QCD as seen by the detectors

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QCD features

Does QCD describes the world?
Compute observable, measure it and compare

We do not know how to solve QCD equations exactly.

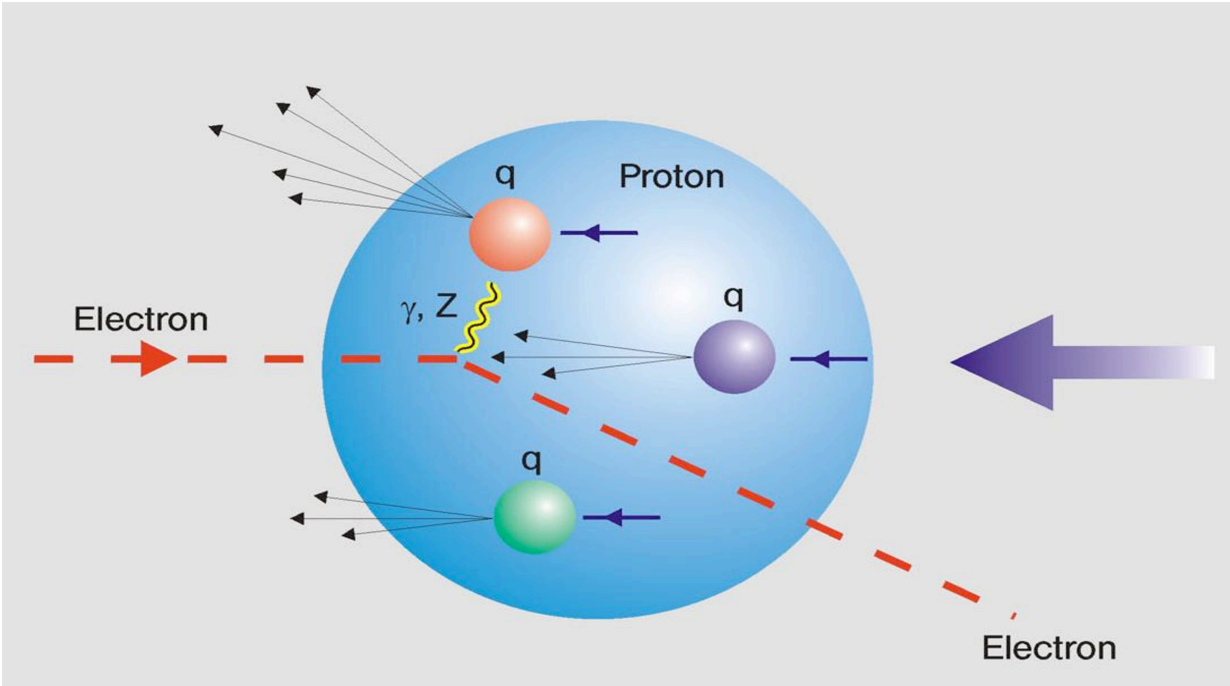
Approximations have to be used and completed with models based on assumptions.

There are no free quarks nor gluons; i.e., the world is white.

The existence of quarks and gluons and their properties are obtained indirectly from the experiment

What to do?

Take a convinient bag of quark and gluons, look inside it and try to make sense of what you see …



You need the bag (say a proton) and a probe (say an electron)
To look inside, you need good resolution
This means lots of momentum; i.e. you need an accelerator

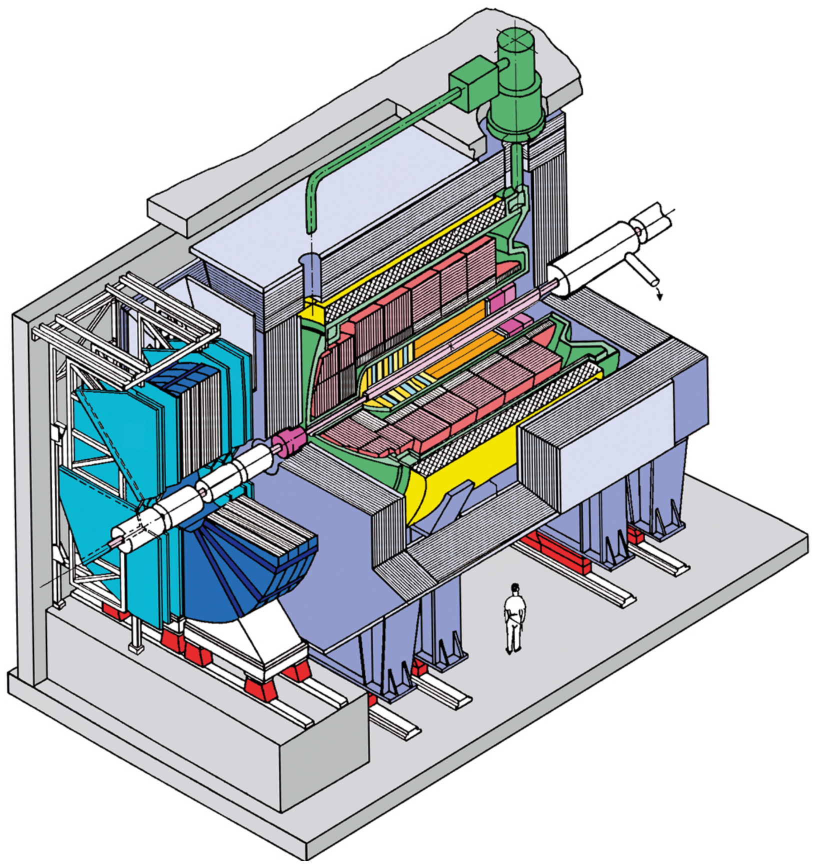
HERA

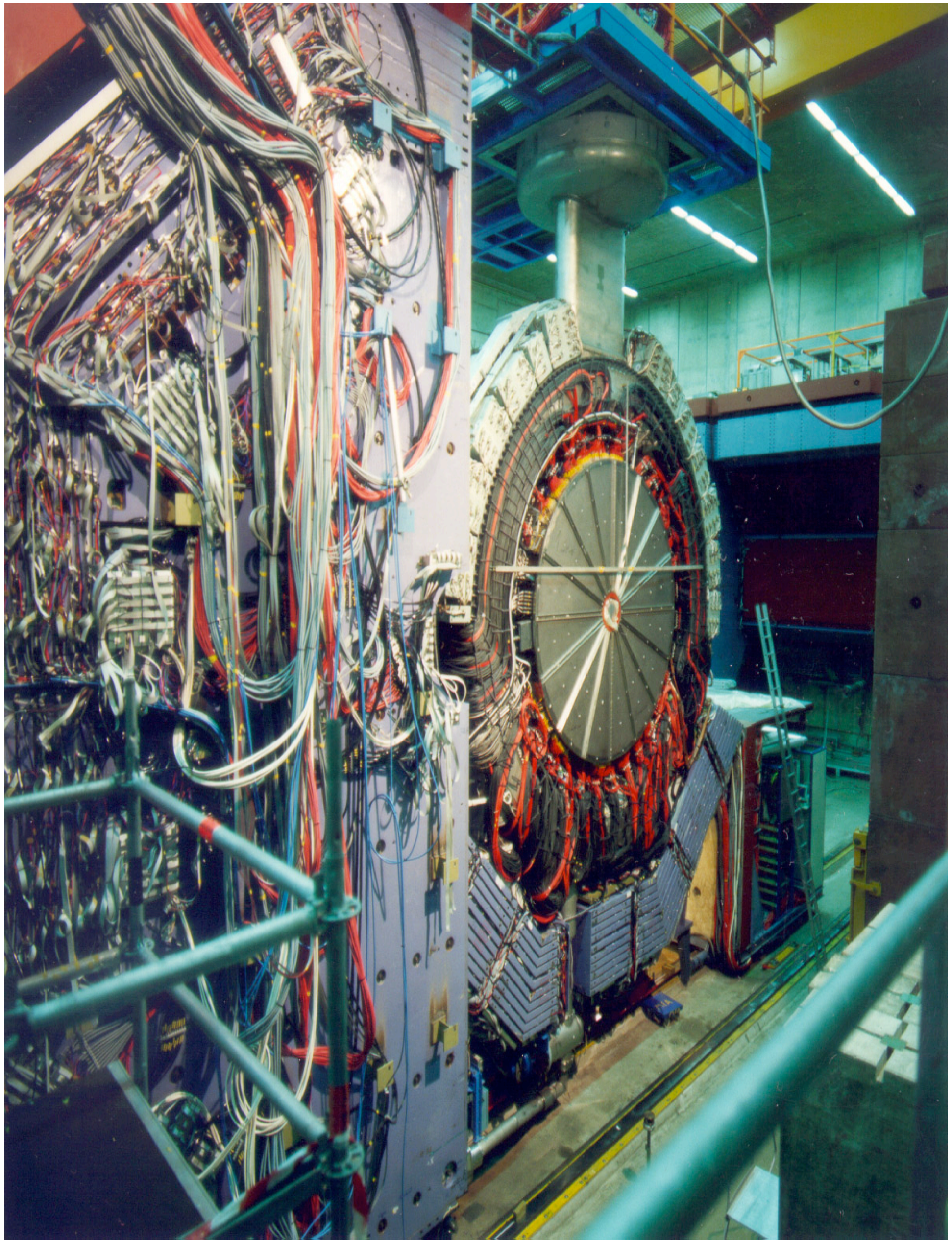
HERA took data from 1992 to 2007
Located in Hamburg at DESY.
ep collider @ 320 GeV in CMS.
Superconducting accelerator for proton.
Underground:10-25m. Length: 6.3 km
10^{11}x180 protons, 0.5x10^{11}x189 electrons
4 big detectors:
2 fixed target (Hermes, Hera-B)
2 collider exp. (H1 and Zeus)

The H1 Collaboration

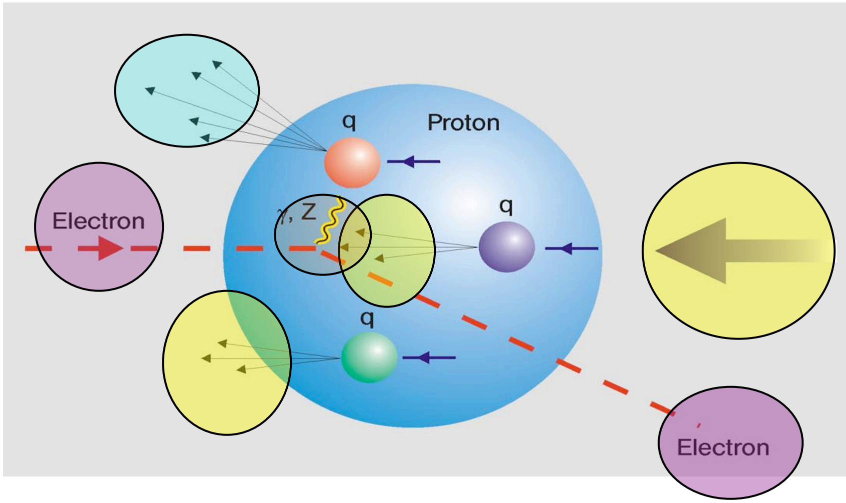
International collaboration of some 350 scientists from some 40 institutions

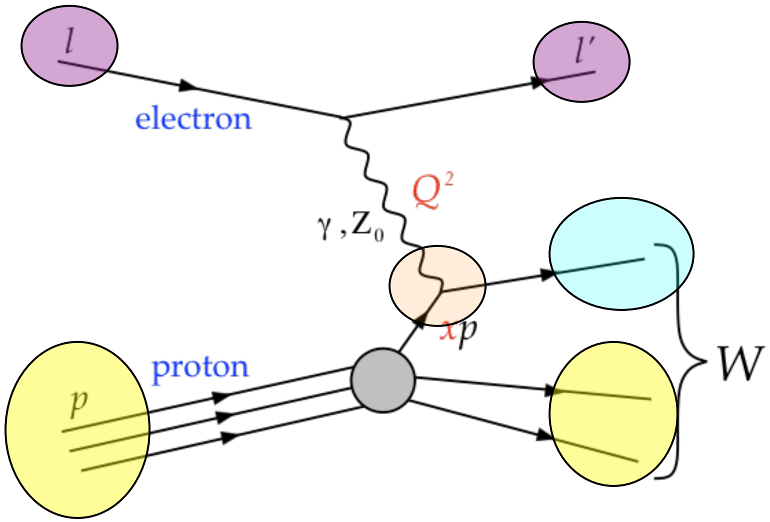
More than 150 articles, many thousand citations, hundreds of thesis

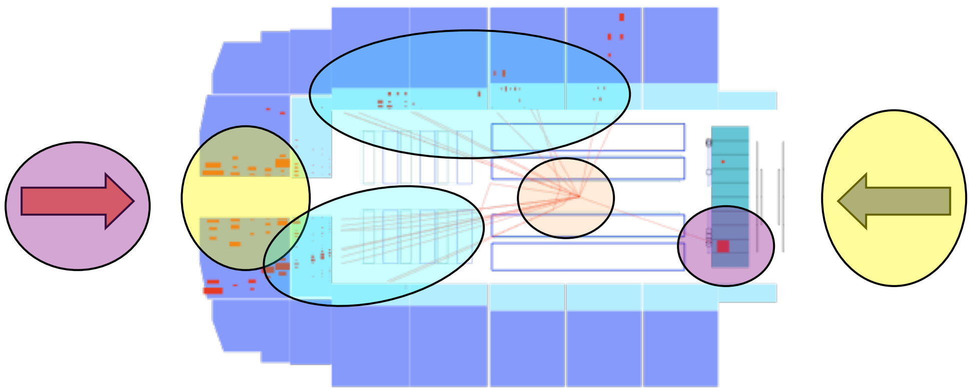




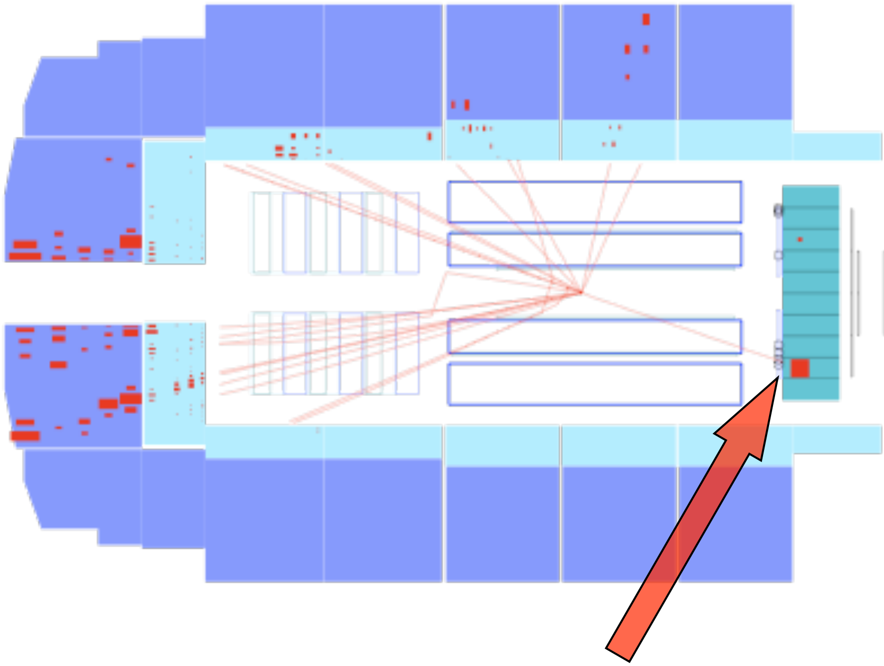
Three views of a ep collision







By the way, how do you know that …

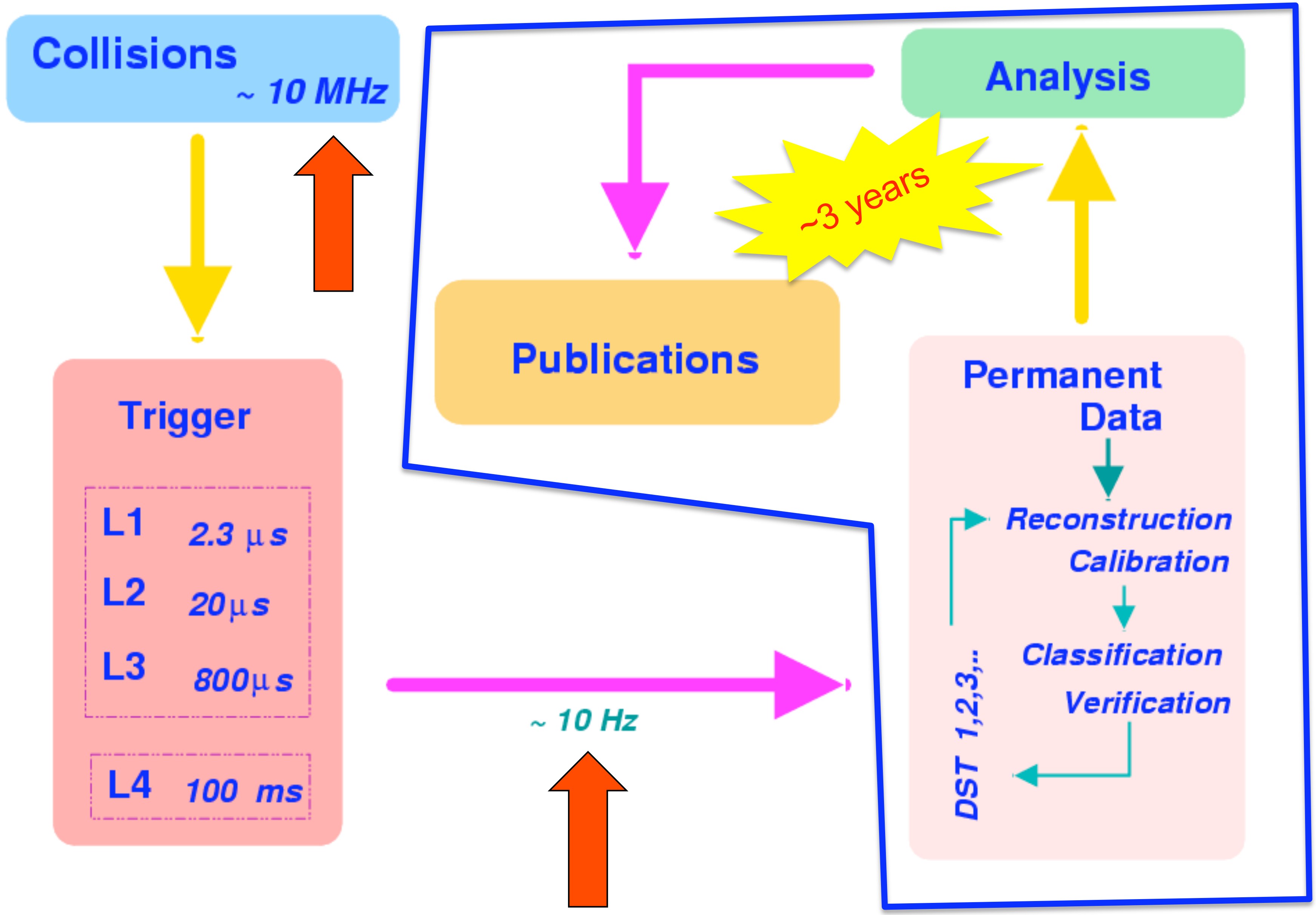


… for example, this is an electron?
(and why do you care? This is about QCD, isn't it?)

Well, as my students say: here is where you earn your PhD …

- Learn lots of physics (EM, QM, …)
- Design, construct, test a prototype … and then do it again
- Measure its response to different probes
- Construct the real thing under the given contraints in precision, time, people, money, …
- Calibrate, align and determine the acceptance and efficiency all the time
- Simulate its response and its noise
- Design overall experiment to have enough cross checks
- For the electron in particular:
  - ✓ Right topology
  - ✓ Right charge
  - ✓ Right place
  - ✓ Consistent kinematics
- You never know it was an electron, only the it looked like one!

From the collision to the physics



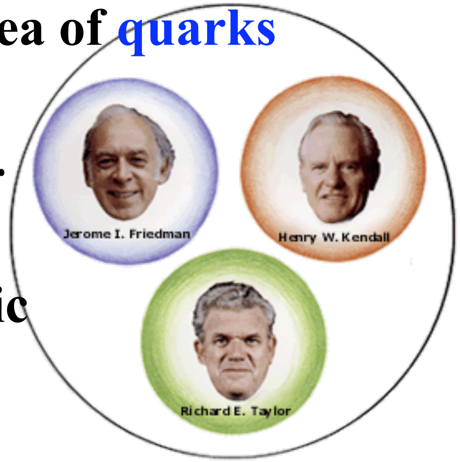
Intermezzo

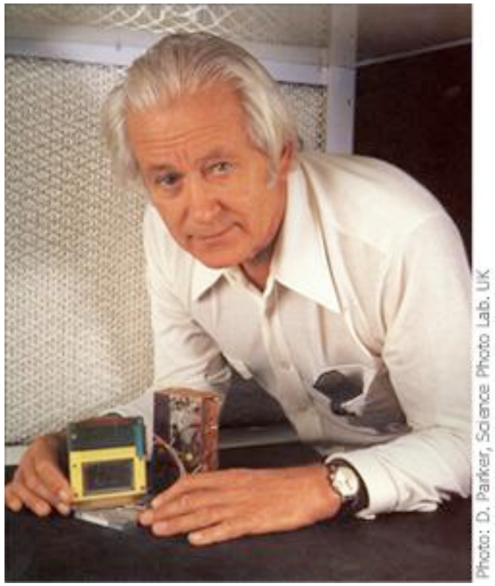
Deeply inelastic scattering or how to see the quarks in the proton

Nobel history

1969: Murral Gell-Mann: Proposes in 1964 the idea of quarks

1990: Friedman, Kendall and Taylor for DIS experiments in the late 60's which confirmed that the proton had a partonic structure

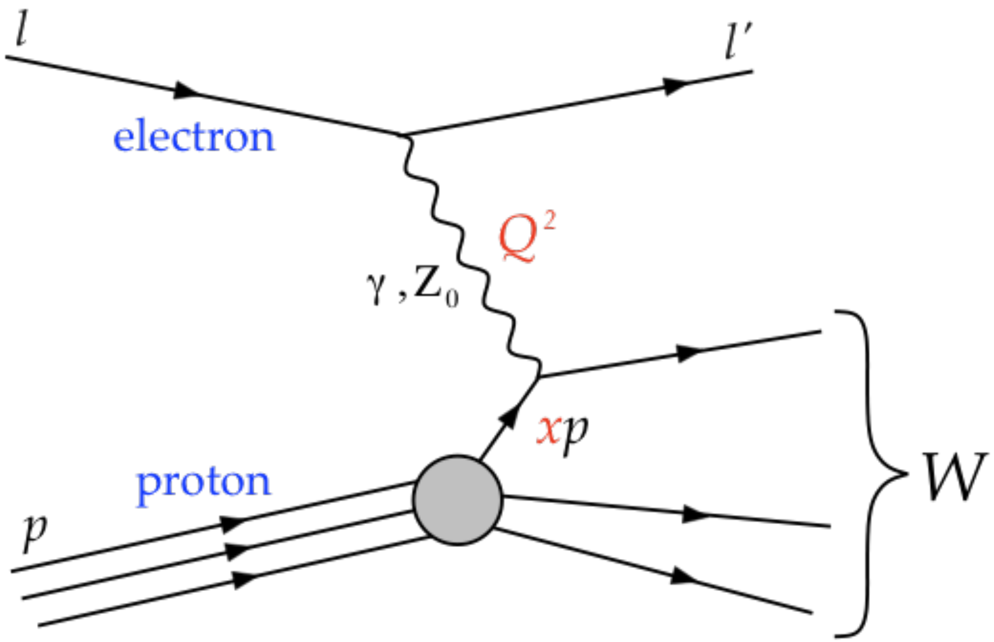




1992: George Charpak, who in 1968 invented the MWPC which hooked-up detectors/electronics/computers

2004: Gross, Politzer and Wilczek for finding the theoretical fundaments of QCD

Deeply inelastic scattering (DIS)



The high energy collision of an electron and a proton depends only on two kinematic variables

- **the resolution of the probe: Q^2**
- **the energy of the hit parton: x**

If the interaction is fast enough; i.e., Q^2 is big enough, the partons (quarks and gluons) are almost free

This process is called deeply inelastic scattering

Let's measure the structure of the proton and compare to QCD

… well to perturbative QCD: we can compute only the evolution of the structure, not the structure itself …

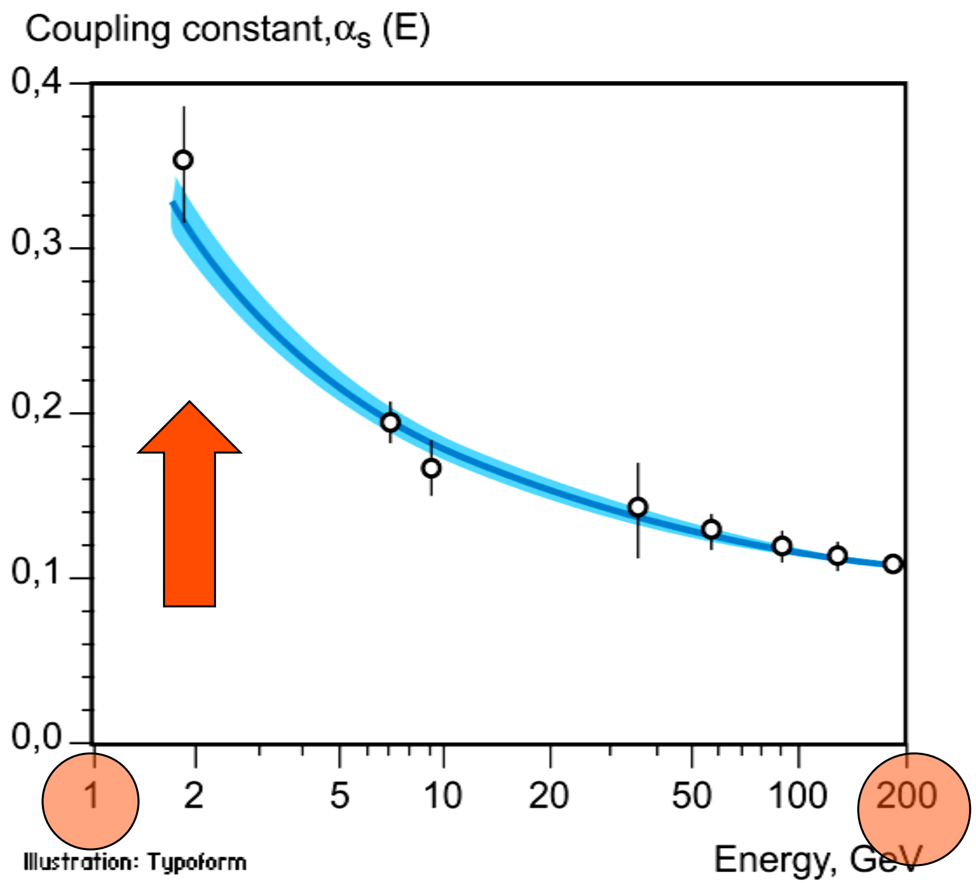
Fast enough? pQCD

We can expand QCD in terms of its only parameter: α_s

The expansion will be useful if the parameter is small

But the parameter depends on the resolution; i.e., on the time needed by the probe to interact with the parton

The faster the interaction is, the smaller is the parameter and the approximation gets more reliable



DIS: experiment, theory and QCD

Experiment **General theory requirements**

$$\frac{d\sigma}{dx\,dQ^2} \approx \frac{4\pi\alpha^2}{x}\boxed{\left[\frac{1}{Q^2}\right]^2}\left[\left(1-y+\frac{y^2}{2}\right)F_2-\frac{\boxed{y^2}}{2}F_L\right]$$

Small x, Q^2

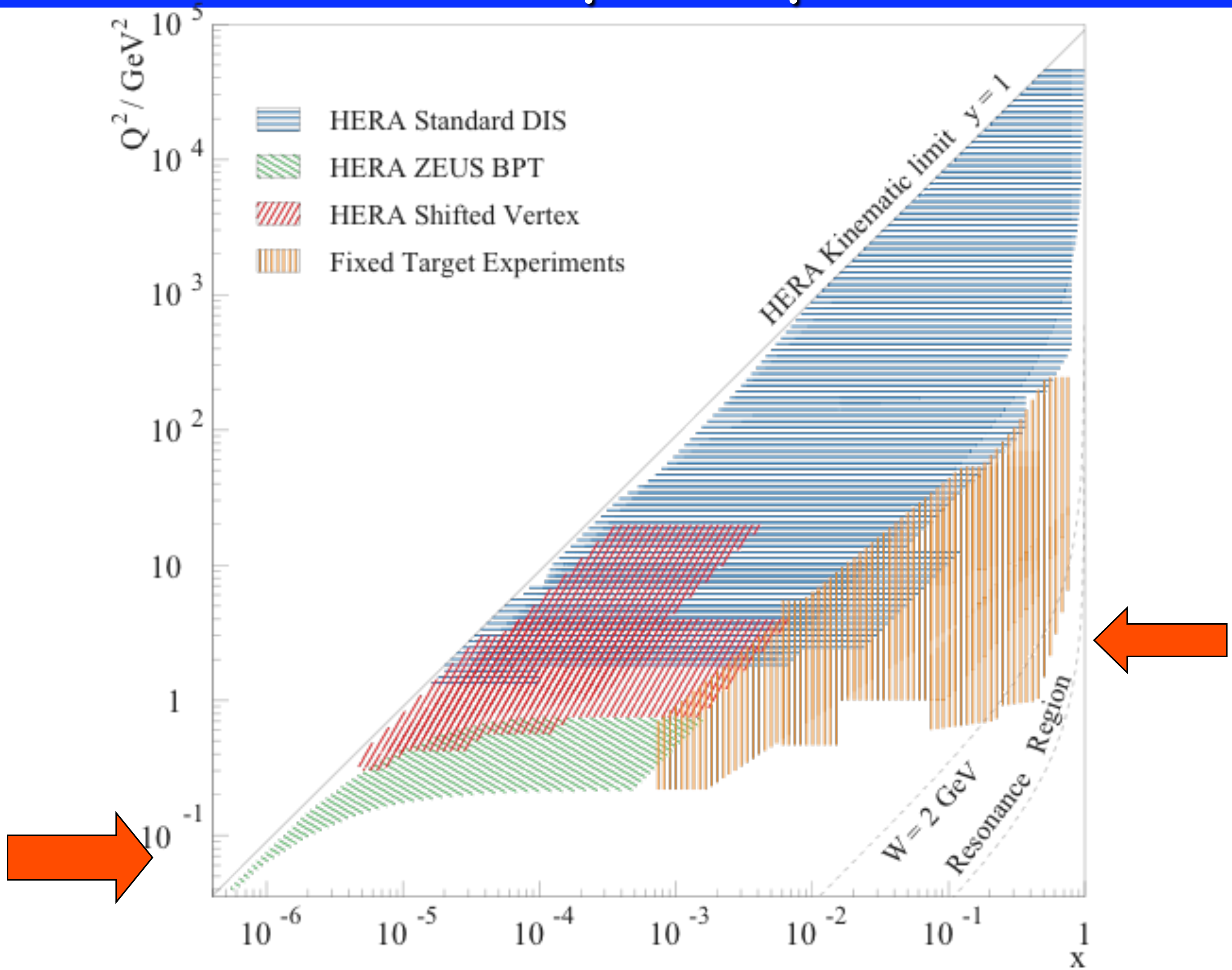
pQCD

$$F_2 \propto \sum partons(x,Q^2)$$

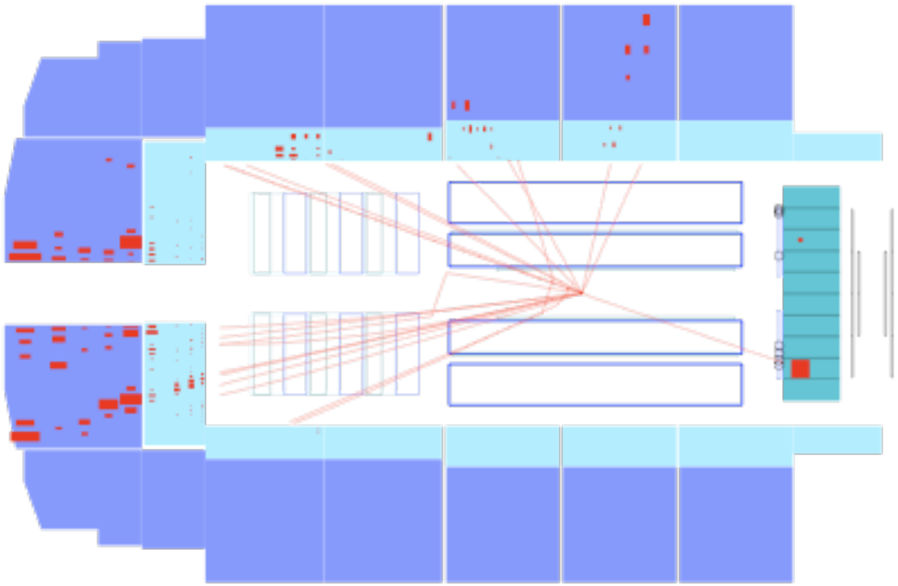
$$F_L \propto \boxed{xg}(x,Q^2)$$

No α_s in the formula? Remember: evolution!

Available phase space



Just count, compare and get F_2



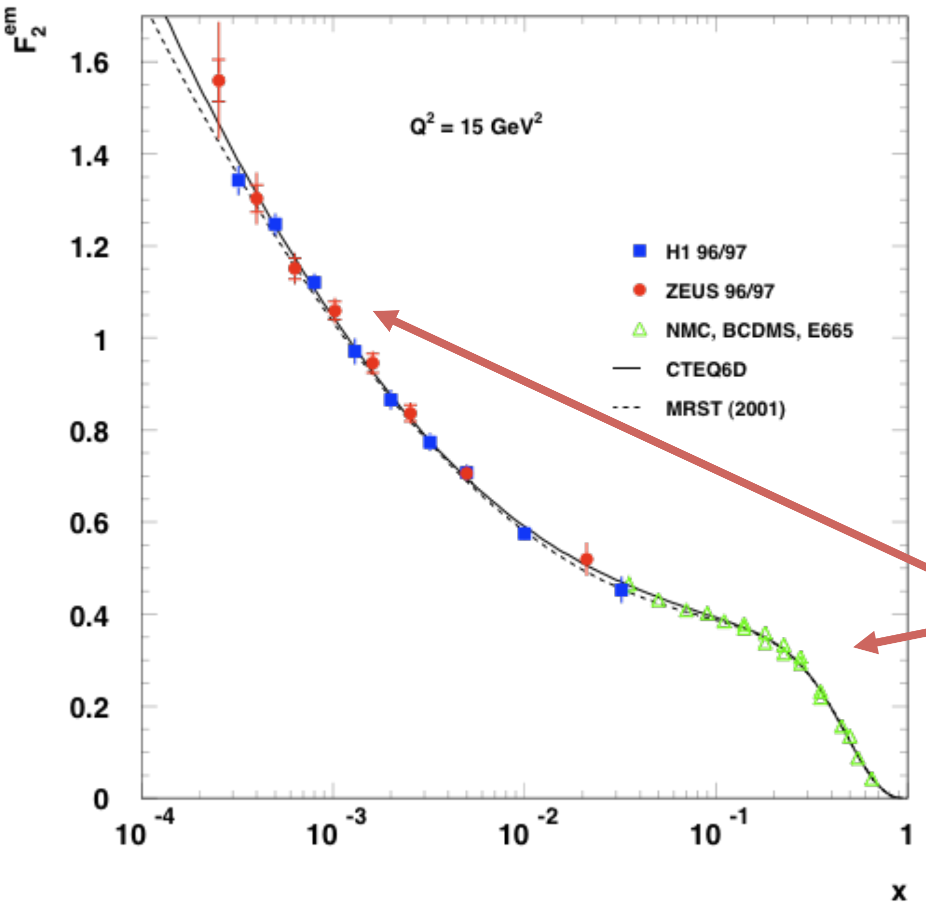
Analyze many collisions

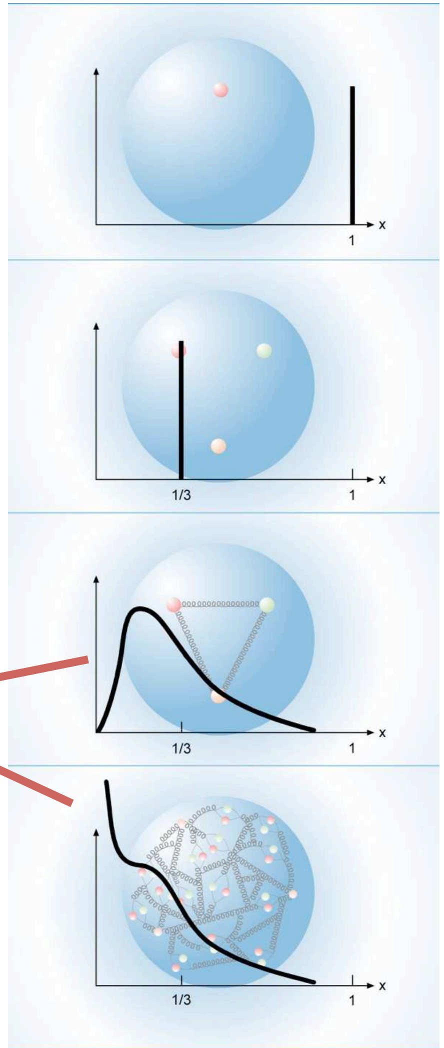
Count how many events you have at each x and Q^2 value

Normalize to the total number of collisions you had (luminosity)

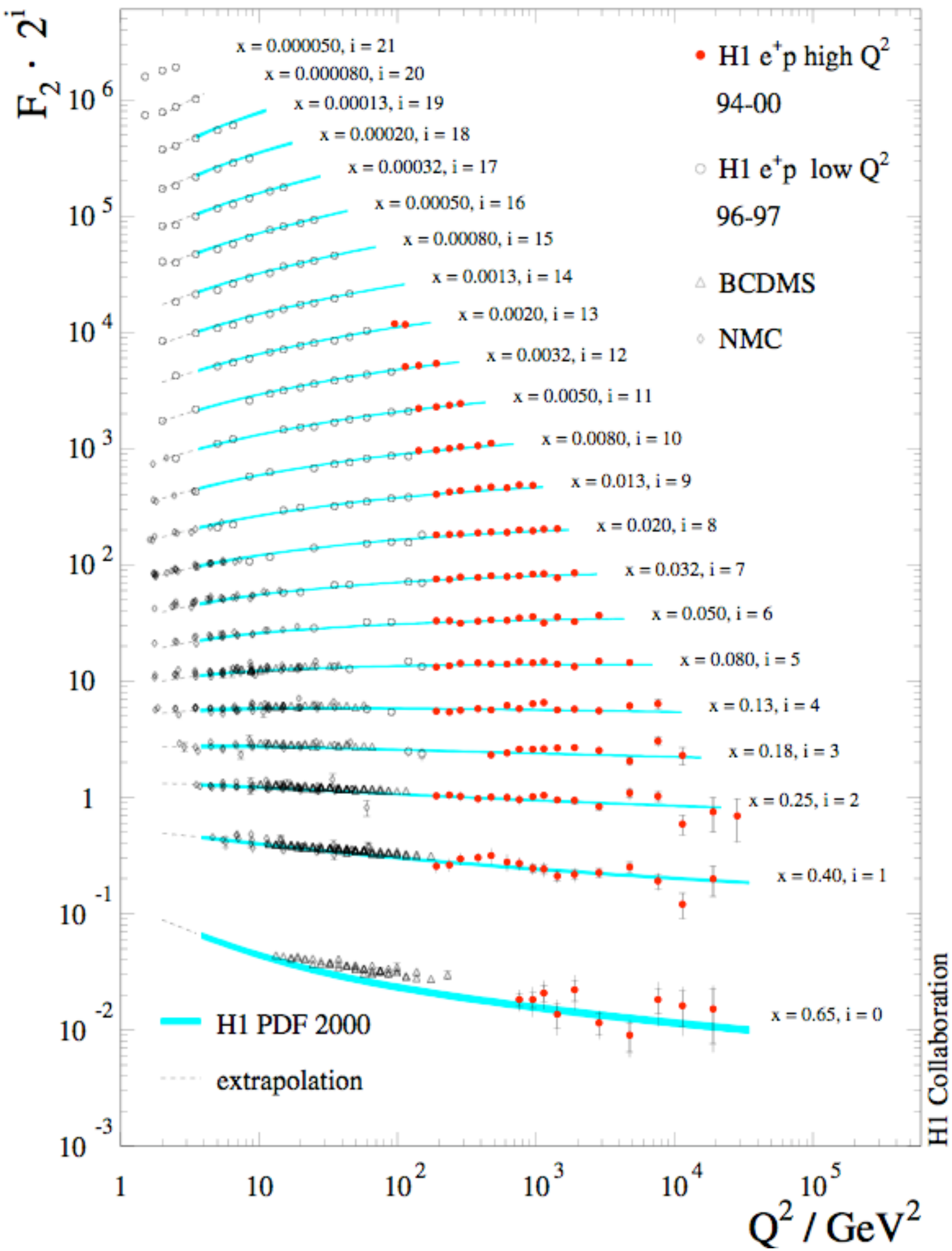
Compare to expectations of QCD

Understanding F_2





F_2 evolution



Around x=1/3 there is no slope: Bjorken scaling

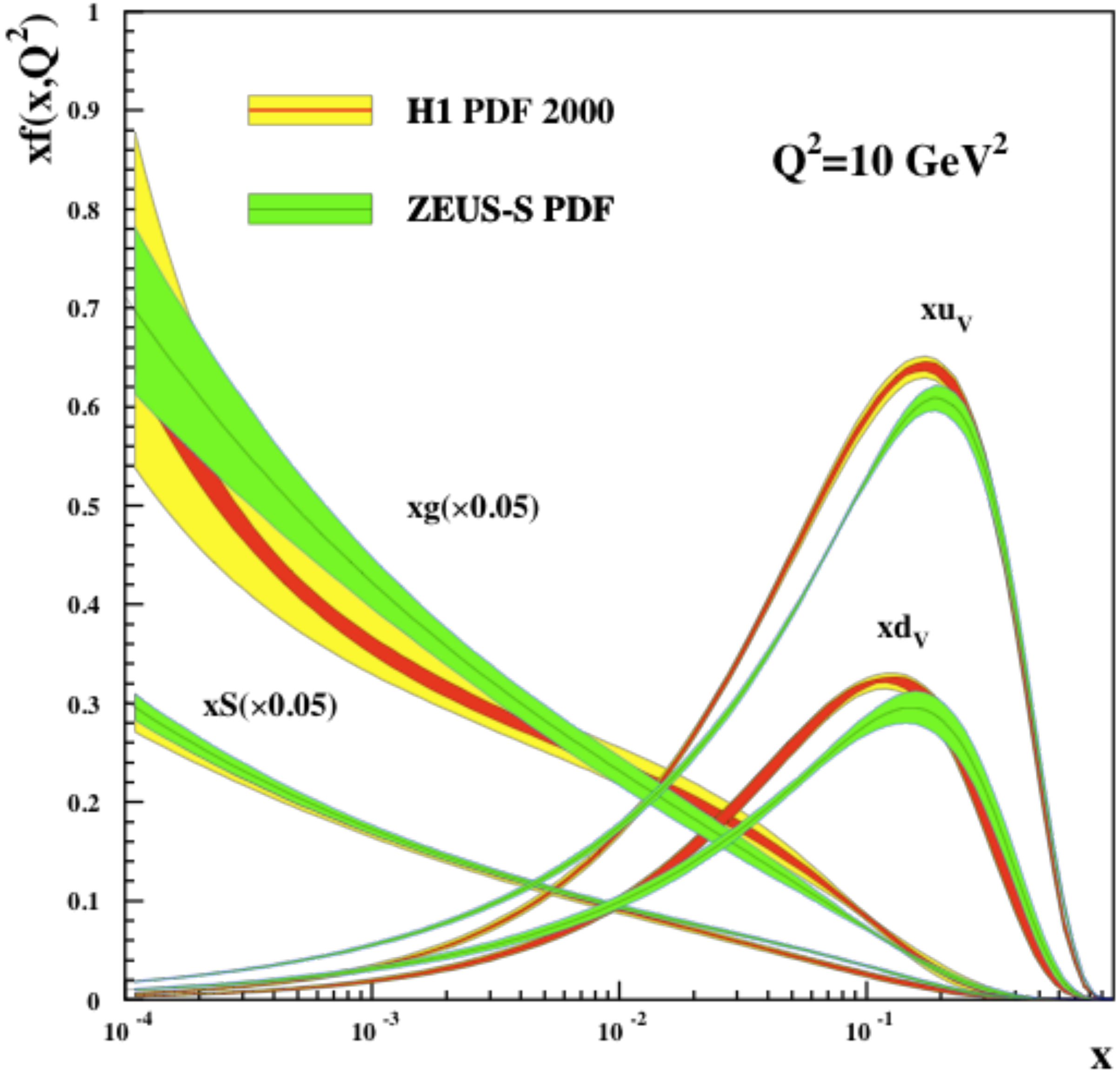
The slope for fixed x, depends on x: Scaling violations

At small, fixed, x if you have more resolution, you see more

At high x, you see less

Line is a fit based on the DGLAP approximation: Compute F_2 at each x and Q^2 using pQCD, and fit to the measurments … you'll get a Great description!

Parton distribution functions (PDFs)



In pQCD F_2 is at first approximation, just the sum of partons in the proton.

So, from the fit you get the so called parton distribution functions:

At small x the gluons dominate

At high x are the so called valence quarks

That was easy … but …

A bit more on evolution equations

The perturbative expansion of QCD yields and integro-differential equation

A boundary condition is required: it has to be extracted from the experiment (for DGLAP it is given by the measurement of F_2 at a given fixed Q^2)

There are different ways of performing the appoximation:

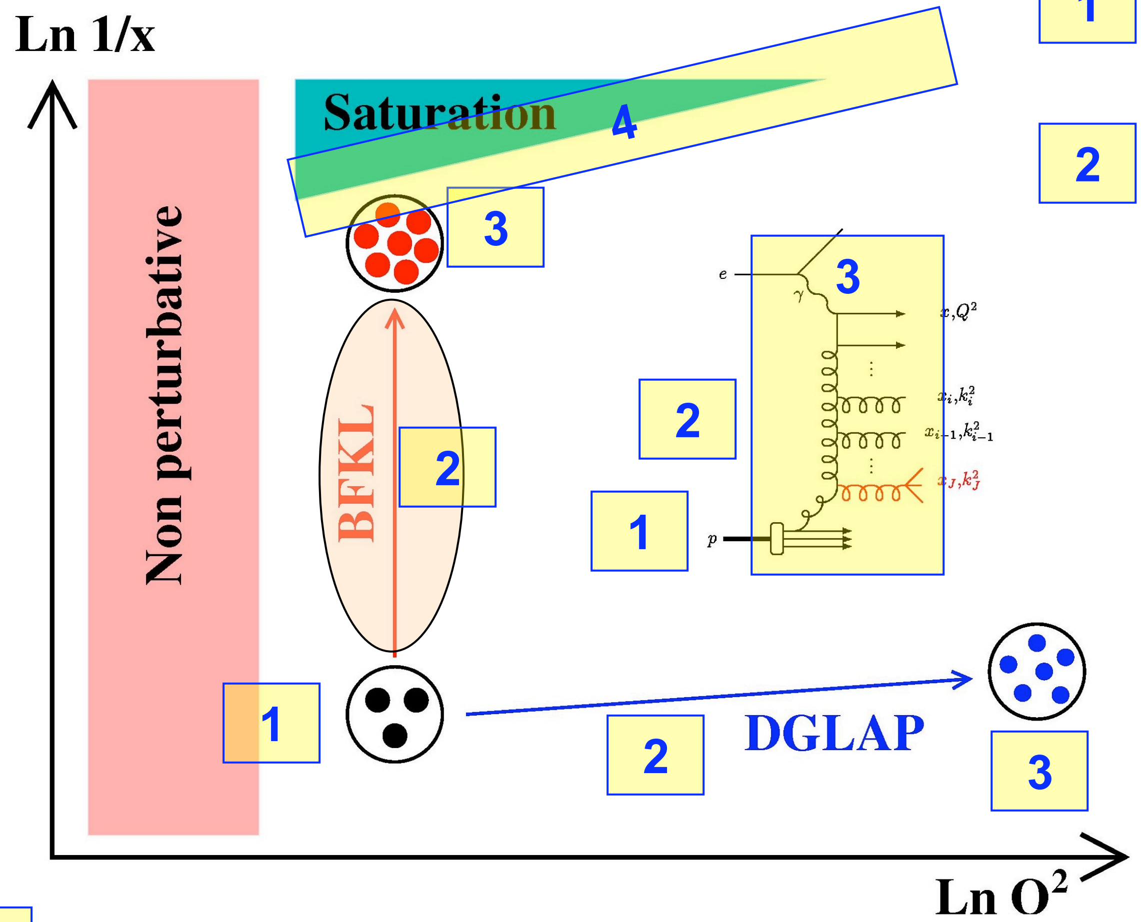
DGLAP: expand in terms of $[\alpha_s \ln(Q^2/\Lambda^2)]^n$, ignore terms in $[\alpha \ln(1/x)]^n$
BFKL: fix Q^2 and take into account $[\alpha \ln(1/x)]^n$ terms

At small x, DGLAP should break down because it ignores $[\alpha \ln(1/x)]^n$ terms

Furhtermore at small x in HERA, Q^2 is also very small: is a perturbative treatment justified?

Finally, both DGLAP and BFKL are linear equations. At small x there are many partons, which may interact among them (this is called saturation)
➔ non linear terms needed!

And now in pictures



1 Boundary condition ← exp

2 One emission …
… and another … and …

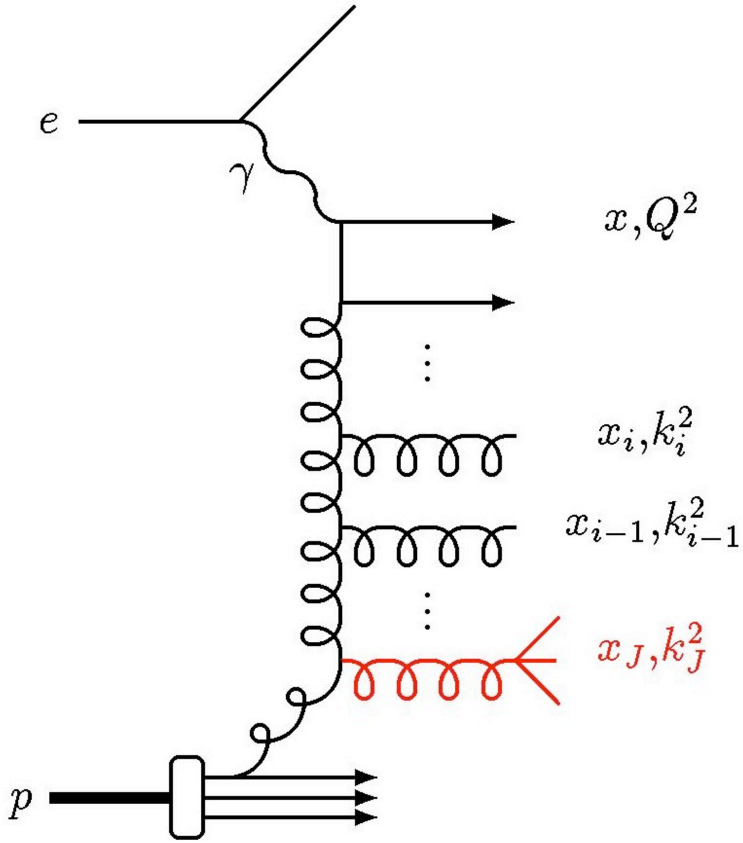
BFKL:
big steps in x
diffusion in Q^2

DGLAP:
small steps in x
big steps in Q^2

3 Structure after emissions

4 We are interested in this region … but there is no scale in plot …

BFKL and forward jets



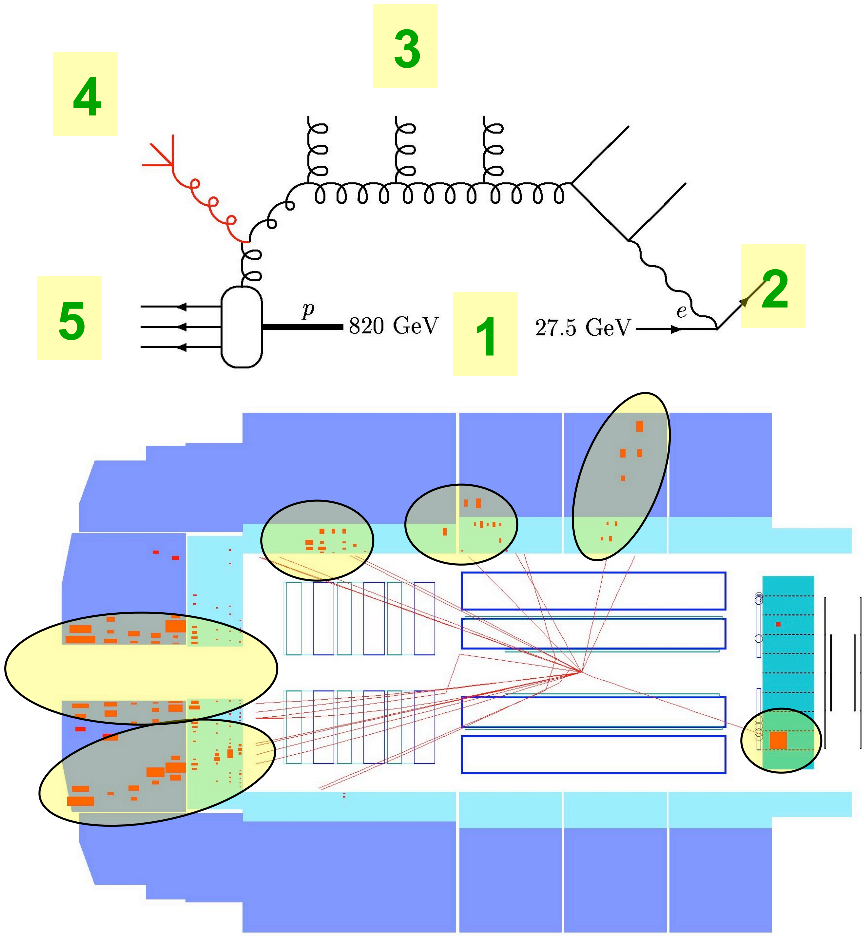
Looking for BFKL effects:

Fix Q^2 during the evolution:
➔Jet scale $k^2 \sim Q^2$
➔ Note that this suppresses DGLAP

Evolve as much as possible in x
(remember, *ln(1/x)* dependence …)
➔ Small x scattering
➔ and high x jet

Very nice idea, very difficult measurement!

Forward jets as seen by H1



1 Initial electron and proton

2 Scattered electron

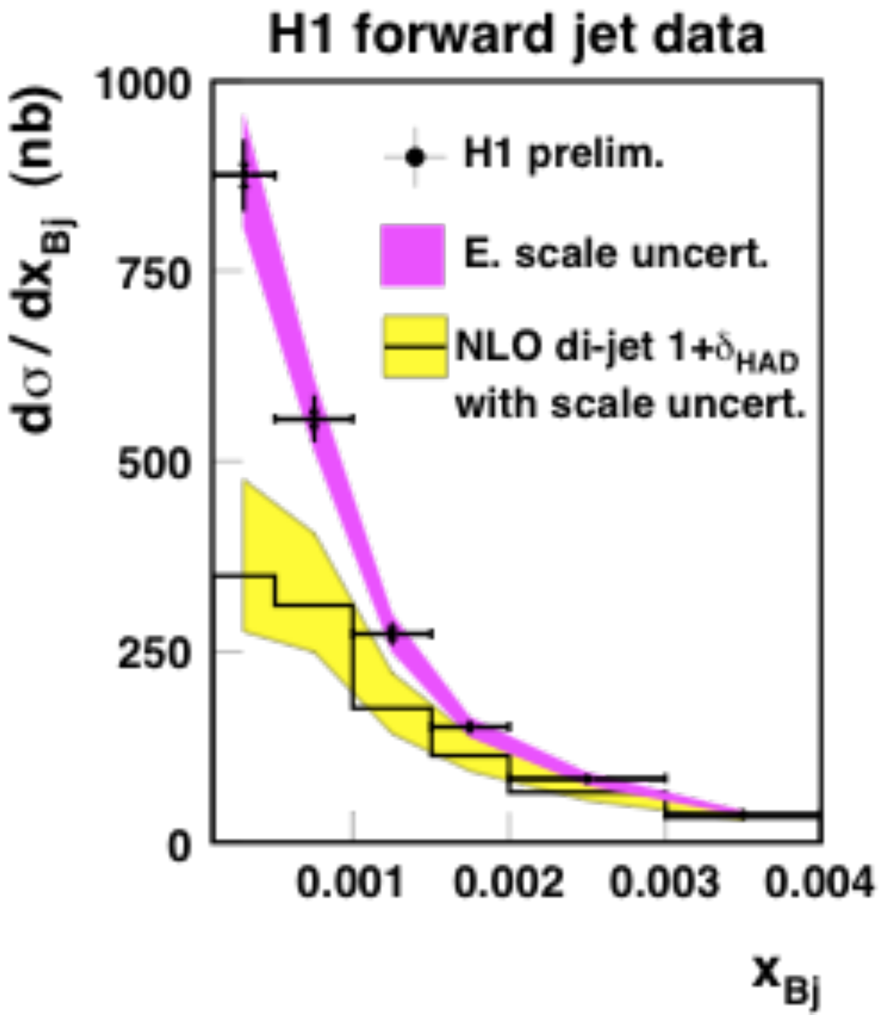
3 Emissions along the ladder

4 Forward Jet

5 Proton remnant

Very nice idea, very difficult measurement!

Forward jet cross section



Small x and x-jet around 0.05, so evolution between one and two orders

Very small pt, and thus Q^2, very close to validity of perturbation theory and at the limit of finding a jet

NLO prediction similar to DGLAP prediction: describes data at higher x but fails at smaller x

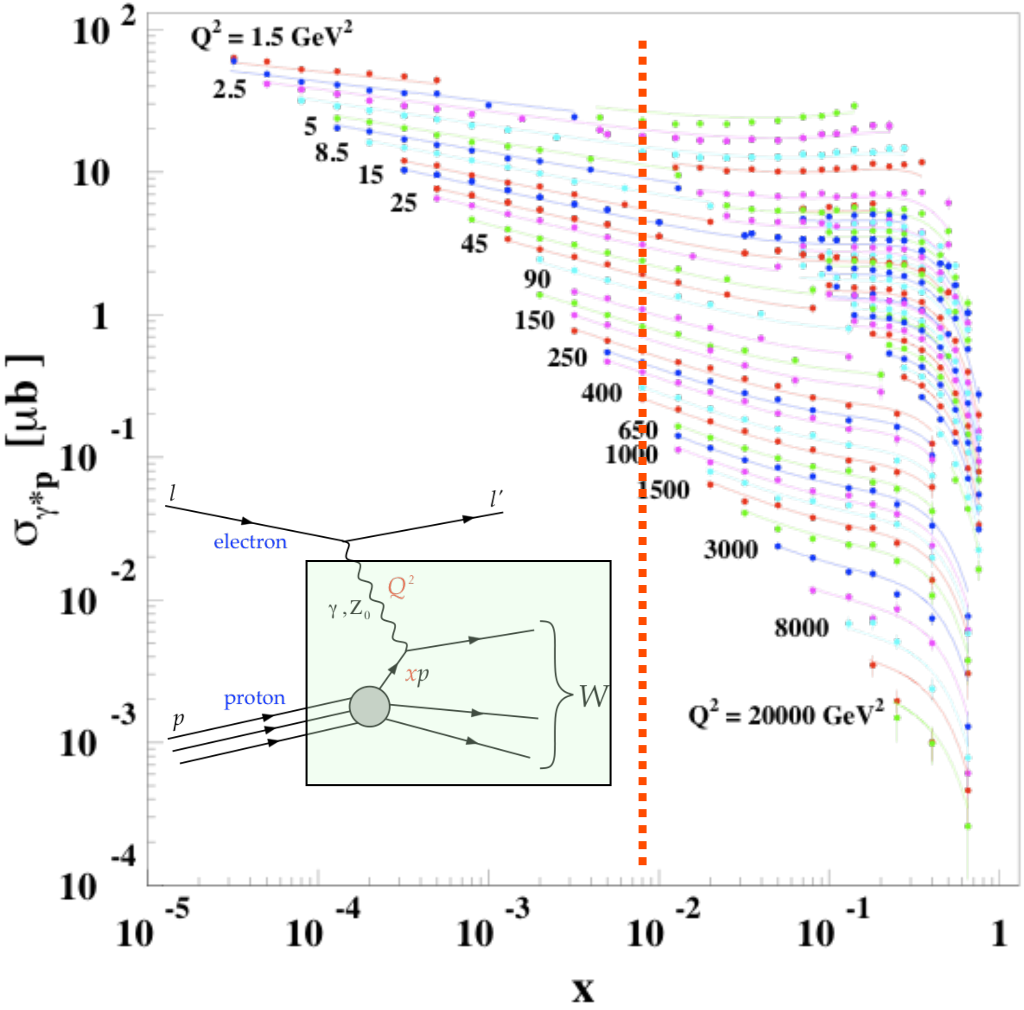
Data compatible with BFKL-like behaviour, but other models also describe the data

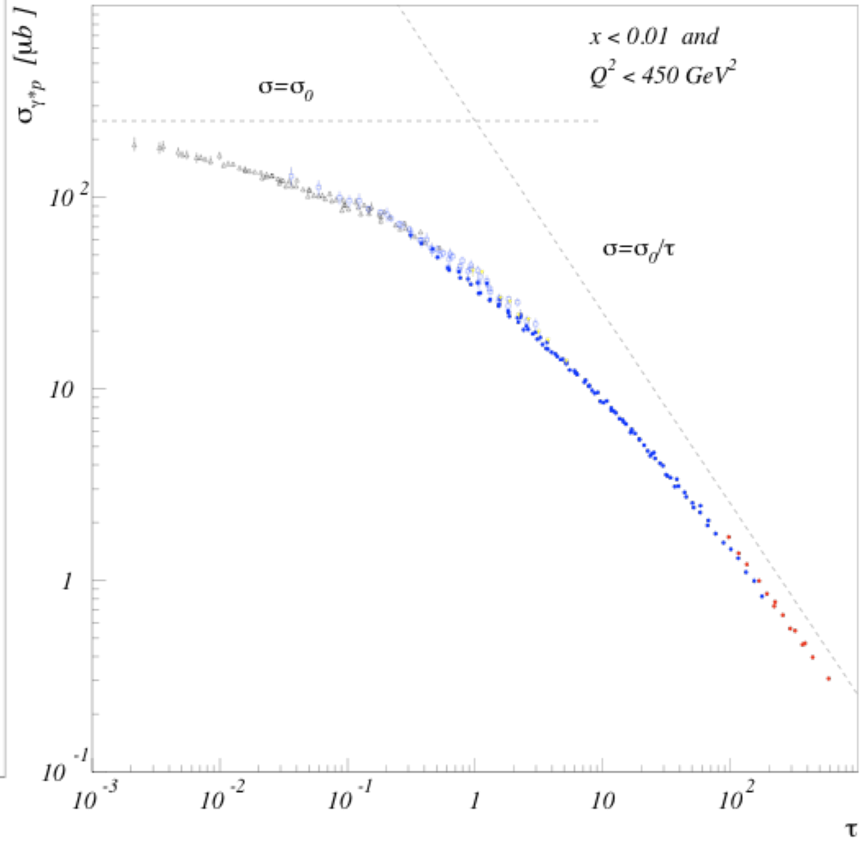
Geometric scaling: a sign of saturation?

At small x the F_2 data collaps into a single curve.
This behaviour is one of the hallmarks of saturation.

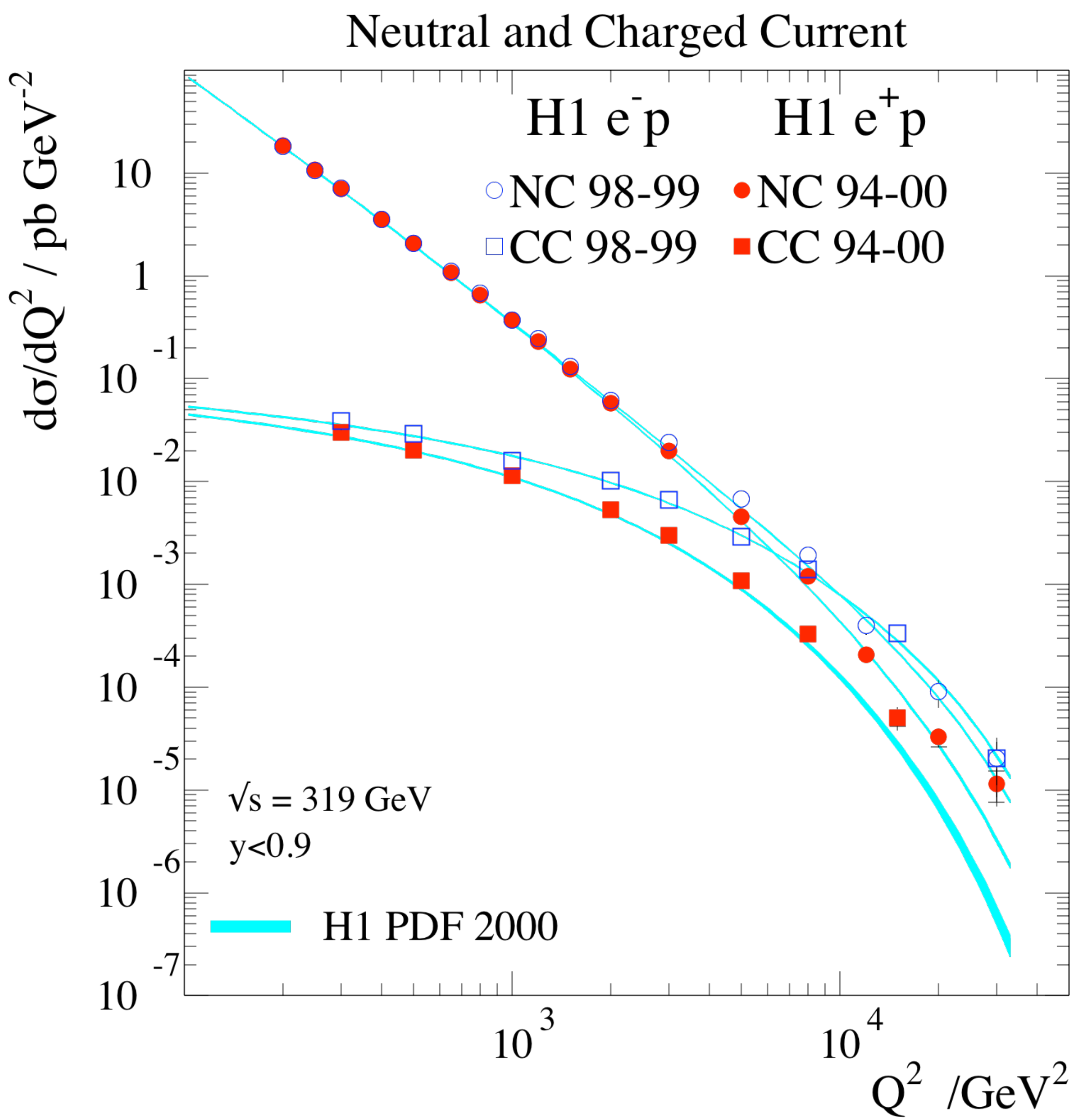
Beware of some theoretical problems and of other possible explanations …

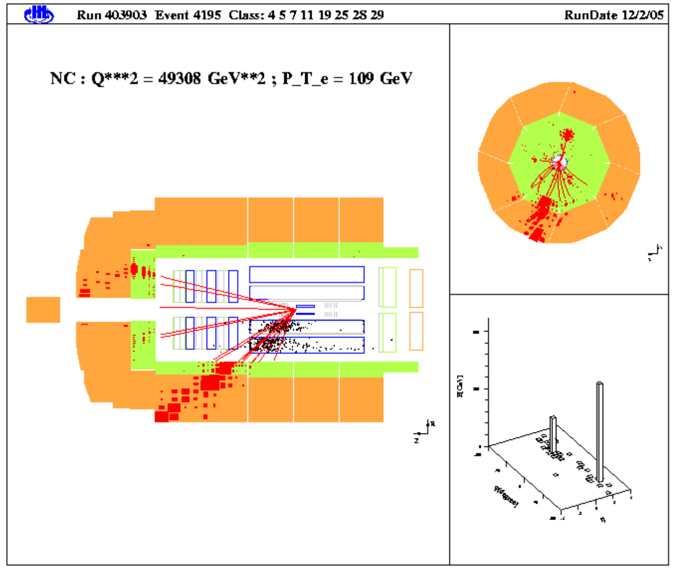
but it is beautiful!



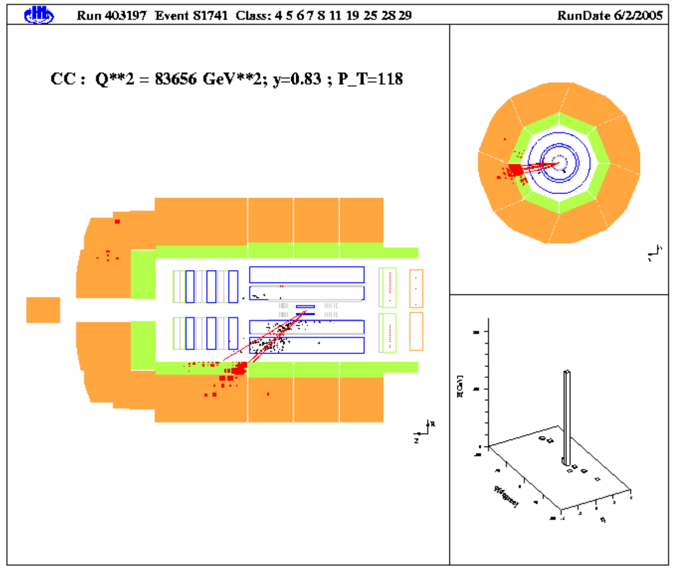


DIS, but not QCD: EW unification!





Count both types of events as the energy grows…



H1 Collaboration

In summary, with the right detector, and lots of fun work, you can see QCD (and much more) in action!