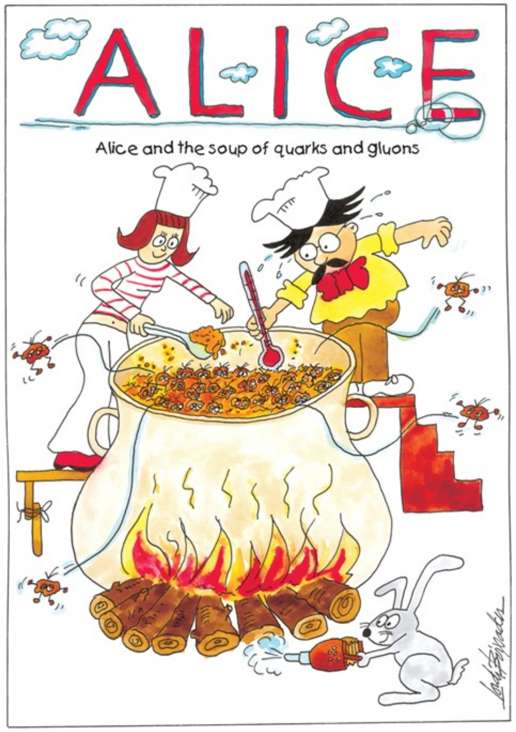
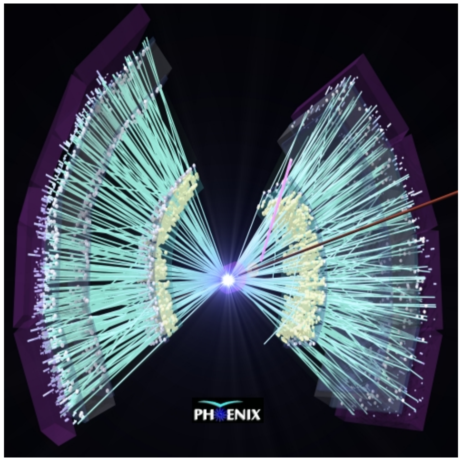
Last Monday: e^+e^-, LEP-II & B Factories

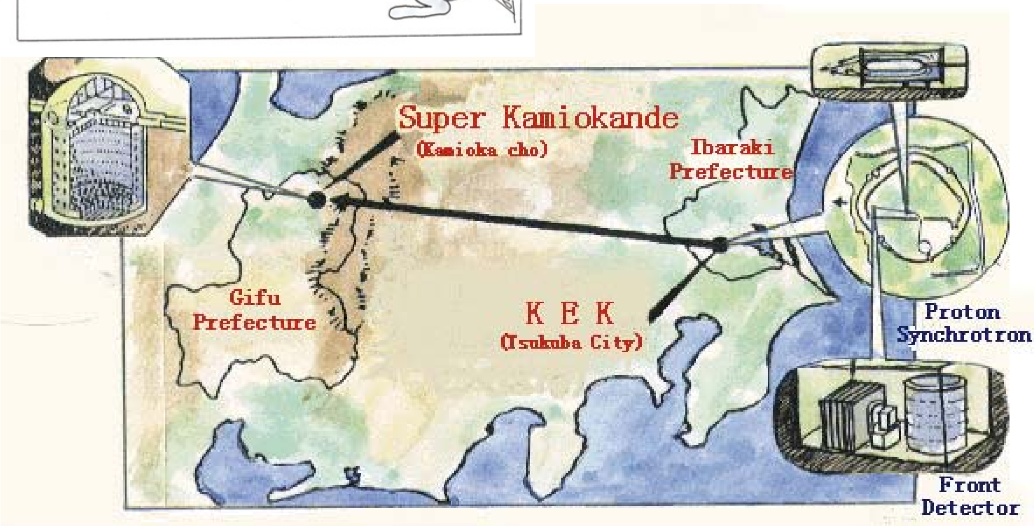
Last Friday: Directed private study …

Heavy ion collisions

Neutrino oscillations



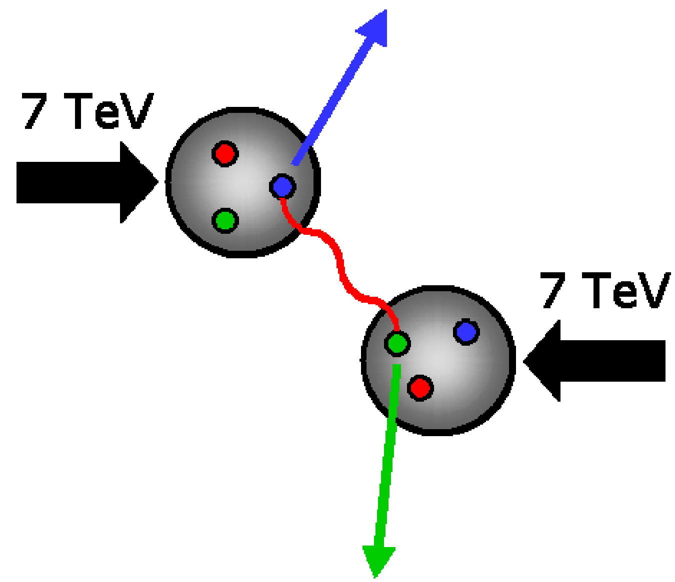




… plan to have one
Further `private
Reading' lecture on
These topics when I
Am next away
… there will also be
An opportunity to
Discuss open questions
In a following lecture.

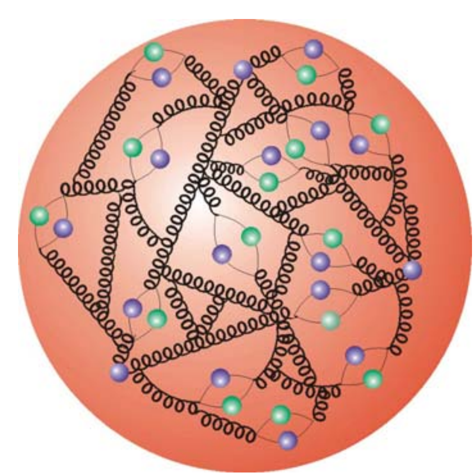
Today's Lecture: ep Physics and Proton Structure

... when two protons collide hard at the LHC, it is the quarks and gluons inside them that interact with one another

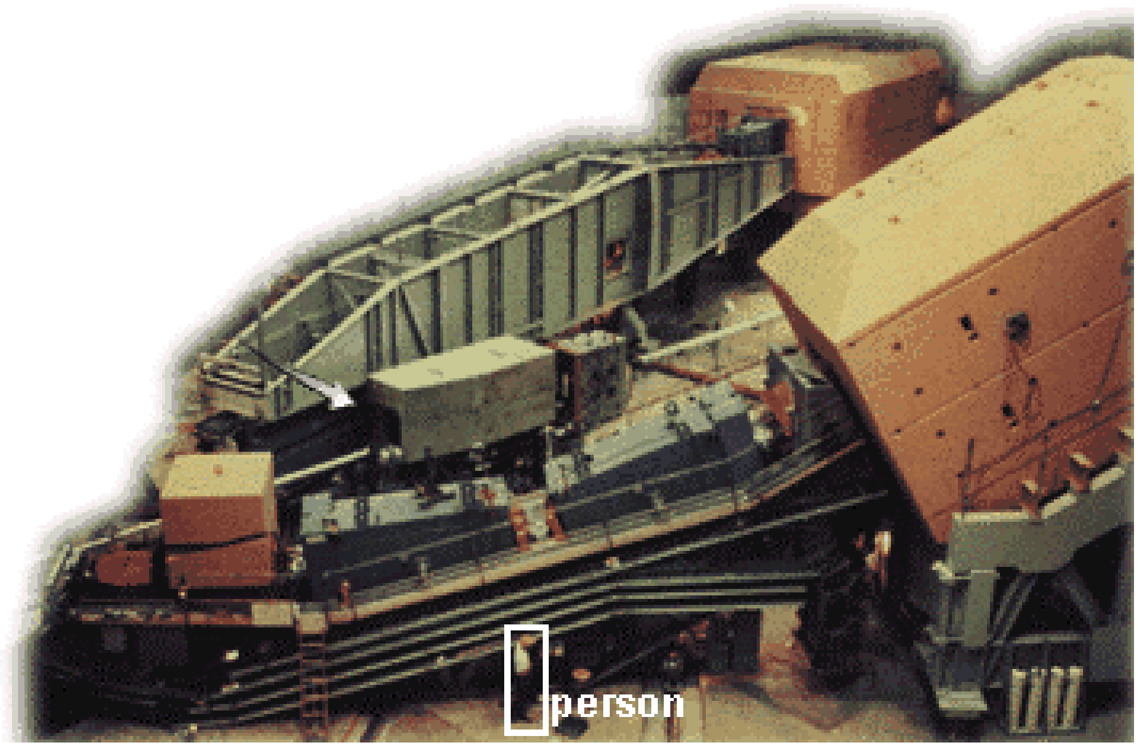


... a knowledge of the quark and gluon content of the proton is essential to understand LHC data

... through the `Deep Inelastic scattering' process, electrons may be used to `photograph' the proton in very fine detail ...



First Direct Observation of Quarks (1969)

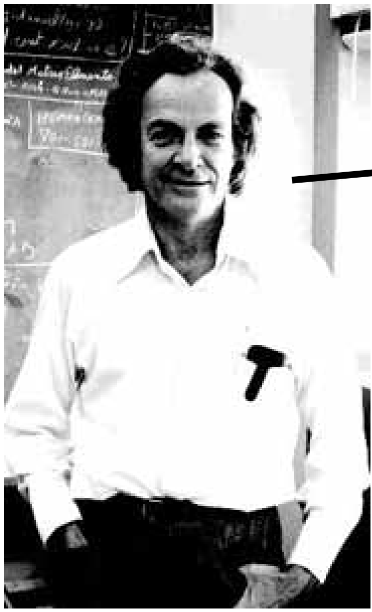


ESA experiment
At SLAC

Nobel prize (1990)

- Linear electron accelerator
- Fixed proton target
- Measure cross section v scattered electron energy and angle
- Results make sense only if proton contains point-like constituents

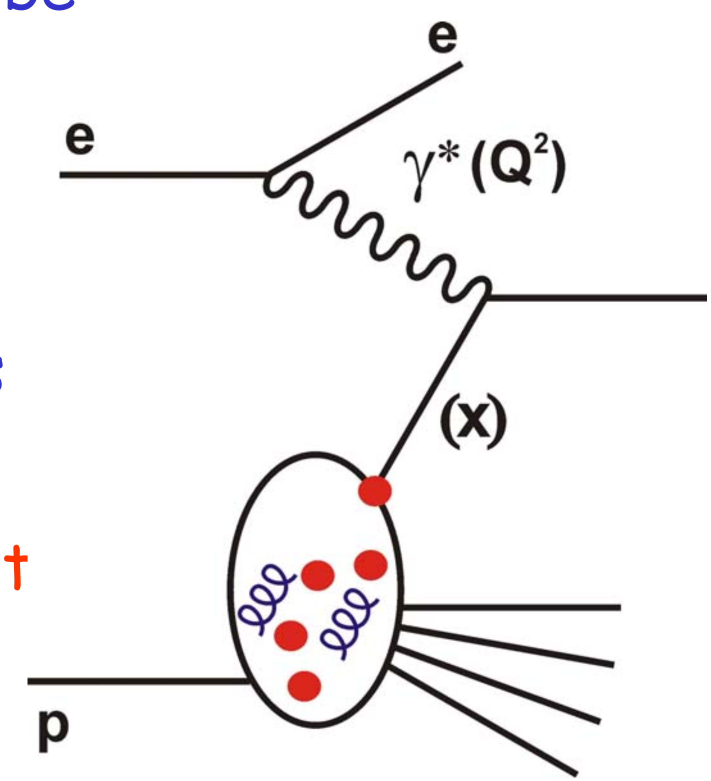
Why Deep Inelastic Scattering?



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

`Deep Inelastic Scattering' (DIS): electrons …

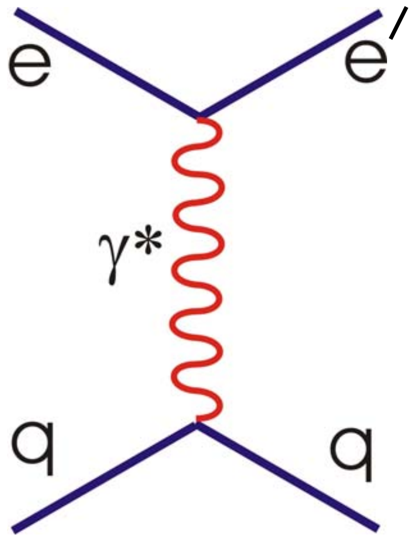
- → Are a point-like probe
- → Don't feel strong colour field
- → An electromagnetic `snapshot' of the strong interactions going on in proton



x = Momentum fraction of struck part

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

Basics of Deep Inelastic Scattering

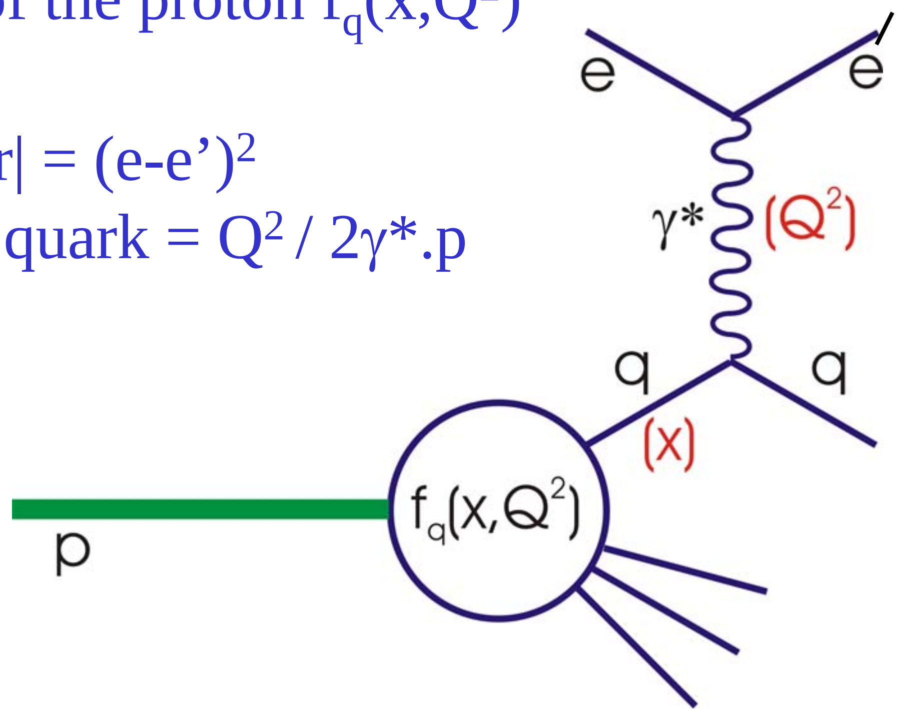


- Underlying process is just QED
- (LEP rotated through 90 degrees)
- t-channel (virtual) photon exchange

- The `unknown' is the quark Density of the proton $f_q(x,Q^2)$

- Q^2 = |squared 4-momentum transfer| = $(e-e')^2$
- x = fractional momentum of struck quark = $Q^2 / 2\gamma^*.p$

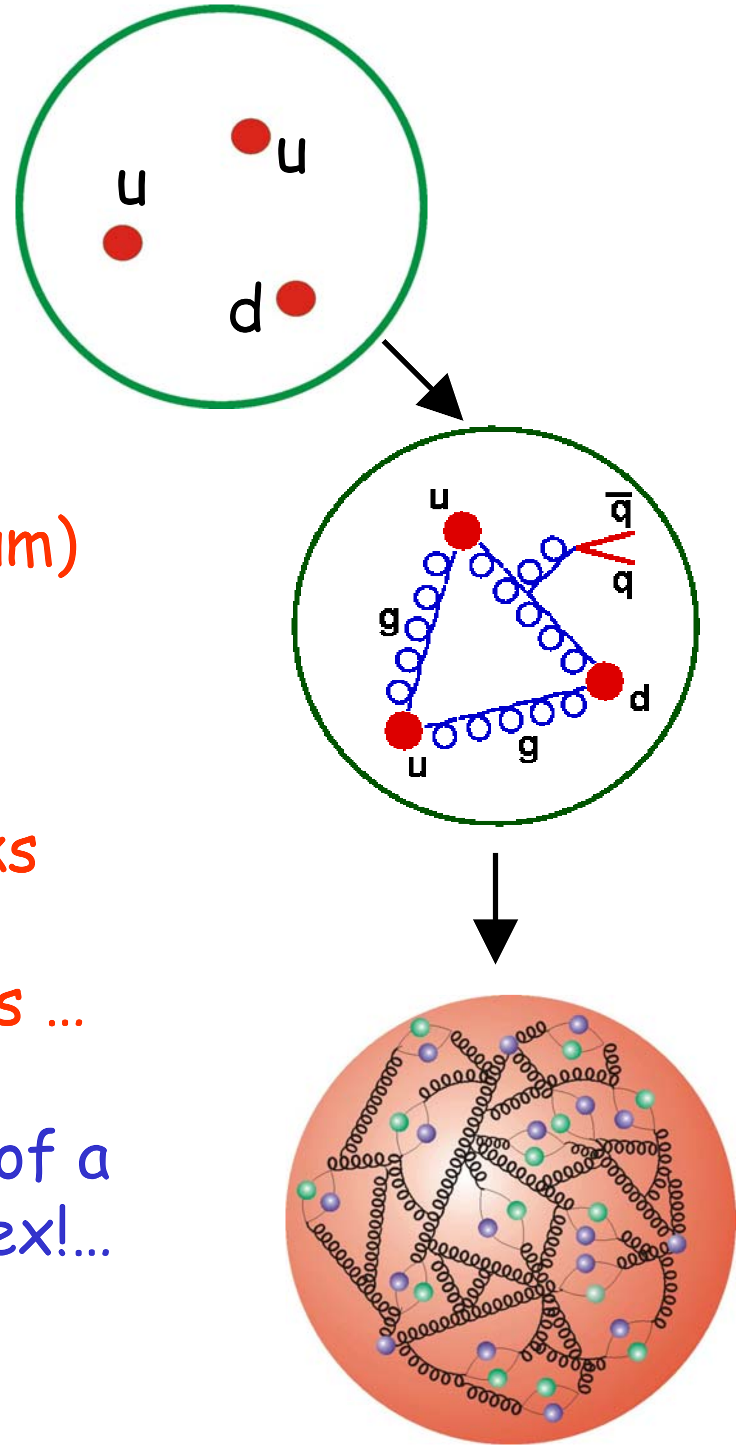
ep cross section determines
quark density via photon coupling:
$\Sigma_q e_q^2 f_q(x,Q^2)$



So What is a Proton?…

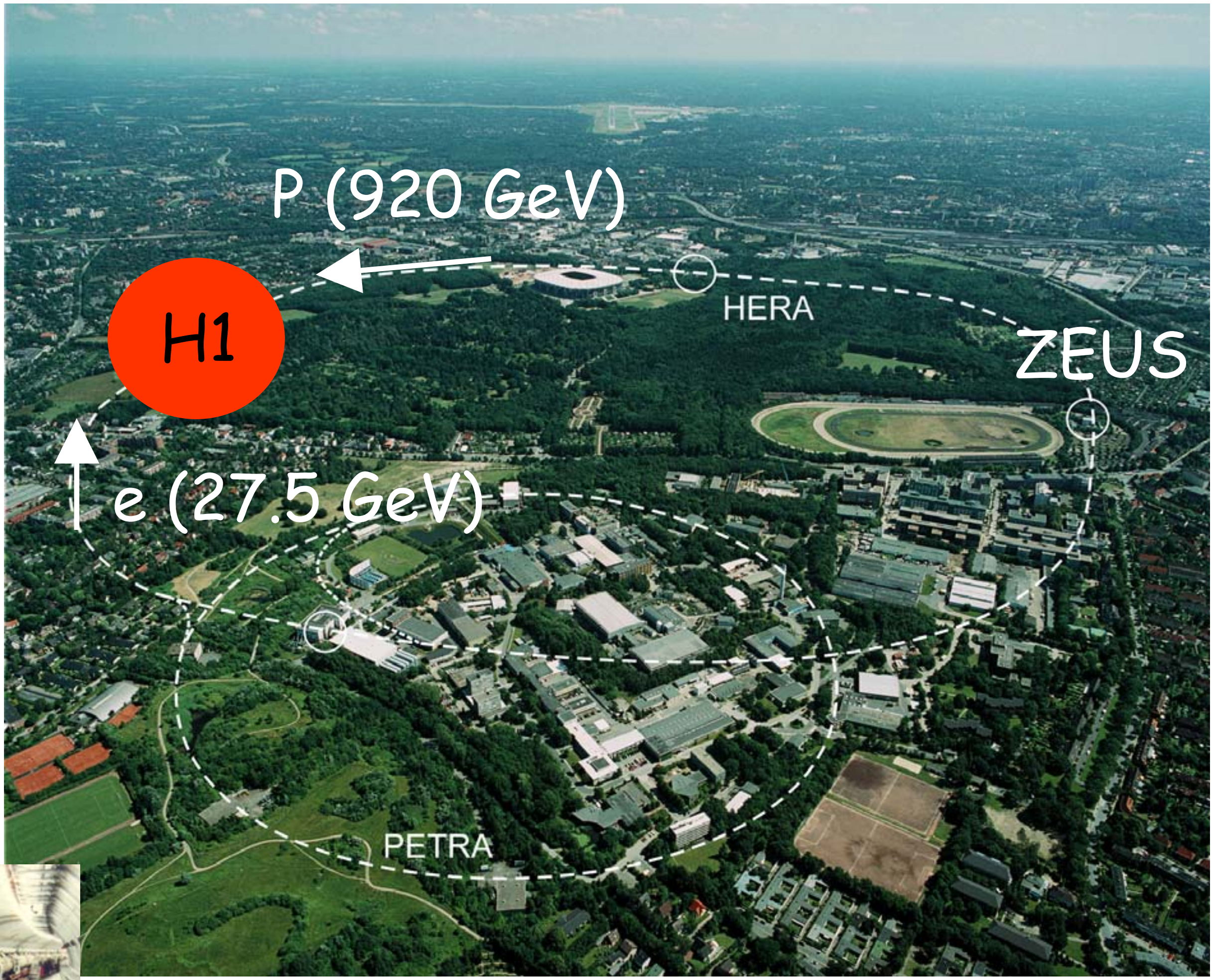
Many DIS experiments in the 1970s and 1980s …

- 2 up and 1 down **valence quarks**, silly!
- … and some **gluons** (~50% of momentum)
- … 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!…
- → Quantum Chromodynamics (1974)



HERA

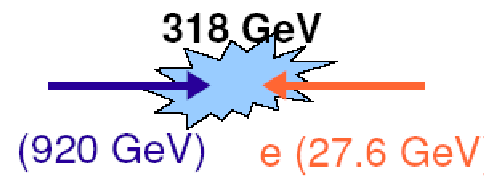
- DESY, Hamburg (1992-2007)
- The world's only ever ep Collider
- Fixed target equiv. energy of 50TeV



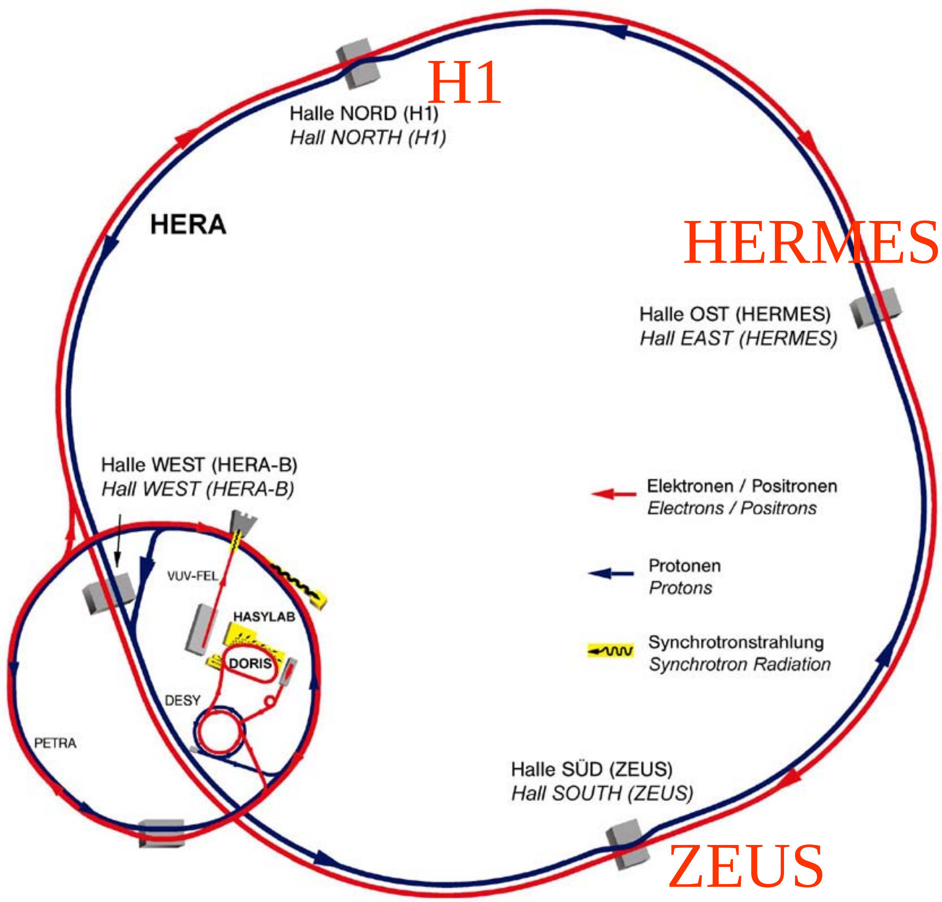
"World's most powerful microscope"
Operational 1992-2007

… many physics topics, but today we will stick to proton structure

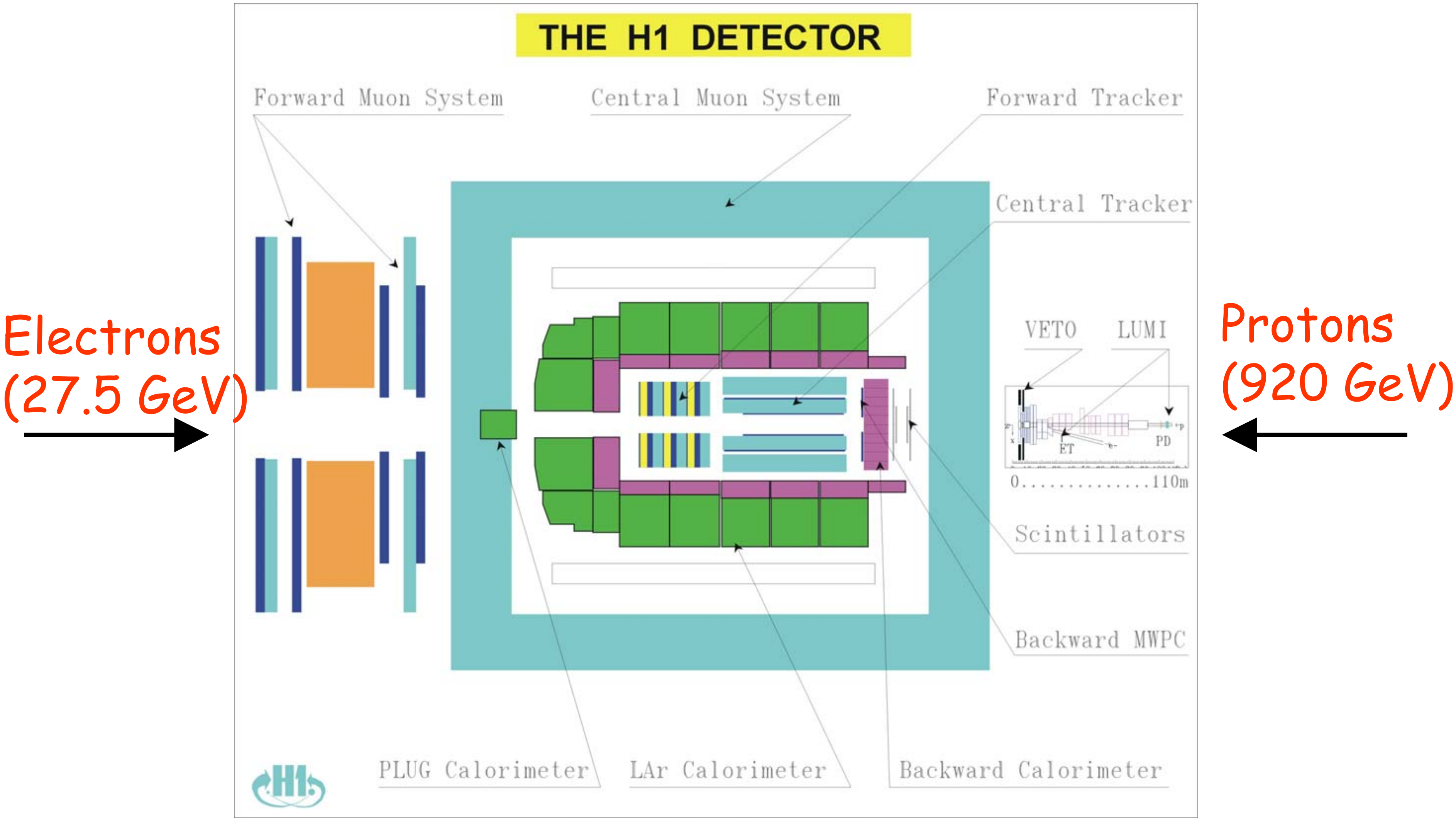
HERA lay-out and kinematics



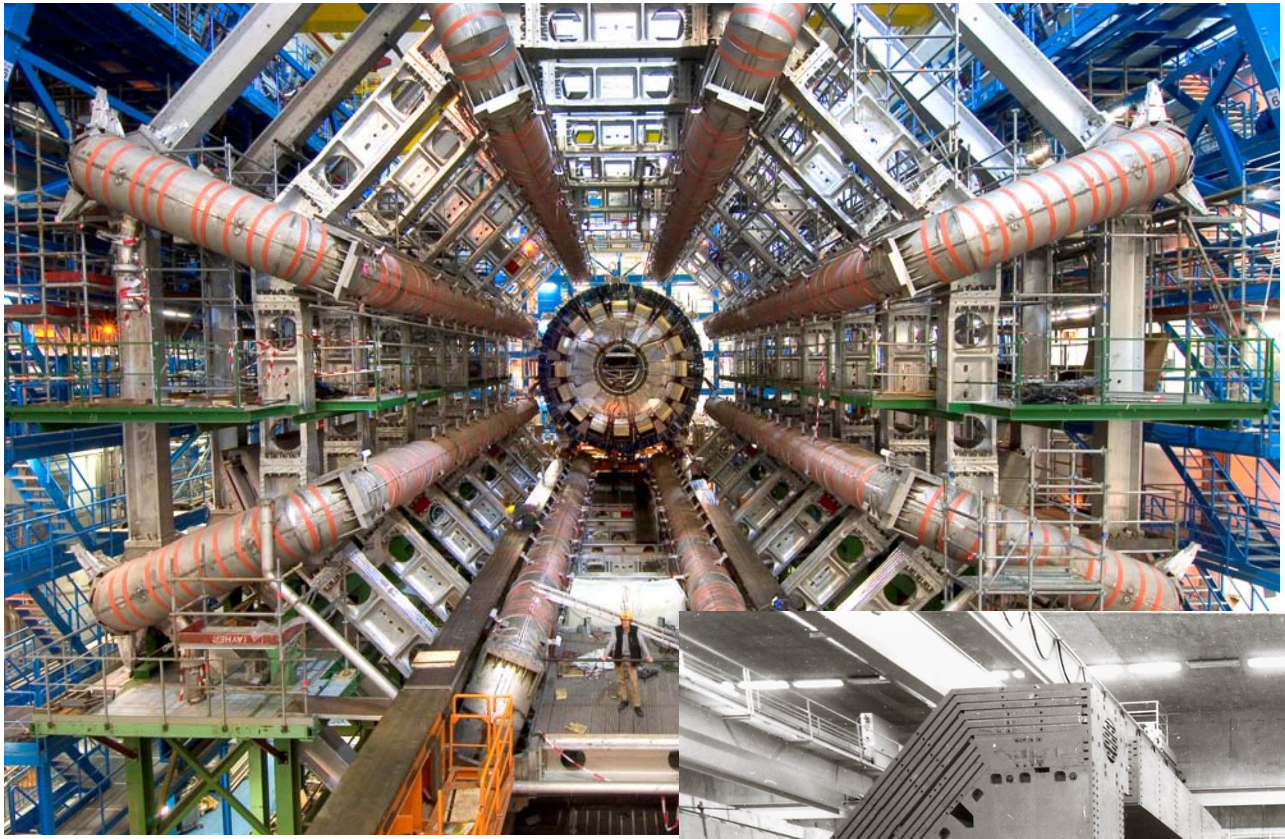
Electrons at 27.5 GeV
Protons at 920 GeV



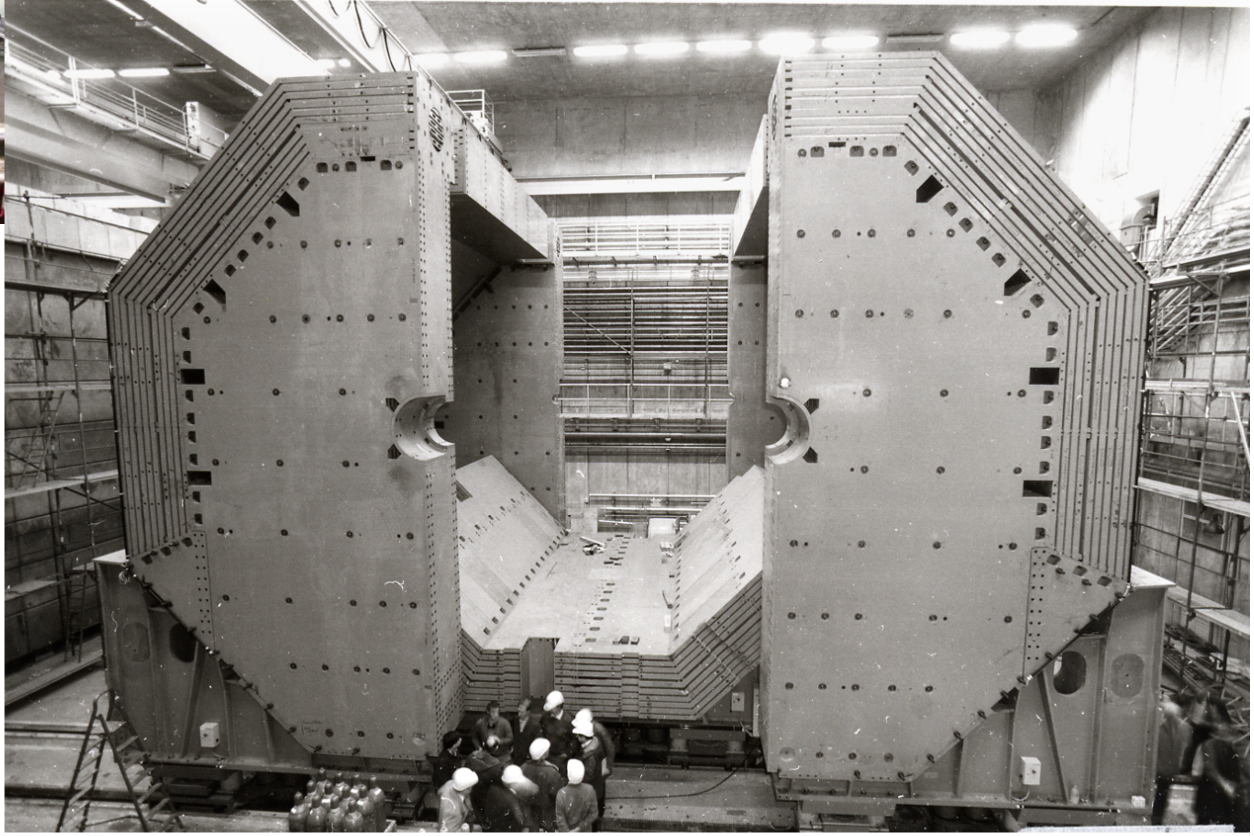
- CMS energy = 318 GeV
- Equivalent to fixed target experiment with an electron beam energy of 54 TeV!
- Max $Q^2 = s = 101200\ \text{GeV}^2$
- Sensitive to structures on scale of 10^{-18} m (uncertainty ppl)
- For $Q^2 = 1\ \text{GeV}^2$, min $x = 10^{-5}$
- cf Fixed Target: min $x \sim 0.001$
  max $Q^2 \sim 1000\ \text{GeV}^2$



- H1 and ZEUS built to study DIS at high Q^2 and low x
- Asymmetric design, reflecting asymmetric beam energies
- Hermetic detector → measure hadrons as well as electron

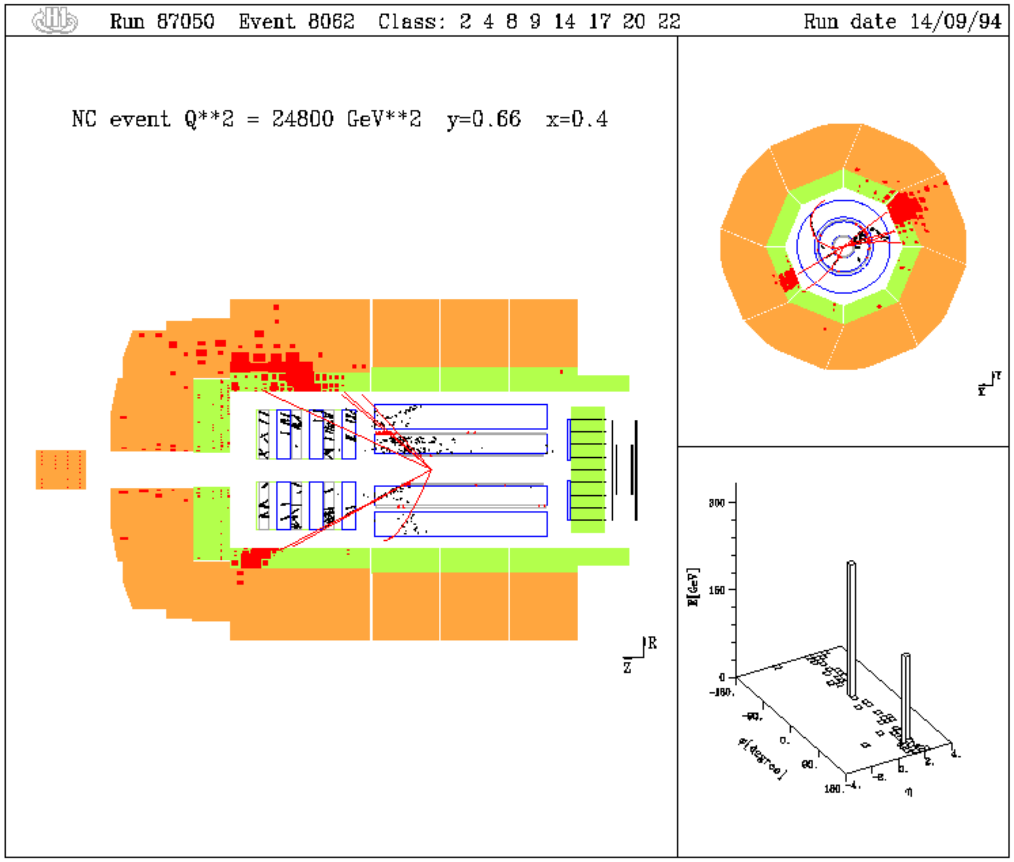


Scale:
H1 v
ATLAS

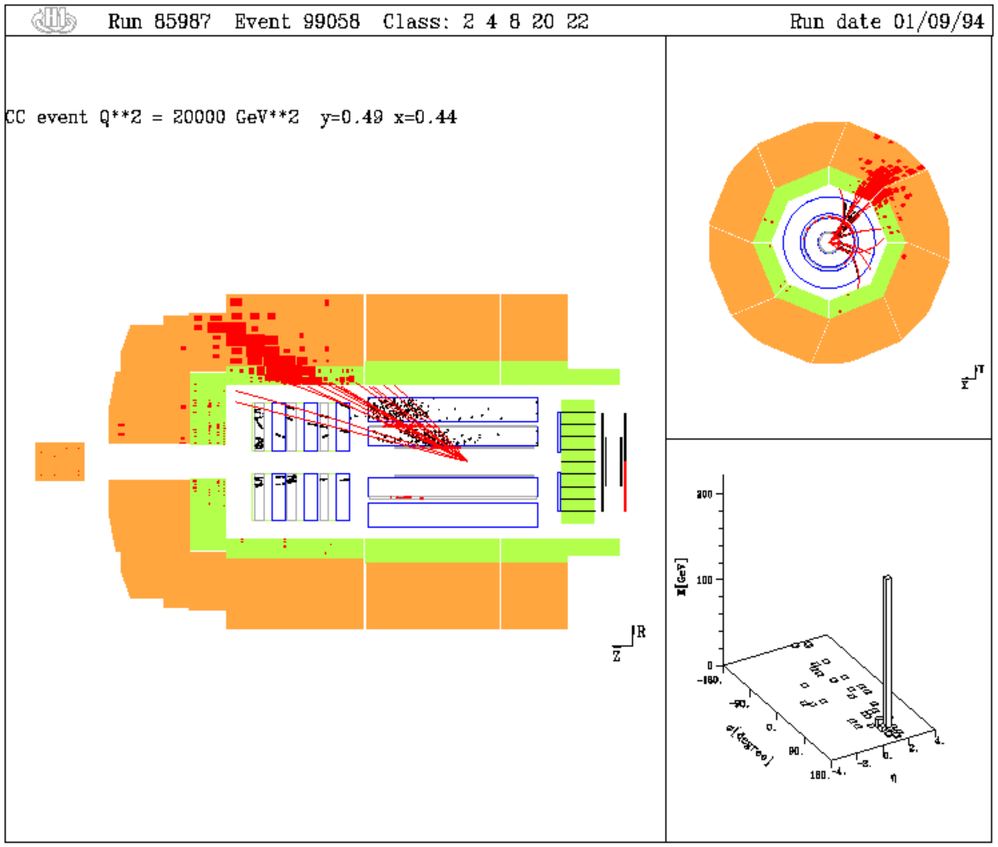


Early H1 Collaboration Mugshot

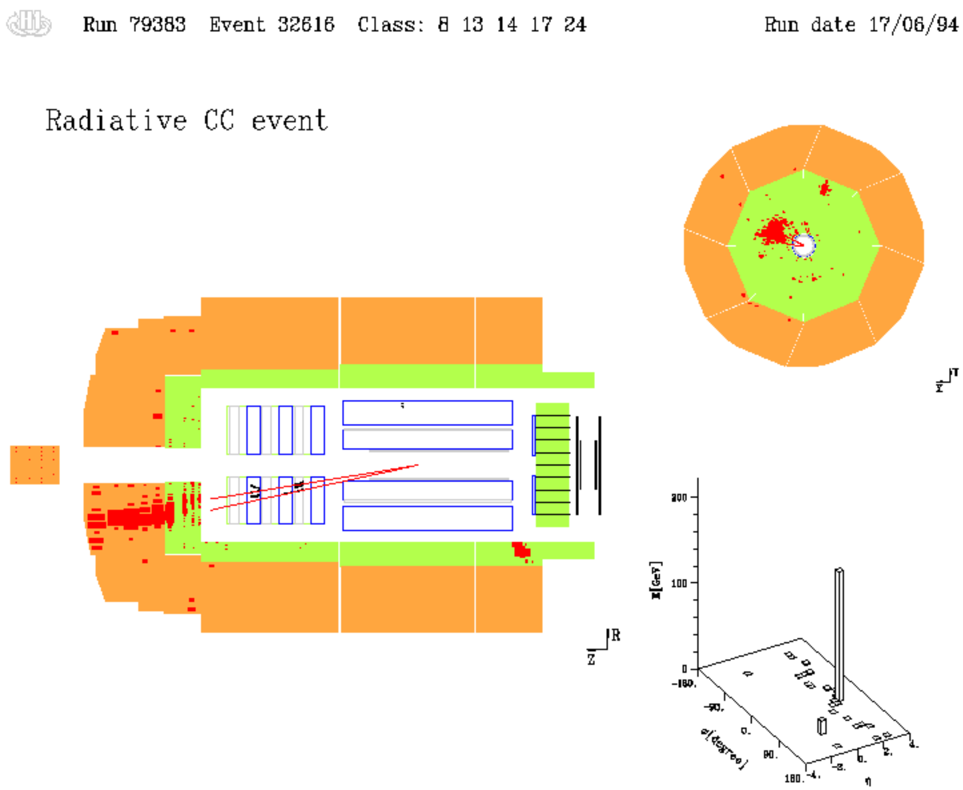
A HERA event to interpret ….



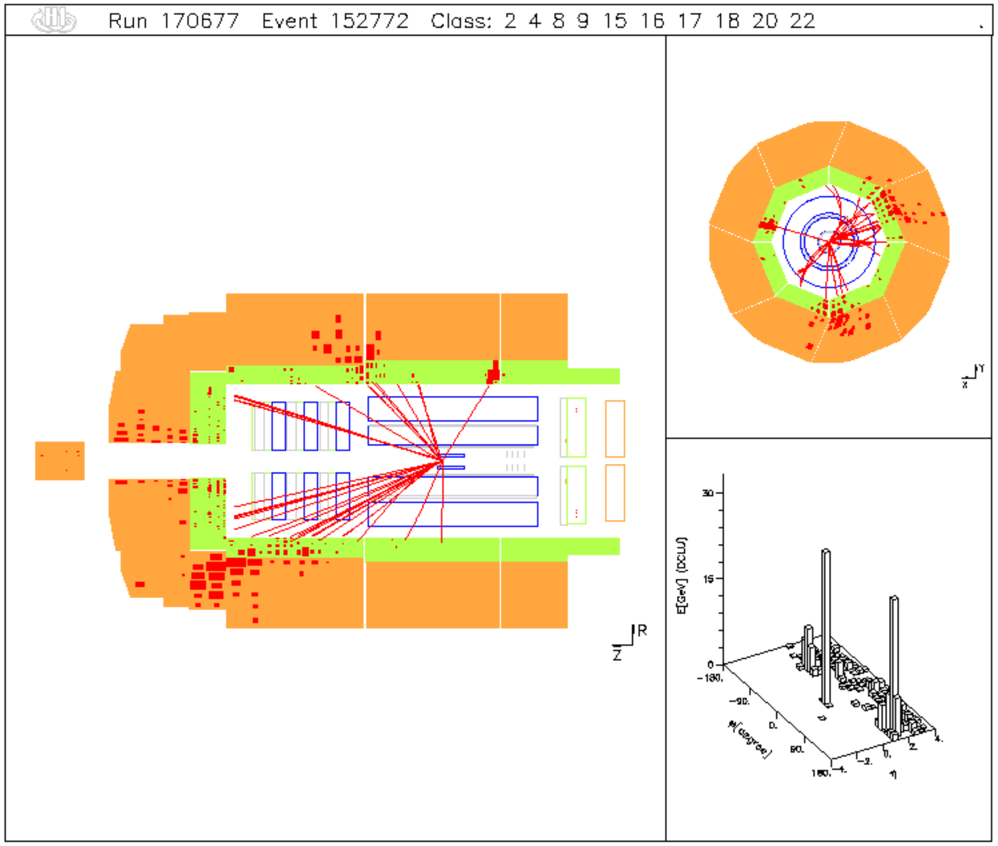
Another one


Run 85987 Event 99058 Class: 2 4 8 20 22
Run date 01/09/94
CC event Q**2 = 20000 GeV**2 y=0.49 x=0.44

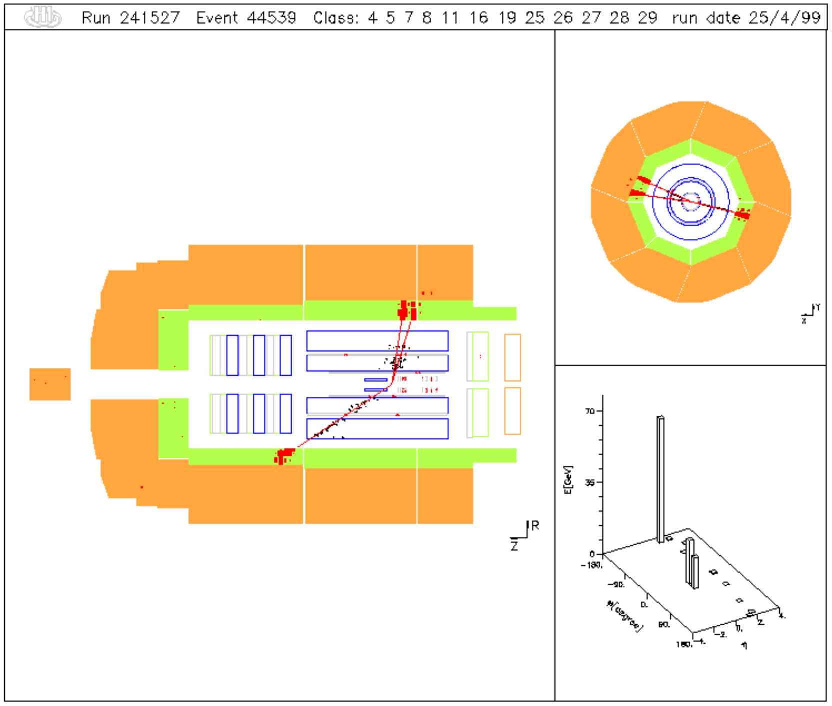
…. And another one



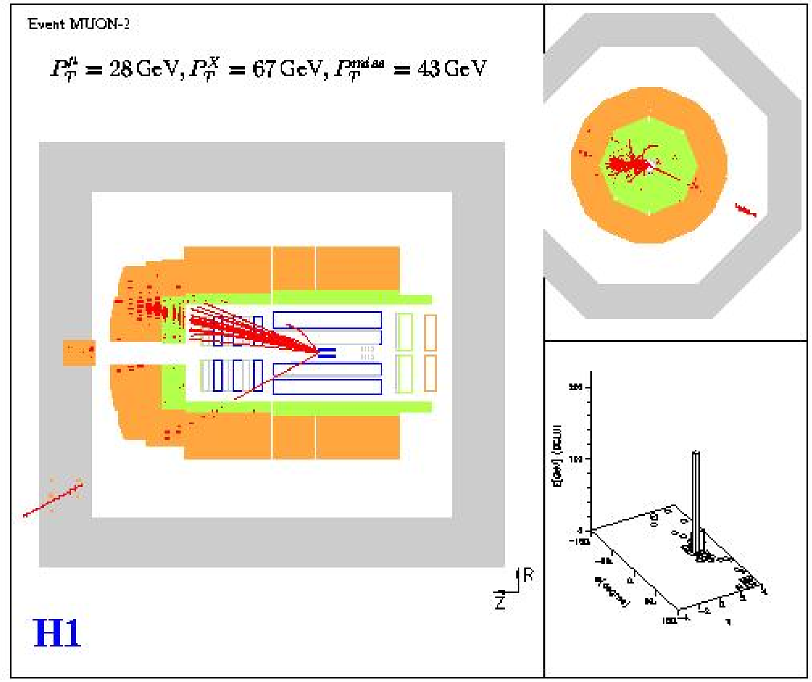
…. One more


Run 170677 Event 152772 Class: 2 4 8 9 15 16 17 18 20 22
R
Z
Y
X
E[GeV] (ocu)
30
15
0

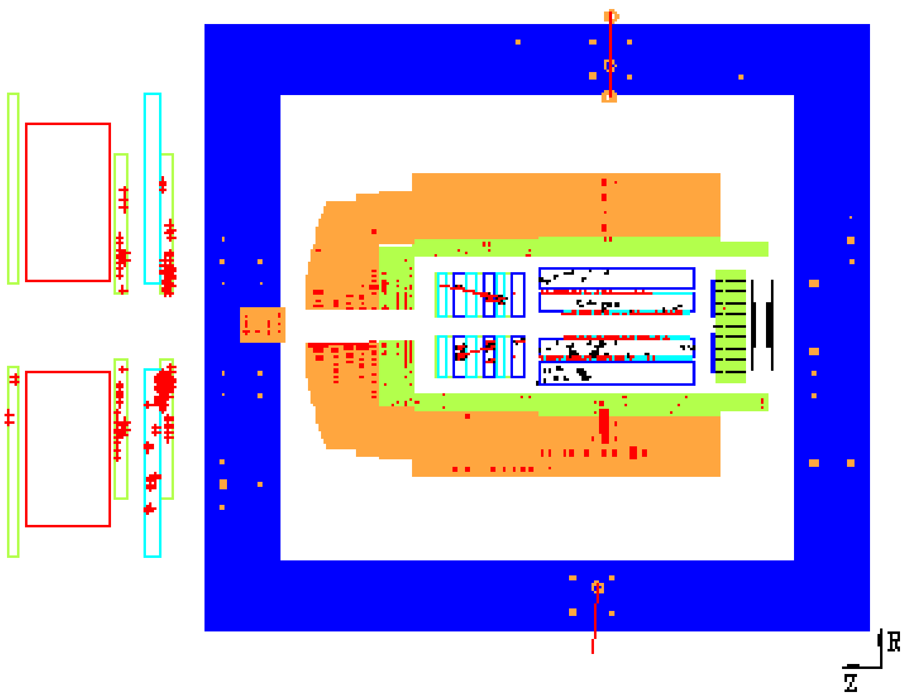
2 harder ones …. What are they?

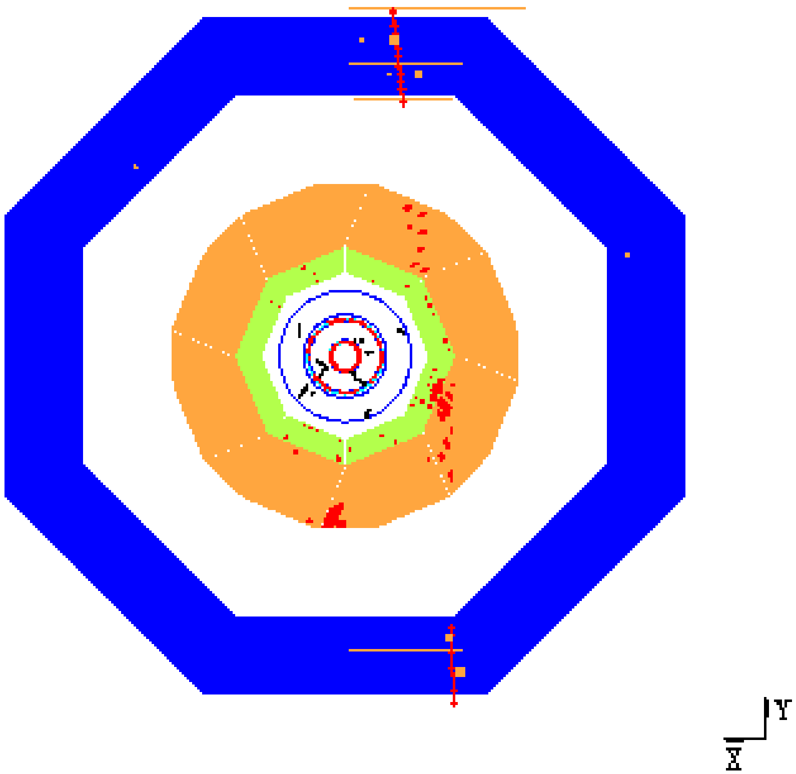


$e \, ' \, p \rightarrow \mu \, ' \, X$



A really nasty one …..



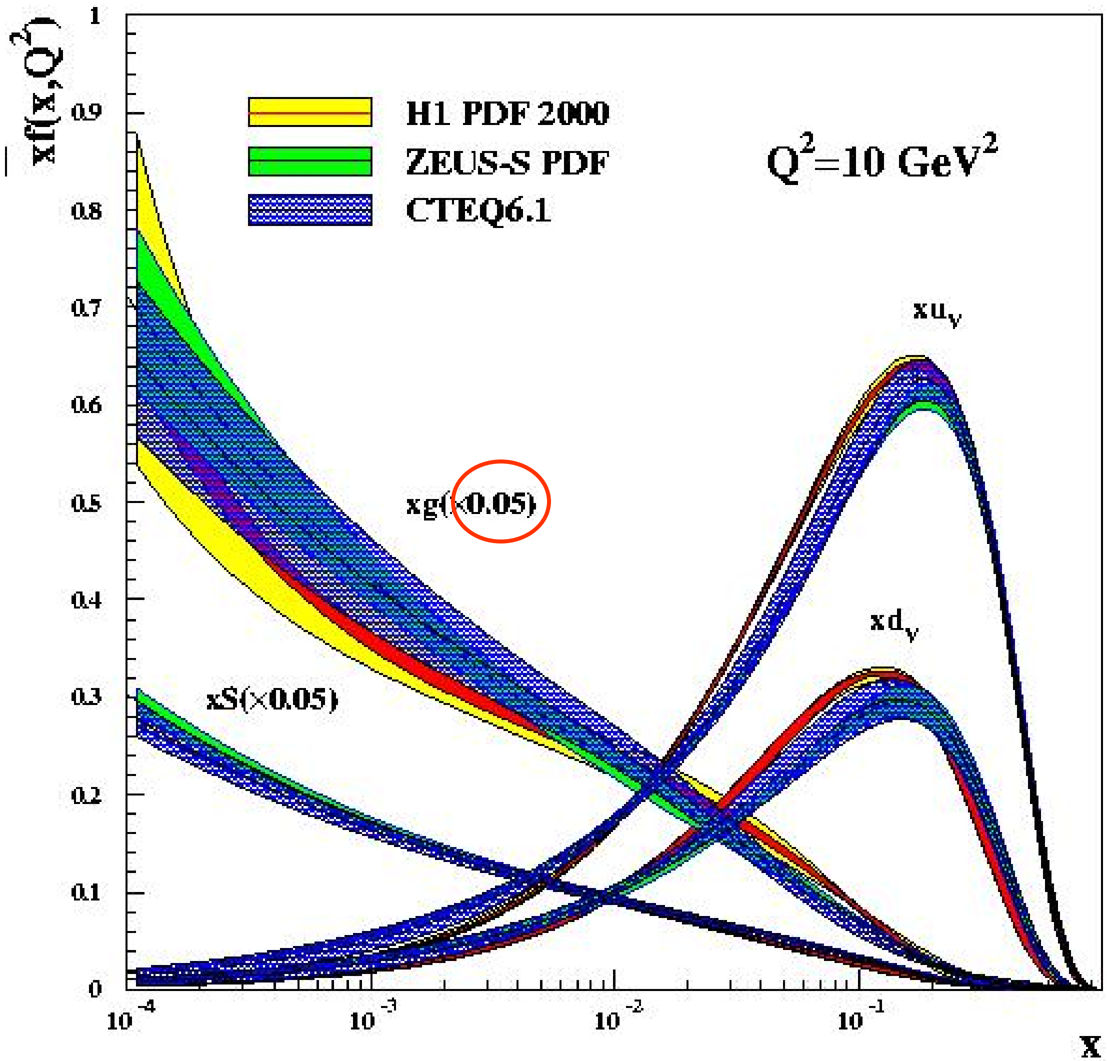


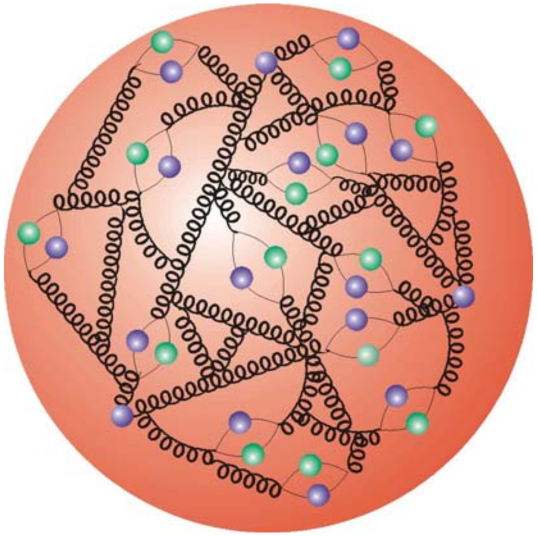
Nightmare event! Simultaneous overlay of …..

- Cosmic muon travelling vertically
- Beam halo muon travelling horizontally
- Proton beam interaction with gas in beampipe

The Quark and Gluon Content of the Proton

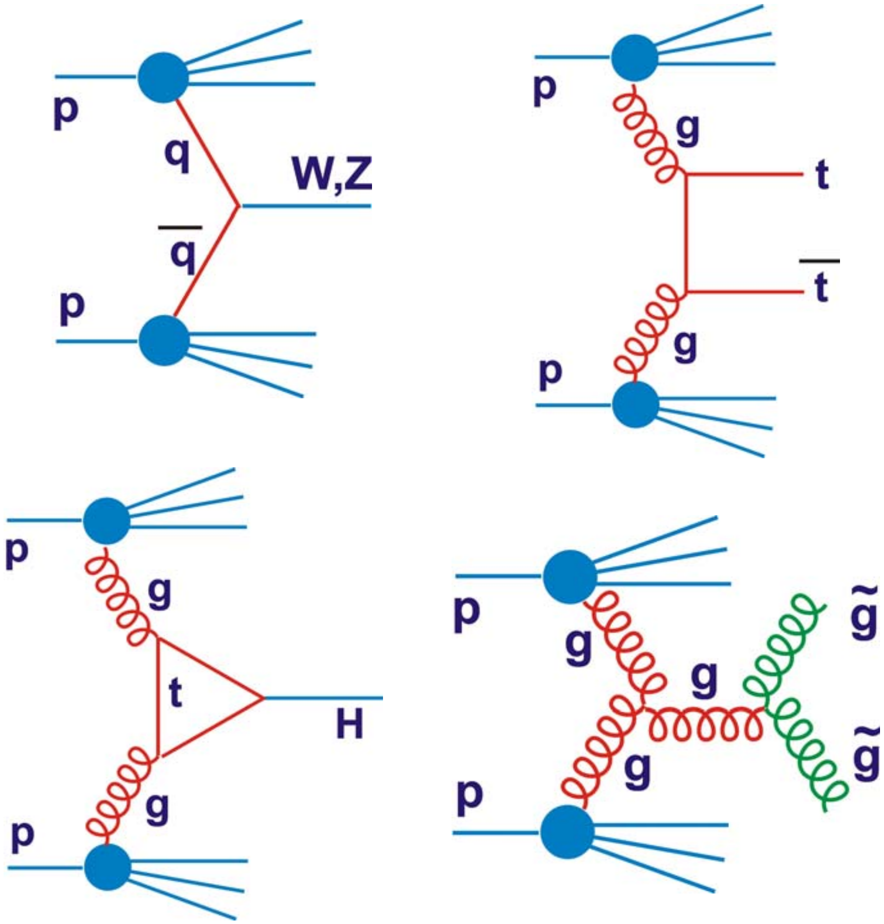
u_v and d_v are valence quarks
S is sea, g is gluon

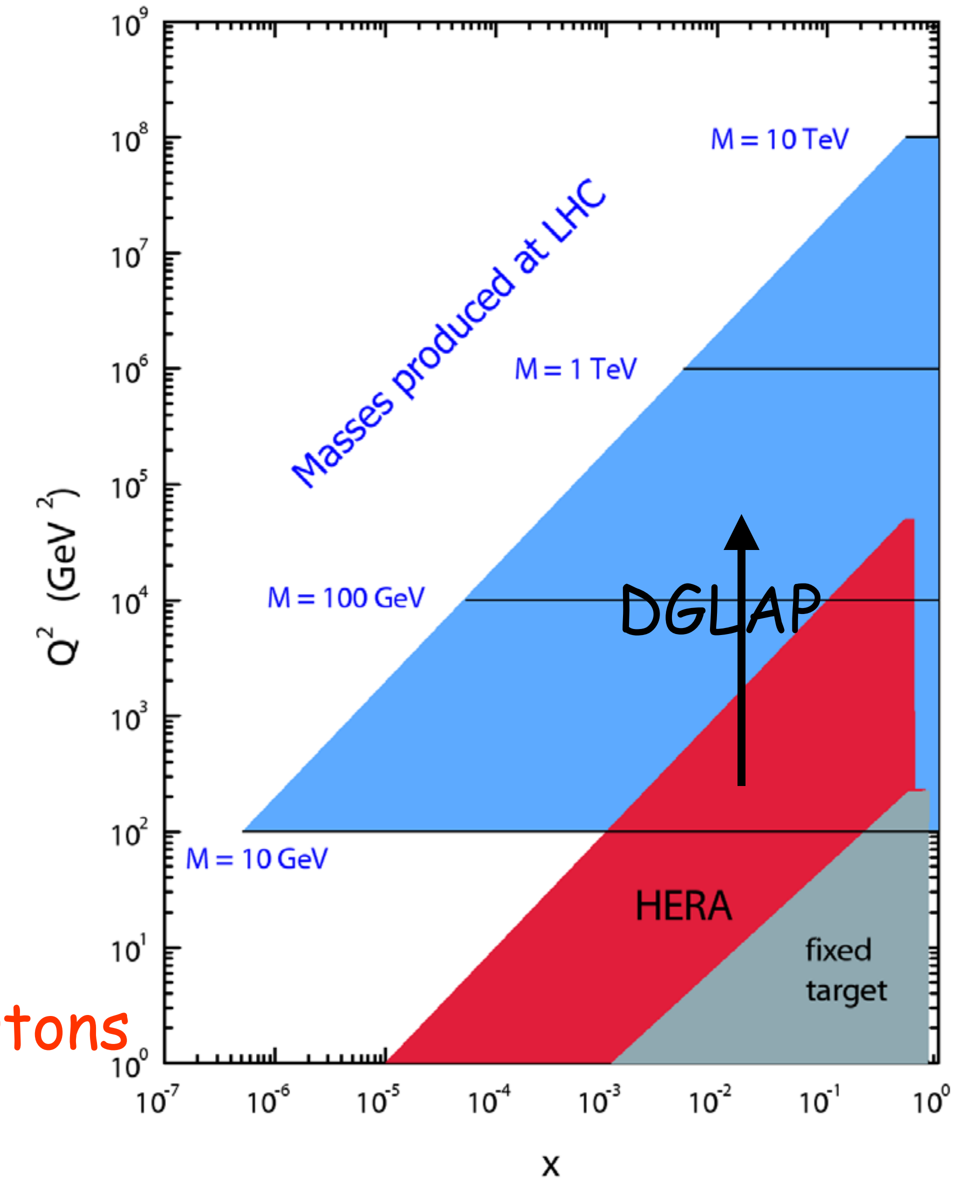




Detailed and precise HERA charged and neutral current data lead to new understanding of the proton and QCD, especially at low x … just How big can the gluon density become?!?

HERA as Input to the LHC

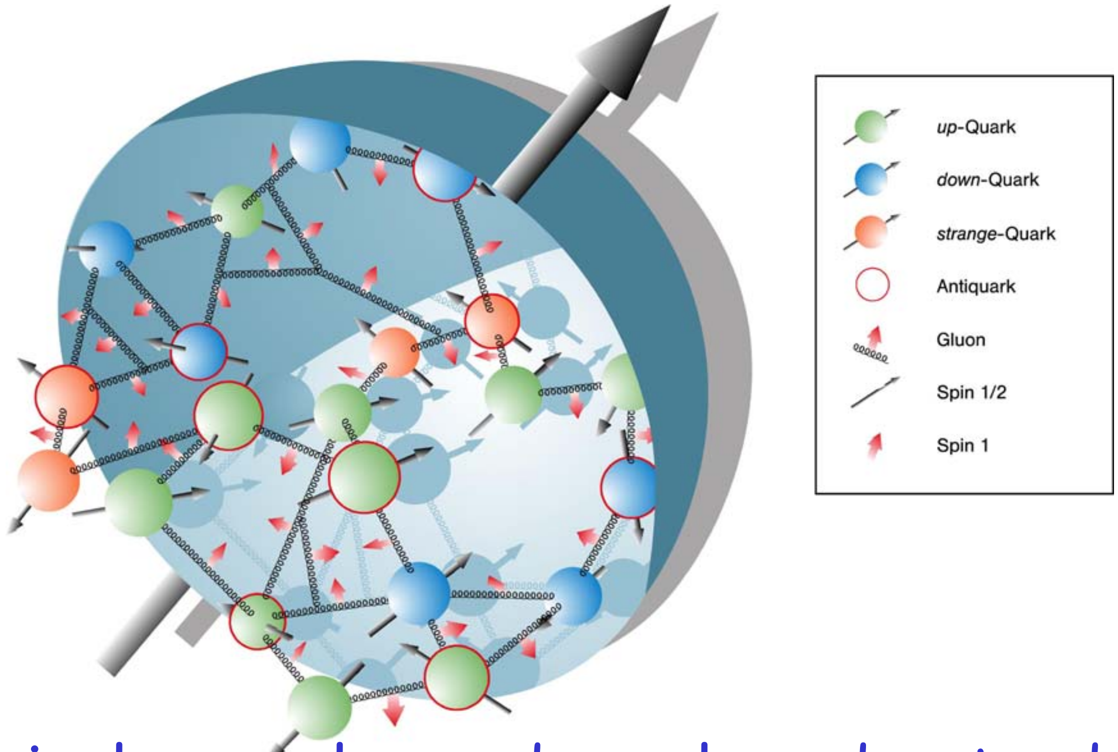




- All pp physics starts from partons
- LHC uses partons over very similar range in x to HERA!

Polarised DIS?

Fixed target experiments with polarised protons (HERMES, COMPASS) study **proton spin**



… surprisingly complex and poorly understood subject!… spin <u>not</u> just carried by valence quarks … gluons, sea quarks, orbital angular momentum all play a role (which changes with Q^2) … **somehow always add up to ½ !!!**

What next in DIS? … LHeC?

DESY 06-006
Cockcroft-06-05

Deep Inelastic Electron-Nucleon Scattering at the LHC*

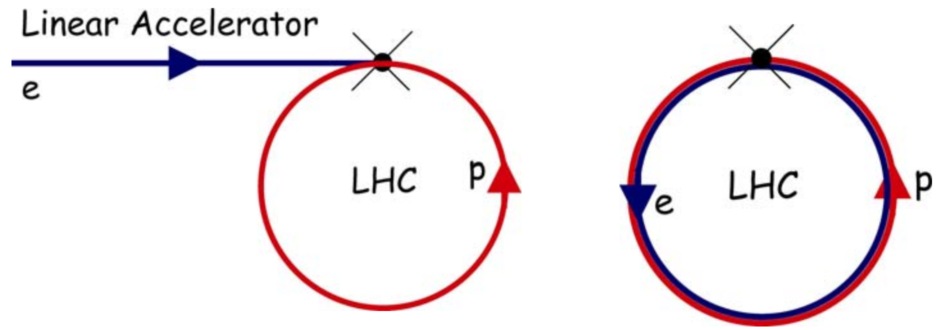
J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

[1] Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

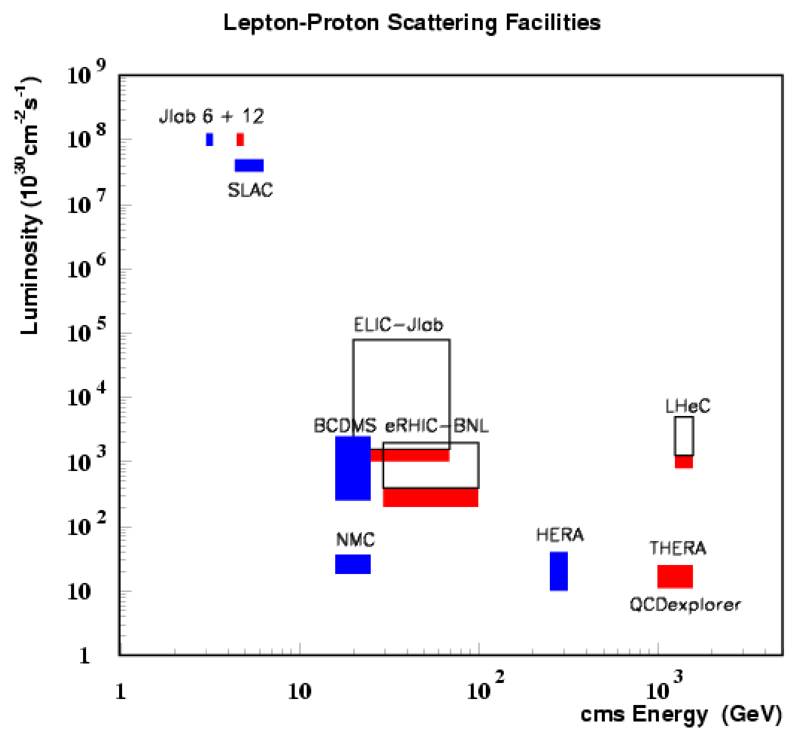
Abstract

The physics, and a design, of a Large Hadron Electron Collider (LHeC) are sketched. With high luminosity, $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and high energy, $\sqrt{s} =$ 1.4 TeV, such a collider can be built in which a 70 GeV electron (positron) beam in the LHC tunnel is in collision with one of the LHC hadron beams and which operates simultaneously with the LHC. The LHeC makes possible deep-inelastic lepton-hadron (ep, eD and eA) scattering for momentum transfers Q^2 beyond $10^6\,\mathrm{GeV}^2$ and for Bjorken x down to the 10^{-6}. New sensitivity to the existence of new states of matter, primarily in the lepton-quark sector and in dense partonic systems, is achieved. The precision possible with an electron-hadron experiment brings in addition crucial accuracy in the determination of hadron structure, as described in Quantum Chromodynamics, and of parton dynamics at the TeV energy scale. The LHeC thus complements the proton-proton and ion programmes, adds substantial new discovery potential to them, and is important for a full understanding of physics in the LHC energy range.

*Contributed to the Open Symposium on European Strategy for Particle Physics Research, LAL Orsay, France, January 30[th] to February 1[st], 2006.



A promising idea for future DIS Involves adding an electron beam (linear or circular) to the LHC …



Detailed Proposals under Consideration ;-)

(LHeC)

DESY 06-006
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PARTICLE PHYSICS GROUP STUDIES 2007

TRIPELIE – Detector design for high energy e⁻ p interactions

J Angus, R Bedwell, R Comber, S Fox, R Harrison, C Heath, R Hicks, K Hill, L Hill, H Jetha, R Lawless, A Loach, T Martin, R Milham, P Petrov and C Sanders, of the TRIPELIE Collaboration.

The School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK.

Co-ordinator: L Hill.
Production Theory: L Hill, H Jetha, R Lawless, T Martin.
Beam Analysis: R Bedwell, R Comber, R Harrison, R Hicks.
Tracking Detectors: J Angus, K Hill, A Loach, C Sanders.
Calorimetery: S Fox, C Heath, R Milham, P Petrov.
Executive editor: H Jetha.
Editors: R Harrison, R Hicks, H Jetha, A Loach.
Website: R Harrison.
Secretary: H Jetha.
Communications: S Fox.

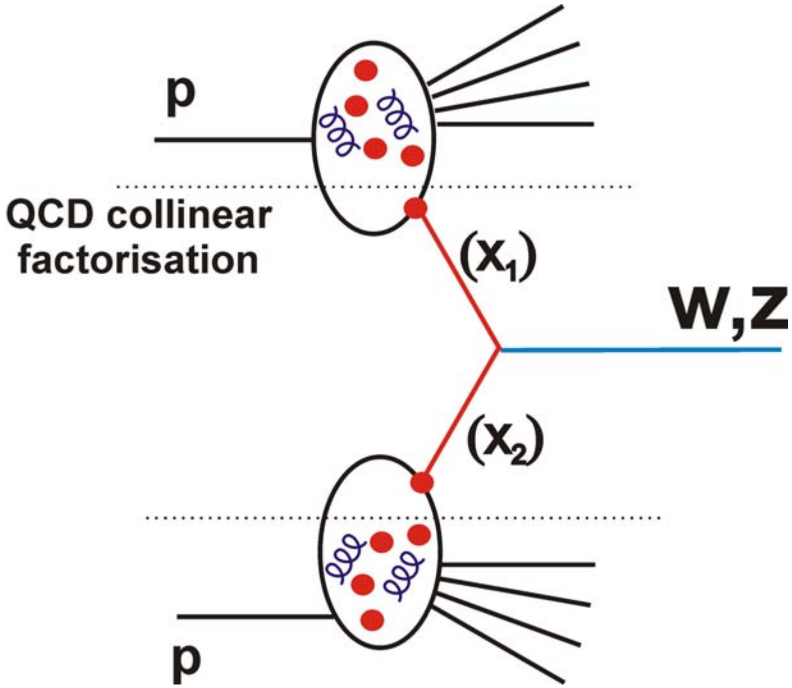
Acknowledgements

The group as a whole would like to extend their thanks to the University of Birmingham Particle Physics group for their advice and assistance. Particular thanks go to Dr D. Charlton, Dr C. Hawkes, Dr P. Thompson, Dr J. Wilson and Dr N. Watson.

Abstract

A complete detection system, TRIPELIE, was designed to undertake a search for the leptoquark particle. Theory regarding leptoquark production and decay has been studied. Simulated data from the PYTHIA Monte Carlo simulation program has been used to find ways of distinguishing these from background events using kinematic reconstruction. Subsequently, an arrangement of vertex detectors, time projection chambers and multi-wire proportional chambers for charged particle detection were designed. In addition, a system of liquid argon electromagnetic calorimeters, lead-plastic hadronic calorimeters and Čerenkov detectors will be employed for particle energy measurement. Complementary triggering and magnet systems are also included in the design. All components will possess a high resolution in order to gain an accurate measurement of the leptoquark mass.

Factorising away the Unknown

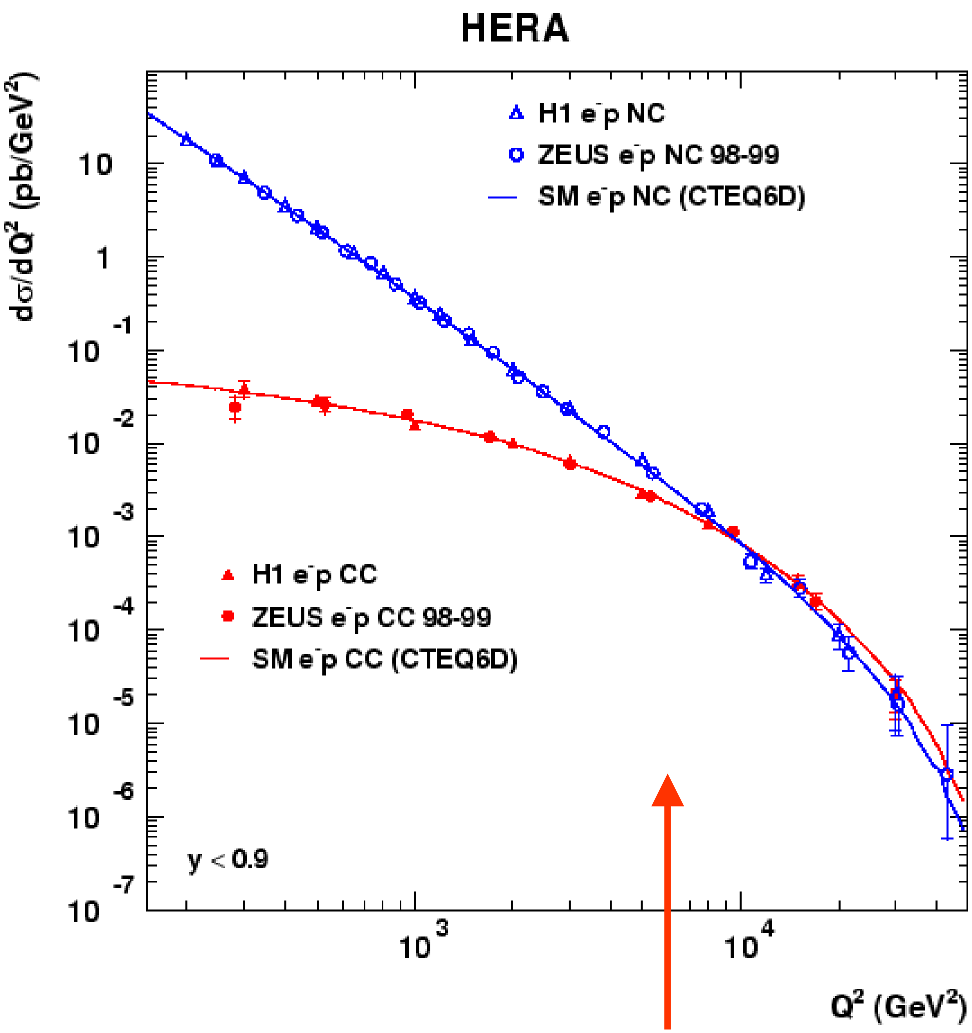


- **QCD factorisation theorem** allows us to define universal parton density functions (PDFs), same for proton in all contexts.

- **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

Electroweak Unification at HERA



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

Neutral Current x-sec

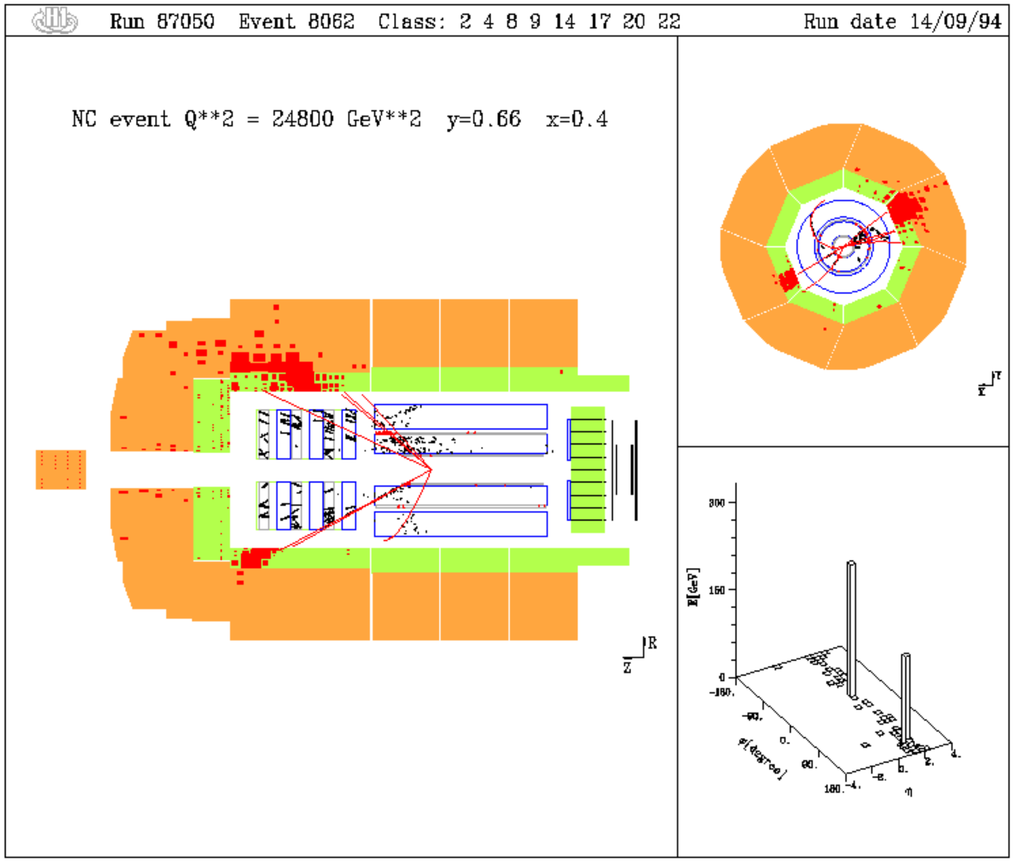
$$\frac{d\sigma^{NC}}{dx\, dQ^2} \sim \alpha_{em}^2 \bullet \left(\frac{1}{Q^2}\right)^2 \bullet \tilde{\sigma}_{NC}$$

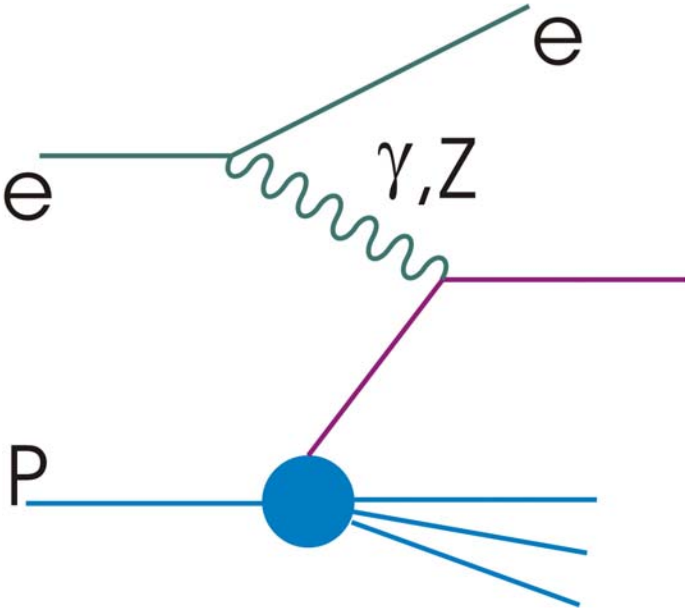
Charged Current x-sec

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

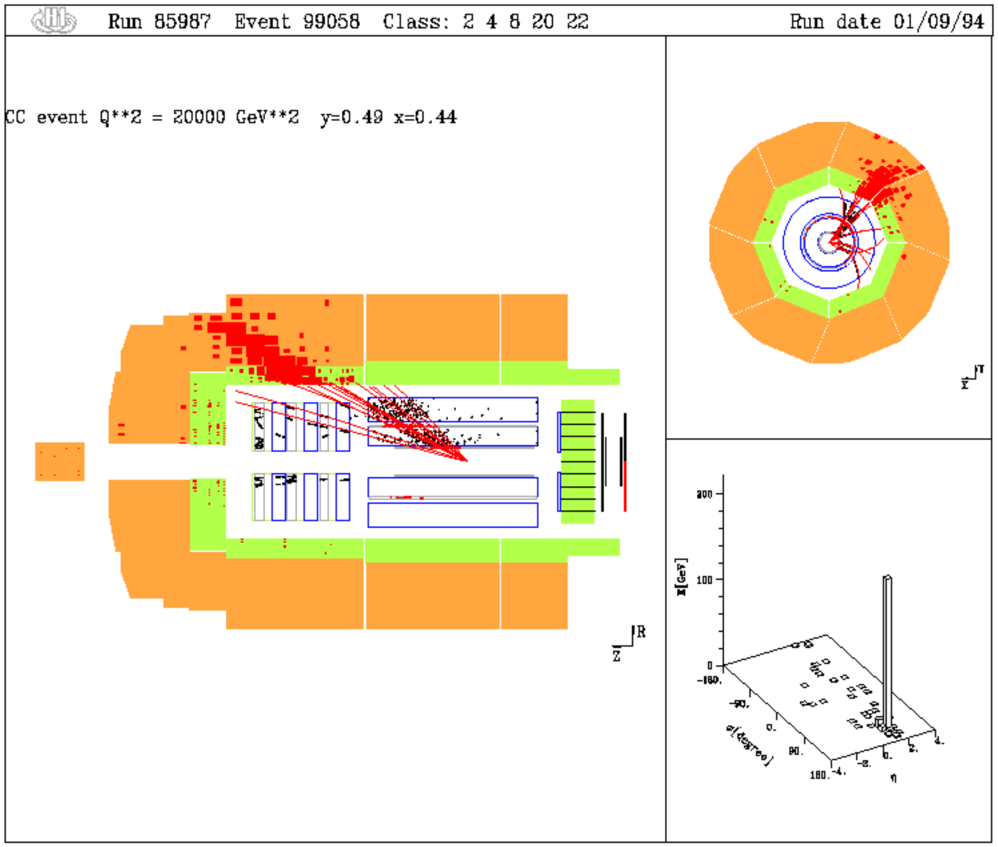
NC and CC cross sections become comparable at EW unification scale (couplings unified)

A HERA event to interpret ….

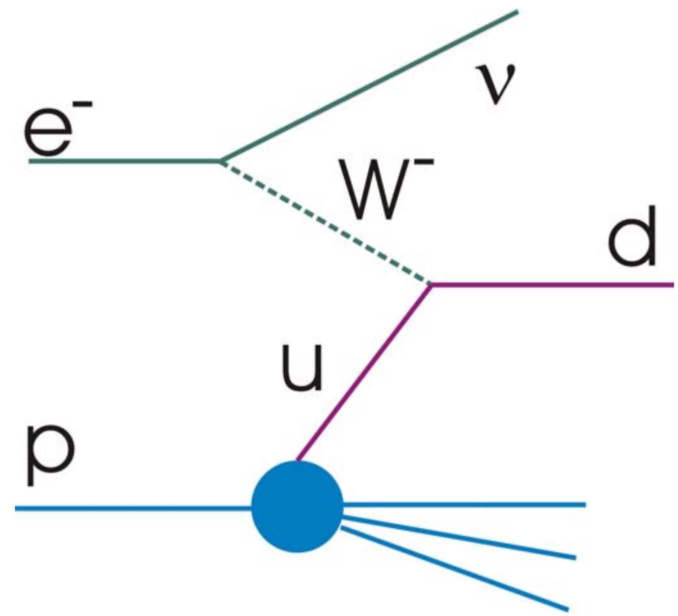




Another one



Run 85987 Event 99058 Class: 2 4 8 20 22
Run date 01/09/94
CC event Q**2 = 20000 GeV**2 y=0.49 x=0.44



e-
ν
W-
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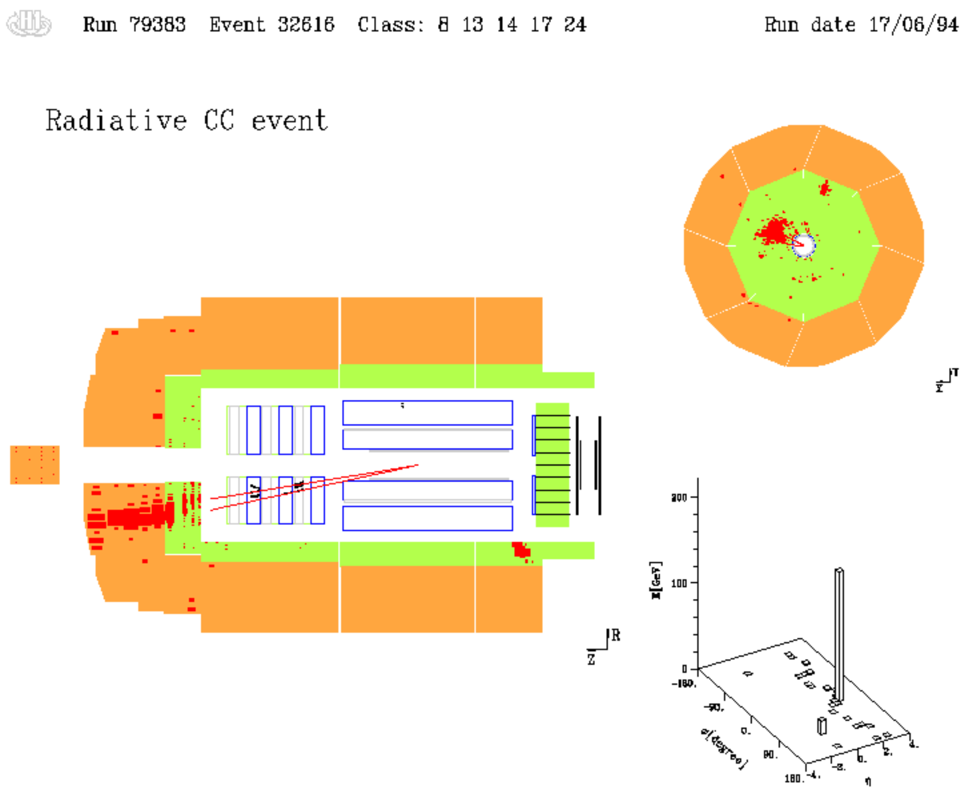
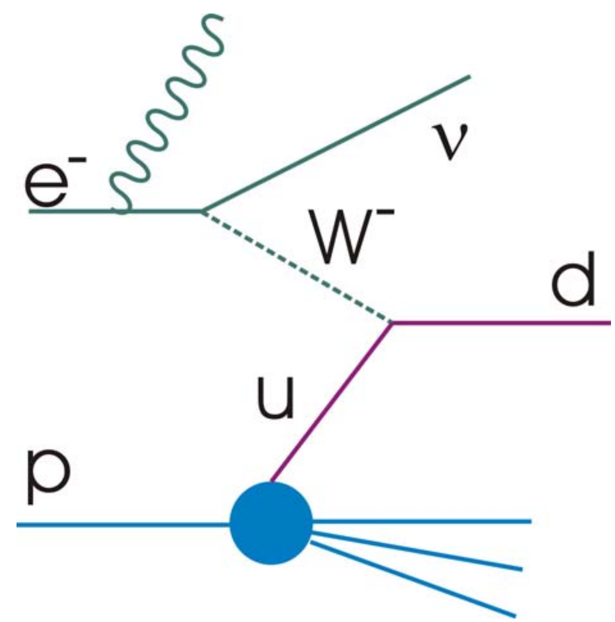
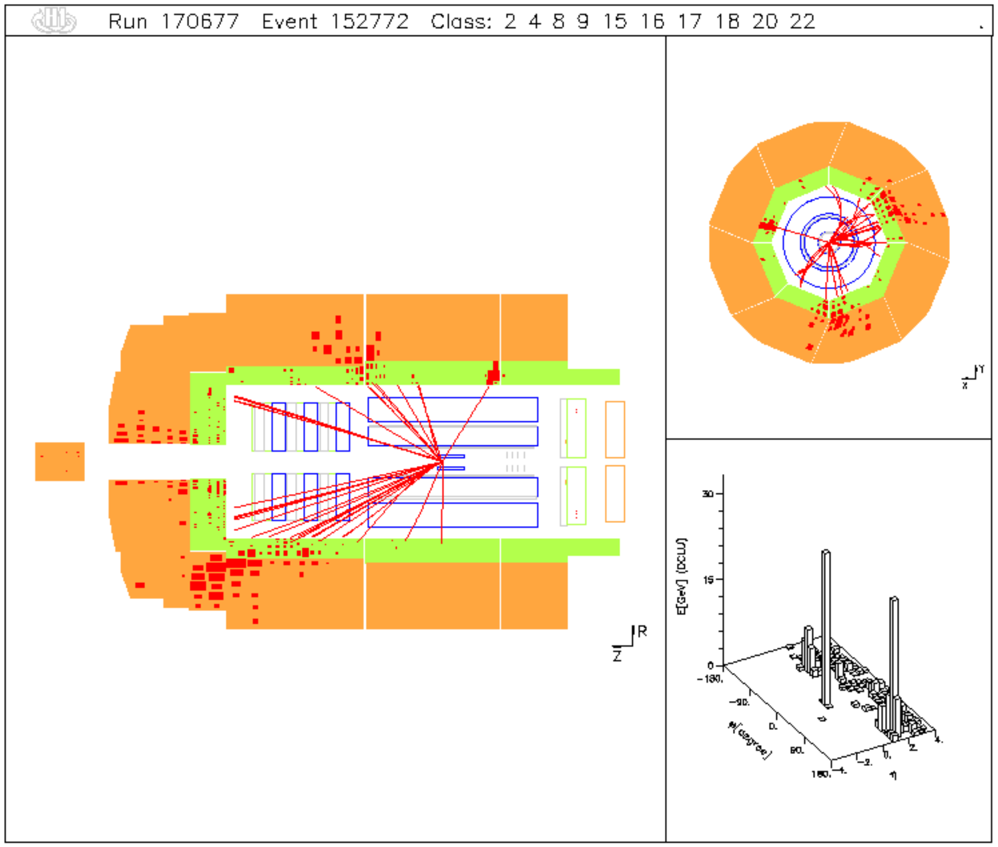
u
p

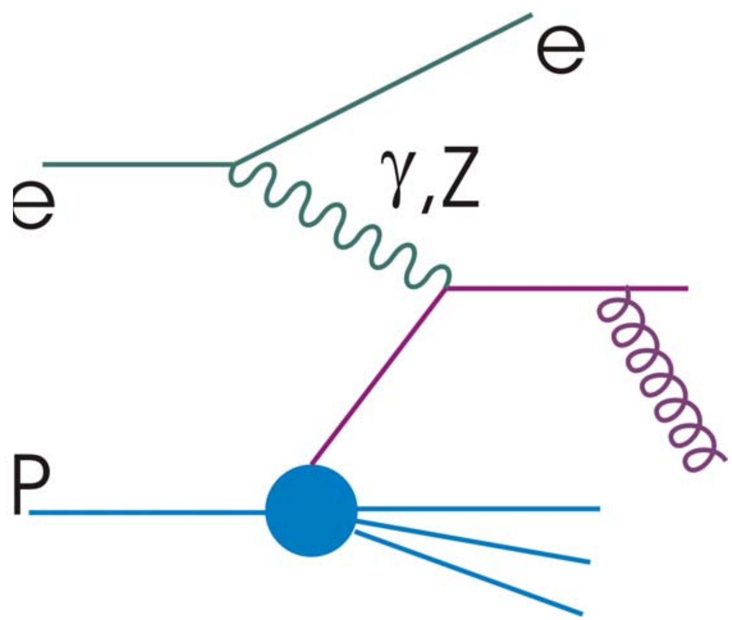
…. And another one



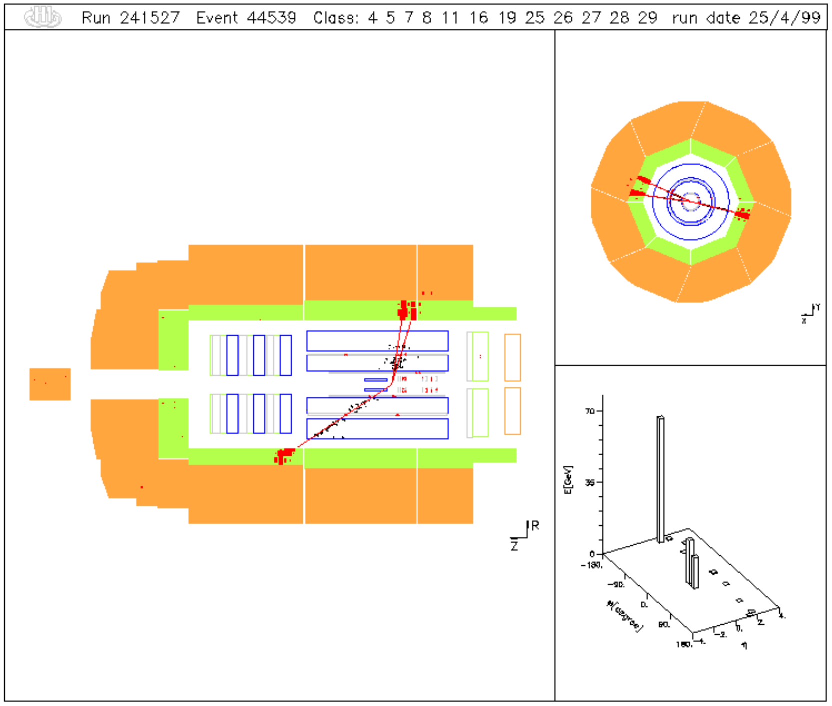


…. One more





2 harder ones …. What are they?



$e^+ p \to \mu^+ X$