Introduction to Particle Physics

Vaibhavi Gawas, Vivan Bhatt

Horizon Club
Centre for Innovation IIT Madras

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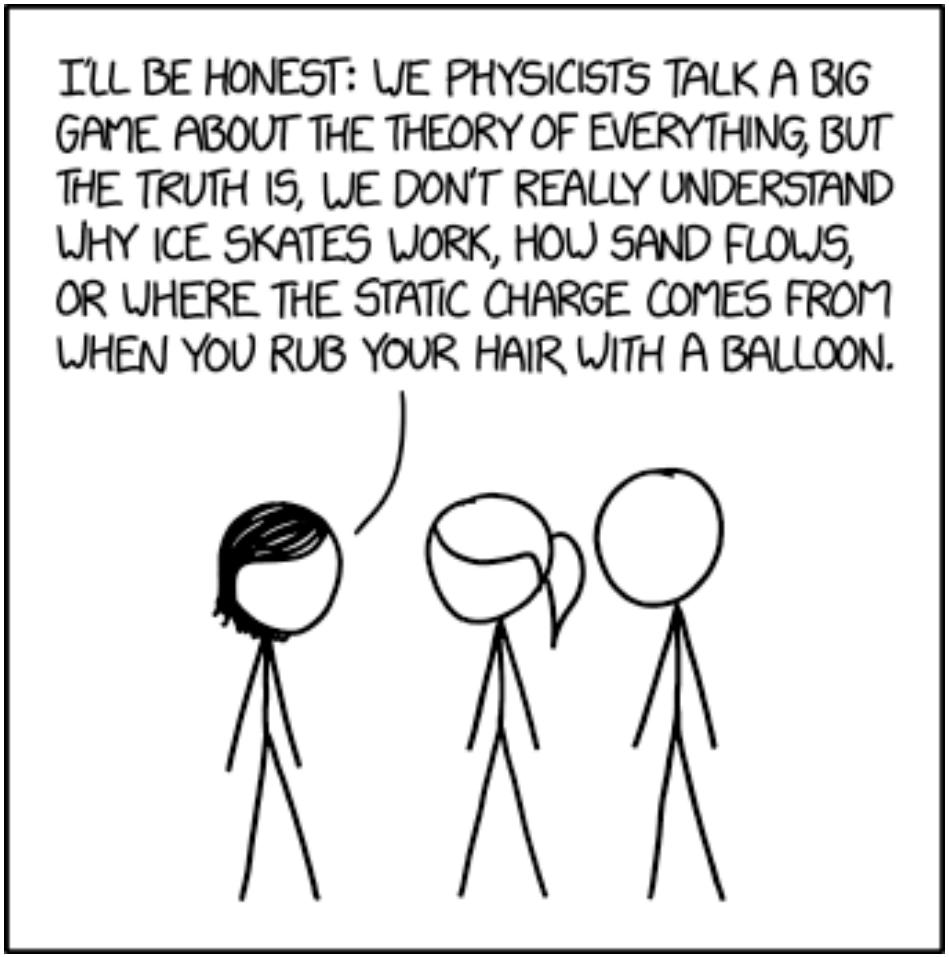
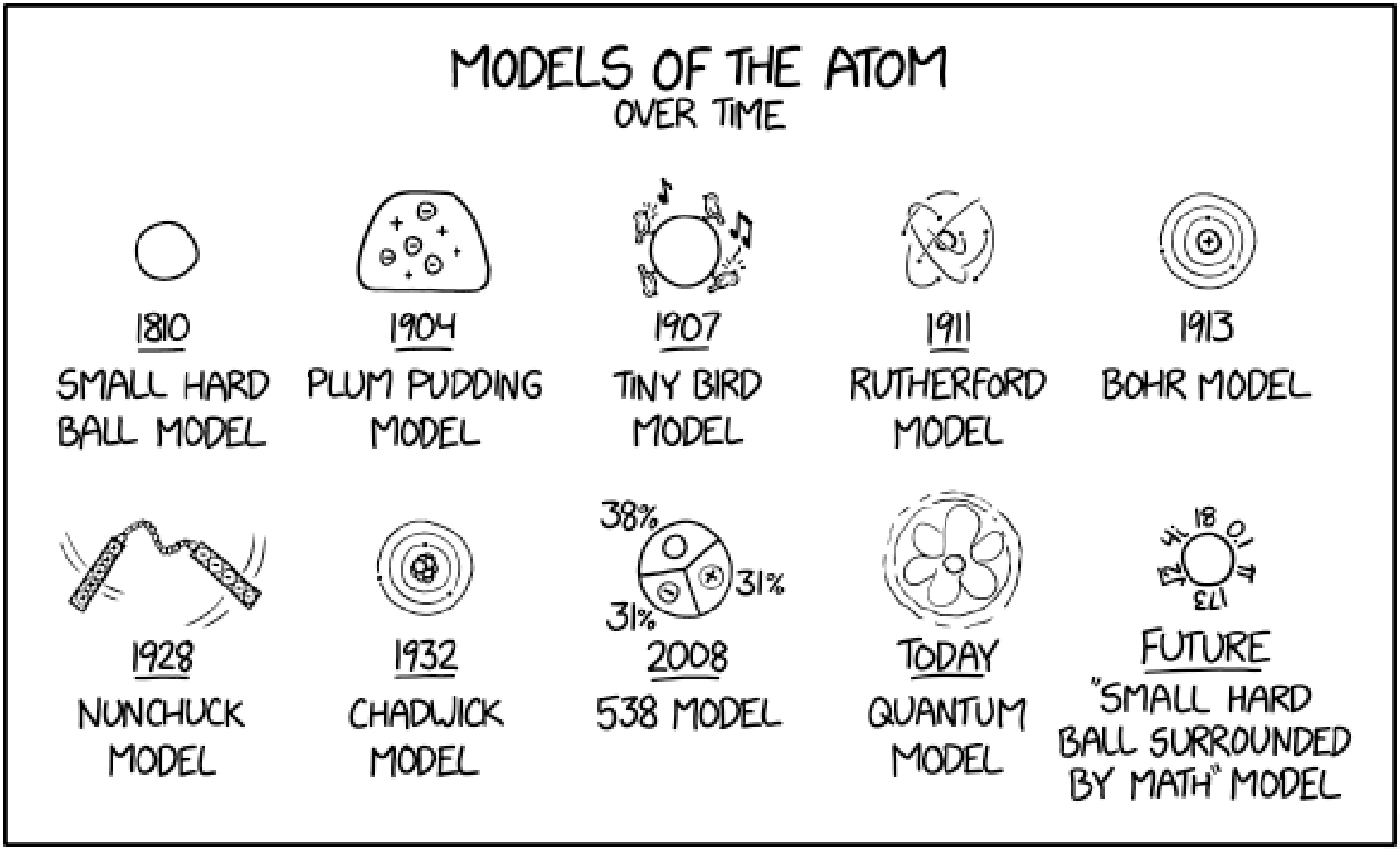
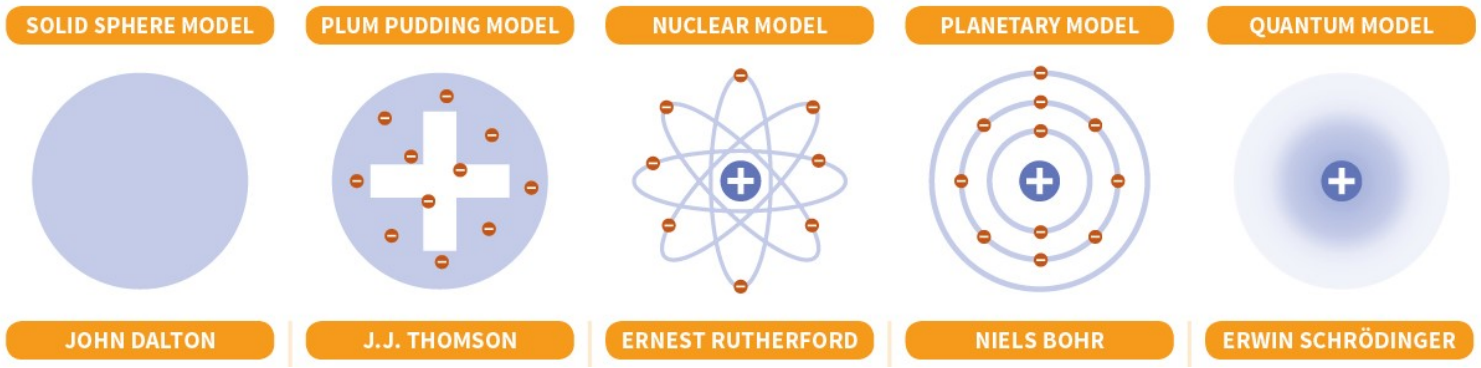
Why Particle Physics



What are we made of?



Atomic Theory through the years

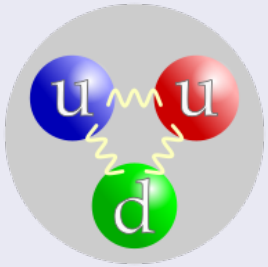


The indivisible Atom

- "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.

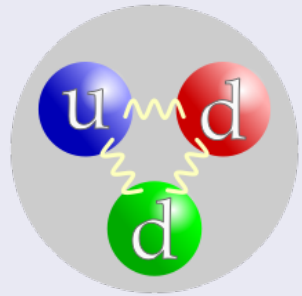
Structure of Proton and Neutron

Proton



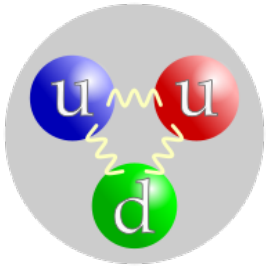
- Charge $= +1$
- Colour $=$ "White"
- Mass $= 938.27 MeV/c^2$
- Mean lifetime $> 2.110^29$ years
- Proton Decay??

Neutron



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

A Proton has three Quarks?



- Proton mass $= 938.27 MeV/c^2$
- Sum of quark masses $= 9.4 MeV/c^2$
- 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 $= 2.2 MeV/c^2$; 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

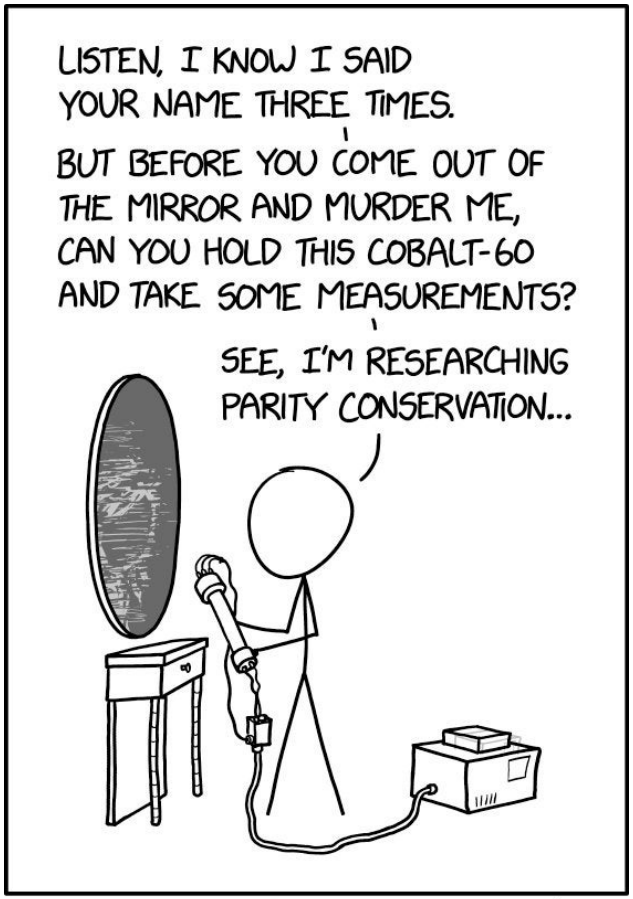
Top/truth Quark

- Mass $= 172.76 GeV/c^2$
- Mean lifetime $= 5x10^{-25}s$, decays into bottom quark
- No hadronization, Higgs coupling

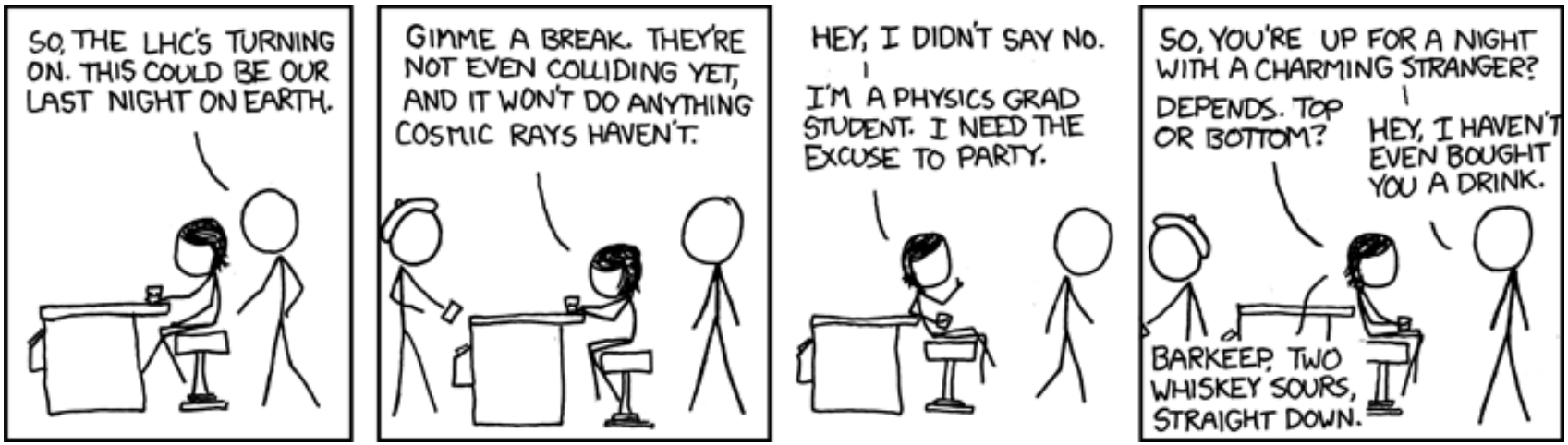
Bottom/beauty Quark

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

What is parity violation?

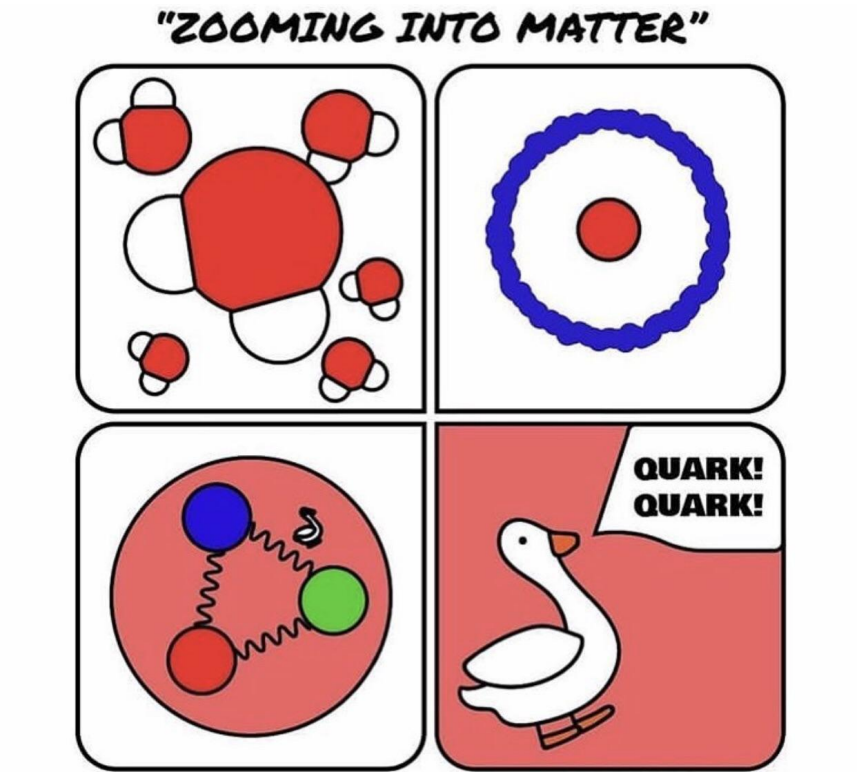


Third generation sounds fishy...



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."



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

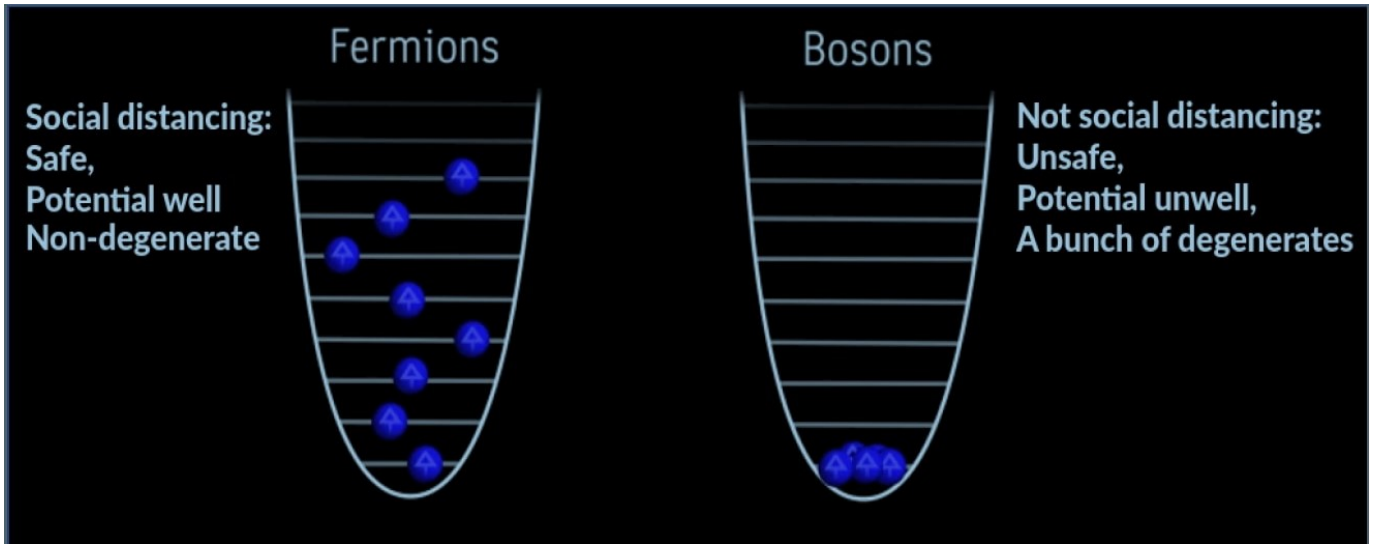
Charged leptons

- Electron
- Muon
- Tau

Uncharged leptons

- Electron neutrino
- Muon neutrino
- Tau neutrino

Types of Statistics



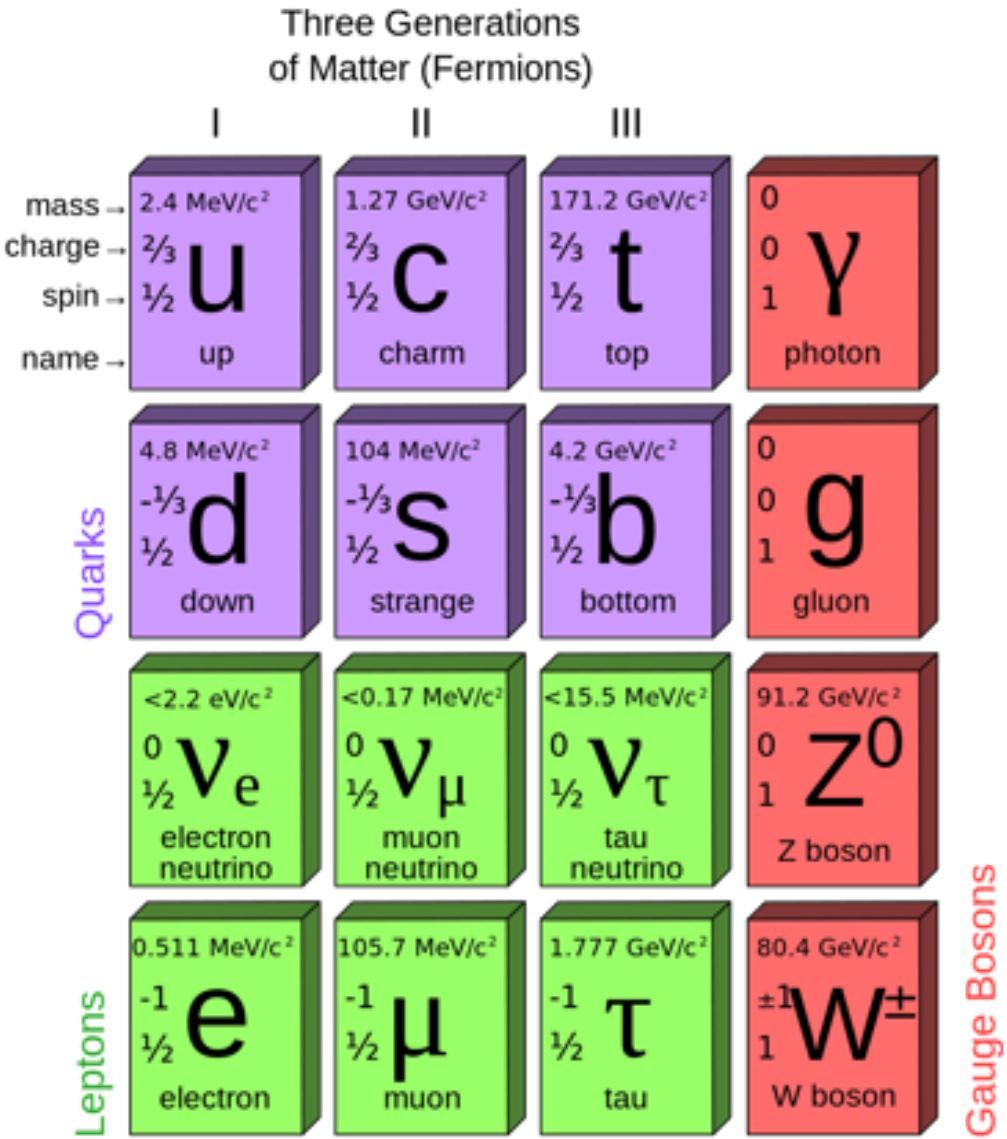
Fermions

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

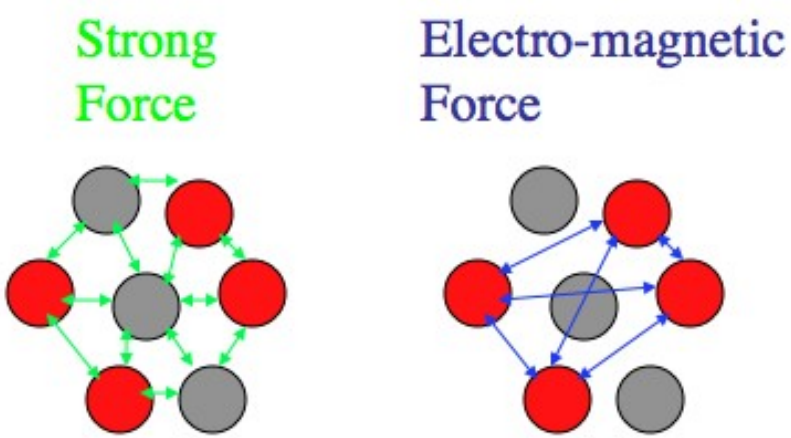
Bosons

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

What else?- The Fundamental Forces

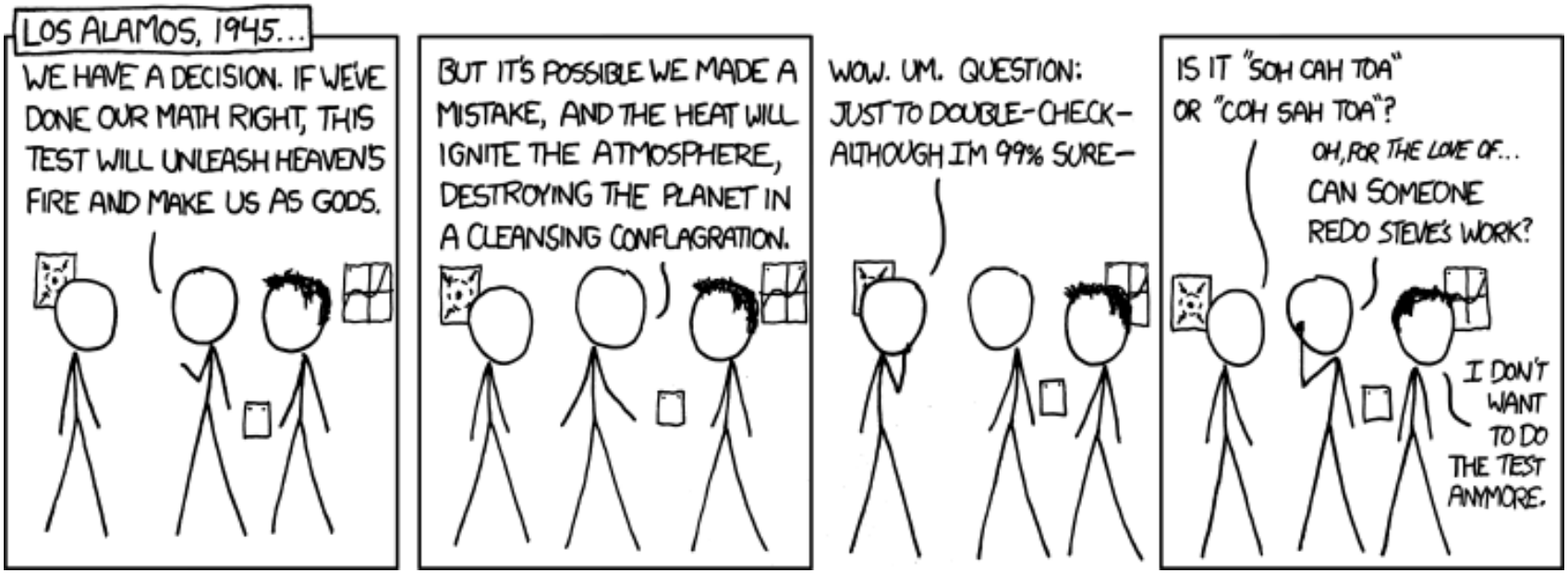


Strong Force

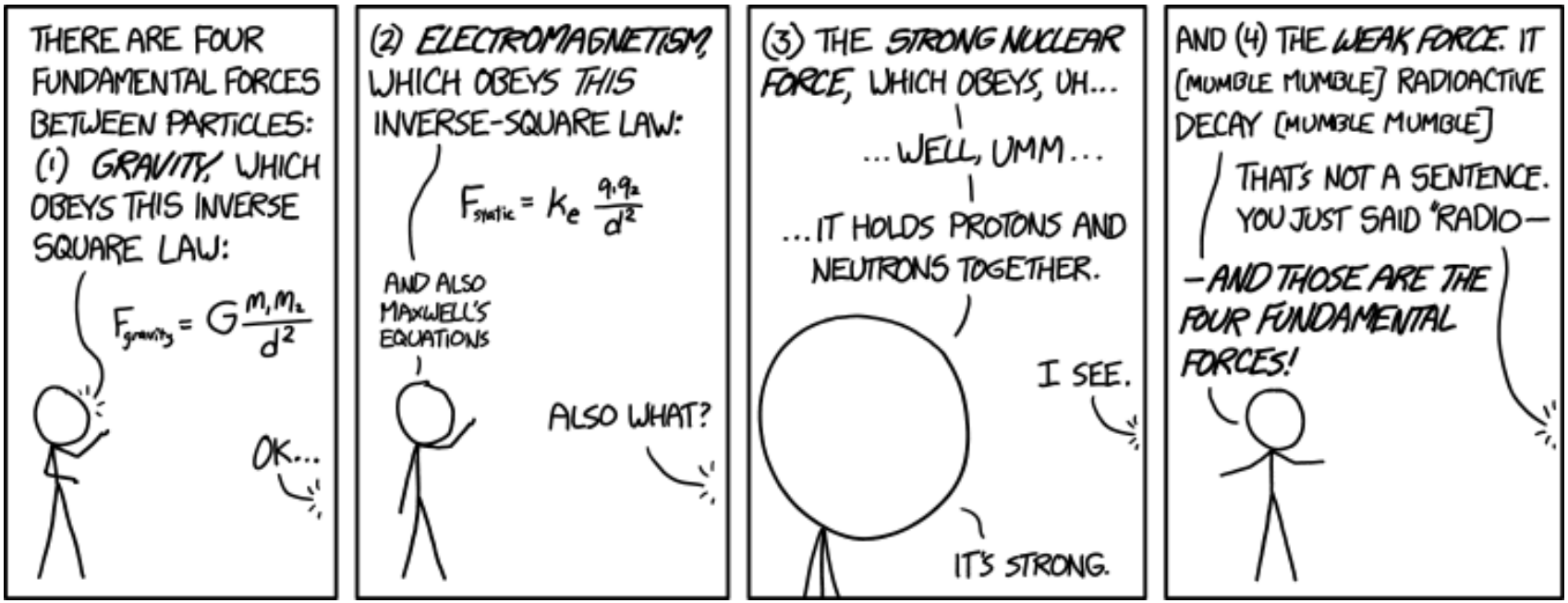


- How strong is "strong"?
- Quantum *Chromo*Dynamics
- Colour Confinement
- Hadron mass, residual strong force
- Two ranges, two particles - Mesons and Gluons
- Van der Waals-like behaviour
- Unification?

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?
I DON'T WANT TO DO THE TEST ANYMORE.

Weak Force

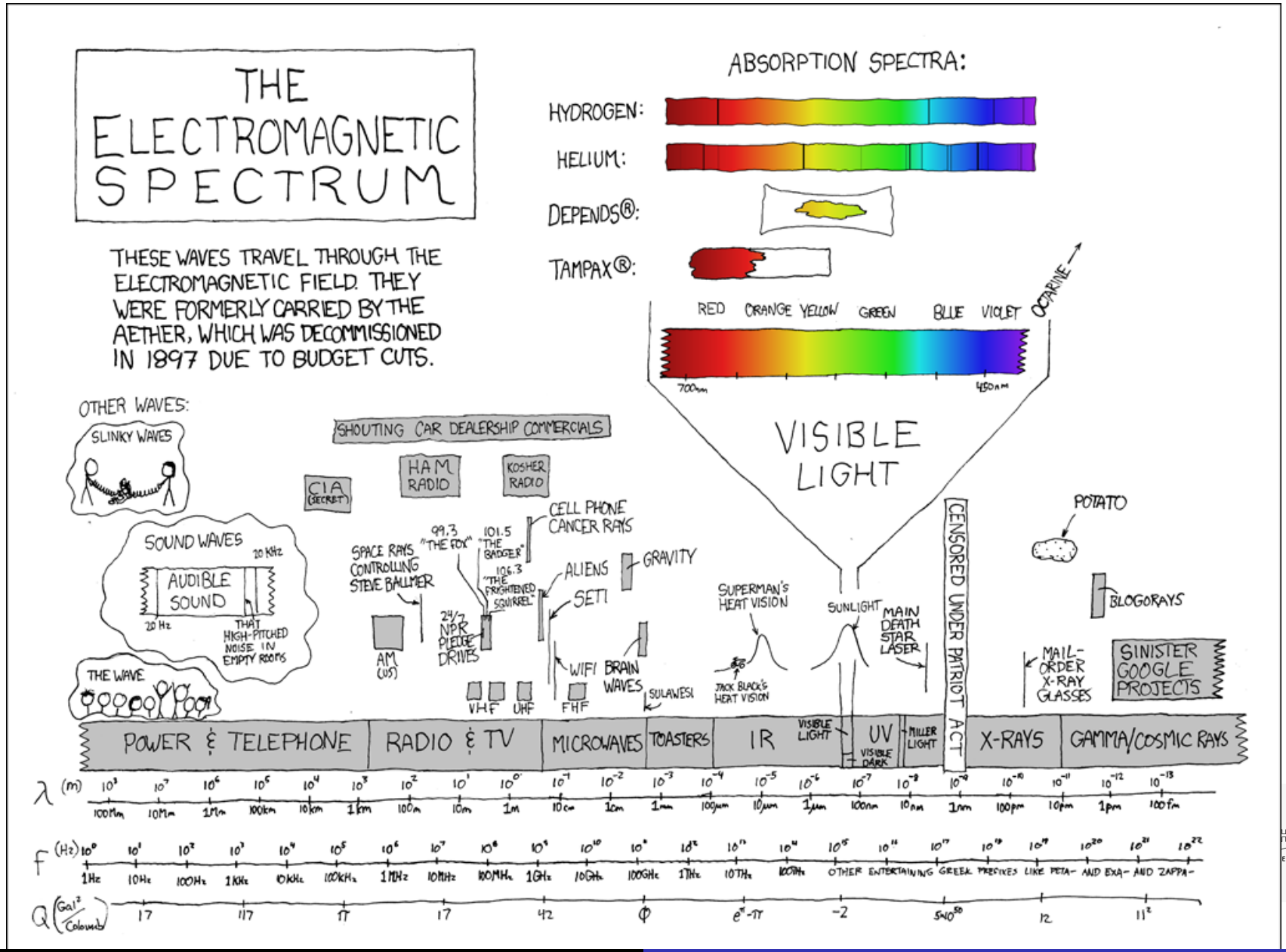

THERE ARE FOUR FUNDAMENTAL FORCES BETWEEN PARTICLES:
(1) GRAVITY, WHICH OBEYS THIS INVERSE SQUARE LAW:
$F_{gravity} = G\frac{m_1 m_2}{d^2}$
OK...
(2) ELECTROMAGNETISM, WHICH OBEYS THIS INVERSE-SQUARE LAW:
$F_{static} = k_e\frac{q_1 q_2}{d^2}$
AND ALSO MAXWELL'S EQUATIONS
ALSO WHAT?
(3) THE STRONG NUCLEAR FORCE, WHICH OBEYS, UH...
...WELL, UMM...
...IT HOLDS PROTONS AND NEUTRONS TOGETHER.
I SEE.
IT'S STRONG.
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!

Weak Force

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?



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.

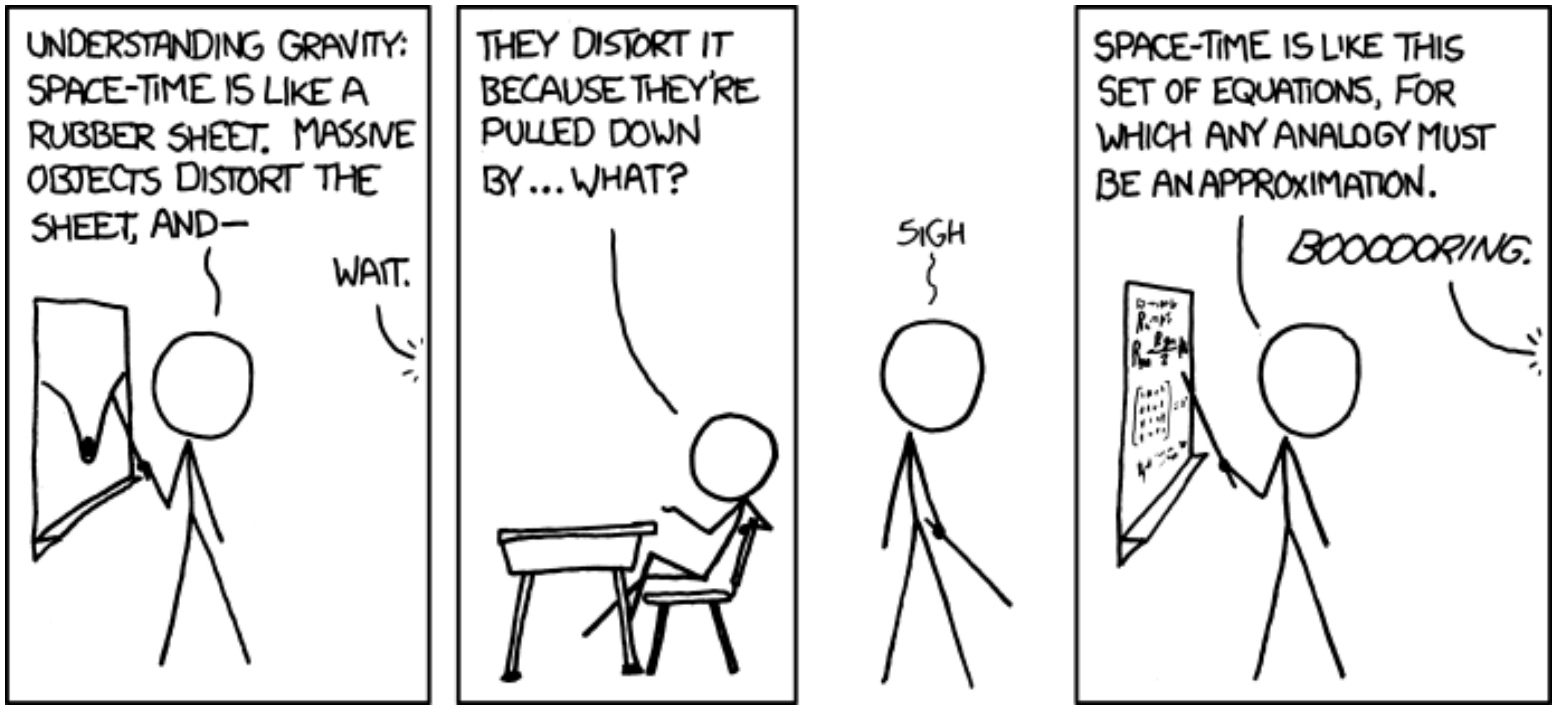
Properties

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

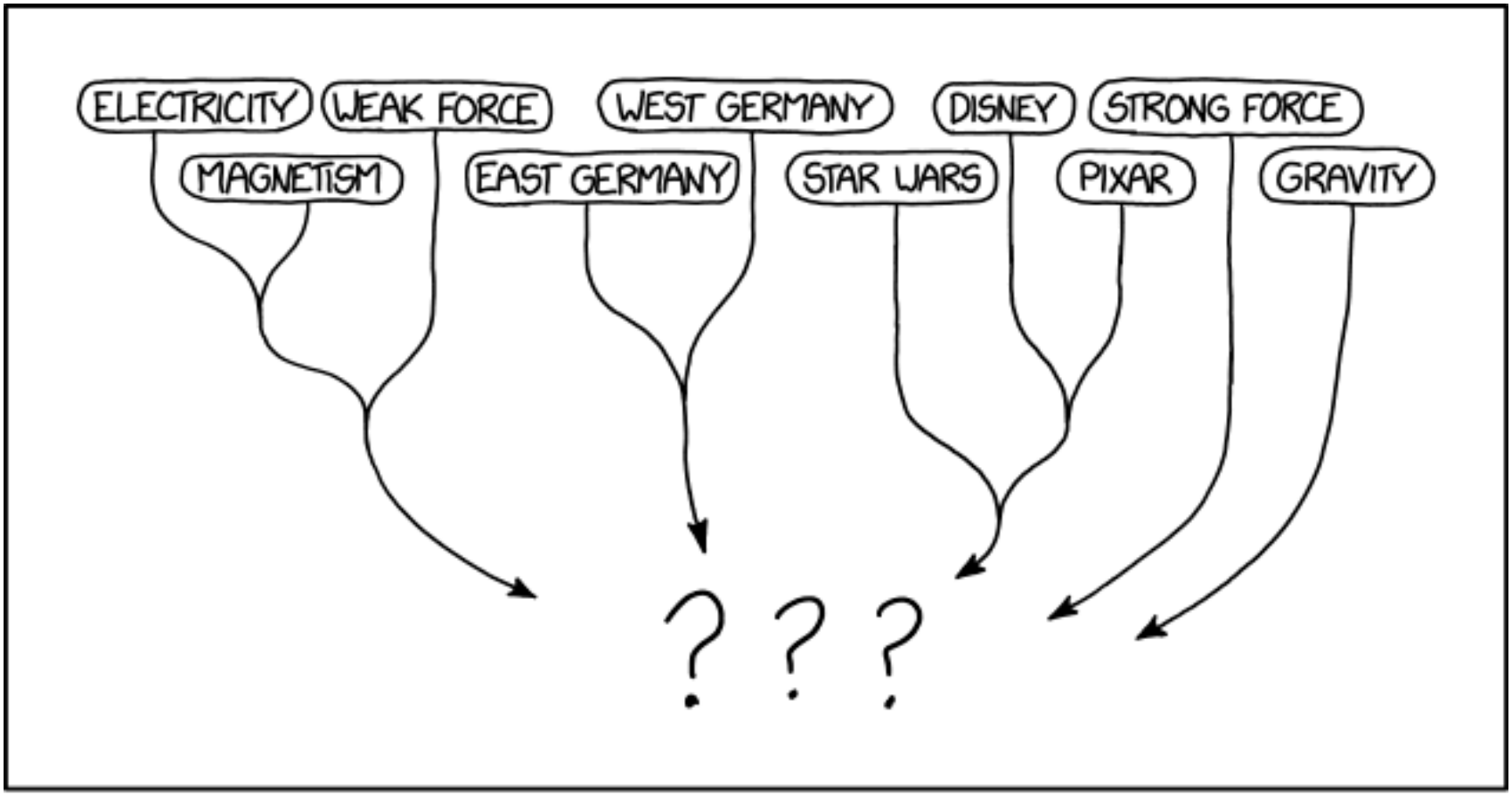
Theory:

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

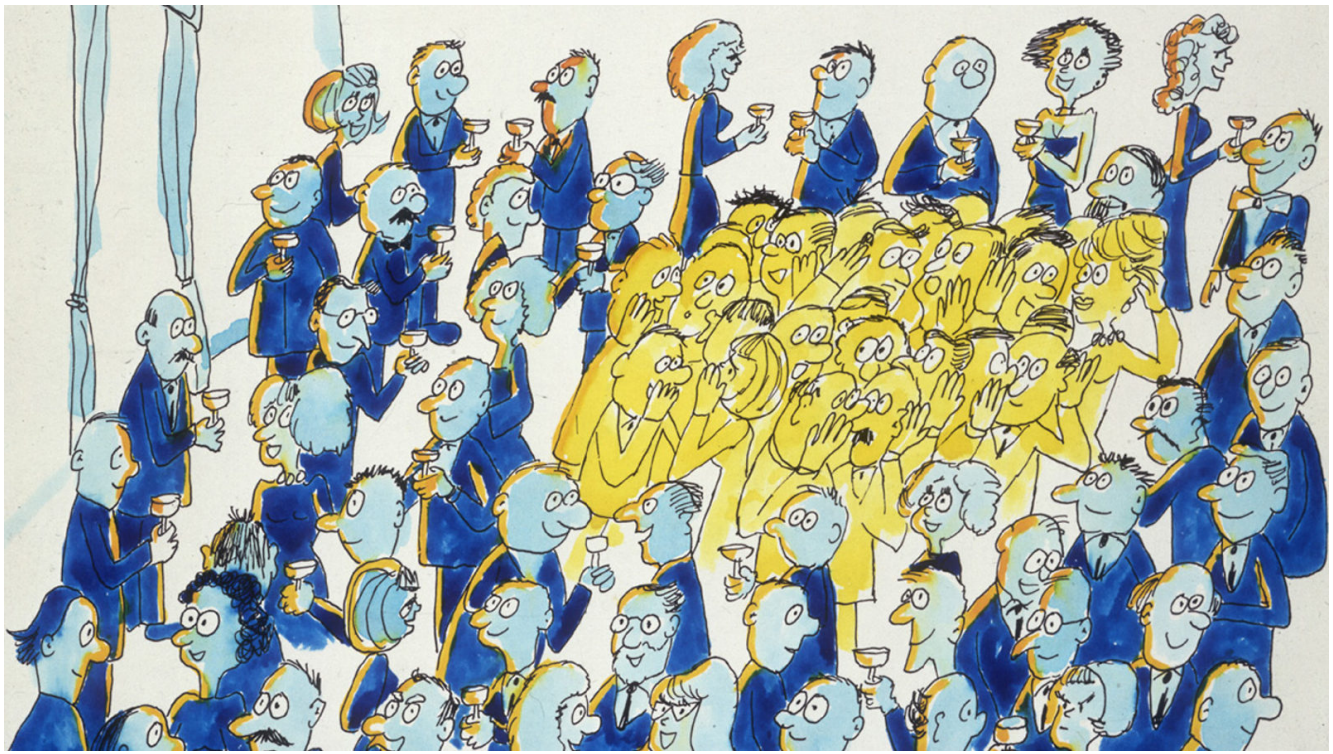
Force particles

Leptons

??

Oops! The Higgs Boson

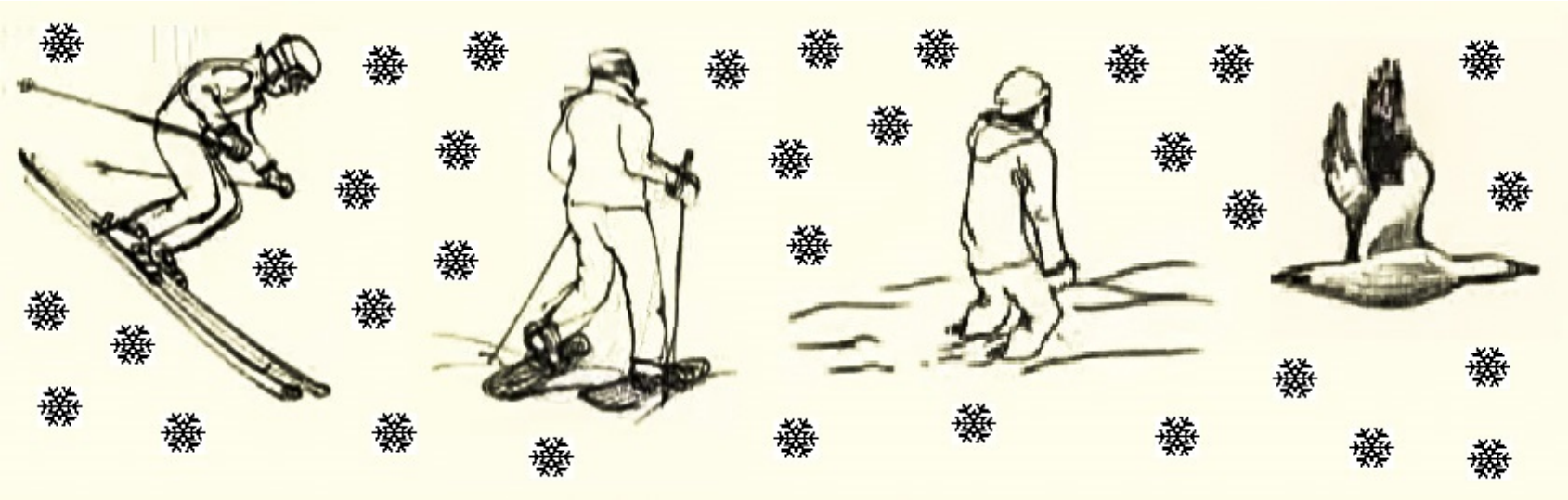
- The interaction with Higgs field gives mass to particles, while Higgs boson is the partcile associated with it.



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

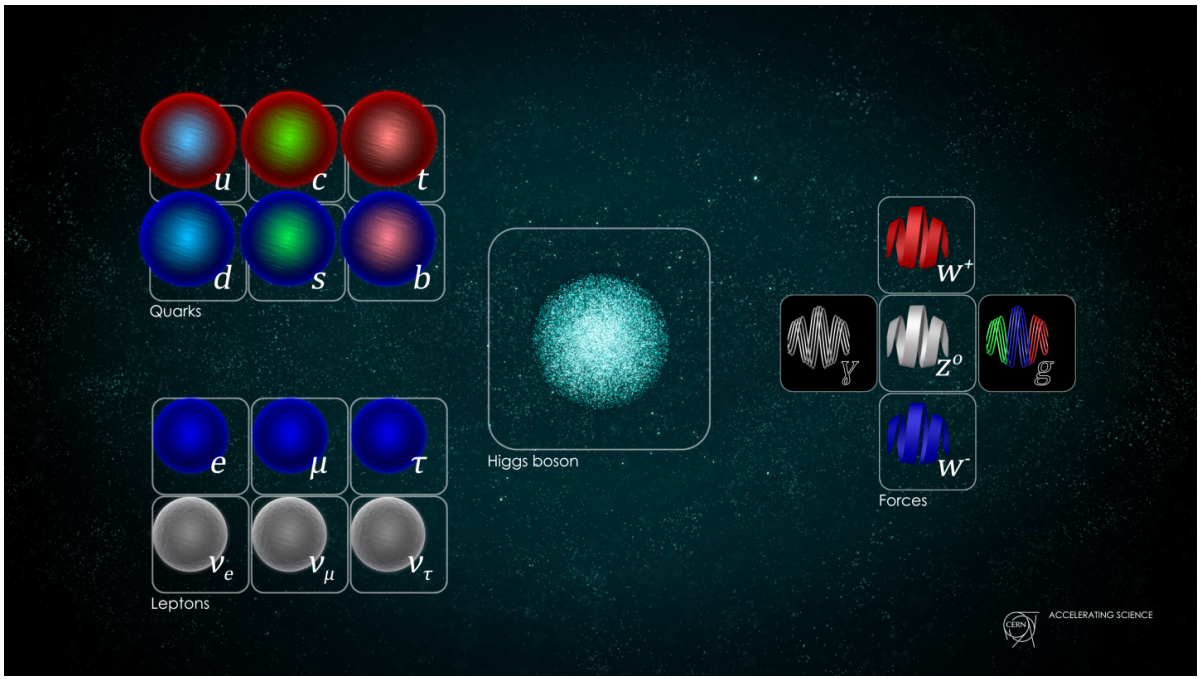
The Whole Picture now?

Quarks

Leptons

Force particles

Higgs Boson



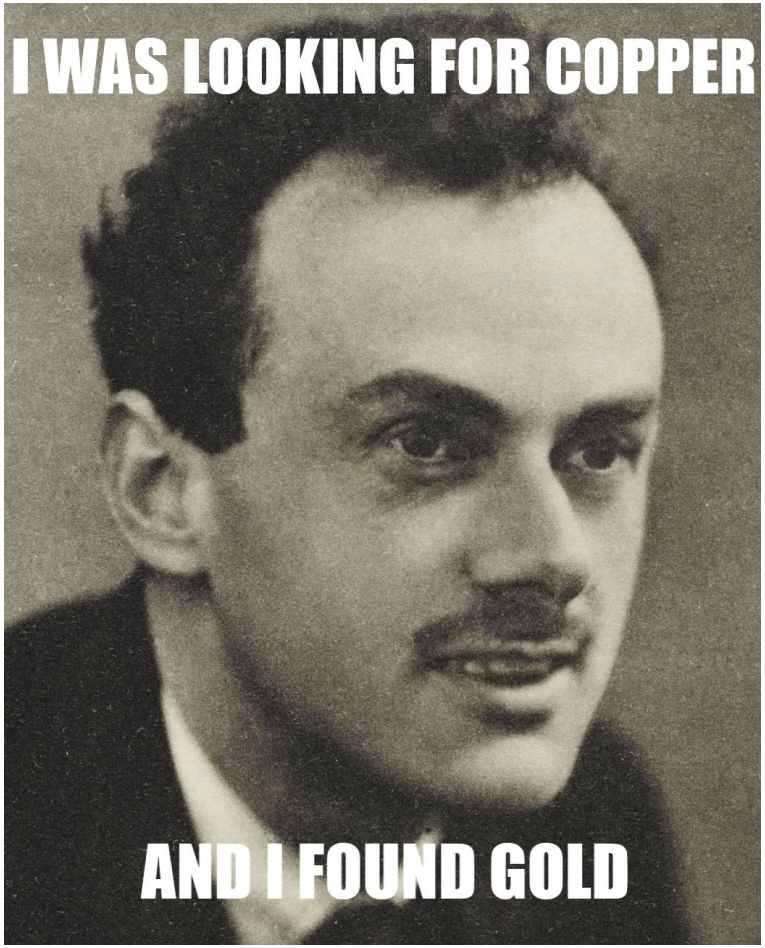
???

The Antimatter

Dirac's Equation for Relativistic Electron

$$(i\partial\!\!\!/ - m)\psi = 0$$

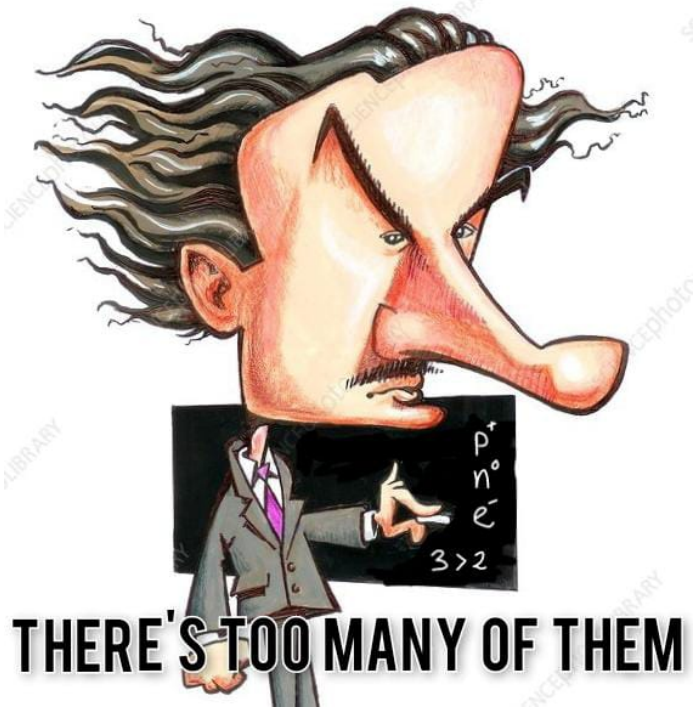
Negative Energy Solutions



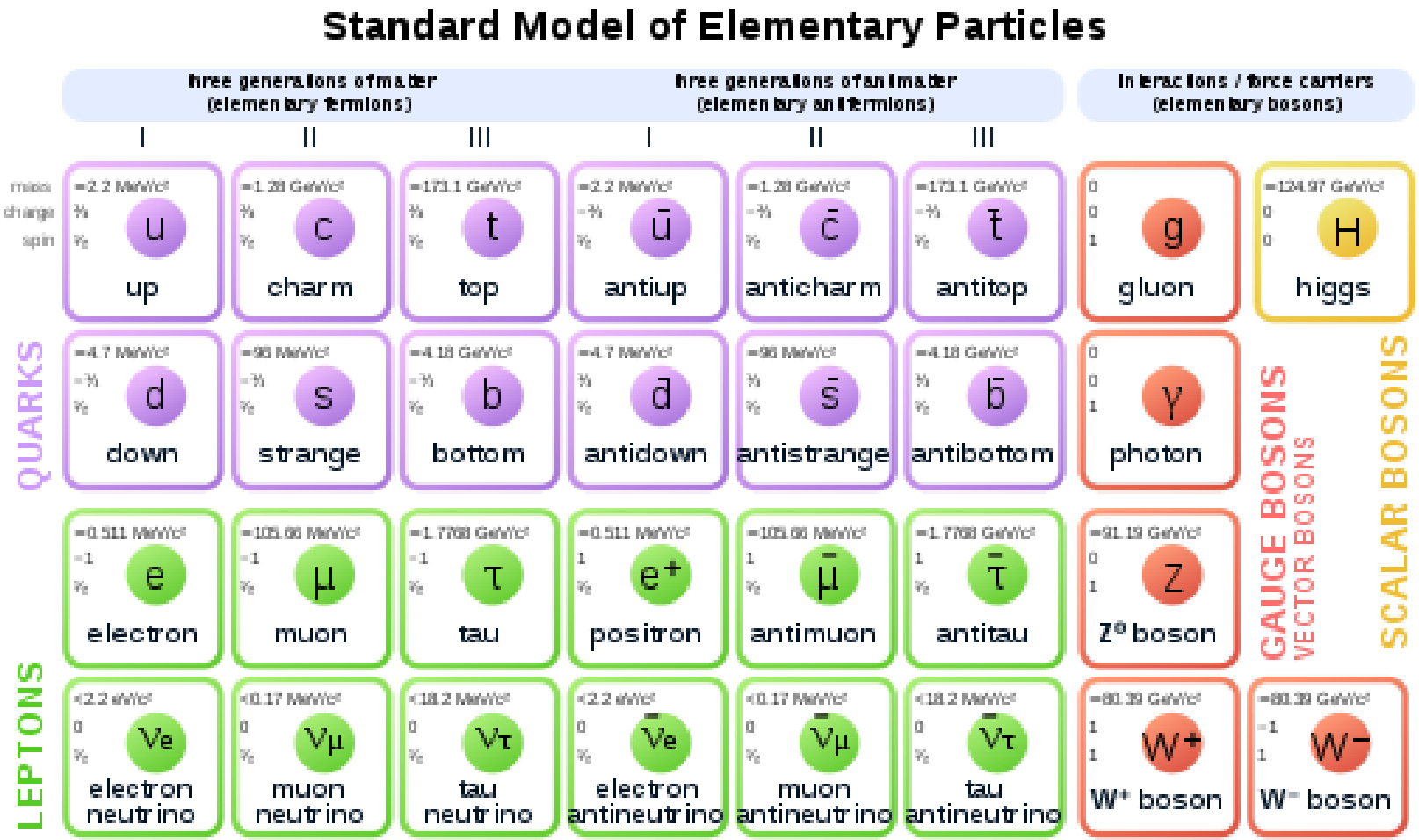
Dirac's Thoughts on having three fundamental particles

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."



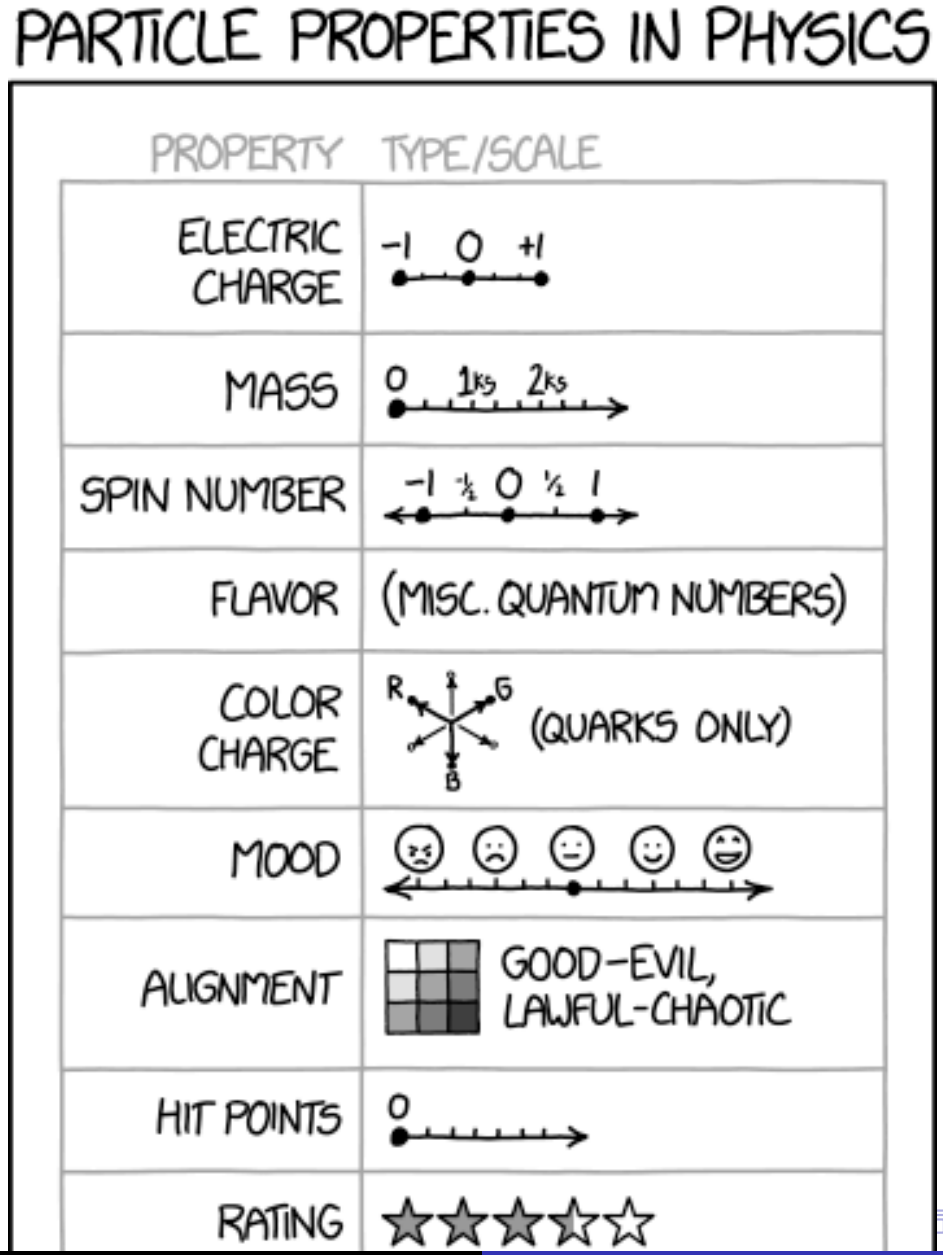
Standard Model



The complete picture now?

Join us later for Beyond Standard Model session later!

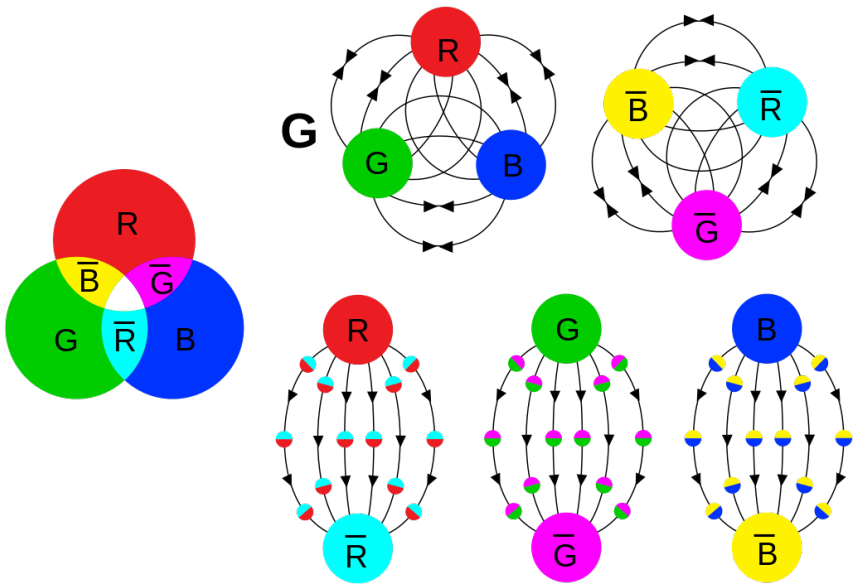
Particle properties



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 may conserved in one or more specific type of interaction.

Conservation Laws- Baryon Number

Baryon Number

B = $\frac{1}{3}$(no. of quark) - $\frac{1}{3}$(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 ν_e)
- Muon number (μ and ν_μ)
- Tau number (τ and ν_τ)

All three leptons are seperately conserved

In 'all' interactions the three lepton numbers are always conserved.
Associated Symmetry is the global gauge invariance

Beta Decay

$$n \hookrightarrow p + e + \overline{\nu_e}$$

Tau decay

$$\tau \hookrightarrow e^- + \overline{\nu_e} + \nu_\tau$$

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,μ,τ,ν_e,ν_μ,ν_τ

Cosmic Rays and Strangeness

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

$\pi^-(d\bar{u}) + p(uud) \hookrightarrow \Lambda^0(uds) + K^0(d\bar{s})$
$\Lambda^0(uds) \hookrightarrow \pi^-(d\bar{u}) + p(uud)$
$K^0(d\bar{s}) \hookleftarrow \pi^-(u\bar{d}) + \pi^+(d\bar{u})$

Conservation Laws

Parity

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

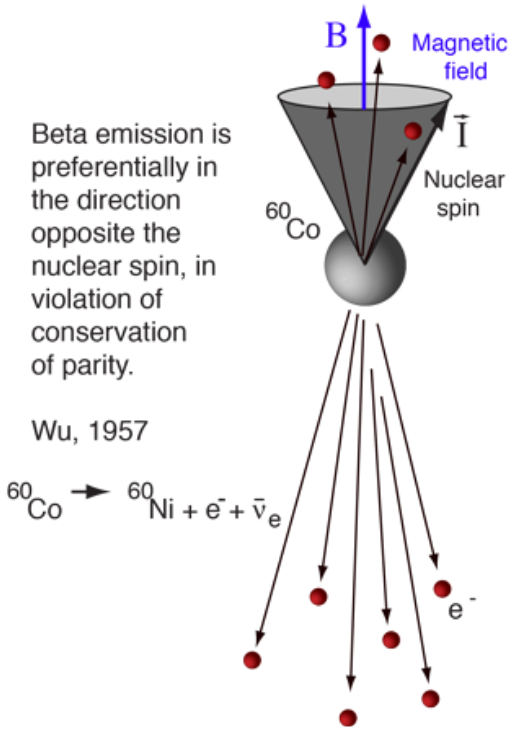
Charge Conjugation

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

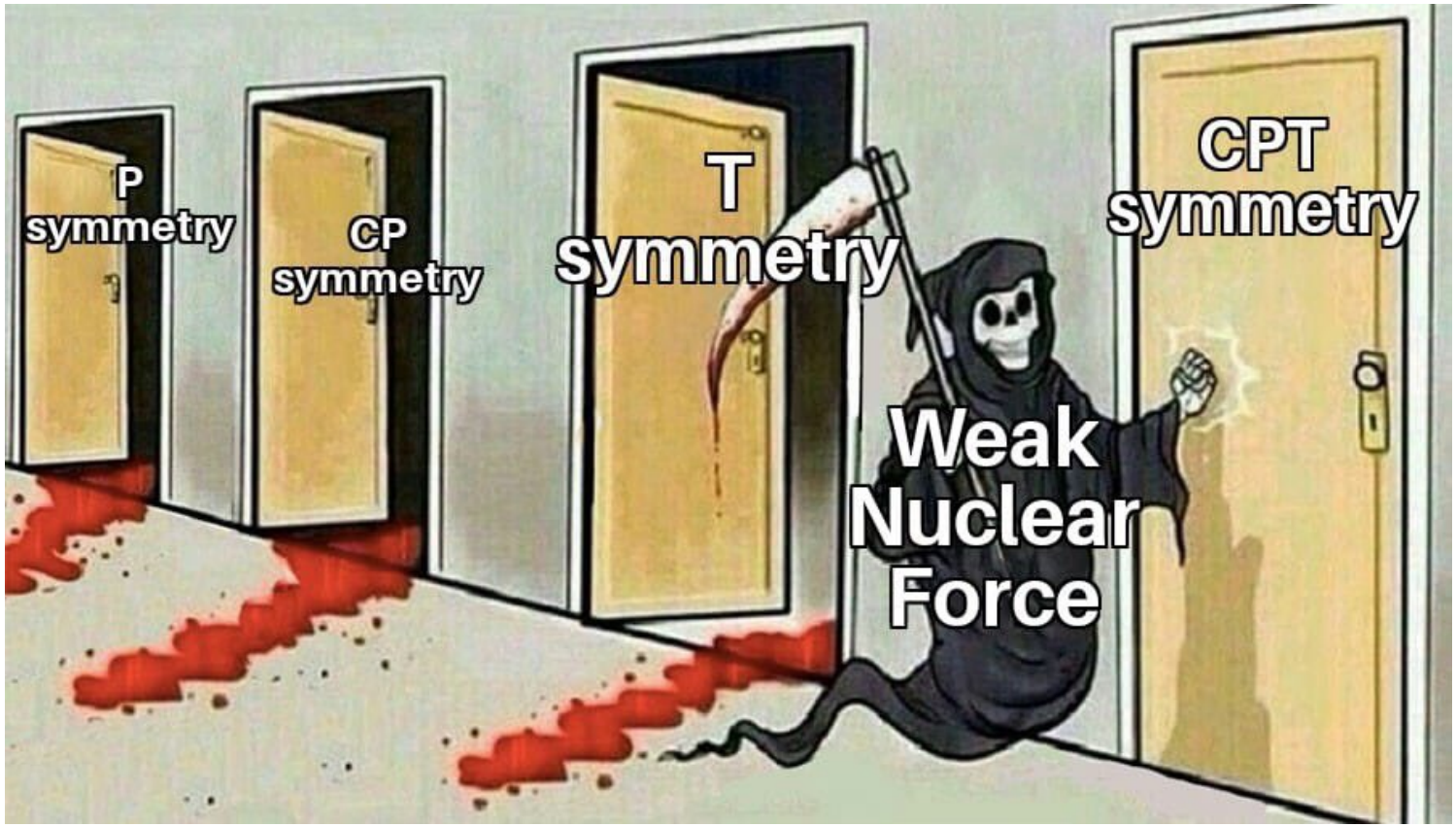
kaon Oscillations

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

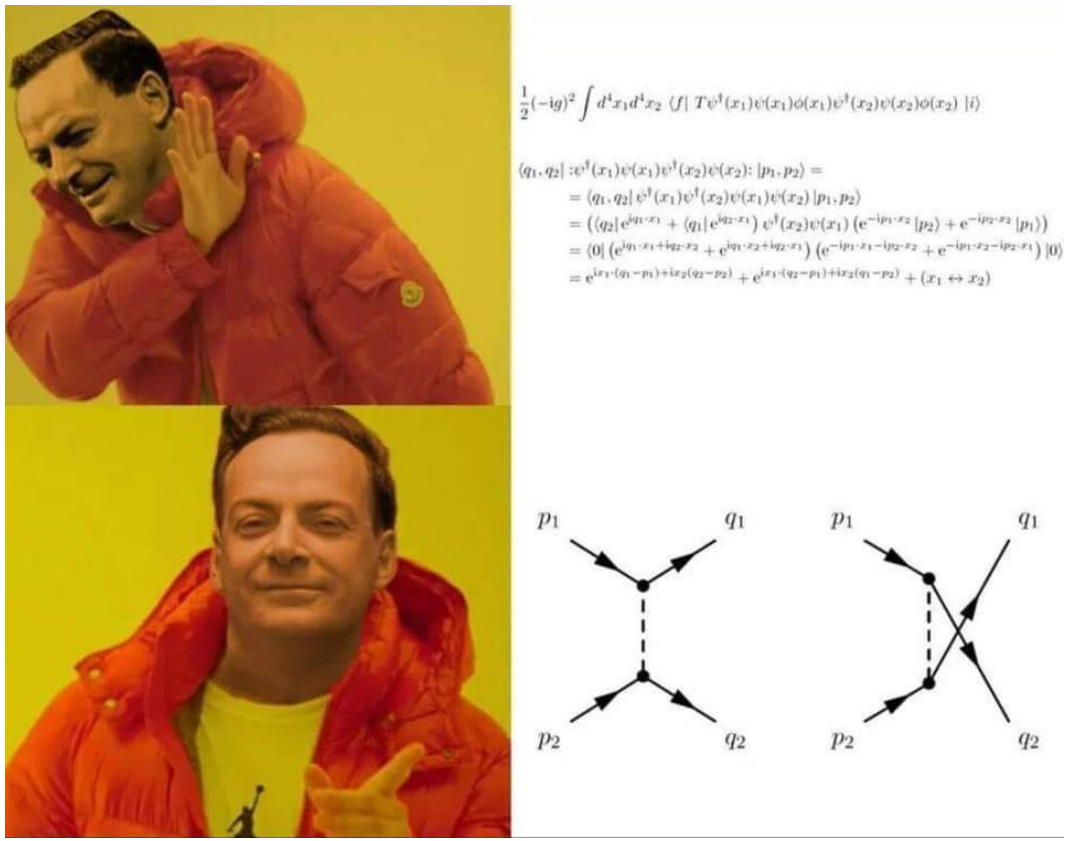
Feeling Blue with our Blue slides?

Feynman could help a bit a maybe

But Before that...

Feynman Diagrams: FBDs for Particle Physicists

1. Electromagnetic Interactions
2. Weak Interactions
3. Strong Interactions



Some Simple Features and Rules

Space-Time axis

Antiparticles are represented with backward arrow

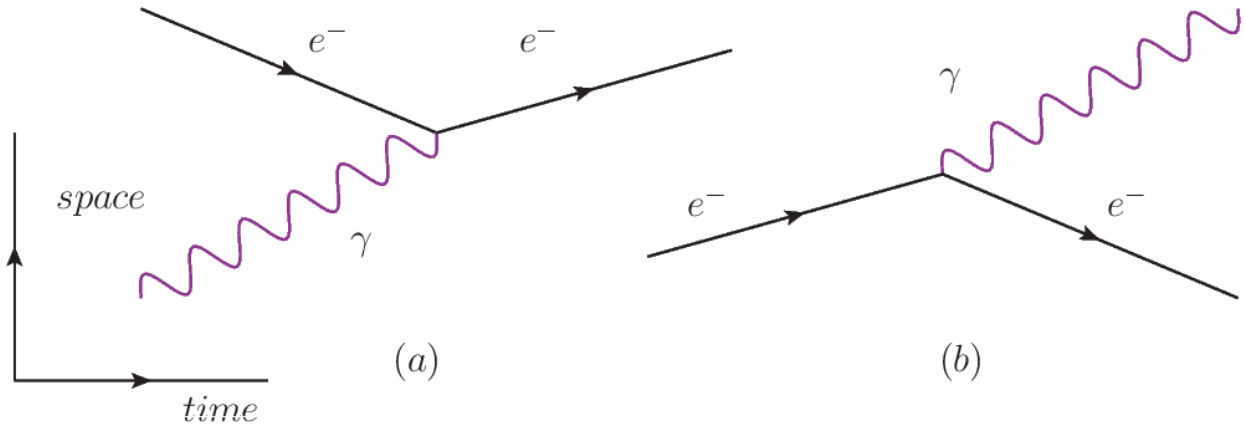
Identify the initial and final states
Initial state: points towards vertex
Final state: points away from vertex

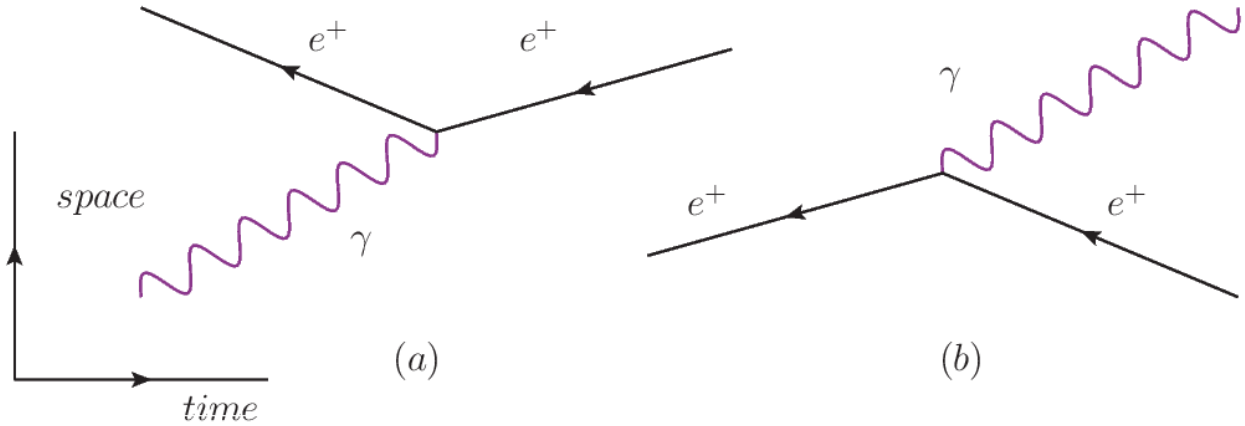
Conservation laws are applied at the vertices

Fermions: Solid Lines
Bosons: Wiggly lines

Virtual Particles

Electromagnetic: Photon emission and absorption

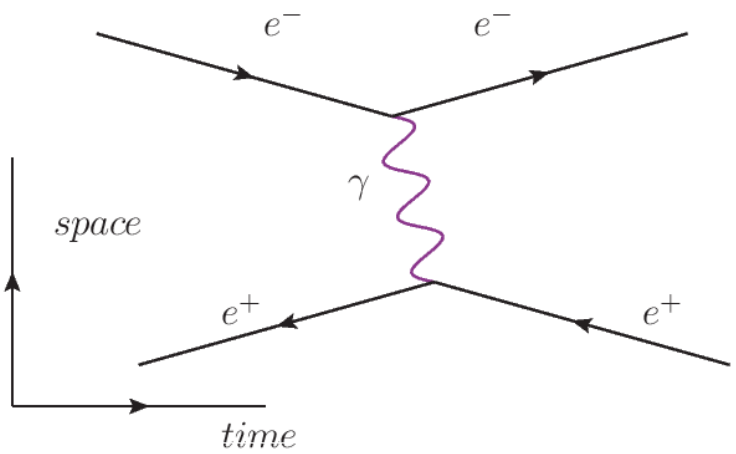




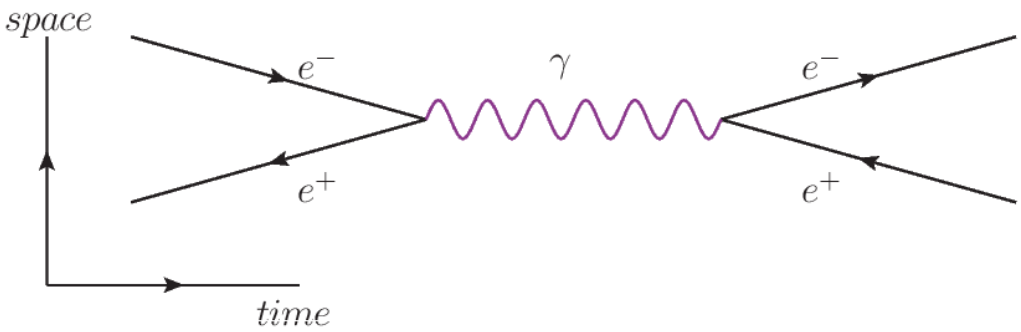
Feynman Diagrams: FBDs for Particle Physicists

Electromagnetic: Scattering, pair Annihilation and Production

Bhabha Scattering

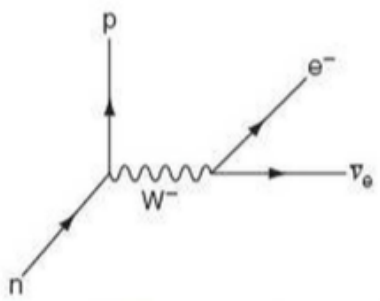


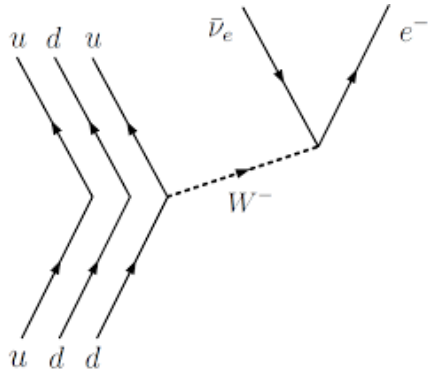
Pair annihilation and pair production

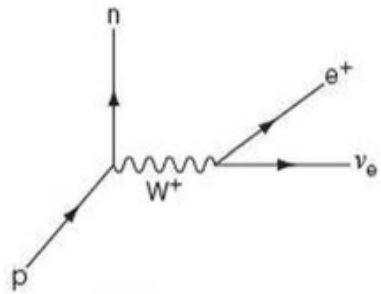


Feynman Diagrams: FBDs for Particle Physicists

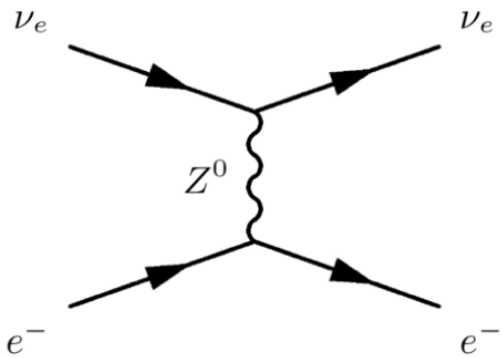
Weak Interaction: Beta Decay





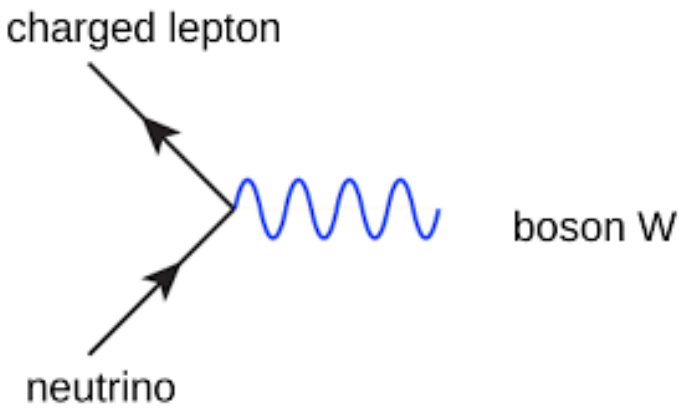


Neutral Current Interaction

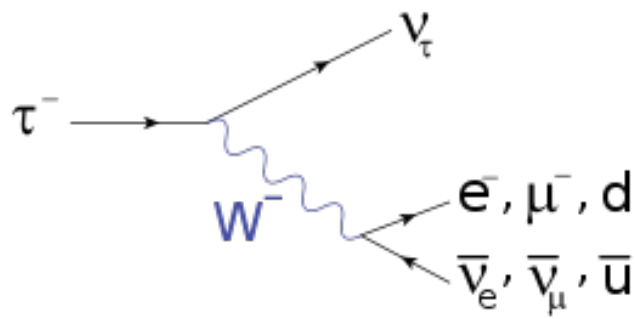


Weak Interactions: Some more

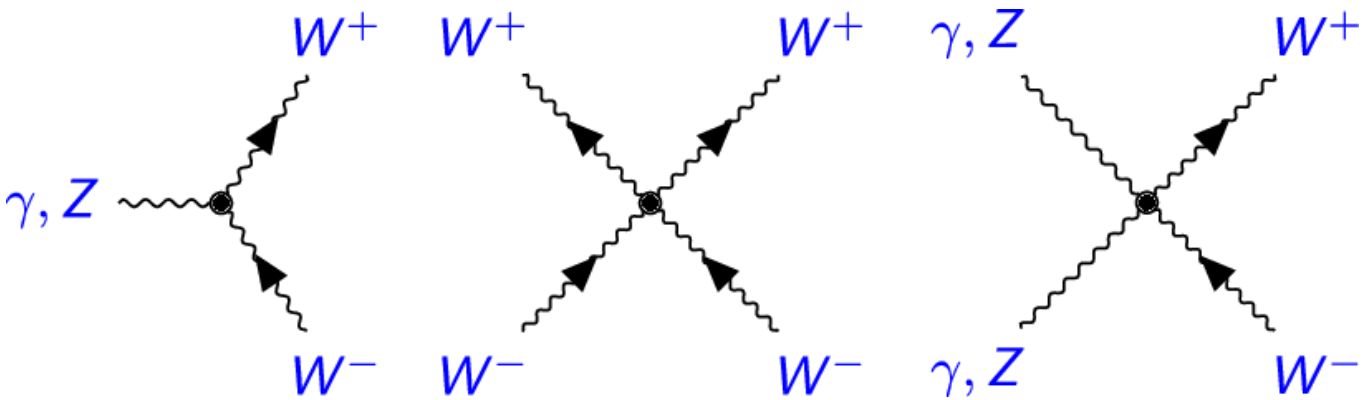
W Boson



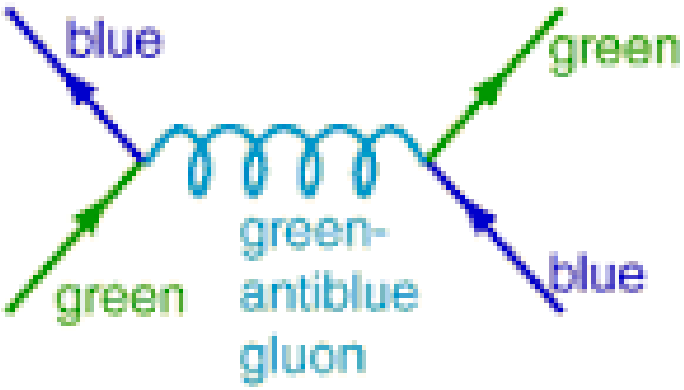
Tau Decay



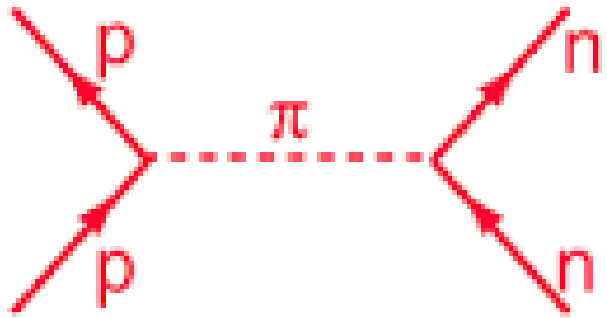
Self Interactions



Strong Interaction

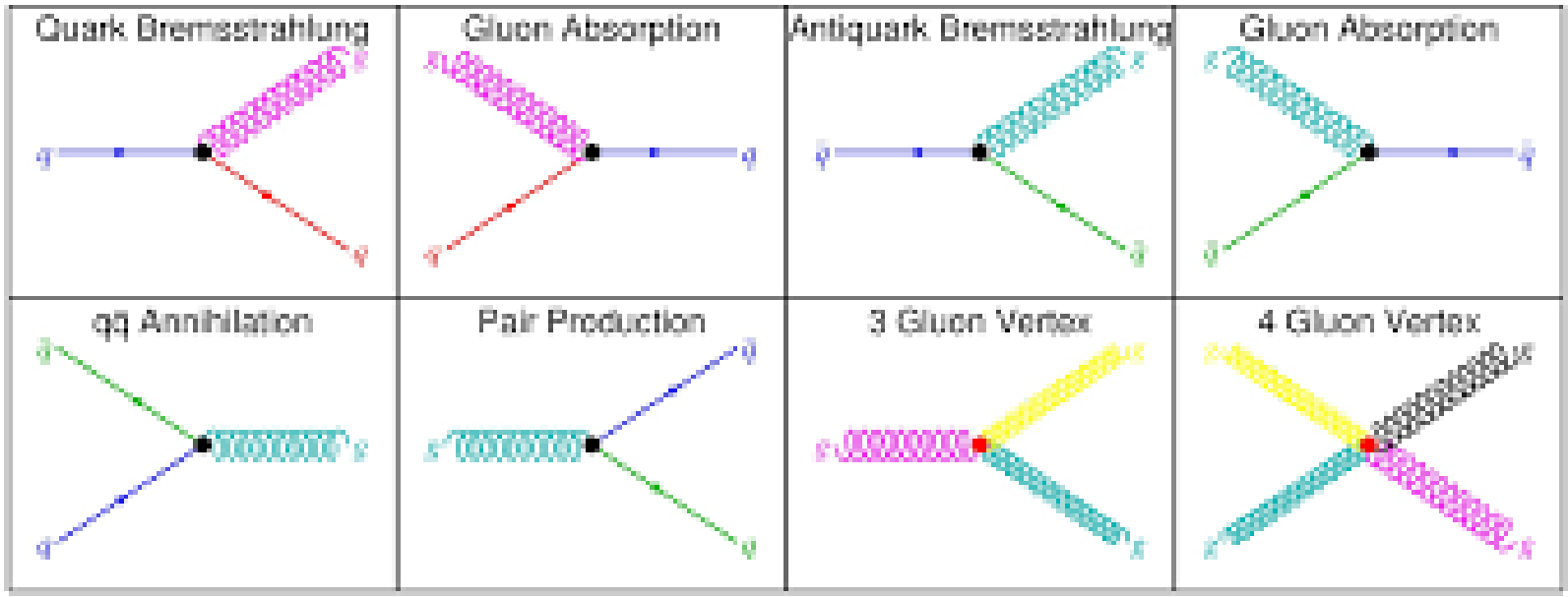


between quarks



between nucleons

Strong Interaction: Gluons



End of Feynman Diagram discussion

Particle Physics Experimental Facilities

The Experiments

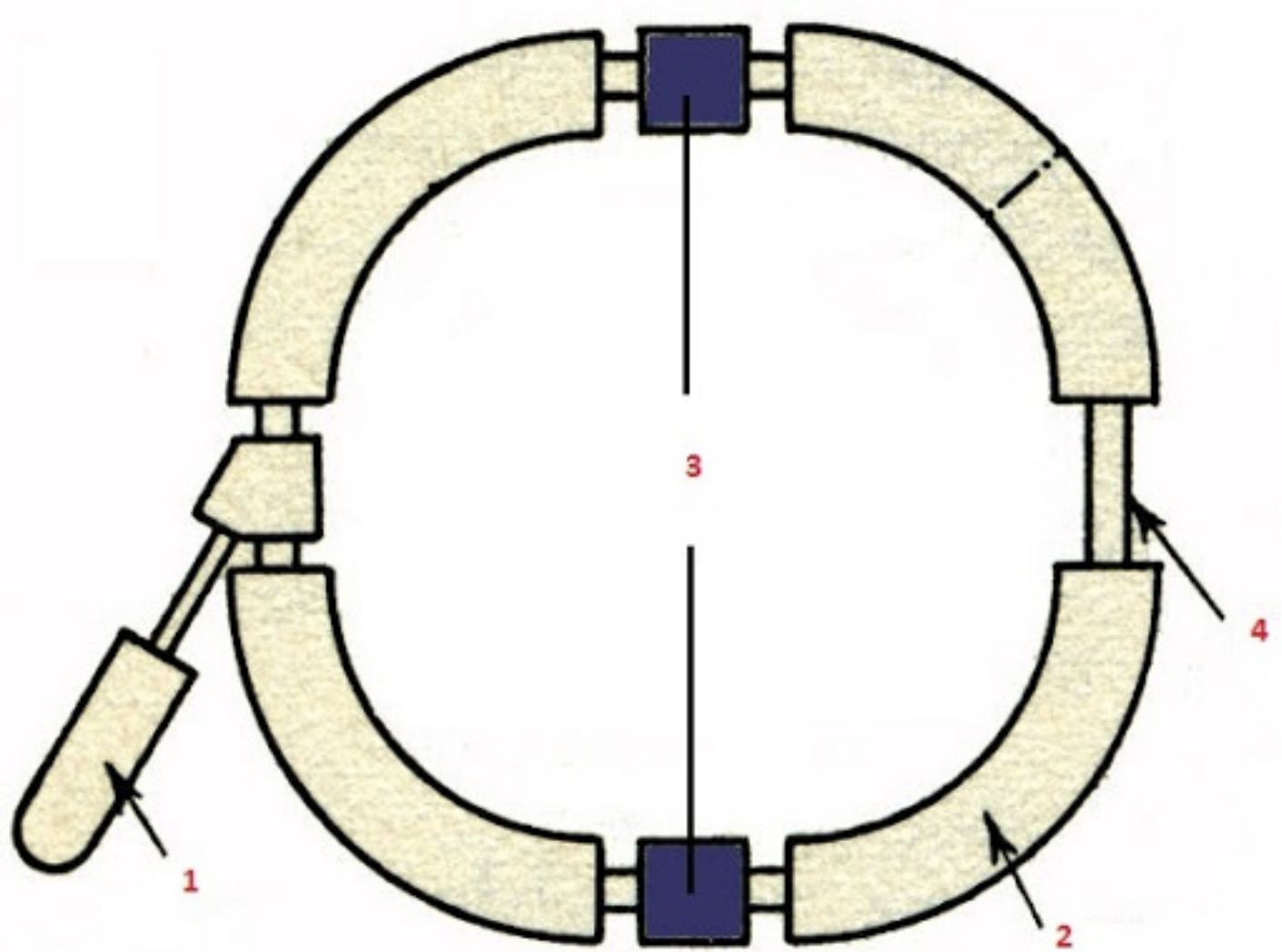
At CERN

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

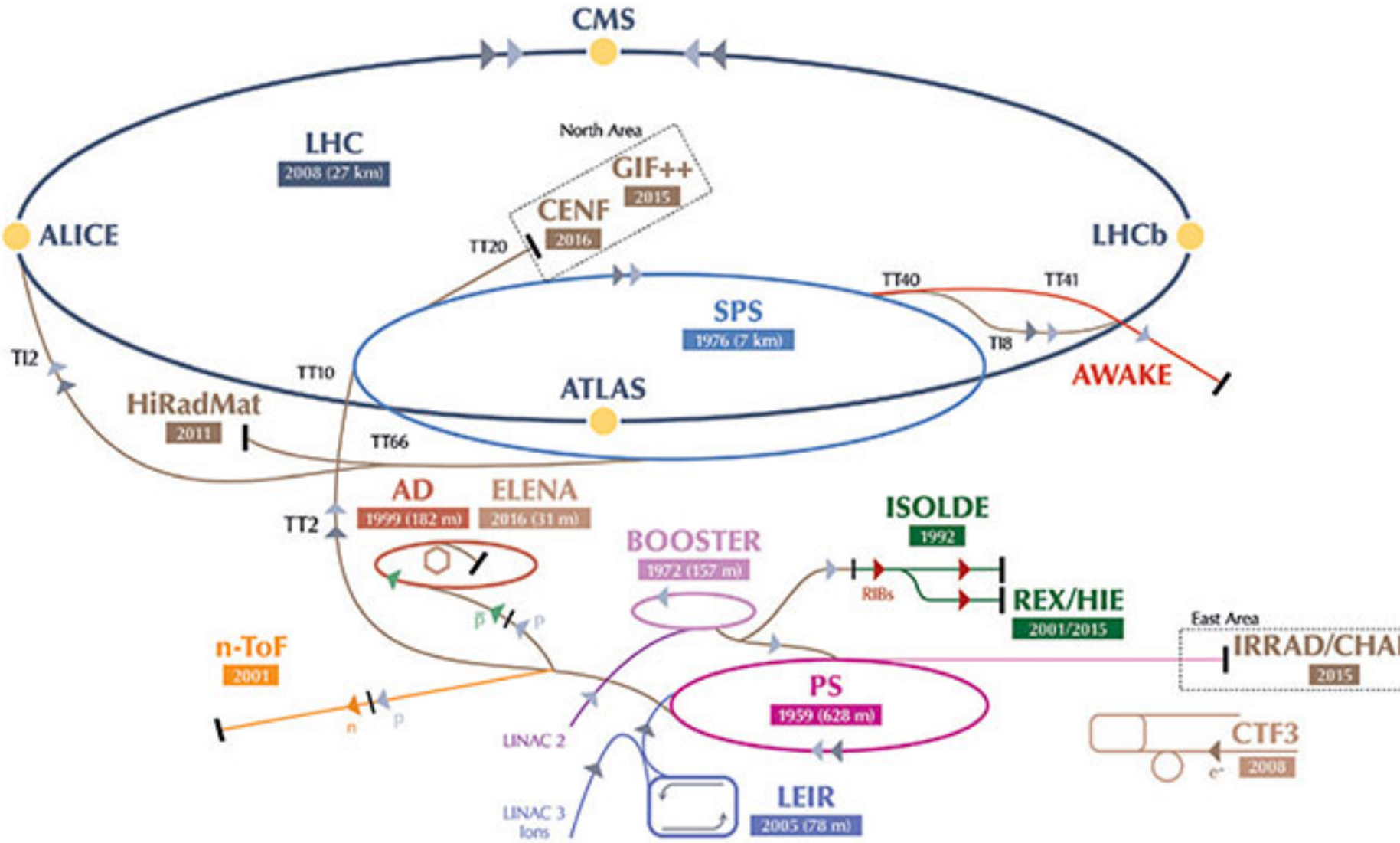
Others

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

A Simple Synchrotron



Large Hadron Collider



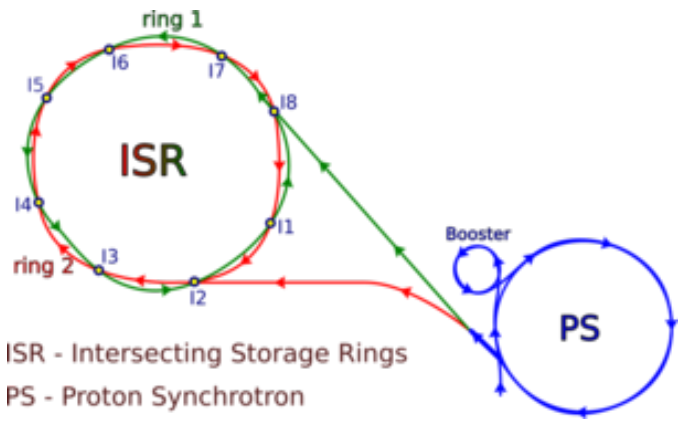
Goals of LHC Experiments

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

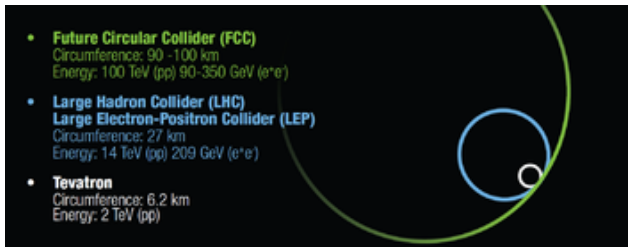
- J and Upsilon meson
- QCD and quarks
- Proton Structure

The Future LHC

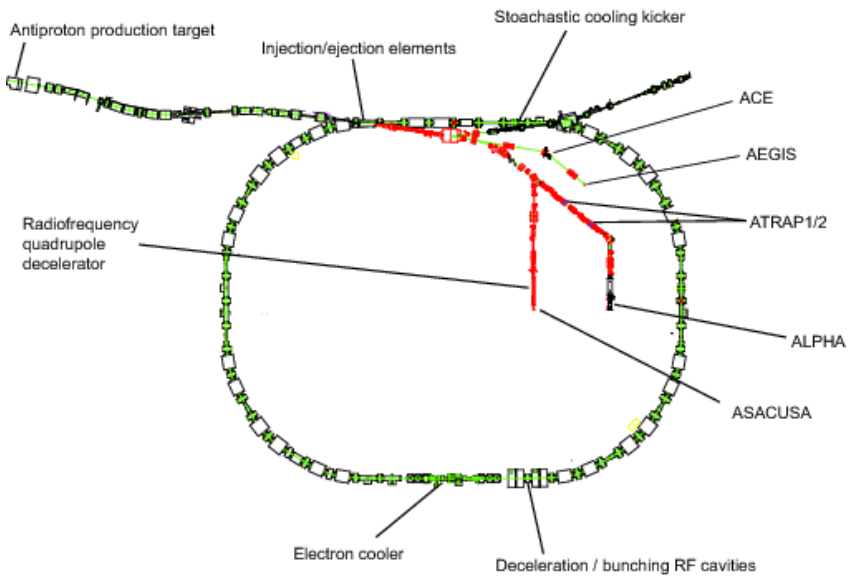
High Luminosity LHC 2028

Increase the number of collisions and datasets

Future Circular Collider



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?

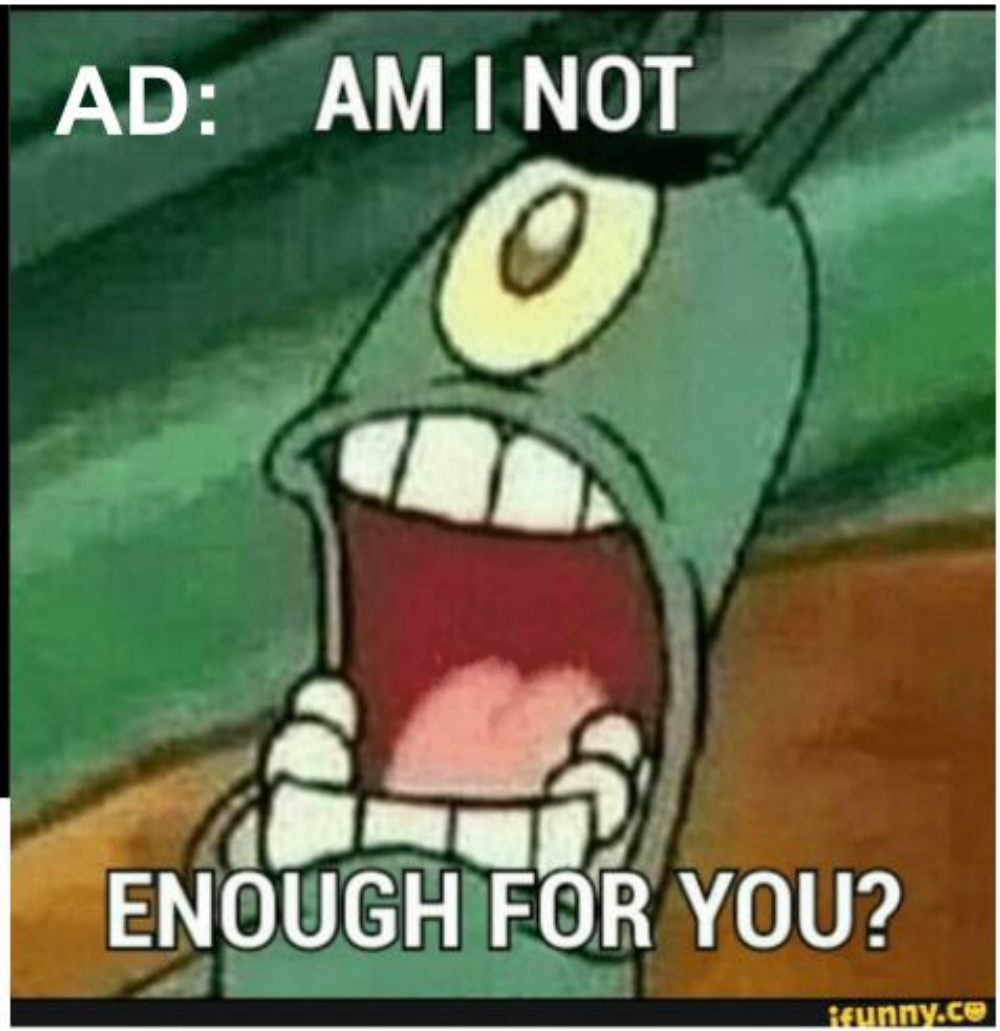
Fun-Fact

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

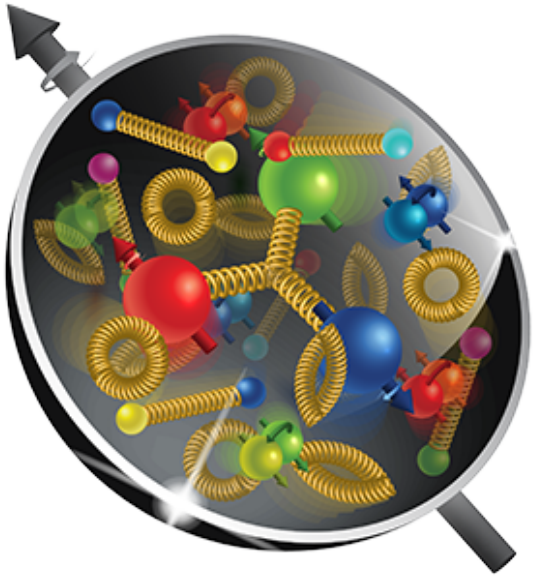


The Antimatter Factory

HERA and EIC

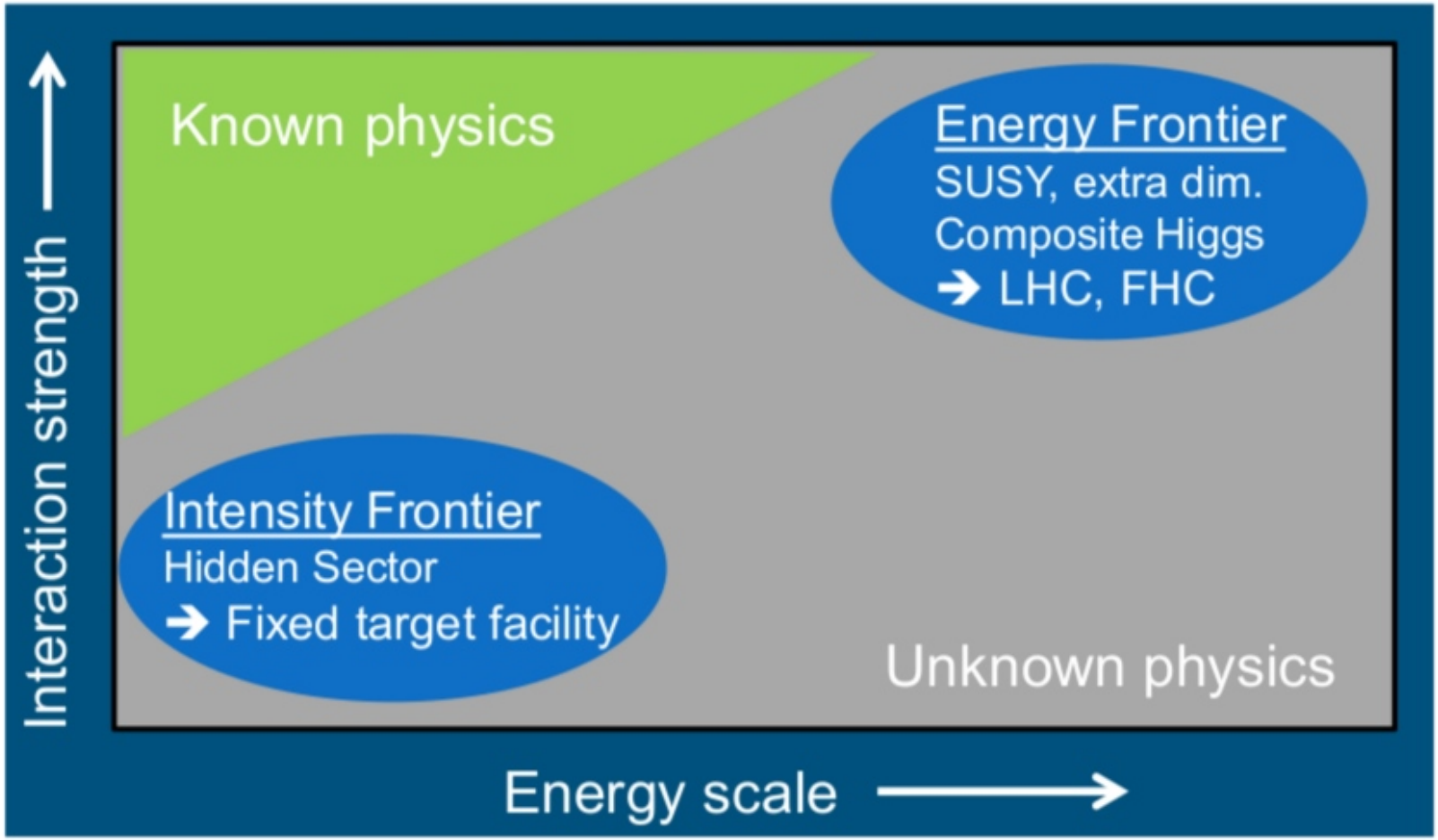
Legacy of HERA

- 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


Known physics
Energy Frontier
SUSY, extra dim.
Composite Higgs
➔ LHC, FHC
Intensity Frontier
Hidden Sector
➔ Fixed target facility
Unknown physics
Interaction strength
Energy scale

Fun-Fact

How was 'world wide web' invented at CERN?

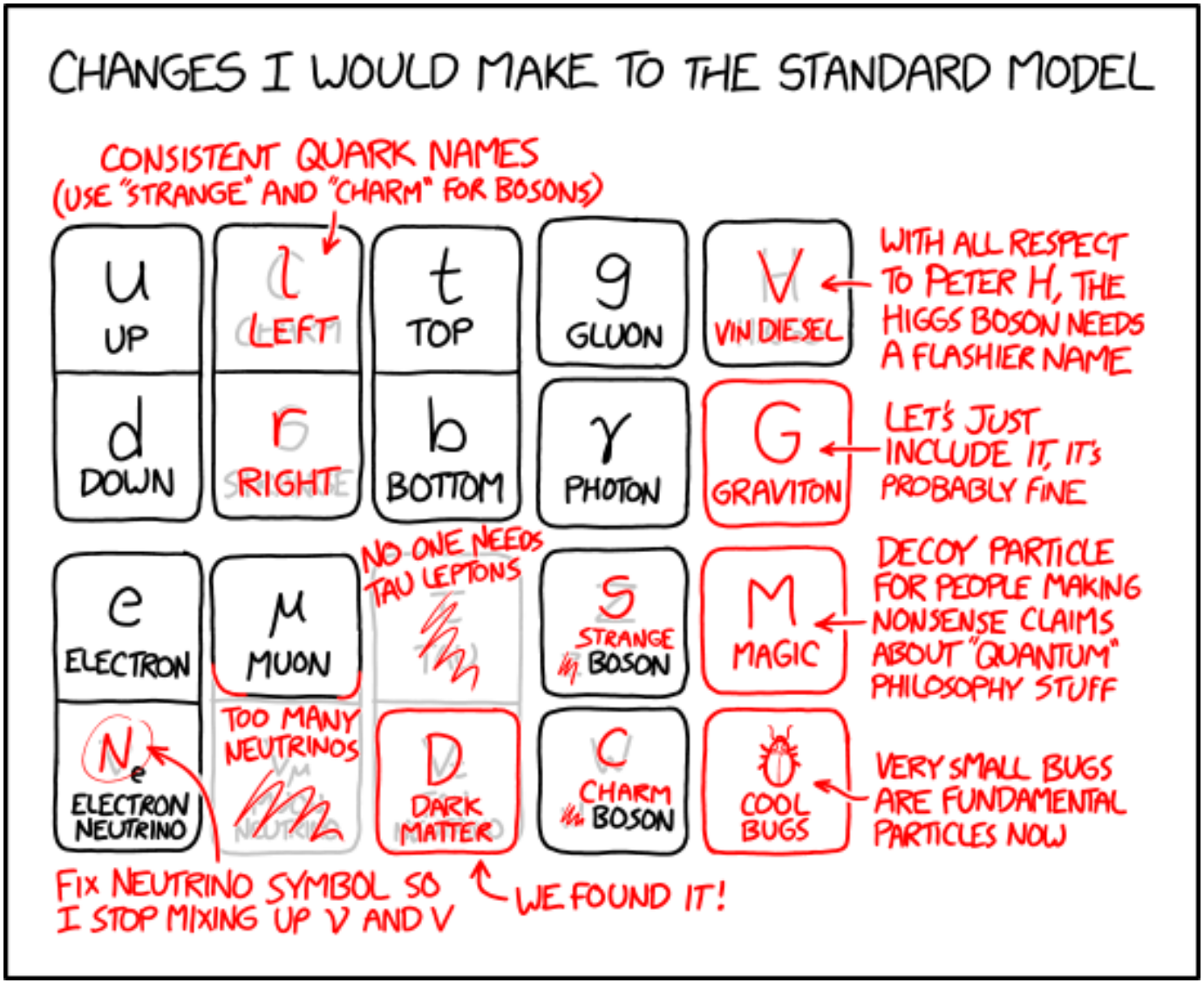
While working at CERN, Tim Berners-Lee became frustrated with the inefficiencies and difficulties in finding information stored on different computers. So he proposed to CERN management a more elaborate network he called 'web'.

Fun fact within a fun fact

Sir Timothy John Berners-Lee is also known as TimBL

.

Beyond Standard Model Physics



Shortcomings of SM

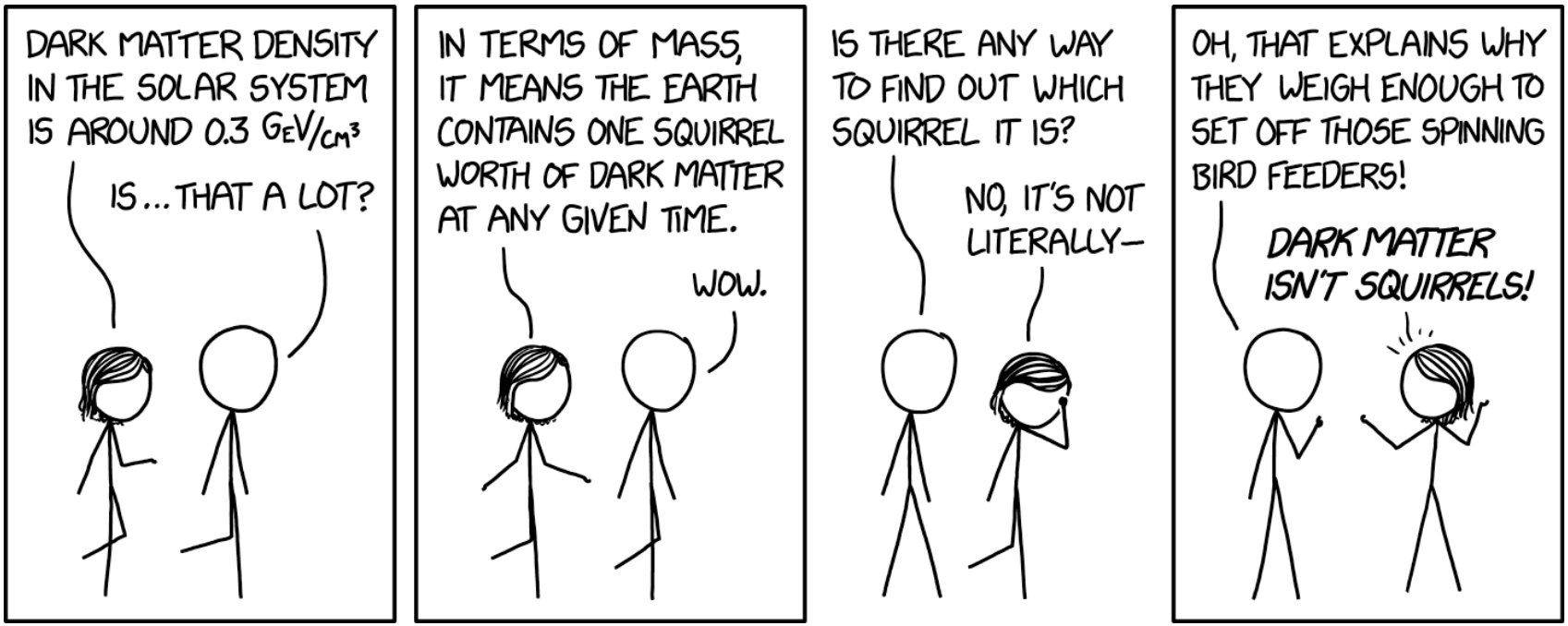
Unexplained Phenomena

- 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 $SU(3)_c \times SU(2)_L \times U(1)_Y$

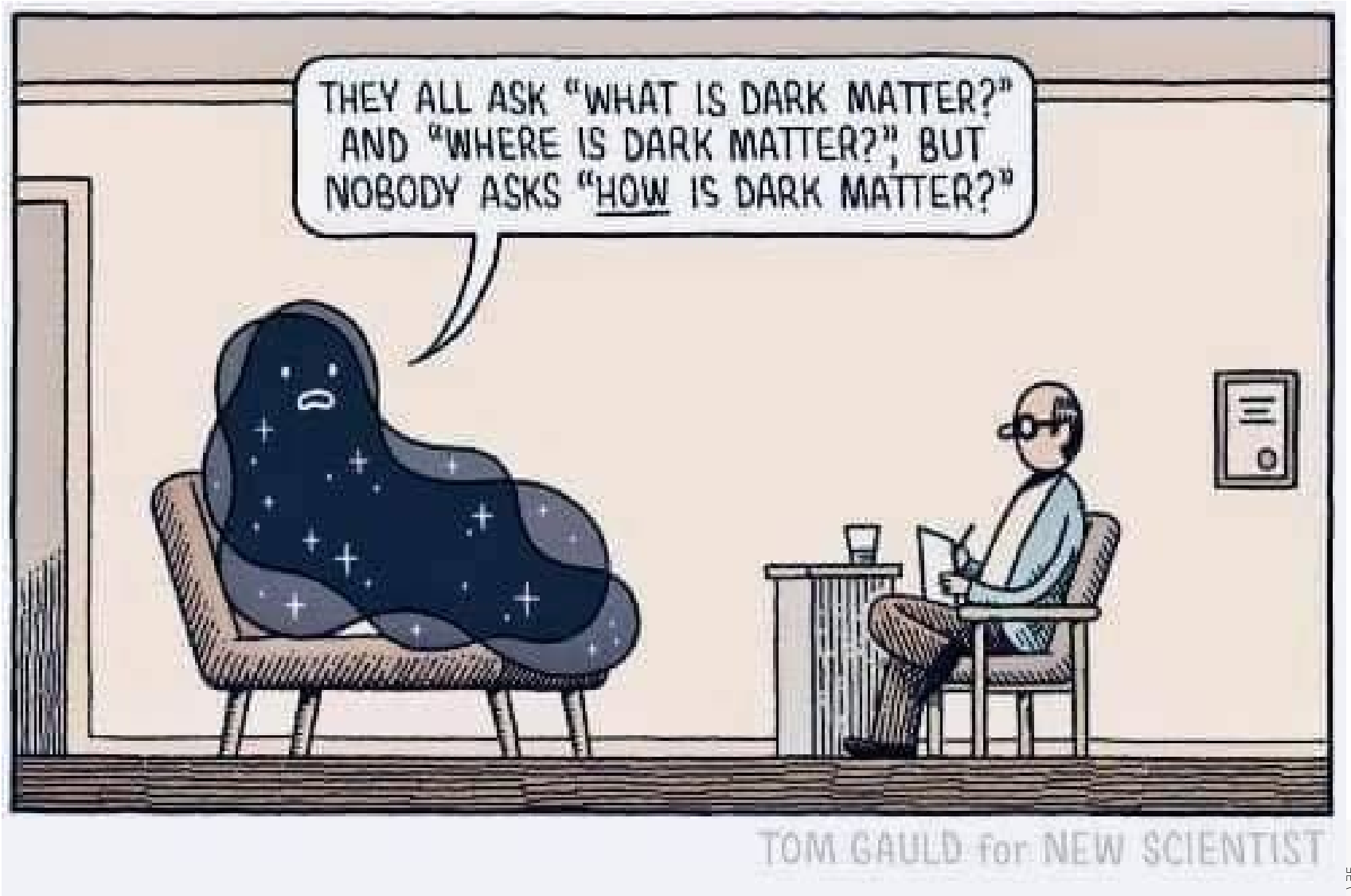
Experimental issues

- B Meson decay
- Muon magnetic dipole moment

Dark Matter candidates



Dark Matter and Dark Energy



Beyond the Standard Model

Major Theories

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

The solution to all Standard Model Problems