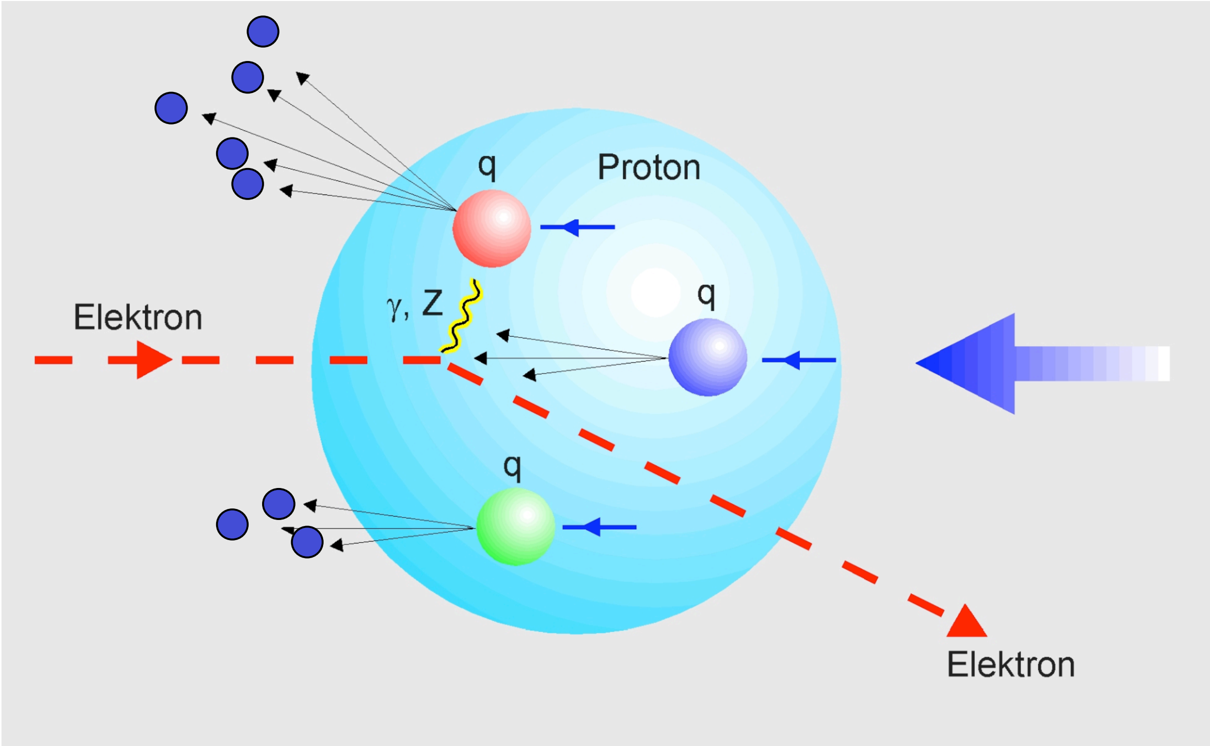
Resolving the Inner Structure of Matter

The H1 Experiment at HERA



Max Klein (DESY)

Particle physics

And you're glue

Nature Vol 400 1 July 1999

Frank Wilczek

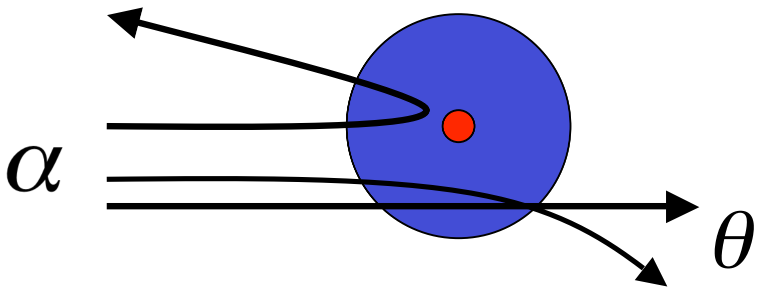
It's a widely believed half-truth that protons and neutrons are made out of quarks. Actually, physicists are increasingly discovering that it's considerably less than half the truth. The modern theory of the strong force, which binds quarks inside protons and neutrons, and these particles in turn to make atomic nuclei, is quantum chromodynamics (QCD). The other ingredients of QCD, the colour gluons, were once conceived as mere paste that somehow links together more substantial stuff (their name reflects this). No longer. On closer inspection, the quarks appear as the showier, but gluons as the weightier and more dynamic, constituents of matter. Definitive images[1] from a microscope capable of looking inside protons, the HERA accelerator in Hamburg, Germany, reveal as well that there is more to gluons than meets the eye.

To understand these evolving views, you must consider how one goes about looking inside a proton, to 'see' what it is made of. An ordinary microscope, using ordinary light, is woefully inadequate, because the wavelength of light is about one billion times larger than the size of the proton. Even fancy electron or scanning tunnelling microscopes can barely resolve single atoms, and fall far short of seeing the nucleus inside. The right tool for the job is a high-energy accelerator. They produce virtual photons of very short wavelength (and lifetime), that can be used to take snapshots of the proton's interior (Box 1, overleaf).

There's a catch, however, to this seemingly straightforward procedure. You get to see only what the virtual photon allows you to see. And because the photons couple only to electrically charged particles, constituents of

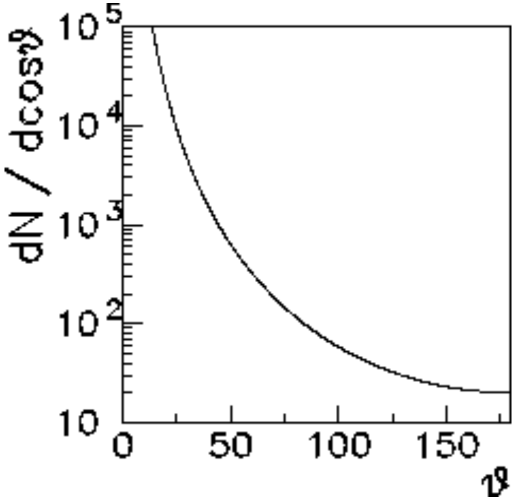
- History
- HERA
- Physics with H1
- Future Developments

Discovery of the atomic nucleus 1909



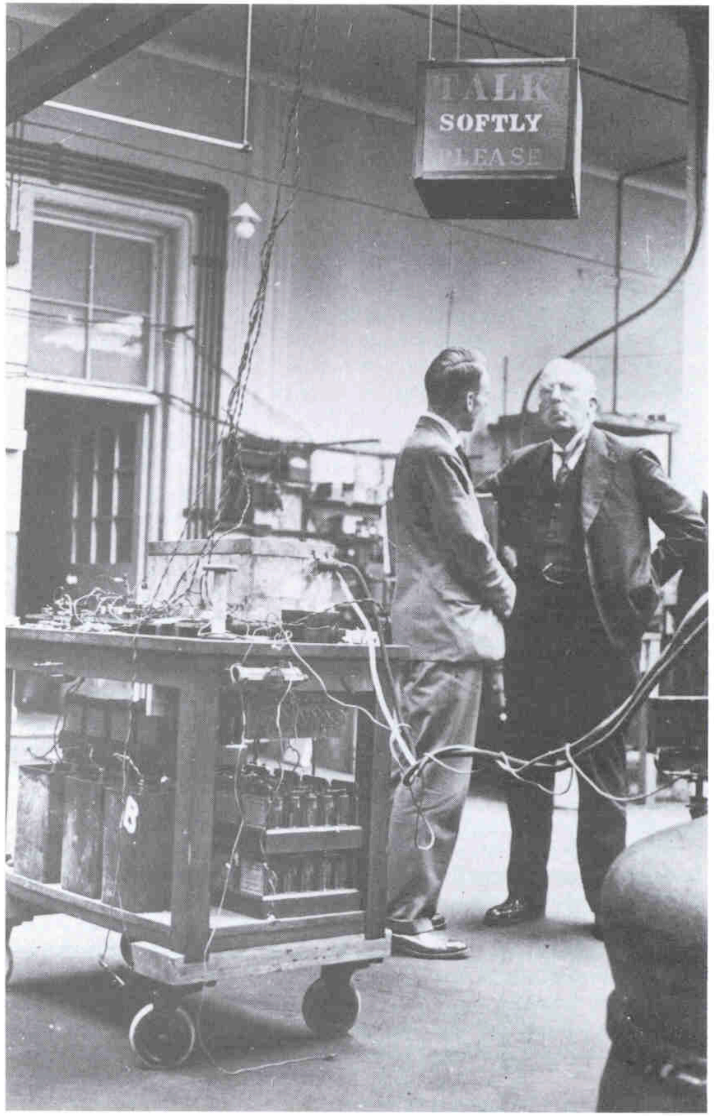
↳ positively charged massive atomic nucleus

$$r_{nucleus} \approx r_{atom}/10000 \approx 10^{-14}\,\mathrm{m}$$



$$\frac{dN}{d\Omega} \propto \frac{Z^2}{E^2}\frac{1}{4\sin^4\theta/2}$$

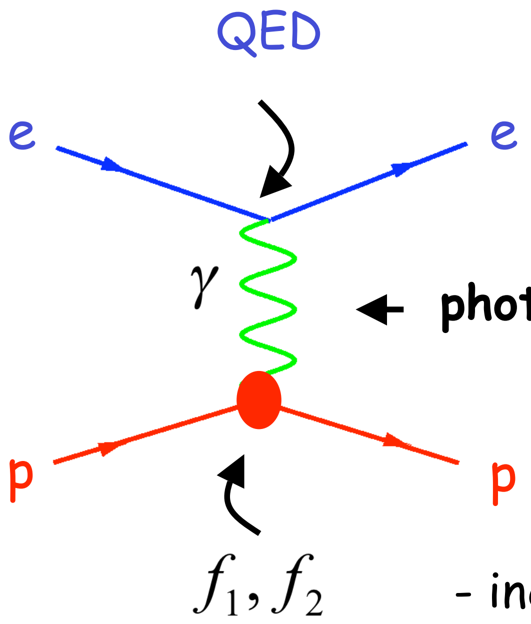
$$E_\alpha = 5.5\mathrm{MeV}$$



Ernest Rutherford (1871-1937)

H. Geiger und E. Marsden

Elastic electron scattering ep → ep



Feynman diagrams 1949

photon exchange $\propto \frac{1}{Q^2} \rightarrow \frac{1}{\sin^4\theta/2} \propto \frac{d\sigma}{d\Omega}_{Rutherford}$

Momentum transferred to p

- incalculabe formfactors (charge, magn. moment)

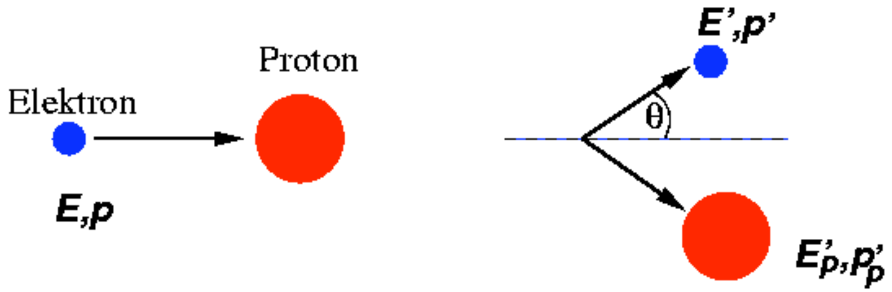
elastic scattering off a proton with charge distribution $\rho(r)$

$$f(Q^2) = \int d^3 r e^{iq\mathbf{r}} \rho(r) \approx 1 + \frac{Q^2}{6}\left\langle r^2_{\text{Proton}} \right\rangle$$

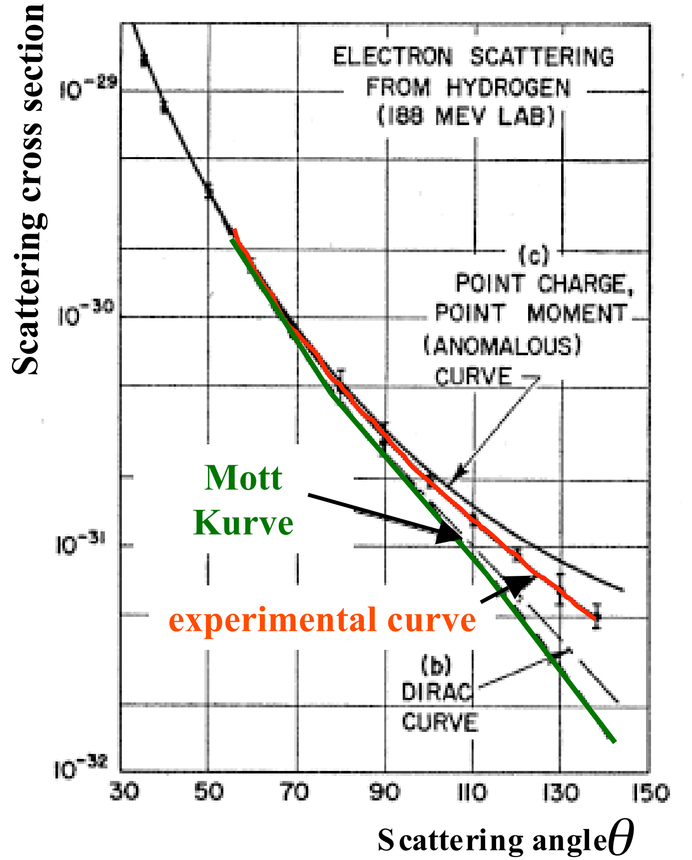
Protons have finite size

- 1955 R.Hofstadter and R.McAllister

  elastic ep scattering $E_e = 188\text{MeV}$



$$\mathrm{r_{Proton}} = (0.74 \pm 0.24)\cdot 10^{-15}\,\mathrm{m}$$



experimental curve (-) above the theoretical prediction of Mott (-)

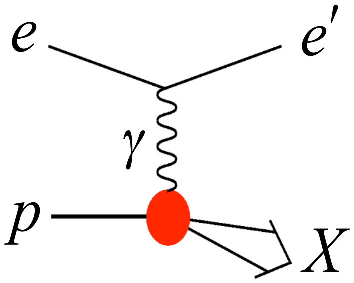
Mott 1929:

$\left.\frac{d\sigma}{d\Omega}\right|_{Mott}$: electron-scattering of pointlike particles

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{Mott} \cdot f\left(Q^2\right)$$

formfactor

Deep Inelastic Scattering ep → eX (1969)

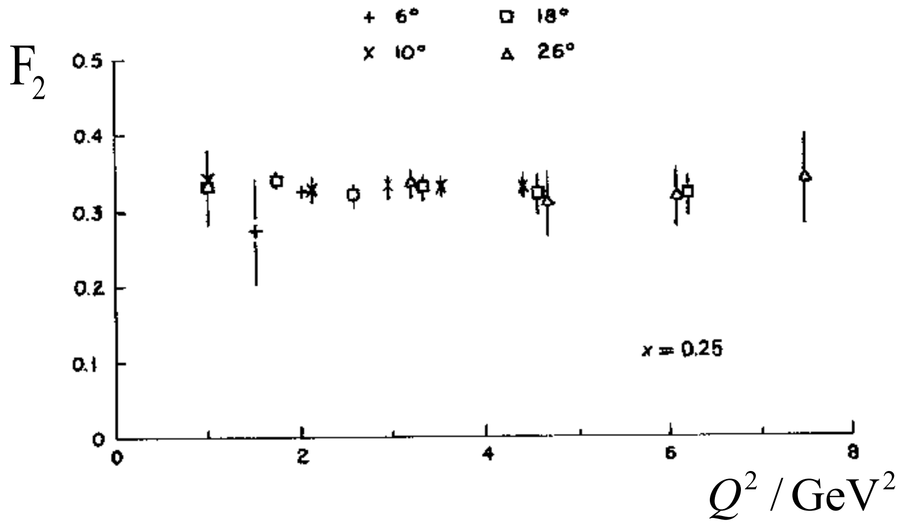


$E_e = 1.5 \ldots 20\,\mathrm{GeV}$

$\theta = 6° \ldots 26°$

$Q^2 = 1 \ldots 7\,\mathrm{GeV}^2$

resolution $\propto \frac{1}{Q} \approx 10^{-16}\,\mathrm{m}$



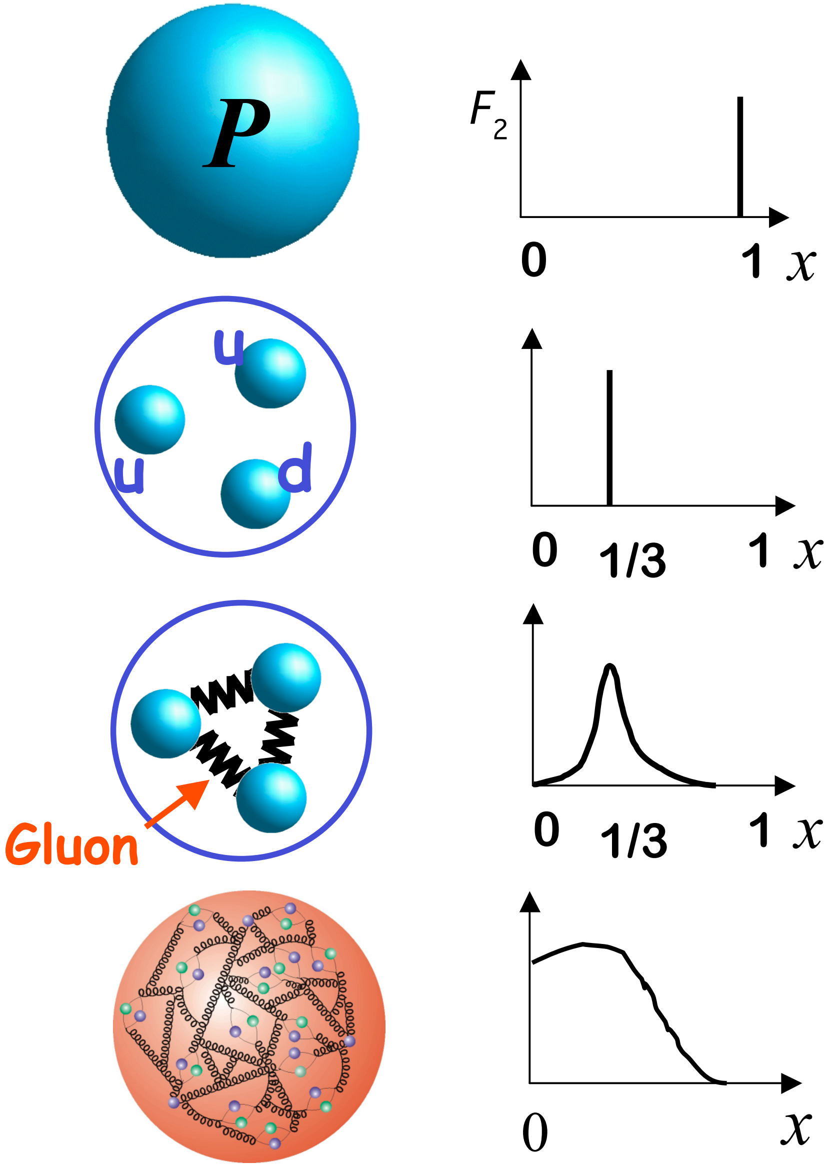
$$F_2(Q^2, \nu) \rightarrow F_2(x)$$

pointlike scattering centers inside the proton

x = momentum fraction carried by quarks

Friedman, Kendall, Taylor

$F_2(x,Q^2)$ – The function characterising the proton's structure



no substructure

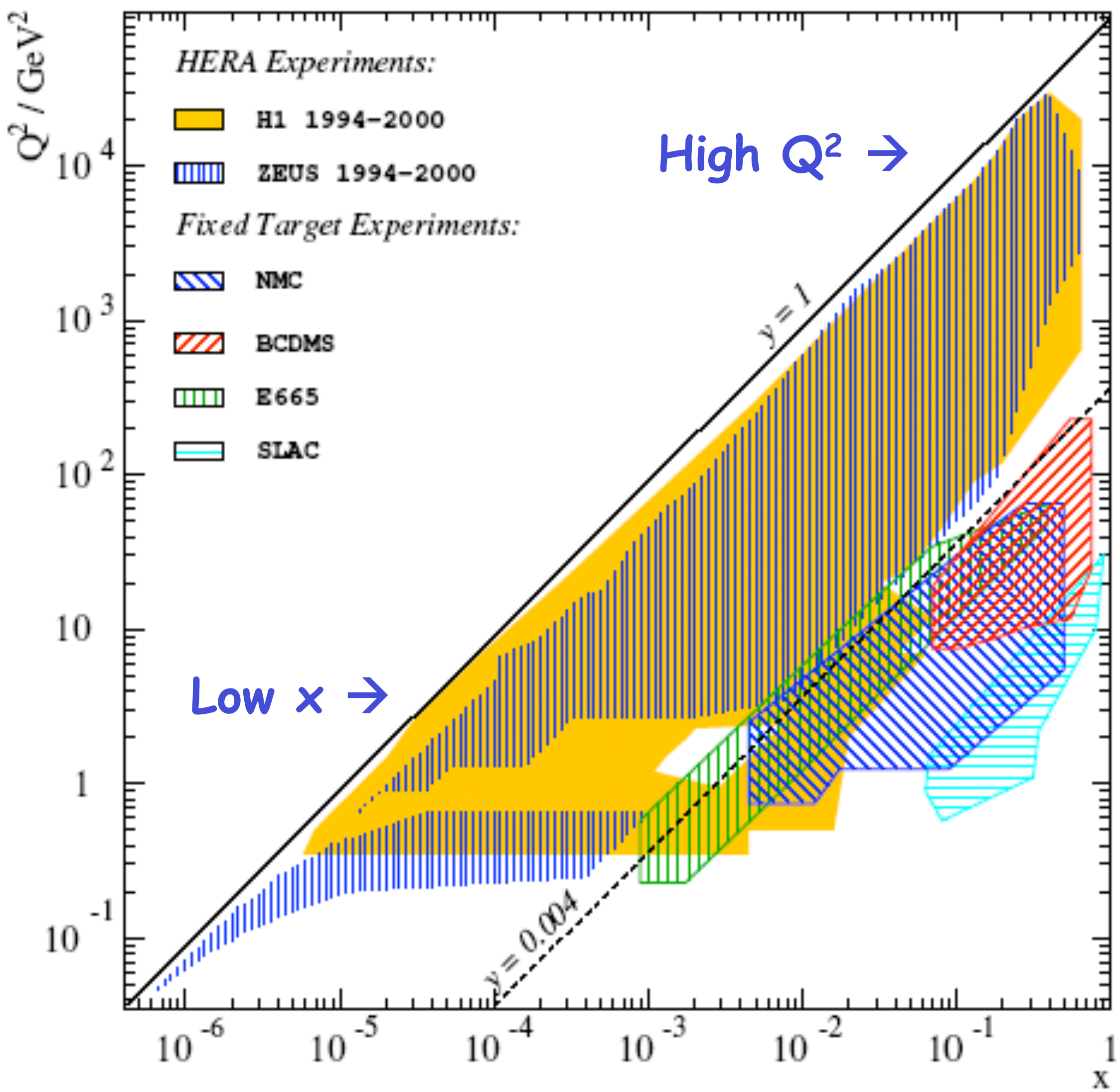
3 free valence quarks

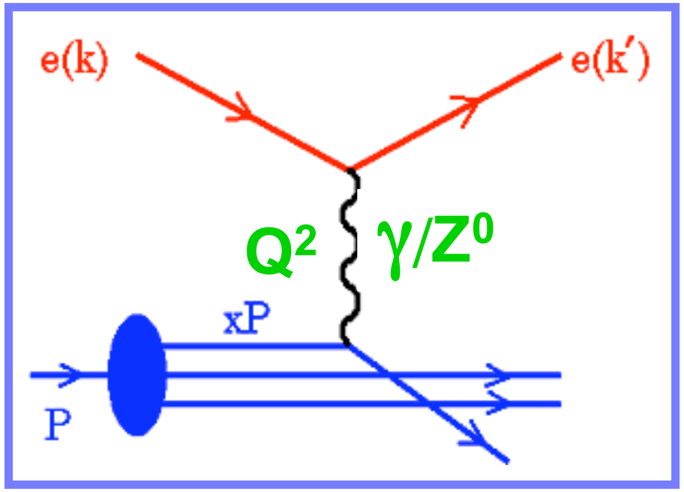
3 bound quarks

Valence quarks
Sea quarks
gluons

Q^2 ↓

HERA - Deep inelastic scattering and searches at the energy frontier





$$E_e = 27.6GeV, E_p = 920GeV$$

$$\sqrt{s} = 2\sqrt{E_e E_p} = 319GeV$$

$$\Leftrightarrow E_e^{ft} = 54.100GeV$$

$$Q^2 = sxy - high$$

$$x = Q^2 / sy - low$$

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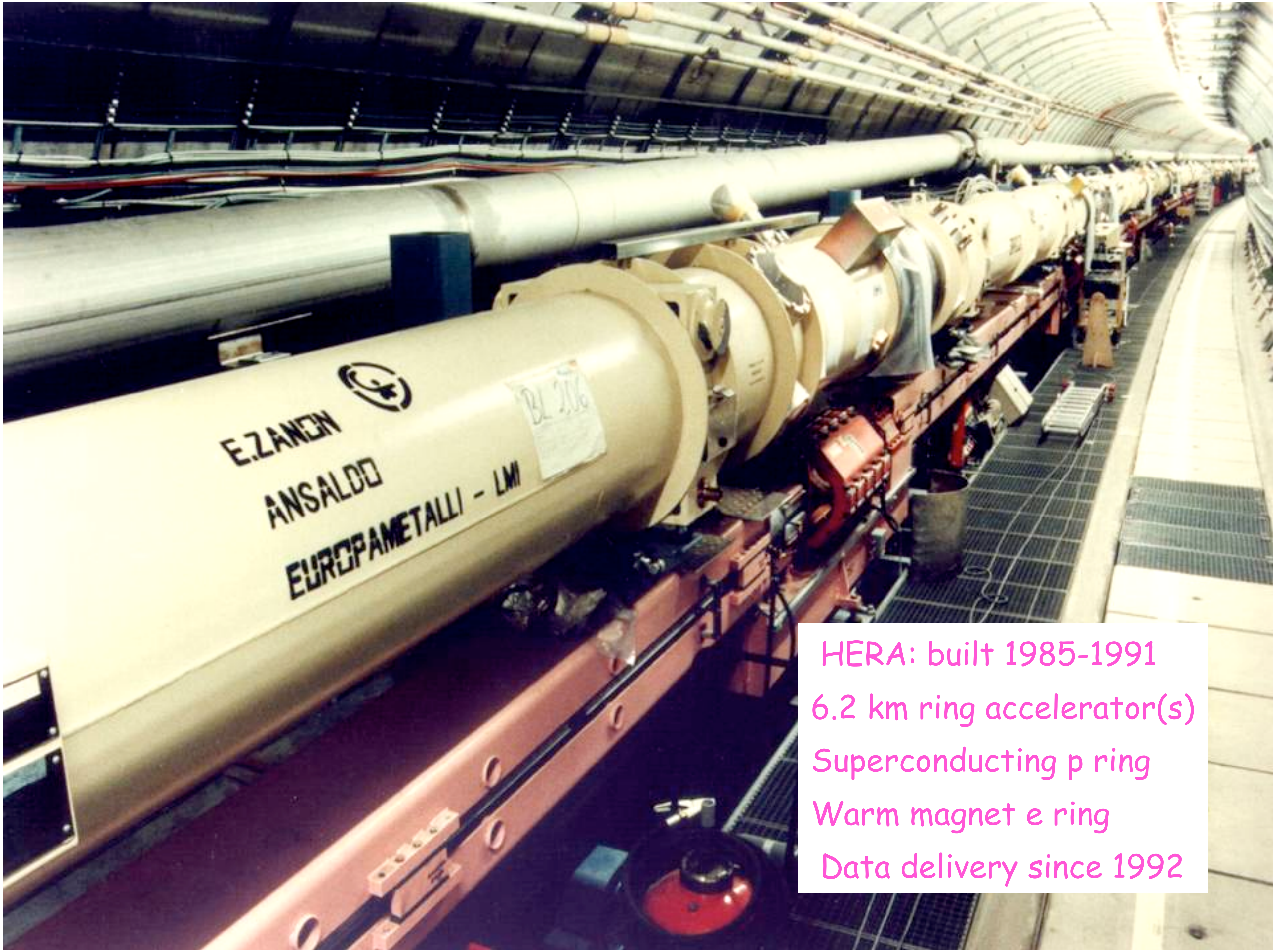


HERA: built 1985-1991

6.2 km ring accelerator(s)

Superconducting p ring

Warm magnet e ring

Data delivery since 1992

HERA and its Pre-Accelerator Chain

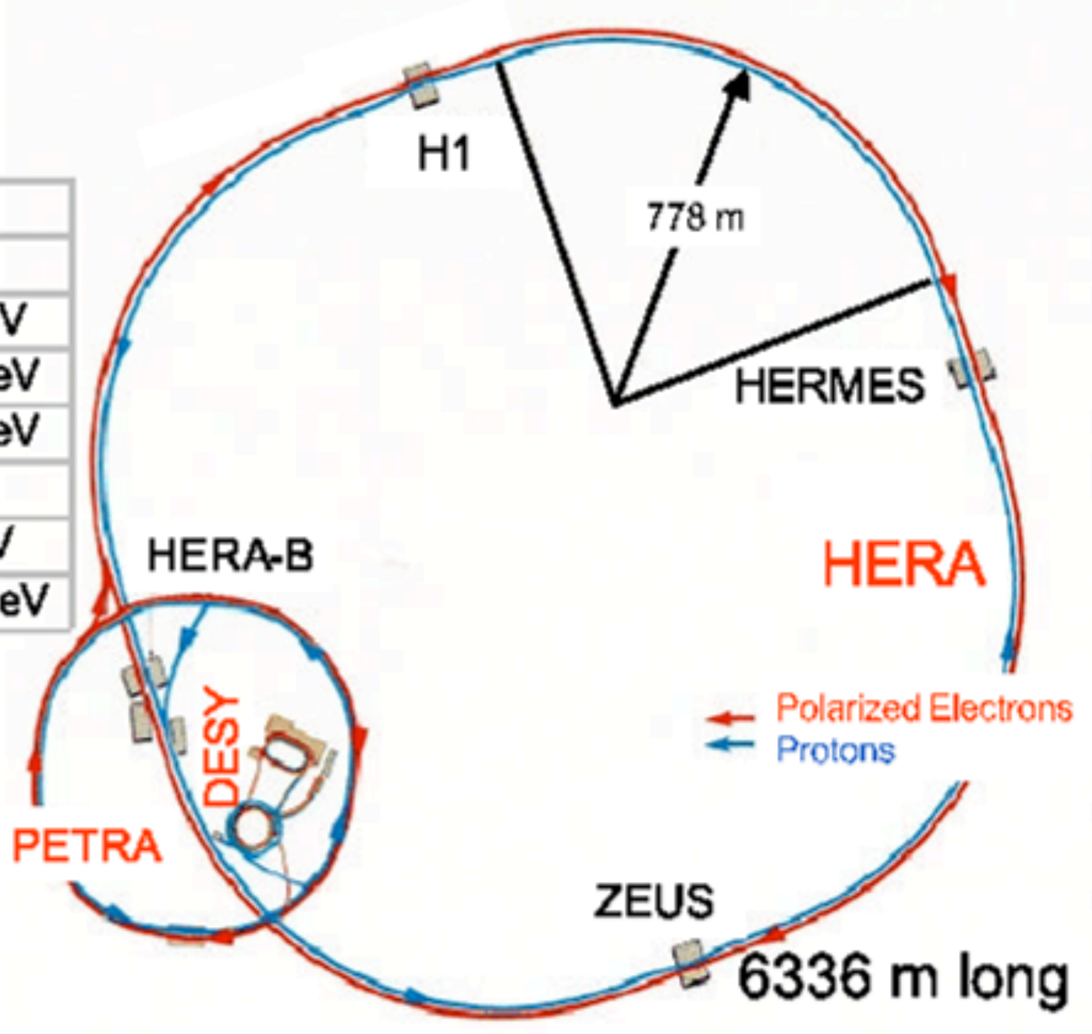
	Protons	Electrons	
20 keV	Source	Source	150 keV
750 keV	RFQ	Linac II	450 MeV
50 MeV	Linac III	Pia	450 MeV
8 GeV	DESY III	DESY II	7 GeV
40 GeV	PETRA	PETRA	12 GeV
920 GeV	HERA-p	HERA-e	27.5 GeV

$E_e = 15..30 GeV, E_p = 400..1000 GeV$

$polarisation: P(e) = -0.5...0...+0.5$

$L_{spec} \approx 0.4...2 \cdot 10^{30} cm^{-2} s^{-1} mA^{-2}$

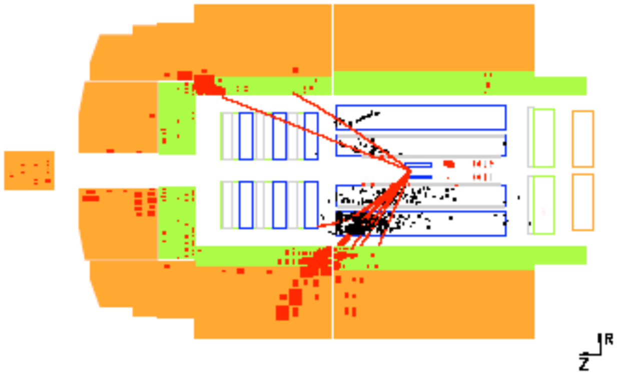
$I_e = 20...50 mA, I_p = 60...100 mA$



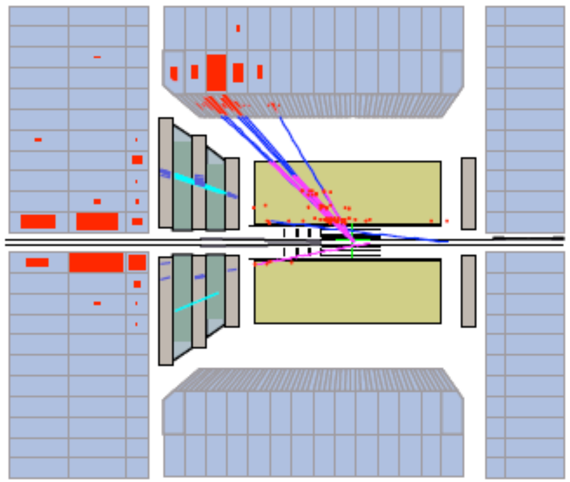

H1
ZEUS
HERA
protons 920 GeV
electrons 27.6 GeV
PETRA

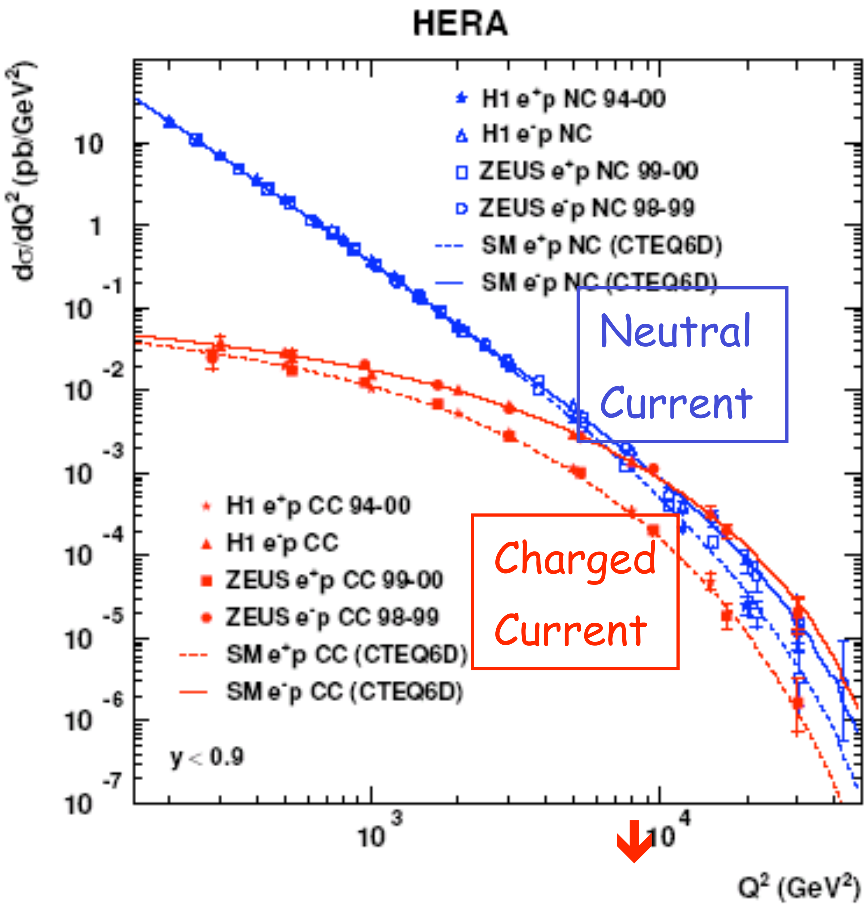
HERA was built to study Rutherford backscattering
and the unification of electromagnetic and weak interactions at high Q^2

Neutral current $e^+ p \rightarrow e^+ X$



Charged current $e^+ p \rightarrow \bar{\nu} X$

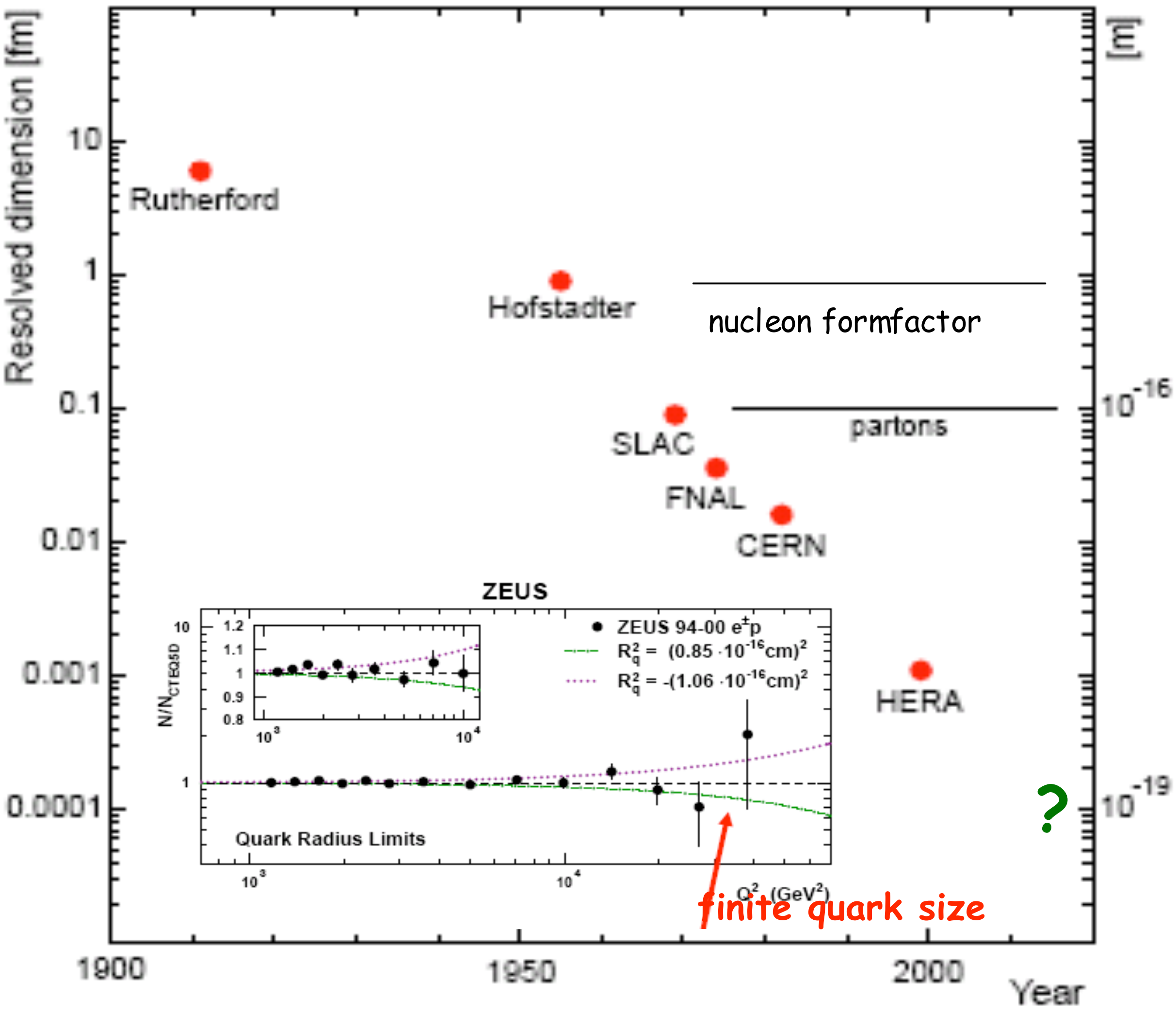




$$\sigma^{\pm}_{NC} \approx \sigma^{\pm}_{CC} \leftrightarrow Q^2 \approx M_Z^2 \approx 10^4\, GeV^2$$

… its physics is much richer

HERA: quarks are pointlike down to proton radius/1000



Inclusive cross section ep → eX exhibits so far no extra formfactor

→ Limits on SUSY, leptoquarks, extra dimensions, quark radius…

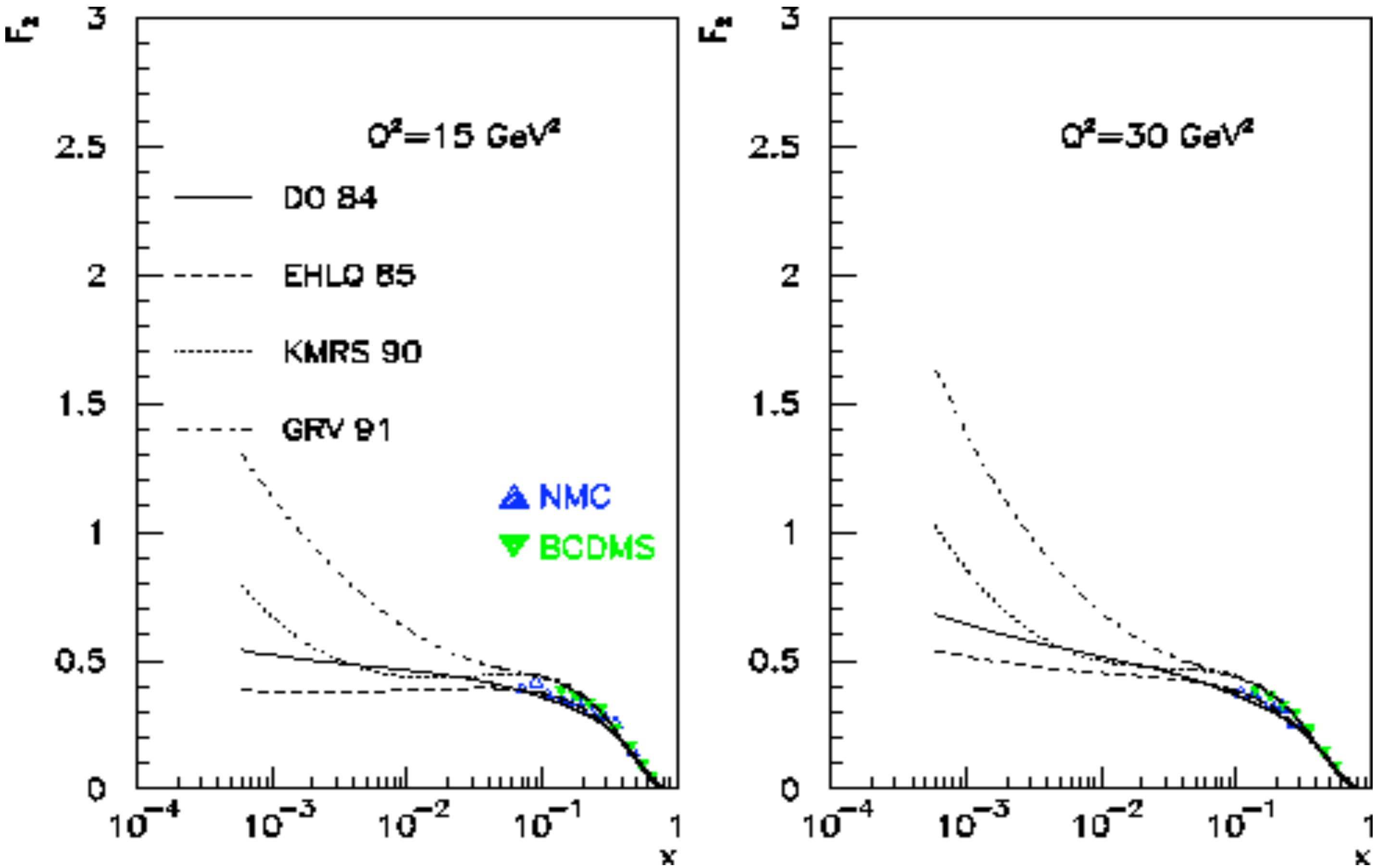
→Luminosity upgrade to probe deeper the smallest dimensions

present limits

ZEUS r < 0.85

H1 r < 1.0 10^{-18}m

•Expectations on the density of partons before HERA

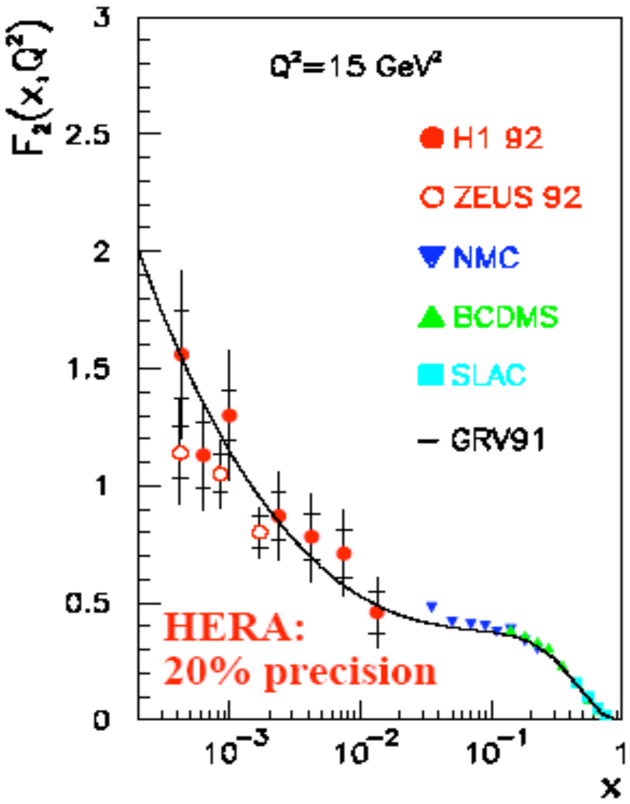


$$F_2 = x \sum e_q^2 [q + \bar{q}]$$

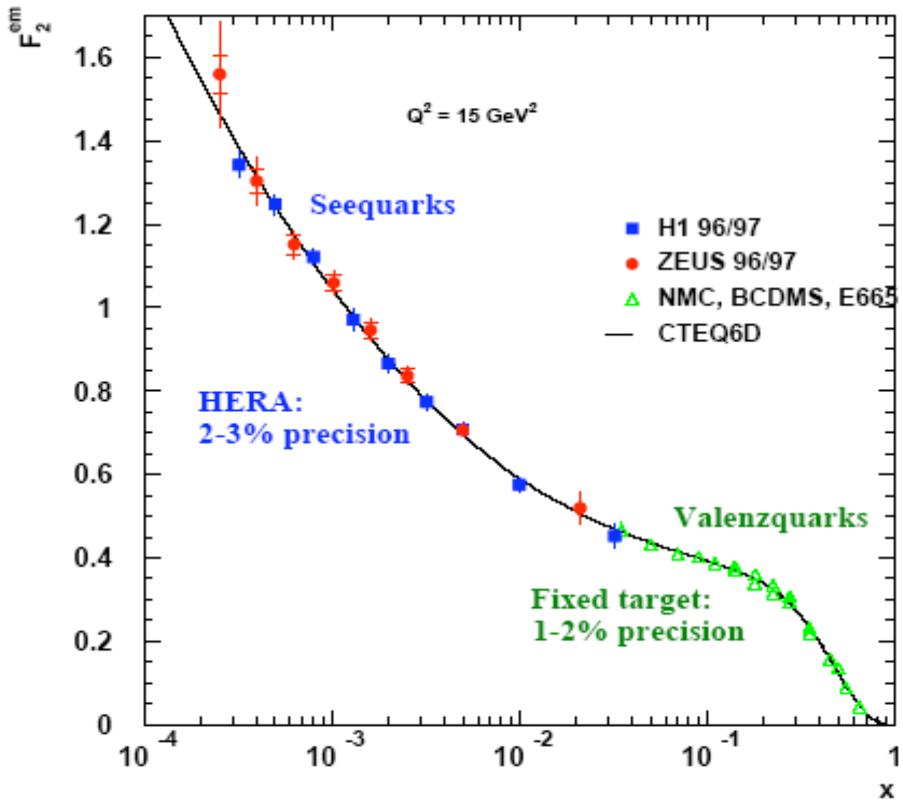
$$u = u_v + u_s, \bar{u} = u_s, d, s = \bar{s}, c = \bar{c}, \ldots$$

HERA discovered high density state of matter (QCD, neutrino astrophysics, ..)

1992 data ~30nb-1



1997 data ~30pb-1



consequences, regarding the pointwise evolution of structure functions, were derived. The most dramatic of these, that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later.

F. Wilczek

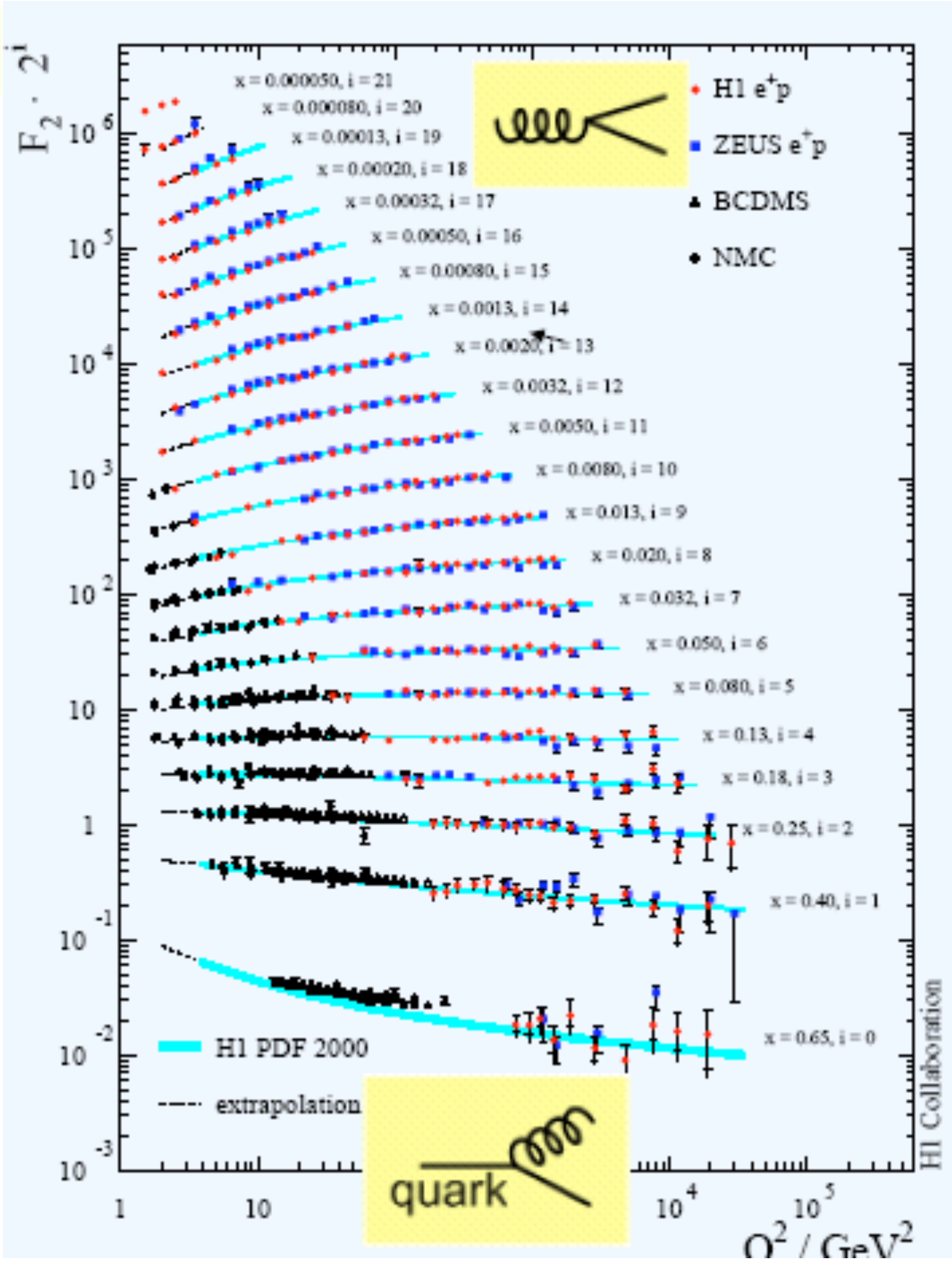
strong coupling and the gluon

$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)xg(x,Q^2)$$

resolve correlation
of coupling and gluon
by accessing wide
range of x and Q^2

assume DGLAP evolution
though that neglects ln(1/x)

$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s(Q^2)q(x,Q^2)$$



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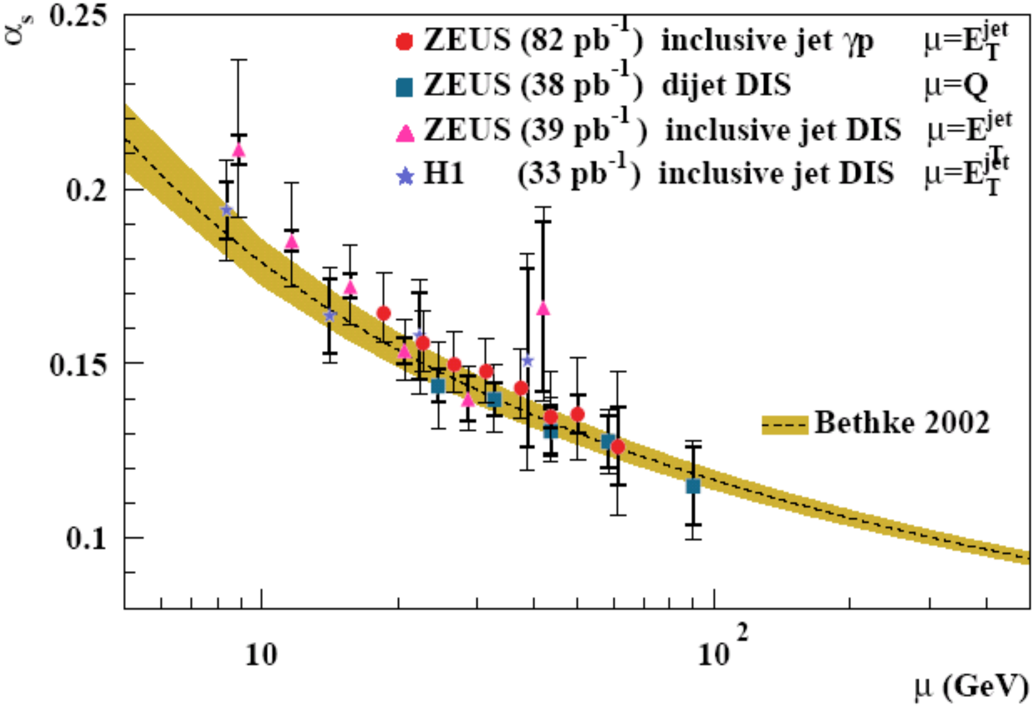
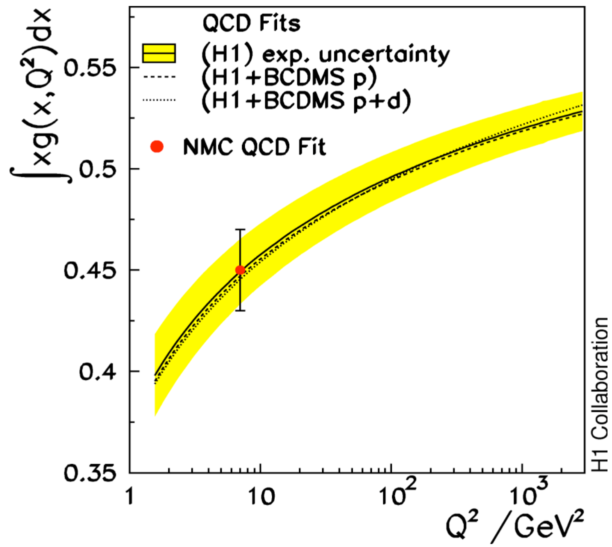
The strong interaction gets larger at small distances [asymptotic freedom] and gluons carry half of proton's momentum: QCD non Abelian qg field theory



quarks carry only about 1/2 of the nucleon momentum:

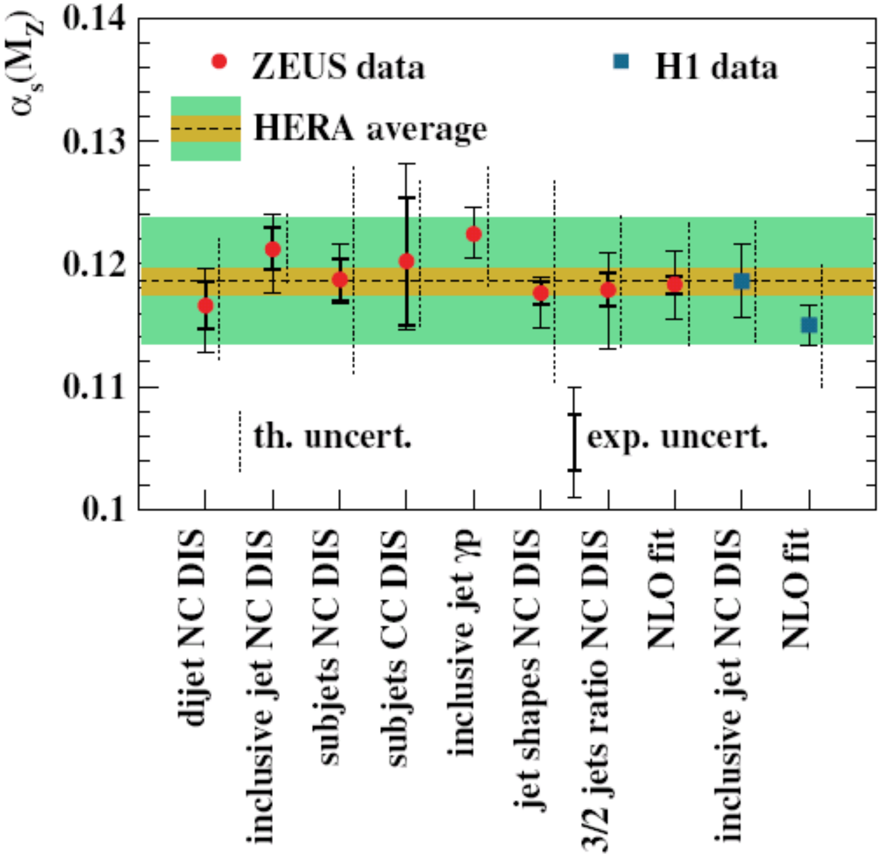


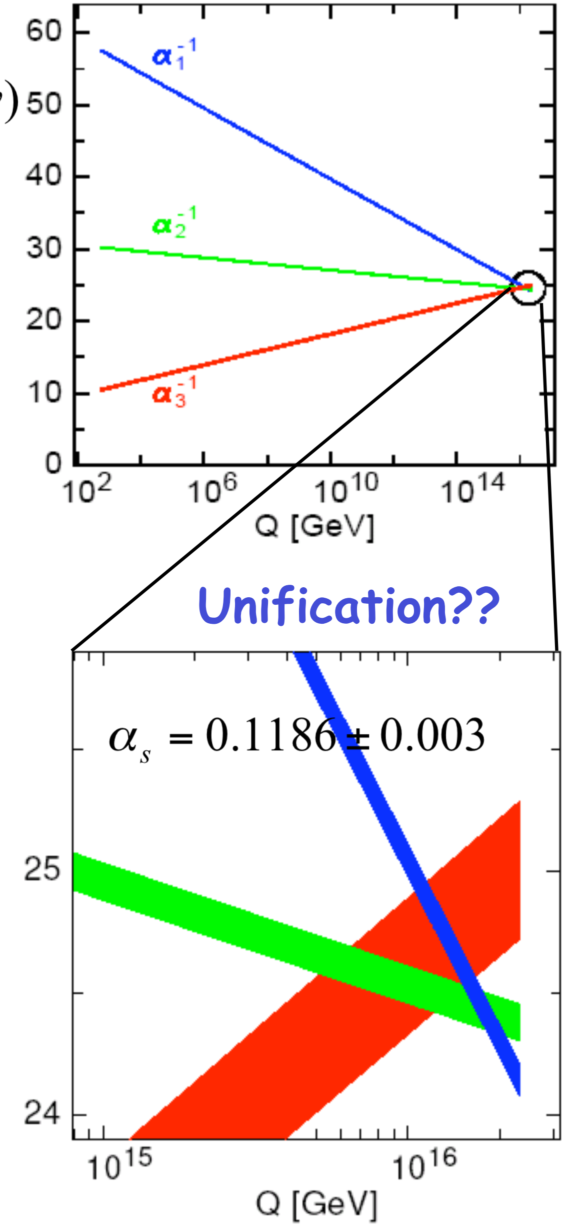
•Nobel prize 2004: Gross, Politzer, Wilczek

no doubt it "runs" - BUT how large is the coupling? and is the field so simple? HERA has a fundamental role to answer these ?'s

HERA may determine strong coupling best

$$HERA(prel.) - \alpha_s(M_Z^2) = 0.1186 \pm 0.0011(\exp) \pm 0.005(thy)$$





Next steps: higher accuracy data and NNLO

QCD represents ongoing exciting theory development,
from hadronic interactions to a field theory of quarks and gluons

- Landau 1955:
  „weak coupling electrodynamics is …
  fundamentally logically incomplete."

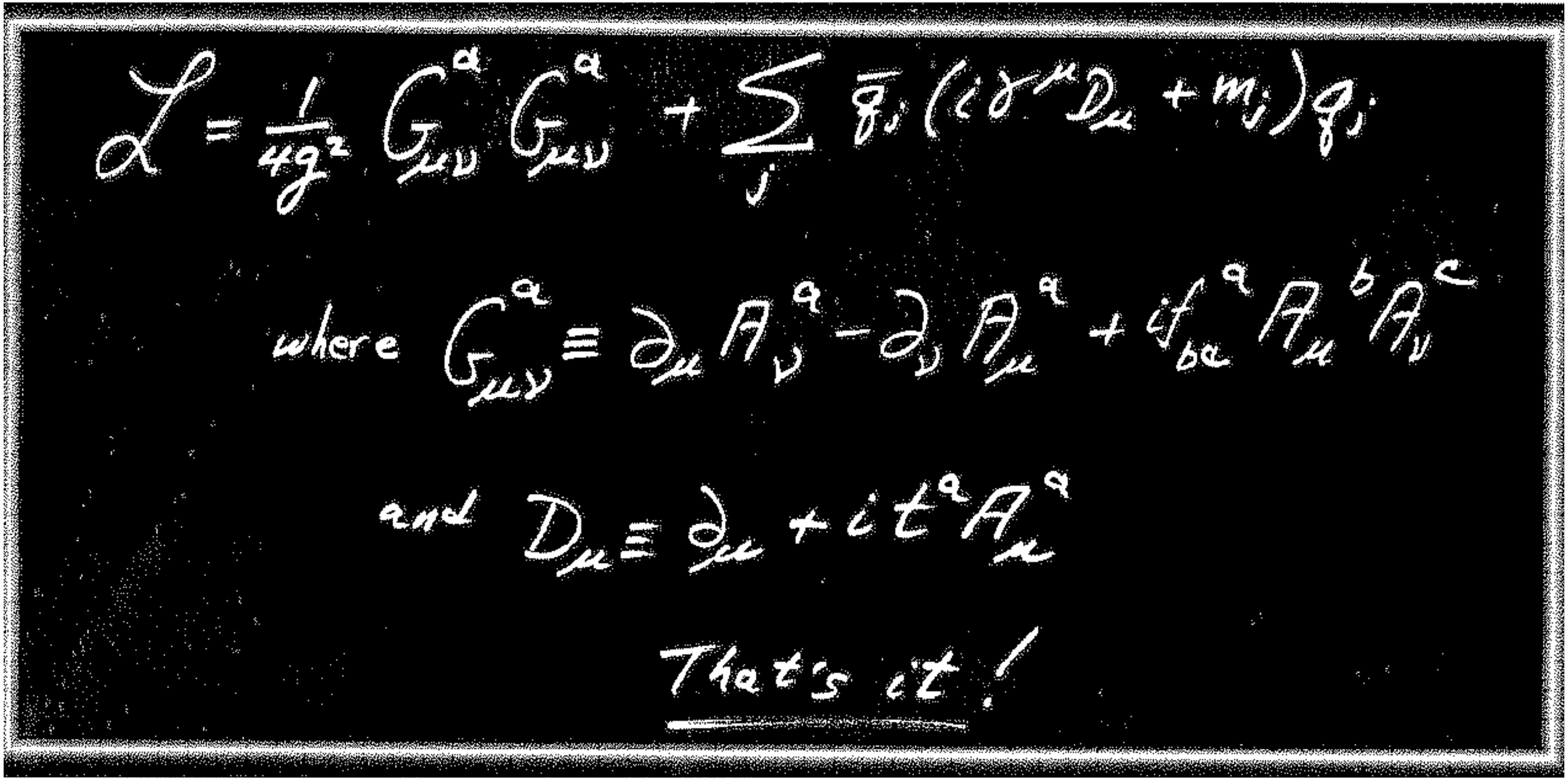
  „within the limits of formal electrodynamics
  a point interaction is equivalent … to no interaction at all."

- Dyson 1960:
  "The correct theory will not be found within the next 100 years."

- Feynman 1961:
  "I still … do not subscribe to the philosophy of renormalization."

- Weinberg 1972, Gravitation + Cosmology:
  „we encounter theoretical difficulties beyond the range
  of modern statistical mechanics."

The QCD Lagrangian



j ... quark flavours   a,b,c ... 3 colours   μ,ν ... space-time

F.Wilczek, Physics Today, August 2000.

Physics at HERA (the expected and the unexpected)

•classic DIS

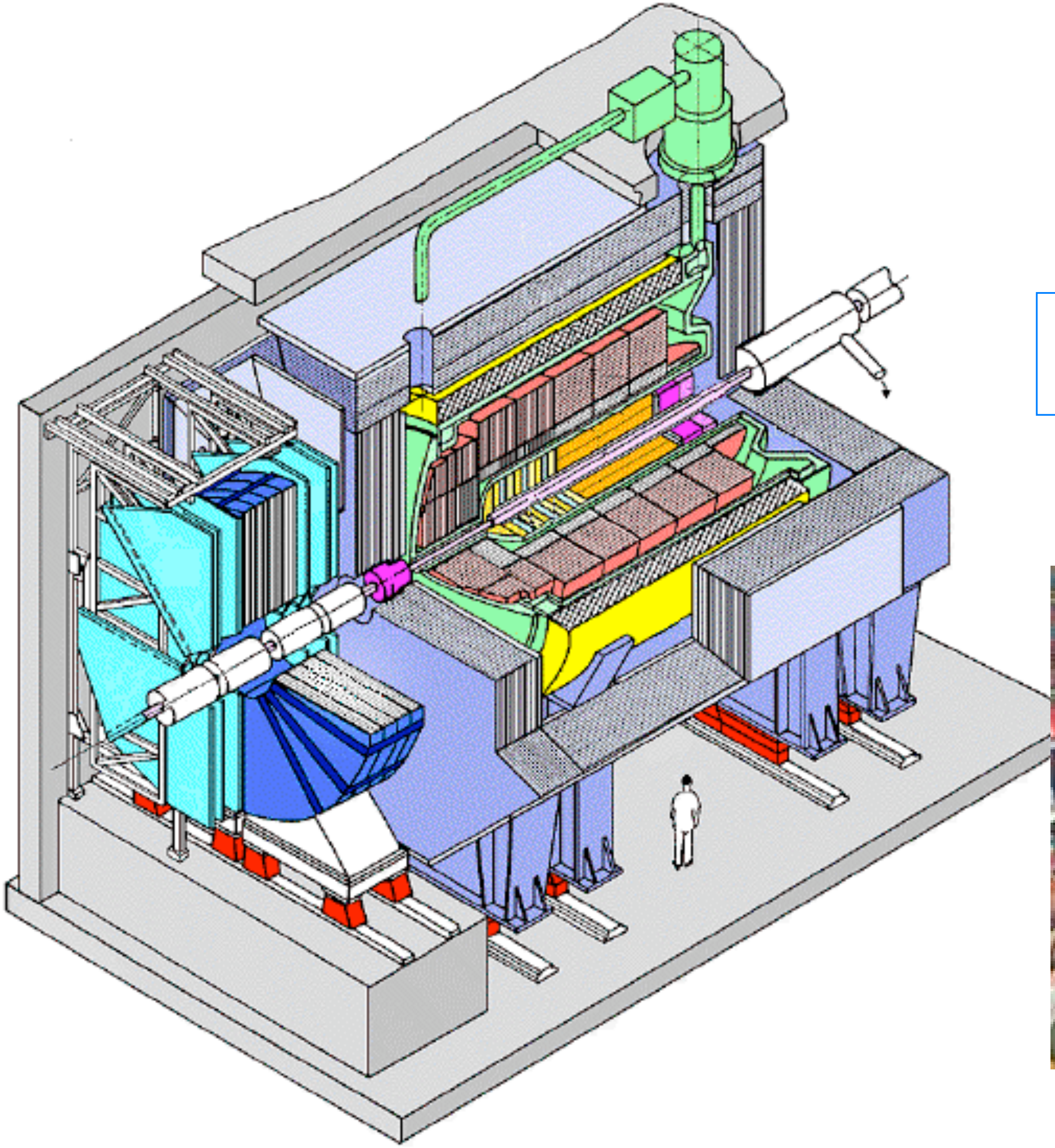
•QCD

•Searches

- Inclusive ep measurements (NC, CC-inverse neutrino i.a.) → pdf's, gluon,
- Low x physics: small coupling and high density of partons → "CGC, BFKL.."
- Heavy flavour physics (c and b: production and fragmentation dynamics)
- Final state physics (parton emission,,jets, γ structure, dijet correlations)
- Diffraction [all related: e.g. "the structure of charm jets in diffraction"]
- Parton amplitudes (DVCS)
- Searches for exotic states (pentaquarks) and less? exotic ones (instantons)
- Searches: substructure, leptoquarks, SUSY, isolated lepton events (17/5)
- Electroweak physics (spacelike region)

for HERA physics see also:

- Talks at DIS05, April 2005, Madison
- Ringberg Workshop (2003) Proceedings ed by G.Grindhammer, B.Kniehl, G.Kramer

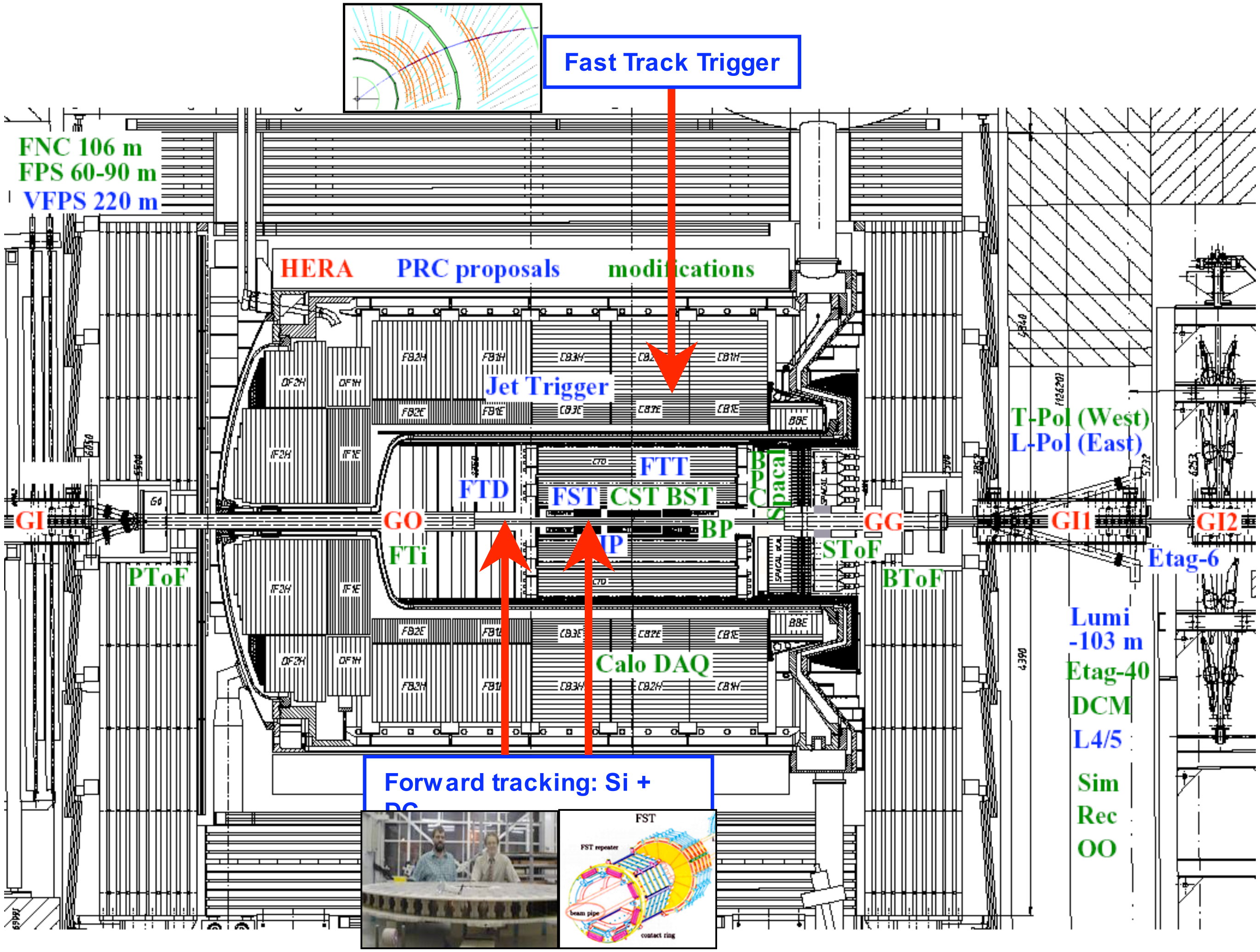


~320 authors, 40 institutes

100 PhD students, 50 engineers

Forward Proton and Neutron Spectro-meters

Fast Track Trigger



Luminosity spectrometer

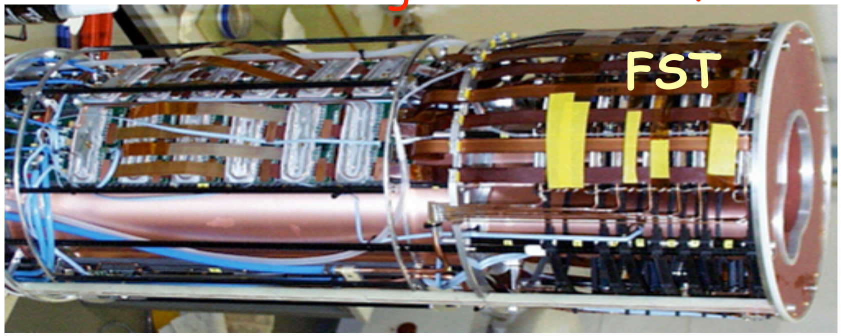
e

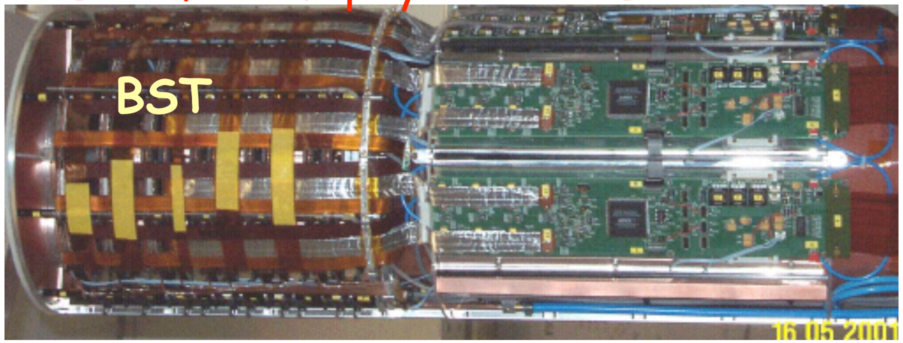
27.5 GeV

p

920 GeV

New tracking detectors of H1 and ZEUS for HF physics in HERA II



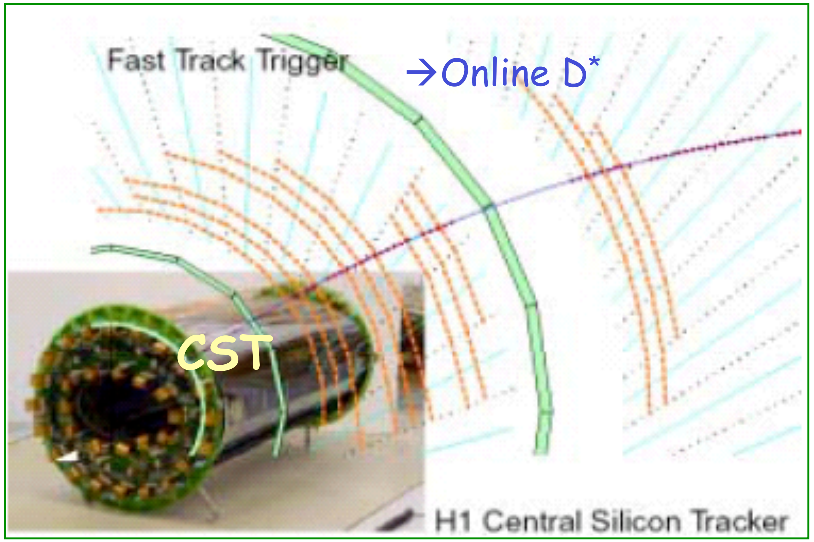


charm and beauty

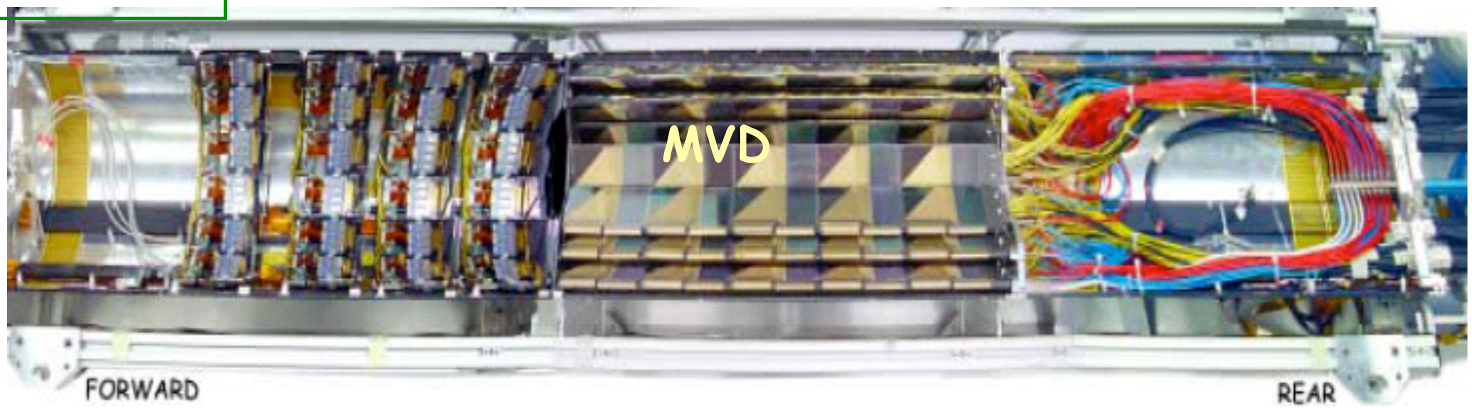
evt vtx (lo and hi y)

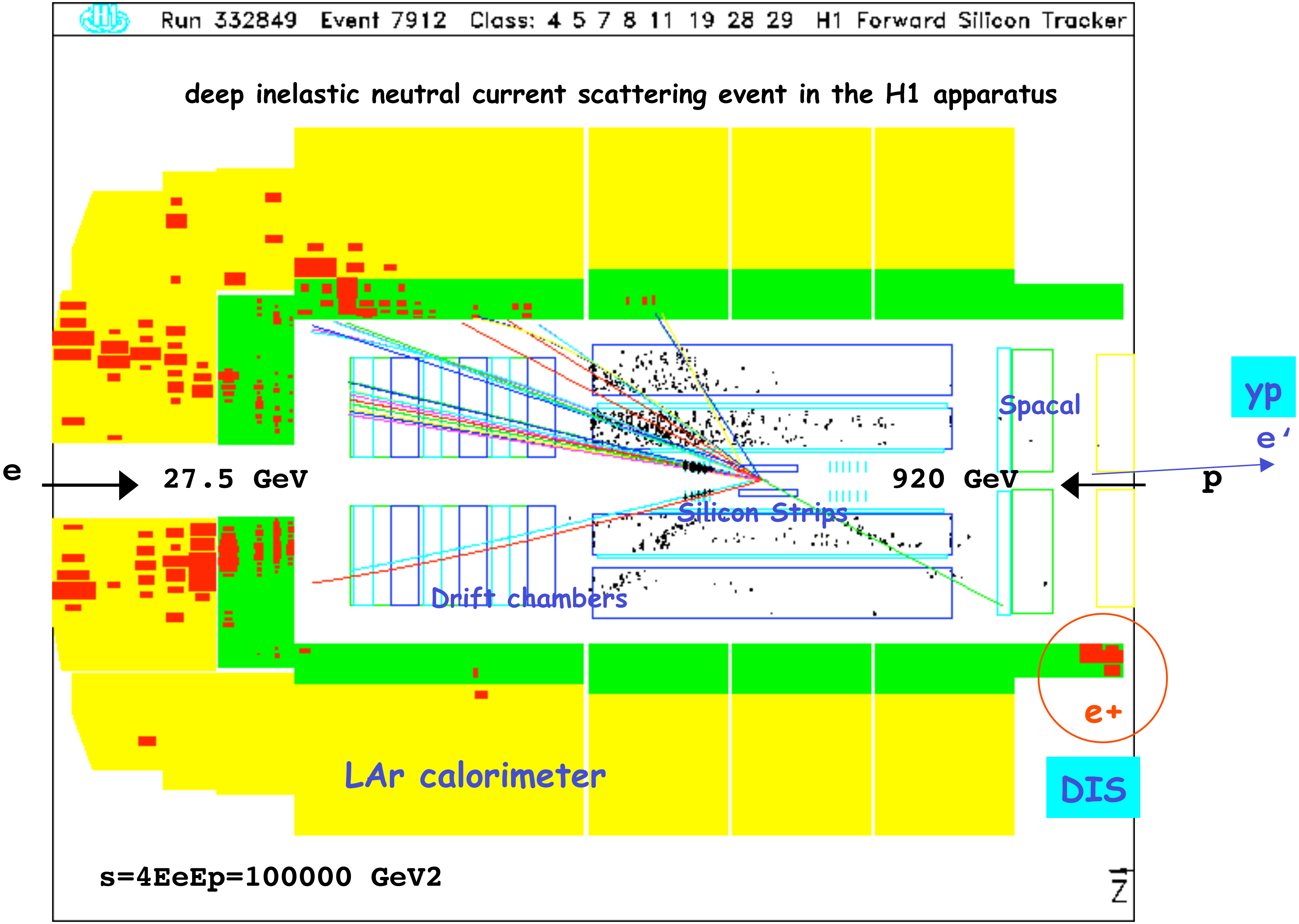
eID (DVCS, J/Ψ, searches)

F_L



Huge investments for high lumi phase by H1 and ZEUS & fwd chambers





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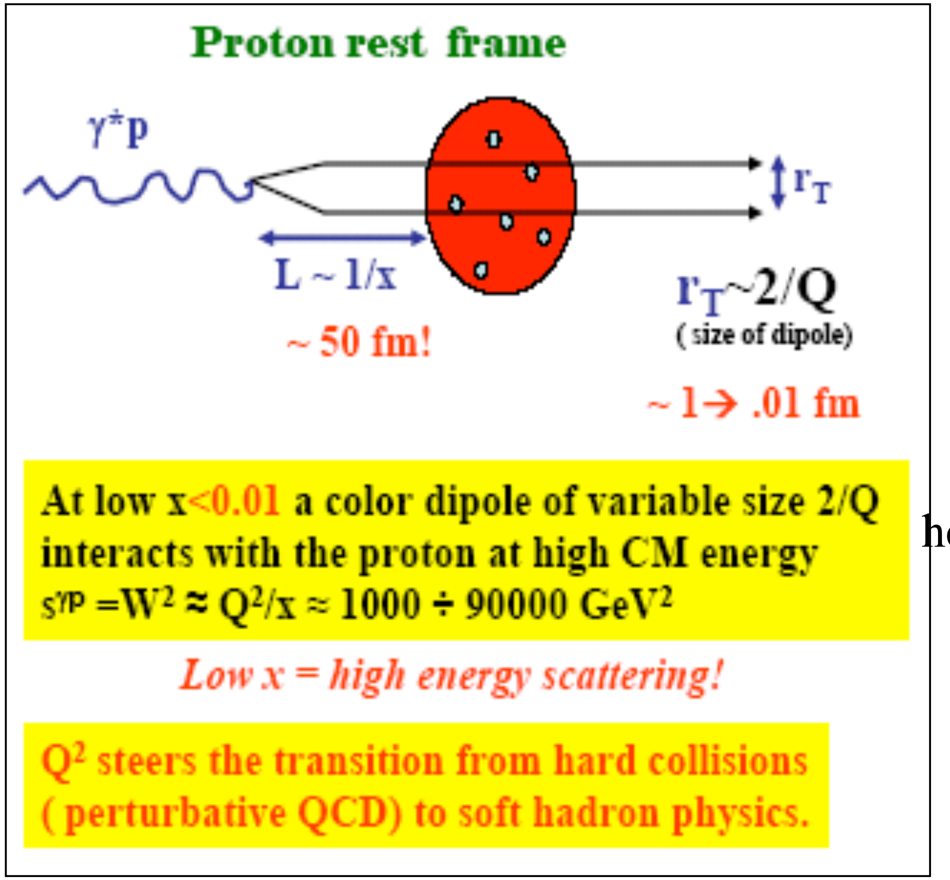
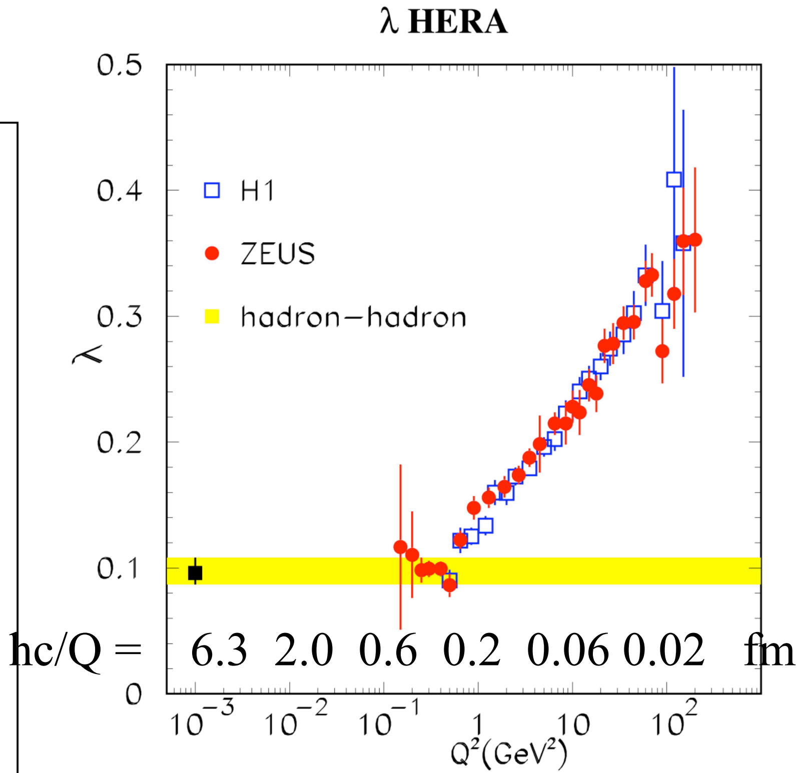
High energy allows to take snapshots of proton structure: photon fluctuates into colour dipol. Its virtuality allows to scan through p's structure.
HERA measured the transition from hadronic (soft) to partonic (hard) behaviour which occurs at 0.3fm --> new data to come

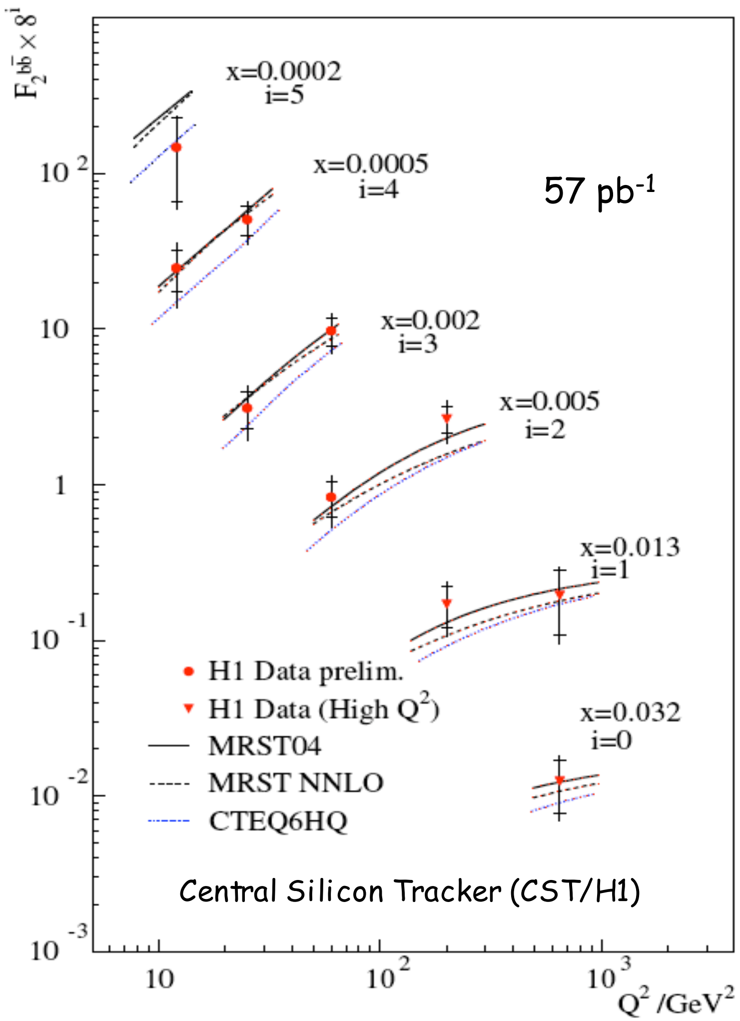


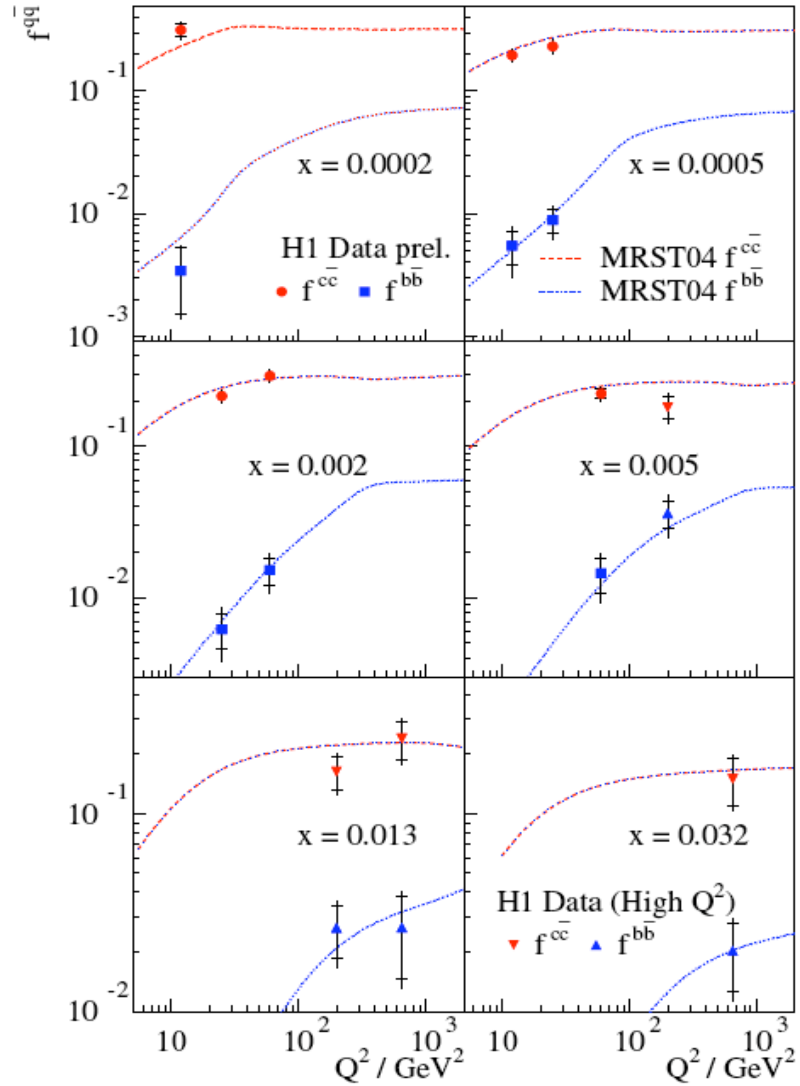


$F_2 \propto x^{-\lambda}$ at small x
rise of the parton densities

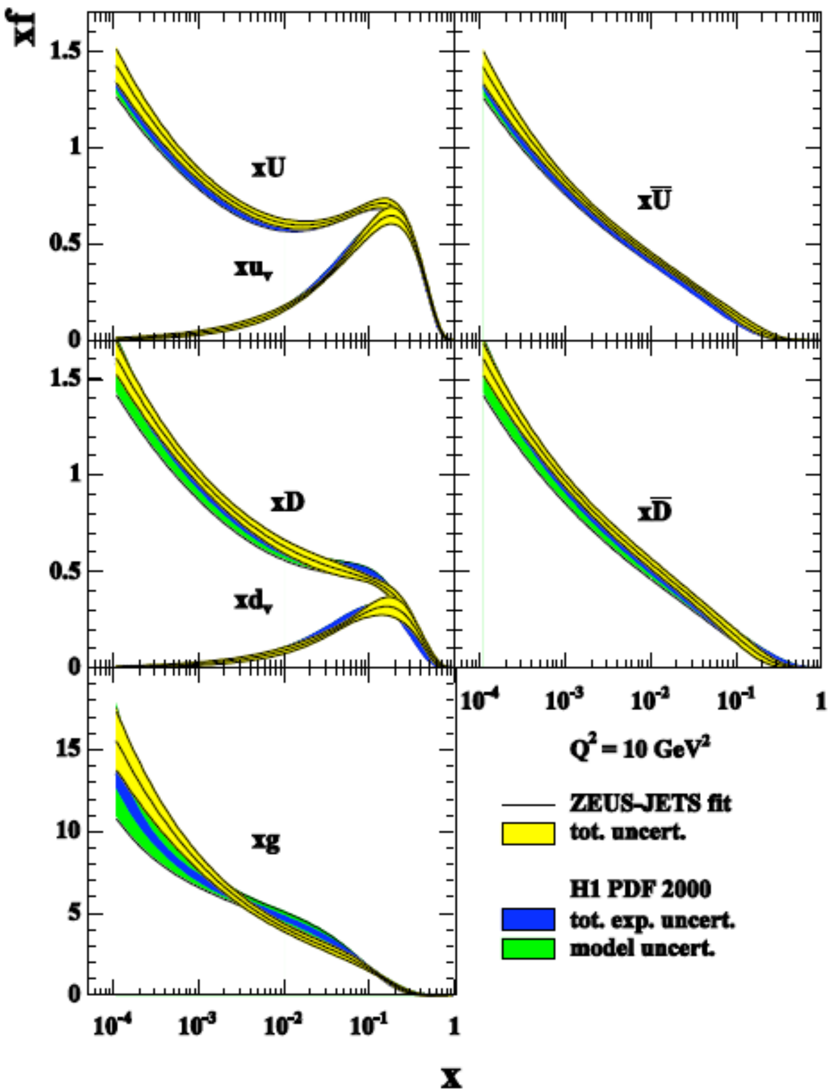
The first ever measurement of the beauty contents of the proton F_2^b [lifetime tag]

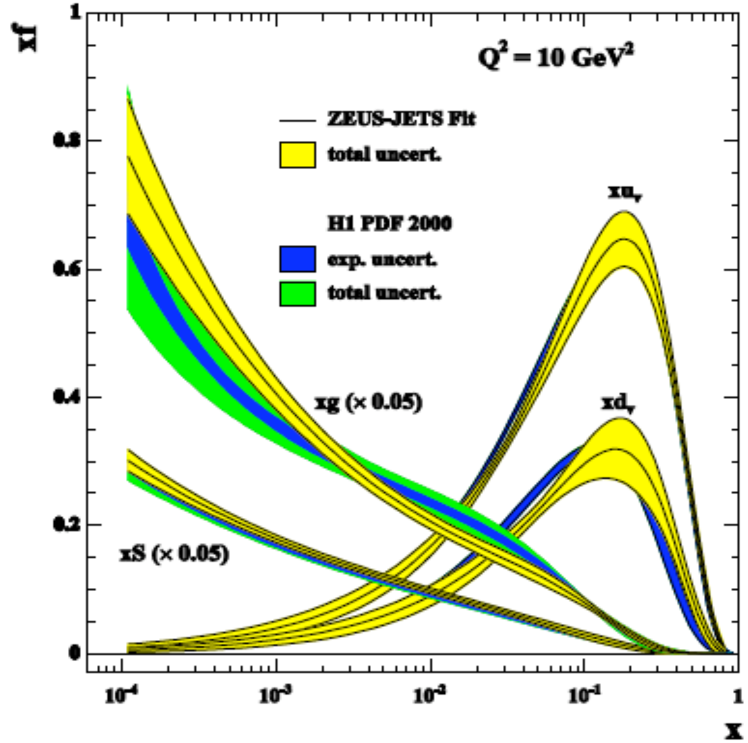
Small fraction of cross section. [Beauty in pt(rel) and μ still above NLO QCD].





Neutral and charged current data and heavy flavour data determine full set of pdf's





exp uncertainties of H1 pdfs based on HERA I data using Lagrange method for fit:

x	0.01	0.4	0.65
xU	1%	3%	7%
xD	2%	10%	30%

HERA 2 Temple

in Paestum, Italy

before and after

the luminosity upgrade

HERA 1: 1991-2000, HERA 2: 2003-2007 --> data analysis till 2012

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Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

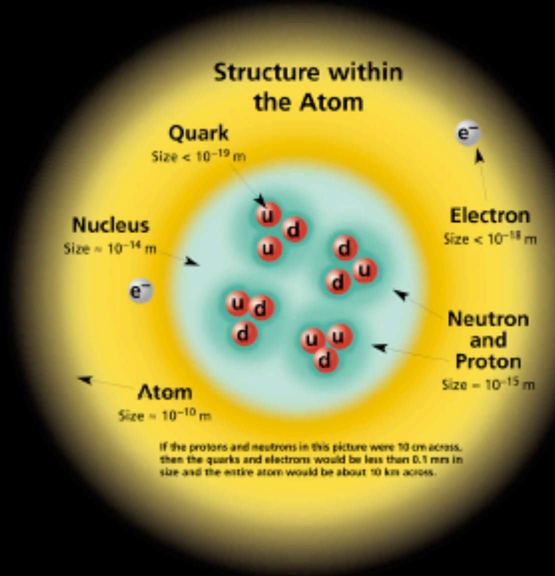
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c² = 1.67×10^{-27} kg.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

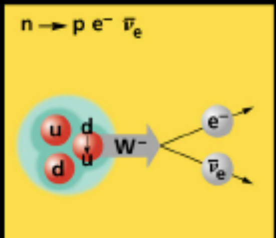
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

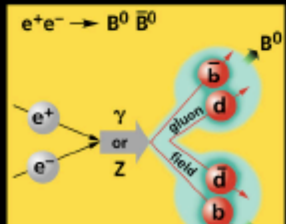
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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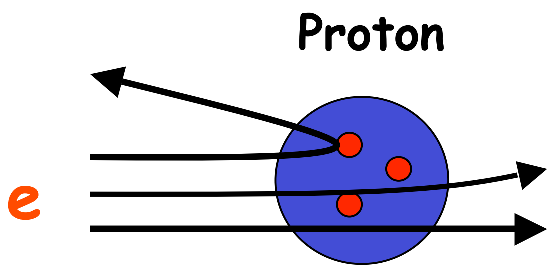
BURLE INDUSTRIES, INC.

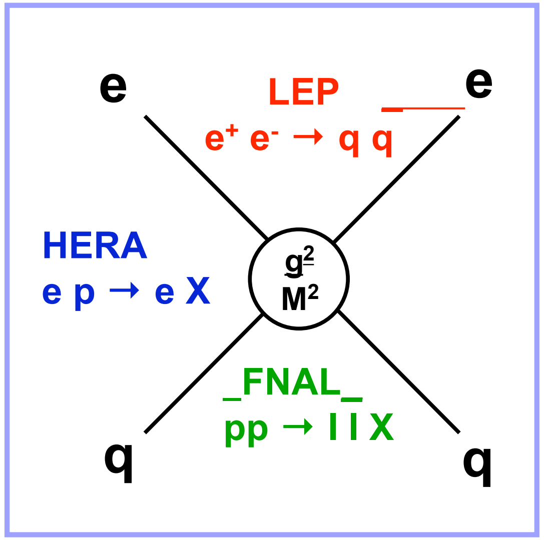
http://CPEPweb.org



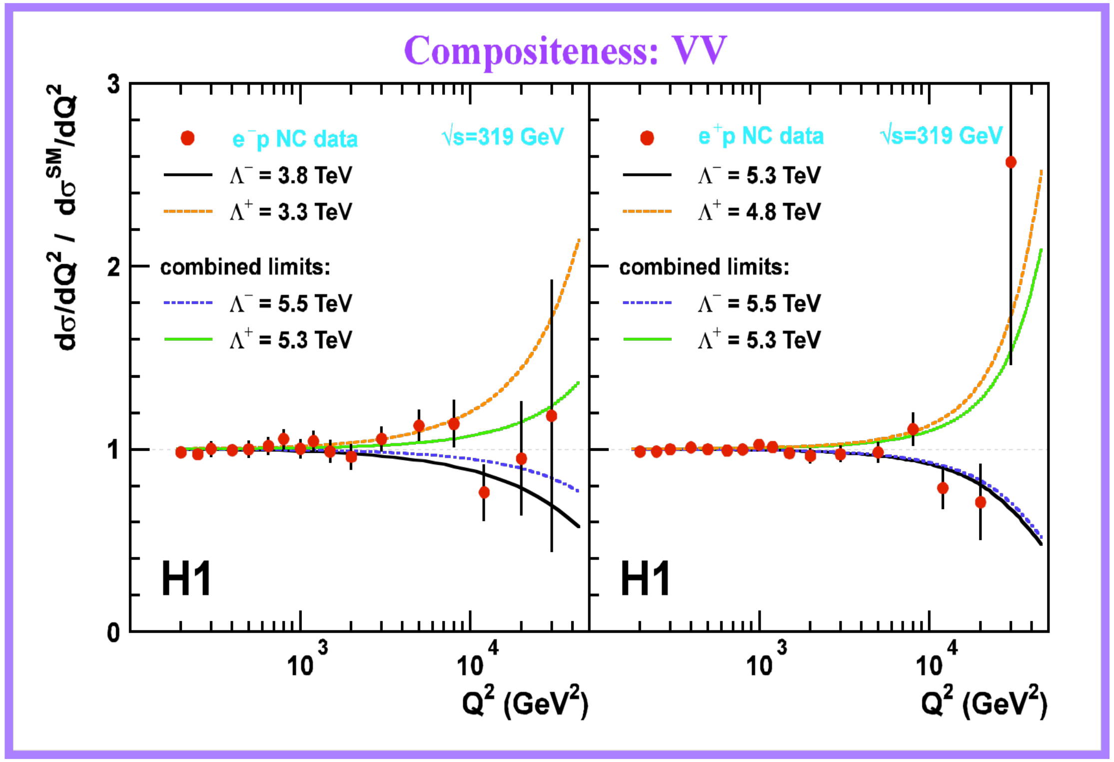
•Substructure of quarks? Leptoquarks?

$$\propto \frac{1}{Q} \approx 10^{-18}\,\mathrm{m}$$

New physics?



4 Fermion Contact-Term

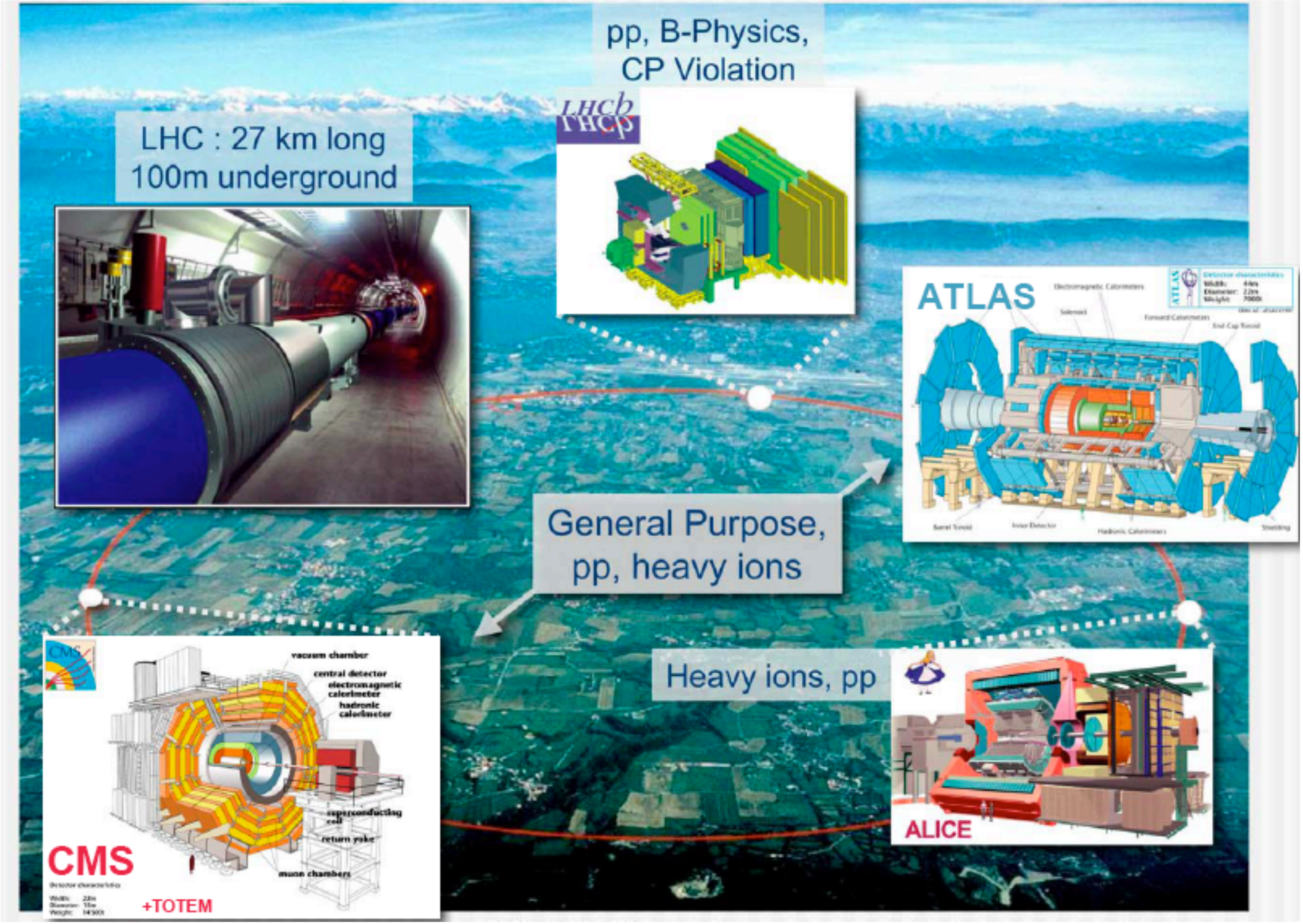


Symbiosis of ee, ep, pp

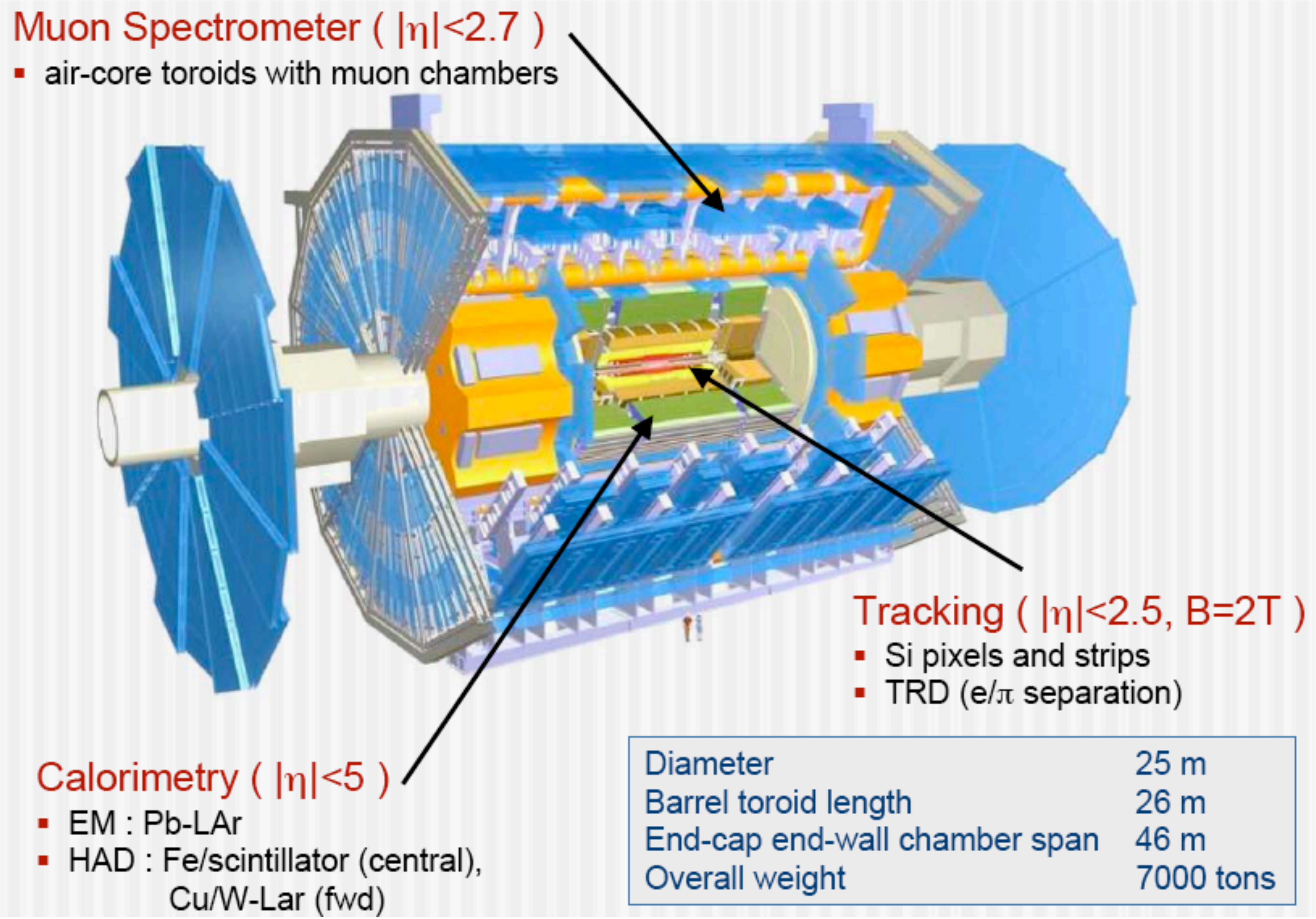
HERA :

Standard Model ok up to Λ = 5 TeV

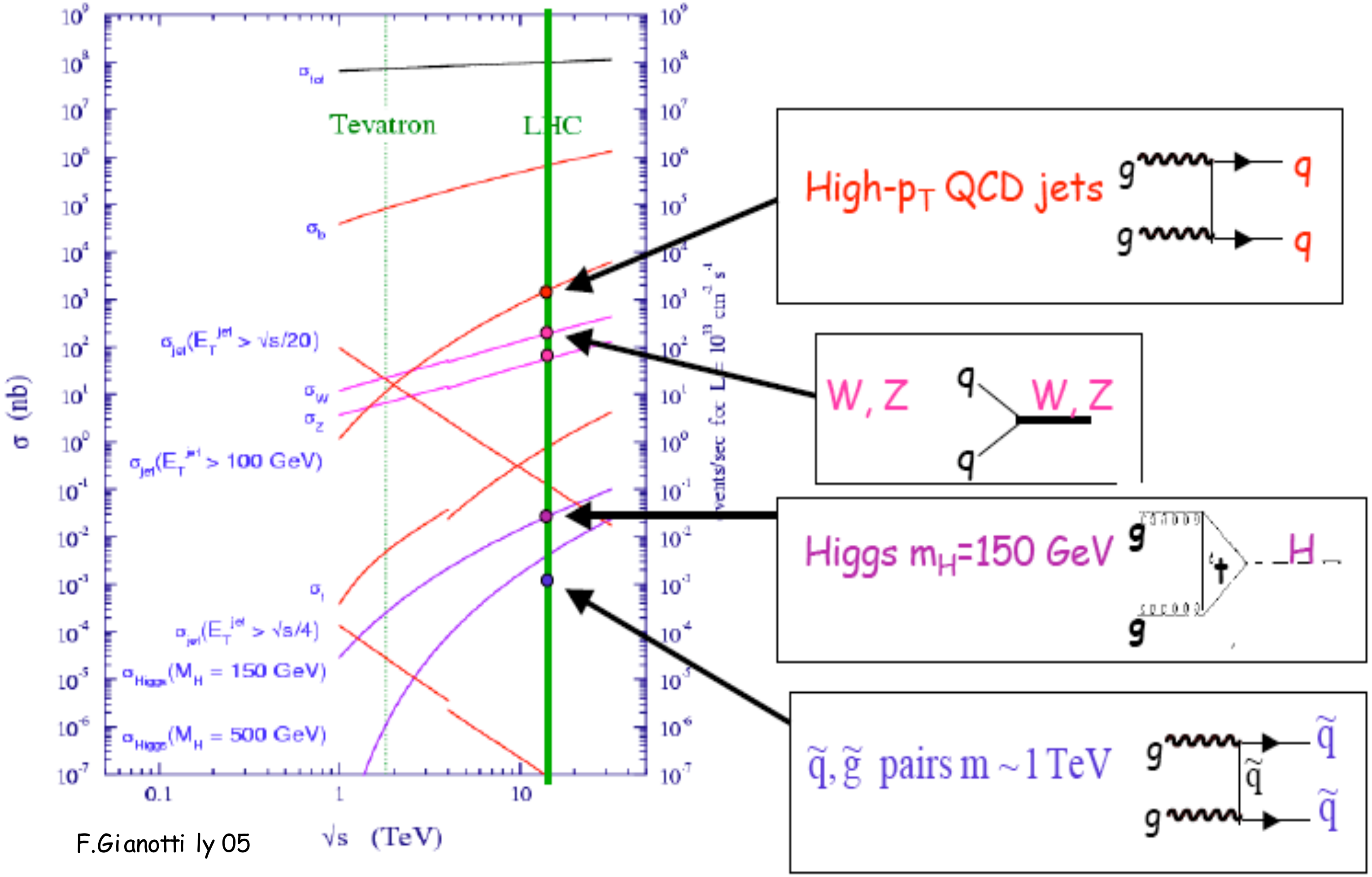
The next huge step of accelerator based particle physics: 2007..2020



The next huge step of collider detectors: ATLAS & CMS: 2007..2020



The LHC is a discovery machine based on developping QCD



F.Gianotti ly 05

- History: has been extremely rich and impressive
  [Einstein, Rutherford, Pauli, Gell Man]

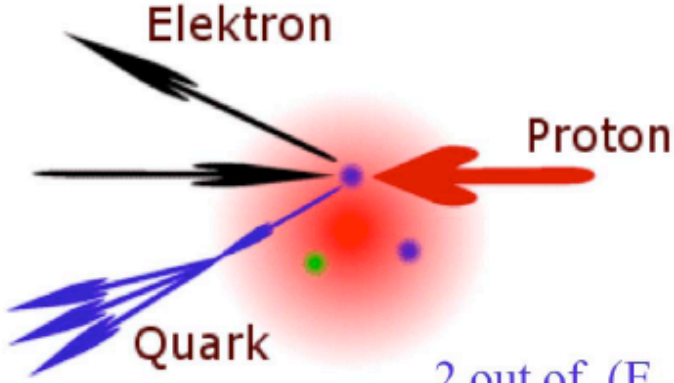
- HERA is the highest resolution microscope of the world
  [a tribute to Bjoern Wiik]

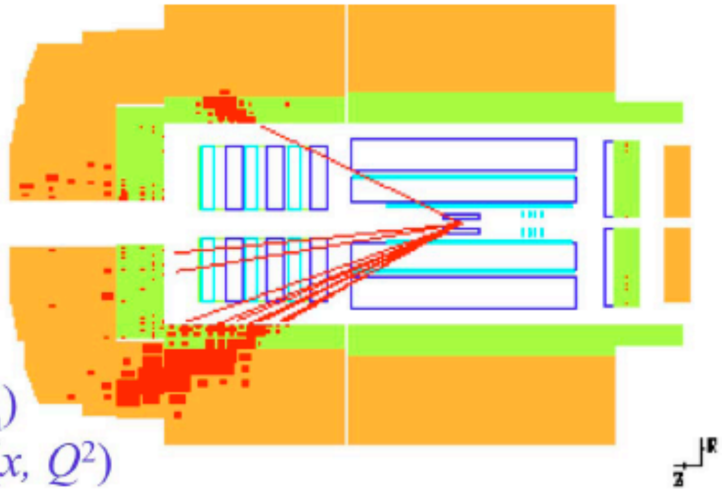
- H1 is a big laboratory for particle physics
  [operated by 300 physicists from 39 institutes]

- "Predicting is difficult, in particular if it concerns the future"
  [the LHC is the next step, ILC?, ep@TeV??]

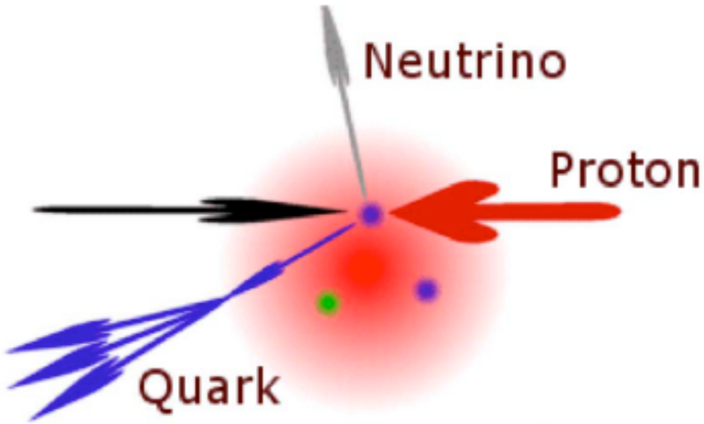
- Congratulations to the anniversary and congratulations to the many, impressive contributions by your faculty group to H1
  [low x, CC/NC, trigger, Silicon, heavy quarks]

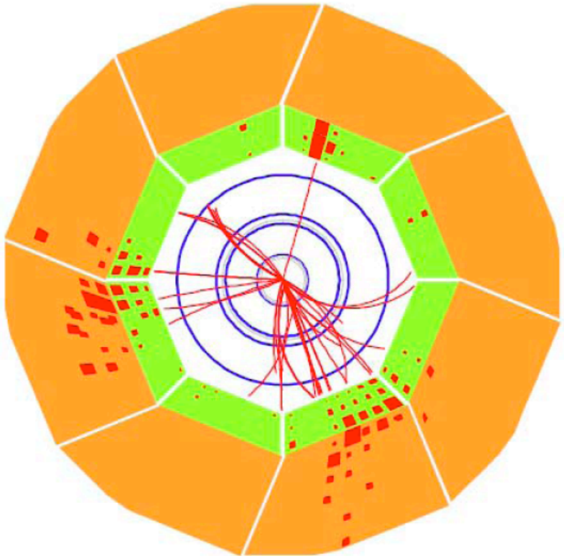
Deep Inelastic Electron-Proton Scattering





2 out of $(E_e, \theta_e, E_h, \theta_h)$
$\rightarrow$ Reconstruction of (x, Q^2)





$(E_h, \theta_h) \rightarrow (x, Q^2)$