Introduction to Hadron Collider Physics

Part 1. Introduction to the course and to Feynman diagrams

Caterina Doglioni - Lund University

Heavily drawing from lectures written in collaboration with
Peter Christiansen & Alice Ohlson - Lund University

Note on references: all the images from experiments are taken from the experiment websites unless otherwise noted

About me

Only < 1/10 of the ATLAS collaboration shown here

Master's thesis in Rome (Italy)
Summer Student at CERN (Switzerland)
PhD in Oxford (UK)
Post-doc in Geneva (Switzerland)
Permanent academic (senior lecturer) in Lund since April 2015

Member of the ATLAS Collaboration
Dark Matter and hadronic jet enthusiast
ERC Starting Grant DARKJETS 2016-2021
ERC Consolidator Grant REALDARK 2021-2026

Found online at some of the HASCO events this week
Always found at caterina.doglioni@cern.ch
Web page: http://www.hep.lu.se/staff/doglioni/ [work in progress]
[if you like these lectures…] interested in interviewing for a PhD? Follow this link
@catdoglund

What this set of intro lectures is meant to be

A (rather quick) trip into particle physics:

A taster of particle physics: theory and experiment – detectors, and accelerators

- These lectures contain what it takes to "explain what we are made of" to a layman audience (e.g. friends/family)
- But also some insight on what a particle physicist does every day
- You will see each of the topics **in much more detail** in this week's lectures!
  - Topics not introduced here: statistics, heavy ions, flavor physics

Our "contract"

What do I expect from you?

- **Learning**:
  - keep up with lectures day by day (workload: ~2h in class / 30' for re-reading lectures on your own)
- **Feedback**:
  - if something is not clear, just ask!
- **Remember also**:
  - Here you really learn for yourself, not for the ECTS credits!

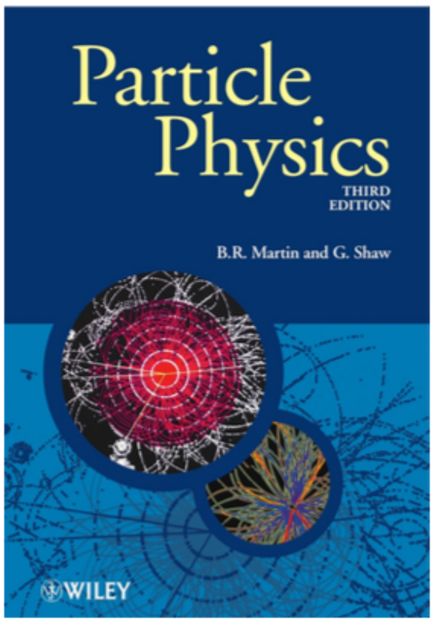
Our "contract"

What you should expect from me

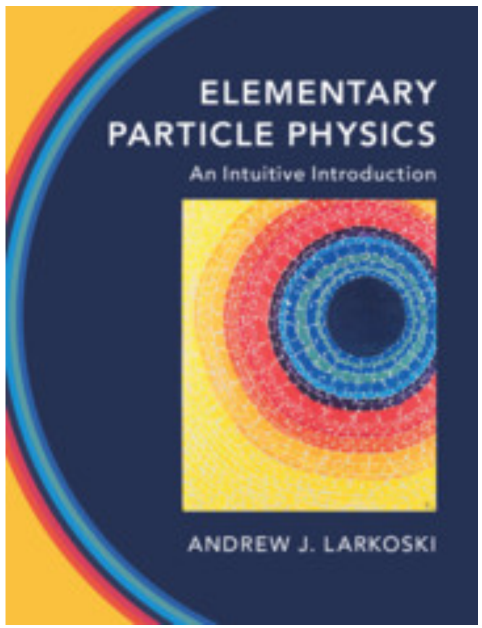
- **Teaching**:
  - lectures taught as per schedule
  - sufficient breaks / activities to digest lectures
- **Q&A**:
  - if I don't know something I'll look it up!
  - available upon request (except for Tuesday/ Thursday I can also meet 1:1)
- **Remember also**:
  - We are all human and we don't know everything (at least I am learning every day)

Particle physics books that I used/liked

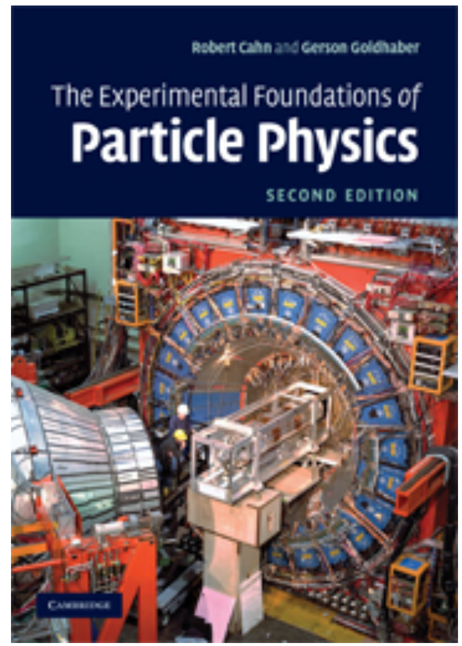
Particle Physics
Martin & Shaw



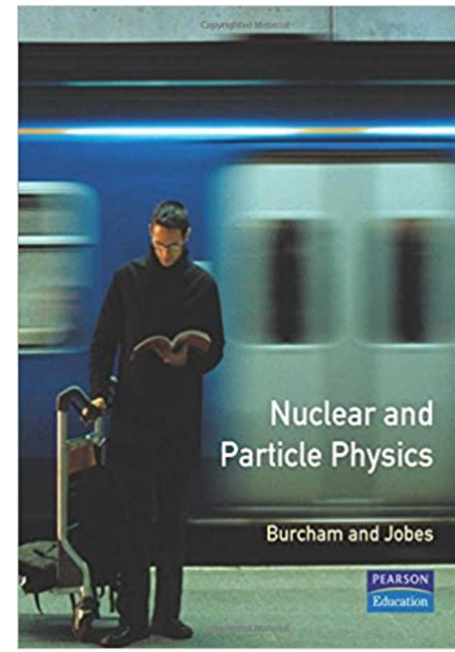
Elementary Particle Physics
An Intuitive Introduction
Andrew J. Larkoski



The Experimental Foundations of Particle Physics
Cahn & Goldhaber



Nuclear & Particle Physics
Burcham & Jobes



Outline of these introductory lectures

- **Part 1: Introduction**
  - Fundamental components of matter
  - Drawing particles and interactions: Feynman diagrams

10' Q&A + break

- **Part 2: Standard Model forces and interactions**
  - Electromagnetism
  - Weak interactions
  - Quantum Chromodynamics

- **Part 3: Tools**
  - Particle accelerators: the LHC
  - Detectors for particle physics
  - CERN and particle physics collaborations

10' Q&A + break

- **Part 4: Beyond the Standard Model**
  - The Higgs discovery
  - Problems of the Standard Model
  - Solutions beyond the Standard Model
  - Dark Matter

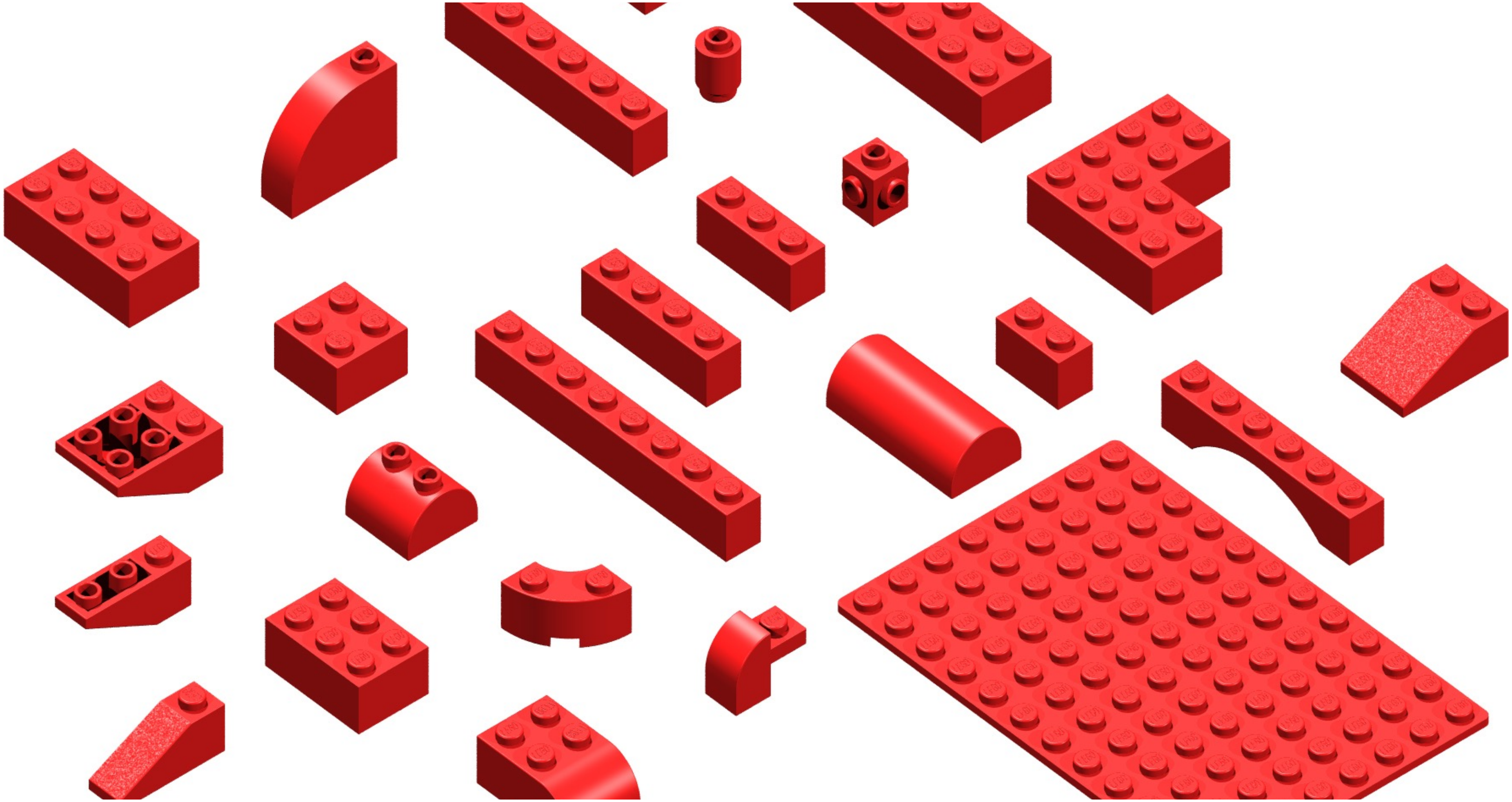
10' Q&A + break

Putting particle / hadron collider physics into context

What is matter made of?

Idea from Pauline Gagnon's talk, Beamline For Schools

What is matter made of?



Idea from Pauline Gagnon’s talk, Beamline For Schools

What are we made of?

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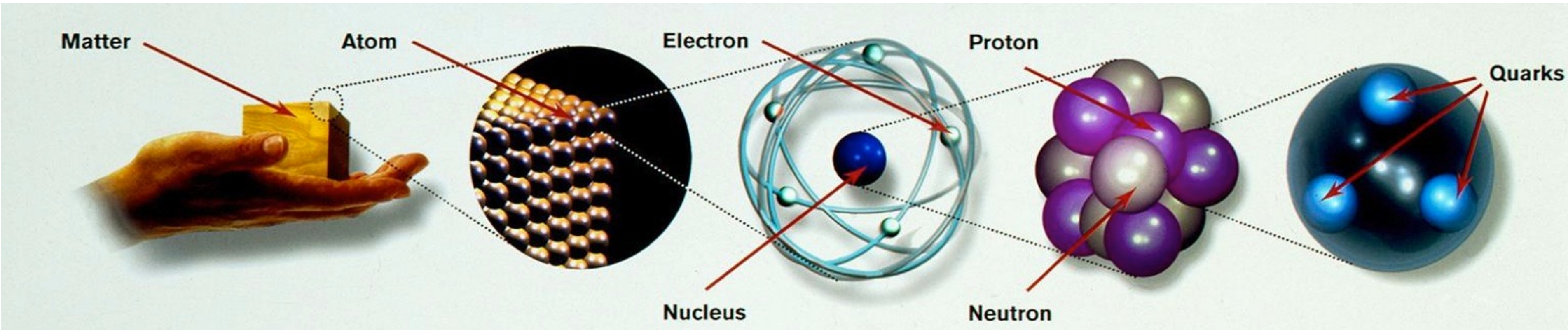

~10 cm ~0.00000001 cm $\sim 10^{-12}$ cm $\sim 10^{-13}$ cm $<10^{-16}$ cm

$\frac{1}{1{,}000{,}000{,}000}$ $\frac{1}{10{,}000}$ $\frac{1}{10}$ $\frac{1}{100{,}000}$

Particle physics: study of *fundamental* components of matter

(1000000000000000 times smaller than what we're used to)

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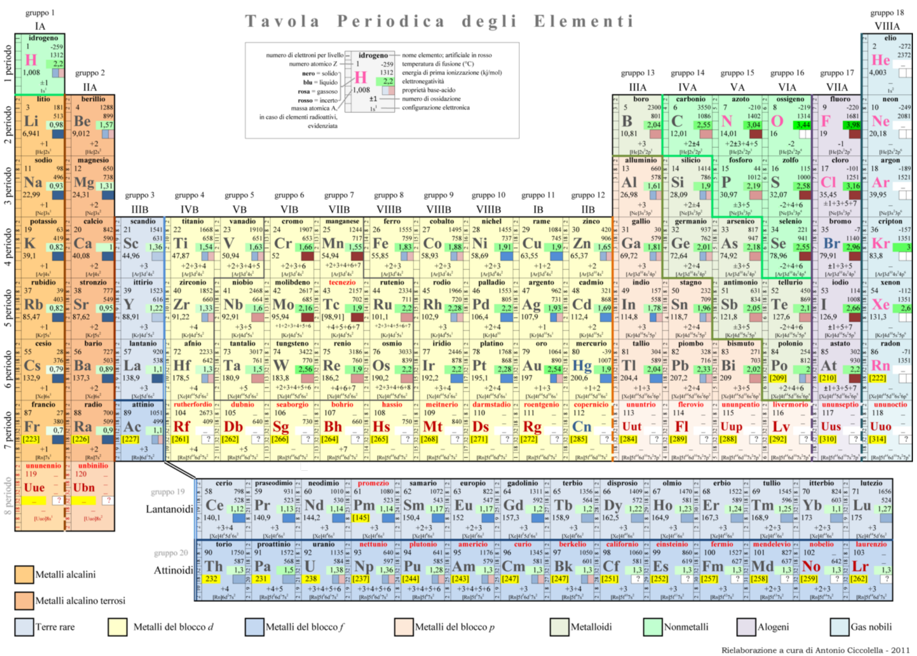
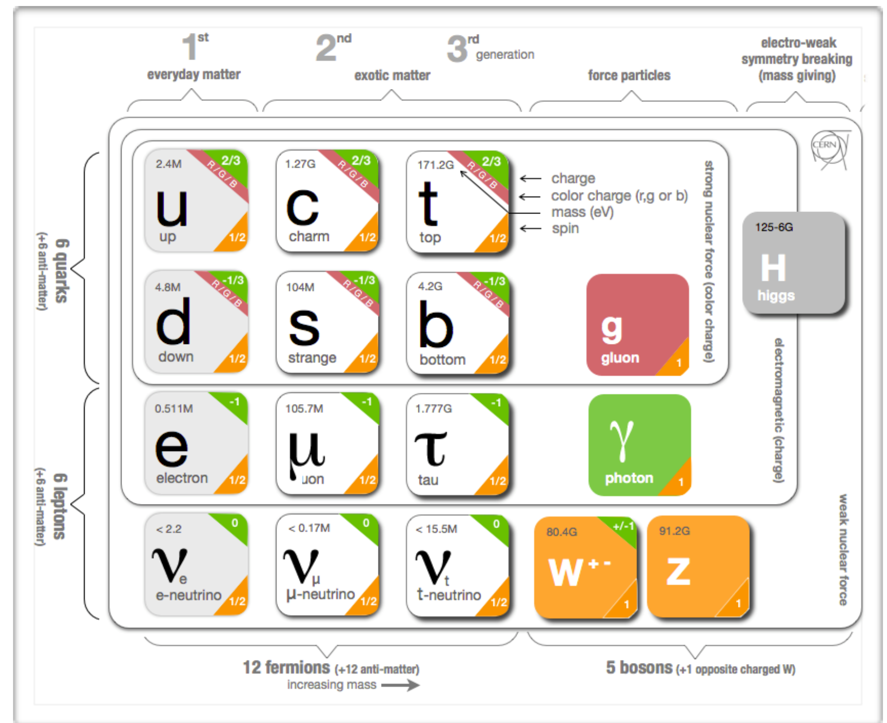
The Standard Model

Chemistry



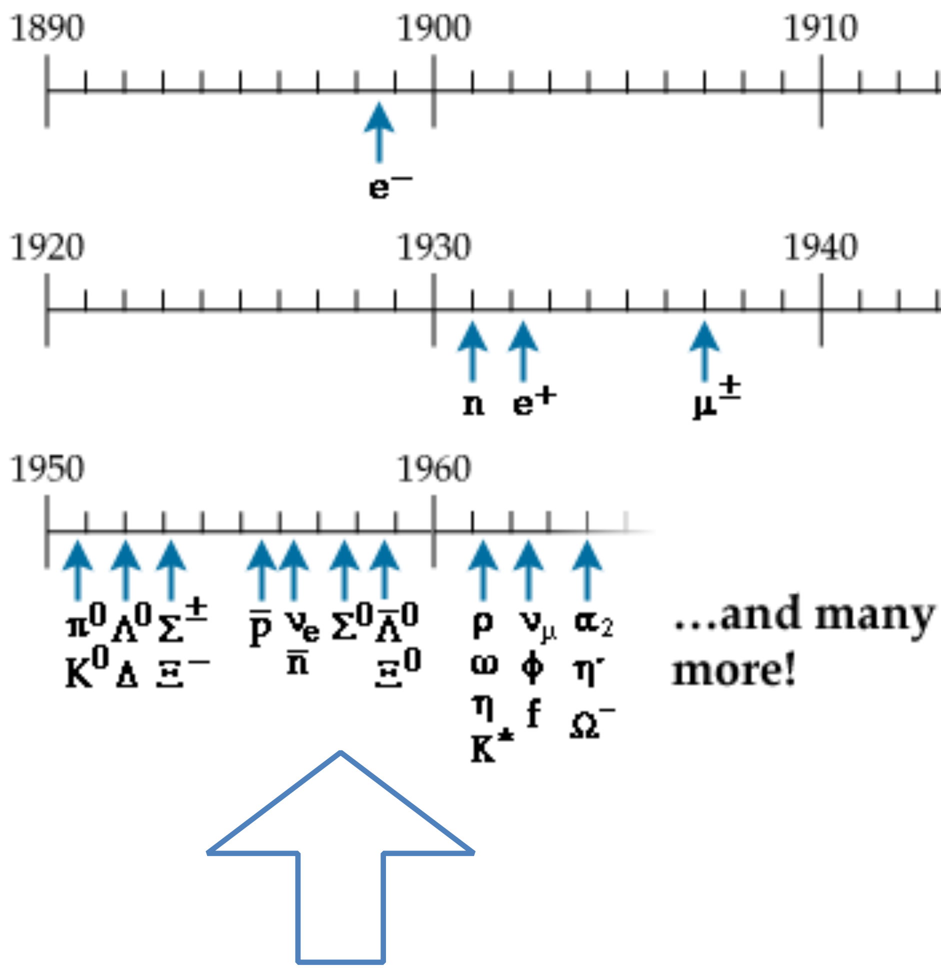
Particle physics



The Standard Model(ca 1960) describes **particles** and their **interactions** through the **four fundamental forces**

How did we get here? From a zoo of particles

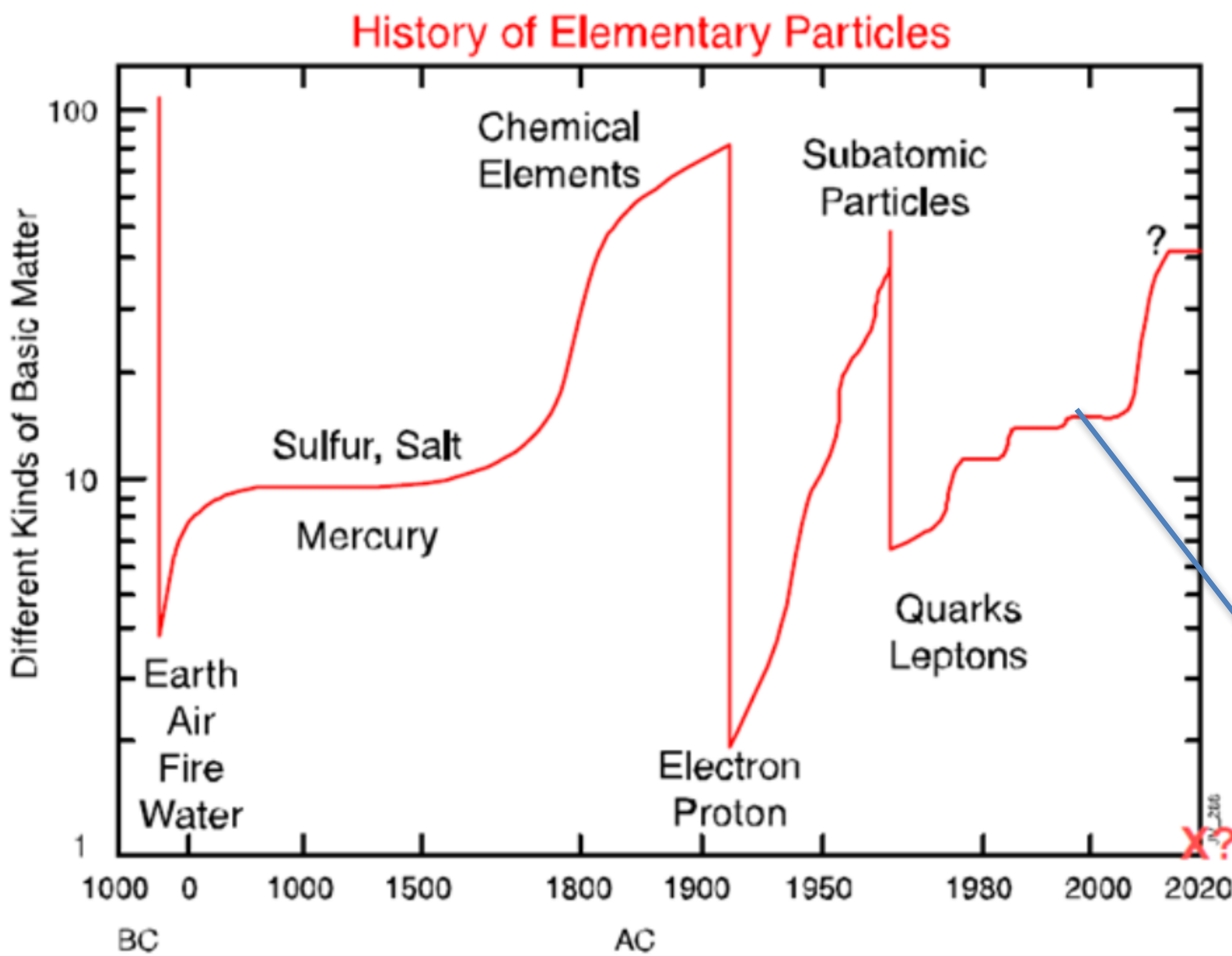
Particle Adventure website



Is there an order in this apparent chaos?
This is how the Standard Model was born!

Tidying particles up: the Standard Model

Lecture 2



(at least we hope!)

The SM as it stands today:
6 leptons
"6" quarks
"4" force mediators
1 Higgs boson
+ antiparticles

http://arxiv.org/abs/1311.1769

The Four Forces

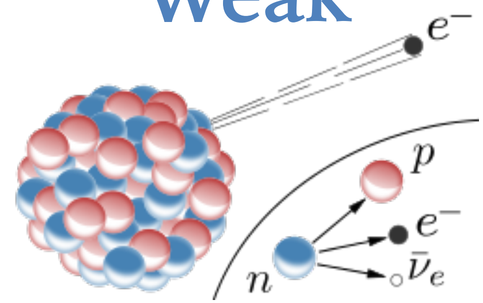
More in Part 2

Electromagnetic


Wikipedia - by ThorstenS


Wikipedia - by Oguraclutch

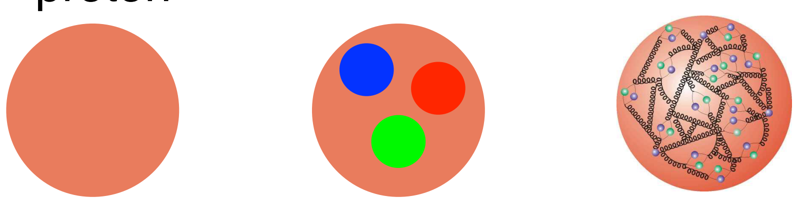
Weak



Wikipedia - By Inductiveload

Strong

proton

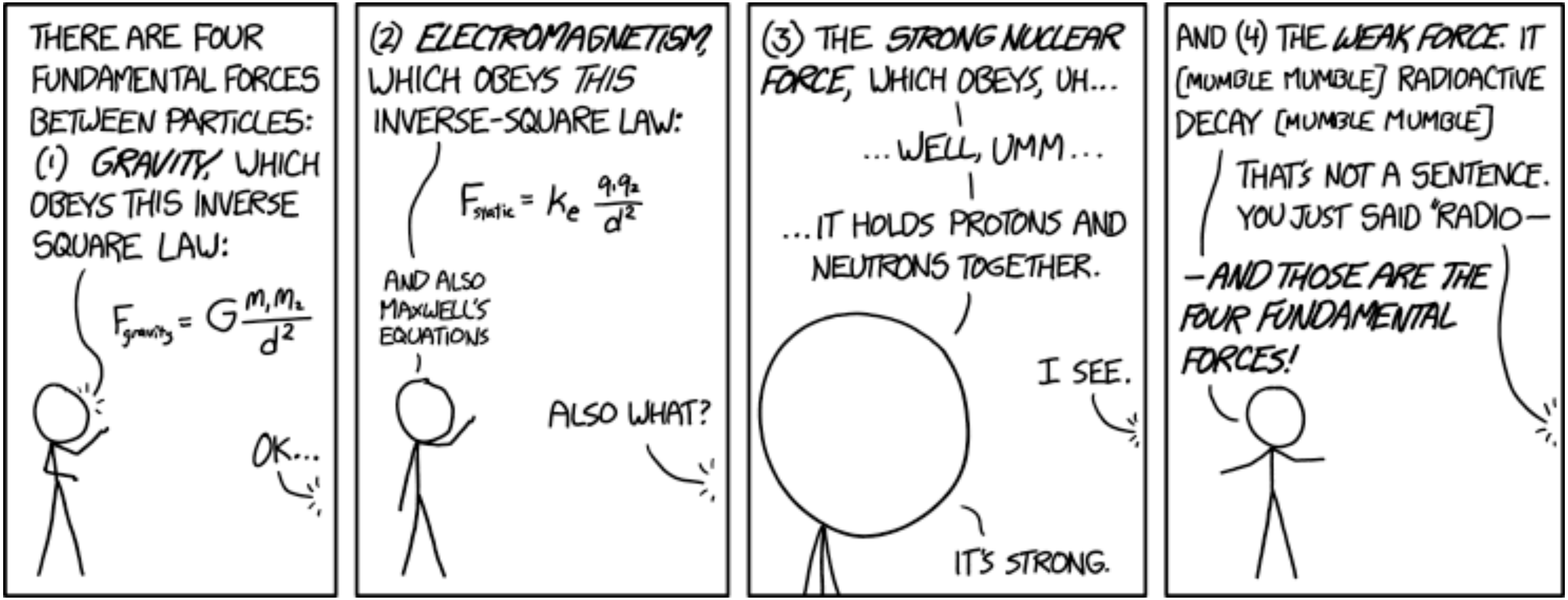

Hyperphysics

Gravitational

Not in Standard Model

To be detected, particles must interact

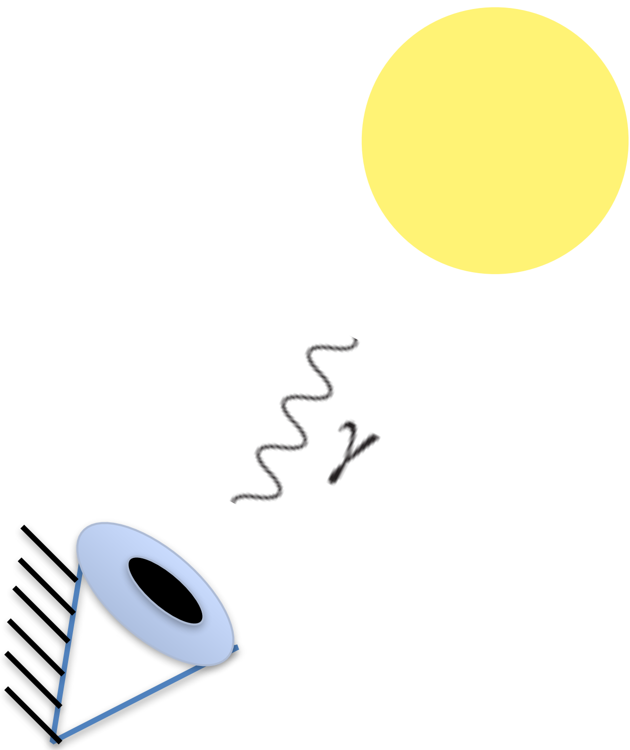
Maybe we'll fix this in Part 2

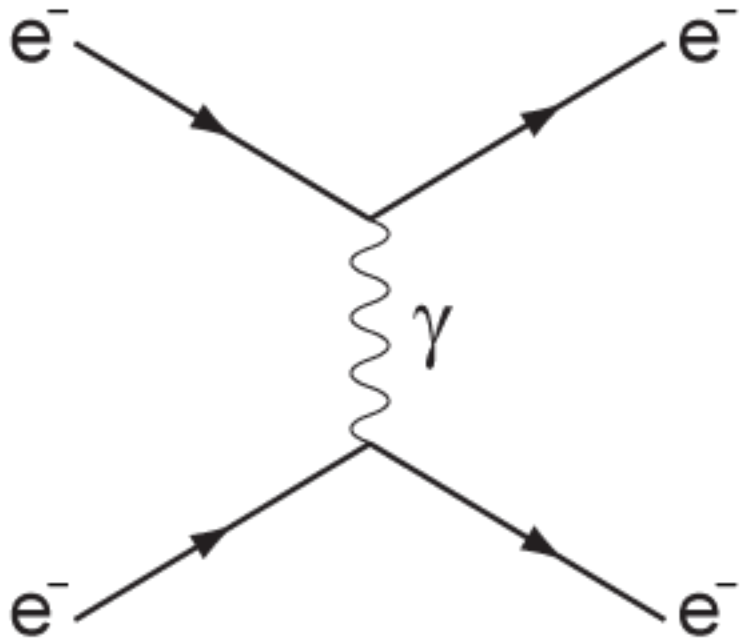


https://xkcd.com/1489/

How do forces act on particles?

More in Part 2





By [[:en:User:{{{1}}}|{{{1}}}]] at Wikipedia

Every force needs particles

that act as **mediators: gluons, photon, W and Z bosons**

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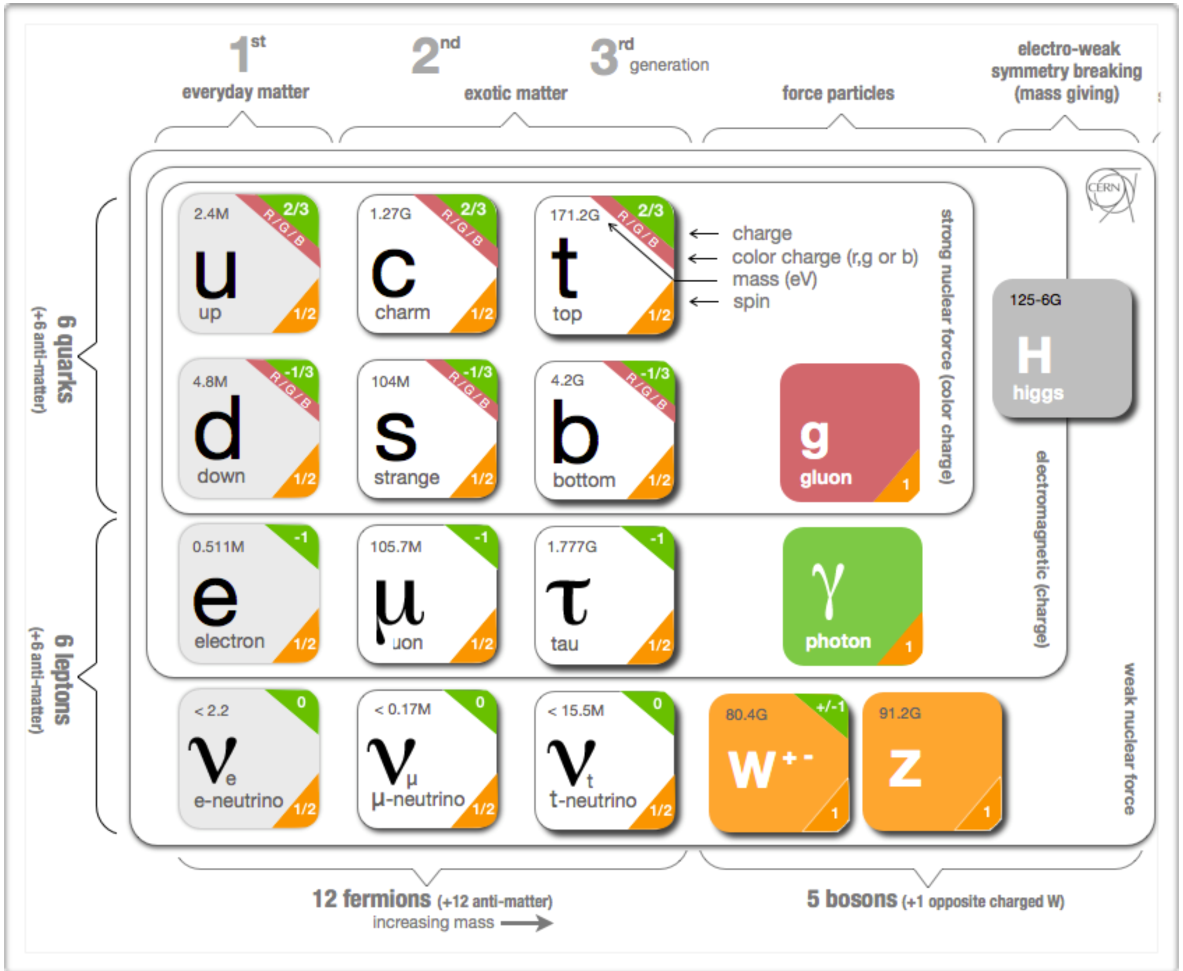
The SM particles & its forces

More in Part 2



Electromagnetic force acts o
anything with electric charge
+ **photons** (force mediators)

Weak force (mediated by W/Z bosons):
Anything except the gluon
Note: electromagnetic and weak forces are two sides of the same force

Strong force:
quarks and **gluons** (mediators)

This forms the basis of how we can see particles in particle detectors: particles **interact**!

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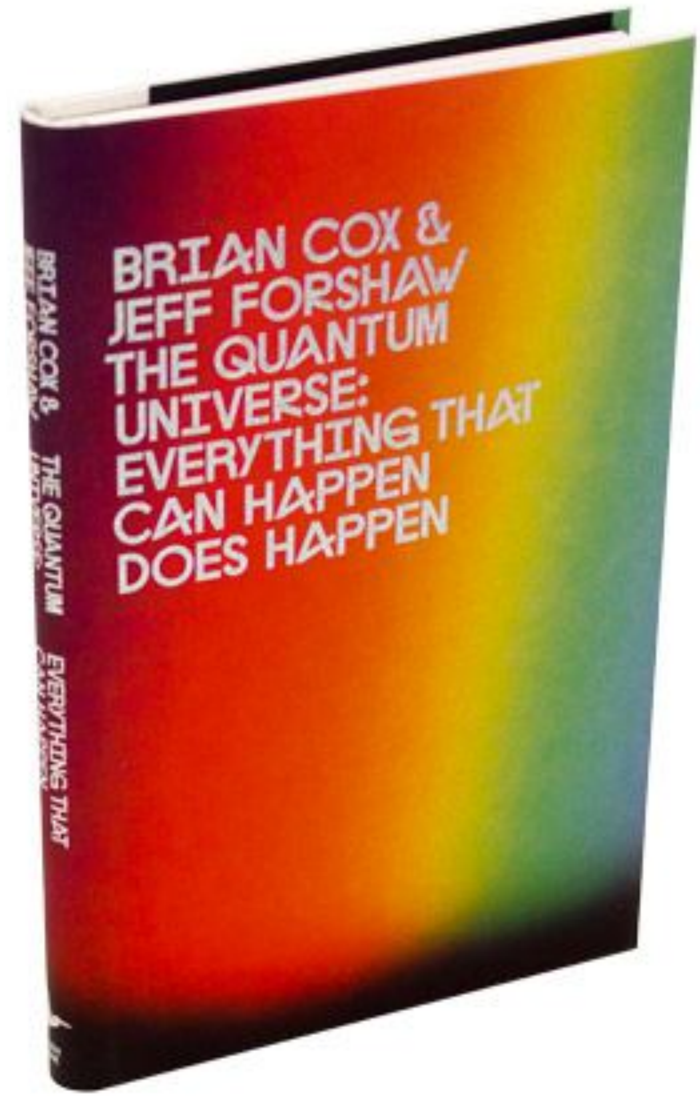
A good quote for ~~life~~ the Standard Model

Murphy's Laws

1. In any field of endeavor, anything that can go wrong, will go wrong.

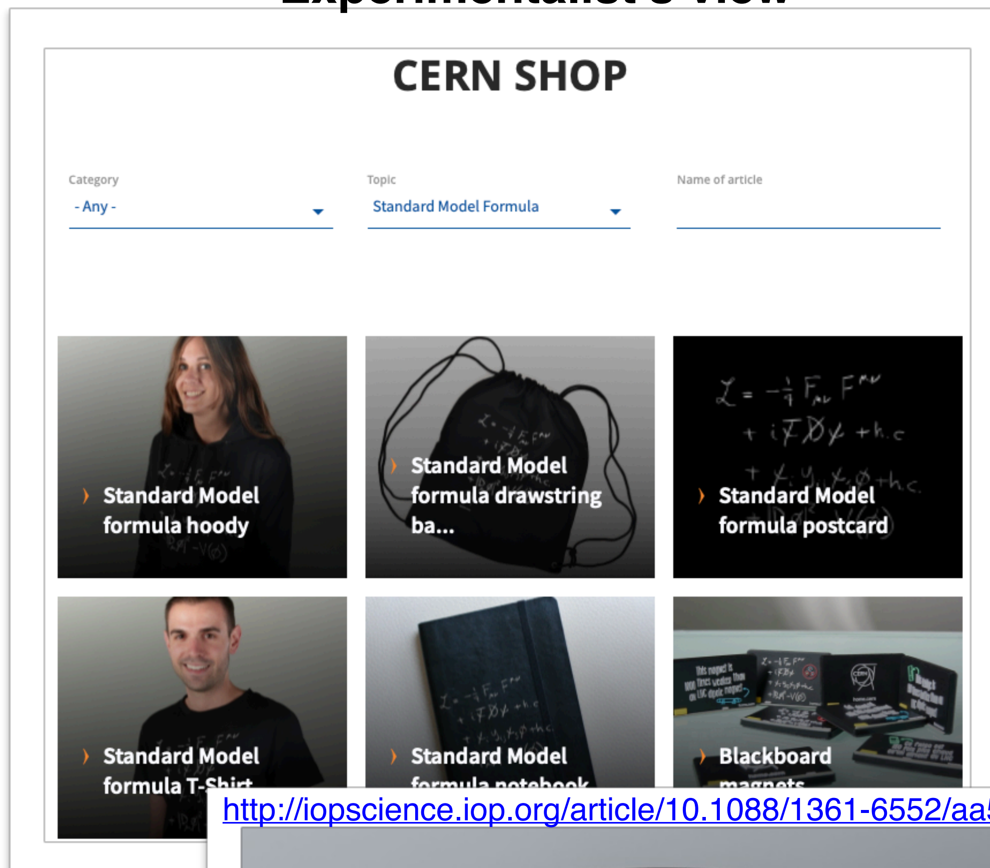


Now let’s not go overboard

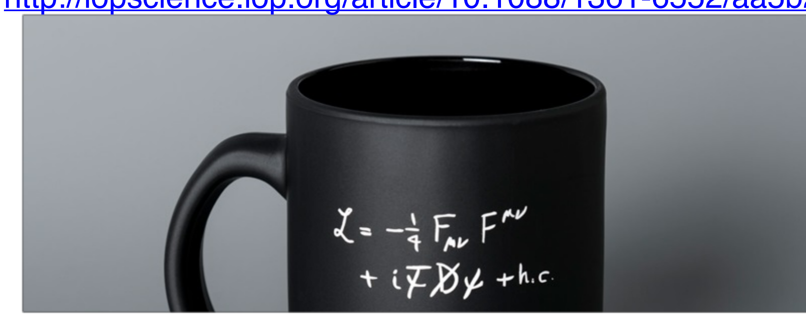
Theorist’s view

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

Experimentalist’s view

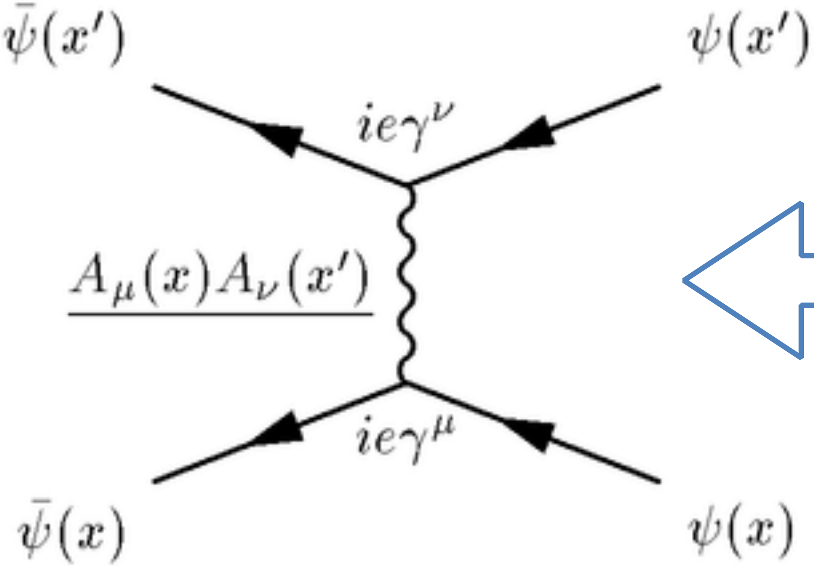


http://iopscience.iop.org/article/10.1088/1361-6552/aa5b25



Why Feynman diagrams

Intuitive (!) way of expressing QED/QCD formulae into pictures!



$$N\bar{\psi}(x)ie\gamma^{\mu}\psi(x)\bar{\psi}(x')ie\gamma^{\nu}\psi(x')\underline{A_{\mu}(x)A_{\nu}(x')}$$

TABLE 8–2

The correspondence between diagrams and S-matrix elements in momentum space

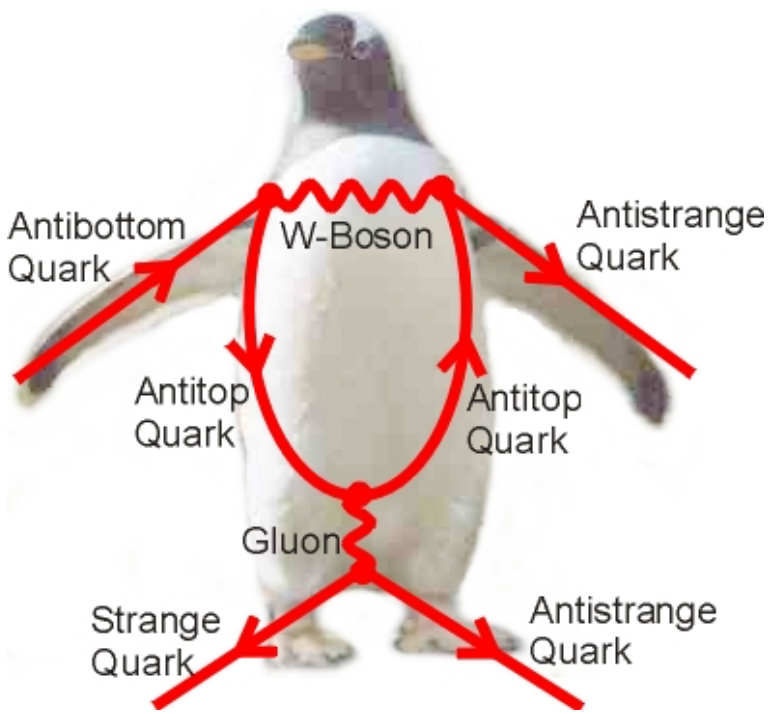
Component of Diagram		Factor in S-Matrix Element	
Internal photon line	ν - - - → - - - λ	$g_{\nu\lambda}\dfrac{1}{k^2 - i\mu}$	photon propagation function
Internal electron line	——→——	$\dfrac{i\not{p} - m}{p^2 + m^2 - i\mu}$	electron propagation function
Corner	p', ν k, p	$\gamma^{\nu}\delta(p - p' - k)$	

The history of Feynman Diagrams: http://web.mit.edu/dikaiser/www/FdsAmSci.pdf

https://archive.org

~~Feynman~~ Penguin Diagrams

How did this come to be? https://en.wikipedia.org/wiki/Penguin_diagram



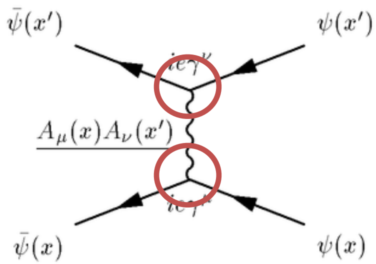
Let's draw for 5'

On a computer: https://www.aidansean.com/feynman/

1. Look at slide 18 again and choose some particles
2. Start with two lines at the beginning/end
    1. straight lines (quarks/leptons), wiggly lines (force mediator)
        - connect particles that are subject to the same force
    2. draw some lines on the left and on the right
3. Connect them, always attaching one wiggly line to two straight lines
4. Straight lines can also "emit" force mediators
5. Share your screen / Feynman diagram and we will discuss in light of the rules

Feynman Diagrams: time & conservation laws

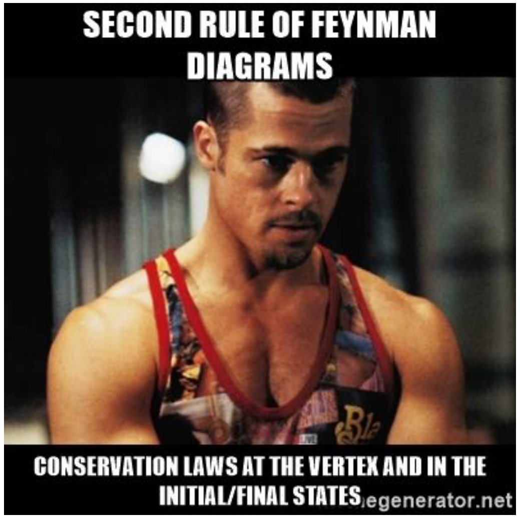
Initial state



Final state

Vertices

This is a convention and can change, but this is the rule we'll follow



1. Electrical Charge

2. Lepton number, <u>within each of the families</u>

This means that we cannot connect different families of leptons…if we found experimental evidence of that, it would be a discovery of new physics!

Electrons, muons, tau & their antineutrinos: +1
Positron, antimuon, antitau & their neutrinos: -1

3. Baryon number (easy enough…)

QUARKS					
Particle Name	Symbol	Mass(MeV)	Charge	Strangeness	Baryon Number
UP	u	310	+2/3	0	1/3
DOWN	d	310	-1/3	0	1/3
STRANGE	s	505	-1/3	-1	1/3
CHARM	c	1500	+2/3	0	1/3
TRUTH	t	22500	+2/3	0	1/3
BEAUTY	b	5000	-1/3	0	1/3

Antiquarks have baryon number of -1/3

Force mediators have no baryon/lepton numbers

What about conservation of energy?

- Assuming you have seen this before: $\mathbf{E^2 = (mc^2)^2+(pc)^2}$
  - This must be valid for processes that are observable (~long time) —> initial / final state
  - Heisenberg's principle: this <u>can</u> be violated on short timescales, e.g. within the middle of a Feynman diagram

Would you like to try on your own?

1. Can you draw a diagram with an electron in the initial state, and a positron in the final state?

2. Can you draw a Feynman diagram of a Z boson decay?

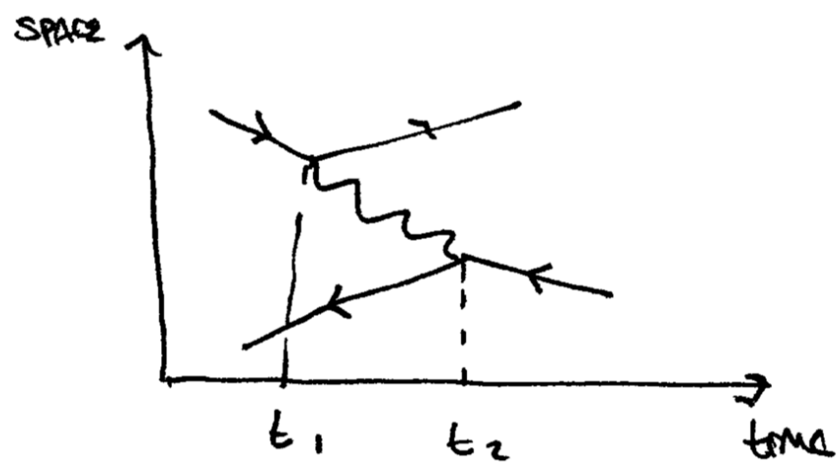
3. Draw a random Feynman diagram, then decide if it's an interaction that is possible

5-10' for a break (or questions)

Backup slides - Part 1

Feynman diagrams are space-time paths for particles

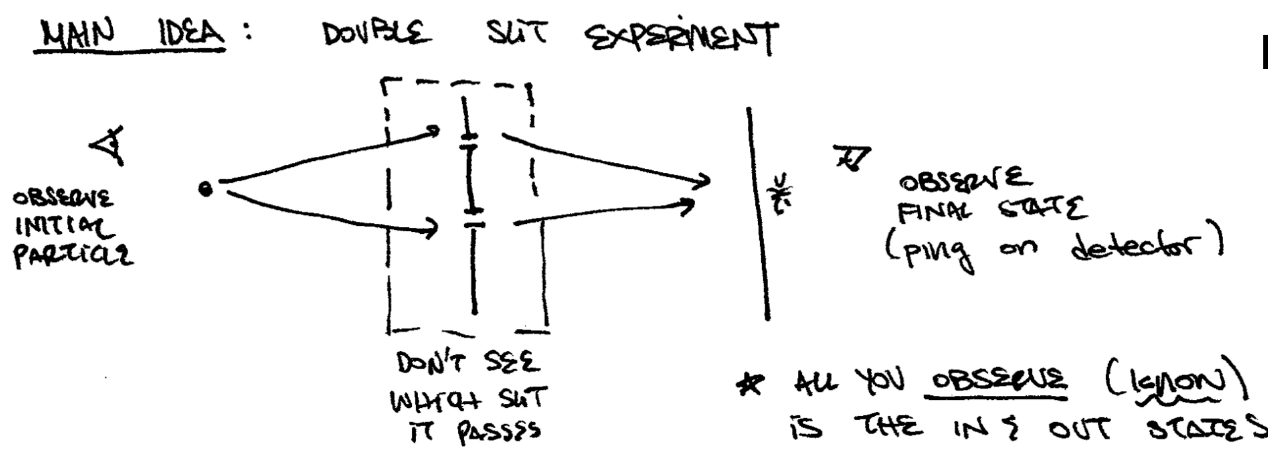
A good tutorial by Prof. Flip Tanedo:
http://www.quantumdiaries.org/2010/02/14/lets-draw-feynman-diagams/
[basic level]
https://www.classe.cornell.edu/~pt267/files/teaching/undergradparticles1.pdf
[more info]



F. Tanedo

What do these lines mean?

- Sum over histories in quantum mechanics



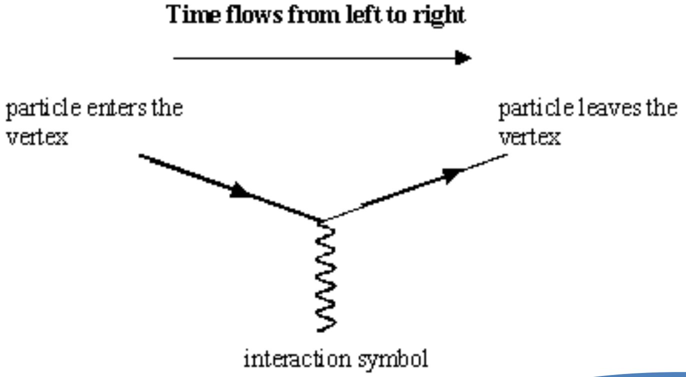
F. Tanedo

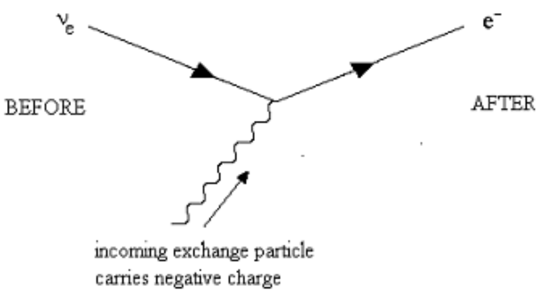
- Each path from initial to final state is assigned a number
- The sum squared of these numbers is related to the probability of a given final state
  - Different wrt the sum of the squares!

Feynman diagrams & conservation laws

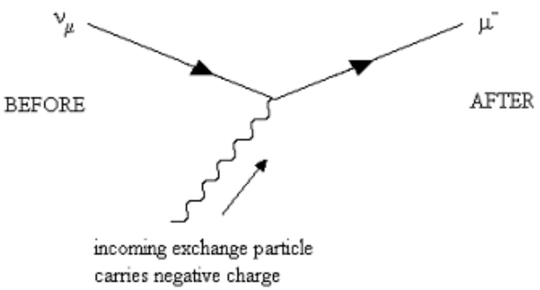
How to treat "vertical" vertices?

http://teachers.web.cern.ch/teachers/archiv/HST2002/





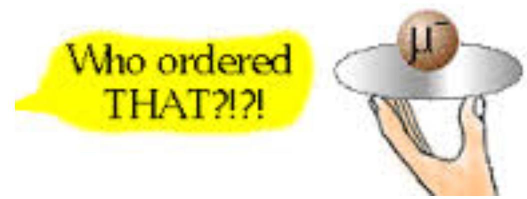
Laime joke



Feynman diagrams with muons (and taus)

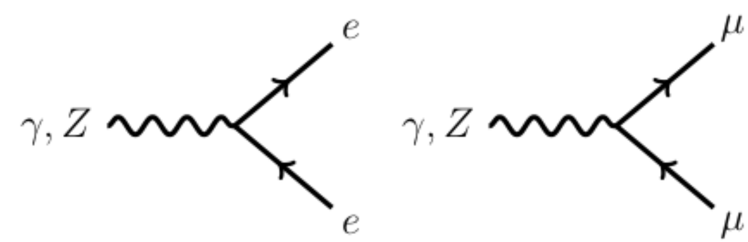
https://timeline.web.cern.ch/anderson-and-neddermeyer-discover-the-muon

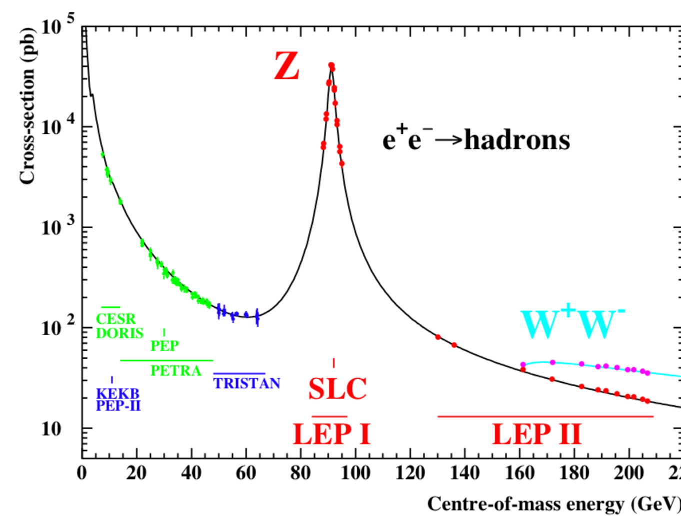
I. Rabi



Because of its mass, **it was at first thought to be the particle predicted by the Japanese physicist Yukawa Hideki in 1935 to explain the strong force** that binds protons and neutrons together in atomic nuclei. It was subsequently discovered, however, that a muon is correctly assigned as a member of the lepton group of subatomic particles—it never reacts with nuclei or other particles through the strong interaction. A **muon is relatively unstable, with a lifetime of only 2.2 microseconds before it decays by the weak force into an electron and two kinds of neutrinos.** Because muons are charged, before decaying they lose energy by displacing electrons from atoms (ionization). At **high-particle velocities** close to the speed of light, ionization dissipates energy in relatively small amounts, so **muons in cosmic radiation are extremely penetrating and can travel thousands of metres below the Earth's surface.**

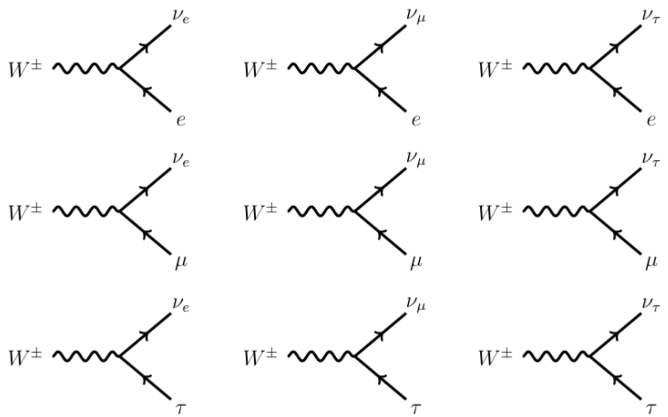
Feynman diagrams with the Z boson

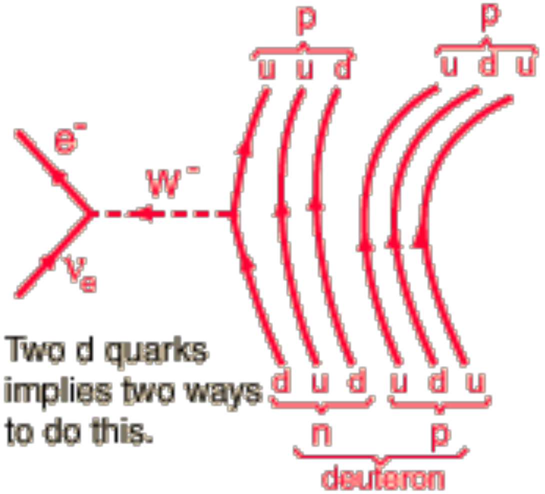




http://www.symmetrymagazine.org/cms/?pid=1000630

Feynman diagrams with the W boson





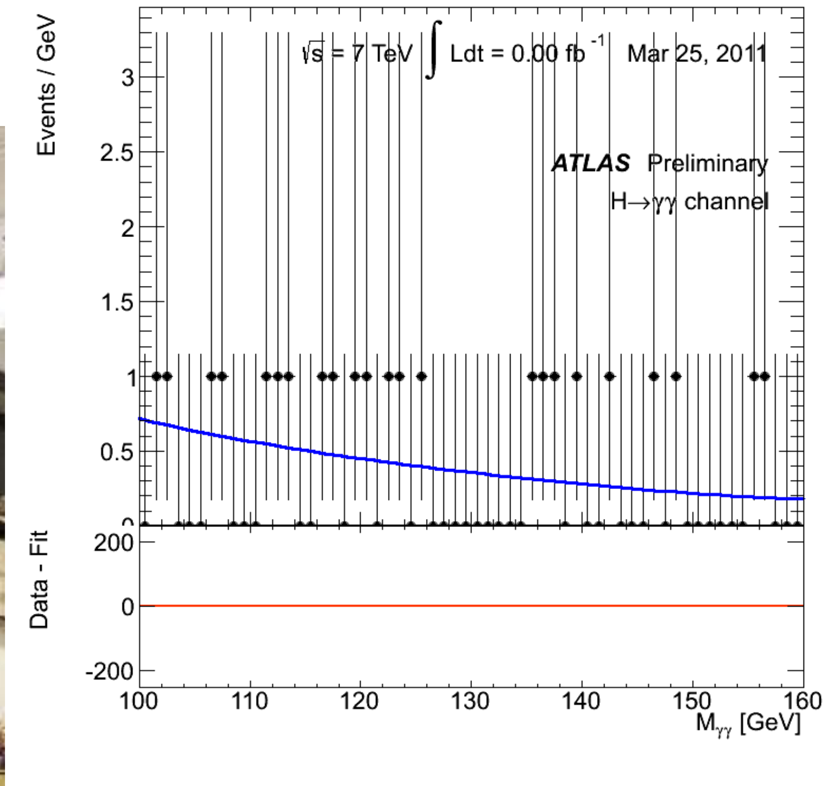
Two d quarks implies two ways to do this.

Charged current reaction, electron neutrinos only.

More details about mixing during weak interaction lectures

The end end end

Newest particle: the Higgs boson

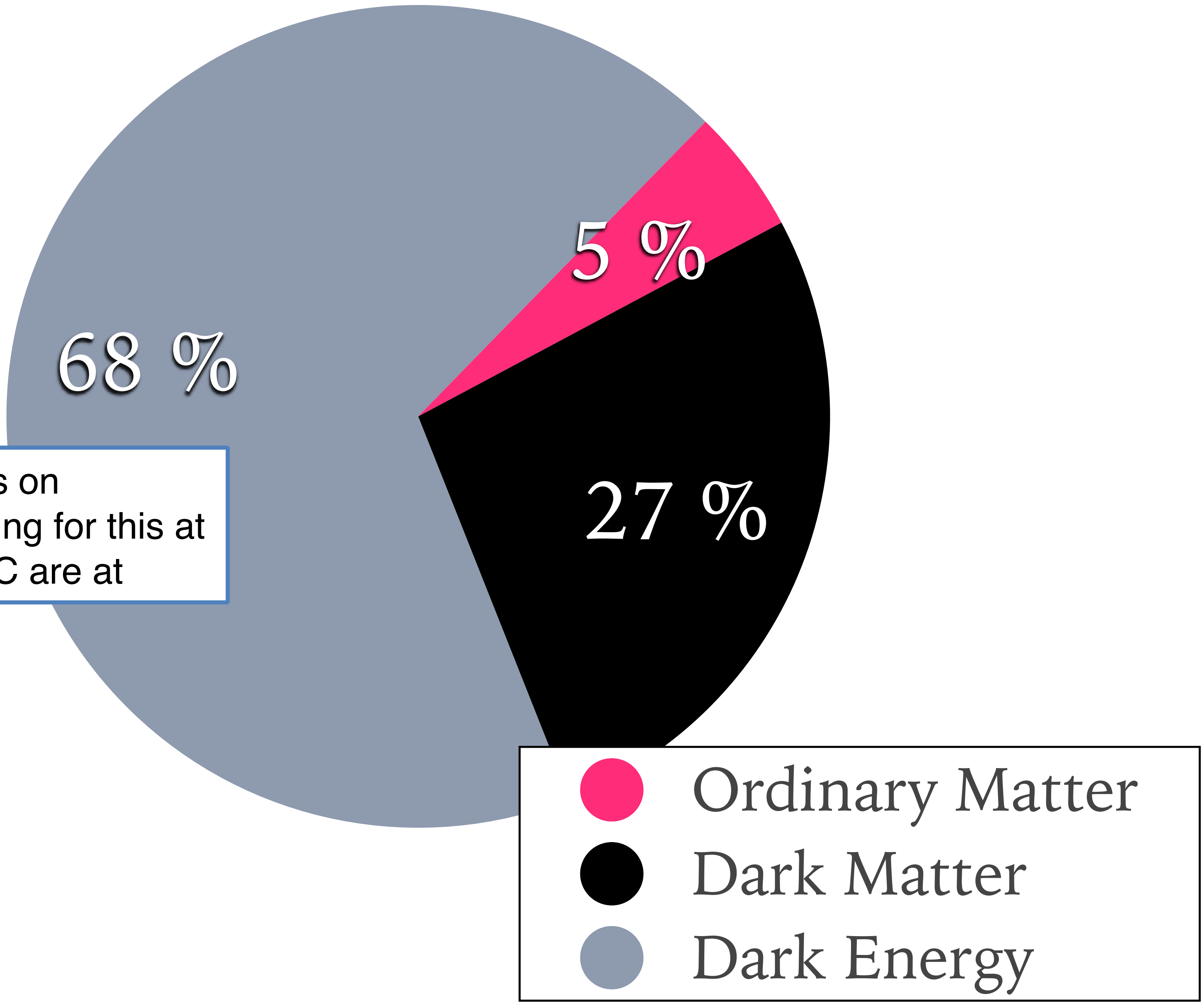


What does the Higgs boson do?

Gives mass to (most)other particles!

This is excellent, we know everything about what we are made of!

Or not?



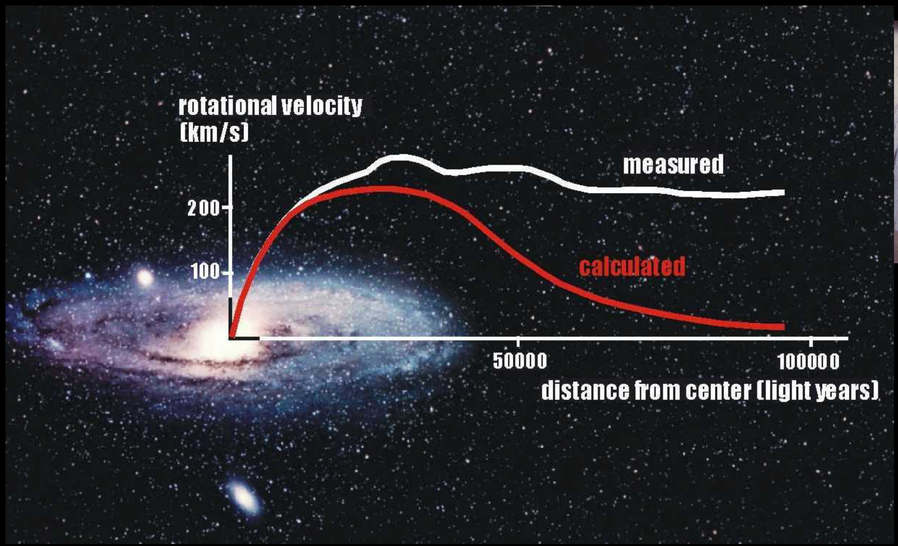
Experts on searching for this at the LHC are at

Lecture 4

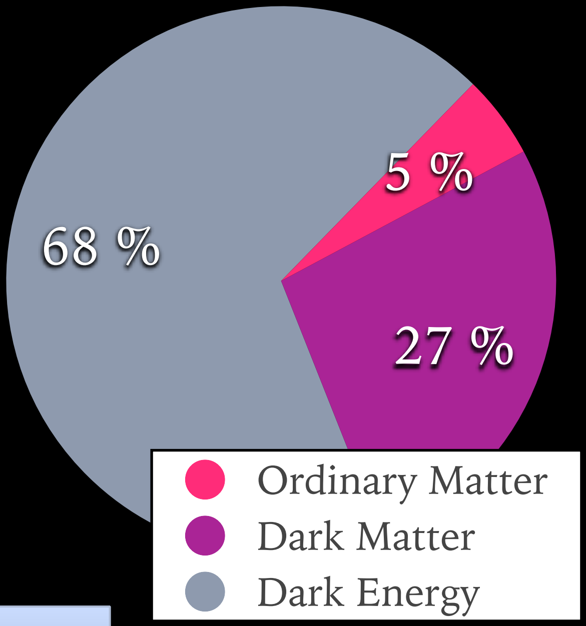
What do we know about dark matter?

Dark Matter?

it's dark



it has mass and feels the gravitational force



it is the main component of matter in the universe

We don't know what it is, but it does not belong to the Standard Model (yet)!