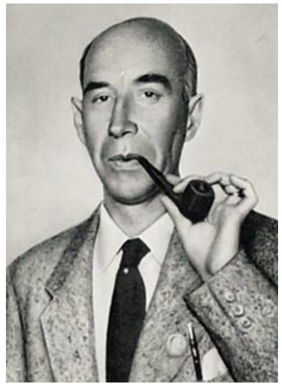
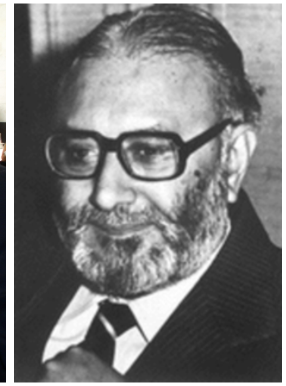
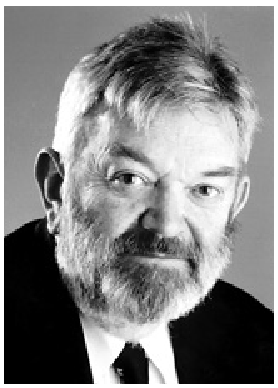
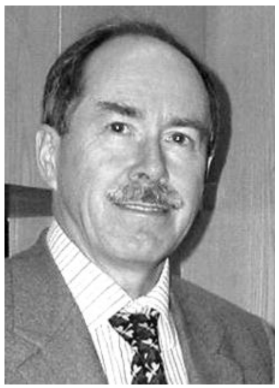
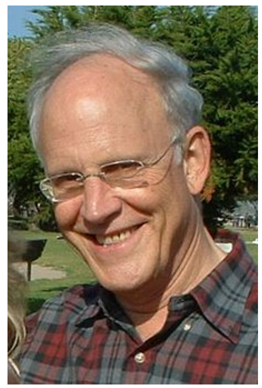
Experimental Foundations of the Standard Model I



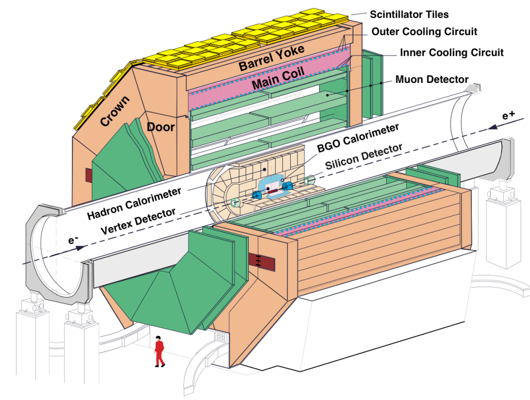




Postgraduate Course, UC Louvain, 2009

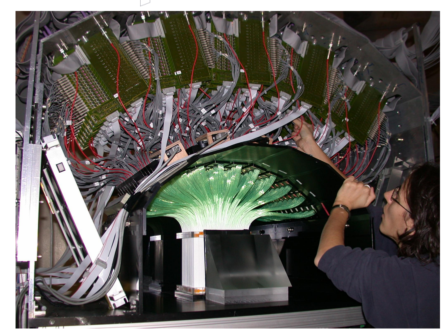
UNIVERSITÉ DE GENÈVE

Martin Pohl

A Road Map for 4 Lectures



- Observables: calculation and measurements
- Electroweak interactions:
  - Neutral currents: photons and Z
  - Charged currents: the Ws
  - Testing the electroweak Standard Model
- Strong interactions: gluons



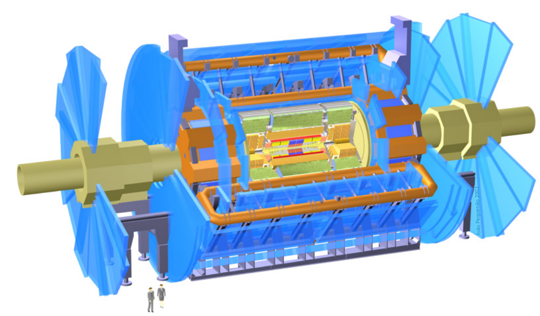
Many thanks to:

- The Electroweak Working Group:

  `http://lepewwg.web.cern.ch/LEPEWWG/`

- The 2008 lectures by Salvatore Mele in *3ième Cycle de la Physique en Suisse Romande*:

  `http://www.cuso.ch/3e-cycle/physique/programme/`



- The 2009 Moriond meeting for latest results:

  `http://indico.in2p3.fr/conferenceDisplay.py?confId=1399`

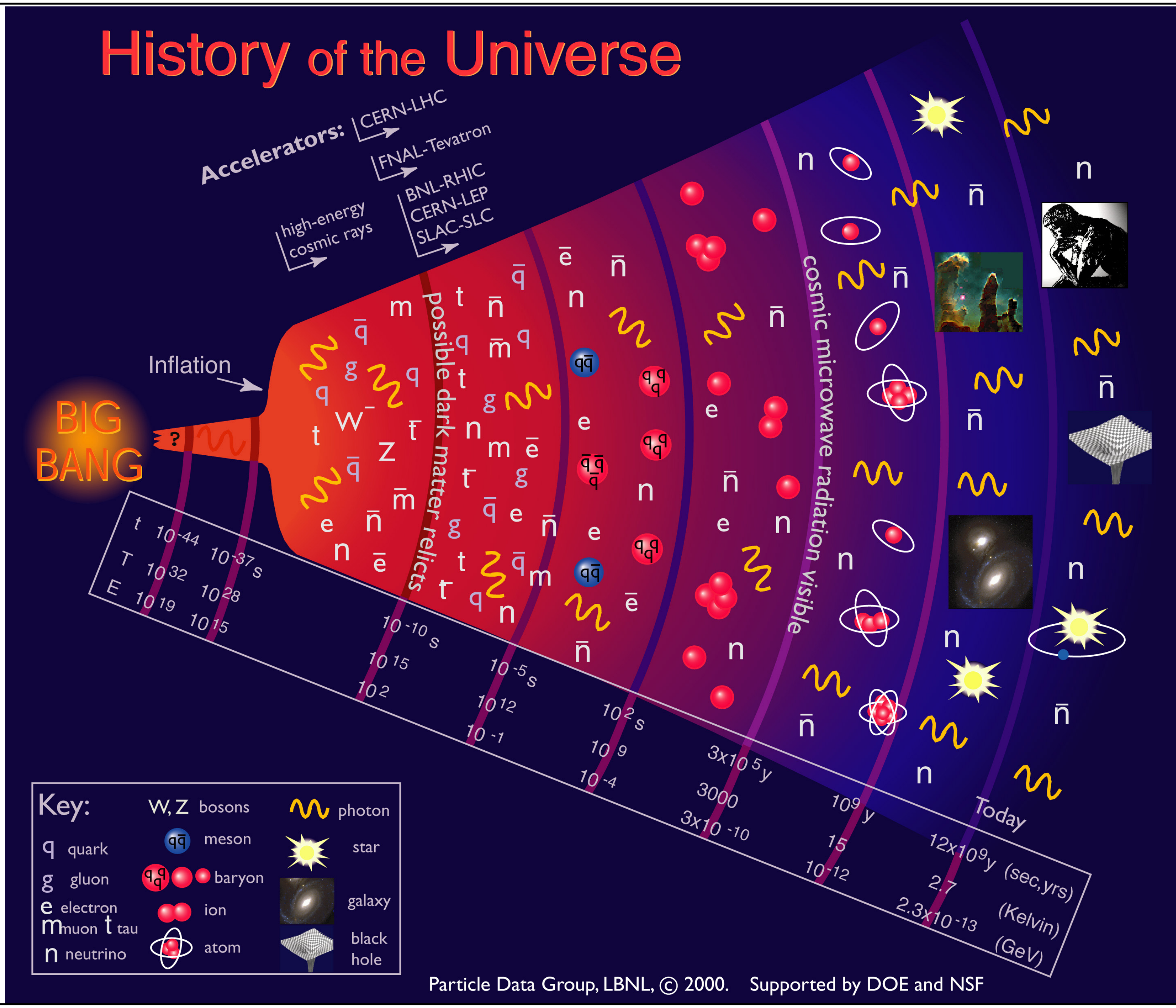
Negative List

What is not covered (explicitly):

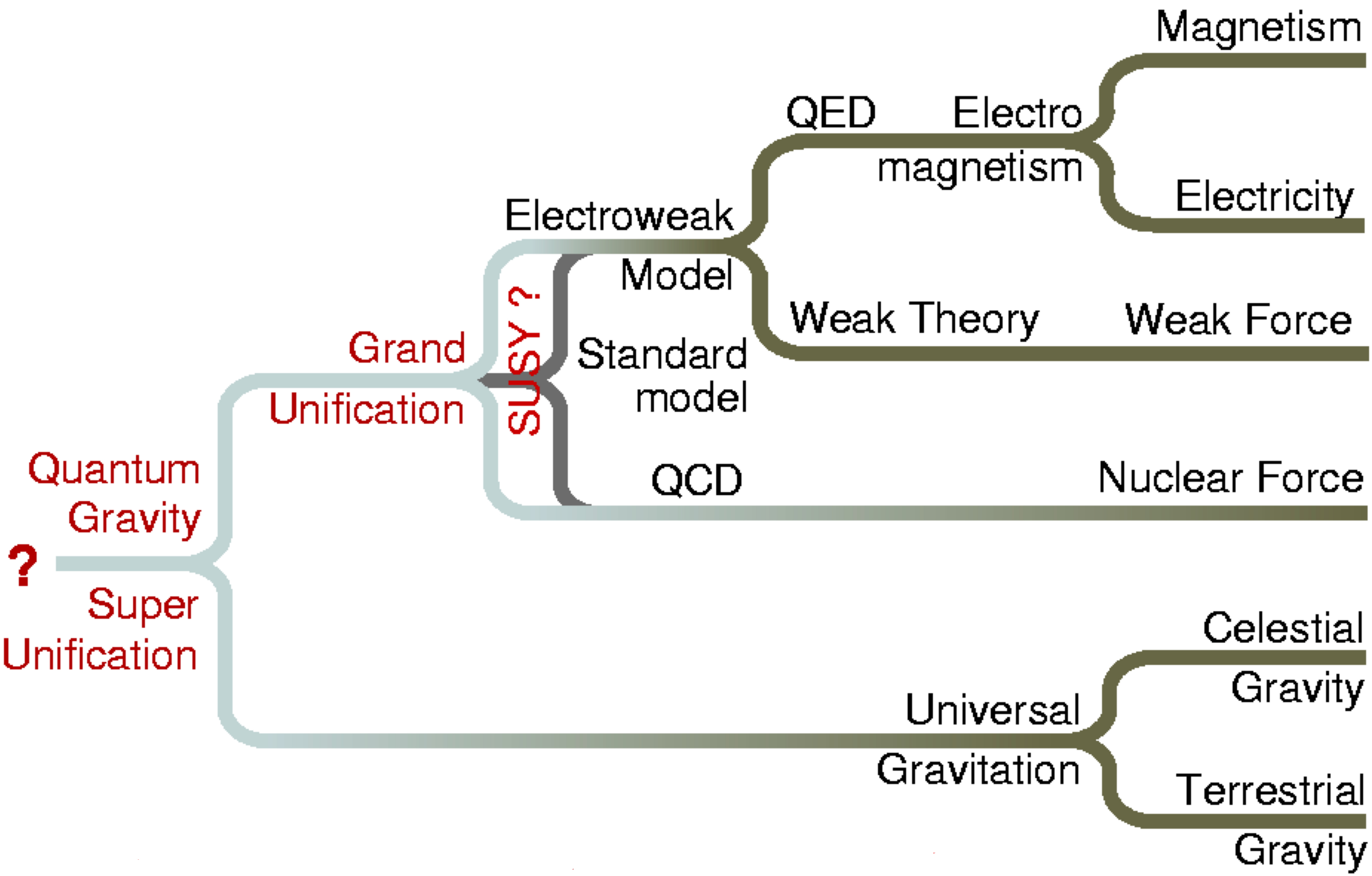
- Many fascinating experimental methods
- Direct, unsuccessful searches for the Higgs boson
- Electroweak measurements at hadron colliders and at HERA
- Electroweak couplings to quarks
- Mixing in the quark sector, CP violation
- Neutrino physics, oscillations, mixing in the leptonic sector

...so far to the attempt of an overview!

A History of the Universe



Increasing energy allows to turn back time



Reminder: Concepts of Classical Physics

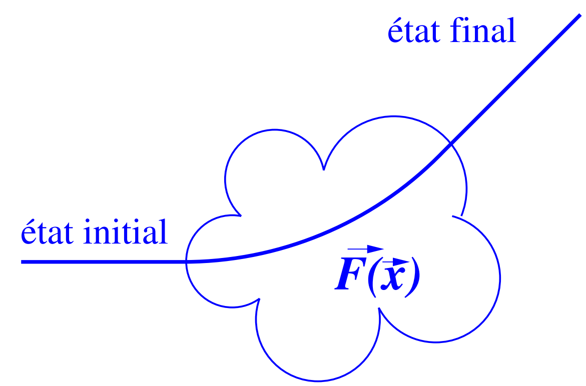
- Particles are mass points, their positions $\vec{x}$ and momenta $\vec{p}$ are certain.
- The trajectory is determined by Newton's law, if all forces and initial conditions are known:

$$m\frac{d^2\vec{x}}{dt^2} = \sum_i \vec{F}_i$$

- The action of forces is continuous.
- The number of particles is conserved.
- Field and potential are subordinate to force and energy. Example from electricity:

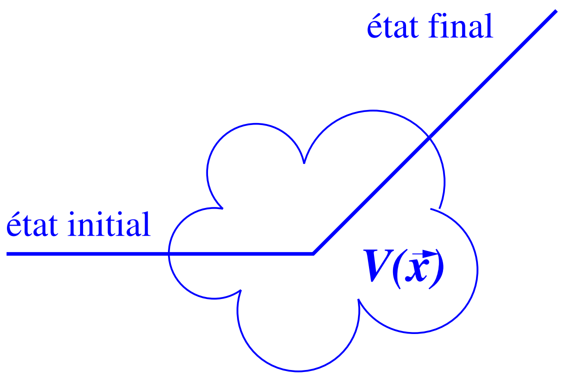
$$\vec{F} = q\vec{E} \quad ; \quad \vec{E} = -\vec{\nabla}V \quad ; \quad E_{pot} = qV$$

Validity: $v \ll c$
$\Delta x \gg 10^{-10}$m



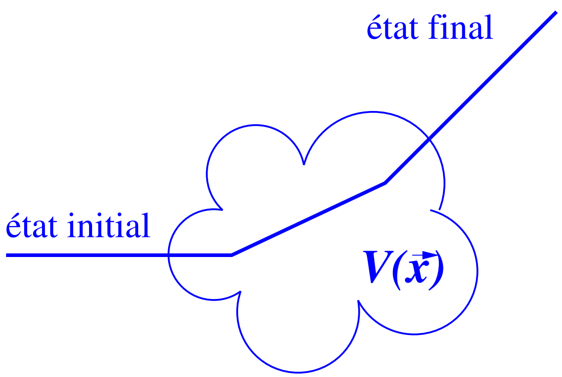
Reminder: Concepts of Quantum Mechanics

Validity: $v \ll c$



- Particles are fields, described by a probability amplitude $\psi(\vec{x}, t)$. The square of this amplitude, $\rho = |\psi|^2 \geq 0$ indicates the probability top find the particle at $(\vec{x}, t)$.
- The trajectory does not exist, but amplitude and probability evolve starting from an initial state. The evolution is described by Schrödinger's equation:

$$-\frac{1}{2m}\vec{\nabla}^2\psi = i\frac{\partial}{\partial t}\psi \quad ; \quad i\frac{\partial}{\partial t}\psi + \frac{1}{2m}\vec{\nabla}^2\psi = V\psi$$



- Particles interact with the potential. The action of the potential is continuous, but can be approximated by a perturbative approach.
- The number of particles is conserved:

$$\rho = (\psi\psi^*) \quad ; \quad \vec{j} = -\frac{i}{2m}(\psi^*\vec{\nabla}\psi - \psi\vec{\nabla}\psi^*) \quad ; \quad \partial\rho/\partial t + \vec{\nabla}\vec{j} = 0$$

- The origin and transport of the potential stay unexplained.

Reminder: Concepts of Relativistic Field Theory

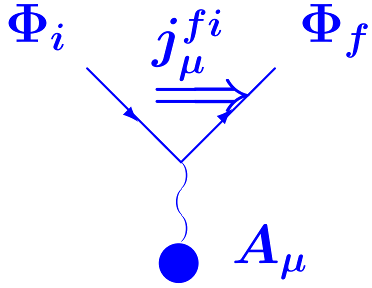
Validity: ???

- The evolution of fields is described by a relativistic equation of motion:

$$E^2 - \vec{p}^2 = m^2 \quad ; \quad -\frac{\partial^2}{\partial t^2}\phi + \vec{\nabla}^2\phi = m^2\phi$$

- The number of particles is no longer conserved, but the electromagnetic current is:

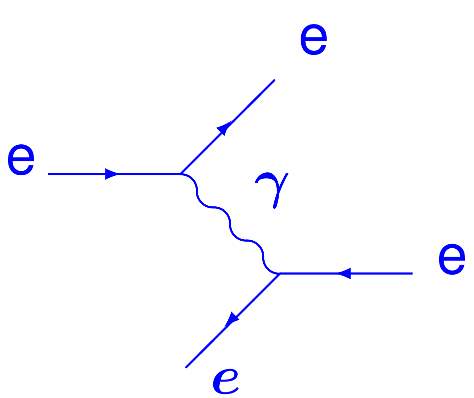
$$j^\mu = -2ep^\mu$$



This opens the possibility to create particle-antiparticle pairs.

- The potential is generated by a second current, following Maxwell's equations:

$$A^\mu = -\frac{1}{q^2} j^\mu_{(2)}$$



The propagator $1/q^2 = (E_\gamma^2 - p_\gamma^2)^{-1}$ describes the probability amplitude for the exchange of a photon with mass q^2 between the two currents.

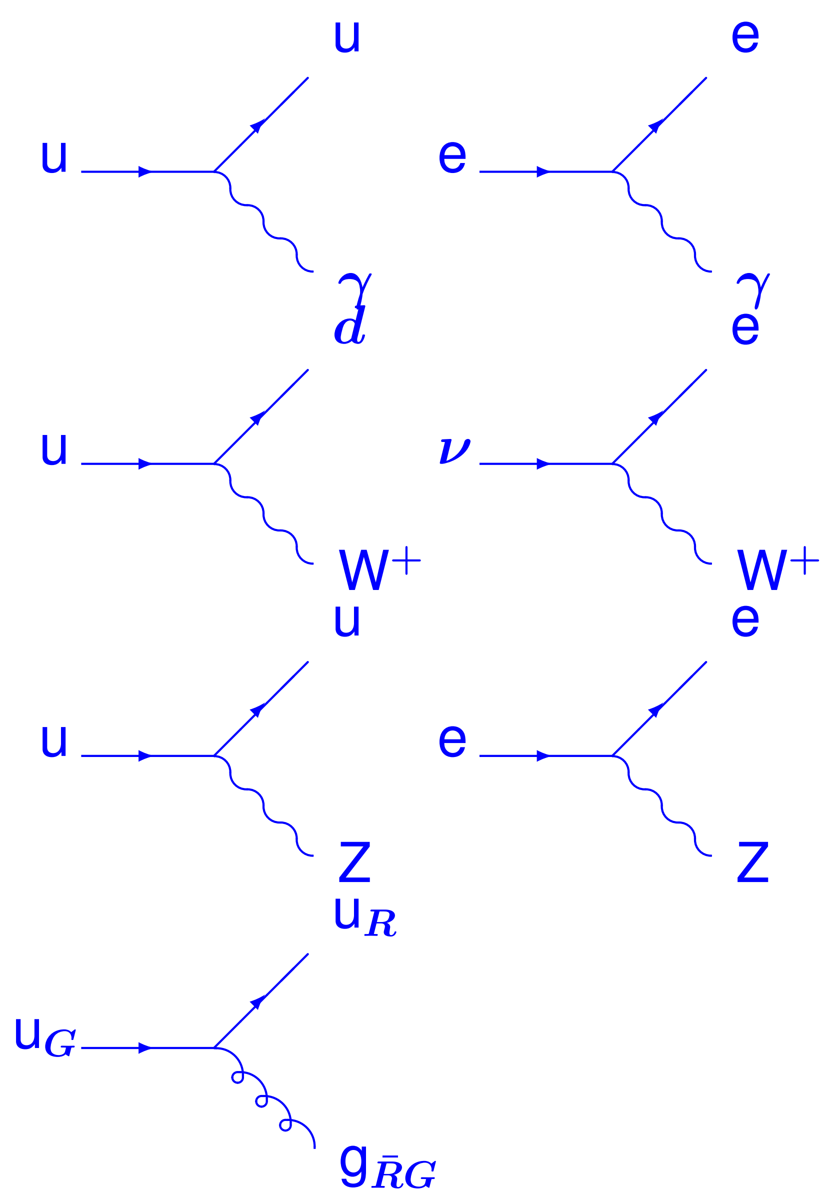
Forces

Electromagnetic Int.

Weak interaction
(charged current)

Weak interaction
(neutral current)

Strong interaction

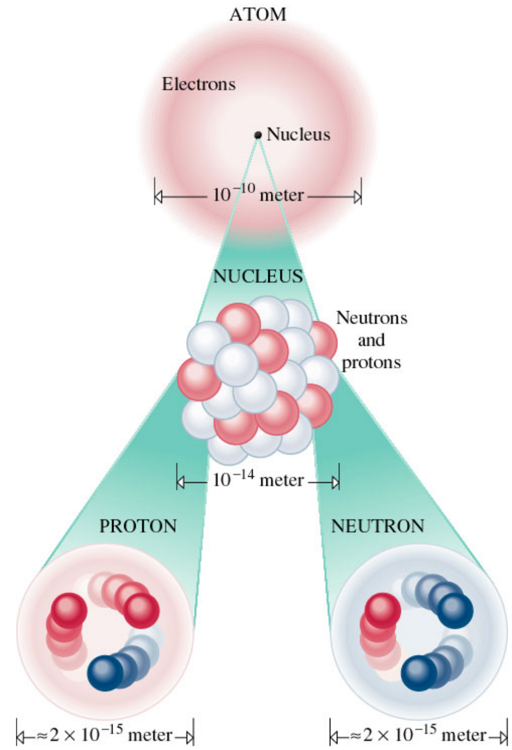


QED

Glashow-
Weinberg-Salam
theory

QCD

The constituents of matter

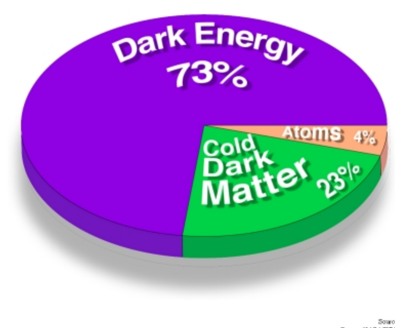


Families, with different properties:

- Leptons: electron, determines properties of atoms. Weak and electromagnetic interactions.
- Neutrinos: produced in radioactive decays. Weak interactions only.
- Quarks: constituents of protons and neutrons, nuclei. All interactions.

Generations, with different masses:

- Three generations for each family.
- Generations are distinguished by mass, and a partially conserved flavor quantum number.
- Very similar properties.



Attention: This describes less than 5% of the Universe!

Remember: The Standard Model is a theory of forces, it doesn't have much to say about matter...

Periodic Table of matter

Name	Spin	Baryon Number	Lepton Number	Electric Charge
Leptons:				
e, μ, τ	$1/2$	0	1	-1
ν_e, ν_μ, ν_τ	$1/2$	0	1	0
Quarks:				
u, c, t	$1/2$	$1/3$	0	$+2/3$
d, s, b	$1/2$	$1/3$	0	$-1/3$
Bosons de jauge:				
γ	1	0	0	0
Z, $W^\pm$	1	0	0	$0, \pm 1$
Gluons	1	0	0	0
Vide	0	0	0	0

Univers consists of matter (fermions), forces (gauge bosons) and the vacuum. For every particle there is an antiparticle, distinguished by the sign of all charge-like quantum numbers.

Family	Generation 1	2	3
Neutrinos	ν_e	ν_μ	ν_τ
Leptons	e	μ	τ
Quarks Up	u	c	t
Quarks Down	d	s	b

The Standard Model

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

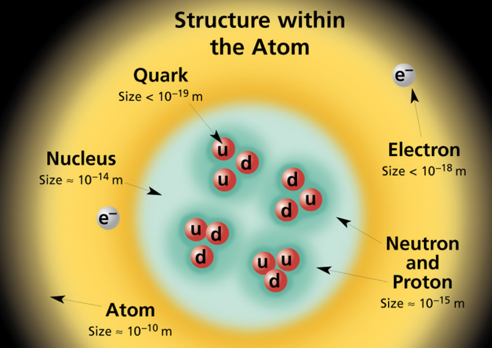
Quarks spin = 1/2

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 = 1.05×10^{-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/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

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

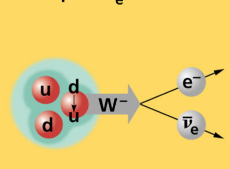
Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

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.

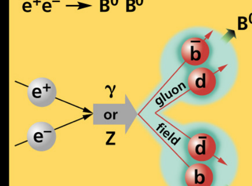
Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



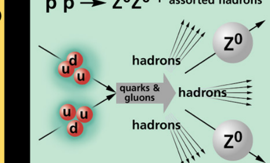
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



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.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



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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American Physical Society, Division of Particles and Fields
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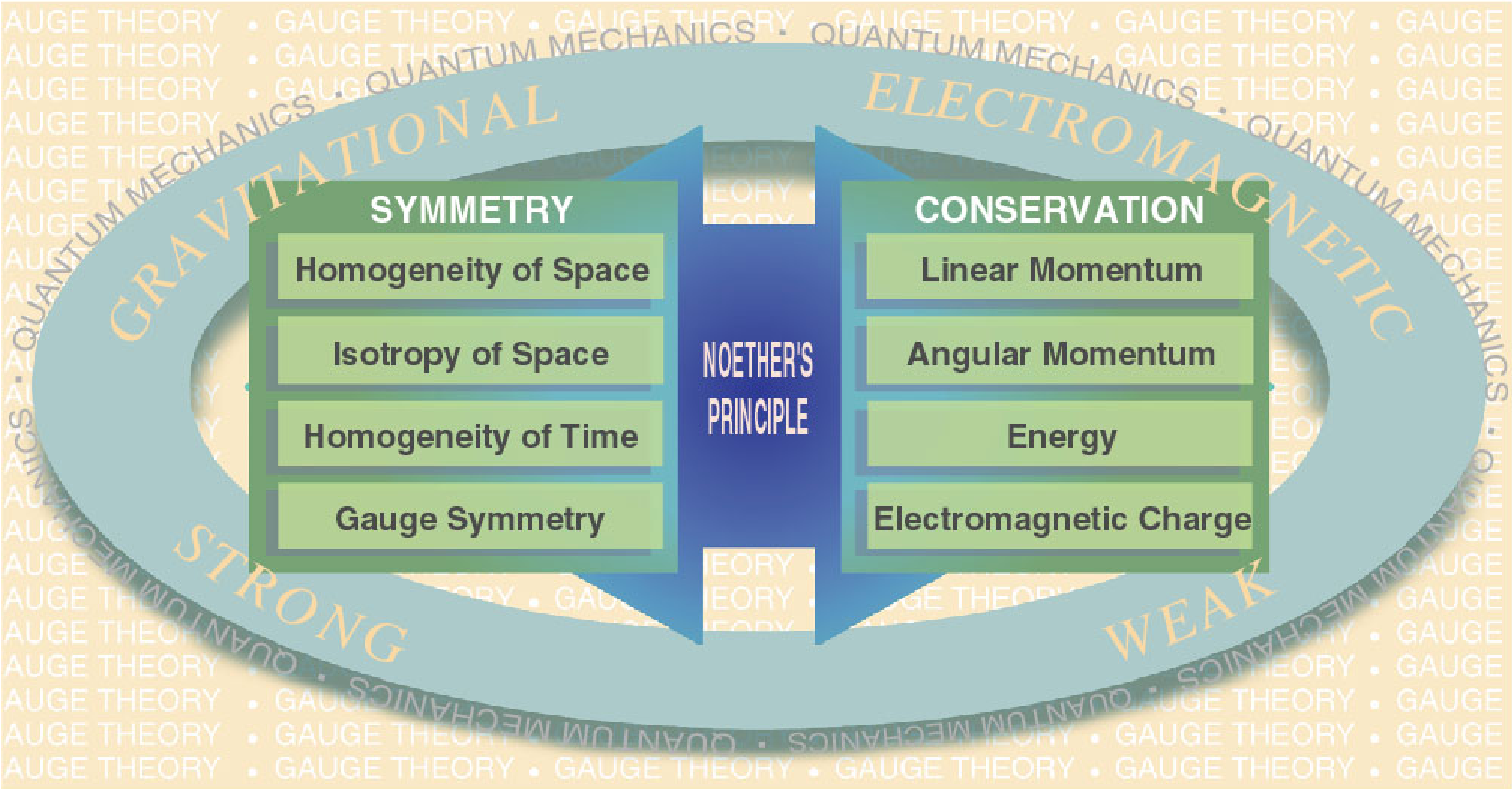
Symmetries and Conserved Quantities

Noether's theorem:

- To each continuous symmetry of a system corresponds a conserved quantity.

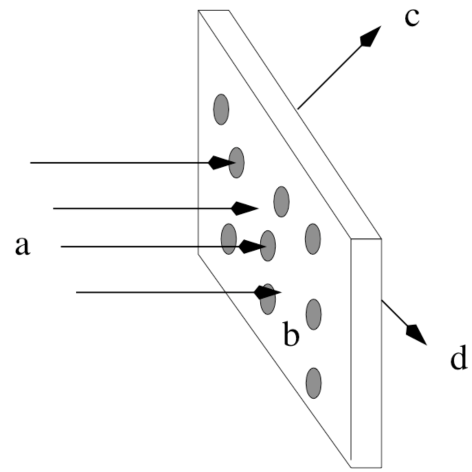
A. Noether (1882-1935)



Observables: Measurement and Calculation

Since quantum physics is based on a statistical approach, the basic problem of particle physics is the measurement and the calculation of the probability for a process, using the cross section.

The concept of the cross section is a purely geometrical one, as its name indicates. Consider a reaction $a + b \rightarrow c + d$. The reaction rate will be proportional to the incoming flux and the density of targets. In the laboratory, the flux F_a of projectiles a, i.e. their number per unit surface and time, is $F_a = \rho_a v_a$, with their density ρ_a and their velocity v_a, with respect to the targets b at rest.



If the target particles have a cross section σ, representing the probability to 'hit' them, the reaction rate will be:

$$W = F_a N_b \sigma$$

with the number N_b of targets. The cross section is thus defined as the reaction rate per unit projectile flux and target particle density. It represents the likelihood of a reaction, independent of experimental details.

Observables: Measurement and Calculation

In the laboratory system, the relation between counting rate and cross section is:

$$\frac{\text{Reactions}}{\text{Unit time}} = \frac{\text{Incident particles}}{\text{Unit surface and time}}(\text{Targets}) \times (\text{Cross Section})$$

In the center-of-mass system, e.g. at a collider, one finds for the counting rate:

$$\frac{\text{Reactions}}{\text{Unit time}} = \frac{(\text{Particles})_A(\text{Particles})_B}{\text{Unit surface and time}} \times (\text{Cross Section})$$

The first factor is called the luminosity $\mathcal{L}$ of the collider. It depends on the frequency ν, with which the two beams cross each other, the dimensions σ_x and σ_y of their intersection transverse to the direction z of the beams, and the numbers of particles N_i in each beam:

$$\mathcal{L} = \frac{N_A N_B \nu}{4\pi\sigma_x\sigma_y}$$

The cross section has the dimension of a surface. It is measured in the enormous unit of barn, $1\text{b} = 10^{-28}\text{m}^2$. Lepton and quark cross sections are rather of the order of nanobarn, $1\text{nb} = 10^{-9}\text{b}$, ou picobarn, $1\text{pb} = 10^{-12}\text{b} = 10^{-40}\text{m}^2$.

Distributions and Differential Cross Section

Integrating the relation between cross section and counting rate over the measurement time, we obtain the total number of reactions observed. In the center-of-mass frame:

$$N = \int W\, dt = \sigma \int \mathcal{L}\, dt$$

with the integrated luminosity $\int \mathcal{L}\, dt$.

Instead of just counting the total rate of a reaction, one can measure a distribution, for example as a function of solid angle Ω:

$$\frac{dN}{d\Omega} = \frac{d^2N}{d\cos\theta\; d\phi}$$

with the polar and azimuthal scattering angles θ and ϕ.

After normalizing by the initial flux and the target particle density, one measures the differential cross section $d\sigma/d\Omega$, with the normalization condition:

$$\sigma = \int \frac{d\sigma}{d\Omega} d\Omega$$

Invariant Amplitude and Cross Section

Considering a single projectile impinging on a single target particle, the cross section becomes a calculable quantity. The central ingredient is again the probability that the two particles interact. Its amplitude, the invariant amplitude $\mathcal{M}$, is calculable in a gauge theory, based on a gauge symmetry and thus renormalizable. One can thus compare theory and experiment, to the precision of both. This allows to test the theory, and to fix its parameters, like masses and coupling constants.

The calculation prescription of the cross section is given by Fermi's Golden Rule :

$$d\sigma = \frac{|\mathcal{M}|^2}{F} dQ$$

with the incident relative flux factor F for collinear beams ($\vec{v}_A \parallel \vec{v}_B$) :

$$F = |\vec{v}_A - \vec{v}_B| 2E_A 2E_B = 4((p_A p_B)^2 - m_A^2 m_B^2)^{1/2}$$

This factor is thus invariant under Lorentz transformations, just like the phase space factor dQ:

$$dQ = (2\pi)^4 \delta^{(4)}(p_C + p_D - p_A - p_B) \frac{d^3 p_C}{(2\pi)^3 2E_C} \frac{d^3 p_D}{(2\pi)^3 2E_D}$$

Decay Rate and Decay Width

When one considers a decay $(A \longrightarrow 1 + 2 + ... + n)$, i.e. a reaction without target, one obtains an analogous relation of the differential decay rate $d\Gamma$ towards the phase space elements $d^3p_1...d^3p_n$:

$$d\Gamma = \frac{1}{2E_A}|\mathcal{M}|^2(2\pi)^4\delta^{(4)}(p_A - p_1... - p_n)\frac{d^3p_1}{(2\pi)^3 2E_1}...\frac{d^3p_n}{(2\pi)^3 2E_n}$$

Take for example a two-particle decay $(A \longrightarrow 1 + 2)$, and integrate over the final state momenta. This produces the partial decay rate $\Gamma(A \longrightarrow 1 + 2)$ in the rest system of particle A:

$$\Gamma(A \rightarrow 1 + 2) = \frac{p_f}{32\pi^2 m_A^2}\int |\mathcal{M}|^2 \, d\Omega$$

with $p_f = |p_1| = |p_2|$. Summing over all possible final states, one obtains the total decay rate Γ_{tot} :

$$\Gamma_{tot} = \sum_{i,j,...} \Gamma(A \rightarrow i + j + ...) = -\frac{1}{N_A}\frac{dN_A}{dt}$$

Decay Rate and Decay Width

Since the left term of the equation is a constant, we obtain by integration the exponential decay law:

$$N_A(t) = N_A(0)e^{-\Gamma_{tot}t}$$

We recognize in Γ_{tot}^{-1} the lifetime τ. Heisenberg's uncertainty relation $\Delta t \cdot \Delta E \geq 1$, with $\Delta t \leq \tau$, produces a relation between Γ_{tot} and the energy uncertainty, $\Delta E = \Delta m$ at rest :

$$\Delta m \simeq \Gamma_{tot}$$

Consequently, the mass distribution, as measured by the invariant mass of the final state, is narrow for long lifetime particles, wide for short lifetimes. One thus also calls Γ_{tot} the decay width. The ratio of the partial and total width:

$$\frac{\Gamma(A \rightarrow 1 + 2)}{\Gamma_{tot}} = \frac{\text{partial width}}{\text{total width}}$$

is called the branching ratio. It gives the probability to find the final state $1 + 2$ among all decays of A.

Acceptance, Efficiency and Background

To determine the cross section, we must identify and count all events of a process, in its complete phase space, and without accepting reactions of another process. It is evident, that real experiments are never this perfect. We must correct for incomplete phase space coverage, detection efficiency and background.

The acceptance of the measurement is defined as the fraction of the phase space covered by the experimental set-up:

$$\epsilon_a = \frac{\int_{acc} \frac{d\sigma}{d\Omega} d\Omega}{\int_{4\pi} \frac{d\sigma}{d\Omega} d\Omega}$$

One can measure the cross section σ_a just inside the acceptance, or extrapolate the observed reaction rate to 4π acceptance by dividing by ϵ_a.

Acceptance, Efficiency and Background

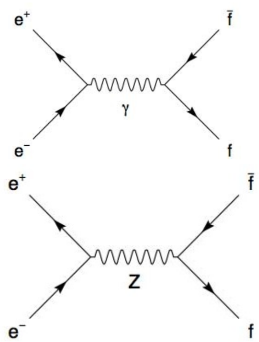
Even inside the geometrical acceptance, the efficiency ϵ to trigger and identify a signal event must be corrected for. In addition, a background N_b must be subtracted from the observed rate, if it is not negligible. In total, the cross section is thus given by:

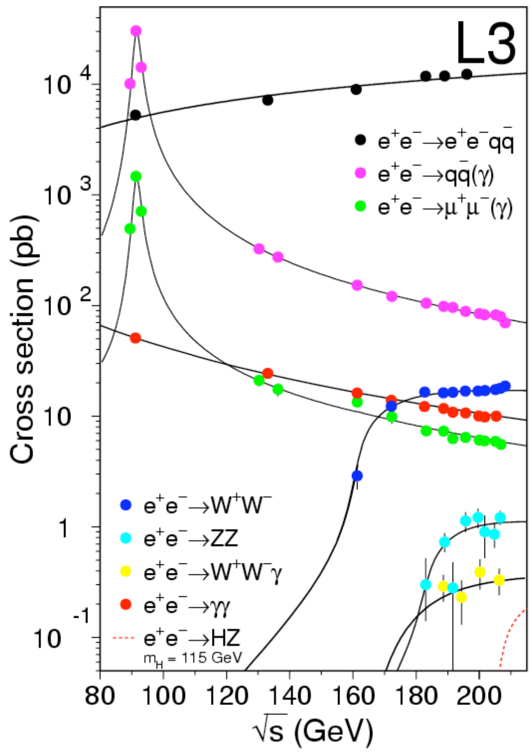
$$\sigma_{exp} = \frac{N_{exp} - N_b}{\epsilon_a \epsilon \, \mathcal{L}}$$

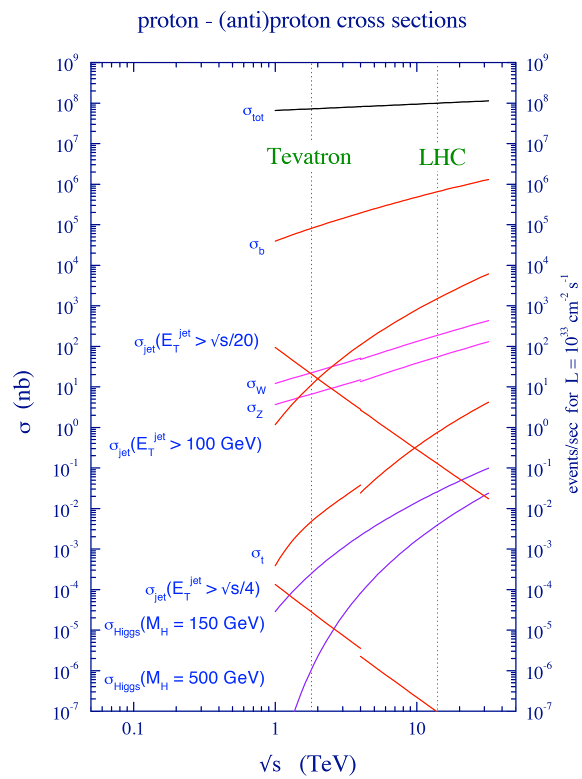
with the observed number of candidates N_{exp} and the corrections mentioned above.

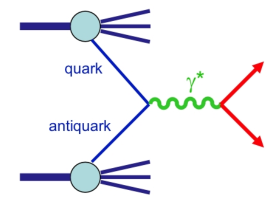
It is evident, that the inclusion of the corrections increases the measurement error. The additional error coming from the corrections is usually included in the systematic error of the measurement.

Lepton and Hadron Colliders









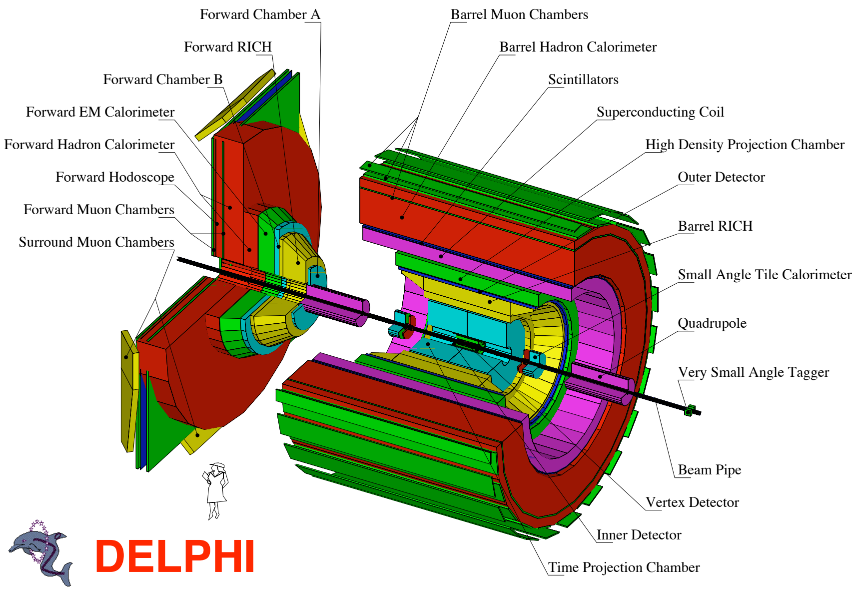
- Small cross sections
- Wide open trigger, exhaustive analysis, low background
- Point-like initial state, defined cms energy (100% up to radiative corrections)

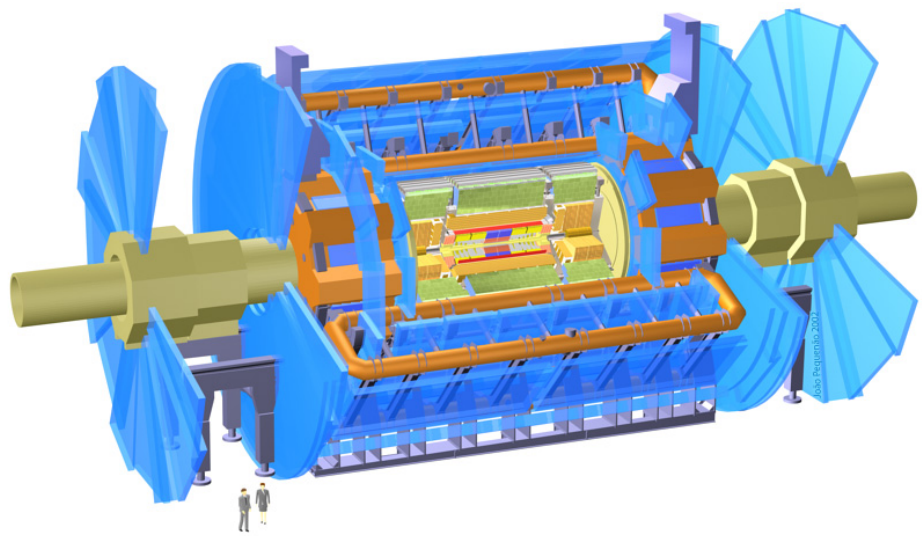
- Large total cross section, small hard scatter rate
- Selective trigger, semi-inclusive analysis, large background
- Complex initial state, wide range of cms energies (typically 10%)

Lepton and Hadron Collider Detectors

$\cos^2\theta$

$\eta = -\log\tan\frac{\theta}{2}$





short and fat detectors

long and fat detectors