November 18, 2015
NTHU Physics Colloquium

We Found a Higgs Boson, So What?

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DISCLAIMERS

- Do not be surprised if you do not understand my talk, and do not feel too great if you do!
  ➠ about a topic of Nobel prize level

- Will use HEP unit: ħ=c=1.
  ex. m_p = 940 MeV/c^2 ➠ 940 MeV ~ 1 GeV

$E = mc^2$

$$1\,\mathrm{GeV} \simeq 1.6 \times 10^{-10}\,\mathrm{Joules} \simeq 1.78 \times 10^{-24}\,\mathrm{g}$$

Terms Related to Higgs Boson

God particle

Holy Grail in particle physics

Origin of mass

Symmetry breaking

Secret of Universe

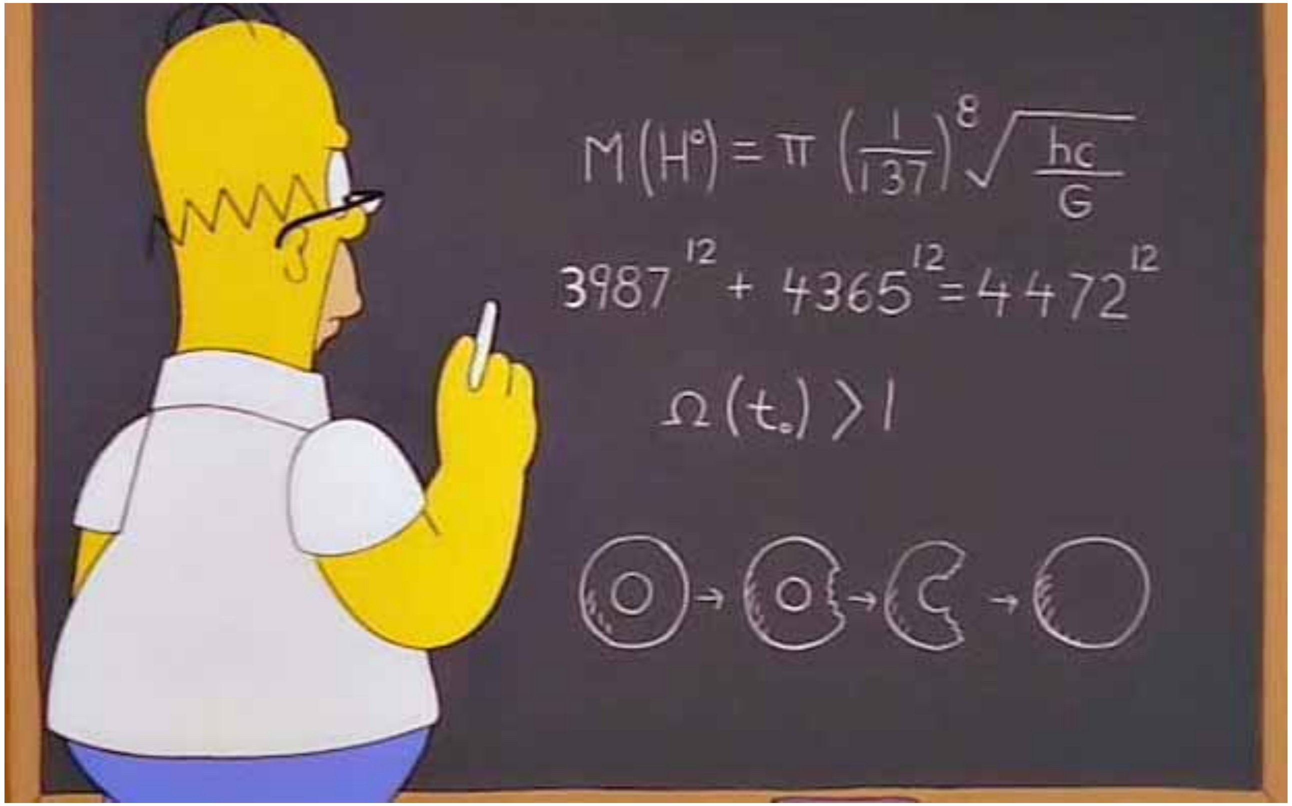
Hope to explain them all...

The Story Goes Like This...

- A speculation about origin of mass started in 1964.
- A long scientific expedition of searching for this mysterious particle then set off and continued ever since then...

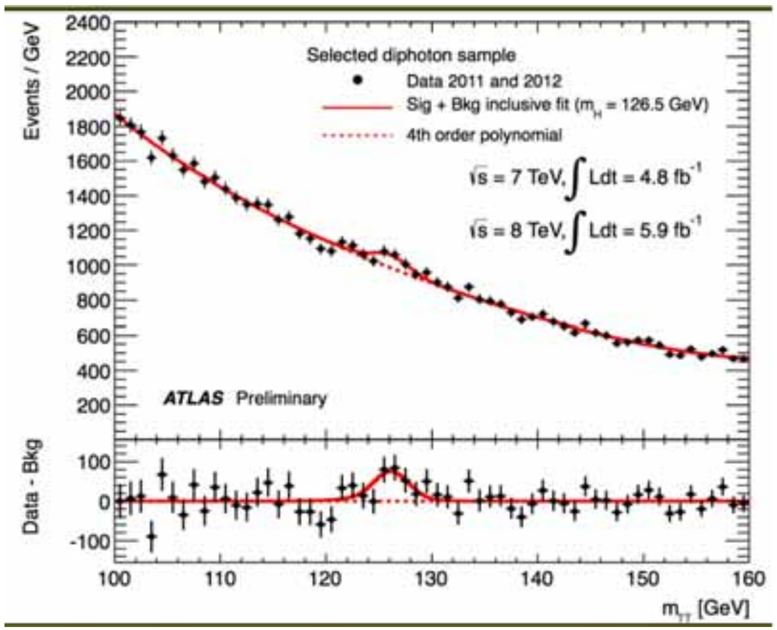
The Story Goes Like This...

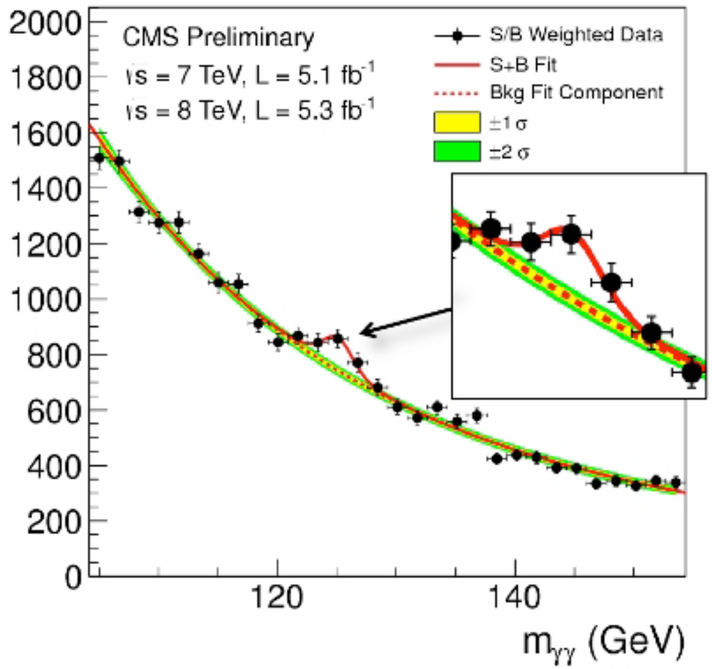
- According to a science writer, Homer Simpson predicted the mass of the Higgs boson in a 1998 episode of The Simpsons.



The Story Goes Like This…

- On a breezy summer day in 2012, CERN experimentalists announced the discovery of a Higgs-like particle by showing the following plots:

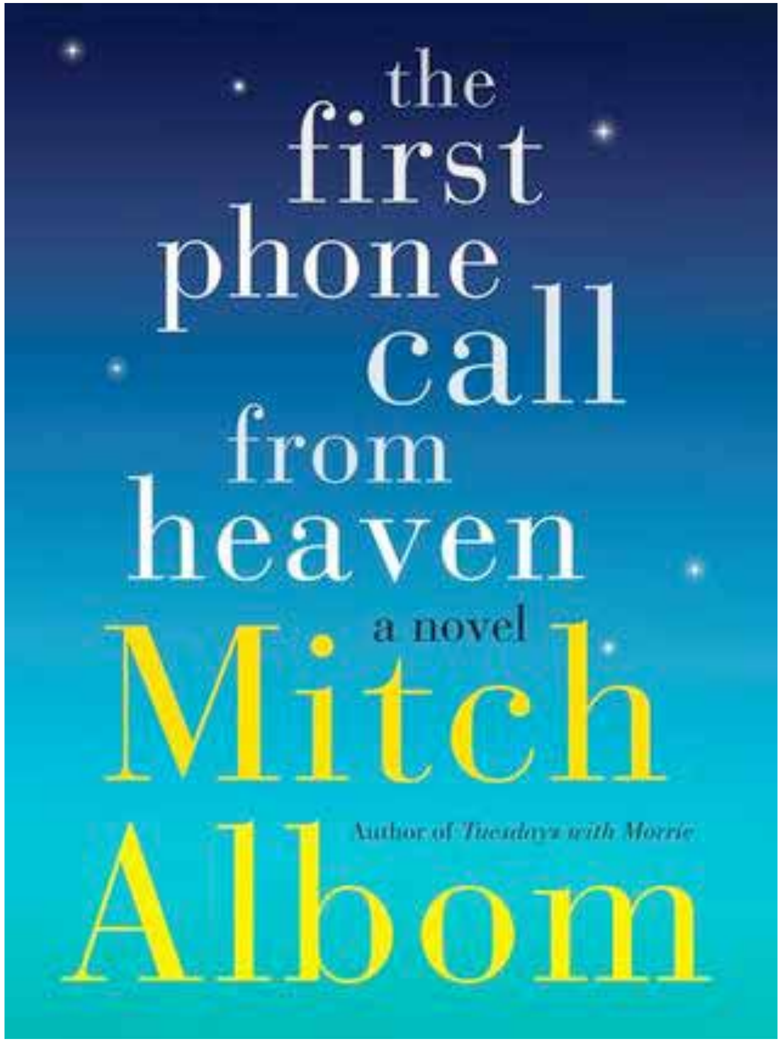




- It was later confirmed as a SM-like Higgs boson after examining more data and cross checks.

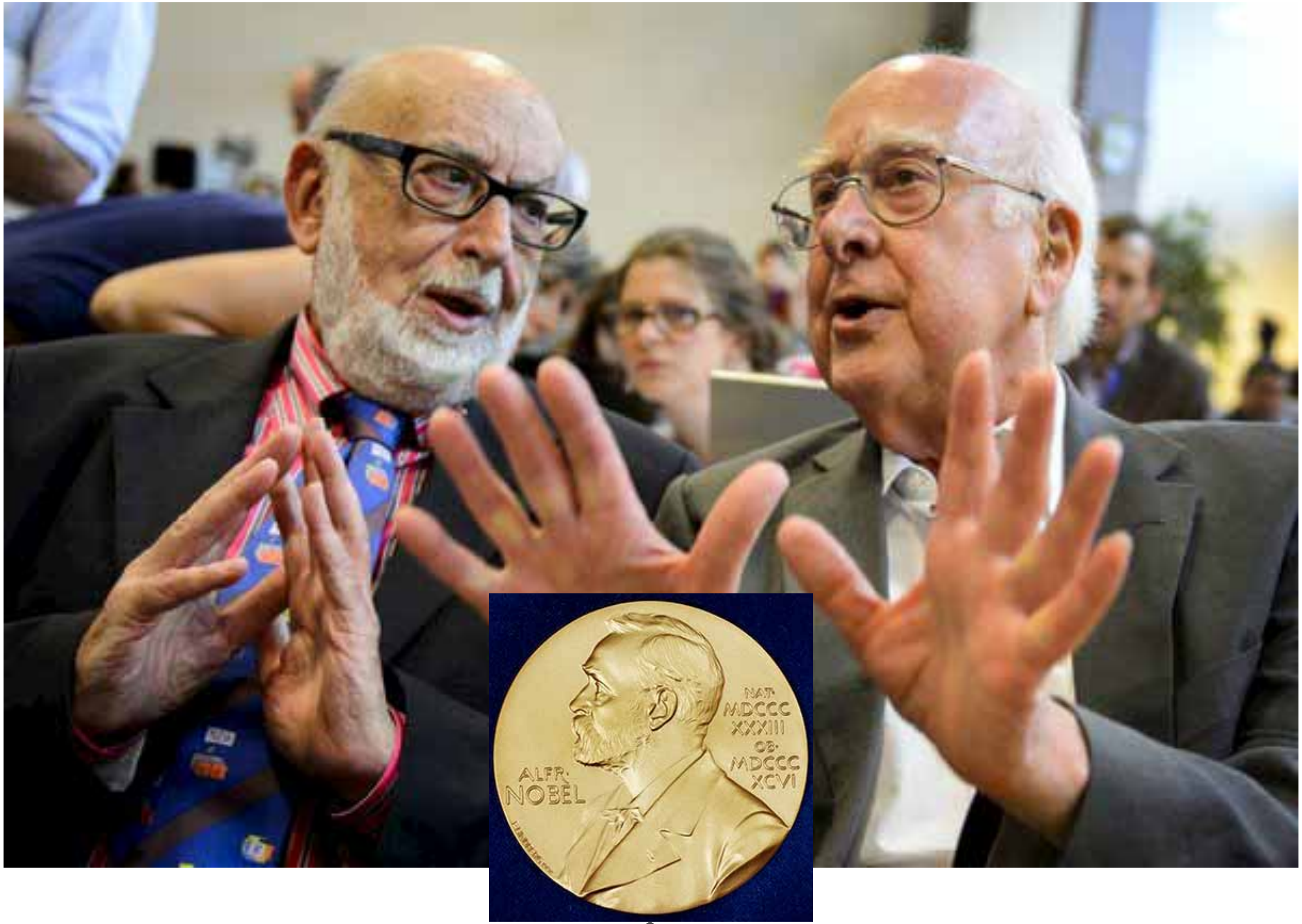
Mitch Albom's New Book

In book stores on 11/12/2013



~ OCTOBER 8, 2013 ~
PHONE CALLS FROM STOCKHOLM ABOUT GOD PARTICLE

Nobel Laureates of 2013



Reactions to Higgs Discovery

Reactions to Higgs Discovery

Reactions to Higgs Discovery

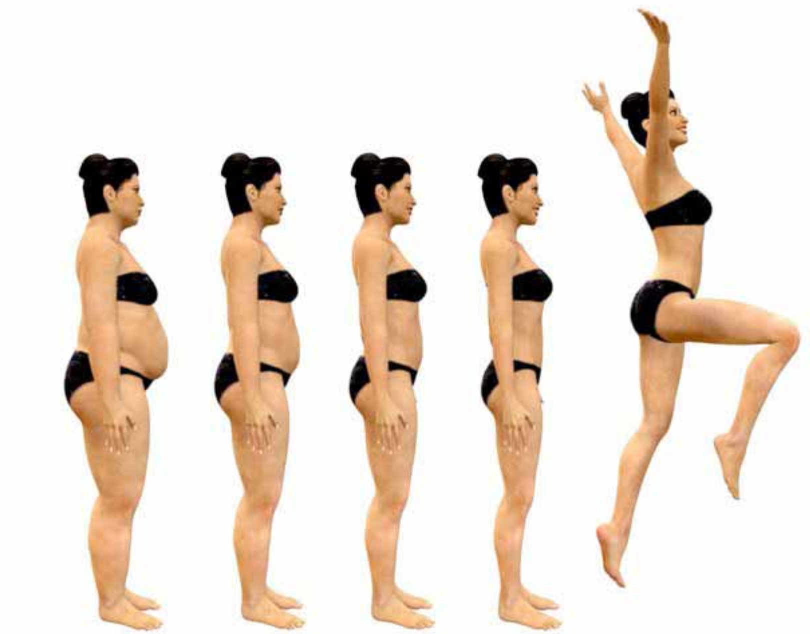
WHAT'S THE BIG DEAL?

- According to the Standard Model of particle physics,
  - last missing piece (before 2012 summer)
  - the only spin-0 particle
    ➠ nonzero Higgs vacuum expectation value allowed
  - mechanism to unite/discern EM and weak interactions
  - coupling to most particles and giving mass to them
  - (maybe) part of mechanism to generate baryons
- Great achievement in international collaborations and cutting-edge experimental techniques
- Starting the era of Higgs physics and possibly a portal to otherwise hidden new physics sector

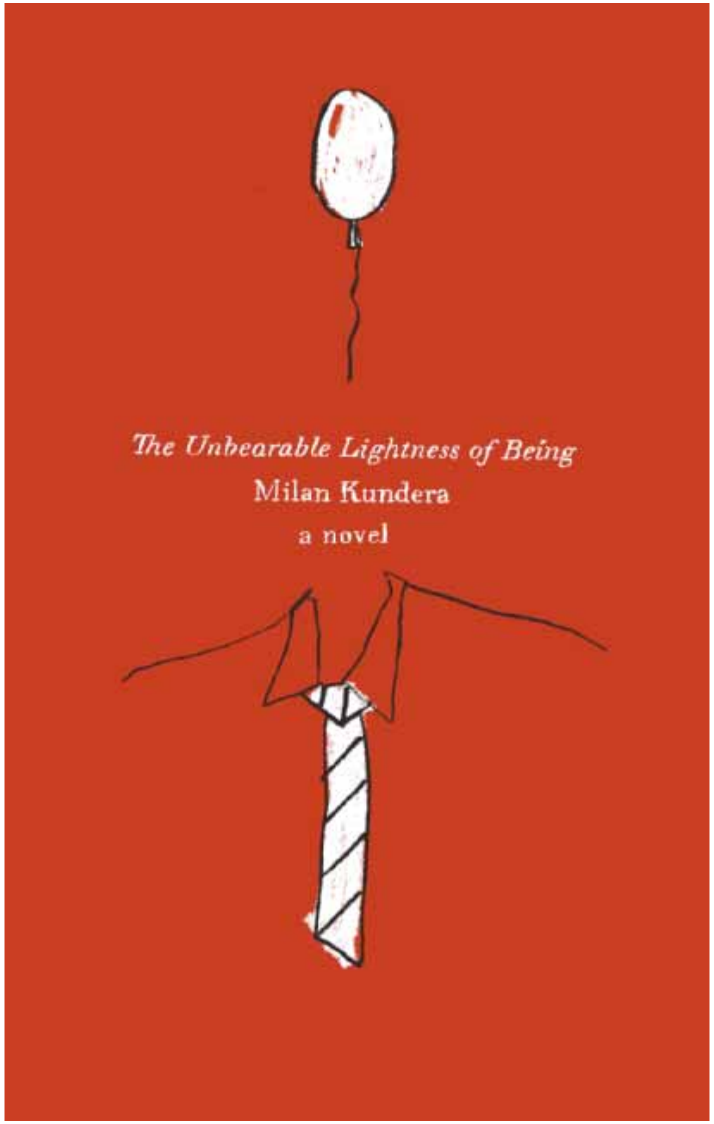
ORIGIN OF MASS

WEIGHT / MASS

- A lot of people care very much about heaviness or lightness or, in other words, the mass.



The Unbearable Lightness of Being (1984)-- Milan Kundera



"LIFE IS VERY HEAVY TO ME, BUT IT IS SO LIGHT TO YOU."
– *TEREZA, The Unbearable Lightness of Being*

MASS

- Mass is one of the earliest, most important, yet still puzzling concepts that we have learned in physics.

- Mass buoys life!
  ➠ massless particles always hurtling at speed of light
  ➠ impossible to form structures
  ➠ no civilization

- Fortunately, most matters have nonzero mass.
  ➠ but what is its origin?
  ➠ put in by hand?

WHAT IS MASS?

- How heavy an object "weighs."

--- layman's term

WHAT IS MASS?

- [physics] The property of a body that is a measure of its inertia and that is commonly taken as a measure of the amount of material it contains and causes it to have weight in a gravitational field.

--- online Webster's Dictionary

What Is Mass?

- Mass of inertia: a measure of resistance to acceleration caused by a force.

$$F = ma$$ Newton's Second Law of Motion

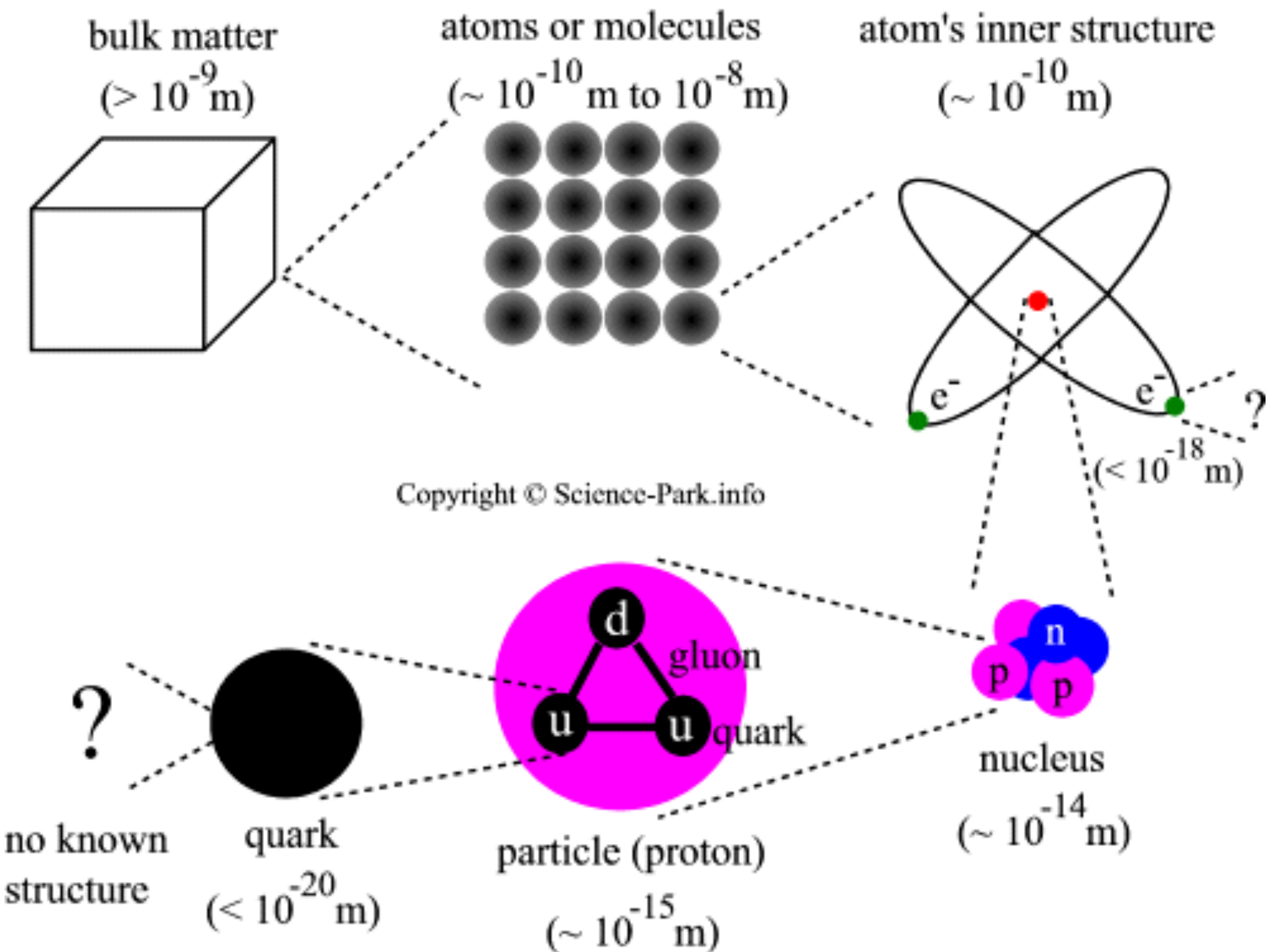
- Mass of gravity: a source ("charge") of gravitational forces.

$$F = G_N \frac{Mm}{r^2}$$ Newton's Law of Universal Gravitation

$$F = k \frac{Qq}{r^2}$$ Coulomb's Law of Static Electric Force

--- freshman physics

Structure of Matter



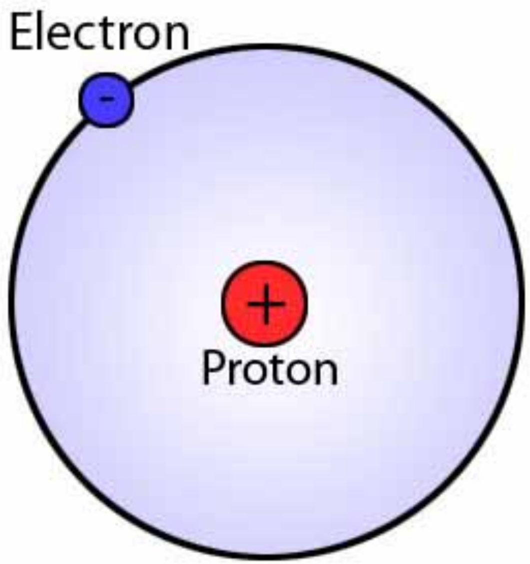
WHAT IS MASS?

- Mass is an intrinsic property of matter, and is additive from its smallest constituents.

- Ordinary matter is made of atoms.
- Atoms are made of protons, neutrons, and electrons.
- Most (> 99.95%) of the mass of an atoms comes from the nucleons located inside the tiny nucleus.

Hydrogen

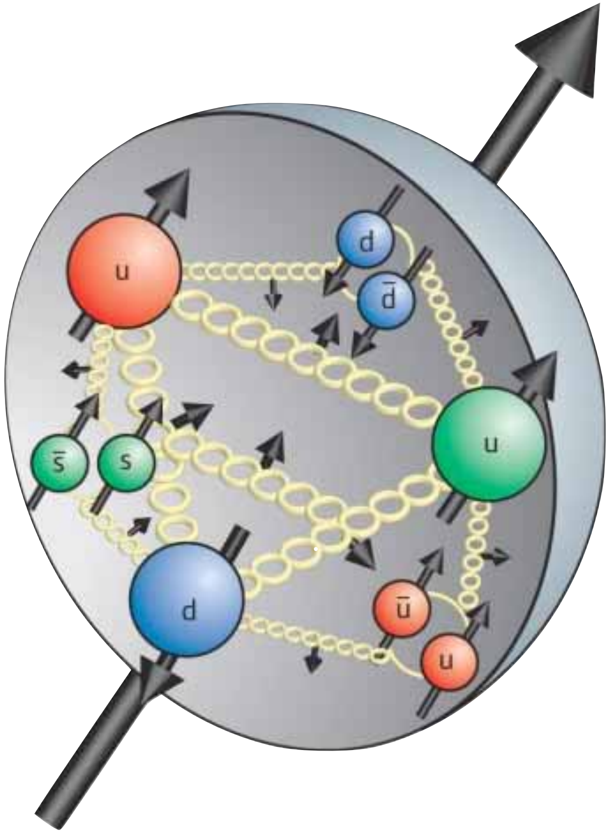
- Hydrogen atom is a composite particle with a radius about 0.0529 nm.



$$m_H = m_p + m_e$$

Proton / Neutron

- Proton (likewise neutron) is a composite particle with a charge radius about 0.877 fm*.

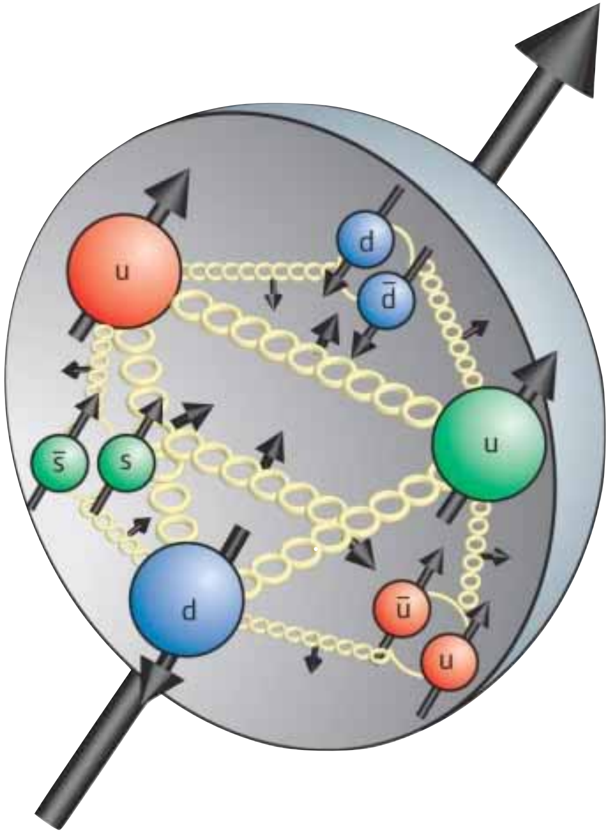


$$\underbrace{m_p}_{940\ \text{MeV}} \gg 2 \underbrace{m_u}_{2.5\ \text{MeV}} + \underbrace{m_d}_{5\ \text{MeV}}$$

$E = mc^2$

Proton / Neutron

- Most mass (~ 98%) inside nucleons come from gluon interactions, instead of constituent quarks.



$$\underbrace{m_p}_{940\ \text{MeV}} \gg 2\underbrace{m_u}_{2.5\ \text{MeV}} + \underbrace{m_d}_{5\ \text{MeV}}$$

$E = mc^2$

Origin of Mass

- Most mass of ordinary matter in Universe comes from potential energy of strong interaction, not elementary particles.
  ➠ ~ 98% mass explained

- What is the origin of mass for elementary particles?
- How do some particles (e.g., W and Z bosons) that should be massless become massive?
- Why do different particles have different masses?

Symmetry Rules

- "Symmetry dictates interactions."

  --- C.N. Yang

- Fundamental interactions in Nature are governed by local symmetries (gauge field theories):
  - electromagnetic interaction (first unification)
    ➠ U(1) gauge symmetry (unbroken!)
  - electro-weak interaction (second unification)
    ➠ $SU(2)_L \times U(1)_Y$ gauge symmetry (broken!)

Massive Gauge Boson

- Gauge invariance forbids gauge bosons to obtain mass.

- Take a U(1) gauge theory (e.g., EM) as an example,

$$m_A^2 A_\mu A^\mu$$

  is NOT invariant under the gauge transformation

$$A^\mu(x) \to A^\mu(x) - \partial^\mu \Lambda(x) \quad \text{or} \quad \begin{cases} V \to V - \partial_t \Lambda \\ \mathbf{A} \to \mathbf{A} + \nabla \Lambda \end{cases}$$

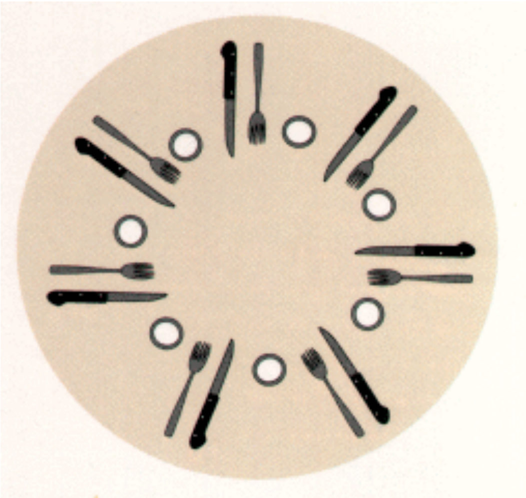
- The corresponding gauge boson (e.g., photon) should be massless and have long-distance interactions.

- How do we consistently give masses to weak force mediators (to render a short-range interaction)?

ELECTROWEAK SYMMETRY BREAKING

Explicit Symmetry Breaking

- Round-table puzzle: who should start the dish first?



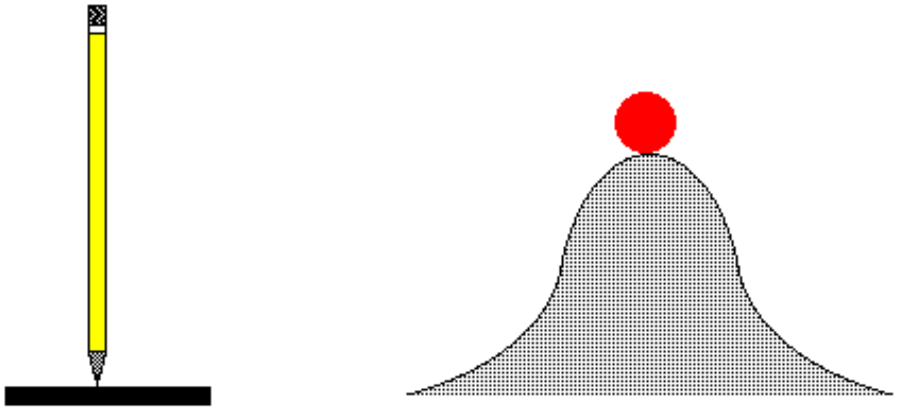
- In particle physics, explicit symmetry breaking refers to the situations when one purposely puts into the Lagrangian terms that do not respect the symmetry.
  Ex: parity (P) and charge-parity (CP) violation

SPONTANEOUS SYMMETRY BREAKING

- Spontaneous symmetry breaking (SSB) refers to situations when the theory has some symmetry that is not respected by the ground state (or more technically the Green functions) of a system.

Instability

there are many examples in Nature of balance points that are unstable



pencil on its point

ball at the top of a hill

any perturbation on these objects causes a runaway to a more stable point

A Simplified Version

- The mechanism involves a complex scalar field with a global U(1) symmetry (or SO(2) in components), a two-dimensional rotation symmetry in internal space:

$$\mathcal{L}_\phi = \partial_\mu \phi^* \partial^\mu \phi - V(\phi^* \phi)$$

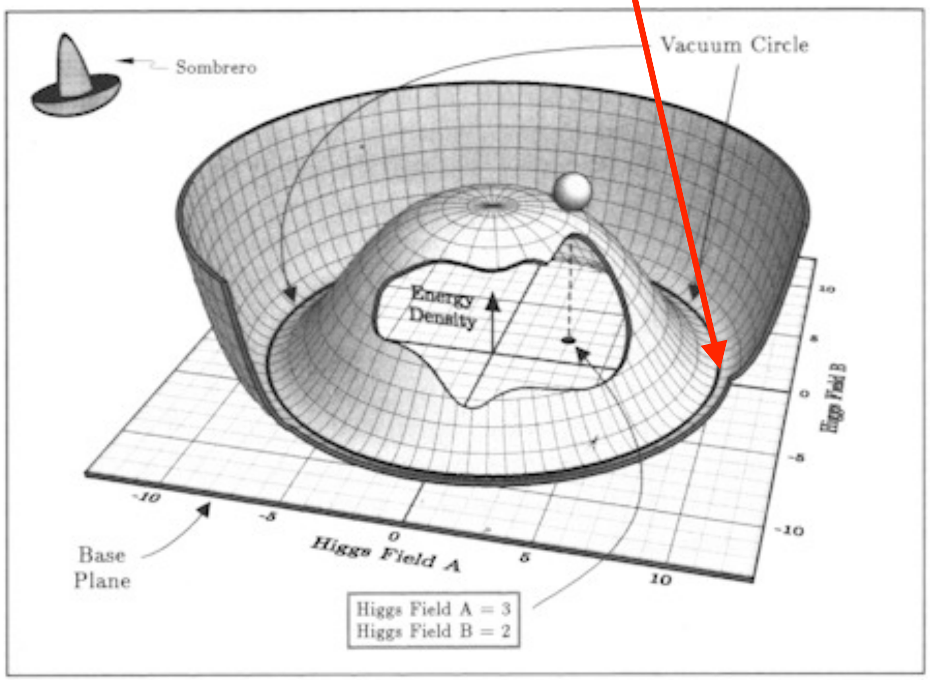
$$V = -\mu^2 |\phi|^2 + \frac{\lambda}{4} |\phi|^4 \qquad (\mu^2, \lambda > 0)$$

Mexican-hat or wine-bottle potential

$$|\phi|^2 = 2\mu^2/\lambda \equiv v^2$$

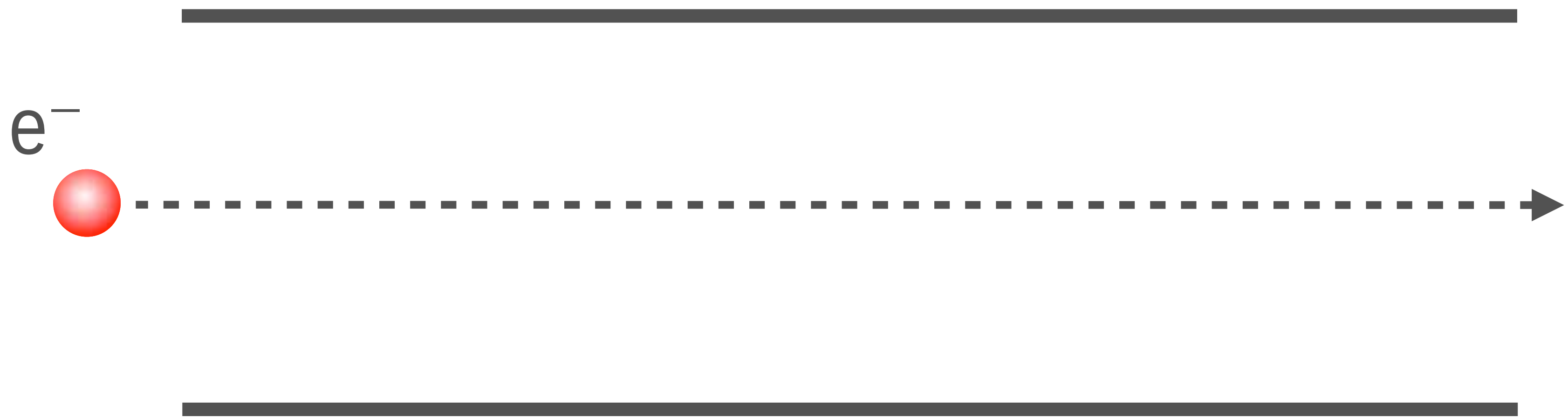
v ~ O(200 GeV) at T = 0.

- The process of turning on the VEV is triggered by an unstable symmetry origin.



Charged Particle in Electric Field

- What does it mean to have a vacuum expectation value?



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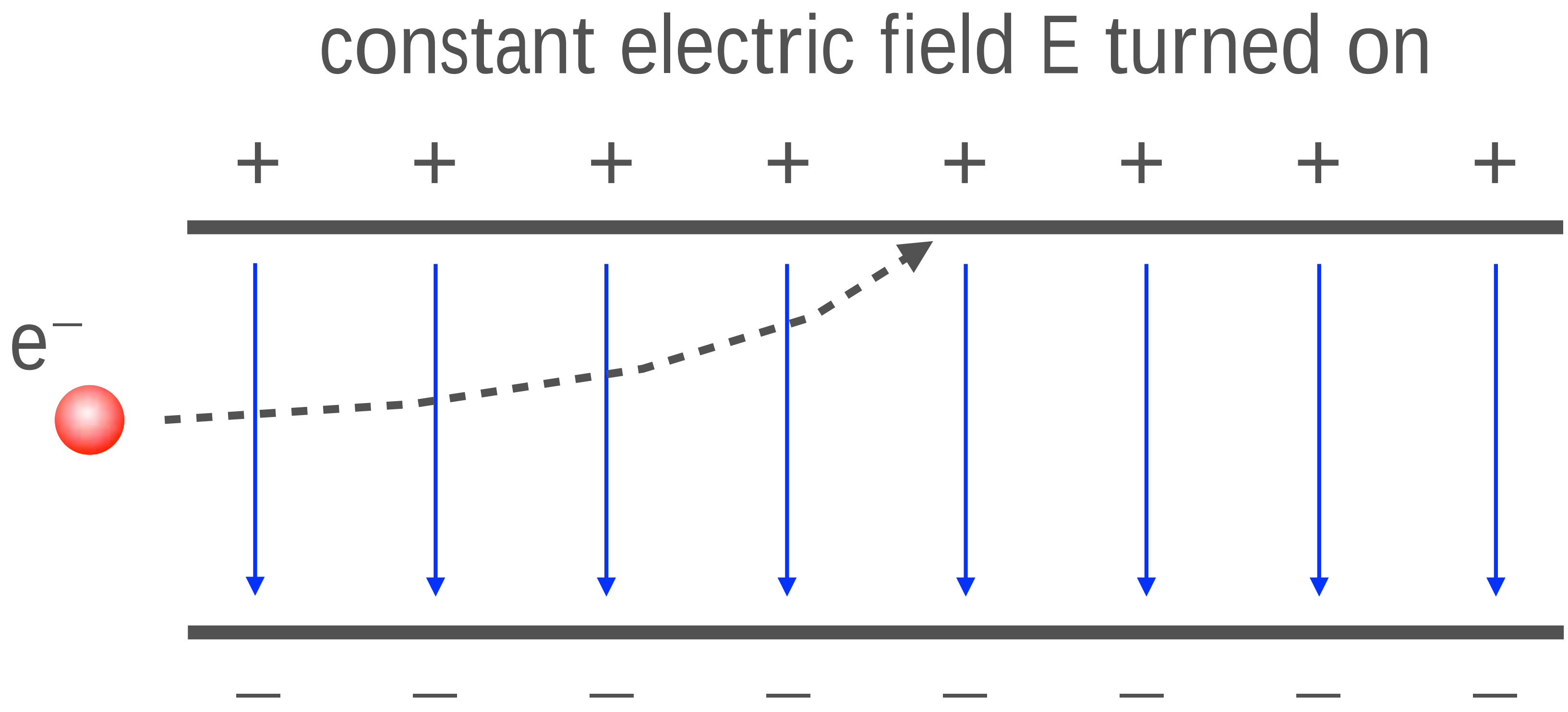
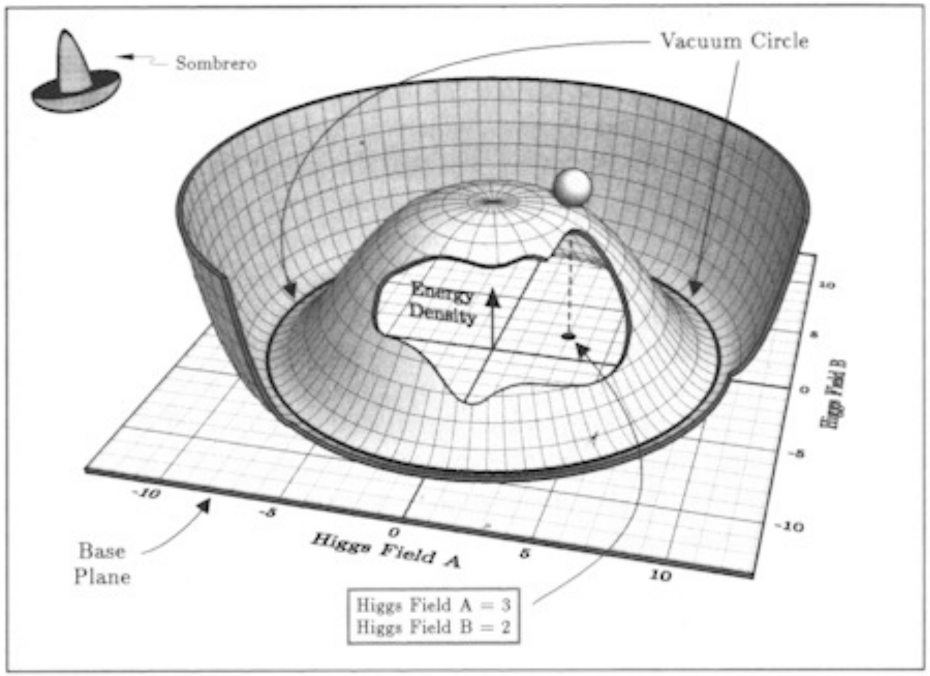


- There is a constant force F = –eE.
- Physical laws are correspondingly modified for such charged particles in this constant background field space.

Electroweak Phase Transition

- As the Universe cools down, the Higgs field throughout the Universe undergoes a phase transition, from the unstable symmetry phase to a more stable but symmetry-broken phase, like water going from vapor phase to liquid phase.
- Particles are then traveling in Higgs "ocean" rather than Higgs "atmosphere," thus acquiring their masses.

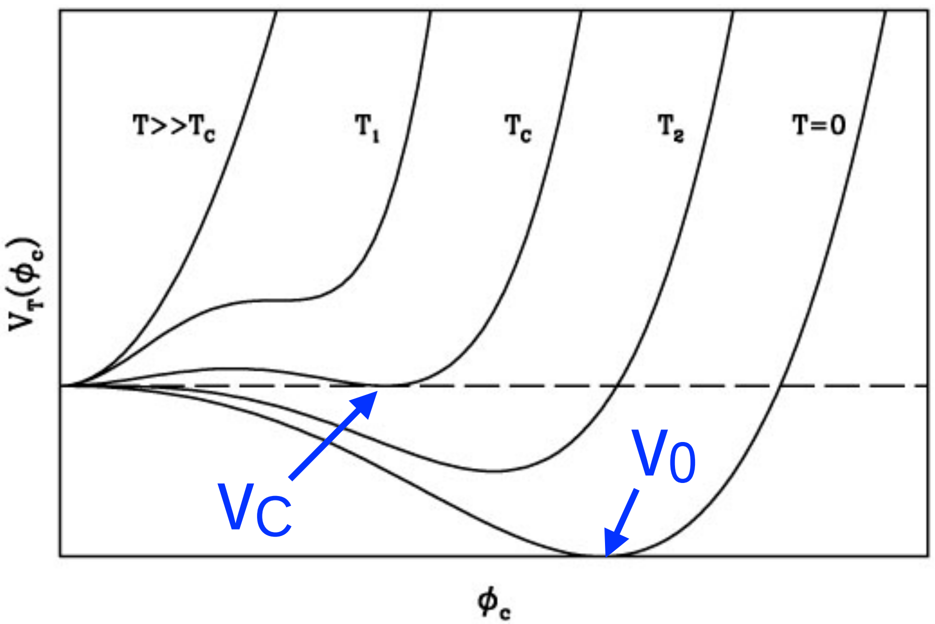


Electroweak Phase Transition

- The strength of electroweak phase transition is characterized by the order parameter $R \equiv v_C/T_C$, where T_C is the critical temperature and v_C the Higgs VEV at T_C.
- Condition on R for successful baryogenesis

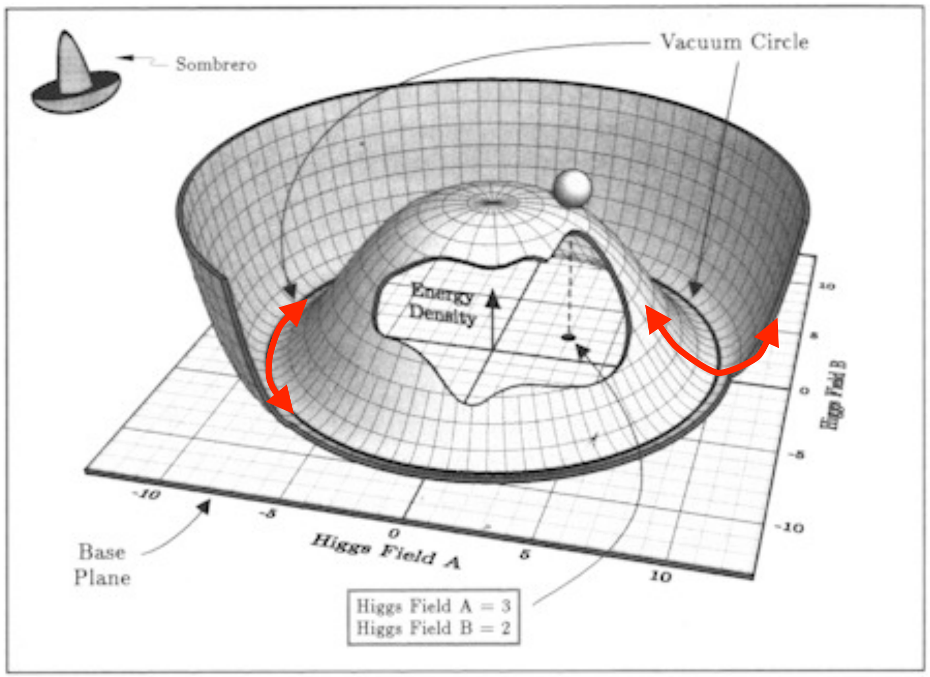
$$R \gtrsim \zeta$$

with $\zeta \sim 1$ in most cases.



The Higgs Boson

- After the symmetry breaking, we still have two dof's:
  - one in the radial direction with mass $m^2 = 2\lambda v^2$;
  - the other in the azimuthal direction with zero mass!
- Zero-mass mode is the Nambu-Goldstone (NG) boson, to become longitudinal modes of the gauge bosons.
- Peter Higgs along noted the massive mode and discussed its phenomenology; the corresponding particle was thus named the Higgs boson.
- Higgs' sad story...



BEH or Higgs Mechanism

Higgs 1964; Englert and Brout 1964; Guralnik, Hagen and Kibble 1964 (not just Higgs!)

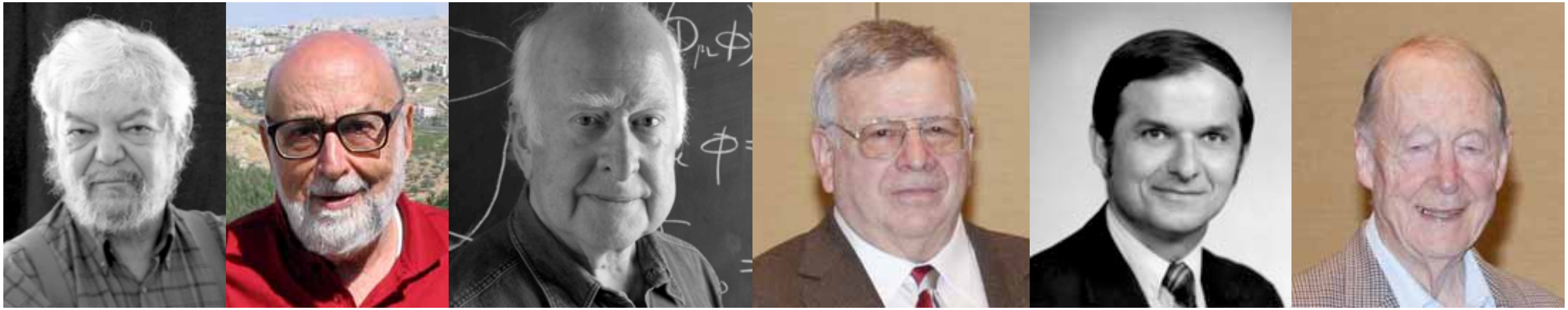
- When a scalar field is coupled to a gauge field, endowing a vacuum expectation value (VEV) to the scalar field makes the gauge boson massive:

$$\mathcal{L} \ni |D_\mu \phi|^2 \qquad \text{where } D_\mu = \partial_\mu - igQA_\mu$$

$$\ni -g^2 v^2 A_\mu A^\mu$$

m_A^2, squared mass of A_μ

- Gauge symmetry is not 'broken', but simply 'hidden'.
- This is the so-called BEH or Higgs mechanism.



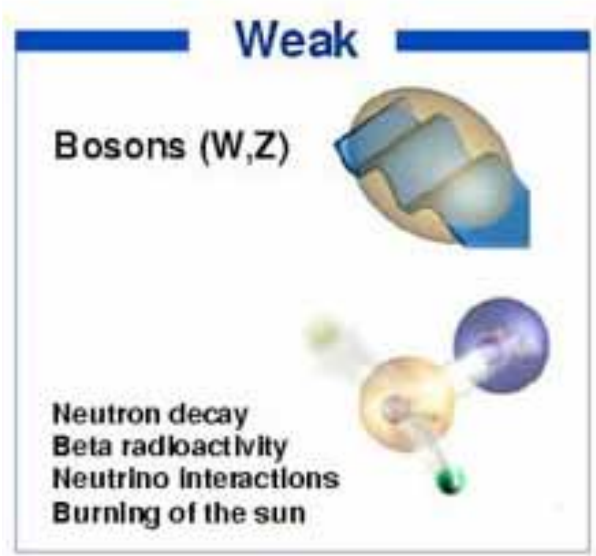
Electroweak Unification

Glashow 1961; Weinberg 1967; Salam 1968

- Employ the BEH mechanism to break the $SU(2)_L \times U(1)_Y$ symmetry down to the $U(1)_{EM}$ symmetry.
  ➠ Standard Model of particle physics

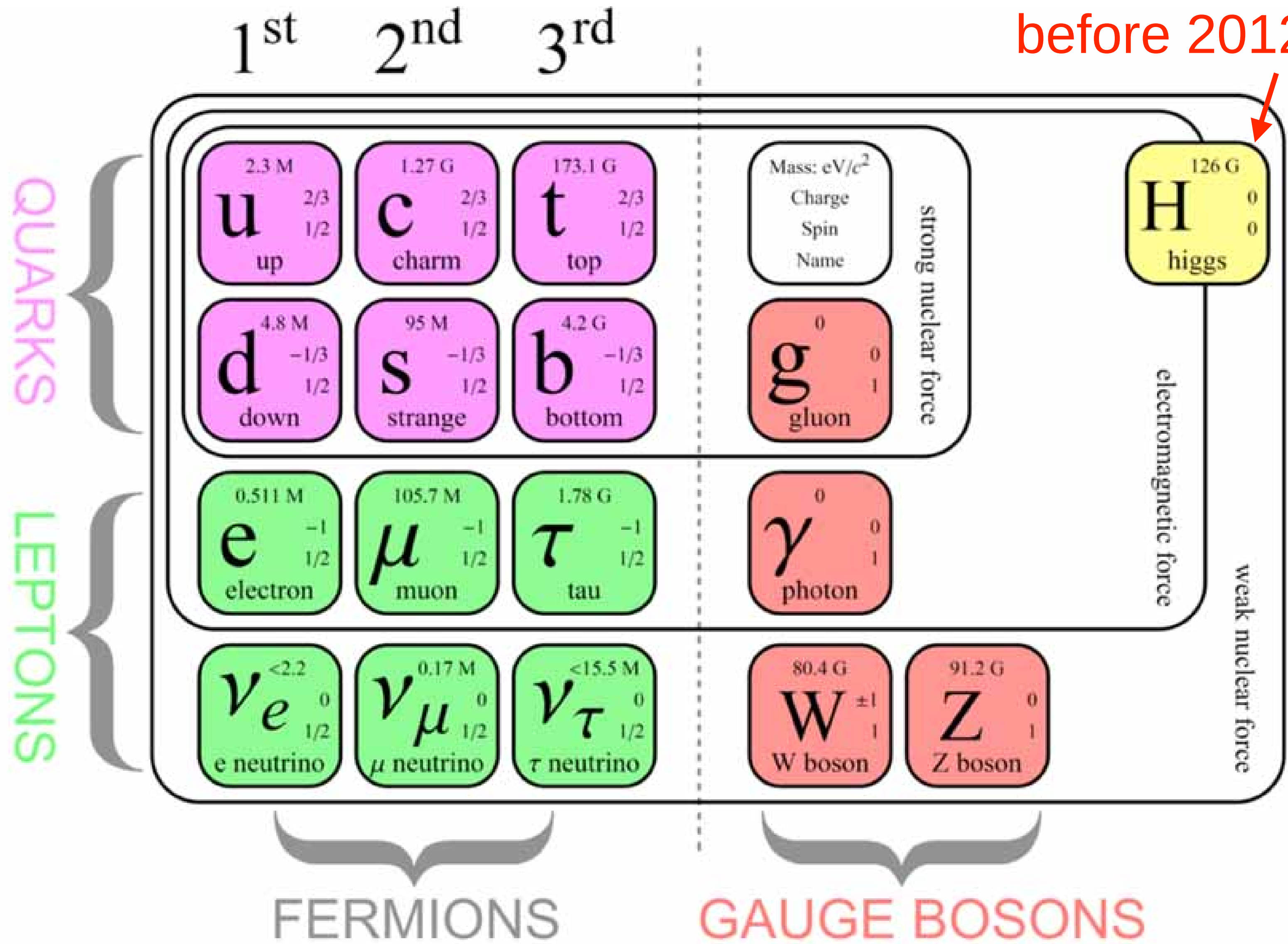
"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"

1979 Nobel Prize in Physics



STANDARD MODEL

last piece yet seen
before 2012 summer



spin-0

spin-1/2

spin-1

Electroweak Gauge Bosons

- SM predicts the existence of:
  - one massless photon (no direct interaction with Higgs boson),
  - a pair of massive $W^{\pm}$ bosons, and
  - one massive Z boson.

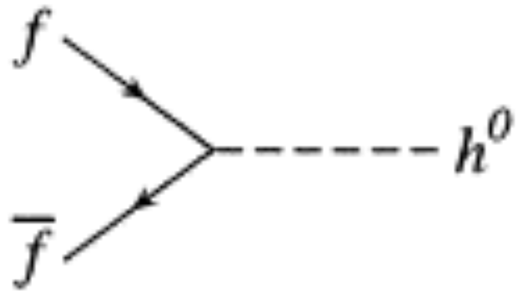
- W and Z bosons were discovered at CERN in 1982 and 1983 to have masses ~80 GeV and ~91 GeV, respectively.

- Studying symmetry breaking enables us to find underlying relations among ostensibly unrelated things.

Fermion Masses

- In the SM, an economic/necessary* way of giving masses to fermions (quarks and charged leptons) is through the so-called Yukawa interactions with the Higgs field:

$$\mathcal{L} \ni -y_f \phi \bar{\psi}_f \psi_f$$
$$\Rightarrow m_f = y_f \langle \phi \rangle$$

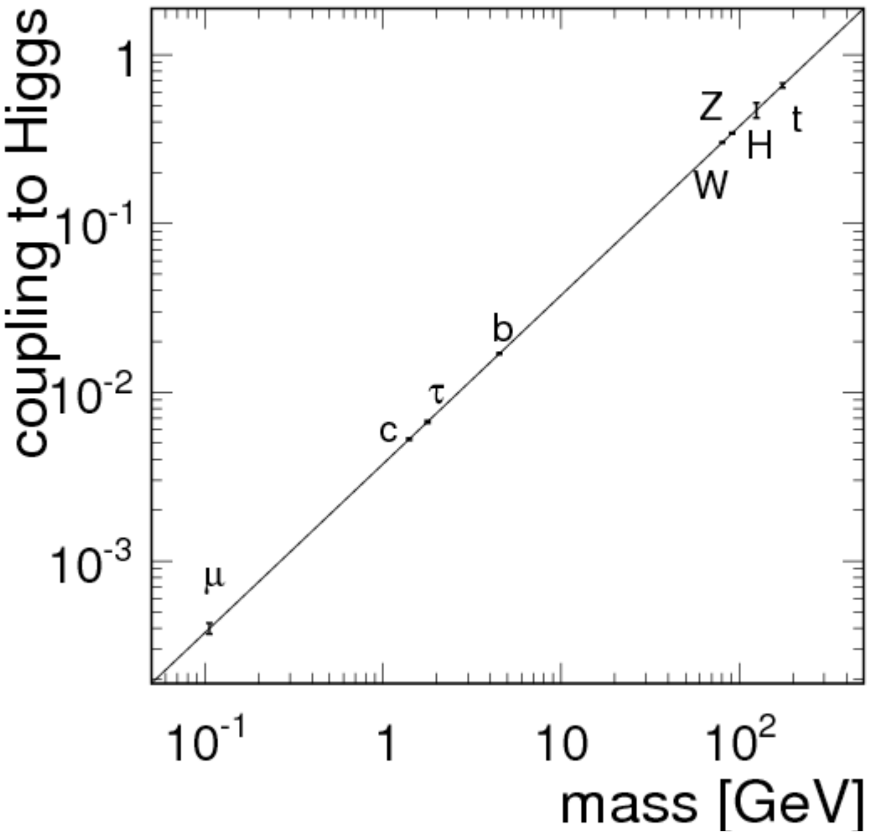


- The fermion masses are thus also proportional to the VEV of the Higgs field.
  ➠ killing two birds with one stone!

* Weinberg's view on effective theory: all terms allowed by gauge symmetry should be included in Lagrangian.

Higgs Couplings to Particles

- It is important to verify the linear relation of SM particle couplings to the Higgs boson –– a unique feature of SM



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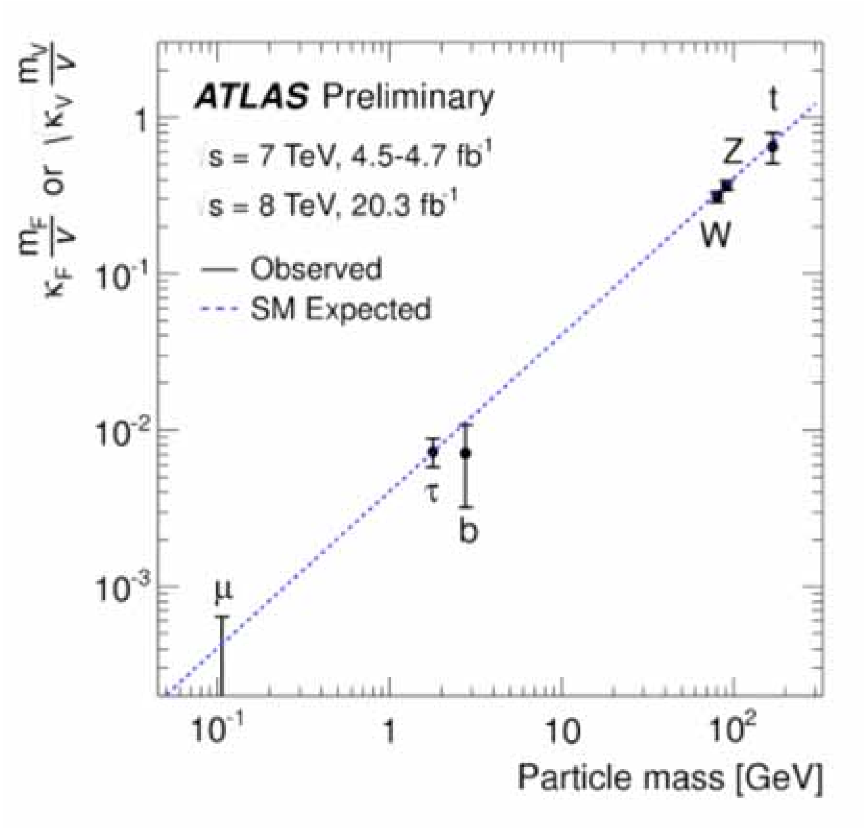
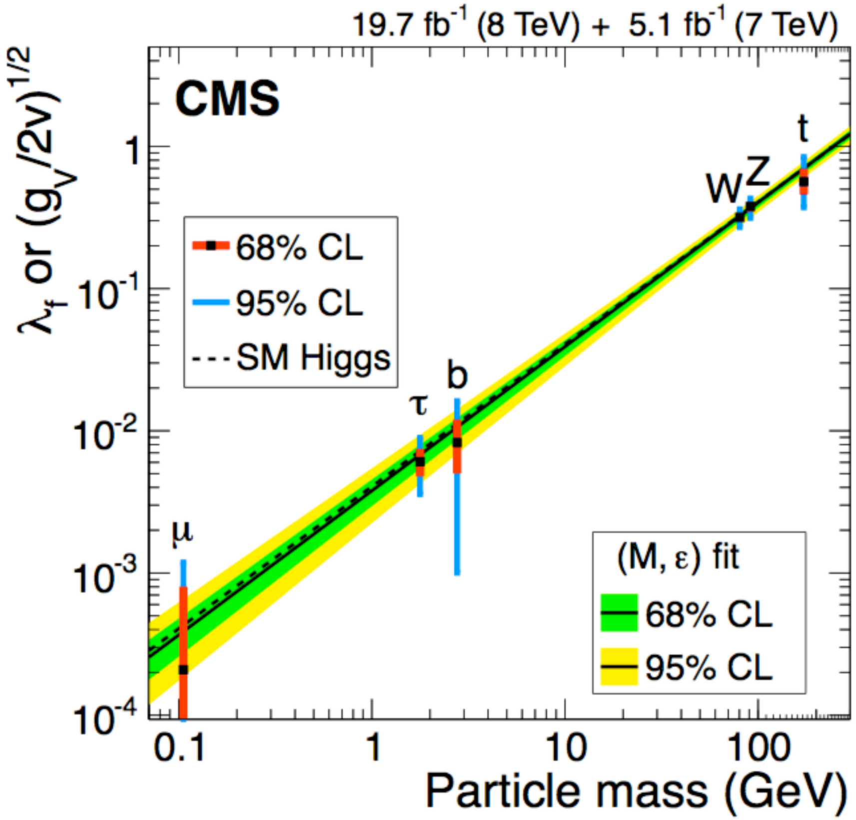
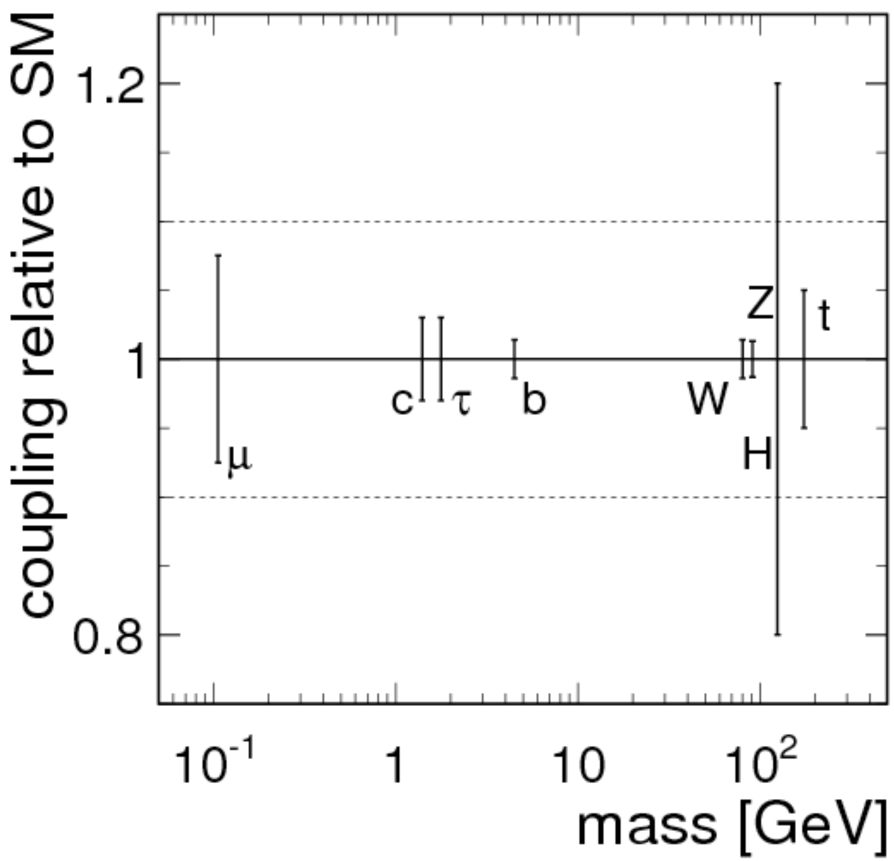




- So far, the particle is very much standard model-like.

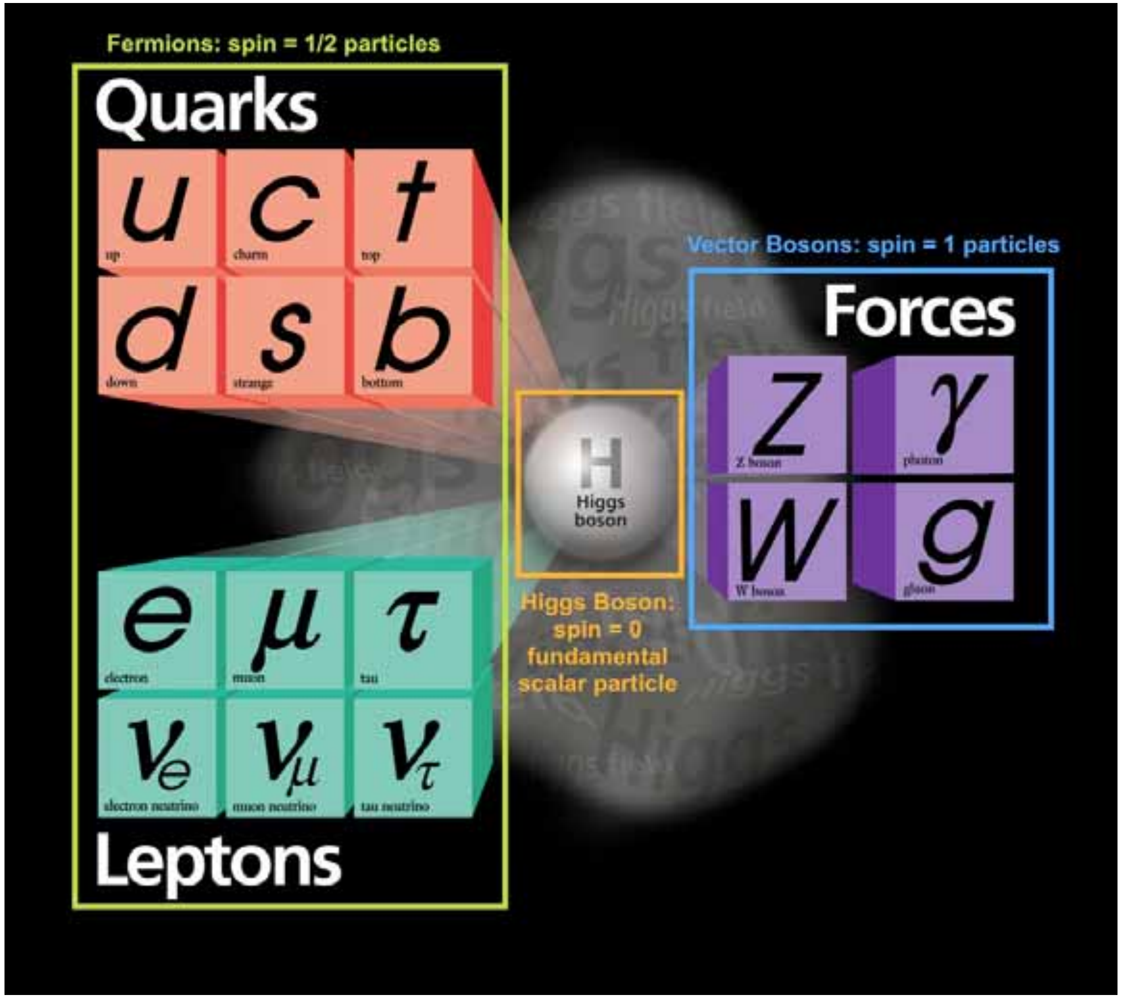
Future Linear Collider

- Relative precision of coupling measurements for a full linear collider Higgs physics program extending from 250/350 GeV up to TeV region in several energy stages.



THE HOLY GRAIL

- The Higgs boson holds the secret to the origin of mass for elementary particles.

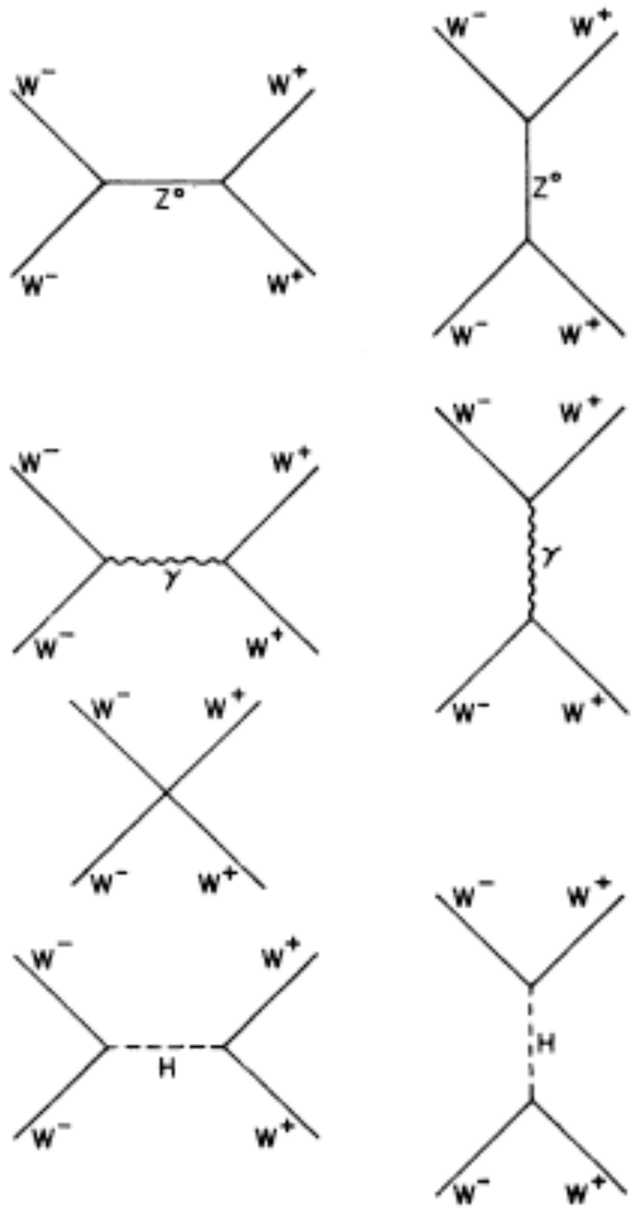


ANOTHER REASON: UNITARITY

$W_L W_L \to W_L W_L$

- Consider this process in the SM in the $s \gg m_h^2$, M_W^2 limit.
- Tree-level Feynman diagrams in the unitarity gauge:
  - 1 four-point interaction;
  - Z and γ in s and t channels; and
  - Higgs boson in s and t channels.
- Other $V_L V_L \to V_L V_L$ scatterings have similar structures.

Lee, Quigg,Thacker 1977



$W_L W_L \to W_L W_L$

- Individual amplitudes of gauge diagrams are functions of scattering energy, angle, and particle masses:

$$i\mathcal{M}_4 = i\frac{g^2}{4M_W^4}\left[s^2 + 4st + t^2 - 4M_W^2(s+t) - \frac{8M_W^2}{s}ut\right]$$

$$i\mathcal{M}_t^{\gamma+Z} = -i\frac{g^2}{4M_W^4}\left[(s-u)t - 3M_W^2(s-u) + \frac{8M_W^2}{s}u^2\right]$$

$$i\mathcal{M}_s^{\gamma+Z} = -i\frac{g^2}{4M_W^4}\left[s(t-u) - 3M_W^2(t-u)\right]$$

where s,t ~ E^2 .

➠ Individual diagrams grow like $(E/M_W)^4$!

- The sum of them nicely cancel with each other to remove such a divergence.

$W_L W_L \to W_L W_L$

- However, there is still an $O((E/M_W)^2)$ divergence in the sum, which needs a sufficiently light Higgs boson to cure:

$$i\mathcal{M}^{\text{gauge}} = -i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) \;, \quad \sim \left(\frac{E}{M_W}\right)^2$$

$$i\mathcal{M}^{\text{Higgs}} = -i\frac{g^2}{4M_W^2}\left[\frac{(s-2M_W^2)^2}{s-m_h^2} + \frac{(t-2M_W^2)^2}{t-m_h^2}\right]$$

$$\simeq i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) \;.$$

$$\Rightarrow \quad \text{complete } (E/M_W)^2 \text{ cancellation}$$

- Success of SM is seen to rely on nice relations among gauge bosons couplings (due to gauge structure) and a suitable Higgs boson (depending on EWSB structure).

$W_L W_L \to W_L W_L$

- However, the story changes dramatically if $g_{hVV} = \sqrt{\delta}\, g_{hVV}^{\rm SM}$ is assumed (e.g., 2HDM):

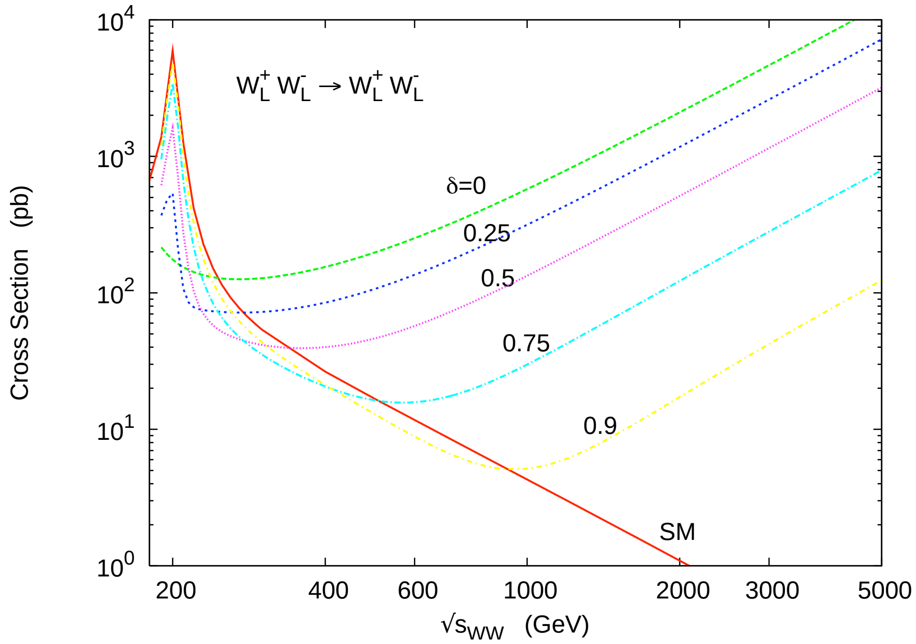
$$i\mathcal{M}^{\rm gauge} = -i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) \;,$$

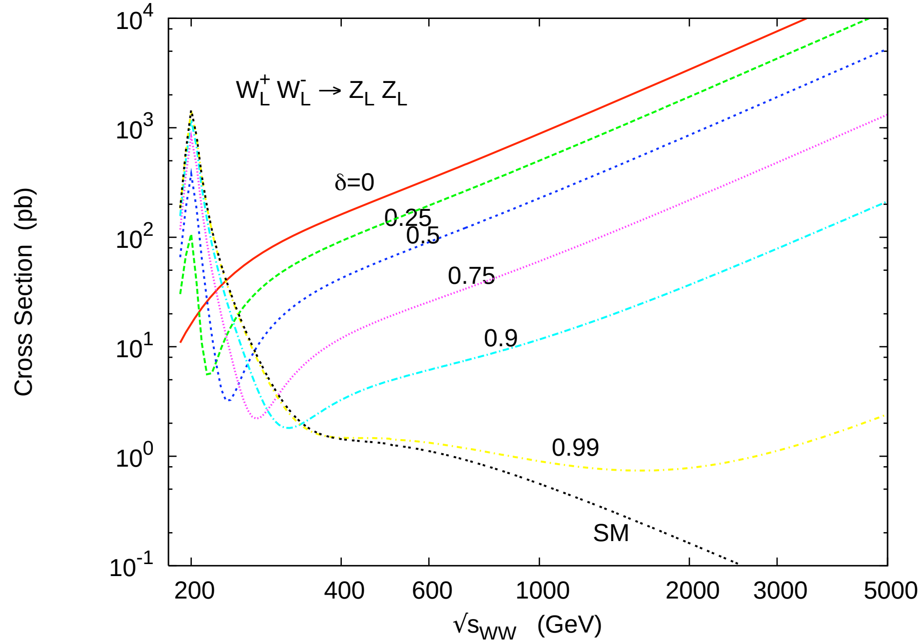
$$\begin{aligned} i\mathcal{M}^{\rm Higgs} &= -i\,\delta\frac{g^2}{4M_W^2}\left[\frac{(s-2M_W^2)^2}{s-m_h^2} + \frac{(t-2M_W^2)^2}{t-m_h^2}\right] \\ &\simeq i\,\delta\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) \;. \end{aligned}$$

$$\Rightarrow \;\; \text{only partial } (E/M_W)^2 \text{ cancellation}$$

- This gives rise to the “bad” high-energy behavior in the scattering cross section.

CROSS SECTIONS



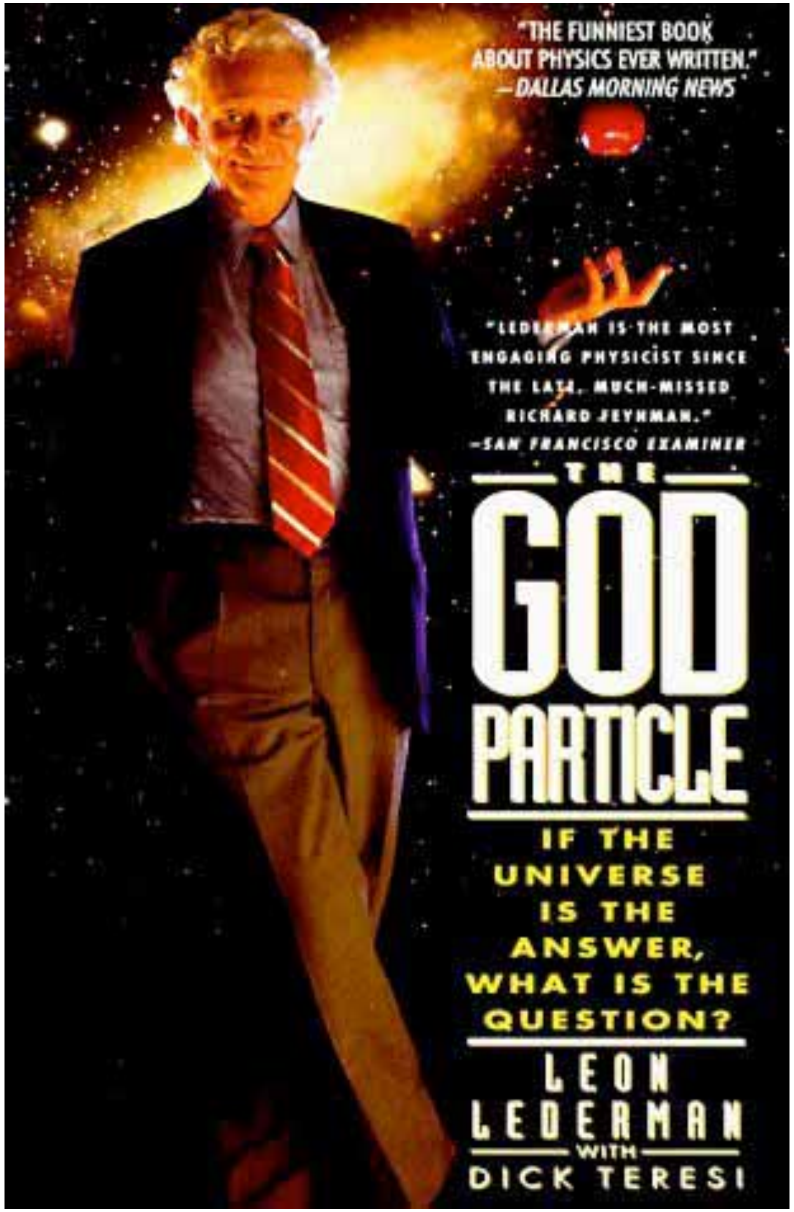


- Cross sections as functions of the scattering energy.
- Assume $m_h = 200$ GeV and an angular cut $|\cos\theta| \leq 0.8$.
- The turn-over effect is different from SM both qualitatively and quantitatively, even if effects of heavy Higgs bosons of TeV masses are included.

GOD PARTICLE OR GODDAMN PARTICLE?

THE GOD PARTICLE

- *The God Particle: If the Universe Is the Answer, What is the Question?* is a 1993 popular science book by Nobel laureate Leon M. Lederman and science writer Dick Teresi.
- Official reason: the particle is "so central to the state of physics today, so crucial to our final understanding of the structure of matter, yet so elusive."



The God Particle

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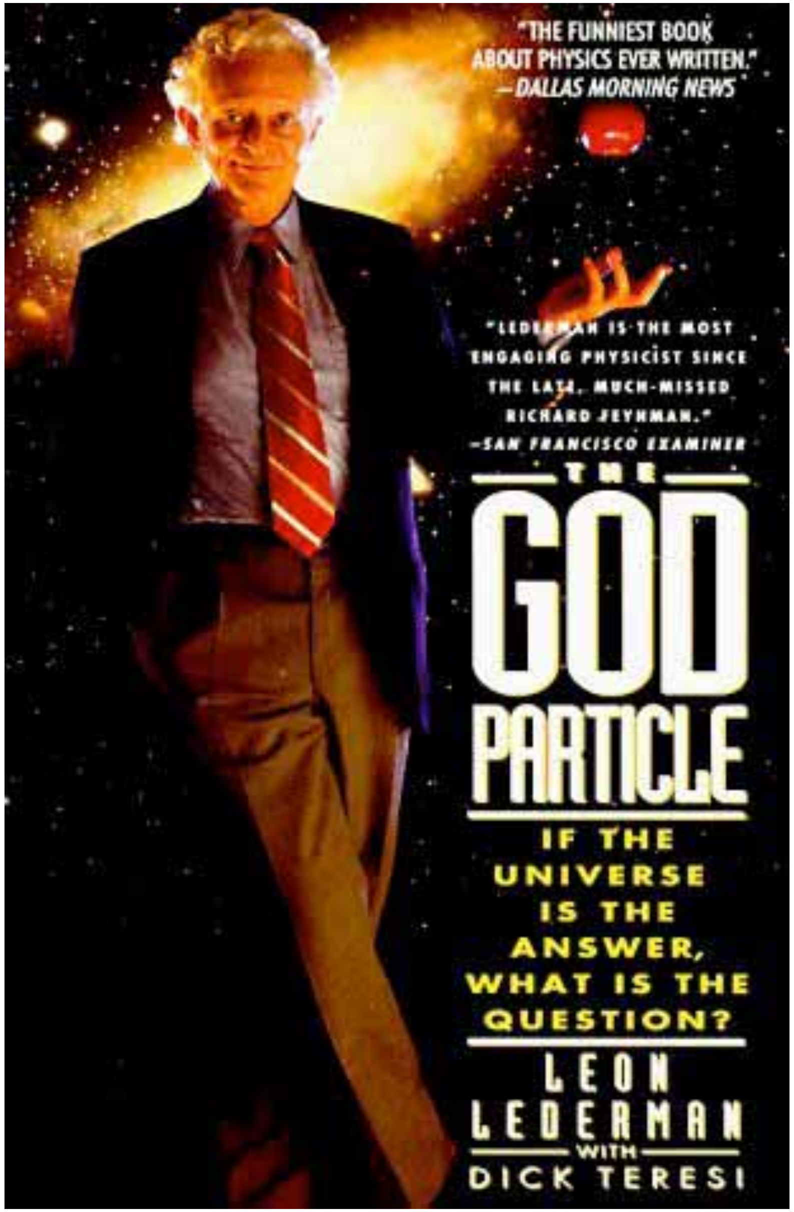
- Second reason: “I was planning to call my book ‘The Higgs Particle’, but the editor said that no one had ever heard of Higgs.”



The God Particle

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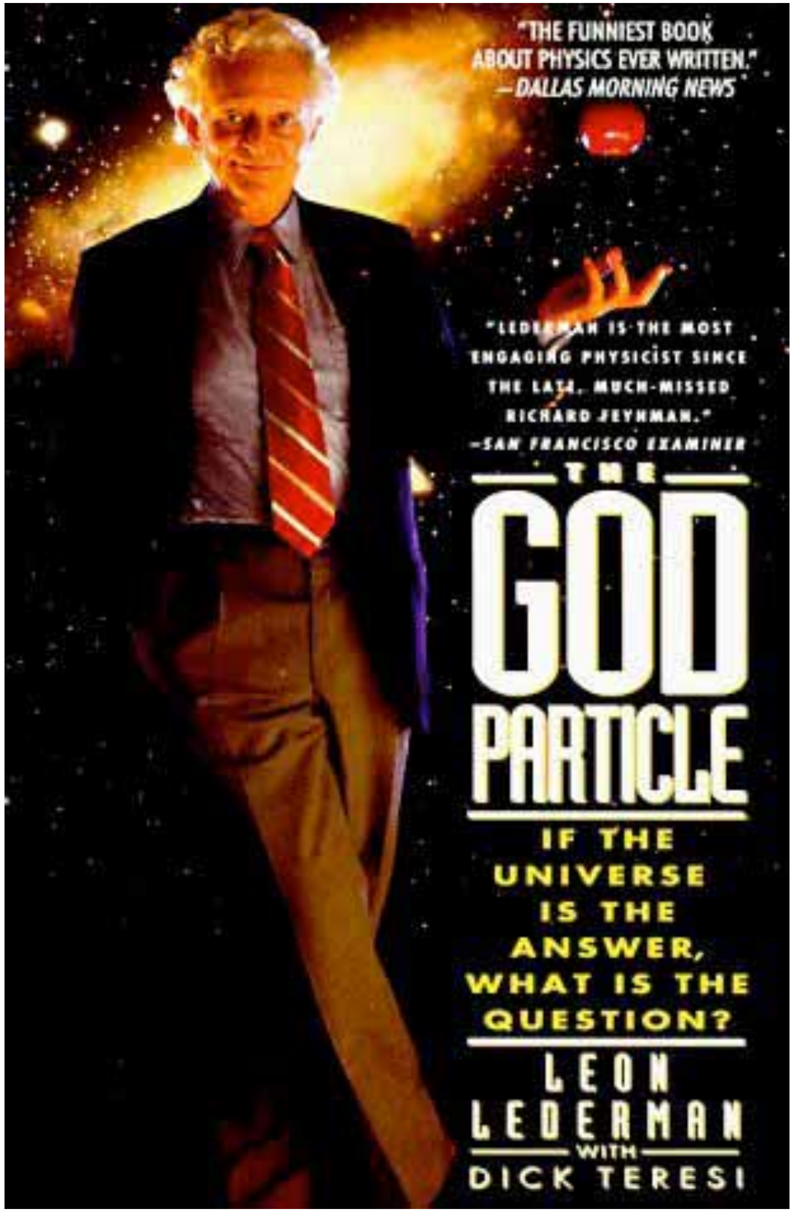
- Third reason: “the publisher wouldn’t let us call it the Goddamn Particle, though that might be a more appropriate title, given its villainous nature and the expense it is causing.”



PANDORA'S BOX

- Almost all current particle physics problems are rooted in the Higgs field! ➠ The stone hits a beehive!

$$\mathcal{L}_{\text{Higgs}} = |D_\mu \phi|^2 - V_0 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2 - \sum_{ij} y_{ij} \overline{\psi}_{iL} \psi_{jR} \phi + \text{h.c.}$$

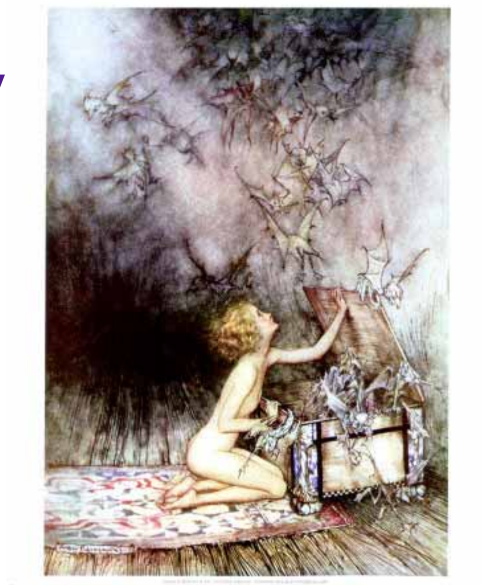
$|D_\mu \phi|^2$ → massive weak gauge bosons

V_0 → tiny vacuum energy $V_{obs} \sim (2\times10^{-3}\ \text{eV})^4$

μ^2 → origin of the negative coefficient unclear; quadratic divergence in Higgs mass correction

λ → possible instability of the potential at high energies

y_{ij} → source of flavor problems: mass hierarchy, CP violation, etc



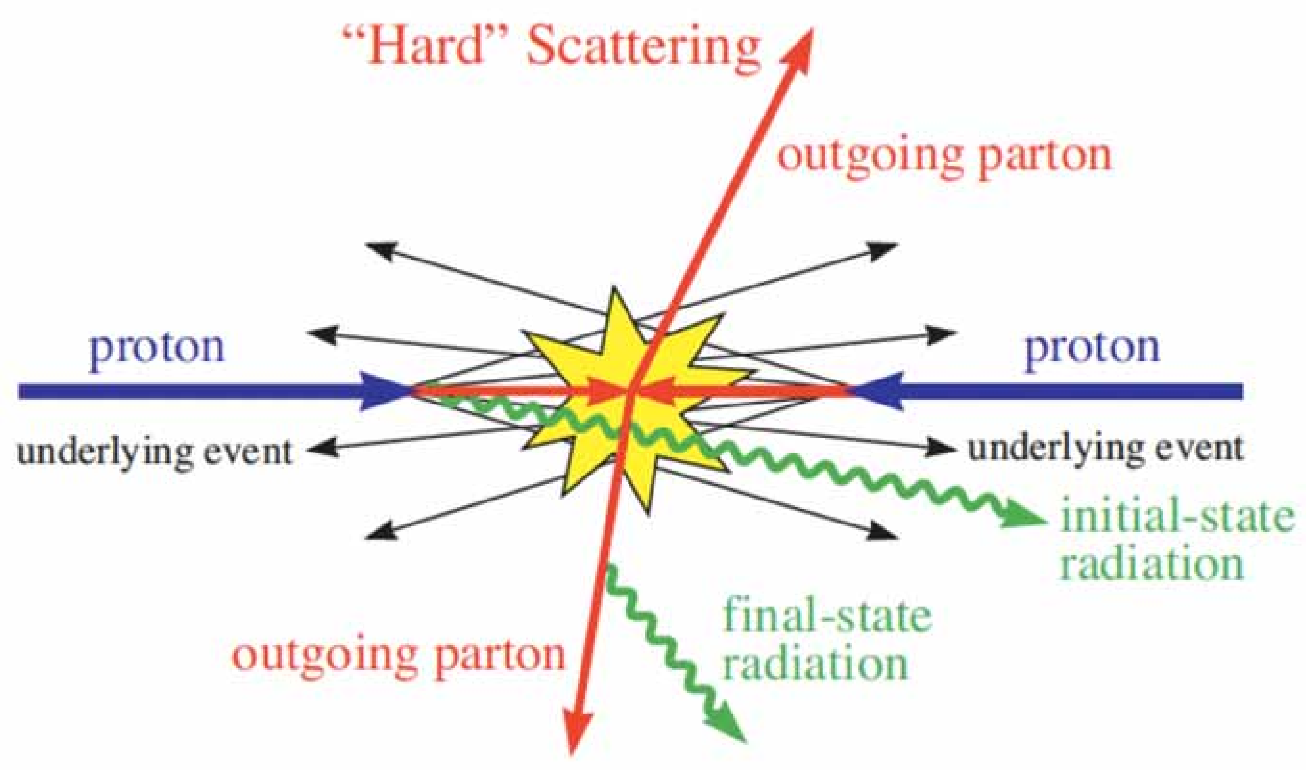
What Are The Difficulties?

- Discovery of the Higgs boson is thus very essential:
  - ➠ completes the spectrum of SM
  - ➠ answers origin of elementary particle mass
  - ➠ justifies previously mentioned problems
  - ➠ possibly points us to physics beyond SM
- It has been searched for for almost half a century!
- Why is it so elusive?

- How can we produce the Higgs boson?
  - ➠ how many per unit time we can create at colliders
- How does it decay?
  - ➠ which modes we should use for detection

SMASHING PROTONS

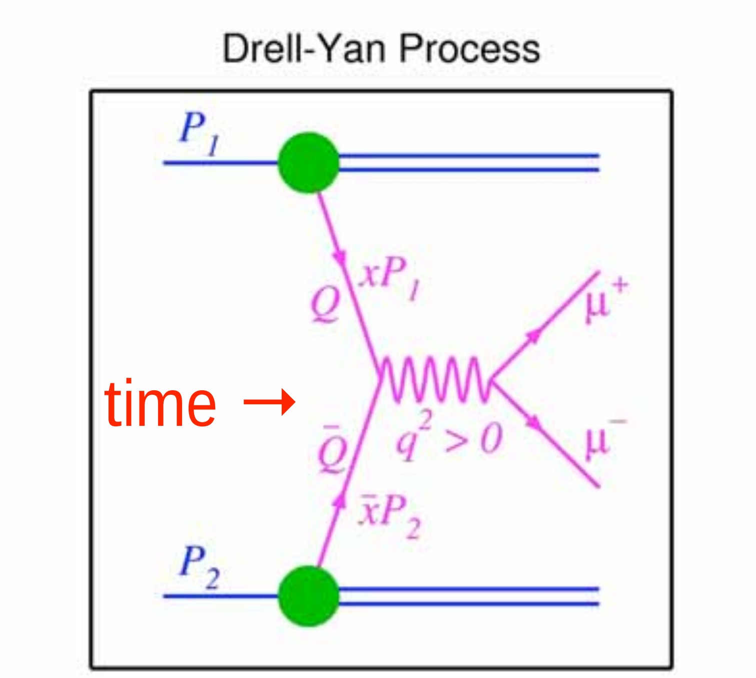
- Protons collide at high energy to hopefully produce new particles, according to $E = mc^2$.



- Newly produced particles usually decay fast into more stable particles to be seen at the detector.

Proton-Proton Collision

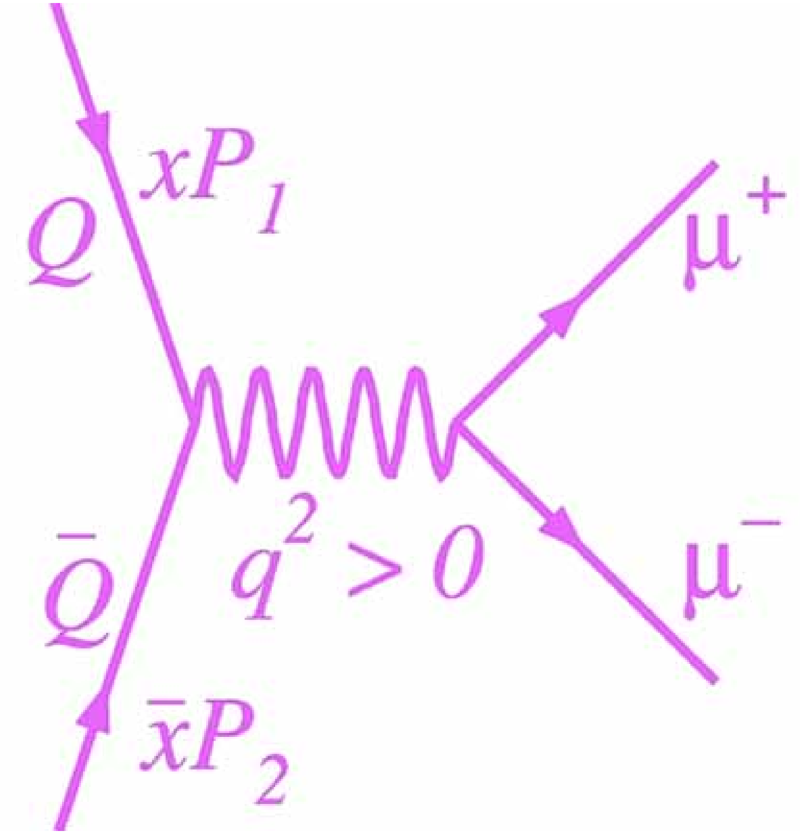
- A typical proton-proton (or proton-anti-proton) scattering process at colliders:

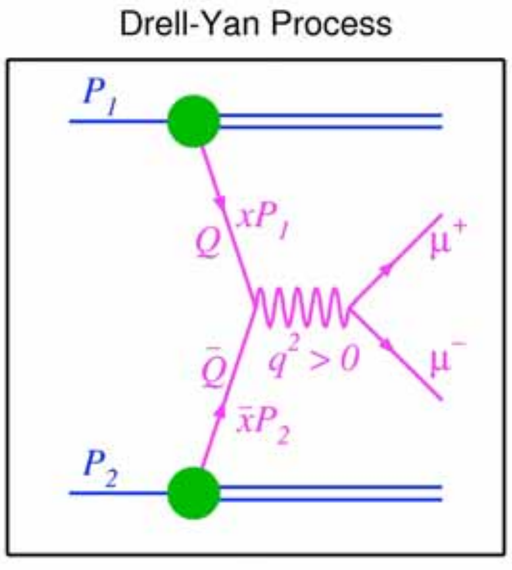


elementary processes explained in so-called Feynman diagrams

Proton-Proton Collision

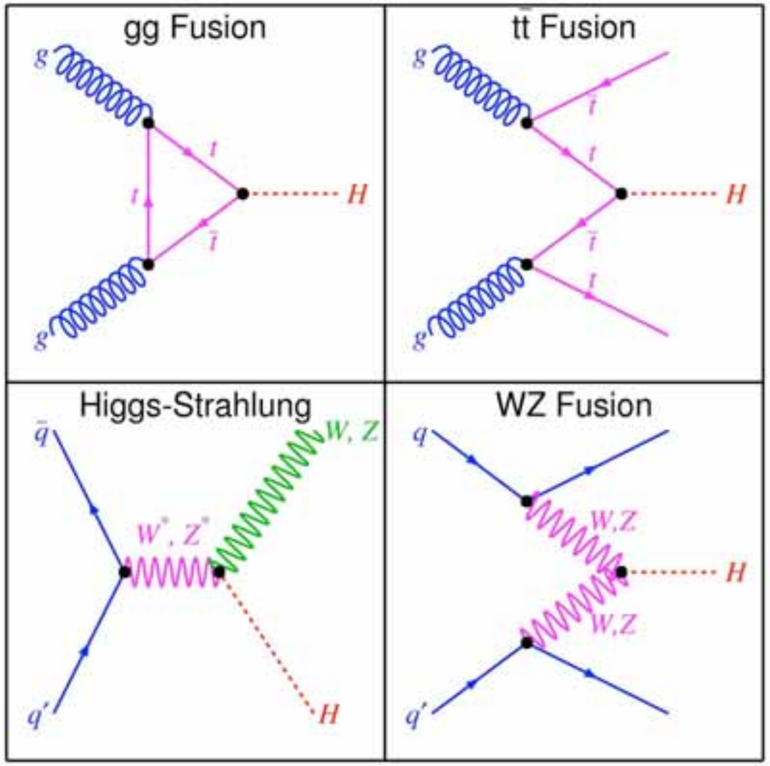
- Zoom in on the core (hard), parton-level, process that is calculable using Feynman rules and perturbation techniques:

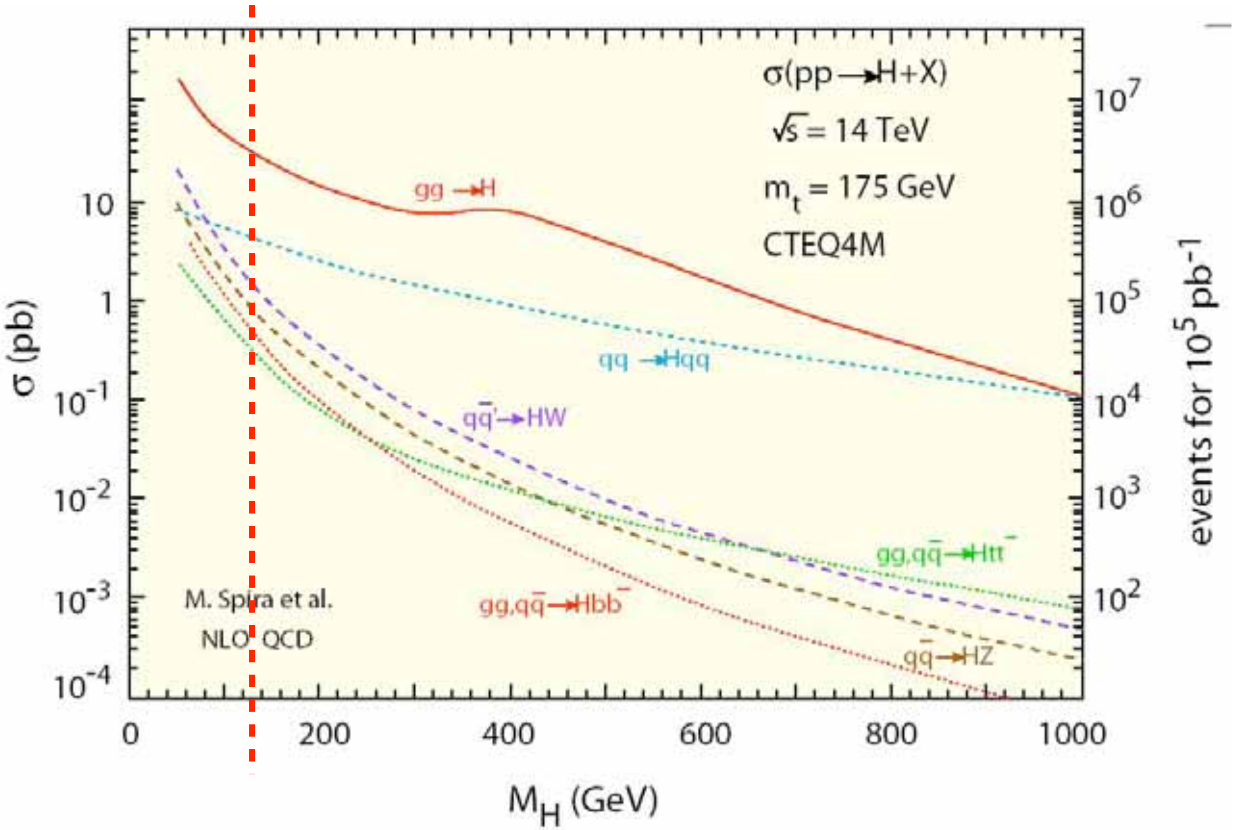




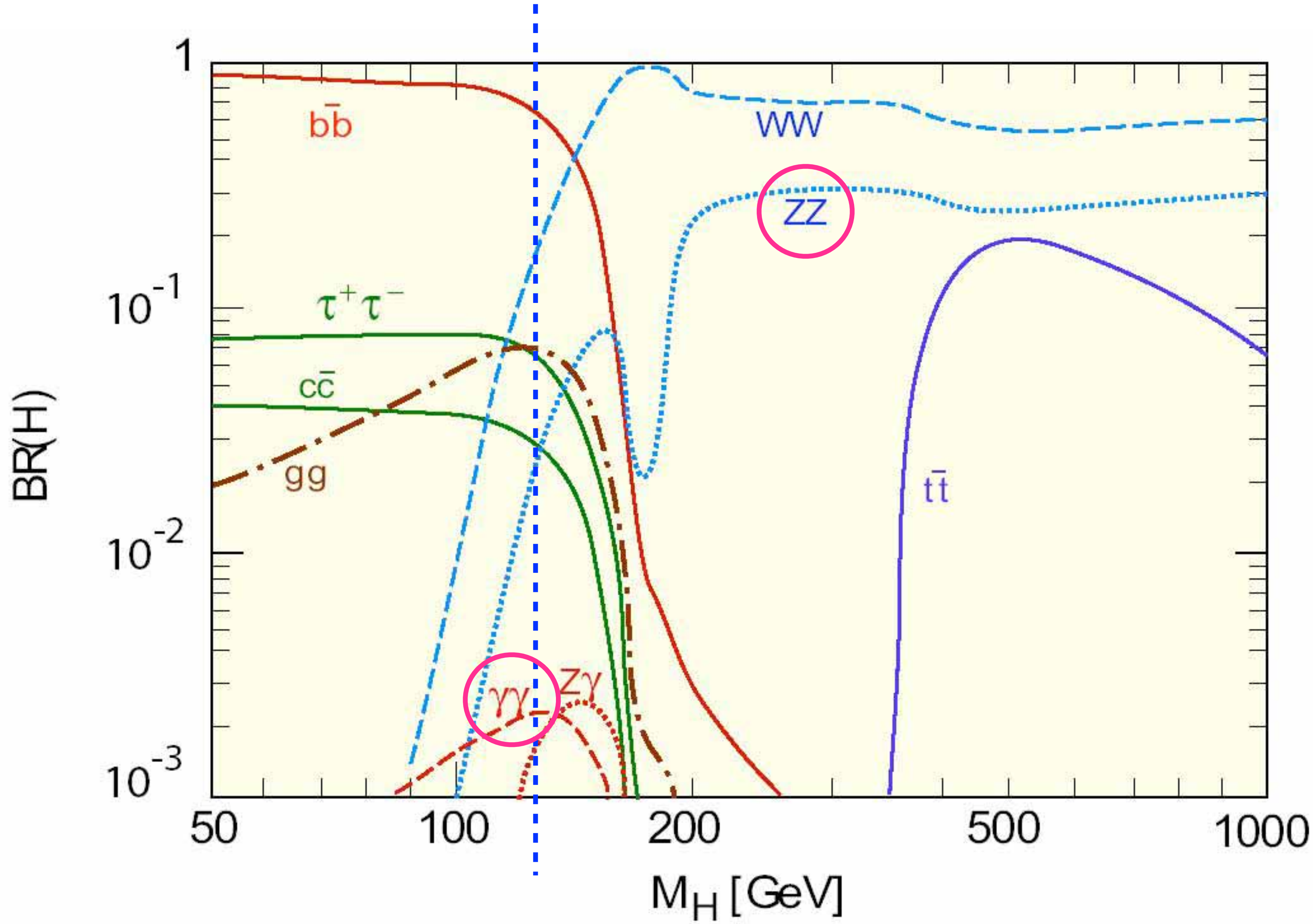
MAJOR HIGGS PRODUCTION

- Hard processes:

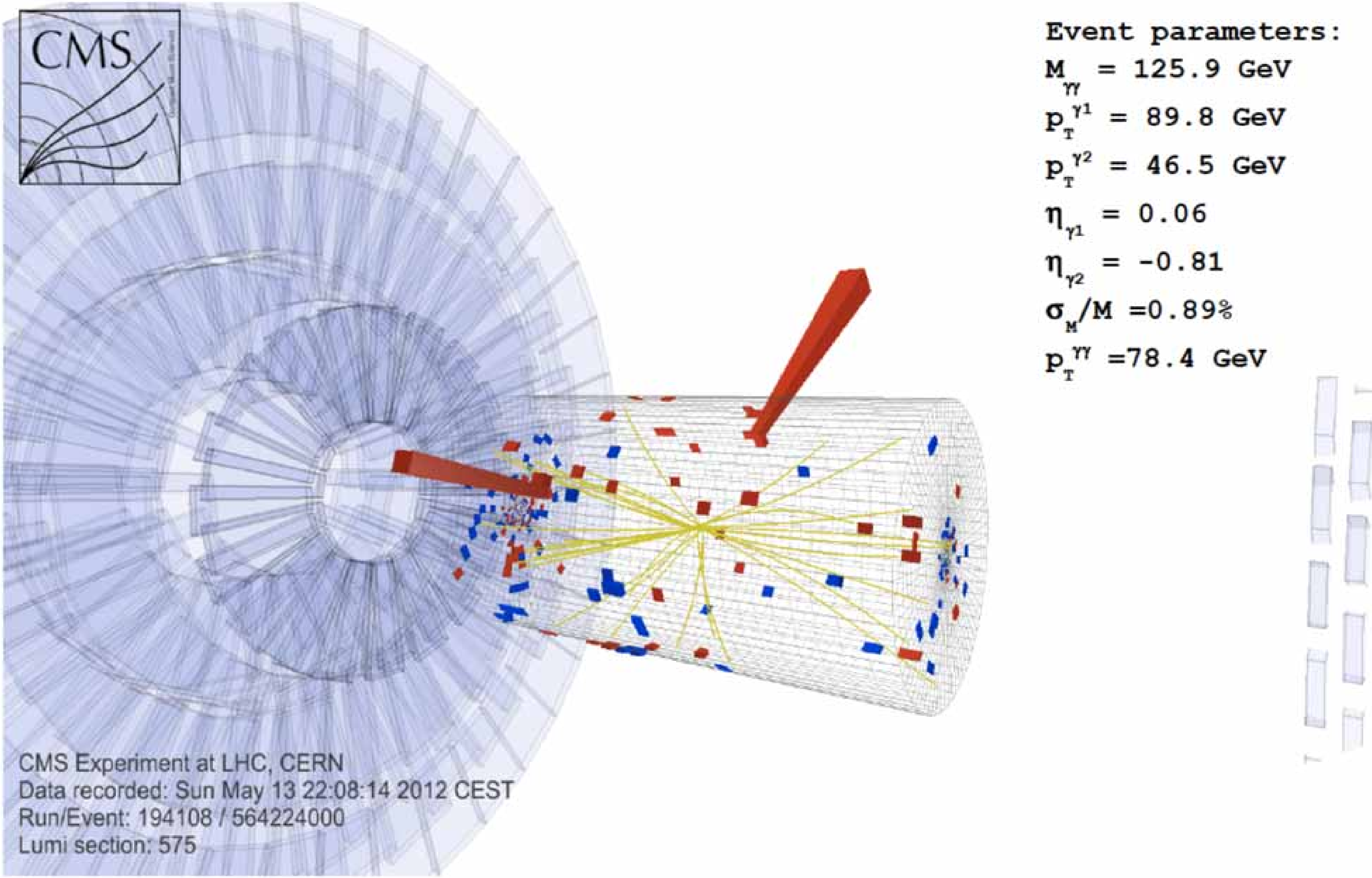




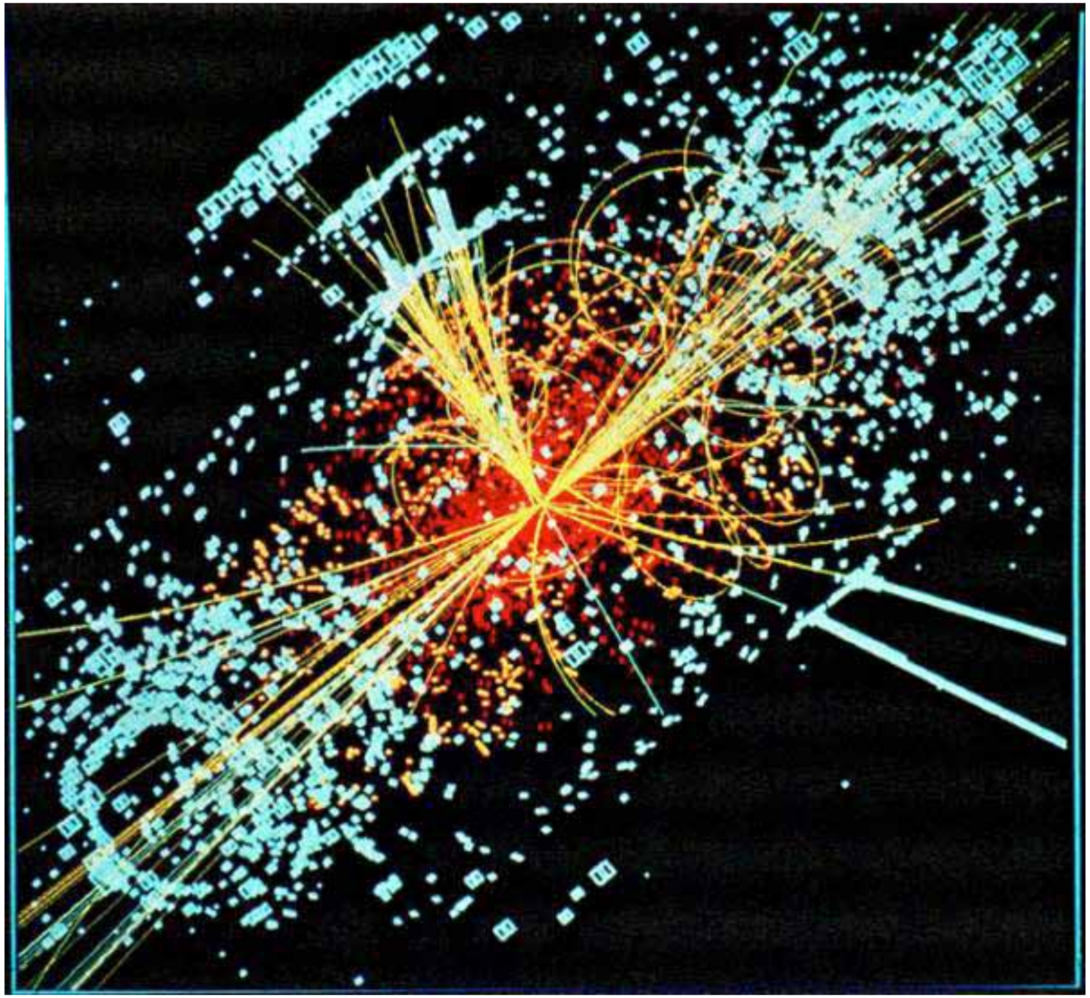
Higgs BR's in SM



A Higgs To Diphoton Event



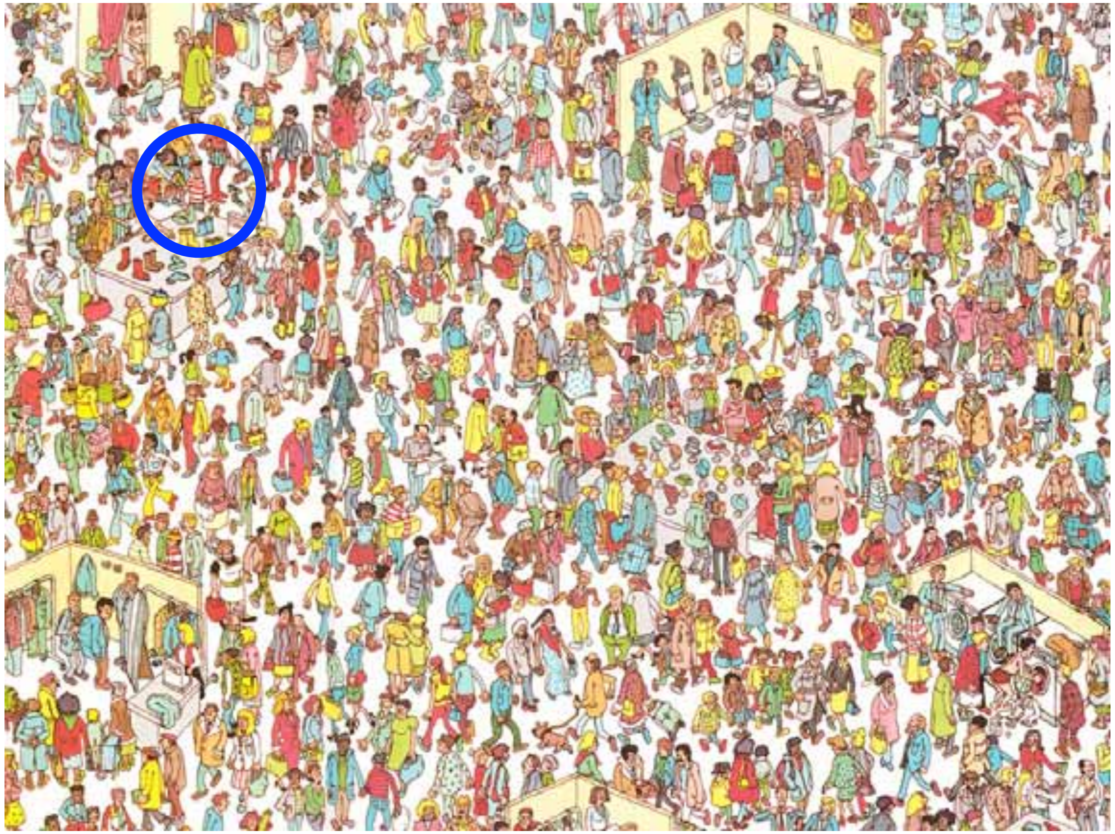
WHAT IT REALLY LOOKS LIKE



- Our experimental colleagues constantly face the challenge of finding interesting physics from events like this.

Frantic Collisions

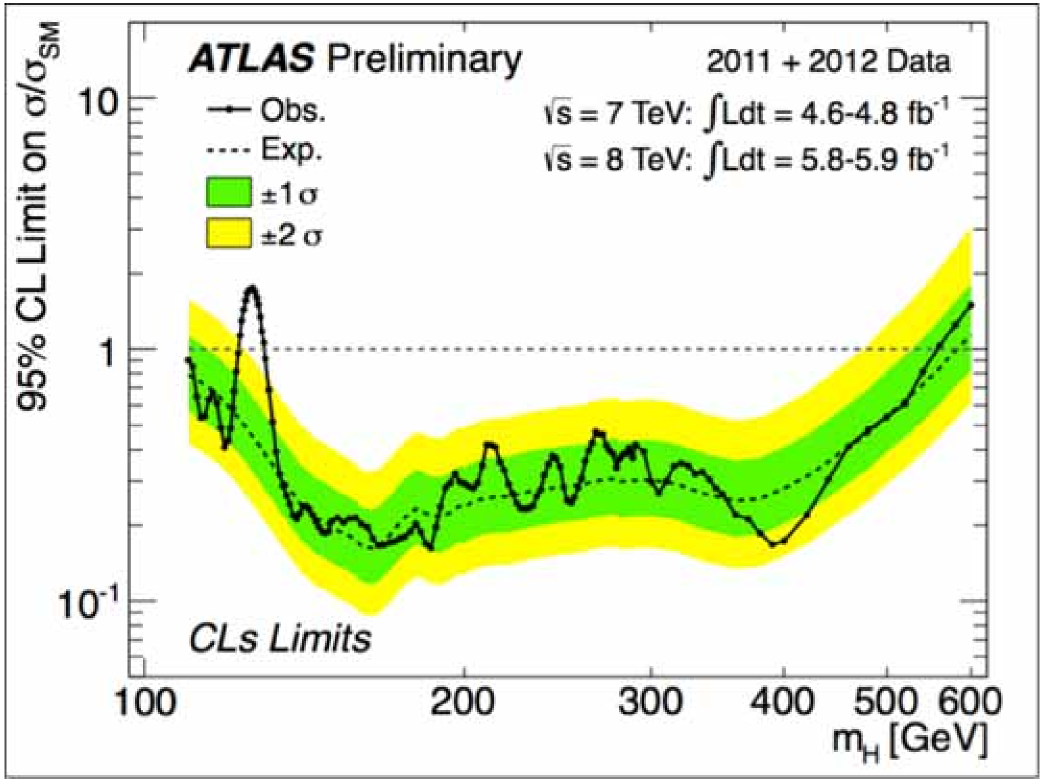
- At design luminosity of LHC, there are ~ 20 interactions every time beams cross. Beams will cross about 40 million times/sec at final configuration.
  ➠ about a billion interactions/sec (a billion frames/sec!)

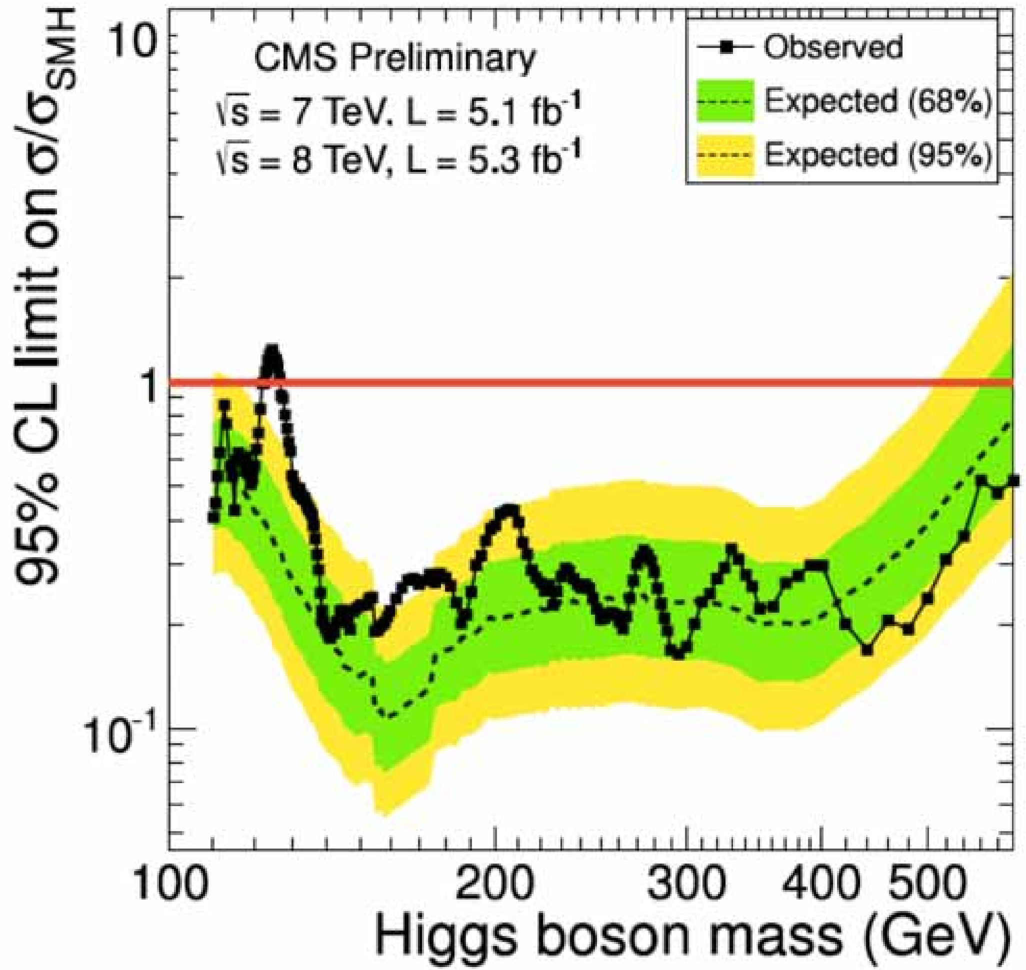


Where's Waldo?

Discovery of Higgs -- 2012

- Both ATLAS and CMS confirmed a Higgs-like particle at ~125 GeV at 5σ level from a combination of various decay modes on July 4, 2012!





EXTENDED HIGGS SECTOR AND DARK UNIVERSE

Neutrino Mass

- Neutrino mass is an interesting topic on its own.
  ➠ this year's Nobel prize
- Within SM and without right-handed (RH) neutrino fields, left-handed (LH) neutrinos have to be massless
  ➠ in conflict with data –– neutrinos have sub-eV mass
- Possible solutions:
  - Neutrinos have RH components at low energy and Dirac mass, from Higgs VEV as other fermions
    ➠ still within SM; even more serious hierarchy problem
  - Neutrinos have no RH components at low energy and Majorana mass due to the so-called seesaw mechanism
    ➠ beyond SM; three types; involving new particles

Type-I Seesaw Mechanism

Minkowski 1977; Gell-Mann, Ramond, Slansky 1979;
Yanagida 1979; Glashow 1980; Mohapatra, Senjanovic 1980

- Suppose neutrino mass matrix is in the form

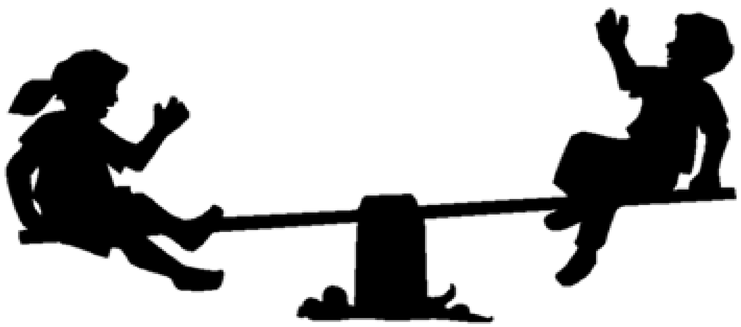
$$\mathcal{L} \supset -\frac{1}{2} \begin{pmatrix} \nu_L^c & \nu_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

for all generations.

- If $M_R \gg m_D$, the eigenmasses are

$$m_\nu \simeq -m_D M_R^{-1} m_D^T \qquad m_N \simeq M_R$$

which can be naturally light.



Type-II Seesaw Mechanism

- Introduce a new Higgs triplet field, Δ, which gets a VEV as triggered by electroweak symmetry breaking

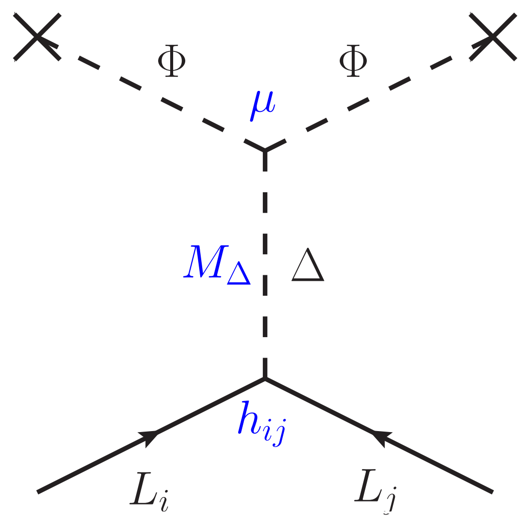
$$\langle \delta^0 \rangle = \frac{v_\Delta}{\sqrt{2}} \quad \text{and} \quad v_\Delta = \frac{\mu v_0^2}{\sqrt{2} M_\Delta^2}$$

- Renormalizable interaction with LH neutrinos allowed

$$h_{ij} \psi_{iL}^T C i \sigma_2 \Delta \psi_{jL} + \text{h.c.}$$

- Majorana neutrino mass matrix

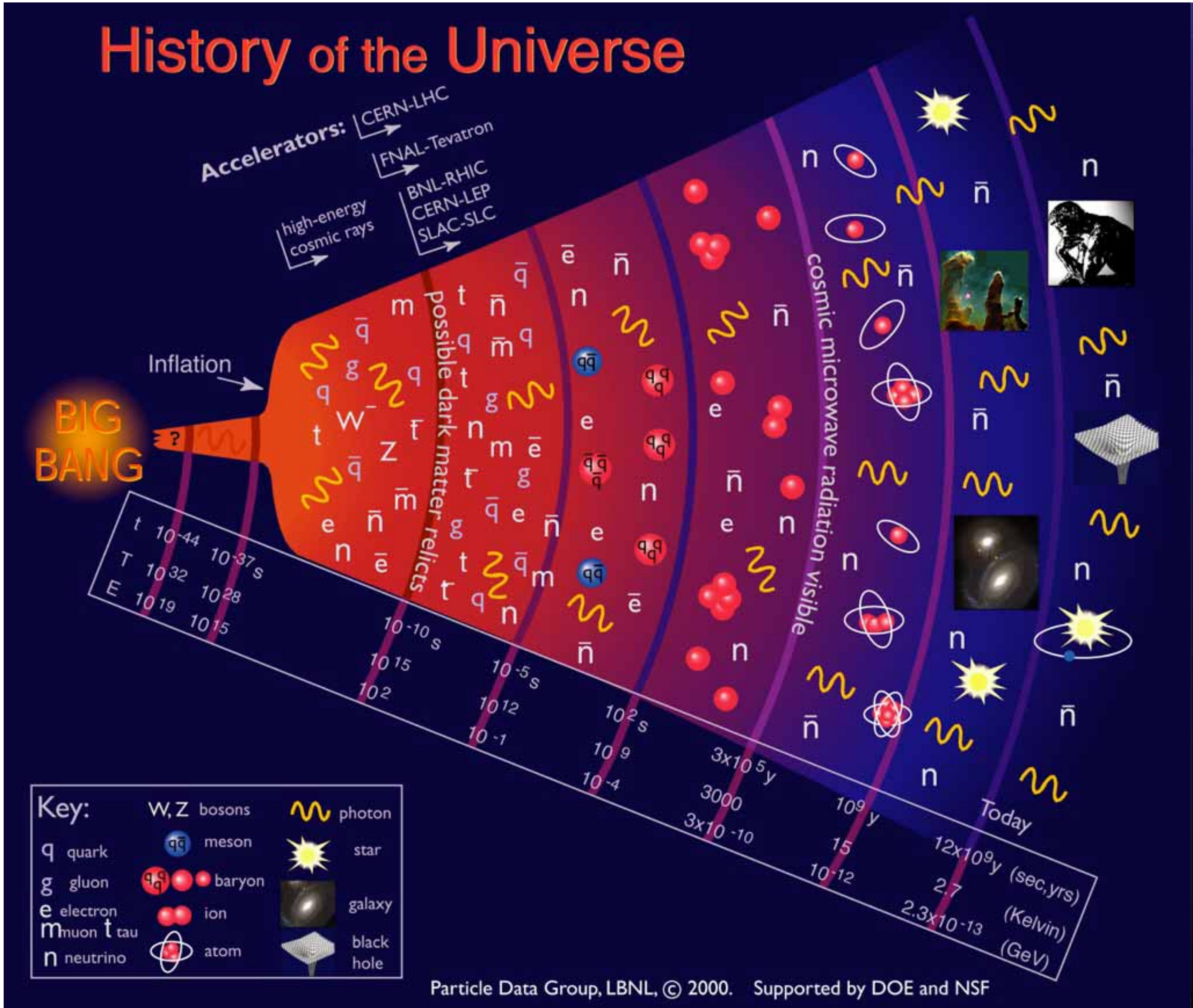
$$M_\nu = \sqrt{2} h v_\Delta = h \frac{\mu v_0^2}{M_\Delta^2}$$

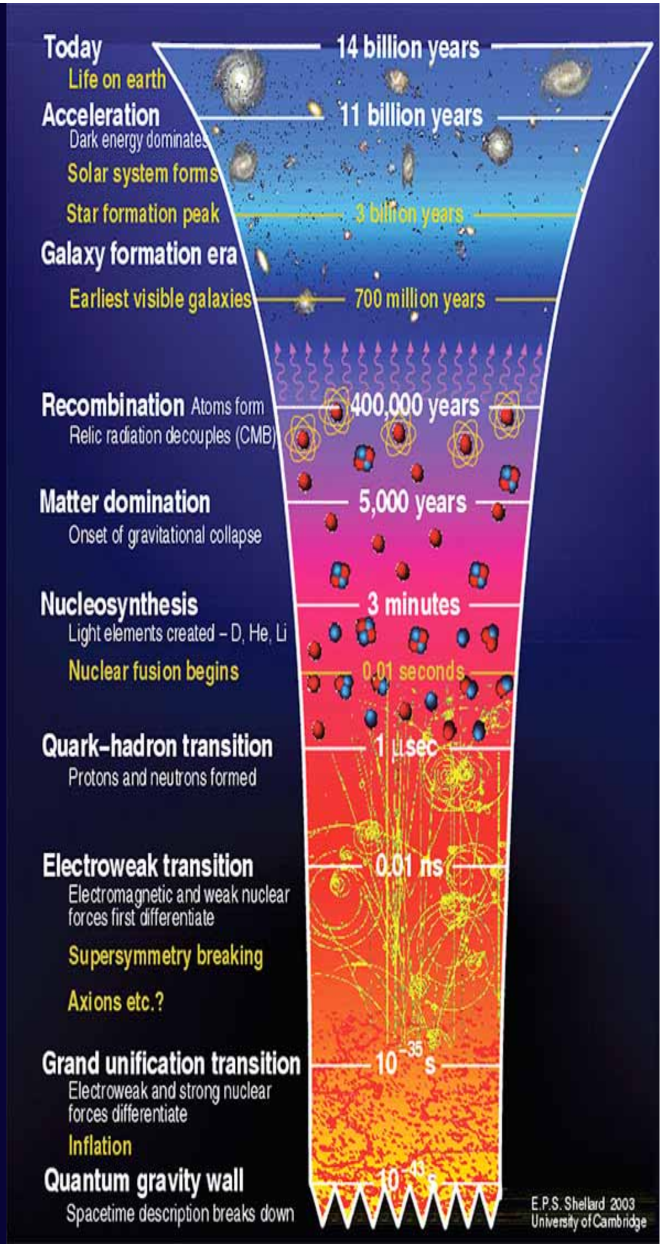


ADVENTURES IN HIGGSLAND

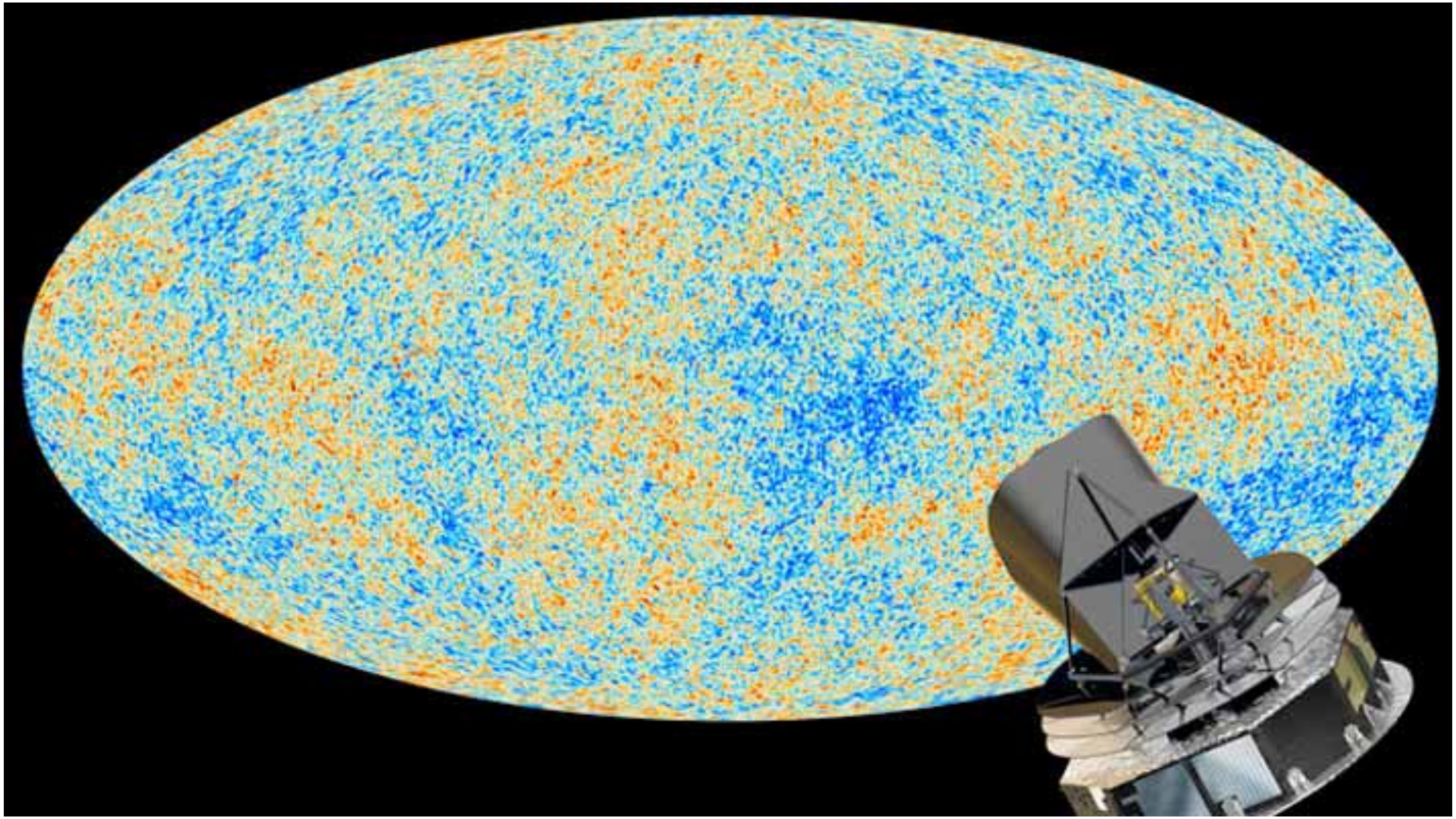
- The Higgs sector is least known experimentally and has no guiding principle other than gauge and Lorentz symmetries (e.g., kinds and number of representations).
- An extended Higgs sector may
  ➠ lead to new Higgs phenomenology (CP-odd / charged Higgs bosons, CP violation, etc)
  ➠ be a portal to a hidden sector for DM or NP in general
  Silveira and Zee 1985; Patt and Wilczek 2006; Wells 2008
  ➠ provide origin of neutrino mass and/or DM
- Like Alice in Wonderland, we are having an adventure in Higgsland, exploring various theme parks to find out which one(s) can better fit data.

Brief History of Universe



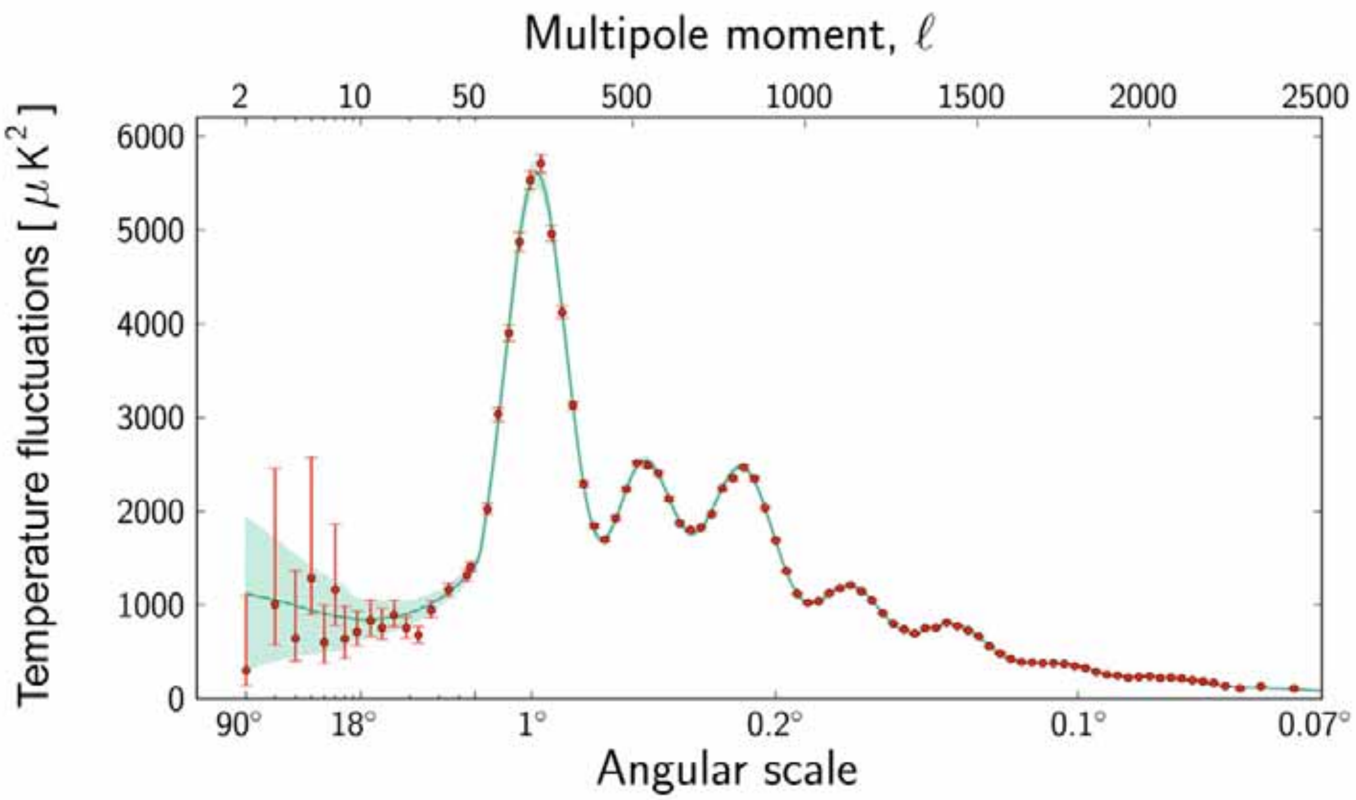


Planck Observation



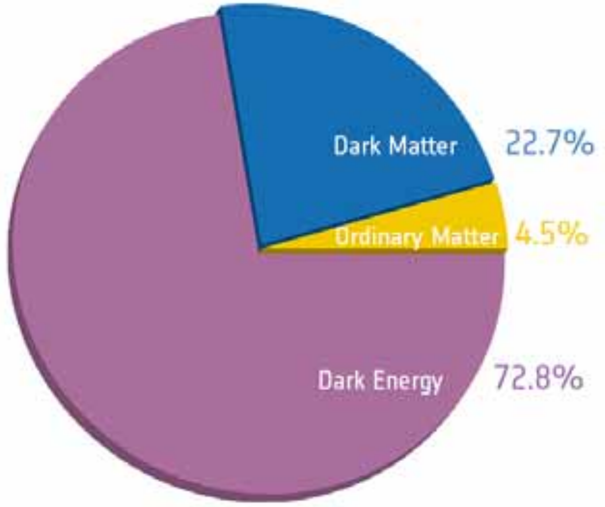
Planck Power Spectrum

- Power spectrum –– temperature fluctuations in the Cosmic Microwave Background detected by Planck at different angular scales on the sky.

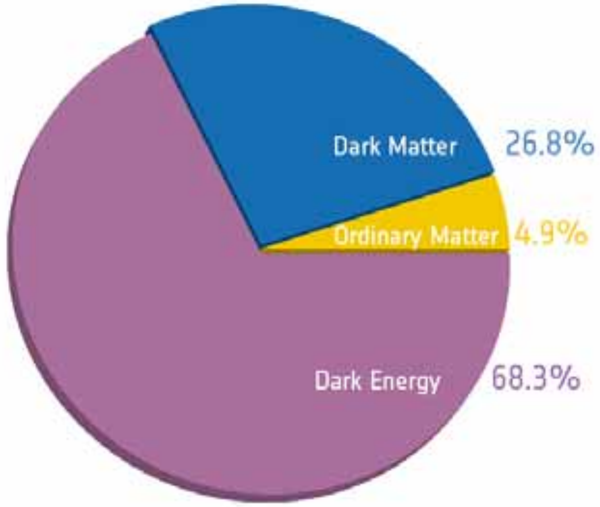


PLANCK IMPLICATIONS

- The Universe is 13.82 billion years old.
- It is made of 4.9% ordinary matter, 26.8% dark matter, and 68.3% dark energy.
- It has an accelerated expansion, current rate at ~70 km/sec/Mpc.
- It is pretty flat in space geometry.



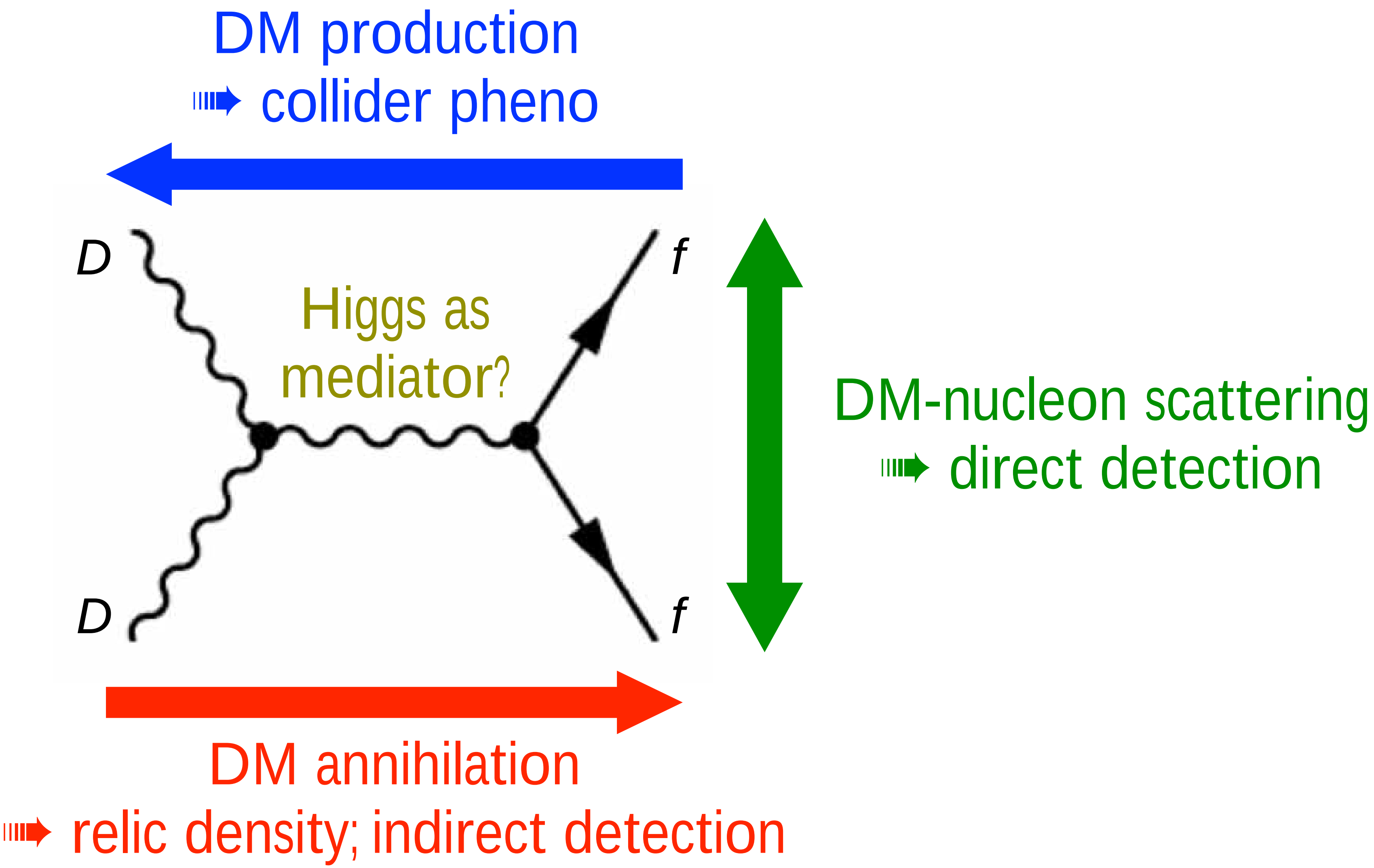
Before Planck



After Planck

Higgs Portal

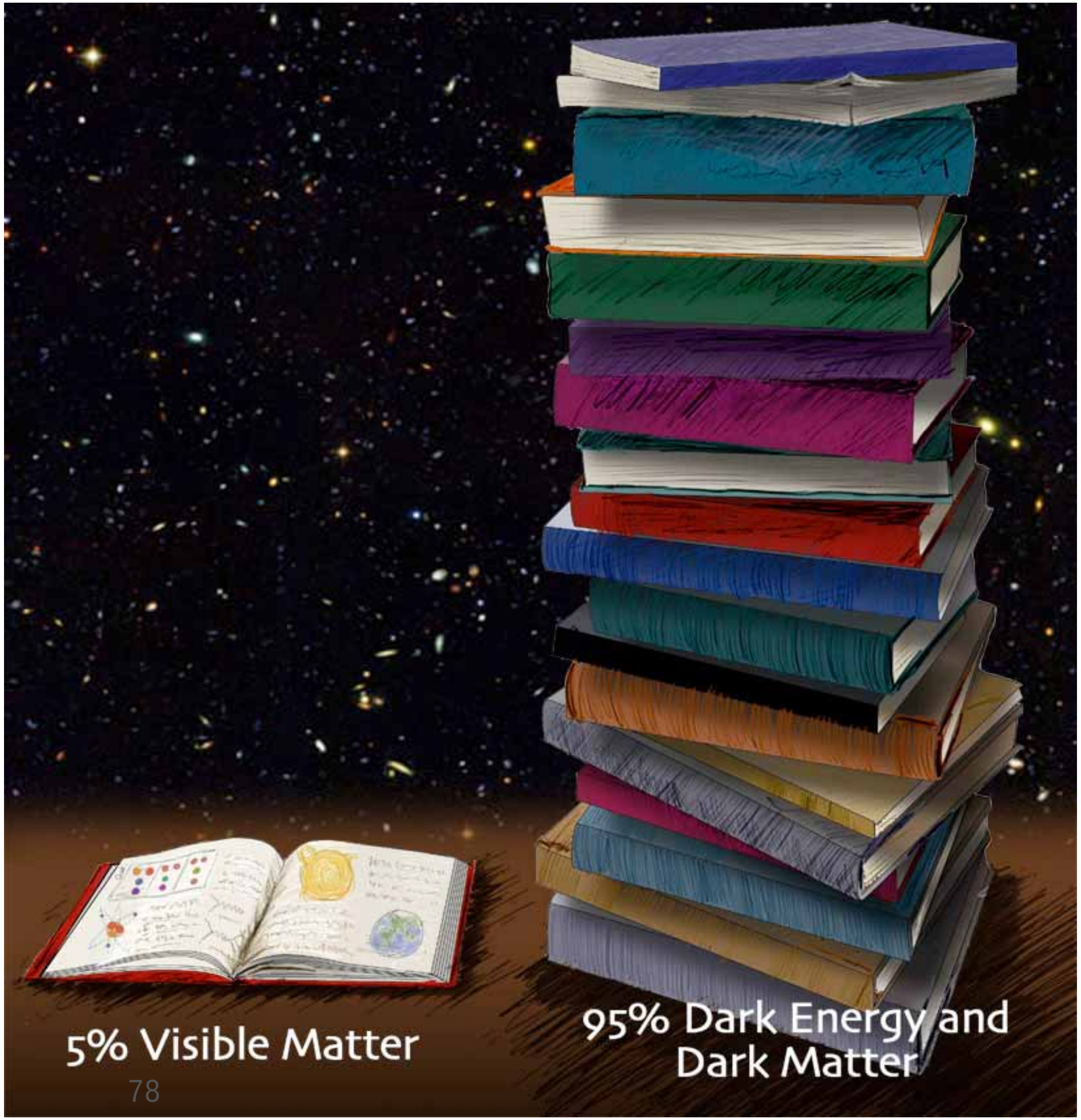
- Only gravitational effects of DM are observed up to now.



Books Yet to Read

- All we have been trying to comprehend in the past two millennia are only 5% of what God has assigned to us.

- Unbearable lightness of visible matter!



Epilogue

- The discovery of Higgs boson and verification of its interactions with other particles prove that our standard model of particle physics is basically correct.
- Breakdown of electroweak symmetry is induced by the vacuum expectation value of the Higgs field and gives rise to mass for elementary particles.
- Ongoing LHC experiments keep probing physics at the TeV scale and give us more insight into the nature of EWSB.
  ➠ new Higgs particles and interactions?
- We still do not understand why each particle has its distinct mass and what dark matter and dark energy are.
- History has taught us that every time we look deeper into things, we discover more dazzling beauty and amazement.
  ➠ let’s keep learning how subtle the Lord is!

Thank You!