

# Introduction to Particle Physics

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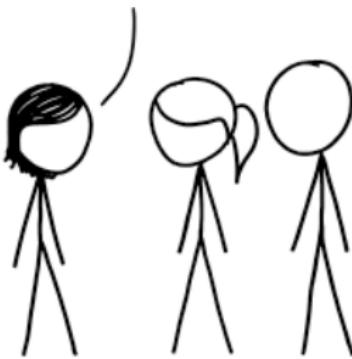
Horizon Club  
Centre for Innovation IIT Madras

July, 2021



# Why Particle Physics

I'LL BE HONEST: WE PHYSICISTS TALK A BIG GAME ABOUT THE THEORY OF EVERYTHING, BUT THE TRUTH IS, WE DON'T REALLY UNDERSTAND WHY ICE SKATES WORK, HOW SAND FLOWS, OR WHERE THE STATIC CHARGE COMES FROM WHEN YOU RUB YOUR HAIR WITH A BALLOON.

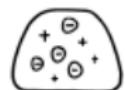


# What are we made of?

## MODELS OF THE ATOM OVER TIME



1800  
SMALL HARD  
BALL MODEL



1904  
PLUM PUDDING  
MODEL



1907  
TINY BIRD  
MODEL



1911  
RUTHERFORD  
MODEL



1913  
BOHR MODEL



1928  
NUNCHUCK  
MODEL



1932  
CHADWICK  
MODEL



2008  
538 MODEL

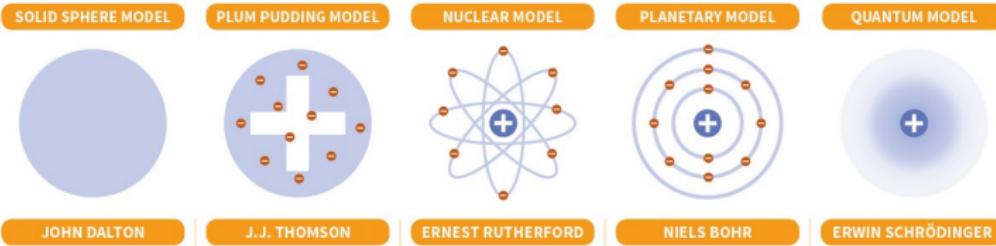


TODAY  
QUANTUM  
MODEL



FUTURE  
"SMALL HARD  
BALL SURROUNDED  
BY MATH" MODEL

# Atomic Theory through the years

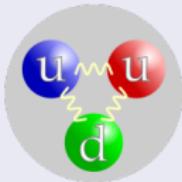


## The indivisible Atom

- "Atomos" meaning indivisible: Protons, neutrons and electrons.
- "Quarks" hypothesized to explain the ordering scheme for hadrons.
- Quarks experimentally confirmed via deep inelastic scattering in 1968.

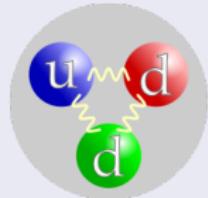
# Structure of Proton and Neutron

Proton



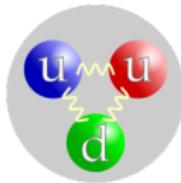
- Charge = +1
- Colour = "White"
- Mass  
 $= 938.27 \text{ MeV}/c^2$
- Mean lifetime  
 $> 2.110^9 \text{ years}$
- Proton Decay??

Neutron



- Charge = 0
- Colour = "White"
- Mass  
 $= 939.57 \text{ MeV}/c^2$
- Mean lifetime =  
 $879.4(6)s$
- Neutron Decay

# A Proton has three Quarks?



- Proton mass =  $938.27 \text{ MeV}/c^2$
- Sum of quark masses =  $9.4 \text{ MeV}/c^2$
- Where does the proton's mass come from?

# Quarks!

- Only elementary particles to interact via all fundamental forces
- Fundamental unit of charge
- Role in particle decay - W Boson
- "Flavour"
- "Colour" charge
- So what do quarks actually look like?

Please find a picture of a quark and insert here

# Up and Down

## First Generation

- Most stable and thus abundant
- Least massive
- Particle zoo and eightfold way

### Up Quark

- Charge =  $+\frac{2}{3}e$
- Lightest quark with estimated mass  $= 2.2\text{MeV}/c^2$ ; uncertain
- Usually stable; can decay into down quark + positron + electron neutrino

### Down Quark

- Charge =  $-\frac{1}{3}e$
- Along with up quark and electron, makes up most of the matter observed today
- Usually stable; can decay into up quark + electron + electron antineutrino

# Charm and Strange; Top and Bottom

## Charm Quark

- Charge =  $+\frac{2}{3}e$
- First of the "heavy" quarks
- Decays into strange/down quark

## Strange/sideways Quark

- Charge =  $-\frac{1}{3}e$
- Last light quark, essential for explaining "Strangeness"
- Decays into up quark

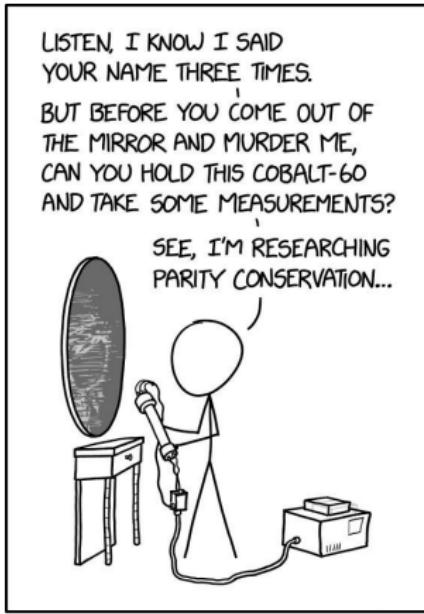
## Top/truth Quark

- Mass =  $172.76 \text{ GeV}/c^2$
- Mean lifetime =  $5 \times 10^{-25} \text{ s}$ , decays into bottom quark
- No hadronization, Higgs coupling

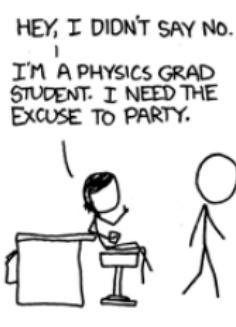
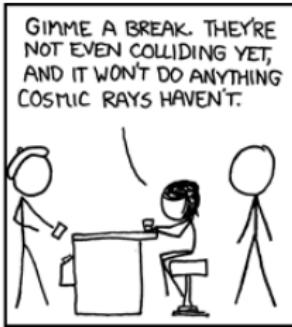
## Bottom/beauty Quark

- Extremely low rate of decay into charm/up quark
- B-tagging
- B mesons to study CP violation

# What is parity violation?



# Third generation sounds fishy...



HEY, I HAVEN'T EVEN BOUGHT YOU A DRINK.

BARKEEP, TWO WHISKEY SOURS, STRAIGHT DOWN.

## Fun Fact-1

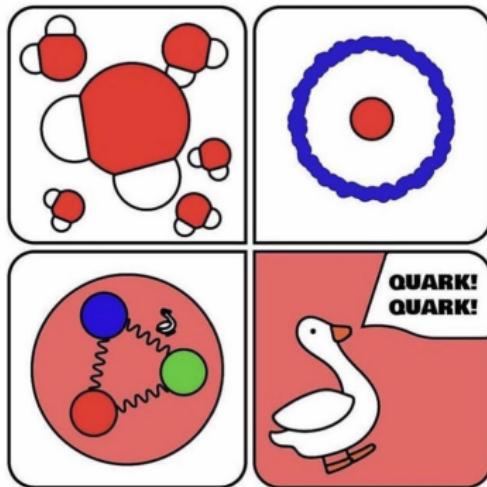
Why are quarks named the way they are?

Murray Gell-Mann was unsure what term to coin until he found the word quark in James Joyce's 1939 book Finnegans Wake :

"Three quarks for Muster Mark!

Sure he hasn't got much of a bark."

*"ZOOMING INTO MATTER"*



# Hadrons, Baryons, Mesons!

## Hadrons

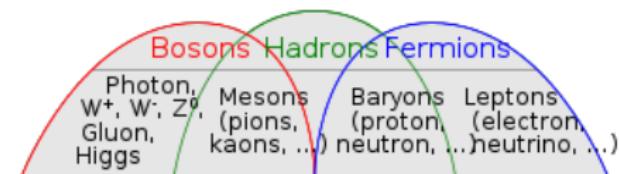
- Composite particles, not fundamental
- Combination of Quarks held together by Strong Interaction
- Exotic hadrons

## Baryons

- Odd number of quarks
- Fermions

## Mesons

- Even number of quarks
- Bosons



# More Particles- The Leptons

## Quarks v/s Leptons

- No colour
- Integral charge
- Massless (?) particles

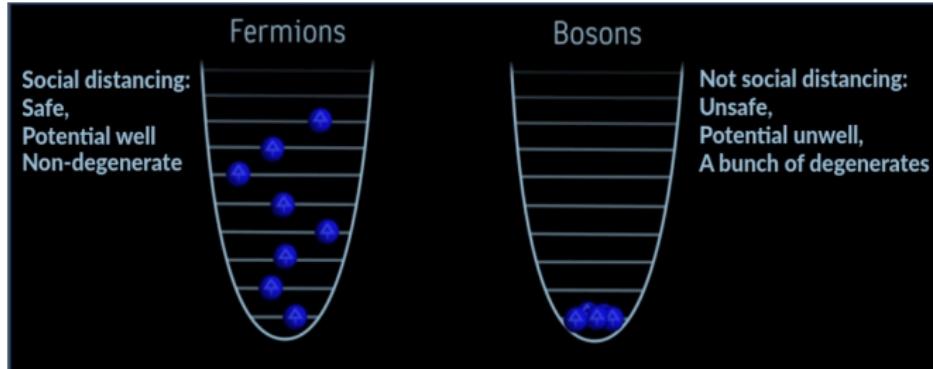
## Charged leptons

- Electron
- Muon
- Tau

## Uncharged leptons

- Electron neutrino
- Muon neutrino
- Tau neutrino

# Types of Statistics



## Fermions

- Fermi - Dirac Statistics
- Antisymmetric wavefunction
- Half-integer spins
- "Matter"

## Bosons

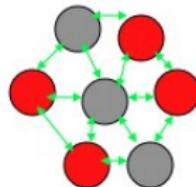
- Bose - Einstein Statistics
- Symmetric wavefunctions
- Integer spins
- "Force carriers"

# What else?- The Fundamental Forces

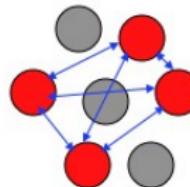
Three Generations of Matter (Fermions)				
	I	II	III	
mass	2.4 MeV/c <sup>2</sup>	1.27 GeV/c <sup>2</sup>	171.2 GeV/c <sup>2</sup>	0
charge	2/3	2/3	2/3	0
spin	1/2	1/2	1/2	1
name	u	c	t	γ
Quarks				photon
mass	4.8 MeV/c <sup>2</sup>	104 MeV/c <sup>2</sup>	4.2 GeV/c <sup>2</sup>	0
charge	-1/3	-1/3	-1/3	0
spin	1/2	1/2	1/2	1
name	d	s	b	g
	down	strange	bottom	gluon
Leptons				Z boson
mass	<2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	0
charge	0	0	0	1
spin	1/2	1/2	1/2	1
name	e	μ	τ	Z <sup>0</sup>
	electron neutrino	muon neutrino	tau neutrino	Z boson
Gauge Bosons				
mass	0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>
charge	-1	-1	-1	+1
spin	1/2	1/2	1/2	1
name	e	μ	τ	W <sup>+</sup>
	electron	muon	tau	W boson

# Strong Force

Strong  
Force



Electro-magnetic  
Force

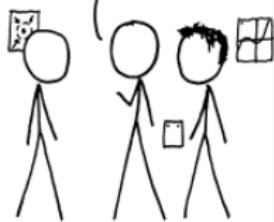


- How strong is "strong"?
- Quantum ChromoDynamics
- Colour Confinement
- Hadron mass, residual strong force
- Two ranges, two particles - Mesons and Gluons
- Van der Waals-like behaviour
- Unification?

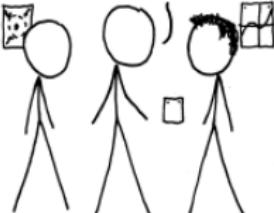
# Weak Force

LOS ALAMOS, 1945...

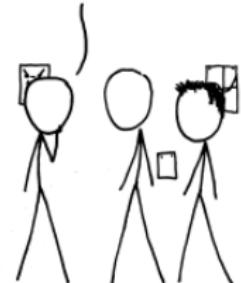
WE HAVE A DECISION. IF WE'VE  
DONE OUR MATH RIGHT, THIS  
TEST WILL UNLEASH HEAVEN'S  
FIRE AND MAKE US AS GODS.



BUT IT'S POSSIBLE WE MADE A  
MISTAKE, AND THE HEAT WILL  
IGNITE THE ATMOSPHERE,  
DESTROYING THE PLANET IN  
A CLEANSING CONFLAGRATION.



WOW. UM. QUESTION:  
JUST TO DOUBLE-CHECK—  
ALTHOUGH I'M 99% SURE—



IS IT "SOH CAH TOA"  
OR "COH SAH TOA"?

OH, FOR THE LOVE OF...  
CAN SOMEONE  
REDO STEVE'S WORK?



# Weak Force

THERE ARE FOUR FUNDAMENTAL FORCES BETWEEN PARTICLES:  
(1) GRAVITY, WHICH OBEYS THIS INVERSE SQUARE LAW:

$$F_{\text{gravity}} = G \frac{m_1 m_2}{d^2}$$



OK...

(2) ELECTROMAGNETISM, WHICH OBEYS THIS INVERSE-SQUARE LAW:

$$F_{\text{static}} = k_e \frac{q_1 q_2}{d^2}$$

AND ALSO MAXWELL'S EQUATIONS



ALSO WHAT?

(3) THE STRONG NUCLEAR FORCE, WHICH OBEYS, UH...

...WELL, UMM...

...IT HOLDS PROTONS AND NEUTRONS TOGETHER.



AND (4) THE WEAK FORCE. IT [MUMBLE MUMBLE] RADIOACTIVE DECAY [MUMBLE MUMBLE]

THAT'S NOT A SENTENCE.  
YOU JUST SAID 'RADIO-'  
-AND THOSE ARE THE  
FOUR FUNDAMENTAL  
FORCES!



## Radioactive Decay...

- Subatomic range only due to massive carriers
- $W^+$ ,  $W^-$  and  $Z^0$  Bosons - charge, antiparticles and spin
- Quantum *Flavour*Dynamics
- Only force that can change the flavour of Quarks
- P and CP violation
- Electroweak Theory
- Weak isospin and weak hypercharge

# Electromagnetism?

## THE ELECTROMAGNETIC SPECTRUM

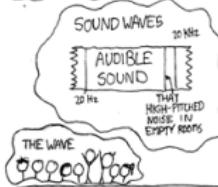
THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.



SLINKY WAVES



SHOUTING CAR DEALERSHIP COMMERCIALS  
HAM RADIO  
KOMER RADIO



SOUND WAVES

20 kHz

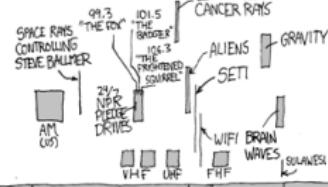
20 Hz

THAT HIGH-PITCHED NOISE IN EMPTY ROOMS

AUDIBLE SOUND



THE WAVE



POWER & TELEPHONE  
10<sup>3</sup> 10<sup>2</sup> 10<sup>1</sup> 10<sup>0</sup> 10<sup>-1</sup> 10<sup>-2</sup> 10<sup>-3</sup> 10<sup>-4</sup> 10<sup>-5</sup> 10<sup>-6</sup> 10<sup>-7</sup> 10<sup>-8</sup> 10<sup>-9</sup> 10<sup>-10</sup> 10<sup>-11</sup> 10<sup>-12</sup> 10<sup>-13</sup> 10<sup>-14</sup> m  
100mm 10mm 1mm 10cm 1cm 1mm 100μm 10μm 1μm 100nm 10nm 100fm 10fm

RADIO & TV  
10<sup>3</sup> 10<sup>2</sup> 10<sup>1</sup> 10<sup>0</sup> 10<sup>-1</sup> 10<sup>-2</sup> 10<sup>-3</sup> 10<sup>-4</sup> 10<sup>-5</sup> 10<sup>-6</sup> 10<sup>-7</sup> 10<sup>-8</sup> 10<sup>-9</sup> 10<sup>-10</sup> 10<sup>-11</sup> 10<sup>-12</sup> m  
100mm 10mm 1mm 100μm 10μm 100nm 10nm 100fm 10fm

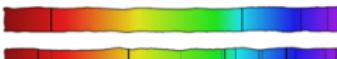
MICROWAVES  
10<sup>3</sup> 10<sup>2</sup> 10<sup>1</sup> 10<sup>0</sup> 10<sup>-1</sup> 10<sup>-2</sup> 10<sup>-3</sup> 10<sup>-4</sup> 10<sup>-5</sup> 10<sup>-6</sup> 10<sup>-7</sup> 10<sup>-8</sup> 10<sup>-9</sup> 10<sup>-10</sup> 10<sup>-11</sup> 10<sup>-12</sup> m  
100mm 10mm 1mm 100μm 10μm 100nm 10nm 100fm 10fm

IR  
10<sup>3</sup> 10<sup>2</sup> 10<sup>1</sup> 10<sup>0</sup> 10<sup>-1</sup> 10<sup>-2</sup> 10<sup>-3</sup> 10<sup>-4</sup> 10<sup>-5</sup> 10<sup>-6</sup> 10<sup>-7</sup> 10<sup>-8</sup> 10<sup>-9</sup> 10<sup>-10</sup> 10<sup>-11</sup> 10<sup>-12</sup> m  
100mm 10mm 1mm 100μm 10μm 100nm 10nm 100fm 10fm

X-RAYS  
10<sup>3</sup> 10<sup>2</sup> 10<sup>1</sup> 10<sup>0</sup> 10<sup>-1</sup> 10<sup>-2</sup> 10<sup>-3</sup> 10<sup>-4</sup> 10<sup>-5</sup> 10<sup>-6</sup> 10<sup>-7</sup> 10<sup>-8</sup> 10<sup>-9</sup> 10<sup>-10</sup> 10<sup>-11</sup> 10<sup>-12</sup> m  
100mm 10mm 1mm 100μm 10μm 100nm 10nm 100fm 10fm

GAMMA/COSMIC RAYS  
10<sup>3</sup> 10<sup>2</sup> 10<sup>1</sup> 10<sup>0</sup> 10<sup>-1</sup> 10<sup>-2</sup> 10<sup>-3</sup> 10<sup>-4</sup> 10<sup>-5</sup> 10<sup>-6</sup> 10<sup>-7</sup> 10<sup>-8</sup> 10<sup>-9</sup> 10<sup>-10</sup> 10<sup>-11</sup> 10<sup>-12</sup> m  
100mm 10mm 1mm 100μm 10μm 100nm 10nm 100fm 10fm

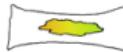
HYDROGEN:



HELIUM:



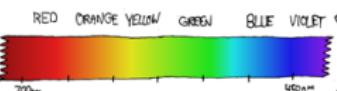
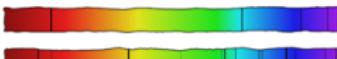
DEPENDS®:



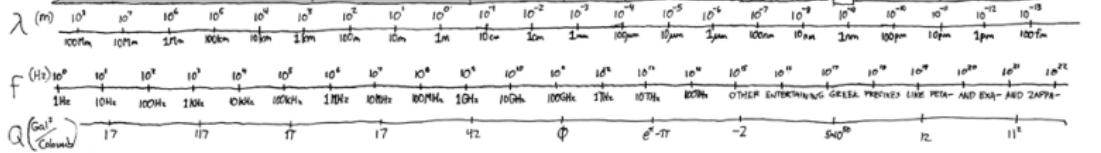
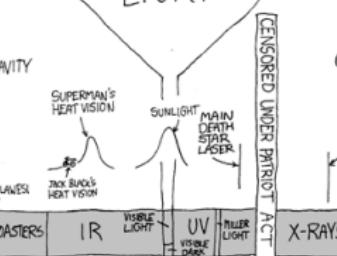
TAMPAX®:



### ABSORPTION SPECTRA:



### VISIBLE LIGHT



# Electromagnetism

- Leads to most common non-gravitational interactions
- Maxwell's equations
- Speed of light
- Duality
- Photon - massless, uncharged

# Is Gravity part of SM- umm no, but there is Graviton

Graviton, although undetected yet, is a hypothetical particle, mediating the force of gravity.

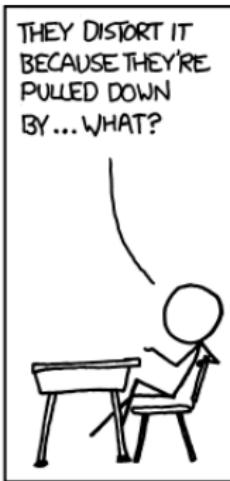
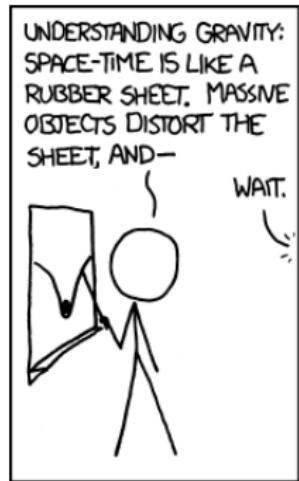
## Properties

- Massless
- Spin-2
- Same as anti-graviton

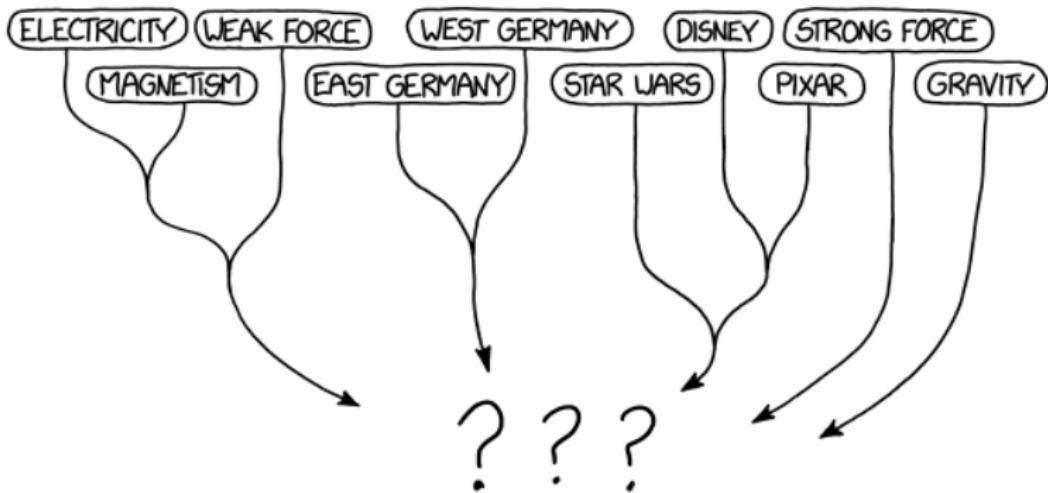
## Theory:

In the classical limit, the Standard Model description of graviton must reduce to General Relativity.

# So what is Gravity?



# Unification



PROGRESS TOWARD UNIFYING THE FUNDAMENTAL FORCES OF NATURE



# The Whole Picture

Quarks

Force particles

Leptons

??



# Oops! The Higgs Boson

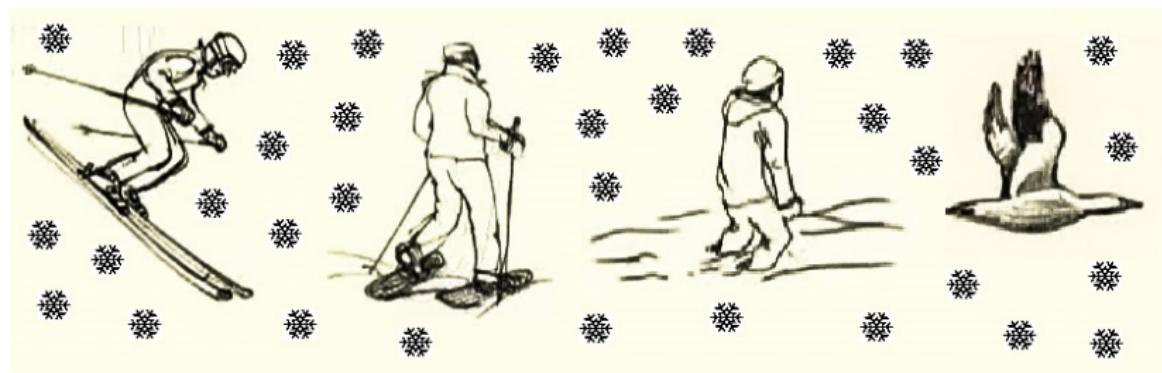
- The interaction with Higgs field gives mass to particles, while Higgs boson is the particle associated with it.



# The Higgs Boson

## Theory

- Robert Brout, François Englert and Peter Higgs proposed the existence of Higgs Field to explain how the W and Z boson would acquire mass in electroweak theory.



# Finding the Higgs Boson



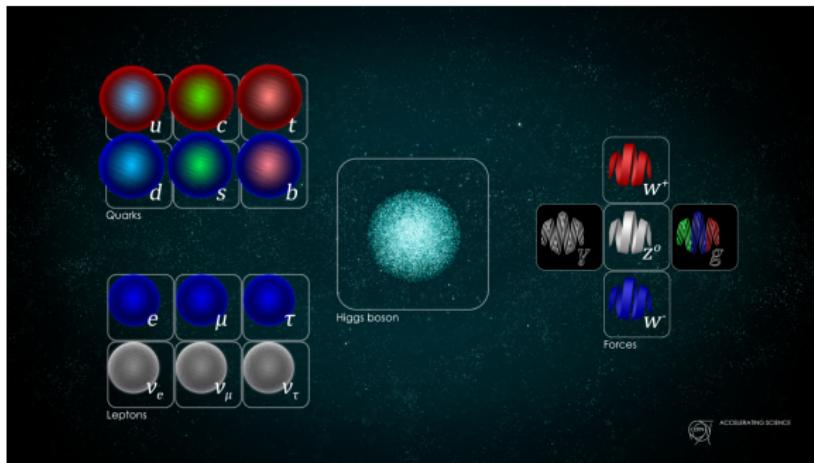
# The Whole Picture now?

Quarks

Force particles

Leptons

Higgs Boson



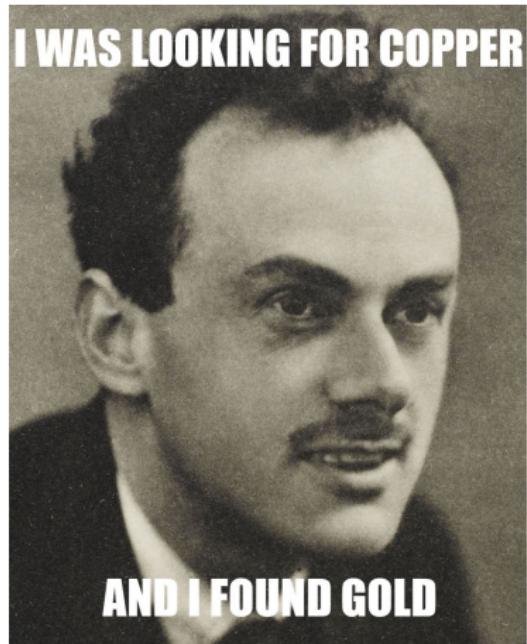
???

# The Antimatter

Dirac's Equation for  
Relativistic Electron

$$(i\vec{\partial} - m)\psi = 0$$

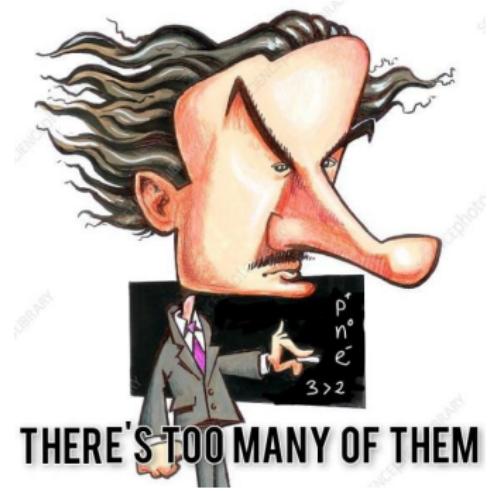
Negative Energy  
Solutions



# Dirac's Thoughts on having three fundamental particles

Paul Dirac at Solvay Conference, 1933

If we consider protons and neutrons as elementary particles, we would have three kinds of elementary particles [p,n,e].... This number may seem large but, from that point of view, two is already a large number."



# Standard Model

## Standard Model of Elementary Particles

Three generations of matter (elementary fermions)			Three generations of antimatter (elementary antifermions)			Interactions / force carriers (elementary bosons)	
I	II	III	I	II	III		
mass $\frac{1}{2}$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ up	mass $\frac{1}{2}$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ charm	mass $\frac{1}{2}$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ top	mass $\frac{1}{2}$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ antiup	mass $\frac{1}{2}$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ anticharm	mass $\frac{1}{2}$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ antitop	mass $0$ charge $0$ spin $1$ gluon	mass $0$ charge $0$ spin $0$ Higgs
mass $-4.7$ MeV/c <sup>2</sup> $\frac{-1}{2}$ charge $\frac{-1}{3}$ spin $\frac{1}{2}$ down	mass $-98$ MeV/c <sup>2</sup> $\frac{-1}{2}$ charge $\frac{-1}{3}$ spin $\frac{1}{2}$ strange	mass $-418$ MeV/c <sup>2</sup> $\frac{-1}{2}$ charge $\frac{-1}{3}$ spin $\frac{1}{2}$ bottom	mass $-4.7$ MeV/c <sup>2</sup> $\frac{1}{2}$ charge $\frac{-1}{3}$ spin $\frac{1}{2}$ antidown	mass $-98$ MeV/c <sup>2</sup> $\frac{1}{2}$ charge $\frac{-1}{3}$ spin $\frac{1}{2}$ antistrange	mass $-418$ MeV/c <sup>2</sup> $\frac{1}{2}$ charge $\frac{-1}{3}$ spin $\frac{1}{2}$ antibottom	mass $0$ charge $0$ spin $1$ photon	mass $124.97$ GeV/c <sup>2</sup> $0$ charge $0$ spin $0$ Higgs
mass $-0.511$ MeV/c <sup>2</sup> $-1$ charge $-1$ spin $\frac{1}{2}$ electron	mass $-105.66$ MeV/c <sup>2</sup> $-1$ charge $-1$ spin $\frac{1}{2}$ muon	mass $-1.7783$ GeV/c <sup>2</sup> $-1$ charge $-1$ spin $\frac{1}{2}$ tau	mass $-0.511$ MeV/c <sup>2</sup> $1$ charge $-1$ spin $\frac{1}{2}$ positron	mass $-105.66$ MeV/c <sup>2</sup> $1$ charge $-1$ spin $\frac{1}{2}$ antimuon	mass $-1.7783$ GeV/c <sup>2</sup> $1$ charge $-1$ spin $\frac{1}{2}$ antitau	mass $91.19$ GeV/c <sup>2</sup> $0$ charge $1$ spin $1$ $Z^0$ boson	mass $80.39$ GeV/c <sup>2</sup> $1$ charge $-1$ spin $1$ $W^+$ boson
mass $<2.2$ eV/c <sup>2</sup> $0$ charge $0$ spin $\frac{1}{2}$ electron neutrino	mass $<0.17$ MeV/c <sup>2</sup> $0$ charge $0$ spin $\frac{1}{2}$ muon neutrino	mass $<18.2$ MeV/c <sup>2</sup> $0$ charge $0$ spin $\frac{1}{2}$ tau neutrino	mass $<2.2$ eV/c <sup>2</sup> $0$ charge $0$ spin $\frac{1}{2}$ electron antineutrino	mass $<0.17$ MeV/c <sup>2</sup> $0$ charge $0$ spin $\frac{1}{2}$ muon antineutrino	mass $<18.2$ MeV/c <sup>2</sup> $0$ charge $0$ spin $\frac{1}{2}$ tau antineutrino	mass $>80.39$ GeV/c <sup>2</sup> $1$ charge $-1$ spin $1$ $W^-$ boson	mass $>80.39$ GeV/c <sup>2</sup> $-1$ charge $1$ spin $1$ $W^-$ boson

The complete picture now?



Join us later for Beyond Standard Model session later!



# Particle properties

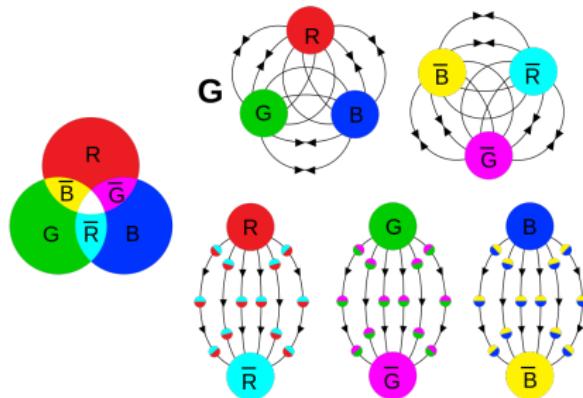
## PARTICLE PROPERTIES IN PHYSICS

PROPERTY	TYPE/SCALE
ELECTRIC CHARGE	-1   0   +1 
MASS	0   1kg   2kg 
SPIN NUMBER	-1/2   0   1/2   1 
FLAVOR	(MISC. QUANTUM NUMBERS)
COLOR CHARGE	R   G   B  (QUARKS ONLY)
MOOD	
ALIGNMENT	 GOOD-EVIL, LAWFUL-CHAOTIC
HIT POINTS	0 
RATING	

# A little deeper into Standard Model- Colored Quarks

## Color Charge

Red, Blue, Green, Anti-red, Anti-blue, Anti-green



## Color neutrality in free particles

"red + blue + green = 0" : The Baryons

"anti-red + red = 0" : The Mesons

Q. Why Standard Models needs these color charges ?

# A little deeper into Standard Model- Conservation Laws

Time Translation

Conservation of  
Mass-Energy

Space Translation

Conservation of  
Momentum

Rotational Translation

Conservation of Angular  
Momentum

Gauge Translation

Conservation of Charge



# A little deeper into Standard Model

## Approximate Conservation Laws and Symmetry

- ① Baryon Number
- ② Lepton Number
- ③ Strangeness
- ④ Flavor
- ⑤ Parity
- ⑥ Charge Conjugation
- ⑦ Time Reversal

These conservation laws depends on the type of interaction

They are therefore approximate laws, and may not be conserved in one or more specific type of interaction.

# Conservation Laws- Baryon Number

## Baryon Number

$$B = \frac{1}{3}(\text{no. of quark}) - \frac{1}{3}(\text{no. of anti-quark})$$

For a proton( $uud$ ),  $B = 1$

For a meson( $q\bar{q}$ ),  $B = 0$

In all interactions the Baryon number is always conserved.

Can also be stated as quark number conservation.

Associated Symmetry is the global gauge invariance (The SU(3) Symmetry- you can forget this)

# Conservation Laws- Lepton Number

## Lepton Number

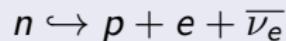
- Electron number ( $e$  and  $\nu_e$ )
- Muon number ( $\mu$  and  $\nu_\mu$ )
- Tau number ( $\tau$  and  $\nu_\tau$ )

All three leptons are separately conserved

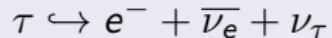
In 'all' interactions the three lepton numbers are always conserved.

Associated Symmetry is the global gauge invariance

## Beta Decay



## Tau decay



# Conservation Laws

## Strangeness

no. of anti-strange quarks -  
no. of strange quarks =  
constant

Strangeness Conservation is  
not an absolute law.

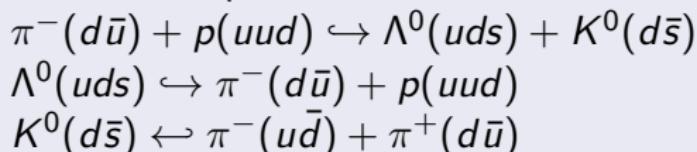
Weak interactions violate it.

## Flavor Conservation

- Fermion-flavors are conserved in strong and EM interaction.
- $u, d, s, c, t, b, e, \mu, \tau, v_e, v_\mu, v_\tau$

## Cosmic Rays and Strangeness

Set of strange interactions observed around 1950s pointed at a new kind of particle



# Conservation Laws

## Parity

- Transforms the spacial-coordinates
- $(x, y, z) \leftrightarrow (-x, -y, -z)$
- Not conserved- weak interactions

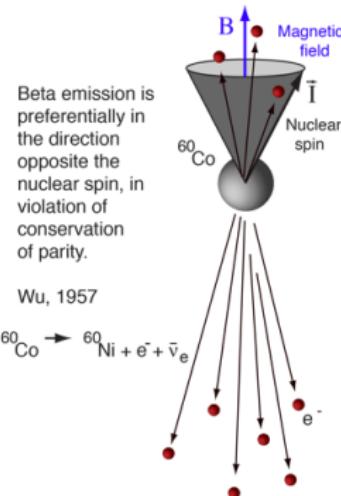
## Charge Conjugation

This operator replaces the particles with their antiparticles

## Time Reversal

Inverting the direction of flow of time

## Experiment by Wu



# Conservation Laws

## CP Violation

CP symmetry stated that if particles are interchanged with antiparticles and spatial coordinates are inverted, laws of physics would not change. However it was observed that neutral kaon decays and other interactions violates CP symmetry

## kaon Oscillations

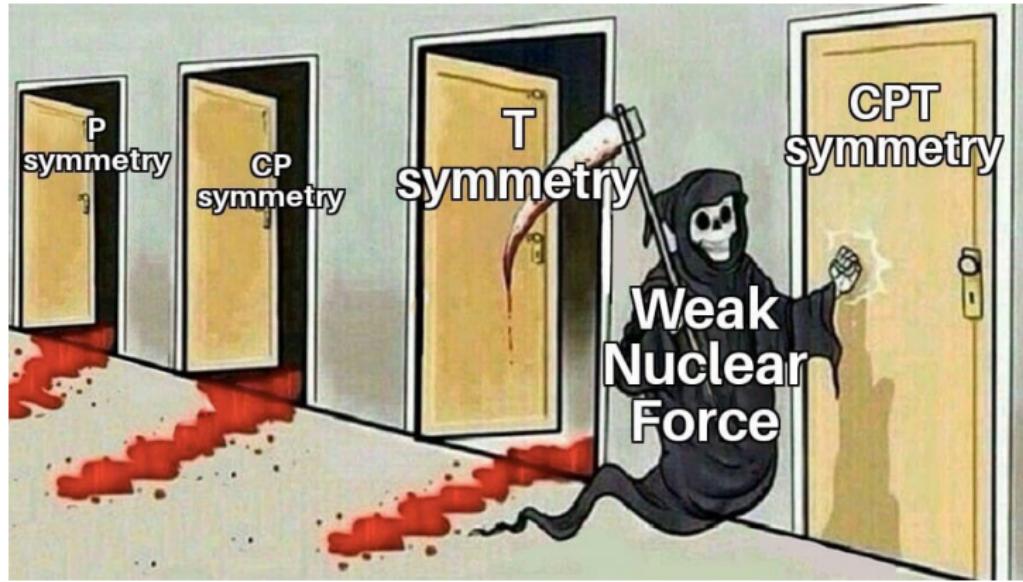
$$K^0 : d\bar{s}$$
$$\bar{K}^0 : s\bar{d}$$

Decay of kaons:

## CPT Symmetry

Charge conjugation, Parity and time reversal together leads to CPT Symmetry. CPT is consistent with all known experiments, and leads to CPT invariance. Fundamental properties such as same mass of particles and their antiparticles, opposite quantum numbers, arise as a result of CPT symmetry

# Conservation Laws- CPT



Feeling Blue with our Blue slides?



Feeling Blue with our Blue slides?

Feynman could help a bit a maybe



But Before that...



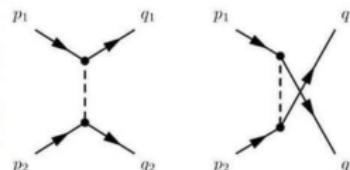
***Have a break,  
have a KitKat®.***

# Feynman Diagrams: FBDs for Particle Physicists

- ➊ Electromagnetic Interactions
- ➋ Weak Interactions
- ➌ Strong Interactions



$$\begin{aligned} \frac{1}{2}(-ig)^2 \int d^4x_1 d^4x_2 & \langle f | T\psi^\dagger(x_1)\psi(x_1)\phi(x_1)\psi^\dagger(x_2)\psi(x_2)\phi(x_2) | i \rangle \\ & = \langle q_1, q_2 | \psi^\dagger(x_1)\psi(x_1)\psi^\dagger(x_2)\psi(x_2) | p_1, p_2 \rangle \\ & = (\langle q_1 | e^{ip_1 \cdot x_1} + \langle q_1 | e^{ip_2 \cdot x_1} ) \psi^\dagger(x_2)\psi(x_1) (e^{-ip_1 \cdot x_2} | p_2 \rangle + e^{-ip_2 \cdot x_2} | p_1 \rangle) \\ & = \langle 0 | (e^{ip_1 \cdot x_1 + ip_2 \cdot x_2} + e^{ip_1 \cdot x_2 + ip_2 \cdot x_1}) (e^{-ip_1 \cdot x_1 - ip_2 \cdot x_2} + e^{-ip_2 \cdot x_1 - ip_1 \cdot x_2}) | 0 \rangle \\ & = e^{ix_1 \cdot (q_1 - p_1) + ix_2 \cdot (q_2 - p_2)} + e^{ix_1 \cdot (q_2 - p_1) + ix_2 \cdot (q_1 - p_2)} + (x_1 \leftrightarrow x_2) \end{aligned}$$



# Some Simple Features and Rules

Space-Time axis

Antiparticles are represented with backward arrow

Identify the initial and final states

Initial state: points towards vertex

Final state: points away from vertex

Conservation laws are applied at the vertices

Fermions: Solid Lines

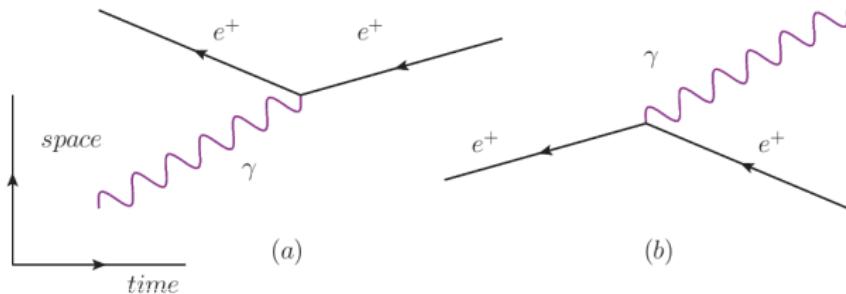
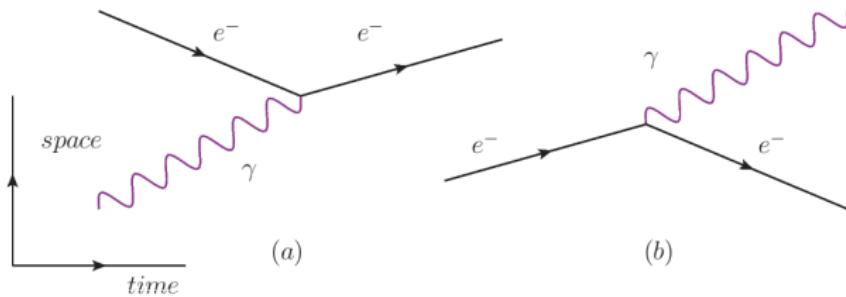
Bosons: Wiggly lines

Virtual Particles



# Feynman Diagrams: FBDs for Particle Physicists

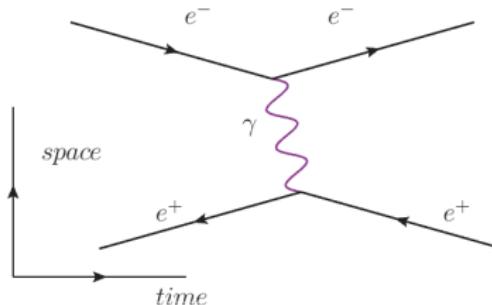
## Electromagnetic: Photon emission and absorption



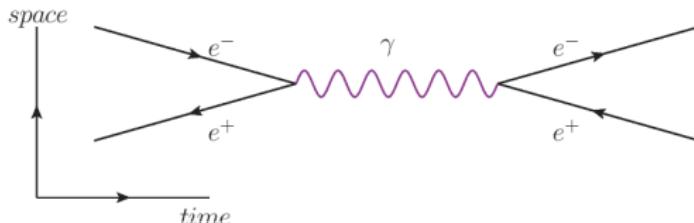
# Feynman Diagrams: FBDs for Particle Physicists

## Electromagnetic: Scattering, pair Annihilation and Production

### Bhabha Scattering

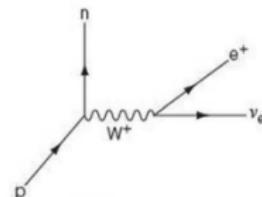
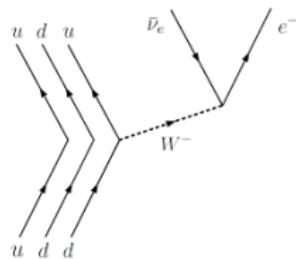
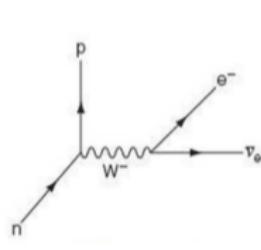


### Pair annihilation and pair production

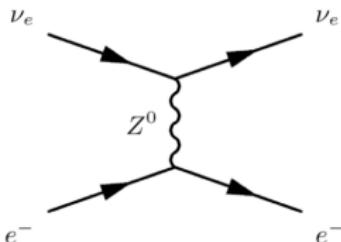


# Feynman Diagrams: FBDs for Particle Physicists

## Weak Interaction: Beta Decay



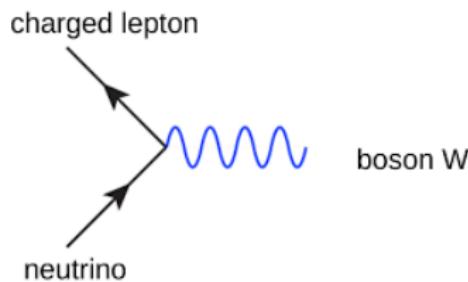
## Neutral Current Interaction



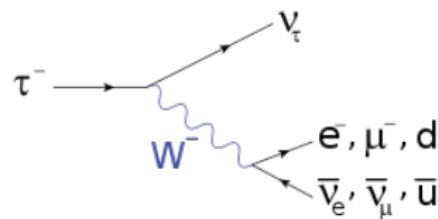
# Feynman Diagrams: FBDs for Particle Physicists

## Weak Interactions: Some more

### W Boson

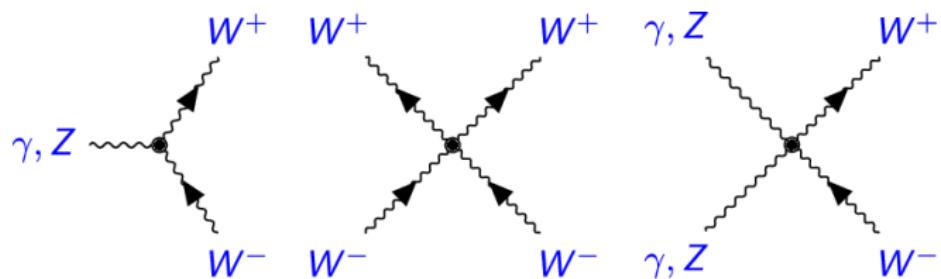


### Tau Decay



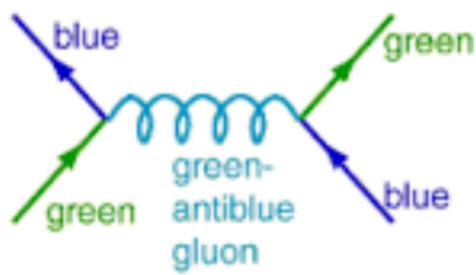
# Feynman Diagrams: FBDs for Particle Physicists

## Self Interactions

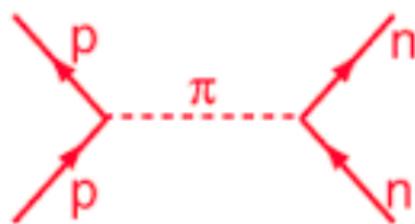


# Feynman Diagrams: FBDs for Particle Physicists

## Strong Interaction



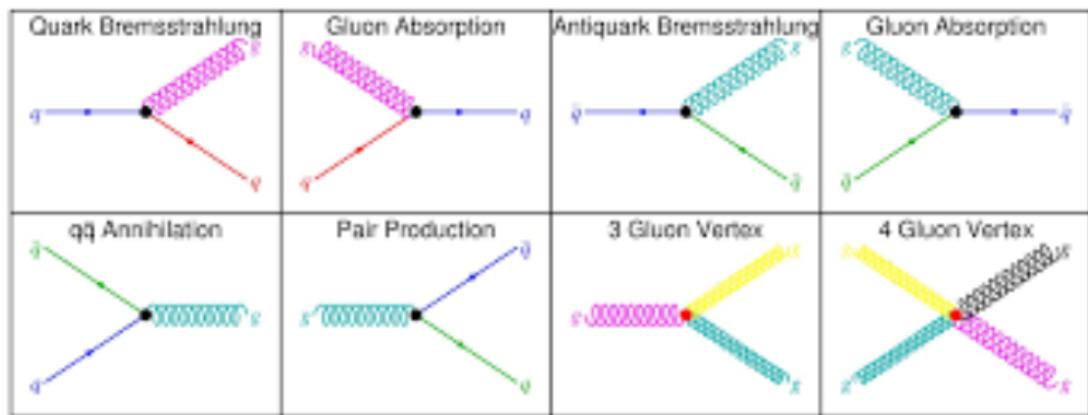
between quarks



between nucleons

# Feynman Diagrams: FBDs for Particle Physicists

## Strong Interaction: Gluons



# End of Feynman Diagram discussion



# Particle Physics Experimental Facilities

# The Experiments

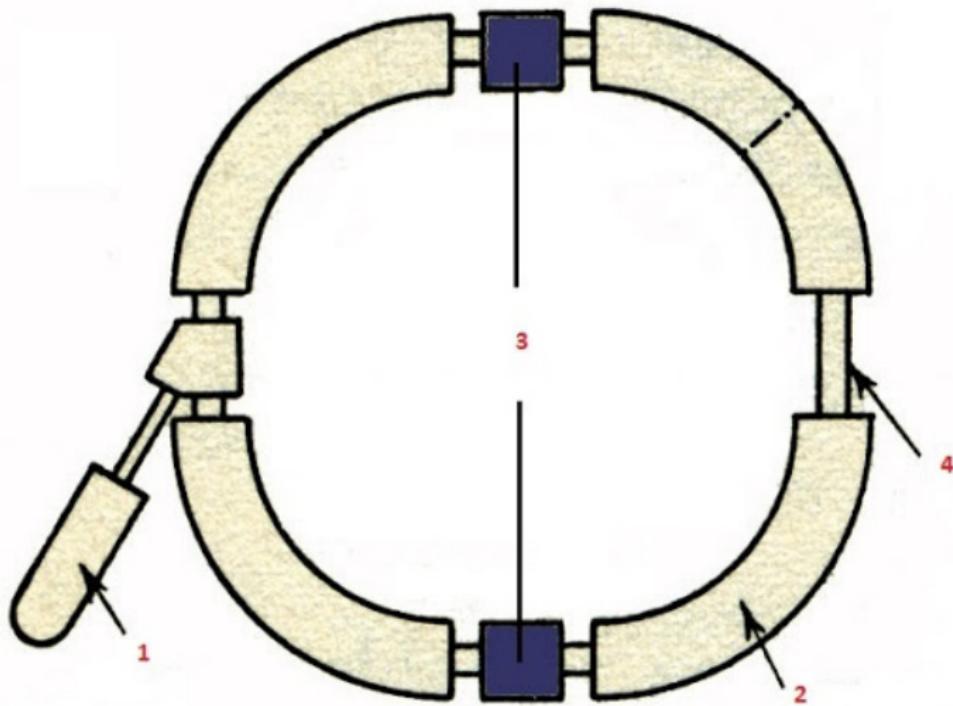
## At CERN

- ① Large Hadron Collider
- ② Intersecting Storage Rings
- ③ Antiproton Decelerator
- ④ High Luminosity LHC

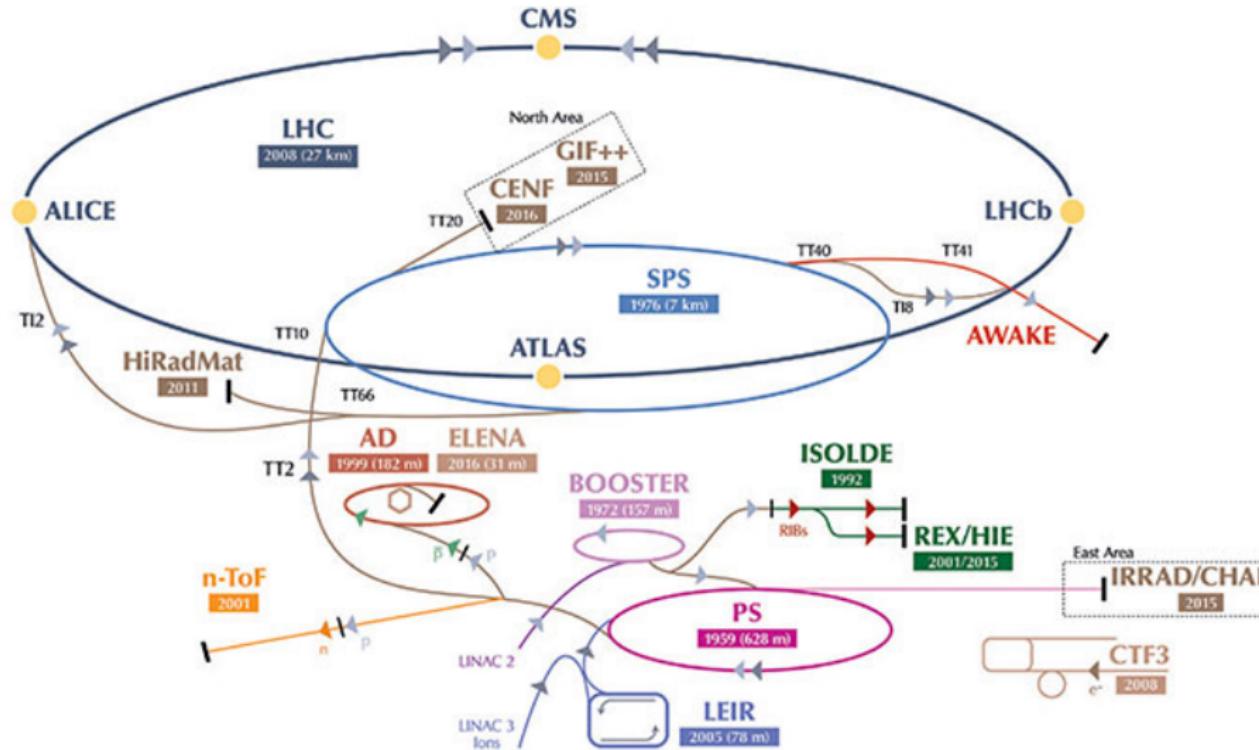
## Others

- ① Tevatron
- ② RHIC
- ③ Bevatron
- ④ HERA
- ⑤ SLAC
- ⑥ EIC

# A Simple Synchrotron



# Large Hadron Collider



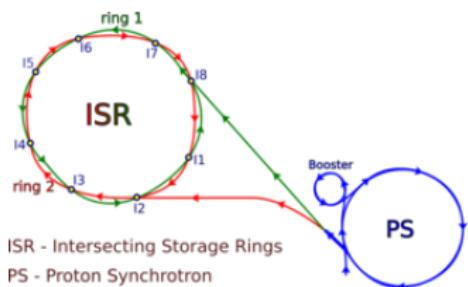
# Goals of LHC Experiments

## Testing the Theories

- Search for New Particle: Higgs boson was detected in 2012
- Quark Gluon Plasma Formation
- Grand Unification Theory
- Fundamental Forces and Particles

# The Intersecting Storage Rings

## The First Hadron Collider



### Legacy

- Stochastic cooling
- RF stacking
- Magnetic Detectors
- J and Upsilon meson
- QCD and quarks
- Proton Structure

# The Future LHC

## High Luminosity LHC 2028

Increase the number of collisions and datasets

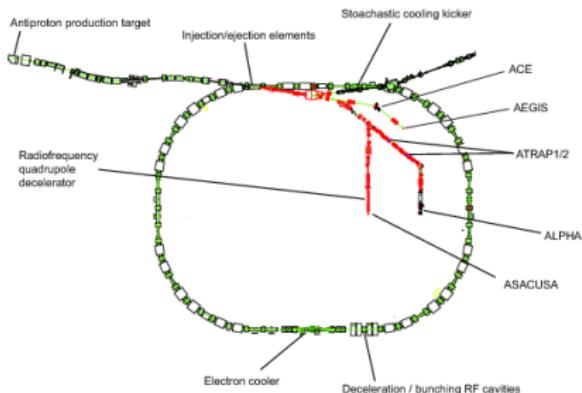


## Future Circular Collider

- **Future Circular Collider (FCC)**  
Circumference: 90–100 km  
Energy: 100 TeV ( $p\bar{p}$ ) 90–350 GeV ( $e^+e^-$ )
- **Large Hadron Collider (LHC)**  
**Large Electron-Positron Collider (LEP)**  
Circumference: 27 km  
Energy: 14 TeV ( $p\bar{p}$ ) 209 GeV ( $e^+e^-$ )
- **Tevatron**  
Circumference: 6.2 km  
Energy: 2 TeV ( $p\bar{p}$ )



## Antiproton Decelerator



### Goals

- Antihydrogen Spectroscopy
- Effects of gravity on Antiprotons
- Fundamental properties of Antiproton
- Antiprotons in Medical Field

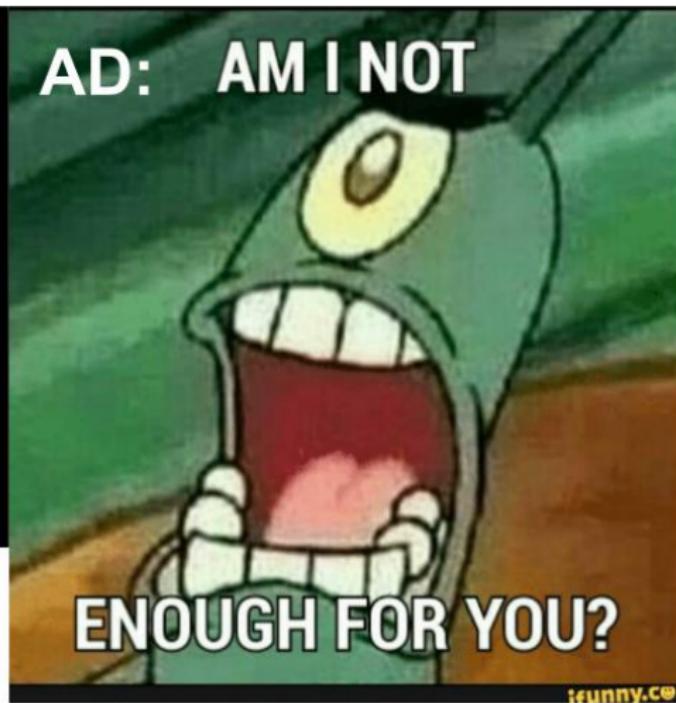
Q: Why not an anti-neutron decelerator?

## How much antimatter has been produced at CERN?

- ① enough to annihilate entire LHC
- ② enough to annihilate a normal room
- ③ enough to make bonfire for horizon members meet
- ④ enough to make a cup of tea
- ⑤ enough for a firefly to get its bioluminescence for couple of seconds

# The Antimatter Factory

CERN  
building  
ELENA  
for more  
anti-  
particles



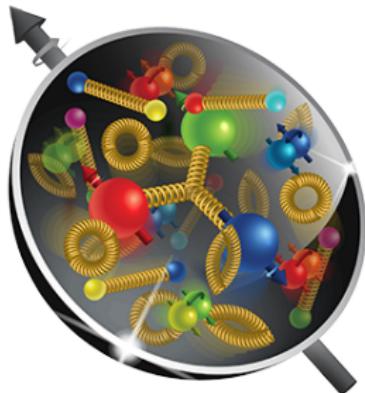
# The Antimatter Factory



# HERA and EIC

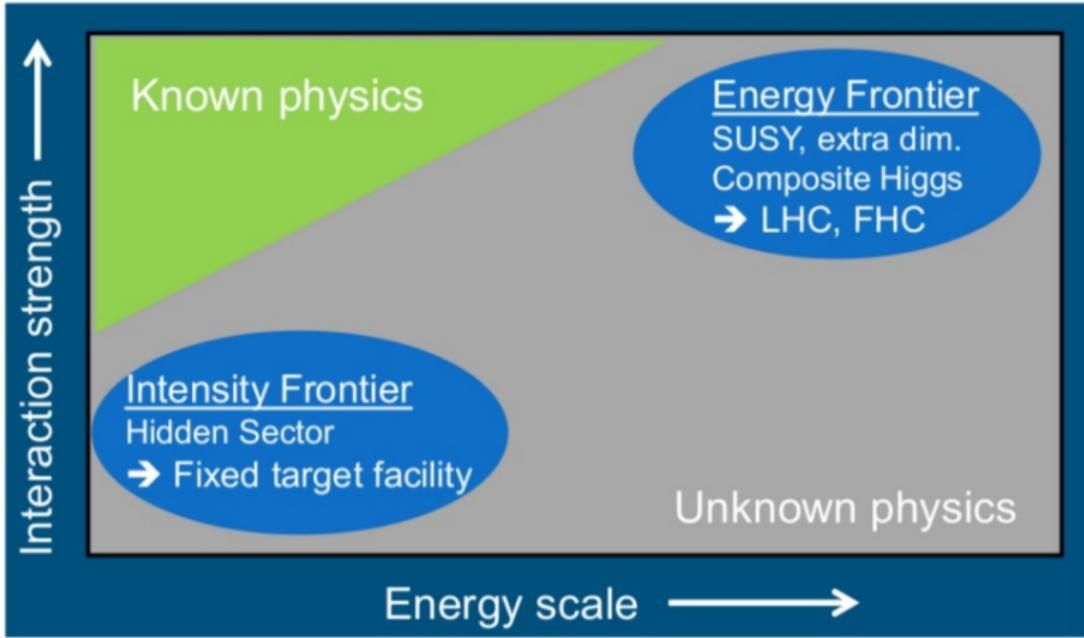
## Legacy of HERA

- Proton Structure, Spin Structure
- QCD tests
- Strong force and heavy quark production



## Electron Ion Collider- Goals

- Internal structure of proton
- Study of quarks and gluons
- Strong force
- How mass of proton arise
- Quark-gluon confinement



# Fun-Fact

How was 'world wide web' invented at CERN?

While working at CERN, Tim Berners-Lee became frustrated with the inefficiencies and difficulties in finding information stored on different computers. So he proposed to CERN management a more elaborate network he called 'web'.

Fun fact within a fun fact

Sir Timothy John Berners-Lee is also known as TimBL



# Beyond Standard Model Physics

## CHANGES I WOULD MAKE TO THE STANDARD MODEL

CONSISTENT QUARK NAMES  
(USE "STRANGE" AND "CHARM" FOR BOSONS)

U  
UP

L  
LEFT

t  
TOP

g  
GLUON

V  
VIN DIESEL

d  
DOWN

R  
RIGHT

b  
BOTTOM

$\gamma$   
PHOTON

G  
GRAVITON

WITH ALL RESPECT  
TO PETER H, THE  
HIGGS BOSON NEEDS  
A FLASHIER NAME

LET'S JUST  
INCLUDE IT, IT'S  
PROBABLY FINE

e  
ELECTRON

M  
MUON

N  
NO ONE NEEDS  
TAU LEPTONS

S  
STRANGE  
BOSON

M  
MAGIC

DECoy PARTICLE  
FOR PEOPLE MAKING  
NONSENSE CLAIMS  
ABOUT "QUANTUM"  
PHILOSOPHY STUFF

$N_e$   
ELECTRON NEUTRINO

T  
TOO MANY  
NEUTRINOS

D  
DARK MATTER

C  
CHARM  
BOSON

B  
COOL BUGS

VERY SMALL BUGS  
ARE FUNDAMENTAL  
PARTICLES NOW

Fix NEUTRINO SYMBOL SO  
I STOP MIXING UP  $\nu$  AND  $\bar{\nu}$   
WE FOUND IT!

# Shortcomings of SM

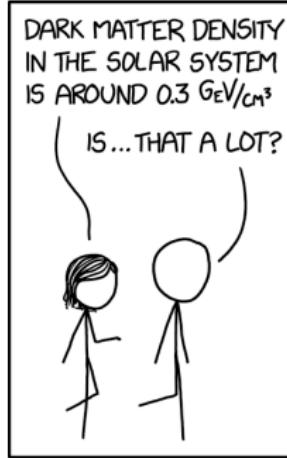
## Unexplained Phenomena

- Strong CP Problem
- Neutrino oscillations and mass
- Matter-Antimatter symmetry
- Dark matter and Dark Energy
- Well, Gravity
- Koide formula
- CKM Matrix
- 19 free parameters
- Gauge group  $SU(3)_c \times SU(2)_L \times U(1)_Y$

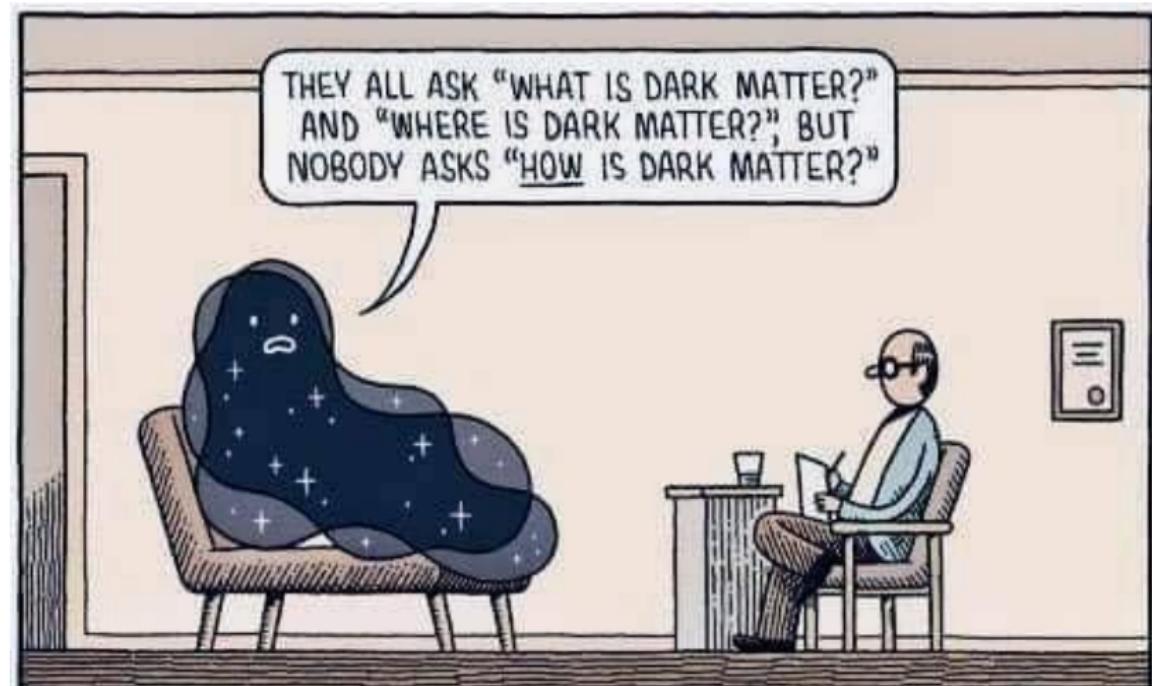
## Experimental issues

- B Meson decay
- Muon magnetic dipole moment

# Dark Matter candidates



# Dark Matter and Dark Energy



TOM GAULD for NEW SCIENTIST



# Beyond the Standard Model

## Major Theories

- GUTs
- Supersymmetry
- Loop Quantum Gravity
- String Theory
- Division Algebras

# The solution to all Standard Model Problems

A CHRISTMAS GIFT FOR PHYSICISTS:

## THE FIXION

A NEW PARTICLE THAT EXPLAINS EVERYTHING

