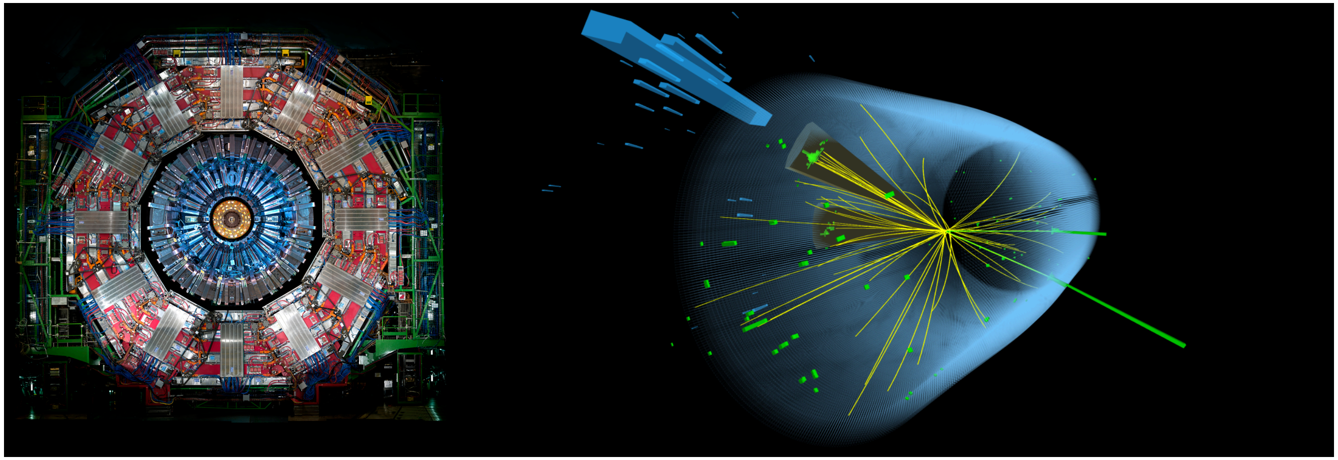

Standard Model and Detector - CMS

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For CAU Particle Physics Lecture Series
January 13 in 2021

What is fundamental?

Problem

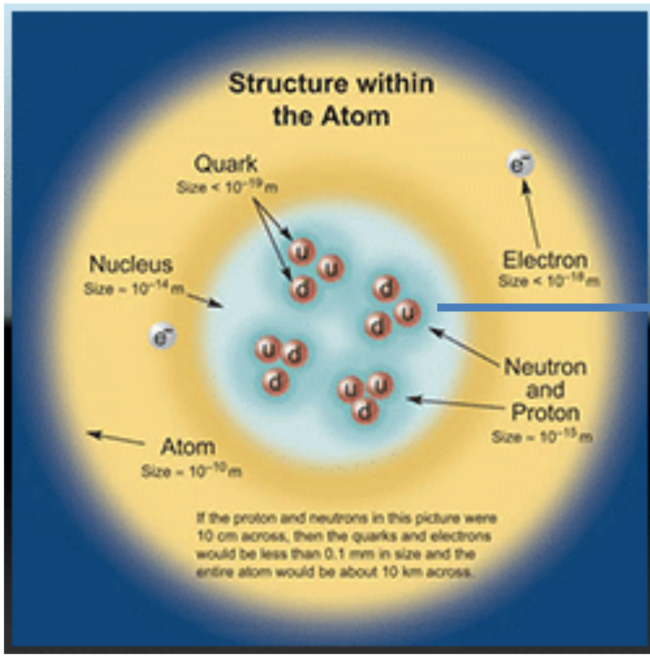
Let's assume that your body is 70 kg and made of only water (partly true because actual percentage is between 60%-90%).

1. **How many water molecule H_2O does your body contain?**
   - ***Hint : mole mass of H_2O is18g/mol***
2. **How many electrons, protons and neutrons in your body?**
   - ***Hydrogen has one electron and one proton***
   - ***Oxygen has 8 electrons, 8 protons and 8 neutrons.***
3. **Mass of electron is 0.5 MeV (9.11×10^{-31}kg) and mass of up quark is around 2.5 MeV and down quark is 5 MeV. Then can you calculate again the mass of your body with electrons, protons, neutrons?**

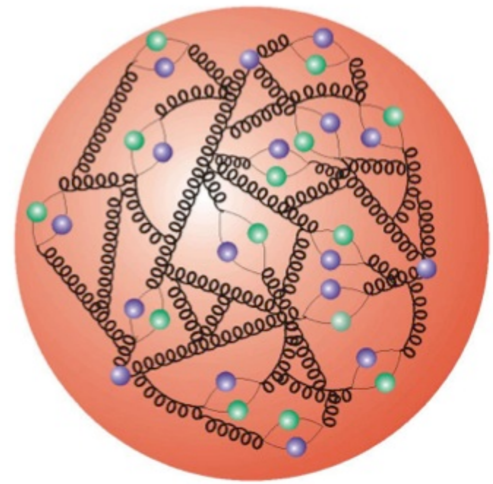
What is the world made of?

The modern atom model

- This is the modern atom model.

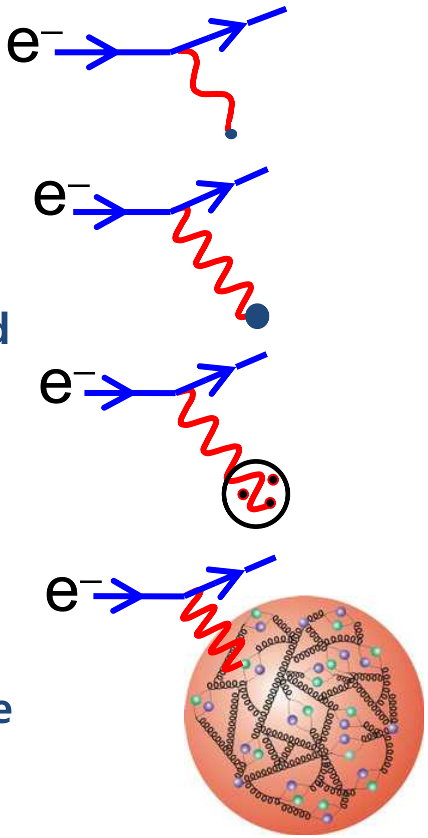


proton



  - Electrons are in constant motion around the nucleus, protons and neutrons jiggle within the nucleus, and quarks jiggle within the protons and neutrons.
  - If electrons and quarks would be less than the diameter of a hair, the entire atom's diameter would be greater than the length of thirty football fields!

Quarks



- In 1964, Murray Gell-Mann and George Zweig suggested that hundreds of the particle could be explained as combinations of just three fundamental particles : “quarks”
- From Deep Inelastic scattering, experiments have since convinced physicists that not only quarks exist, but there are six of them.
  - There are six quarks
  - in terms of three pairs : up/down, charm/strange, and top/bottom.
- Quarks have a fractional electric charge of of 2/3 and -1/3, unlike electron
  - Such charges had never been observed before.
  - Quarks are never observed by themselves, and so initially these quarks were regarded as mathematical fiction.
- Quarks also carry another type of charge called color charge.
- The most elusive quark, the top quark, was discovered in 1995 after its existence had been theorized for 20 years.

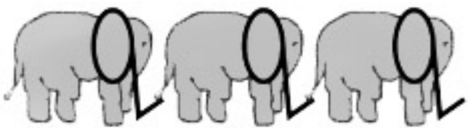
Hadrons, Baryons, and Mesons

- **Quarks only exist in groups with other quarks and are never found alone. Composite particles made of quarks are called**

HADRONS

- **Individual quarks have fractional electrical charges, they combine such that hadrons have a net integer electric charge.**
- **Hadrons have no net color charge.**

BARYONS

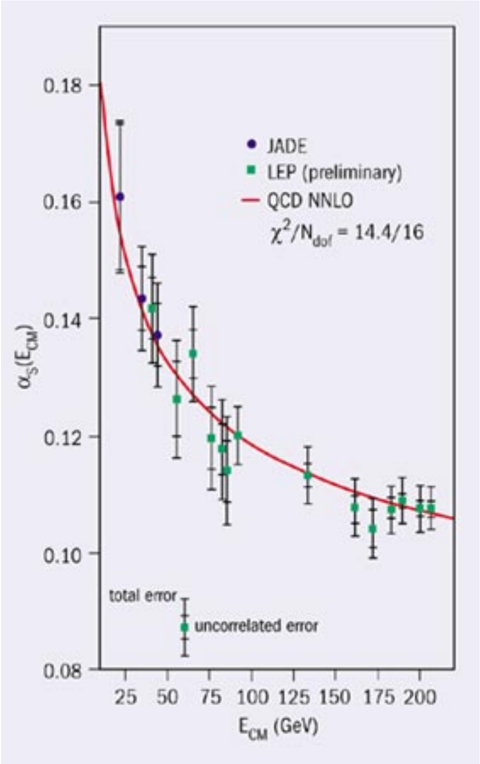


...are any hadron which is made of three quarks (qqq)
Protons (uud) and neutrons (udd) are baryons.

MESONS

...contain one quark (q) and one antiquark ($\bar{q}$).
Pion (π) is made of an up quark and a down antiquark. Anti-pion ($\bar{\pi}$) is made of a down quark and an up antiquark.

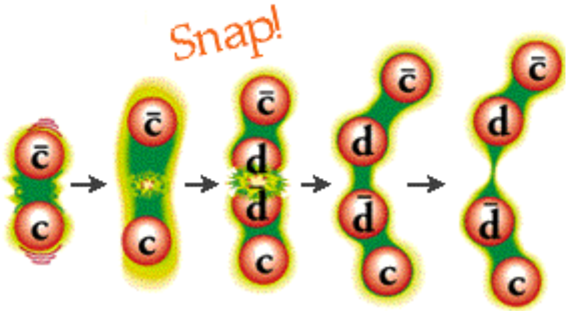
Quark confinement



Asymptotic freedom

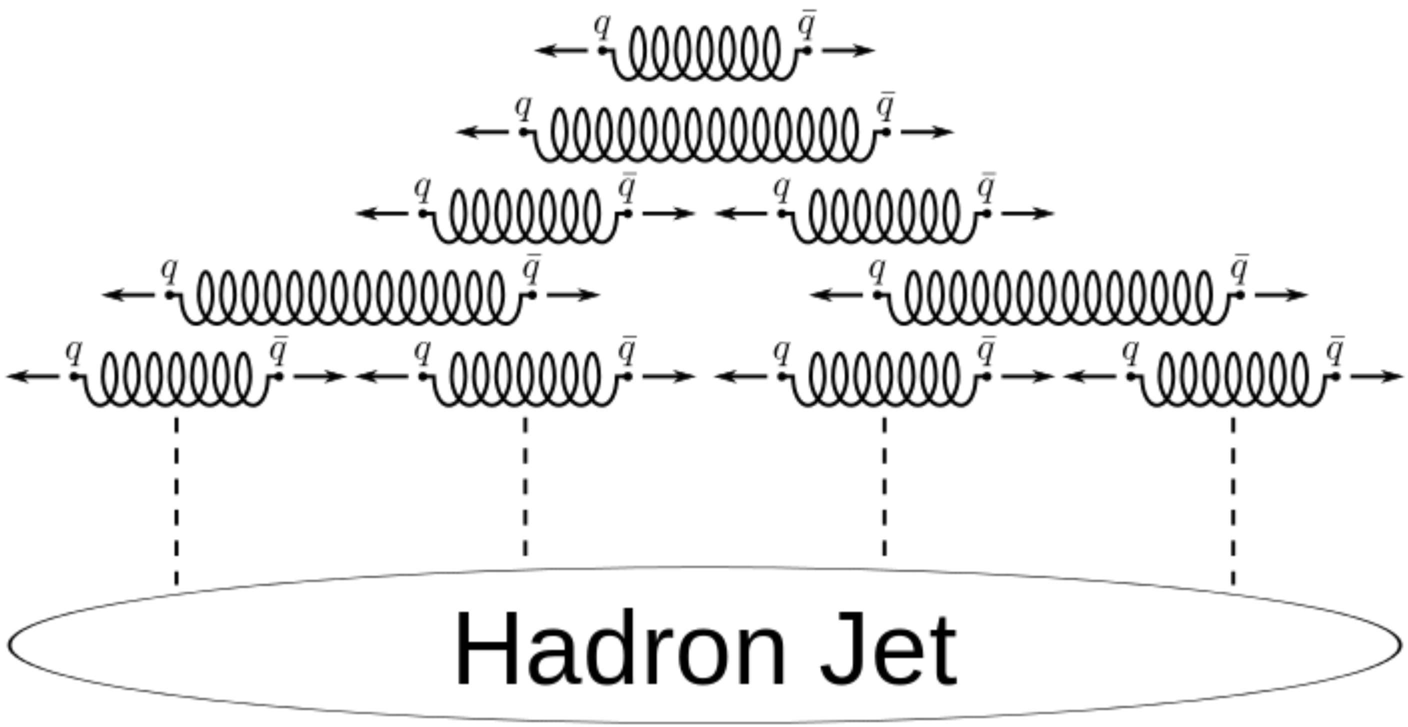
- Quarks can not be found individually. Quarks are confined in groups with other quarks. These composites are color neutral.

- Quarks in hadron madly exchange gluons.
- The Color-force field consists of the gluons holding the bunch of quarks together..



Quarks can not exist individually because the color force increases as they are pulled apart.

A quark becomes a Jet

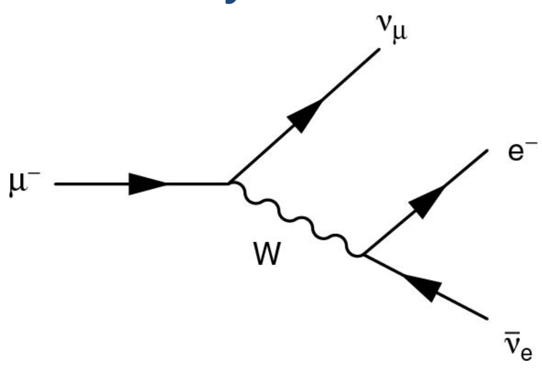


Leptons

- There are six leptons, three of which have electrical charge and three of which do not: electron (e), muon (μ), tau (τ) and the three type of neutrinos (ν).
- Neutrinos have no electrical charge, very little mass, and they are very hard to find.
- Leptons are solitary particles.

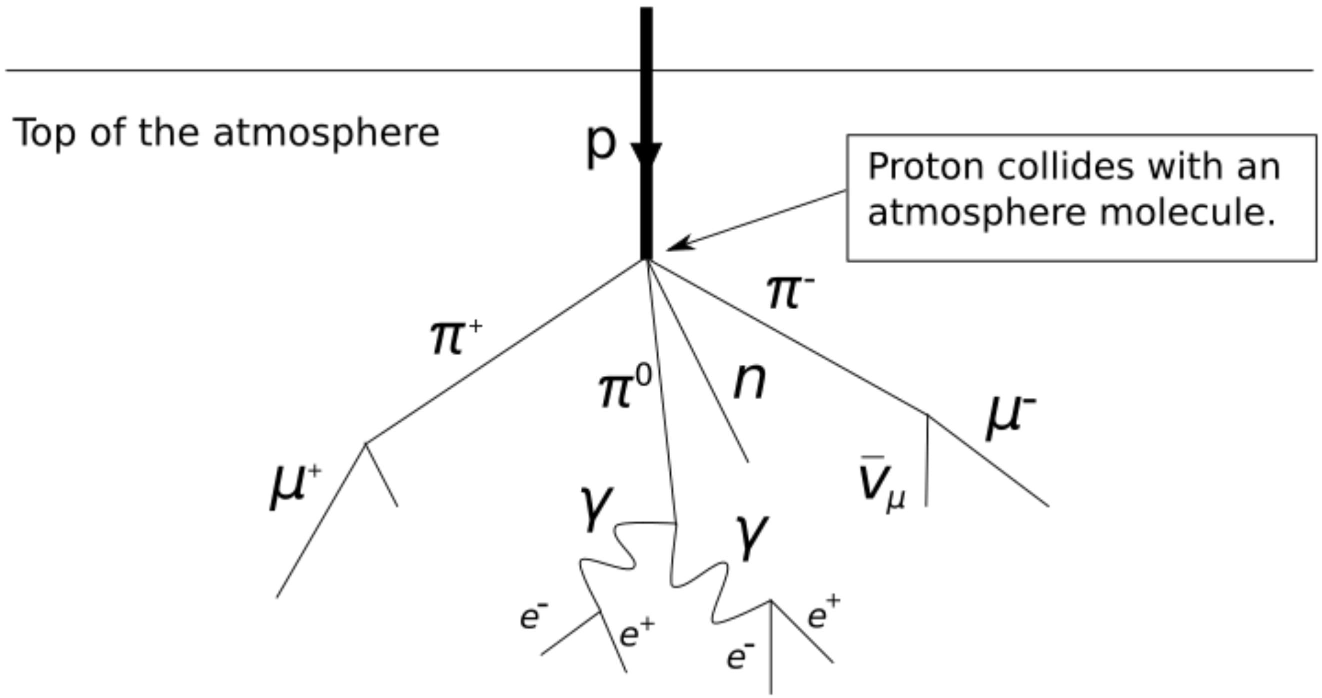
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

- Electrons and the three kinds of neutrinos are stable.
- Leptons are divided into three lepton families: the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino.
- The number of members in each family must remain constant in a decay.



Muon

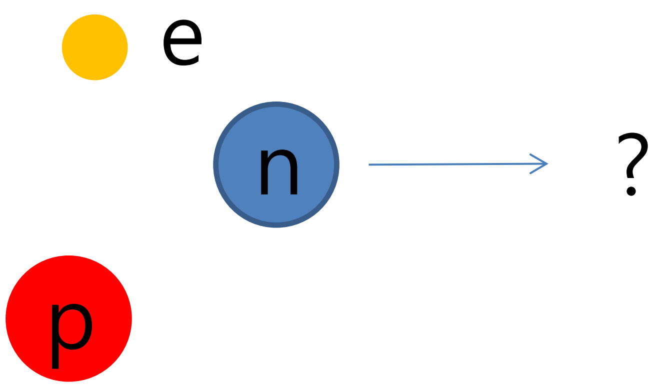
- Muons were discovered by Carl D. Anderson and Seth Neddermeyer at Caltech in 1936
- Muons have a mass of 105.7 MeV, about 207 times that of electron
- Muons can penetrate far more deeply into matter than electron
- So-called "secondary muons", generated by cosmic rays hitting the atmosphere can penetrate to the Earth's surface and even into deep mines



Neutrinos

- Neutrinos pass right through the earth without ever interacting with a single atom of it.
- Neutrinos are produced in a variety of interactions, especially in particle decays.
- It was through a careful study of radioactive decays that physicists hypothesized the neutrino's existence.

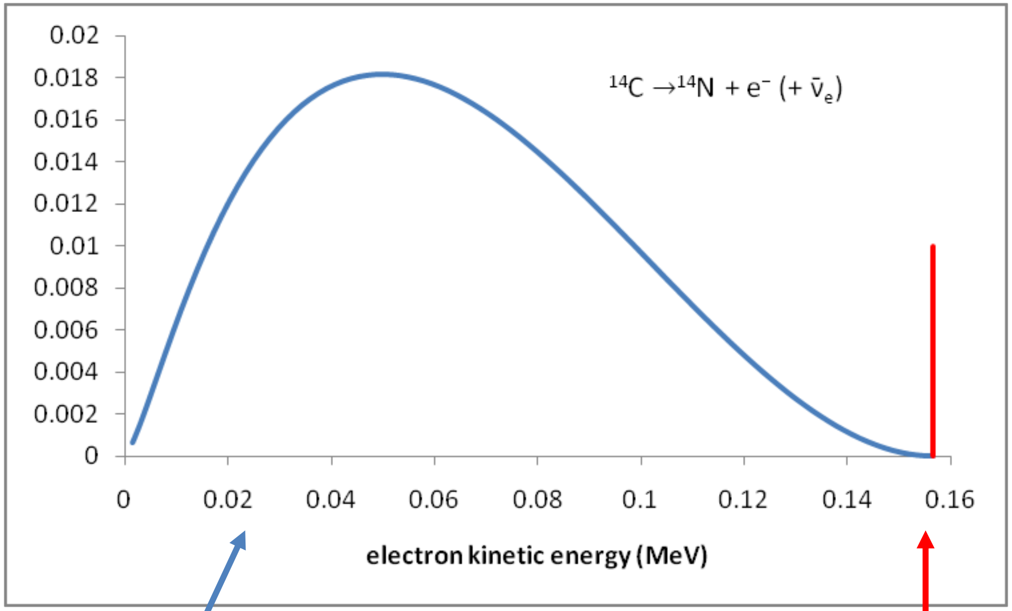
- Wolfgang Pauli compared the momentum and energy before and after a beta decay.
- Because of the law of conservation of momentum, the resulting products of the decay must have a total momentum of zero.



Electron energy spectrum

- **Clearly, it was not the case!**

t2k-experiment.org



Observed

$$m_e < E_e < (\Delta M - m_{\overline{\nu}_e})$$

Expected

$$E_e = \Delta M = M(Z, A) - M(Z + 1, A)$$

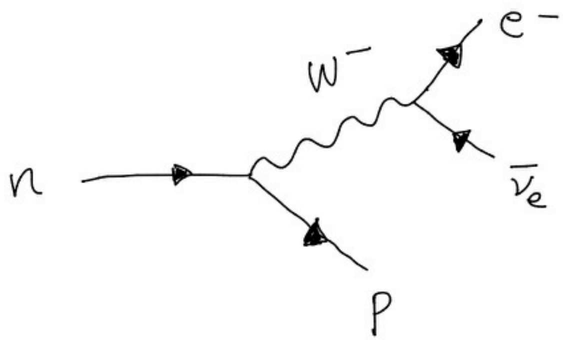
Beta decay

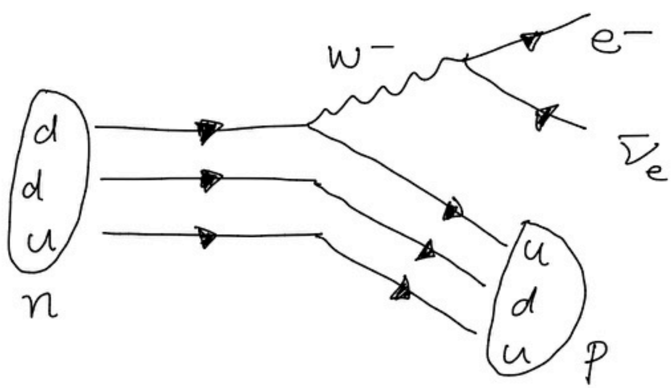
1. The electron energy in the beta decay are found to vary from 0 to a maximum value of the mass lost by decaying nucleus.
2. The direction of the emitted electrons and of the recoiling nuclei are not exactly opposite.
3. The spins of the neutron, proton and electron are all $\frac{1}{2}$ so if it is just neutron involving proton and electron, the spin is not conserved.

- He postulated that there must be some other particle in order for momentum and energy to balance.

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

Feynman diagrams for β decay



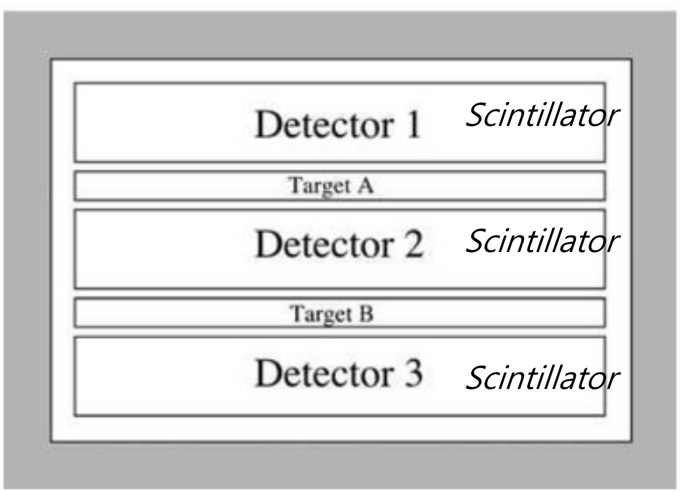


Inverse beta decay

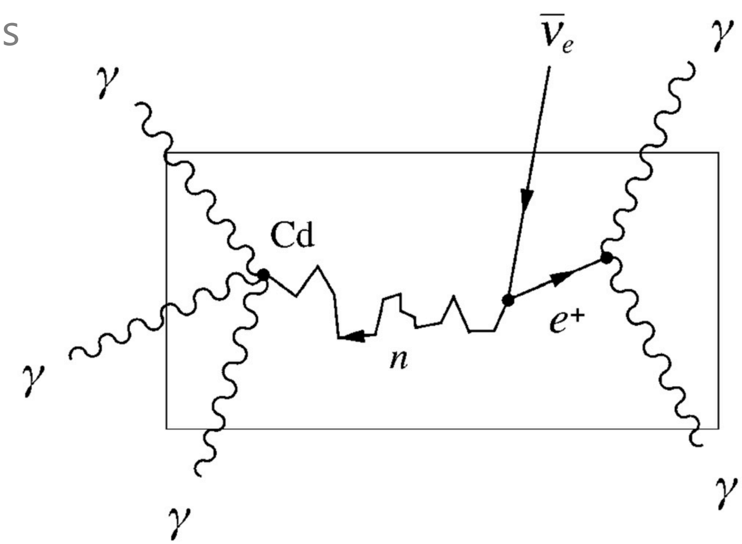
$$p + \bar{\nu} \rightarrow n + e^+$$
$$n + \nu \rightarrow p + e^-$$

- Inverse beta decays have extremely low probabilities but not zero.
- In 1953, a series of experiments was carried out by F. Reines, C. L. Cowan and others.
- Positron finds electron and annihilates each other creating two gamma rays.
- Neutron is captured by Cadmium and gives off gamma ray.

Schematic diagram of the apparatus



Shielding



$$e^+e^- \rightarrow \gamma\gamma$$

$$\mathrm{n} + {}^{108}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd} + \gamma$$

Matter in the Standard Model

- In the Standard Model the fundamental “matter” is described by point-like spine-1/2 fermions
- In the SM, there are three generations – copies of each other differing only in mass
- The neutrinos are much lighter than all other particles
  - We now know that neutrinos have non-zero mass

	LEPTONS			QUARKS		
		q	*mass*		*q*	*mass*
First Generation	e^-	–1	0.5 MeV	u	+2/3	2.2 MeV
	nu_1	0	≈0	d	-1/3	4.7 MeV
Second Generation	mu^-	–1	106 MeV	c	+2/3	1.28 GeV
	nu_2	0	≈0	s	-1/3	96 MeV
Third Generation	tau^-	–1	1.8 GeV	t	+2/3	175 GeV
	nu_3	0	≈0	b	-1/3	4.2 GeV

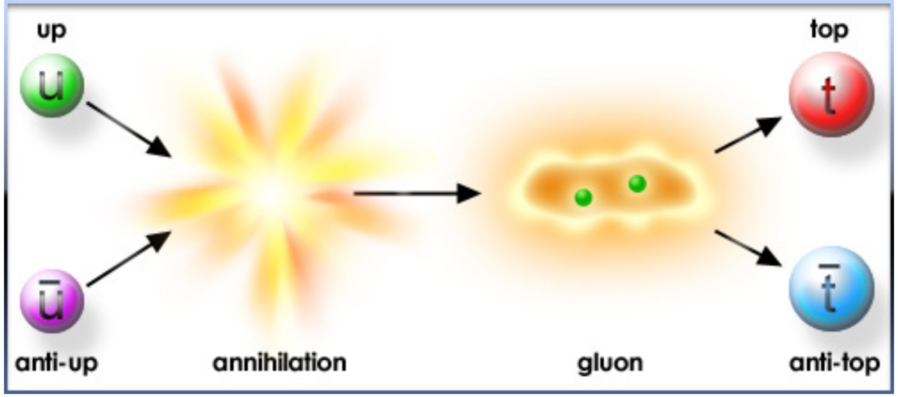
Quarks and leptons

- **Everything from galaxies to mountains to molecules is made from quarks and leptons. This is not the whole story.**
- **Quarks behave differently than leptons.**
- **And there is a corresponding antimatter particle!**

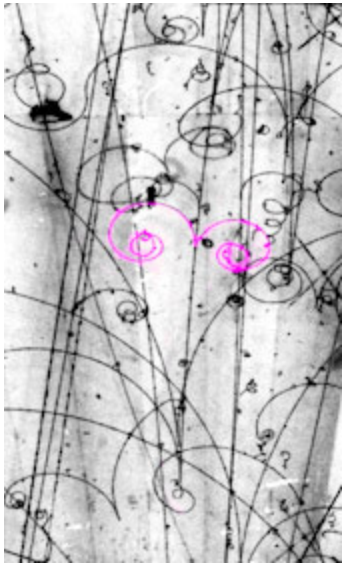
Matter and antimatter

- For every type of matter particle we've found, there also exists a corresponding antimatter particle, or antiparticle.
- Antiparticle look and behave just like their corresponding matter particles except they have opposite charge.
- A proton is electrically positive whereas an antiproton is electrically negative.

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



What is antimatter?



- The universe appears to be composed entirely of matter
- The existence of antimatter was predicted by Paul Dirac in 1928
- But you can see evidence for antimatter in this early bubble chamber photo. The magnetic field in this chamber makes negative particles curl left and positive particles curl right.
- If antimatter and matter are exactly equal but opposite, then why is there so much more matter in the universe than antimatter?
  - We don’t know. It is a question that keeps physicists up at night.

Dirac equation

These problems motivated Dirac (1928) to search for a different formulation of relativistic quantum mechanics in which all particle densities are positive.

Schrödinger equation: $-\frac{1}{2m}\vec{\nabla}^2\psi = i\frac{\partial\psi}{\partial t}$ ⇐ is not Lorentz invariant

→ 1st order in $\frac{\partial}{\partial t}$, 2nd order in $\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}$

Klein-Gordon equation: $(\partial^\mu\partial_\mu + m^2)\psi = 0$ ⇐ $E^2 = |\vec{p}|^2 + m^2$

→ 2nd order throughout

Dirac looked for an alternative, 1st order throughout

$\hat{H}\psi = (\vec{\alpha}\cdot\vec{p} + \beta m)\psi = \frac{i\partial\psi}{\partial t}$

$$\boxed{(i\gamma^\mu\partial_\mu - \mathrm{m})\psi = 0}$$

the four Dirac gamma matrices:
$\gamma^0 \equiv \beta,\ \gamma^1 \equiv \beta\alpha_x, \gamma^2 \equiv \beta\alpha_y, \gamma^3 \equiv \beta\alpha_z$

Dirac equation : Free Particle at Rest

To find free particle solutions:

Wave function $\psi(x,t) = u(E,\vec{p})e^{i(\vec{p}\cdot\vec{r}-Et)}$ **should satisfy the Dirac equation**

$$\left(i\gamma^{\mu}\,\partial_{\mu} - m\,\right)\psi = 0$$

Consider the derivatives of the free particle solution

$$\partial_0\psi = \frac{\partial\psi}{\partial t} = -iE\psi;\, \partial_1\psi = \frac{\partial\psi}{\partial x} = ip_x\psi$$

For a particle at rest $\vec{p} = 0$ **and** $\boldsymbol{\psi = u(E,0)e^{-iEt}}$

$$E\gamma^0 u - mu = 0$$

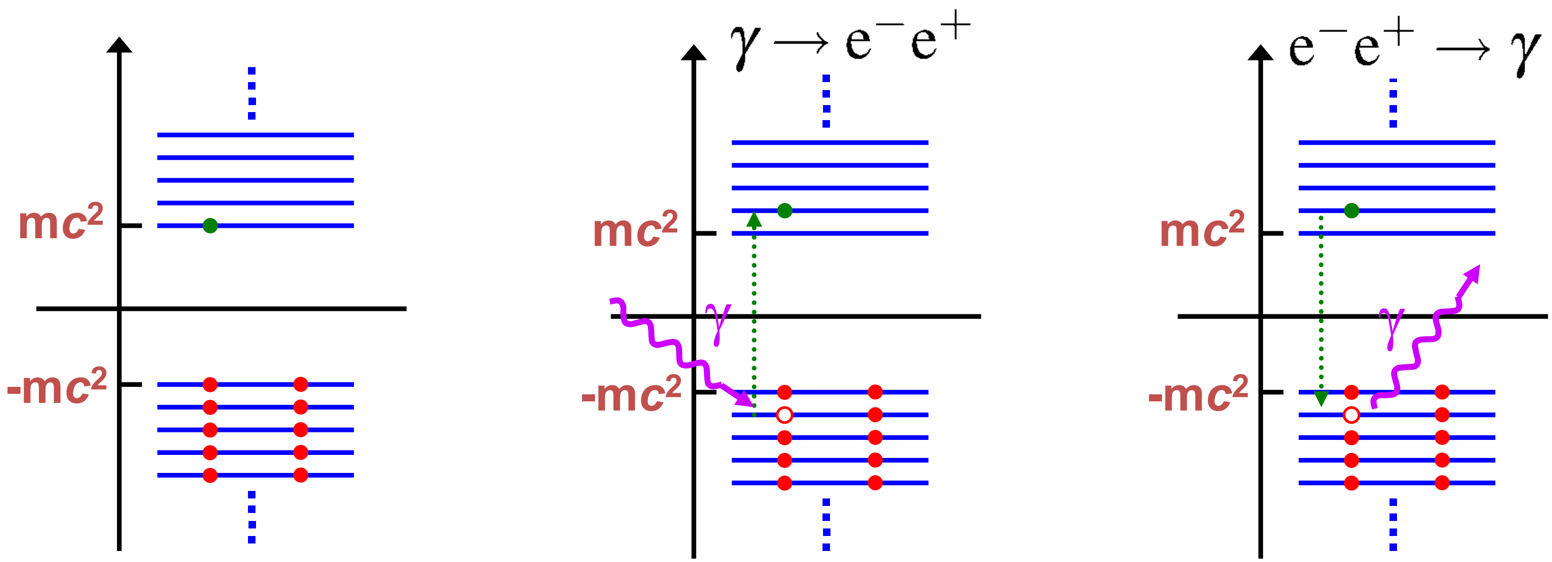
$$E\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & -1 & 0\\ 0 & 0 & 0 & -1\end{pmatrix}\begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\\ \phi_4\end{pmatrix} = m\begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\\ \phi_4\end{pmatrix}$$

$$\underbrace{\psi_1 = \begin{pmatrix}1\\0\\0\\0\end{pmatrix}e^{-imt} \qquad \psi_2 = \begin{pmatrix}0\\1\\0\\0\end{pmatrix}e^{-imt}}_{\text{Two spin (up and down) states with } E>0} \qquad \underbrace{\psi_3 = \begin{pmatrix}0\\0\\1\\0\end{pmatrix}e^{+imt} \qquad \psi_4 = \begin{pmatrix}0\\0\\0\\1\end{pmatrix}e^{+imt}}_{\text{Two spin states with } E<0}$$

Interpretation of negative energy solutions

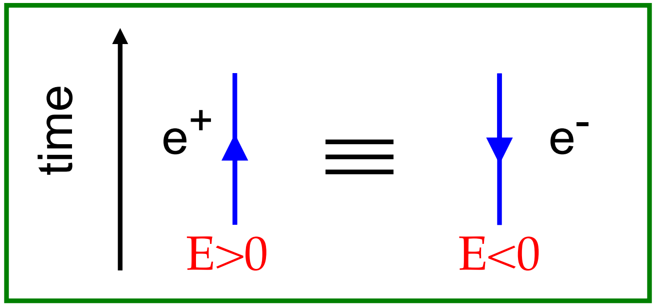
The Dirac equation has negative energy solutions. Unlike the KG equation these have positive probability densities. But how should negative energy solutions be interpreted

<u>Dirac Interpretation:</u> the vacuum corresponds to all negative energy states being full with the Pauli exclusion principle preventing electrons falling into negative energy states. Holes in the negative energy states correspond to positive energy anti-particles with opposite charge. Provides a picture for pair-production and annihilation.

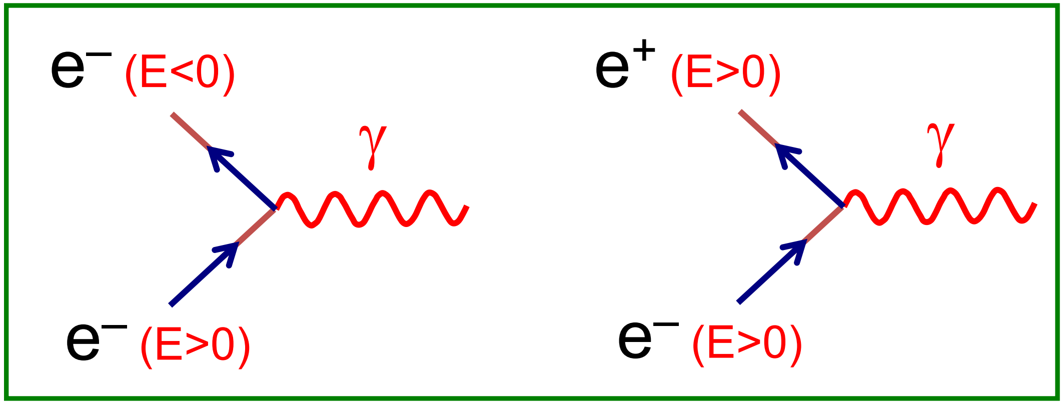


Feynman-Stückelberg Interpretation

Interpret a negative energy solution as
a negative energy particle propagating backwards in time
= a positive energy anti-particle propagating forwards in time.



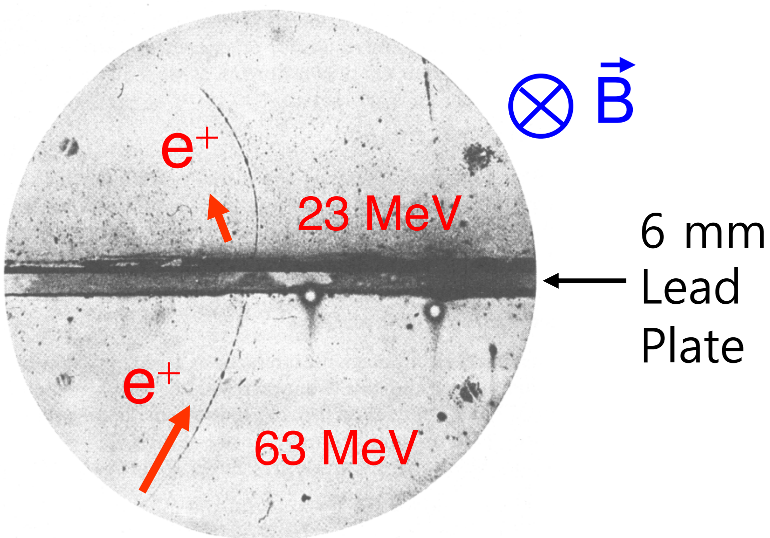
$$e^{-i(-E)(-t)} \rightarrow e^{-iEt}$$



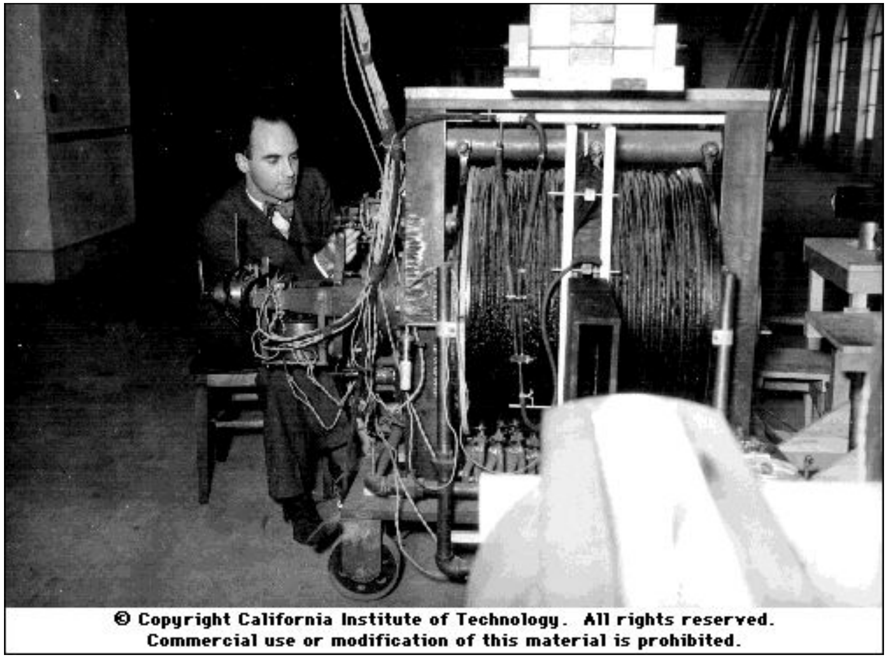
In the Feynman diagram, the arrow on the anti-particle remains in the backwards in time direction to label it an anti-particle solution.

Discovery of Positron

Cosmic ray track in cloud chamber:



C.D.Anderson, Phys Rev 43 (1933) 491



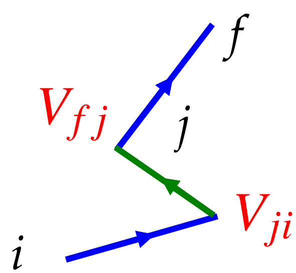
- e^+ enters at bottom, slows down in the lead plate-know direction.
- Curvature in B-field shows that it is a positive particle
- Can't be a proton as would have stopped in the lead

Provided verification of predictions of Dirac equation

What holds it together?

Electromagnetism

- The electromagnetic force causes like-charged things to repel and oppositely-charged things to attract.
  - Friction? Magnetism?
- The carrier particle of the electromagnetic force is the photon (γ).
- Photons have zero mass and always travel at the speed of light, c, which is about 300,000,000 meters per second.



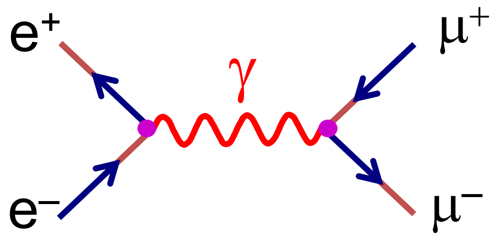
transition rates (Lorentz Invariant quantity)

$$M_{fi} = \frac{g_a g_b}{q^2 - m_x^2}$$

Quantum Field Theory picture – forces arise due to the exchange of virtual particles.

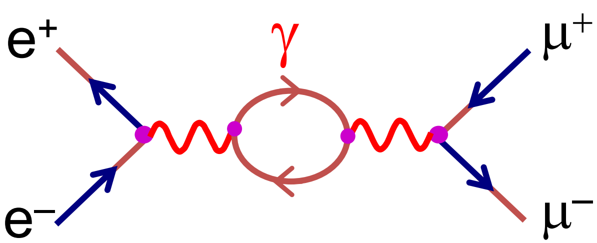
QED Calculation

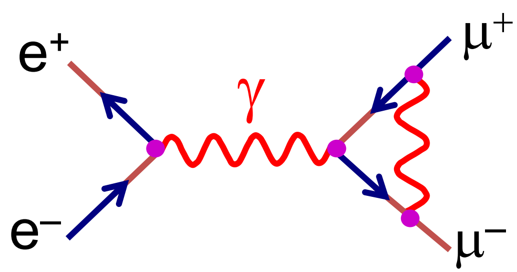
- How to calculate a cross section using QED (e.g. $e^+e^- \to \mu^+\mu^-$):
  1. Draw all possible Feynman Diagrams
     - For $e^+e^- \to \mu^+\mu^-$, there is just one lowest order diagram



$M \propto e^2 \propto \alpha_{em}$ $\boxed{\alpha = \frac{1}{137}}$

     - Then, we need to add next-leading order diagrams…





$M \propto e^4 \propto \alpha_{em}^2$

  2. For each diagram, calculate the matrix using Feynman rules
  3. Sum the individual matrix elements(i.e. sum the amplitudes)

$$M_{fi} = M_1 + M_2 + M_3 + \ldots.$$

Strong force

- Color charge behaves differently than electromagnetic charge.

- Gluons have charge, not like photons.
  - While quarks have color charge, composite particles made out of quarks have no net color charge (color neutral).

- The strong force only takes place on the really small level of quark interactions.

- When two quarks are close to one another, they exchange gluons and create a very strong color force field that binds the quarks together.
  - Gets stronger as the quarks is further apart.
  - Quarks constantly change their color charges as they exchange gluons with other quarks.

Color charge

- There are three color charge and corresponding anti-color charges.
- A mix of red, green and blue light yields white light.
  - In a baryon, a combination of “red”, “green” and “blue” color charges is color neutral.
  - Same for anti-baryon.
  - Mesons are color neutral because they carry combinations such as “red” and “anti-red”.
- Gluons can be thought of as carrying a color and anti-color charge. Since there are nine possible color anti-color combinations, we might expect nine different gluon charges.
- But the mathematics works out such that there are only eight combinations.

Quarks emit gluons

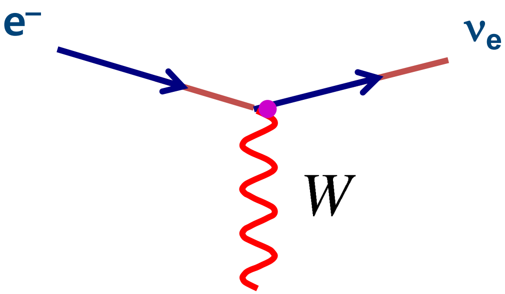
- When a quark emits or absorbs a gluon, that quark's color must change in order to conserve color charge.
- A red quark changes into a blue quark emitting a re/anti-blue gluon.
- Quarks emit and absorb gluons very frequently within a hadron. There is no way to observe the color of an individual quark.

Weak interaction

- When a quark or lepton changes type (a muon changing to an electron), it is said to change flavor. All flavor changes are due to the weak interaction

- The charged current ($W^{\pm}$) weak vertex is: VECTOR - AXIAL-VECTOR (V-A) current

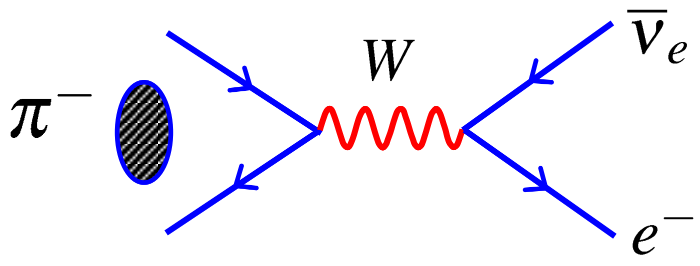
$$\boxed{\frac{-ig_W}{\sqrt{2}}\frac{1}{2}\gamma^{\mu}(1-\gamma^{5})}$$

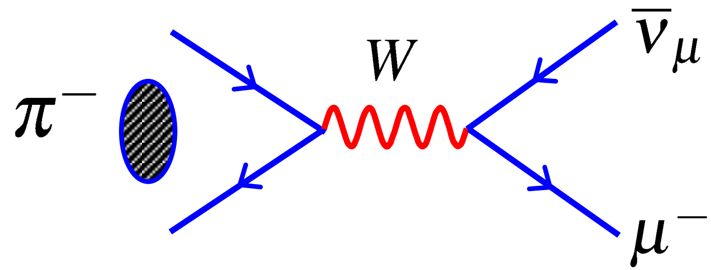


➡ give parity violation

Only the left-handed chiral components of particle spinors and right-handed chiral components of anti-particle spinors participate in charged current weak interactions

Pion Decay





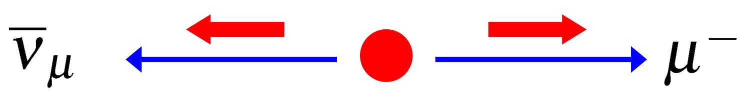
<u>**EXPERIMENTALLY:**</u>

$$\frac{\Gamma(\pi^- \to e^- \overline{\nu}_e)}{\Gamma(\pi^- \to \mu^- \overline{\nu}_\mu)} = 1.23 \times 10^{-4}$$

- **Might expect the decay to electrons to dominate – due to increased phase space…. The opposite happens, the electron decay is helicity suppressed**

★**Consider decay in pion rest frame.**

- **Pion is spin zero: the spins of the ν and μ^- are opposite**
- **Weak interaction only couples to Right-Handed chiral anti-particle states. Since neutrinos are (almost) massless, must be in RH Helicity state**
- **Therefore, to conserve angular mom. muon is emitted in a RH HELICITY state**



- **But only left-handed CHIRAL particle states participate in weak interaction?**
- **Muon has the mass so chiral state is not the same as helicity state.**

Electroweak

- In the Standard Model, the weak and the electromagnetic interactions have been combined into a unified electroweak theory.
  - The weak and electromagnetic forces have essentially equal strengths.
- The strength of the interaction depends strongly on both the mass of the force carrier and the distance of the interaction.
- These two forces became different due to the fact that W and Z particles have huge mass while the photon has no mass.

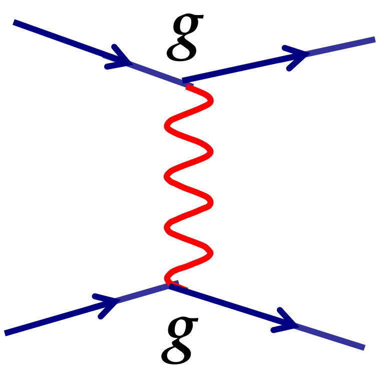
- **How about Gravity?**

- Gravity is clearly one of the four fundamental interactions.
- But the Standard Model can not explain it!
- The carrier of the gravity is graviton: which is not found yet!
- The effects of gravity are extremely tiny in most of particle physics situations compare to other three interactions. So theory and experiment can be compared without including gravity in the calculation.

Forces in the Standard Model

- **Forces mediated by the exchange of spin-1 Gauge Bosons**

Force	Boson(s)	J^P	GeV
EM (QED)	Photon γ	1^-	0
Weak	$W^\pm$ / Z	1^-	80 / 91
Strong (QCD)	8 Gluons g	1^-	0
Gravity (?)	Graviton?	2^+	0



- **Fundamental interaction strength is given by charge** g.
- **Related to the <u>dimensionless</u> coupling "constant"** α

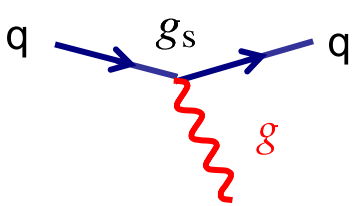
e.g. QED $g_{em} = e = \sqrt{4\pi\alpha\epsilon_0\hbar c}$

- **In Natural Units:** $g = \sqrt{4\,\pi\alpha}$ **(both** g **and** α **are dimensionless but** g **contains a hidden** $\hbar c$**)**
- **Convenient to express couplings in terms of** α **which, being genuinely dimensionless does not depend on the system of units (this is not true for the numerical value for** e**)**

Standard Model Vertices

- Interaction of **gauge bosons** with **fermions** described by SM vertices.
- Properties of the **gauge bosons** and **nature of the interaction** between the bosons and fermions determine the properties of the interaction.

STRONG

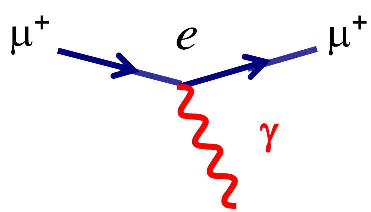


Only quarks

Never changes flavour

$$\alpha_S \sim 1$$

EM

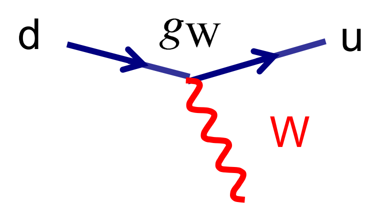


All charged fermions

Never changes flavour

$$\alpha \simeq 1/137$$

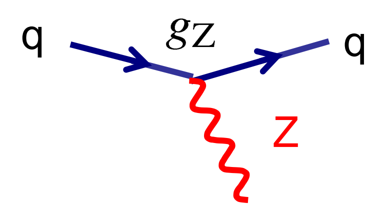
WEAK CC



All fermions

Always changes flavour

WEAK NC



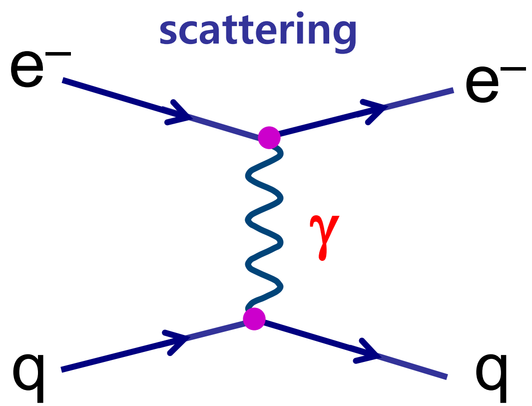
All fermions

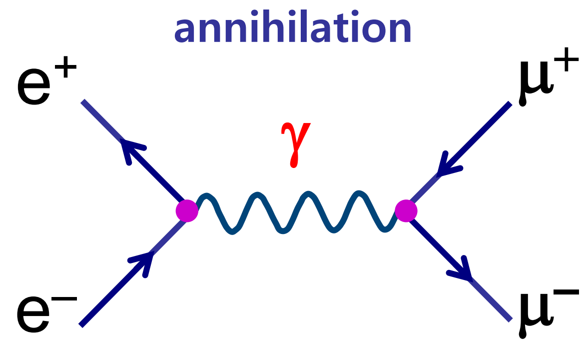
Never changes flavour

$$\alpha_{W/Z} \sim 1/40$$

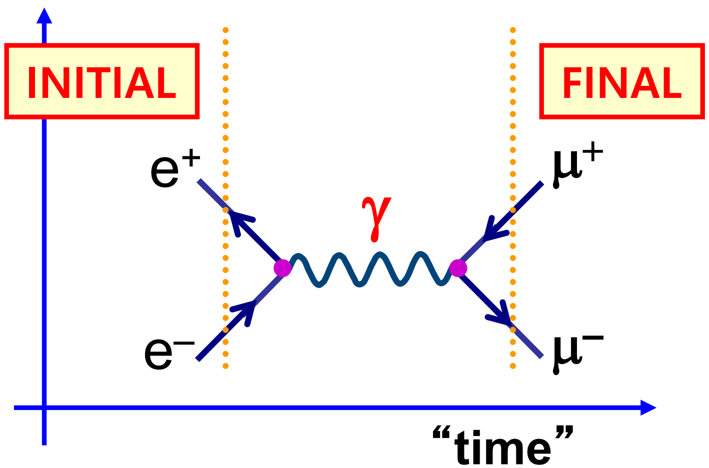
Feynman Diagrams

- Particle interactions described in terms of Feynman diagrams





- Important to remember
  - "time" runs from left to right only in sense that
    - LHS of diagram is initial state
    - RHS of diagram is final state
    - Middle is "how it happened"
  - Anti-particle arrows in negative "time" direction
  - Energy, momentum, angular momentum, etc. conserved at all interaction vertices
  - All intermediate particles are "virtual"
    - $E^2 \neq |\vec{p}|^2 + m^2$

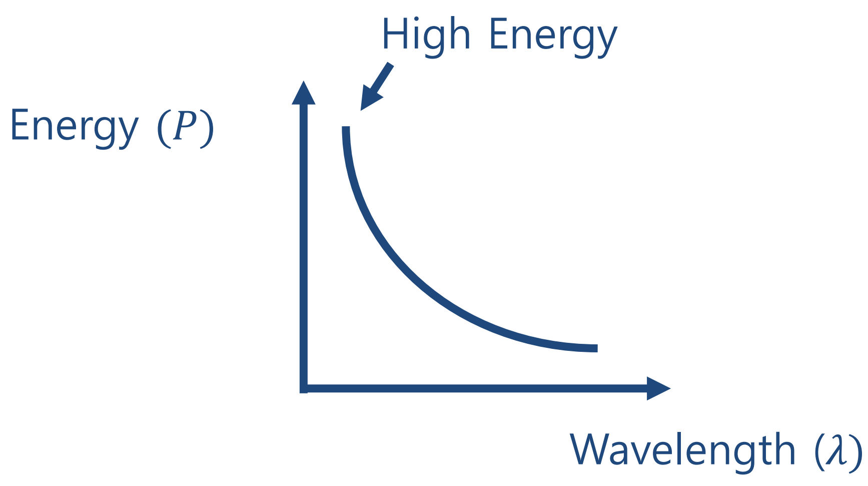


How do we experiment with tiny particles?

The physics tool: the accelerator

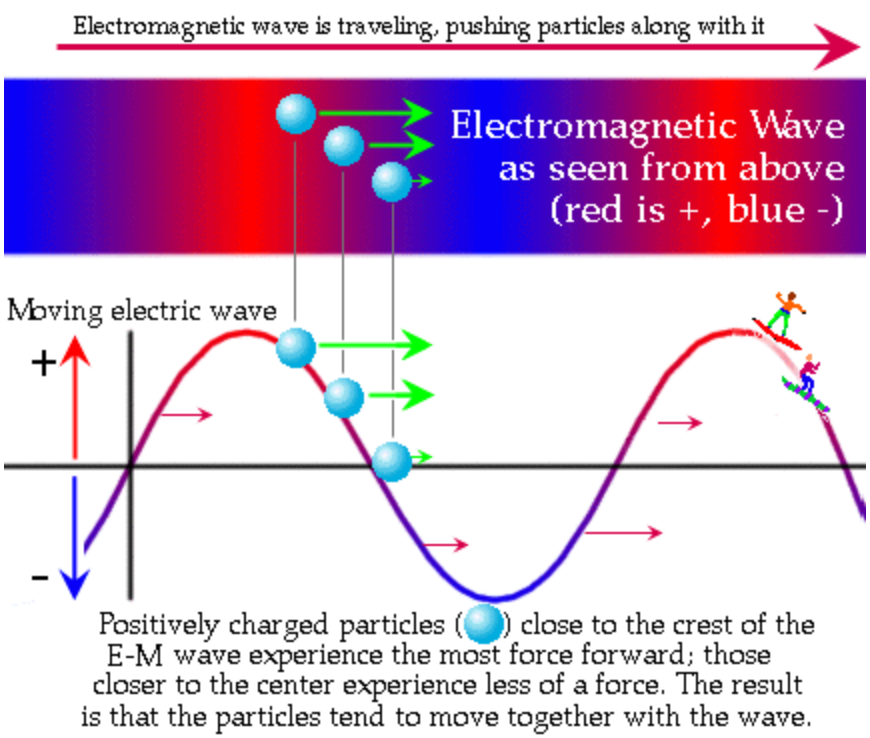
- **How do we decrease the wavelength?**

- **A particle's momentum and its wavelength are inversely related.**
- **High-energy physicists apply this principle when they use particle accelerators to increase the momentum of a probing particle, thus decreasing its wavelength.**



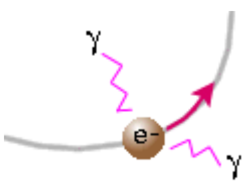
Accelerating particles

- **Accelerators speed up charged particles by creating large electric fields which attract or repel the particles.**



Advantages of accelerator design

- The advantage of a circular accelerator over a liner accelerator:
  - Can provide very high-energy by going around many times
  - Many times around also means higher probability for collisions



- The advantage of a linear accelerator:
  - Easier to build
  - When a charge particle is accelerated, it radiates away energy. This is Bremsstrahlung radiation
  - Much worse for accelerating electrons

Colliding beam experiment

- The center-of-mass energy $\sqrt{s}$ is from Lorentz Invariant quantity $s = (\Sigma E_i)^2 - (\Sigma p_i)^2$ where $c = 1$.

- In a colliding-beam experiment two beams of high-energy particles are made to cross each other.

$$\sqrt{s} = E_p + E_p = 2E_p$$

- A collision between them is more likely to produce a higher mass particle than would a fixed-target collision at the same energy.

$$s = \left(E + m_p\right)^2 - p^2 = 2m_p^2 + 2m_pE \approx 2m_pE \rightarrow \sqrt{s} = \sqrt{2m_pE}$$

Synchrotron radiation

- A particle moving in a circular orbit in a magnetic field radiates away energy in the form of photons

$$\Delta E = \frac{4\pi q^2 \beta^3 \gamma^4}{3\rho}$$

- For highly relativistic particles, $\beta = 1$, $E = \gamma m_0 c^2$

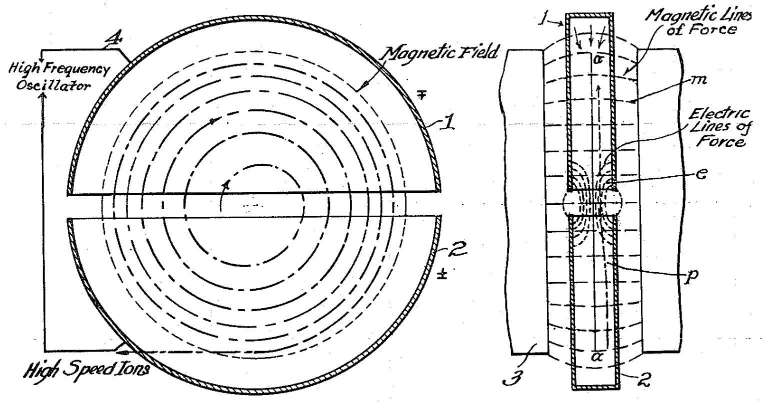
  energy loss is inversely proportional to the fourth power of the particle 's mass

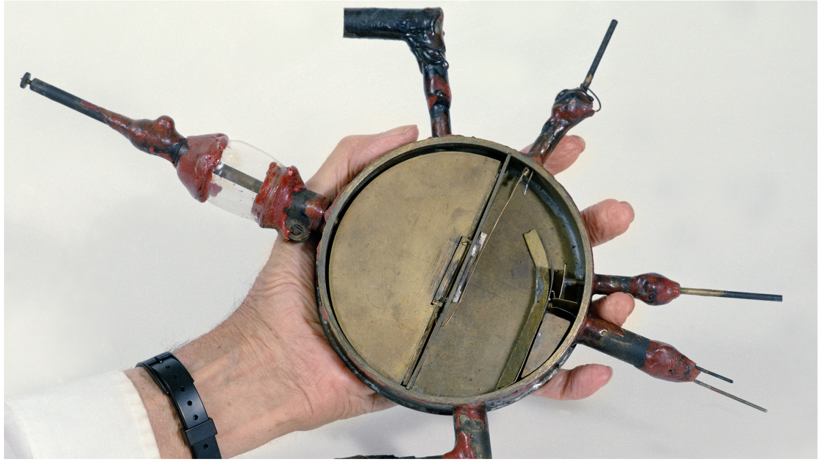
- The losses for electrons are very severe
  - Electron mass ~ 0.5 MeV
  - Proton mass ~ 938 MeV

$$\Longrightarrow \quad \frac{\Delta E}{\Delta E_p} \approx 10^{13}$$

Cyclotron

- Ernest Lawrence invented cyclotron → First cyclotron is only 10 cm
- This was the beginning of a big science because the cyclotron needs to be bigger and bigger in order to obtain particles of high energy





For the circular motion, centripetal force is Lorentz force

Particle reaches its maximum energy at $r = R$

$$\frac{mv^2}{R} = qvB \rightarrow v = \frac{qBR}{m}$$

Frequency $f = \frac{1}{T} = \frac{qB}{2\pi m}$ Energy $E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$

Relativistic considerations

- **The relativistic mass** $m = \frac{m_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \frac{m_0}{\sqrt{1-\beta^2}} = \gamma m_0$ $\quad$ m_0 **is the particle rest mass**

- **Relativistic cyclotron frequency and angular frequency**

$$f = \frac{qB}{2\pi\gamma m_0} = \frac{f_0}{\gamma} = f_0\sqrt{1-\beta^2} = f_0\sqrt{1-\left(\frac{v}{c}\right)^2}$$

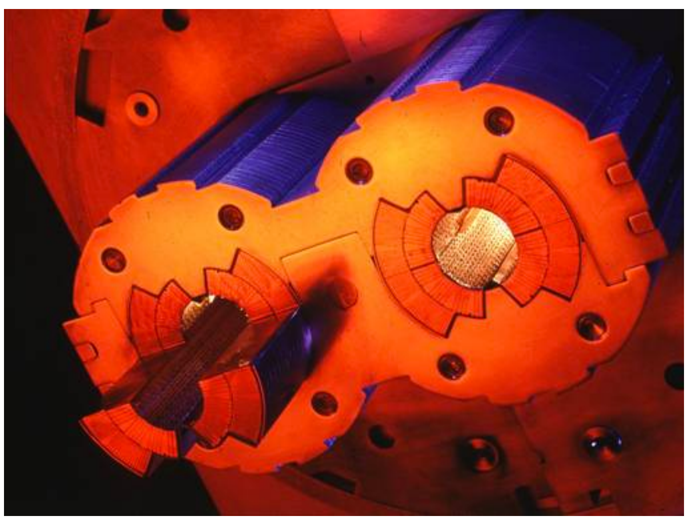
- **Synchrotron : Radius is fixed. To keep the radius r, magnetic field should also increase**

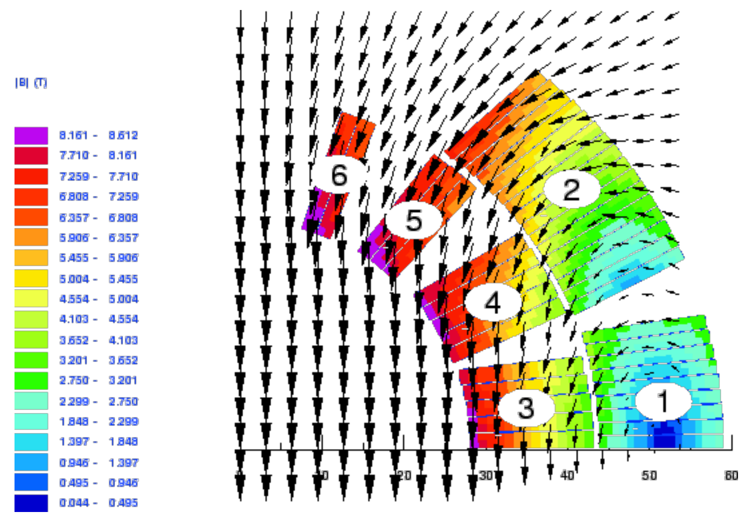
$$B = \frac{vm}{qR}$$

- **The magnetic field and the frequency are increased from their initial values $\mathrm{B_i}$ and ω_i to final values $\mathrm{B_f}$ and $\mathrm{w_f}$**
- **The energy of the bunch of particles is increased during this process from the injection energy $\mathrm{E_i}$ to the final energy $\mathrm{E_f}$**

Main dipole at the LHC

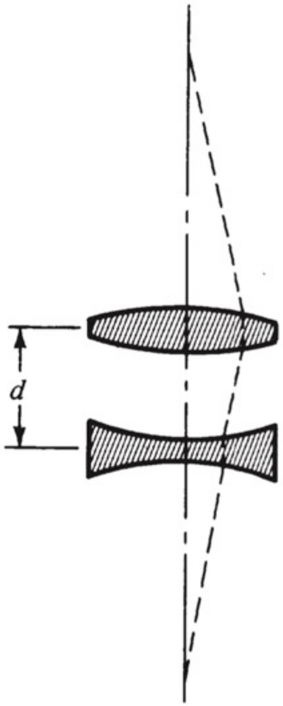
- To bend protons
- 8 Tesla at 1.9 K
- Each one is 14.3 meters long
- A total of 1232 are needed





https://lhc-machine-outreach.web.cern.ch

Focusing magnets



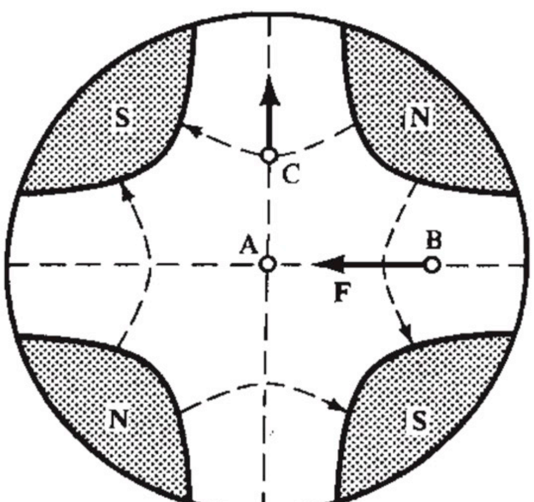
- Combination of a focusing and a defocusing lens with equal focal lengths is always focusing

$$f_{comb} = \frac{f^2}{d}$$

- A train of focusing and defocusing magnets has a net focusing effect

Defocusing plane

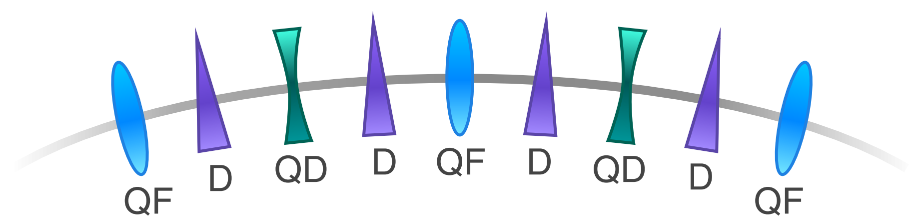
QF – QD – QF – QD -...



Focusing plane ⬅ **Quadrupole magnet**

Synchrotron

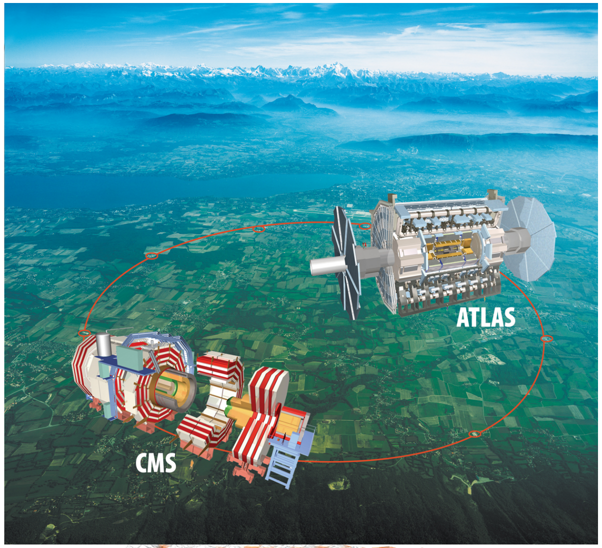
- Synchrotron is a circular ring of magnets in a repeating series

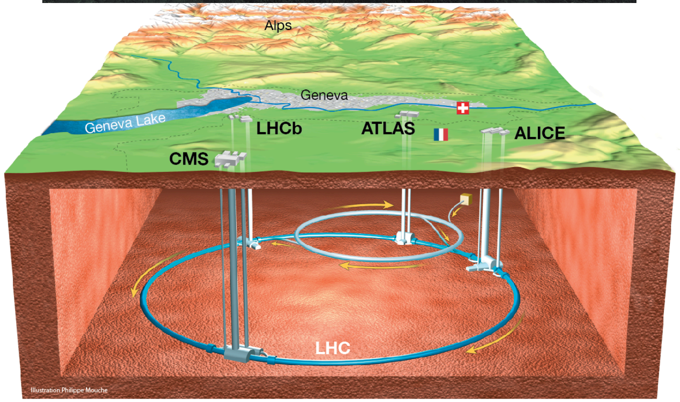


- At one or more points on the ring, insert a cavity in which there is an oscillating RF electromagnetic field
- Set RF frequency such that every time the particles pass, they are accelerated in the direction of the field (hence the name synchrotron)

Large Hadron Collider (LHC)

- Circumference 27 km
- Detectors 100 meters below
- 9593 magnets at 1.9 K
- Helium 120 tonnes
- Protons travel at the speed of light
- 2808 bunch/beam
- 1.14×10^{11} protons/bunch
- Proton beams circulate 11245 times/sec
- 1 billion collisions per second
- Luminosity $= 10^{34}\ cm^{-2}s^{-1}$
- Center of the mass energy 13 TeV
- Collisions are billion times hotter than the center of the sun
  - Can create new particles





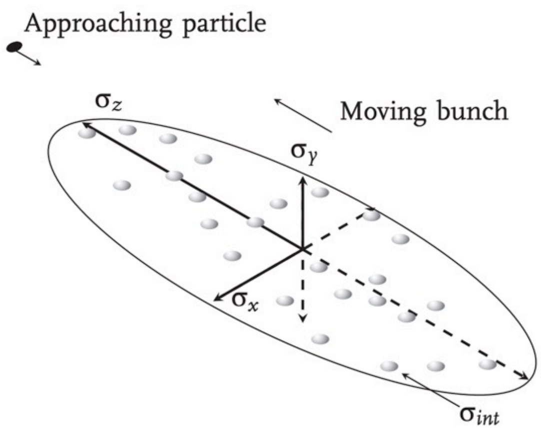
LHC tunnel

Measurements at particle accelerators

- Two important features of an accelerator.
  - Its center of mass energy
  - Instantaneous luminosity L, which determines the event rates.
- Number of interactions

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

$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$



- σ_x and σ_y are the RMS horizontal and vertical beam size
- $\sigma_x\sigma_y$ = effective area.
- n_1 and n_2 are the number of particles in the colliding bunches.
- f is the frequency at which the bunches collides.

Luminosity

- **The luminosity (L) of a machine determines the interactions rate**

Rate (interactions per second) = $L \cdot \sigma_{\text{interaction}}$

- **The luminosity is in units of** $\mathcal{L}\ (cm^{-2}s^{-1})$

- **Top quark cross section** $\sigma_{t\bar{t}} = 831\ pb$

$1\ \text{barn} = 1\ \text{b} = 10^{-24}\ cm^2 = 10^{-28}\ m^2$

- **Integrated luminosity** $\int_0^t \mathcal{L}\ dt = 100\ fb^{-1}$

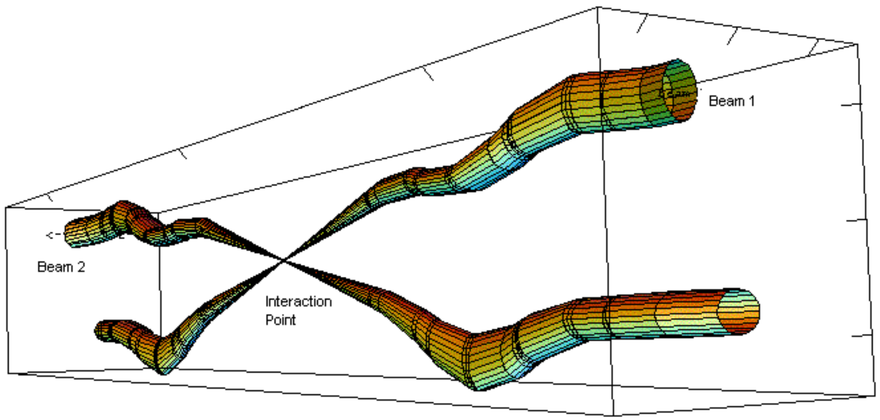
- **The rate (events/s) is**

$$\boxed{100\ fb^{-1} \times 831\ pb = 100000\ pb^{-1} \times 831\ pb = 83100000}$$

Collisions

- **After an accelerator has pumped enough energy into its particles, they collide either with a target or each other**

squeeze the beam size down as much as possible at the collision point

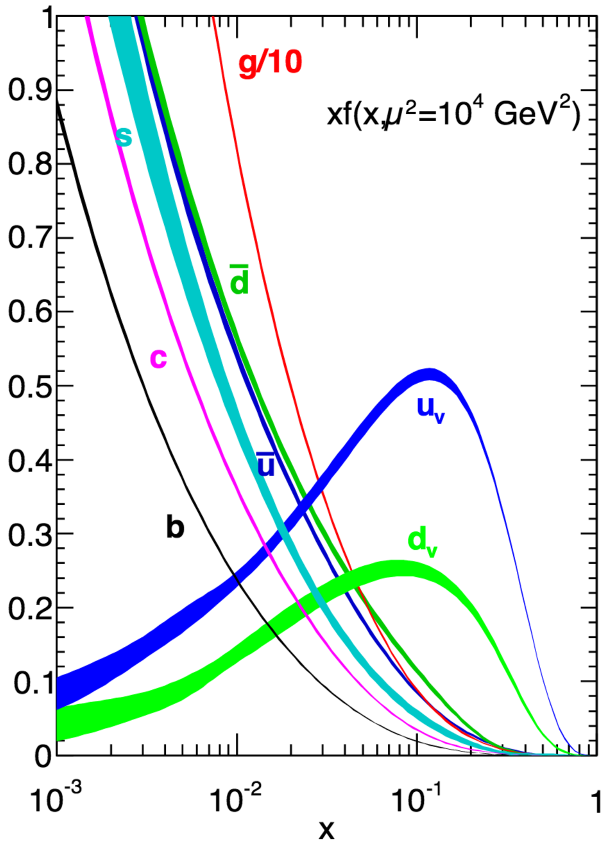


Relative beam sizes around IP1 (Atlas) in collision

- **For example, 100,000 million protons per bunch down to 64 microns (a human hair) → around 20 collisions per crossing**
- **At the LHC, bunches cross every 25 ns**

Proton collisions

Parton Distribution Functions

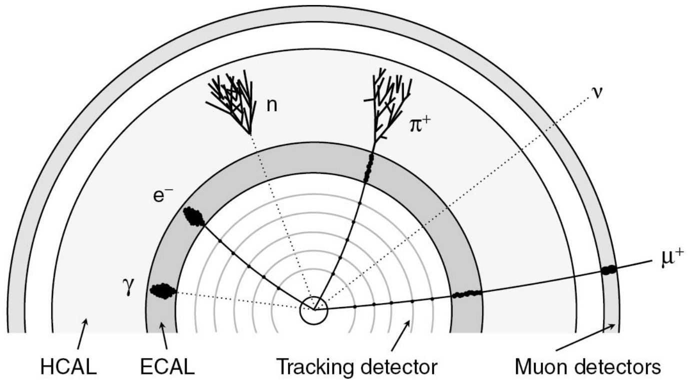


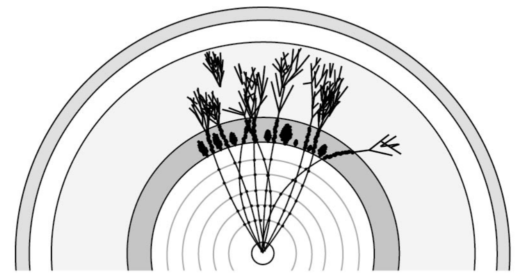
- Tevatron 0.98TeV proton on anti-proton beam
- LHC 13 TeV proton on proton beam
- For example, top quark mass = 172.5 GeV
- To produce a top quark pair ~ 350 GeV threshold, x should be above 0.025 at the LHC while x ~ 0.2 at the Tevatron.

How do we interpret our data?

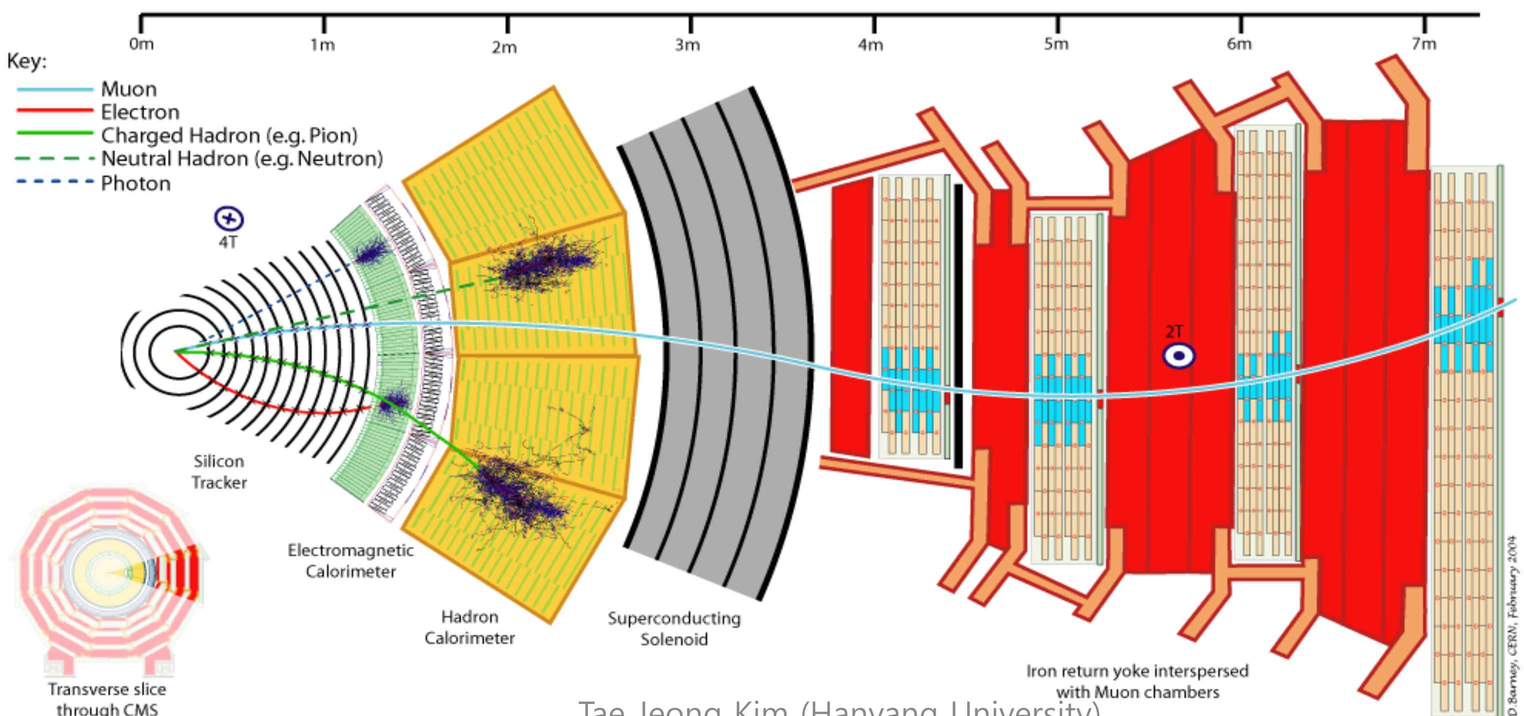
Detector cross section

General detector cross section



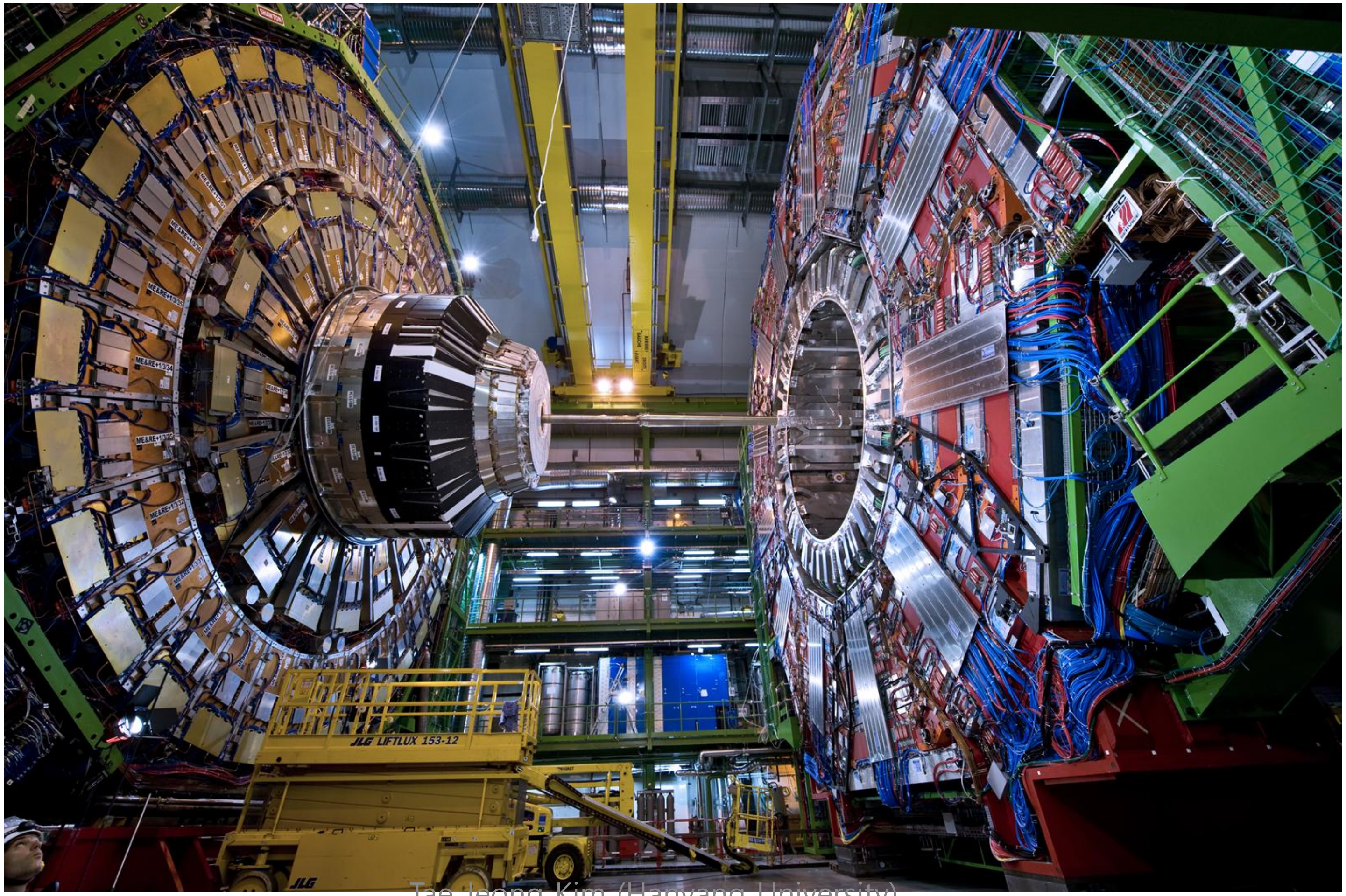


CMS detector



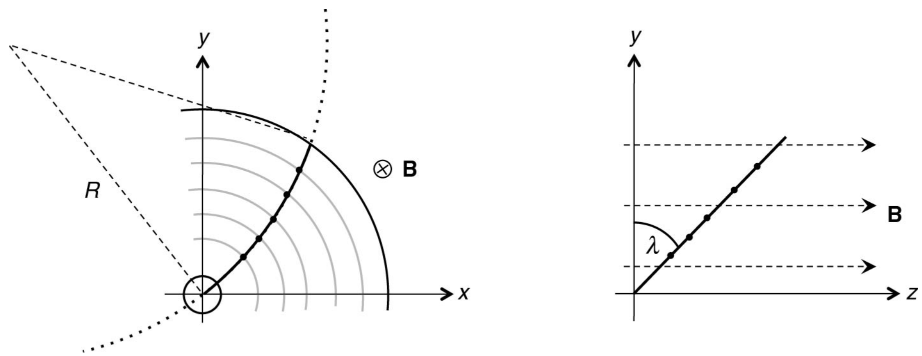
CMS detector

- **Compact Muon Solenoid**



Measuring charge & momentum

One important function of the detector is to measure a particle's charge and momentum. For this reason, there is a strong field in the inner parts of detector.



- **The signs of the charged particles can be easily reconstructed from their path.**
- **The momenta of particles can be calculated with its curvature :** $\boldsymbol{p = 0.3 \cdot BR\ (\frac{GeV}{c})}$

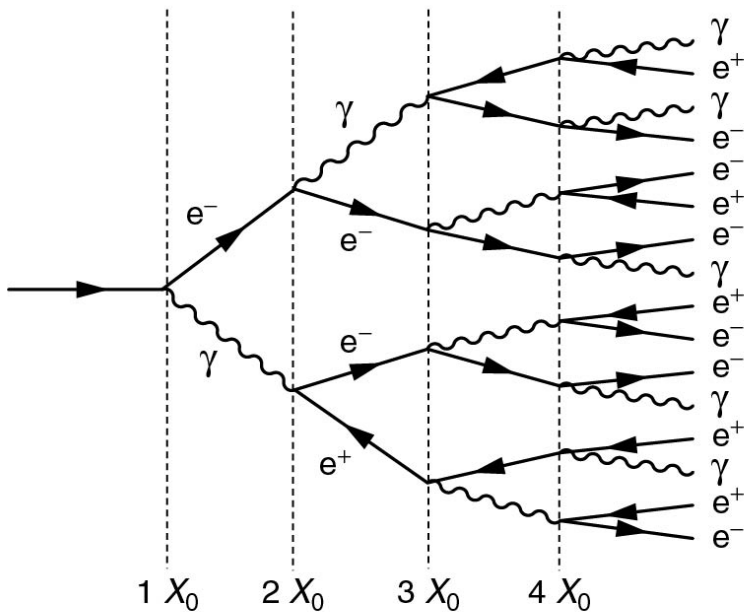
Muon detector

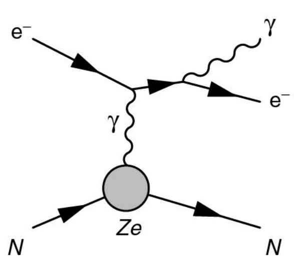
- One of muon detector is Resistive Plate Chamber (RPC).
- Fast gaseous detectors that provide a muon trigger system.
- Consist of two parallel plates, a positively charged anode and a negatively-charge cathode, both made of a very high resistivity plastic material separated by a gas volume.

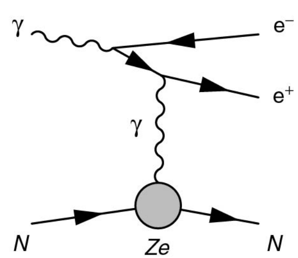
Electromagnetic showers

Bremsstrahlung

E ~ More than 5-10 MeV







- **The radiation length (X_0) is defined as the distance over which a high-energy electron or positron loses, on average., 63.2% $(1 - e^{-1})$ of its energy to bremsstrahlung.**
- **For example, high-energy electrons lose the same fraction of their energy in 18 cm of water (0.5 X_0) as in 2.8 mm of lead (0.5 X_0).**

- **Average Energy after x radiation length**

$$< \mathbf{E} > \approx \frac{\mathbf{E}}{\mathbf{2^x}}$$

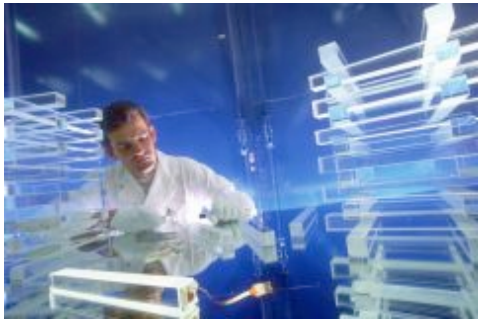
- **Radiation length**

$$\mathbf{x_{max}} = \frac{\mathbf{ln(E/E_c)}}{\mathbf{ln2}}$$

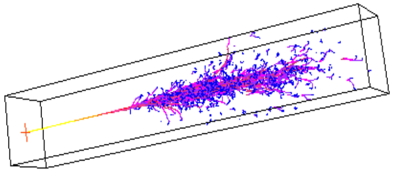
Electromagnetic Calorimeter

For CMS detector:

- **Electrons and photons are are measured using an electromagnetic calorimeter (ECAL).**
- **Lead tungstate ($\mathrm{PbWO_4}$) crystal is used for ECAL.**
- **Highly transparent and scintillate when electrons and photons pass through it.**
- **It produces light in proportion to the particle's energy.**
- **High-density crystals produce light in fast, short, well-defined photon bursts.**
- **Photodetectors are glued onto the back of each of the crystals to detect the scintillation light and convert it to an electrical signal that is amplified and sent for analysis.**



- **Lead tungstate ($PbWO_4$) crystals each weigh 1.5 kg but with a volume roughly equal to that of a small coffee cup.**
- **X_0=0.85 cm**
- **Contains nearly 80000 such crystals.**

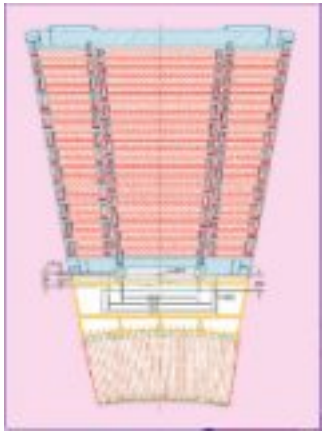


Hadron Calorimeter

- Measures the energy of hadrons.
- Neutrons, protons, pions etc. interact with nuclei through the **strong interaction**.
- The HCAL is a sampling calorimeter: find a particle's position, energy and arrival time using alternating layers of brass "absorber" and fluorescent plastic "scintillator" material.

- The interaction length (λ_{int}) is the average distance a high-energy hadron has to travel inside that medium before a nuclear interaction occurs.
- CMS HCal has ~5 λ_{int}

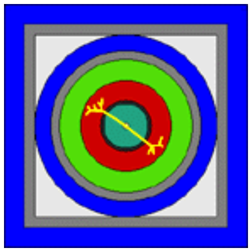
- The particles pass through the active scintillation material causing them to emit blue-violet light.
- Tiny optical "wavelength-shifting fibers" absorb this light and shift the blue-violet light into the green region and carry the light away to readout boxes.



Quiz

There are 6 possible decays of a Z particle.
Try to identify the particles that left these tracks.

1



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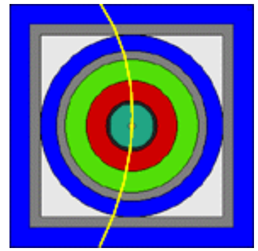

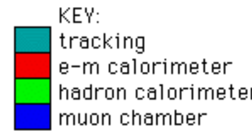

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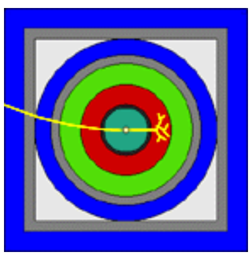

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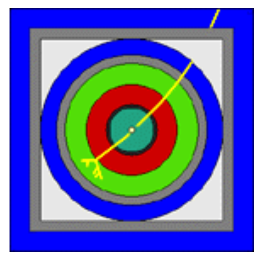

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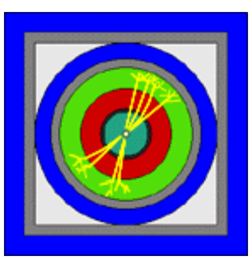

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