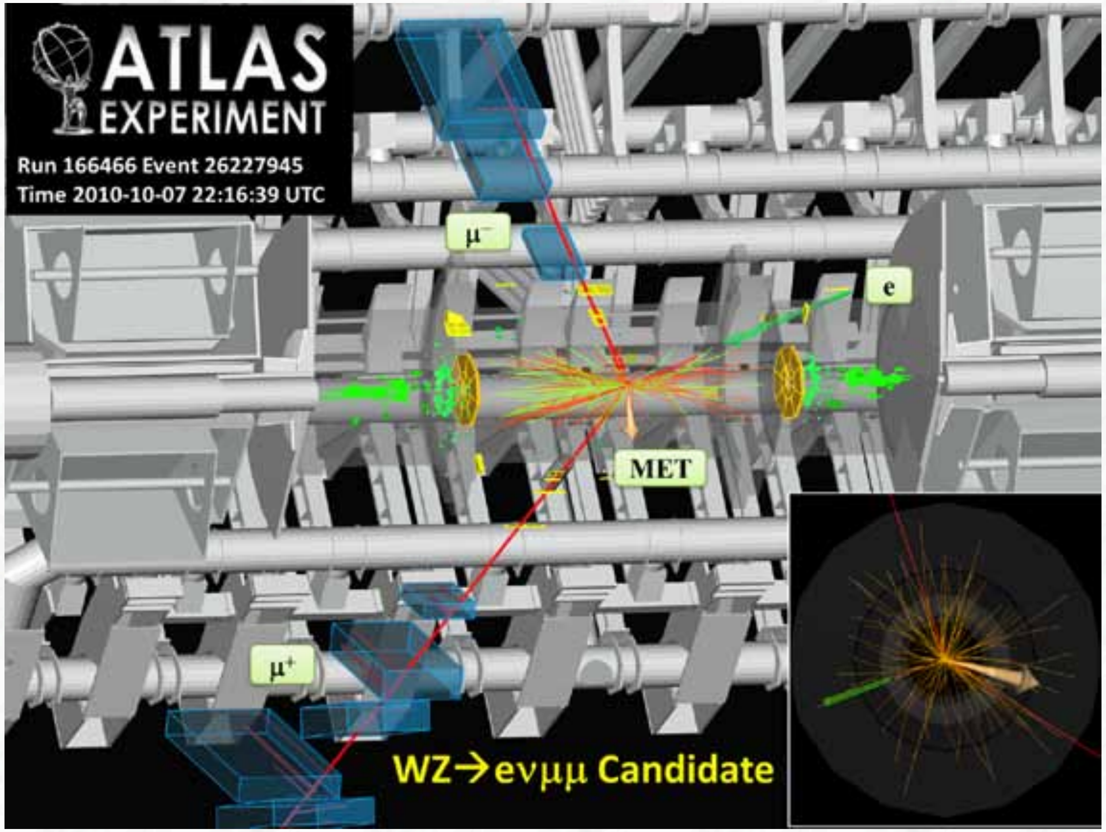
Particle Detection and First Physics Results from the LHC



Karl Jakobs
Physikalisches Institut
Universität Freiburg / Germany

Outline of the lectures:

Part I: Introduction to LHC physics and detectors

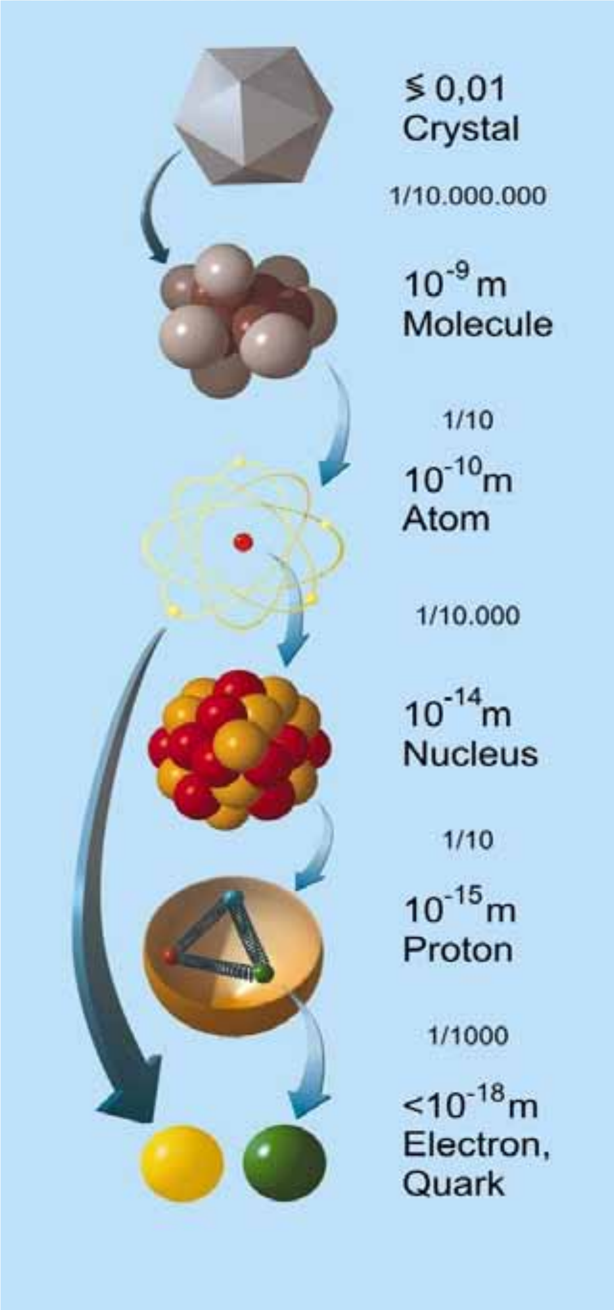
Part II: Detection techniques and LHC detectors

- Interaction of charged particles with matter
- Measurement of Charged Particles
  (Momentum measurements, tracking of charged particles
- Energy measurement
  - Interaction of neutral particles with matter
  - Energy measurements in calorimeters
- Muon detection at the LHC
- Experimental conditions at the LHC (triggering, data acquisition,…)

Part III: First Physics Results from the LHC

- Measurement of Standard Model Processes at the LHC
- Search for the Higgs Boson at the LHC
- Search for Physics Beyond the Standard Model

Exploring the interior of matter



eye, microscope
(light)

electron microscope
(electrons)

particle accelerators
(synchrotron radiation)

particle accelerators
(high energy particles)

increasing energy / momentum

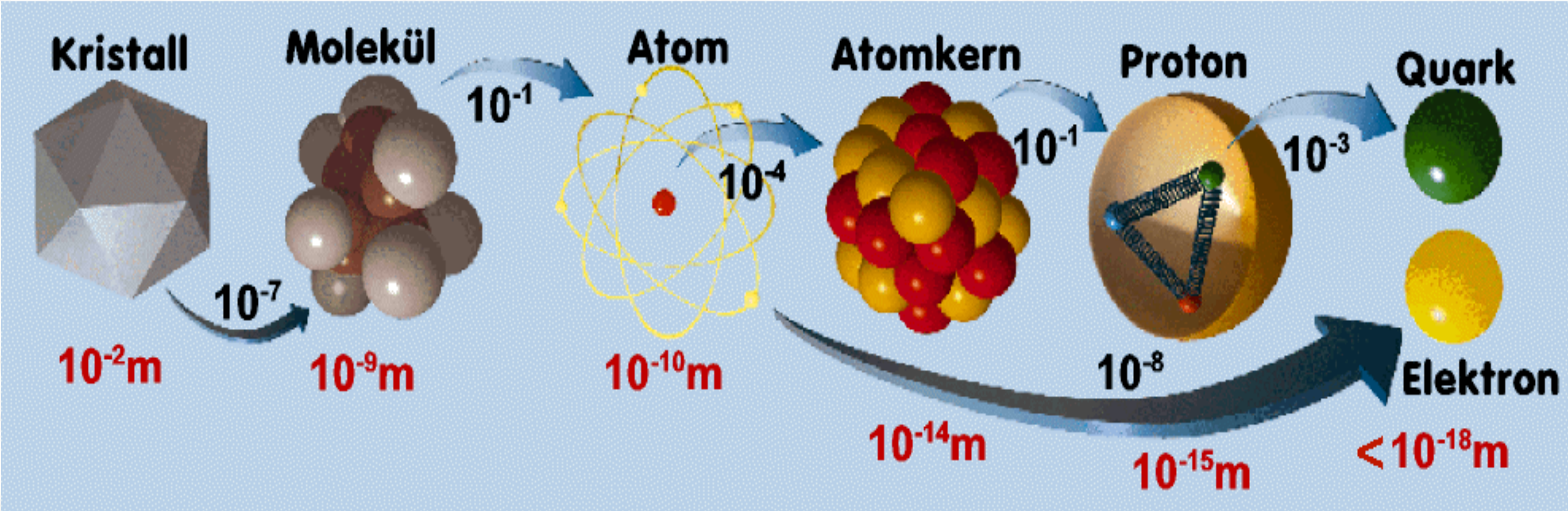
increasing resolution

$$\Delta x \propto \frac{1}{p}$$

New mass states accessible: $E = mc^2$

The Methods of Particle Physics

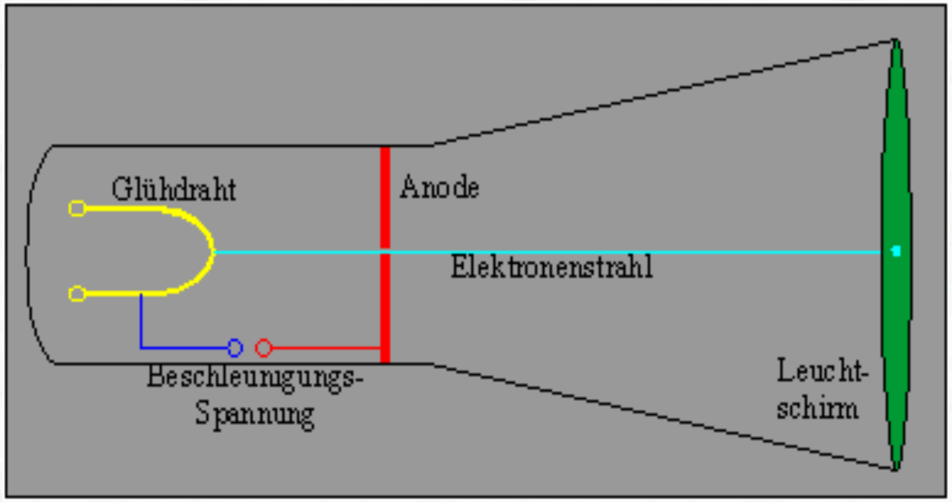
(i) Investigate the structure of matter



The discovery of the first elementary particle: the electron

1869: J.W. Hittorf (Germany)

"Heated cathodes in vacuum tubes emit radiation, which penetrates through space, and can be deflected in magnetic fields"



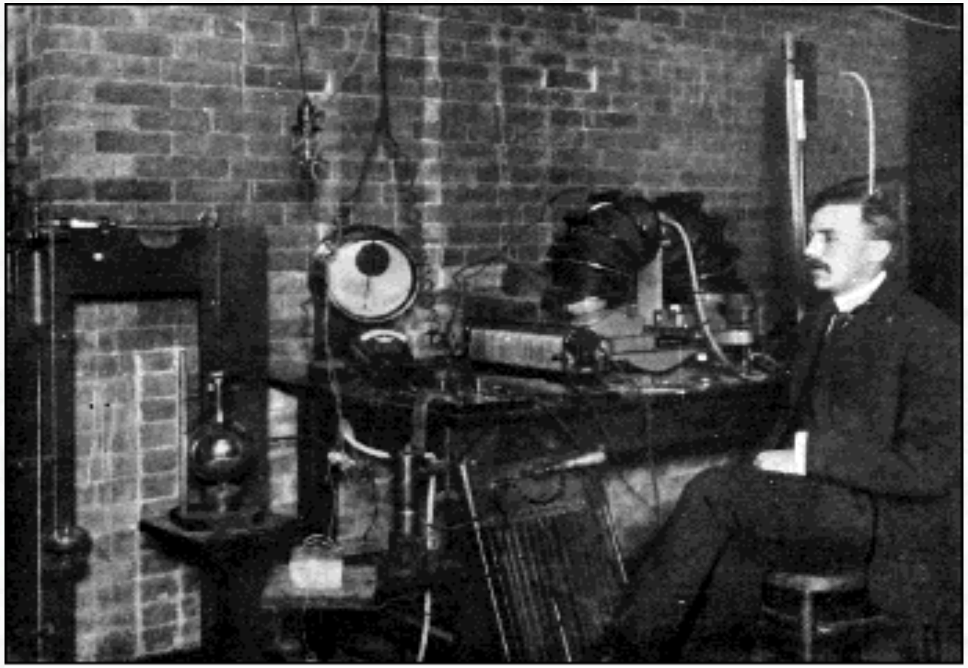
1897: J.J. Thomson (England)

Determines the ratio of charge to mass (e/m) using electric and magnetic fields

"These particles are a constituent of all matter. They are lighter than the lightest known atom (hydrogen) by a factor of more than 1000."

The prototype scattering experiment:

Rutherford's experiment 1911



Ernest Rutherford with Gold Foil Experiment

1871 (Nelson, New Zealand) - 1937

[669]

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom. By* Professor E. RUTHERFORD, *F.R.S., University of Manchester* *.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden † on the scattering of α rays indicate that some of the α particles must suffer a deflexion of more than a right angle at a single encounter. They found, for example, that a small fraction of the incident α particles, about 1 in 20,000, were turned through an average angle of 90° in passing through a layer of gold-foil about ·00004 cm. thick, which was equivalent in stopping-power of the α particle to 1·6 millimetres of air. Geiger ‡ showed later that the most probable angle of deflexion for a pencil of α particles traversing a gold-foil of this thickness was about 0°·87. A simple calculation based on the theory of probability shows that the chance of an α particle being deflected through 90° is vanishingly small. In addition, it will be seen later that the distribution of the α particles for various angles of large deflexion does not follow the probability law to be expected if such large deflexions are made up of a large number of small deviations. It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

Recently Sir J. J. Thomson § has put forward a theory to

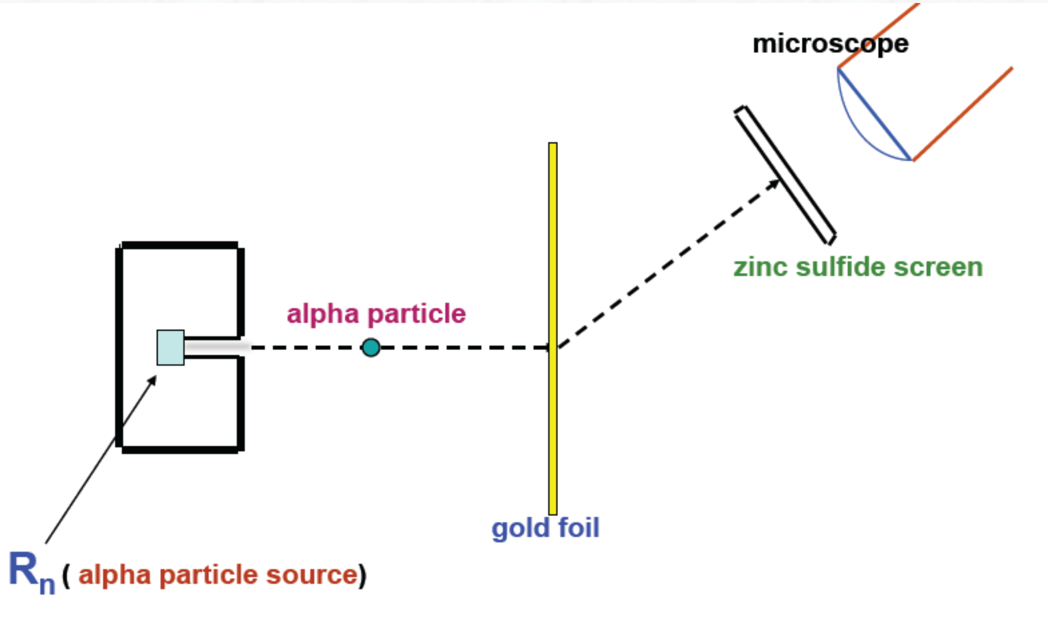
* Communicated by the Author. A brief account of this paper was communicated to the Manchester Literary and Philosophical Society in February, 1911.

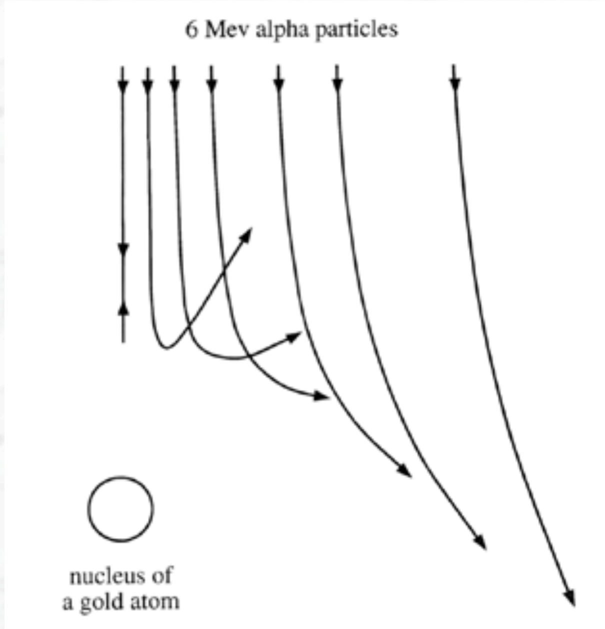
† Proc. Roy. Soc. lxxxii. p. 495 (1909).

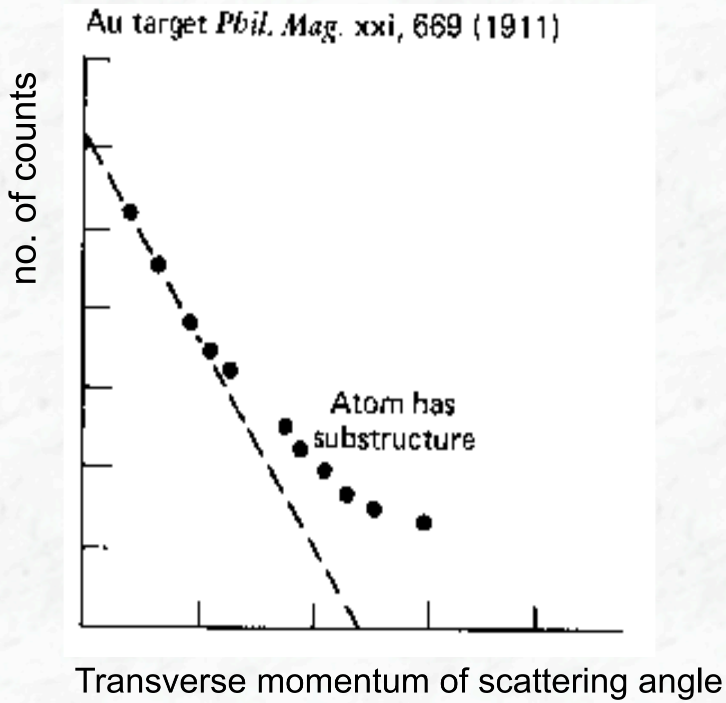
‡ Proc. Roy. Soc. lxxxiii. p. 492 (1910).

§ Camb. Lit. & Phil. Soc. xv. pt. 5 (1910).

Rutherford experiment (cont.):







Clear evidence for a hard scattering in the centre of the nucleus

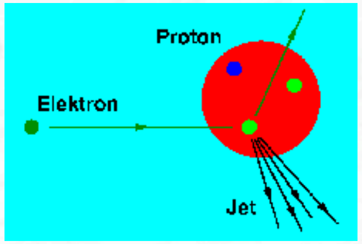
High particle momenta (energies) are necessary to explore the interior of matter, the subatomic scale

Quantum mechanics: the spatial resolution is inversely proportional to the particle momentum

$$\Delta x = \frac{\hbar}{p}$$

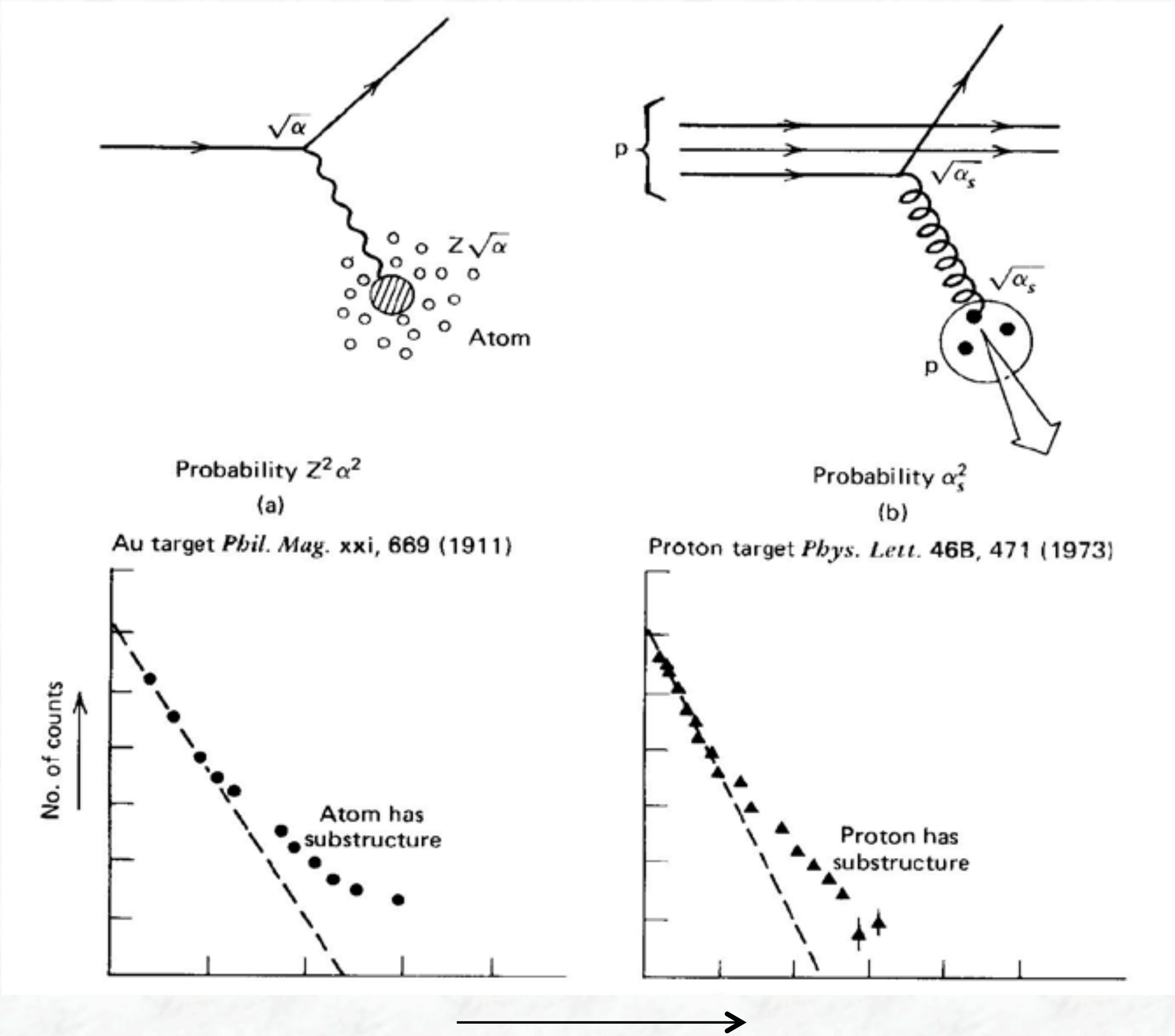
The Rutherford experiment of the second generation:

1967: Stanford Linear Accelerator Centre (SLAC)
Scattering of high energy electrons on protons
Do protons have a substructure ?



SLAC Magnetic Spectrometers

Results / comparisons of Rutherford experiment and SLAC

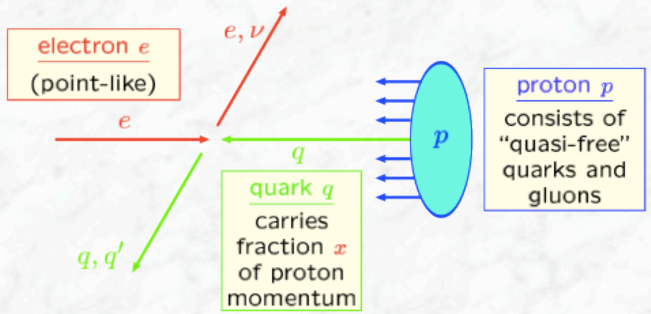


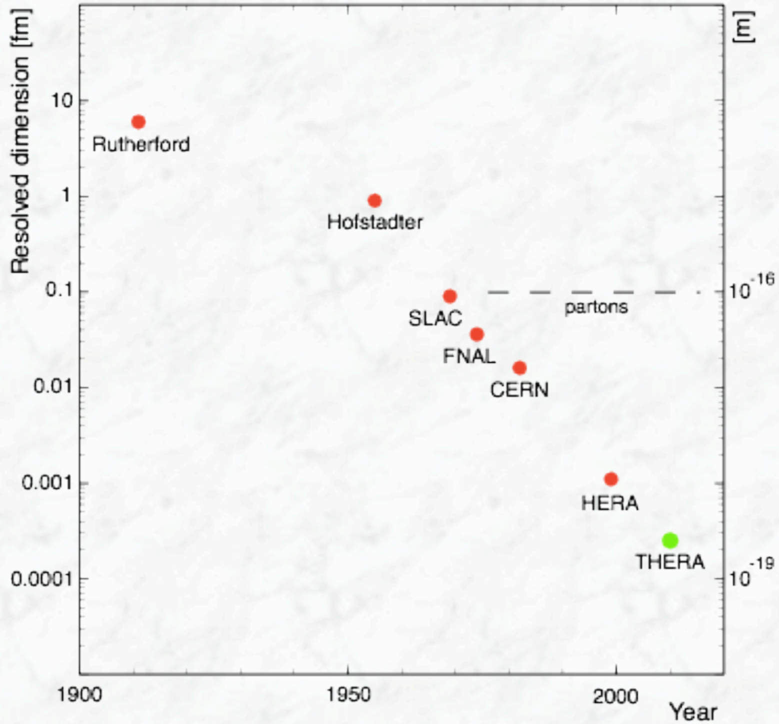
Transverse momentum of scattering angle

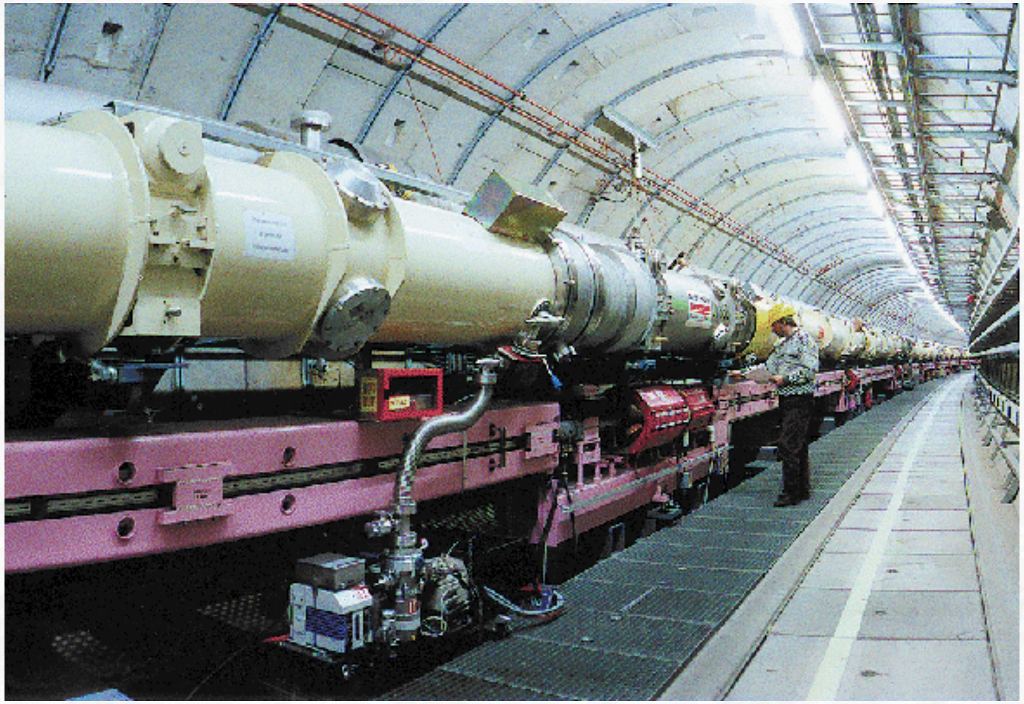
Deep inelastic scattering experiments:

This triggered a whole series of experiment over the last 50 years

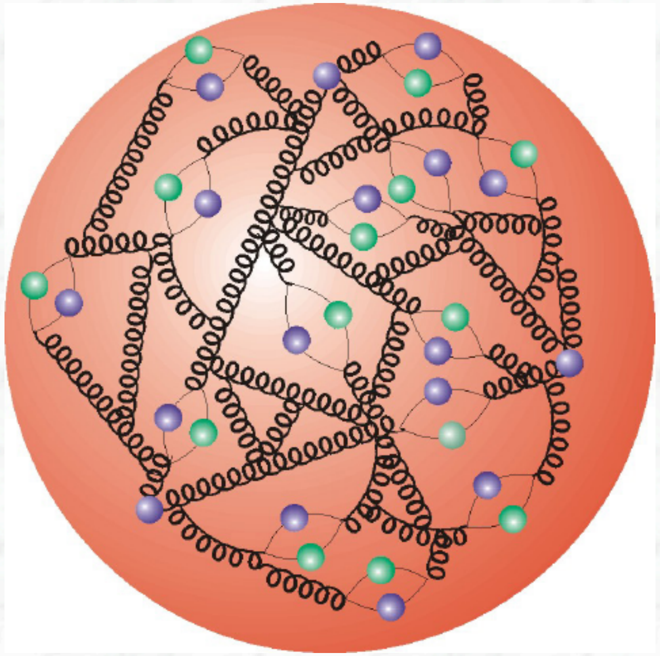
- From SLAC ep, en scattering (1967)
  → HERA experiments (e-p collider)
  at DESY/Germany (1991 – 2007)







The proton, as seen in the light of deep inelastic scattering:



- The proton is a composite particle made up of so called partons

- Partons = quarks and gluons

  valence quarks: u, u, d

  sea quarks, u-ubar, d-dbar, s-sbar, …..

  gluons

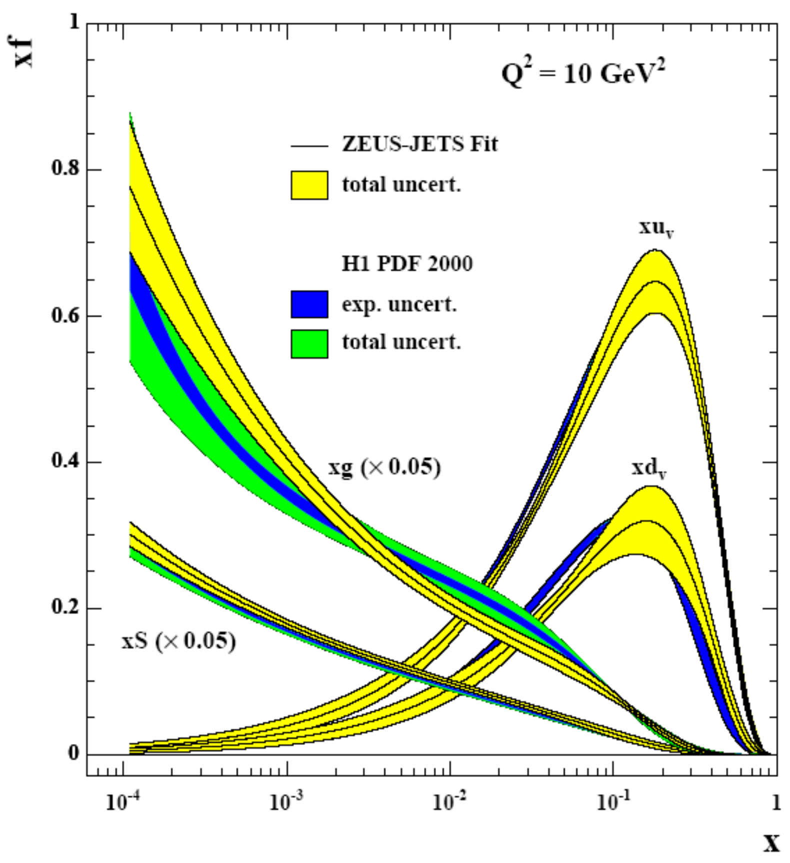
- The density of partons in the proton cannot be calculated from first principles, has to be determined from experiments

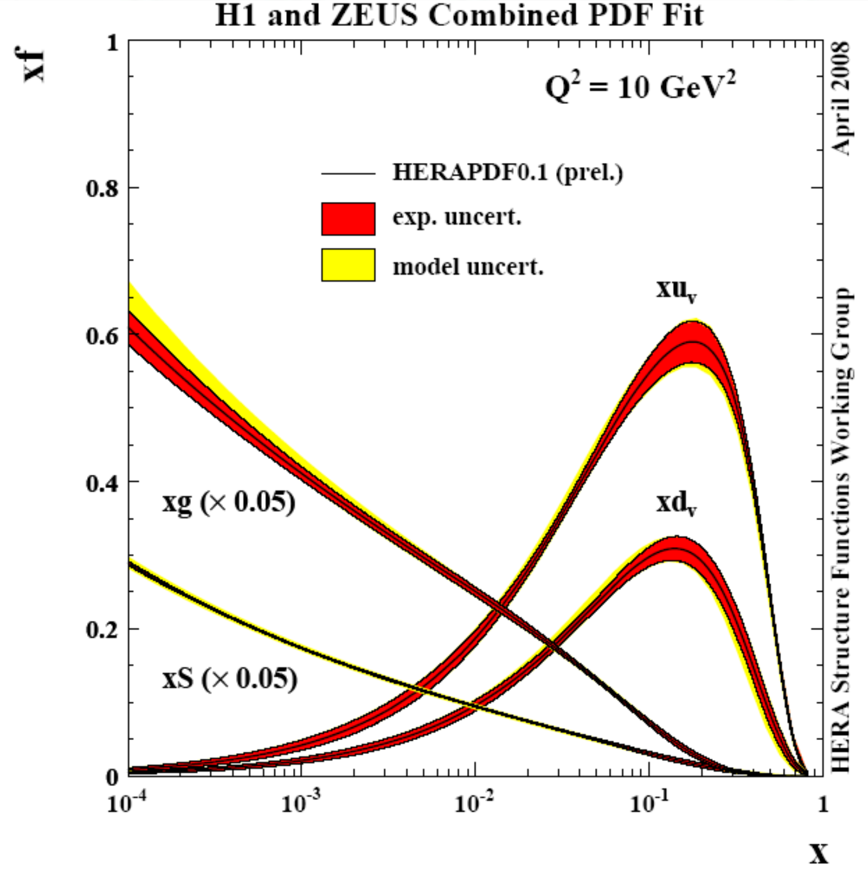
- Proton-proton scattering at high energies is equivalent to parton-parton scattering

  Very relevant for the LHC

Parton Distribution functions (pdf)

Results from the extensive measurements at the HERA ep collider



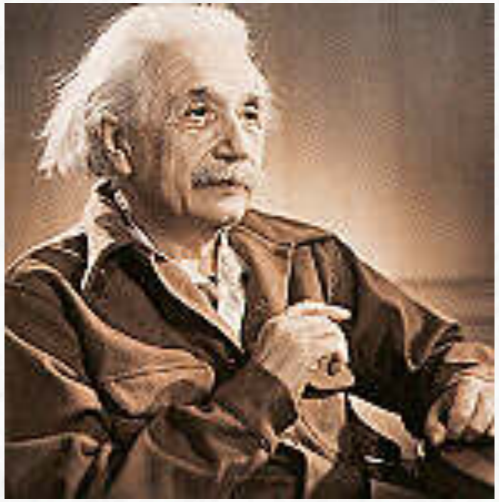


x = momentum fraction of the parton

The methods of particle physics (cont.)

(ii) Search for New Particles / new states of matter

High energies are needed as well, according to Einstein's formula:



$$E = \sqrt{p^2c^2 + m^2c^4}$$

E = energy, p = momentum
m = mass (rest mass)

For p = 0 this leads to: $\boxed{E = mc^2}$

energy ↔ matter

Units in particle physics:

$$E = mc^2$$

	unit	conversion factor to SI units
Energy:	eV	1 eV = $1{,}6 \cdot 10^{-19}$ J
Momentum:	eV/c	
Mass:	eV/c^2	1 eV/c^2 = $1{,}8 \cdot 10^{-36}$ kg

A few examples, particle masses:

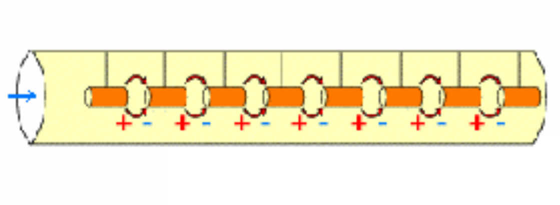
m(p) = 938.3 MeV/c^2 — baryons (heavy hadrons, bound states, three valence quarks)
m(n) = 939.6 MeV/c^2
….

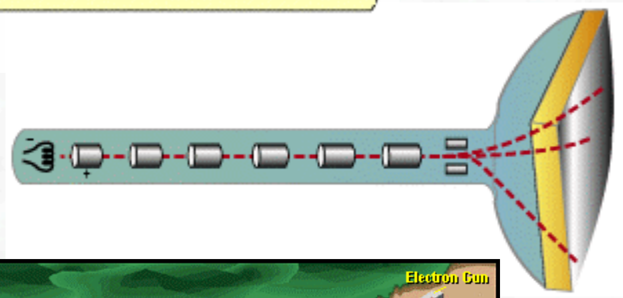
m(e) = 0.511 MeV/c^2 — leptons (light particles, no strong interaction, no substructure seen so far)
m(μ) = 105.7 MeV/c^2
m(ν) < 0.3 eV c^2 ….

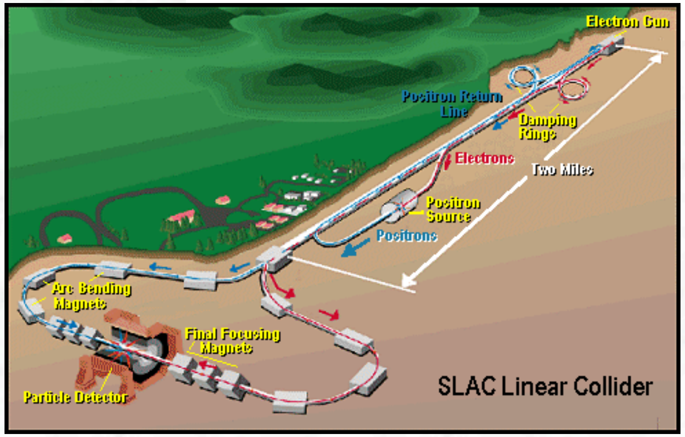
m($\pi^\pm$) = 139.6 MeV/c^2 — mesons (hadrons, q-qbar bound states)
m($K^\pm$) = 493.7 MeV/c^2 …

Experimental methods: particle accelerators

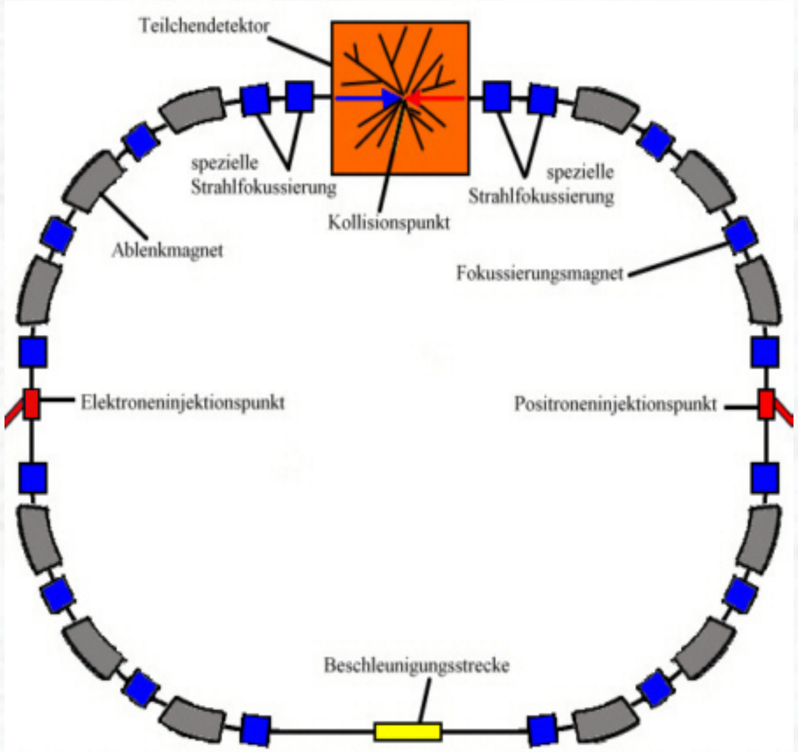
Linear accelerators





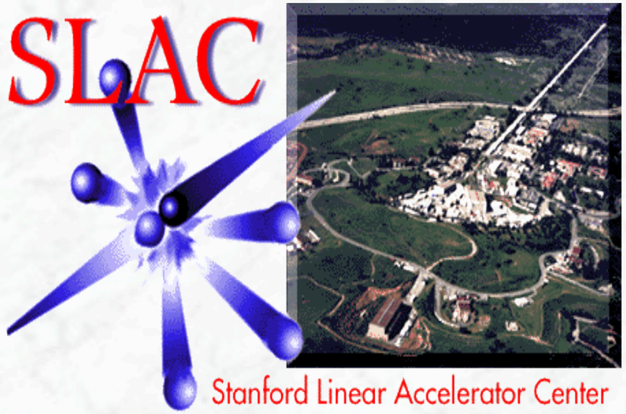


Storage rings



Important accelerator laboratories

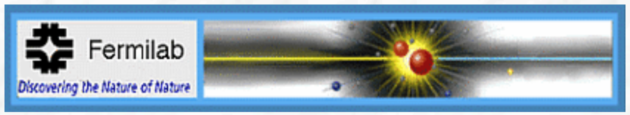
Deutsches-Elektronen-Synchrotron,
DESY, Hamburg, Germany



Stanford Linear Accelerator Center
Stanford, USA

KEK Tsukuba, Japan

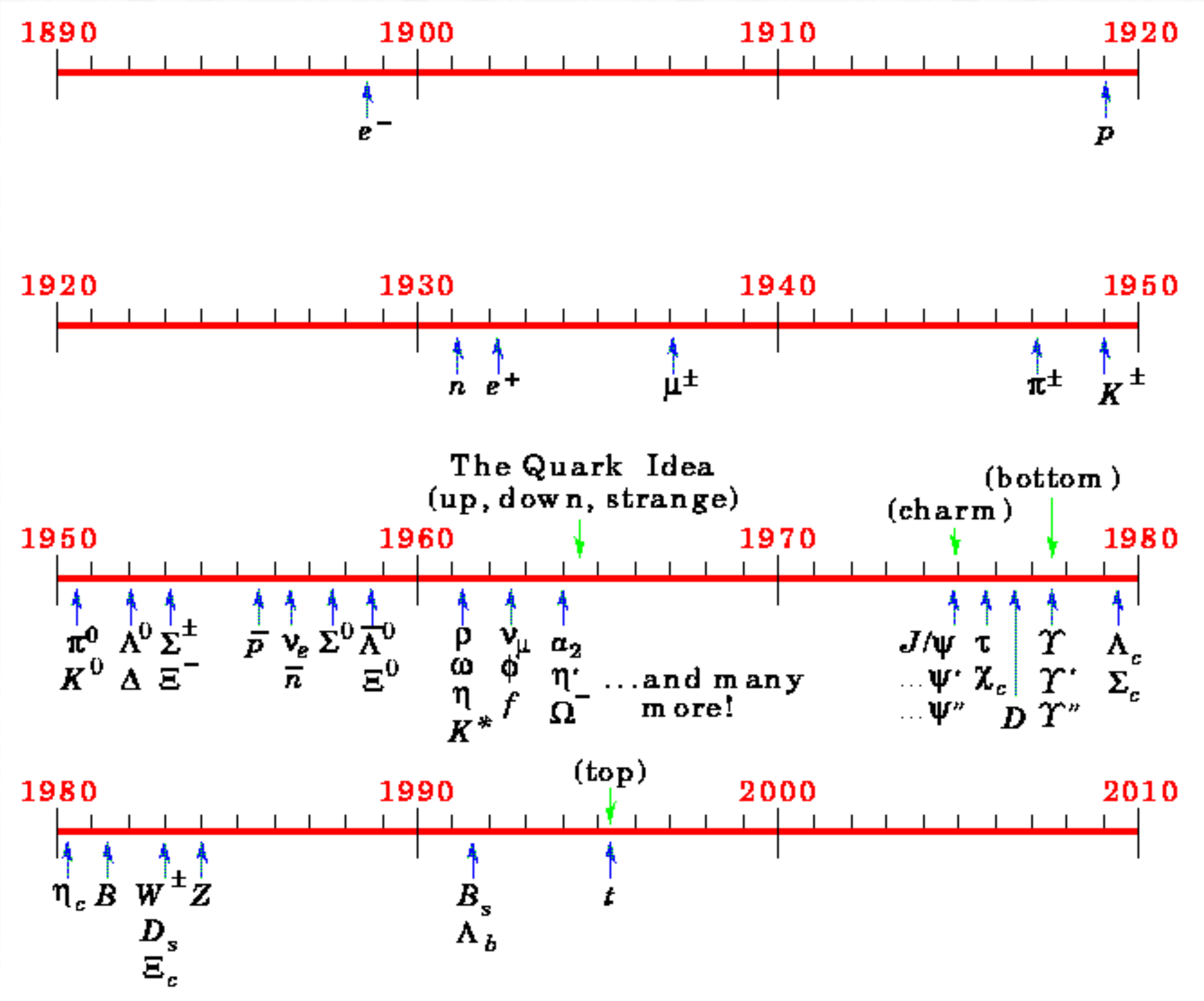
Fermi-National-Accelerator-
Laboratory, Chicago, USA



European Centre for Particle Physics, CERN,
Geneva, Switzerland

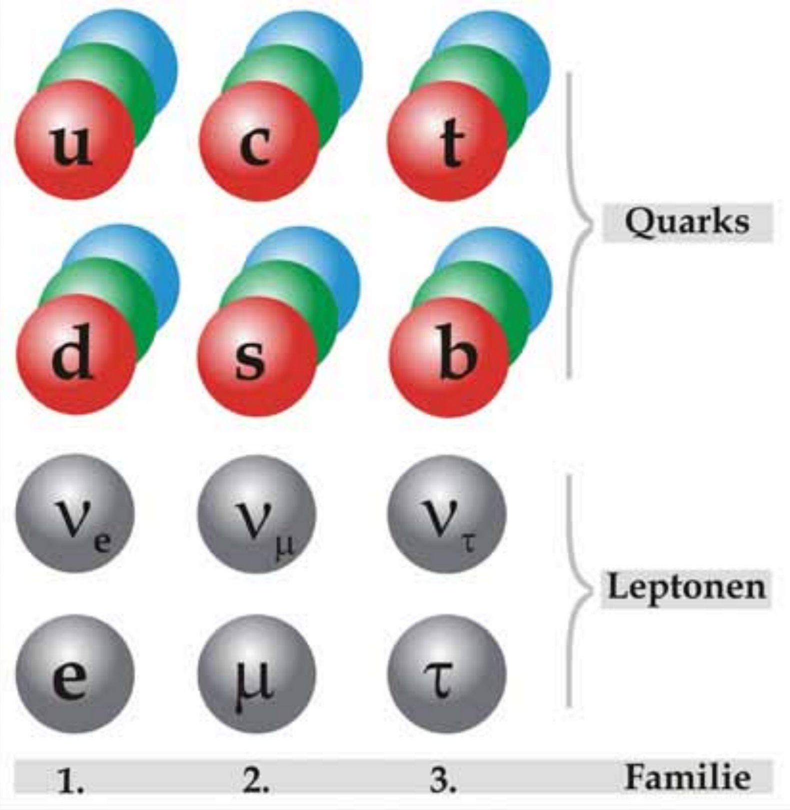
LEP	CERN	e^+e^-	1989 – 2000	91 – 209 GeV
B-factory	KEK		1998 –	10 GeV
B-factory	SLAC		1998 – 2008	10 GeV
ILC	??		20xx - (??)	> 500 GeV
HERA	DESY	$e^\pm p$	1992 - 2007	300 GeV
Tevatron	FNAL	$p\bar{p}$	1987 – 2011	1.96 TeV
LHC	CERN	pp	since 2009	7.0 TeV

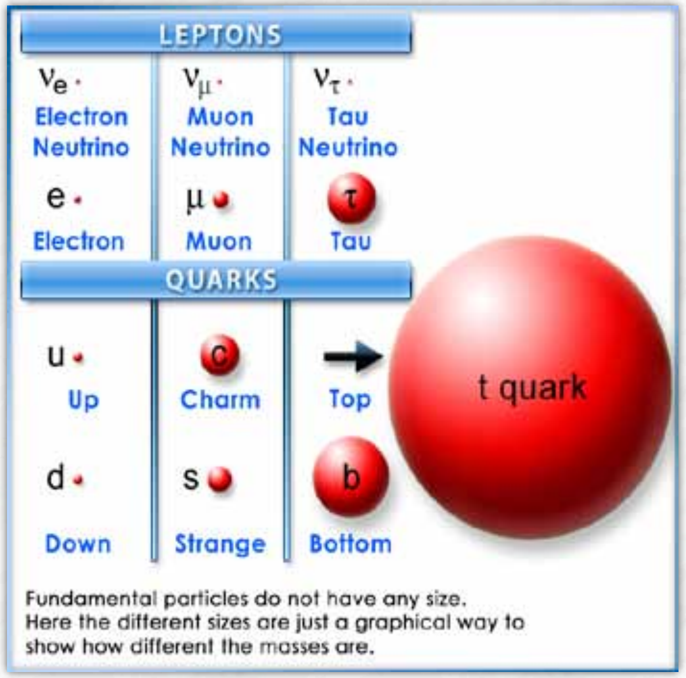
History on discovery of particles



Where do we stand today?

The building blocks of matter: Quarks und leptons



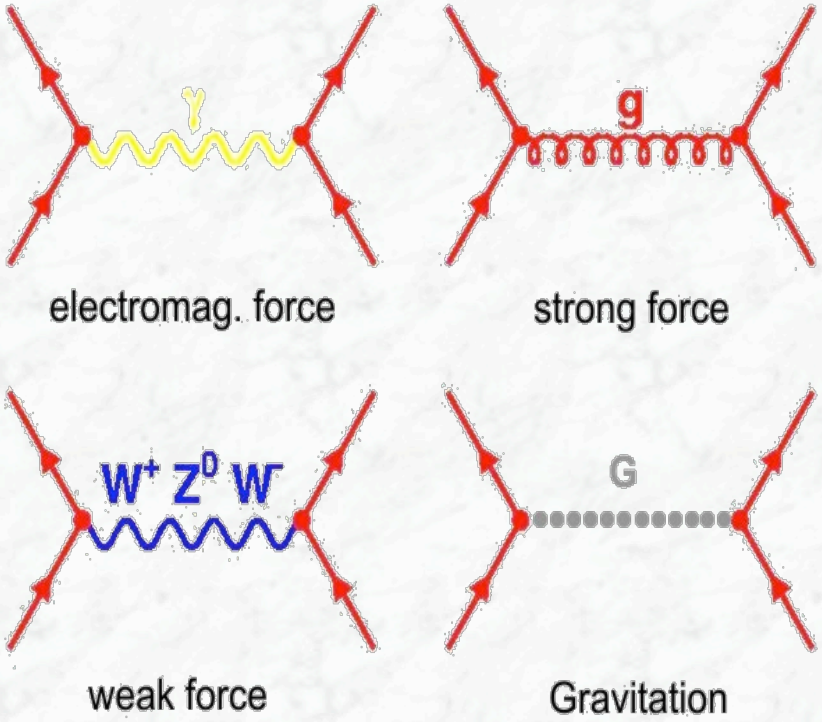


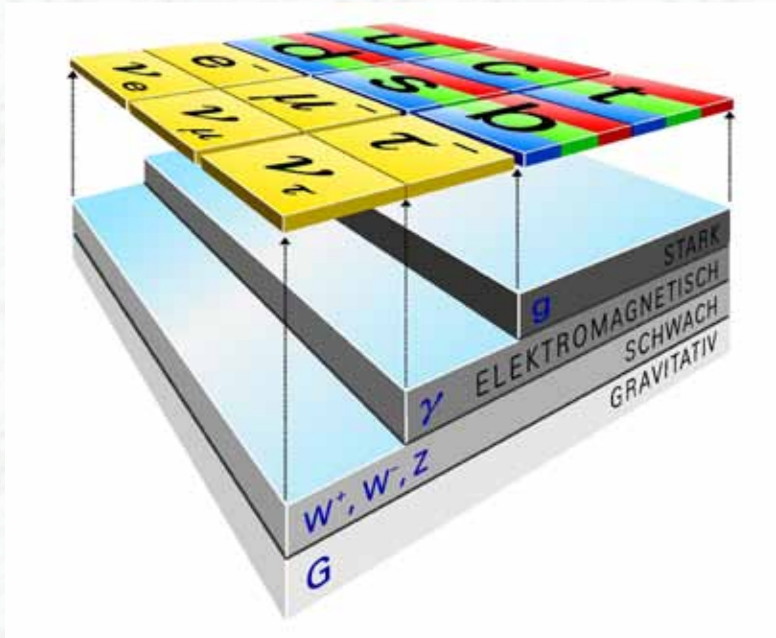
$m(e) = 0.000511\ \mathrm{GeV}/c^2$
$m(\mu) = 0.1057\ \mathrm{GeV}/c^2$
$m(\tau) = 1.777\ \mathrm{GeV}/c^2$

$m(u) = 0{,}005\ \mathrm{GeV}/c^2$
$m(t) = \sim 173\ \mathrm{GeV}/c^2$

for comparison: $m(p) = 0{,}9383\ \mathrm{GeV}/c^2$

Forces and force carriers





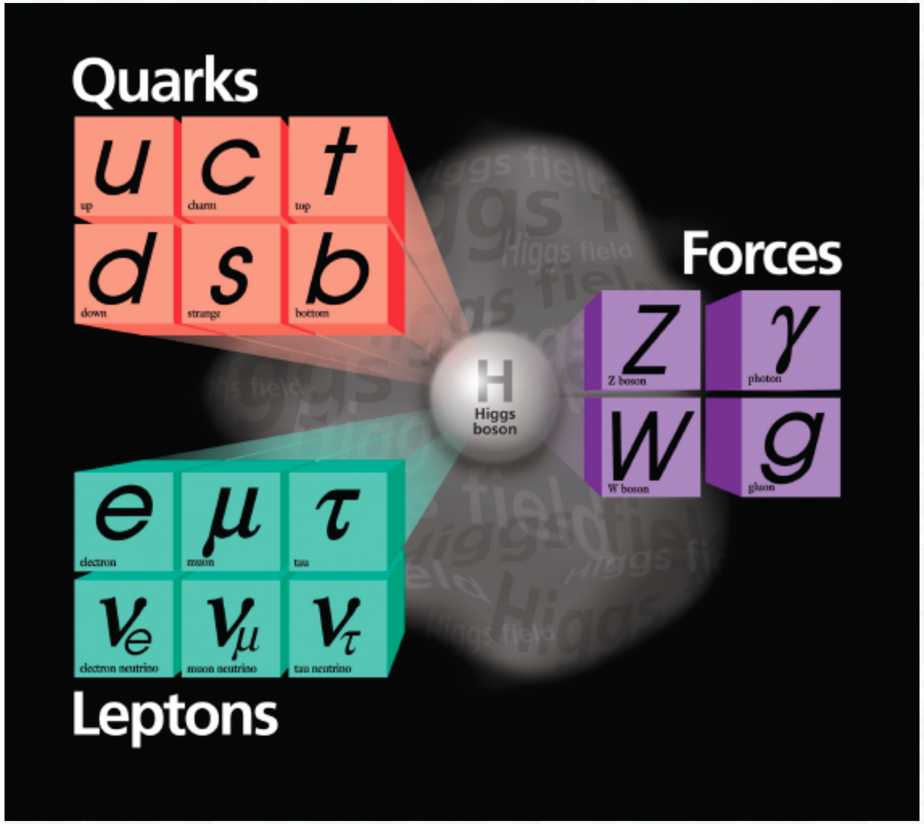
<u>Masses:</u>

$m_\gamma = 0$ (Photon)

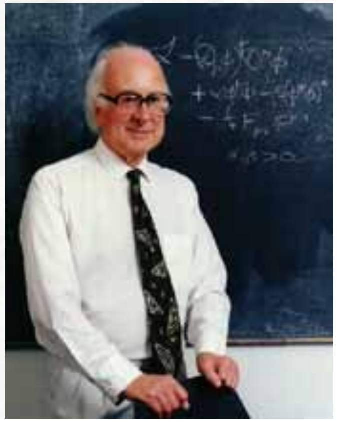
$m_g = 0$ (Gluon)

$M_W = 80.399 \pm 0.023$ GeV/c^2
$M_Z = 91.1875 \pm 0.0021$ GeV/c^2

The problem of mass



- Theoretical description (Quantum field theories) → massless particles
- A new (scalar) field (Higgs field) is postulated, penetrates vacuum (non-zero field content)
- Mass is „created“ via interaction of particles with this field
- <u>Prediction</u>: new particle, the Higgs boson



proposed by P. Higgs (Scottish pyhsicist)
[Theorry: 1964, P. Higgs, R. Brout und F. Englert]

Why do we need the Higgs boson?

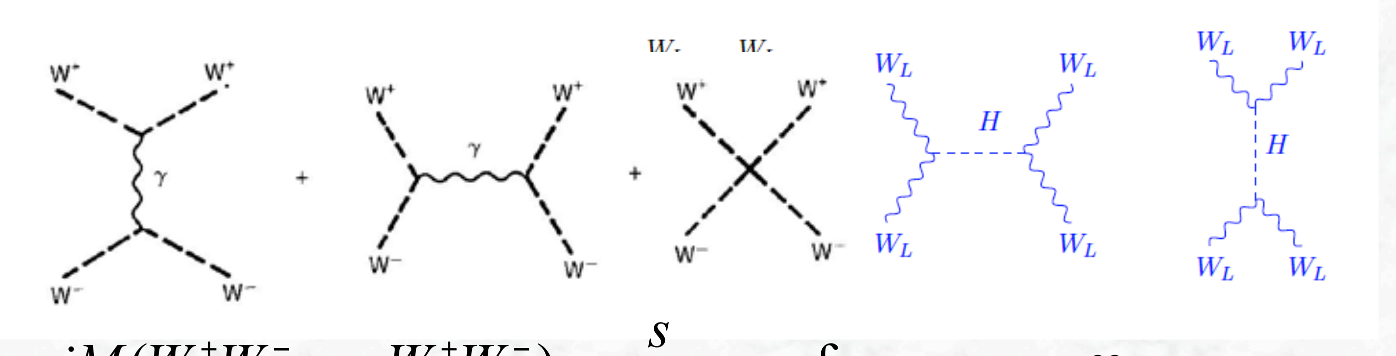
The Higgs boson enters the Standard Model to solve two fundamental problems:

- Masses of the vector bosons W and Z:

  Experimental results: $M_W = 80.399 \pm 0.023$ GeV / c^2
  $M_Z = 91.1875 \pm 0.0021$ GeV / c^2

  A local gauge invariant theory requires massless gauge fields

- Divergences in the theory (scattering of W bosons)



$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$

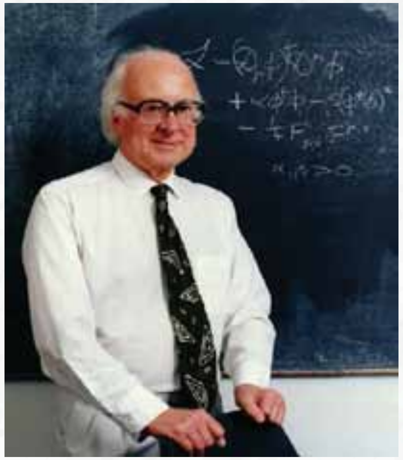
(no Higgs boson)

$$-iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty$$

(with Higgs boson)

Where do we stand today?

- The energy range up to ~100 GeV has been explored with incredible precision
- The Standard Model is consistent with all experimental data !
  (except clear evidence for neutrino masses)
- No Higgs boson seen (yet)

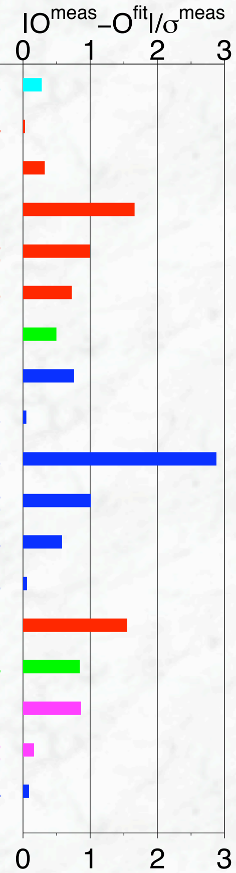


Only unambiguous example
of observed Higgs

(P. Higgs, Univ. Edinburgh)

Summer 2010

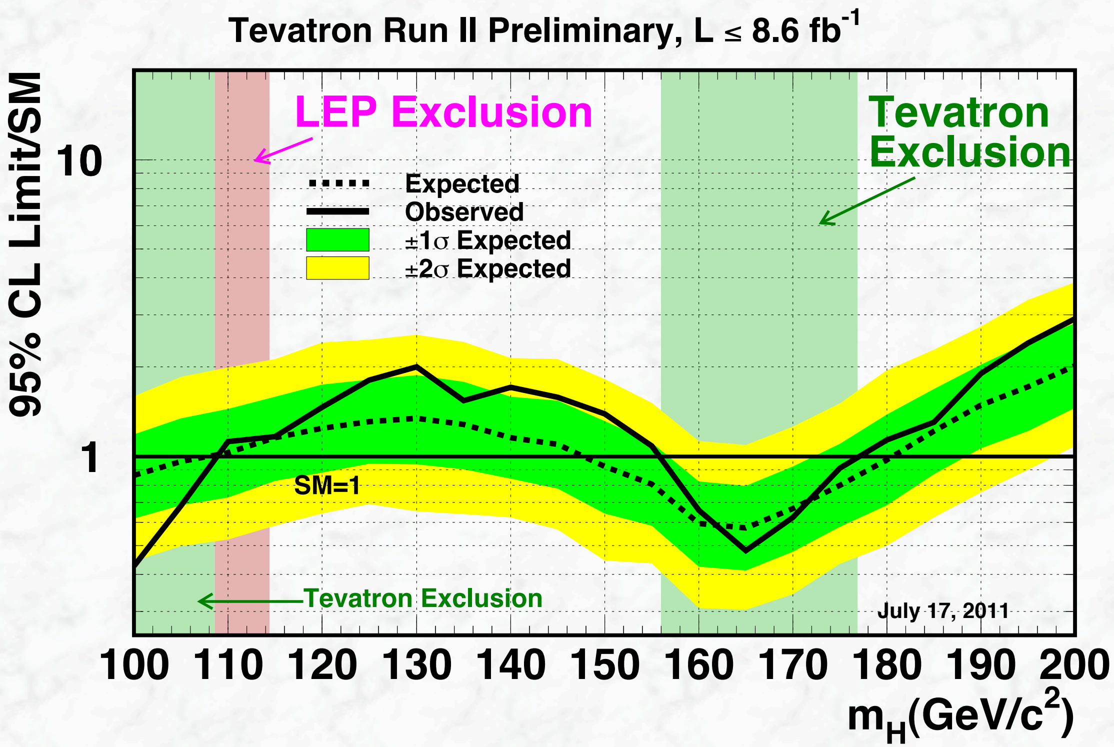
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4



July 2010

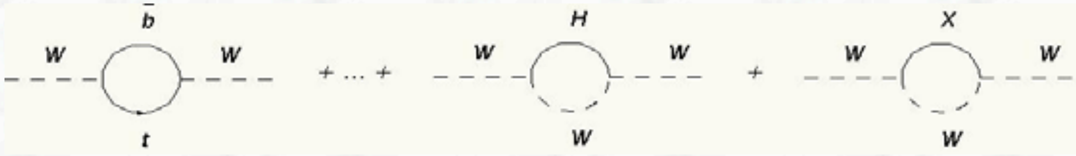
Constraints on the Higgs boson mass

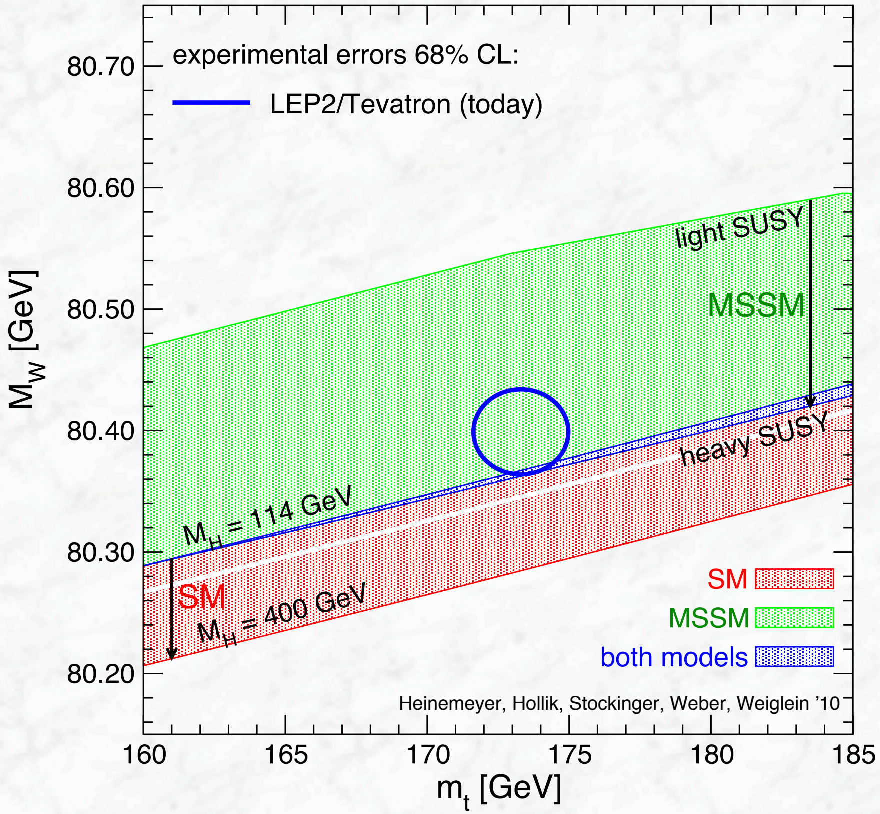
- $m_H > 114.4$ GeV from direct searches at LEP
- $m_H < 156$ GeV .or. $m_H > 177$ GeV from direct searches at the Tevatron

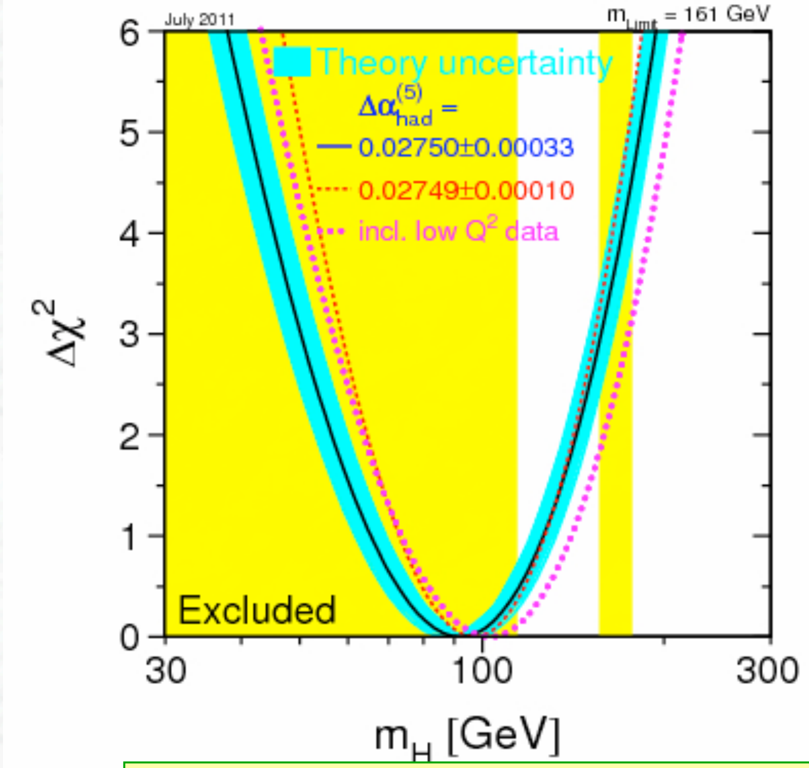


Indirect limits from electroweak precision data (m$_W$ and m$_t$)

Sensitivity to the Higgs boson and other new particles via quantum corrections:



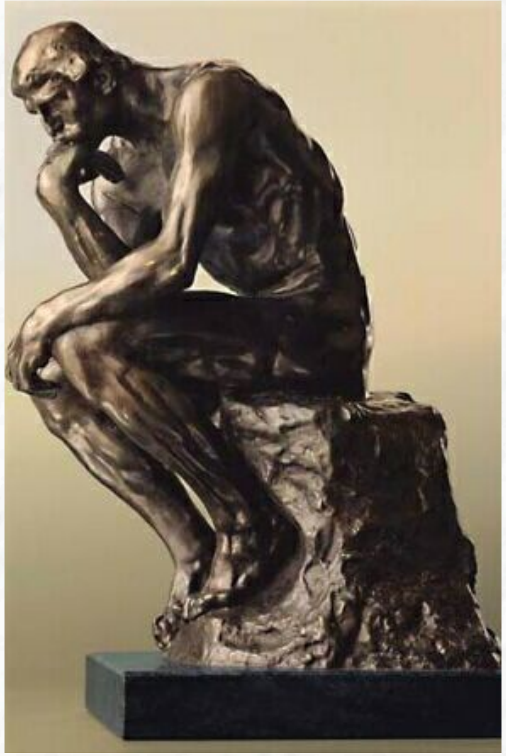




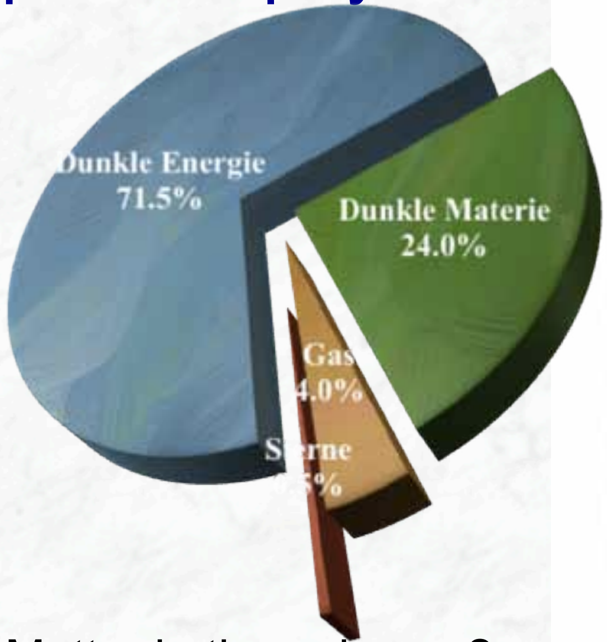
$m_H \;=\; 92\,^{+34}_{-26}$ GeV/c^2

$m_H \;<\; 161$ GeV/c^2 (95 % CL)

The open questions



Key questions of particle physics



1. Mass

What is the origin of mass?

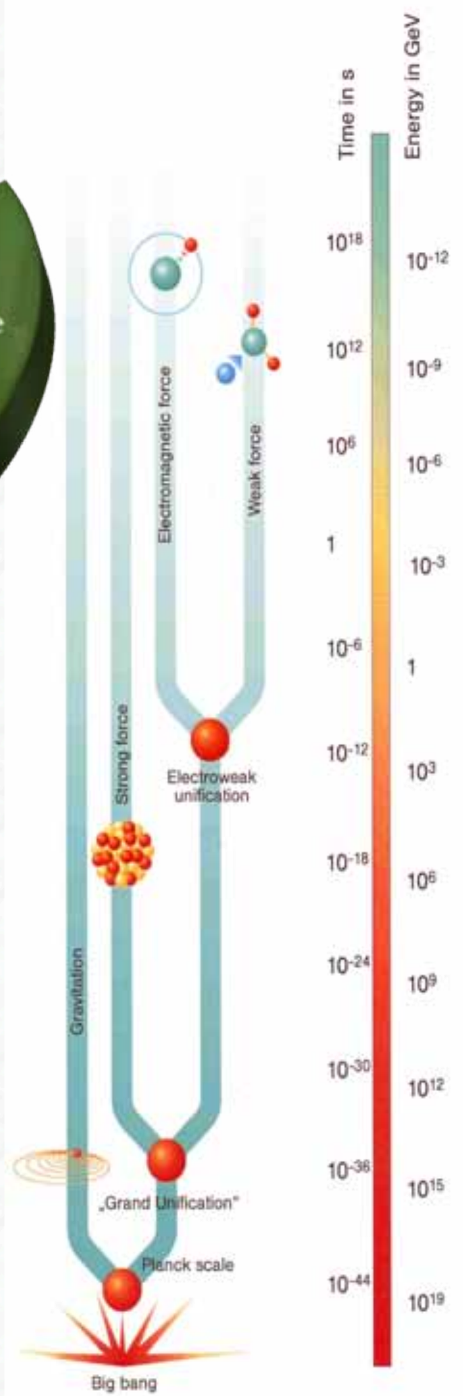
Does the Higgs particle exist?

2. Unification

- Can the interactions be unified?
- Are there new types of matter, e.g. supersymmetric particles ?
  Are they responsible for the Dark Matter in the universe?

3. Flavour

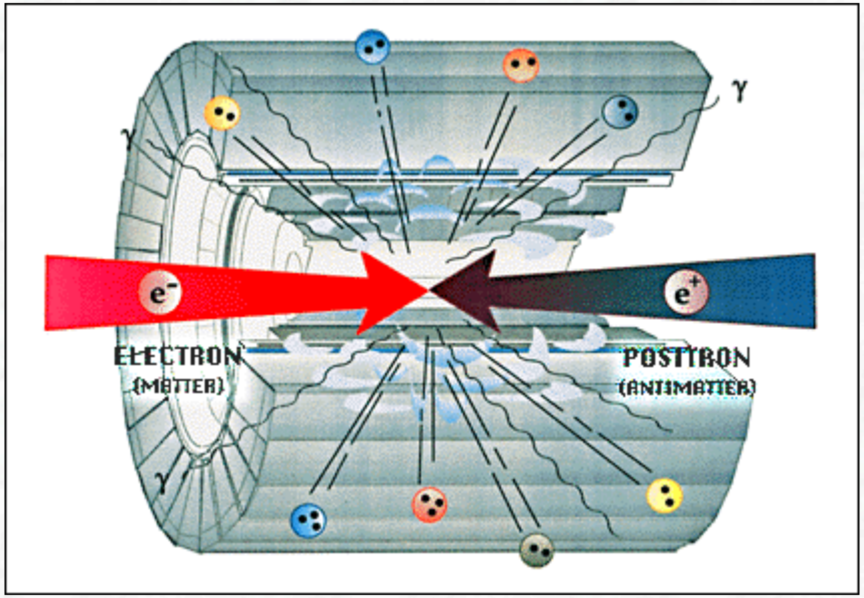
- Why are there three generations of particles?
- What is the origin of the matter-antimatter asymmetry (Origin of CP violation)

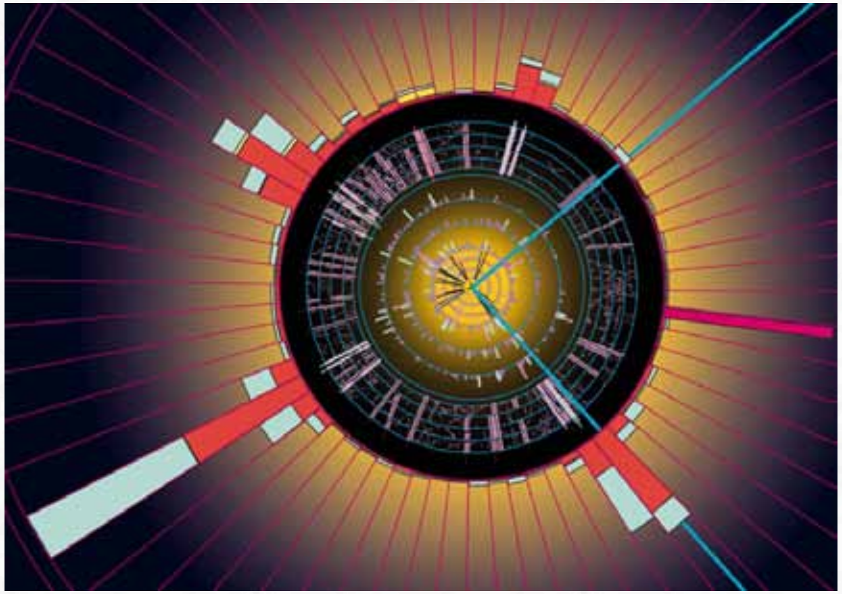


Answers to some of these questions are expected on the TeV energy scale, i.e. at the LHC

Theoretical models for physics Beyond the Standard Model

Experimental methods: Detectors





The detectors measure: - The energy and momentum of particles

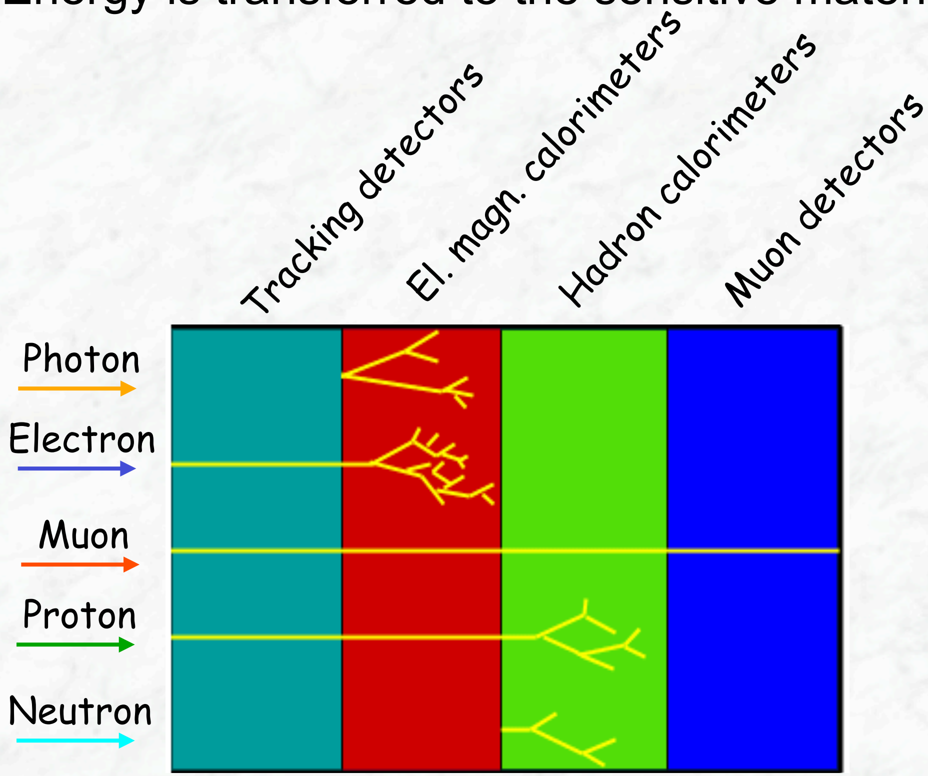
- The identity of particles

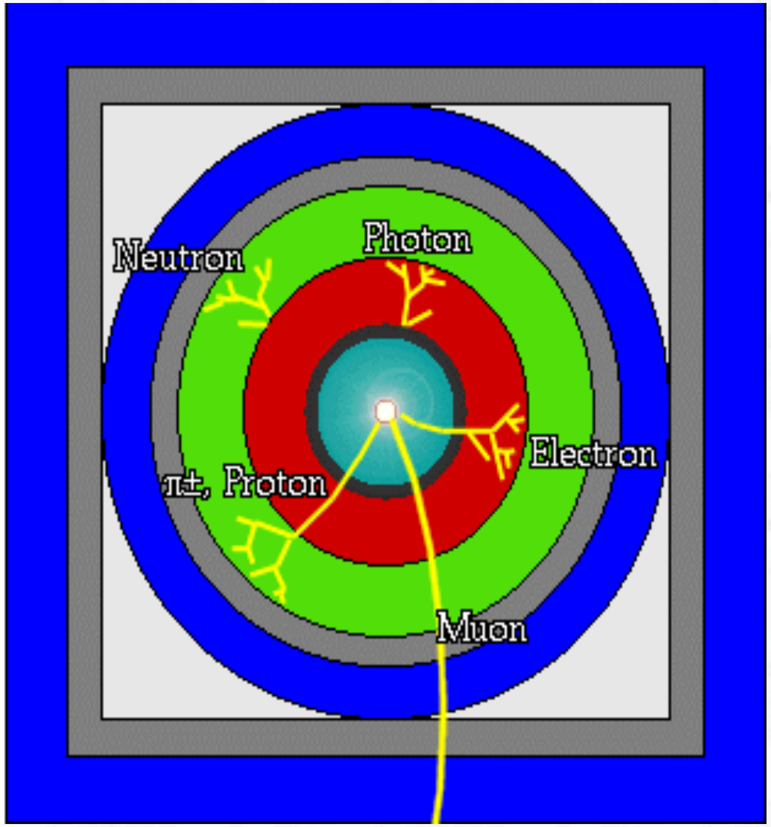
The measurements are used to reconstruct the interaction process

→ Answers to physics questions

Detection principle

- Particles are detected via their interaction with matter, i.e. with the detector material; in general: full solid angle (4π) is covered; many particles → high segmentation of detectors
- Different particles interact differently with the detector media → possibility for their identification
- Energy is transferred to the sensitive material layers → electrical or light signal

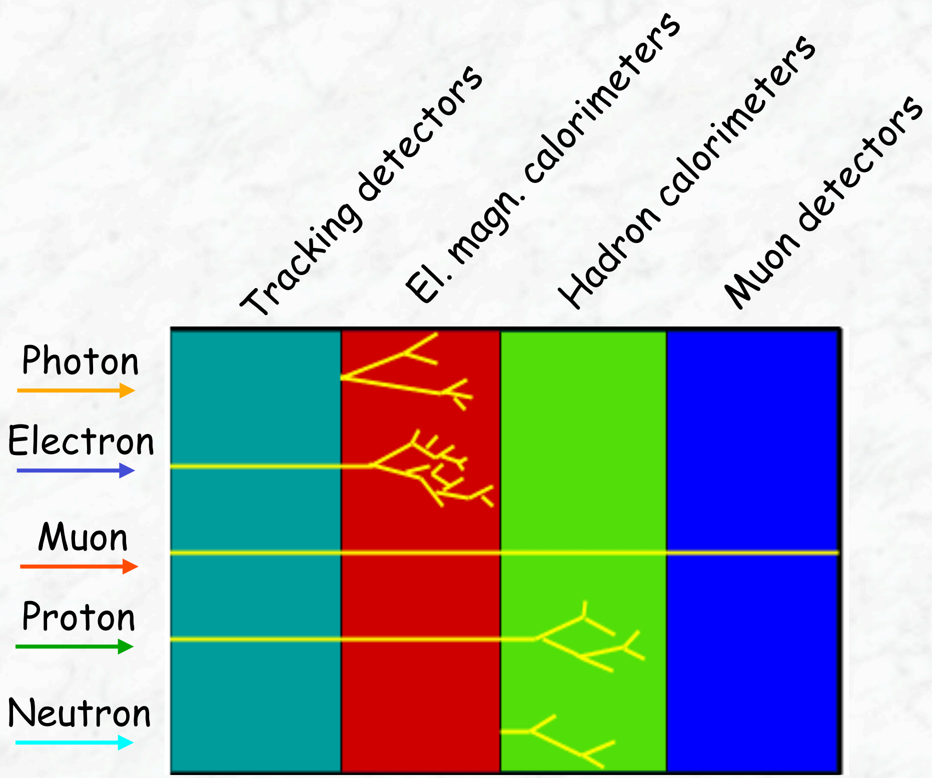


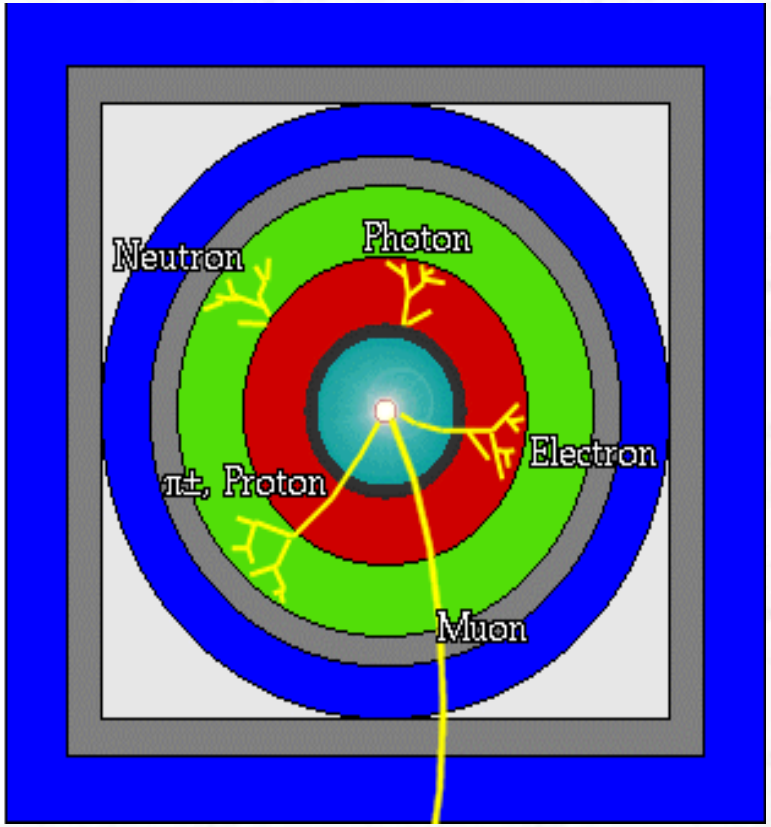


Detection principle (cont.)

(i) Tracking detectors:

- Measure the position (space information) of the particle several times; based on electromagnetic interaction, electric charge required
  → track of charged particles
- If a magnetic field in tracking volume → Lorentz force on charged particle
  → curvature of track
  → momentum p of charged particles



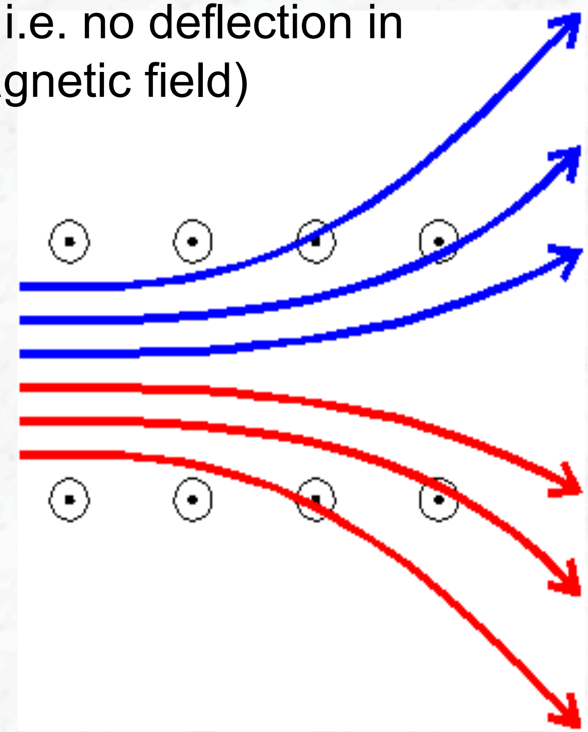


Lorentz force: $\vec{F} = -q\,\vec{v} \times \vec{B}$

For a homogenous magnetic field B perpendicular to the particle direction (velocity v, charge q):

→ circle (more general: a helix, i.e. no deflection in the direction of the magnetic field)

Radius of curvature: $R = \dfrac{p}{q \cdot B}$



negatively charged particles

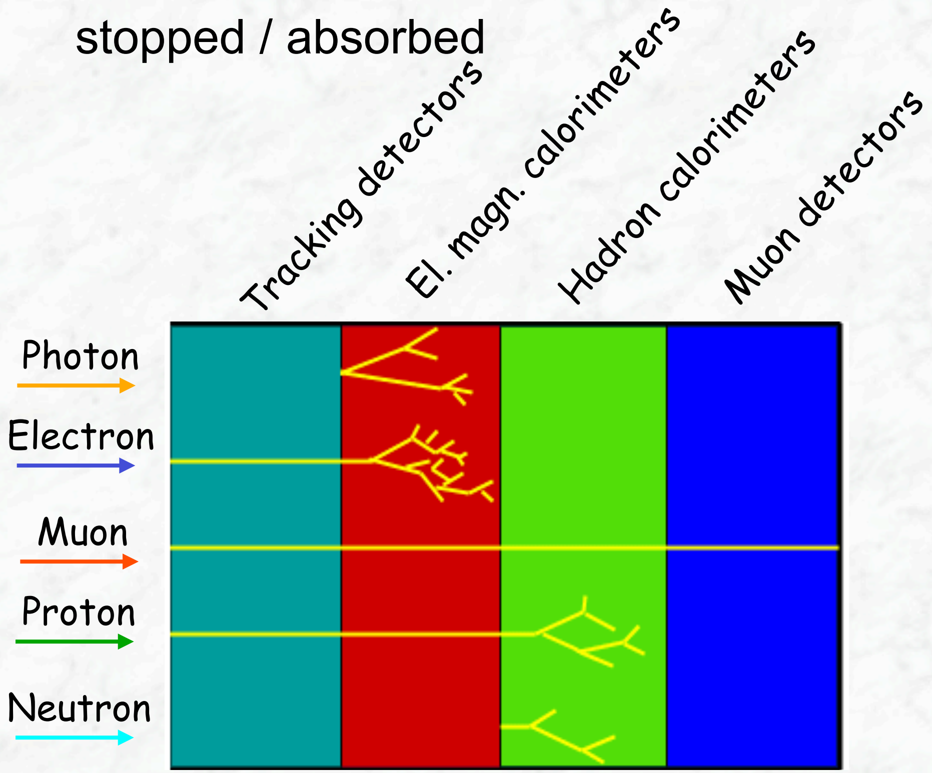
positively charged particles

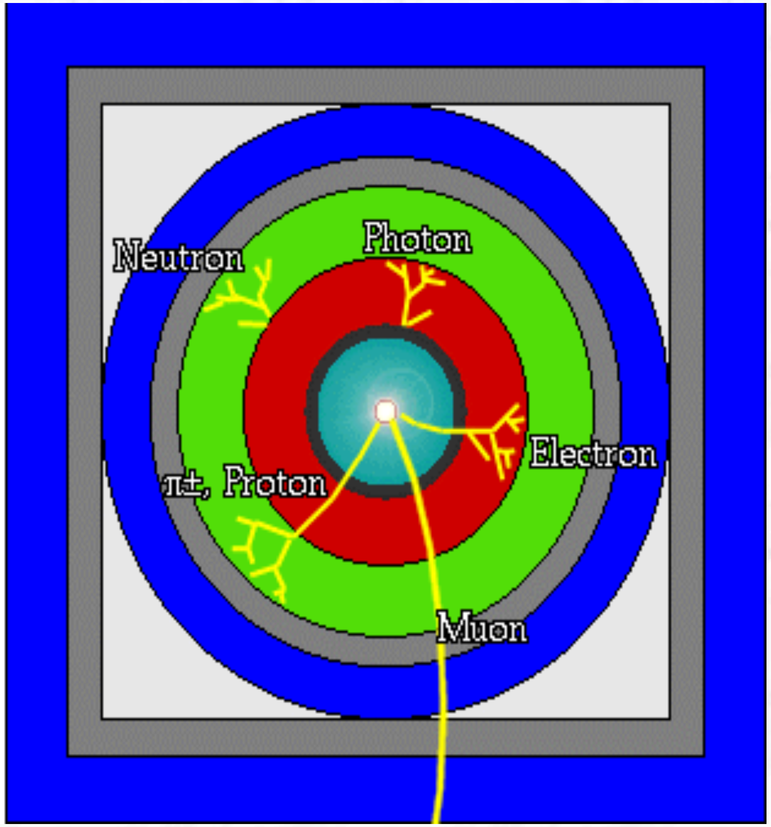
magnetic field exits the plane

(ii) Calorimeters: measure the energy of the particles, particles are stopped, their full energy is deposited, part of it is transferred to a detector medium

Different particles (e, γ, π, K,…) differ in interactions and penetration length;

Usually two sections of the calorimeters:
- Electromagnetic calorimeter: (e, γ) are stopped / absorbed;
- Hadronic calorimeter: hadrons are stopped (π, K, p, n, …..)
- note: muons and neutrinos are NOT stopped / absorbed

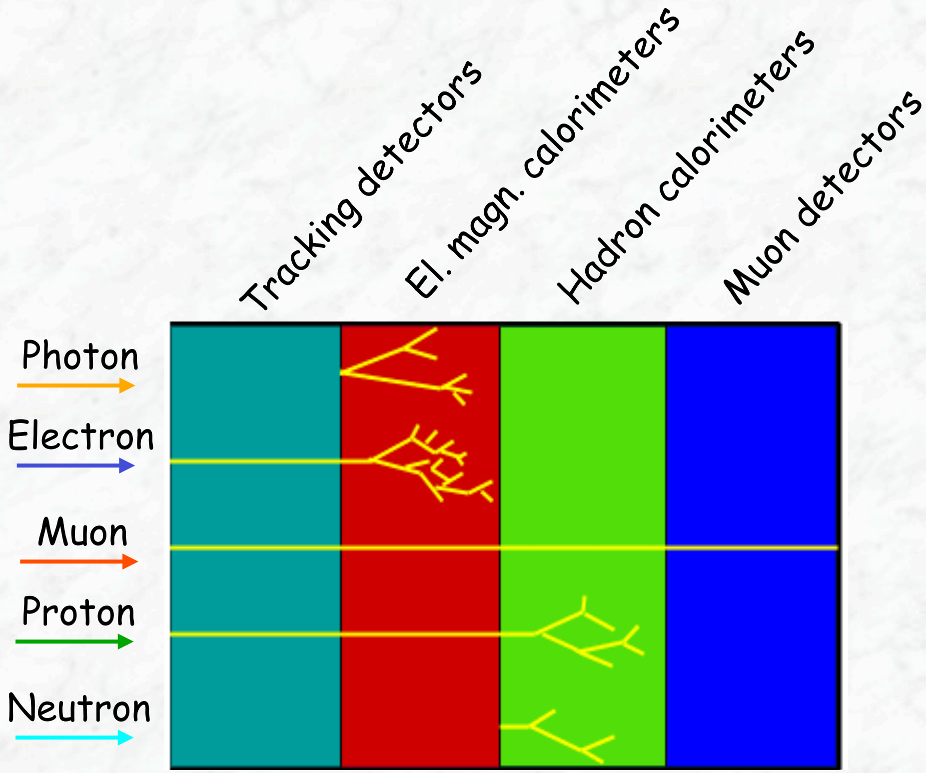


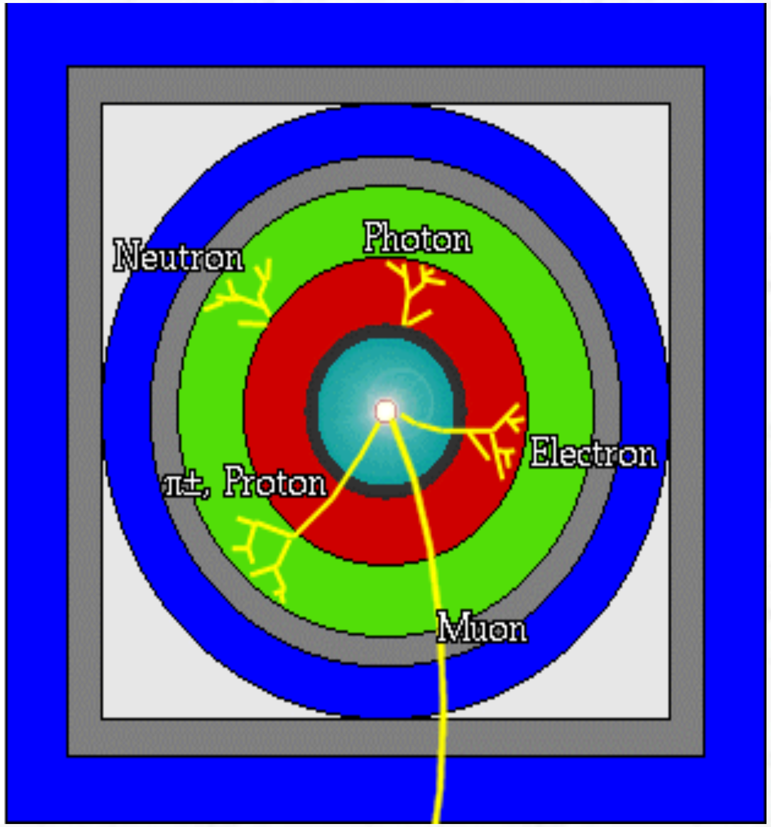


Detection principle

(iii) Muon detectors:

- Due to their relatively large mass and their lepton nature, muons have a “small” interaction with the detector material;
- They penetrate the calorimeters and give signals in “tracking detectors” behind the calorimeters; these are called muon detectors;
- Signature: track, small signals in calorimeters, track in muon detector





Detection principle

(iv) How to detect neutrinos?

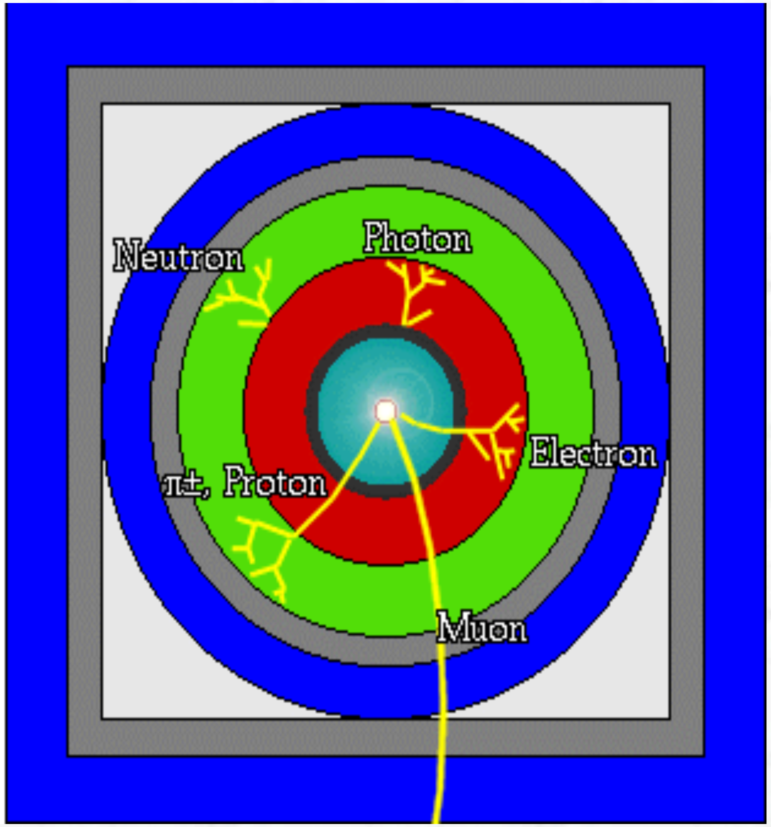
- Neutrinos interact only weakly, i.e. via the weak interaction, with the detector material

- Detector thickness is far !! too small to stop/absorb them

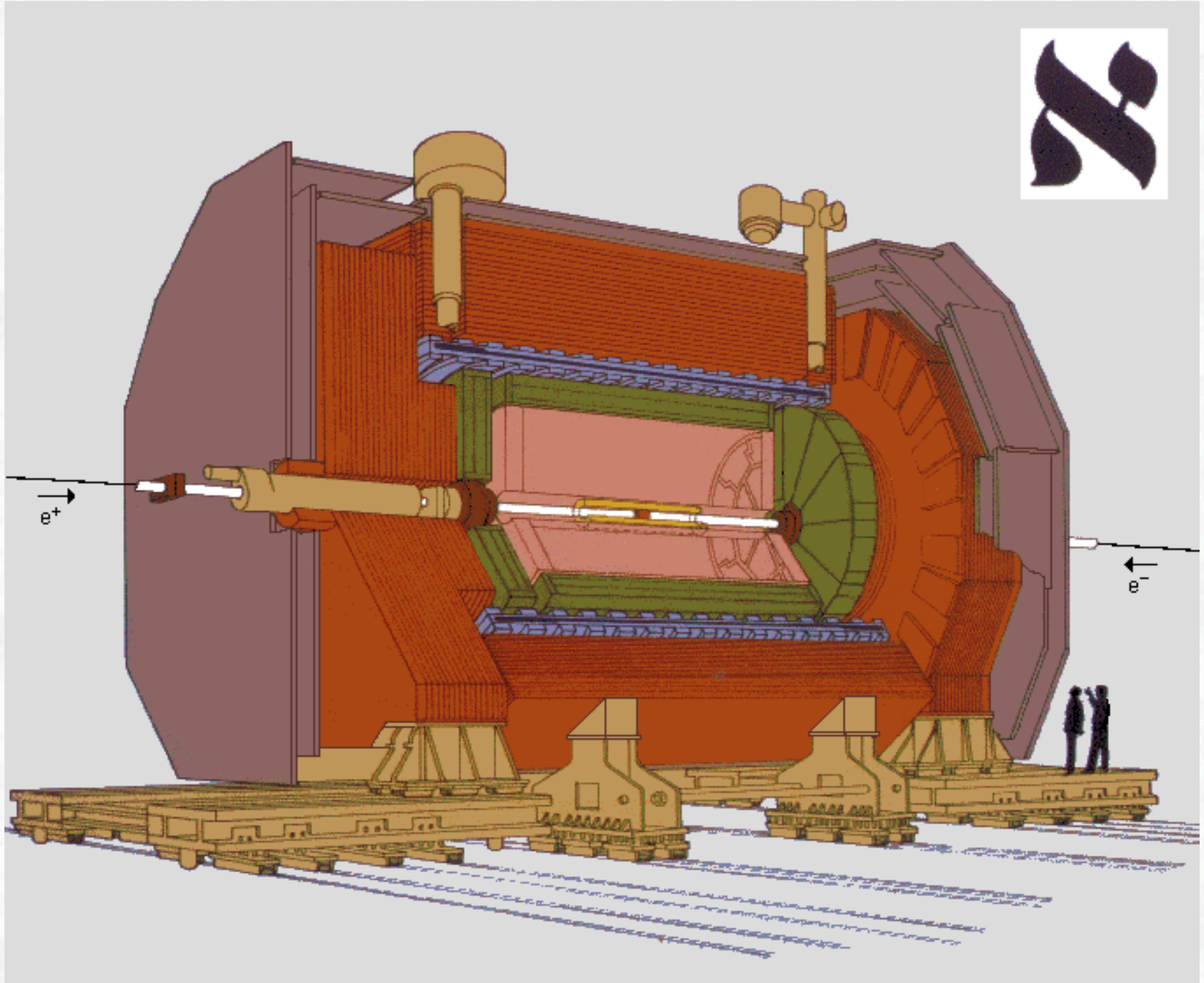
- They carry away energy and momentum

- Their presence can only be inferred via an apparent violation of energy and momentum conservations

  i.e. indirect detection of neutrinos
  (and other purely weakly interacting particles)



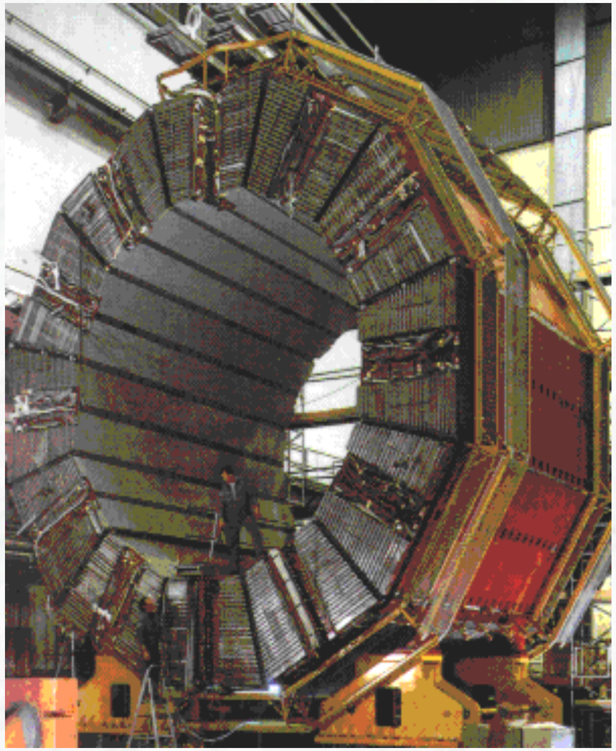
A typical particle detector
-ALEPH at LEP (~1990) as an example-



1. Central region:
   large tracking detector
2. Electromagnetic part of
   the calorimeter
3. Superconducting coil,
   high currents
   → high solenoidal
   magnetic field
4. Hadronic part of the
   calorimeter
5. Muon detector system

Experimental hall,
~140 m underground

Hadronic calorimeter in the "barrel" part of the detector
(iron absober +
gas as sensitive medium)



A few collision events

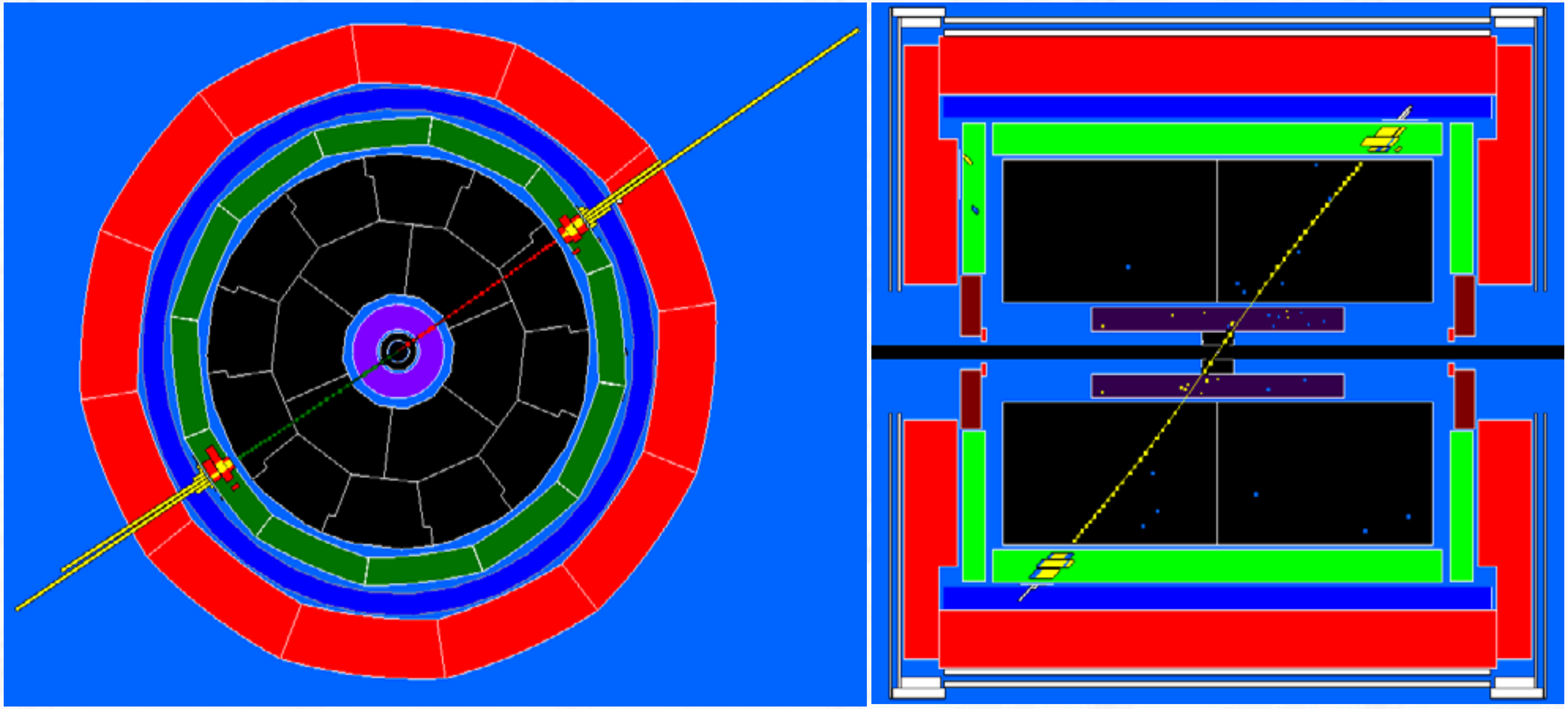
recorded with the

ALEPH detector at LEP

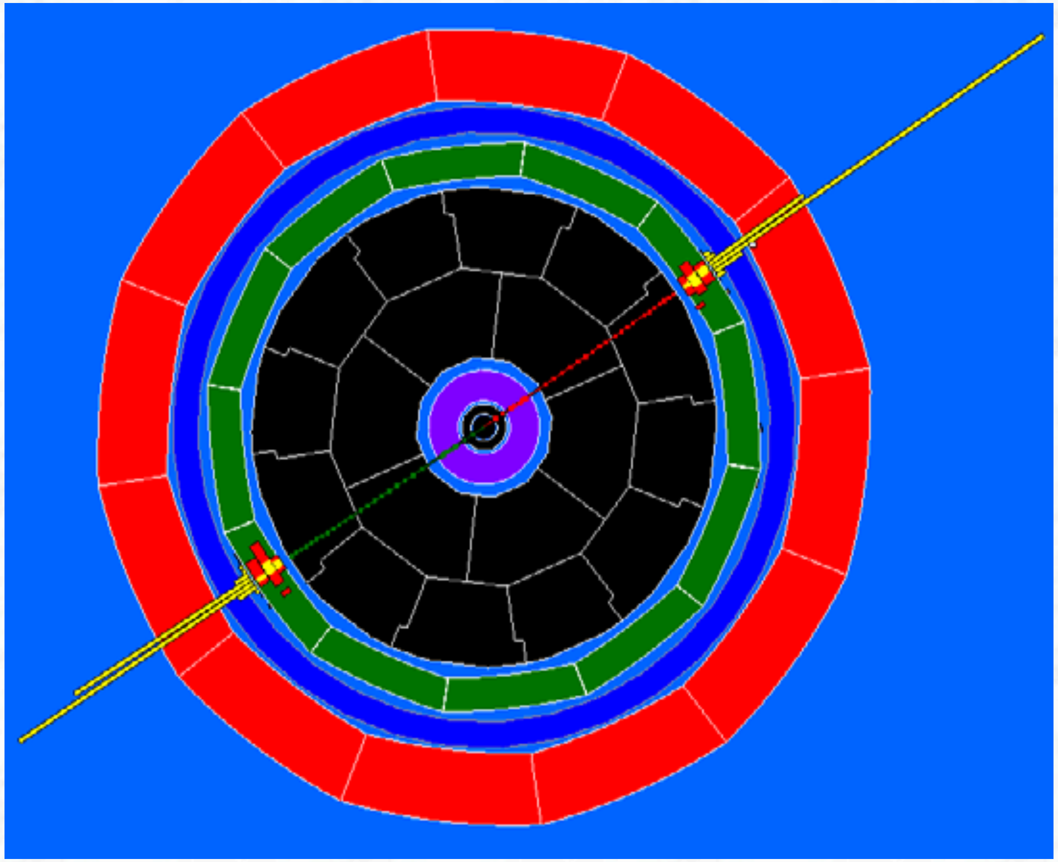
Initial state: $e^+ e^-$ collisions

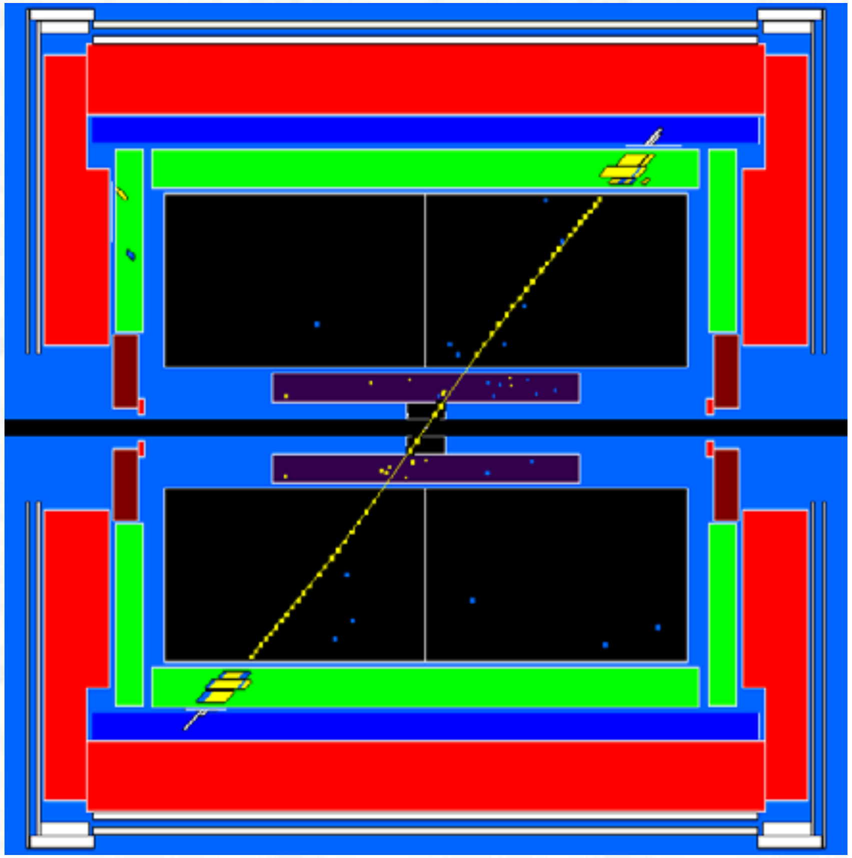
centre-of-mass energy $\sqrt{s}$ = 91 GeV

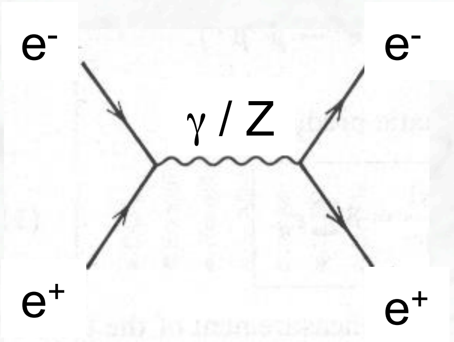
What process has occurred here ?



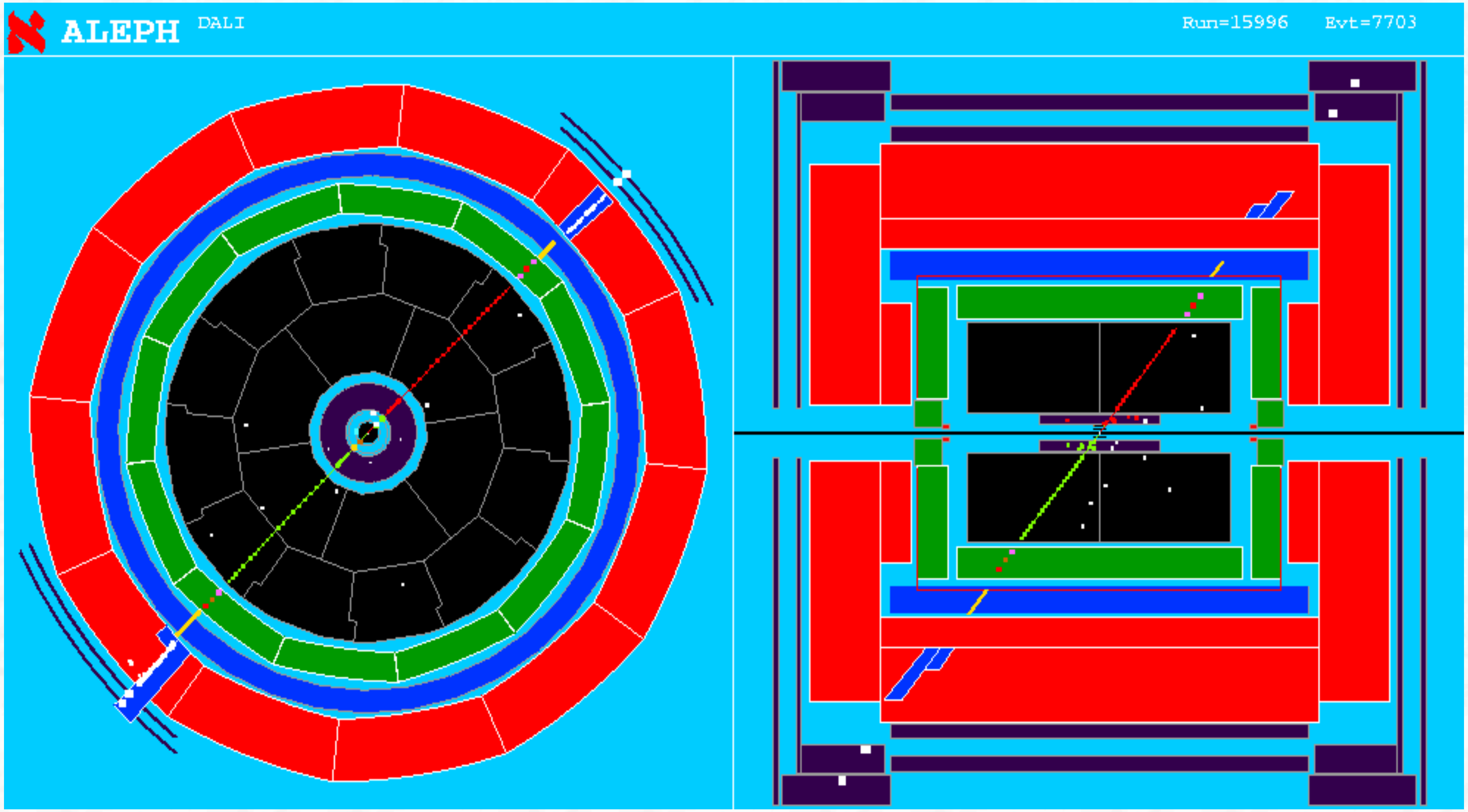
What process has occurred here ?



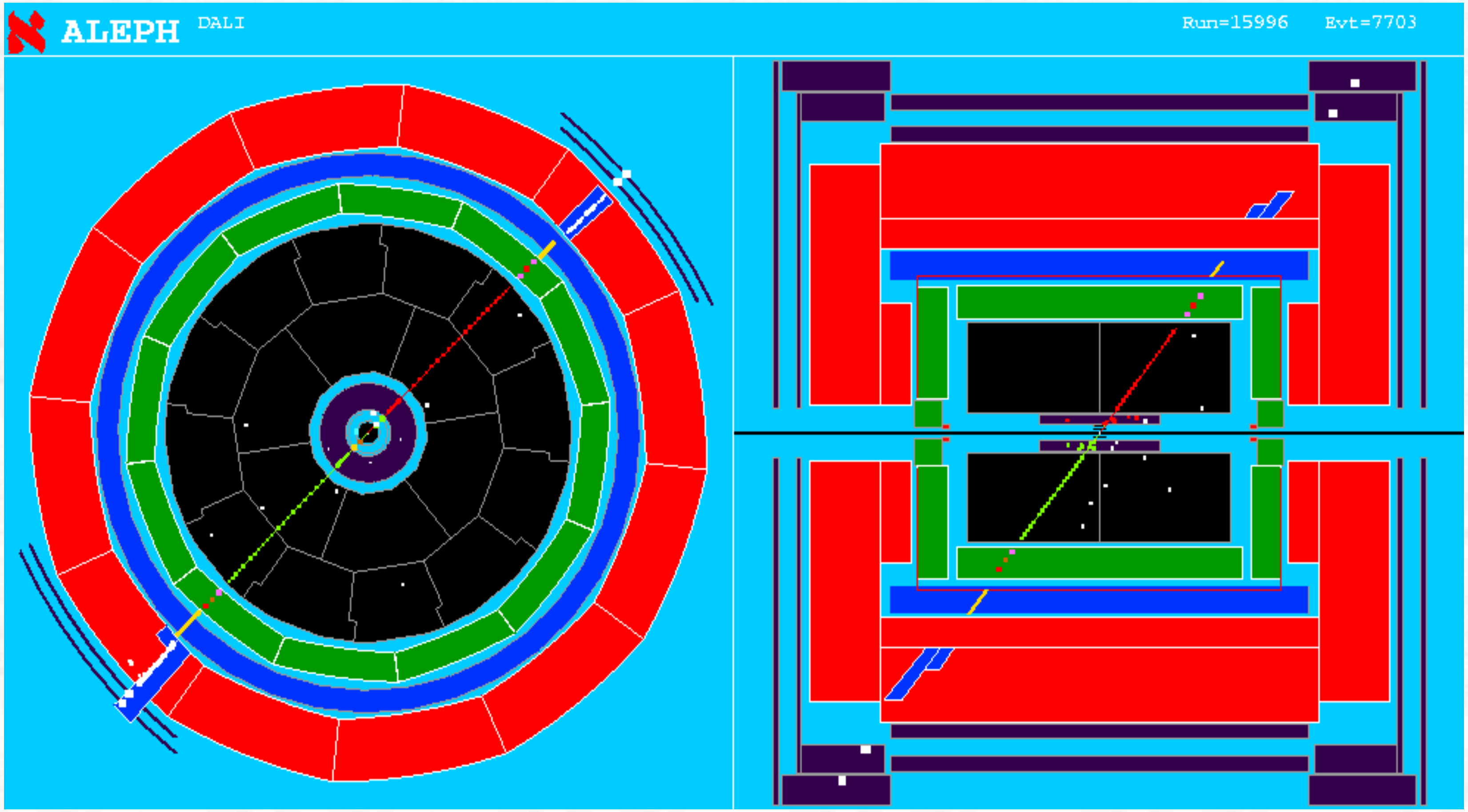


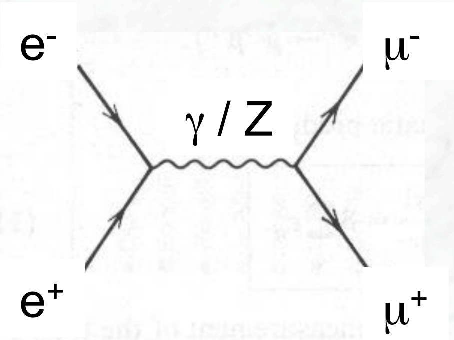


What process has occurred here ?

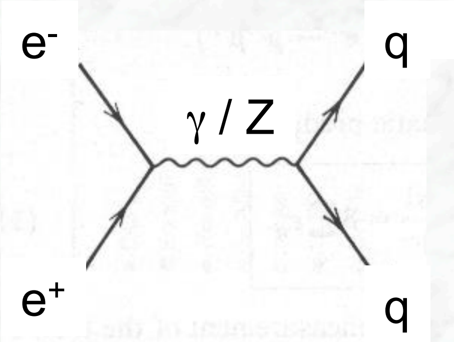


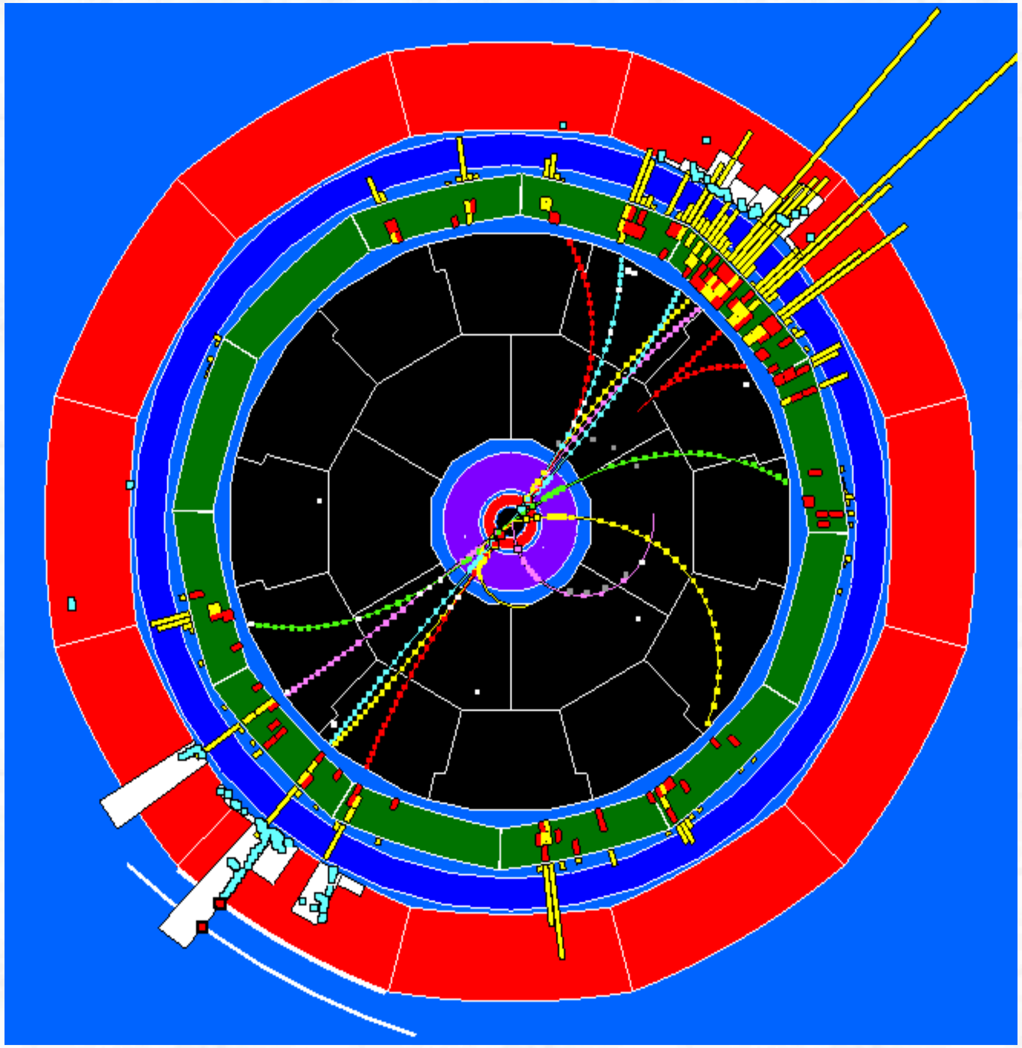
What process has occurred here ?





What process has occurred here ?





- Production of a quark-antiquark pair in the final state
- Quarks cannot exist as “free particles” and undergo fragmentation into final state hadrons ($\pi^{\pm}$, π^0, $K^{\pm}$, K^0, p, n, …, $B^{\pm}$, B^0, ….)
- Depending on their lifetime, these particles decay inside the detector

prompt decays: e.g.	$\pi^0 \rightarrow \gamma\gamma$	$\tau = 8.4 \cdot 10^{-17}$ s	$c\tau = 25.1$ nm
medium lifetime: B-hadrons:	$B^0 \rightarrow D^0 \pi^+\pi^-$	$\tau = 1.55 \cdot 10^{-12}$ s	$c\tau = 464$ μm
“stable” particles:	$\pi^{\pm}$	$\tau = 2.6 \cdot 10^{-8}$ s	$c\tau = 7.8$ m