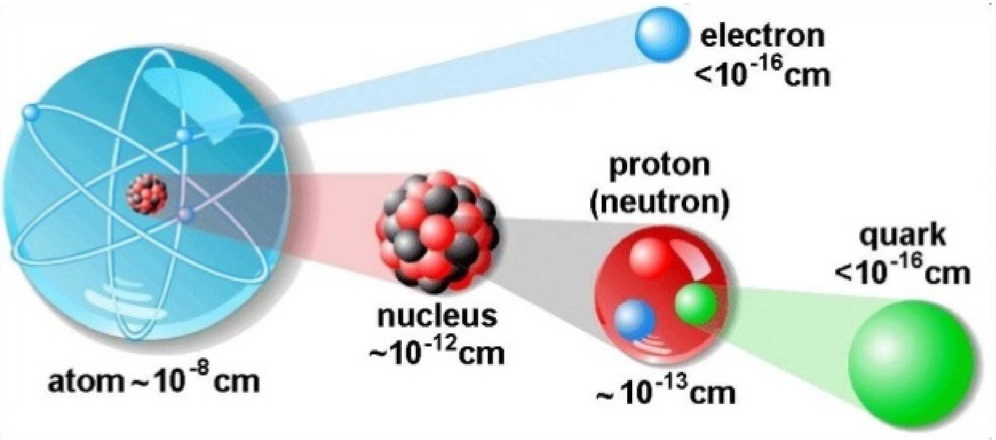
Basic Concepts

- Particle physics studies the elementary “building blocks” of ***matter*** and interaction between them.
- Matter consists of ***particles*** and ***fields***.
- Particles interact via ***forces*** caused by fields.
- Forces are being carried by special particles, called ***gauge bosons***.



Forces of nature:

1) gravitational
2) weak $n \rightarrow p + e^- + \bar{\nu}_e$
3) electromagnetic $e^+ + e^- \rightarrow \gamma + \gamma$
4) strong $\pi^-(d\bar{u}) + p(uud) \rightarrow K^+(u\bar{s}) + \Sigma^-(dds)$

Forces of Nature

	Acts on:	Carrier	Range	Strength	Stable systems	Induced reaction
Gravity	all particles	graviton	long $F \propto 1/r^2$	$\sim 10^{-39}$	Solar system	Object falling
Weak force	fermions	bosons W and Z	$< 10^{-17} m$	10^{-5}	None	β-decay
Electromagnetism	particles with electric charge	photon	long $F \propto 1/r^2$	$1/137$	Atoms, stones	Chemical reactions
Strong force	quarks and gluons	gluon	$10^{-15}\ m$	1	Hadrons, nuclei	Nuclear reactions

- Two people are standing in boats. One person moves their arm and is pushed backwards; a moment later the other person grabs at an invisible object and is driven backwards. Even though you cannot see a basketball, you can assume that one person threw a basketball to the other person because you see its effect on the people.

- It turns out that all interactions which affect matter particles are due to an exchange of ***force carrier particles***, a different type of particle altogether. These particles are like basketballs tossed between matter particles (which are like the basketball players). What we normally think of as "forces" are actually the effects of force carrier particles on matter particles.

The Standard Model

- Electromagnetic and weak forces can be described by a single theory ⇒ the ***"Electroweak Theory"*** was developed in 1960s (Glashow, Weinberg, Salam).
- Theory of strong interactions appeared in 1970s: ***"Quantum Chromodynamics"*** (QCD)
- The ***"Standard Model"*** (SM) combines both.

Abdus Salam, Steven Weinberg, Sheldon L. Glashow

Main postulates of SM:

1) Basic constituents of matter are ***quarks*** and ***leptons*** (spin 1/2).

2) They interact by means of gauge bosons (spin 1).

3) Quarks and leptons are subdivided into ***3 generations***.

The Standard Model

Fermions		Bosons	
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = 1^*	Force Carrier Particles
Baryons (qqq)	Spin = $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \cdots$	Spin = $0, 1, 2, \cdots$	**Meson $(q\bar{q})$**

Baryons (qqq) and Mesons $(q\bar{q})$ are **Hadrons**

Baryon # = $(qqq) = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$ and $(q\bar{q}) = \frac{1}{3} + \left(-\frac{1}{3}\right) = 0$

Lepton	lepton #	electron #	muon #
e^-	1	1	0
ν_e	1	1	0
μ	1	0	1
ν_μ	1	0	1

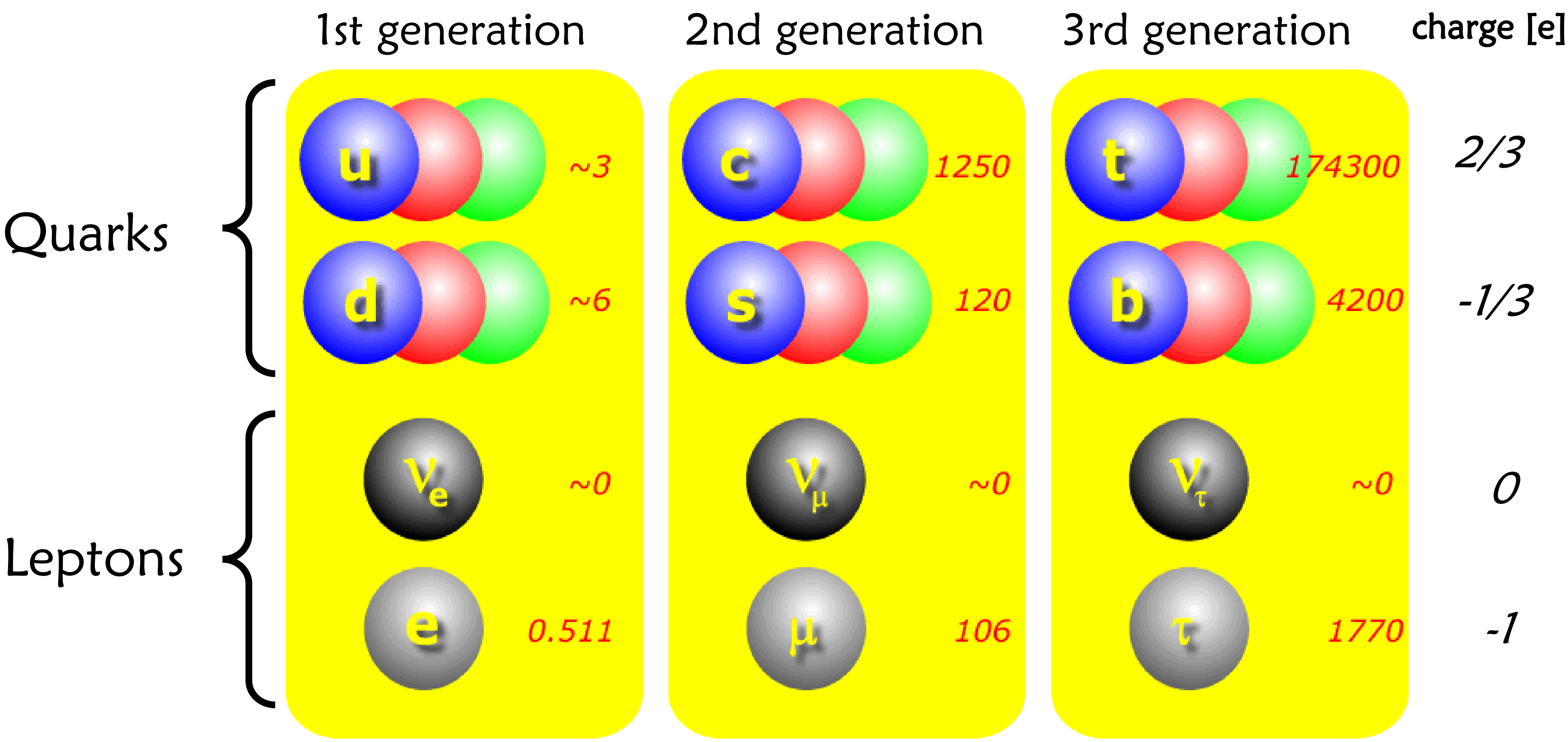
Lepton numbers are conserved in any reaction

(for anti-leptons L = -1)

Consequence of Lepton-Number Conservation

reaction	lepton #	electron #	muon #
$\nu_e + n \rightarrow p + e^-$	1 → 1	1 → 1	0 → 0
$\overline{\nu_e} + n \rightarrow p + e^-$	-1 → 1	-1 → 1	0 → 0
$\mu^- \rightarrow e^- + \gamma$	1 → 1	0 → 1	1 → 0
$\overline{\nu_\mu} + p \rightarrow \mu^+ + n$	-1 → -1	0 → 0	-1 → -1
$\overline{\nu_\mu} + p \rightarrow e^+ + n$	-1 → -1	0 → -1	-1 → 0

Fermions: The Elementary Players



Quantum Numbers and Flavours

"Strangeness" $S = -[N(s) - N(\bar{s})]$

$$K^+ = u\bar{s}, \qquad K^0 = d\bar{s}$$
$$K^- = \bar{u}s, \qquad \bar{K}^0 = \bar{d}s$$
$$\Sigma^+ = uus, \Sigma^0 = uds, \Sigma^- = dds$$

"Charm" $C = [N(c) - N(\bar{c})]$

$$D^+ = c\bar{d}, \qquad D^0 = c\bar{u}$$
$$D^- = \bar{c}d, \qquad \bar{D}^0 = \bar{c}u$$

"Bottomness" $\tilde{B} = -[N(b) - N(\bar{b})]$

$$B^+ = u\bar{b}, \qquad B^0 = d\bar{b}$$
$$B^- = \bar{u}b, \qquad \bar{B}^0 = \bar{d}b$$

"Topness" $T = [N(t) - N(\bar{t})]$

No composite hadrons are formed that contain the top (anti) quark

- Majority of hadrons are unstable and tend to decay by the strong interaction to the state with the lowest possible mass ($\tau \sim 10^{-23}\ s$)
- Hadrons with the lowest possible mass for each quark number (C, S, etc.) may live much longer before decaying weakly ($\tau \sim 10^{-7} - 10^{13}\ s$) or electromagnetically (mesons, $\tau \sim 10^{-16} - 10^{-21}\ s$)

Quantum Numbers and Flavours

Some examples of baryons:

particle	mass (GeV/c^2)	quark composition	charge (units of e)	S	C	B
p	0.938	uud	1	0	0	0
n	0.940	udd	0	0	0	0
Λ	1.116	uds	0	-1	0	0
Λ_c	2.285	udc	1	0	1	0

Some examples of mesons:

particle	mass (GeV/c^2)	quark composition	charge (units of e)	S	C	B
π^+	0.140	$u\bar{d}$	1	0	0	0
K^-	0.494	$s\bar{u}$	-1	-1	0	0
D^-	1.869	$d\bar{c}$	-1	0	-1	0
D_s^+	1.969	$c\bar{s}$	1	1	1	0
B^-	5.279	$b\bar{u}$	-1	0	0	-1
Υ	9.460	$b\bar{b}$	0	0	0	0

Table of Baryons and Mesons

Table of Baryons

Particle	Symbol	Makeup	Rest mass MeV/c^2	Spin	B	S	Lifetime (seconds>	Decay Modes
Proton	p	uud	938.3	1/2	+1	0	Stable	...
Neutron	n	ddu	939.6	1/2	+1	0	920	$pe^-\underline{\nu}_e$
Lambda	Λ^0	uds	1115.6	1/2	+1	-1	2.6 x10^{-10}	$p\pi^-$, $n\pi^0$
Sigma	Σ^+	uus	1189.4	1/2	+1	-1	0.8 x10^{-10}	$p\pi^0$, $n\pi^+$
Sigma	Σ^0	uds	1192.5	1/2	+1	-1	6x10^{-20}	$\Lambda^0\gamma$
Sigma	Σ^-	dds	1197.3	1/2	+1	-1	1.5 x10^{-10}	$n\pi^-$
Delta	Δ^{++}	uuu	1232	3/2	+1	0	0.6 x10^{-23}	$p\pi^+$
Delta	Δ^+	uud	1232	3/2	+1	0	0.6 x10^{-23}	$p\pi^0$
Delta	Δ^0	udd	1232	3/2	+1	0	0.6 x10^{-23}	$n\pi^0$
Delta	Δ^-	ddd	1232	3/2	+1	0	0.6 x10^{-23}	$n\pi^-$
Xi Cascade	Ξ^0	uss	1315	1/2	+1	-2	2.9 x10^{-10}	$\Lambda^0\pi^0$
Xi Cascade	Ξ^-	dss	1321	1/2	+1	-2	1.64 x10^{-10}	$\Lambda^0\pi^-$
Omega	Ω^-	sss	1672	3/2	+1	-3	0.82 x10^{-10}	$\Xi^0\pi^-$, Λ^0K^-
Lambda	Λ^+_c	udc	2281	1/2	+1	0	2x10^{-13}	...

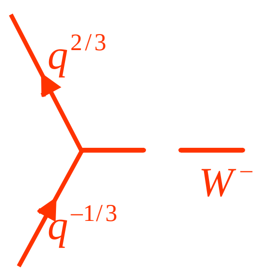
Mesons

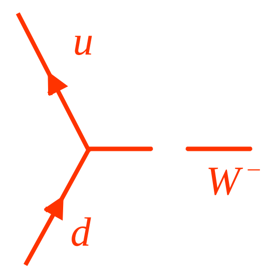
Particle	Symbol	Anti-particle	Makeup	Rest mass MeV/c^2	S	C	B	Lifetime	Decay Modes
Pion	π^+	π^-	$u\underline{d}$	139.6	0	0	0	2.60 x10^{-8}	$\mu^+\nu_\mu$
Pion	π^0	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	135.0	0	0	0	0.83 x10^{-16}	2γ
Kaon	K^+	K^-	$u\underline{s}$	493.7	+1	0	0	1.24 x10^{-8}	$\mu^+\nu_\mu$, $\pi^+\pi^0$
Kaon	K^0_s	K^0_s	1*	497.7	+1	0	0	0.89 x10^{-10}	$\pi^+\pi^-$,$2\pi^0$
Kaon	K^0_L	K^0_L	1*	497.7	+1	0	0	5.2 x10^{-8}	$\pi^+e^-\underline{\nu}_e$
Eta	η^0	Self	2*	548.8	0	0	0	<10^{-18}	2γ, 3μ
Eta prime	$\eta^{0'}$	Self	2*	958	0	0	0	...	$\pi^+\pi^-\eta$
Rho	ρ^+	ρ^-	$u\underline{d}$	770	0	0	0	0.4 x10^{-23}	$\pi^+\pi^0$
Rho	ρ^0	Self	$u\underline{u}$, $d\underline{d}$	770	0	0	0	0.4 x10^{-23}	$\pi^+\pi^-$
Omega	ω^0	Self	$u\underline{u}$, $d\underline{d}$	782	0	0	0	0.8 x10^{-22}	$\pi^+\pi^-\pi^0$
Phi	φ	Self	$s\underline{s}$	1020	0	0	0	20 x10^{-23}	K^+K^-,$K^0\underline{K}^0$
D	D^+	D^-	$c\underline{d}$	1869.4	0	+1	0	10.6 x10^{-13}	K + _, e + _
D	D^0	$\underline{D}^0$	$c\underline{u}$	1864.6	0	+1	0	4.2 x10^{-13}	[K,μ,e] + _
D	D^+_s	D^-_s	$c\underline{s}$	1969	+1	+1	0	4.7 x10^{-13}	K + _
J/Psi	J/ψ	Self	$c\underline{c}$	3096.9	0	0	0	0.8 x10^{-20}	e^+e^-, $\mu^+\mu^-$...
B	B^-	B^+	$b\underline{u}$	5279	0	0	-1	1.5 x10^{-12}	D^0 + _
B	B^0	$\underline{B}^0$	$d\underline{b}$	5279	0	0	-1	1.5 x10^{-12}	D^0 + _
B_s	B_s^0	$\underline{B}_s^0$	$s\underline{b}$	5370	-1	0	-1	...	B^-_s + _
Upsilon	Υ	Self	$b\underline{b}$	9460.4	0	0	0	1.3 x10^{-20}	e^+e^-, $\mu^+\mu^-$..

Consequence of Quark-Number Conservation

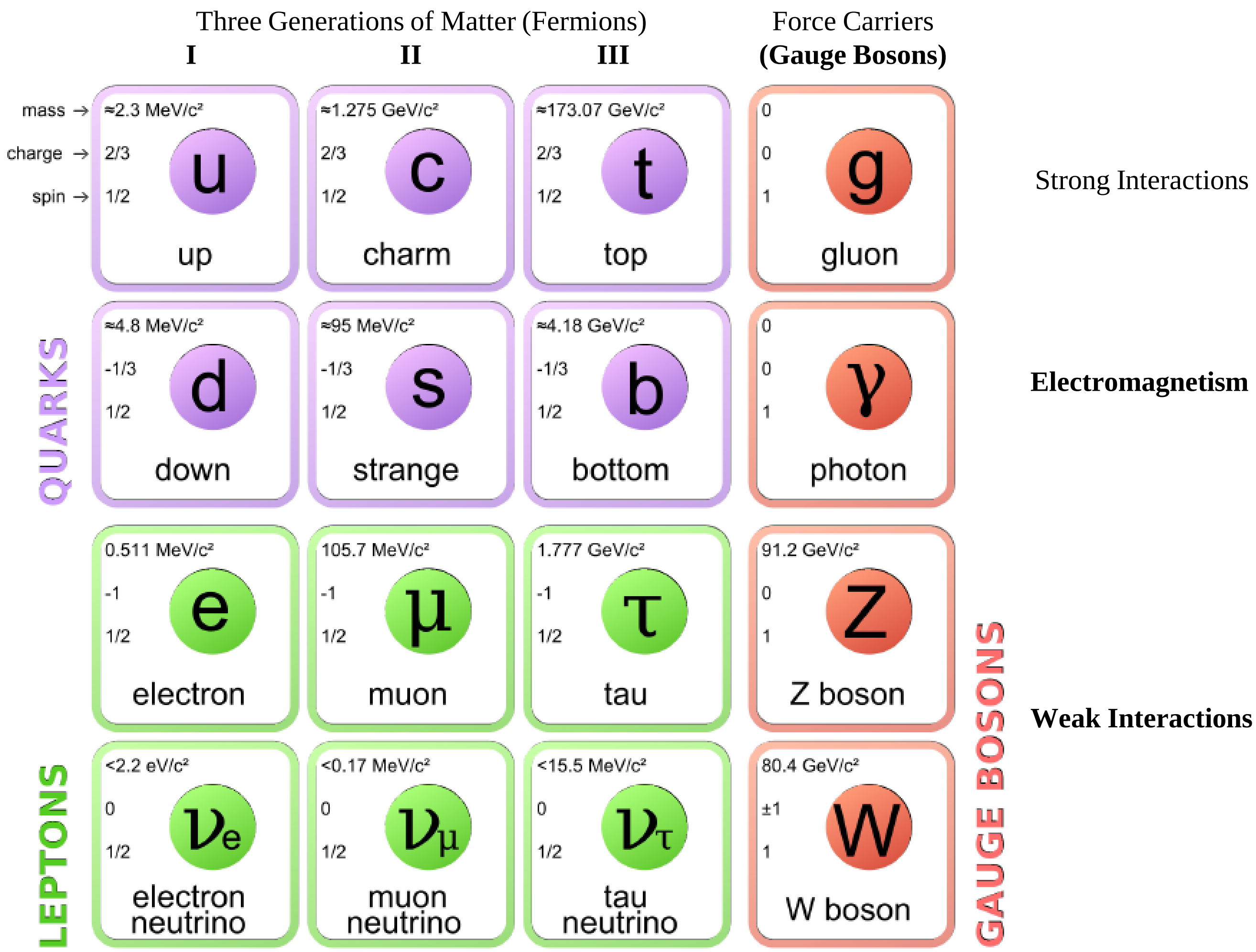
reaction	Quark configuration	charge	baryon #	strangeness #
$\bar{p}+p\rightarrow\pi^0+n$	$(\bar{u}\bar{u}\bar{d})+(uud)\rightarrow(u\bar{u}-d\bar{d})+(udd)$	yes	no	yes
$\pi^-+p\rightarrow K^0(d\bar{s})+n$	$(\bar{u}d)+(uud)\rightarrow(d\bar{s})+(udd)$	yes	yes	no
$p+p\rightarrow\pi^++n+n$	$(uud)+(uud)\rightarrow(u\bar{d})+(udd)+(udd)$	no	yes	yes

decay	Quark configuration	
$\Omega^-\rightarrow\Lambda^0+K^-$	$(sss)\rightarrow(uds)+(\bar{u}s)$	$s\rightarrow u+W^-$ and $W^-\rightarrow\bar{u}+d$
$K^+\rightarrow\pi^++\pi^0$	$(u\bar{s})\rightarrow(u\bar{d})+(u\bar{u}-d\bar{d})$	$\bar{s}\rightarrow\bar{u}+W^+$ and $W^+\rightarrow u+\bar{d}$
$\Xi^+\rightarrow\Lambda^0+\pi^-$	$(dss)\rightarrow(uds)+(\bar{u}d)$	$s\rightarrow u+W^-$ and $W^-\rightarrow\bar{u}+d$





The Standard Model Chart

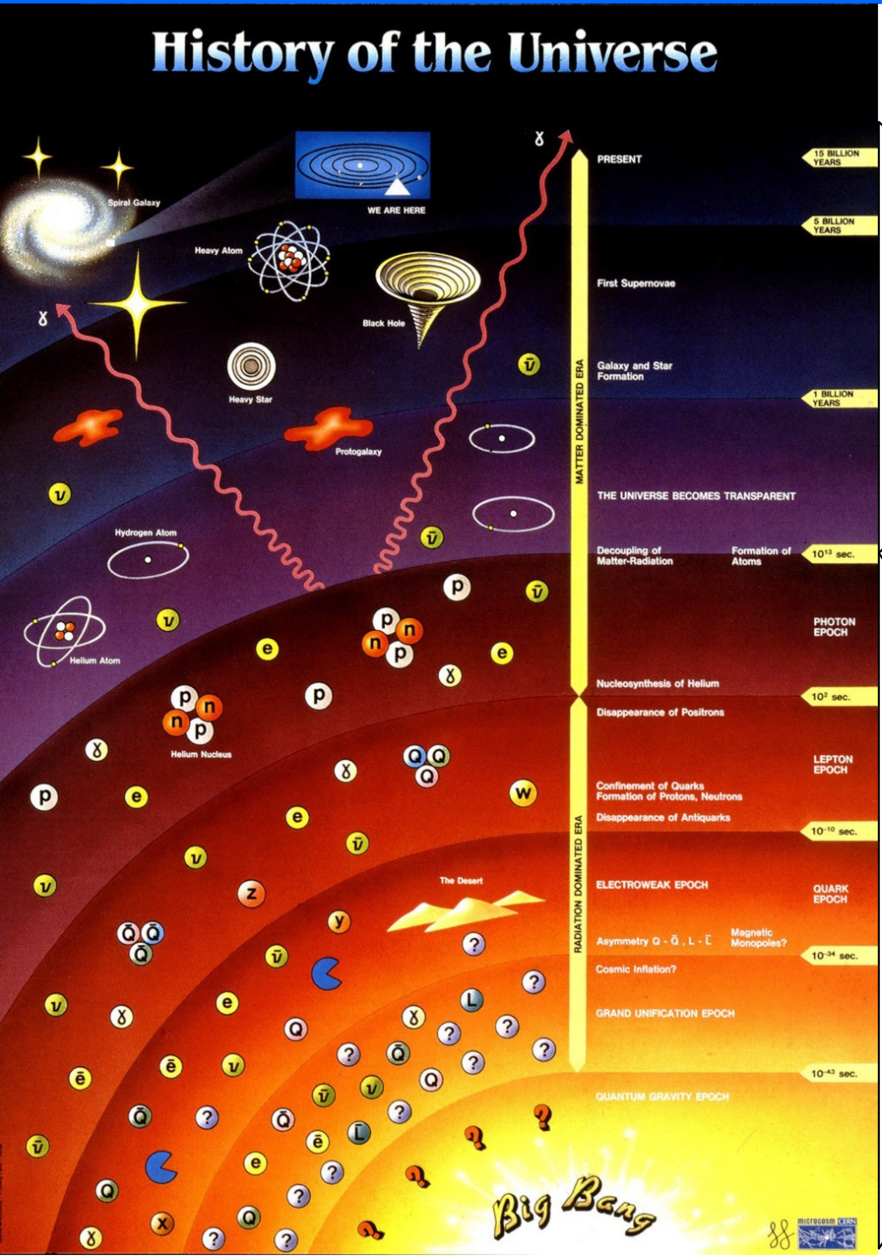


❖ Standard Model does not explain neither appearance of the mass nor the reason for existence of 3 generations.

Particles and Interactions

Force \ Particles	Quarks	Charged Leptons	Neutrinos
Strong	yes	no	no
Electromagnetic	yes	yes	no
Weak	yes	yes	yes

Quarks (hence hadrons) have all types of interactions!



era of gravitation

$10^{13}\ s$

era of particle physics

Units and Dimensions

- The energy is measured in electron-Volts:

$$1\ eV = 1.602 \cdot 10^{-19}\ J$$

1 keV = 10^3 eV; 1 MeV = 10^6 eV; 1GeV = 10^9 eV; 1 TeV = 10^{12} eV

- The Planck constant (reduced) is:

$$\hbar \equiv h/2\pi = 6.582 \cdot 10^{-22}\ MeV\ s$$

and the "conversion constant" is:

$$\hbar c = 197.327 \cdot 10^{-15}\ MeV\ m$$

$$\begin{aligned} \Delta E \cdot \Delta t = \hbar &= energy * time \\ \therefore \hbar c &= energy * time * velocity \\ &= energy * distance \end{aligned}$$

- Charges measured in terms of electronic charges $e = 1.6 \cdot 10^{-19} C$

- Cross sections measured in terms of barns. $1\ barn = 10^{-28}\ m^2$

Units and Dimensions

Because $E^2 = p^2c^2 + m^2c^4$ where E is the energy, p the momentum, m the rest mass: pc and mc^2 have dimensions of energy and it is convenient to measure momentum in units of GeV/c and mass in units of GeV/c^2.

$$[E(GeV)]^2 = [p(GeV/c)]^2c^2 + [m(GeV/c^2)]^2c^4$$

$$1\ eV/c^2 = 1.78 \cdot 10^{-36}\ kg$$

Because c cancels out we often omit the c i.e. put $c=1$ (and $\hbar = 1$), so momenta and masses are also measured in GeV.

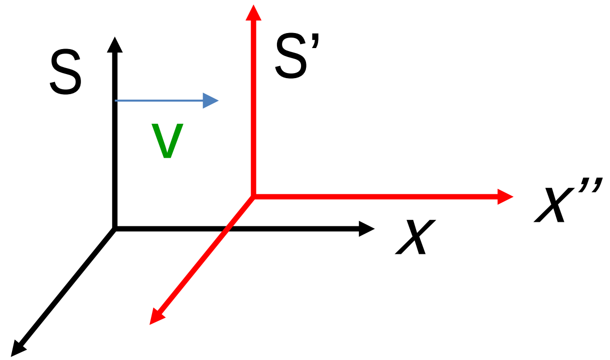
This implies, however, that the results of calculations must be translated back to measureable quantities in the end. Conversion factors are the following:

quantity	conversion factor	natural unit	normal unit
mass	$1kg = 5.61 \cdot 10^{26}\ GeV$	GeV	GeV/c^2
length	$1m = 5.07 \cdot 10^{15} GeV^{-1}$	GeV^{-1}	$\hbar c/GeV$
time	$1s = 1.52 \cdot 10^{24} GeV^{-1}$	GeV^{-1}	$\hbar/GeV$
unit charge	$e = \sqrt{4\pi\alpha}$	1	$\sqrt{\hbar c}$

Excercise-1:
Derive the conversion factors for mass, length and time in the table above.

Lorentz Transformation

Co-moving coordinate systems



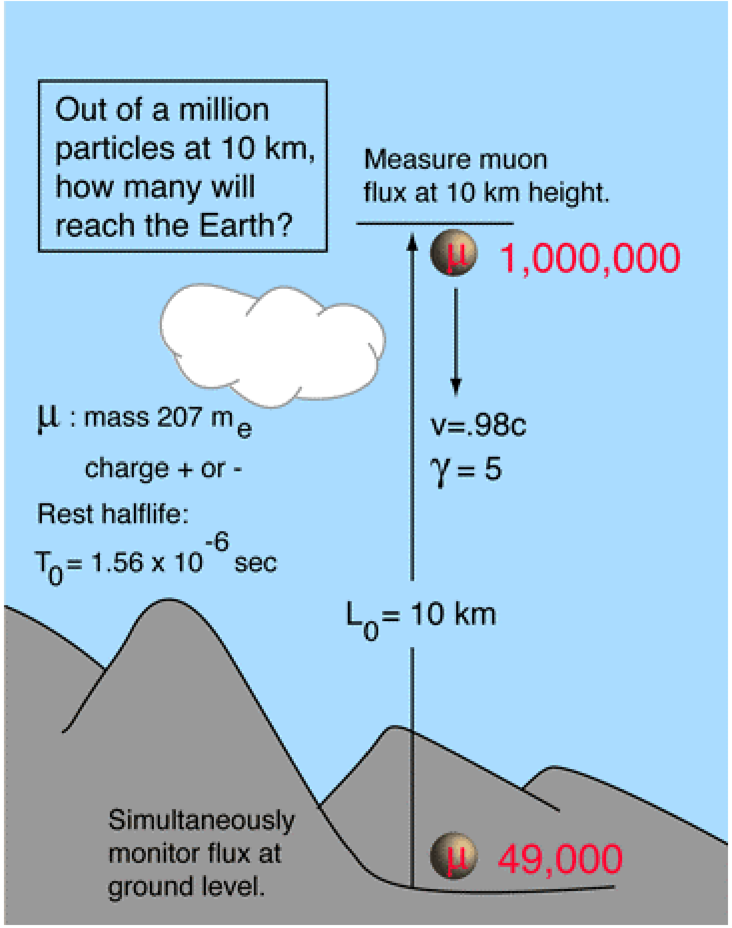
$$S \rightarrow S' : \begin{cases} t' = \gamma(t - \frac{vx}{c^2}) \\ x' = \gamma(x - vt) \\ y' = y \\ z' = z \end{cases} \qquad S' \rightarrow S : \begin{cases} t = \gamma(t' + \frac{vx'}{c^2}) \\ x = \gamma(x' + vt') \\ y = y' \\ z = z' \end{cases}$$

$$\gamma \equiv \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = \frac{v}{c}$$

Lorentz contraction: $L = L_0/\gamma$

Time dilatation: $t = t_0 \cdot \gamma$

Time Dilatation



non-relativistic

Earth-frame observer

Distance: $L_0 = 10^4\ meters$

Time: $T = \frac{10^4\ m}{(0.98)\cdot(3\cdot 10^8\ m/s)}$

$T = 34 \cdot 10^{-6}\ s = 21.8\ halflives$ $= 4.36\ halflives$

Survival rate:

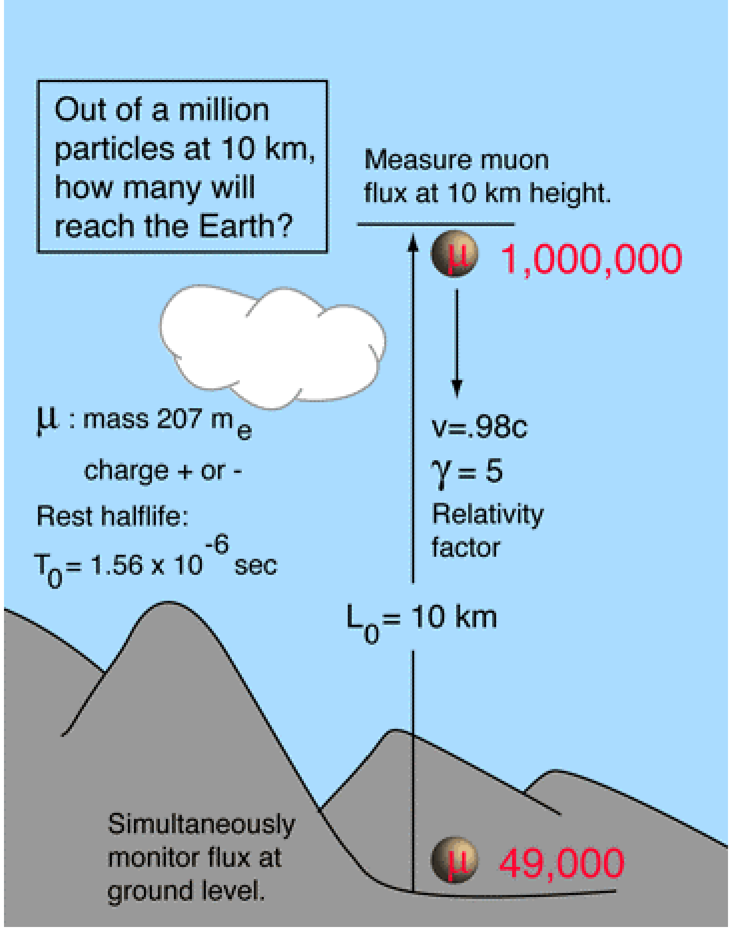
$\frac{I}{I_0} = 2^{-21.8} = 0.27 \cdot 10^{-6}$ $\frac{I}{I_0} = 2^{-4.36} = 0.049$

Or only about 0.3 out of a million

Or only about 49000 out of a million

The muon´s clock is time-dilated, or running slow by a factor $T = \gamma \cdot T_0$ so its measured half-life is $5 \cdot 1.56\ \mu s = 7.8\ \mu s$.

Lorentz Contraction



non-relativistic

Muon-frame observer

Distance: $L_0 = 10^4\ meters$

Time: $T = \frac{10^4\ m}{(0.98)\cdot(3\cdot 10^8\ m/s)}$ $= \frac{2000\ m}{(0.98)\cdot(3\cdot 10^8\ m/s)}$

$T = 34 \cdot 10^{-6}\ s = 21.8\ halflives$ $= 6.8 \cdot 10^6\ s$ $= 4.36\ halflives$

Survival rate:

$\frac{I}{I_0} = 2^{-21.8} = 0.27 \cdot 10^{-6}$ $\frac{I}{I_0} = 2^{-4.36} = 0.049$

Or only about 0.3 out of a million

Or only about 49000 out of a million

The muon sees distance as length-contracted , so that $L = L_0/\gamma = 0.2 \cdot L_0 = 2\ km$.

Relativistic Kinematics

The relativistic relationship between the total energy E, momentum p and rest mass m is

$$E^2 = p^2c^2 + m^2c^4$$

or

$$E^2 = p_x^2c^2 + p_y^2c^2 + {}_z^2pc^2 + m^2c^4$$

Non relativistic ($p \ll m$):

$$\begin{aligned} E &= (p^2c^2 + m^2c^4)^{1/2} \\ &= mc^2 \cdot (1 + p^2c^2/m^2c^4)^{1/2} \\ &= mc^2 \cdot (1 + p^2/2m^2c^2 + \cdots) \\ &\cong mc^2 + p^2/2m \qquad (p = mv) \\ &\cong mc^2 + \tfrac{1}{2}mv^2 \end{aligned}$$

The particle velocity $v = \beta c$ or $\beta = v/c$ and the Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{1}{\sqrt{1-\beta^2}}$$

So that $\gamma^2(1-\beta^2) = 1$ or $\gamma^2 = \gamma^2\beta^2 + 1$ - multiplied by m^2c^4

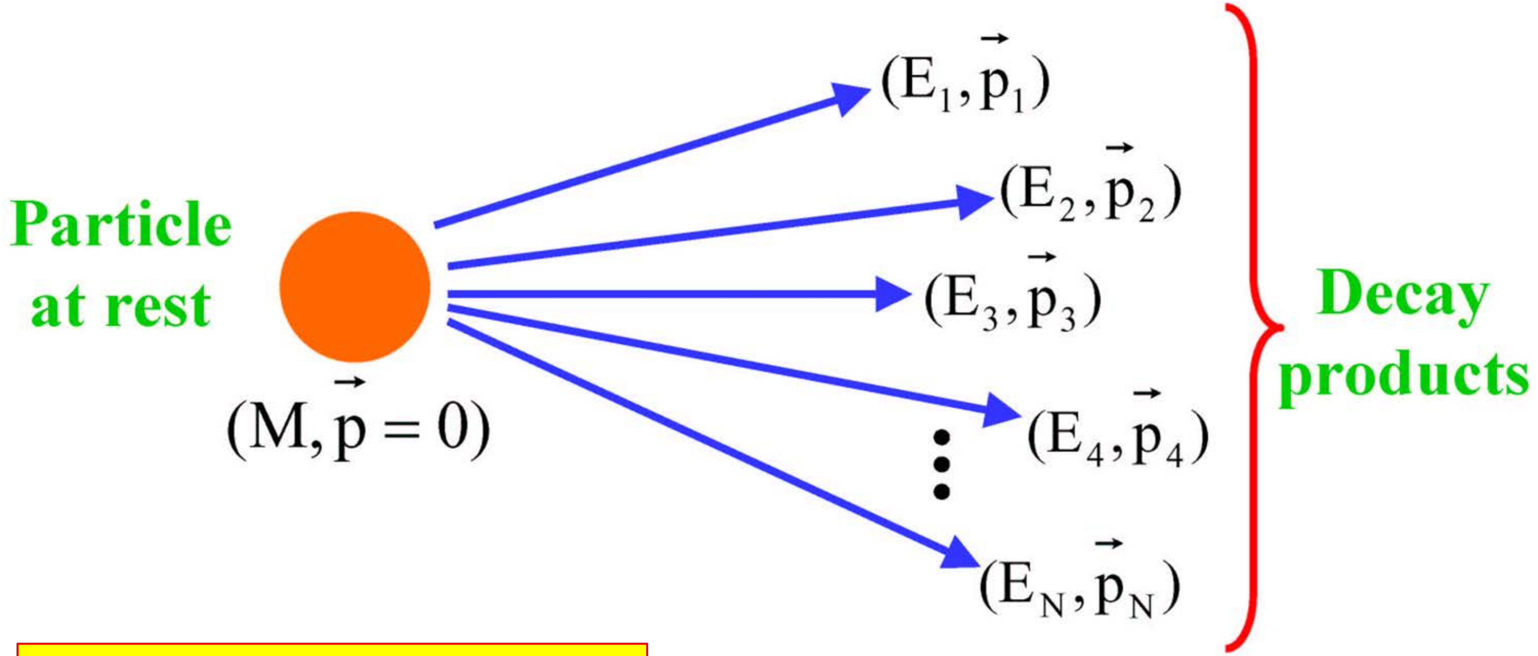
$$\gamma^2m^2c^4 = \gamma^2\beta^2m^2c^4 + m^2c^4$$

Compare with

$$E^2 = p^2c^2 + m^2c^4$$

$E = \gamma mc^2$ and $p = \gamma\beta mc$ or $\gamma = E/mc^2$ and $\beta = p/\gamma mc = pc/E$

Invariant Mass



$$M^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p_i}\right)^2$$

$\pi^0 \rightarrow \gamma\gamma$ decay: (two massless particles)

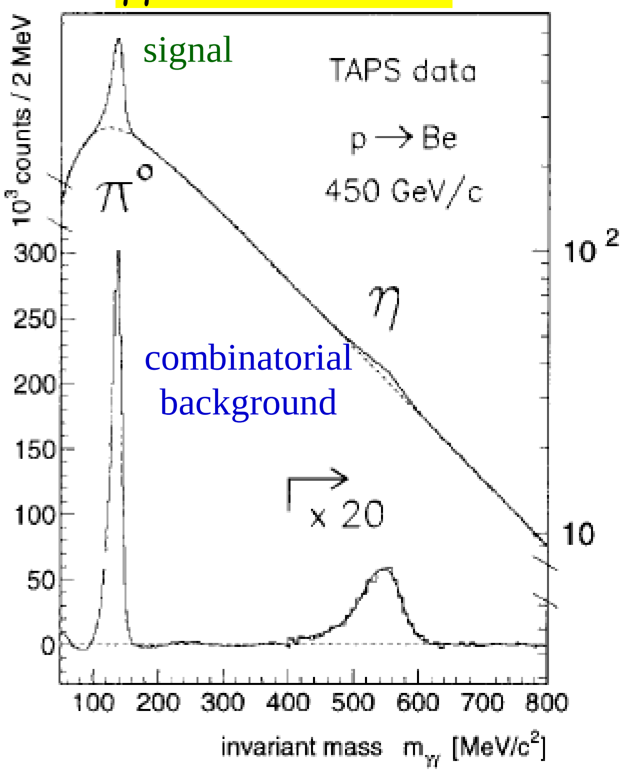
$$M^2 = [(p_1, 0, 0, p_1) + (p_2, 0, p_2 sin\theta, p_2 cos\theta)]^2 = (p_1 + p_2)^2 - p_2^2 sin^2\theta - (p_1 + p_2 cos\theta)^2$$

$$= 2p_1 p_2 (1 - cos\theta)$$

(E, p_x, p_y, p_z)

Example: Data from Two Arm Photon Spectrometer TAPS

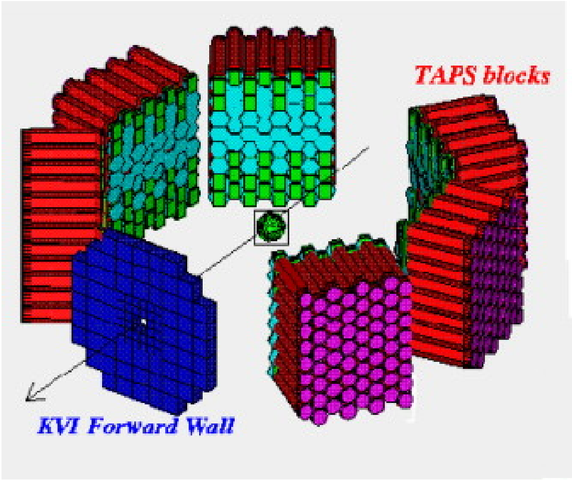
γγ invariant mass



$$\pi^0 \rightarrow \gamma\gamma$$

Compute invariant mass $m_{\gamma\gamma}$ for all possible photon pairs

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - cos\theta_{\gamma\gamma})}$$



Observables

- Scattering ➡ **Cross section** (**σ**)
- Decays ➡ **Decay rate** (**Γ**)

Both **σ** and **Γ** are related to the probability for the considered process to occur

Cross Section

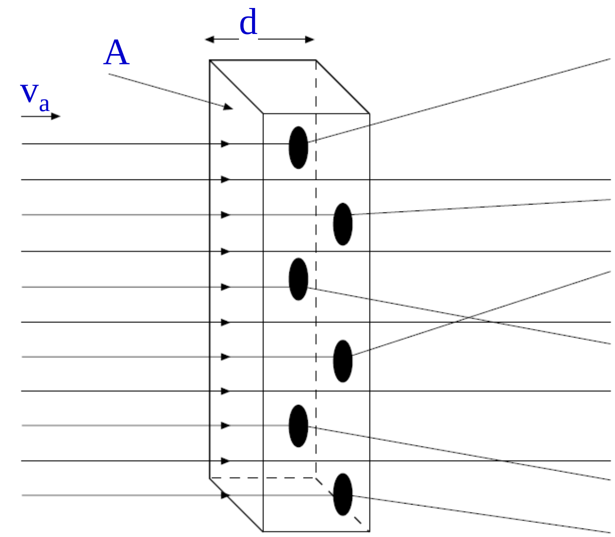
Consider a beam of projectiles of intensity $\mathbf{\Phi_a}$ particles/sec which hits a thin foil of target nuclei with the result that the beam is attenuated by reactions in the foil such that the transmitted intensity is $\mathbf{\Phi}$ particles/sec.
The fraction of the incident particles disappear from the beam, i.e. react, in passing through the foil is given by

$$d\Phi = -\Phi \cdot n_b \cdot \sigma \cdot dx$$

The number of reactions that are occurring is the difference between the initial and transmitted flux

$$\Phi_{initial} - \Phi_{trans} = \Phi_{initial}(1 - exp[-n_b \cdot d \cdot \sigma])$$

$$\approx \Phi_{initial} \cdot N_b \cdot \sigma \qquad \text{(for thin target)}$$



$\Phi_a = n_a \cdot v_a$ $\qquad N_b = n_b \cdot A \cdot d$

Example:

A particle current of 1 pnA consists of $6 \cdot 10^9$ projectiles/s.

A ^{132}Sn target (1 mg/cm²) consists of $5 \cdot 10^{18}$ nuclei/cm²

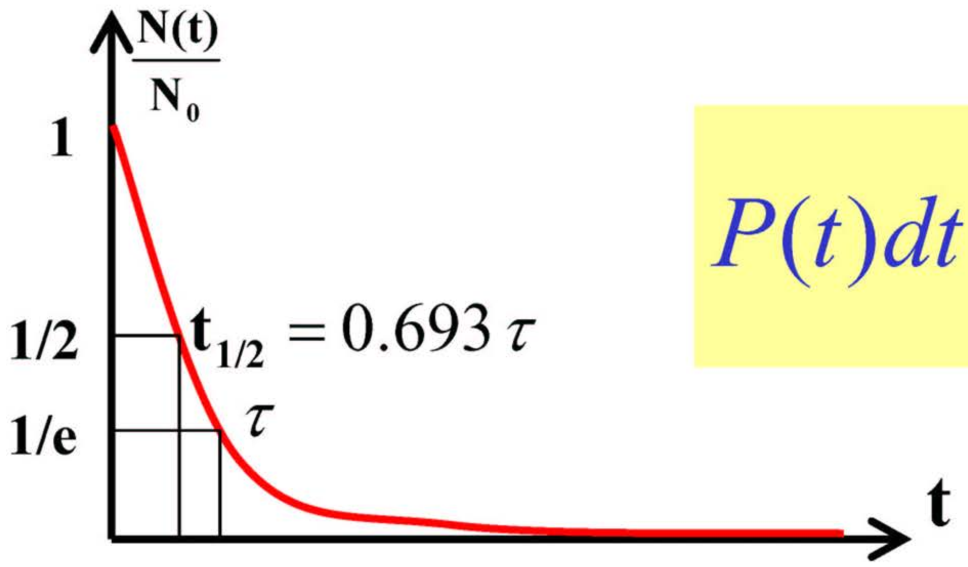
$$\frac{6 \cdot 10^{23} \cdot 10^{-3} \;\; g/cm^2}{132g} = 4.5 \cdot 10^{18} \qquad \left[\frac{target\ nuclei}{cm^2}\right]$$

Luminosity = projectiles [s^{-1}] · target nuclei [cm^{-2}]

Luminosity (projectile → ^{132}Sn) = $3 \cdot 10^{28}$ [$s^{-1}cm^{-2}$]

Reaction rate [s^{-1}] = luminosity · cross section [cm^2]
= projectiles [s^{-1}] · target nuclei [cm^{-2}] · cross section [cm^2]

Decay Time and Lifetime

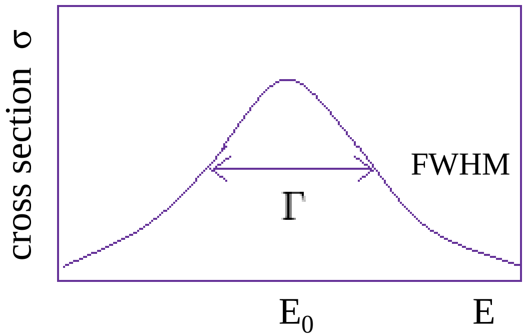


$$P(t)dt = \frac{1}{\tau} e^{-t/\tau} dt$$

$\tau = proper\ time$ $(measured\ in\ the\ particle\ rest\ frame)$

In laboratory frame: $\lambda_{decay} = \gamma\beta c \cdot \tau$

Decay Width



Uncertainty principle → $\Gamma \equiv \frac{\hbar}{\tau}$

If a particle has a finite lifetime τ, it decays with probability $e^{-t/\tau}$ and a decay width Γ can be defined. One can interpret $\Gamma \cdot \tau = \hbar$ as a relationship between uncertainty in energy (mass) and lifetime i.e. $\Delta E \cdot \Delta t = \hbar$.

Strongly decaying particles have very short lifetimes and hence large width. The $\rho(770)$ has $\Gamma = 151\ MeV$ and $\tau = 4.4 \cdot 10^{-24}\ s$.

Weakly decaying particles have longer lifetimes and hence much smaller widths. The K^0 meson has $\Gamma = 7.3 \cdot 10^{-12}\ MeV$ and $\tau = 0.9 \cdot 10^{-10}\ s$.