What is a Higgs boson, and why do we study it?

Johannes Braathen (DESY)

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Emmy Noether-Programm
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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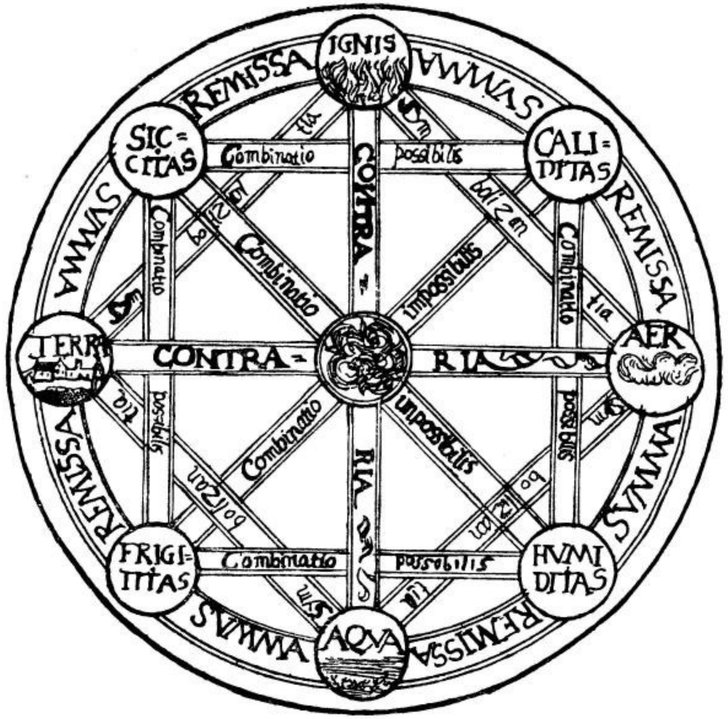
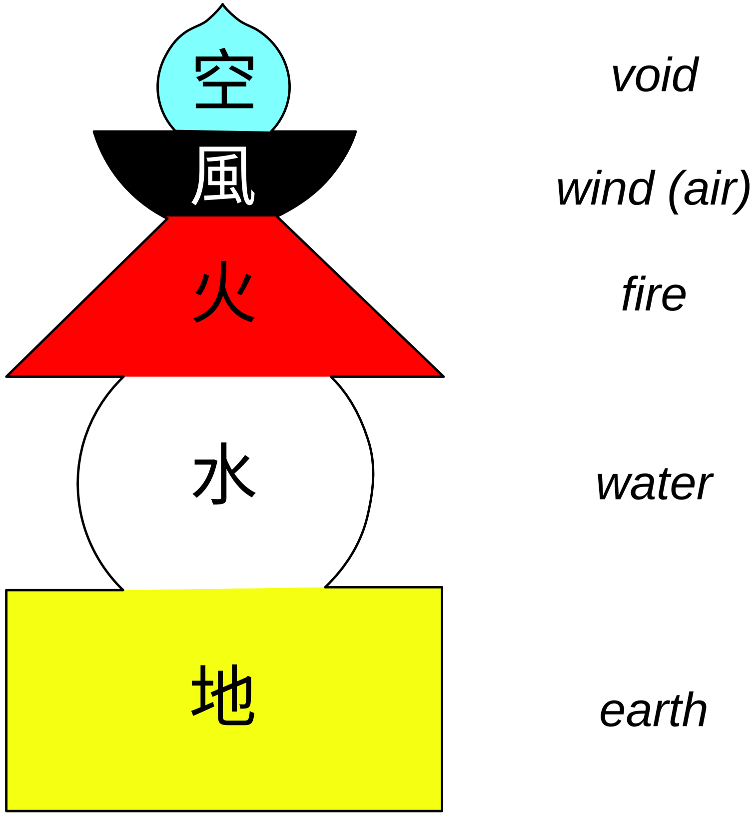
  - → 4 (or 5) ***classical elements***: earth / fire / air / water / (void)
  - → From Greek: "atomos" = uncuttable

Example 1:
Classical Greek elements
(here in drawing by Leibnitz)



Example 2:
"Godai" (五大)
in Japan



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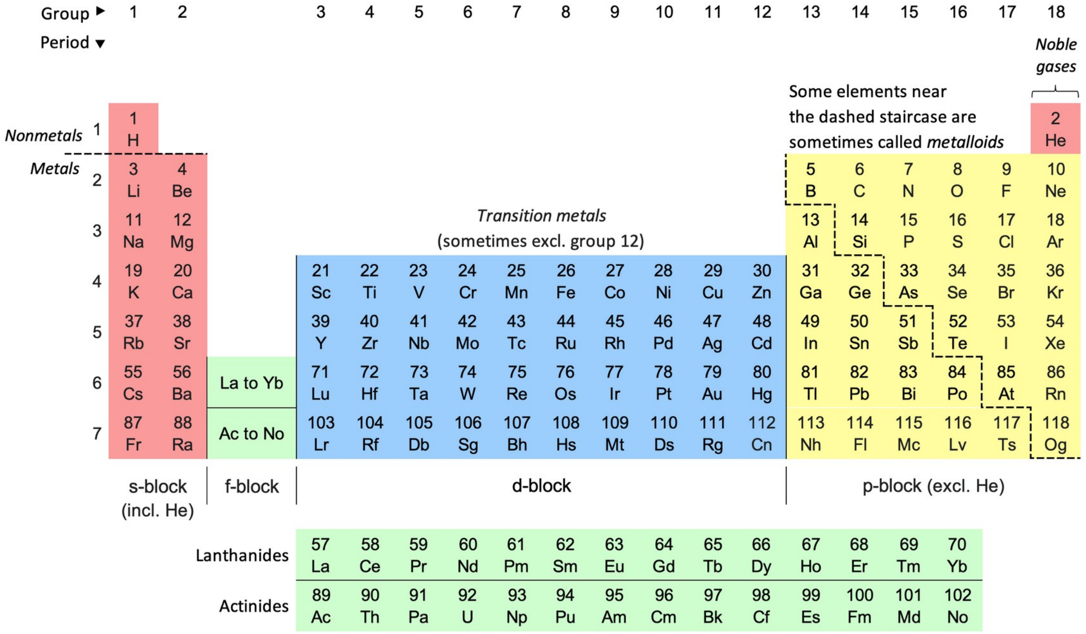
- XVIIIth/XIXth centuries: advent of chemistry
  - → discovery of ***chemical elements*** → now ~120 known, 94 occur in Nature
  - → classified in ***periodic table of elements*** [Mendeleev 1869]



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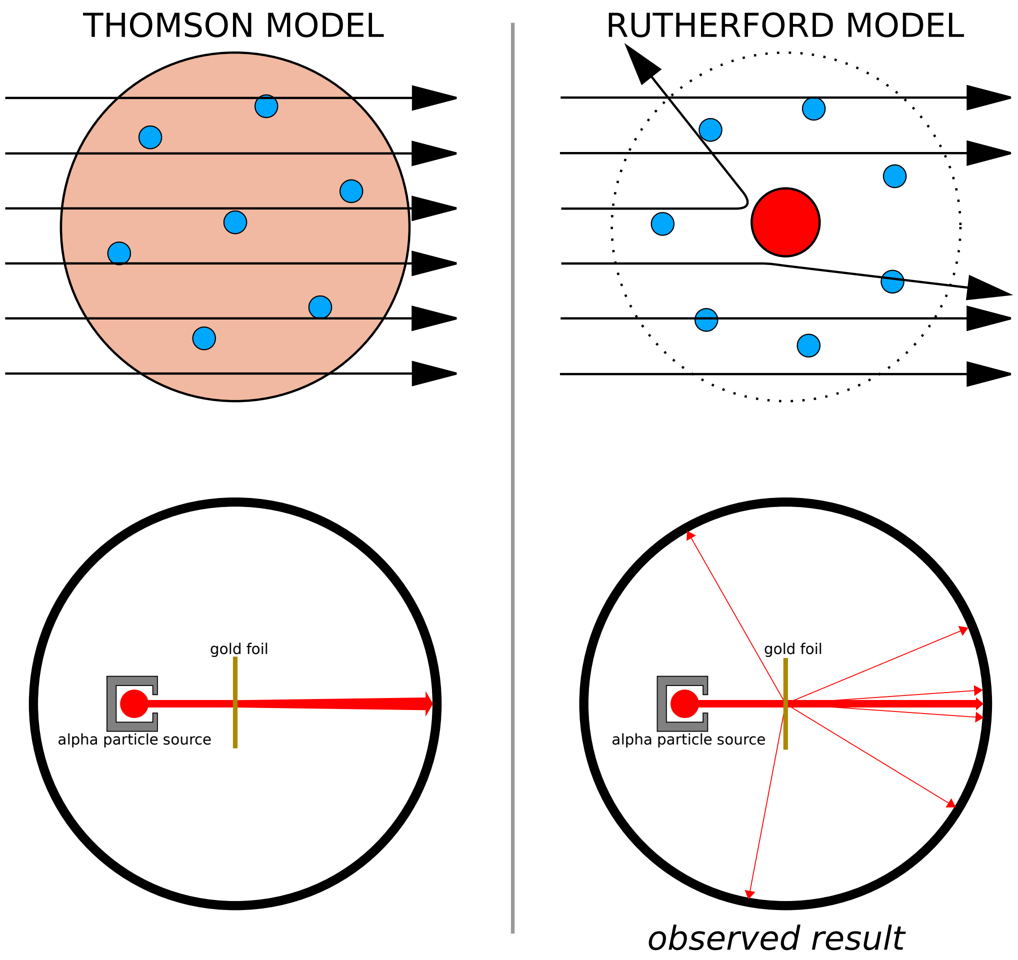
- End of XIXth/beginning of XXth century: birth of atomic theory
  - → discovery of ***electron*** (1st known subatomic particle) [Thomson 1897]
  - → discovery of ***atomic nucleus***, e.g. [Rutherford experiments 1908-1913]



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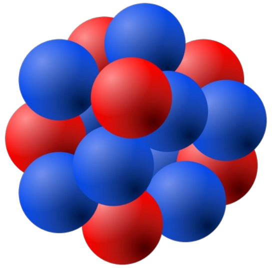

Atomic nucleus, made of protons and neutrons

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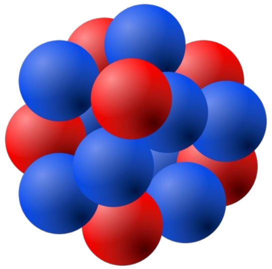
  → atomic nuclei made of ***protons*** [Rutherford 1917-1920] and ***neutrons*** [Chadwick 1932]
  → zoo of subatomic particles ("*baryons*" and "*mesons*") discovered in 1940's and 1950's in cosmic rays
  → understood to be made of ***quarks*** – theorised by [Gell-Mann 1964] and [Zweig 1964], first types discovered at SLAC in 1968



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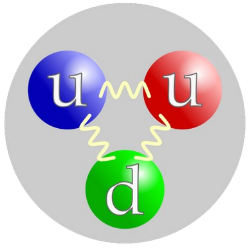
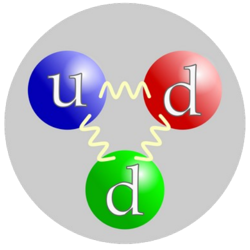
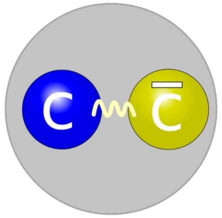


Proton = 3 quarks u, u, d

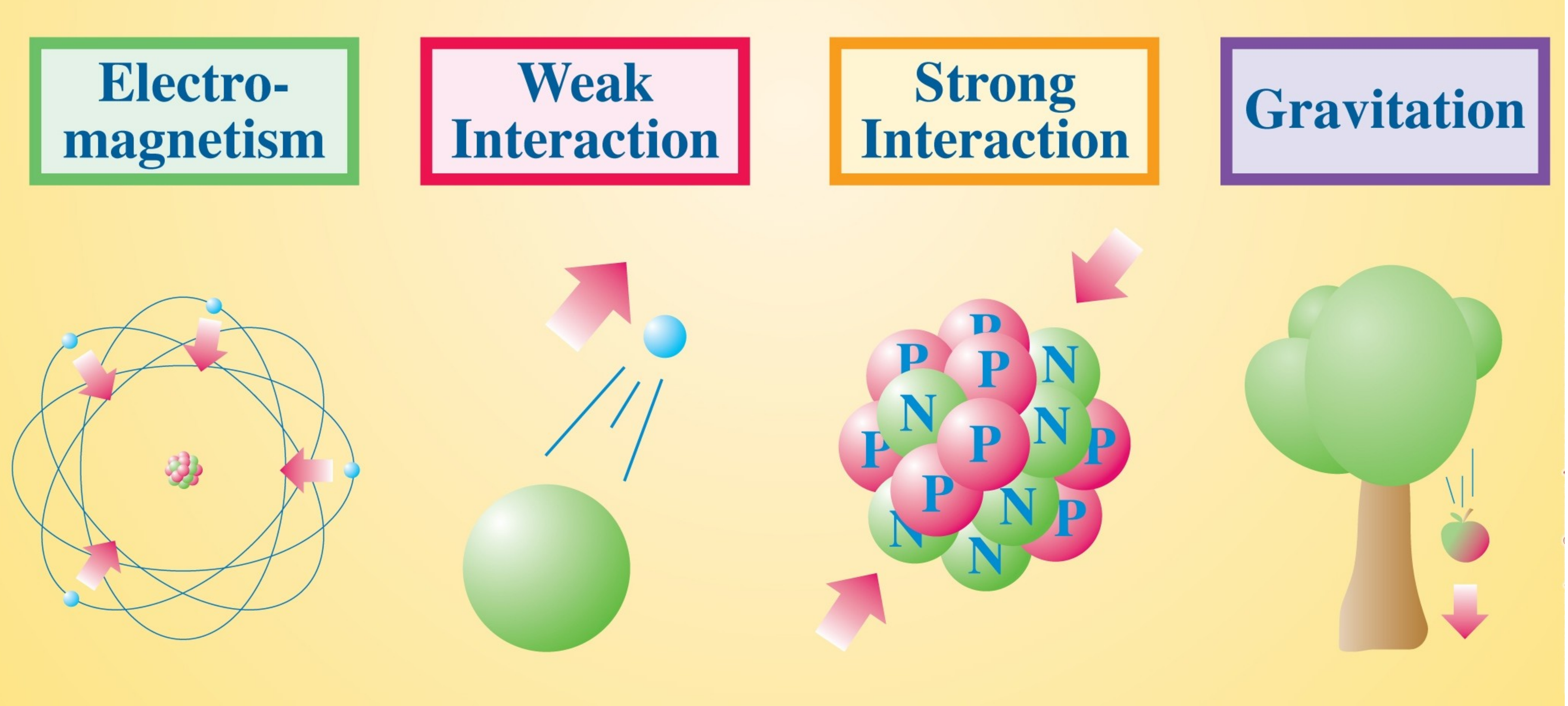


Neutron = 3 quarks u, d, d



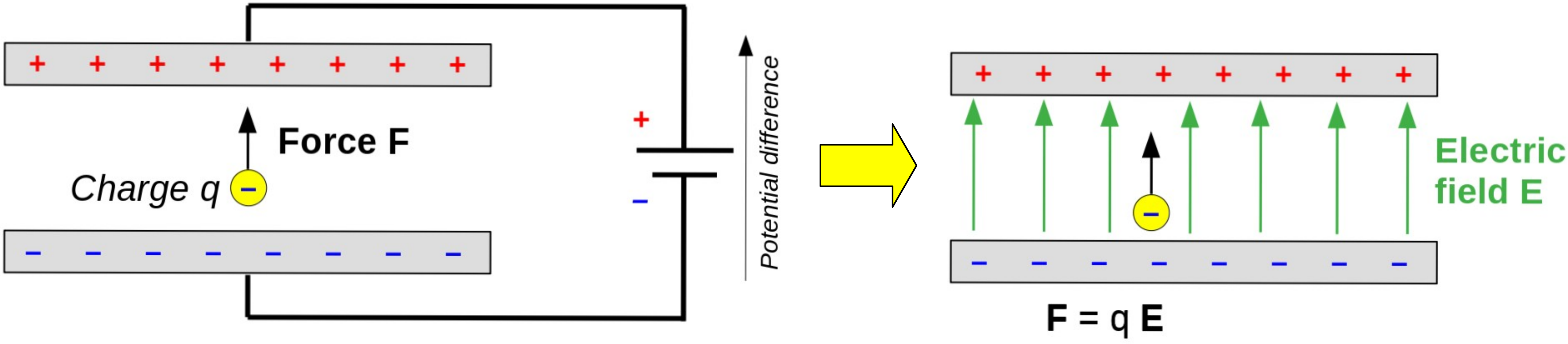
A meson (here J/ψ = quark c + antiquark $\bar{c}$)

Four fundamental interactions



Forces, fields, and particles

- Forces are described via “fields,” e.g. electric field:

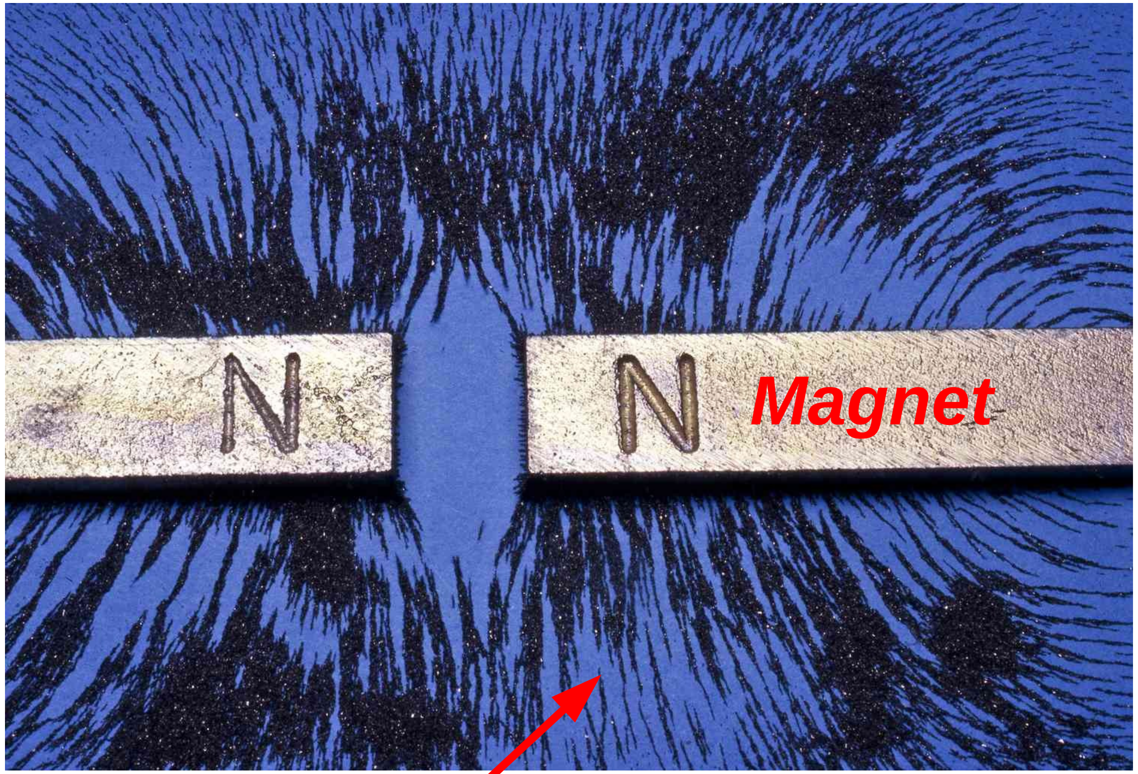


- Force **F** and electric field **E** are related: **F** = q **E**

- Electric charge q = how much a particle interacts with the electric field

Forces, fields, and particles

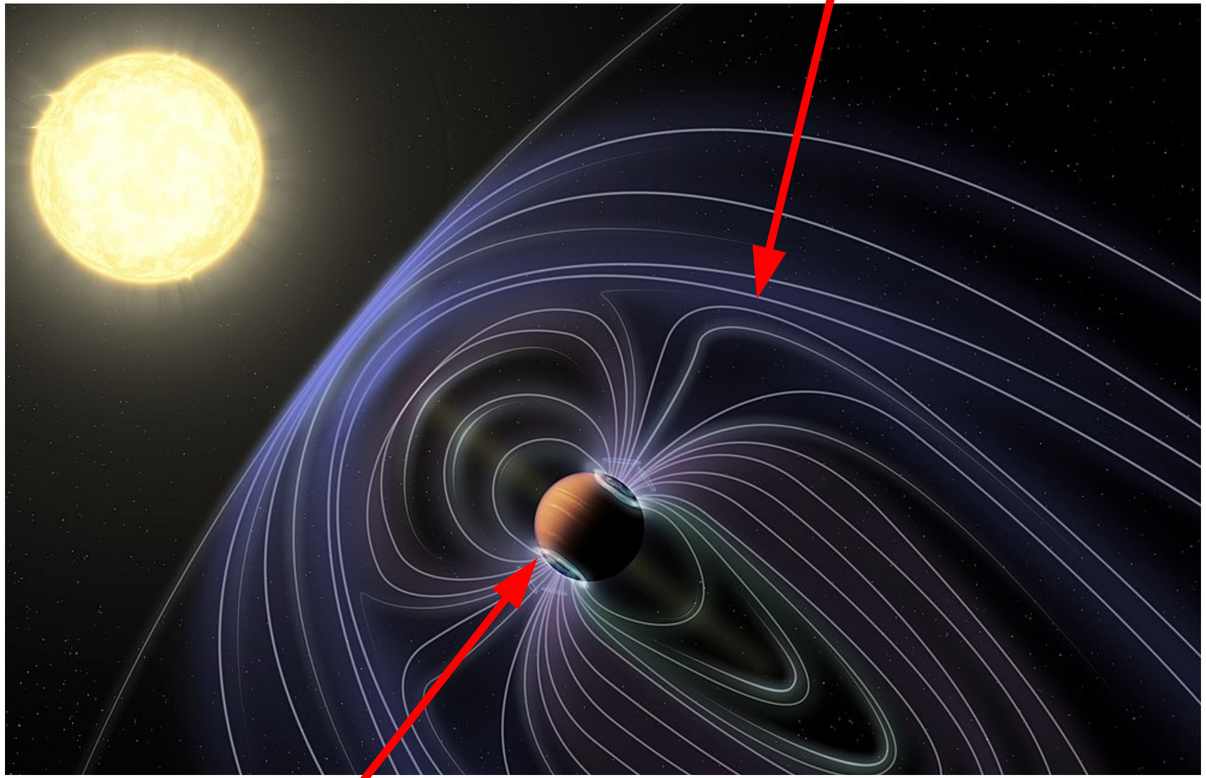
- Field lines can be visualised, e.g. with magnetic field



[Figure source]

Magnetite powder, following magnetic field lines

Magnetosphere

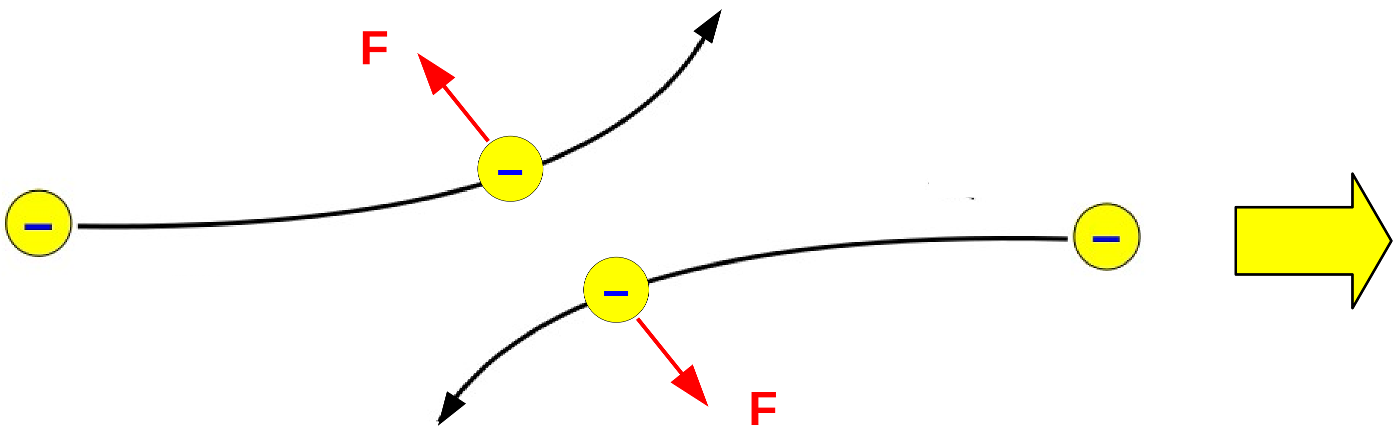


Aurora

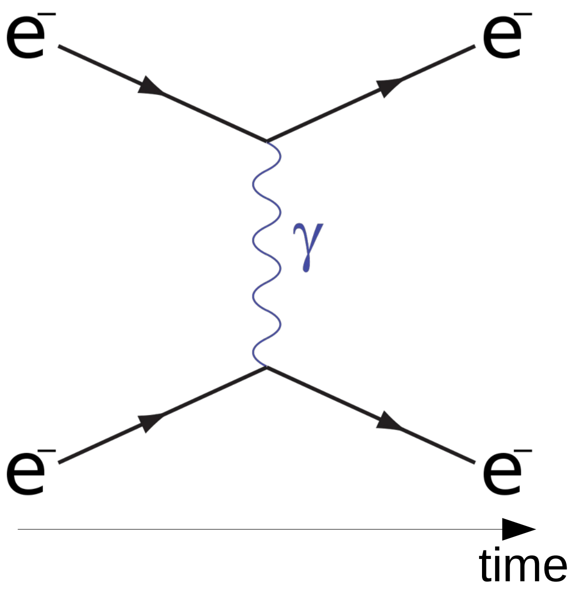
[Figure source]

Forces, fields, and particles

- Mathematical language of Particle Physics = **Quantum Field Theory**
  → fields are "***quantised***"
- Quanta of a field = particle
- E.g. a quanta of the electromagnetic field is a photon ("light particle")

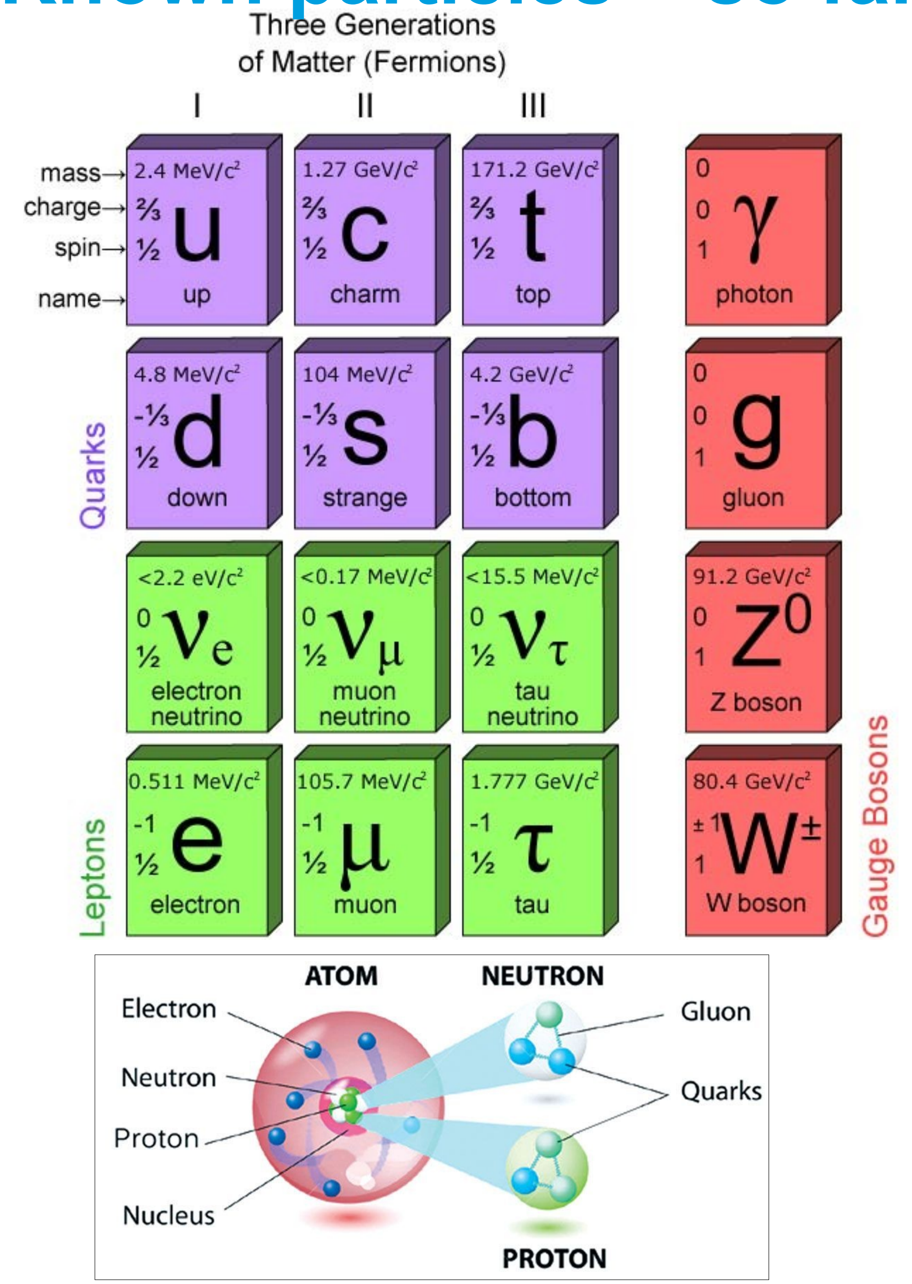


Two electrons repulse each other via electromagnetic interaction



Feynman diagram for this process, force (repulsion) mediated by exchange of photon

Known particles – so far



- **Force mediators = gauge bosons**
  - electromagnetic (EM) interactions → ***photons***

  - strong interactions → ***gluons***
  → **discovered here in HH at DESY's PETRA collider!**

  - weak interactions → ***W and Z bosons***

- **Matter = fermions (quarks and leptons)**
  - ***leptons***: electron, muon, tau, neutrinos
  → sensitive to EM and weak forces only

  - ***quarks***: making up baryons (proton, neutron, etc.) and mesons
  → sensitive to strong, EM, weak forces

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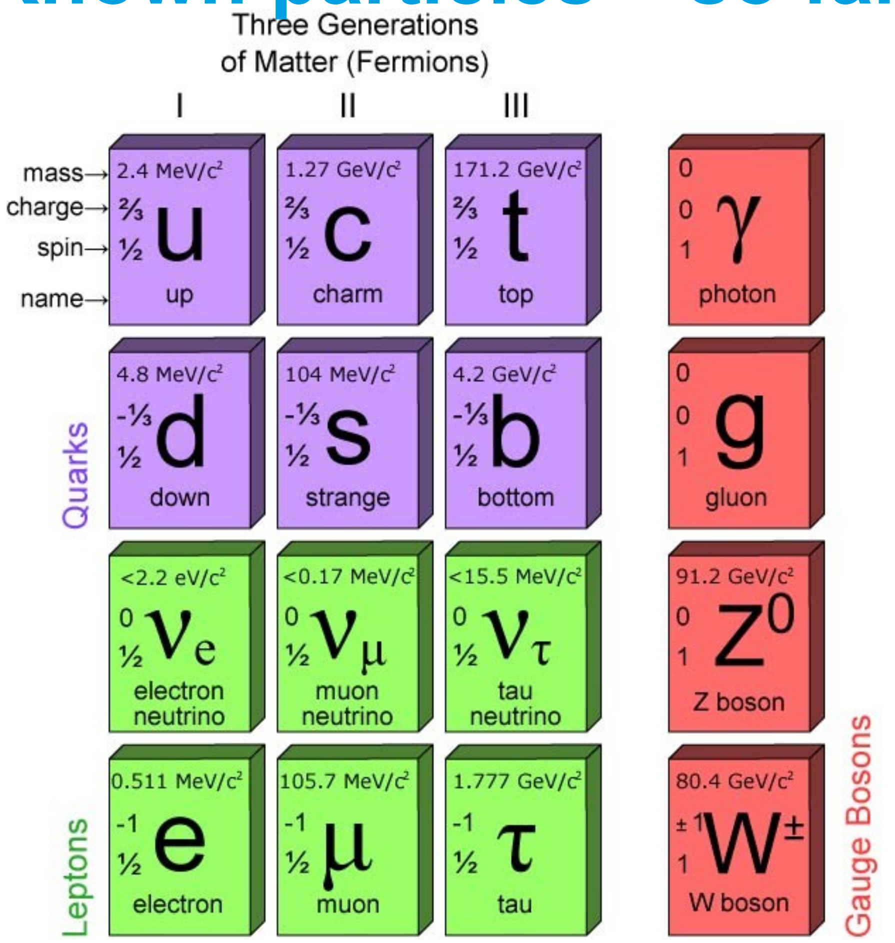

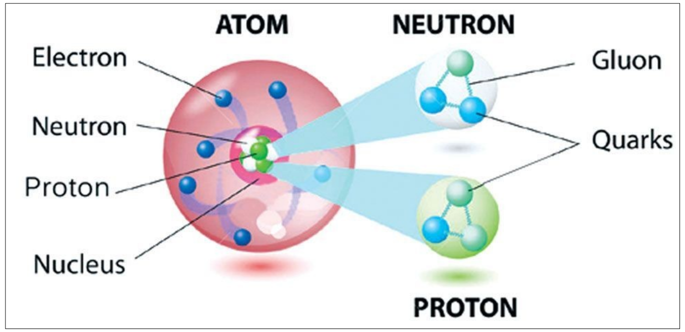

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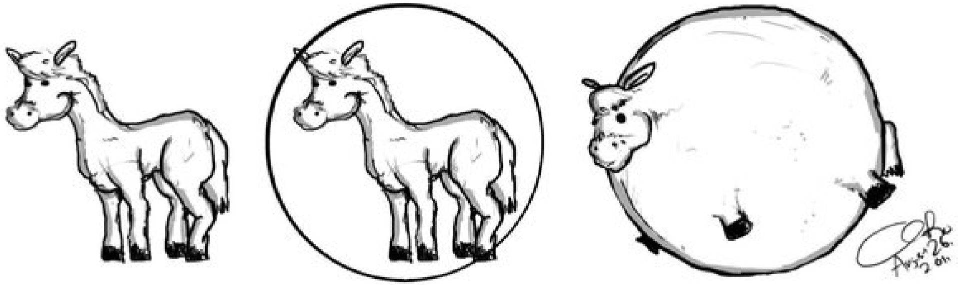
- One more particle: the Higgs boson

Symmetries and masses of elementary particles

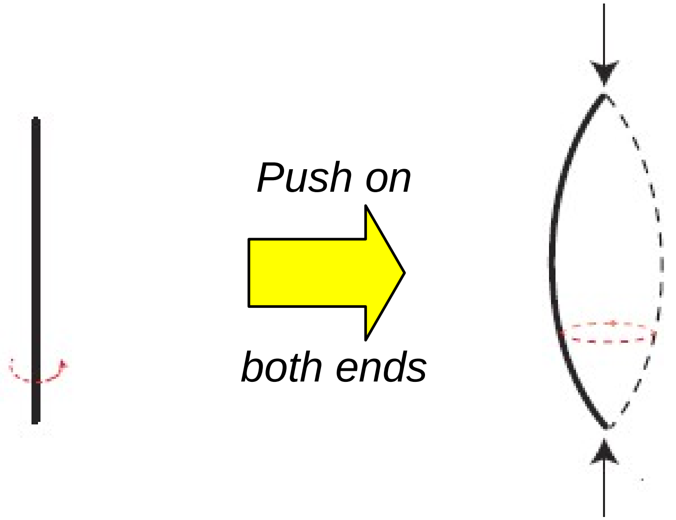


- Symmetries (exact or approximate) play a central role in how we construct **theories** to describe Nature
- E.g., space-time symmetries: the laws of Nature are the same at any point of space and time
- **Problem**: fundamental symmetry of theory in particle physics does not allow masses for particles
- However, **most elementary particles** (except photons and gluons) **have a mass**
  - E.g. electron: 511 keV/c^2 ~ 9.11 x 10^{-31} kg
    If the electron had no mass, it would fly at the speed of light → no atoms, no electricity, no chemistry...
  - Weak interactions have a very short range (~10^{-15} m), as opposed to electromagnetism
    → W and Z bosons (mediators of weak interactions) must be massive
- **How can elementary particles obtain masses, without breaking the fundamental symmetry of Nature?**

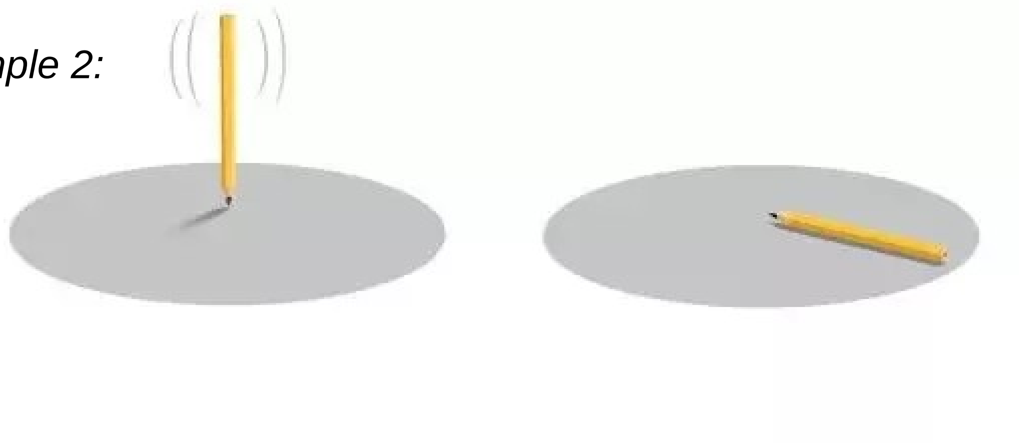
Spontaneous symmetry breaking

- *Idea*: theory preserves the symmetry, but the state of lowest energy does not
  → **spontaneous symmetry breaking**
- Many examples in Nature: ferromagnets, superconductors, daily life, ...

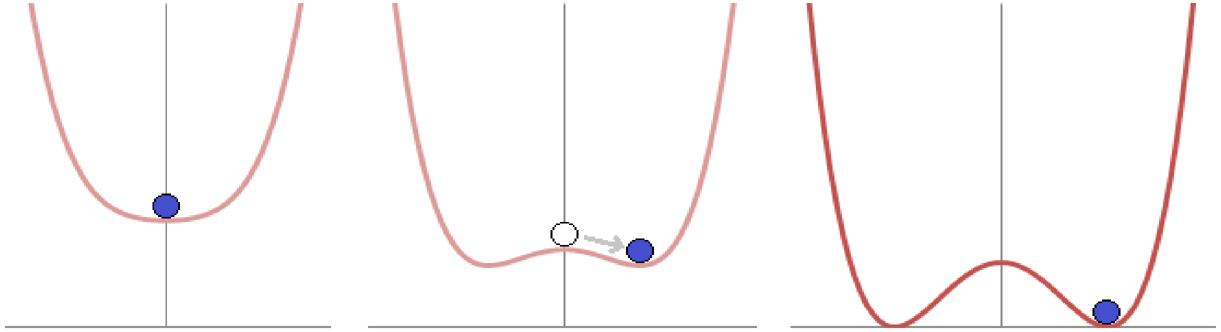
Example 1:



Example 2:

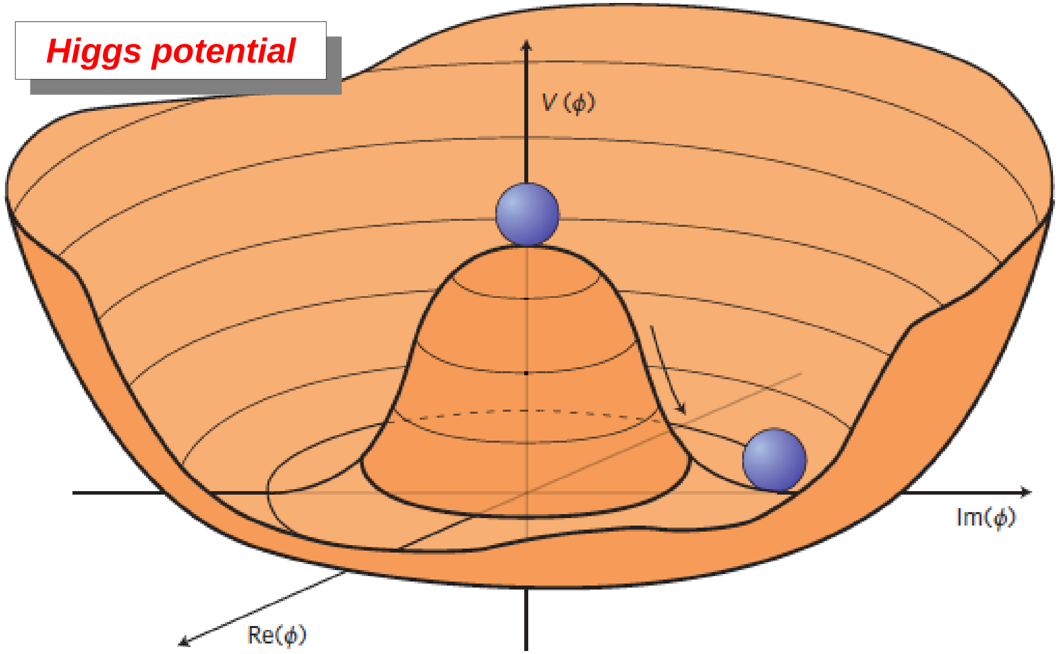


Example 3:



Brout-Englert-Higgs mechanism and the Higgs particle

[Brout, Englert 1964], [Higgs 1964], [Guralnik, Hagen, Kibble 1964], ...



- Introduce a new field, filling all of space: the **Higgs field**
- Give it a particular potential energy
  → Mexican hat/wine bottle shape
- Potential respects symmetry of theory but state of lowest energy, the **vacuum** (in which we live), does not
- Quanta of Higgs field = **Higgs boson**

Brout-Englert-Higgs mechanism

(how particles acquire their masses)

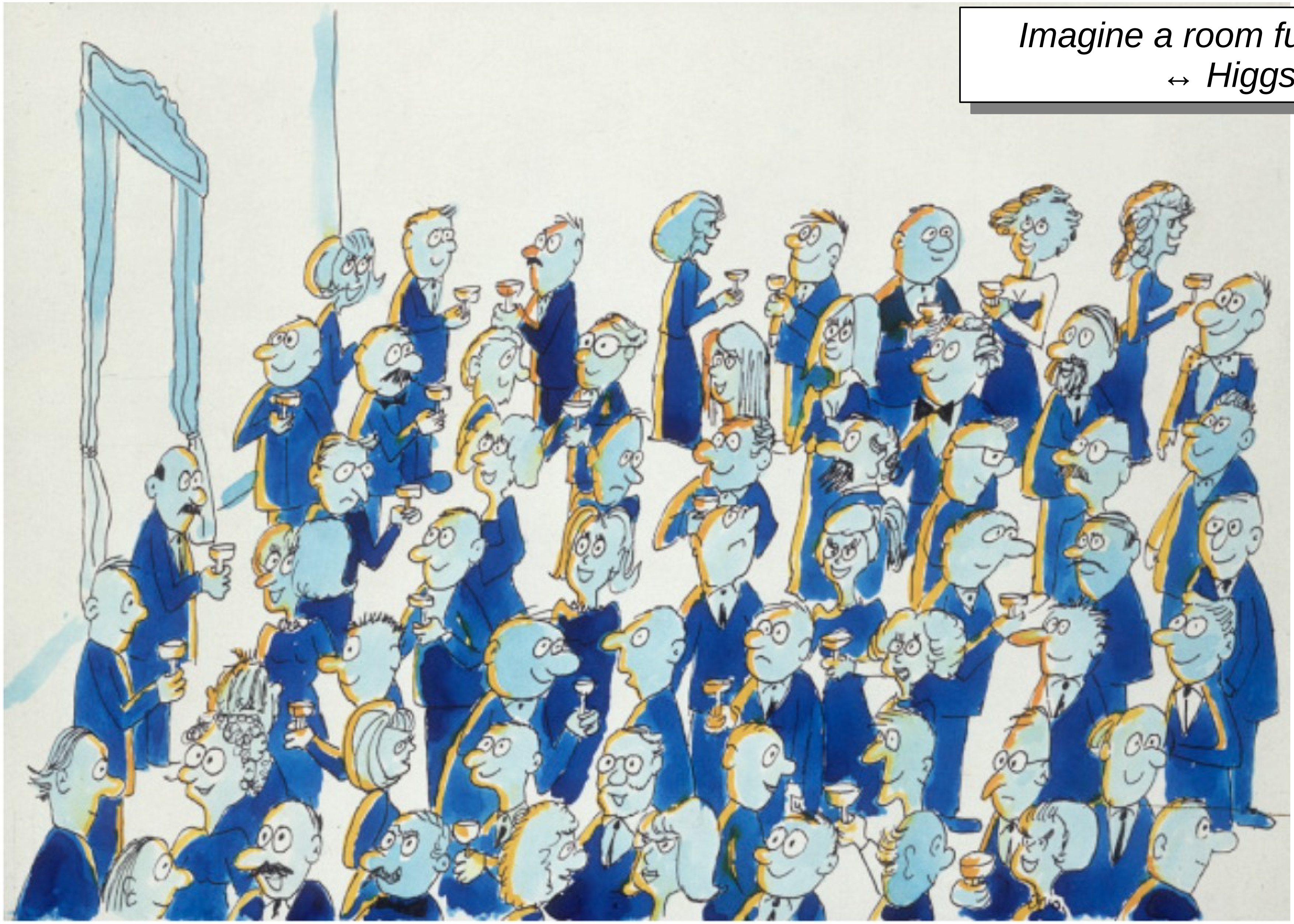
$$m = g\,v$$

Mass of elementary particle

How strongly does the particle interact with the Higgs field

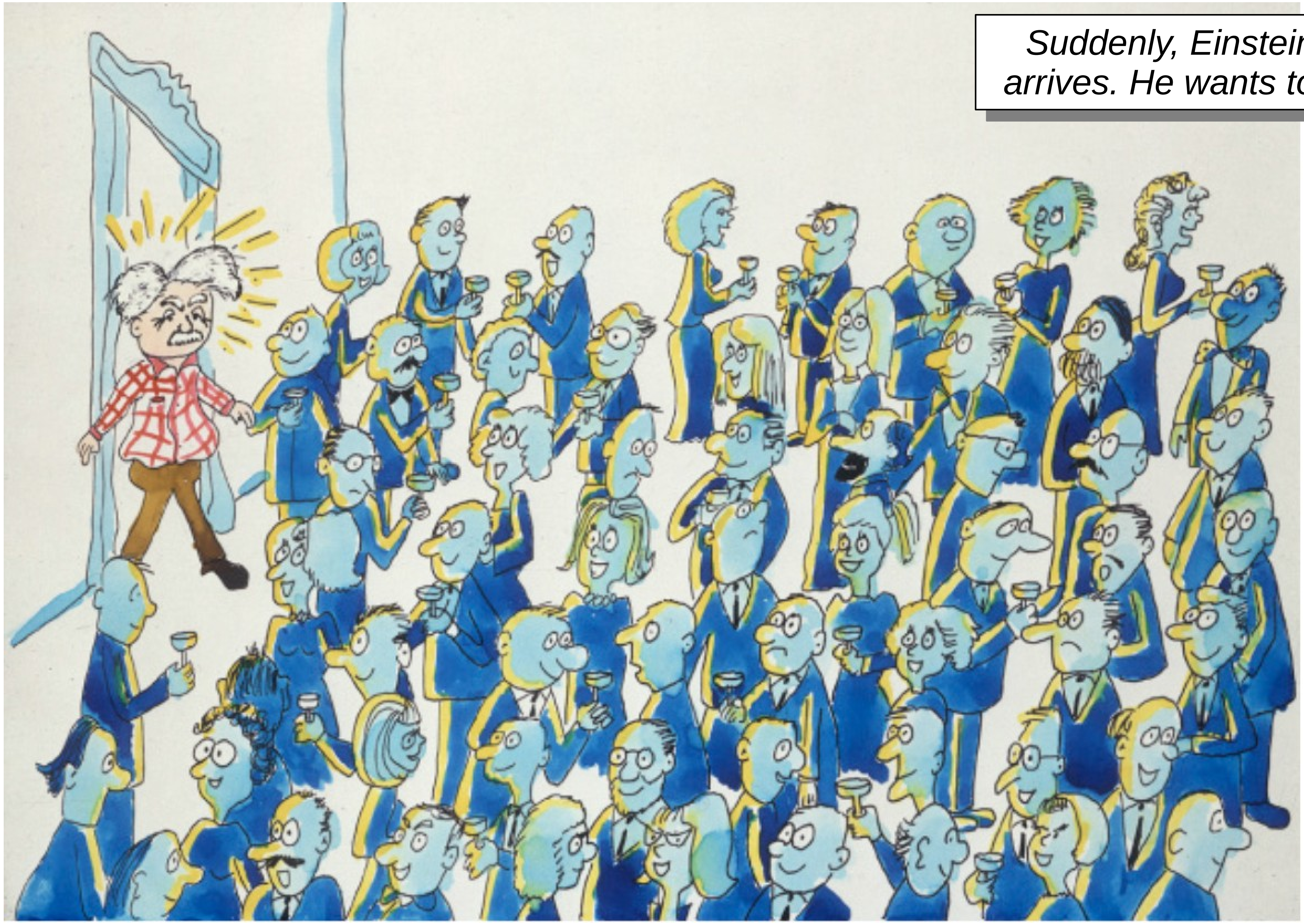
"Higgs vacuum expectation value," i.e. a constant which is a fundamental property of vacuum

Analogy for BEH mechanism 1: a famous scientist in a room



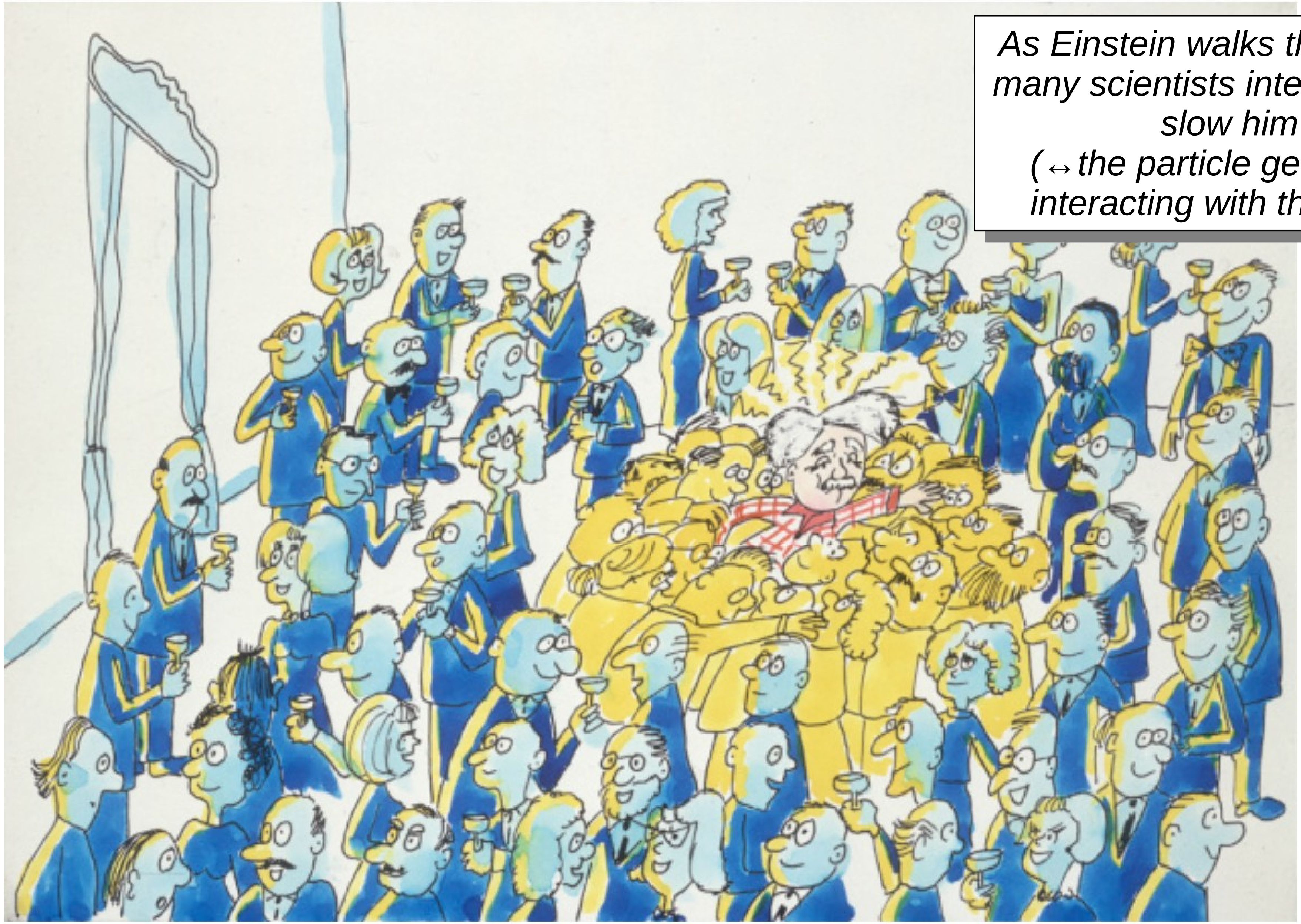
Imagine a room full of scientists
↔ Higgs field

Analogy for BEH mechanism 1: a famous scientist in a room



Suddenly, Einstein (↔ a particle) arrives. He wants to cross the room

Analogy for BEH mechanism 1: a famous scientist in a room



As Einstein walks through the room, many scientists interact with him and slow him down
(↔ the particle gets a mass from interacting with the Higgs field)

Analogy for BEH mechanism 1: a famous scientist in a room

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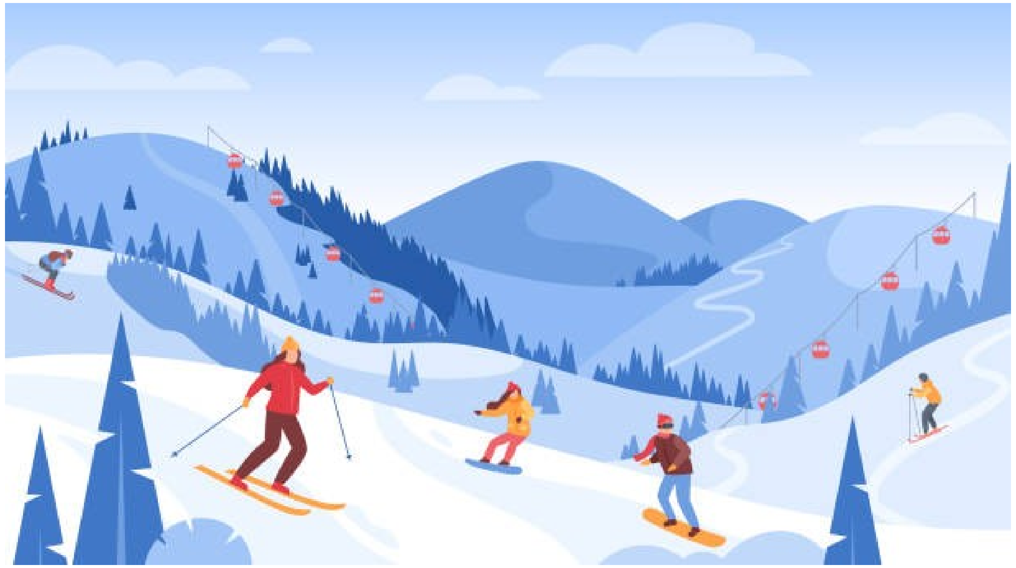
$$m = g\,v$$

How fast Einstein can walk (how "heavy" is he) → m

How famous Einstein is (how strongly the scientists want to interact with him) → g

How many scientists are in the room (if no one, Einstein is never slowed) → v

Analogy for BEH mechanism 2: a trip in the snow



Snow ↔ Higgs field
Person/animal ↔ particle

$$m = g\,v$$

How fast can one go in the snow (light → fast; heavy → slow) → m

How deep does one step in (interact with) the snow → g

How deep is the snow (no snow → no slowdown) → v

Light / fast → *Heavy / slow*

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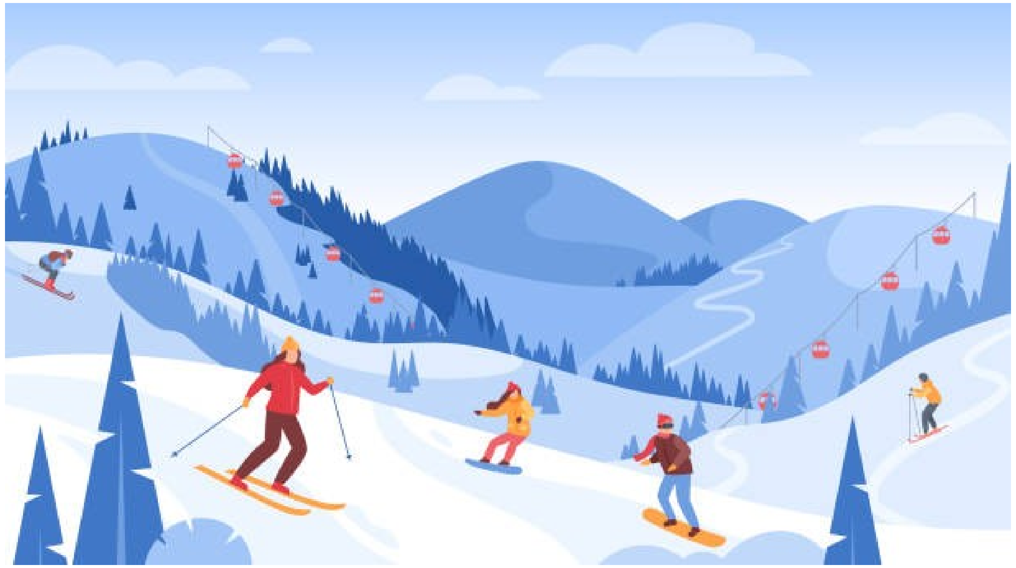

A running moose/elk

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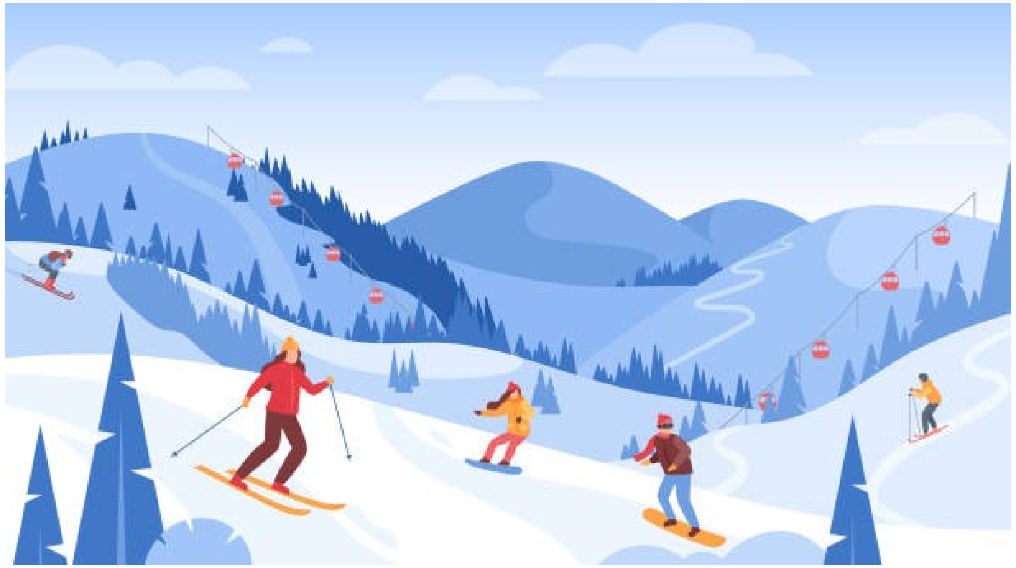

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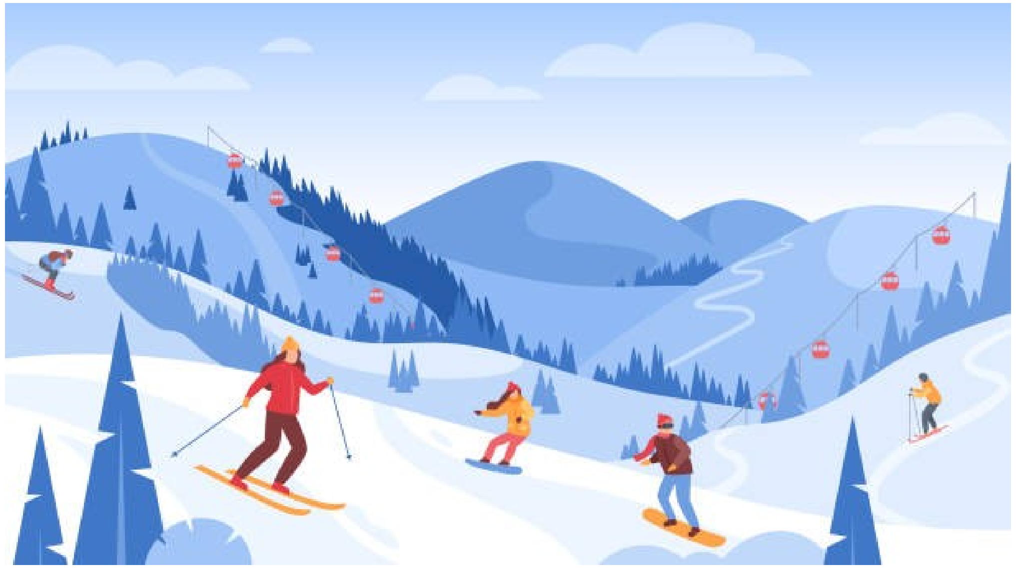

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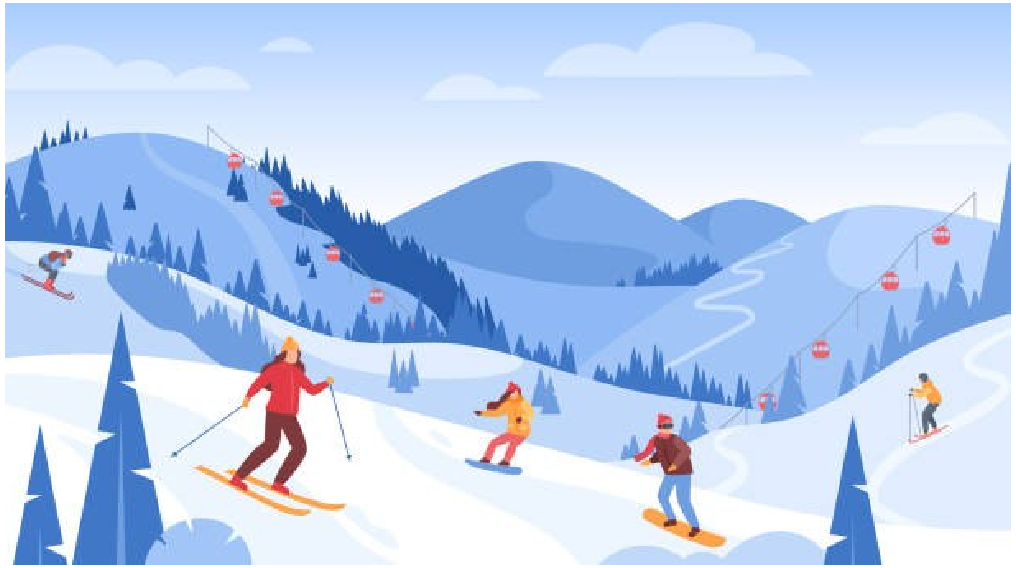

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A normal person with boots

This fox

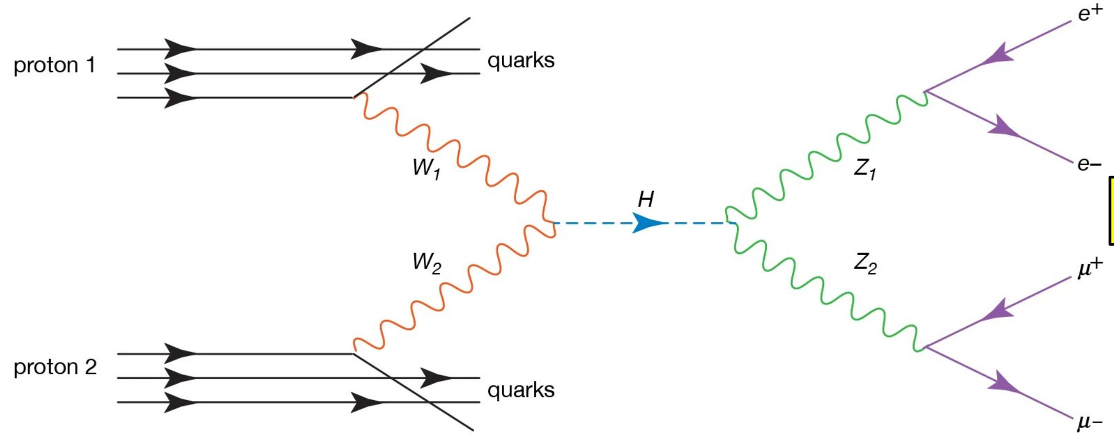
Light / fast → *Heavy / slow*

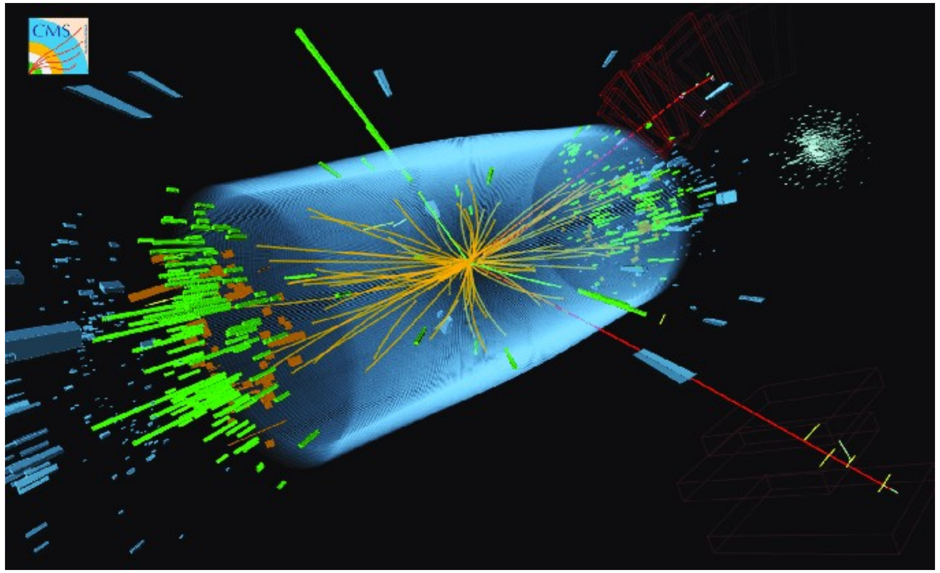
2012: discovery of a Higgs boson at CERN

- In collisions at CERN Large Hadron Collider (LHC), experimentalists can search for production of Higgs bosons (particle associated with Higgs field)

Example of process involving a Higgs boson, decaying to 4 leptons

[source: Encyclopaedia Britannica]





- 2012: ATLAS and CMS collaborations at CERN announced the discovery of a Higgs boson, with a mass of about 125 times that of a proton (or half the mass of an atom of uranium)
- Confirms the idea of Brout, Englert, Higgs, … almost 50 years after their articles

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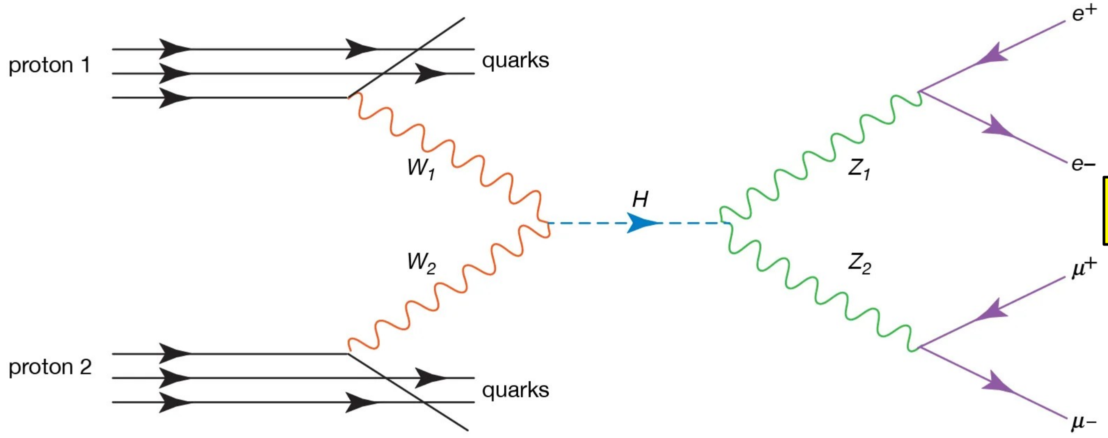

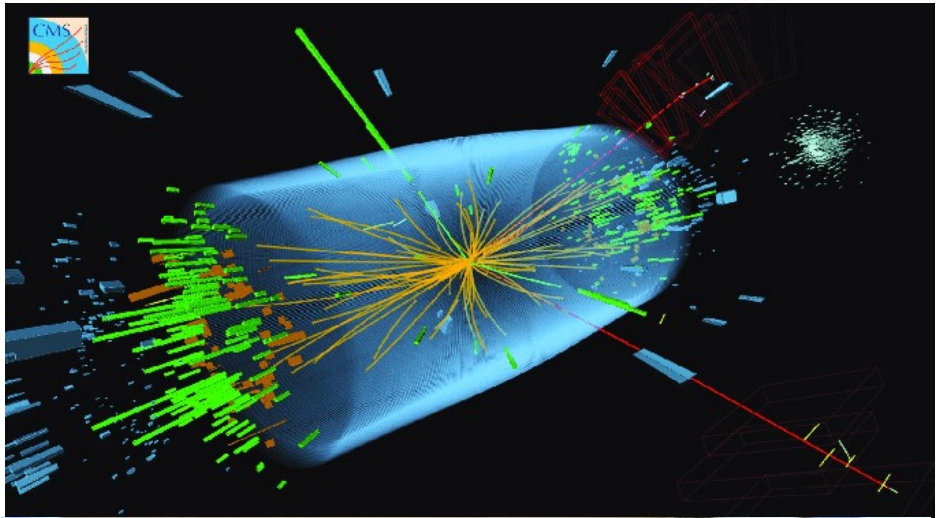

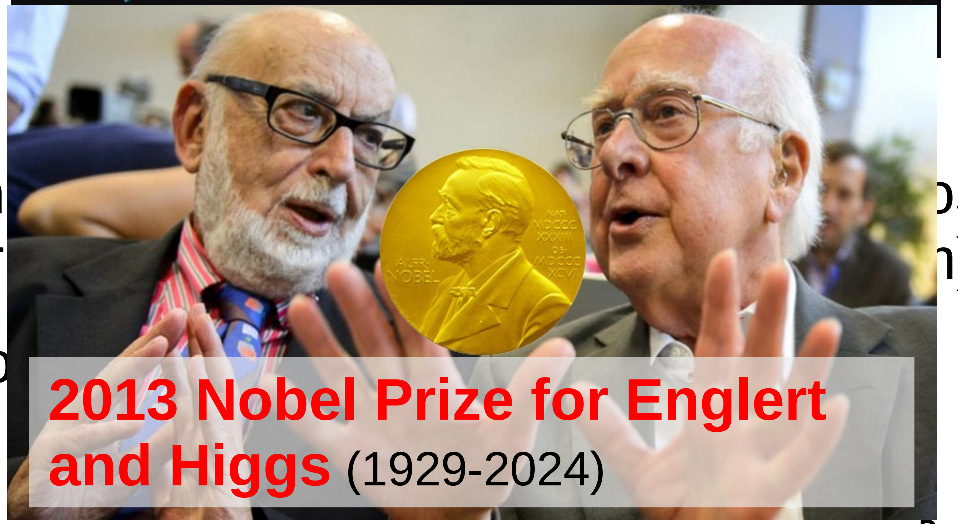

2013 Nobel Prize for Englert and Higgs (1929-2024)

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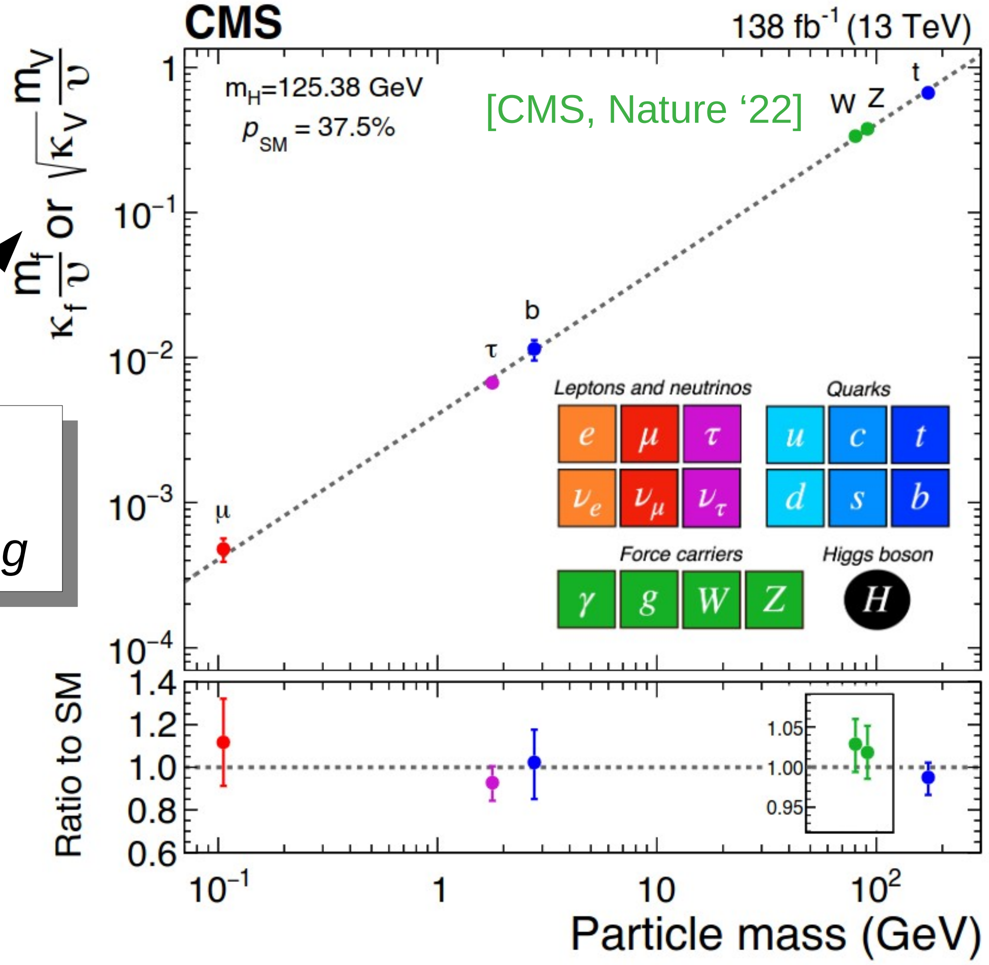
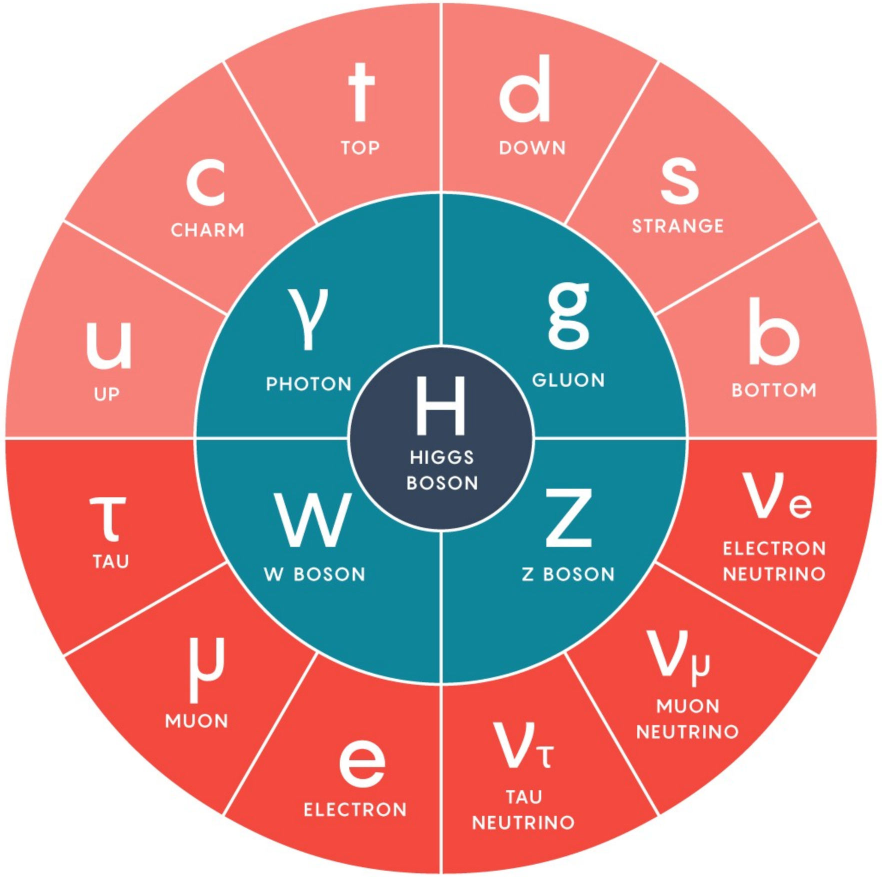
Does the Brout-Englert-Higgs mechanism occur in Nature?

- Can we verify that $m = g\, v$?



Coupling to Higgs boson ↔ g



→ confirmed so far for W and Z bosons (mediators of weak interactions) and heaviest fermions

Is this all there is to know?

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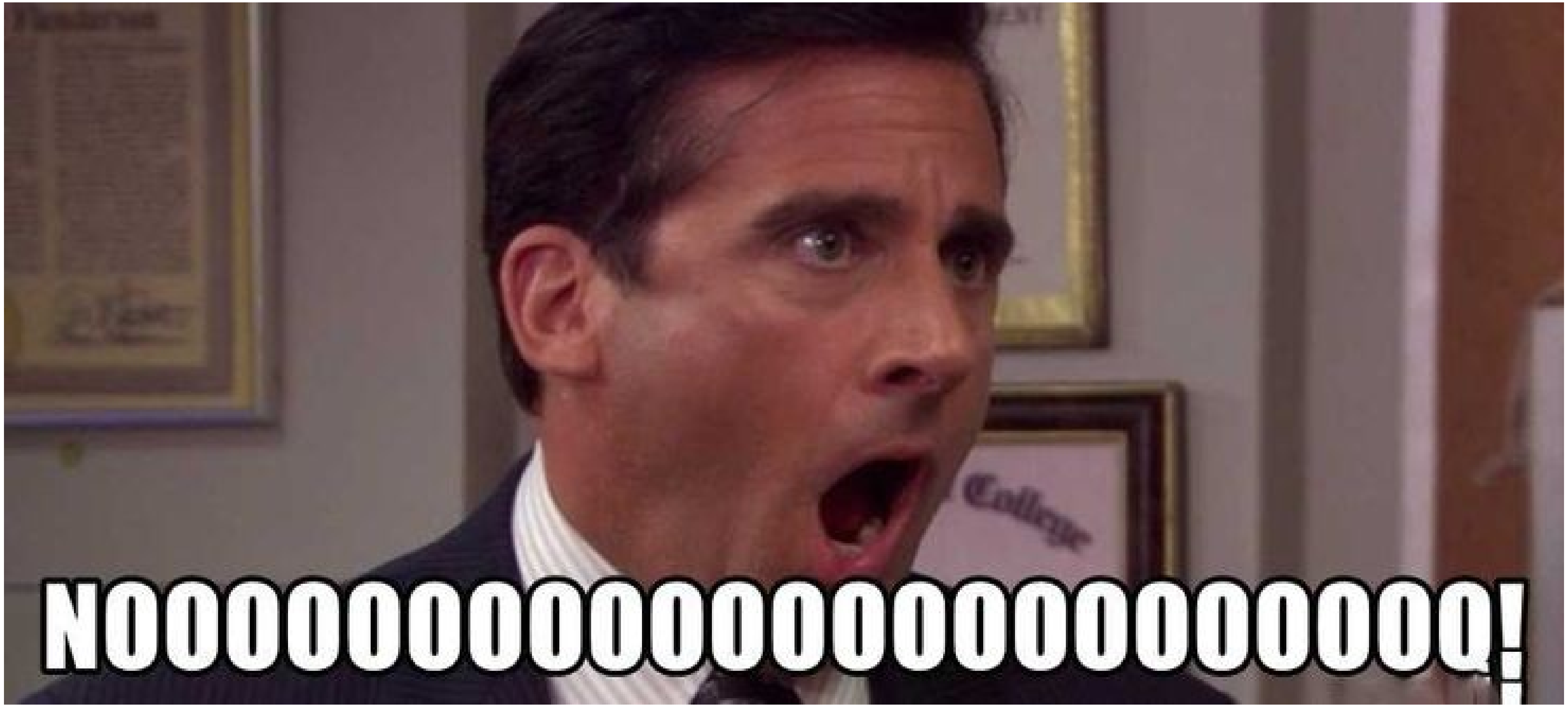
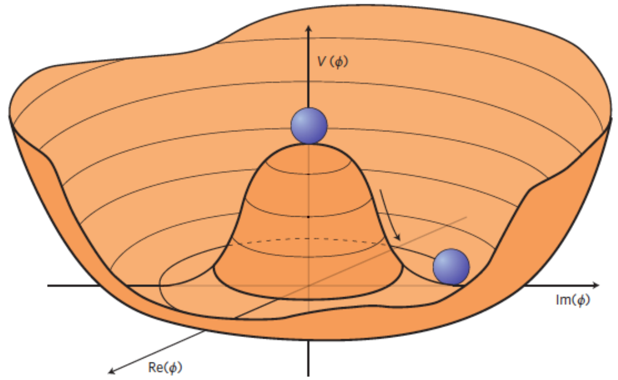


Is this all there is to know?

Much remains to understand/discover!

- **How many Higgs bosons** are there?



- What is the **origin and the shape of the Higgs potential**?

- Is the vacuum, in which we live, stable? metastable? unstable?

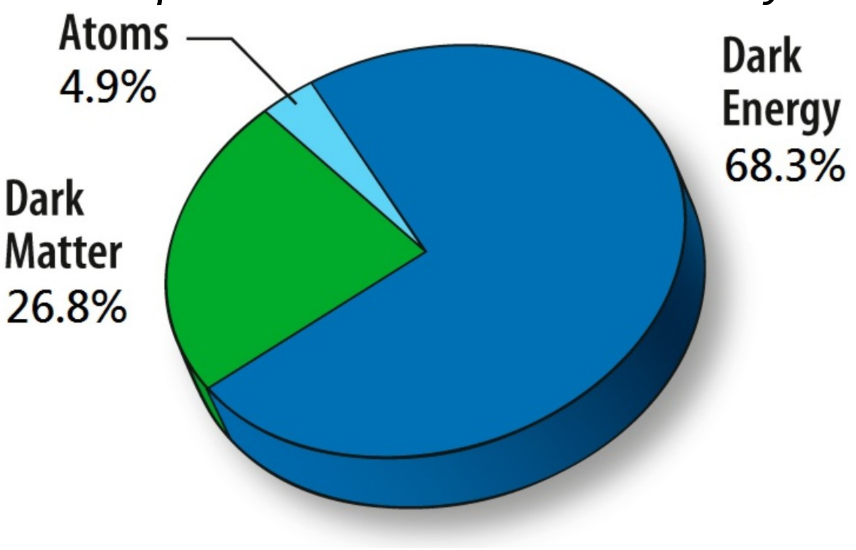
- What is **dark matter**? What is **dark energy**?

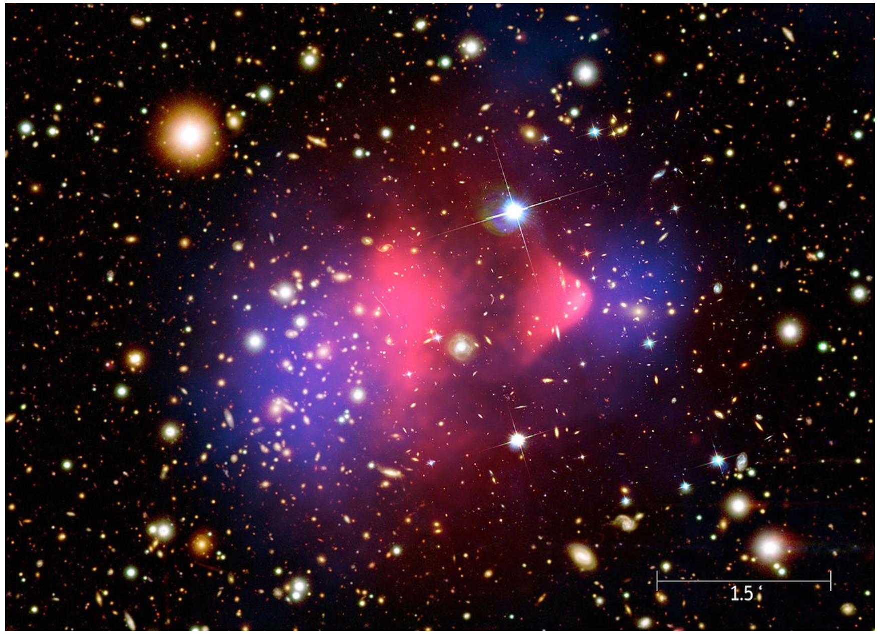
- Why is there **more matter than antimatter** in the Universe?

and many many more...

Dark Matter and the Higgs boson

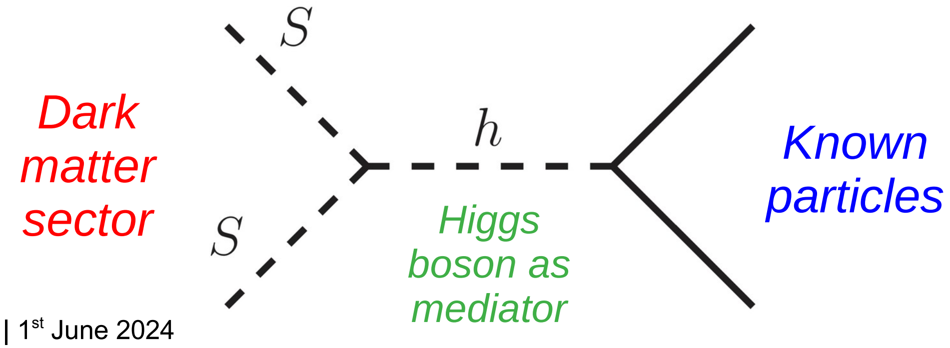
Composition of the Universe today



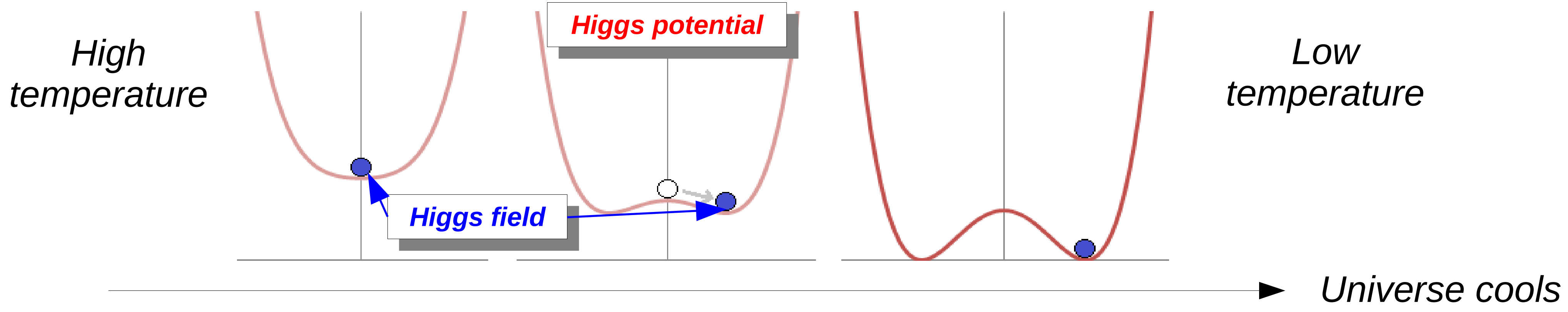


The Bullet Cluster, an example of evidence for dark matter

- 95% of the Universe today consists of **dark matter** and **dark energy**, both of which we know almost nothing of
- Dark matter only interacts very weakly with normal matter, but it could interact more with the Higgs boson, e.g. "***Higgs portal***"



The Higgs boson and the early Universe



- Early Universe: high temperature → vacuum is symmetric
- As the Universe cools, a broken phase appears → spontaneous symmetry breaking
- This transition is called the ***Electroweak Phase Transition***
- We now know it occurred, but ***not how it did***
  - Continuous phase transition?
  - Discontinuous phase transition? (Like boiling water, for example)
    - → could help explain asymmetry between matter and antimatter in the Universe
    - → possible effects in early Universe such as gravitational waves
- Dynamics of phase transition at the interface of Higgs physics and early-Universe evolution

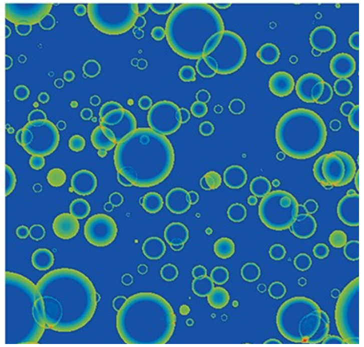


Figure from [Jinno, Konstandin, Rubira '20] *and* [Servant '22]

Exciting times ahead

- ***Direct searches***: try to produce new particles, directly, at LHC at CERN
- ***Indirect searches***: look for deviations in properties of known particles, like the Higgs boson, caused by new phenomena/particles, via precision measurements at LHC and possible future colliders (ILC, FCC, HALHF, ...)
- Direct and indirect searches for dark matter
- Gravitational waves searches (LIGO/VIRGO, LISA, ...)
- Precision measurements at low energies

Etc.

→ much more to learn ahead of us, through interplay of **experiment** and **theory**

→ experimentalists devise, operate, and analyse data from wide range of experiments

→ theorists devise theories to solve unanswered questions and ways to test them

Thank you very much for your attention!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

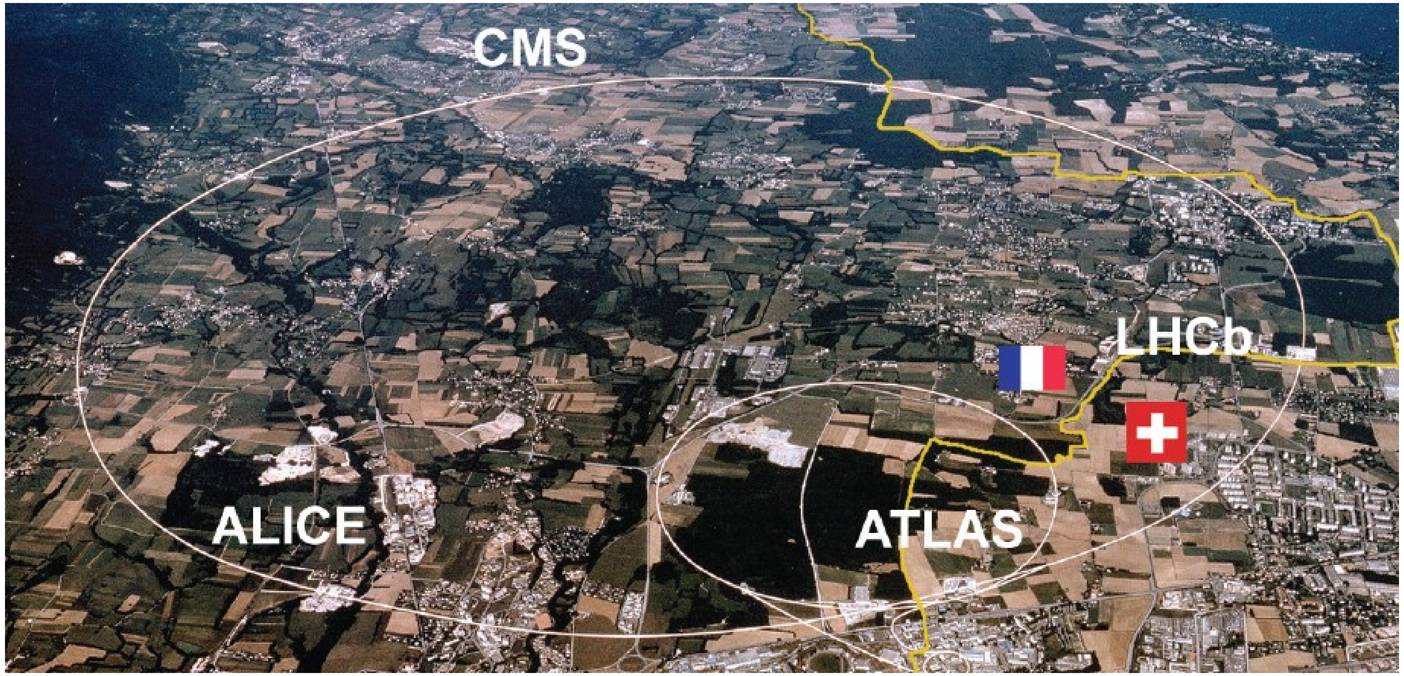
Johannes Braathen
DESY Theory group
johannes.braathen@desy.de

Backup

Searching for the Higgs boson at CERN

$$E = m c^2$$

Energy → E, *Mass* → m, *Speed of light* → c (for a particle at rest)



Collide protons at very high energy: currently at **13.6 TeV**
(each proton has the same kinetic energy as a flying mosquito*)
→ kinetic energy converted to mass
→ produce heavy particles during collisions
→ heavy particles decay quickly, but their decay products can be detected and analysed
→ reproduce conditions in very early Universe

*: *a mosquito is ~1 million billion billion (10^{24}) times heavier than a proton*