Intro to Particle Physics and The Standard Model

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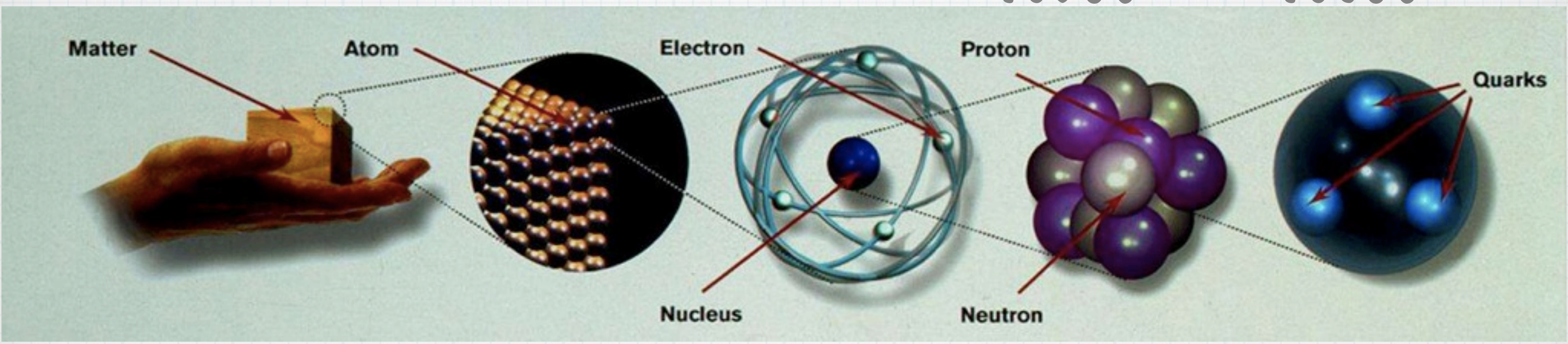
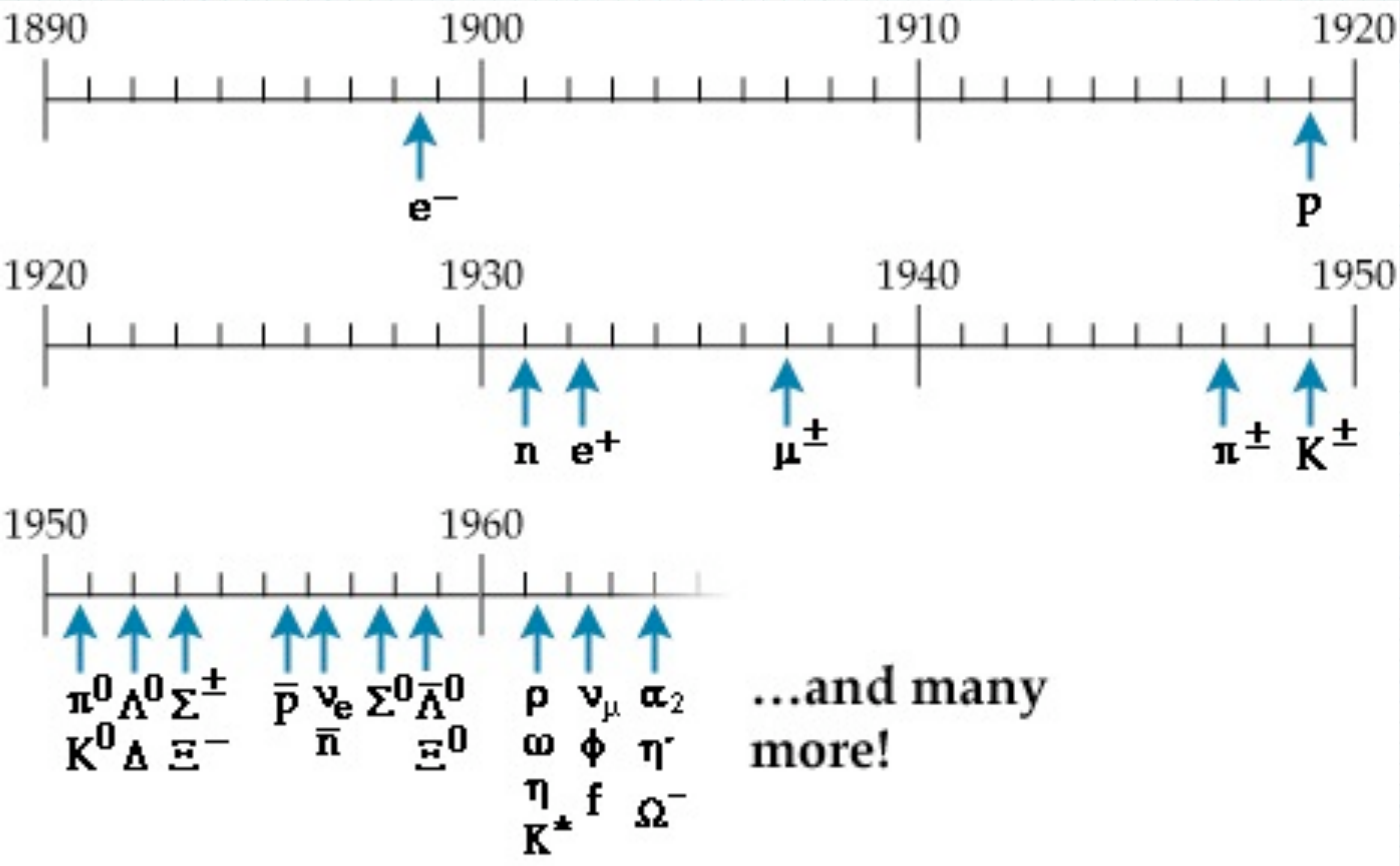
Timeline of particle physics

Ancient Greeks	Rutherford 1911	Rutherford Chadwick Heisenberg 1930's	Hofstader Gell-Mann Ne'eman 1960's



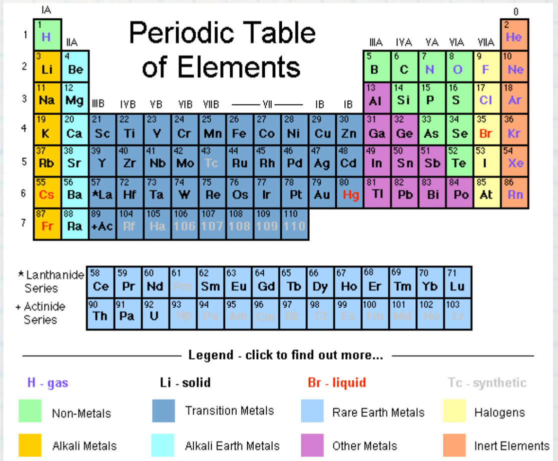
Timeline of particle physics



By the mid-60's there were almost a hundred "fundamental" particles... Something **had** to be wrong with this idea!

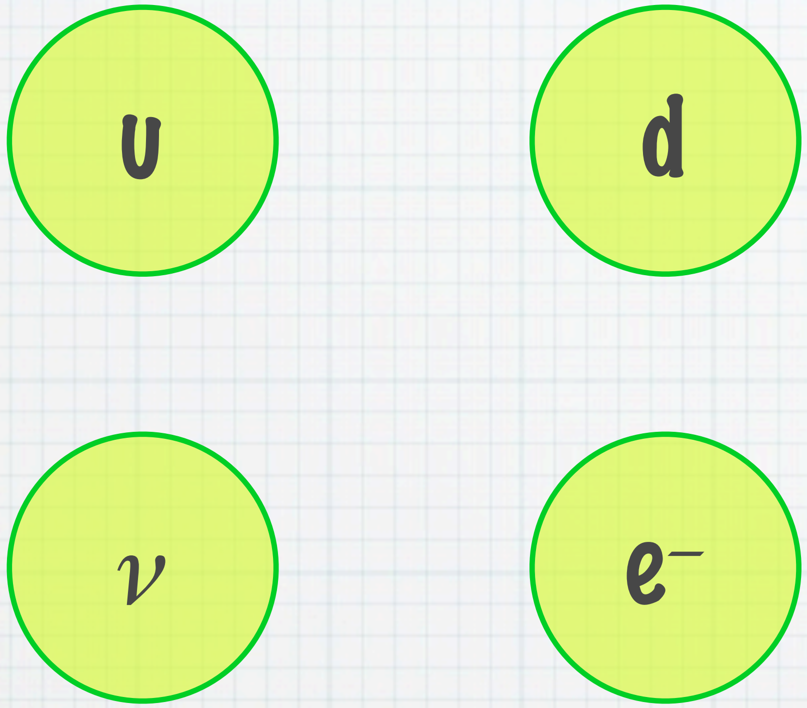
What physicists do...

- Collecting facts is important.
- More important, perhaps, is looking for relationships between these facts.
- This can lead to important understandings of how things work and interact.
- Example: Mendeleev's periodic table
  - We now know that the behavior of chemical elements depends primarily on the structure of their electrons



- By cataloging the myriad 'fundamental' particles, relationships were found.

The Matter Particles



These come in 3 varieties, called 'colors,' usually denoted as 'red', 'green' and 'blue'. Why 3 colors? Good question!

The nucleus is made of protons and neutrons. A proton is made of 2 u and 1 d quark, one of each color. A neutron is 2 d and 1 u. Adding red, blue and green gives white. All particles that we can isolate are 'colorless'.

The atom is composed of protons, neutrons and electrons.

These are all we need to describe most of the visible universe: you, me, the sun, the moon, Jupiter, Alpha Centauri, et cetera.

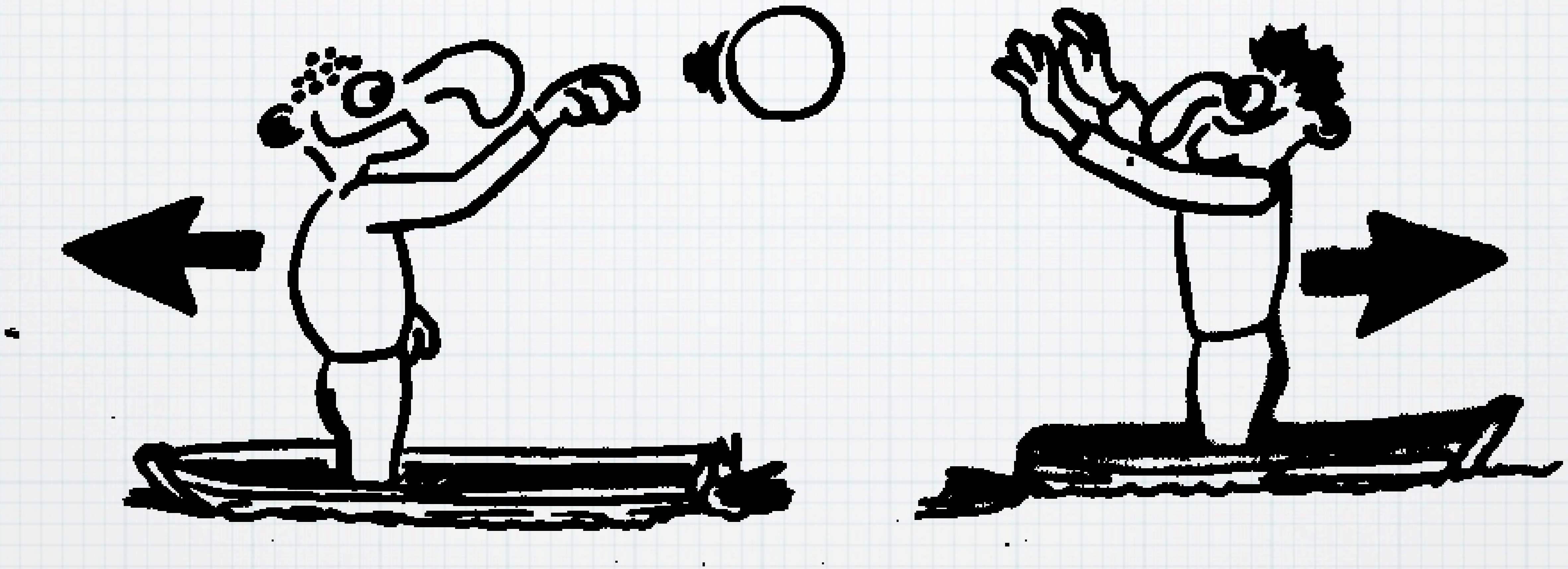
But wait! There's more!

	Charge			
Leptons	0	ν_e 0.1×10^-9 GeV	ν_μ 0.1×10^-9 GeV	ν_τ 0.1×10^-9 GeV
	-1	e^- 0.000511 GeV	μ^- 0.106 GeV	τ^- 1.777 GeV
Quarks	+2/3	u 0.002 GeV	c 1.3 GeV	t 173 GeV
	-1/3	d 0.005 GeV	s 0.1 GeV	b 4.2 GeV
			Cosmic rays	Accelerators

Why 3 copies? Good question!

Why the wide variation in mass? Good question!

Understanding forces



In the Quantum regime, forces can be repulsive or attractive. In either case, the force is transmitted by a particle, usually called a "Gauge Boson".

The Forces

The Gauge Bosons

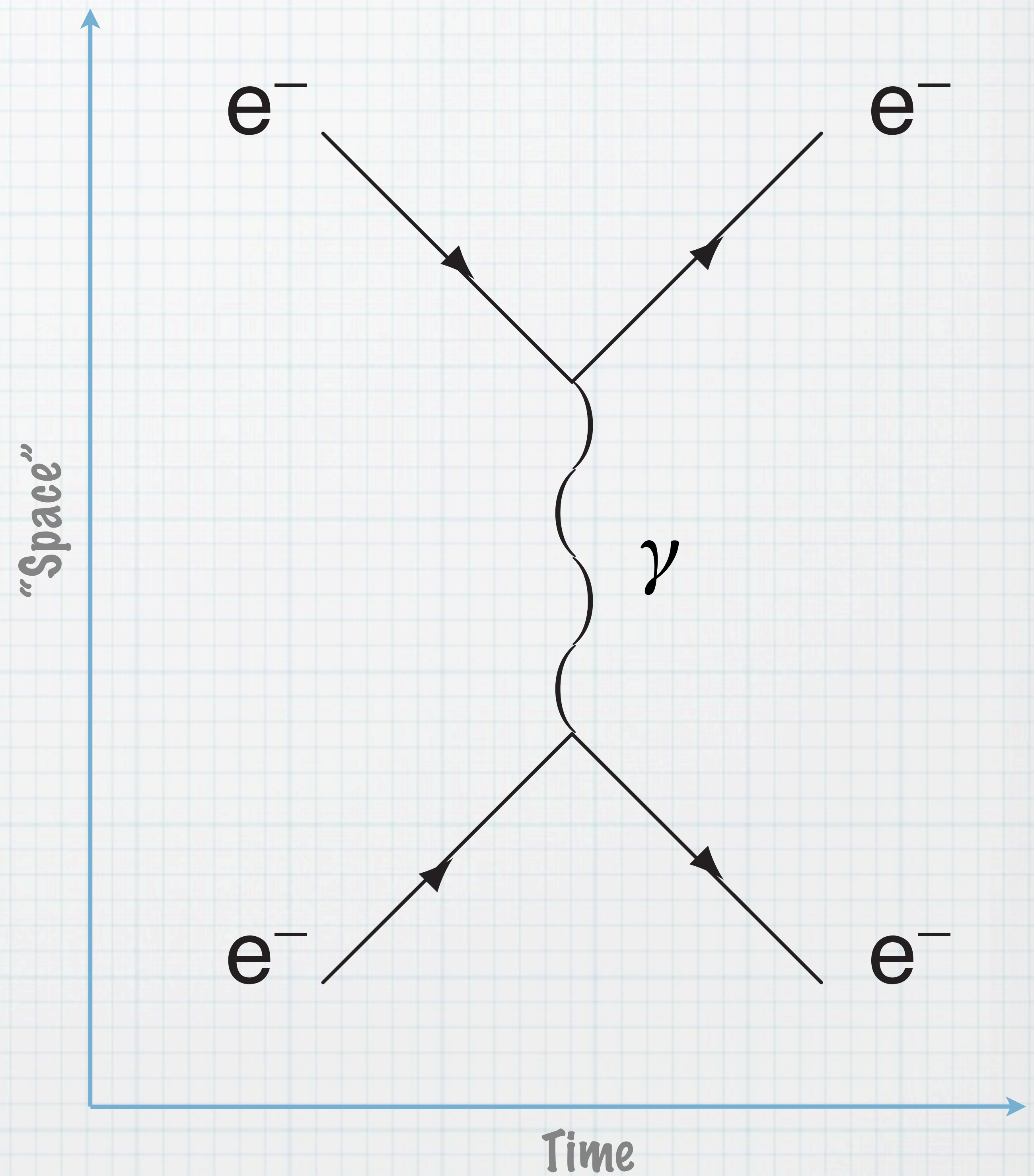
γ		Electricity; Magnetism
Z	W	Weak Interaction; beta decay
g		Strong interaction
G		Gravity: important for the universe; can't be handled (yet) in particle physics...

Visualizing interactions

We use “Feynman” diagrams to help understand interactions.

This is an example of one electron interacting with another electron.

The interaction proceeds via the exchange of a photon.



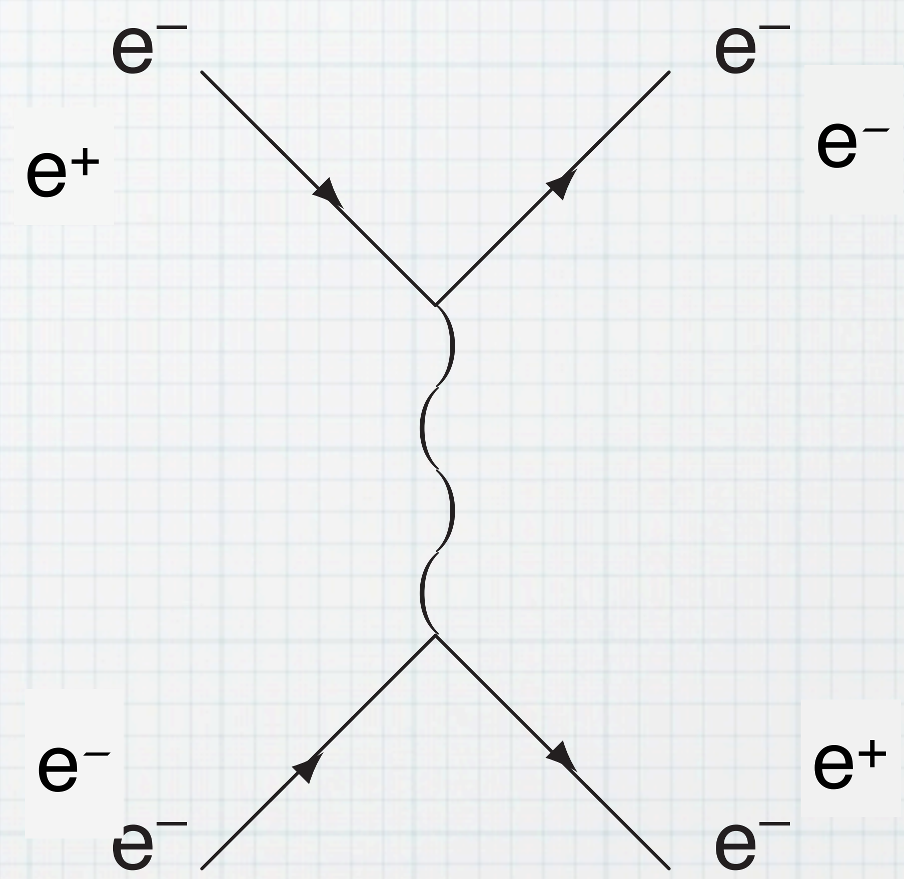
Fun with Feynman diagrams

Take the previous diagram and turn it sideways.

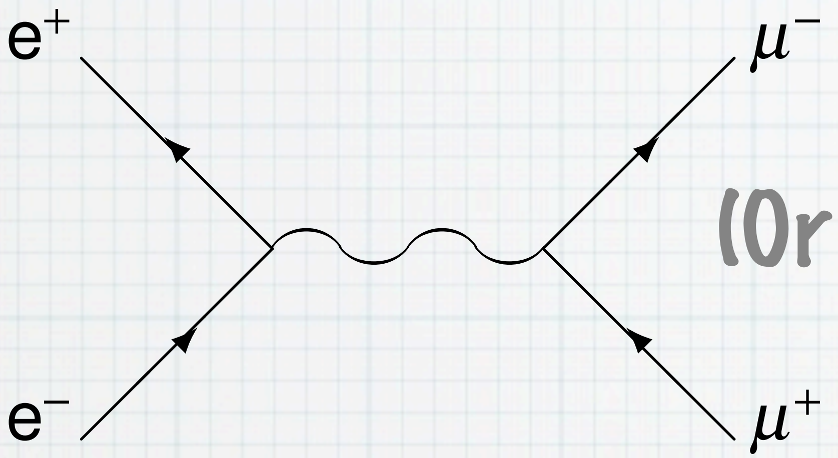
It now describes the annihilation of an electron with its anti-particle, the positron. (Note that the arrow for the e^+ is going backward in time!)

All particles have antiparticles.
Electron: antielectron (aka positron)
Proton: antiproton

For some, like the photon, it is its own anti-particle.



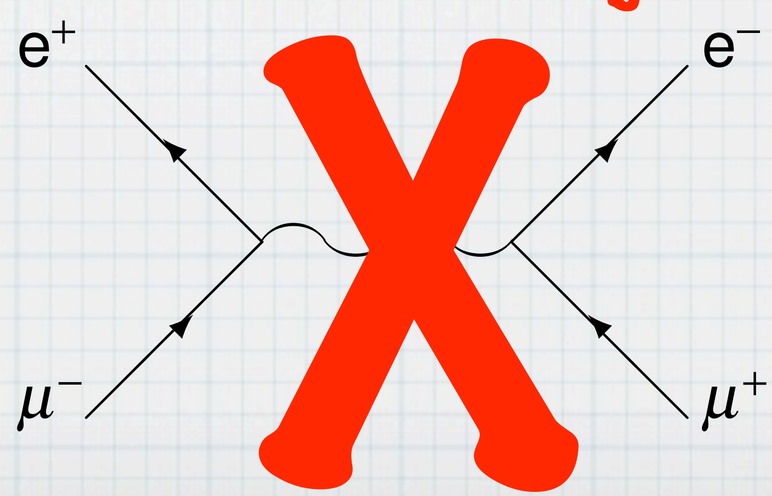
Electromagnetic Interaction



(Or turn it on its side for $e\mu \rightarrow e\mu$)

Photons couple only to charged particles, such as electrons, u quarks (they have +2/3 of an electron charge), d quarks (-1/3 of an electron charge), protons, W bosons ...

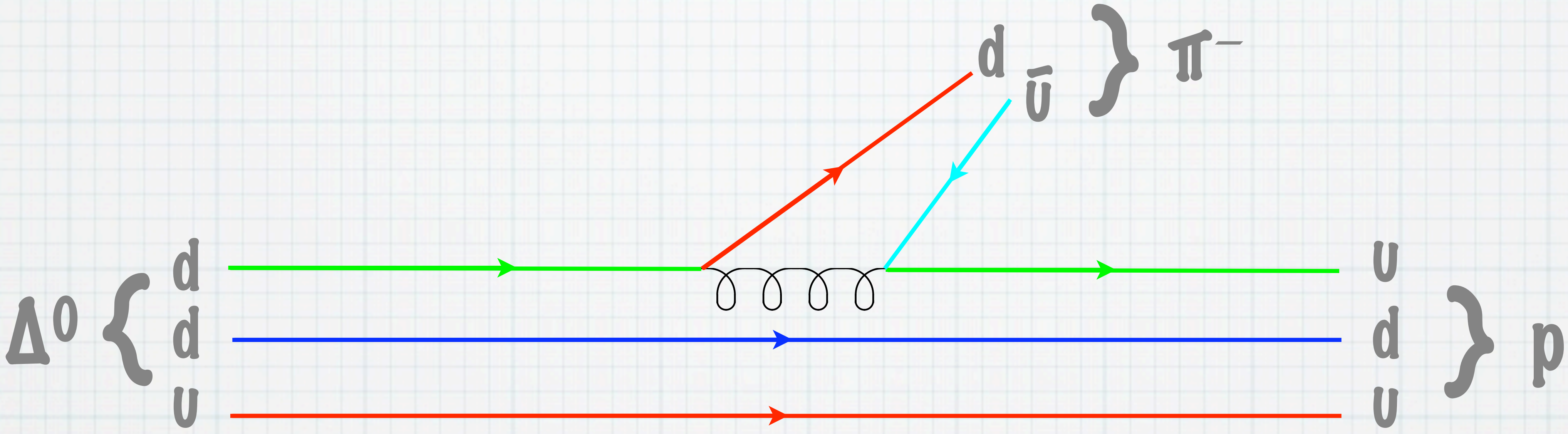
The electromagnetic interaction **can't change** the flavor of a particle. This is impossible:



Strong Interaction

* The force carrier is called the "gluon"
* The strong force interacts with 'color'ed particles.
  * Only quarks and gluons have color.
  * So, it doesn't affect electrons, muons, neutrinos...
* It is very strong: inside the proton it's 25-50 times as strong as the electromagnetic interaction.
  * Good thing, since the two u quarks would repel each other!
  * Gluons are the glue that holds quarks together!
* Like the EM interaction, it can't change the flavor of particles.

Example Strong Interaction

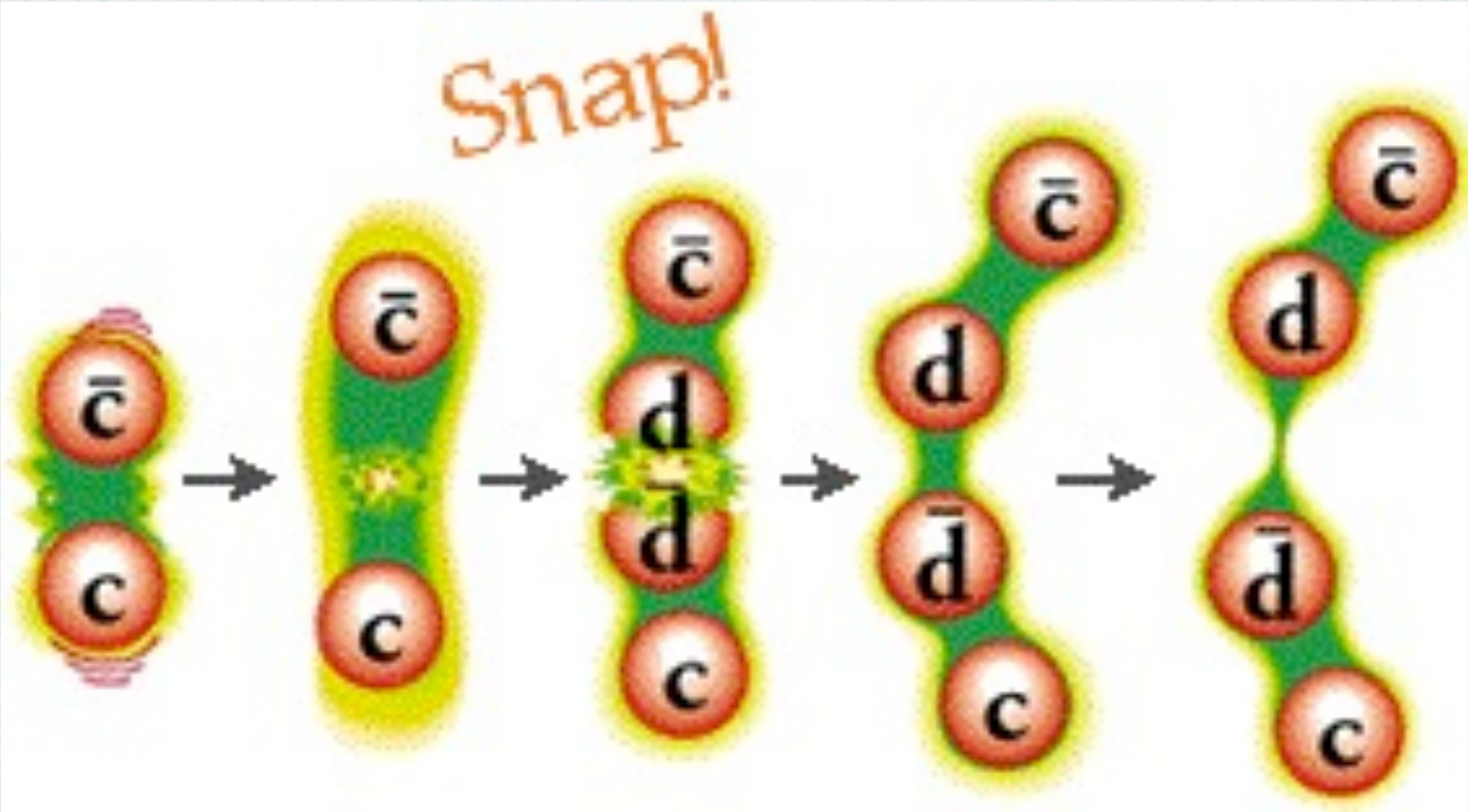


The decay of a Delta particle into a proton and a pion.

Notice that the gluon can change the color of a quark, but the d quark remained a d quark. The gluon then 'decayed' into a u quark and an anti-u. But if you follow the direction of the arrow, the 'u'-ness of the quark doesn't change...

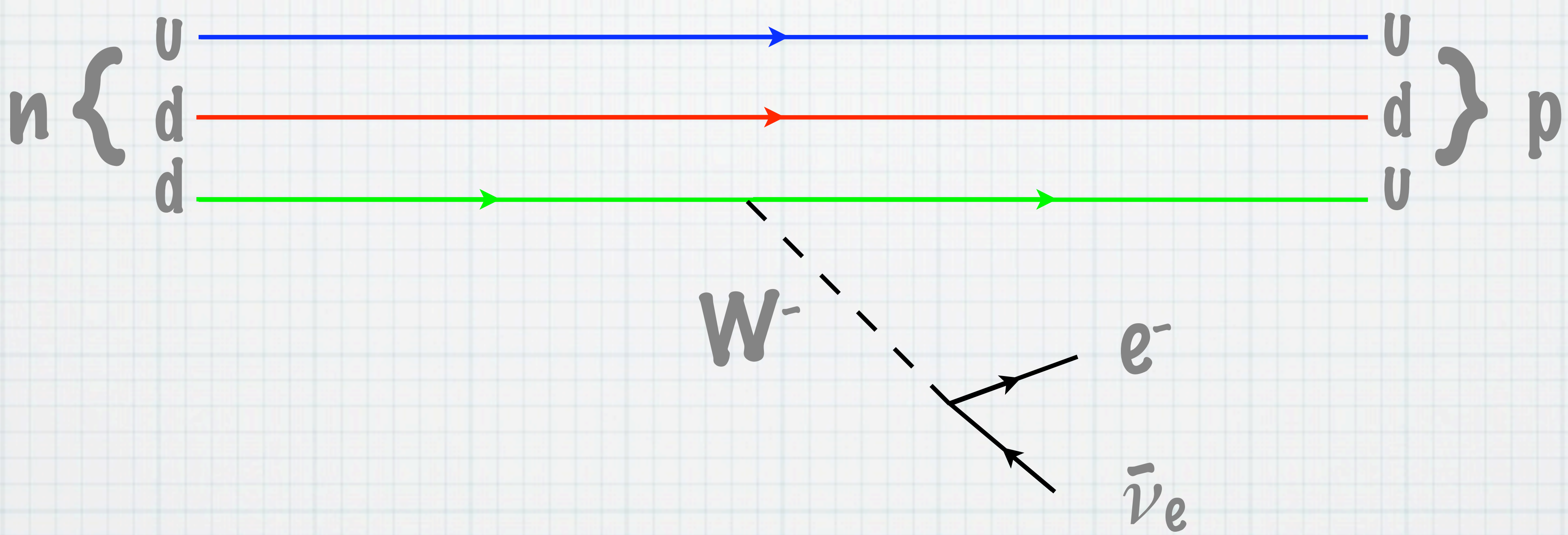
Free Quarks?

* The strong interaction doesn't allow us to isolate individual quarks.
* If you try to pull quarks apart, the force gets so strong that new particles are created. (Remember Einstein!)



The Weak Interaction

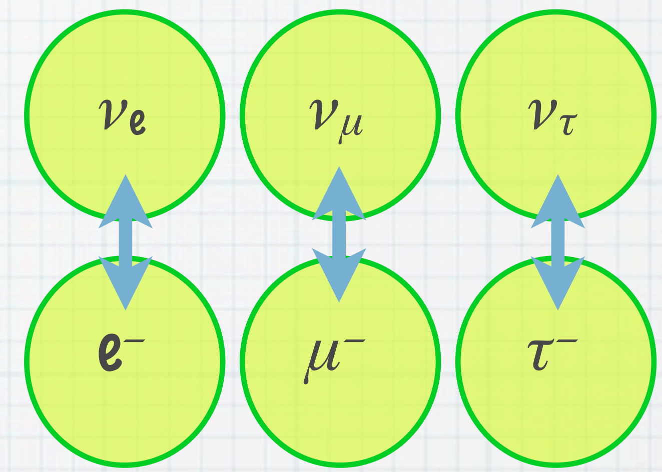
- Responsible for 'beta' decay:
  - $n \rightarrow p + e^- + \nu$

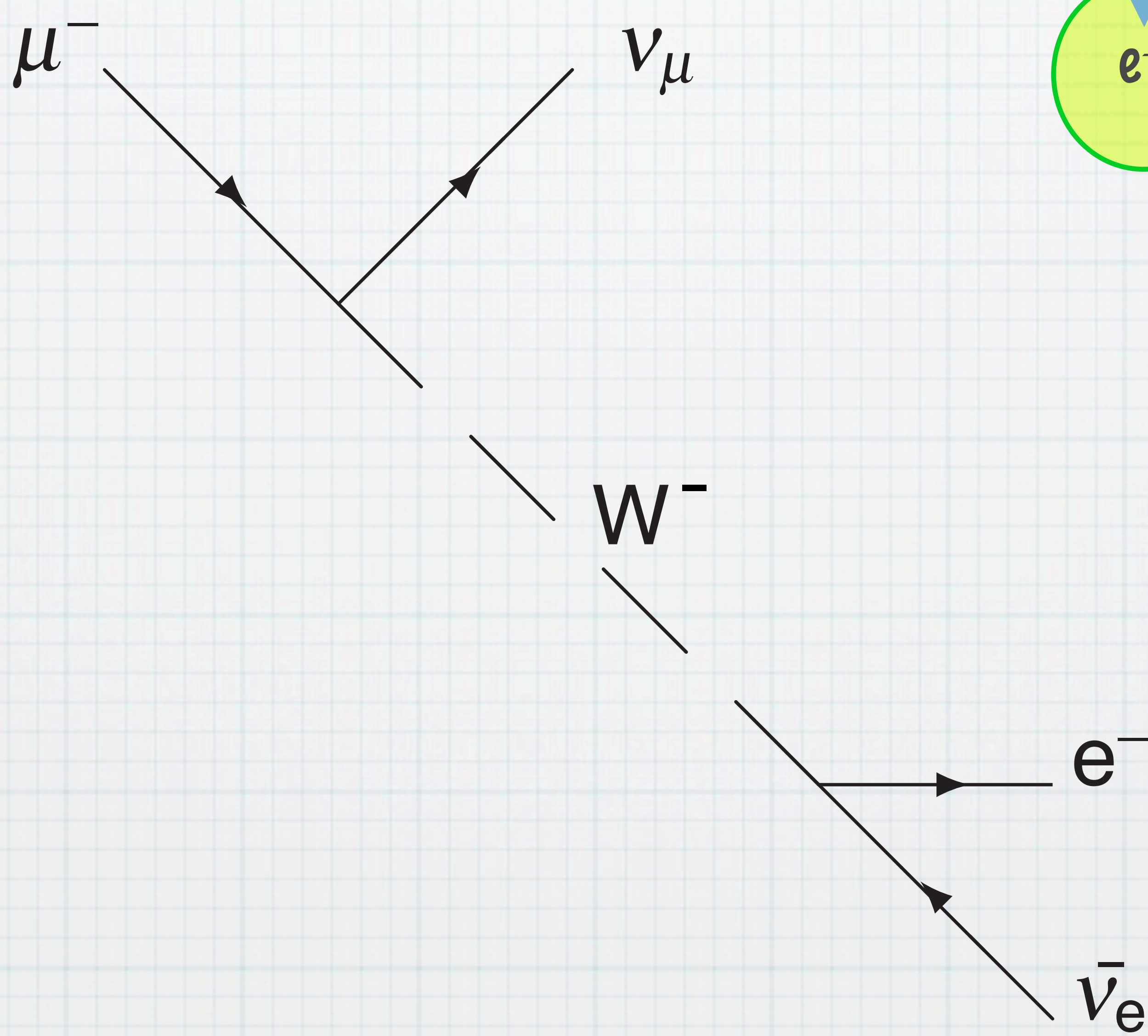


- The W changes the d quark into a u quark.
  - It then decays into an electron and a antineutrino.
  - Note that although the neutrino changes into an electron (follow arrow!), it stays 'first generation'.

Another example

- The decay of a muon:
  - $\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu$



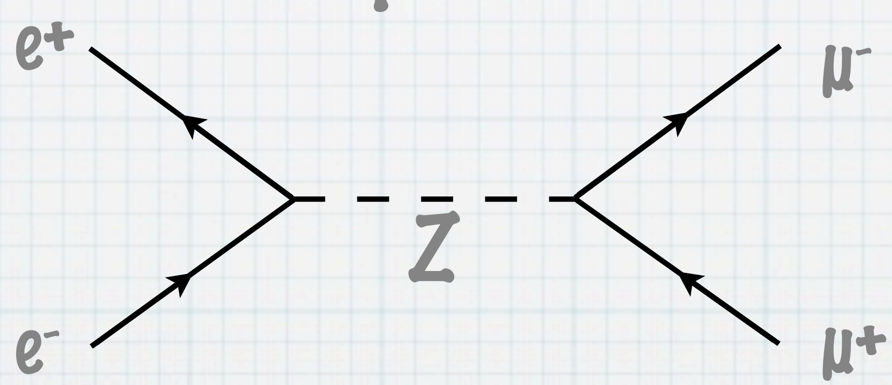


What about that W Boson?

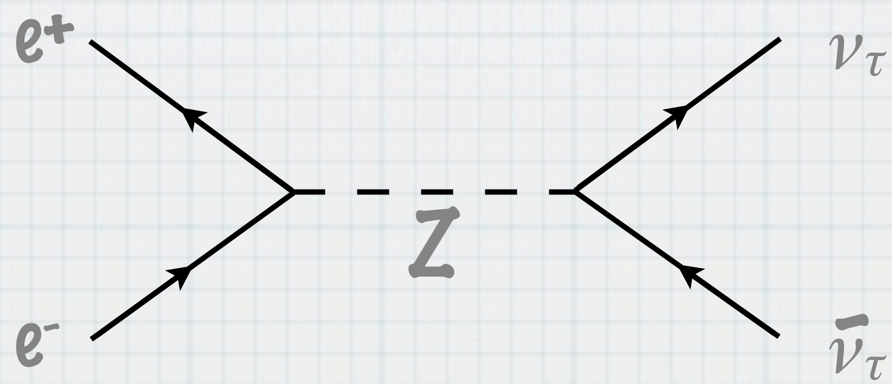
* All these decays involve a W boson. What happens to it?
* It can decay into any particles that it couples to, provided energy is conserved.
* So $\tau^- \rightarrow \nu_\tau W^-$
* The tau has a mass of 1.8 GeV, the neutrino is practically massless. So, the W can decay to $e^-\nu_e$, $\mu^-\nu_\mu$, or $d\bar{u}$. The quarks can each have 3 colors, so in total there are 5 different ways for the tau to decay. The quark pair will most often yield a pion. In other words, the Branching Ratio for the tau into an electron and two neutrinos is about 20%.

More on the Weak Interaction

* The W boson part of the weak interaction changes the 'flavor' and the charge of the particles.
* The Z boson is more like the photon: it doesn't change the flavor or charge.
* But unlike the photon, it can couple to neutrinos, which have no charge. So, for example:



* But also:

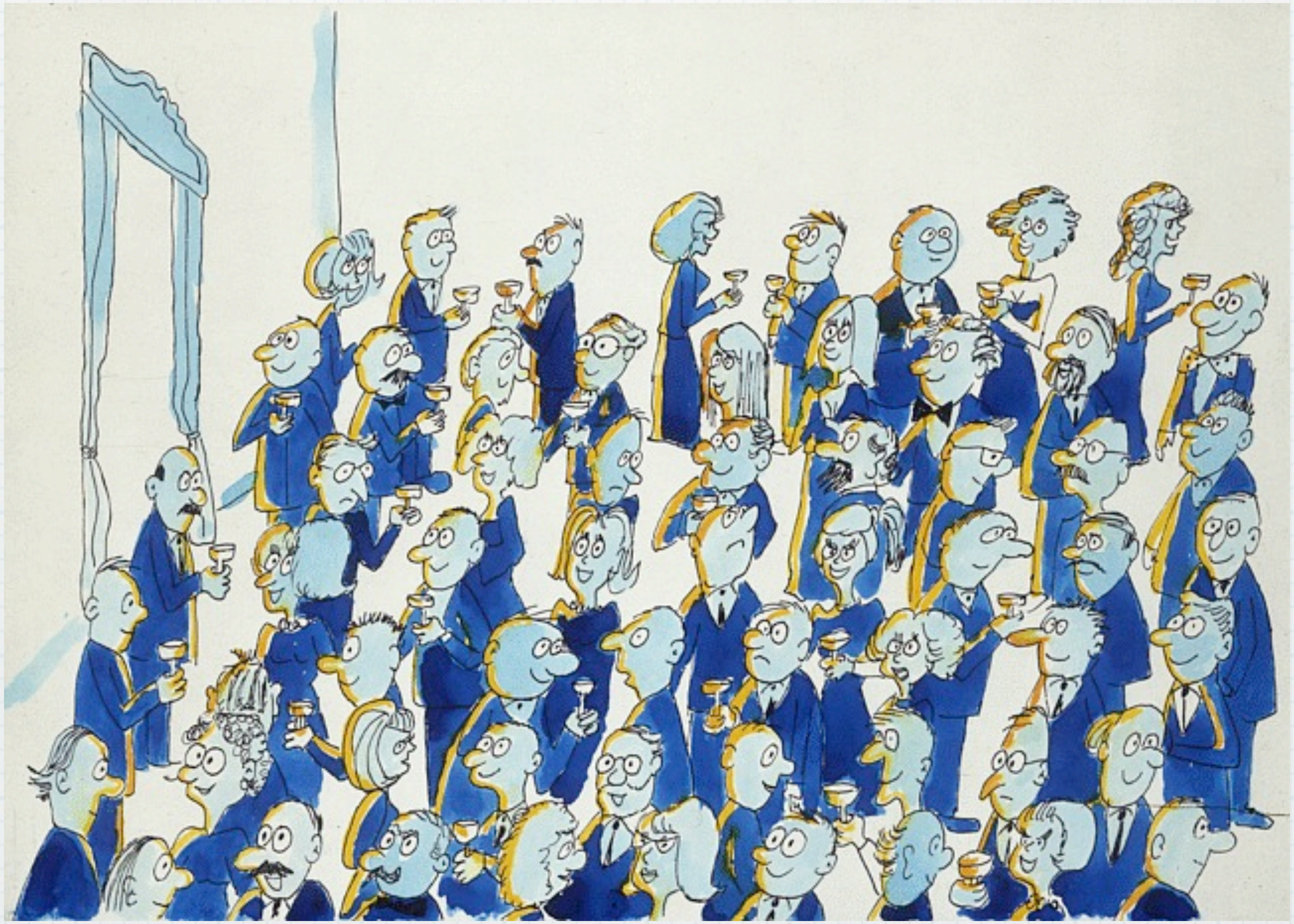


A small problem...

- The equations that describe particles and their interactions have a tiny problem:
  - All particles must be massless...
    - That works for the photon
    - But the W has a mass of 80 GeV, the Z 91 GeV and the top comes in at 173 GeV. (Remember, the electron is 0.0005 GeV and the proton 0.9 GeV, so these are massive particles!)
- This is pretty much a disaster, except that particle physics was saved by the Higgs mechanism...
  - Postulates a new particle called the Higgs Boson, which is responsible for giving mass to all particles.

The Higgs boson

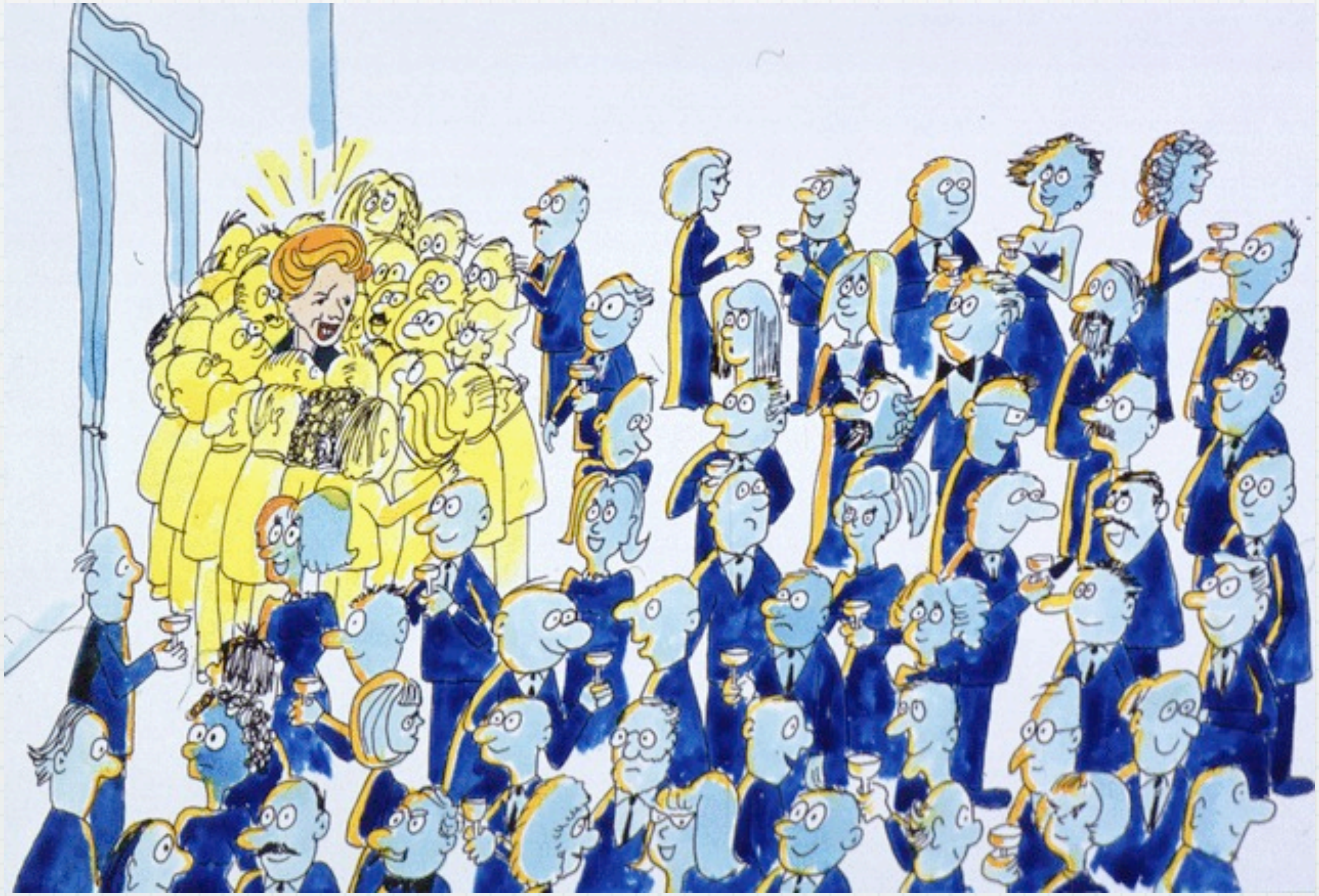
* A room full of people at a cocktail party.



Formulated by David Miller of University College London

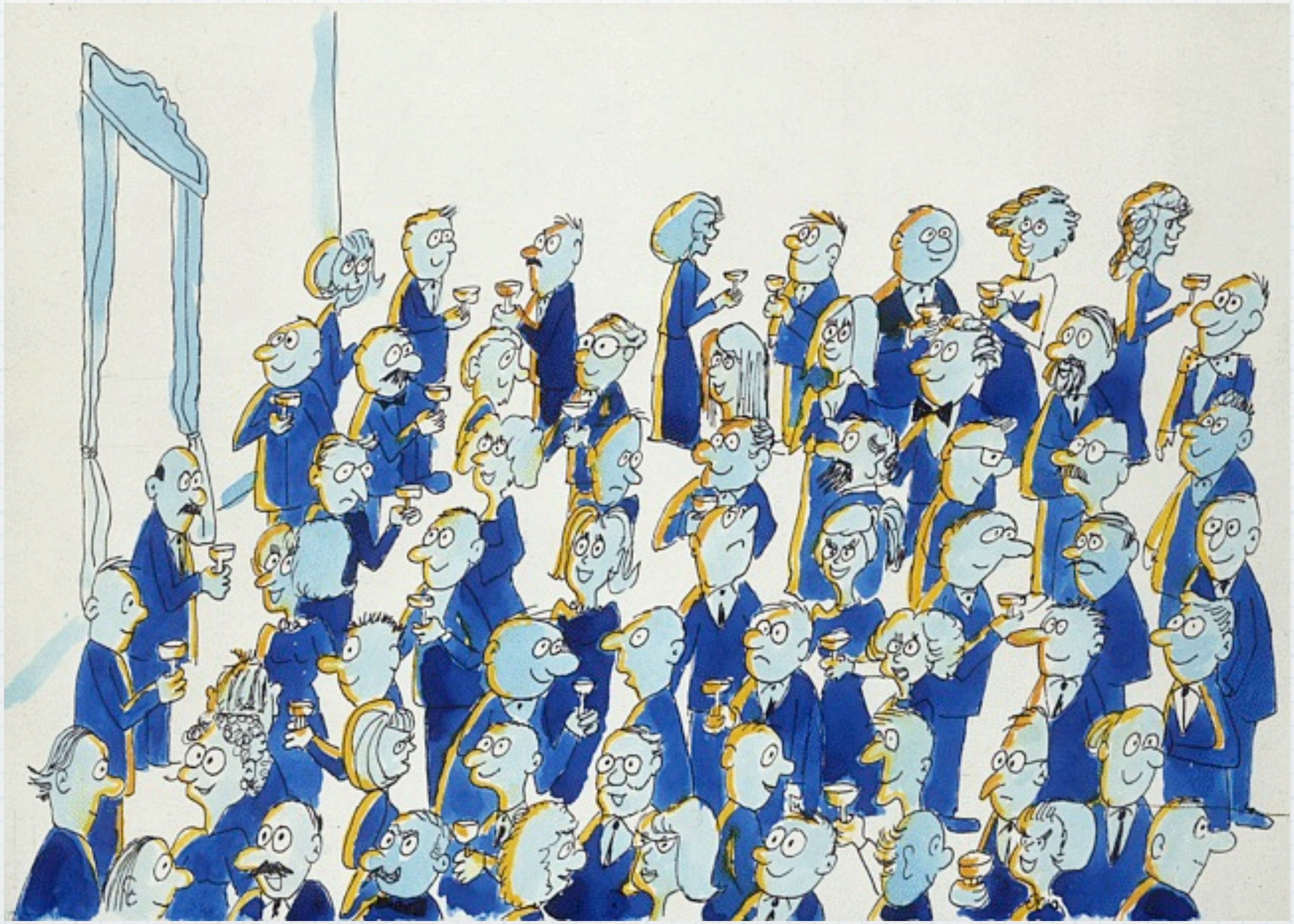
The Higgs Boson

* A big celebrity walks in... People surround her and she finds it difficult to walk through the room...
* This is analogous to the generation of mass.



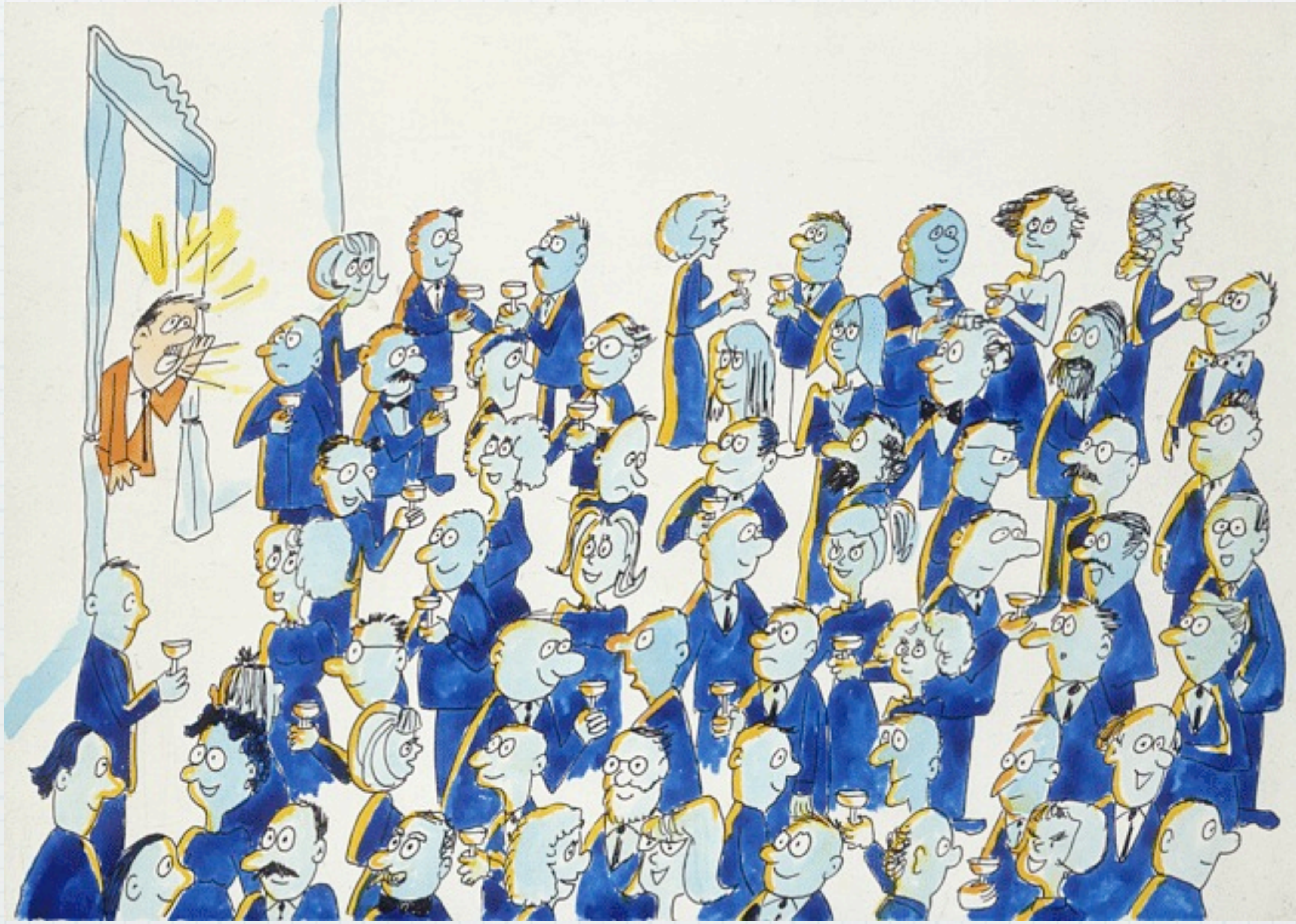
The Higgs boson

* Take the same room again.



The Higgs Boson

* Someone shouts a juicy rumor.



* The rumor moves through the room. But it is just like a cluster of people, so it too has a mass. This is the Higgs boson!

The Standard Model

* Does a fantastic job of describing particle physics.
* But:
  * Why 3 generations?
  * Why 3 colors?
  * Can we include gravity?
    * All our attempts have given ludicrous answers...
  * Does the Higgs boson exist?
    * Looks to be light, but we haven't found it yet!
    * Even if it doesn't exist, something like it is still needed, we believe!
  * What happened to all the anti-matter?

The Future

* Hopefully at least some of these questions will be answered by data coming from the next big collider, the Large Hadron Collider (LHC).
    * Currently scheduled to come on line later this year...
* There will be a bit more about the LHC and one of the experiments (CMS) next week.