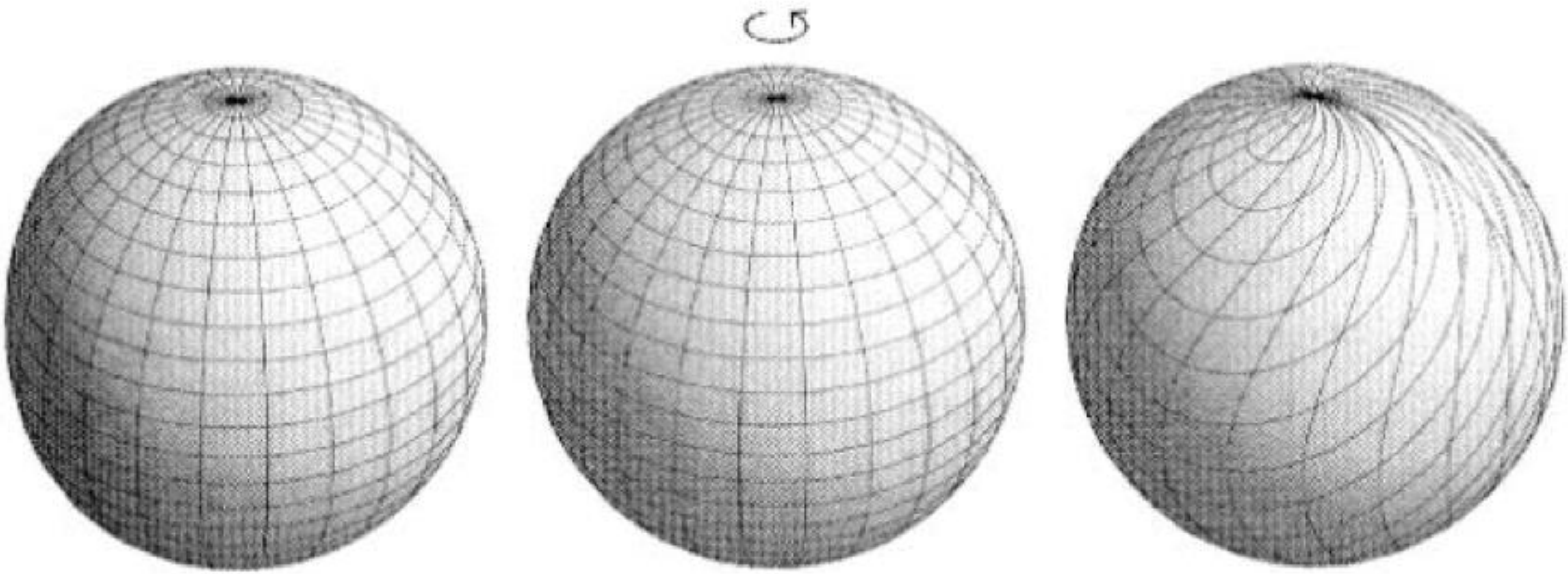
Continuous symmetries in Physics



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The Abdus Salam
International Centre
for Theoretical Physics
Physics Without Frontiers

IAEA
International Atomic Energy Agency

unesco
United Nations
Educational, Scientific
and Cultural Organization

Lecture 3: intro to the Standard Model

Part I: particles and interactions

- What is an elementary particle?
- How do elementary particles interact?
- What are gauge bosons

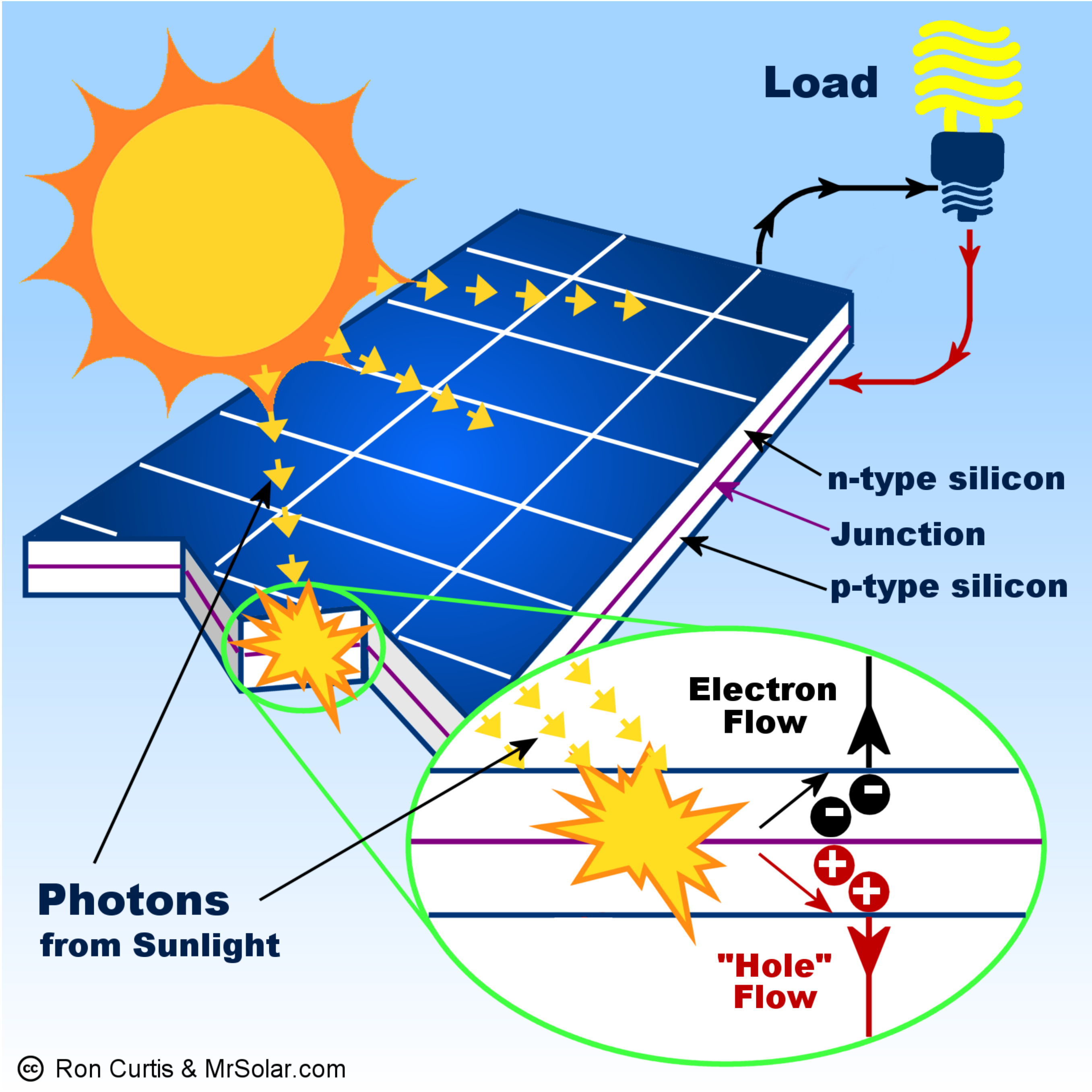
Part II: forces and symmetries

- Strong and electroweak forces
- The Standard Model of elementary particles

What are particles and how do they interact?

What exactly is a particle?

- The electromagnetic field carries energy, and is able to transfer energy
- Electromagnetic energy comes in small packets, called “photons”
- Each photon is called a “quantum” of the electromagnetic field
- Such quanta carry energy and transfer impulse, i.e. they are particles
- In general, each particle is the quantum of a field



Gauge particles

A quantum of the electromagnetic field is a photon

A quantum of a gauge field is a gauge particle

Force carriers

- When we say that an electron orbits around a proton, we implicitly assume electrostatic force exerts an action at a distance

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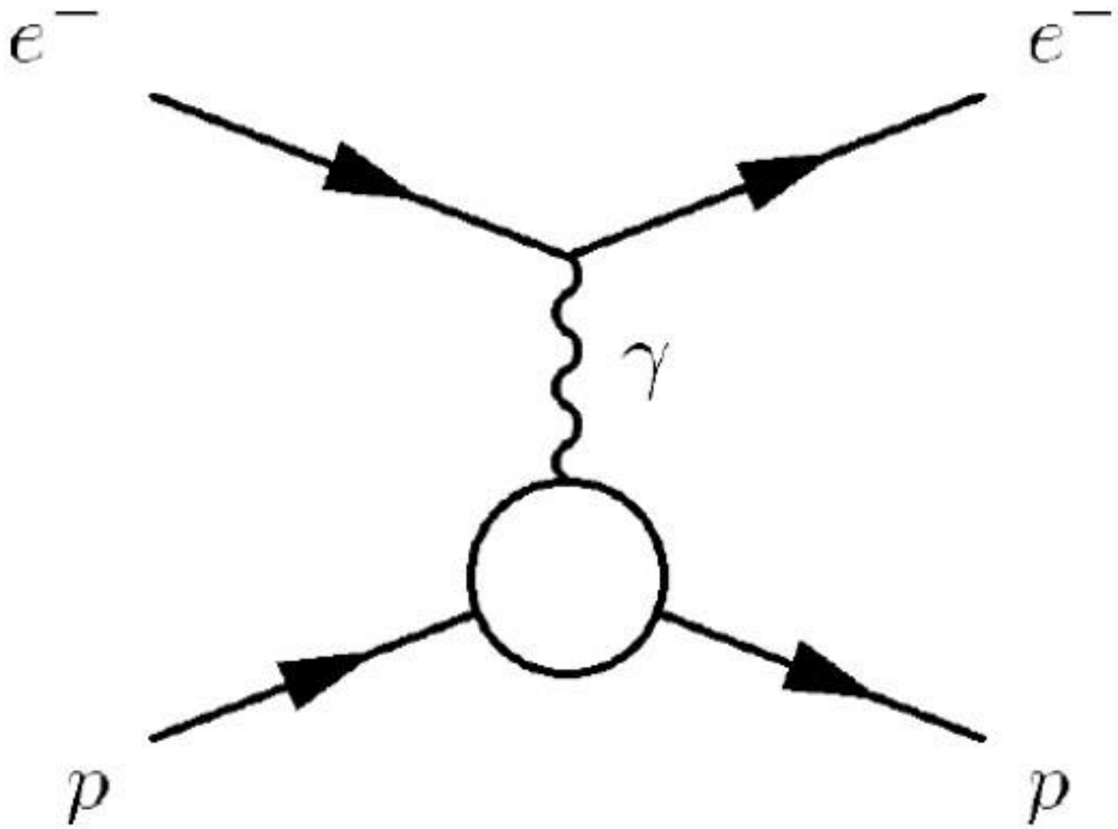
It is inconceivable that inanimate Matter should, without the Mediation of something else, which is not material, operate upon, and affect other matter without mutual Contact…That Gravity should be innate, inherent and essential to Matter, so that one body may act upon another at a distance thro' a Vacuum, without the Mediation of anything else, by and through which their Action and Force may be conveyed from one to another, is to me so great an Absurdity that I believe no Man who has in philosophical Matters a competent Faculty of thinking can ever fall into it. Gravity must be caused by an Agent acting constantly according to certain laws; but whether this Agent be material or immaterial, I have left to the Consideration of my readers.

— Isaac Newton, Letters to Bentley, 1692/3

Force carriers

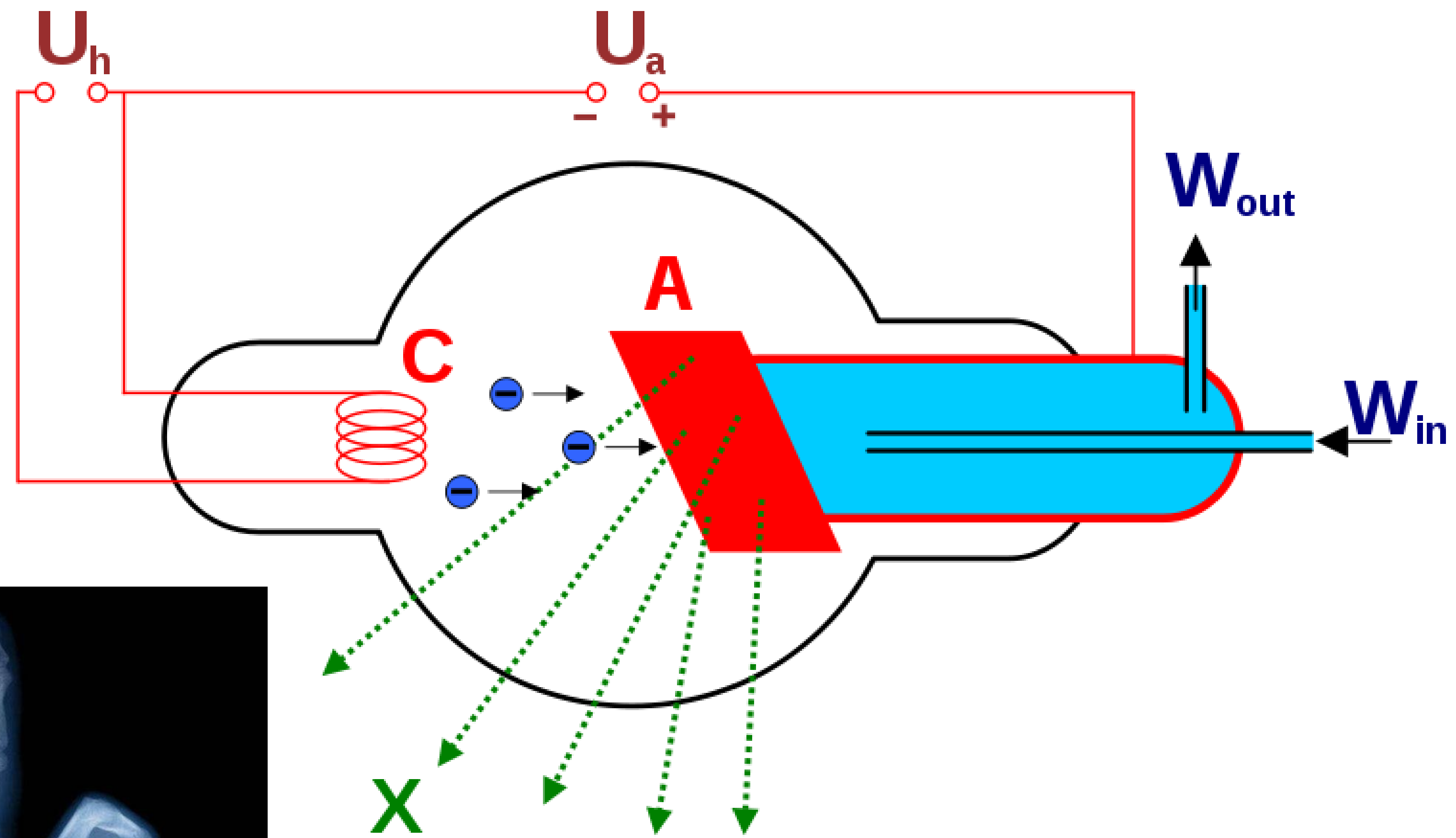
- Gauge particles (e.g. photons) mediate the forces (interactions) between (e.g. electrically) charged particles



- The photons that mediate electromagnetic interactions are called “virtual”, they cannot be observed as such, but only through the force they mediate

Direct observation of photons

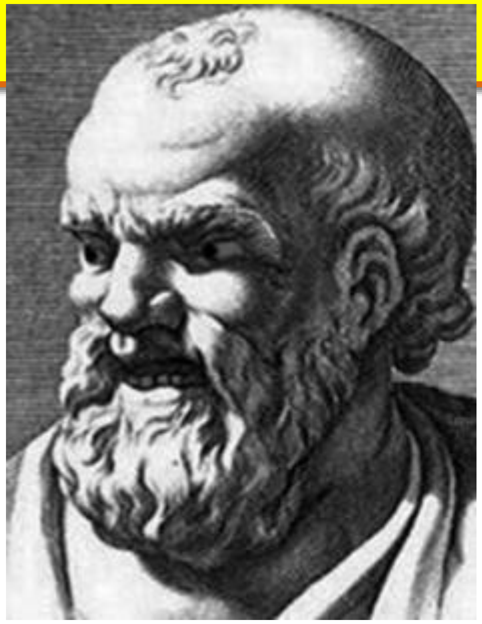
- It is possible to observe “real” photons through electromagnetic radiation, obtained e.g. by smashing electrons onto a target



What has gauge principle to do with the forces we observe in nature?

Atoms

"ἀρχὰς εἶναι τῶν ὅλων ἀτόμους καὶ κενόν, τὰ δ'ἀλλα πάντα νενομίσθαι"
"In the beginning there were only atoms and the vacuum all the rest is an opinion" (Democritus)



- Atom means "indivisible"

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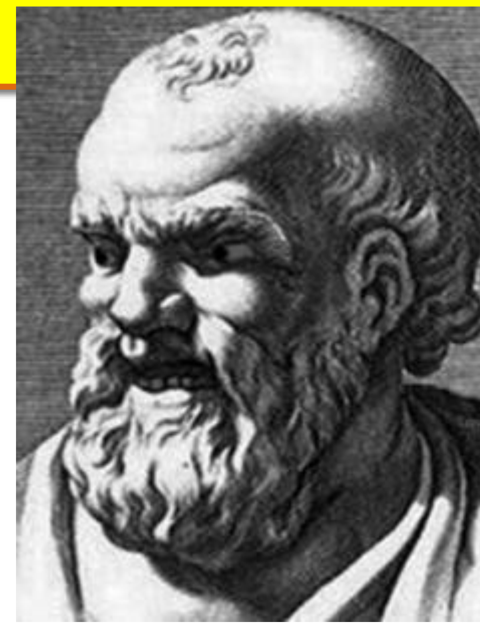
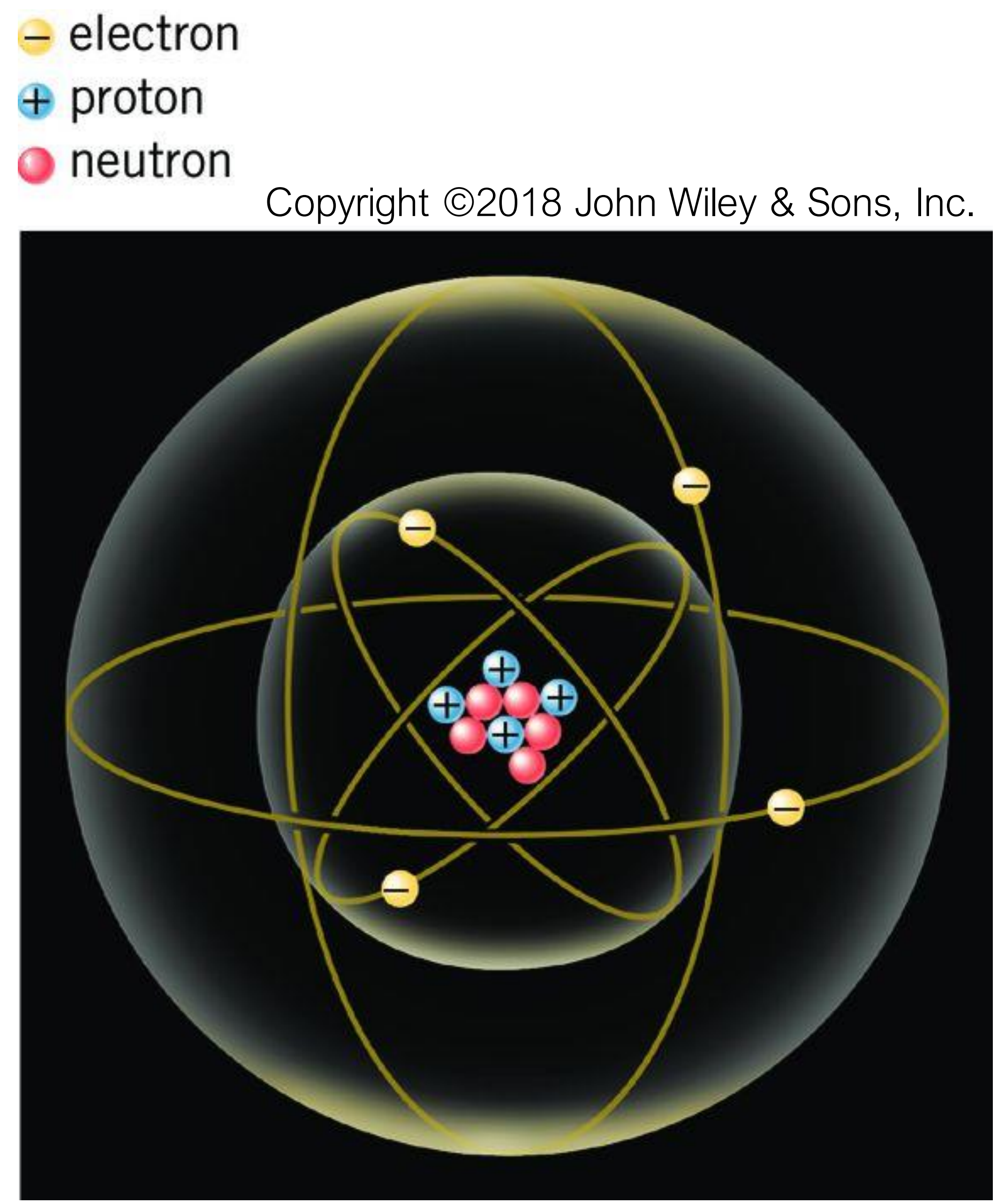
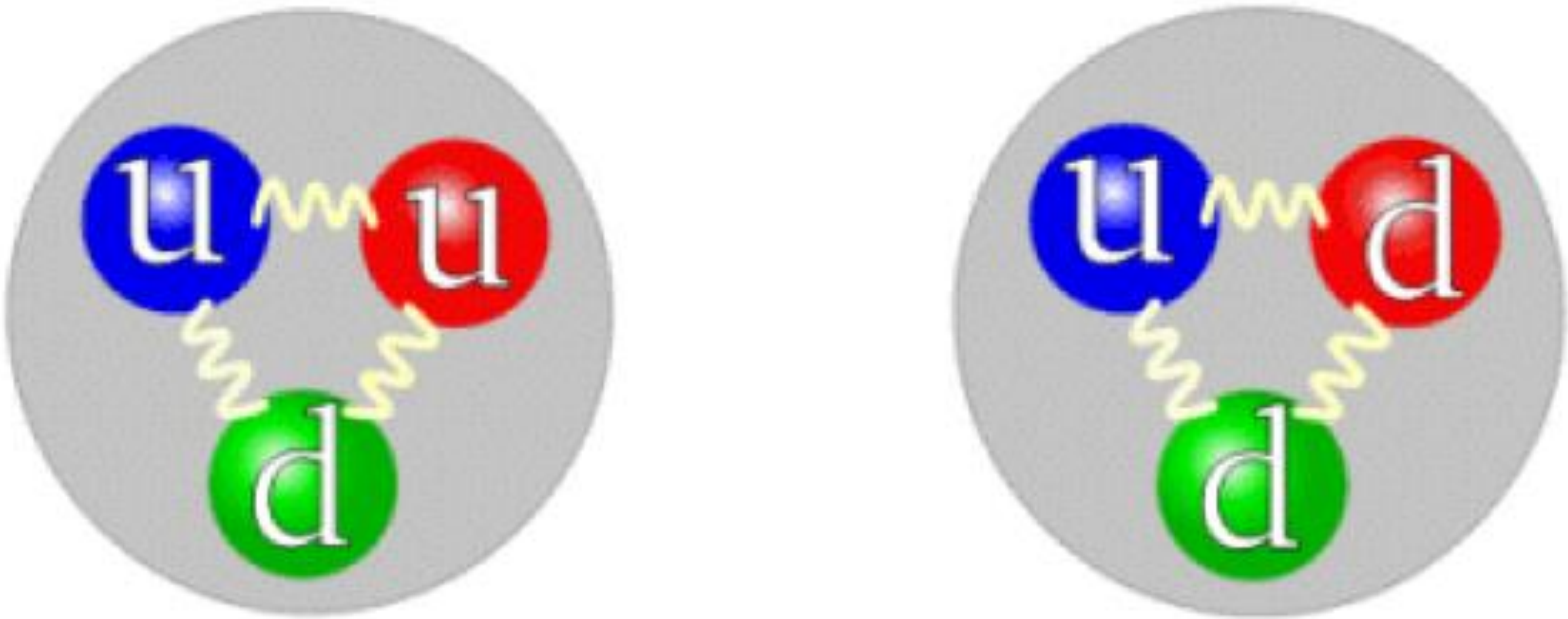


- Atom means “indivisible”
- We now know that atoms are made of smaller components, electrons, protons and neutrons



Quarks

- Protons and neutrons (a.k.a. "nucleons") are not elementary particles, but are made up of elementary particles called quarks



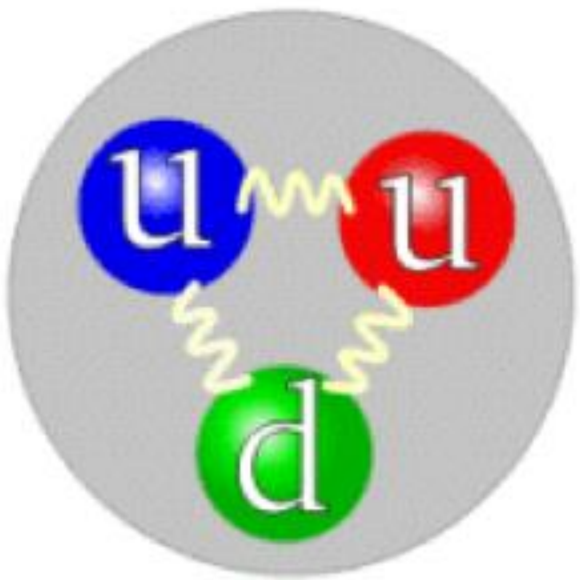
Proton

Neutron

What kind of force keeps the quarks bound together inside protons and neutrons?

Strong interactions

- The quarks have a new property, the colour, red, green and blue



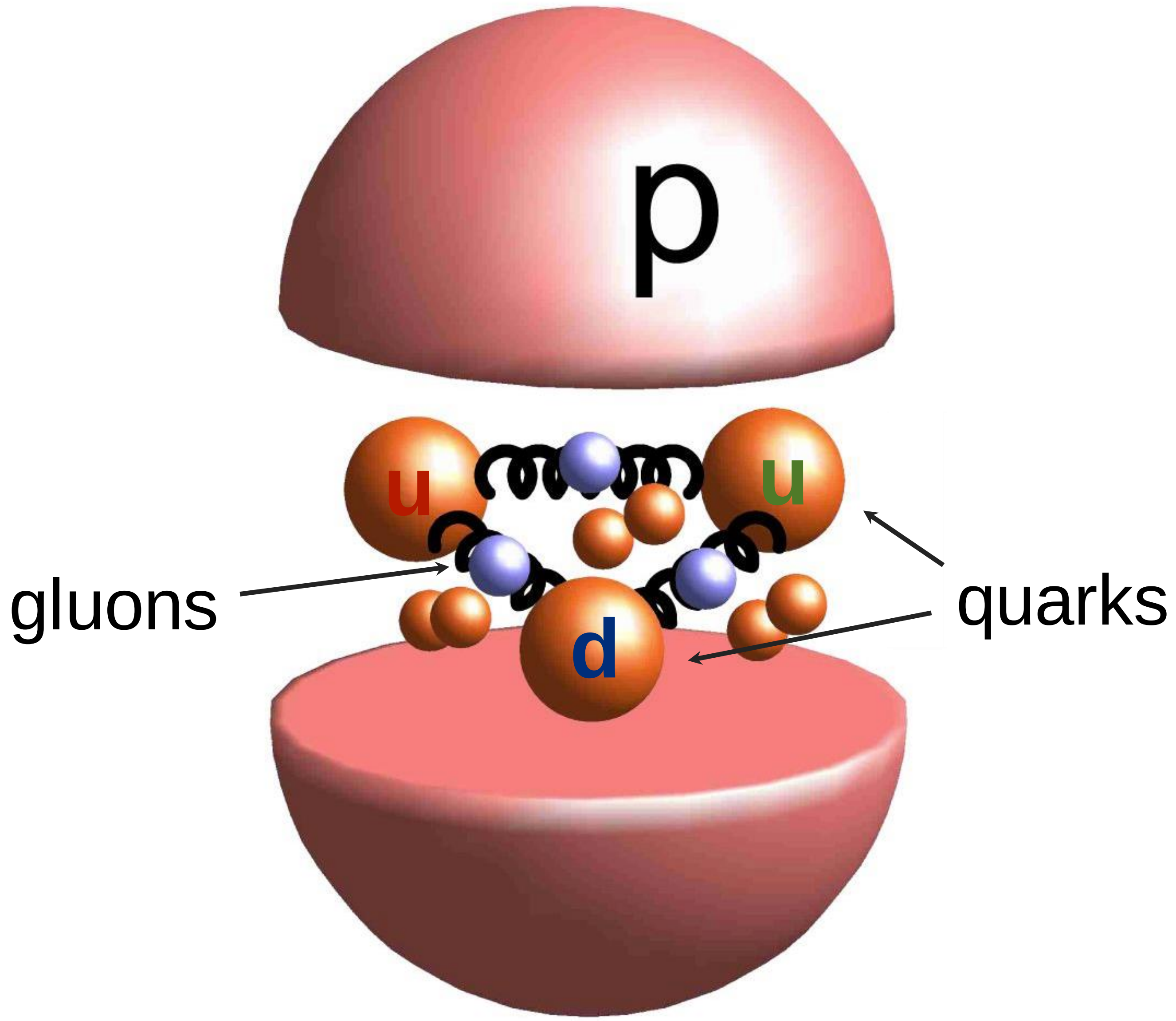
Proton

$$\psi_u = \begin{pmatrix} u \\ u \\ u \end{pmatrix}$$

- We say that the wave function of a quark is a colour "triplet"
- We can "mix" the colours of a quark wave function to obtain another wave function
- If such "mixing" is the same in every point of space and time we obtain a new continuous symmetry
- The corresponding conserved charge is, as expected, the colour

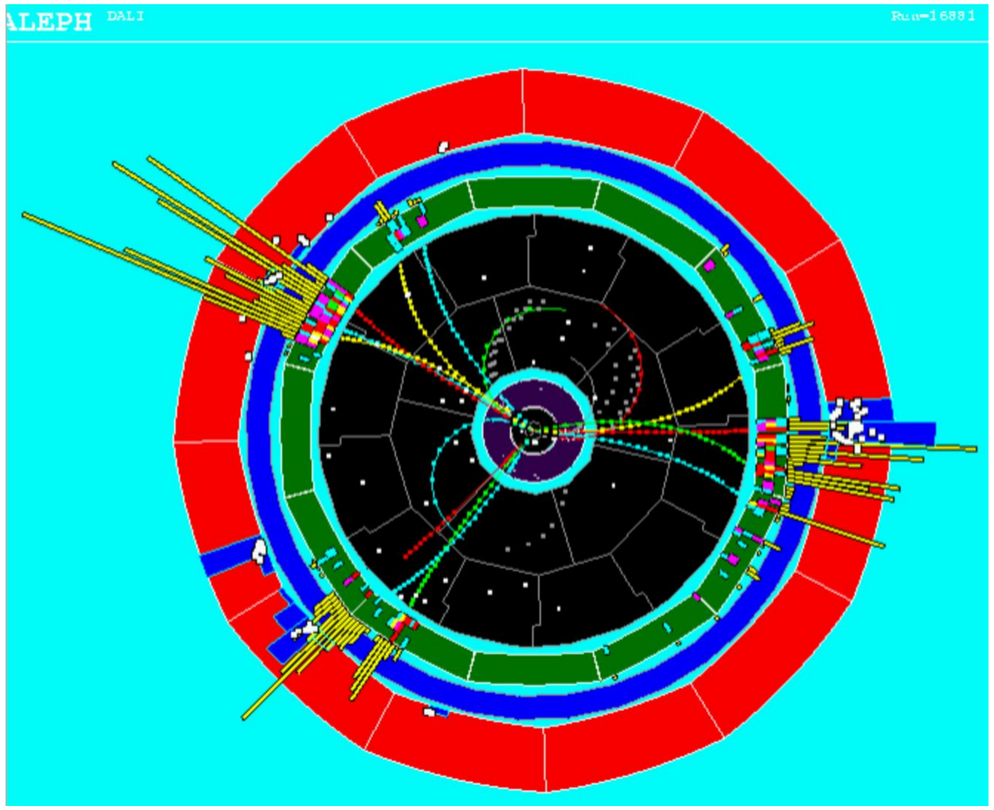
Gluons

- Make the mixing of different colours a gauge symmetry $\Rightarrow$ eight new gauge particles appear, the gluons, which bind quarks together inside nucleons



Gluons

- Gluons binding together quarks inside nucleons are virtual particles
- Like the photons, gluons can be radiated
- Radiated gluons appear as highly collimated jets of particles



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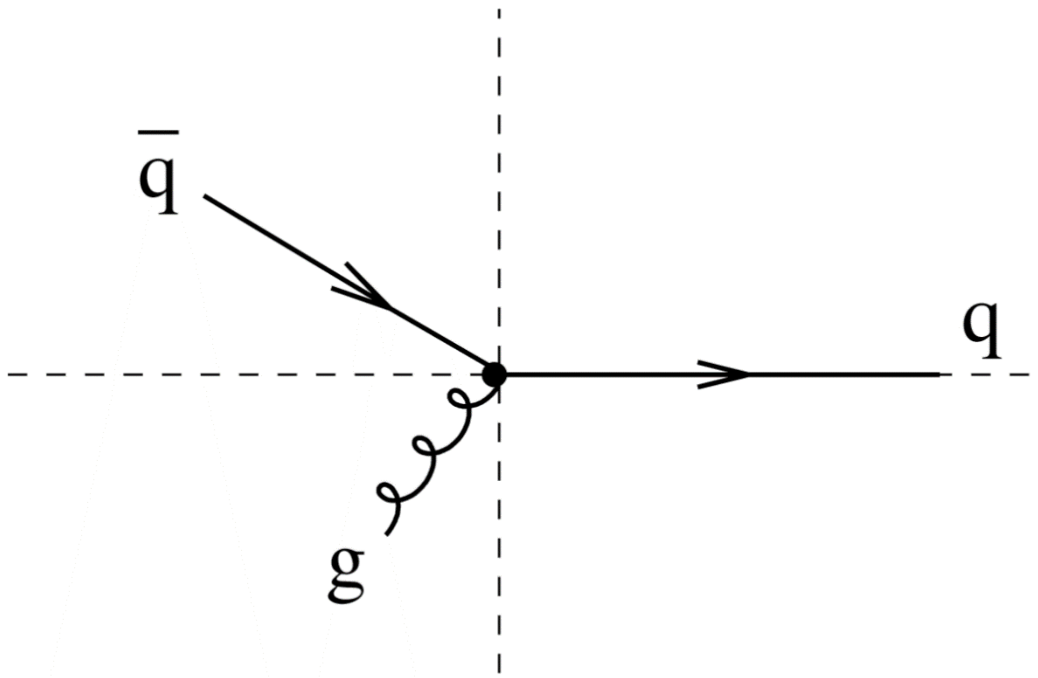
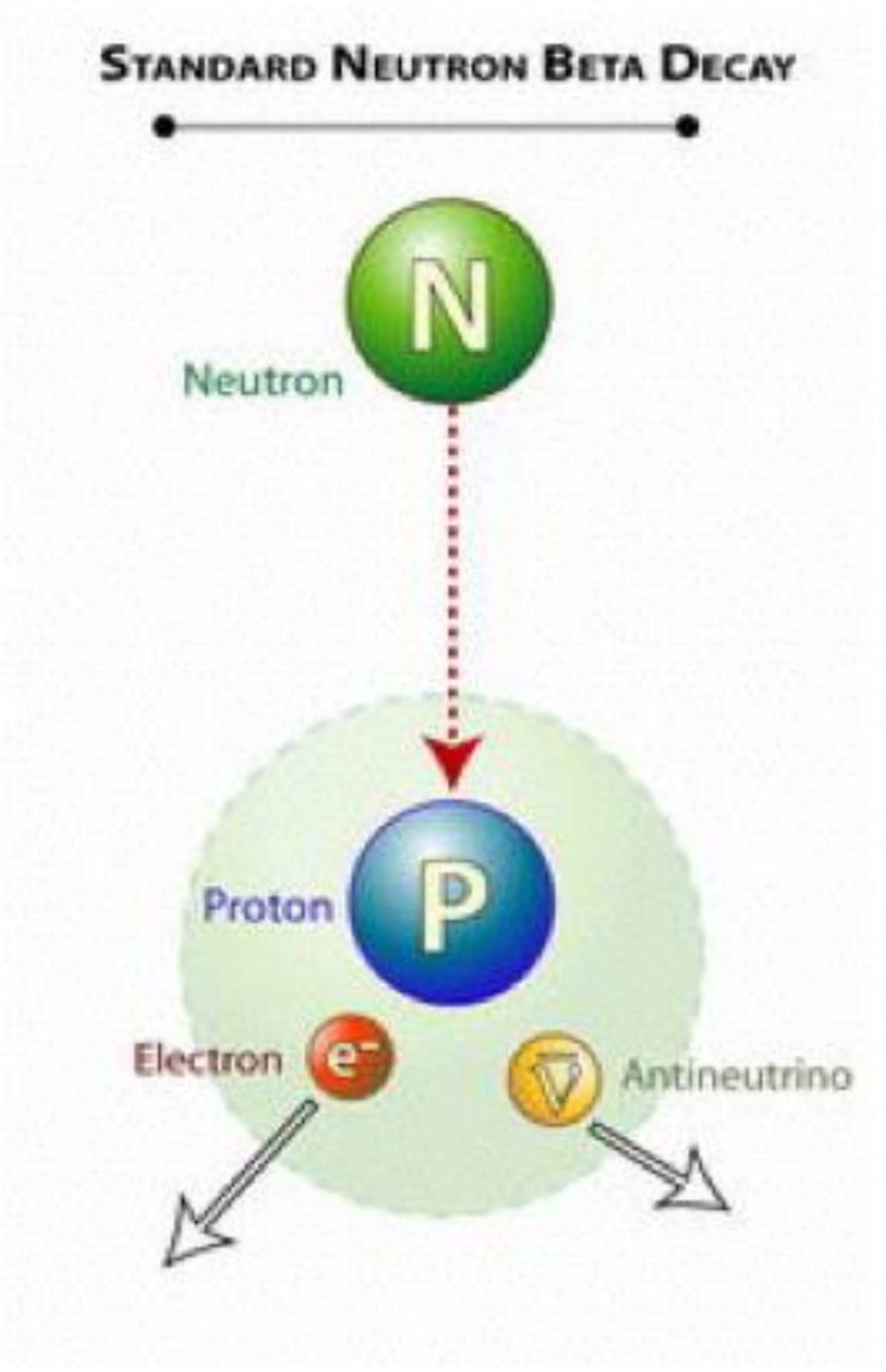


- Quarks and gluons can never be observed: jets of particles are their footprints in our experimental detectors

What kind of force is responsible for radioactive decay?

Radioactive decay

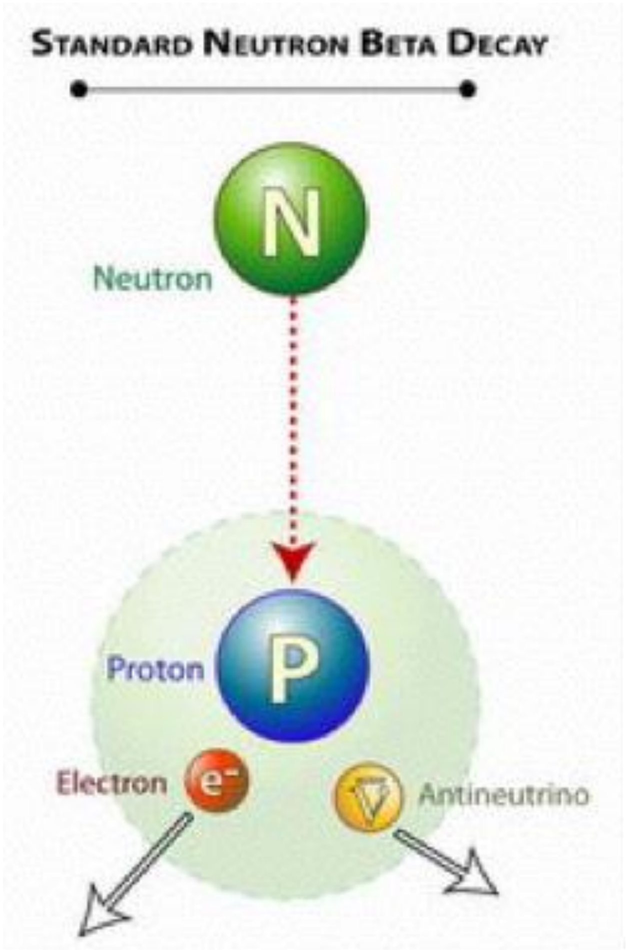
- Weak interactions are responsible for radioactive beta decay



Can we describe beta decay with a gauge symmetry?

Weak interactions

- Organise wave functions into pairs, giving each member of the pair a new property, the weak isospin T_3

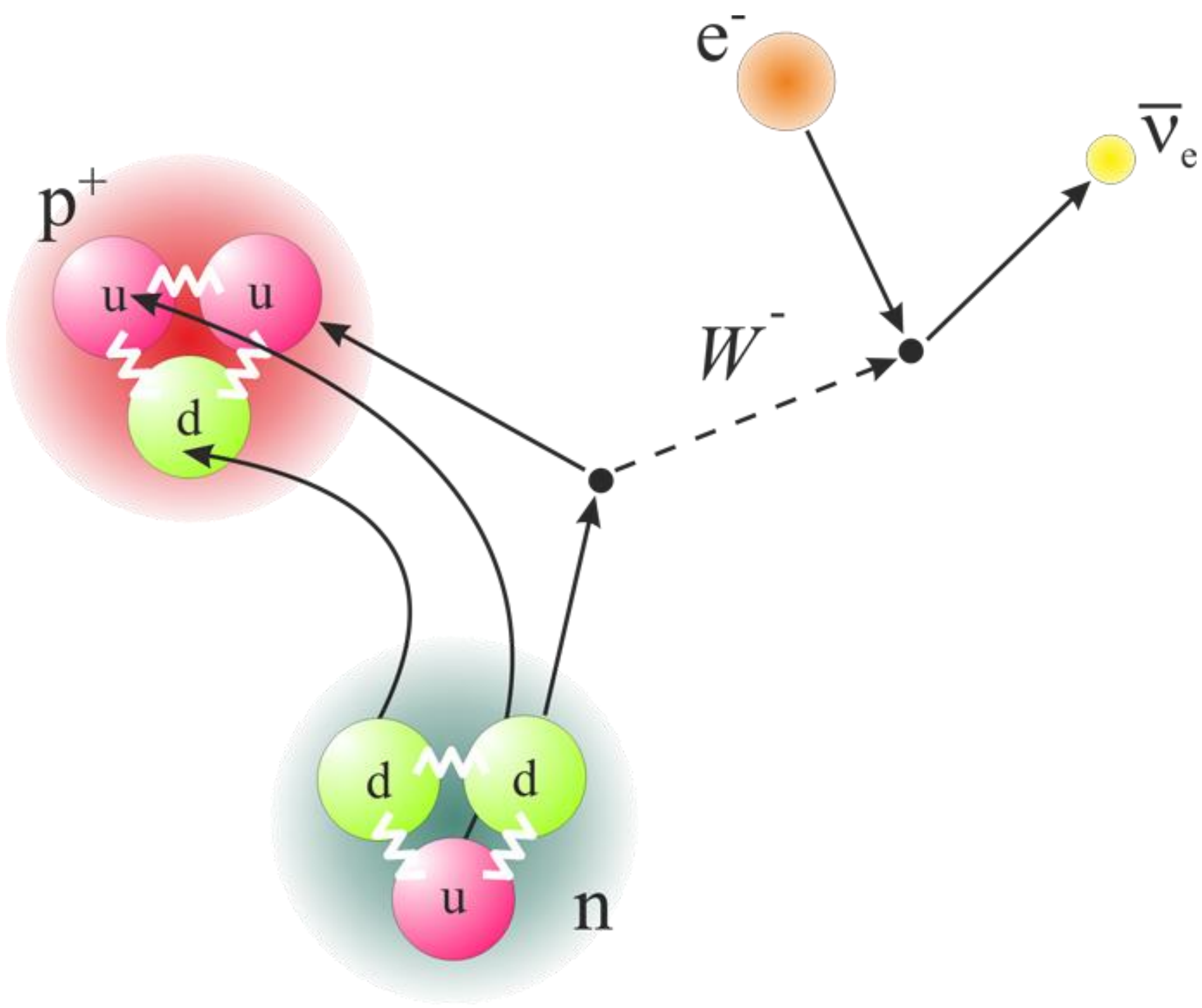


$$\psi = \begin{pmatrix} \nu \\ e \end{pmatrix} \quad \begin{matrix} \leftarrow T_3 = 1/2 \\ \leftarrow T_3 = -1/2 \end{matrix}$$

- New continuous symmetry: suitable mixing of the neutrino and electron wave functions in the same fashion at every point of space and time
- Corresponding conserved charge: weak isospin

Weak bosons

- Make the mixing of different isospin states a gauge symmetry $\Rightarrow$ three new particles, the "weak bosons" W^+, W^-, W^3



- The electrically charged W^+ and W^- are responsible for beta decay
- What about the electrically neutral W^3?

Hypercharge

- Glashow, Weinberg and Salam introduced a new conserved charge, the hyper-charge Y, very similar to the electric charge


Steven Weinberg

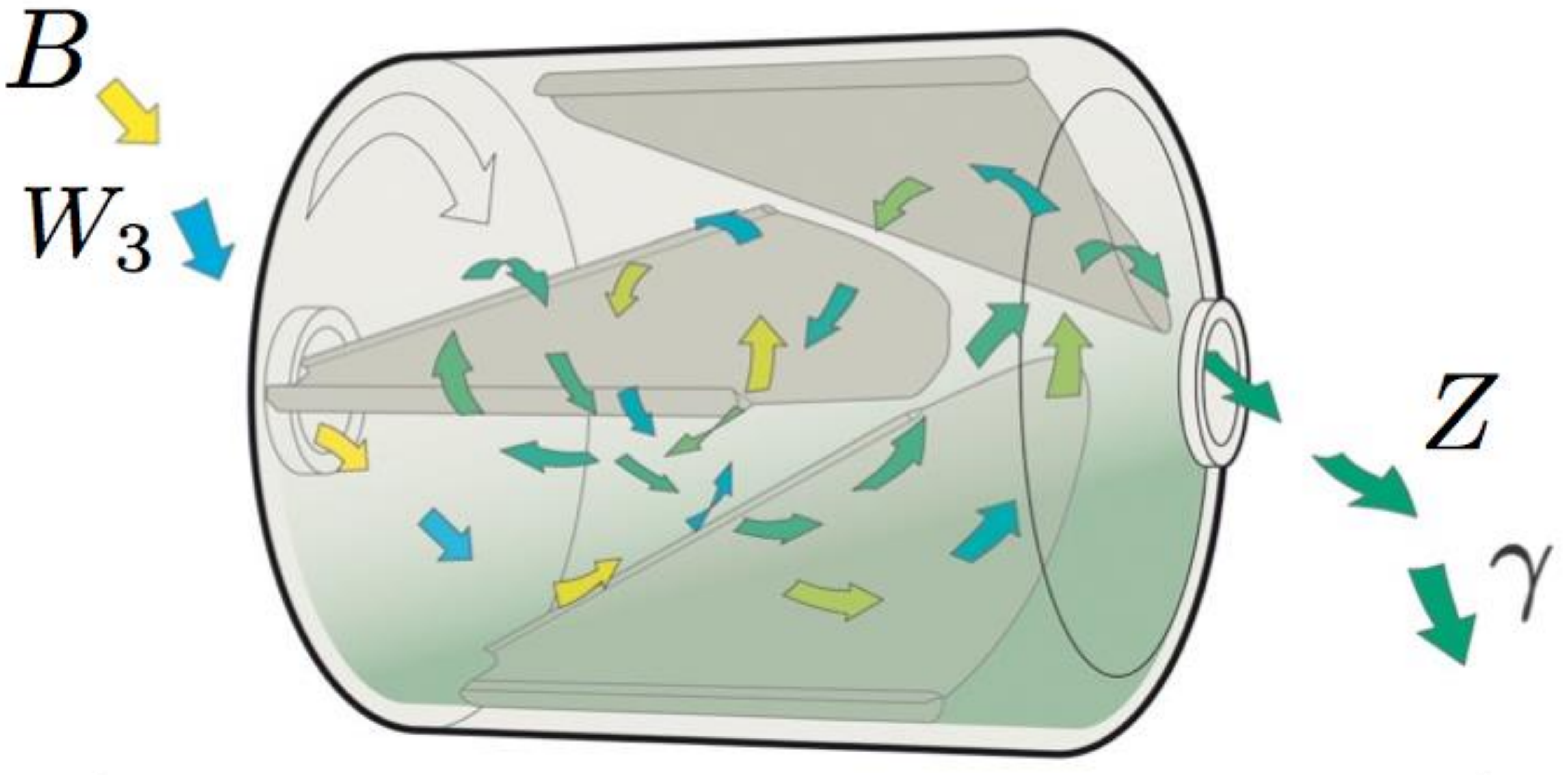

Abdus Salam


Sheldon Glashow

- The corresponding gauge symmetry gives a new gauge particle, very similar to the photon, the “B boson”

Electroweak unification

- The new B boson has no electric charge, and mixes with the weak boson W^3



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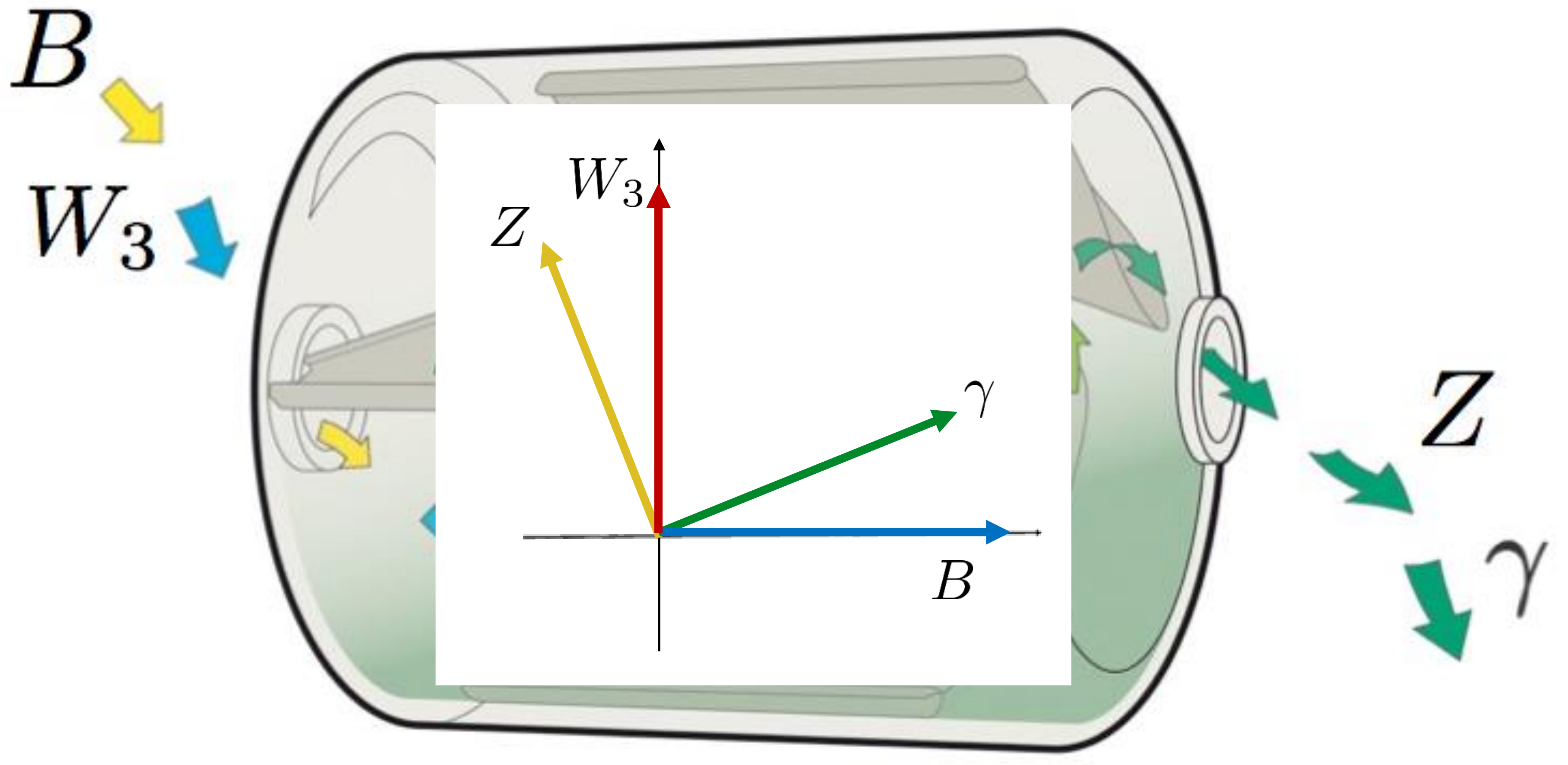
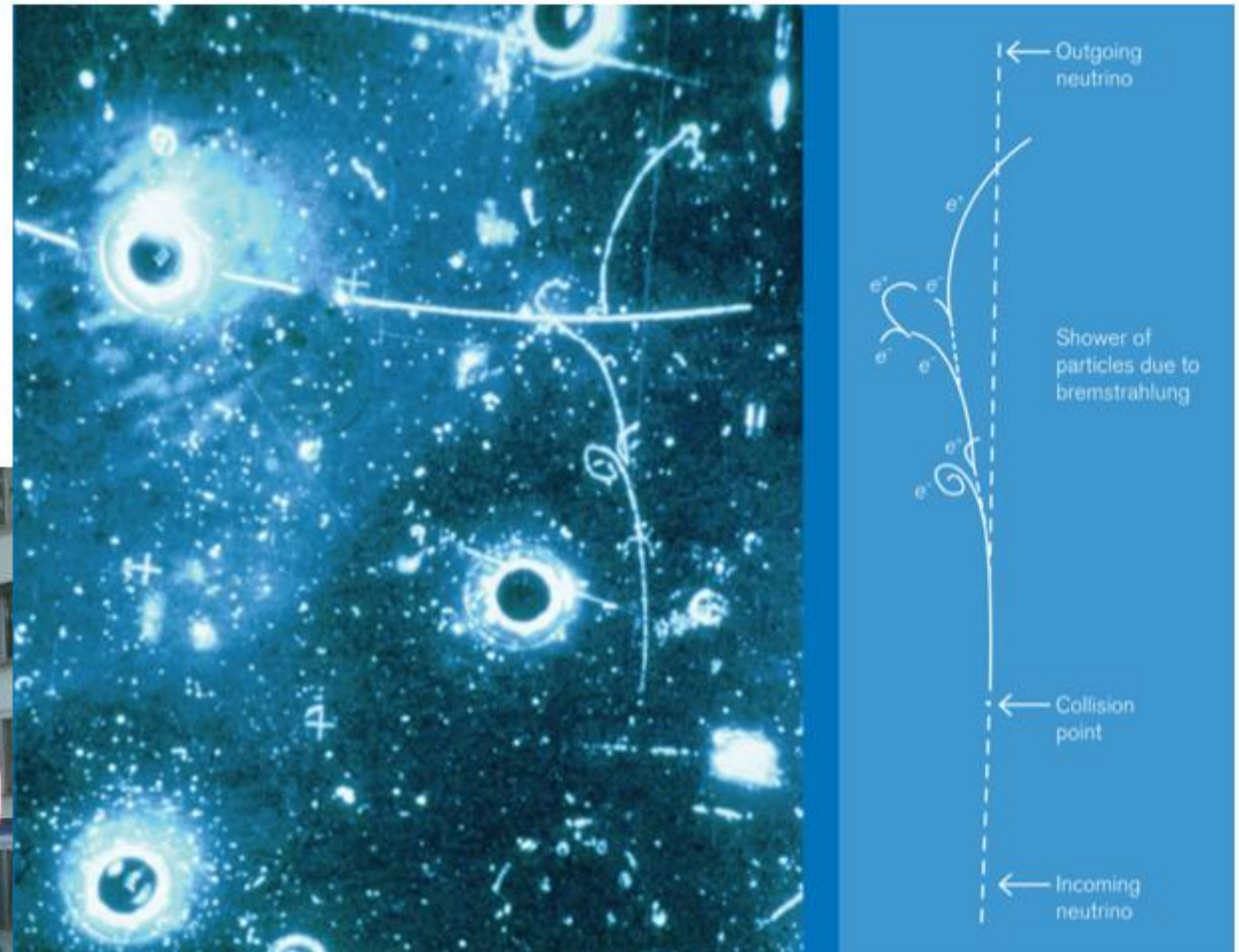


- The result of the mixing is the photon, and another electrically neutral particle, the Z boson

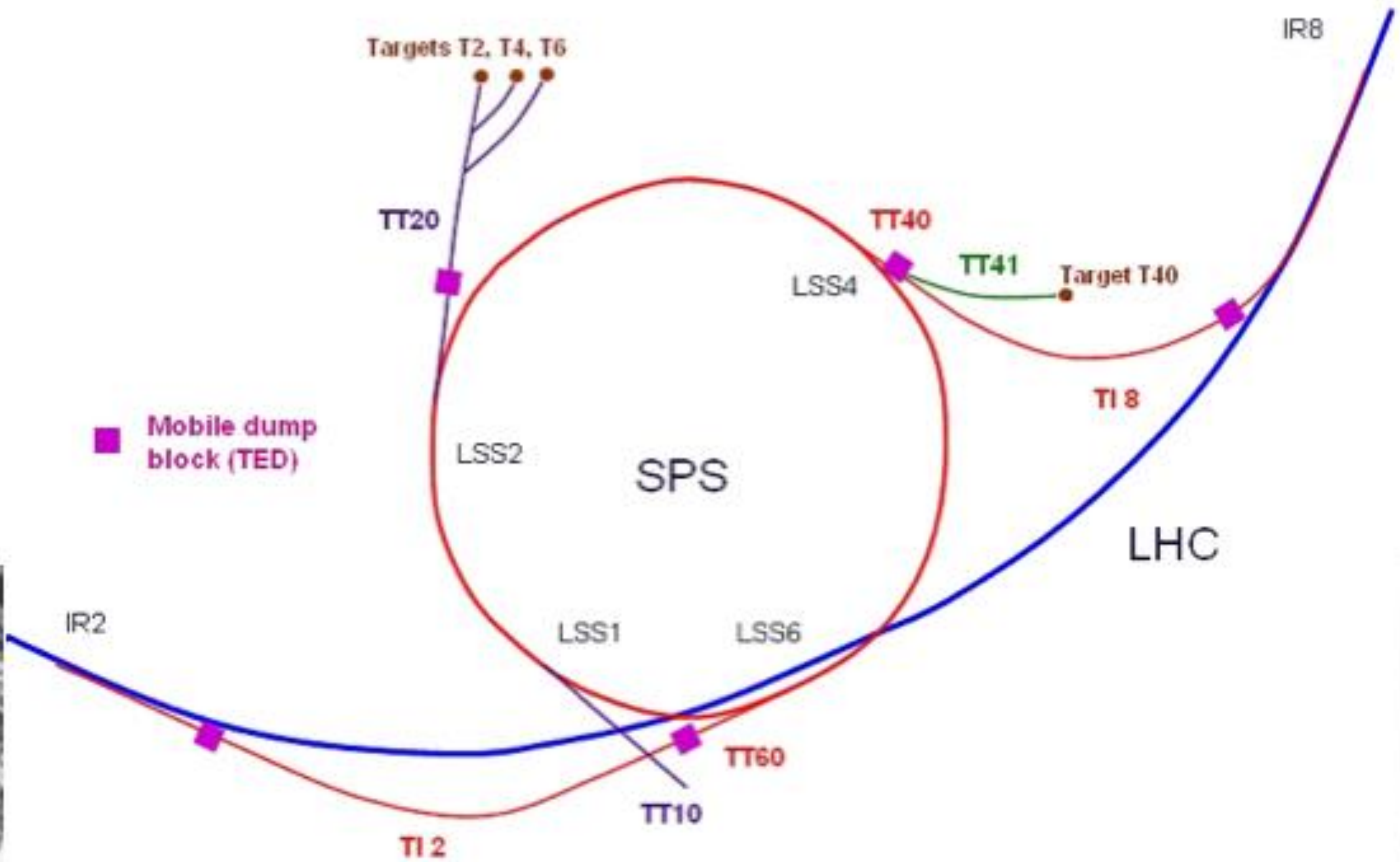
Neutral currents

- Interactions of particles mediated by the Z boson (a.k.a. neutral currents) have been discovered by the Gargamelle experiment in 1973



Production of Z and W bosons

- Ten years later, in 1983, W and Z bosons were actually produced at CERN



Carlo Rubbia

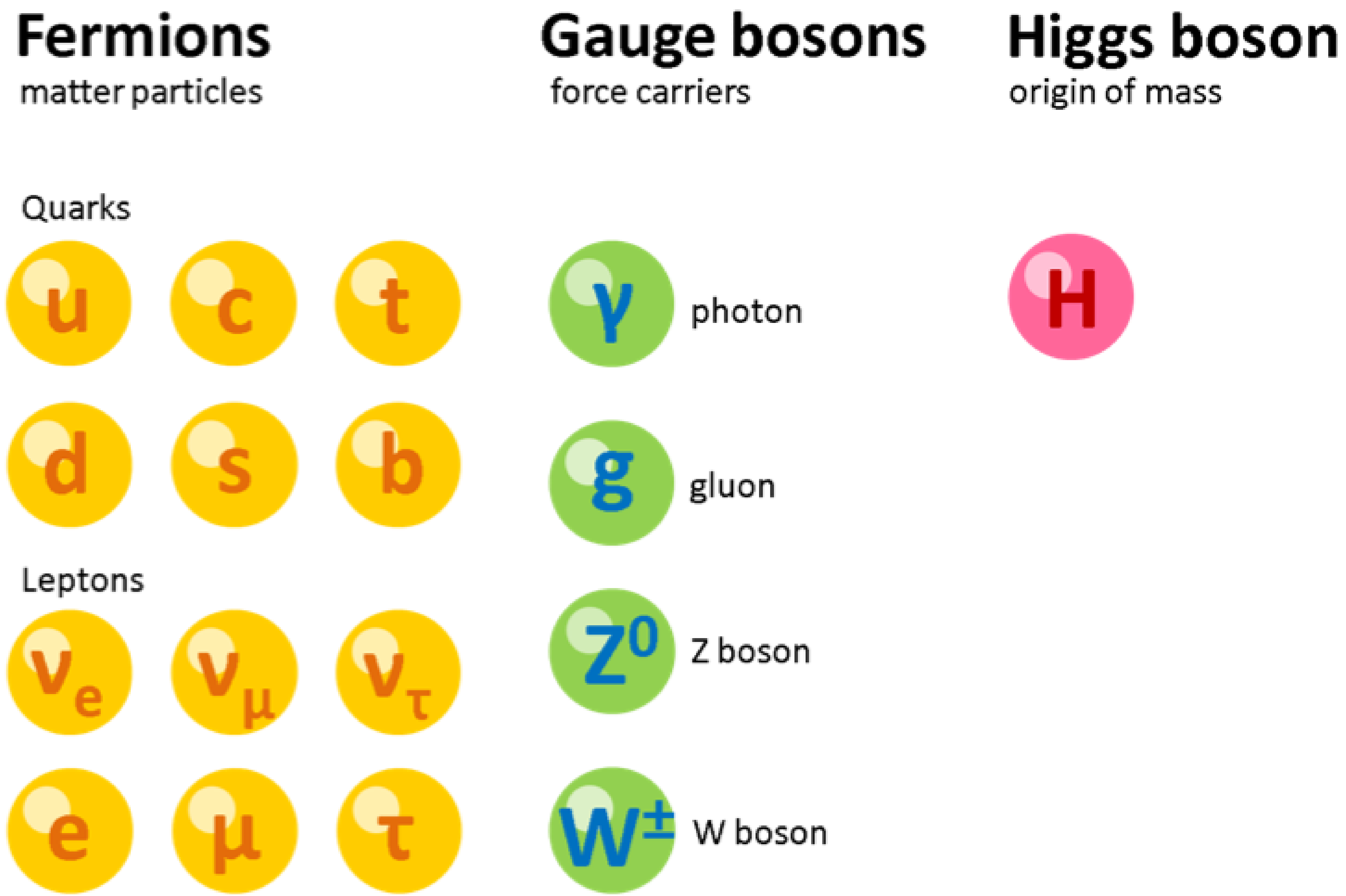
Simon van der Meer

SPS vs LHC


Mont Blanc (4,808m)
Geneva (pop. 190'000)
Lake Geneva (310m deep)
LHCb
ATLAS
CERN
CERN
ALICE
CMS
SUISSE
FRANCE
Andrzej Nowak - Collaboration, Big Data and the search for the Higgs Boson

The Standard Model

- All particles and forces described so far build up the Standard Model of elementary particles



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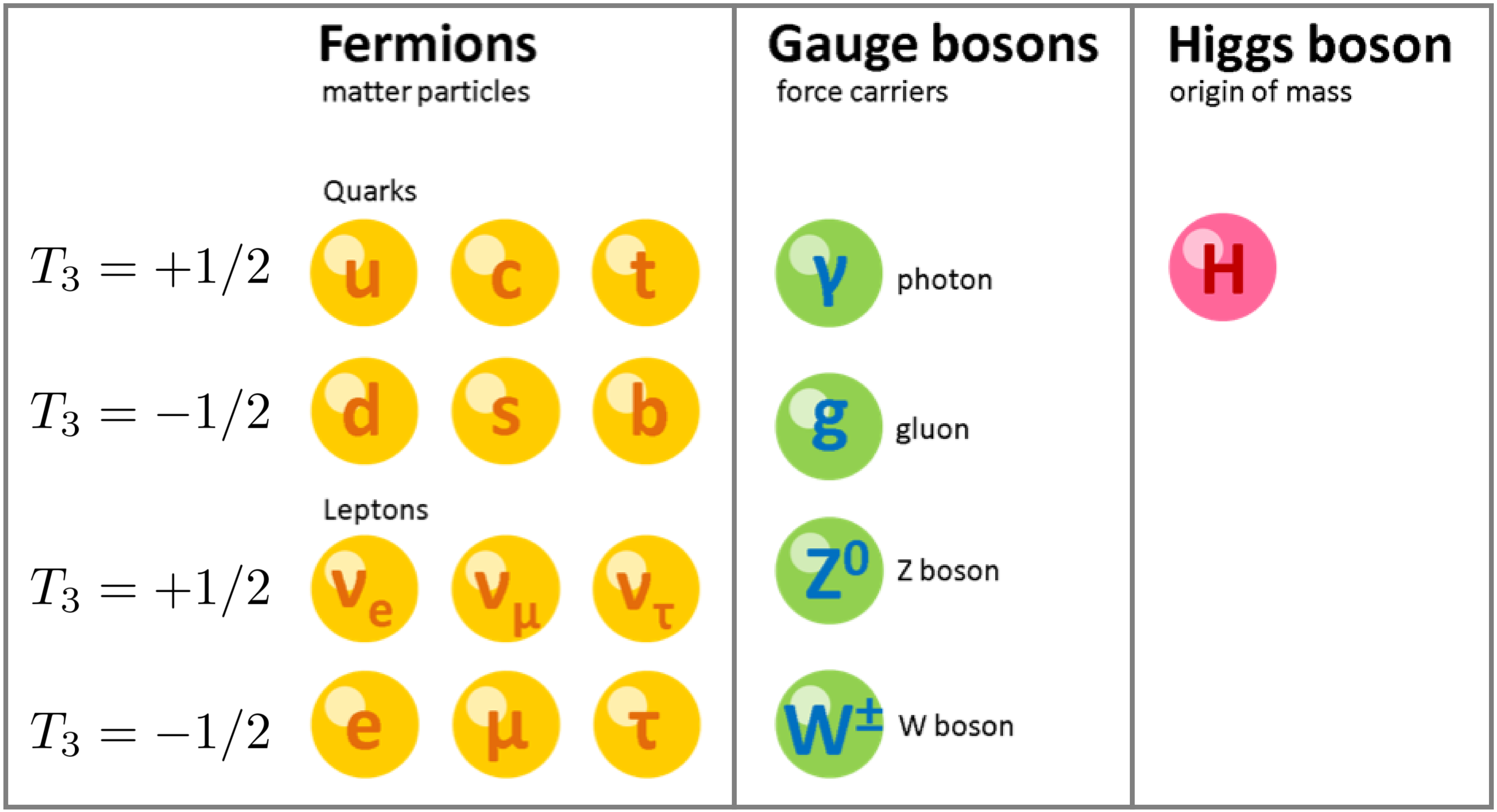


Why do theoretical physicists love gauge theories?

The path to a successful theory

- Consider all the symmetries the theory should have
- Write the most general theory (action) compatible with those symmetries
- If you are lucky enough, the resulting theory is predictive, with a finite number of parameters you can predict the value of any physical observable

Richard Feynman

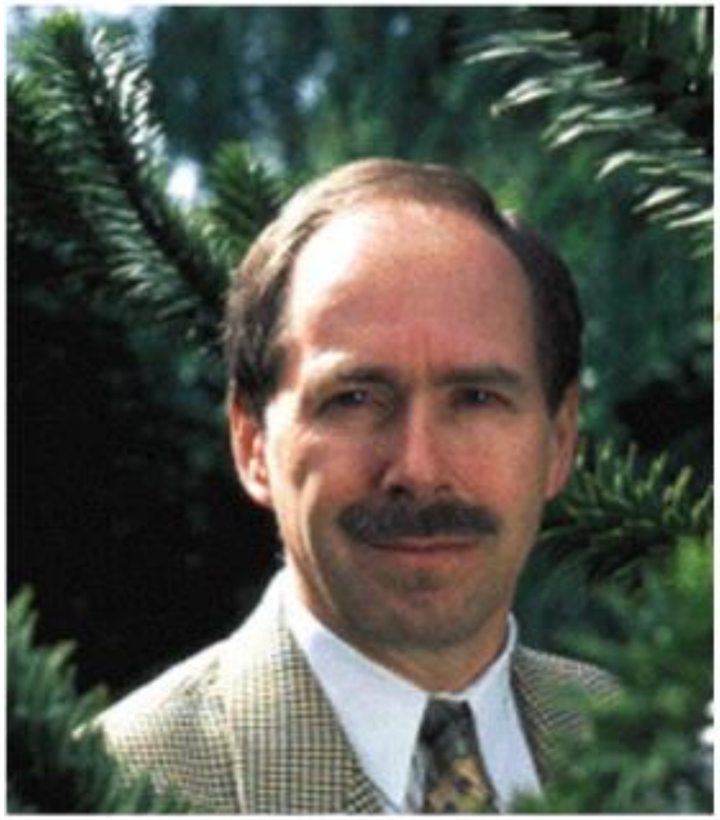
Julian Schwinger

Sin-Itiro Tomonaga

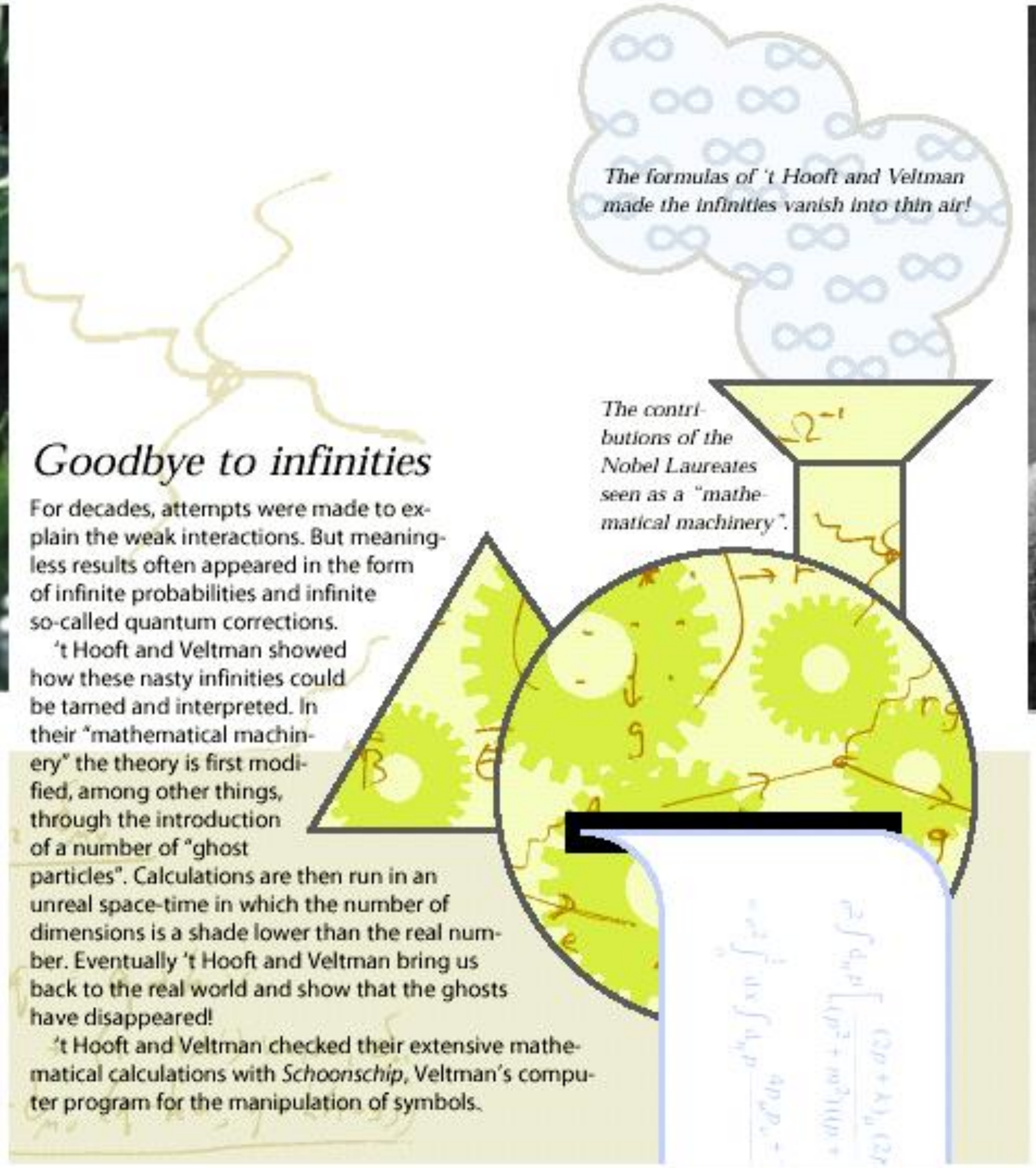
- Example: given the mass and the charge of the electron you can explain all phenomena related to electromagnetism

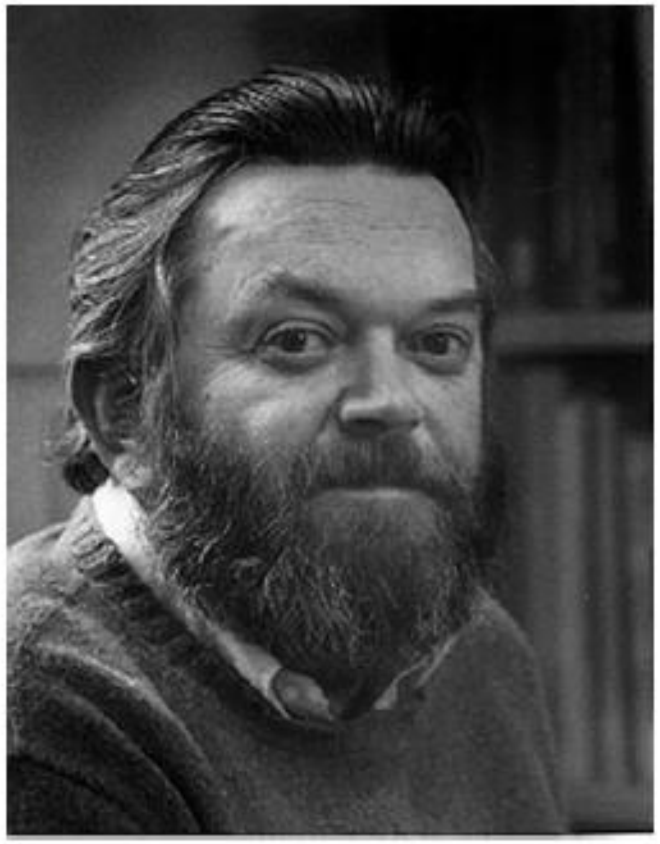
Gauge theories are predictive

- Gauging an internal symmetry gives always a predictive theory: only a finite number of parameters are needed to compute any physical quantity



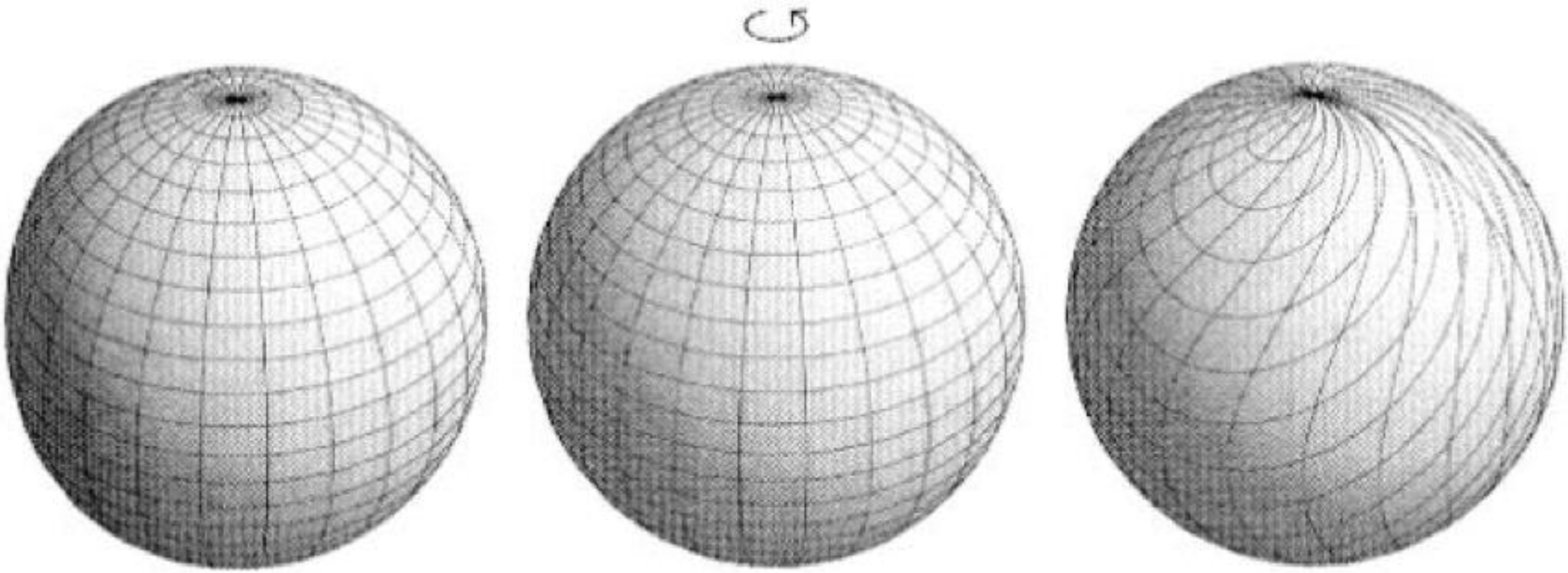
Gerard t'Hooft



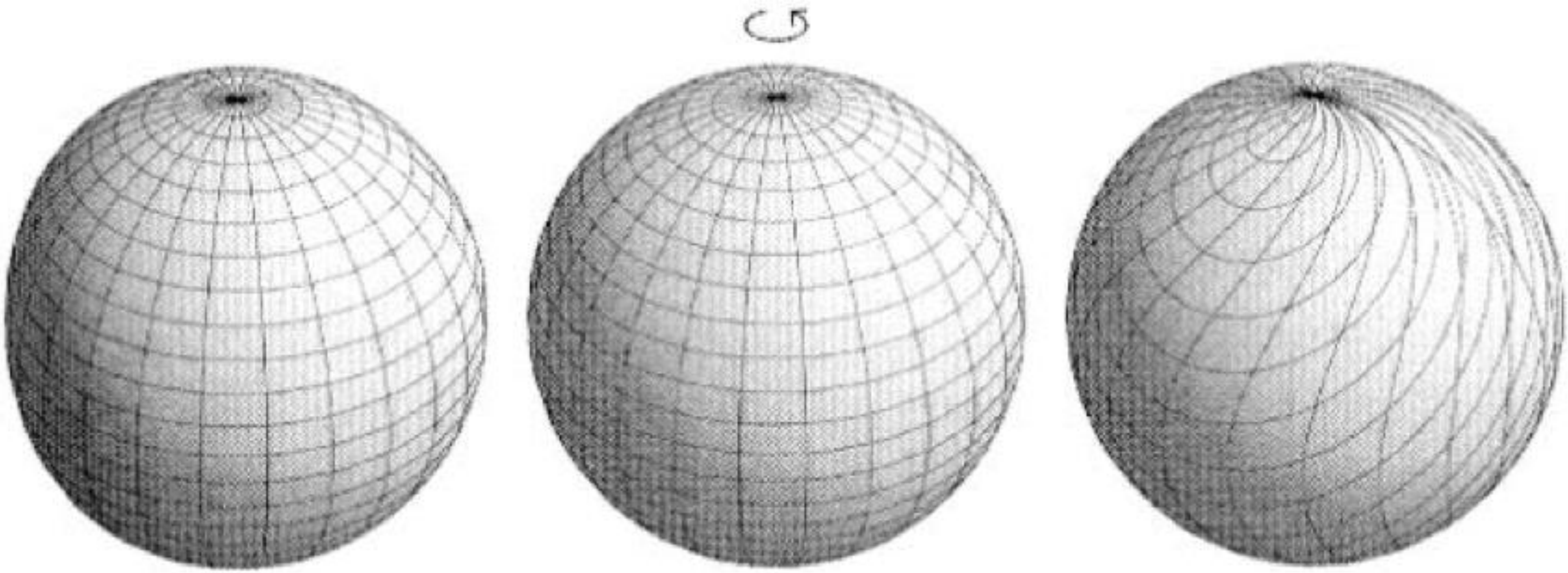


Martinus Veltman

Gauge transformations of space-time



Gauge transformations of space-time



Gauge symmetries of space-time ⇒ gravity!

Level
4

Lecture 3: learning outcomes

In this lecture, we have learnt

- What an elementary particle is
- What gauge bosons are and their role in interactions
- How gauge symmetries give us the strong and electroweak force
- The role of gauge symmetries in theoretical physics