Higgs Boson and the Fate of Our Universe

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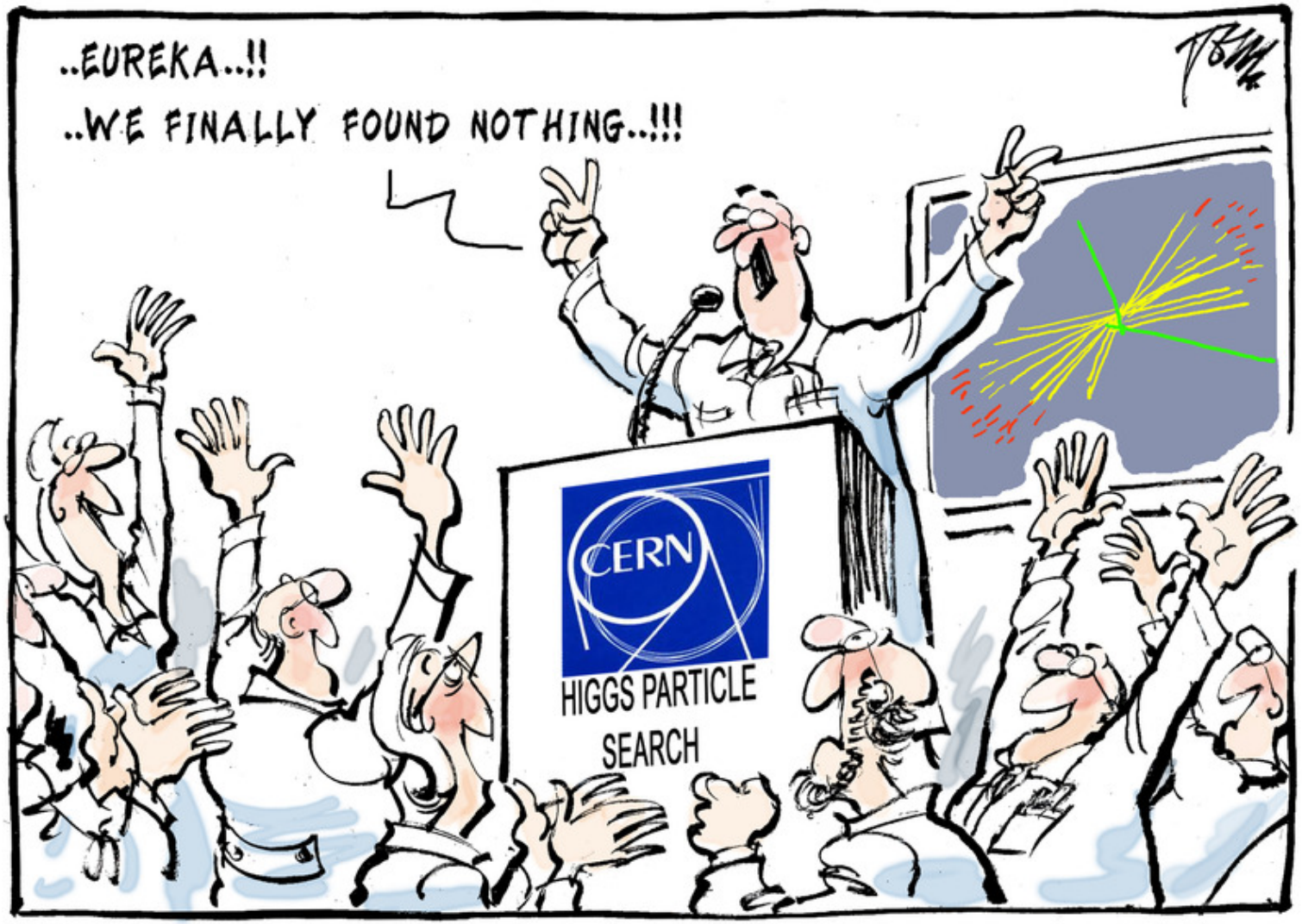
Hands on JuliaHEP Workshop
NED University of Engineering and Technology, Karachi.

On 4th July, 2012 it was announced ...



World press coverage ...


The New York Times

Wednesday, July 4, 2012 Last Update: 6:54 AM ET

Discovery of New Particle Could Redefine Physical World

By DENNIS OVERBYE
21 minutes ago

The discovery by physicists at CERN's Large Hadron Collider, if confirmed to be the Higgs boson particle, could lead to a new understanding of how the universe began.

- The Lede Blog: What in the World Is a Higgs Boson? 4:16 AM ET

Fabrice Coffrini/Agence France-Presse — Getty Images

CERN officials held a press conference near Geneva on Wednesday.


LA NEWS DEL GIORNO | Politica 10:21

Il Bosone di Higgs esiste, oggi l'annuncio del Cern a Ginevra

Tanti indizi per il "Santo Graal" della fisica quantistica teorizzato nel 1964. E' l'ultima particella ancora da scoprire

Roma, 4 lug. (TMNews) - L'enigma relativo all'esistenza del "bosone di Higgs", il "Santo Graal" della fisica delle particelle elementari, potrebbe essere oramai vicino alla soluzione: la conferenza stampa in programma oggi al Cern potrebbe dissipare gli ultimi dubbi.


LENTA.RU вторник, Прогресс
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04. 07. 2012, 12:13:02 Версия для печати | PDA

Изображение с сайта CERN

Физики обнаружили претендента на роль бозона Хиггса

Physicists discover a candidate for the boson Higgs

Plan of the talk

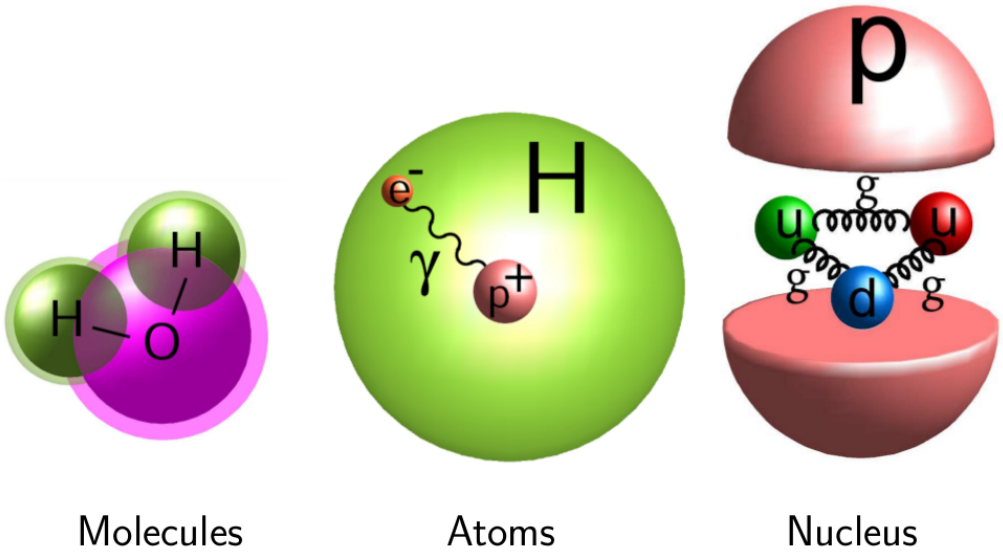
This talk is divided into two parts and I would like to discuss:

- Part-I
  What is the Higgs boson and why do we need it? what is its relation to the origin of mass?

- Part-II
  Why Higgs boson is so important and what is its relation to the fate of our universe?

- This baby is a symbol of life, happiness, love and hope
- She (her body) is also composed of atoms (matter)!
- Babies have about 80% water in their bodies
- Water is just H_2O

Structure of Matter



- Mass of up-quark (u) is 2.4 MeV (electric charge $\frac{2}{3}e$) and down-quark (d) is 4.8 MeV (electric charge $-\frac{1}{3}e$), while gluon (g)(carrier of nuclear strong force) have zero mass and zero electric charge!
- Mass of a proton is 937 MeV
- Where does rest of the mass come from?

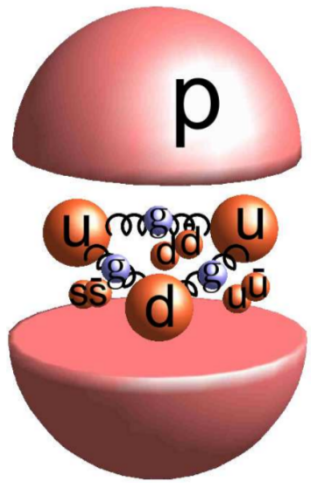
Origin of Mass-I

- In Newtonian world, mass is a conserved quantity
- No mass, no matter, no concept of origin of mass!!
- Light was not a matter (recall $\Sigma \vec{F} = m \vec{a}$)
- Einstein tells us, it is energy which is conserved and not the mass [1]
- He wrote $m = E/c^2$

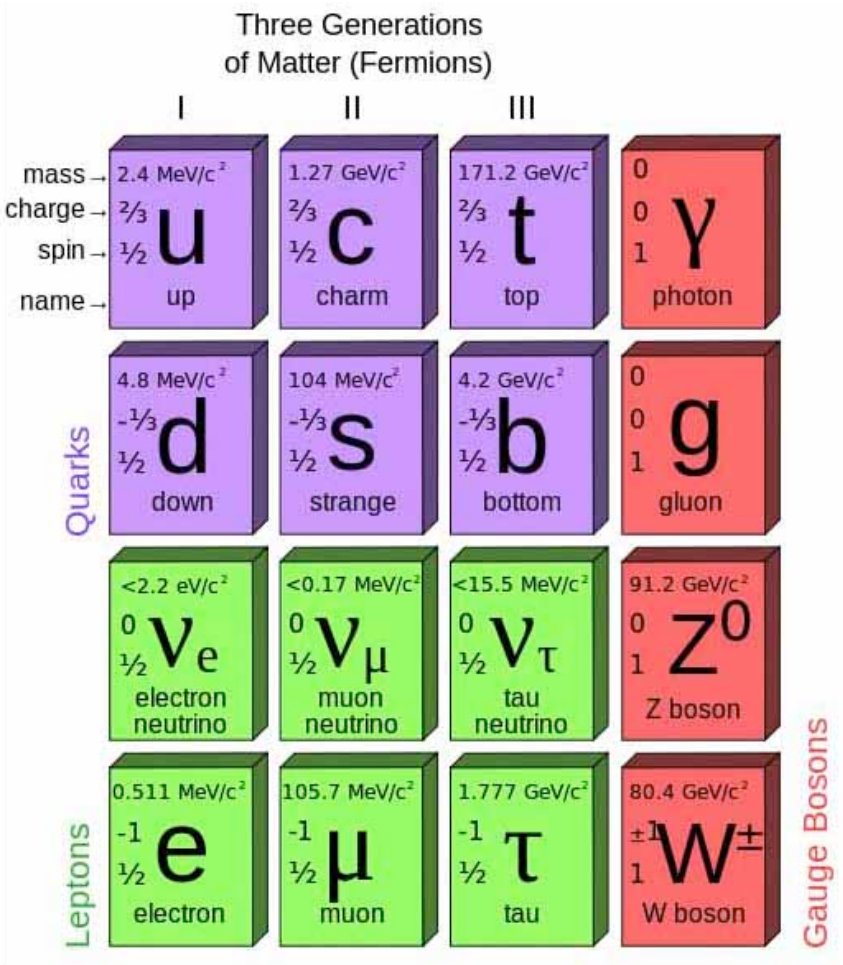
[1] Does the Inertia of a body depend upon its energy-content?, September 27, 1905

A closer Look at Proton Structure

- Rest of the mass of a proton comes from the binding energy of quarks and gluons in it!!
- Heisenberg uncertainty principle is in full swing! ($\Delta E \Delta t \gtrsim \frac{\hbar}{2}$)
- Quark-pairs can come out of nothing i.e vacuum!!
- Most of the mass of the luminous matter originates from quark-gluons binding energy



Fundamental Building Blocks of Luminous Matter

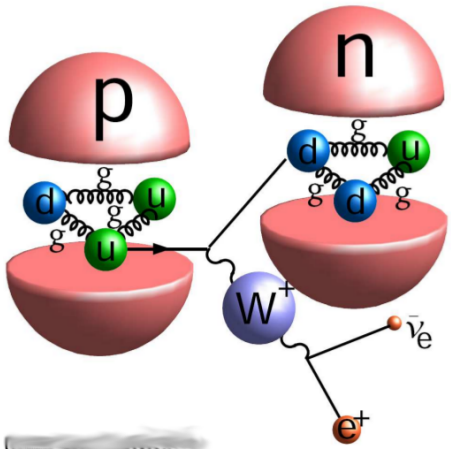


Some Deep Questions

- *How do fundamental particles get mass?*
  We know how and we have evidences!
- *Why some particles have mass, and some do not?*
  We almost know it, but looking for more data!
- *Also notice mass hierarchies ($m_d > m_u$ etc..)*
- *Why are three copies of quarks and leptons?*
  We have some speculations, need more work to do!

Some Important Observations

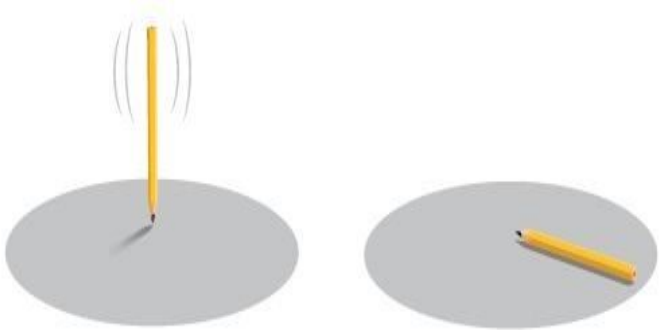
- Sunlight is needed for life on Earth
- In the Sun, nuclear fusion is taking place, which is governed by nuclear weak-force
- Any variation in W boson mass can alter the nuclear reactions in the Sun, can cause catastrophic effects for life on Earth

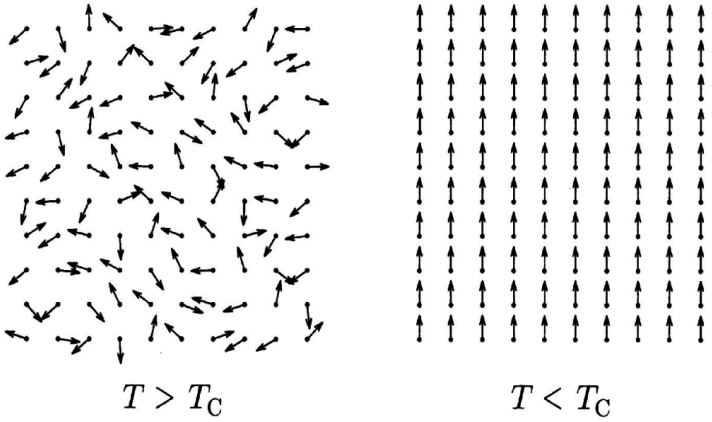


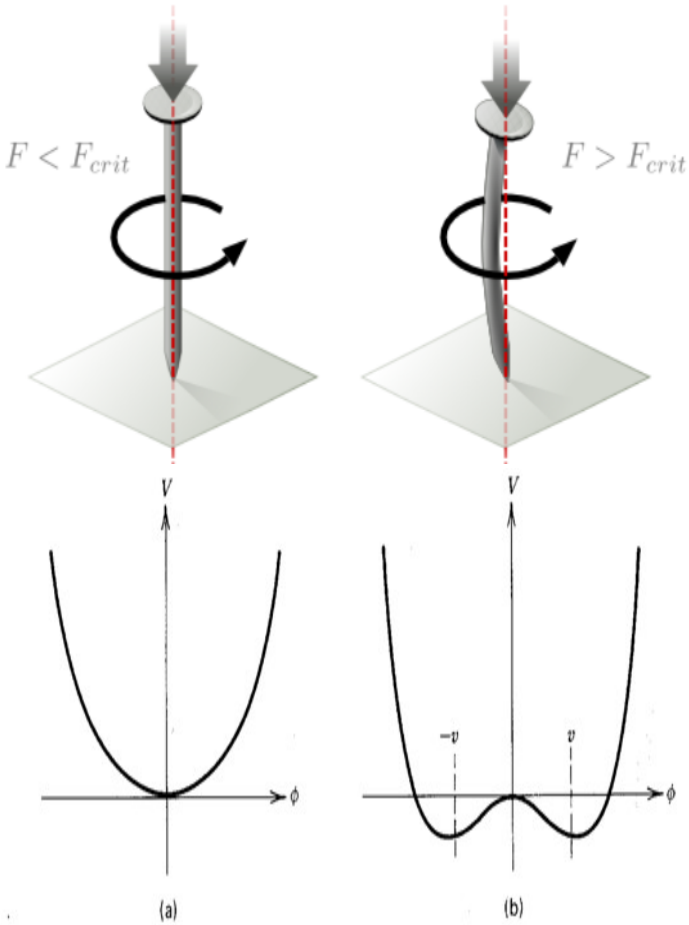
- $m_u < m_d$, otherwise proton can decay to neutron, no atom could form, no life could originate !!

How do fundamental particles get their mass?

Spontaneous Symmetry Breaking (SSB)-Examples



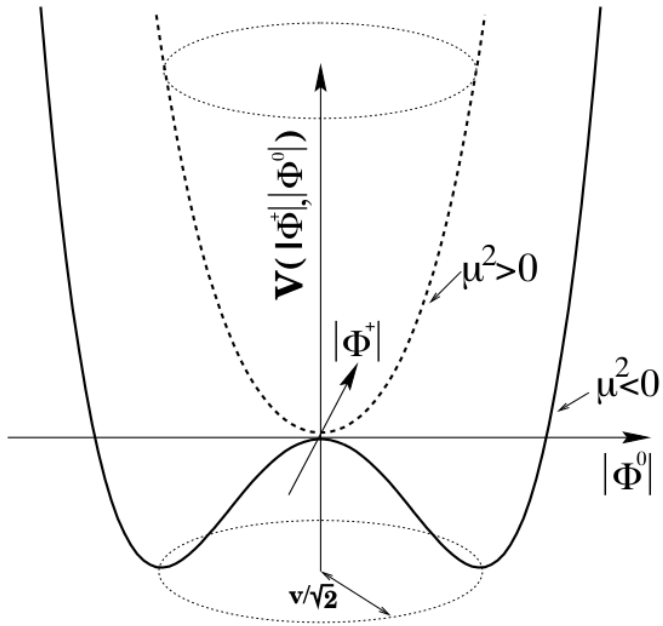




Origin of Mass-II Higgs Mechanism

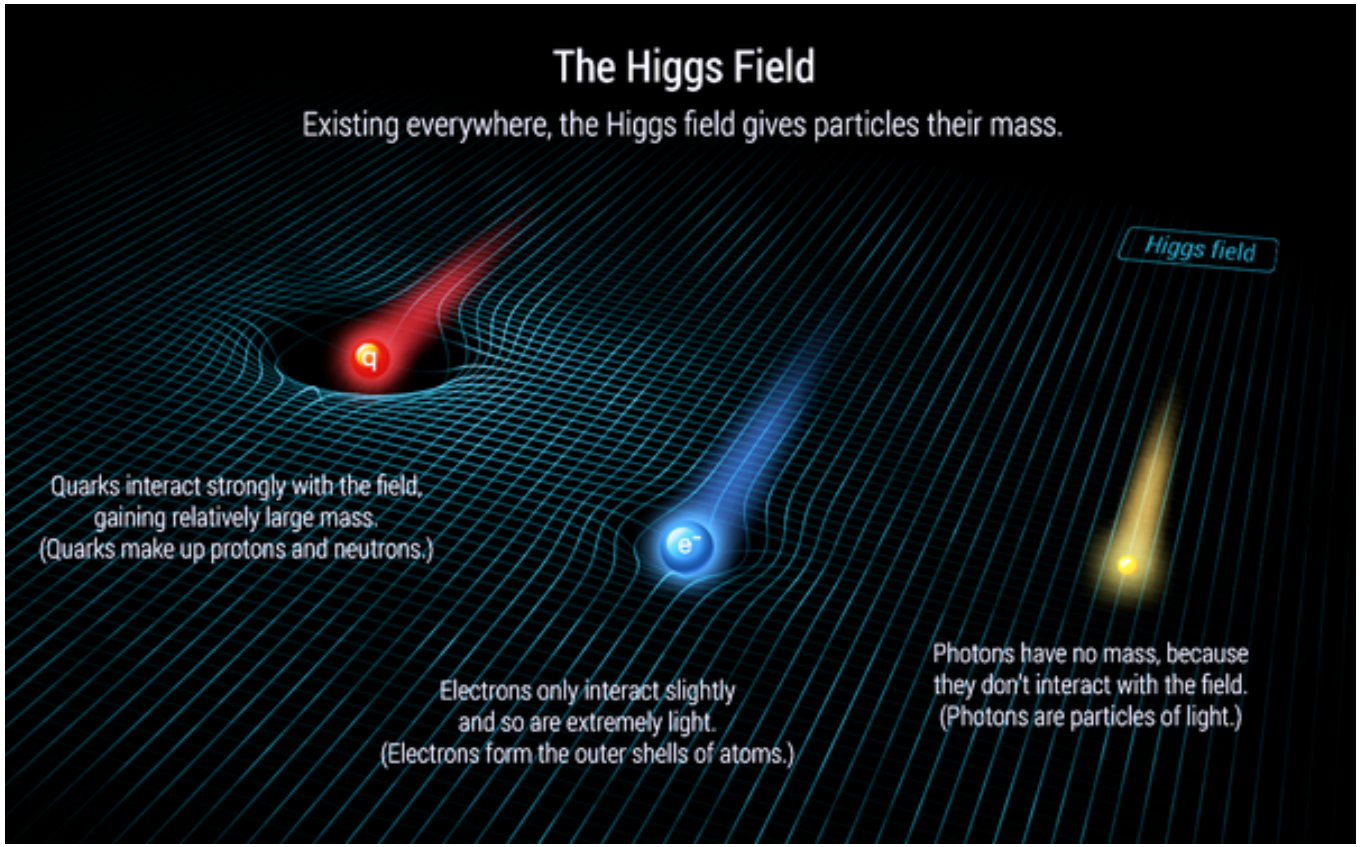
Spontaneous Symmetry Breaking of
Electroweak Symmetry

- Higgs potential
  $V = \mu^2|\Phi^\dagger\Phi| + \lambda|\Phi^\dagger\Phi|^2$
- $\mu^2 < 0 \longrightarrow$ SSB
- $\langle\Phi\rangle_{min} = \frac{1}{\sqrt{2}}\sqrt{\frac{-\mu^2}{\lambda}} \equiv \frac{v}{\sqrt{2}}$
- Due to phase transition Higgs field appeared and permeated the whole universe (it is a vacuum field!)



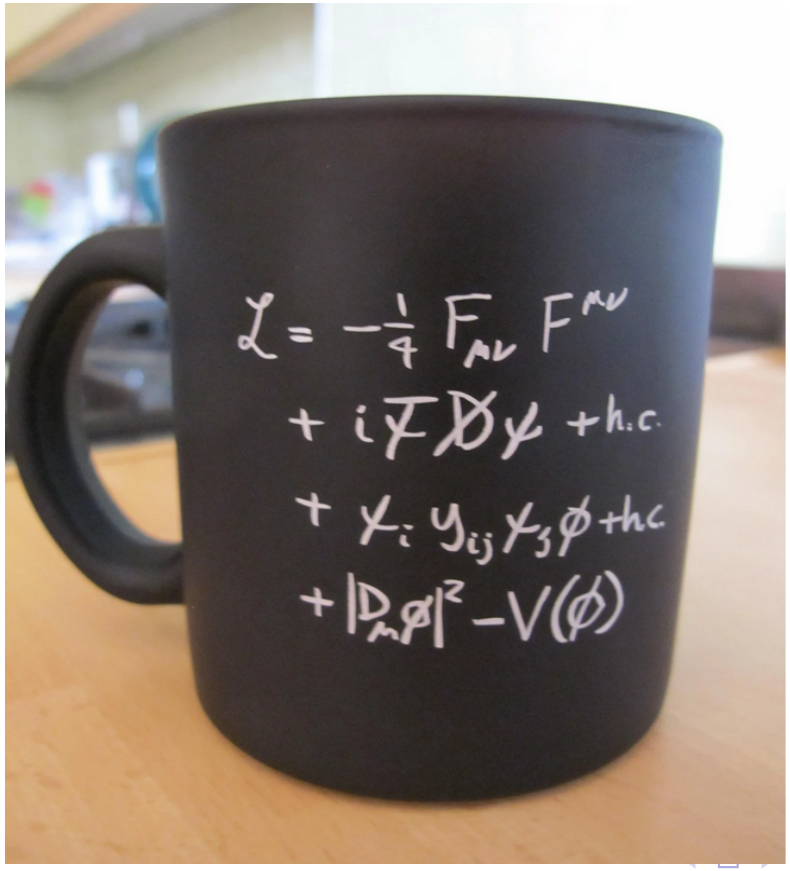
Higgs Mechanism- A Metaphor

Higgs Mechanism- Another Metaphor

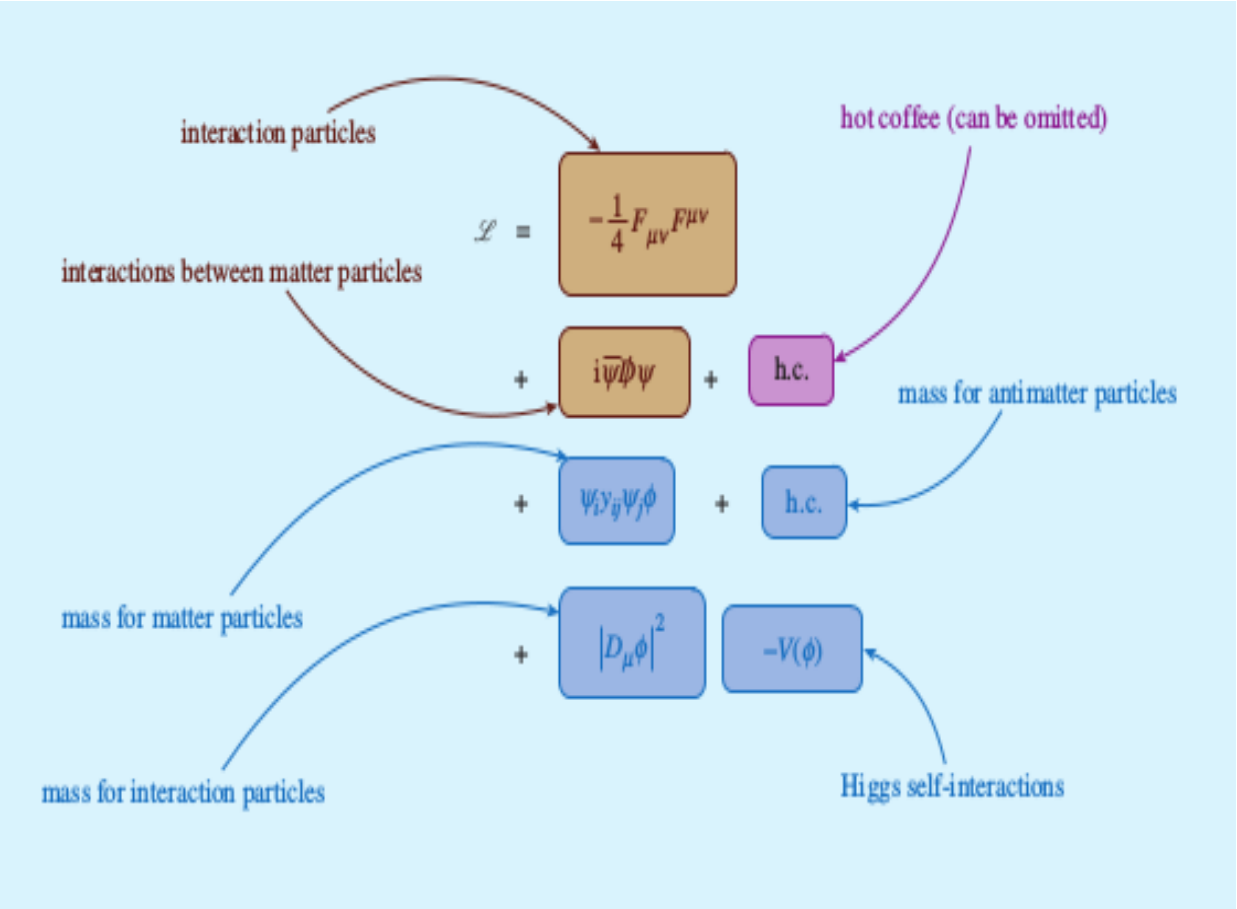


Salam-Weinberg Model a.k.a The Standard Model of Particle Physics

All the luminous matter and its interactions (except gravity)

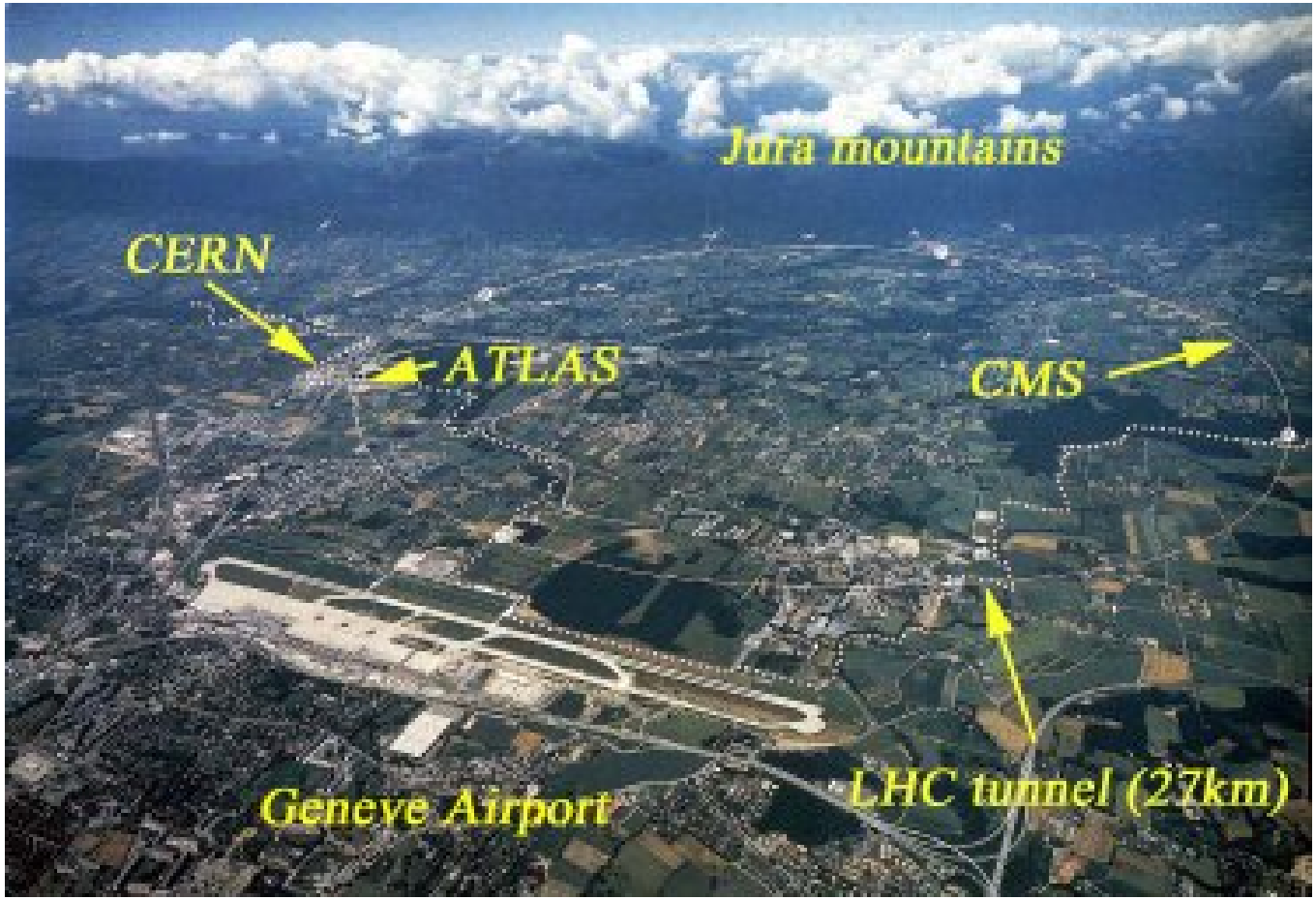


Salam-Weinberg Model- Deconstruction

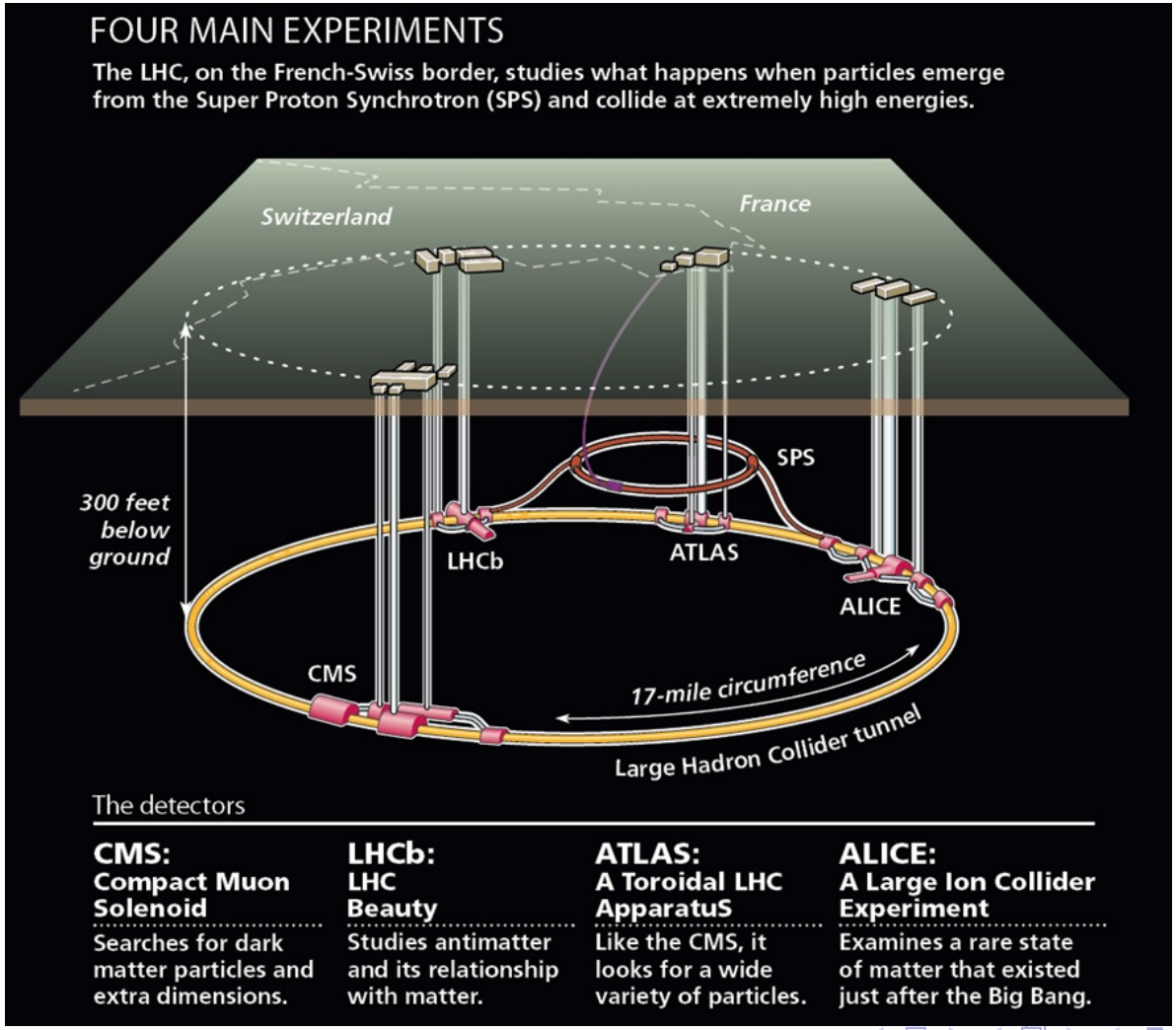


The Large Hadron Collider (LHC) @ CERN

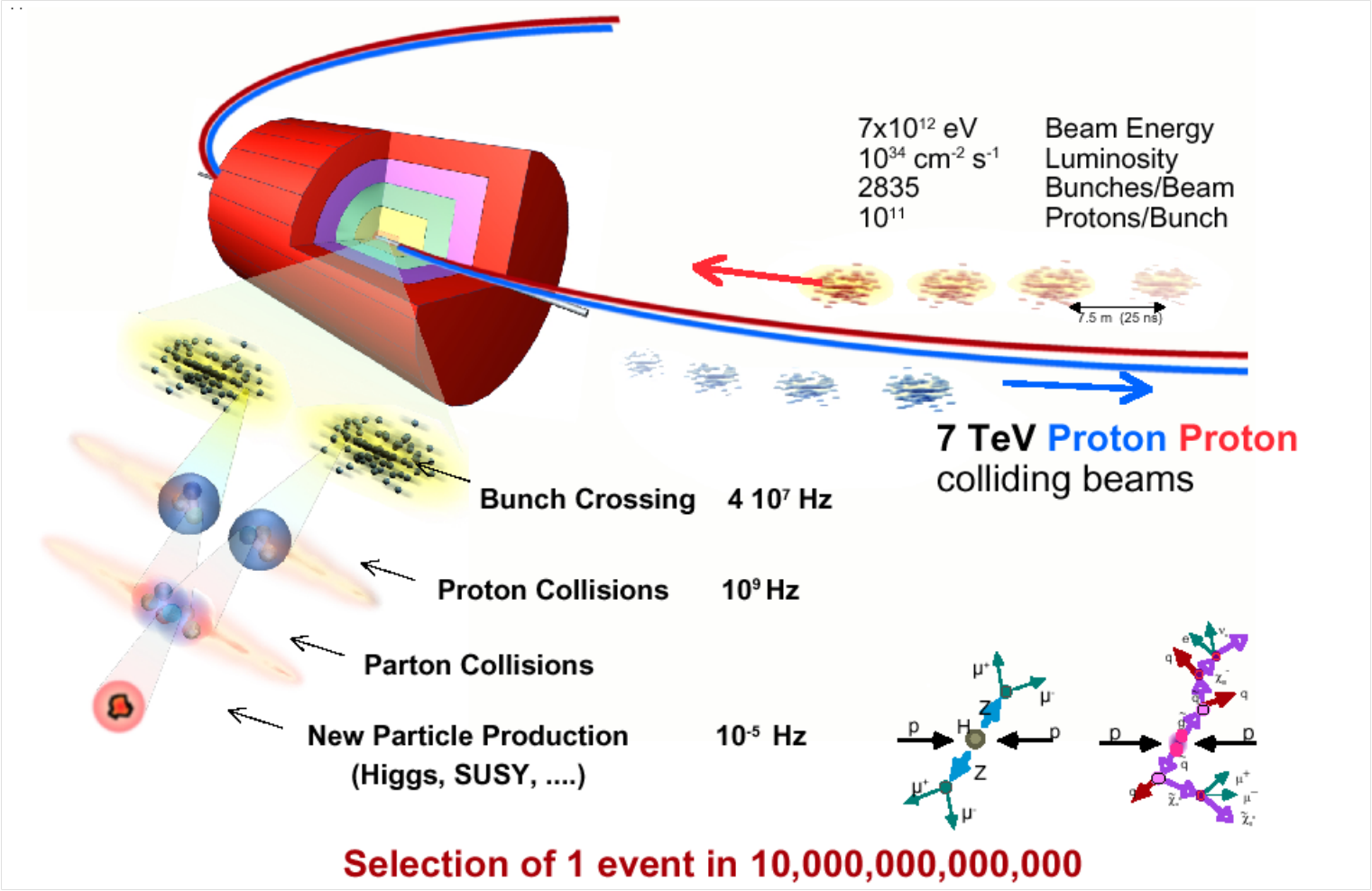
A more than 10 billion dollars machine!!



Four LHC Detectors

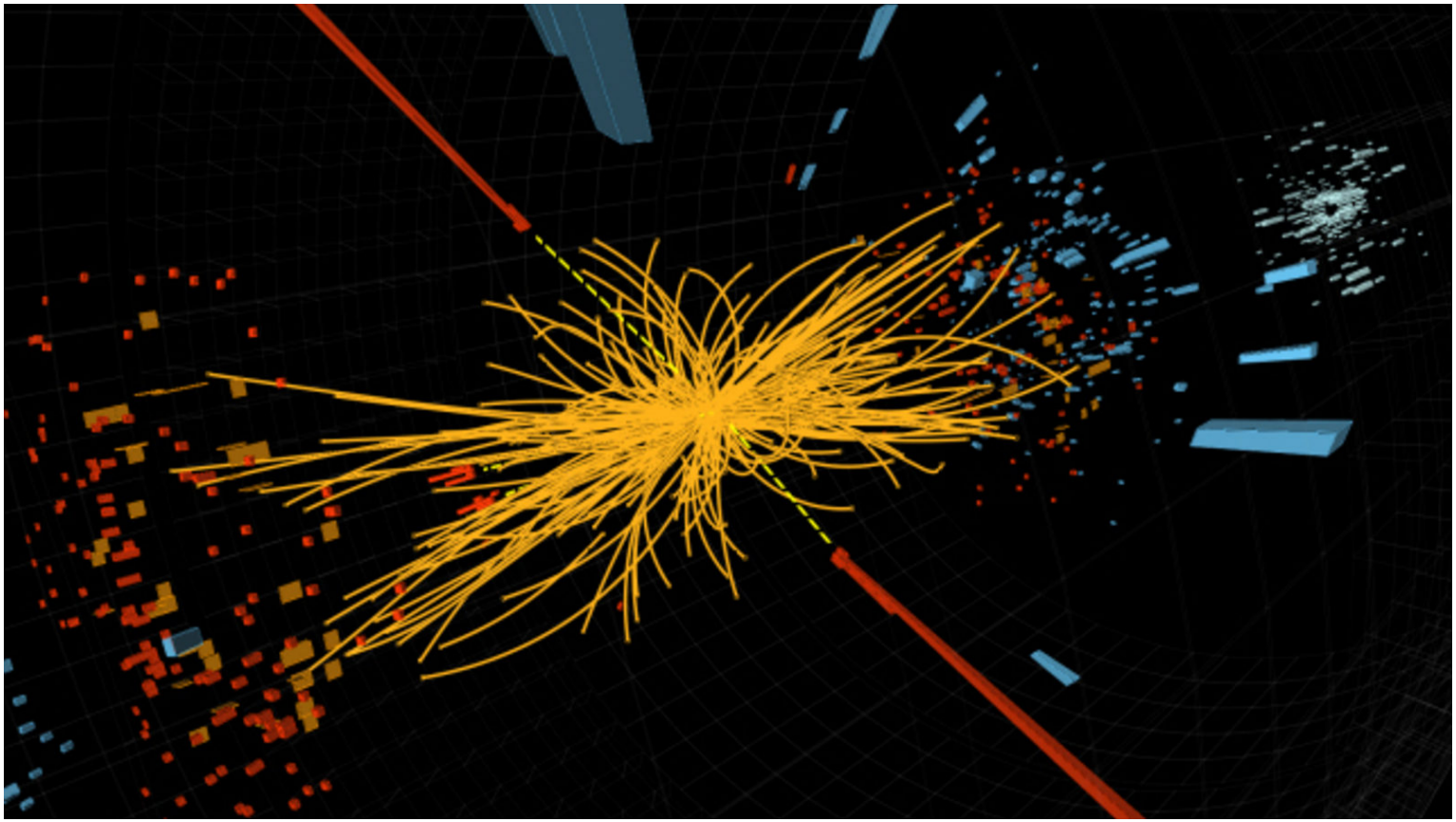


Inside a LHC Detector



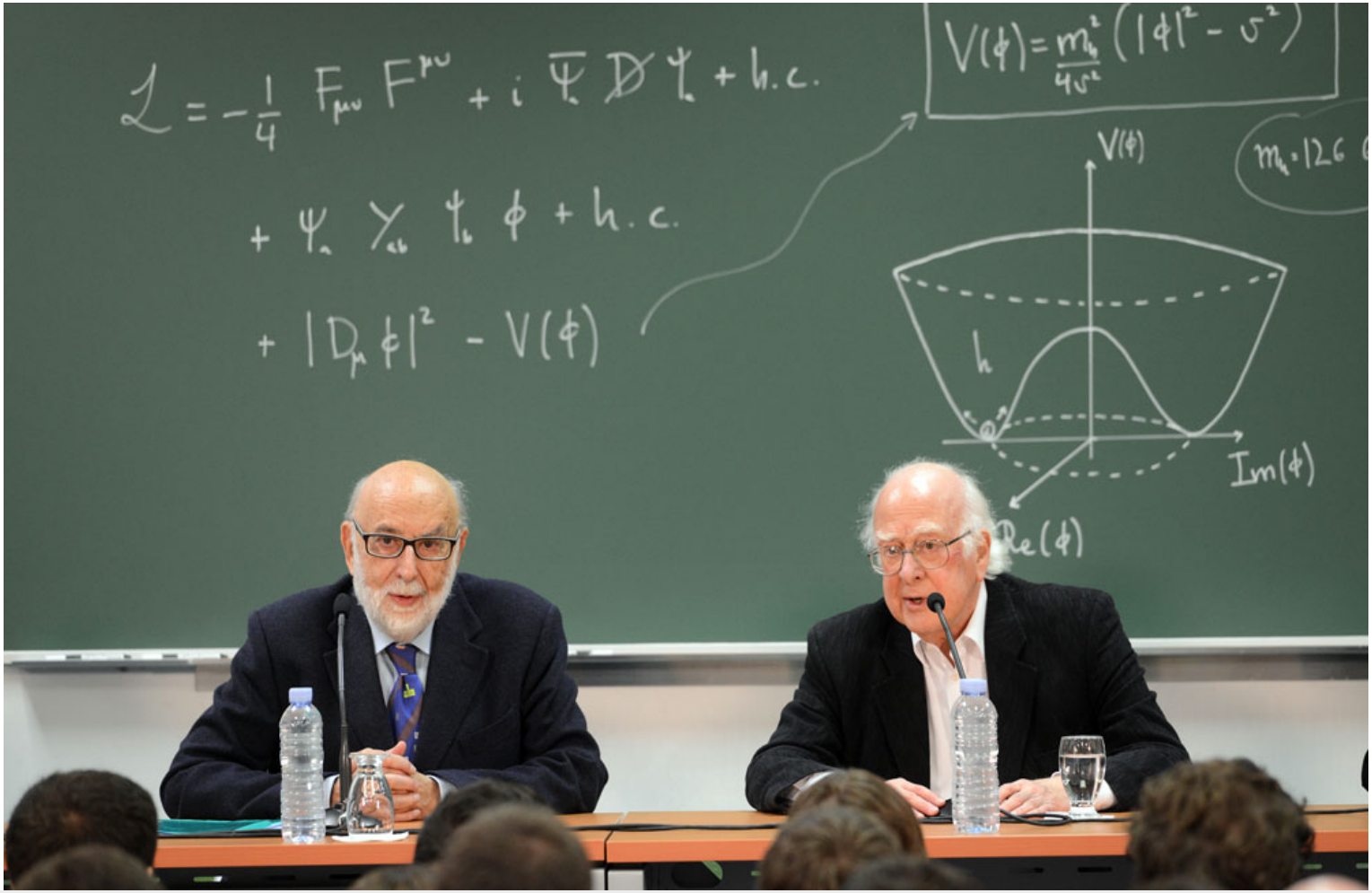
A Typical Higgs Boson Decay

The production rate is extremely small, half life is about 10^{-24} s



Winners of 2013 Nobel Prize in Physics

François Englert and Peter Higgs



What We have learned About Higgs Boson So Far

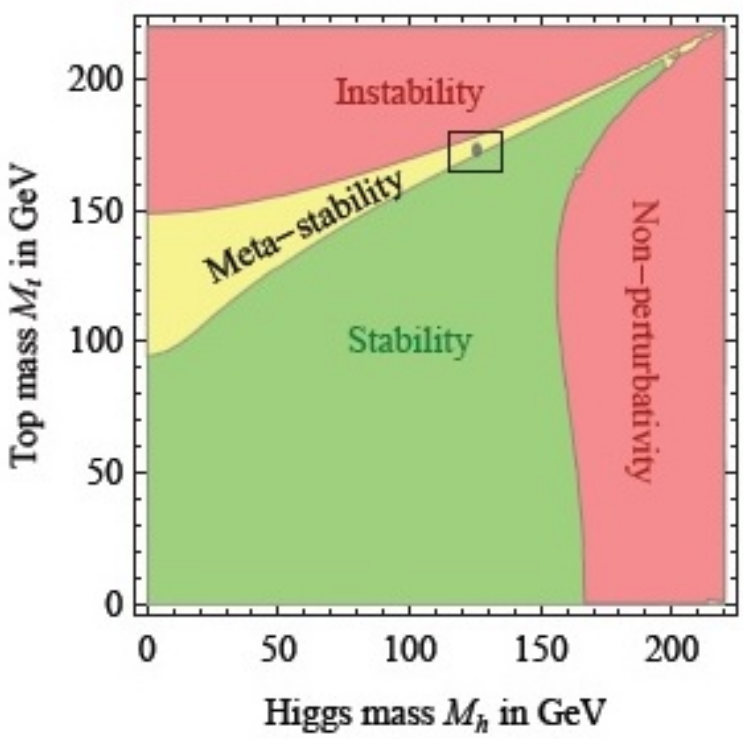
- Higgs field is the *vacuum field* and ripples in the vacuum field are *Higgs bosons*
- Higgs field is needed for Spontaneous Electroweak Symmetry Breaking (SEWSB)
- It gives masses to matter particles (except neutrinos) and force particles $W^{\pm}$ and Z^0
- Now the SM is completed
- This is it ??

Part-II Party Is not Over

- Yes, party is not over, rather becoming more exciting!!
- We need to scrutinize its properties thoroughly
- We need to know if it is *"the Higgs"* or *"a Higgs"*!!
- Why Higgs boson mass is around 125 GeV?
- Is Higgs field in the *"false vacuum"* or *"true vacuum"* of our universe?

False or True Vacuum?

125 GeV Higgs has another very important implication!!!



False or True Vacuum?

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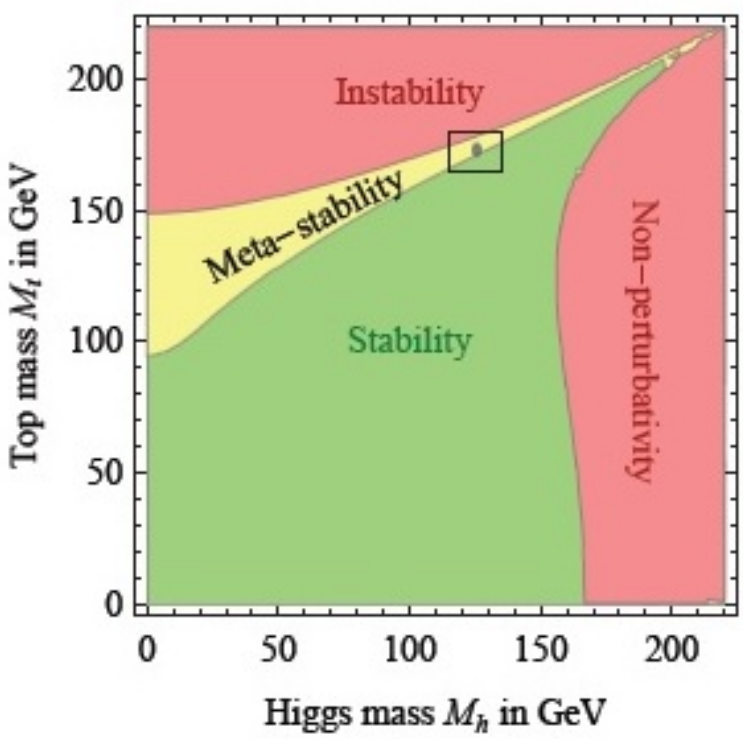
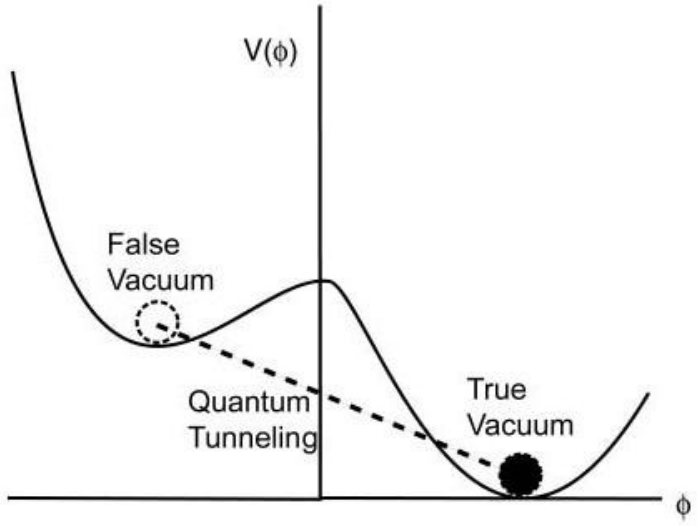




Higgs Physics-A Burning Research Topic for Next Decades!

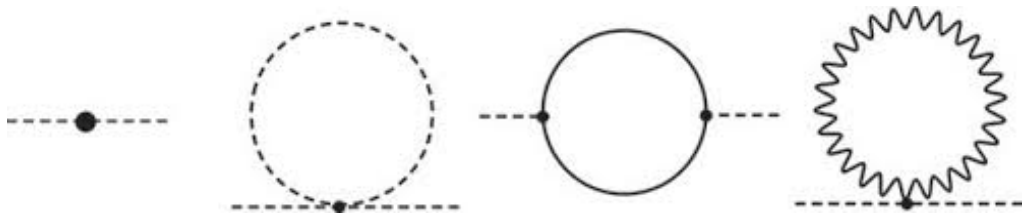
- 2018 is the year of "Yukawa Couplings" at the LHC
- The High-Luminosity LHC will study Higgs properties
- Chinese "Higgs Factory" is coming up
- Japan's International Linear Collider (ILC) is also in the race
- CERN has also plans to upgrade the LHC to Future Circular Collider (FCC)

Why so much excitement about Higgs physics?

The Hierarchy Problem

- The 125 GeV Higgs generates the *"hierarchy problem"* or problem of *"naturalness"* in particle physics!

- Quantum corrections to Higgs mass $\delta m_h^2 \propto (scale)^2$



$$m_h^2 \approx m_{h_0}^2 + \frac{y_f^2}{8\pi^2} N_c^f \Lambda^2 \qquad (1)$$

If we define $N^0 \equiv \frac{\frac{y_f^2}{8\pi^2} N_c^f \Lambda^2}{m_h^2}$, for $\Lambda \sim M_{Planck} = 10^{19} GeV$ and the top quark Yukawa coupling with $y_t \simeq 1$, (1) implies $N^0 \sim 10^{30}$, ie, a fine-tuning of 1 part in 10^{30}

Possible Solution

- Supersymmetry
  - Supersymmetry (SUSY) is a spacetime symmetry
  - It relates $Fermion \rightleftarrows Boson$
  - SUSY provides Gauge Coupling Unification in SUSY version of the Standard Model (SM).
  - It provides possible solutions to Hierarchy problem or the Fine Tuning problem.
  - It predicts Higgs mass less than 135 GeV
  - It also provides dark matter candidates.
  - Needed by String Theory

Summary and Outlook

- Higgs Field is the vacuum field with Higgs bosons as its excitations!!
- Matter and the weak-force particles get mass after EWSB
- Even if we are in false vacuum, the lifetime of our universe is Huge!! but we still need to conform it or reject it.
- Vacuum can be stable, if we have physics beyond the SM (BSM)
- 125 GeV Higgs is problematic for particle physics due to hierarchy and naturalness problems! (needs physics BSM)
- SUSY is the best bet for physics BSM
- We need to find physics BSM, or get ready for "Nightmare scenario" which leads to "Multiverse" (which is almost end of particle physics)

Thank you very much

Backup slides

The Minimal Supersymmetric Standard Model (MSSM)

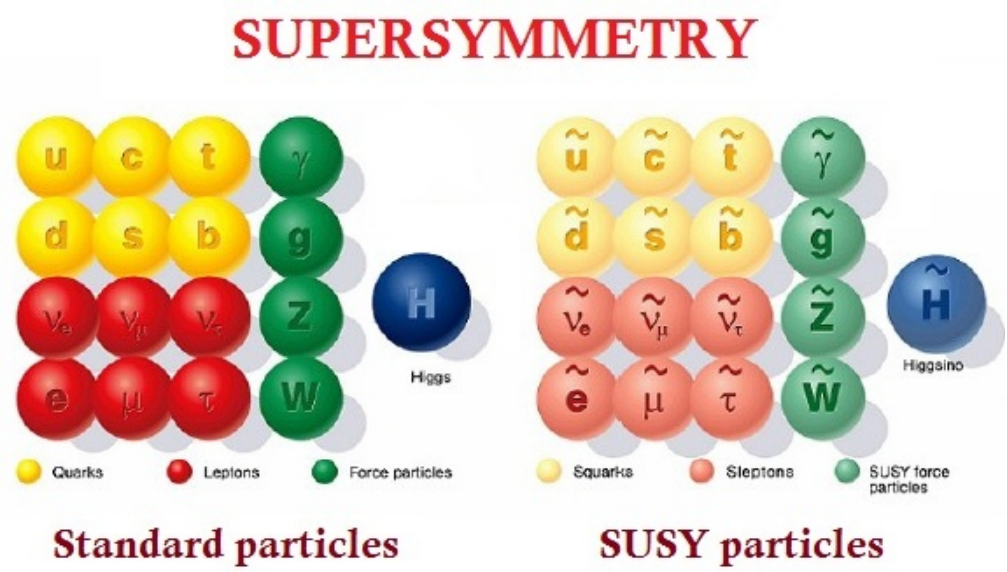
- Since SUSY relates fermions to bosons and vice versa;

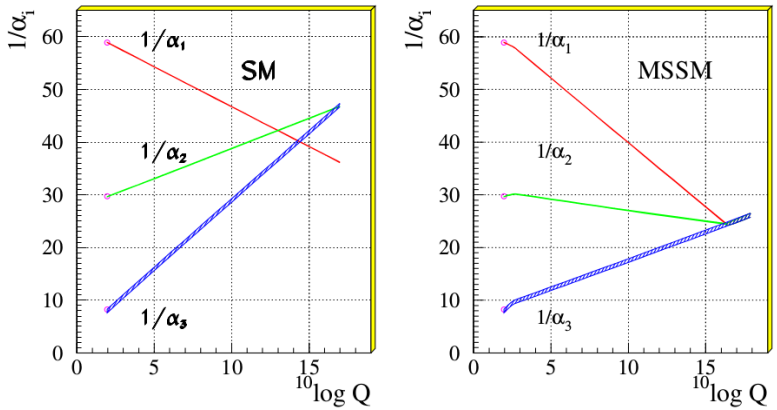
$$\widehat{O}_{SUSY}|FERMION\rangle = |BOSON\rangle,$$
$$\widehat{O}_{SUSY}|BOSON\rangle = |FERMION\rangle.$$

- The MSSM should have SUSY (super) partners of all the SM particles.
- All fermions have their scalar partners or sfermions (leptons and sleptons,quarks and squarks etc..)
- All bosons have fermionic partners (Higgs and higgsinos, gauge bosons, gauginos etc..)
- The MSSM is minimal in the sense that only one more Higgs doublet has been added.

MSSM Continues

SUSY in one the most compelling extension of the SM





5 Higgs particles in the Minimal Supersymmetric SM (MSSM)

SUSY Solution to Hierarchy Problem

$$m_h^2 \approx m_{h\,0}^2 + \frac{\lambda_f^2}{8\pi^2} N_c^f \left(m_{\tilde{f}}^2 - m_f^2\right) \ln\left(\Lambda^2/m_{\tilde{f}}^2\right) \ , \qquad (2)$$

If SUSY particles are around 1 TeV, we can address hierarchy problem with minimal fine-tuning!!