep Inelastic Scattering?
  - HERA
  - H1
  - How we know what we know a proton is

- **… and back to the LHC**
  - Impact of HERA results
  - A possible future for DIS?


The LHC … where all good HEP talks start
LHC tunnel
(50-100m underground)
The LHC
ATLAS site
Proton-proton collisions at ultra-high energy (E_{CMS} = 14 TeV) and luminosity (10^{34} cm^{-2} s^{-1})
CERN main site

The ATLAS Experiment

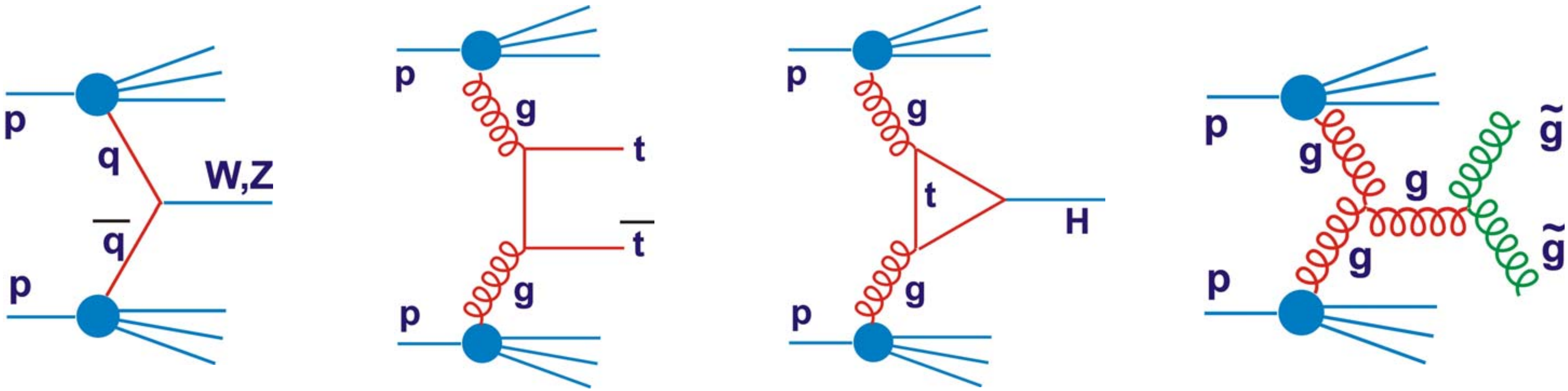




... twice size of the Poynting building!

See recent talks by e.g.
D. Charlton, P.Watkins

Some Physics at the LHC

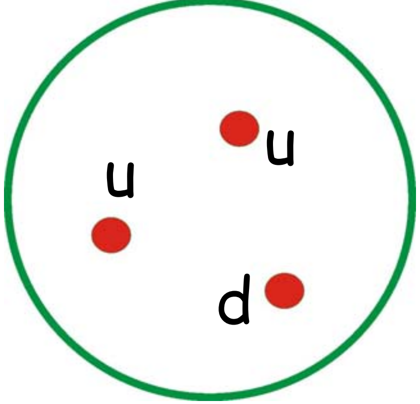


EW SM   Top   Higgs   Exotics

... all initiated by quarks and gluons in the proton ...
... but what are they and how do we know?

Tiny cross sections on huge backgrounds ...
...unless we understand the initial state, it will be very hard to unravel the exciting final states!

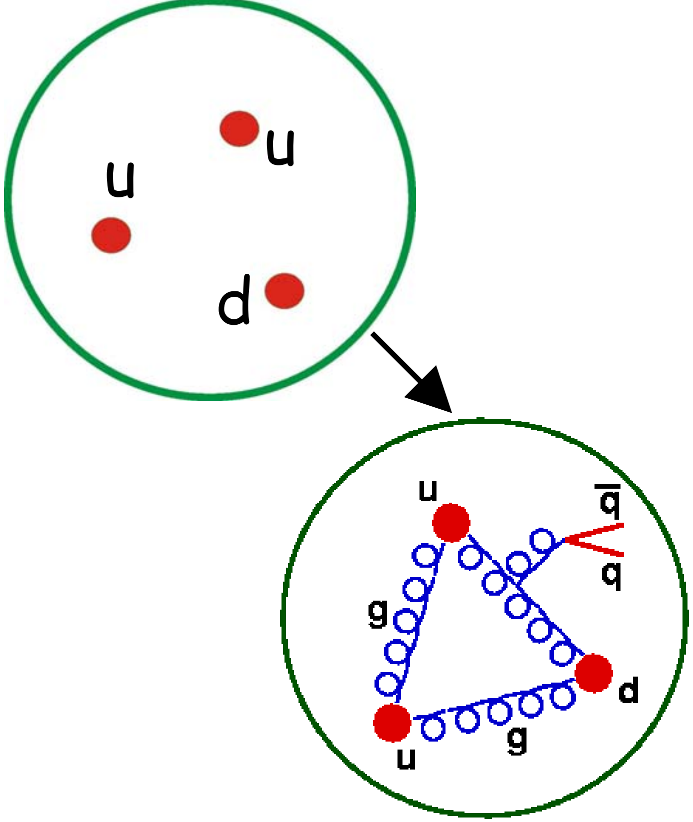
So What is a Proton?…



- 2 up and 1 down **valence quarks**, silly!

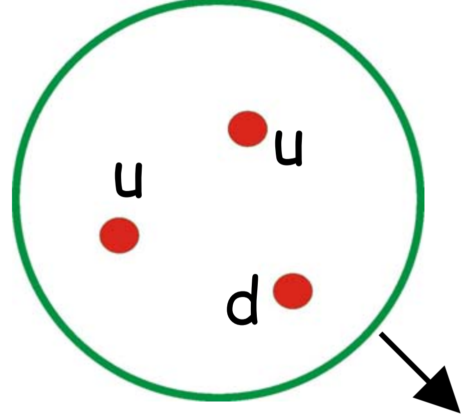
So What is a Proton?...

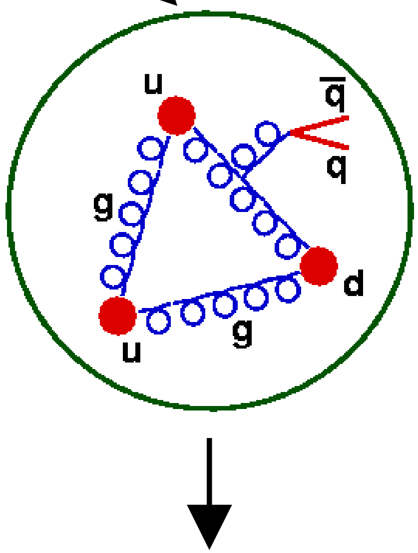
- 2 up and 1 down **valence quarks**, silly!
- ... and some **gluons**
- ... and some **sea quarks**

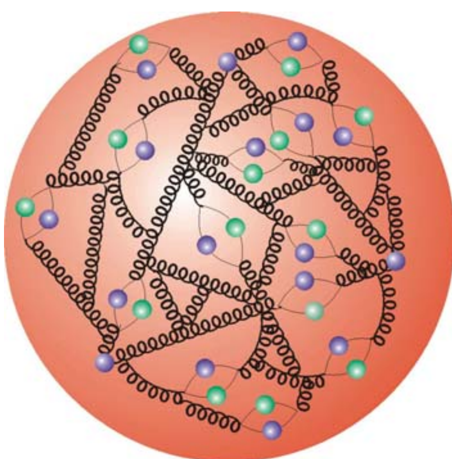


So What is a Proton?...

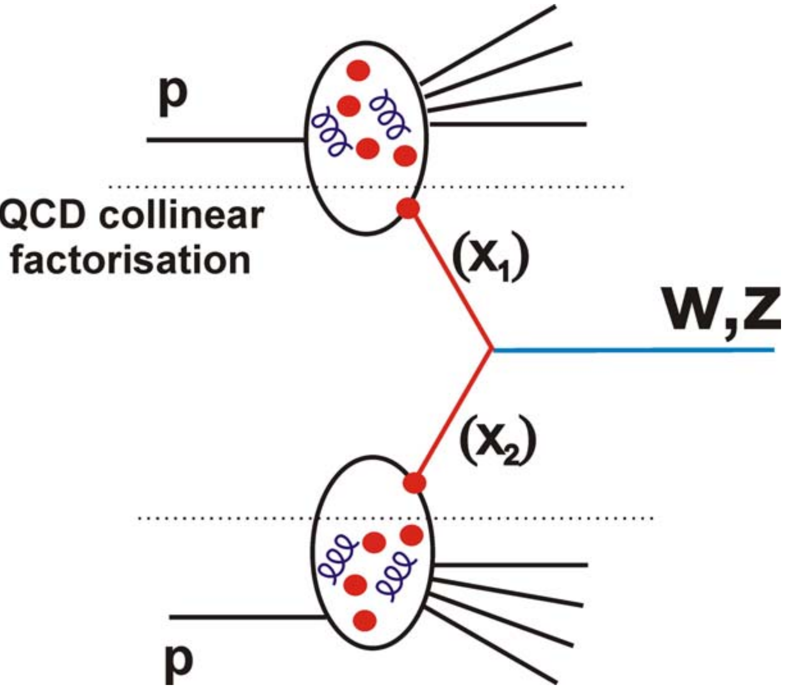
- 2 up and 1 down **valence quarks**, silly!
- ... and some **gluons**
- ... and some **sea quarks**
- ... and more gluons and more sea quarks
- ... and even more gluons and sea quarks ...
- The strong interaction consequences of a basic uud structure are rich and complex!...
- We can't solve QCD ...
but we know some things about it!







Factorising away the Unknown



- **QCD factorisation theorem** allows us to define universal parton density functions (PDFs), same for proton in all contexts.

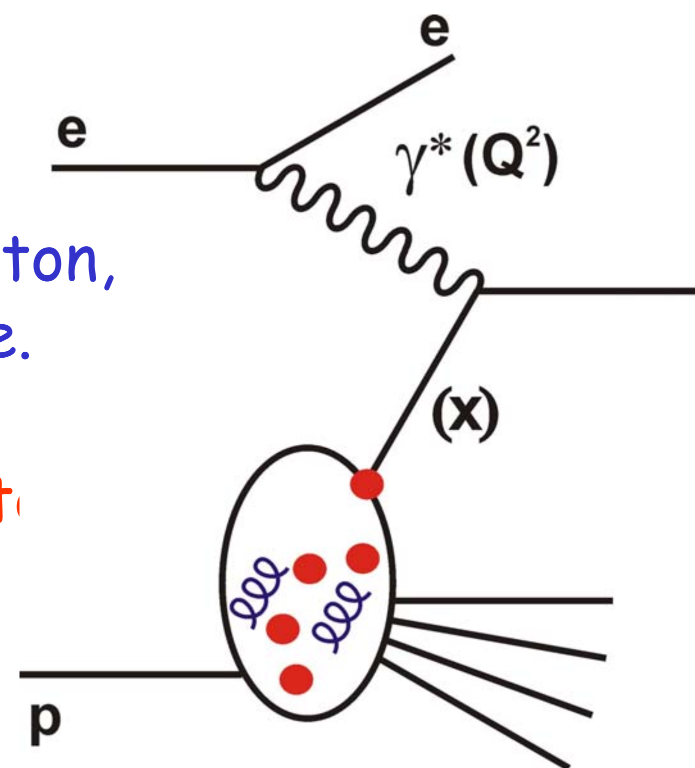
- **QCD evolution (`DGLAP' approx^n)** tells us how the partons evolve as scale (e.g. mass produced) changes.

We cannot calculate PDFs (maybe one day on lattice)
… so we have to determine the PDFs experimentally

Parton Densities from Experiment… DIS

"You don't find out how a watch works by throwing other watches at it!"

Most precise measurements come from **`Deep inelastic lepton-nucleon Scattering'** …
Point-like probe, which doesn't feel strong colour field … a `snapshot' of proton, mainly via photon exchange.



x = Momentum fraction of struck part

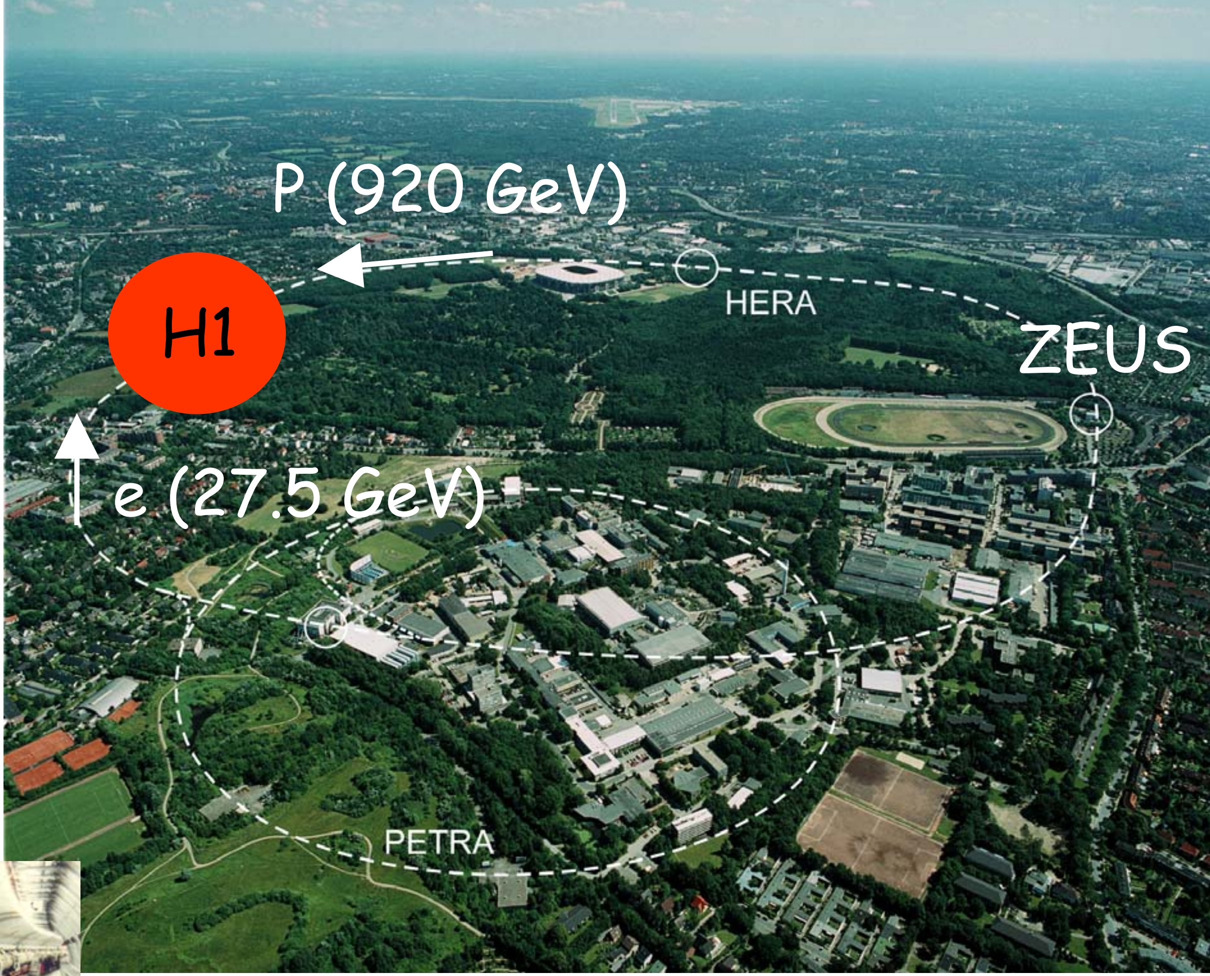
Q^2 = Exchanged boson virtuality … scale or resolving power!

HERA

- From Geneva to Hamburg …

- The world's only ever ep Collider

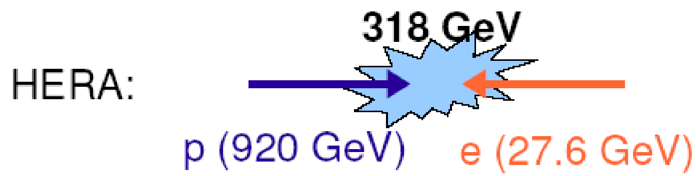
- Fixed target equiv. energy of 50TeV



"World's most powerful microscope"

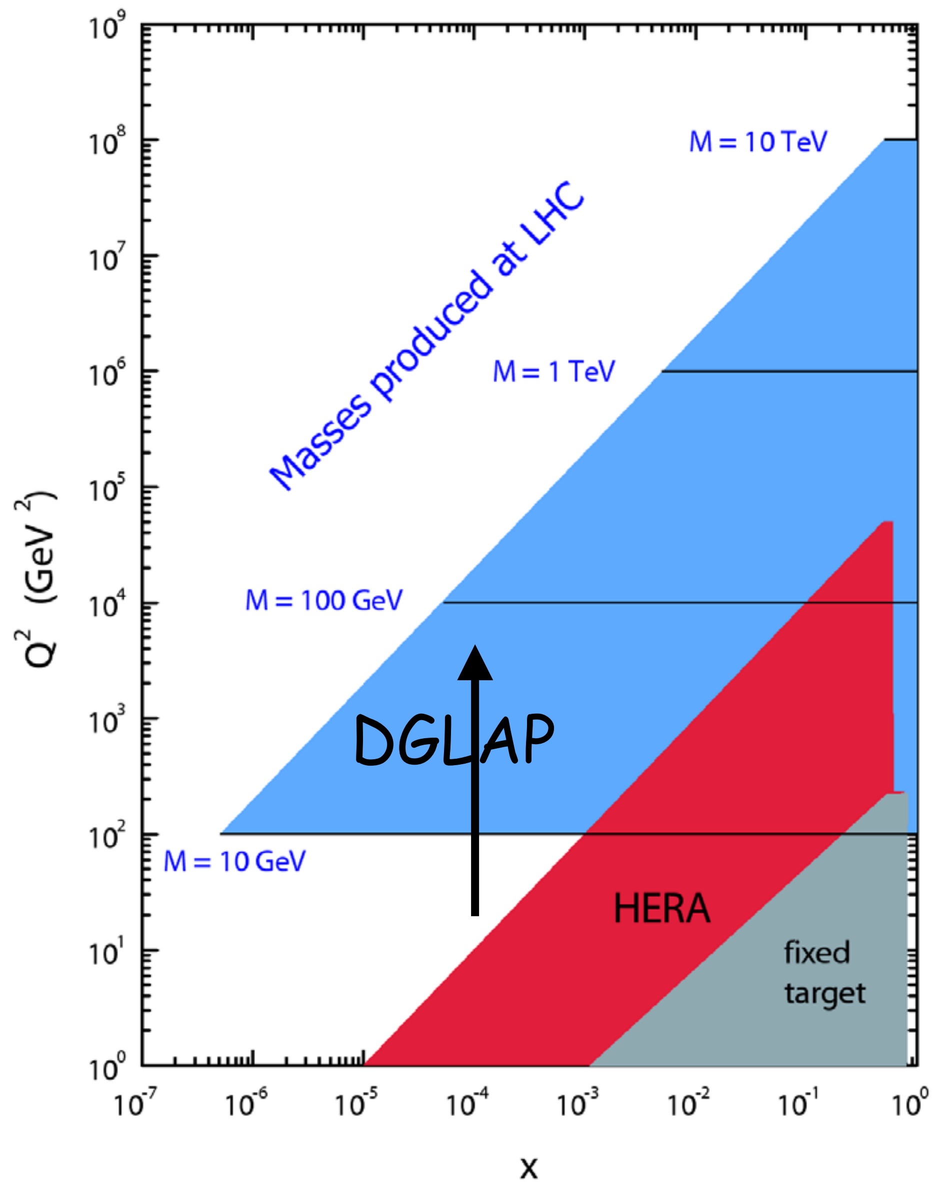
Operational 1992-2007

HERA … kinematic range



• Unprecedented low x and high Q^2 kinematic coverage

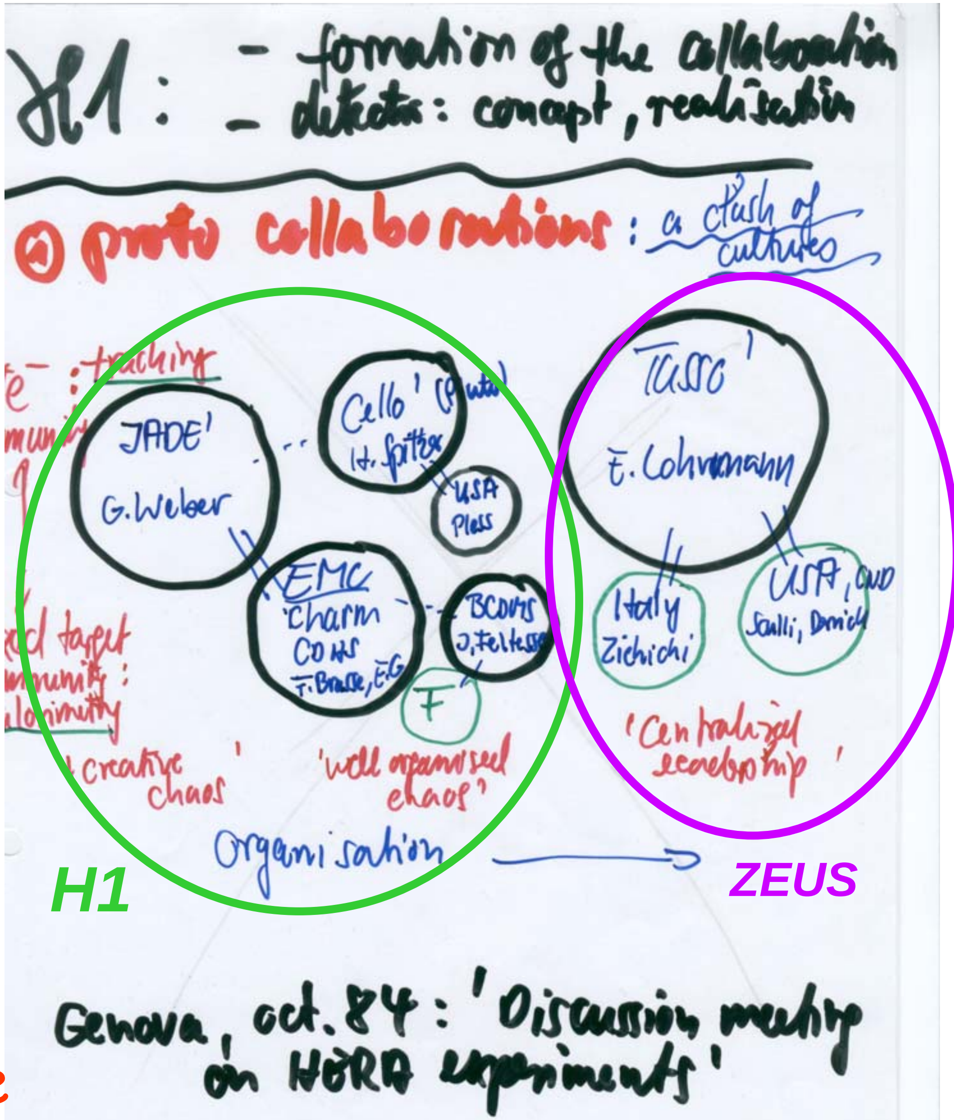
• LHC needs PDFs over very similar range in x!



H1: How Collaborations Form

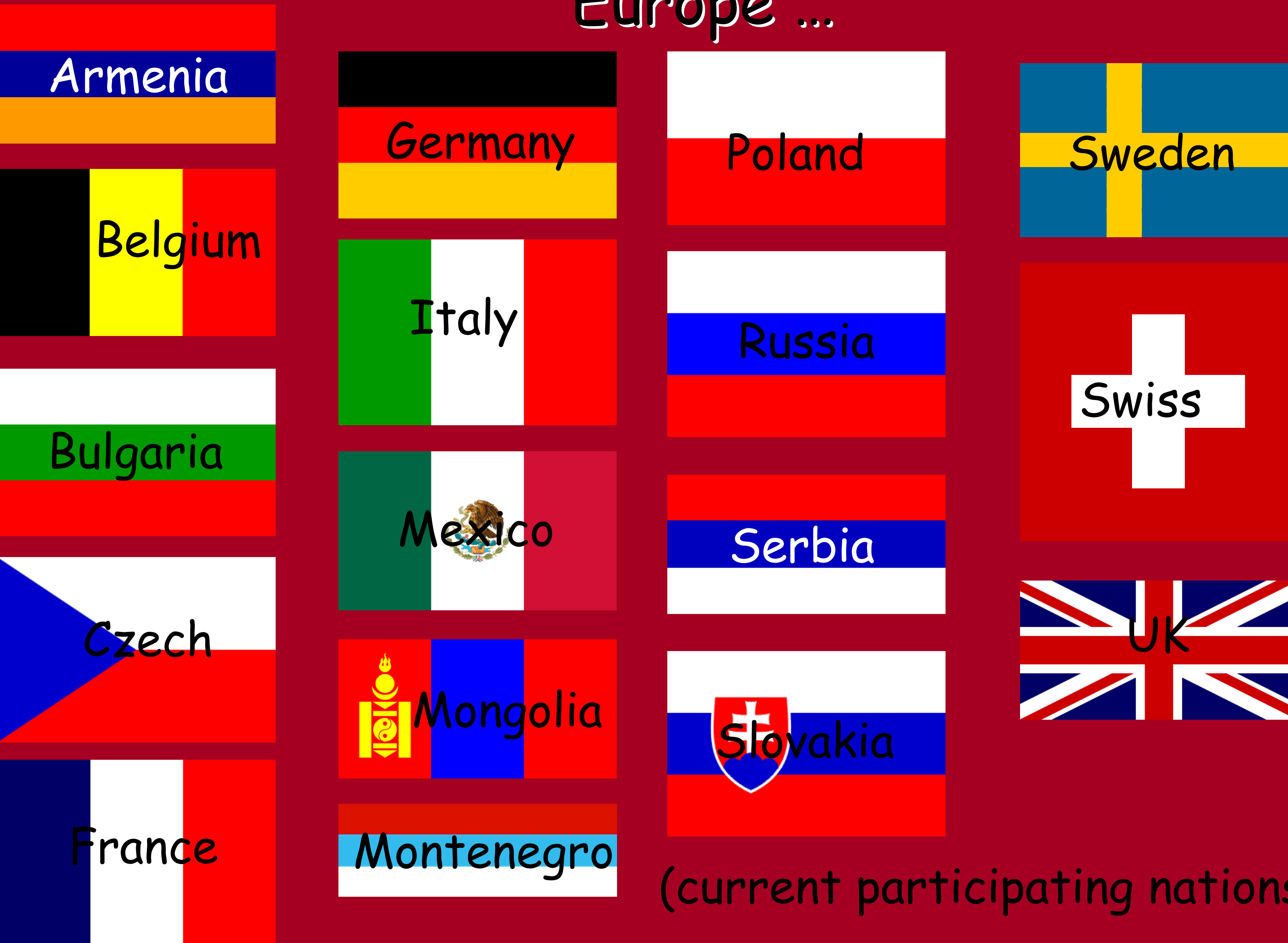
H1 emerged from a mixture of previous DESY experiments and previous fixed target DIS experiments from elsewhere … JADE, PLUTO, CELLO, EMC, BCDMS …

- "Clash of cultures"
- Not much in common except dislike for TASSO
- Letter of Intent in June 1985
- Poorer resources than TASSO / ZEUS … financing and manpower was a major issue for several years



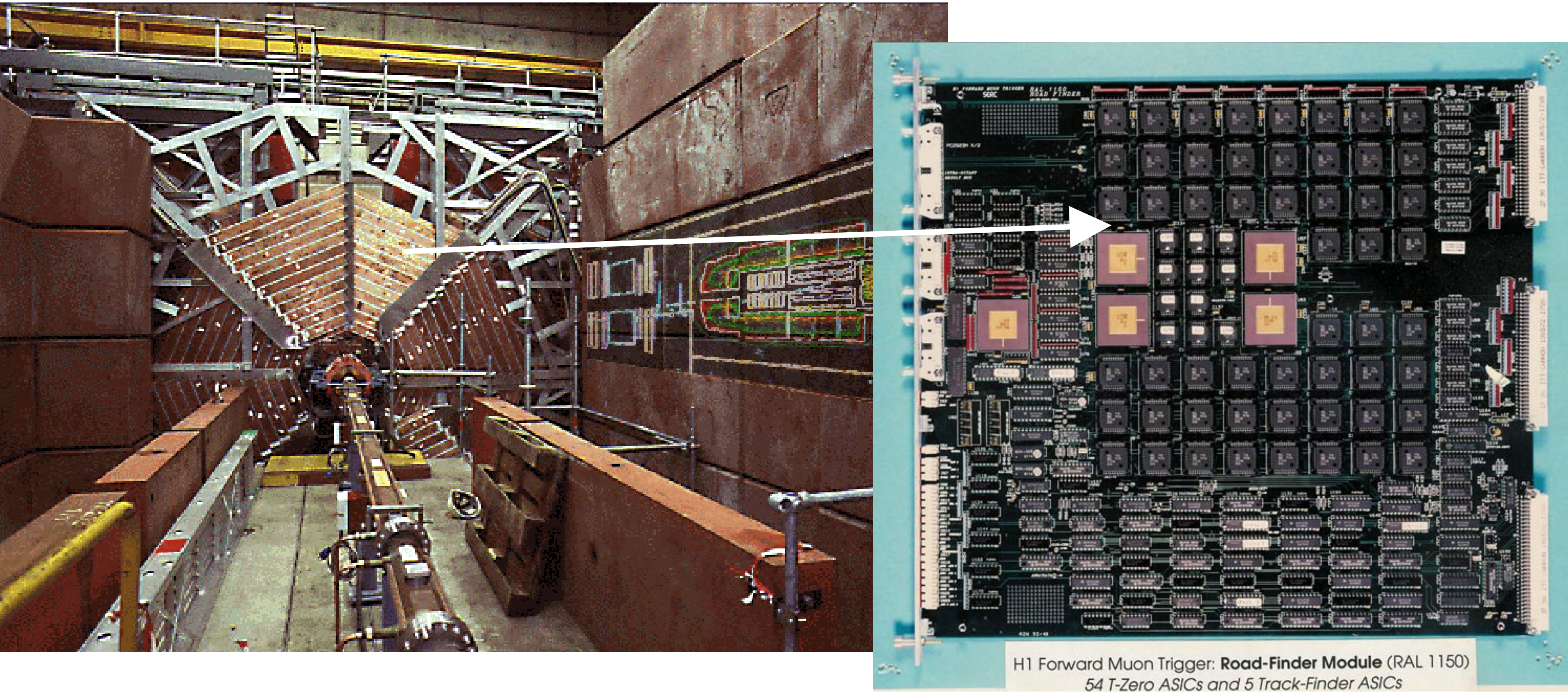
(F. Eisele)

Saved by Pioneering Collaboration with Eastern Europe ...

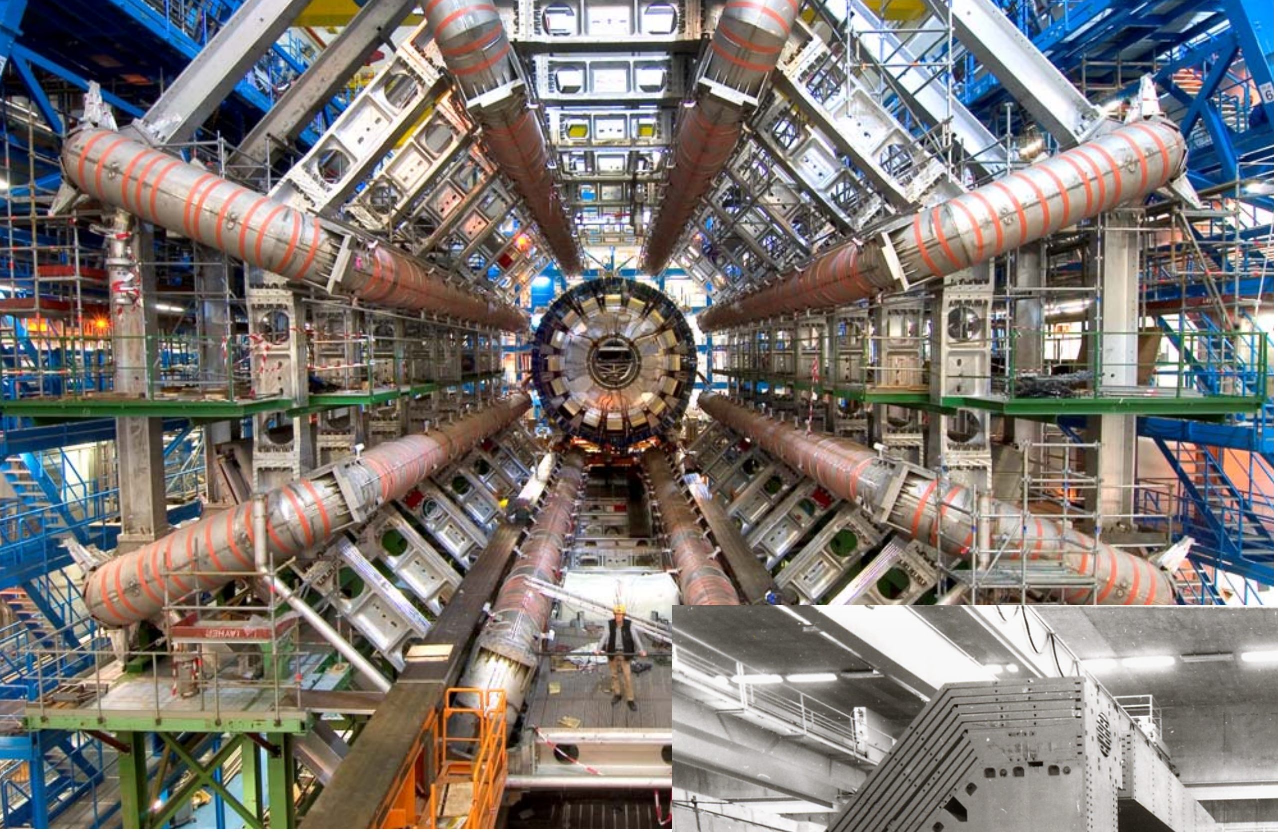


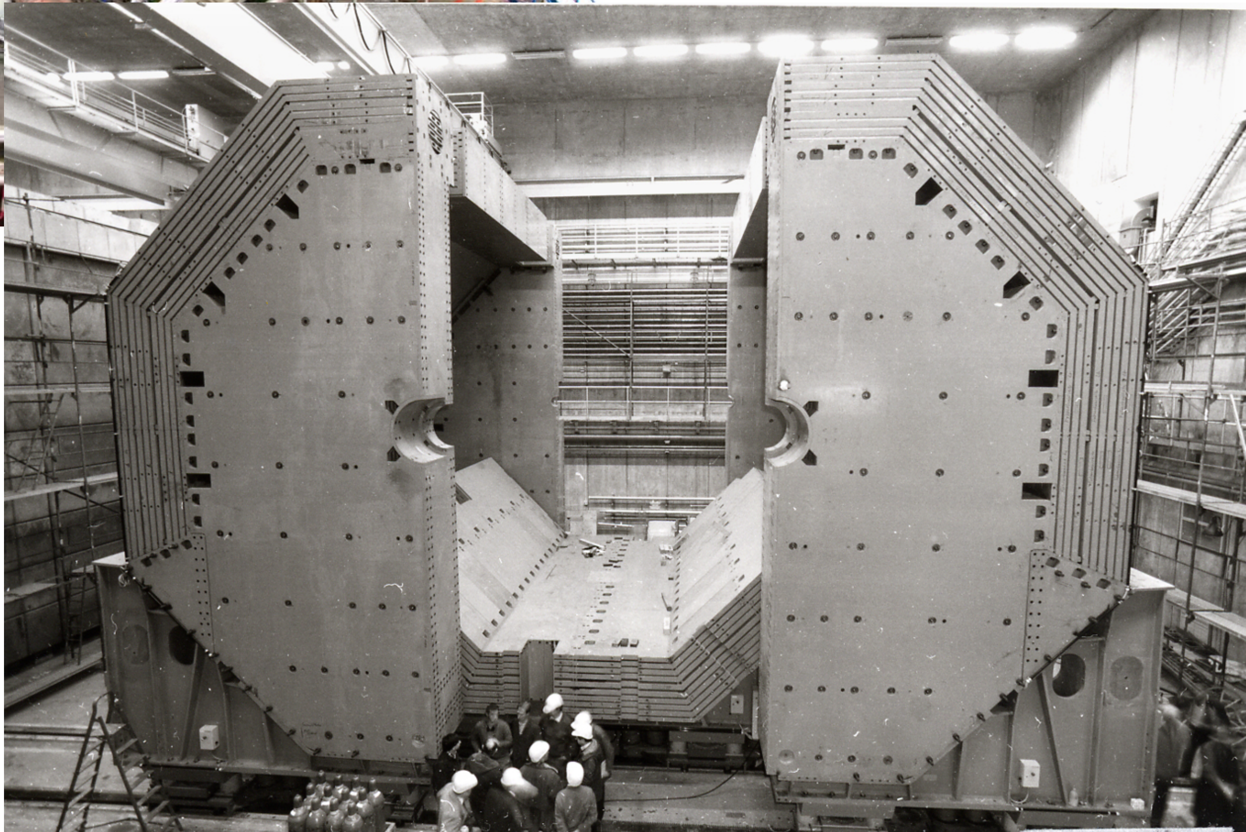
(current participating nations)

… and by arrival of Birmingham (Dec 1989)…



- First contribution was in building trigger for forward muons with RAL … semi-custom field programmable ASIC's
- Other electronics / trigger hardware followed
- Many contributions to physics, still ongoing!
- 15 Ph.D. theses so far



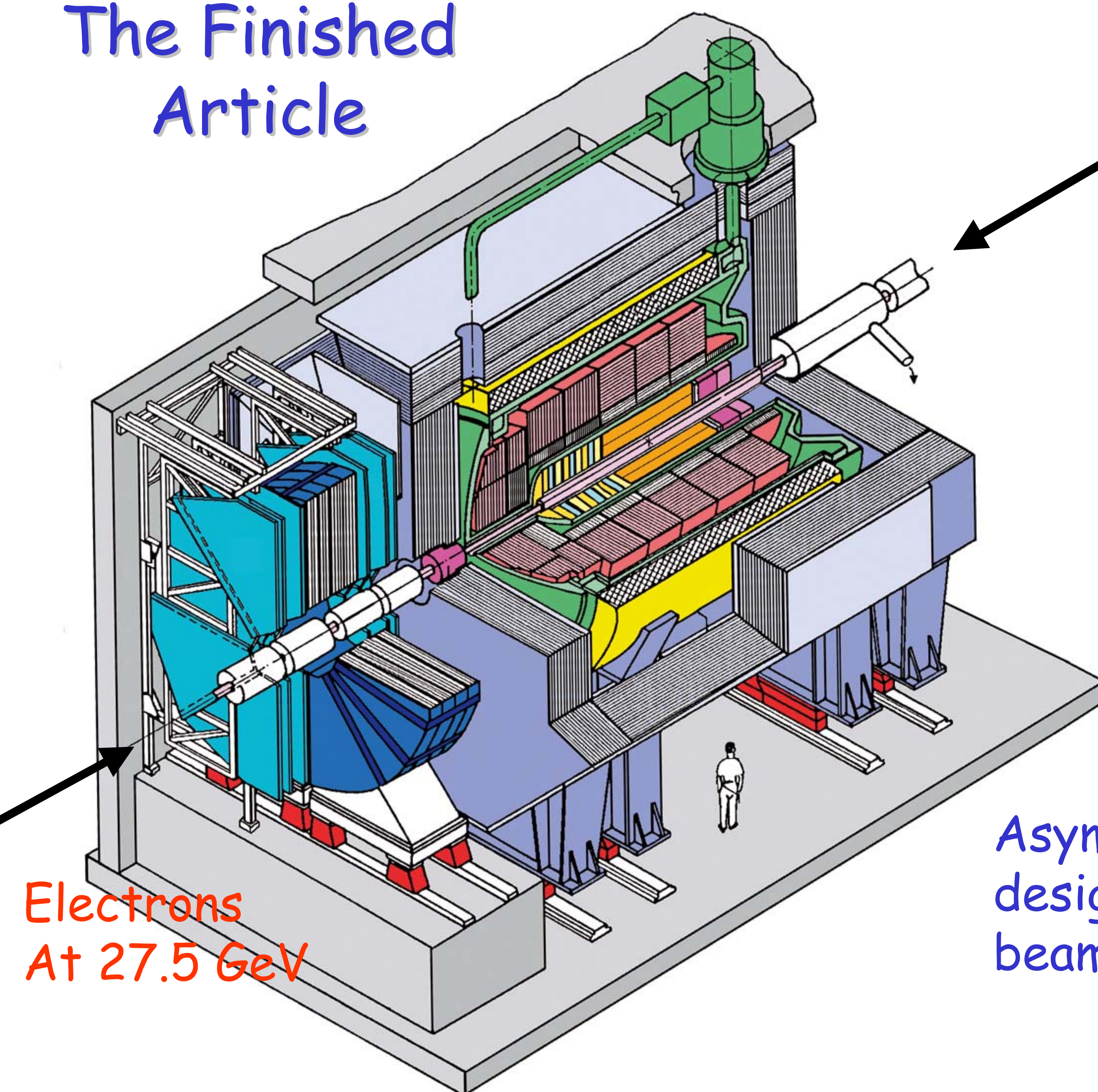


Scale:
H1 v
ATLAS

Construction

Size of lift determines size of experiment?

The Finished Article

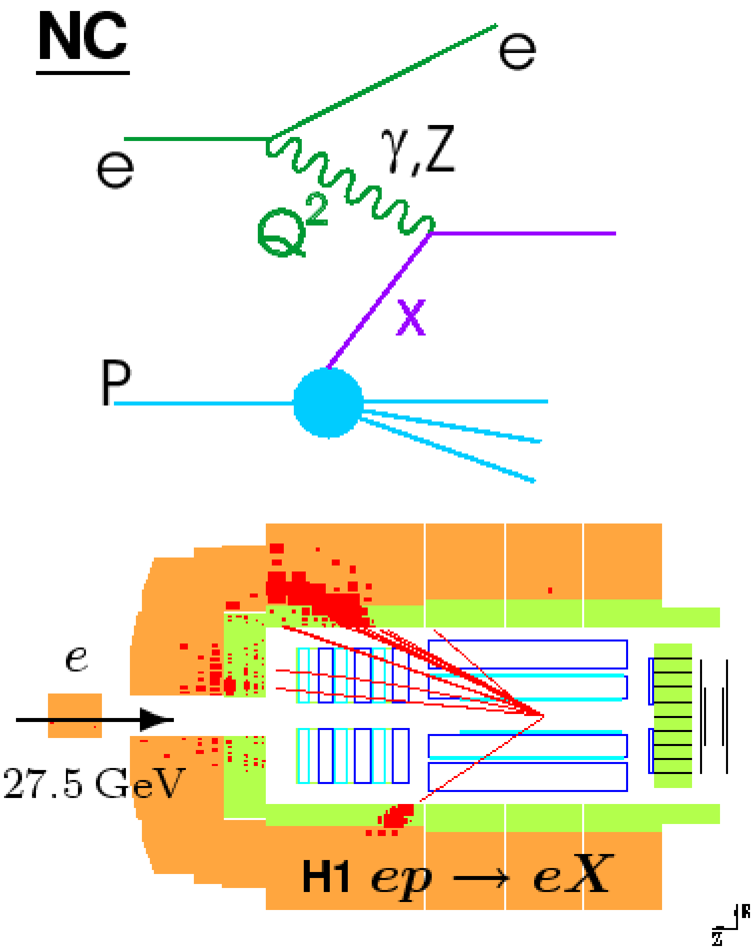


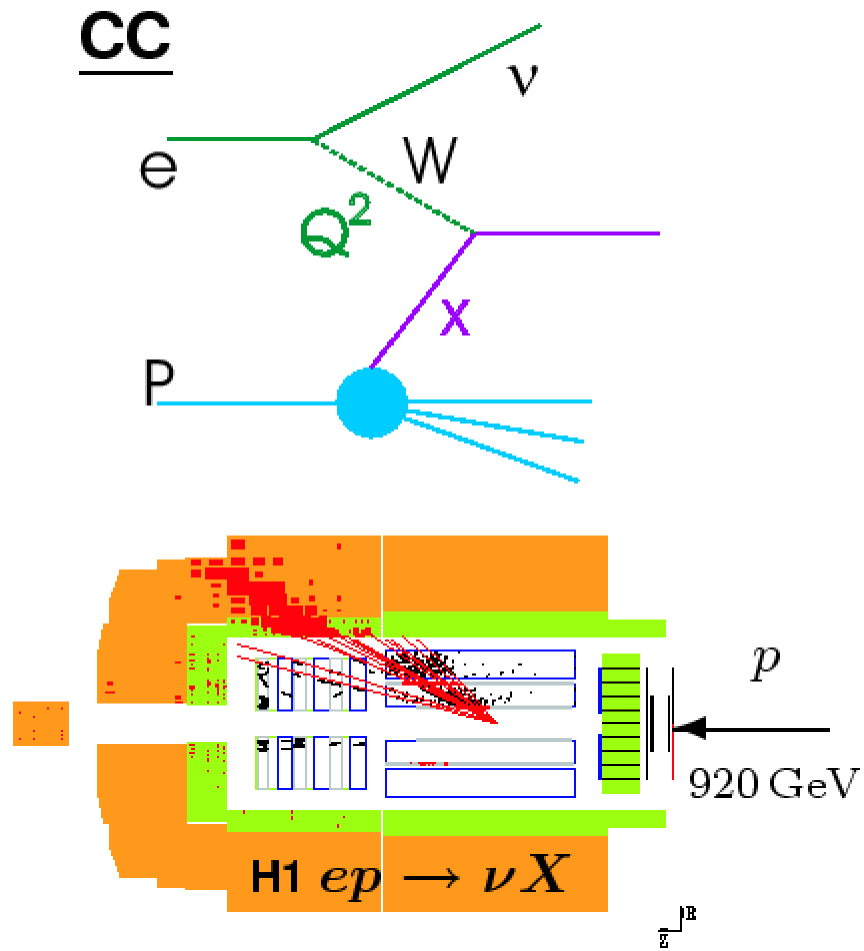
Asymmetric design, reflecting beam energies

Early Collaboration Mugshot

Early Collaboration Mugshot

Charged and Neutral Current Scattering

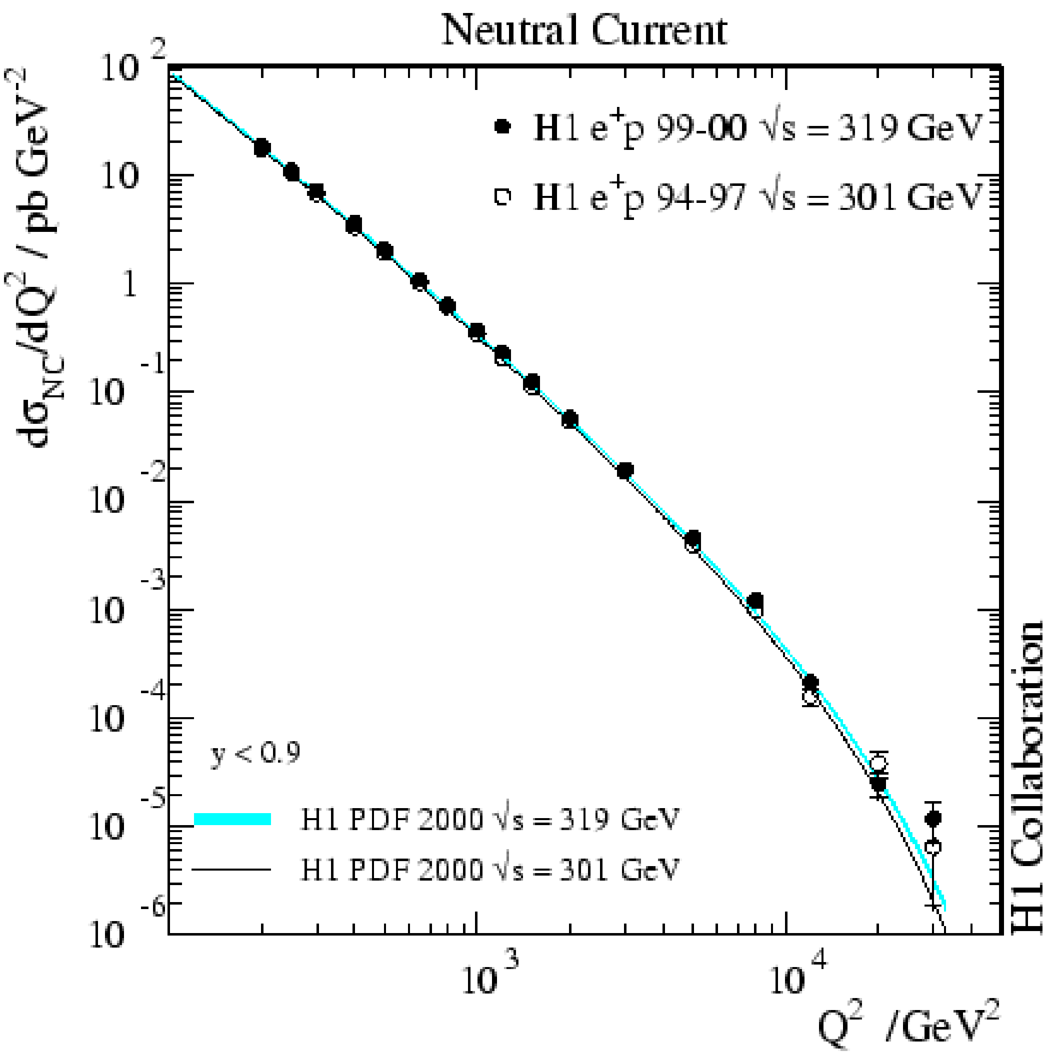


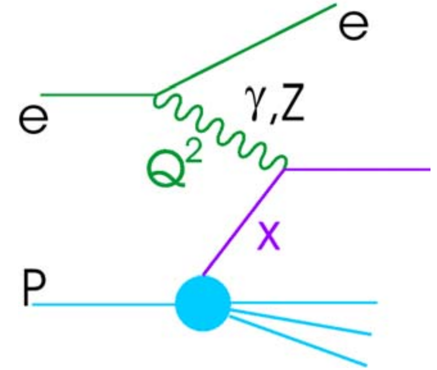


Cross section dominated by γ^* exchange (measures e_q^2 weighted quark distribution).

W, Z exchange at high Q^2 sensitive to flavour decomposition

Neutral Current





Neutral Current x-sec

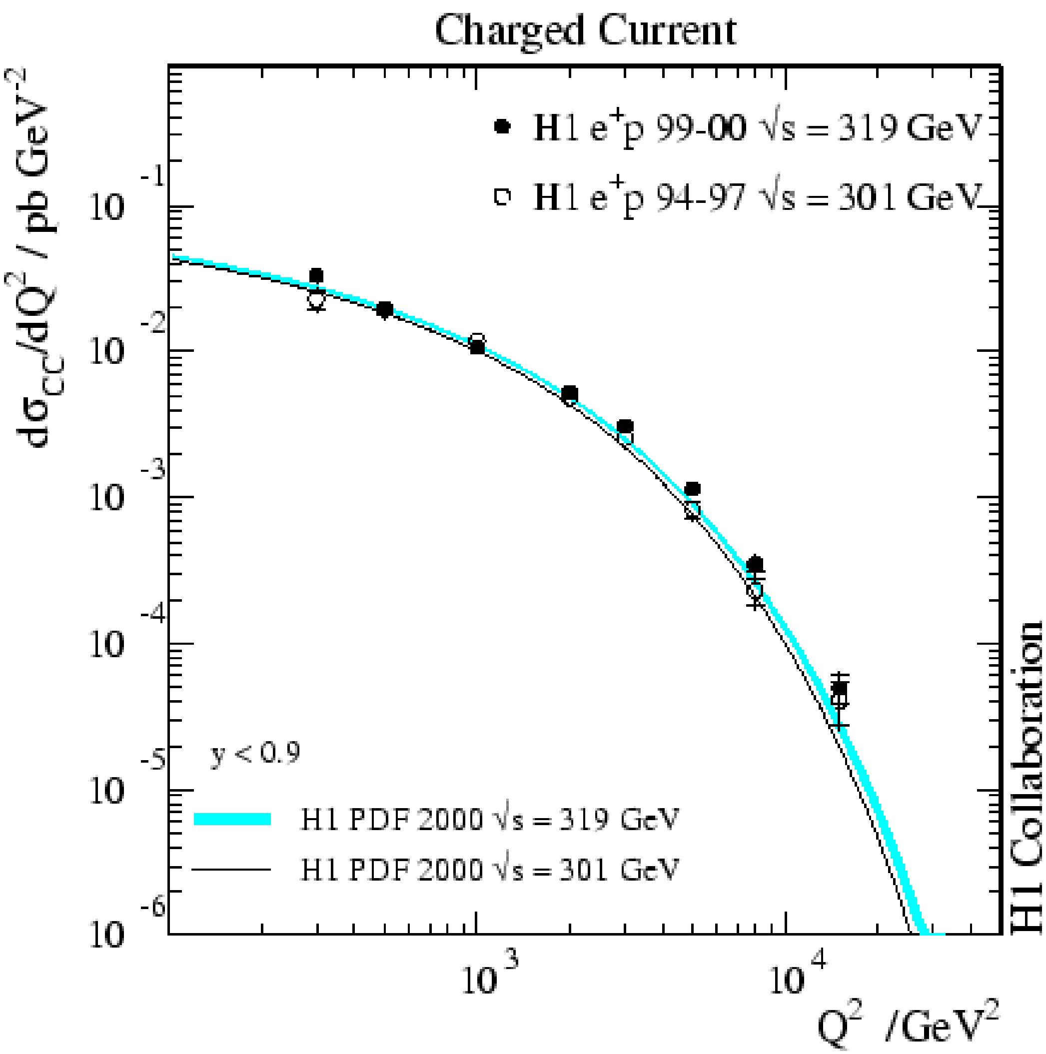
$$\frac{d\sigma^{NC}}{dx\, dQ^2} \sim \alpha_{em}^2 \quad \bullet \quad \left(\frac{1}{Q^2}\right)^2 \quad \bullet \quad \tilde{\sigma}_{NC}$$

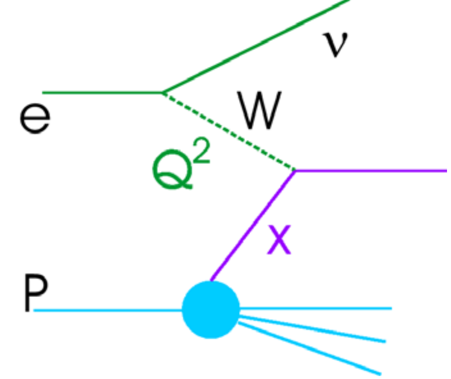
Coupling

Propagator

Quark Densities

Charged Current





Charged Current x-sec

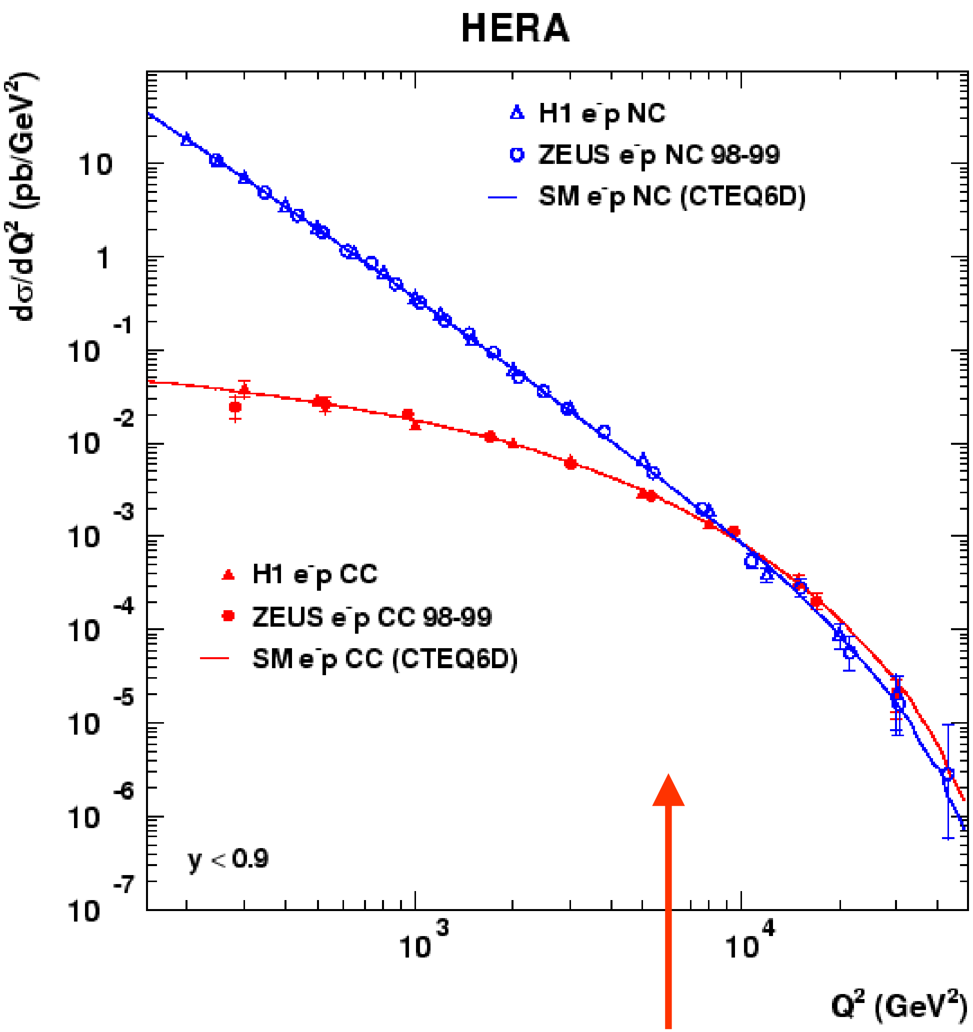
$$\frac{d\sigma^{CC}}{dx\, dQ^2} \sim G_F^2 M_W^2 \bullet \left(\frac{1}{Q^2 + M_W^2} \right)^2 \bullet \tilde{\sigma}_{CC}$$

Coupling

Propagator

Quark Densities

Electroweak Unification for Space-like Bosons



$Q^2 \sim M_W^2, M_Z^2$

Neutral Current x-sec

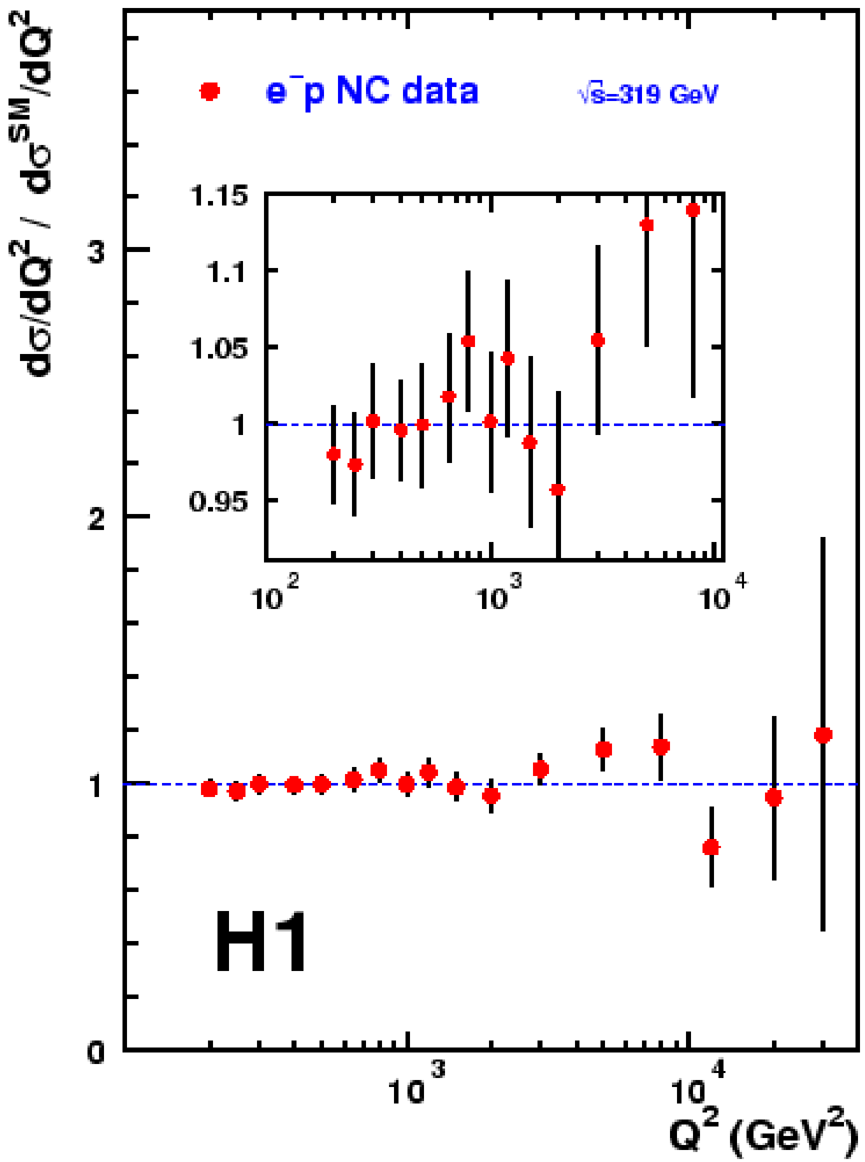
$$\frac{d\sigma^{NC}}{dx\, dQ^2} \sim \alpha_{em}^2 \bullet \left(\frac{1}{Q^2}\right)^2 \bullet \tilde{\sigma}_{NC}$$

Charged Current x-sec

$$\frac{d\sigma^{CC}}{dx\, dQ^2} \sim G_F^2 M_W^2 \bullet \left(\frac{1}{Q^2 + M_W^2}\right)^2 \bullet \tilde{\sigma}_{CC}$$

NC and CC cross sections become comparable at EW unification scale (couplings unified)

New Physics?



- Close agreement between data and Standard Model prediction up to highest Q^2 ~ 30 000 GeV^2…

…no quark sub-structure found on distance scales of 10^{-18} m.

- Many other dedicated searches performed for Signatures of new physics.

- Nothing convincing (yet!)

Neutral Current Sensitivity to the Quarks

NC cross section depends on 3 structure functions …

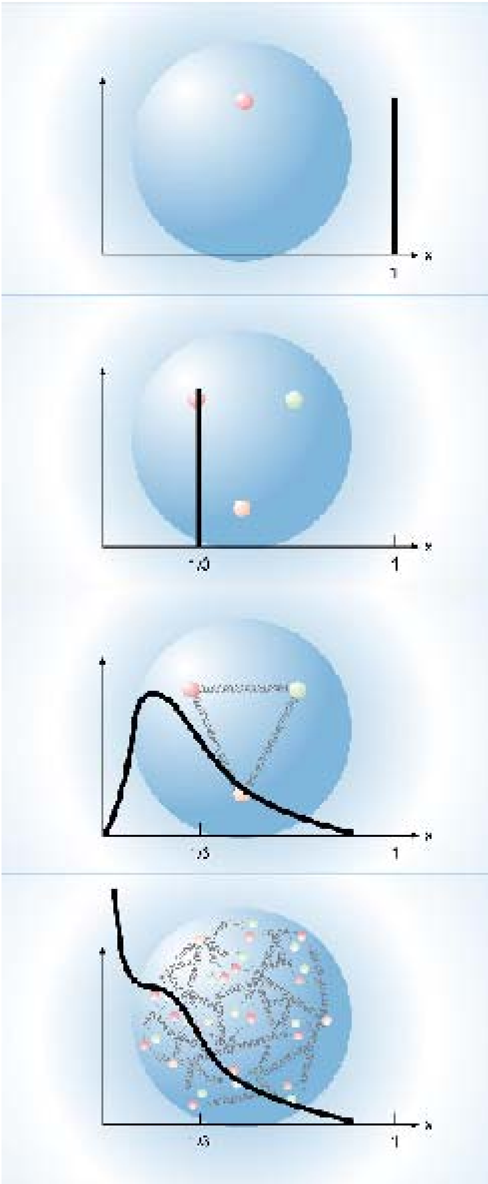
$$\tilde{\sigma}^{NC}(e^{\pm}p) = \boxed{F_2} \mp \frac{Y_-}{Y_+}\boxed{xF_3} - \frac{y^2}{Y_+}\boxed{F_L}$$

… where $Y_{\pm} = 1 \pm (1-y)^2$

… and y measures the process inelasticity

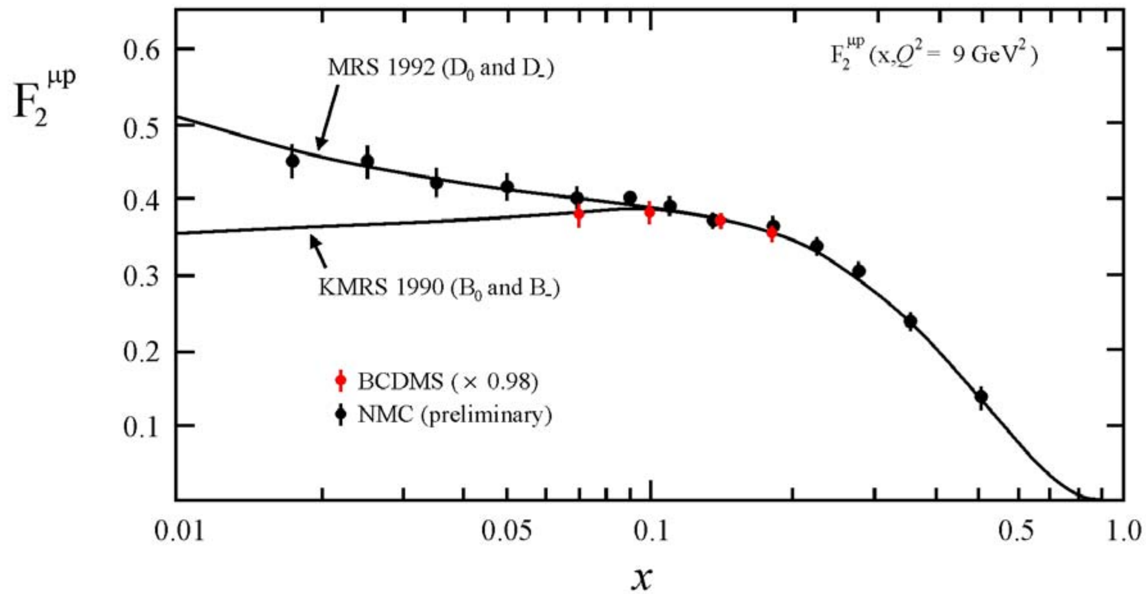
- F_2 dominates throughout most of the phase space
- xF_3 contributes at high Q2 (Z exchange) can be obtained from difference between e^+p and e^-p cross sections
- F_L contributes at high y (longitudinally polarised photons)

Structure Function $F_2(x, Q^2)$



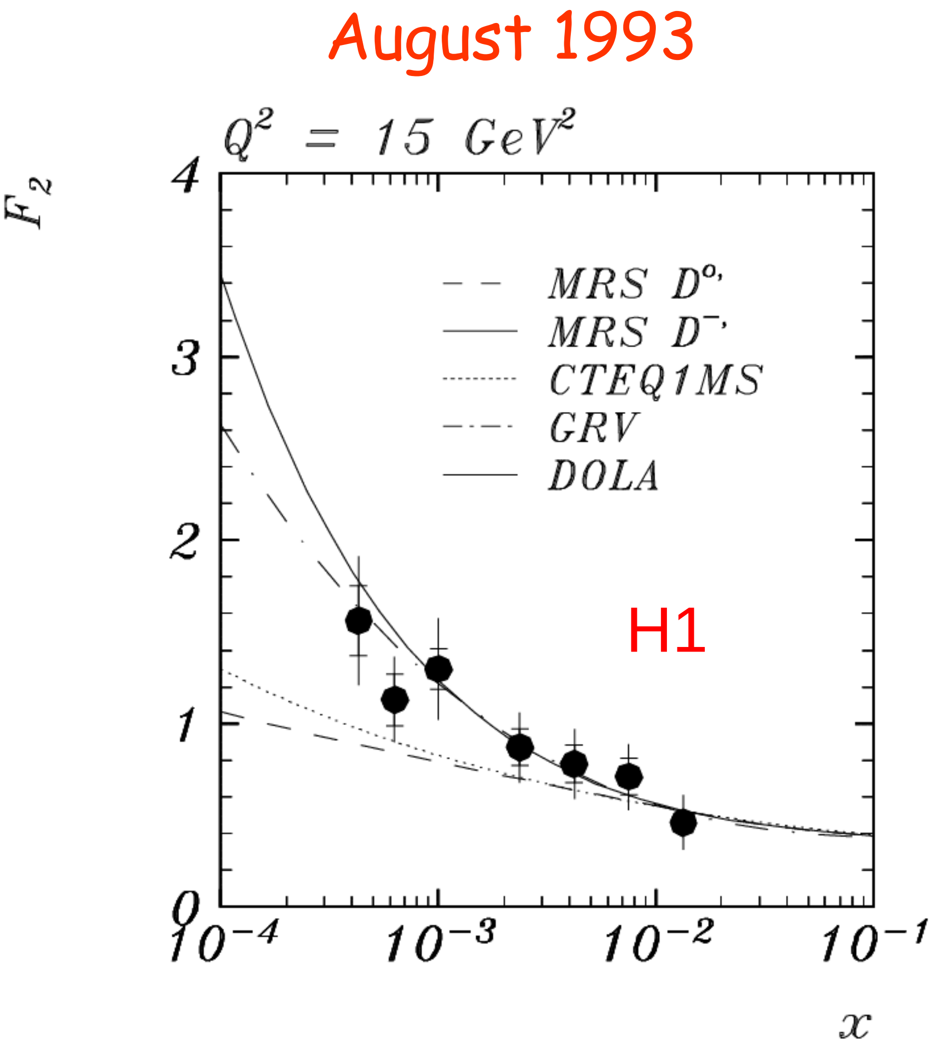
$$F_2(x,Q^2) \sim x\sum_q e_q^2(q+\overline{q})$$

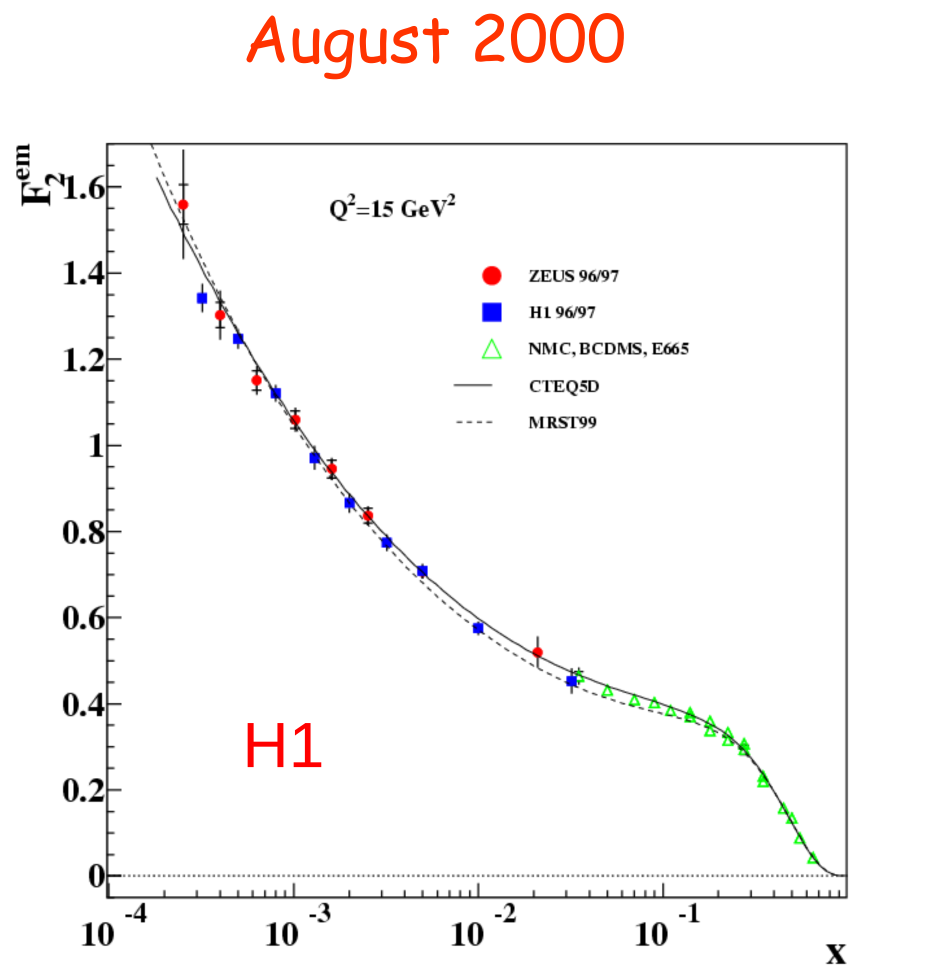
The data before HERA …



In 1992, low x physics was an obscure field, known only to Russians!

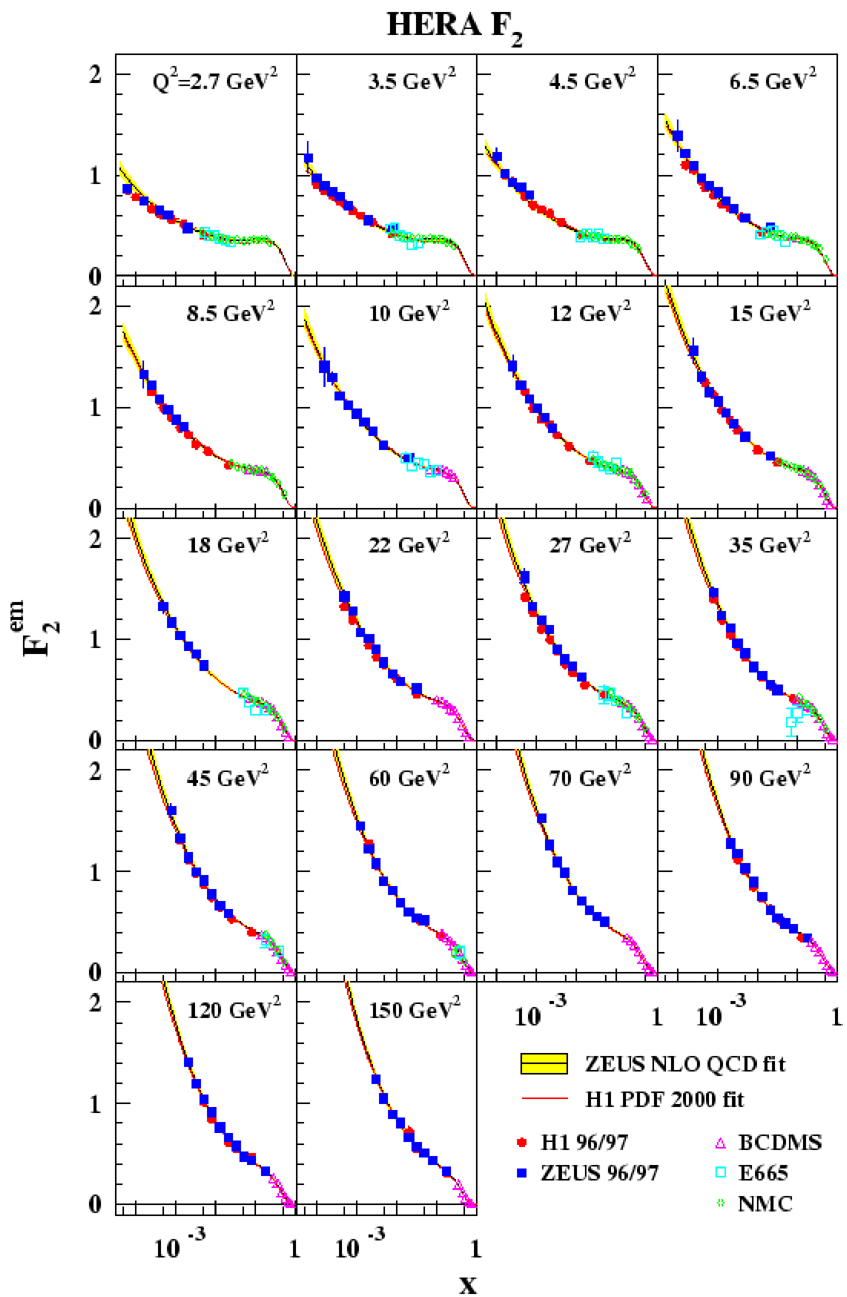
The First Measurement





Biggest HERA discovery … rise of F_2 at low x …
… already apparent from first data … published to 2-3%
… now working towards 1% measurement.

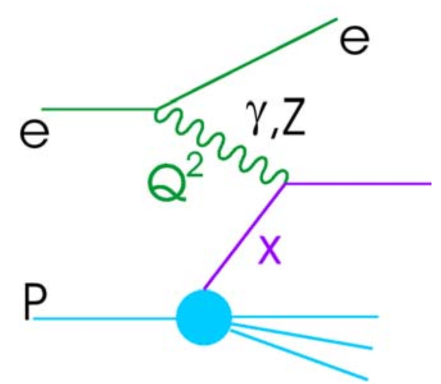
F_2 and the up Density!



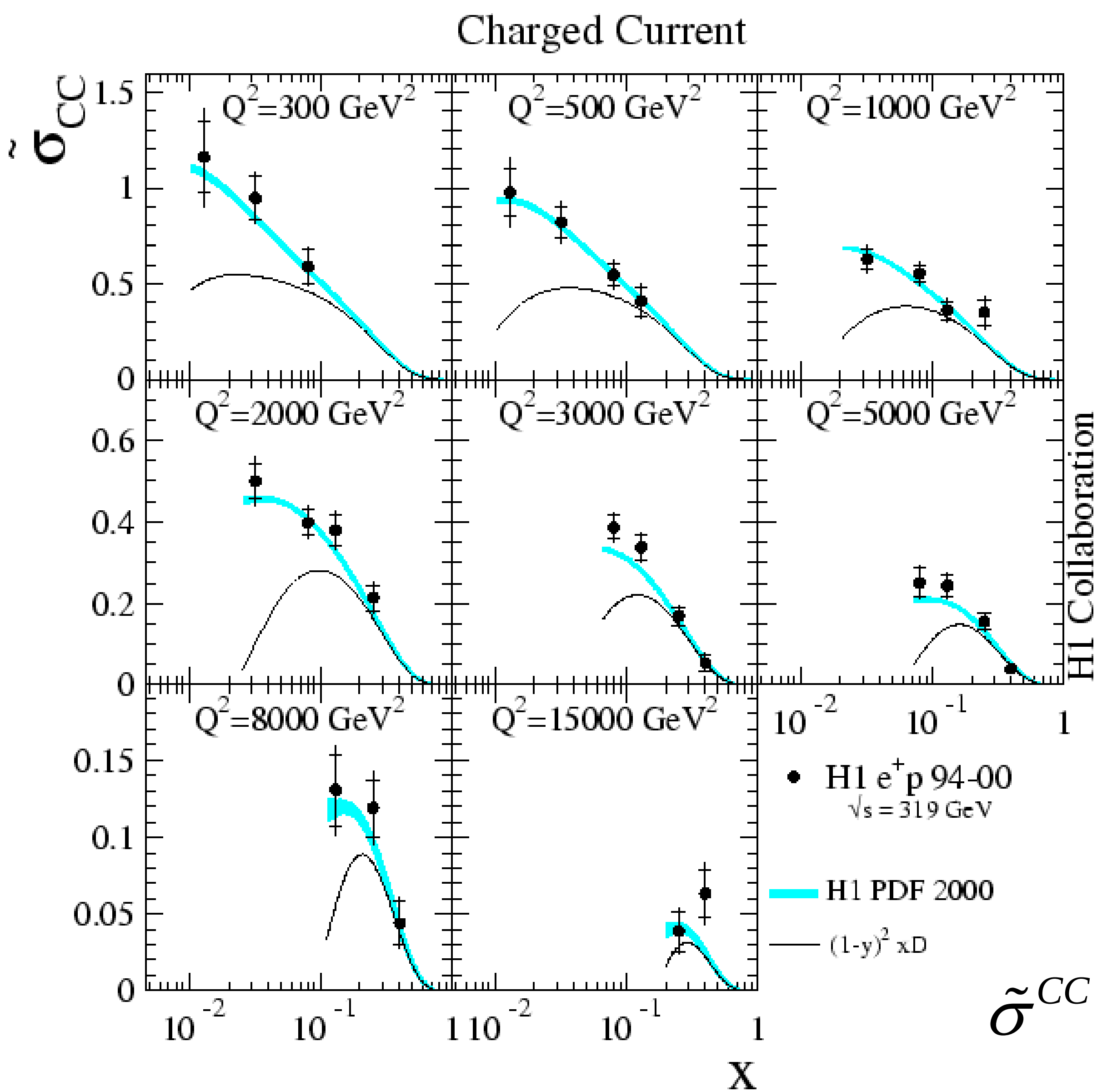
- Just some of the F2 data …

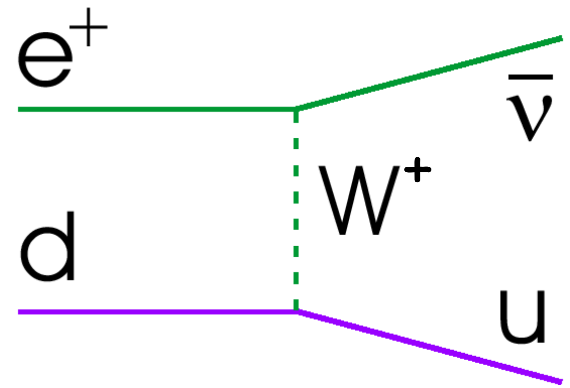
- Due to e_q^2 weighting, this provides stronger constraint on up density (e_q=2/3) than on down density (e_q=-1/3)

… beautifully described by QCD fits over huge kinematic range!



Charged Current and the down Density



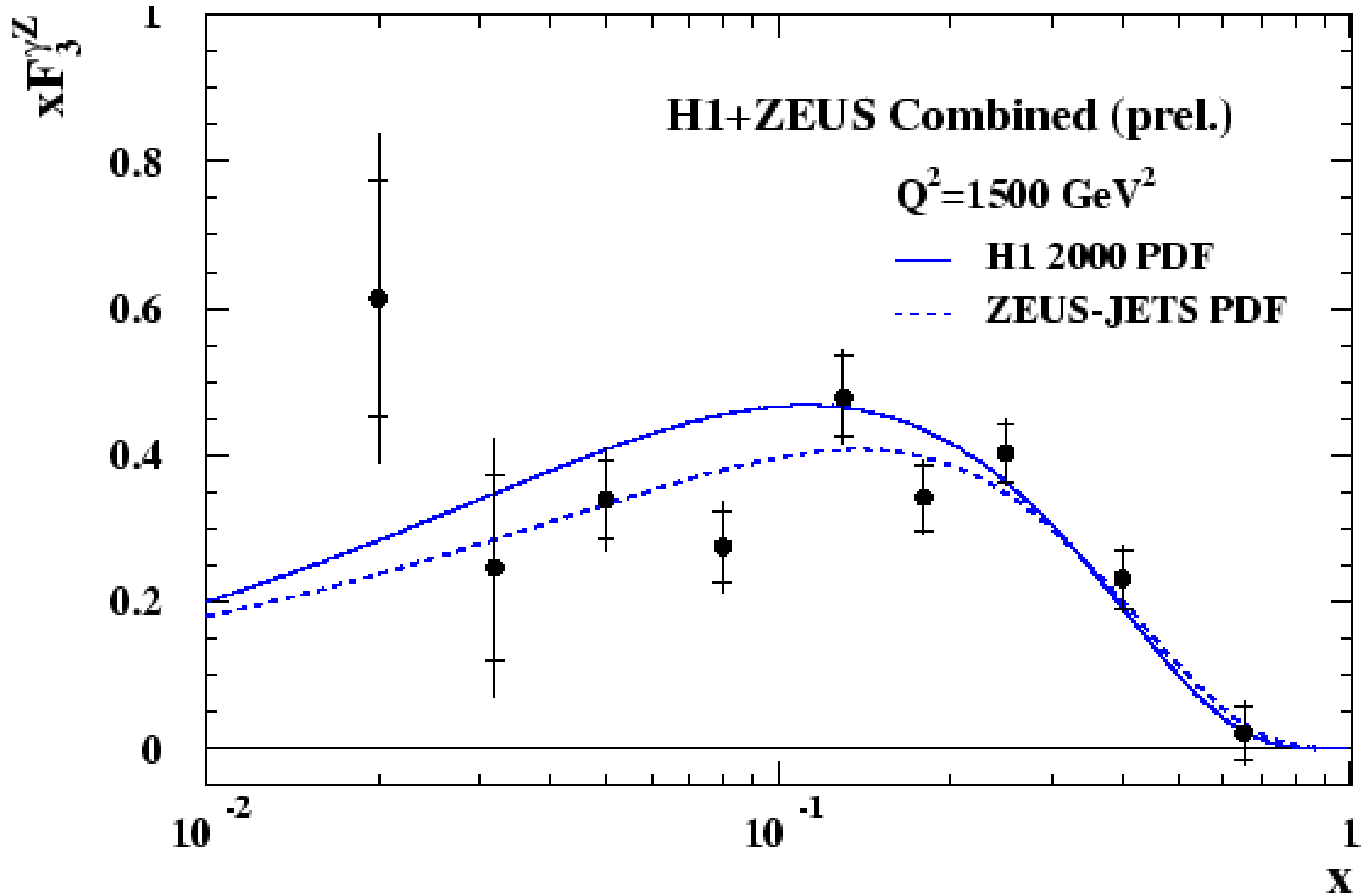


Charged current sensitive to flavour decomposition …
e.g. e+ couples to d and ubar, but not u and dbar.

$$\tilde{\sigma}^{CC}(e^+p) \sim (1-y)^2 d + \bar{u}$$

xF_3 and the Valence Quarks

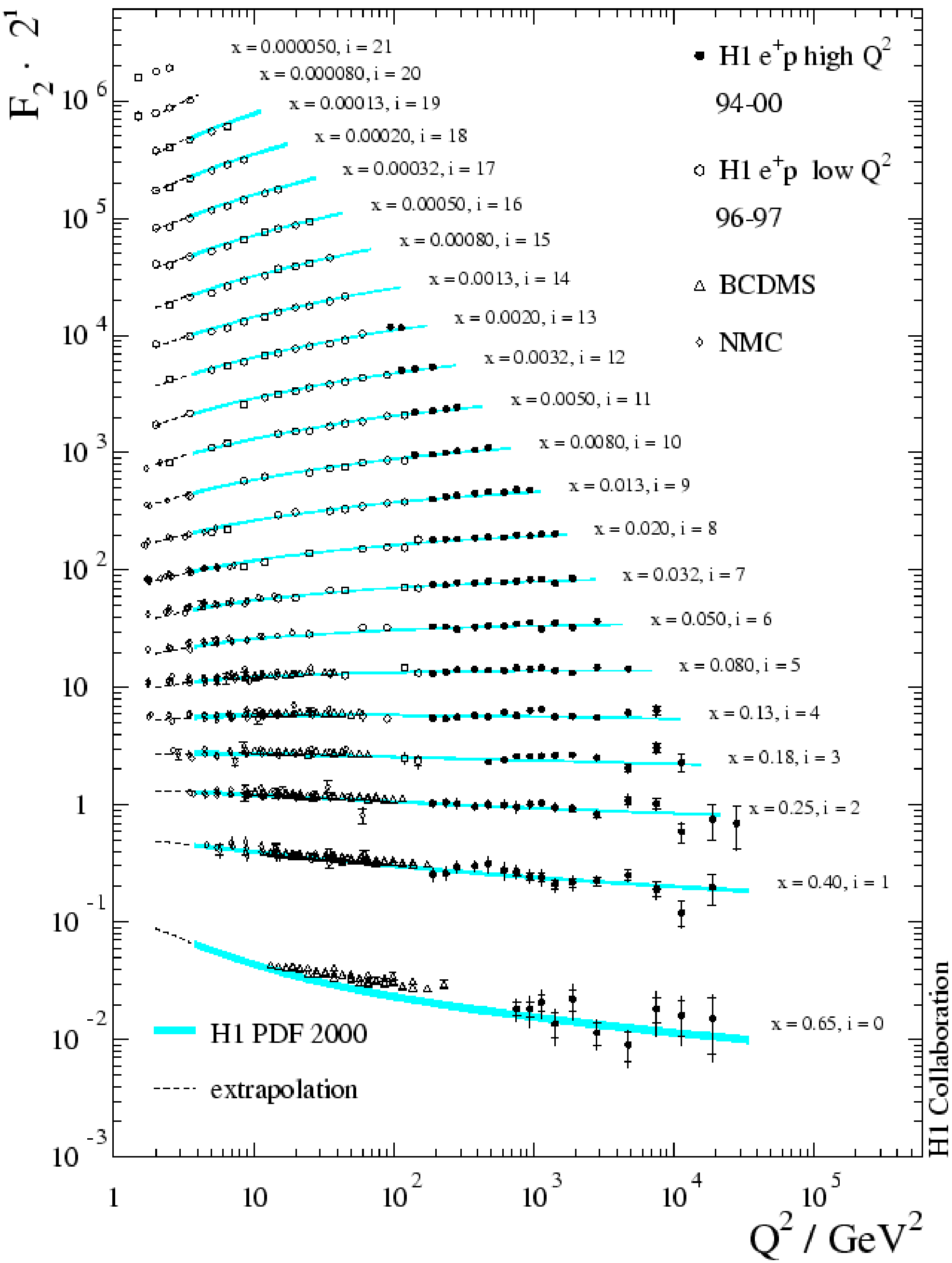
$$xF_3 = \frac{Y_+}{2Y_-}\left\{\tilde{\sigma}^{NC}(e^- p) - \tilde{\sigma}^{NC}(e^+ p)\right\}$$



$$xF_3 \sim 2x\sum_q e_q a_q (q - \bar{q}) \sim q_v$$

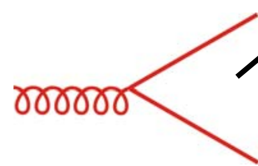
… unique sensitivity to valence quarks

The Gluon Density!

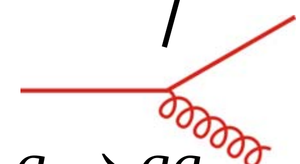


Q^2 evolution of F_2 is used to extract gluon density, assuming DGLAP evolution.

$$\frac{dF_2}{d\ln Q^2} \sim \alpha_s \left(P_{qg} \otimes g \; + \; P_{qq} \otimes q \right)$$



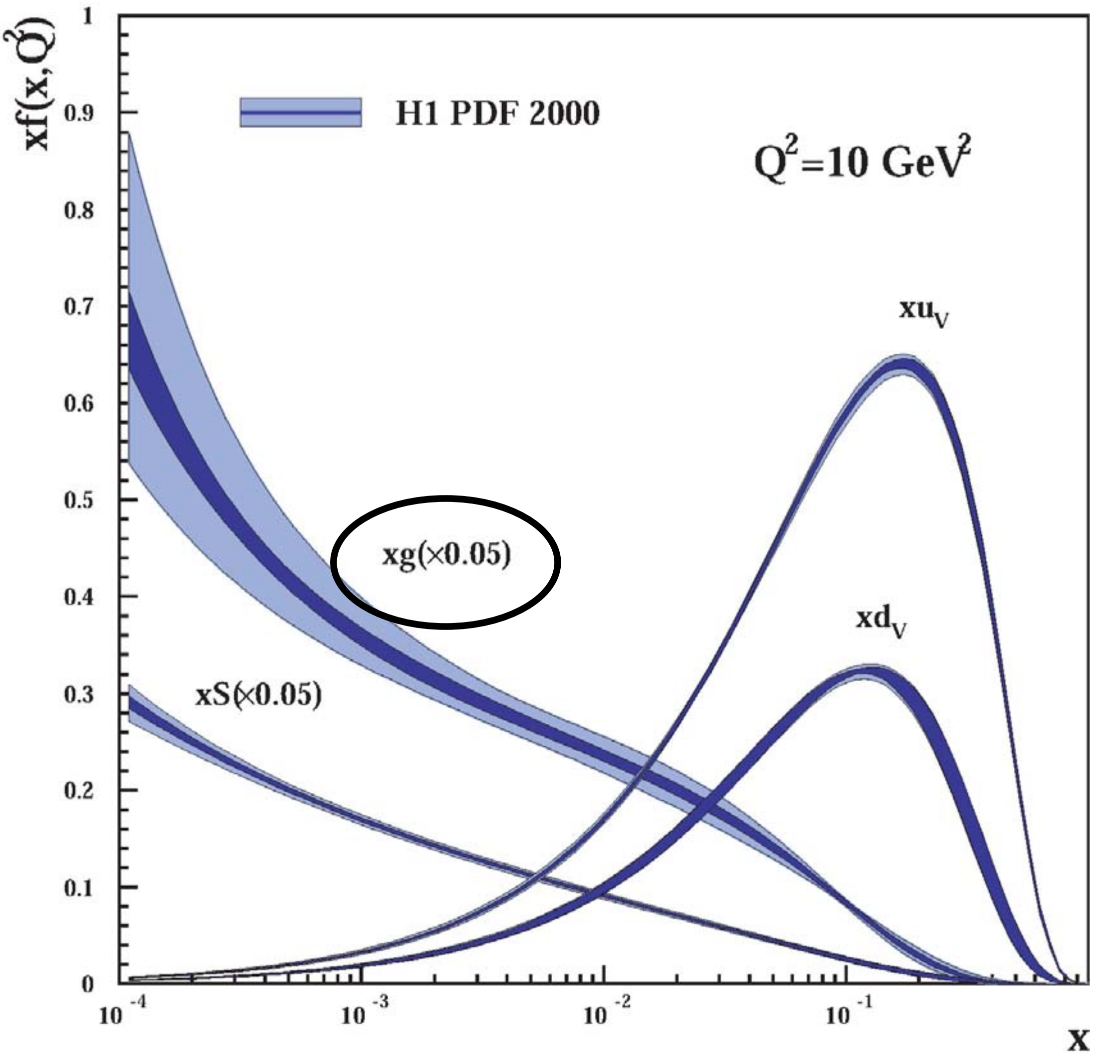
$g \rightarrow q\bar{q}$



$q \rightarrow qg$

Internally self-consistent, but (unlike quark density extractions), this is model (DGLAP) dependent!

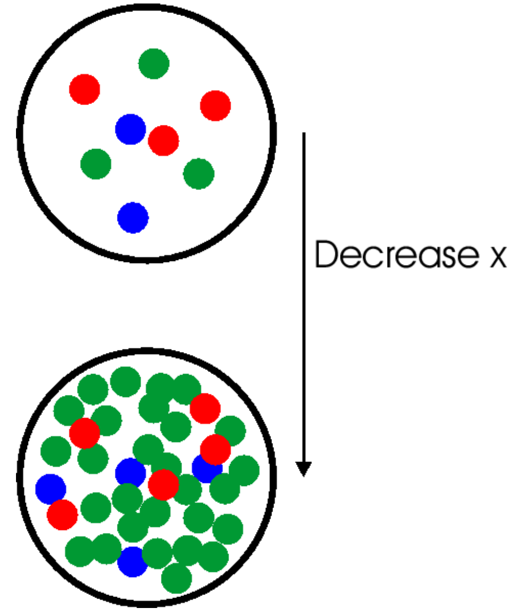
So what *is* a Proton?



- DGLAP fits to NC and CC data, up to order α_s^2 in QCD used to obtain valence, sea quarks and gluon.
- Can be done using H1 data alone.
- Also `global' fits by MRST, CTEQ … use some input from pp and elsewhere.

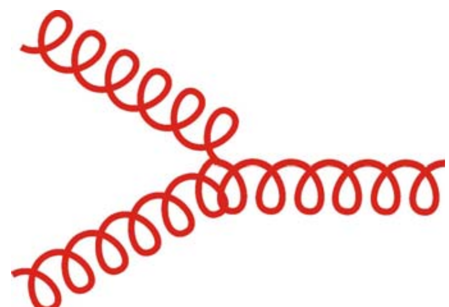
Gluon density at low x becomes enormous!

Can the Rise of Gluon be True?

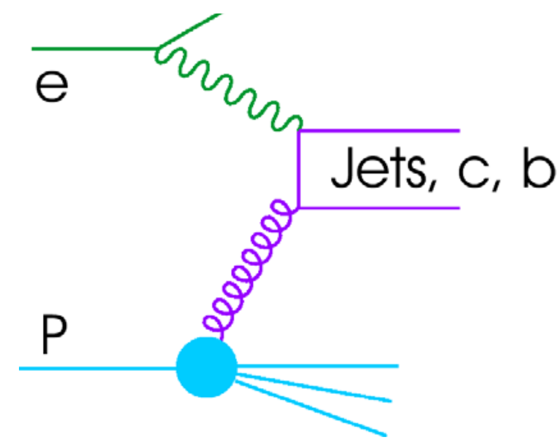


• Gluon density cannot rise indefinitely as x decreases (unitarity effects / parton `saturation' ?...)

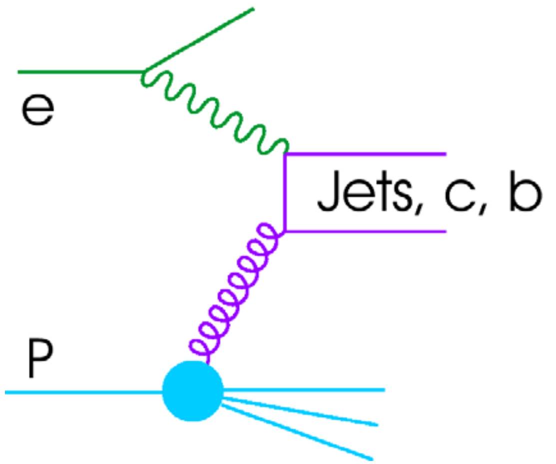
• DGLAP approximation to QCD evolution may become insufficient, e.g. due to neglect of $gg \rightarrow g$ `recombination'.

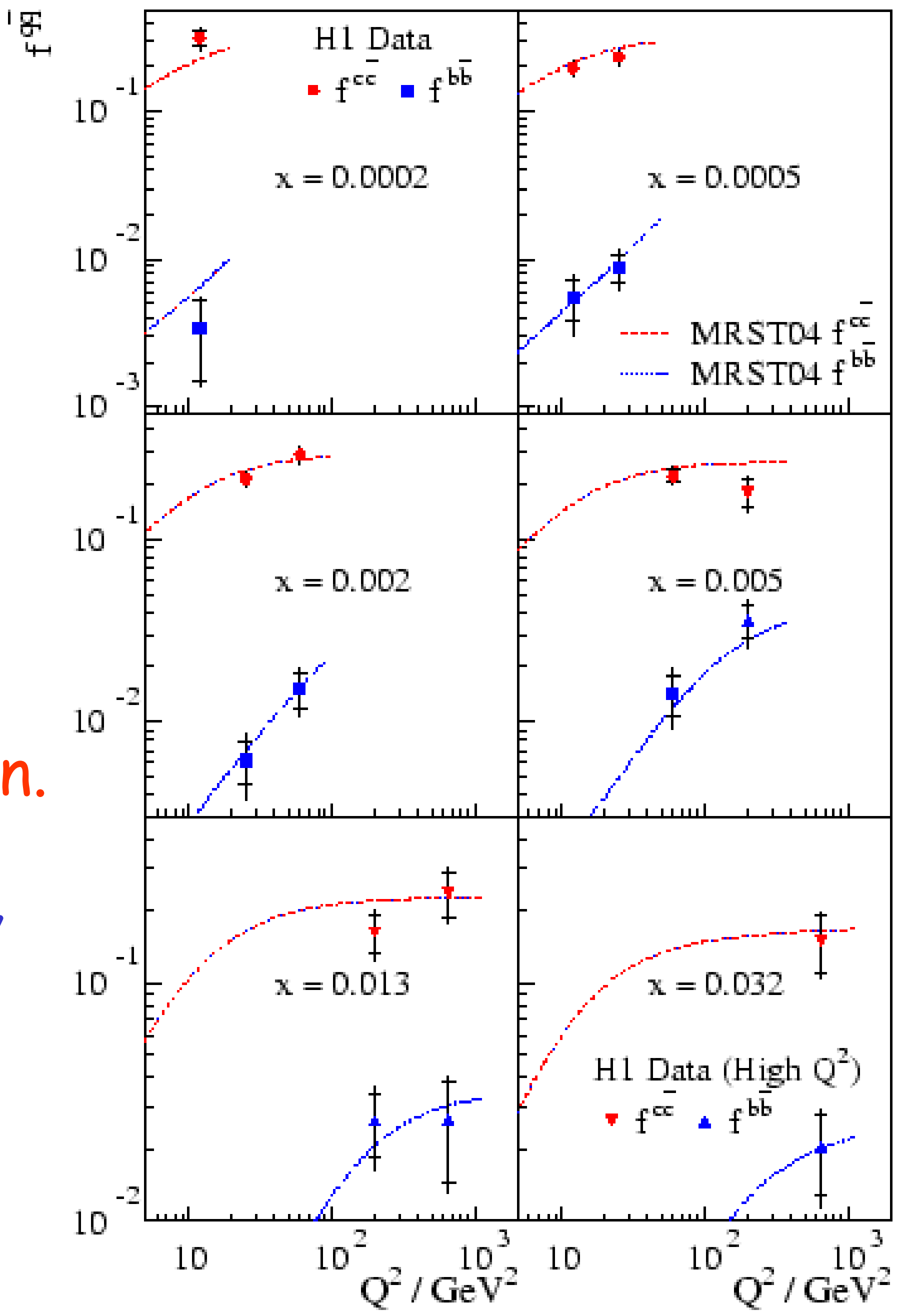


• Same approximations are used for evolution to LHC … essential to test the gluon density through direct measurement …
… e.g. `boson-gluon fusion' → many Dijet, charm, beauty measurements!



Example: Heavy Flavour Contributions





Fractions of total cross section From ccbar and bbbar production.

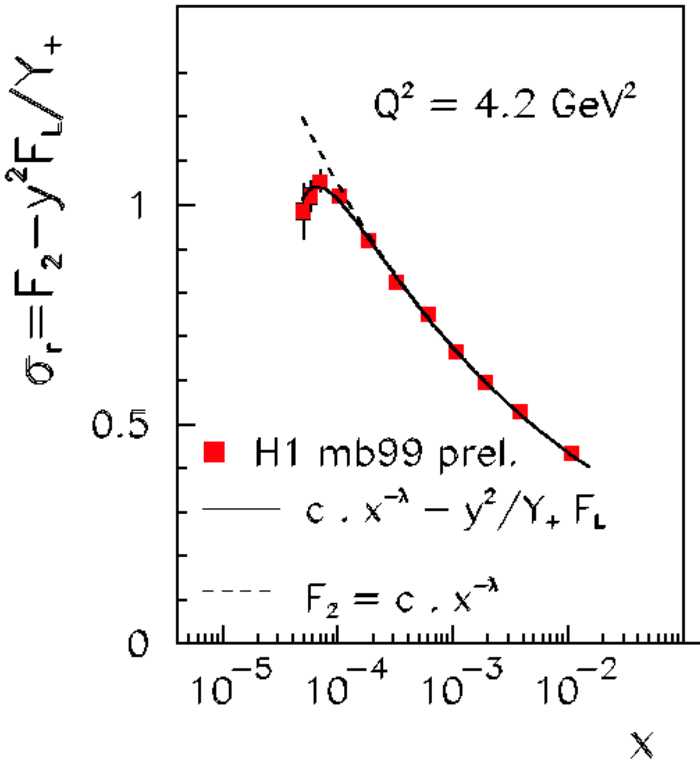
Measured from secondary decay vertices in silicon Microvertex detector.

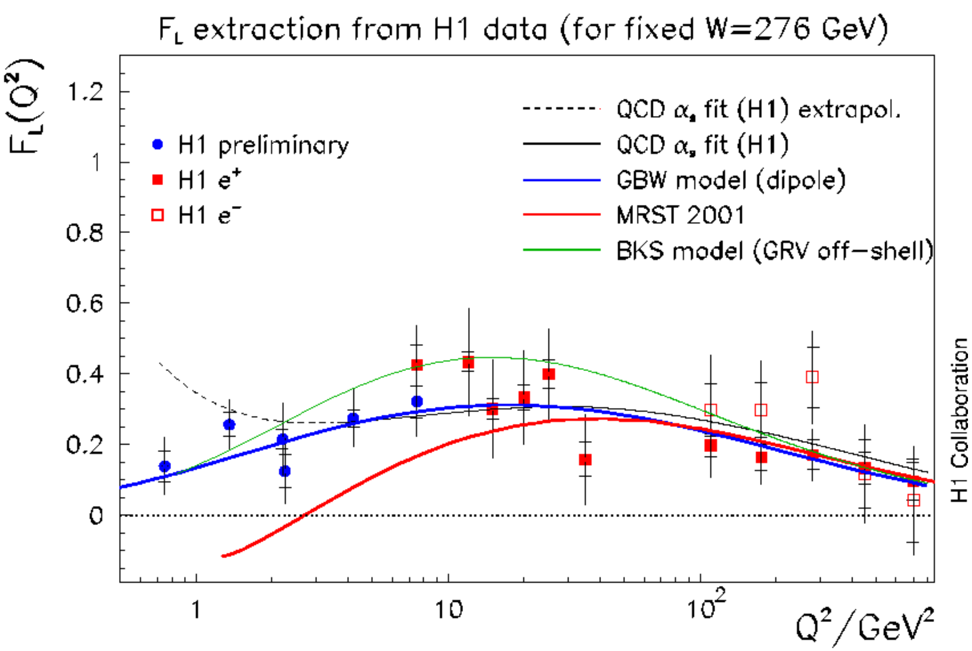
Good agreement ... but not really so low x!

Structure Function $F_L(x,Q^2)$

If gluon dominates, **$F_L \sim \alpha_s \, xg(x)$**, provides another test of self-consistency and gluon.

$$\tilde{\sigma}^{NC} = F_2 - \frac{y^2}{Y_+} F_L$$

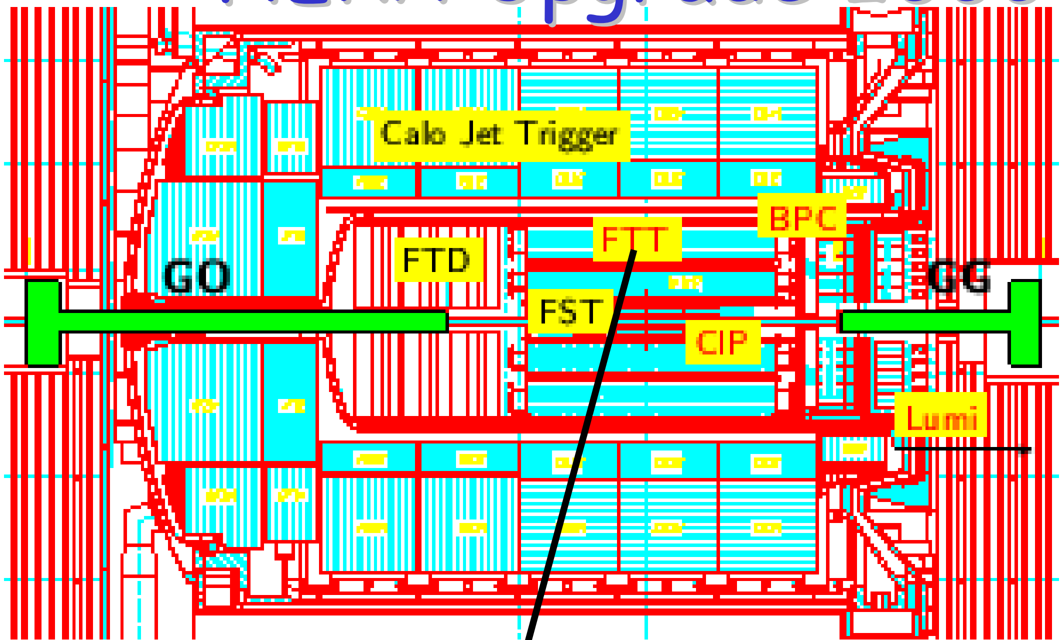


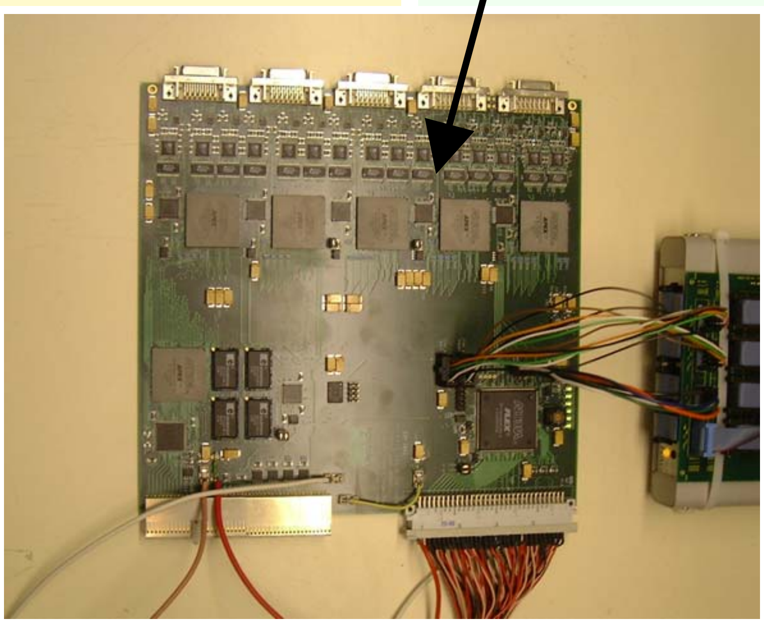


Influence visible at low x and low Q^2, consistent with expectations if F_2 is well behaved

Model-free extraction requires changes to beam energies …

HERA Upgrade 2000 … `HERA-II'





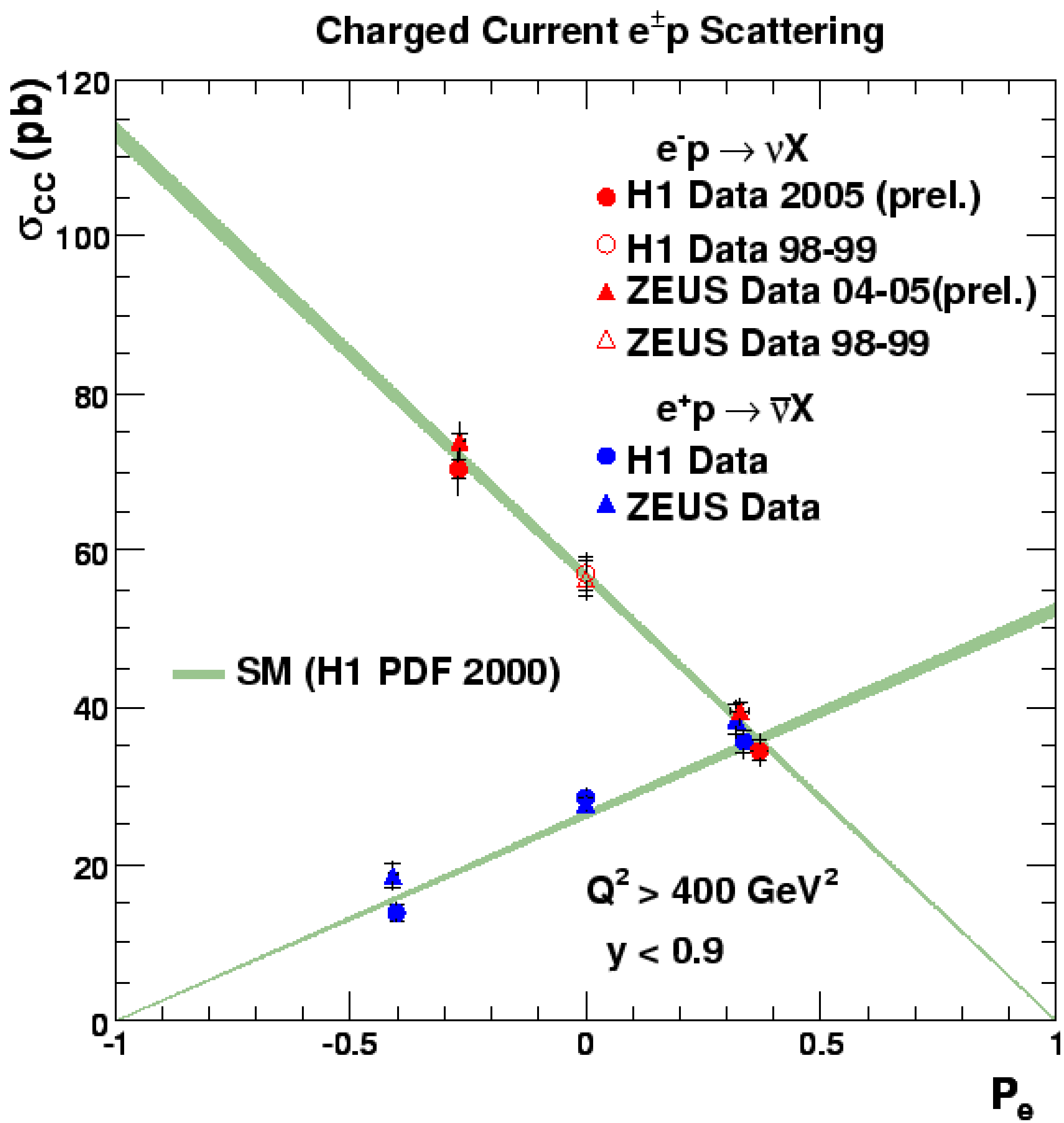
Beam focusing magnets …
- increased luminosity

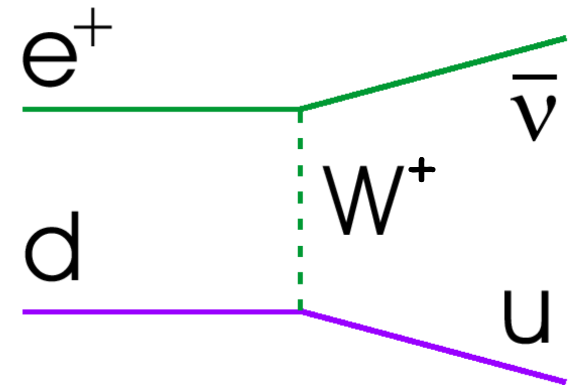
Polarised leptons …
- Chiral structure of Standard Model in DIS
- Complementary PDF information

Many H1 components upgraded

Birmingham involvement in `Fast Track Trigger', reconstructing complex decays to charged particles using drift chambers and FPGAs on-line (<100μs)

Polarised Charged Current Cross Section

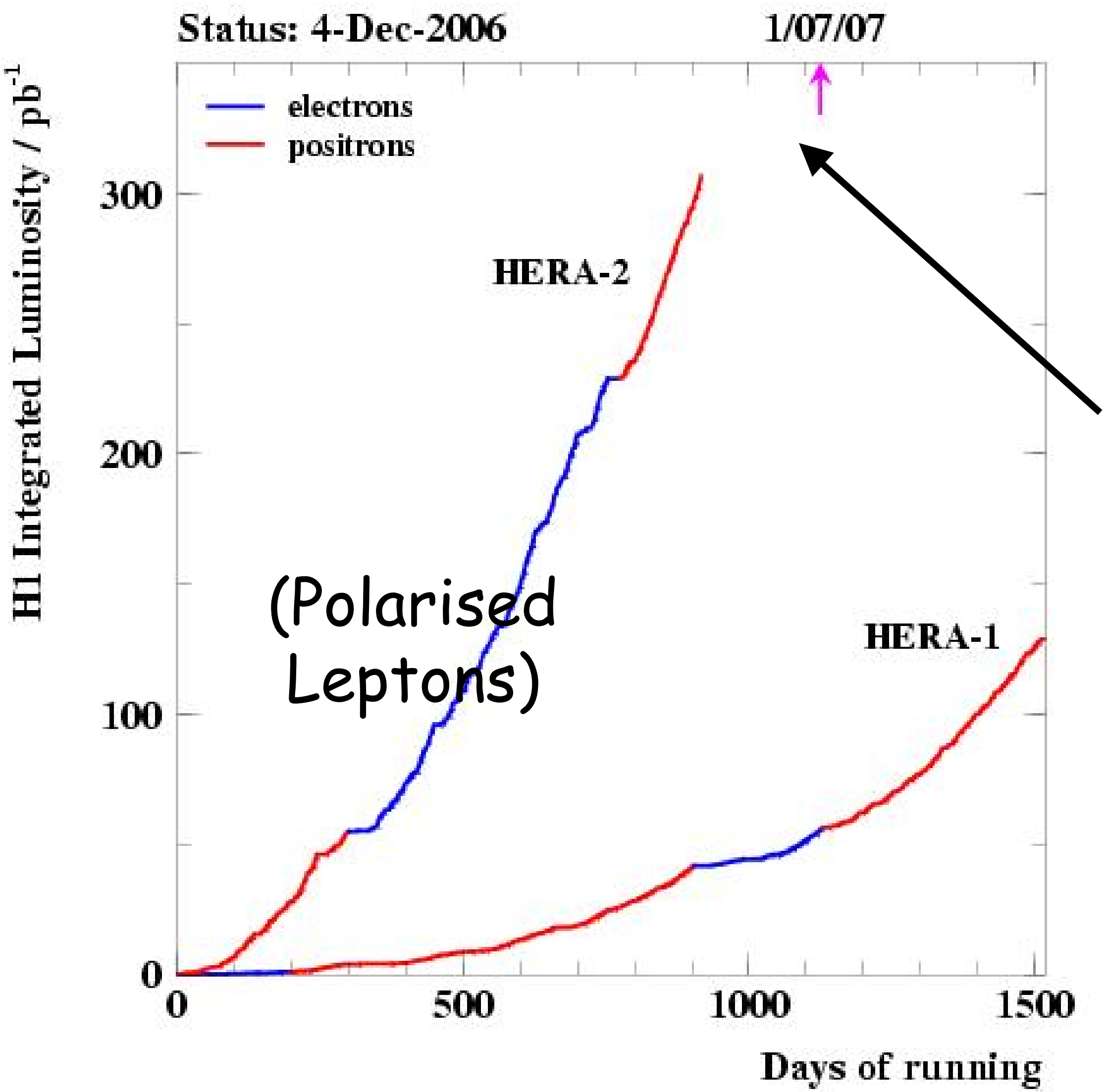




- Standard model does not allow right handed charged currents

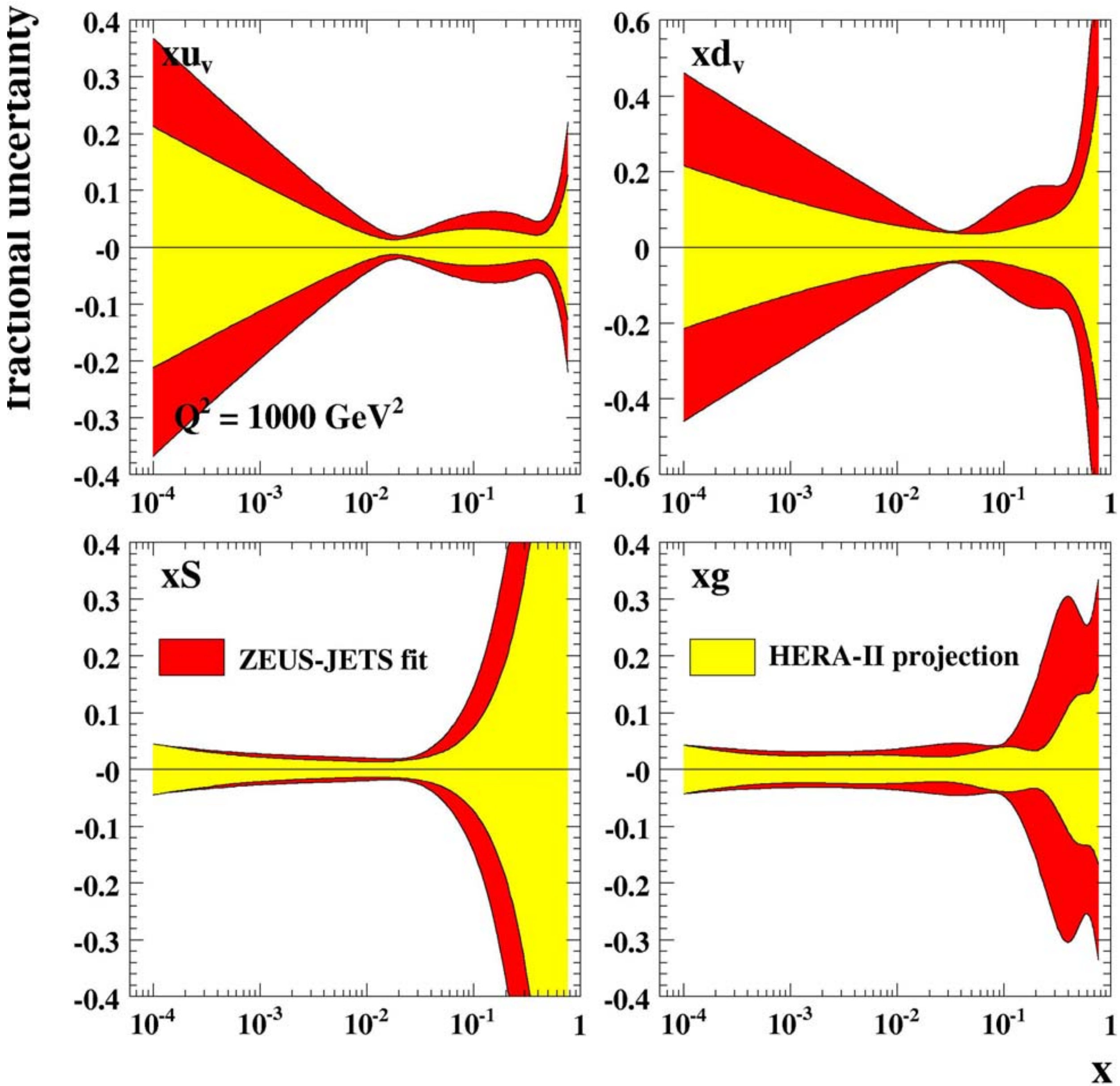
- Data consistent with prediction of linear dependence…
… $M(W_R) > 200$ GeV

HERA-II and the Future



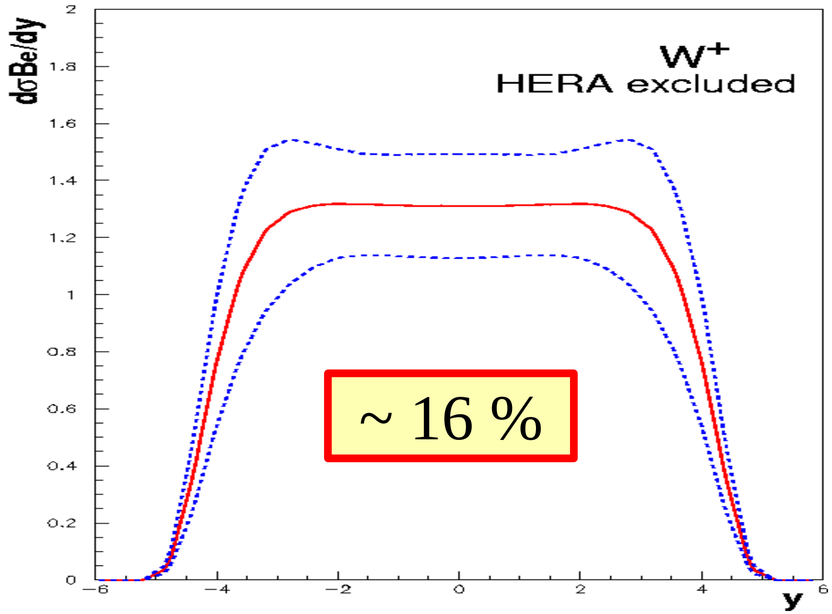
- HERA-I was ~ 130 pb^{-1}
- HERA-II will be ~ 320 pb^{-1} at full energy, plus a reduced Ep run at the end to measure F_L properly and test gluon density
- Data analysis underway, … first results appearing … many more high precision results to come!

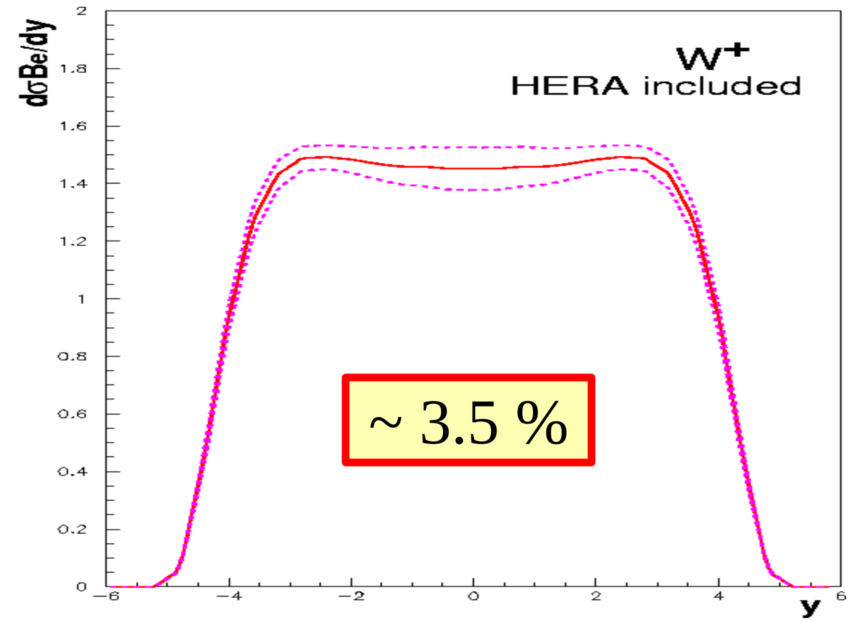
Current and Projected PDF Uncertainties



- Fractional uncertainty on quarks and gluons at high x will improve most with high luminosity data
- Confidence in gluon density will build with further direct tests.

Example of HERA Impact on LHC





LHC W boson cross section v rapidity …
… predictions with and without HERA data as input

Ongoing Workshop …

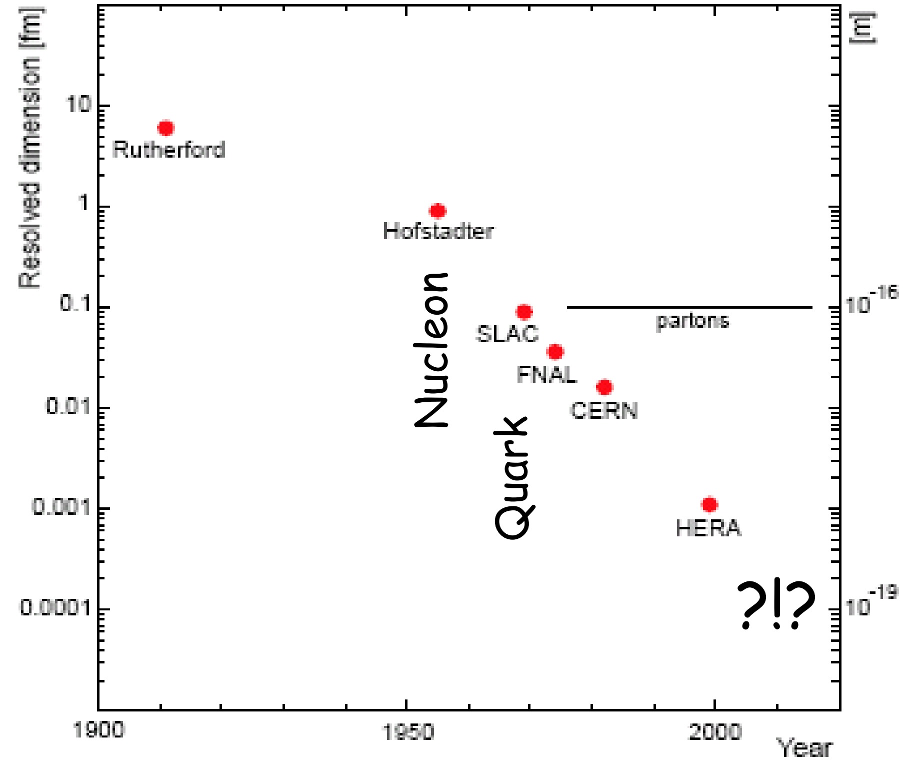
Continuous dialogue between HERA and LHC experiments
- how best to use information from HERA at LHC
- what is still needed from HERA.

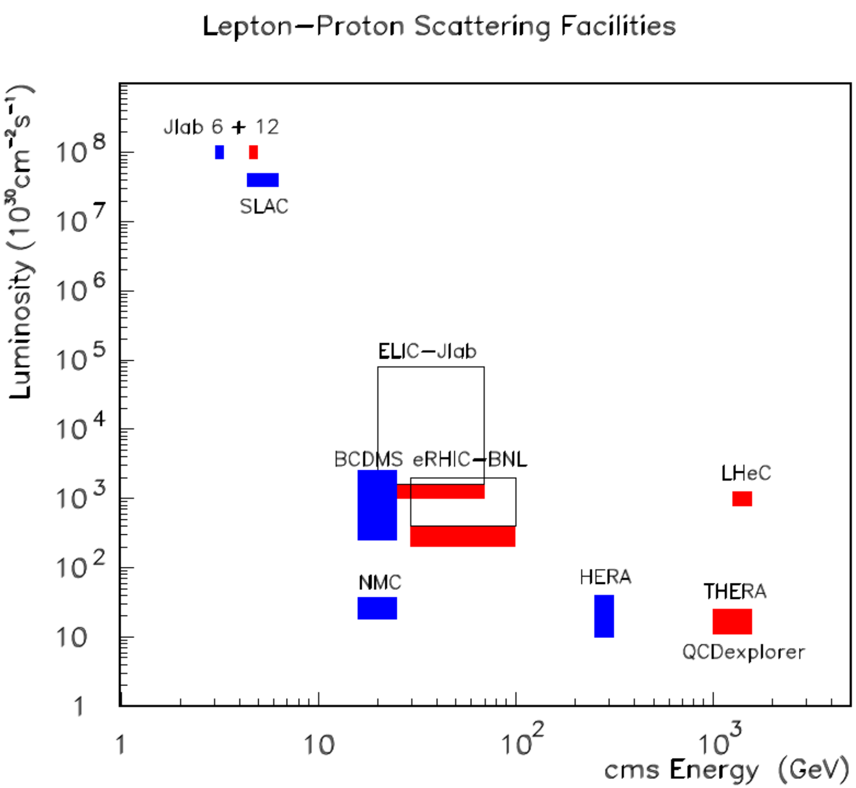
A possible future?

No high energy ep Physics Approved beyond 2007!..

LHeC: Latest of several proposals to take ep physics into the TeV energy range …

… but with unprecedented lumi!





- Combining LHC protons with a new electron beam (70 GeV) Is technically possible and pushes frontiers of ep physics:

… $x \rightarrow 10^{-7}$, $M_{eq} \rightarrow 1.4$TeV,
Resolved dimension $\rightarrow 10^{-19}$m

Summary

• HERA-I data has led to precise constraints on parton densities over a huge range of x and Q^2 ☺

• The proton at low x is a very high density (mostly) gluonic system!

- Already very much of interest at RHIC!
- Will provide essential input to the LHC

• Still requires more tests of gluon / DGLAP evolution theory

- Full consequences of such a high density QCD system In low coupling limit still to be explored

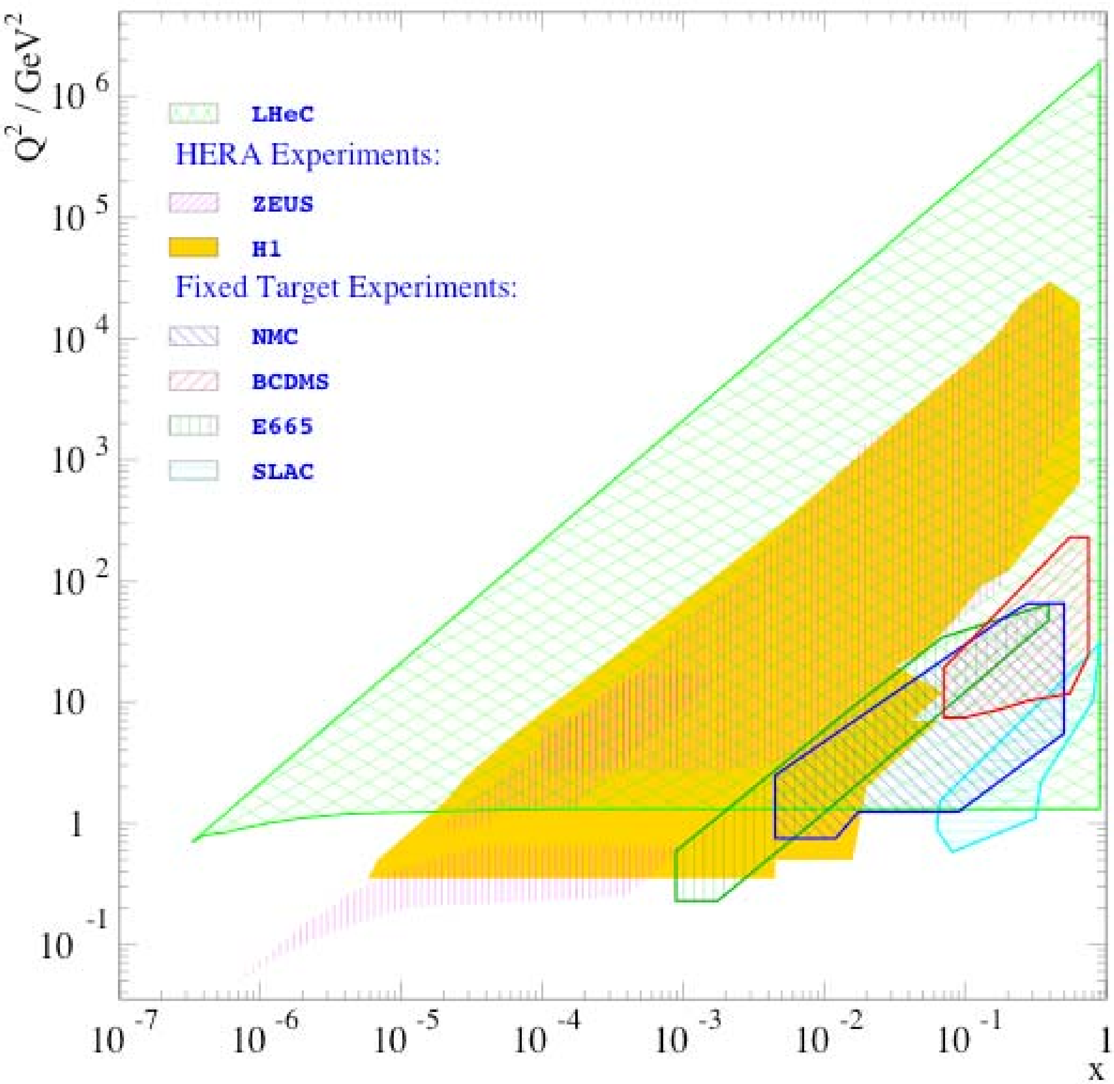
• HERA-II data only just beginning to appear!

much more to come!

• Could Lepton-nucleon scattering itself have a future at LHC?

Back-ups follow …

Inclusive LHeC Kinematics



$$E_e = 70 \text{ GeV}$$
$$E_p = 7 \text{ TeV}$$
$$\sqrt{s} = 1.4 \text{ TeV}$$

High Q^2 Frontier

$$M_{eq} \le 1.4 \text{ TeV}$$
$$Q^2 \le 2.10^6 \text{ GeV}^2$$

Low x Frontier

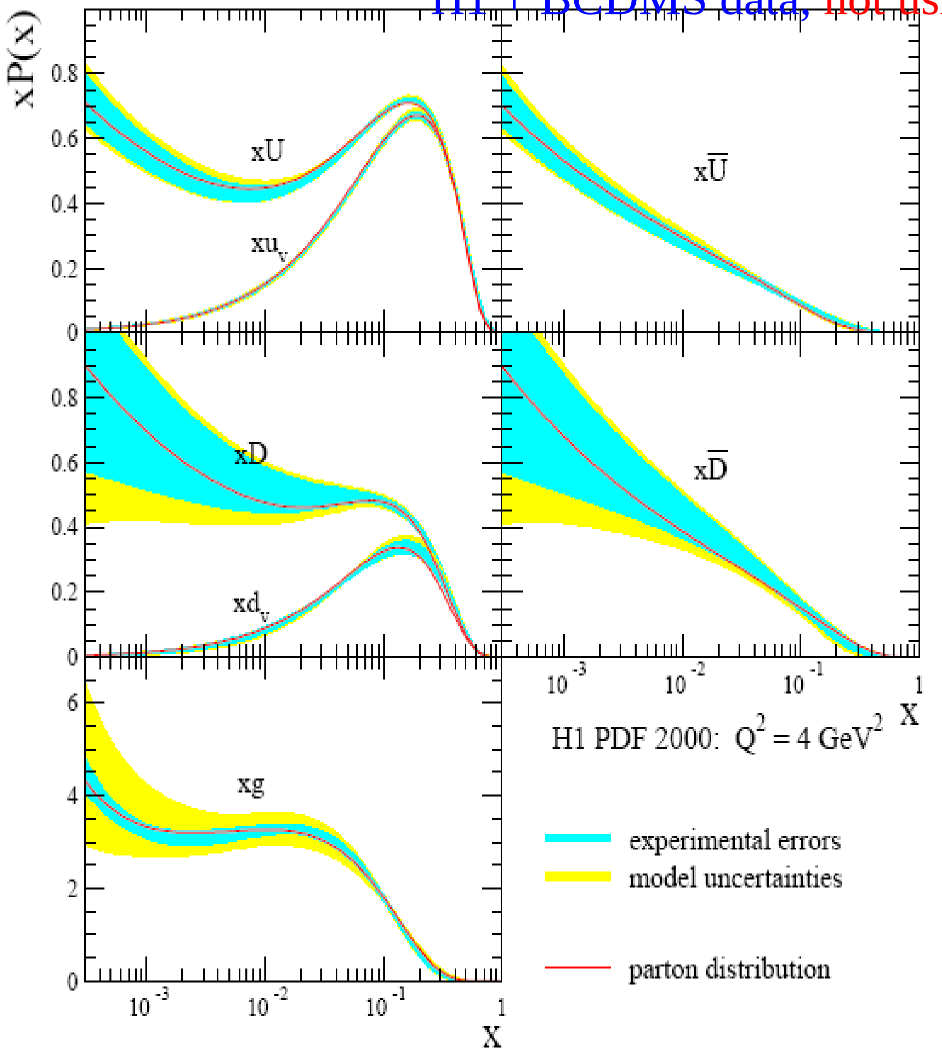
$$W \le 1.4 \text{ TeV}$$
$$x \ge 5.10^{-7} \text{ at } Q^2 \le 1 \text{ GeV}^2$$

Still Many Open Questions

Global fits assume u= d at small x

from M. Klein, B. Reisert

H1 + BCDMS data, not using



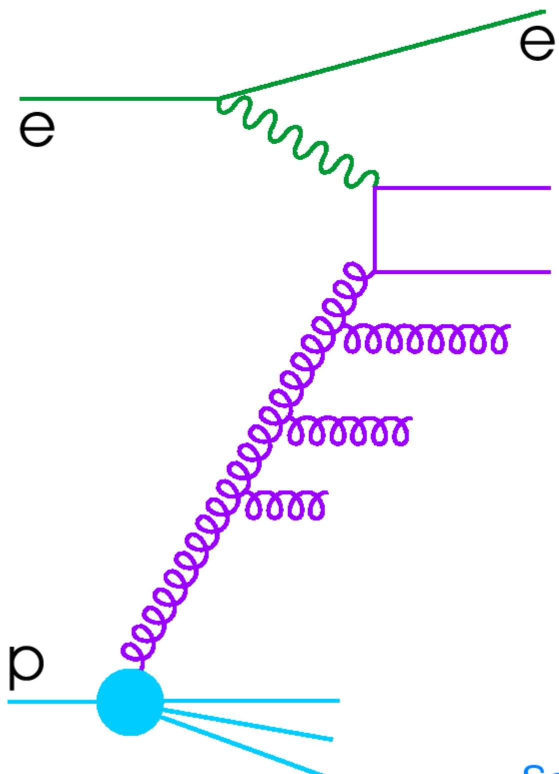
Technological Challenges

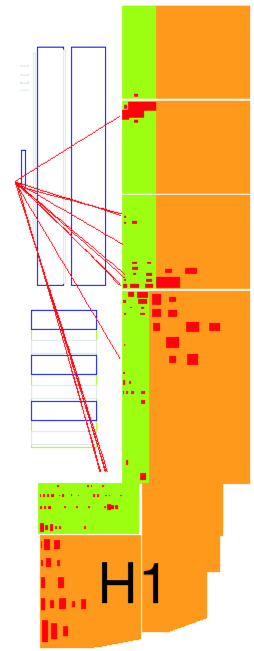
H1 & CMS Data Acquisition Parameters

A comparison of the main DAQ System parameters and the relevance of H1 into the future

Parameter	*H1 1991 to 2006*	*CMS 2007 to 202?*
Bunch crossing interval	96 ns	25 ns
Level-1 Trigger Rate	100 - 300 Hz	100 kHz
Total no. of electronics channels	≈ 750,000	≈ 12,000,000
Average total final event size	≈ 100 kBytes	≈ 1 MByte
Average size from trackers	60 - 80 kBytes	≈ 300 kBytes
Number of Branch/RUs	12	256 / 512
Event builder bandwidth	≈ 25 MBytes/s	≈ 100 GBytes/s
Data production	≈ 10 GByte/day	≈ TByte/day
Number of readout crates	≈ 150	≈ 300
Number of electronics boards	≈ 2,000	≈ 5,000
Total Cost DAQ + Electronics	≈ $15 M	≈ $100 M

Beyond Inclusive Measurements





Structure Functions

Precision QCD tests

Alpha-s

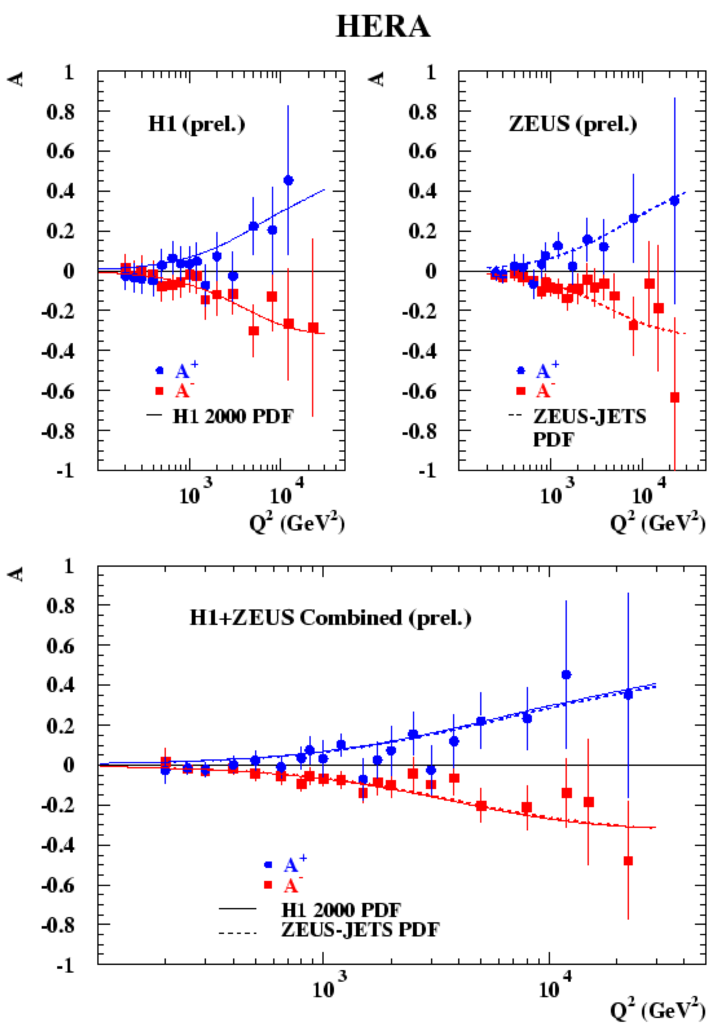
Parton dynamics

Rapidity Gaps, Diffraction

Searches at highest $\sqrt{s}$ with initial state lepton

Hadronic final states test our understanding of parton dynamics in complementary ways..... Is the huge gluon for real?

… and Polarised Neutral Current



Sensitive to axial and Vector couplings, u/d …