

# The Higgs Particle, or the Origin of Mass

Andrei Gritsan

Johns Hopkins University



August, 2009

JHU Quarknet Meeting

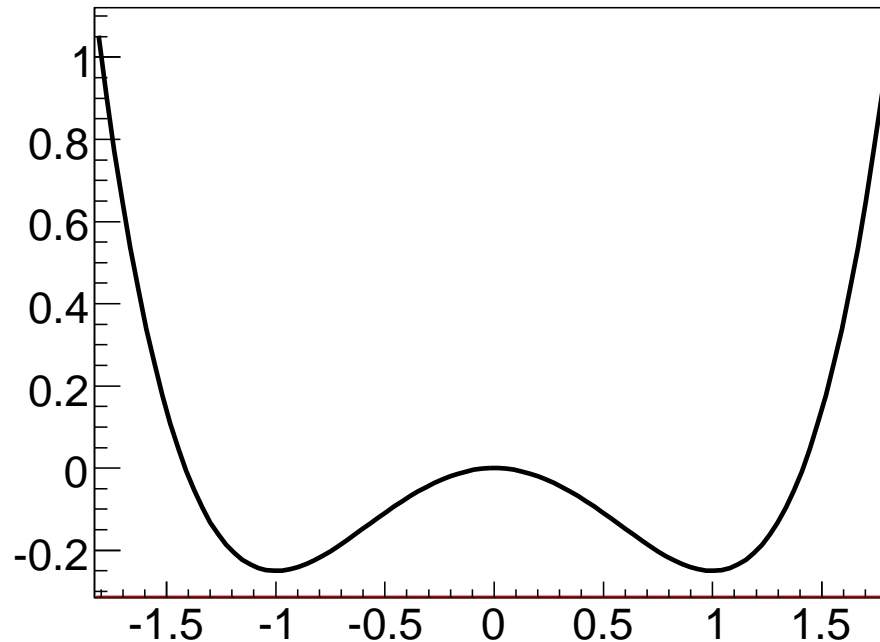
# What is the Higgs Particle?

---

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

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

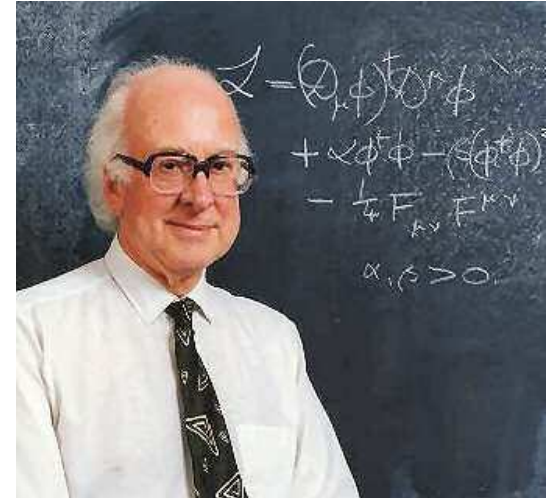
$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)^2 - \left[ \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \right]$$



# 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"



Photo: University of Chicago

**Yoichiro Nambu**

🏆 1/2 of the prize

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



© The Nobel Foundation Photo: U. Montan

**Makoto Kobayashi**

🏆 1/4 of the prize



© The Nobel Foundation Photo: U. Montan

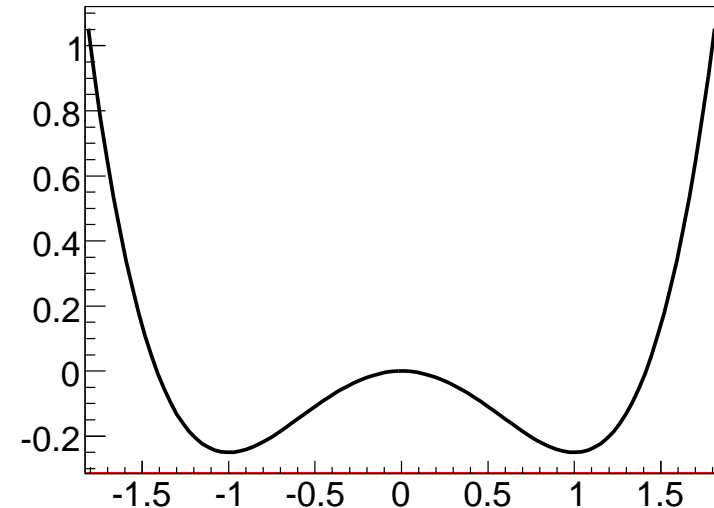
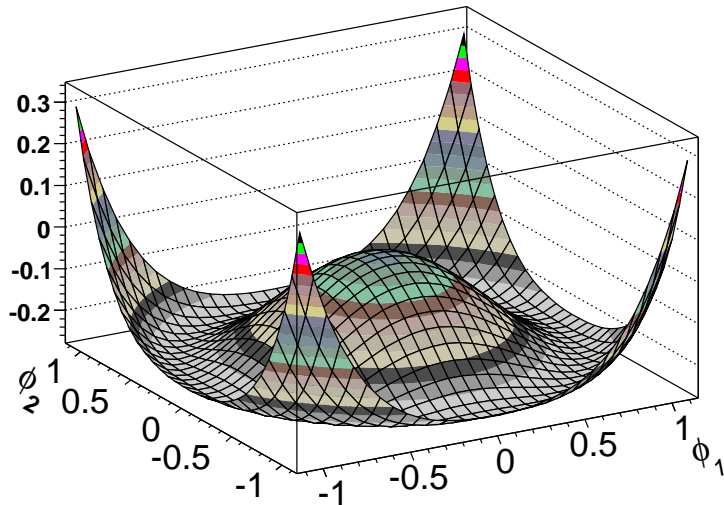
**Toshihide Maskawa**

🏆 1/4 of the prize

# Spontaneous Symmetry Breaking

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

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

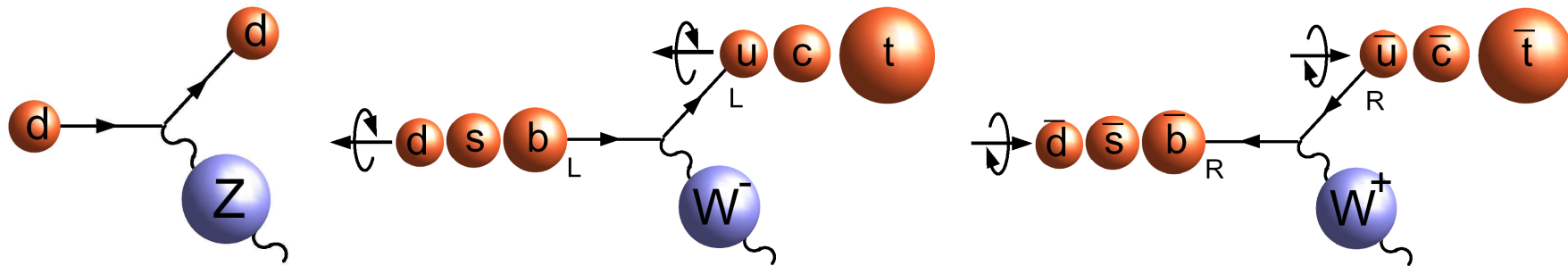


- Higgs particle described by one field component

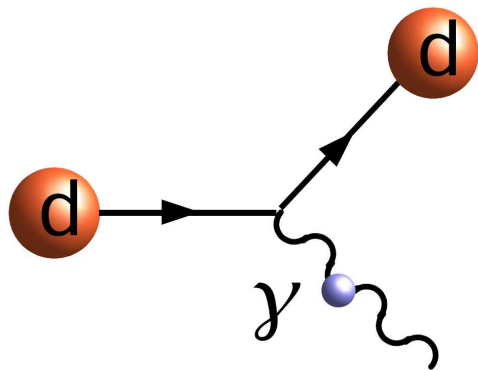
$$\eta = \phi_1 - v$$

# What about other Higgs field components?

- The other field components  $\phi_2, \phi_3, \phi_4$  “couple” to Weak Interaction bosons  $Z, W^-, W^+$  and give them **mass**



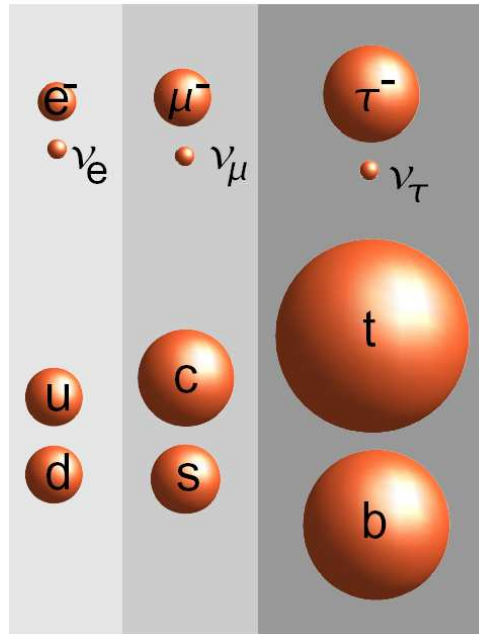
- Photon  $\gamma$  is the same Weak Interaction boson but remains **massless** (does not couple to Higgs field)



# All Elementary Particles get Mass from Higgs Field

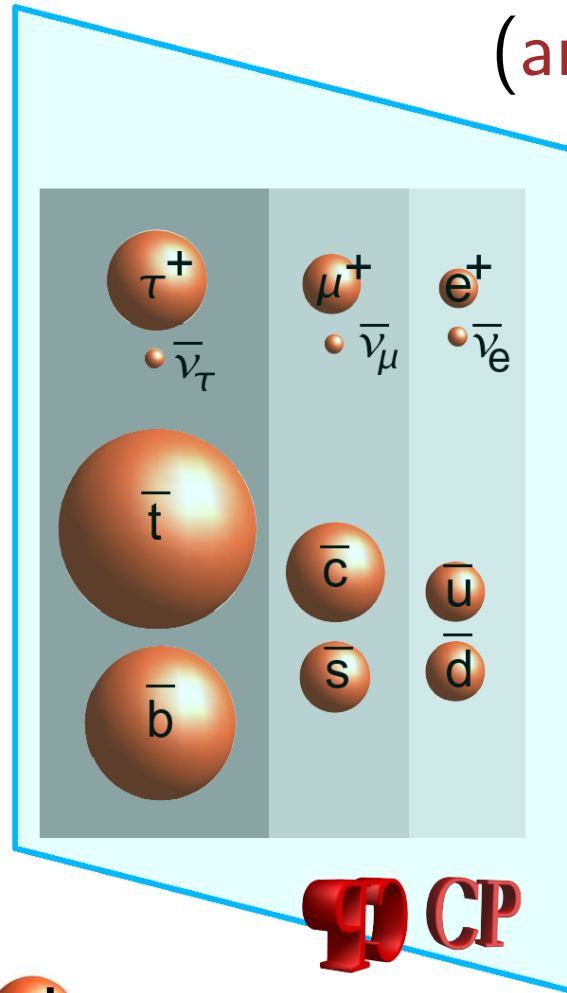
- Fermions  $S = \frac{\hbar}{2}$  (matter)

leptons



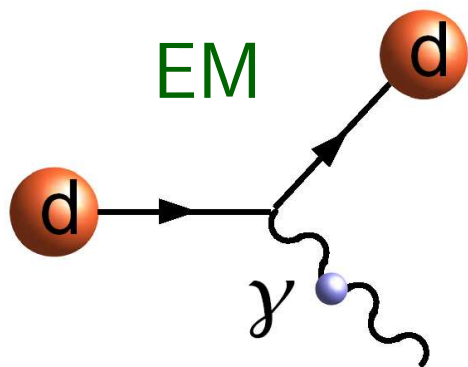
quarks

(anti-matter)

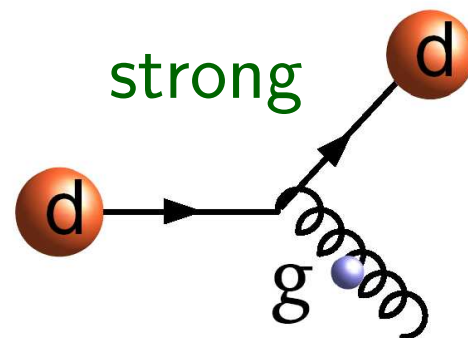


- Bosons  $S = \hbar$  (force carriers):

**CP**



EM



strong

← massless

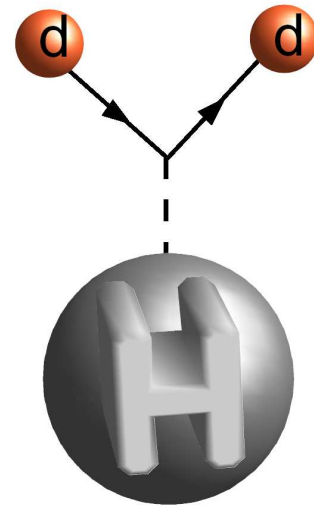
(weak force bosons mass)



# 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?

**PERIODIC TABLE**  
**Atomic Properties of the Elements**

**NIST**  
National Institute of Standards and Technology  
Technology Administration, U.S. Department of Commerce

**Frequently used fundamental physical constants**

For the most accurate values of these and other constants, visit [physics.nist.gov/constants](http://physics.nist.gov/constants)  
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of  $^{133}\text{Cs}$

speed of light in vacuum	$c$	299 792 458 $\text{m s}^{-1}$	(exact)
Planck constant	$h$	$6.6261 \times 10^{-34} \text{ J s}$	$(h = h/2\pi)$
elementary charge	$e$	$1.6022 \times 10^{-19} \text{ C}$	
electron mass	$m_e$	$9.1094 \times 10^{-31} \text{ kg}$	
	$m_e c^2$	0.5110 MeV	
proton mass	$m_p$	$1.6726 \times 10^{-27} \text{ kg}$	
fine-structure constant	$\alpha$	1/137.036	
Rydberg constant	$R_\infty$	$10\,973\,732 \text{ m}^{-1}$	
	$R_\infty c$	$3.289\,842 \times 10^{15} \text{ Hz}$	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	$k$	$1.3807 \times 10^{-23} \text{ J K}^{-1}$	

Solids  
 Liquids  
 Gases  
 Artificially Prepared

Group	PERIODIC TABLE										Physcis Laboratory <a href="http://physics.nist.gov">physics.nist.gov</a>		Standard Reference Data Group <a href="http://www.nist.gov/srd">www.nist.gov/srd</a>		18 VIII				
	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9	10	11 IB	12 IIB	13 IIIA	14 IVA		15 VA	16 VIA	17 VIIA	
1	<b>H</b> Hydrogen 1.00794 $1s$ 13.5984												<b>B</b> Boron 10.811 $1s^2 2s^2 2p$ 8.2980	<b>C</b> Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.2603	<b>N</b> Nitrogen 14.0067 $1s^2 2s^2 2p^3$ 14.5341	<b>O</b> Oxygen 15.9994 $1s^2 2s^2 2p^4$ 13.6181	<b>F</b> Fluorine 18.9984032 $1s^2 2s^2 2p^5$ 17.4228	<b>Ne</b> Neon 20.1797 $1s^2 2s^2 2p^6$ 21.5645	
2	<b>Li</b> Lithium 6.941 $1s^2 2s$ 5.3917	<b>Be</b> Beryllium 9.012182 $1s^2 2s^2$ 9.3227										<b>Al</b> Aluminum 26.981538 $[\text{Ne}]3s^2 3p$ 5.9858	<b>Si</b> Silicon 28.0855 $[\text{Ne}]3s^2 3p^2$ 8.1517	<b>P</b> Phosphorus 30.973761 $[\text{Ne}]3s^2 3p^3$ 10.4867	<b>S</b> Sulfur 32.065 $[\text{Ne}]3s^2 3p^4$ 10.3600	<b>Cl</b> Chlorine 35.453 $[\text{Ne}]3s^2 3p^5$ 12.9676	<b>Ar</b> Argon 39.948 $[\text{Ne}]3s^2 3p^6$ 15.7596		
3	<b>Na</b> Sodium 22.989770 $[\text{Ne}]3s$ 5.1391	<b>Mg</b> Magnesium 24.3050 $[\text{Ne}]3s^2$ 7.6462																	
4	<b>K</b> Potassium 39.0983 $[\text{Ar}]4s$ 4.3407	<b>Ca</b> Calcium 40.078 $[\text{Ar}]3d^1 4s^2$ 6.1132	<b>Sc</b> Scandium 44.955910 $[\text{Ar}]3d^1 4s^2$ 6.5615	<b>Ti</b> Titanium 47.887 $[\text{Ar}]3d^2 4s^2$ 6.8281	<b>V</b> Vanadium 50.9415 $[\text{Ar}]3d^3 4s^2$ 6.7462	<b>Cr</b> Chromium 51.9961 $[\text{Ar}]3d^5 4s^1$ 6.7985	<b>Mn</b> Manganese 54.938049 $[\text{Ar}]3d^5 4s^2$ 7.4340	<b>Fe</b> Iron 55.845 $[\text{Ar}]3d^6 4s^2$ 7.9024	<b>Co</b> Cobalt 58.933200 $[\text{Ar}]3d^7 4s^2$ 7.8810	<b>Ni</b> Nickel 58.6934 $[\text{Ar}]3d^8 4s^2$ 7.6398	<b>Cu</b> Copper 63.546 $[\text{Ar}]3d^9 4s^1$ 7.7264	<b>Zn</b> Zinc 65.409 $[\text{Ar}]3d^10 4s^2$ 9.3942	<b>Ga</b> Gallium 69.723 $[\text{Ar}]3d^10 4s^2 4p$ 5.9993	<b>Ge</b> Germanium 72.64 $[\text{Ar}]3d^10 4s^2 4p^2$ 7.8994	<b>As</b> Arsenic 74.92160 $[\text{Ar}]3d^10 4s^2 4p^3$ 9.7866	<b>Se</b> Selenium 78.96 $[\text{Ar}]3d^10 4s^2 4p^4$ 9.7524	<b>Br</b> Bromine 79.904 $[\text{Ar}]3d^10 4s^2 4p^5$ 11.8138	<b>Kr</b> Krypton 83.798 $[\text{Ar}]3d^10 4s^2 4p^6$ 13.9996	
5	<b>Rb</b> Rubidium 85.4678 $[\text{Kr}]5s$ 4.1771	<b>Sr</b> Strontium 87.62 $[\text{Kr}]5s^2$ 5.6949	<b>Y</b> Yttrium 88.90585 $[\text{Kr}]4d^1 5s^2$ 6.2173	<b>Zr</b> Zirconium 91.224 $[\text{Kr}]4d^2 5s^2$ 6.6339	<b>Nb</b> Niobium 92.90638 $[\text{Kr}]4d^4 5s^1$ 6.7589	<b>Mo</b> Molybdenum 95.94 $[\text{Kr}]4d^5 5s^1$ 7.28	<b>Tc</b> Technetium (98) $[\text{Kr}]4d^5 5s^2$ 7.28	<b>Ru</b> Ruthenium 101.07 $[\text{Kr}]4d^7 5s^1$ 7.3005	<b>Rh</b> Rhodium 102.90550 $[\text{Kr}]4d^8 5s^1$ 7.4589	<b>Pd</b> Palladium 106.42 $[\text{Kr}]4d^10$ 8.3369	<b>Ag</b> Silver 107.8682 $[\text{Kr}]4d^10 5s^1$ 7.5762	<b>Cd</b> Cadmium 112.411 $[\text{Kr}]4d^10 5s^2$ 8.9938	<b>In</b> Indium 114.818 $[\text{Kr}]4d^10 5s^2 5p$ 5.7864	<b>Sn</b> Tin 118.710 $[\text{Kr}]4d^10 5s^2 5p^2$ 7.2439	<b>Sb</b> Antimony 121.760 $[\text{Kr}]4d^10 5s^2 5p^3$ 8.6084	<b>Te</b> Tellurium 127.60 $[\text{Kr}]4d^10 5s^2 5p^4$ 9.0096	<b>I</b> Iodine 126.90447 $[\text{Kr}]4d^10 5s^2 5p^5$ 10.4513	<b>Xe</b> Xenon 131.293 $[\text{Kr}]4d^10 5s^2 5p^6$ 12.1298	
6	<b>Cs</b> Cesium 132.90545 $[\text{Xe}]6s$ 3.8939	<b>Ba</b> Barium 137.327 $[\text{Xe}]6s^2$ 5.2117		<b>Hf</b> Hafnium 178.49 $[\text{Xe}]4f^14 5d^2 6s^2$ 6.8251	<b>Ta</b> Tantalum 180.9479 $[\text{Xe}]4f^14 5d^3 6s^2$ 7.5496	<b>W</b> Tungsten 183.84 $[\text{Xe}]4f^14 5d^4 6s^2$ 7.8640	<b>Re</b> Rhenium 186.207 $[\text{Xe}]4f^14 5d^5 6s^2$ 7.8335	<b>Os</b> Osmium 190.23 $[\text{Xe}]4f^14 5d^6 6s^2$ 8.4382	<b>Ir</b> Iridium 192.217 $[\text{Xe}]4f^14 5d^7 6s^2$ 8.9670	<b>Pt</b> Platinum 195.078 $[\text{Xe}]4f^14 5d^9 6s^1$ 8.9588	<b>Au</b> Gold 196.96655 $[\text{Xe}]4f^14 5d^10 6s^1$ 9.2255	<b>Hg</b> Mercury 200.59 $[\text{Xe}]4f^14 5d^10 6s^2$ 10.4375	<b>Tl</b> Thallium 204.3833 $[\text{Hg}]6p$ 6.1082	<b>Pb</b> Lead 207.2 $[\text{Hg}]6p^2$ 7.4167	<b>Bi</b> Bismuth 208.98038 $[\text{Hg}]6p^3$ 7.2855	<b>Po</b> Polonium (209) $[\text{Hg}]6p^4$ 8.414	<b>At</b> Astatine (210) $[\text{Hg}]6p^5$	<b>Rn</b> Radon (222) $[\text{Hg}]6p^6$ 10.7485	
7	<b>Fr</b> Francium (223) $[\text{Rn}]7s$ 4.0727	<b>Ra</b> Radium (226) $[\text{Rn}]7s^2$ 5.2784		<b>Rf</b> Rutherfordium (261) $[\text{Rn}]5f^14 6d^2 7s^2$ 6.0 ?	<b>Db</b> Dubnium (262)	<b>Sg</b> Seaborgium (266)	<b>Bh</b> Bohrium (264)	<b>Hs</b> Hassium (277)	<b>Mt</b> Meitnerium (268)	<b>Uun</b> Ununnilium (281)	<b>Uuu</b> Ununnilium (272)	<b>Uub</b> Ununbium (285)		<b>Uuq</b> Ununquadium (289)		<b>Uuh</b> Ununhexium (292)			
			<b>Lanthanides</b>	<b>La</b> Lanthanum 138.9055 $[\text{Xe}]5d^1 6s^2$ 5.5789	<b>Ce</b> Cerium 140.116 $[\text{Xe}]4f^1 5d^1 6s^2$ 5.5387	<b>Pr</b> Praseodymium 140.90705 $[\text{Xe}]4f^3 6s^2$ 5.473	<b>Nd</b> Neodymium 144.24 $[\text{Xe}]4f^4 6s^2$ 5.5250	<b>Pm</b> Promethium (145) $[\text{Xe}]4f^5 6s^2$ 5.582	<b>Sm</b> Samarium 150.36 $[\text{Xe}]4f^6 6s^2$ 5.6437	<b>Eu</b> Europium 151.964 $[\text{Xe}]4f^7 6s^2$ 5.6704	<b>Gd</b> Gadolinium 157.25 $[\text{Xe}]4f^7 5d^1 6s^2$ 5.9638	<b>Tb</b> Terbium 158.92534 $[\text{Xe}]4f^9 6s^2$ 5.9389	<b>Dy</b> Dysprosium 162.500 $[\text{Xe}]4f^10 6s^2$ 6.0215	<b>Ho</b> Holmium 164.93032 $[\text{Xe}]4f^11 6s^2$ 6.1077	<b>Er</b> Erbium 167.259 $[\text{Xe}]4f^12 6s^2$ 6.1843	<b>Tm</b> Thulium 168.93421 $[\text{Xe}]4f^13 6s^2$ 6.2542	<b>Yb</b> Ytterbium 173.04 $[\text{Xe}]4f^14 6s^2$ 6.2542	<b>Lu</b> Lutetium 174.967 $[\text{Xe}]4f^14 5d^1 6s^2$ 5.4259	
			<b>Actinides</b>	<b>Ac</b> Actinium (227) $[\text{Rn}]6d^1 7s^2$ 5.17	<b>Th</b> Thorium 232.0381 $[\text{Rn}]6d^2 7s^2$ 6.3067	<b>Pa</b> Protactinium 231.03688 $[\text{Rn}]5f^2 6d^1 7s^2$ 5.89	<b>U</b> Uranium 238.02891 $[\text{Rn}]5f^3 6d^1 7s^2$ 6.1941	<b>Np</b> Neptunium (237) $[\text{Rn}]5f^4 6d^1 7s^2$ 6.2657	<b>Pu</b> Plutonium (244) $[\text{Rn}]5f^6 7s^2$ 6.0260	<b>Am</b> Americium (243) $[\text{Rn}]5f^7 7s^2$ 5.9738	<b>Cm</b> Curium (247) $[\text{Rn}]5f^7 6d^1 7s^2$ 5.9914	<b>Bk</b> Berkelium (247) $[\text{Rn}]5f^9 7s^2$ 6.1979	<b>Cf</b> Californium (251) $[\text{Rn}]5f^10 7s^2$ 6.2817	<b>Es</b> Einsteinium (252) $[\text{Rn}]5f^11 7s^2$ 6.42	<b>Fm</b> Fermium (257) $[\text{Rn}]5f^12 7s^2$ 6.50	<b>Md</b> Mendelevium (258) $[\text{Rn}]5f^13 7s^2$ 6.58	<b>No</b> Nobelium (259) $[\text{Rn}]5f^14 7s^2$ 6.65	<b>Lr</b> Lawrencium (260) $[\text{Rn}]5f^14 7s^2 7p^1$ 4.9 ?	

**Atomic Properties of Cerium (Ce):**  
 Atomic Number: 58  
 Symbol: Ce  
 Name: Cerium  
 Atomic Weight: 140.116  
 Ground-state Configuration:  $[\text{Xe}]4f^1 5d^1 6s^2$   
 Ionization Energy (eV): 5.5387  
 Ground-state Level:  $1G_4^0$

†Based upon  $^{12}\text{C}$ . () indicates the mass number of the most stable isotope.

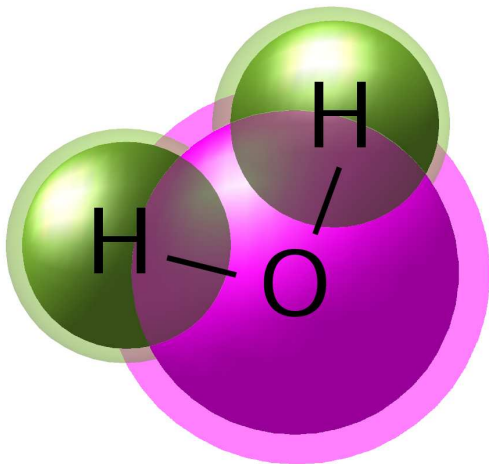
For a description of the data, visit [physics.nist.gov/data](http://physics.nist.gov/data)

NIST SP 966 (September 2003)

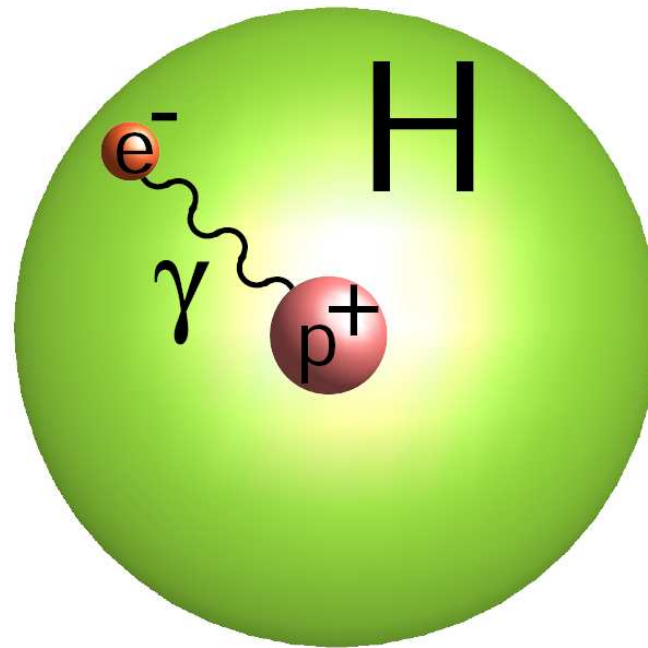
# What does make mass?

---

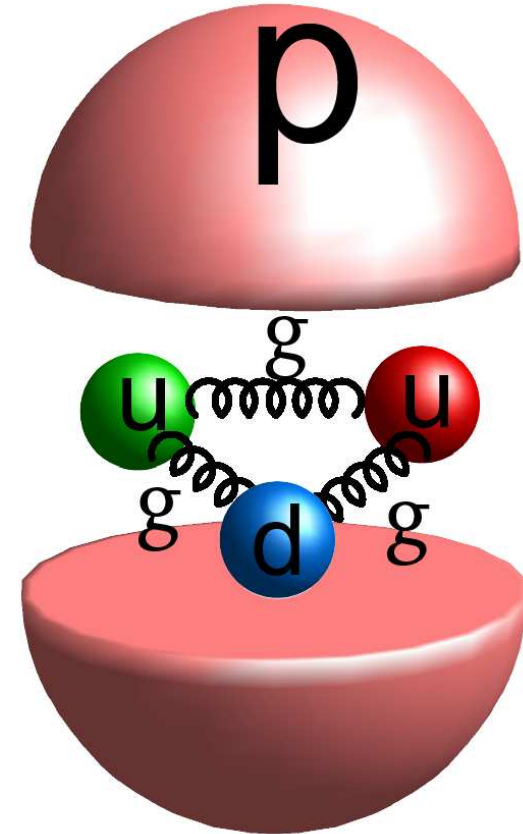
- What gives us mass?



Molecules



Atoms

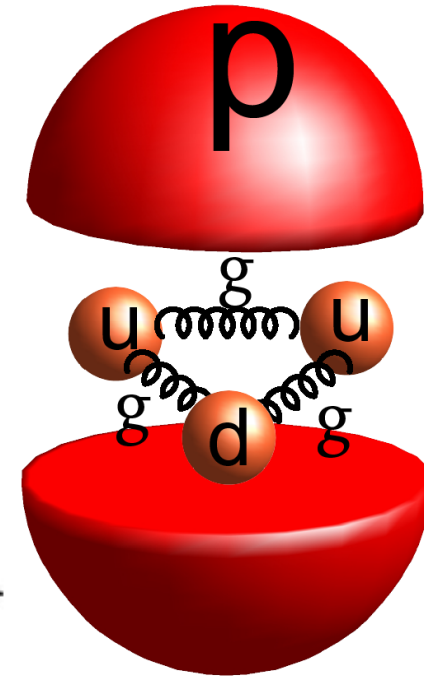
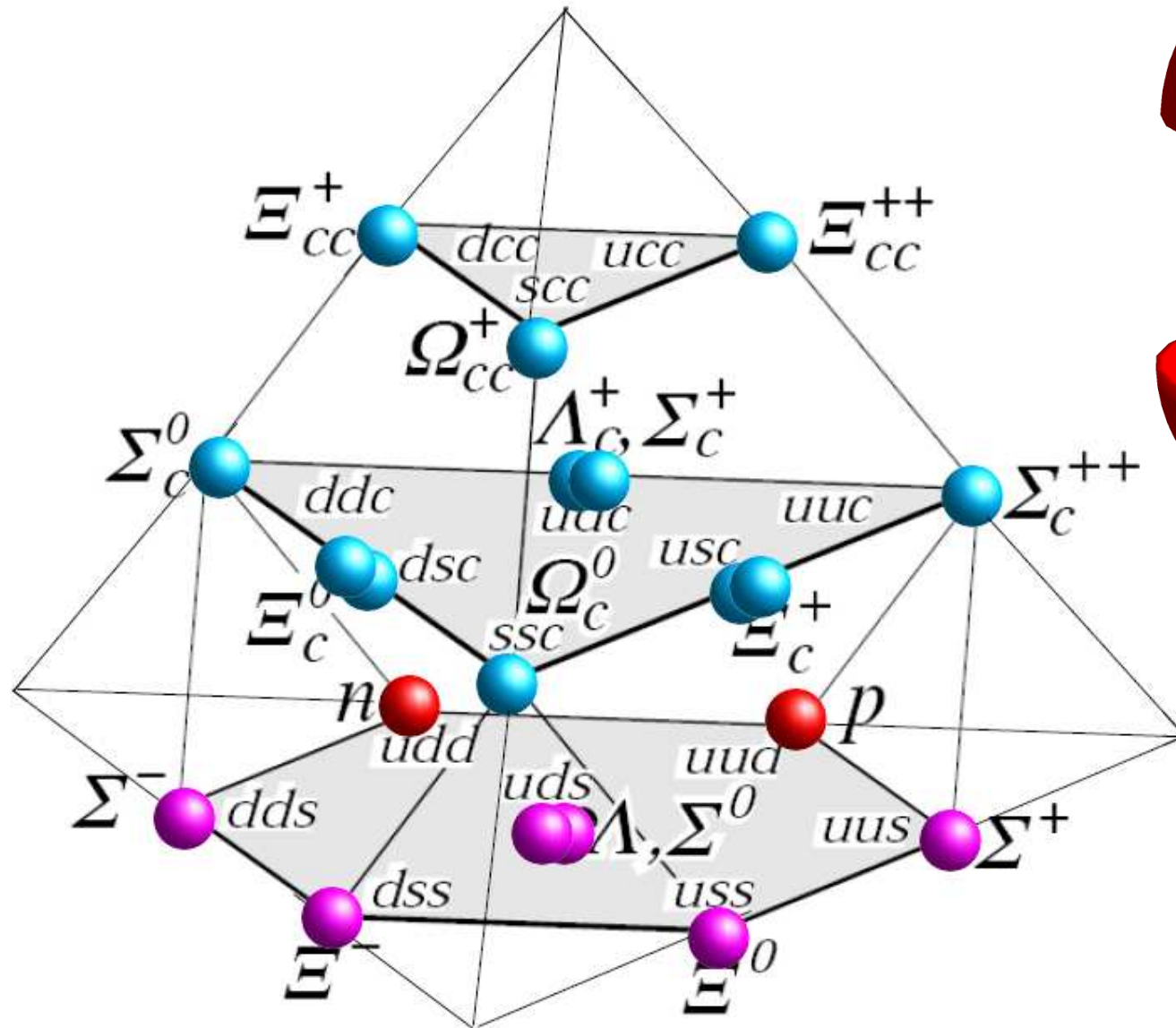


Nucleus



# “Periodic Table” of Baryons: Proton, Neutron,...

- Three quarks make up a **Baryon**:



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

---

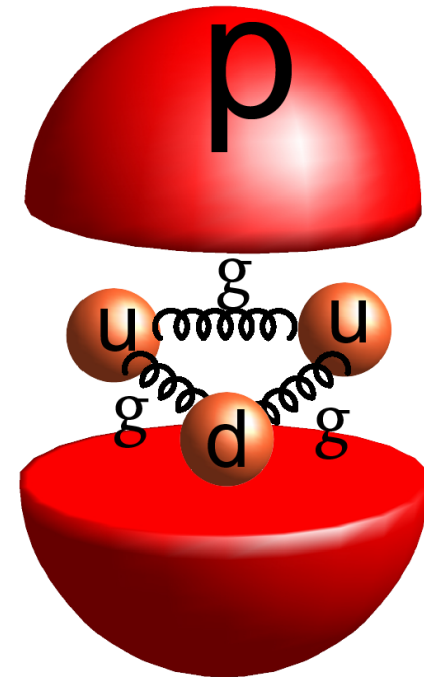
- Remember Einstein's formula

$$E = mc^2$$

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

Mostly energy of gluons and quarks inside gives proton mass

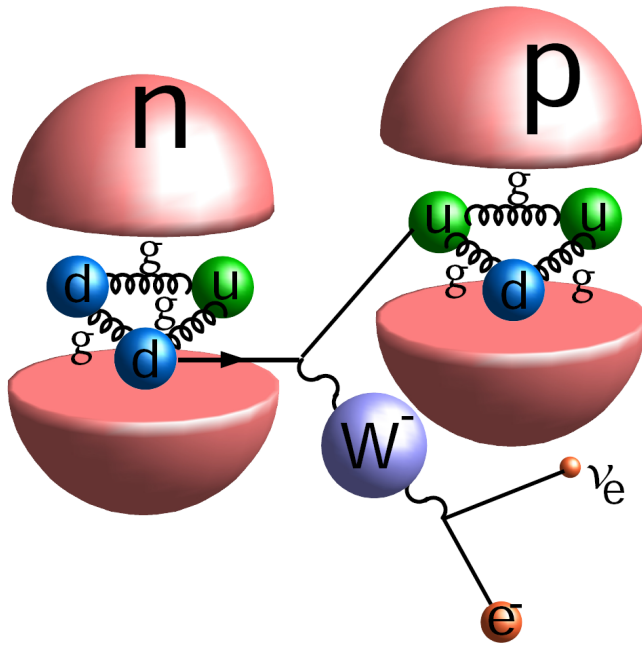
not really the Higgs mechanism



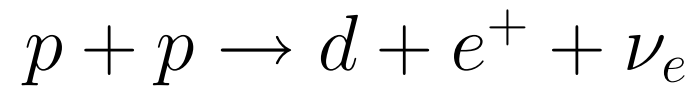
# But Higgs Mechanism is Very Important

---

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



similarly first step in sun fusion



- Makes certain hierarchy of masses  
essential for our existence

# Hypothetical Scenario: Different Quark Mass

---

- Again, normally proton is stable and neutron decays:

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

- Why is  $m(n) > m(p)$

- $m(p) = 938 \text{ MeV}$ ,  $m(n) - m(p) = 1.3 \text{ MeV}$

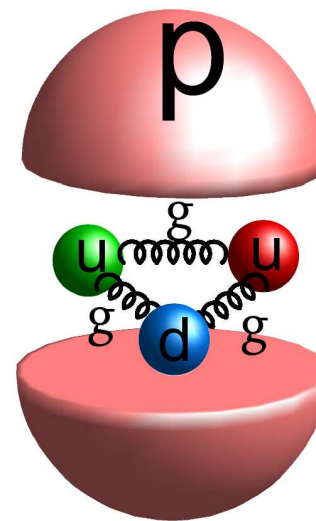
- tiny difference makes a big difference!

- naively expect  $m(p) > m(n)$  if  $u$  and  $d$  were the same

- but  $m(d) > m(u)$

- **New scenario:**

- what if  $m(d) < m(u)$

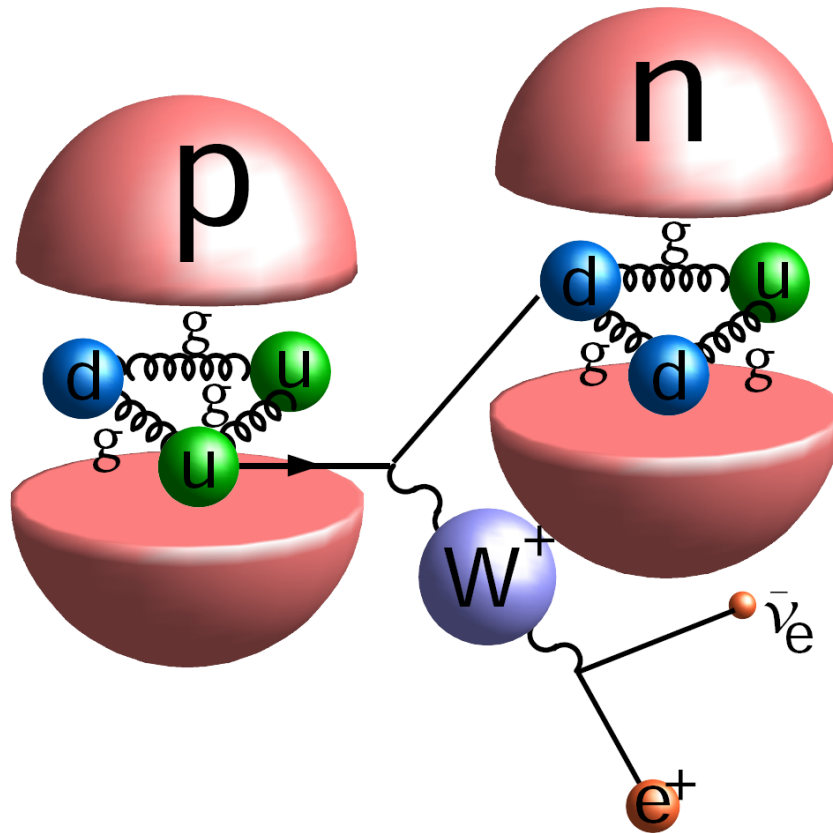




# Hypothetical Scenario: Different Quark Mass

---

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



- Consequence: no Hydrogen, no  $H_2O$ , no life
  - still have  $He^4$ , rapid  $nn$  fusion, instead of slower  $pp$

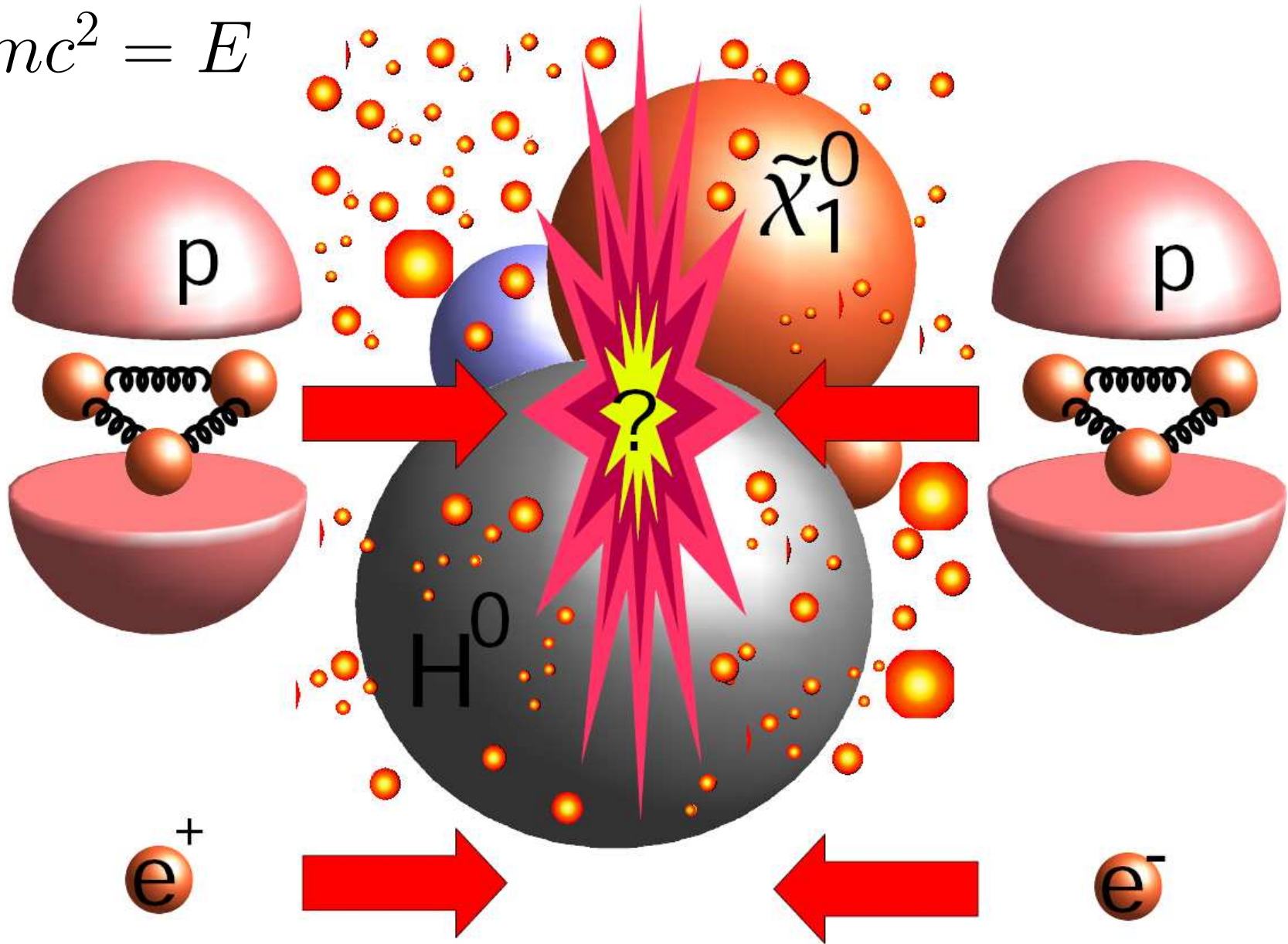
# Finding the Higgs

---

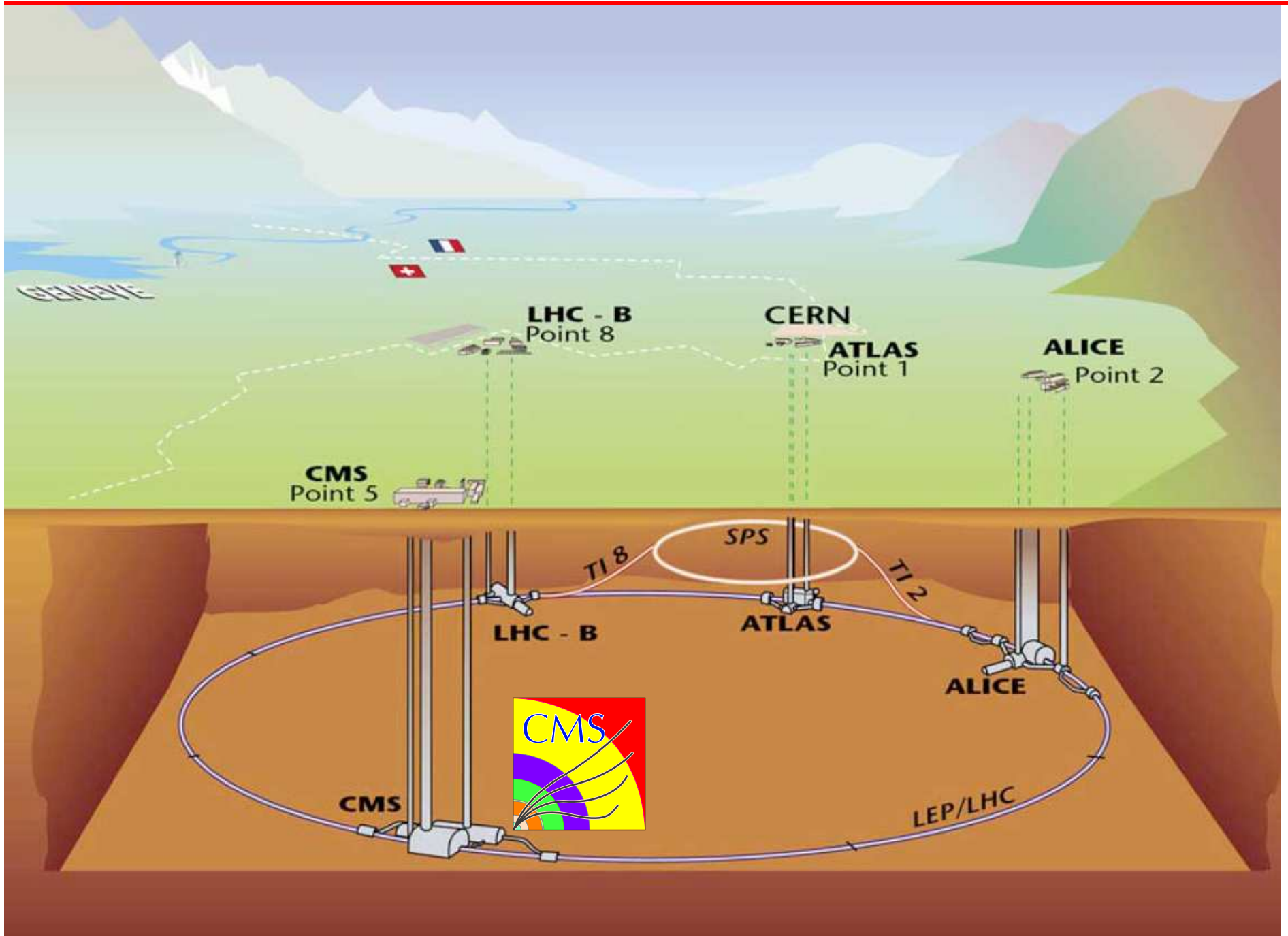
- If Higgs is so important:
  - how do we find the Higgs ?
  - or prove that it does not exist...

# Produce the Higgs: Reaching Highest Energy

- $mc^2 = E$



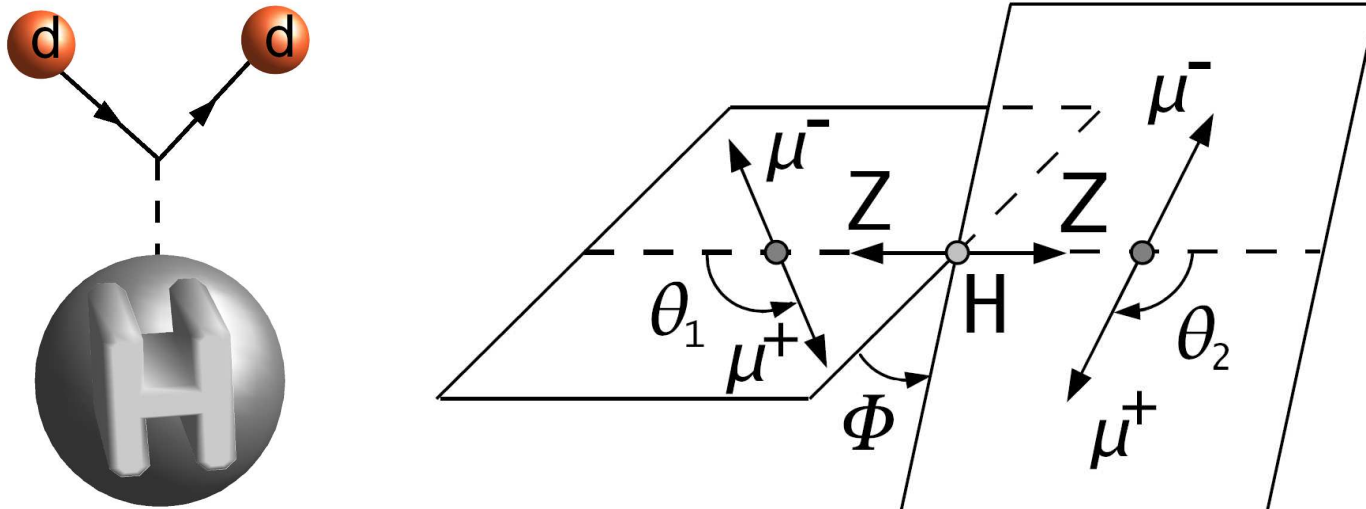
# Large Hadron Collider: Re-Start this Fall



# 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  $m(H) > 2 \times m(Z)$  then

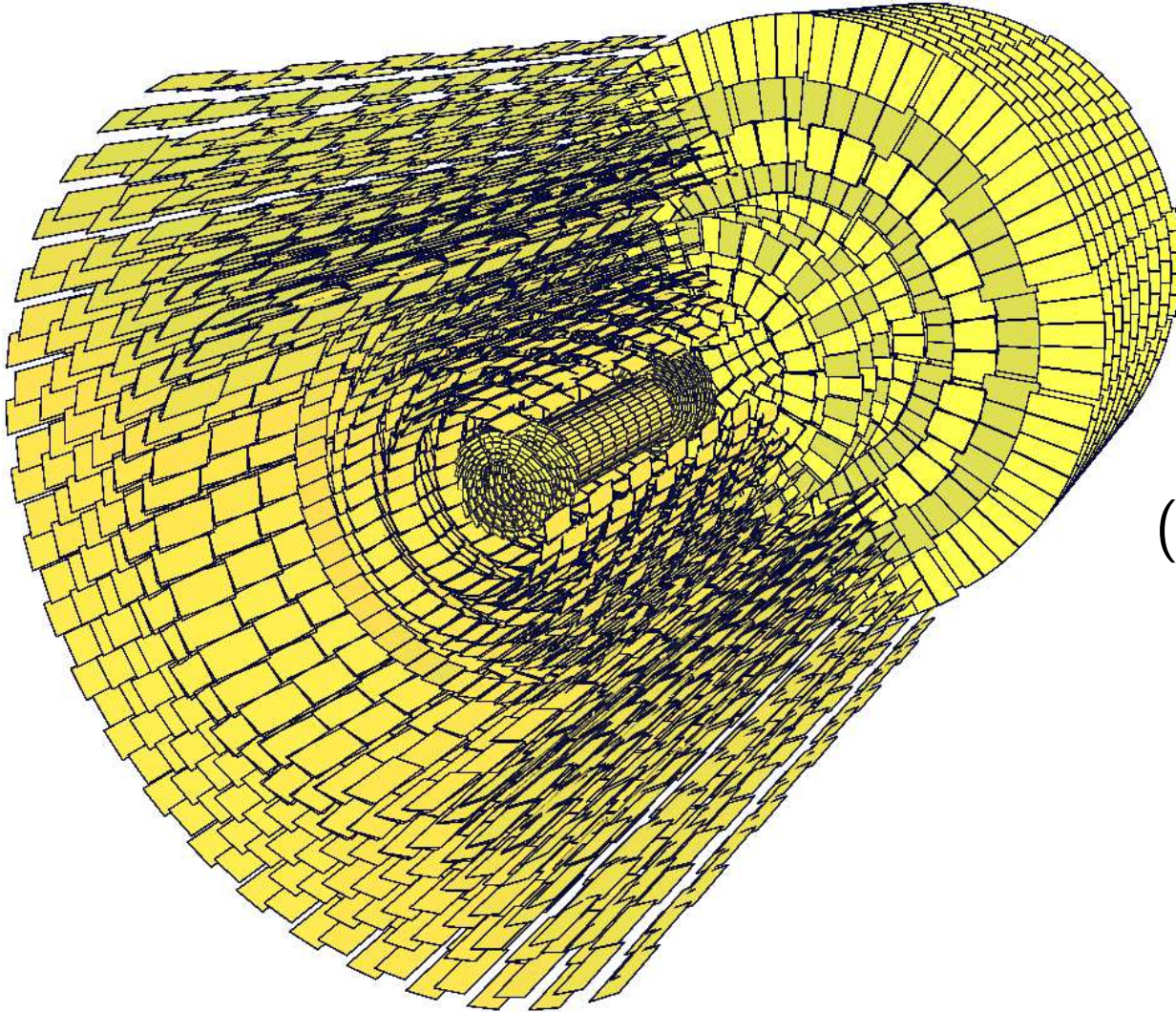
$H \rightarrow ZZ$  most likely, with  $Z \rightarrow \mu^+ \mu^-$  or similar





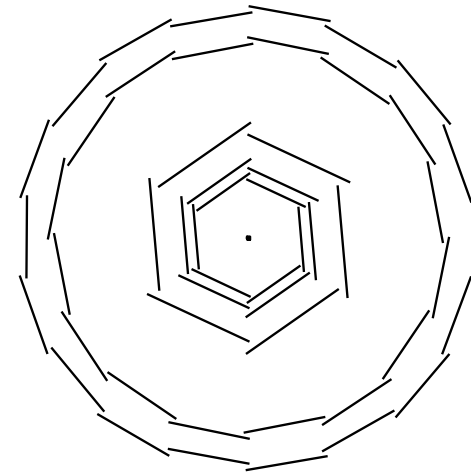
# Modern Tracking Detectors

---



← CMS tracker  
( $>15,000$  sensors)

↓ BABAR silicon  
(340 sensors,  $R \sim 15\text{cm}$ )





# CMS Experiment

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

## TRIGGER & DATA ACQUISITION

Austria, CERN, Finland, France, Greece, Hungary, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

## TRACKER

Austria, Belgium, CERN, Finland, France, New Zealand, Germany, Italy, Japan\*, Switzerland, UK, USA

## CRYSTAL ECAL

Belarus, CERN, China, Croatia, Cyprus, France, Ireland, Italy, Japan\*, Portugal, Russia, Serbia, Switzerland, UK, USA

## PRESHOWER

Armenia, Belarus, CERN, Greece, India, Russia, Taipei, Uzbekistan

## RETURN YOKE

Barrel: Czech Rep., Estonia, Germany, Greece, Russia  
Endcap: Japan\*, USA, Brazil

## SUPERCONDUCTING MAGNET

All countries in CMS contribute to Magnet financing in particular:  
Finland, France, Italy, Japan\*, Korea, Switzerland, USA

## FEET

Pakistan, China

## FORWARD CALORIMETER

Hungary, Iran, Russia, Turkey, USA

## HCAL

Barrel: Bulgaria, India, Spain\*, USA  
Endcap: Belarus, Bulgaria, Russia, Ukraine  
HO: India

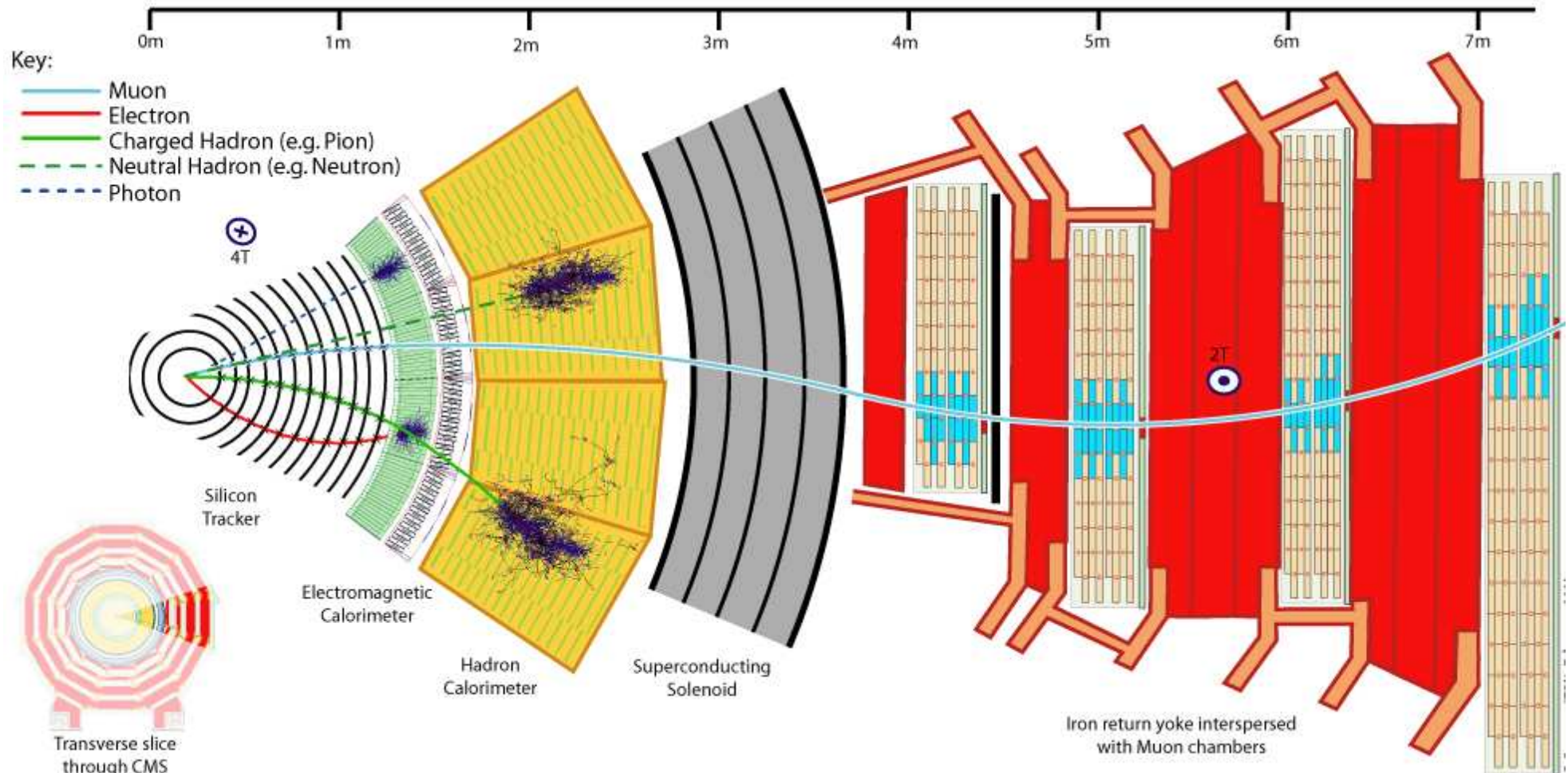
## MUON CHAMBERS

Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain,  
Endcap: Belarus, Bulgaria, China, Korea, Pakistan, Russia, USA

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

\* Only through industrial contracts

# Detecting Particles at CMS





# We are likely to find more than just Higgs

- New (**super**)symmetry:

$$Q|\text{fermion}\rangle = |\text{boson}\rangle$$

$$Q|\text{boson}\rangle = |\text{fermion}\rangle$$

- Solve:

(1) natural light

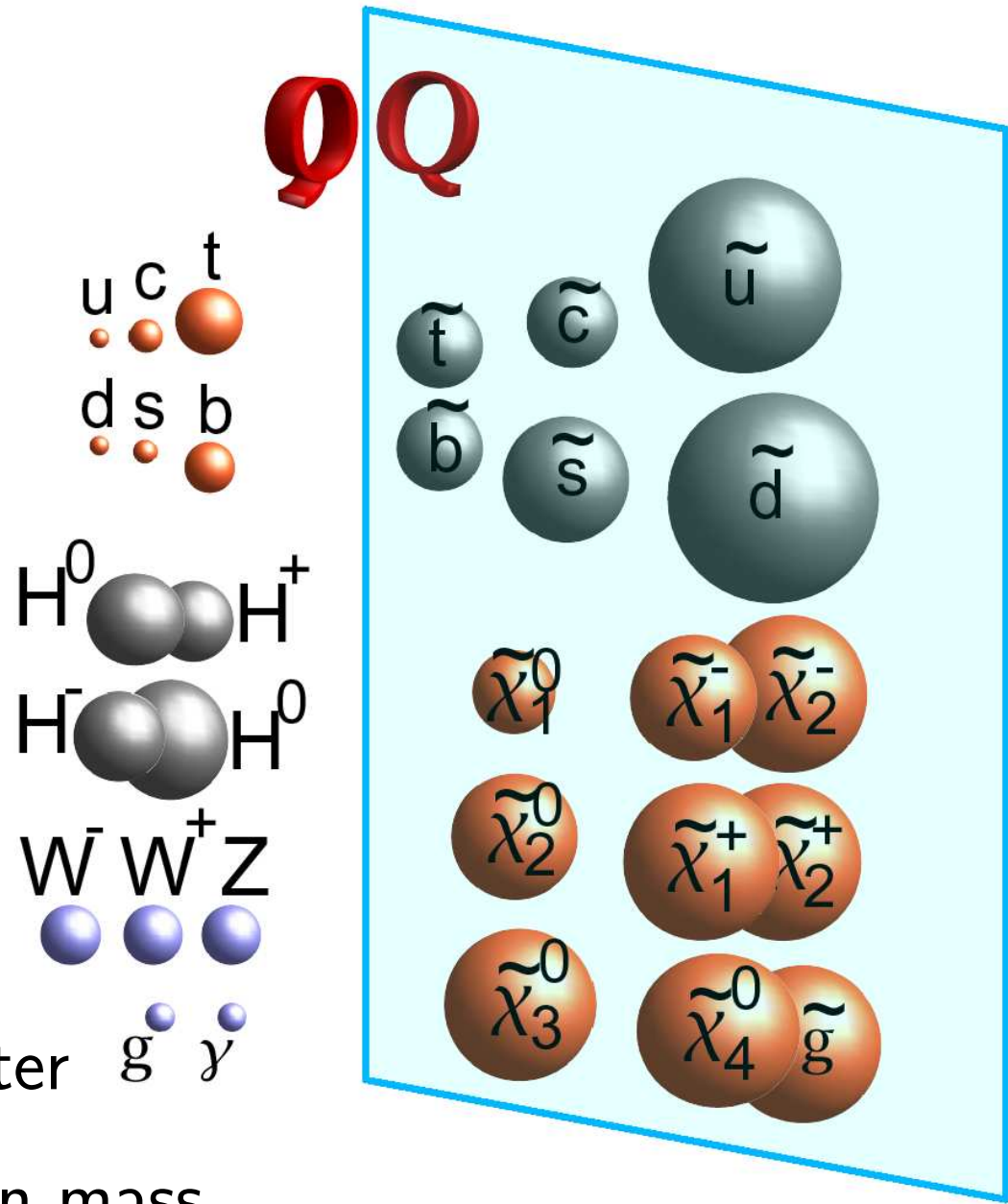
*Higgs*

(2) dark matter

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

(3) large **matter**/antimatter

$g \quad \gamma$



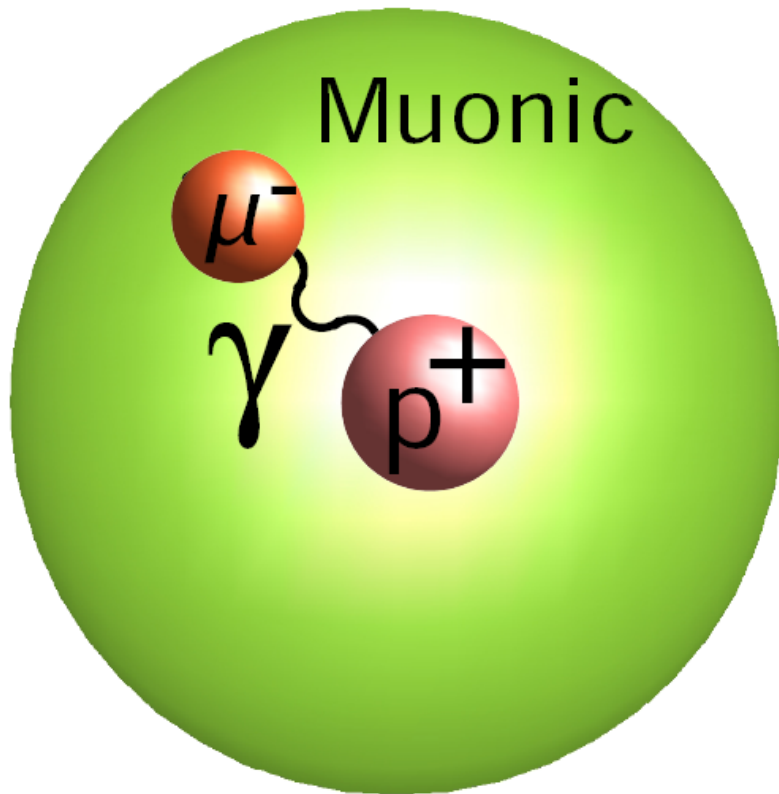
- Just around the corner in mass...

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 !

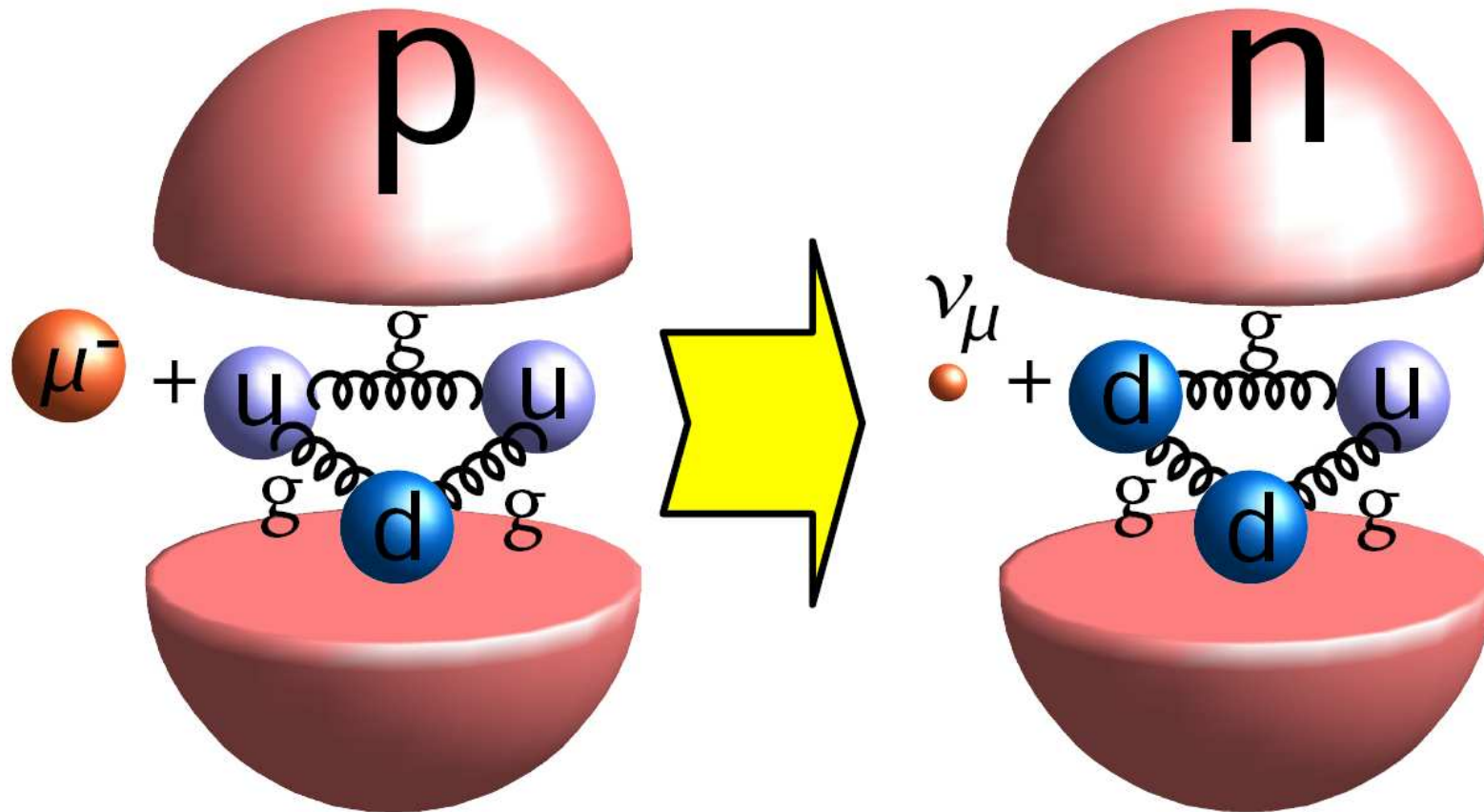
Hydrogen radius

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

# (1) Scenario: Muonic World

---

- However muonic hydrogen would decay:



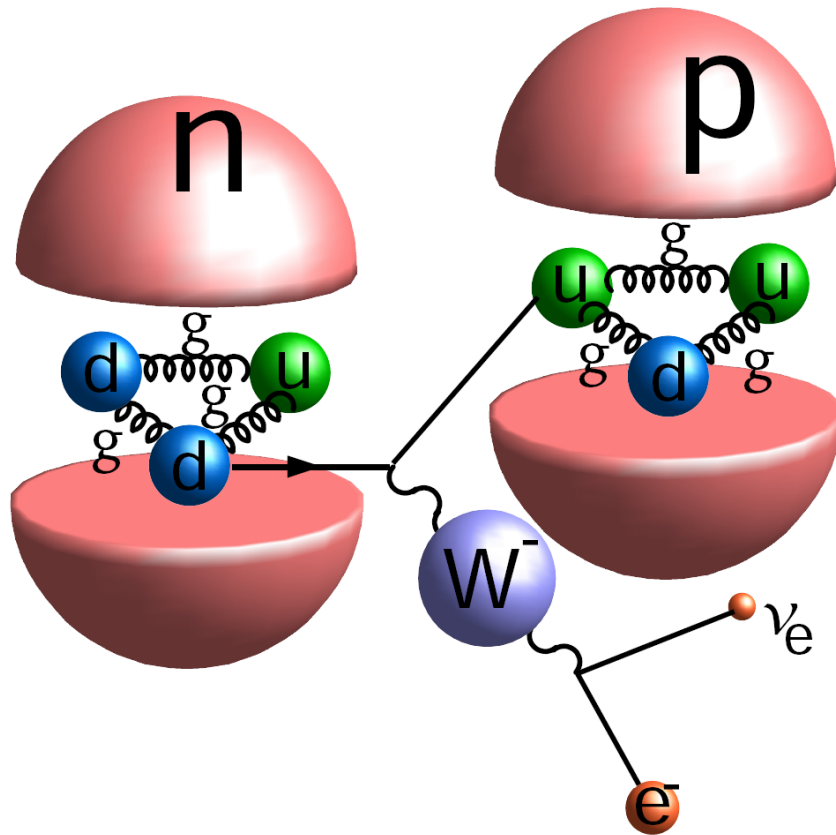
- Not very interesting universe
  - filled with neutral “balls” of neutrons and neutrinos

# (1) Scenario: Muonic World

---

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

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

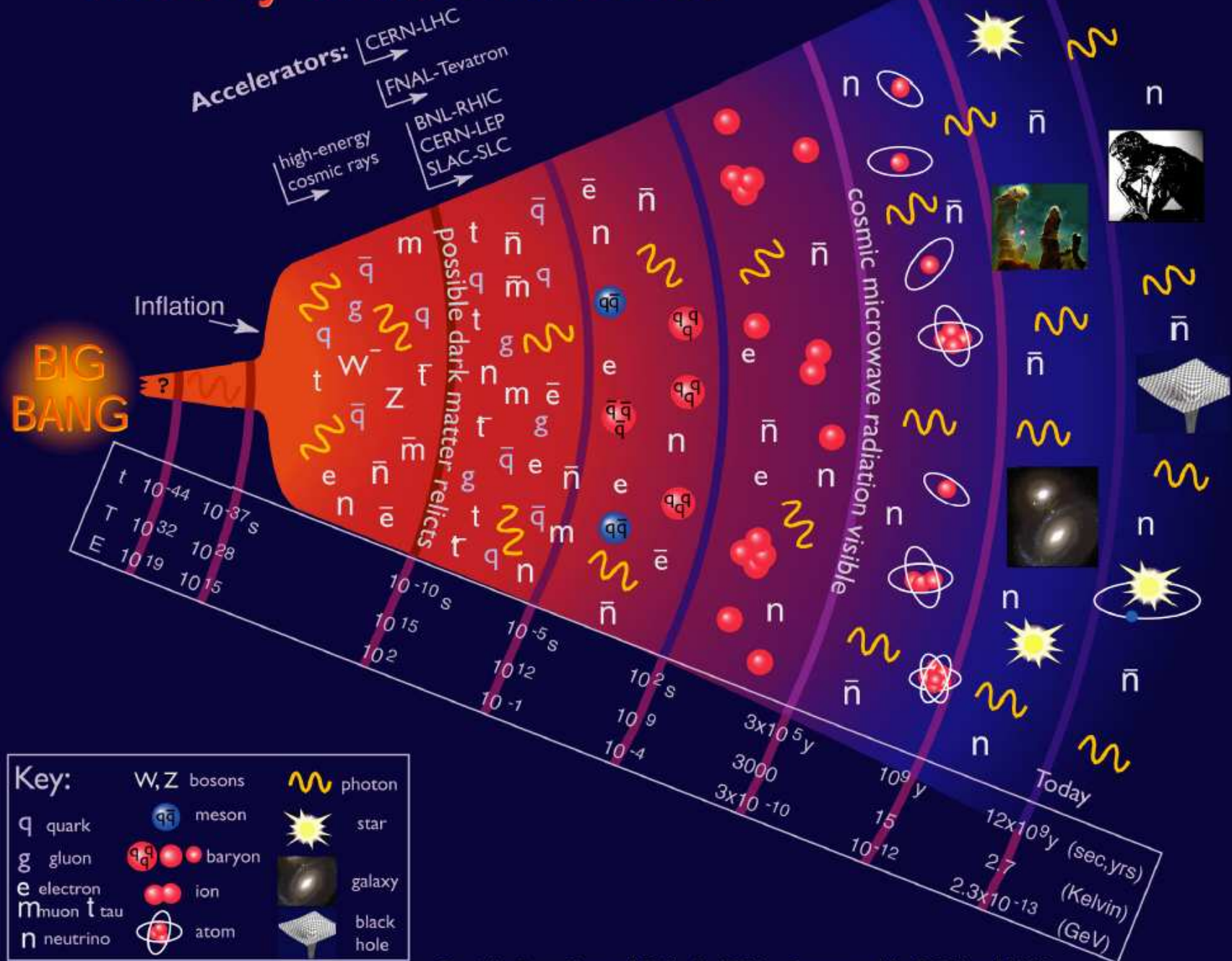


- But stable in the muonic world:

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

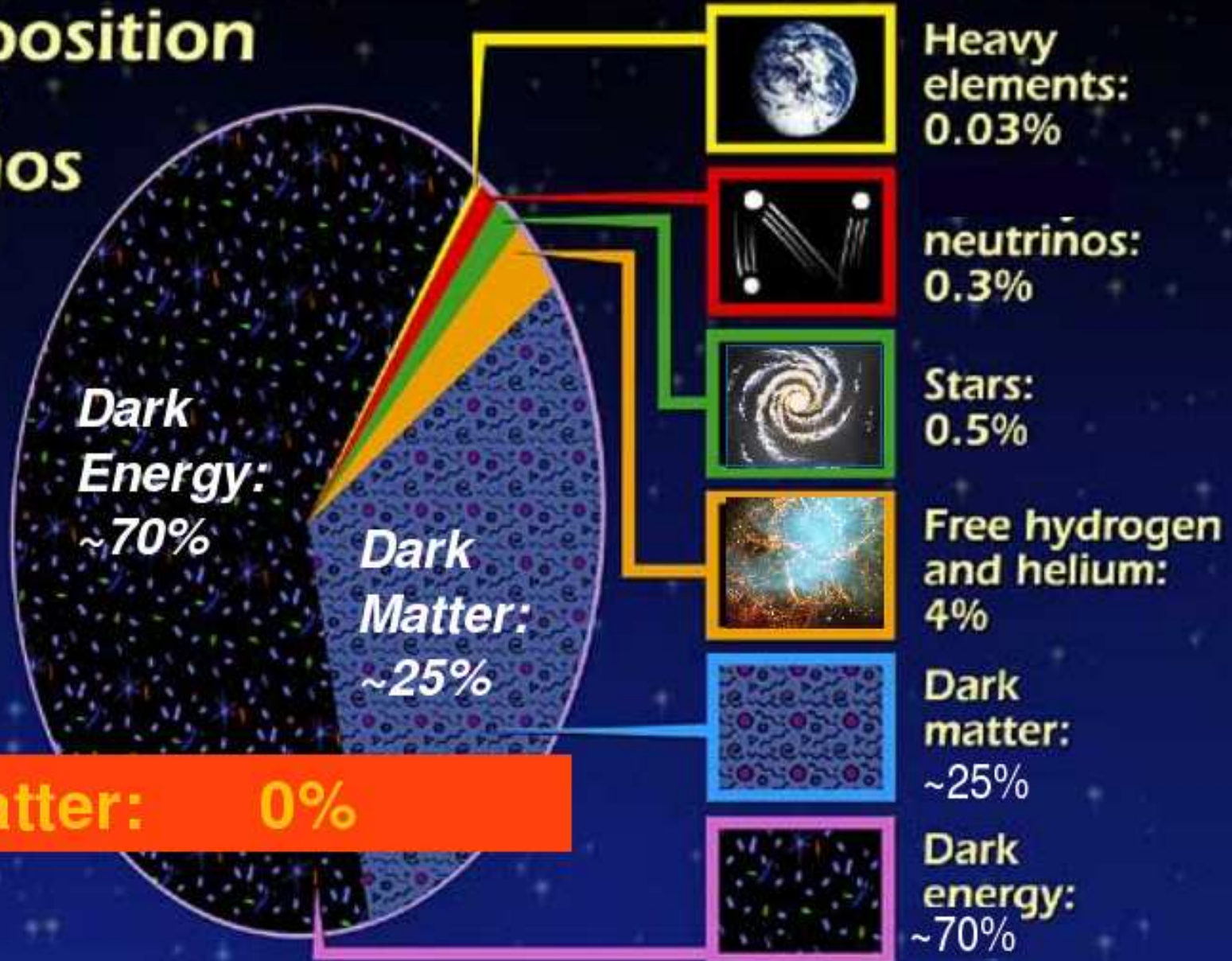


# History of the Universe



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

# Composition of the Cosmos





# 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*

