Introduction:
Small Particles for Big Bang Experiments

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HASCO, Göttingen, 23 July 2018

Outline

1. Recipe for the universe
   - Matter
   - Interactions
   - Going beyond
2. Experimental tools in particle physics
   - Accelerators
   - Detectors
3. Data-analysis

1. Recipe for the universe
   - Matter
   - Interactions
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2. Experimental tools in particle physics
   - Accelerators
   - Detectors
3. Data-analysis

What is the universe made of?

As physicists, our job is to understand what the universe is made of and how it works.

All matter in the universe (including us) is made of a few **fundamental** (simple and structureless) building blocks...

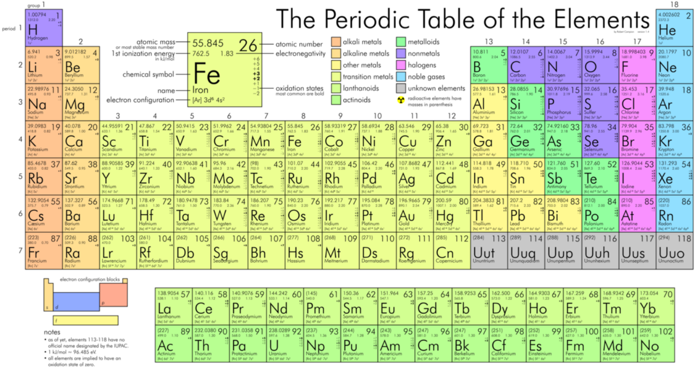
Which ones?

Leucippus and Democritus (2400 years ago):

Everything is composed of "atoms". Between atoms lies empty space. Atoms are eternal and indestructible.

The universe from a chemist's point of view

Classification of atoms based on their physical properties:



The Periodic Table of the Elements

atomic mass — or most stable mass number: 55.845
atomic number: 26
1st ionization energy in kJ/mol: 762.5
electronegativity: 1.83
chemical symbol: Fe
name: Iron
electron configuration: [Ar] $3d^6 4s^2$
oxidation states — most common are bold

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797
11 Na Sodium 22.98976	12 Mg Magnesium 24.3050											13 Al Aluminium 26.98153	14 Si Silicon 28.0855	15 P Phosphorus 30.97696	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9962	25 Mn Manganese 54.93804	26 Fe Iron 55.845	27 Co Cobalt 58.93319	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.441	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.9044	54 Xe Xenon 131.293
55 Cs Cæsium 132.9054	56 Ba Barium 137.327	71 Lu Lutetium 174.9668	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9478	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.9804	84 Po Polonium (210)	85 At Astatine (210)	86 Rn Radon (220)
87 Fr Francium (223)	88 Ra Radium (226)	103 Lr Lawrencium (262)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Cn Copernicium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

57 La Lanthanum 138.9054	58 Ce Cerium 140.116	59 Pr Praseodymium 140.9076	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.9253	66 Dy Dysprosium 162.500	67 Ho Holmium 164.9303	68 Er Erbium 167.259	69 Tm Thulium 168.9342	70 Yb Ytterbium 173.054
89 Ac Actinium (227)	90 Th Thorium 232.0380	91 Pa Protactinium 231.0358	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)

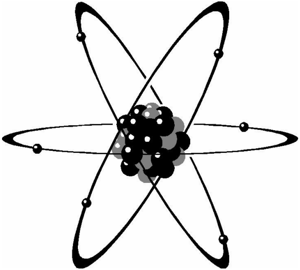
- alkali metals
- alkaline metals
- other metals
- transition metals
- lanthanoids
- actinoids
- metalloids
- nonmetals
- halogens
- noble gases
- unknown elements
- radioactive elements have masses in parentheses

electron configuration blocks

notes
- as of yet, elements 113-118 have no official name designated by the IUPAC.
- 1 kJ/mol ≈ 96.485 eV.
- all elements are implied to have an oxidation state of zero.

Source: Wikimedia Commons

The universe from a physicist's point of view (in the 1930s)



Atoms are not fundamental, since they contain:

- a cloud of electrons,
- a nucleus containing p protons and n neutrons,
- 99.999999999999% of empty space!

But this is not enough to explain the energy spectrum of the beta-decays:

$$N(n,p) \rightarrow N'(n-1,p+1) + e^{-}$$

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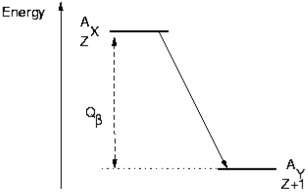
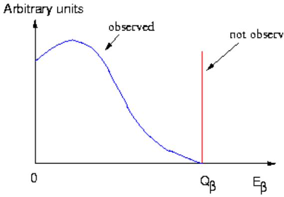
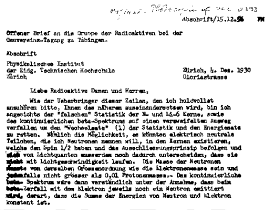




If beta-decays were a 2-body decay process, e^- would carry away the total CONSTANT available energy Q_β.

- 1930: Pauli suggested a 3-body decay to account for the observed energy spectrum.
- He invented *a neutral particle at least as light as the electron and difficult to detect:* the neutrino!



Original: Photocopie of PLC 0393
Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

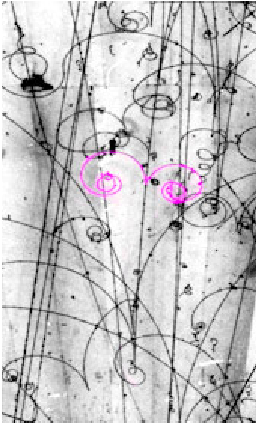
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

The universe from a physicist's point of view (in the 1930s)



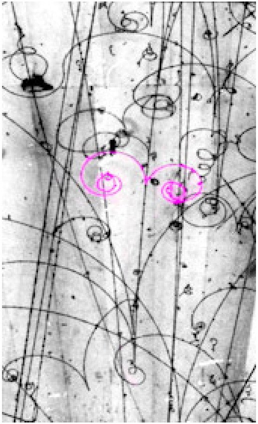
Source: www.particleadventure.org

For every matter particle, there is an anti-particle with the same quantum numbers but with an opposite charge (discovered in 1932).

When a matter particle and anti-matter particle meet, they annihilate into pure energy!

If anti-matter and matter are "exactly equal but opposite", why is there so much more matter in the universe than anti-matter?

The universe from a physicist's point of view (in the 1930s)



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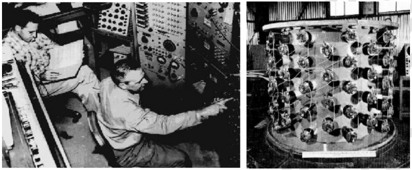
More about neutrinos: discovery

Neutrino detection at the Savannah River experiment through inverse beta-decay: $\bar{\nu}_e + p \to e^+ + n$.

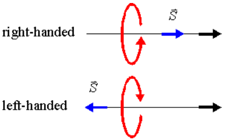
- the positron rapidly annihilates with an electron in the detector, producing 2 gamma rays (first light flash).
- the neutron wanders until it is captured by a nucleus, with energy release (second light flash).
- very rare process, so one needs
  - a large antineutrino flux (nuclear fission reactor),
  - a large detector (400 l of water + cadnium chloride).



The neutrino discovery was announced in June 1956.

More about neutrinos: parity violation

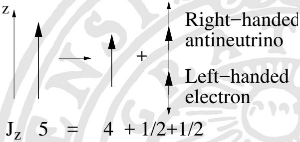
Matter particles carry a spin 1/2 aligned with the momentum (right-handed) or in the opposite direction (left-handed).



1956 → Mrs Wu's beta-decay experiment where the spins of ^{60}Co nuclei were aligned along an external B-field:

$$^{60}\mathrm{Co}_{27} \rightarrow {}^{60}\mathrm{Ni}_{28} + e^- + \bar{\nu}_e$$

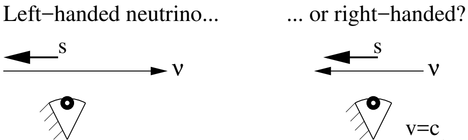
Electrons are only emitted in the direction opposite to the nuclear spins: maximal parity violation!



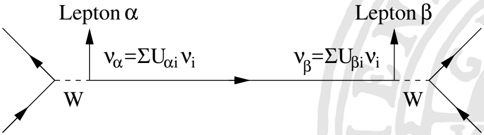
⇒ Two-component neutrino: $\bar{\nu}$ is always right-handed and ν is always left-handed.

More about neutrinos: absence of mass?

If there is no reference frame where ν is right-handed, it must travel at the speed of light and thus be massless!



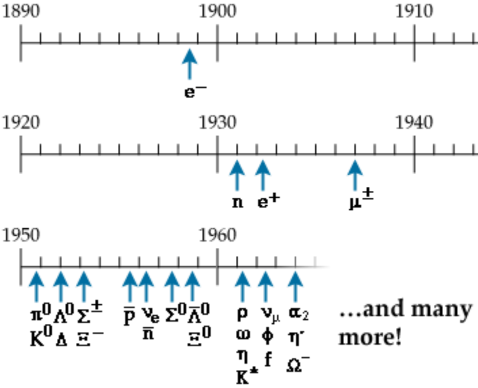
However, neutrinos were found to oscillate. This is only possible with non-zero neutrino masses!



$$P(\nu_\alpha \to \nu_\beta) = |<\nu_\alpha|\nu_\beta(t)>|^2 = \left|\cos\theta \sin\theta \left(1 - e^{i\frac{\Delta m^2 t}{2p_\nu}}\right)\right|^2$$

The universe from a physicist's point of view (in the 1960s)

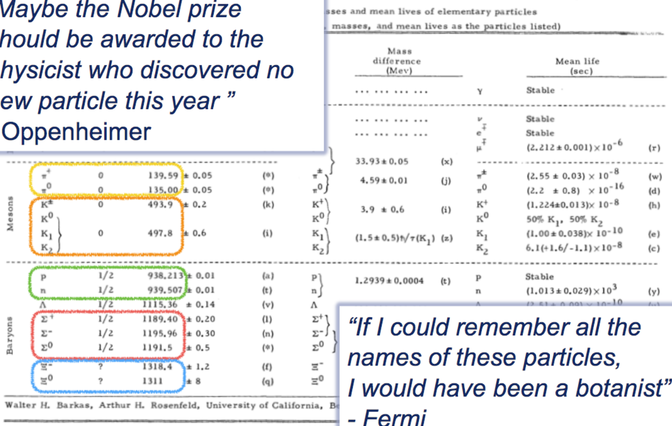
Between 1947 and the early 1960s, a plethora of new particles were discovered. Are they elementary objects?



Source: www.particleadventure.org

The universe from a physicist’s point of view (in the 1960s)

> *“Maybe the Nobel prize should be awarded to the physicist who discovered no new particle this year ”*
> - Oppenheimer



sses and mean lives of elementary particles
, masses, and mean lives as the particles listed)

							Mass difference (Mev)			Mean life (sec)	
							... ...		γ	Stable	
							... ...		ν	Stable	
							... ...		$e^{\mp}$	Stable	
									$\mu^{\mp}$	$(2.212 \pm 0.001) \times 10^{-6}$	(r)
							33.93 ± 0.05	(x)			
Mesons	$\pi^{\pm}$	0	139.59	± 0.05	(*)	$\pi^{\pm}$	4.59 ± 0.01	(j)	$\pi^{\pm}$	$(2.55 \pm 0.03) \times 10^{-8}$	(w)
	π^0	0	135.00	± 0.05	(*)	π^0			π^0	$(2.2 \pm 0.8) \times 10^{-16}$	(d)
	$K^{\pm}$	0	493.9	± 0.2	(k)	K^+	3.9 ± 0.6	(i)	K^+	$(1.224 \pm 0.013) \times 10^{-8}$	(h)
	K^0					K^0			K^0	50% K_1, 50% K_2	
	K_1	0	497.8	± 0.6	(i)	K_1	$(1.5 \pm 0.5)\hbar/\tau(K_1)$	(z)	K_1	$(1.00 \pm 0.038) \times 10^{-10}$	(e)
	K_2					K_2			K_2	$6.1(+1.6/-1.1) \times 10^{-8}$	(c)
Baryons	p	1/2	938.213	± 0.01	(a)	p	1.2939 ± 0.0004	(t)	p	Stable	
	n	1/2	939.507	± 0.01	(t)	n			n	$(1.013 \pm 0.029) \times 10^3$	(y)
	Λ	1/2	1115.36	± 0.14	(v)	Λ			Λ	[illegible]	[illegible]
	Σ^+	1/2	1189.40	± 0.20	(l)	Σ^+					
	Σ^-	1/2	1195.96	± 0.30	(n)	Σ^-					
	Σ^0	1/2	1191.5	± 0.5	(*)	Σ^0					
	Ξ^-	?	1318.4	± 1.2	(f)	Ξ^-					
	Ξ^0	?	1311	± 8	(q)	Ξ^0					

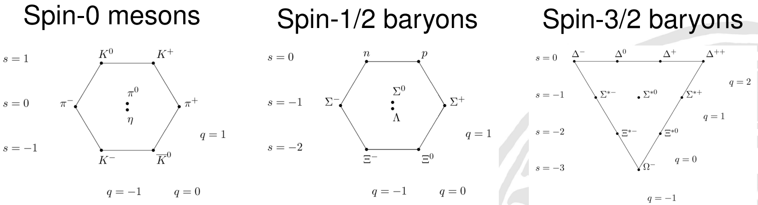
Walter H. Barkas, Arthur H. Rosenfeld, University of California, Be

> *“If I could remember all the names of these particles,*
> *I would have been a botanist”*
> *- Fermi*

Source: Oleg Brandt’s introduction lecture, HASCO 2016

The universe from a physicist’s point of view (in the 1960s)

Looking for patterns, Gell-Mann and Ne´eman introduced a new quantum number (strangeness *s*) to organize these newly-discovered particles into two octets and a decuplet.



Spin-0 mesons

Spin-1/2 baryons

Spin-3/2 baryons

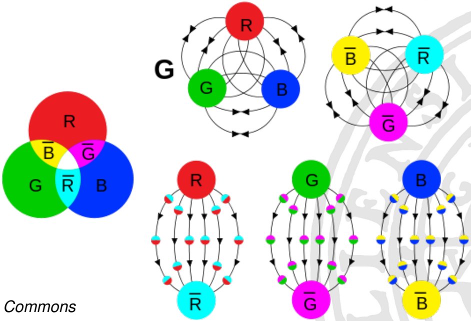
Source: Wikimedia Commons

Ω^- was predicted in 1962 and discovered in 1964 at the AGS in Brookhaven.

The universe from a physicist's point of view (in the 1960s)

Quark model (Gell-Mann and Zweig, 1964): hadrons are not elementary objects, but bound states of quarks and anti-quarks (meson = $q\bar{q}$, baryon = qqq).

Problem: $\Delta^{++} = uuu$ violates Pauli's exclusion principle.
Solution: Color charge!



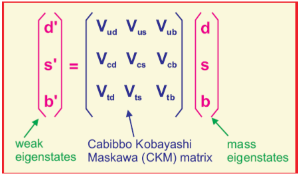
Source: Wikimedia Commons

The universe from a physicist's point of view (in the 1960s)

Problem: $\frac{\Gamma(K^- \to \mu^- \nu_\mu)}{\Gamma(\pi^- \to \mu^- \nu_\mu)} \simeq 0.05$ $[K = us,\ \pi = ud]$
→ Non-universality of weak interactions?

Solution: the quark states mix: the object that couples to u is $d' = \cos\theta_c d + \sin\theta_c s$ (Cabibbo, 1963).

Observing that CP-violation can not be explained with only four quarks, Kobayashi and Maskawa proposed three generations of quarks:



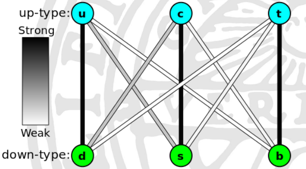
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates

Cabibbo Kobayashi Maskawa (CKM) matrix

mass eigenstates

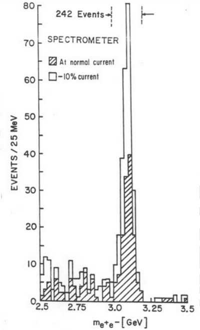
Source: Wikimedia Commons



The universe from a physicist's point of view (1970s–2000s)

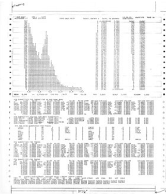
The *c* quark was postulated in the early 1970s to account for the smallness of BR($K_L^0 \to \mu\mu$).

The $c\bar{c}$ bound state was simultaneously discovered at Brookhaven (as J) and at SLAC (as "psi") in 1974. It was named the J/psi meson (3.1 GeV).



Phys. Rev. Lett. 33, 1404

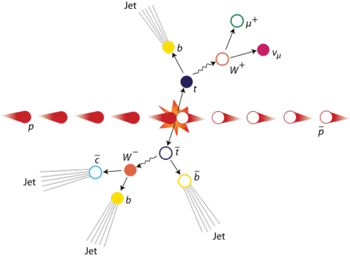
Source: history.fnal.gov



In 1977, the observation of the Υ meson (9.5 GeV) at Fermilab's E288 experiment confirmed the existence of the *b* quark.

The universe from a physicist's point of view (1970s–2000s)

The top quark decays before hadronizing: $t \rightarrow bW$.
It was discovered at Fermilab's Tevatron collider ($p\bar{p}$, 1.8 TeV) in 1995. With a mass of 172.5 GeV, it is the heaviest fundamental particle known today.



Source: Wikimedia Commons

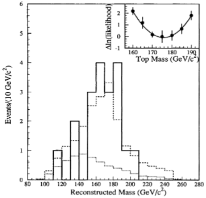


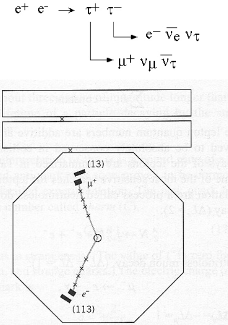
FIG. 3. Reconstructed mass distribution for the b-tagged $W+\geq 4$-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for $M_{\mathrm{top}} = 175\ \mathrm{GeV}/c^2$ (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

Phys. Rev. Lett. 74, 2626

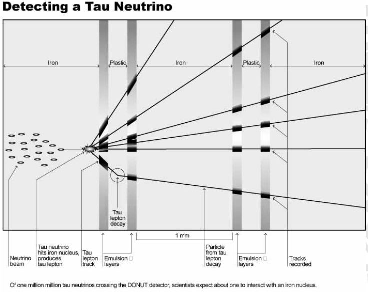
The universe from a physicist's point of view (1970s–2000s)

Discoveries of the third-generation leptons

The τ-lepton (1.78 GeV) was discovered at SLAC's e^+e^- SPEAR collider (1974-1977).



The neutrino ν_τ was discovered at Fermilab's DONUT experiment in 2000.

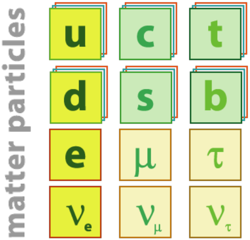


Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

Source: www.fnal.gov

The universe from a physicist’s point of view (nowadays)

All matter consists of 3 families of fermions, divided into quarks and leptons.



Six quarks:

- fractional electric charge: $-\frac{1}{3}$ for d, s, b and $+\frac{2}{3}$ for u, c, t.
- color charge (blue, green, red).

As only colorless objects can be observed, quarks stick together!

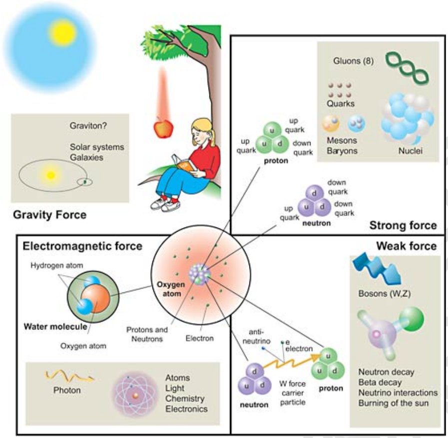
Six leptons:

- three are charged: e^-, μ^-, τ^-.
- three neutrinos: very light, pass through everything and oscillate.

Stable matter (the world around us) mostly has fermions from the first family, the lighest one.

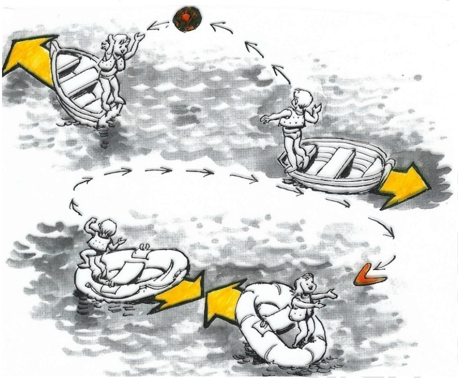
What holds matter together?

The universe exists because fundamental particles interact. The four fundamental interactions include attractive/repulsive forces, decays and annihilations.



What holds matter together?

Each of the four fundamental interactions has its own force carrier (boson).



Such drawings are pedagogical BUT they do not represent the reality of particle interactions...

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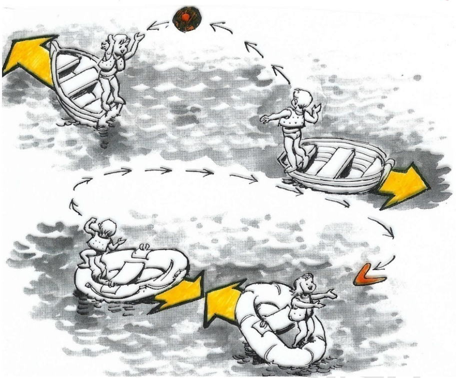

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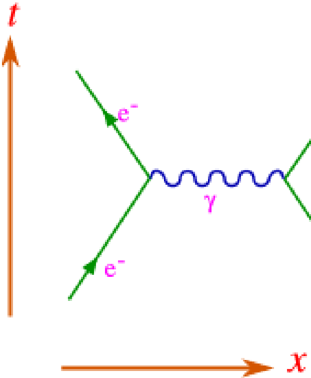

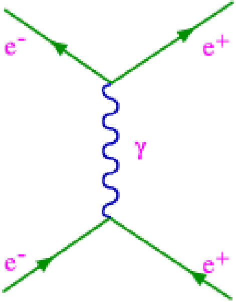

Feynman diagrams are pedagogical AND they do represent the reality of particle interactions...

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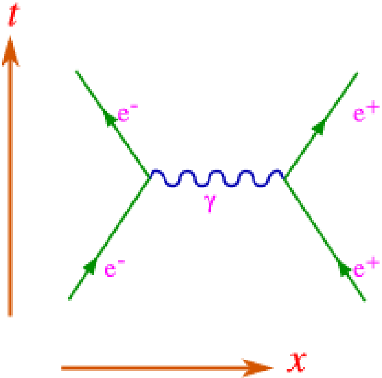
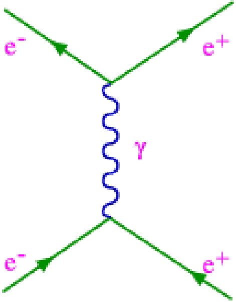


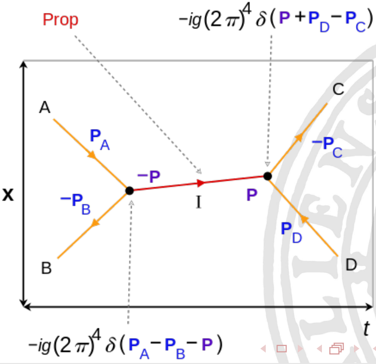


Really?!? Did Richard Feynman win a Nobel prize for inventing funny drawings?!?

Feynman diagrams

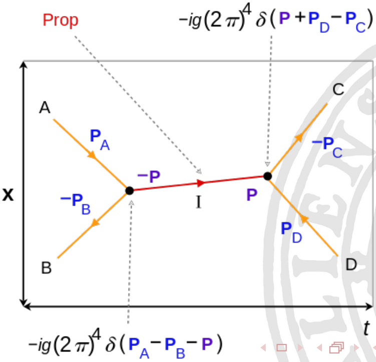
Complicated integrals over a large number of variables must be calculated to compute probability amplitudes in quantum field theory (and thereby the cross sections of processes involving subatomic particles).

Feynman diagrams are graphical representations of such integrals.

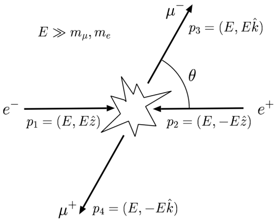


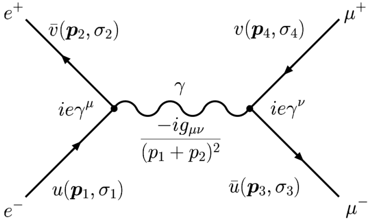
Feynman diagrams

- Incoming lines: from the past to a vertex (initial state);
- Outgoing lines: from a vertex to the future (final state);
- Anti-particle = a line that travels back in time;
- Two vertices are connected by a wavy (straight) internal line representing a bosonic (fermionic) propagator;
- Four-momentum conservation at each vertex (δ function).



Feynman diagrams





$$-i\mathcal{M} = [\bar{u}(\boldsymbol{p}_3, \sigma_3)(ie\gamma^\nu)v(\boldsymbol{p}_4, \sigma_4)]\, \frac{-ig_{\mu\nu}}{(p_1+p_2)^2}\, [\bar{v}(\boldsymbol{p}_2, \sigma_2)(ie\gamma^\mu)u(\boldsymbol{p}_1, \sigma_1)]$$

$$\overline{|\mathcal{M}|^2} = \frac{e^4}{4(p_1+p_2)^4} \sum_{\sigma_{1,2,3,4}} [\bar{v}_4\gamma_\mu u_3][\bar{u}_1\gamma^\mu v_2][\bar{u}_3\gamma_\nu v_4][\bar{v}_2\gamma^\nu u_1]$$

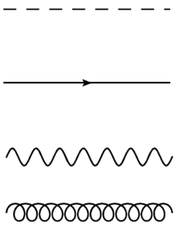
$$\overline{|\mathcal{M}|^2} = \frac{8e^4}{(p_1+p_2)^4}[(p_1 \cdot p_3)(p_2 \cdot p_4) + (p_1 \cdot p_4)(p_2 \cdot p_3)]$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16E^2}(1 + \cos^2\theta)$$

Source: arxiv.org/pdf/1602.04182.pdf

Feynman diagrams

Basic ingredients:



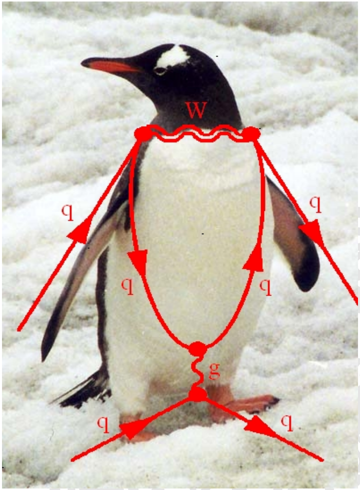
Dashed line:
scalar boson (e.g. Higgs)

Solid line:
fermion spinor
(lepton, quark)

Wavy line:
W, Z boson, photon

Curly line:
gluon

Source: Elin Bergeås Kuutmann, HASCO 2015



Source: Wikimedia Commons

John Ellis (CERN theorist):

"We made a bet that if I lost I had to put the word penguin into my next paper... visit some friends living in Meyrin where I smoked some illegal substance... had a sudden flash that the famous diagrams look like penguins."

Feynman diagrams

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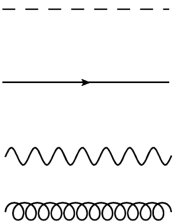

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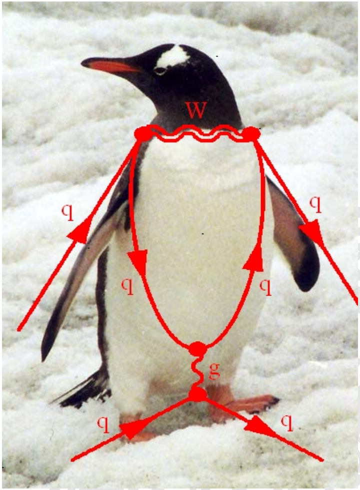

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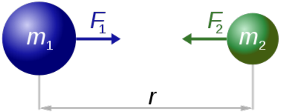
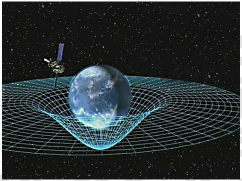
Gravity

Gravity was invented by Newton in 1687. Most modern (non-relativistic) gravitational calculations still make use of Newton's theory.



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

In Einstein's general relativity, the effects of gravitation are associated to space-time curvature instead of a force.



Source: Wikimedia Commons

In the sub-atomic world:

- the effects of gravity are extremely tiny;
- the graviton has never been observed;
- we don't know how to integrate gravity in the mathematics of the quantum theory of the Standard Model.

Strong force

The strong force holds quarks together to form hadrons. The force carrier between color-charged particles is the gluon.

Source: www.particleadventure.org

When two quarks are close to each other, they exchange gluons, creating a very strong color force field that binds them together.

There are eight types of colored gluons.

Quarks cannot exist individually: the color force increases as they are pulled apart, so it is energetically cheaper to create a $q\bar{q}$ pair than to pull apart two quarks.

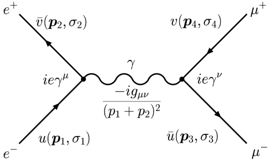
Electromagnetic force

The electromagnetic force is responsible for practically all phenomena in daily life above the nuclear scale (chemical reactions, contact forces, etc), except gravity.

Originally, electricity and magnetism were considered to be two separate forces. They were unified by Maxwell in 1873.

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

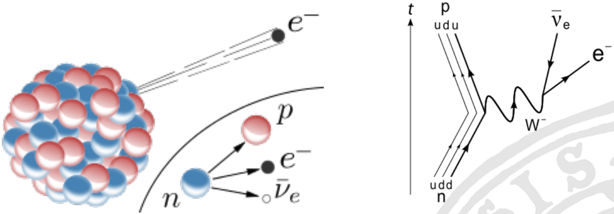
Maxwell's equations have been superseded by quantum electrodynamics (QED).



The electromagnetic field mediates the interaction between the charged spin-1/2 fields. The force carrier is the spin-1 massless photon.

Weak force

The weak force is responsible for radio-active decays. It is the only interaction that allows flavor-changing.



Source: Wikimedia Commons

The force carriers are the $W^{\pm}$ and Z^0 bosons, discovered in 1983, with masses of 80.4 and 91.2 GeV, respectively.
$\Longrightarrow$ very short range!

Electroweak theory

- The massless carrier of the electromagnetic interaction connects two lines of constant electric charge Q.
- The massive carriers of the weak interaction connects two lines of constant weak isospin T_3.

The electroweak interaction is the unified description of the electromagnetic and weak interactions (by Glashow, Salam, Weinberg in the 1960s).

New quantum number = weak hyper-charge: $Y_W = 2(Q - T_3)$.

Four spin-1 gauge bosons in the electroweak interaction (two charged, two neutral):

- Three bosons of weak isospin (W_1, W_2, W_3);
- One boson of weak hyper-charge (B).

PROBLEM: they must all be massless to fulfill some conservation laws!

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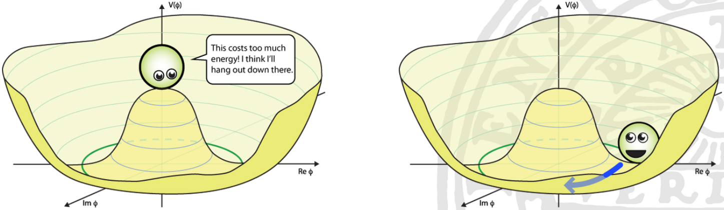
Electroweak theory

$W^{\pm}$, Z^0 and γ are produced via electroweak symmetry breaking, which occurs through the Brout-Englert-Higgs mechanism.

The Higgs field (with weak hyper-charge 1) permeates all space. It has a potential energy function in the shape of a Mexican hat, with a non-zero vacuum expectation value. When choosing the lowest-energy point, the symmetry gets broken.



Source: www.quora.com

Electroweak theory

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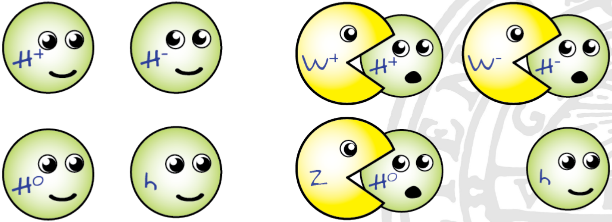
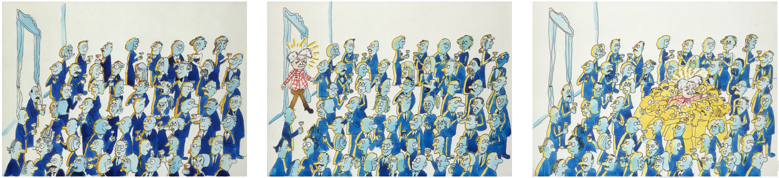
The Higgs field is a scalar complex doublet: spin 0 and four degrees of freedom. After symmetry breaking, three mix with the electroweak bosons and are observable as massive $W^{\pm}$ and Z^0 bosons. The remaining one is the Higgs boson.



Source: www.quantumdiaries.com

What about fermion masses?

Mass is not an intrinsic property of the fermions! It results from its (Yukawa) coupling to the Higgs field.



How to visualize the Higgs boson?

The Higgs boson itself can also couple to the Higgs field: $h \to hh$ decays are possible (but not observed yet).

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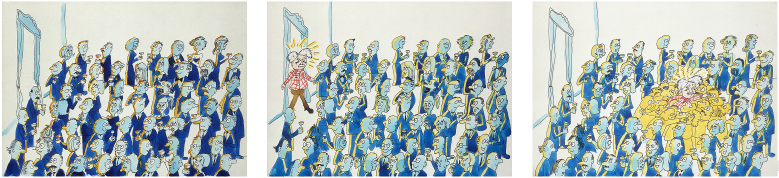

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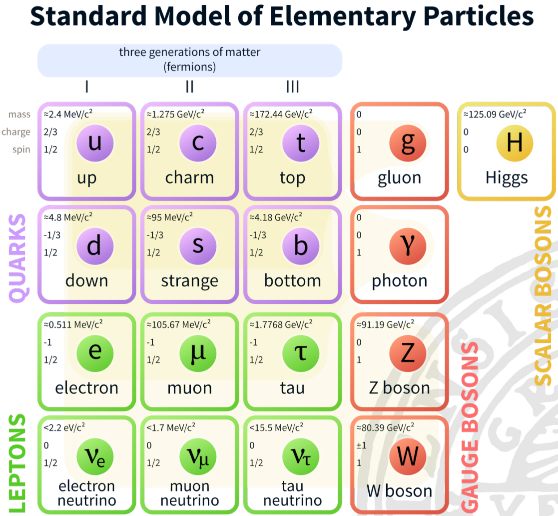
The Standard Model: summary



Standard Model of Elementary Particles

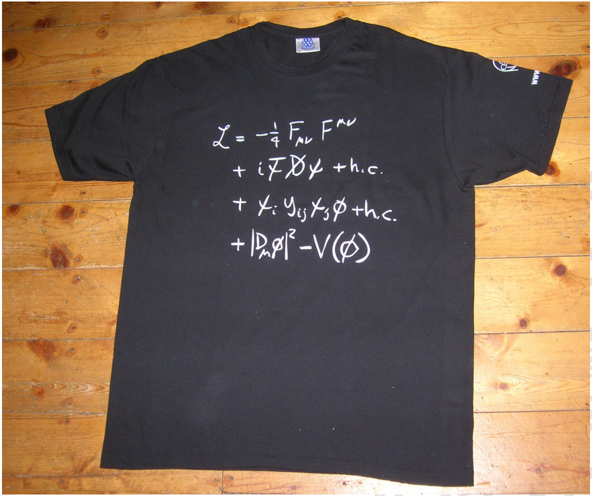
three generations of matter (fermions)

		I	II	III		
QUARKS	mass charge spin	≈2.4 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈172.44 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c² 0 0 H Higgs
		≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	**SCALAR BOSONS**
LEPTONS		≈0.511 MeV/c² -1 1/2 e electron	≈105.67 MeV/c² -1 1/2 μ muon	≈1.7768 GeV/c² -1 1/2 τ tau	≈91.19 GeV/c² 0 1 Z Z boson	**GAUGE BOSONS**
		<2.2 eV/c² 0 1/2 ν_e electron neutrino	<1.7 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c² ±1 1 W W boson	

Source: Wikimedia Commons

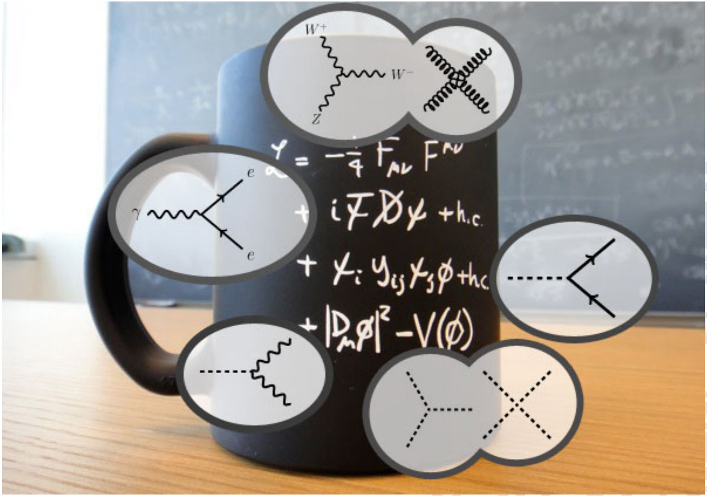
The Standard Model: summary

You can print the whole Standard Model on a tee-shirt!



The Standard Model: summary

Or even on a mug...



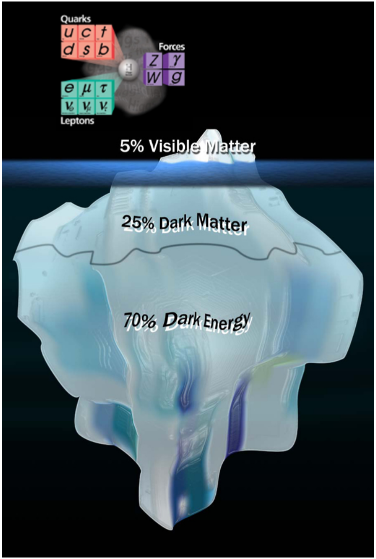
The Standard Model: summary

$$\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \\
\frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \\
\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \\
\bar{d}_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)] + \\
\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(\frac{4}{3}s_w^2 - \\
1 - \gamma^5)u_j^\lambda) + (\bar{d}_j^\lambda\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d_j^\lambda)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + \\
(\bar{u}_j^\lambda\gamma^\mu(1 + \gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
\gamma^5)u_j^\lambda)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \\
\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1 - \gamma^5)d_j^\kappa) + \\
m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1 + \gamma^5)d_j^\kappa] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1 + \gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C^\dagger_{\lambda\kappa}(1 - \\
\gamma^5)u_j^\kappa] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda) - \\
\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5 d_j^\lambda) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}$$

Details about Standard Model physics:

- Electroweak physics: John Kenneth Anders' lectures, on 23-24/07.
- QCD physics: Caterina Doglioni's lectures, on 25/07.
- Top physics: Sandra Leone's lecture, on 25/07.
- Higgs physics: Paolo Francavilla's lecture, on 24/07.

Limitations of the Standard Model

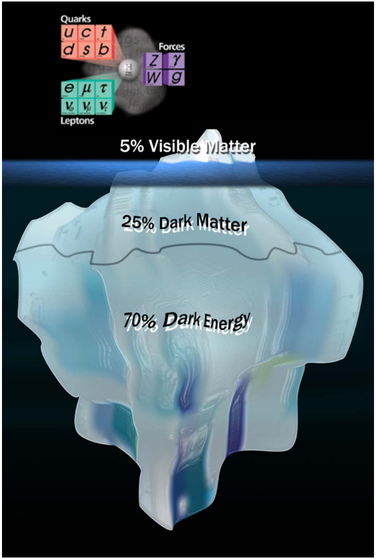


The Standard Model only describes a small fraction of the universe.

- What is the dark matter made of?
- What is dark energy (responsible for the accelerated expansion of the universe)?

And even for the 5% of the universe accounted for by the Standard Model, there are several unanswered questions...

Limitations of the Standard Model



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Limitations of the Standard Model

- Hierarchy problem: the Standard Model explains neither the huge difference in the strength of the fundamental forces, nor the wide range in mass for the elementary particles.
- Why is the Higgs boson mass stable, while every loop of known particles tends to make it diverge?
- Where is all the anti-matter? Why does it behave differently from matter?
- How do neutrinos get their (tiny) mass?
- Are there extra-dimensions and can they explain why gravity is so weak?
- Are there more than one Higgs boson?

More on Beyond-the-Standard-Model (BSM) physics in Federico Meloni and Gerald Eigen's lectures, 24-25/07.

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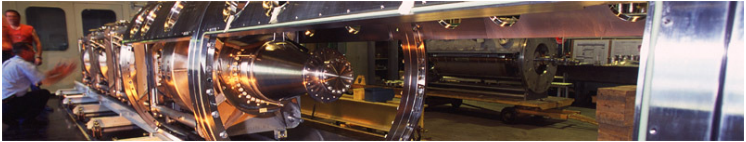
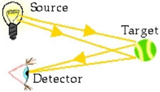
1. Recipe for the universe
   - Matter
   - Interactions
   - Going beyond
2. Experimental tools in particle physics
   - Accelerators
   - Detectors
3. Data-analysis

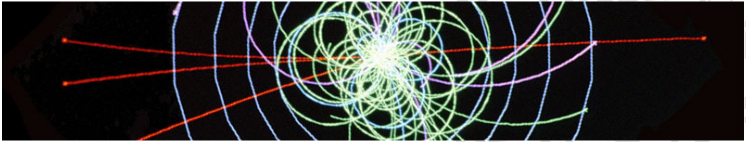
Accelerators and detectors



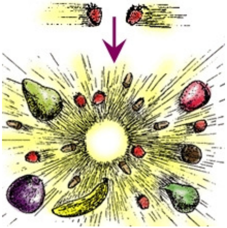
The instruments used to explore the Standard Model and physics beyond it are particle accelerators and detectors.



- Accelerators boost beams of particles to high energy before they collide with each other, or with stationary targets.
- Detectors observe and record the results of these collisions.



How does an accelerator work?



$E = mc^2$: mass is a form of energy!

An accelerator gives a huge energy to light particles and collides them... The available energy is turned into heavier particles.

- Large electric fields accelerate particles.
- Large magnetic fields keep the particles on their path (bending magnets) and focus the beams (quadrupole magnets).

Center-of-mass energy

Consider two beams of particles with the same mass m and with four-vectors $(E_1, \vec{p_1})$ and $(E_2, \vec{p_2})$.

The center-of-mass energy E_{cm} is:

$$E_{cm} = \sqrt{(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2}$$

For a fixed target experiment, $\vec{p_2} = \vec{0}$ and $E_2 = m$, hence:

$$E_{cm} = \sqrt{2m^2 + 2mE_1}.$$

For a collider, $\vec{p_2} = -\vec{p_1}$, hence:

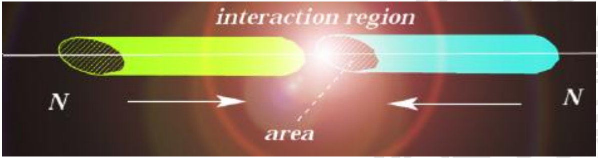
$$E_{cm} = E_1 + E_2.$$

Luminosity at a collider

Given a cross section σ_p for a process, the number of events that can be produced in a detector per second is:

$$\frac{dN}{dt} = \sigma_p \times \mathcal{L}, \text{ with } \mathcal{L} = \text{luminosity.}$$

$\mathcal{L}$ measures the number of collisions per cm^2 and per second. Remember that σ_p can be expressed in cm^2 (1 barn = 10^{-24} cm^2).



Luminosity at a collider

A beam consists of n_b bunches with N particles, spaced by Δt, having a length σ_z and a transverse area $\sigma_x \sigma_y$.

Assumptions:

- Gaussian bunch charge distributions in all directions:

$$\rho_u \propto \frac{1}{\sigma_u \sqrt{2\pi}} \exp\left(-\frac{u^2}{2\sigma_u^2}\right), \quad u = x, y, z$$

- Uncorrelated densities in all planes,
- Same beam sizes (or at least the same $\sigma_x \sigma_y$) for both beams.

Luminosity at a collider

In the simplest case, the luminosity is $\mathcal{L} = \dfrac{N_1 N_2 f}{4\pi\sigma_x\sigma_y}$ where $f = 1/\Delta_t$ is the bunch frequency.

However, one needs to take into account effects such as a crossing angle, beam offsets, beam-beam interactions, etc. They translate into a form factor F, so that:

$$\mathcal{L} = F \times \frac{N_1 N_2 f}{4\pi\sigma_x\sigma_y}.$$

Integrated luminosity and total number of events over a data-taking period:

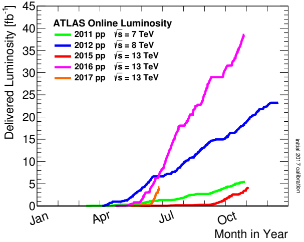
$$\mathcal{L}_{\mathrm{int}} = \int \mathcal{L}(t)dt.$$

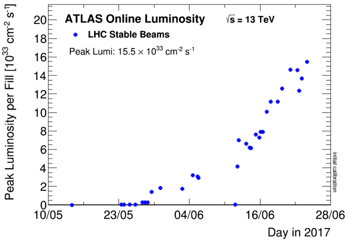
$$N_{tot} = \sigma_p \times \mathcal{L}_{\mathrm{int}}.$$

Note that $\mathcal{L}_{\mathrm{int}}$ is often expressed in fb^{-1}.

Luminosity at a collider

Integrated and peak luminosity plots at the LHC:



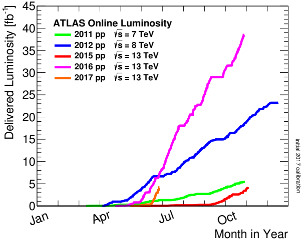


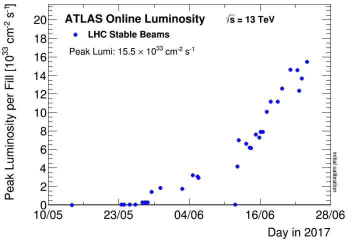
The LHC design luminosity at a center-of-mass energy of 14 TeV is 10^{34} cm^{-2}.s^{-1}. It is obtained by filling the machine with 2808 bunches of 115 billion protons, spaced by 25 ns. Due to the crossing angle at the interaction point, a luminosity reduction factor of 85% is expected. Assume Gaussian round beams, what is their rms transverse size when colliding?

Answer: $\sigma_x = \sigma_y = 0.015$ mm!!

Luminosity at a collider

Integrated and peak luminosity plots at the LHC:





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Answer: $\sigma_x = \sigma_y = 0.015$ mm!!

Basic notions of transverse beam dynamics

In the plane transverse to the beam direction, particles have slightly different *positions* and *directions* than those of the design orbit. Particles in a beam have a *bounded oscillatory motion* around the design orbit.

In the absence of an accelerating $\vec{E}$, the motion of a charged particle obeys:

$$\frac{d\vec{p}}{dt} = q(\vec{v} \times \vec{B})$$

Ideal circular orbit ($p = p_0$):

If ρ is the curvature radius, $\frac{\gamma m v_0^2}{\rho} = e v_0 B$.

$B\rho$ [T.m] $= 3.3356 \times p_0$ [GeV$/c$] is the magnetic rigidity.

Basic notions of transverse beam dynamics

- s: coordinate associated to the design orbit;
- x, y: (small) coordinates in the transverse plane w.r.t the design orbit, with $x', y', \delta = \Delta p/p_0 \ll 1$:

$$B_y(x,y,s) = B_y(0,0,s) + x\left(\frac{\partial B_y}{\partial x}\right)_0$$

$$B_x(x,y,s) = B_x(0,0,s) + y\left(\frac{\partial B_x}{\partial y}\right)_0$$

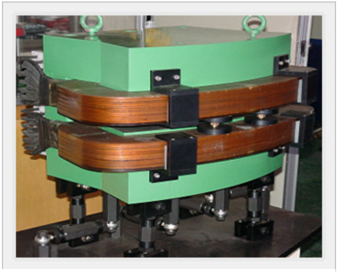
- the design orbit lies in one plane: magnets are used for bending the beam in the horizontal direction only.

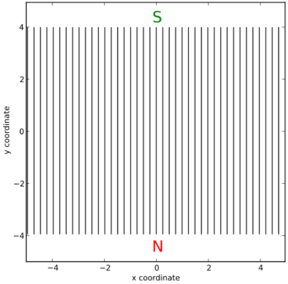
$$\frac{d^2x}{ds^2} + \left(\frac{1}{\rho(s)^2} - k(s)\right)x = \frac{\delta}{\rho(s)} \quad \& \quad \frac{d^2y}{ds^2} + k(s)y = 0,$$

$$\text{where } k = \frac{e}{p_0}\left(\frac{\partial B_y}{\partial x}\right)_0 = \frac{e}{p_0}\left(\frac{\partial B_x}{\partial y}\right)_0.$$

The knowledge of ρ and k along the lattice allows to solve the equations of motion.

Basic notions of transverse beam dynamics

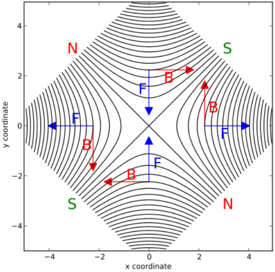




For the design orbit:
$B\rho = 3.3356 \times p_0$.

Particles with $\delta \neq 0$ feel the same field. As a result, they have different trajectories.

Basic notions of transverse beam dynamics



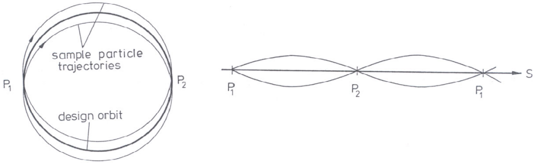
There is no deflecting field on the axis. *B* increases linearly with the distances from the axis.

The gradient of a quadrupole is:

$$k = \frac{e}{p_0}\left(\frac{\partial B_y}{\partial x}\right)_0 = \frac{e}{p_0}\left(\frac{\partial B_x}{\partial y}\right)_0$$

A quadrupole that focuses the beam in the horizontal direction is at the same time defocusing in the vertical direction ⇒ use of e.g. FODO cells to focus in both directions!

Basic notions of transverse beam dynamics



If an individual particle slightly deviates from the design orbit, the magnetic fields around a machine will provide restoring forces to bring it back: betatron oscillations!

Considering only on-momentum particles ($\delta = 0$) and with $u = x$ or y, a solution of $u'' + K(s)u = 0$ is:

$$u(s) = A_0\sqrt{\beta(s)}\cos(\mu(s) - \varphi_0)$$

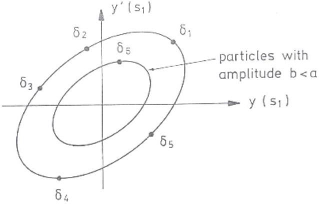
Other useful variables:

$$\mu(s) = \int_0^s \frac{d\sigma}{\beta(\sigma)} \qquad \alpha(s) = -\frac{1}{2}\frac{d\beta}{ds} \qquad \gamma(s) = \frac{1 + \alpha(s)^2}{\beta(s)}$$

Basic notions of transverse beam dynamics

When considering a family of trajectories with the same amplitude A_0 but different phases φ, one gets:

$$\Longrightarrow \gamma u^2 + 2\alpha u u' + \beta u'^2 = A_0^2 \text{ (Courant-Snyder invariant)}$$

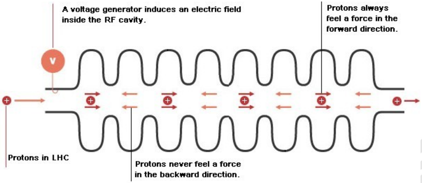


Particle trajectories with the same amplitude A_0 are found along a phase ellipse with an area πA_0^2 in the (u, u') plane.

- The area of the ellipse enclosing the whole beam in the (u, u') phase space is $\pi\varepsilon$: ε is the emittance.
- If there is no acceleration, phase ellipses may change their shape and orientation as the beam travels along the accelerator... but not their area!

Basic notions of longitudinal beam dynamics

In order to accelerate particles, longitudinal electric fields are used. The accelerating field is not constant, instead Radio-Frequency (RF) cavities are used.



In a circular accelerator, particles follow a closed orbit and are accelerated each time they pass in a RF cavity.

$\Rightarrow$ The nominal trajectory is kept at a constant radius by means of a magnetic field variation (and a RF frequency variation to follow the energy increase).

$\Rightarrow$ The revolution period must be an integer times the RF period: $T_{\rm rev} = hT_{\rm RF}$ or $\omega_{\rm rev} = \omega_{\rm RF}/h$.

Basic notions of longitudinal beam dynamics

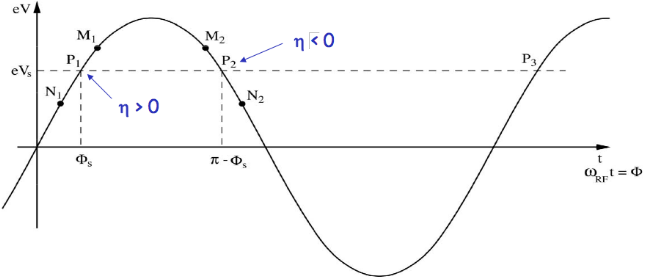
When the beam energy increases, there is simultaneous increasing of the velocity v and of the trajectory radius, affecting $\omega_{\text{rev}} = 2\pi v/C$ in opposite ways!

$$\frac{d\omega}{\omega} = \frac{d\beta}{\beta} - \frac{dC}{C}$$

$\Longrightarrow$ there is a *transition energy* (or γ_t) at which the variation of velocity is compensated by the variation of the trajectory:

$$\eta = \frac{d\omega/\omega}{dp/p} = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}.$$

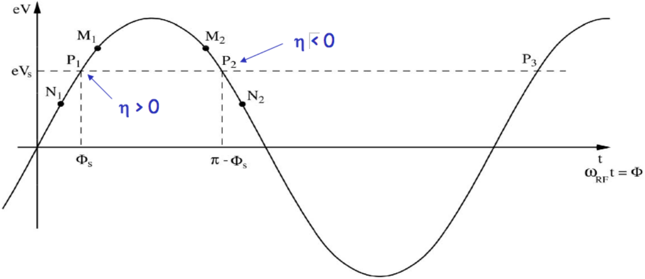
Basic notions of longitudinal beam dynamics



We assume $\eta > 0$ (below the transition energy).

The particle at P_1 that arrives *always* at the same phase Φ_s in the RF cavity is called the synchronous particle. Its energy gain is $\Delta E = eV_{\mathrm{RF}} \sin \Phi_s$.

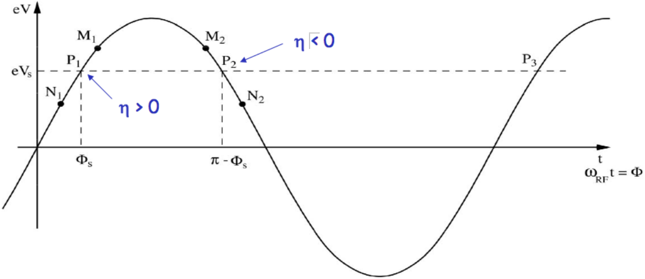
Basic notions of longitudinal beam dynamics



We assume $\eta > 0$ (below the transition energy).

The particle M_1 with a phase $\Phi_{M1} > \Phi_s$ receives more energy than P_1, hence its revolution period is shorter: it arrives earlier (closer to P_1) at the next turn.

Basic notions of longitudinal beam dynamics



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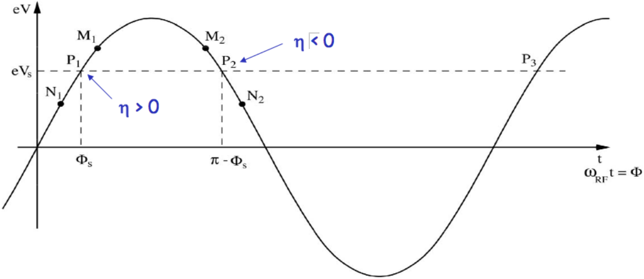

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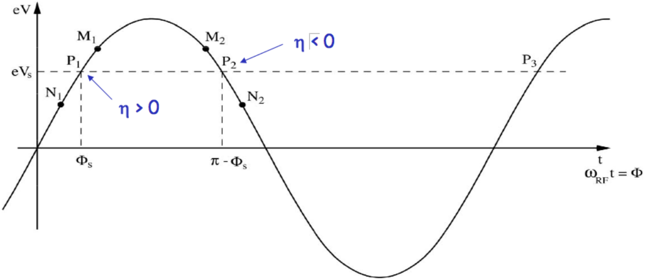
The particles N_1 and M_1 oscillate around the synchronous particle P_1, both in energy and in phase (or in longitudinal position). These are called synchrotron oscillations.

Basic notions of longitudinal beam dynamics



We assume $\eta > 0$ (below the transition energy).

If $\Phi_{M1} > \pi - \Phi_s$, M_1 moves away from the synchronous particles... Similarly, there is an extremum of the stable phase for N_1. Not the whole (ΔE;Φ) plane is stable!

Basic notions of longitudinal beam dynamics

The parameters of the synchronous particle (radius R, momentum p) are generally slowly varying with time. One can then show that:

$$\frac{d^2\Phi}{dt^2} + \frac{\Omega_s^2}{\cos\Phi_s}(\sin\Phi - \sin\Phi_s) = 0 \text{ with } \Omega_s^2 = \frac{\eta h\,\omega_{\mathrm{rev}}\,eV_{\mathrm{RF}}\cos\Phi_s}{2\pi Rp}.$$

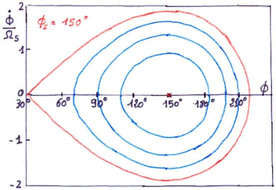
$\Rightarrow$ Synchrotron oscillations in the energy-phase plane around the synchronous particle.

Stability conditions:

- For the synchrotron oscillations to be stable, one must have Ω_s real, hence $\eta\cos\Phi_s > 0$.
- As a result, when crossing the transition energy, one must have a phase jump, from Φ_s to $\pi - \Phi_s$.
- In order to accelerate the synchronous particle, one needs in addition to have $\sin\Phi_s > 0$.

Basic notions of longitudinal beam dynamics

$$\frac{1}{2}\left(\frac{d\Phi}{dt}\right)^2 - \frac{\Omega_s^2}{\cos\Phi_s}(\cos\Phi + \Phi\sin\Phi_s) = \text{constant}.$$



Particles travel on closed paths around the synchronous particle in the phase space $(\Phi;\ \frac{1}{\Omega_s}\frac{d\Phi}{dt})$.

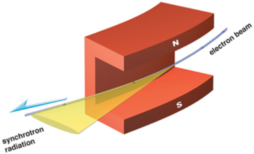
The closed path containing the point with $\Phi = \pi - \Phi_s$ is the separatrix. The (stable) area within the separatrix is the RF bucket. The second extremum Φ_m is where the separatrix cuts the horizontal axis.

There are *h* RF buckets in a circular machine, however not all of them need to be filled with a bunch.

One slide on lepton colliders

HASCO = Hadron Collider Physics School... what's wrong with lepton colliders?

e^+e^- collisions occur between two point-like particles, with a well-defined center-of-mass energy $\sqrt{s}$. But, in a circular machine:



- Major limitation = synchrotron radiation!
- Power loss $\propto \frac{\gamma^4}{\rho^2}$

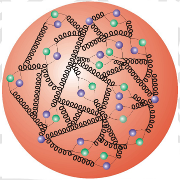
To reach higher energies, reduce γ by increasing the mass of the colliding objects... or increase $\rho \to \infty$:

Source: http://clic-study.web.cern.ch/

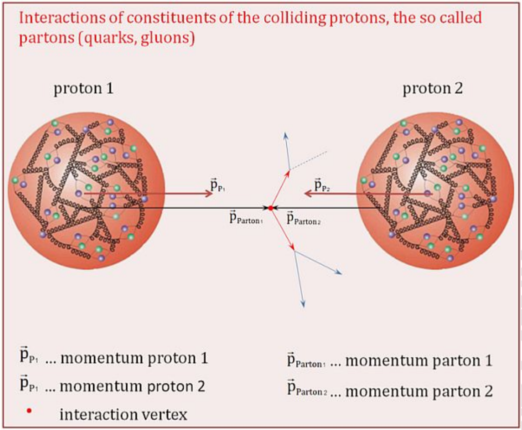
Colliding protons

Source: Elin Bergeås Kuutmann, HASCO 2015

- Higher energies can be reached;
- Not colliding two point-like particles, but partons with an undefined $\sqrt{s}$;
- Busy environment (beam remnants, initial- and final-state radiation).



Colliding protons



Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)

$\vec{p}_{P_1}$ ... momentum proton 1

$\vec{p}_{P_1}$ ... momentum proton 2

• interaction vertex

$\vec{p}_{Parton_1}$ ... momentum parton 1

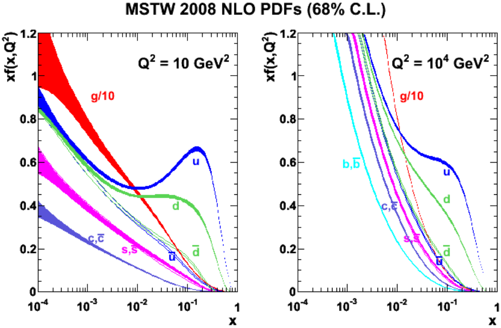
$\vec{p}_{Parton_2}$ ... momentum parton 2

Source: http://atlas.physicsmasterclasses.org

Knowing the fraction of the total momentum carried by the colliding partons is a vital ingredient for making predictions at hadron colliders!

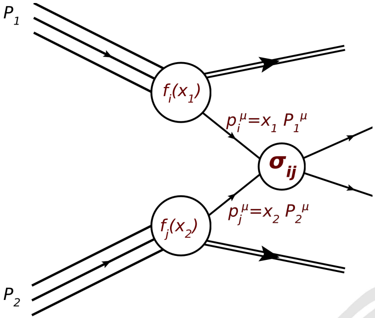
Colliding protons

The distribution of momentum that quarks and gluons carry is quantified by the Parton Distribution Functions (PDFs), which are extracted from experimental data.



Source: www.quantumdiaries.org. Credit: MSTW

Colliding protons

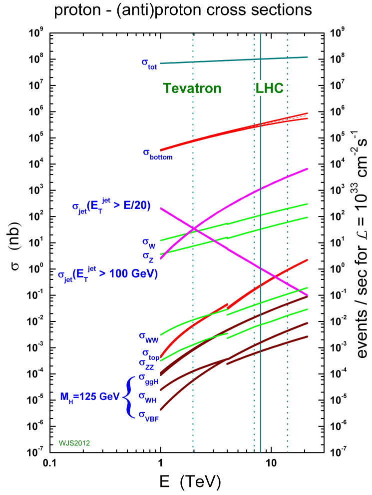


Source: arXiv:1308.6064 [hep-ex]

$$\sigma = \sum_{q_i, q_j} \int_0^1 \int_0^1 dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(x_1, x_2, Q^2)$$

- $\hat{\sigma}$ = partonic cross section (from Feynman rules);
- $f_i(x_1, Q^2)$ and $f_j(x_2, Q^2)$ = PDFs for the colliding partons.

Cross sections at hadron colliders

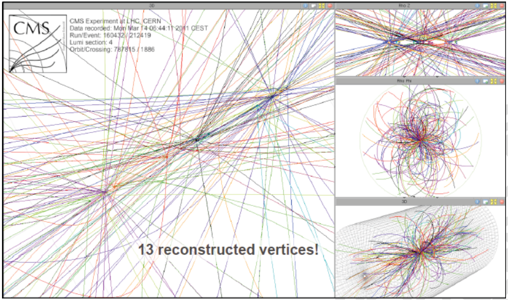


Source: W.J. Stirling, private communication

Looking for interesting physics processes at hadron colliders is like:

Pile-up

Each proton bunch-crossing yields several *pp* collisions, most of them are not interesting from the physics point of view → pile-up of minimum-bias events!



Pile-up leads to several primary vertices, extra energy depositions in the calorimeters, etc. It becomes more significant with increasing luminosity.

Kinematics at hadron colliders

At a *pp* or $p\bar{p}$ collider, the longitudinal momentum of the partons in collision is unknown → one needs kinematical variables that are invariant under longitudinal boosts:

- the transverse energy or momentum (E_{T} or p_{T}) with:

$$E_{\mathrm{T}} = \sqrt{m^2 + p_{\mathrm{T}}^2}$$

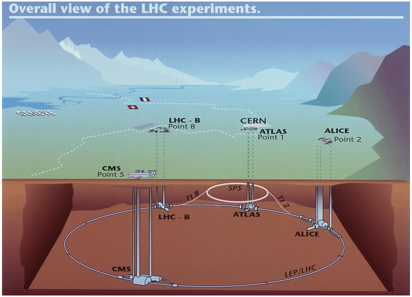
- the azimuthal angle ϕ,
- the pseudo-rapidity $\eta = -\ln\left(\tan\frac{\theta_z}{2}\right)$.

η is an ultra-relativistic approximation of $y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$.

With these kinematic variables, the four-momentum of an (ultra-relativistic) object is defined by:

$$\begin{pmatrix} E \\ \vec{p} \end{pmatrix} = \begin{pmatrix} E_{\mathrm{T}} \cosh y \\ p_{\mathrm{T}} \cos\phi \\ p_{\mathrm{T}} \sin\phi \\ E_{\mathrm{T}} \sinh y \end{pmatrix} \simeq p_{\mathrm{T}} \begin{pmatrix} \cosh\eta \\ \cos\phi \\ \sin\phi \\ \sinh\eta \end{pmatrix}$$

The Large Hadron Collider in one slide



- Circumference = 27 km
- Proton revolutions per second = 11245.5
- Beam energy = 3.5 TeV in 2011, 4 TeV in 2012, 6.5 TeV since 2015
- Delivered luminosity: 5/fb in 2011, 23/fb in 2012, 43/fb in 2015-2016... and much more to come!

The LHC is colder than the outer space but also the hottest spot in the galaxy (the *pp* collisions generate temperatures 100,000 times greater than in the sun).

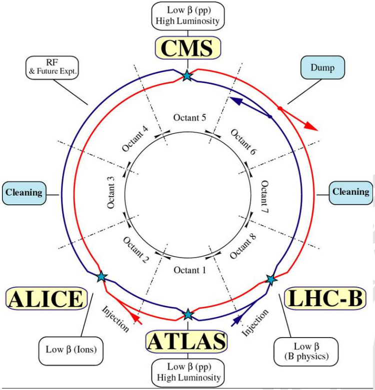
The LHC is also the emptiest space in the Solar System as the beams must travel in an ultra-high vacuum.

Source: CERN PhotoLab

More details on accelerators in Rüdiger Schmidt's lecture, on 26/07.

The LHC experiments

Two general purpose experiments (ATLAS and CMS), one dedicated to studies of *b*-quarks (LHCb) and one dedicated to studies of quark-gluon plasma (ALICE).



The upcoming slides are about detector technology, mostly in ATLAS and CMS.

How does a detector work?

In order to interpret the experimental observations of a high-energy particle collision, one needs to accurately measure:

- the four-vectors of the incident particles (initial state),
- the four-vectors of all outgoing particles (final state).

The mass of intermediate short-lived particles can be reconstructed from the energy-momentum balance of the four-vectors of the final state decay products:

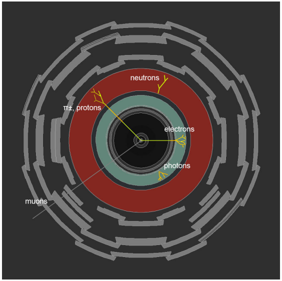
$$E^2 = (mc^2)^2 + (pc)^2.$$

In addition, one needs a good time resolution to separate the collision events from each other.

How does a detector work?

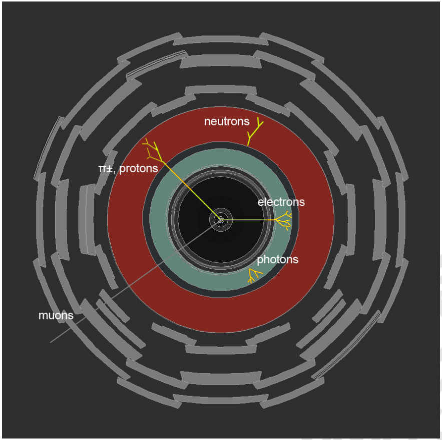
Detectors must measure accurately all decay products of the particle(s) created at the collision point. However:

- In a detector, the basic experimental observables are NOT four-momenta!
- One detector can not provide enough information on its own to identify all final state particles and measure their energies and momenta!



One must gather information from several sub-detectors, each providing some level of particle identification and kinematical measurement.

How does a detector work?

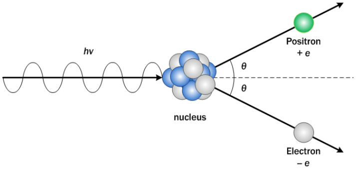


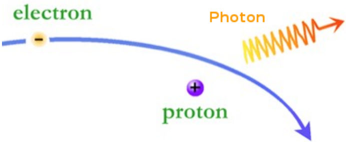
All charged particles are detected in the innermost tracker, electrons/photons (hadrons) in the electromagnetic (hadronic) calorimeter, muons in the outermost muon spectrometer.

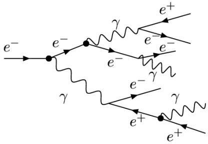
High-energy electromagnetic interactions

Starting from high-energy electrons and photons, two electromagnetic processes with the charged nuclei of the medium are dominant:

- e^+e^- pair production for high-energy photons,
- Bremsstrahlung (braking radiation) emission for high-energy electrons and positrons.







This leads to the development of an electromagnetic shower.

Energy loss for low-energy electrons/photons

Low-energy photons primarily lose energy via:

- Photo-electric absorption: a photon interacts with an atom and disappears, leaving place to a photo-electron ejected by one of the atomic shells, with $E_e = h\nu - E_b$.
- Compton scattering: a photon is deflected and transfers a fraction of its energy to an electron.

Low-energy electrons primarily lose energy via Coulomb forces with orbital electrons in the material. The energy transfer from the incident electron results in the excitation or ionization of an atom $\Rightarrow$ Detection signal from drifting charges!

Positrons lose their energy in the same manner, and annihilation occurs at the end of the positron track.

Energy resolution of electromagnetic calorimeters

$$\frac{\sigma(E)}{E} = \frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C$$

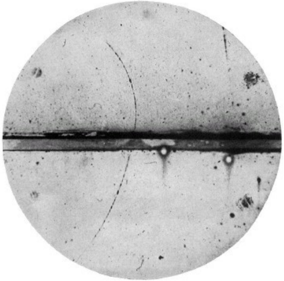
- N is the electronic noise, with also a component from the pile-up (i.e. signals from minimum-bias events in the same or neighbouring bunch crossings).
- S is a stochastic term (statistical fluctuations, e.g. from the shower, light yield, sampling, etc).
- C is a constant term, dominant at high-energy: intrinsic non-uniformities, cell-to-cell calibration inaccuracies, radiation damage, etc.

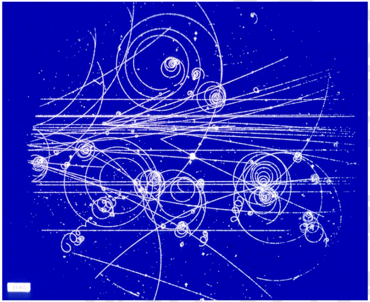
Typically, N = 0.1-0.2 GeV and $C \simeq$ 0.3-0.7%, but S varies from 2-3% for homogeneous calorimeters to 10% for sampling calorimeters.

Basic concepts of tracking detectors

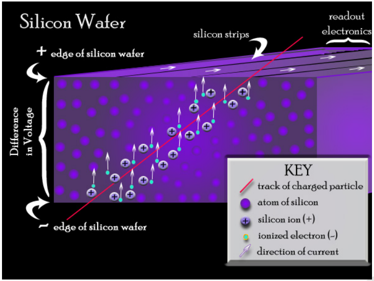
An electron is distinguished from a photon primarily by the presence of a charged track in the inner detector, pointing to the center of the electromagnetic shower.

The footprint of a charged particle in a tracking detector (e.g. a bubble chamber) is an excitation/ionization of the material.



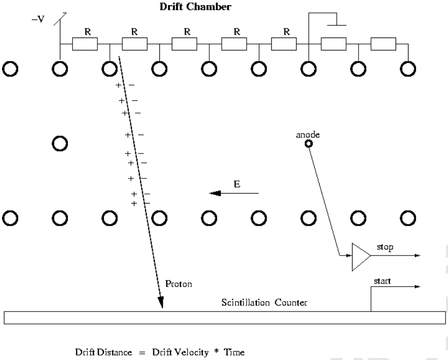


Basic concepts of tracking detectors



1) A charged particle transfers energy to an atom, creating a ion-e^- pair (in a gas) or a hole-e^- pair (in a semi-conductor).
2) An ambient electric field is applied across the medium to separate electrons from ions/holes.
3) The drifting charges are collected on anodes and cathodes, where a signal is measured.

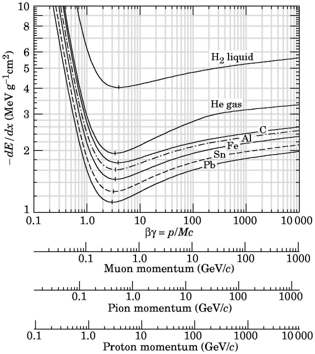
Basic concepts of tracking detectors



Knowing the drift velocity of the charges in the material, then the drift time (that elapses before the charges are incident on the collection electrode) is used to compute the spatial coordinates where ionization first occurred.

Basic concepts of tracking detectors

Energy loss rate expressed in MeV/(g.cm^{-2}), or in MeV/cm when divided by the density ρ:

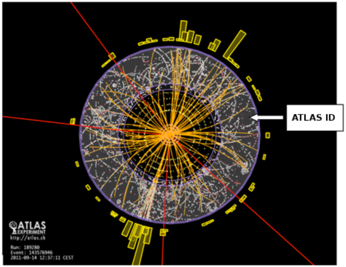


- For a given material, the energy loss rate depends on β and z only.
- Low β: $dE/dx \propto 1/\beta^2$.
- High β: dE/dx grows slowly, then saturates.

The energy loss rate has a minimum for $\beta\gamma \simeq 4$, where all charged particles behave as “Minimum Ionizing Particles” (MIPs), with $dE/dx \simeq$ 1-2 MeV for each g/cm^2 of material (except hydrogen).

Transverse momentum measurement and resolution

A tracker is a detector that measures spatial coordinates *along the trajectory of a charged particle,* in an external magnetic field.



For a circular trajectory in the bending plane, with a radius of curvature R (m) in a magnetic field B (T):

$$p_{\mathrm{T}} = 0.3BR \text{ [GeV/c]}$$

The sagitta (maximum deviation of the track from a straight line) for a tracker level arm L (m) is:

$$s \simeq 0.3BL^2/(8p_{\mathrm{T}})$$

Transverse momentum measurement and resolution

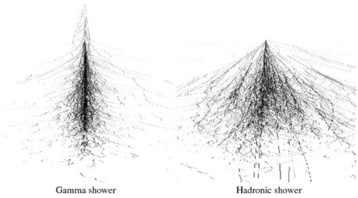
$$\frac{\sigma(p_\mathrm{T})}{p_\mathrm{T}} = C_0 \oplus C_1 \cdot p_\mathrm{T}$$

- The most degrading effect from the material in the tracker is multiple scattering, with random deflecting angles depending on the thickness and density of the detector, but reduced in high magnetic fields: C_0 = 0.5–2%.
- High-p_T tracks have little deflection in the magnetic field, leading to possible charge misidentification: $C_1 = 10^{-3}$–10^{-4} (GeV/c)$^{-1}$.

Note that tracks with less than 50–100 MeV/c in p_T curl in the magnetic field and do not reach the calorimeters.

Basic concepts of hadronic calorimeters

- In order to detect primary quarks or gluons, one must reconstruct hadronic jets.
- The physical processes causing the propagation of hadronic showers rely on the strong interaction, with many secondary particles (pions and nucleons).
- In hadronic showers, due to $\pi^0 \to \gamma\gamma$ decays, there is an electromagnetic component.
- Charged pion decays via the electroweak interaction lead to some loss of signal: $\pi^\pm \to \mu\nu$.



Electromagnetic showers develop in less than 1 ns... whereas hadronic showers need up to 1 μs.

Basic concepts of hadronic calorimeters

Hadronic calorimeters must be:

- massive, thick, and hermetic detectors;
- sampling calorimeters, i.e. repetitive layers of dense absorbers for hadronic shower development and of active material (e.g. scintillators) for signal collection.

Energy resolution:

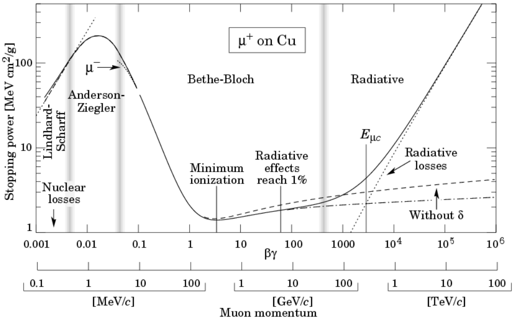
$$\frac{\sigma(E)}{E} = \frac{A}{\sqrt{E}} \oplus B$$

A = (statistical) fluctuations of shower shape, particle content and multiplicity, electromagnetic component in hadron showers, invisible energy (typically 50-100%).

B = inhomogeneities, shower leakage (typically a few %).

Muon interactions

Muons are the only long-lived charged particles with a minimal cross-section up to nearly TeV energies
→ minimum ionizing particle through the whole detector!



In addition to the track left in the inner detector, muons are identified using a large muon spectrometer placed around the calorimeters.

Detecting muons

In order to detect muons, one needs:

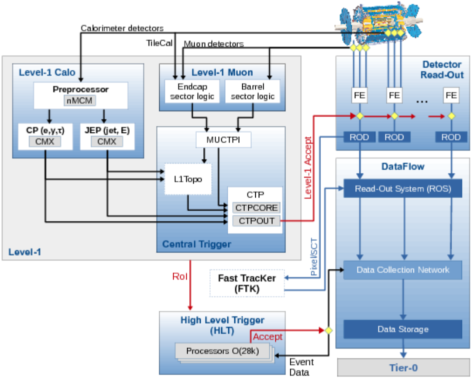
- a large magnetic field to bend the muon trajectories;
- drift chambers to detect muon ionization signals;
- resistive plate chambers for triggering purposes: the electrons from the ionization hit other atoms causing an avalanche (quick measure of the muon p_T);
- enough material upstream to prevent some charged hadrons from punching through.

Reminder: $\frac{\sigma(p_\mathrm{T})}{p_\mathrm{T}} = C_0 \oplus C_1 \cdot p_\mathrm{T}$

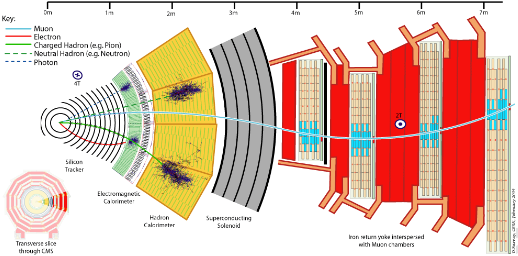
- the stand-alone muon spectrometer usually has a somewhat larger multiple scattering term C_0 than the inner detector,
- the muon spectrometer provides an additional level arm and thereby reduces the effective term C_1 with respect to using only the tracker.

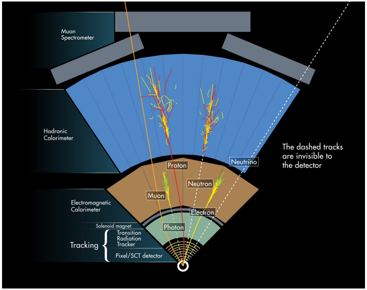
Trigger

It is impossible to keep all events produced in an experiment → trigger menus to keep events with interesting physics and reduce the rate of events from several MHz to below 1 kHz.



Summary of detector technologies

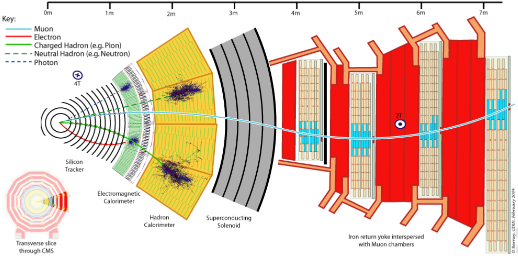


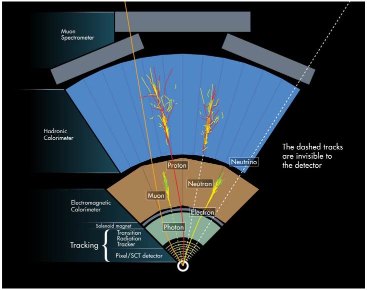


More on detectors in Gerald Eigen's lecture, on 23/07.

In addition, some complex objects need a more special treatment.

Summary of detector technologies





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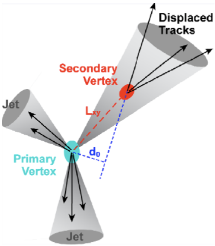
In addition, some complex objects need a more special treatment.

Detection of *b*-jets



Bottom quarks form *B*-hadrons with a finite lifetime and hence a decay length of a few mm.

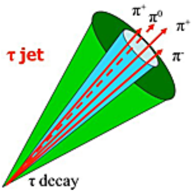
⇒ identification of *b*-jets based on impact parameter information, the presence of a secondary vertex...

- *B*-hadrons usually decay within the beam pipe: the displaced vertex must be reconstructed by **extrapolating** charged particle tracks.
- This is performed by a vertex detector installed close to the beam pipe.
- Special *b*-tagging algorithms are used during the data-analysis to identify *b*-jets.

Detection of τ-leptons

The τ-lepton is unique among the leptons because it can decay hadronically!

A hadronically decaying τ has properties similar to hadronic jets, but with some important differences:



- a low track multiplicity (1 or 3),
- some energy deposition in the electromagnetic calorimeter, due to $\pi^0 \to \gamma\gamma$,
- a high p_T boost leading to a narrow and well isolated jet of particles.

Dedicated algorithms can identify hadronically decaying τ-leptons with efficiencies up to 40% and mis-tag rates around 0.1%.

Missing transverse energy

- At hadron colliders, the longitudinal momenta of the colliding partons is unknown, hence it is impossible to measure any missing energy in the longitudinal direction!
- However, the transverse energy (un)balance can be measured and used as a physics signature for one or several non-interacting particles.

→ The missing transverse energy/momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ is also a detector object:

$$\begin{aligned}\vec{E}_{\mathrm{T}}^{\mathrm{miss}} &= -\sum_n \left(\frac{E_n \cos\phi_n}{\cosh\eta_n}\vec{i} + \frac{E_n \sin\phi_n}{\cosh\eta_n}\vec{j} \right) \\ &= E_x^{\mathrm{miss}}\vec{i} + E_y^{\mathrm{miss}}\vec{j}\end{aligned}$$

1. Recipe for the universe
   - Matter
   - Interactions
   - Going beyond
2. Experimental tools in particle physics
   - Accelerators
   - Detectors
3. Data-analysis

Simulations and data-analysis

The first step of any analysis in particle physics is to choose a model to be tested, and to implement all its predictions into an event generator (usually done with phenomenologists).

The event generators – for a specific model and for all backgrounds – are then interfaced to a detailed detector simulation framework based on GEANT4. Fast simulation (smearing of truth-level distributions) is often used too.

Millions of events are generated, simulated and stored on the world-wide grid (this can take weeks).

Using simulations, event selections must be optimized to obtain the best sensitivity of the signal with respect to the Standard Model backgrounds ⇒ Signal region(s).

Simulations and data-analysis

Control regions (that are free of signal!) are used for a first comparison of simulations and data, in the case of known Standard Model processes. Discrepancies may indicate systematic errors in the detector simulation.

A set of corrections is derived and then applied to the simulations, with associated systematic uncertainties.

Some backgrounds (usually multi-jet events) need to be determined with data-driven methods.

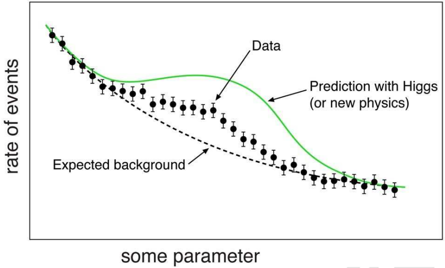
All systematic uncertainties must be accounted for!

The distributions of discriminative variables are compared in the signal region(s) to assess the compatibility of data with predictions in the absence or presence of signal.

→ Statistical analysis!

Hypothesis testing

Let's compare some hypothetical data with the predictions of the Standard Model, with or without a signal.



- black points close to the green curve: there is some evidence for new physics,
- black points on or below the dashed black curve (i.e. background): there is no evidence for new physics and some parameters in the corresponding signal model can be ruled out, with some level of confidence.

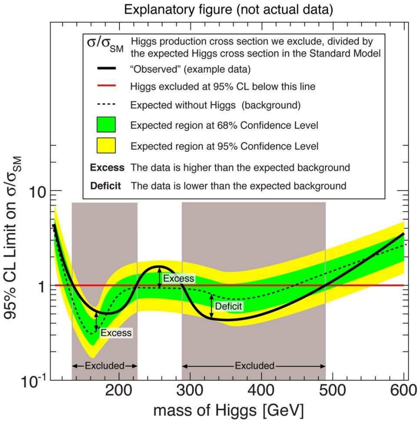
Hypothesis testing

1. state the relevant null and alternative hypotheses,
2. state the relevant test statistic t and derive the distribution of this test statistic under the null hypothesis,
3. select a significance level α, i.e. a probability threshold below which the null hypothesis will be rejected,
4. compute from the measurements (data) the observed value t_{obs} of the test statistic,
5. based on t_{obs}, either fail to reject the null hypothesis or reject it in favor of the alternative hypothesis.

p-value = probability that a measurement is as or less compatible with the null hypothesis.

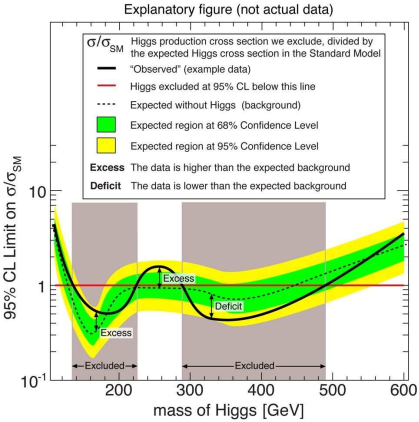
$\Rightarrow$ If the p-value is less than the required significance level ($p < \alpha$), the null hypothesis is rejected with the confidence level $1 - \alpha$.

Data-analysis: exclusion plot



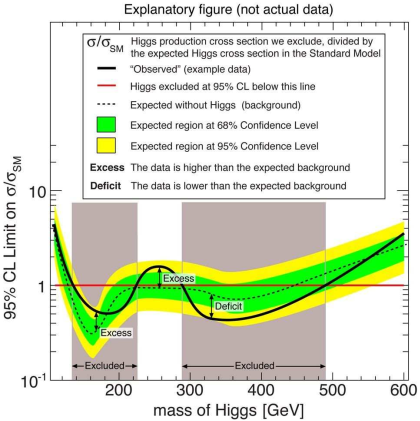
Null hypothesis = signal + background. In the context of excluding this hypothesis at the LHC, α is set to 0.05.

Data-analysis: exclusion plot



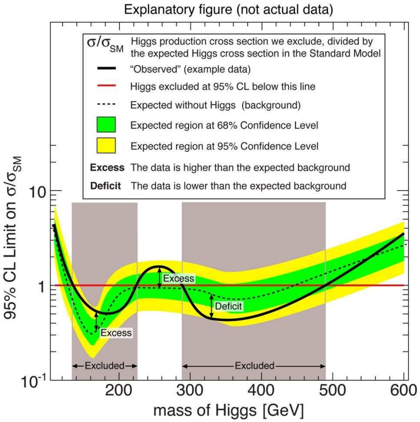
Horizontal and vertical axes → Parameters from a new theory to be excluded, e.g. m_H and σ_H for a Higgs boson.

Data-analysis: exclusion plot


Explanatory figure (not actual data)

Solid black line → Observed upper limit at 95% CL for a Higgs boson with the given mass.

Data-analysis: exclusion plot



Dotted black line → Expected upper limit at 95% CL for a Higgs boson with the given mass.

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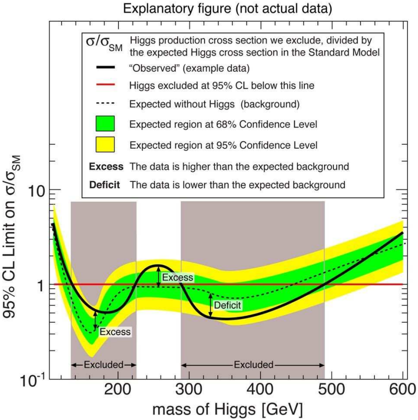
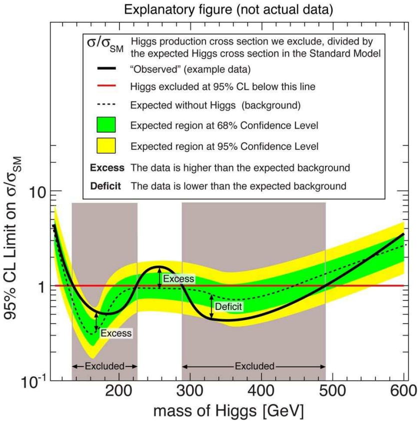


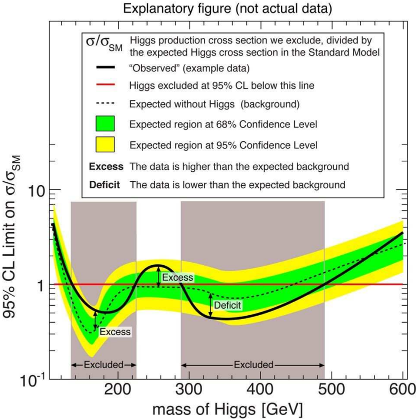
Green and yellow bands → 68% and 95% error bands on the expected limit.

Data-analysis: exclusion plot



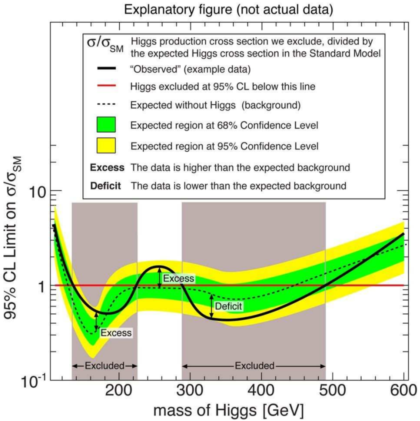
Deficit → less data than the expected background. The observed limit is below the expected limit.

Data-analysis: exclusion plot



Excess → more data than the expected background. The observed limit is above the expected limit.

Data-analysis: exclusion plot



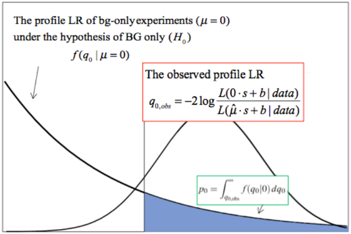
White vertical bands = non-excluded (Standard Model) Higgs boson masses... but it does not mean discovery!

Recipe for a discovery

When the solid black line is above the dotted black line in the exclusion plot, there is an excess of data with respect to the background prediction.
⇒ one can not reject the signal+background hypothesis as well as expected, but this is not a discovery!

For a discovery, we want to reject the background-only hypothesis with a high confidence level. The p_0-value is used to assess the compatibility of data with *background*.

$$\lambda(\mu=0)=\frac{L(0\cdot s+b\,|\,data)}{L(\hat{\mu}\cdot s+b\,|\,data)},\quad q_0=-2\log\lambda(\mu=0)$$



For a discovery, the p_0-value must be at most 2.87×10^{-7}: the chance of a background fluctuation faking the signal is less than one in a million!

More on statistics in Federico Meloni's lecture, on 24/07.

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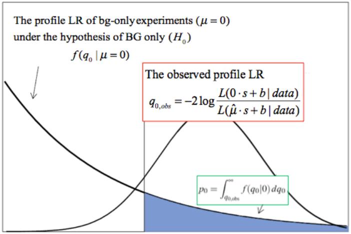

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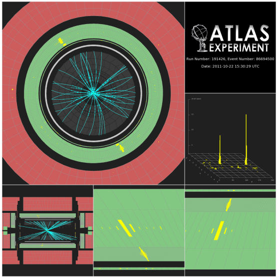
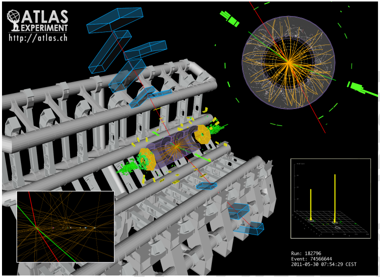
Higgs boson discovery in 2012

Golden search channels: $h \to \gamma\gamma$ (via a top-quark loop) and $h \to ZZ \to 4\ell$.





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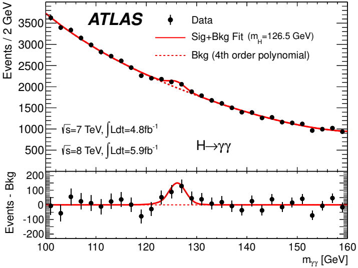

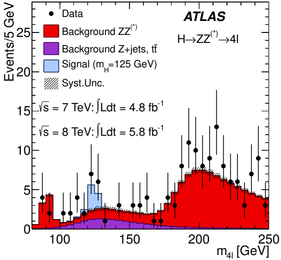

Next: how compatible is data with the signal+background and background-only hypotheses at various Higgs boson masses?

Higgs boson discovery in 2012

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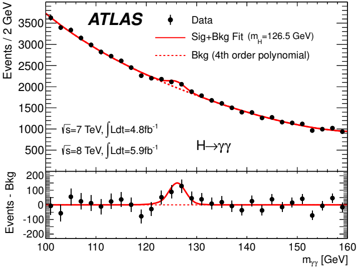

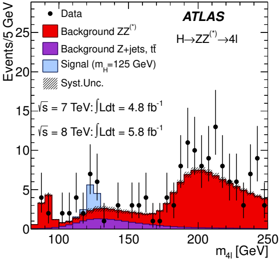

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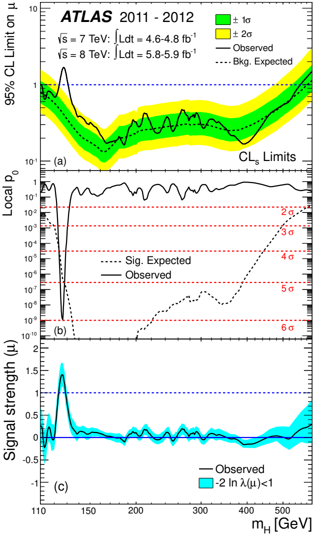

- The observed limit lies well above the expected limit in the Higgs boson mass region around 125 GeV. A Standard Model Higgs boson is excluded at 95% CL everywhere else.
- Very small p_0-value at 125 GeV ⇒ discovery!
- The signal strength that is most compatible with the data at 125 GeV is $\simeq$1.4 times the Standard Model prediction.

The rest is already history!


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Thanks for your attention and enjoy HASCO!