The Higgs Particle, or the Origin of Mass

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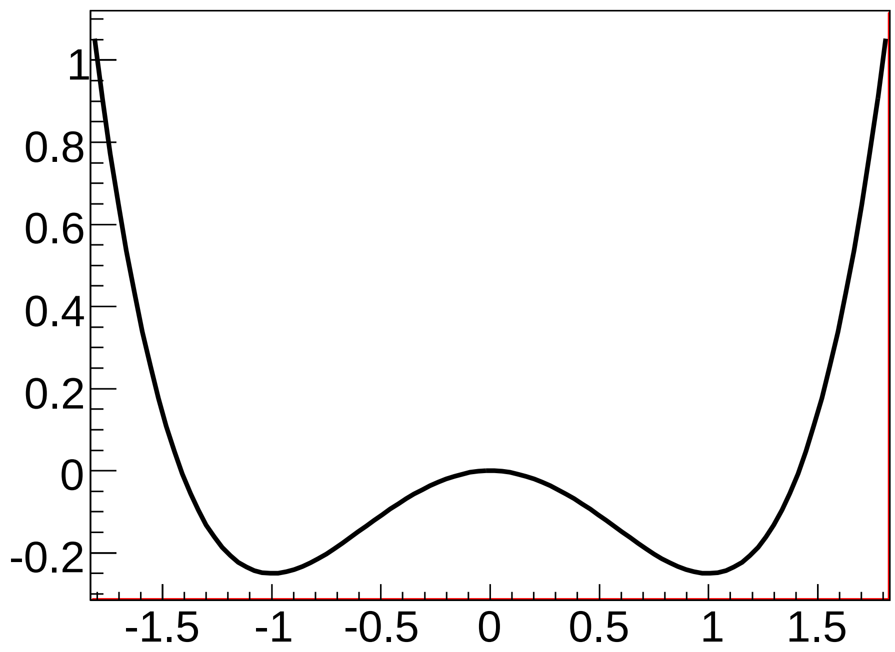
JHU Quarknet Meeting

What is the Higgs Particle?

- This answer is probably not very satisfying to see first:

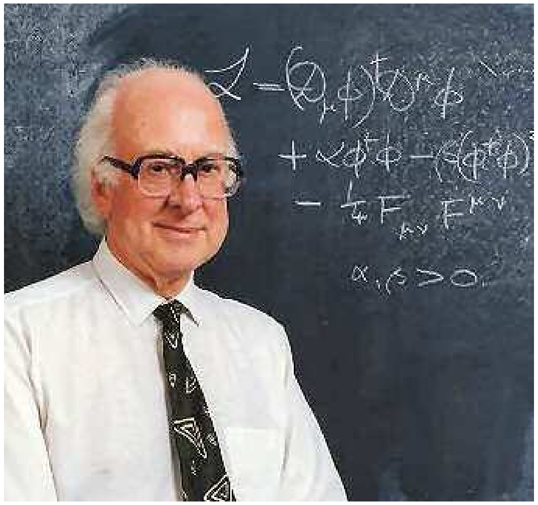
  Higgs appears from introduction of this Lagrangian in the quantum field theory of particles

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \left[\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right]$$



What is Higgs?

- There are several phenomena:
  - Peter Higgs
  - Higgs mechanism
  - Higgs field
  - Higgs particle (still elusive particle)



- People sometimes confuse these phenomena
  - especially the last two
- So far there is hard evidence only for the first:
  - 1964 article by Peter Higgs in *Physics Review Letters*

Why is it Higgs Mechanism ?

- In fact, there are several names of the Higgs mechanism:
  - Brout-Englert-Higgs mechanism
  - Higgs-Brout-Englert-Guralnik-Hagen-Kibble mechanism
  - Anderson-Higgs mechanism
  - Higgs mechanism is just simpler
  - all for authors of independent papers on the topic

- Partly due to ironic history with the paper by Higgs:
  - rejected from European *Physics Letters*
    "of no obvious relevance to physics"
  - added a paragraph predicting a new particle

Spontaneous Symmetry Breaking

- Spontaneous symmetry breaking → Higgs mechanism
- 3 quark families → matter over antimatter asymmetry

Physics

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: University of Chicago

Yoichiro Nambu

1/2 of the prize

© The Nobel Foundation Photo: U. Montan

Makoto Kobayashi

1/4 of the prize

© The Nobel Foundation Photo: U. Montan

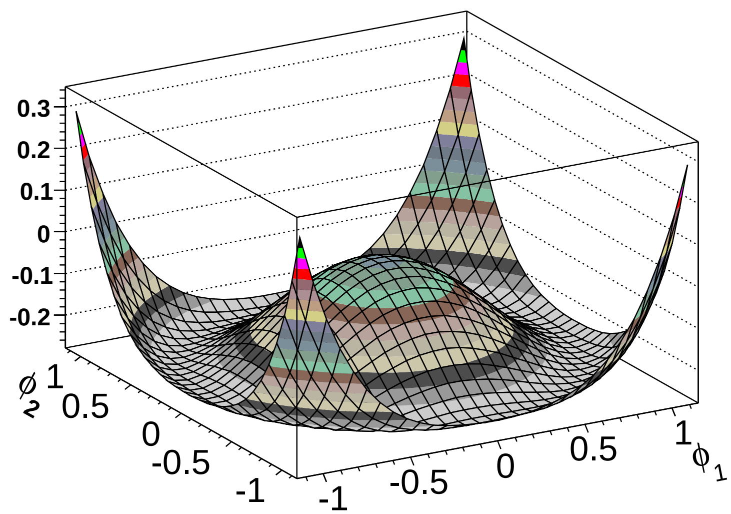
Toshihide Maskawa

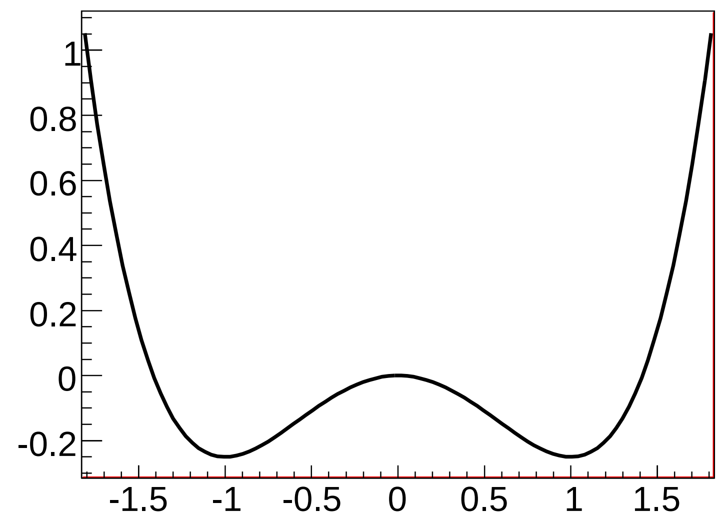
1/4 of the prize

Spontaneous Symmetry Breaking

- Symmetry spontaneously broken: pick $\phi = v$ at minimum of potential energy of Higgs field ($\mu^2 < 0$)

$$V(\phi_1, \phi_2, \phi_3, \phi_4) = \frac{1}{2}\mu^2 \left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right] + \frac{1}{4}\lambda \left[\ldots\right]^2$$



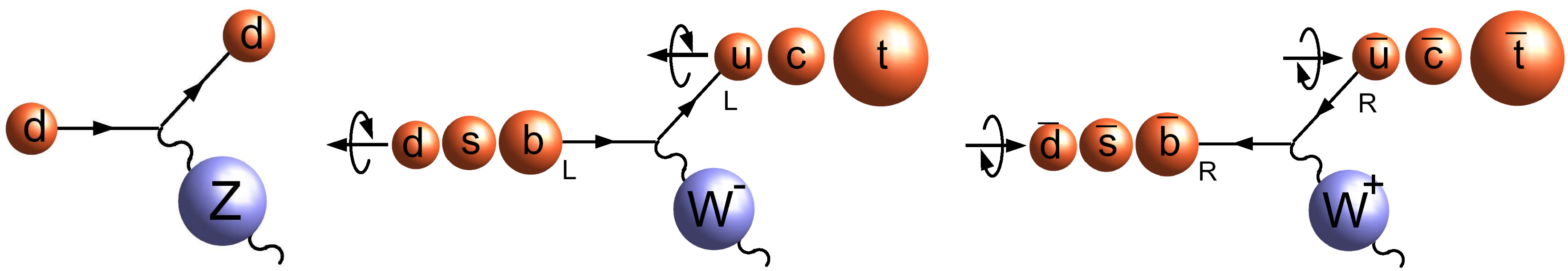


- Higgs particle described by one field component

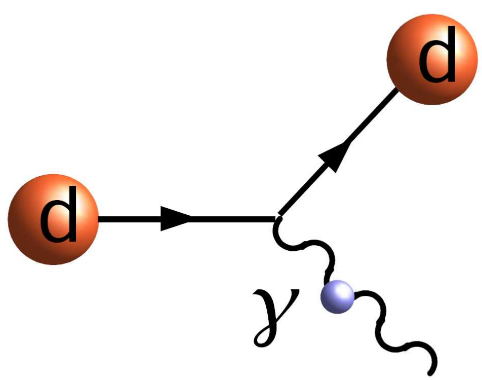
$$\eta = \phi_1 - v$$

What about other Higgs field components?

- The other field components ϕ_2, ϕ_3, ϕ_4 "couple" to Weak Interaction bosons $\boldsymbol{Z}$, $\boldsymbol{W^-}$, $\boldsymbol{W^+}$ and give them mass



- Photon γ is the same Weak Interaction boson but remains massless (does not couple to Higgs field)

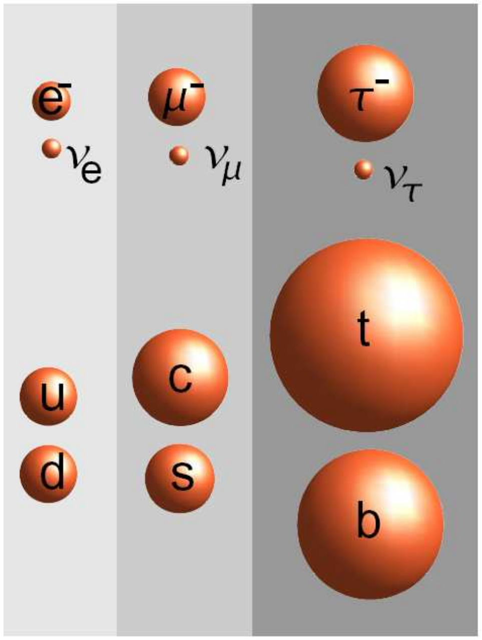


All Elementary Particles get Mass from Higgs Field

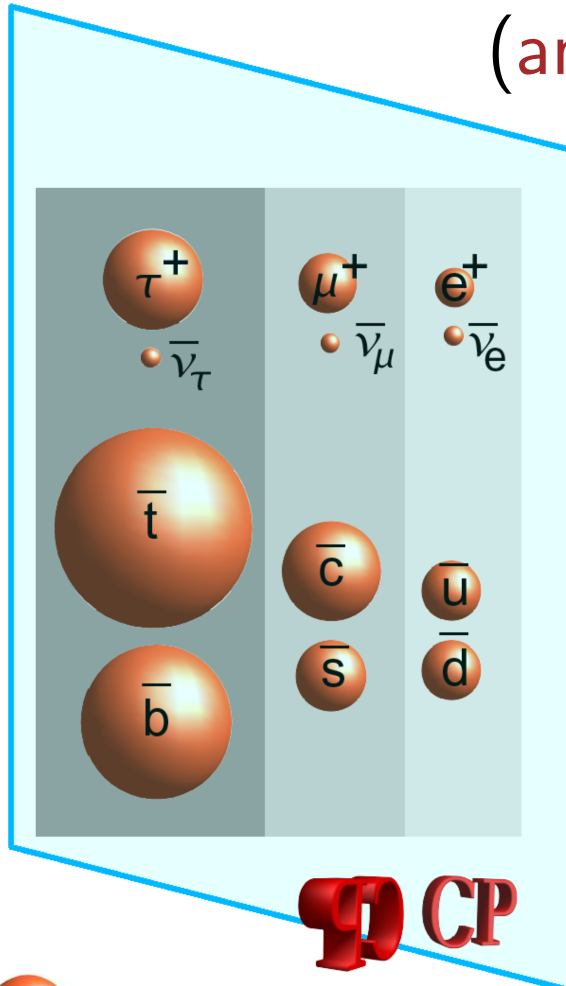
- Fermions $S = \frac{\hbar}{2}$ (matter)

leptons

quarks

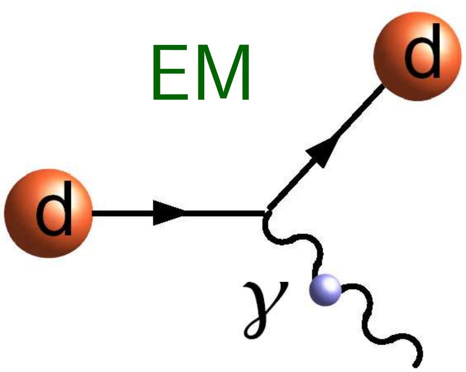


(anti-matter)

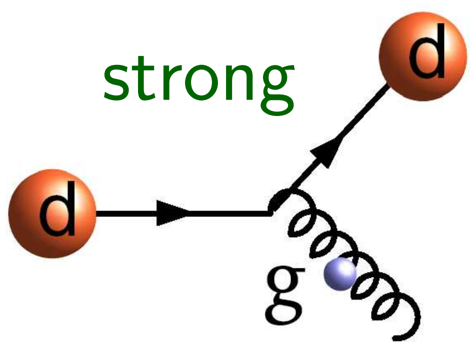


- Bosons $S = \hbar$ (force carries):

EM



strong

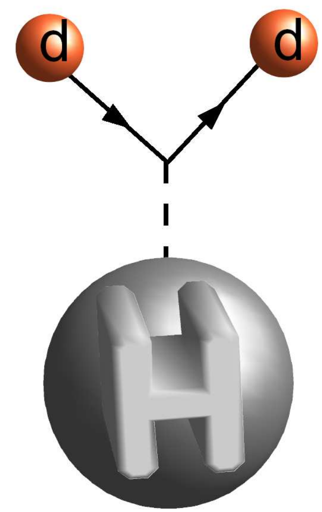


$\leftarrow$ massless

(weak force bosons mass)

What is Higgs?

- Higgs mechanism
  - existence of Higgs field
  - spontaneous symmetry breaking and "gauge" invariance (interaction with $Z, W^{\pm}$)
  - gives mass to all elementary particles
  - predicts existence of Higgs particle

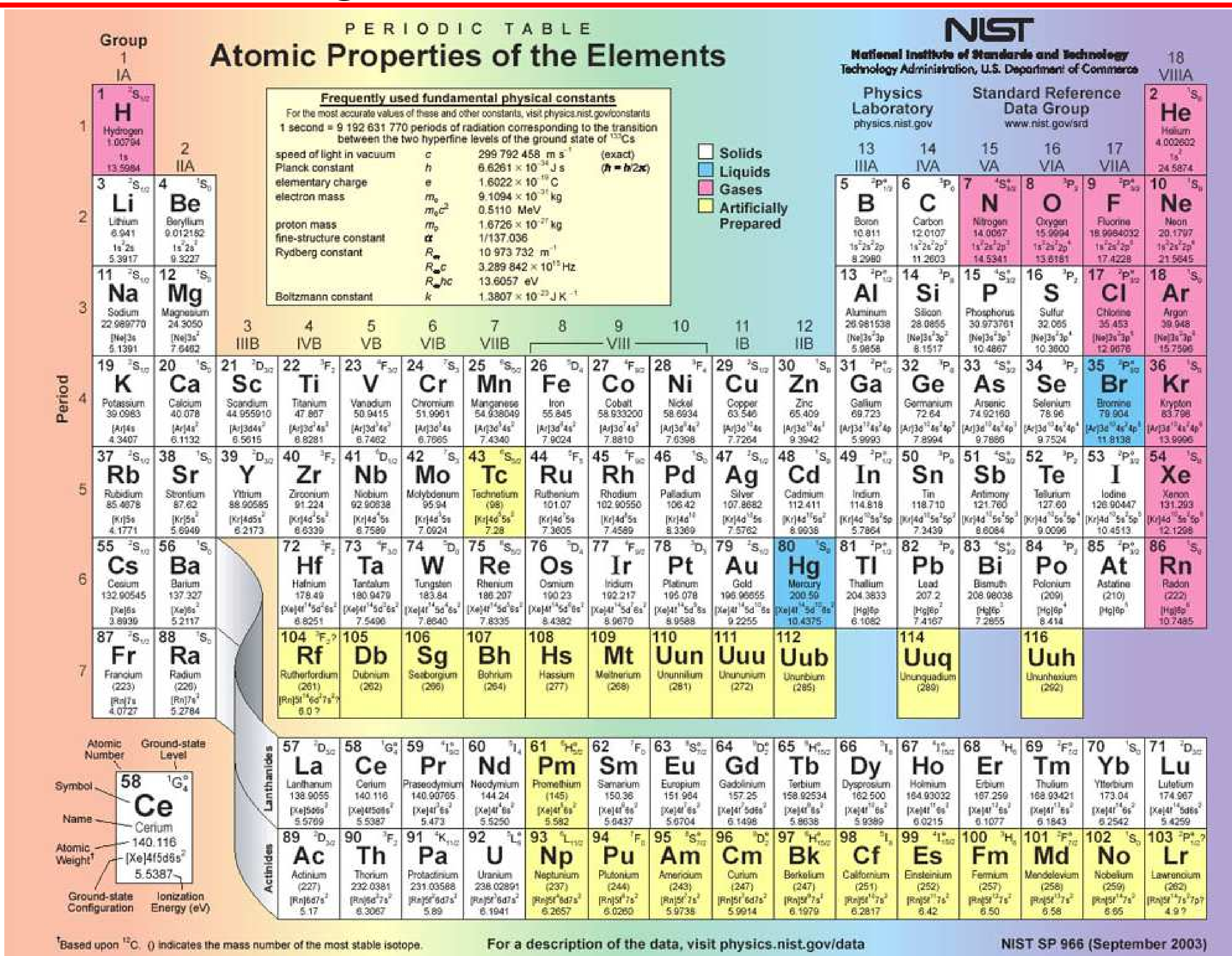


- Everything works perfectly, except:
  - we have not observed the Higgs particle yet
- Why: – Higgs particle is too heavy to produce (if it exists) (more than $100\times$ proton mass)
  - hope to produce or exclude at Large Hadron Collider
  - still possible that Higgs mechanism is not correct

Do we have mass due to Higgs mechanism?

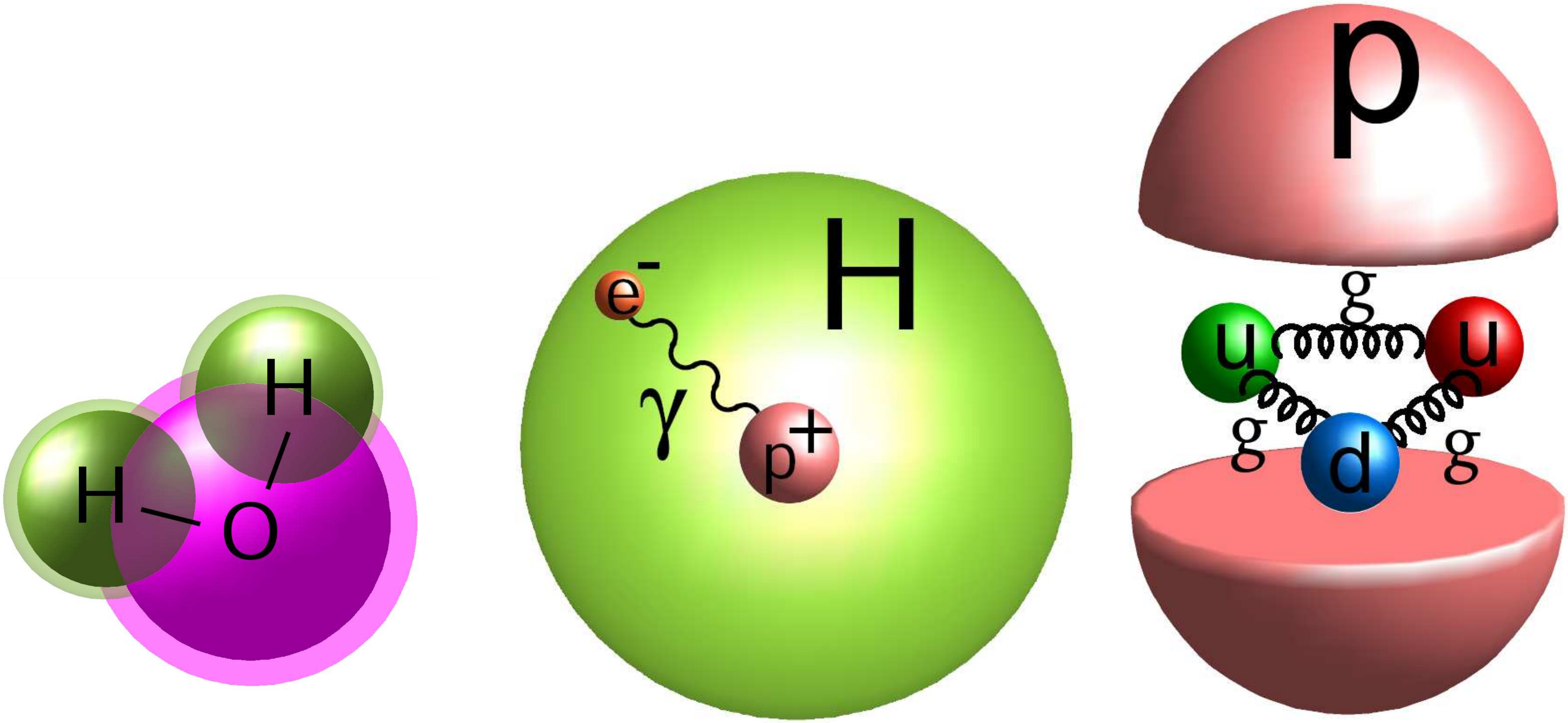
- Yes and no
  - we are not elementary particles...

What does give us mass? Molecules? Atoms?



What does make mass?

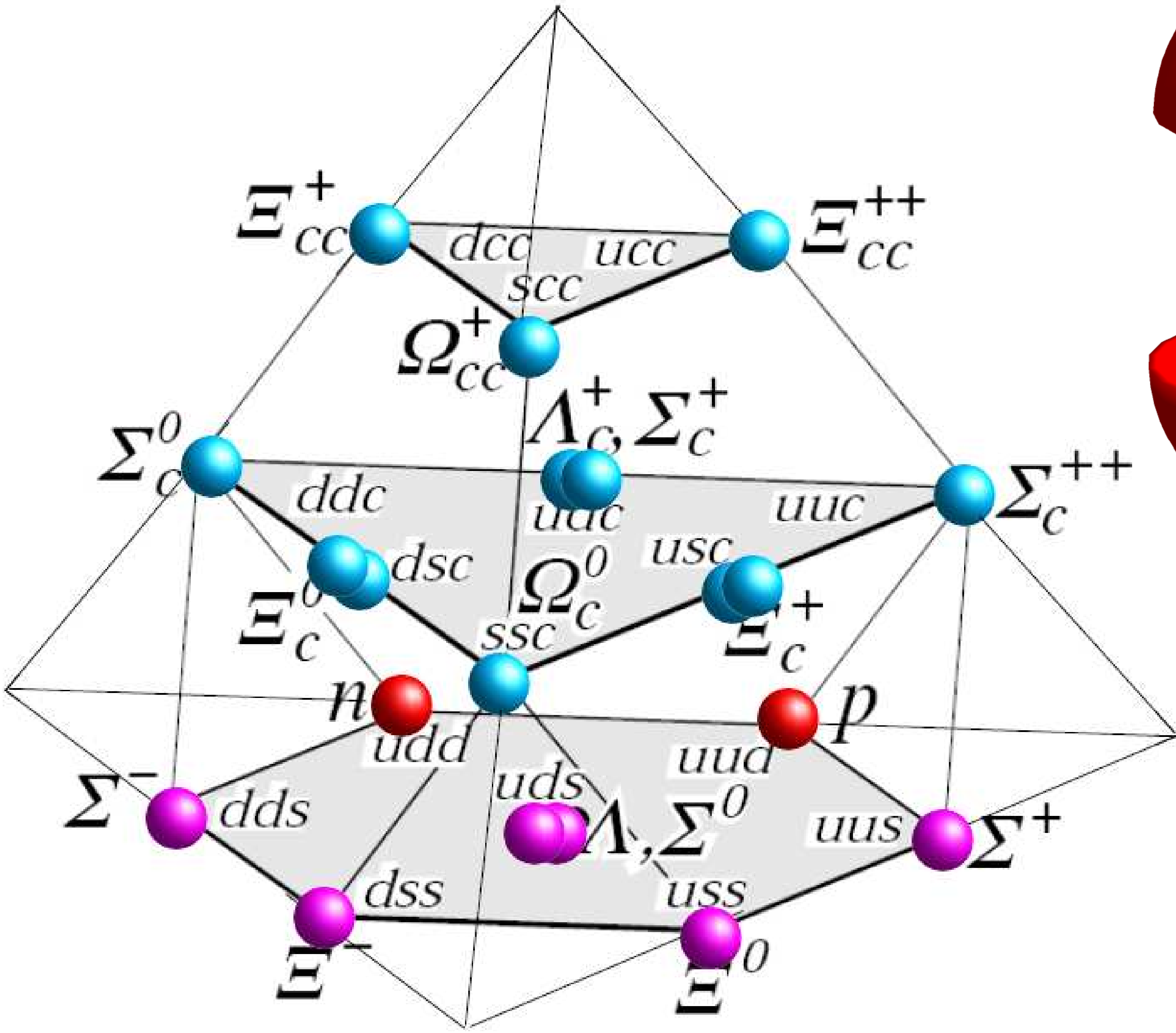
- What gives us mass?

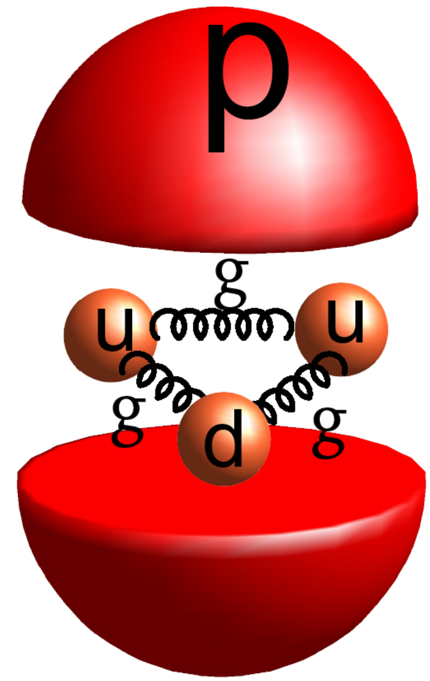


Molecules Atoms Nucleus

"Periodic Table" of Baryons: Proton, Neutron,...

- Three quarks make up a Baryon:





What Gives Mass to Baryons: Proton, Neutron,...

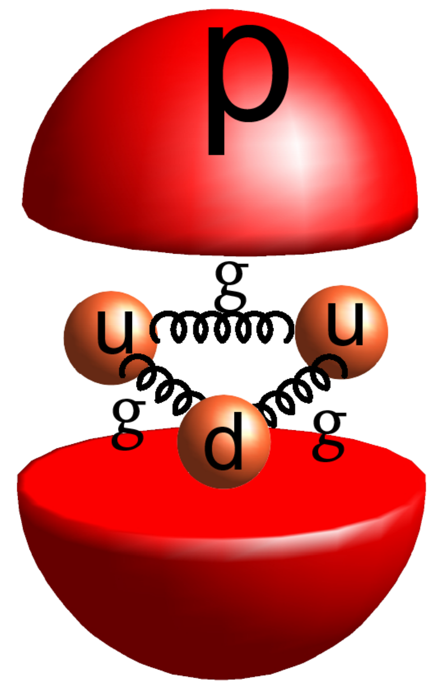
- Remember Einstein's formula

$$E = mc^2$$

m(u or d) $< 1\%$ m(proton)

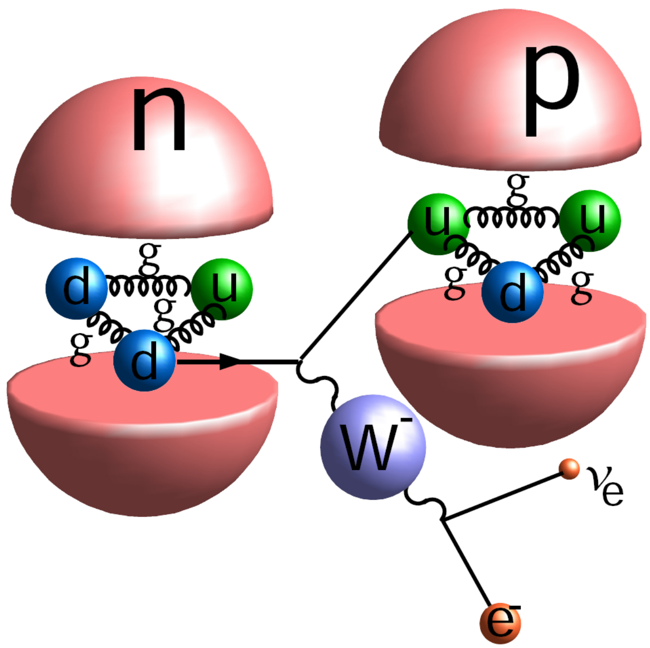
Mostly energy of gluons and quarks inside gives proton mass

not really the Higgs mechanism



But Higgs Mechanism is Very Important

- Makes Weak Interactions weak: mass of Z, W^-, W^+



similarly first step in sun fusion

$$p + p \to d + e^+ + \nu_e$$

- Makes certain hierarchy of masses

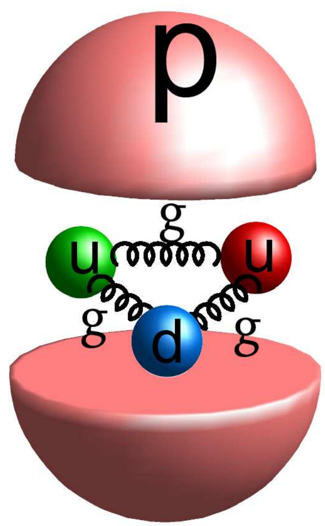
essential for our existence

Hypothetical Scenario: Different Quark Mass

- Again, normally proton is stable and neutron decays:

  $$\mathrm{m}(n) > \mathrm{m}(p) + \mathrm{m}(e) + \mathrm{m}(\nu_e)$$

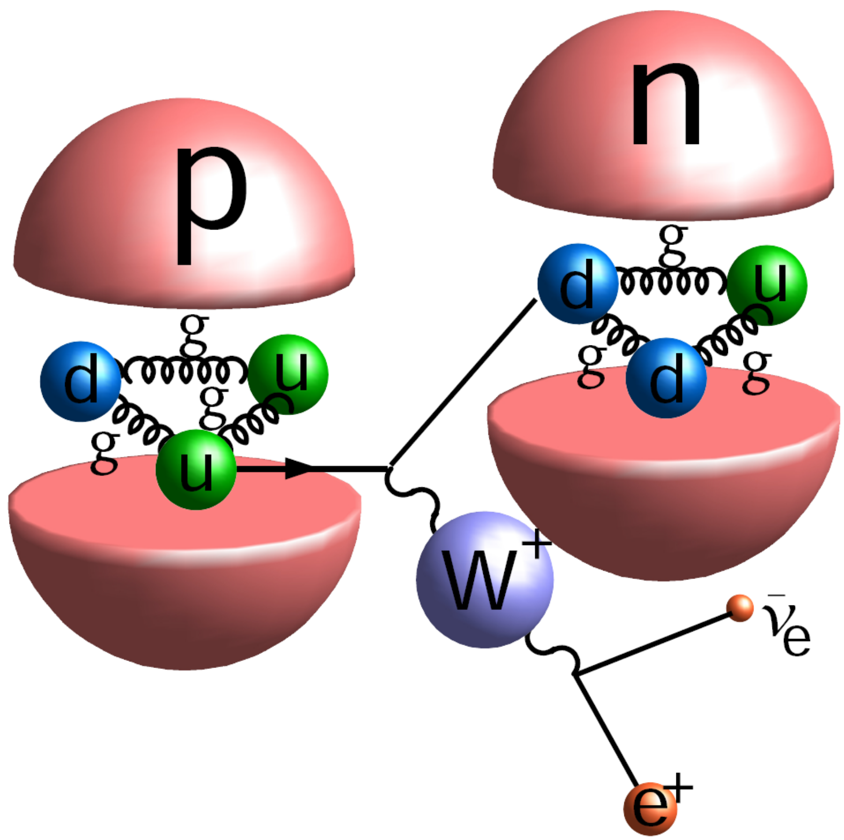
- Why is $\mathrm{m}(n) > \mathrm{m}(p)$
  - $\mathrm{m}(p) = 938$ MeV, $\mathrm{m}(n) - \mathrm{m}(p) = 1.3$ MeV
  - tiny difference makes a big difference!
  - naively expect $\mathrm{m}(p) > \mathrm{m}(n)$ if u and d were the same
  - but $\mathrm{m}(d) > \mathrm{m}(u)$



- New scenario:
  - what if $\mathrm{m}(d) < \mathrm{m}(u)$

Hypothetical Scenario: Different Quark Mass

- If m(d) $<$ m(u), proton decays:



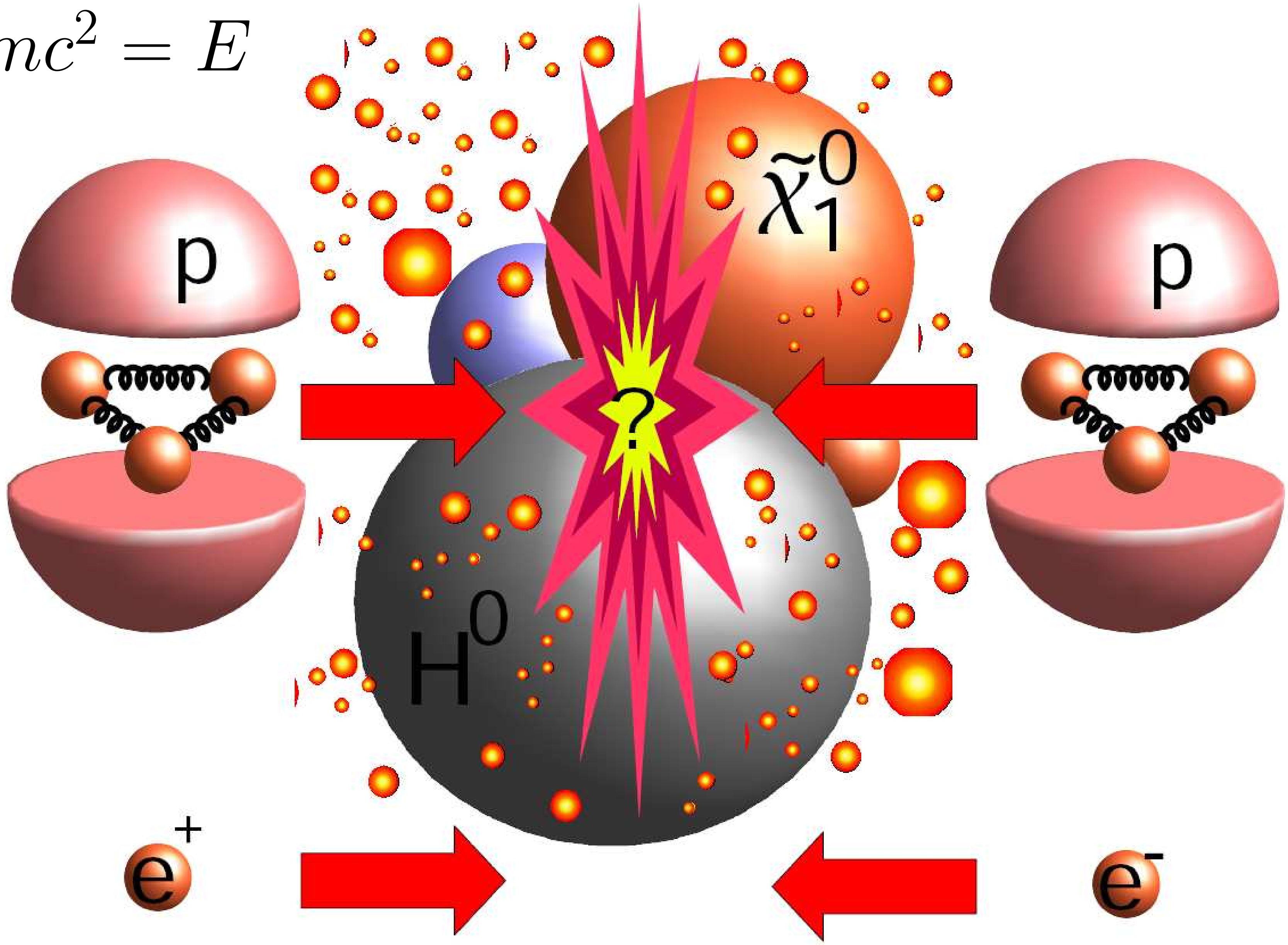
- Consequence: no Hydrogen, no H_20, no life
  - still have He^4, rapid nn fusion, instead of slower pp

Finding the Higgs

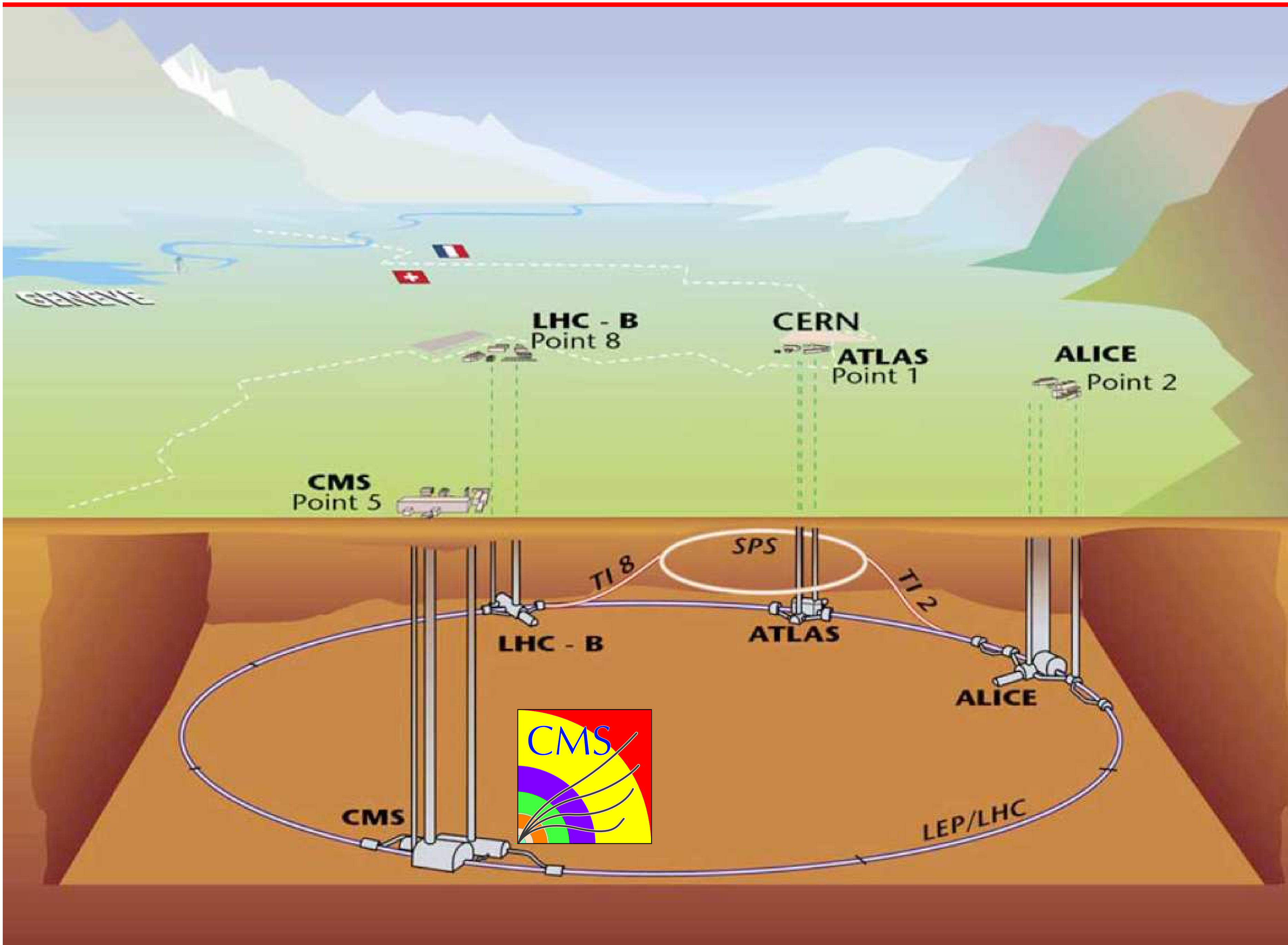
- If Higgs is so important:
  - how do we find the Higgs ?
  - or prove that it does not exist...

Produce the Higgs: Reaching Highest Energy

- $mc^2 = E$



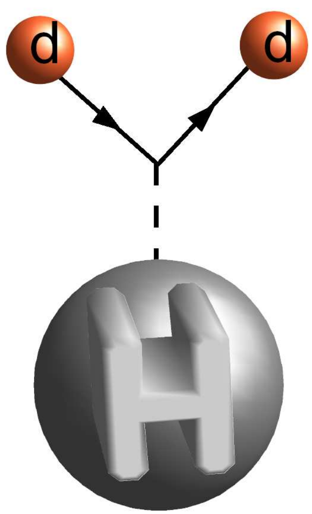
Large Hadron Collider: Re-Start this Fall

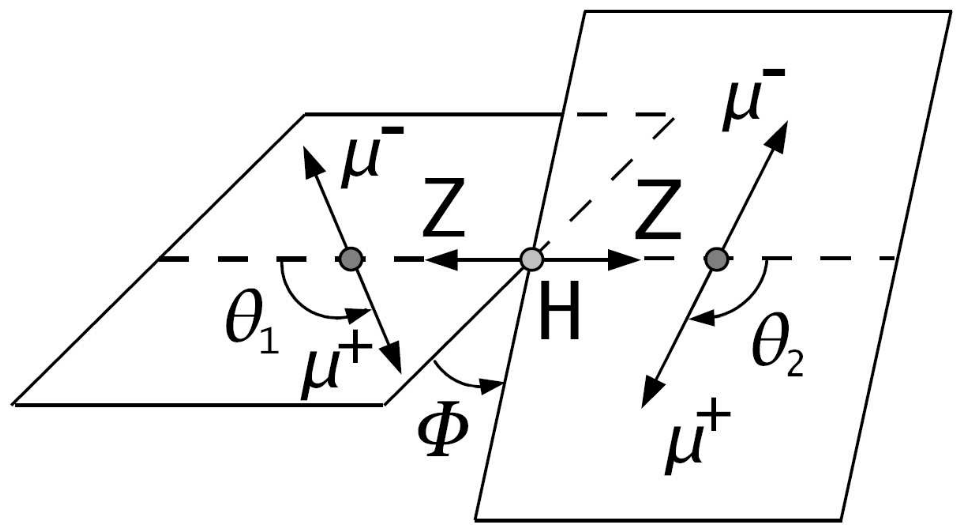


Higgs at LHC

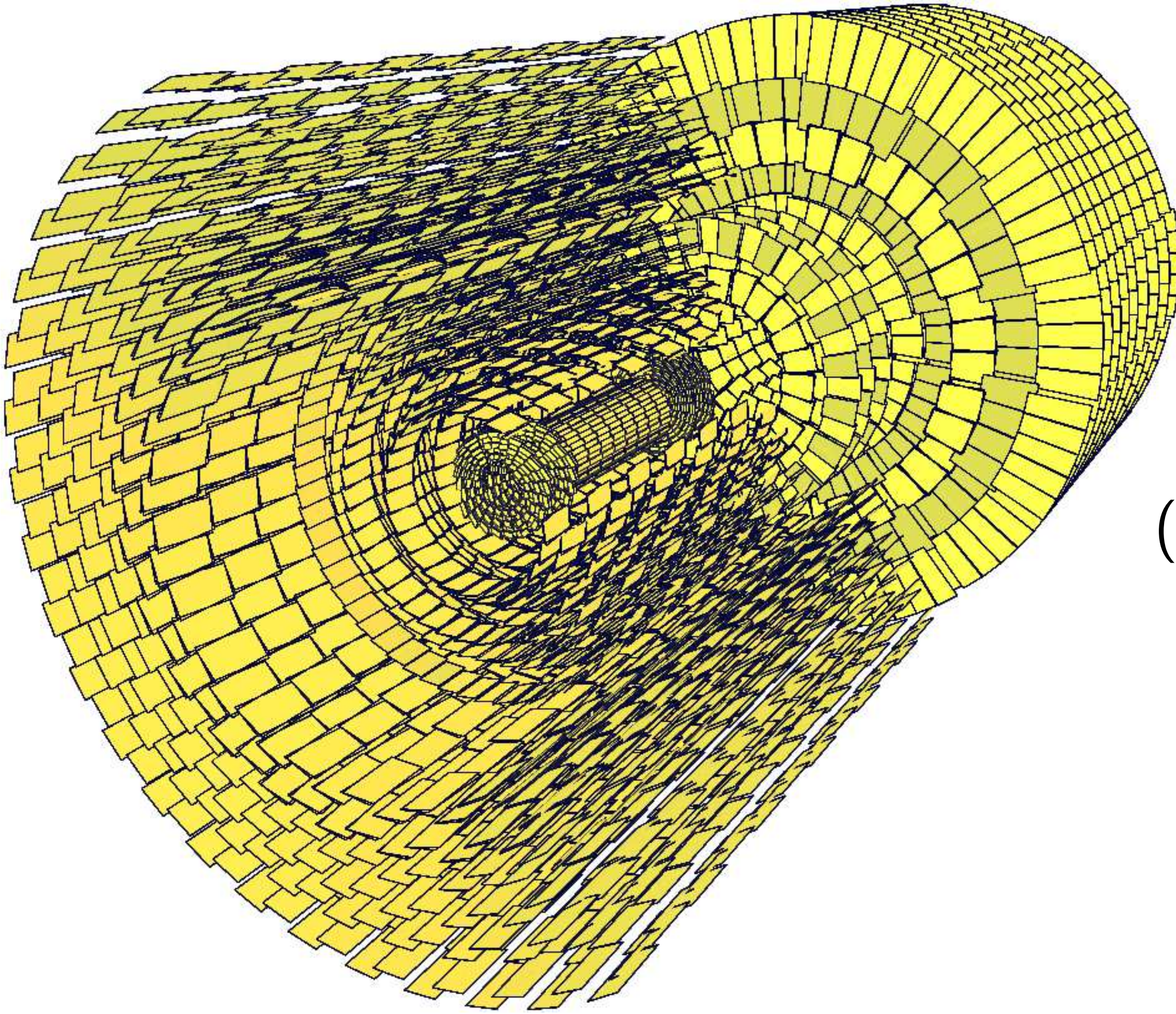
- How to find the Higgs depends on its mass
  - it does not live long, but decays
  - more likely decays to heaviest particles
  - if $\mathrm{m}(H) > 2 \times \mathrm{m}(Z)$ then

    $H \to ZZ$ most likely, with $Z \to \mu^+\mu^-$ or similar





Modern Tracking Detectors

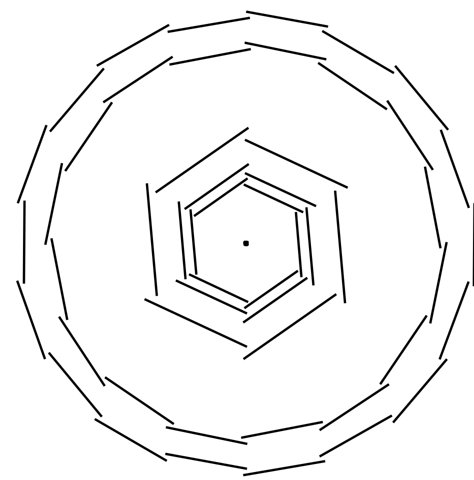


← CMS tracker

(>15,000 sensors)

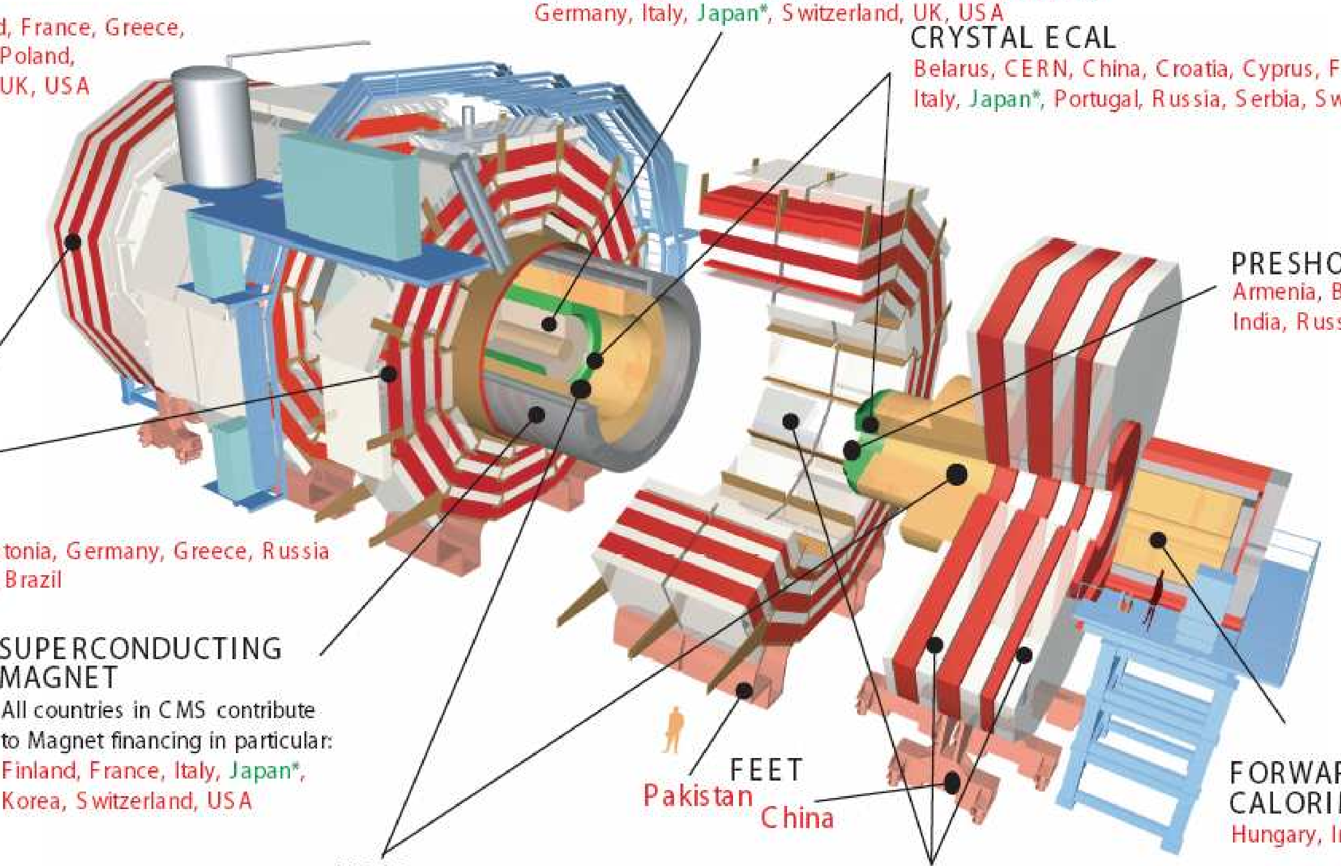
↓ BABAR silicon

(340 sensors, R∼15cm)



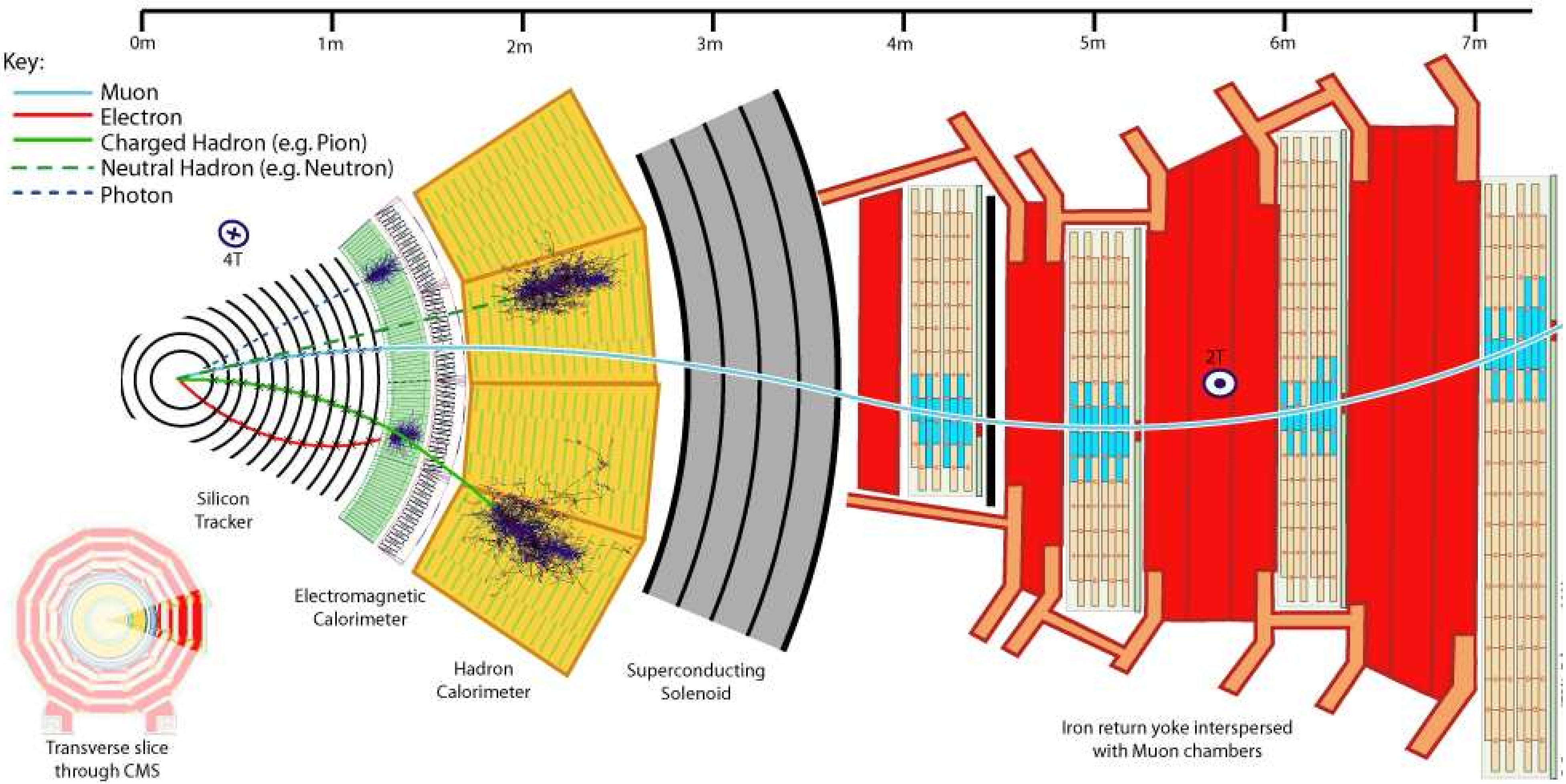
CMS Experiment

36 Nations, 160 Institutions, 2008 Scientists and Engineers (November 2003)



Total weight	:	12500 T
Overall diameter	:	15.0 m
Overall length	:	21.5 m
Magnetic field	:	4 Tesla

Detecting Particles at CMS



We are likely to find more than just Higgs

- New (super)symmetry:

Q|fermion⟩=|boson⟩

Q|boson⟩=|fermion⟩

- Solve:

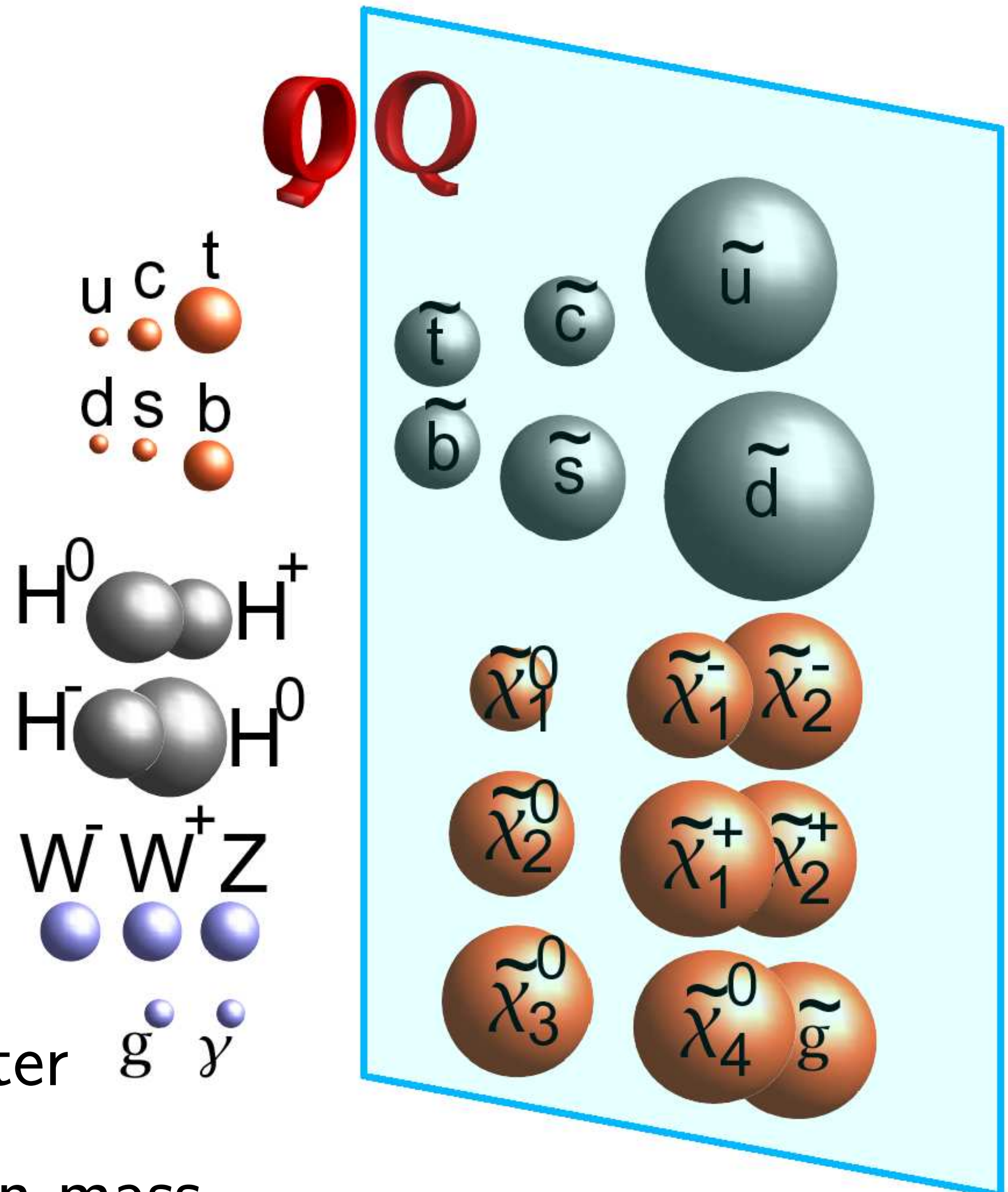
(1) natural light

Higgs

(2) dark matter

lightest $\tilde{\chi}_1^0$

(3) large matter/antimatter

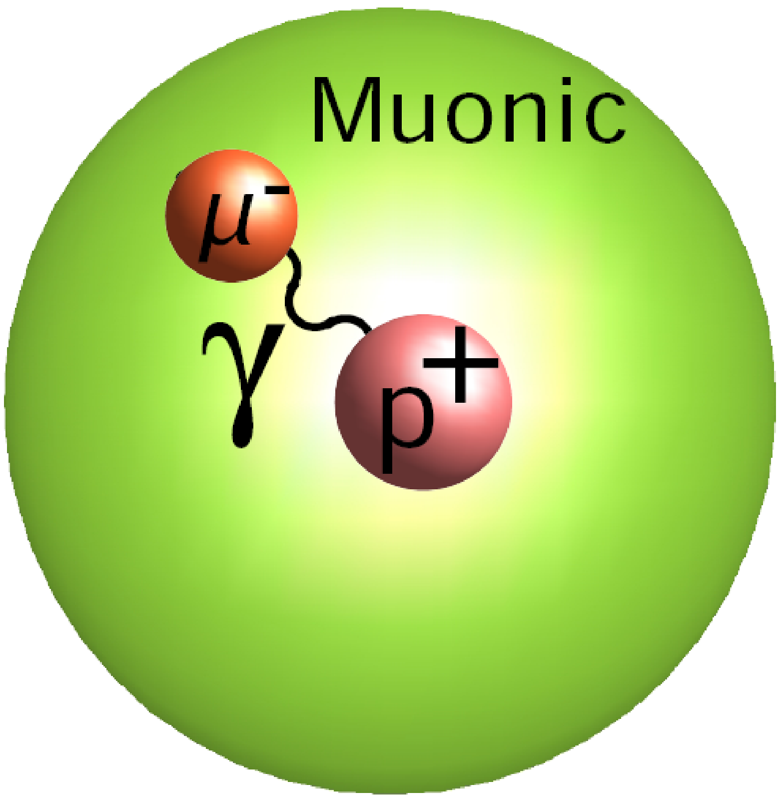


- Just around the corner in mass...

BACKUP SLIDES

(1) Another Scenario: Muonic World

- We would get a muonic atom:



- Size changes:

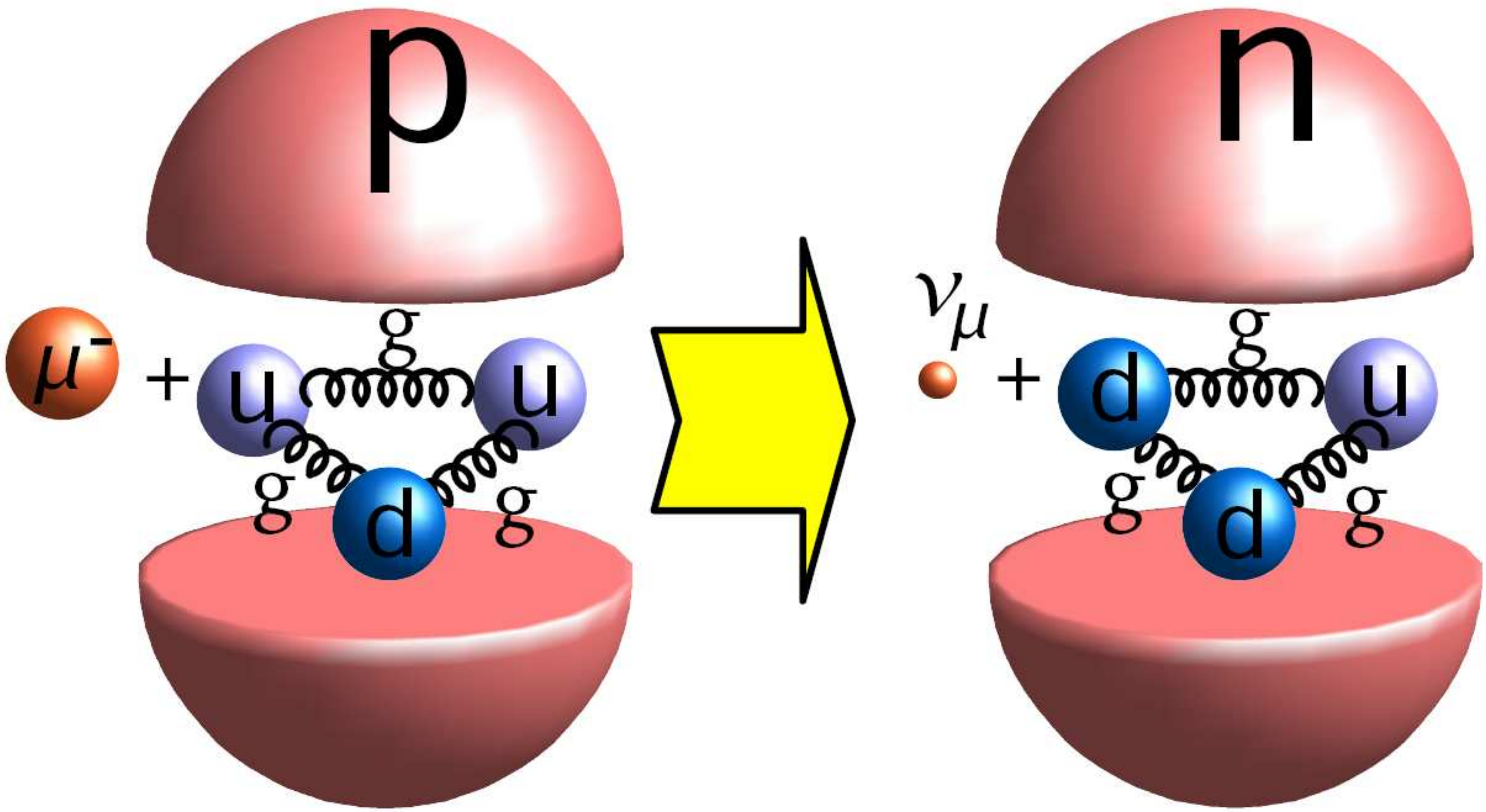
radius $r = \frac{4\pi\epsilon_0\hbar^2}{m_\mu e^2}$, 200 smaller !

Hydrogen radius

$$r = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = 5 \times 10^{-11}\ \text{m}$$

(1) Scenario: Muonic World

- However muonic hydrogen would decay:

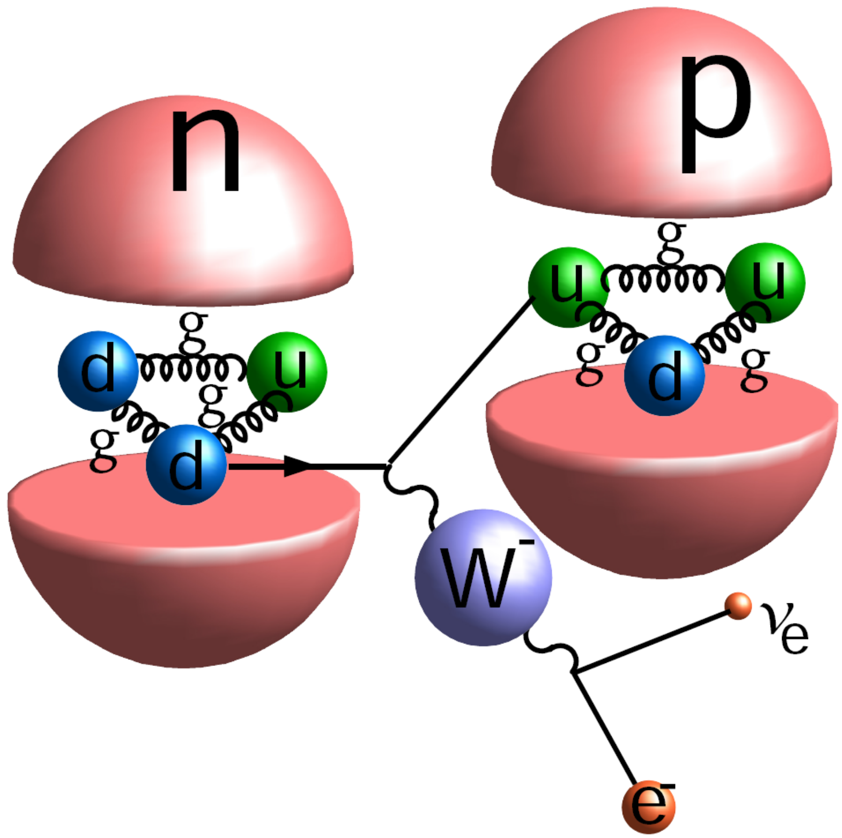


- Not very interesting universe
  - filled with neutral "balls" of neutrons and neutrinos

(1) Scenario: Muonic World

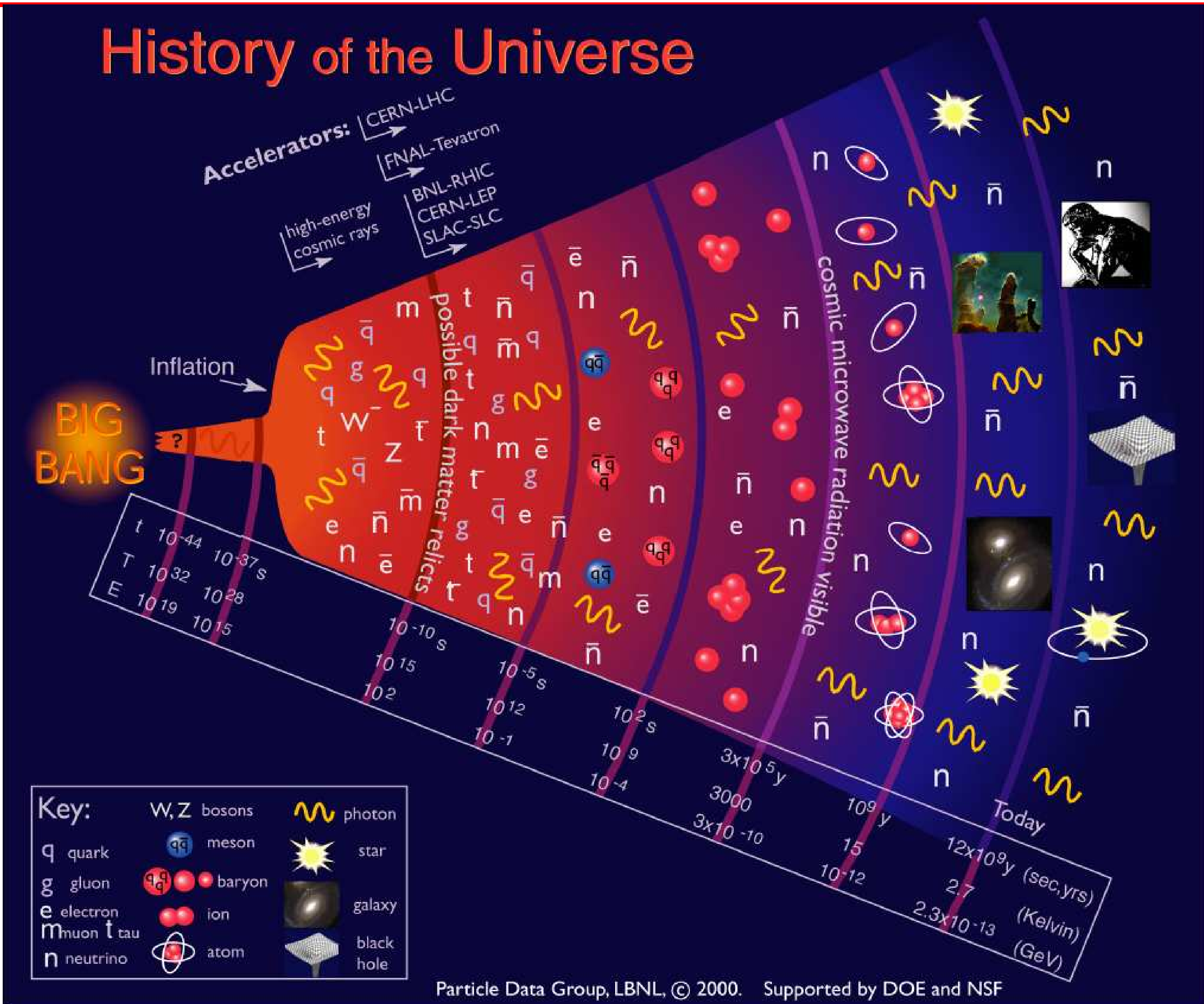
- Normally neutron is not stable (life $\tau \sim 886$ seconds)

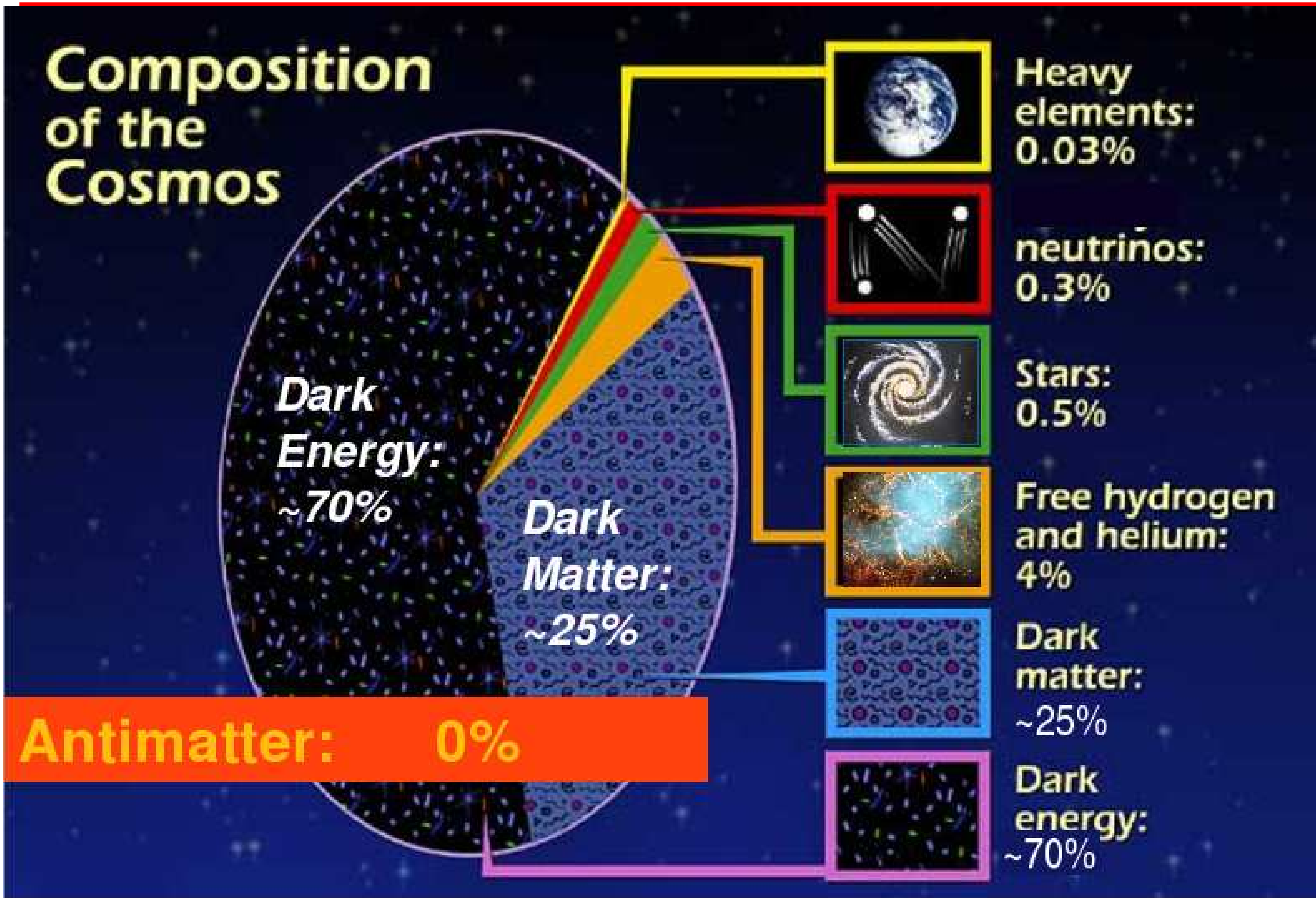
$$m(n) > m(p) + m(e) + m(\nu_e)$$



- But stable in the muonic world:

$$m(n) < m(p) + m(\mu) + m(\nu_\mu)$$


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


Composition of the Cosmos
Dark Energy: ~70%
Dark Matter: ~25%
Antimatter: 0%
Heavy elements: 0.03%
neutrinos: 0.3%
Stars: 0.5%
Free hydrogen and helium: 4%
Dark matter: ~25%
Dark energy: ~70%

Look Beyond the Standard Model

- Why does matter dominate (Sakharov):
  - CP-asymmetry
  - baryon non-conservation
  - non-equilibrium
- Mysterious Higgs field
  - gives mass to particles
- Need something beyond the SM
  - large CP-asymmetry
  - dark matter
  - light Higgs