The World of the Higgs
OLLI talks at Cal State University Fullerton and UC Irvine
October 10 and 11, 2013

Dennis Silverman
Department of Physics and Astronomy
UC Irvine

The Worlds of the Higgs

- Nobel Prize in Physics 2013 to Peter Higgs and Francois Englert
- Experimental
- Theoretical
- The Real World
- Possible New Physics

Nobel Prize in Physics 2013 to Francois Englert and Peter Higgs, shown at the announcement of the discovery of the Higgs Particle, July 4, 2012

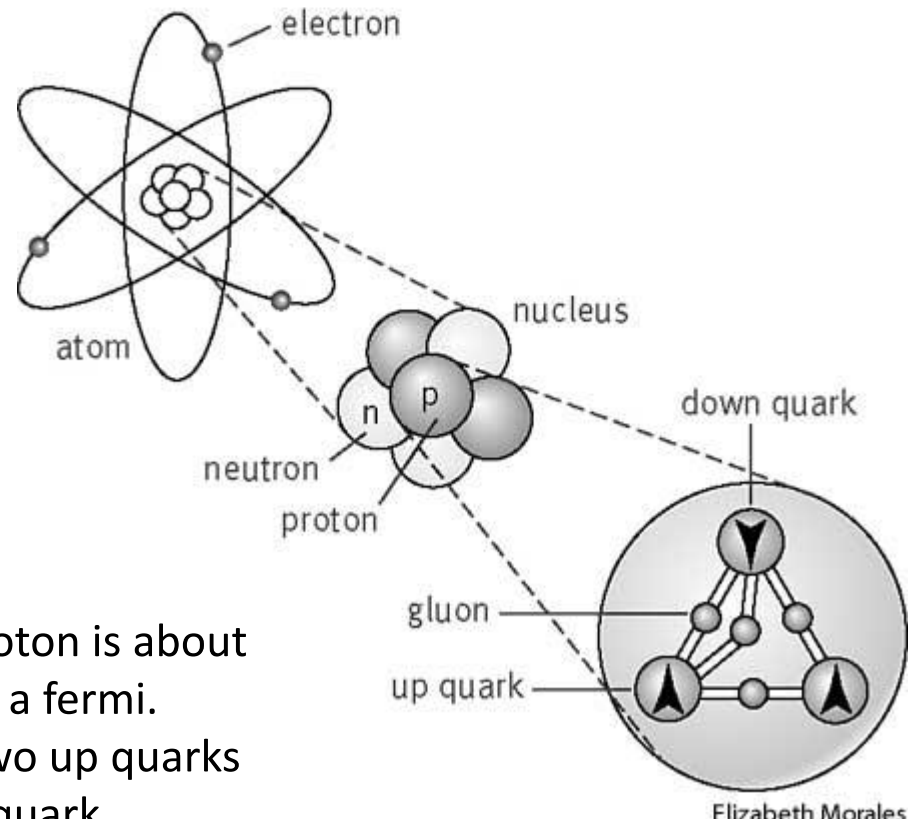
Kudos to simultaneous inventors Robert Brout, co-author with Englert, and Gerald S. Guralnik, Carl R. Hagen, and T. W. B. Kibble

Photo by Maximilien Brice / CERN

Introduction to the Standard Model

www.particleadventure.org

Over 100 Years of Subatomic Physics
Atoms to Electrons and Nuclei to Protons and Neutrons and to Quarks



The size of a proton is about 10^{-13} cm, called a fermi.
Protons have two up quarks and one down quark.
Neutrons have one up quark and two down quarks.

Probing Deeper Mysteries

- To see smaller details, you have to use light with smaller wavelengths.
- Smaller wavelengths corresponds to higher energy light.
- So to probe smaller objects, we need to build higher energy accelerators and colliders.
- Since high energy particles take more matter to stop, or distance to bend magnetically, we also need bigger detectors.
- Today we will go from a centimeter to the atom at 10^{-8} cm.
- Then we go to the nucleus at 10^{-13} cm, and to the highest reach of the Large Hadron Collider, at 10^{-16} cm.
- Finally, we speculate on a unified theory at 10^{-30} cm.
- The Higgs is an important player for each of these scales.

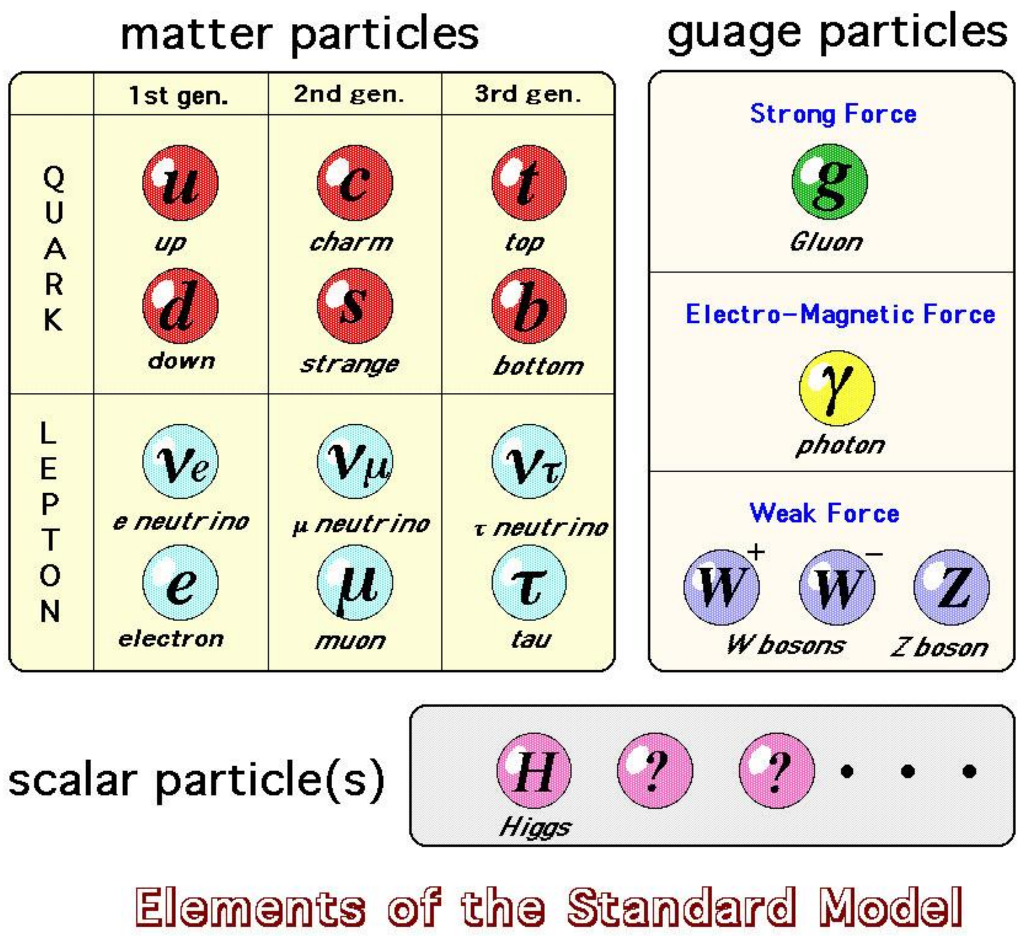
The Standard Model of Quarks and Leptons
Electromagnetic, Weak, and Strong Color Interactions

Q = +2/3 e   up

Q = -1/3 e   down

Q = 0   up

Q = - e   down



The Spin of Particles, Charges, and Anti-particles

- The quarks and leptons all have an intrinsic spin of ½ in units of hbar = h/2π =ħ, a very small number. These are called fermions after Enrico Fermi. They have anti-particles with opposite charges.
- The up quarks have charge +2/3 of that of the electron's magnitude, and the bottom quarks have charge -1/3.
- The force particles have spin 1 times ħ, and are called bosons after S. N. Bose.
- The force particles are their own antiparticles like Z^0 and the photon, or in opposite pairs, like W^+ and W^-, and the colored gluons.

Masses of Elementary Particles

125 GeV →

The Proton and Neutron are about 1 GeV →

A GeV is a giga electron volts in energy, or a billion electron volts

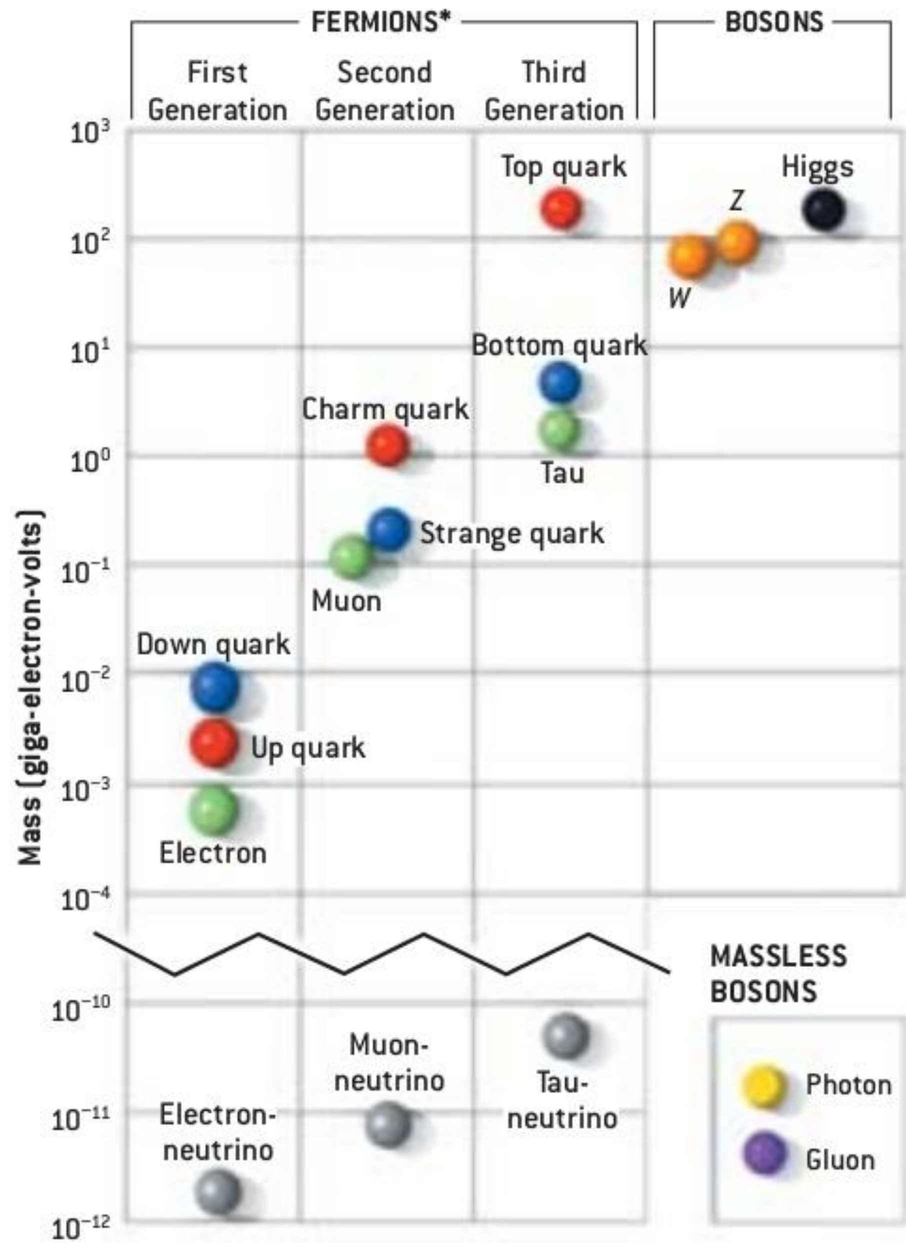
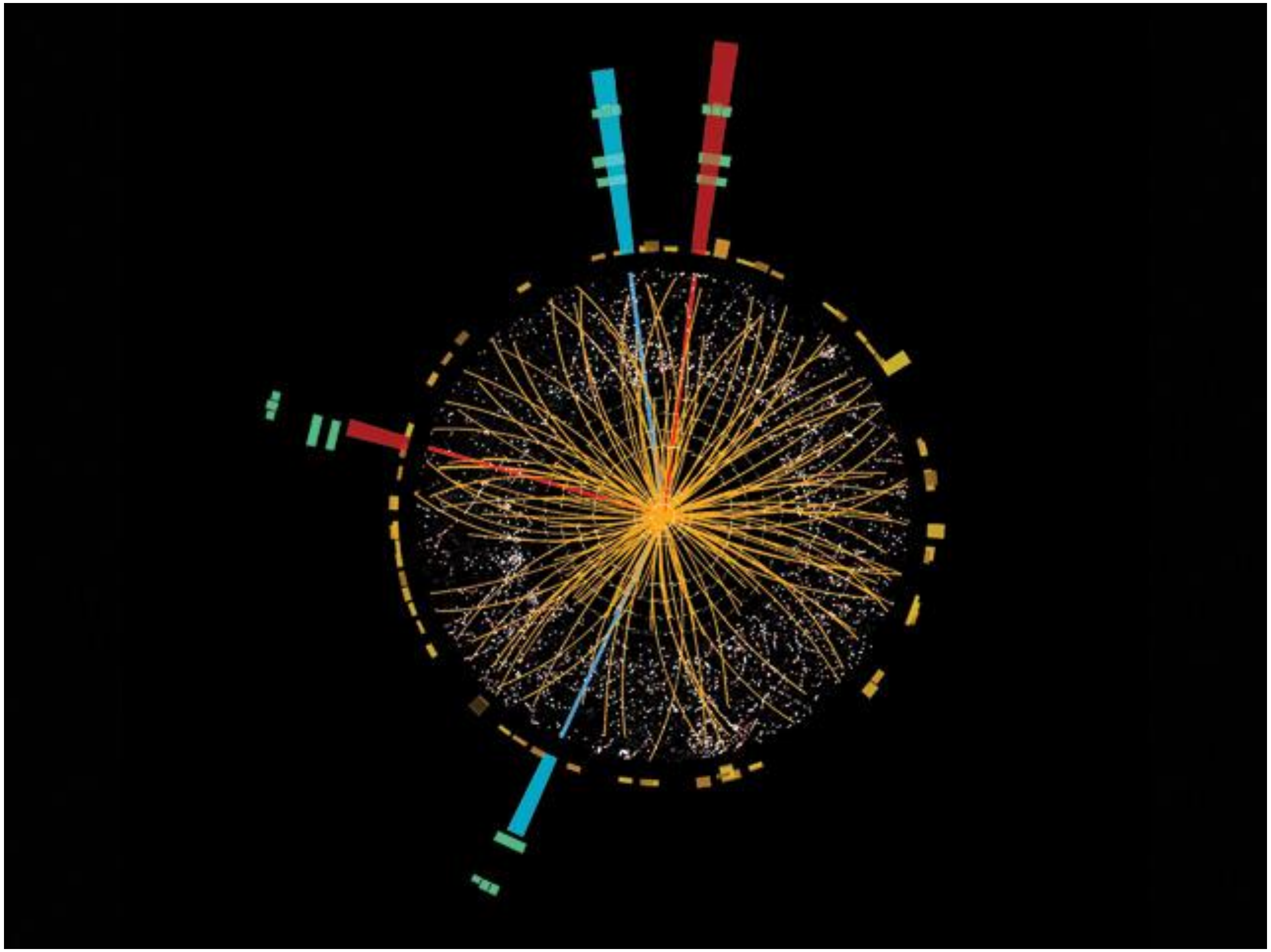


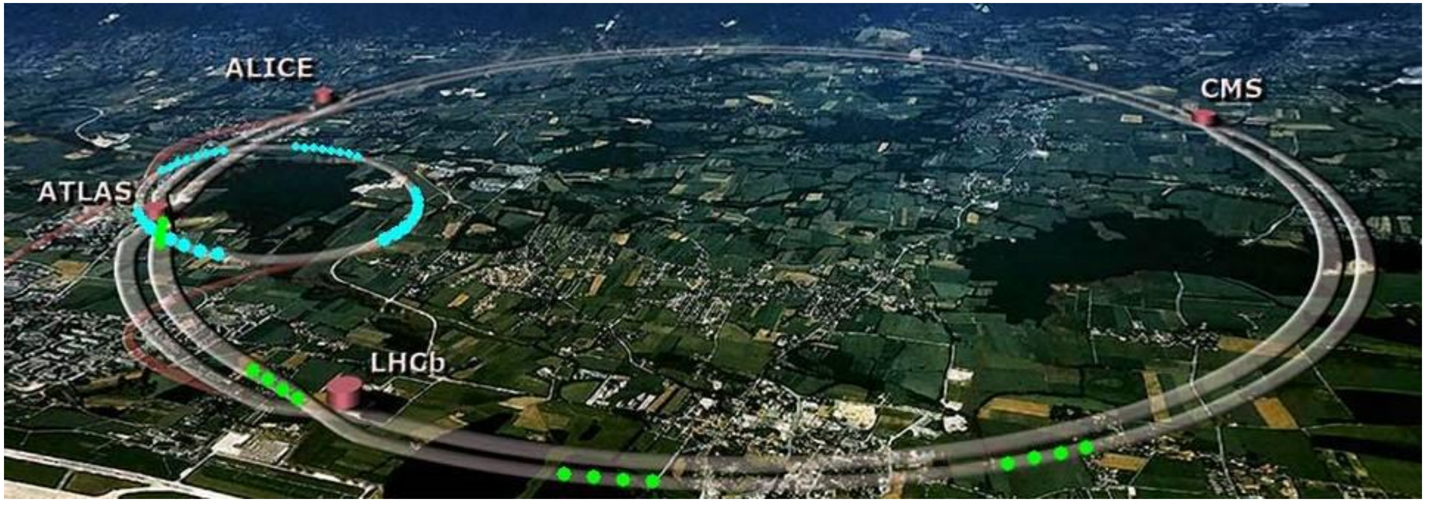
Diagram from Gordon Kane, Scientific American 2003

The Large Hadron Collider and its Detectors ATLAS and CMS

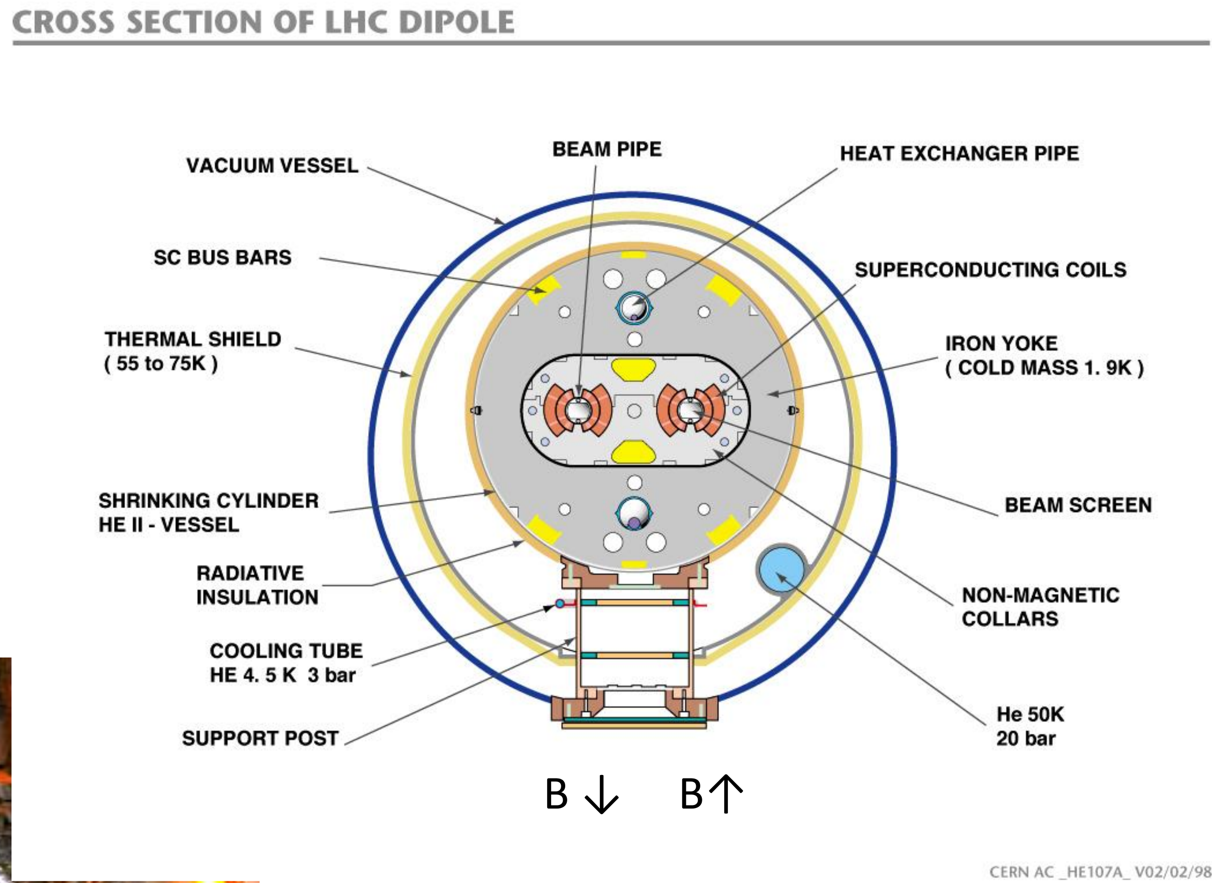


The Large Hadron Collider at CERN in Geneva

- The LHC is a circular collider of protons on protons, which is 27 km or 17 miles in circumference.
- It is a ring of superconducting magnets providing a vertical field, that continuously bends charged protons around in a circle. It collides the opposite directed beams at intersection points.

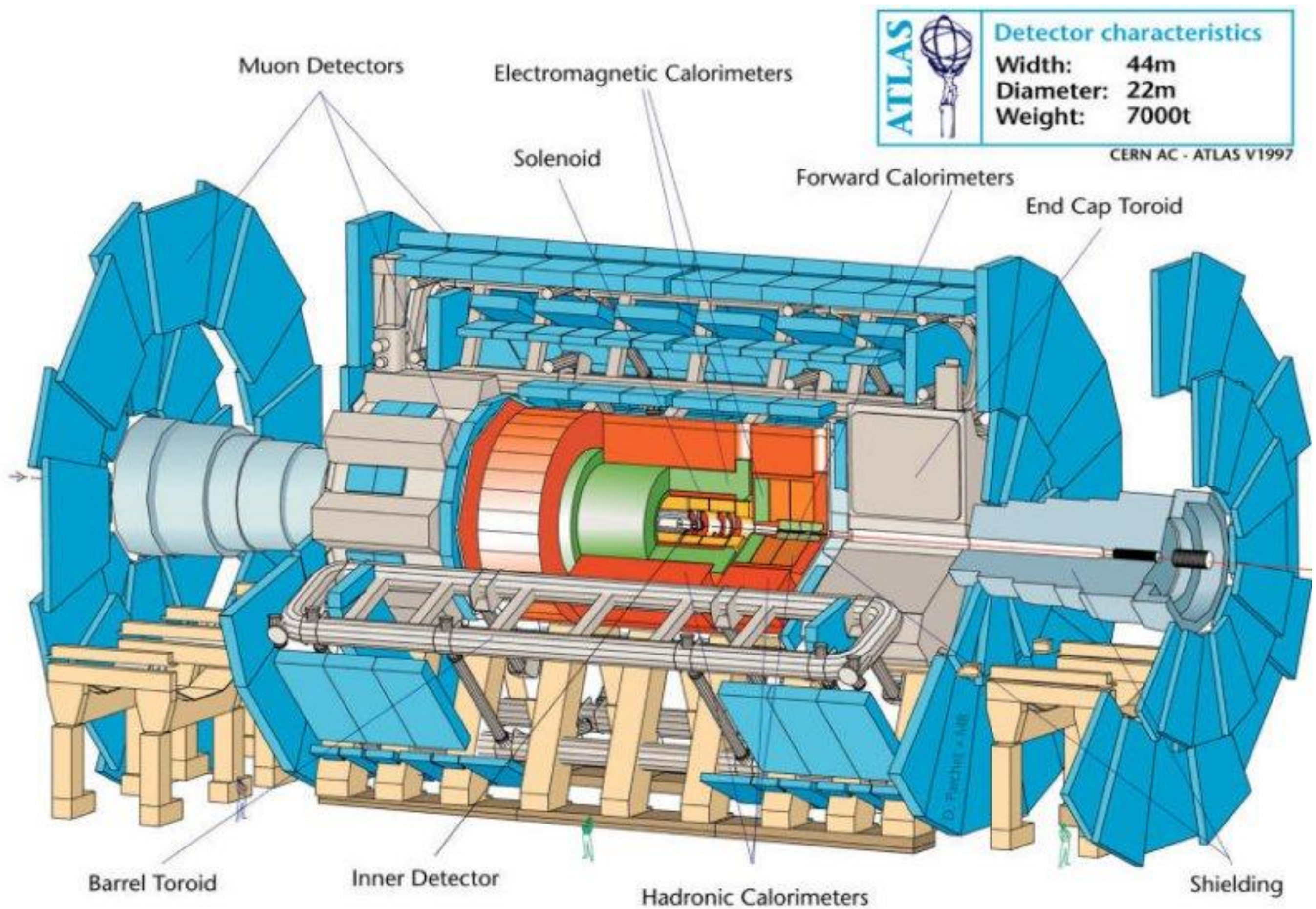


LHC Beams in Magnets. Beams collide at the centers of the detectors. There are 1600 superconducting magnets, each weighing about 27 tons.



The ATLAS Detector

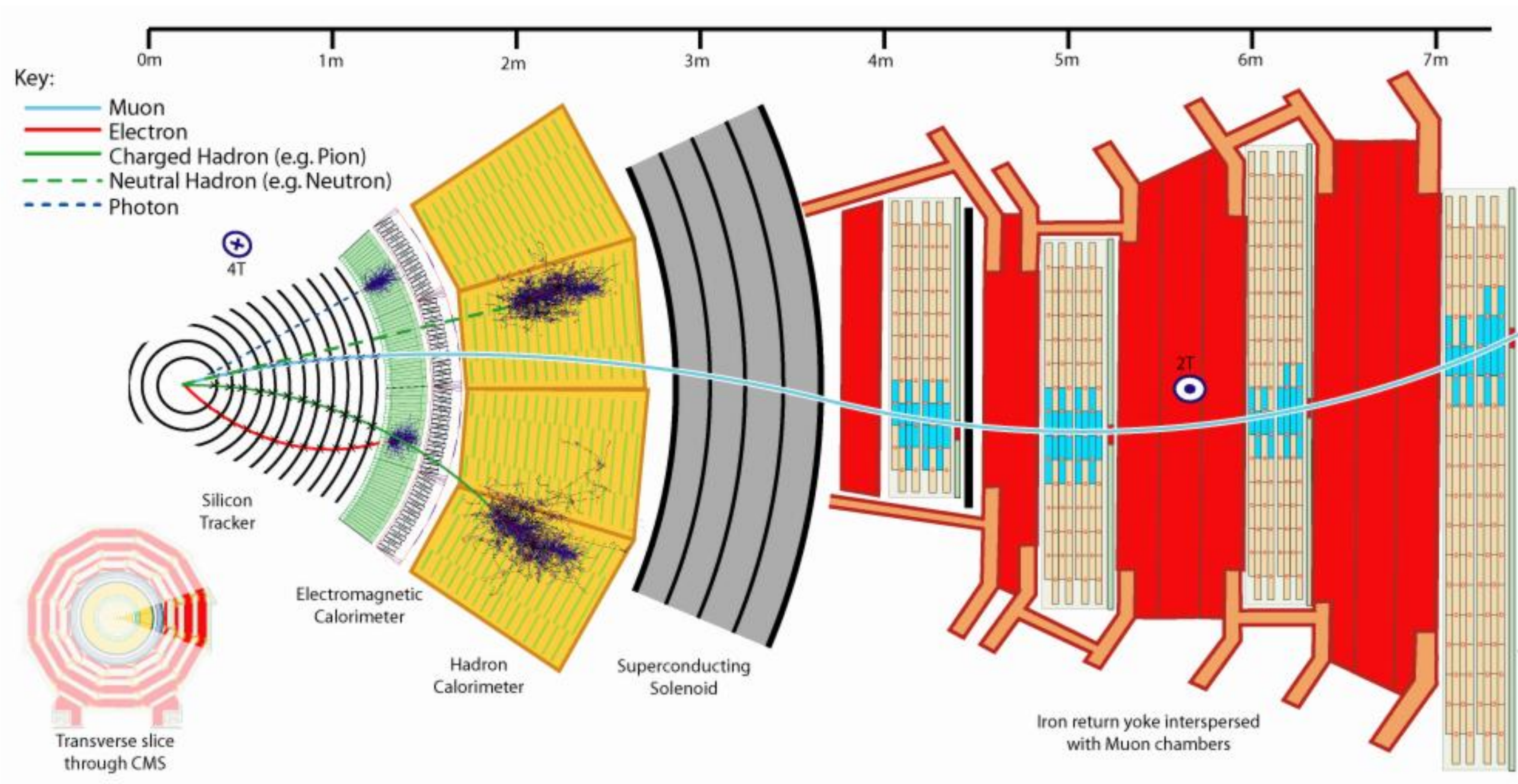
The ATLAS collaboration includes 3,000 physicists, including 1,000 students, from 38 countries and 174 universities and labs. ATLAS weighs 7,000 tons, and is half the size of Notre Dame cathedral. It collects a terabyte of data an hour. (tera = 1,000 giga, or a trillion)



Slice of CMS Detector

Magnetic Field Perpendicular to Screen

Shows Where Each Type of Particle is Tracked and Energy Measured



Event Rates and Data

- There are about 600 million collisions per second in ATLAS.
- They are partly processed on the fly, to keep only hard, high energy exchange collisions.
- Consequently, only about 200 events are kept per second.
- Each event only has about 1.6 megabytes of data.
- There are about 100 megabytes of pixels in ATLAS.
- Stored data is now over 100,000 terabytes, or 700 years of HD movies.
- Fermilab near Chicago and Brookhaven National Lab on Long Island are the US main computing centers for this data.

Costs of the LHC and Detectors

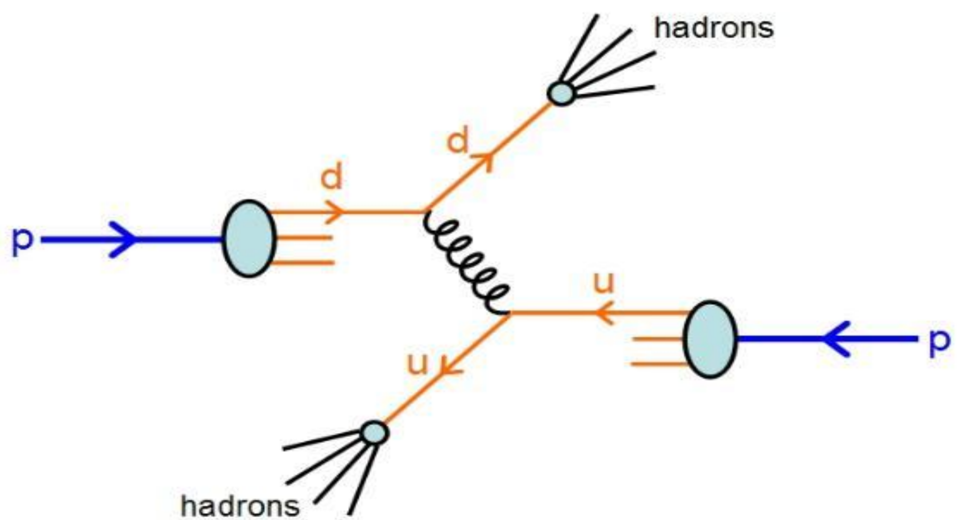
- $5 billion was the cost of the LHC collider.
- Forbes reported that $5 billion was the combined cost of the detectors, and it cost $1 billion a year to run.
- Previous colliders to detect the Higgs and new particles, in addition to many other discoveries were:
  - LEP large electron positron collider in the same tunnel, which got to 114 GeV, just short of the 125 GeV mass needed.
  - SSC Superconducting Super Collider in Texas at 20 TeV on 20 TeV protons. It was abandoned in 1990s due to a recession, lack of backing by other states and labs, CERN's decision not to join in but to build the LHC, and a slowdown which increased costs to $10 billion, after $2 billion was spent. That would have found the Higgs a decade earlier.
  - The Tevatron at Fermilab (Chicago) with 1 TeV protons on 1TeV anti-protons, which has now seen some Higgs events.

US Participation in the LHC

- Of the 6000 physicists at the LHC, 2000 are from the US.
- They come from 96 US Universities and Labs, and 33 states.
- They compose 23% of ATLAS and 33% of CMS personnel.
- Since 2008, 230 US doctoral degrees have been generated at the LHC.
- The US provided about $165 million to each detector. A lot of this was built in the US, funding US hi-tech jobs.
- The US also contributed $200 million to the accelerator.

Proton on Proton Beams as Beams of Quarks, Gluons, and Anti-quarks

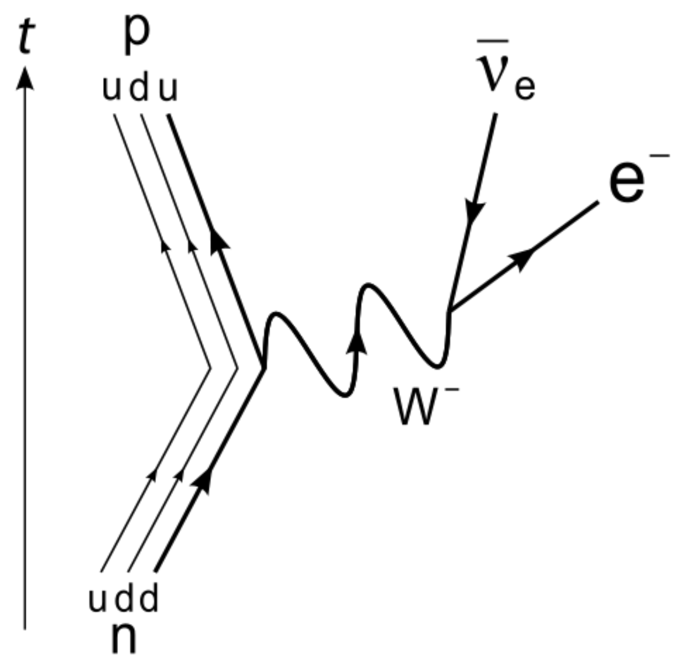
- Current Energy was 4 TeV on 4 TeV protons.
- 2015 Upgrade toward full 7 TeV on 7 TeV protons.
- Quarks can carry about 1/3 the energy of the protons
- Hadrons are protons, neutrons, pions, kaons, etc.



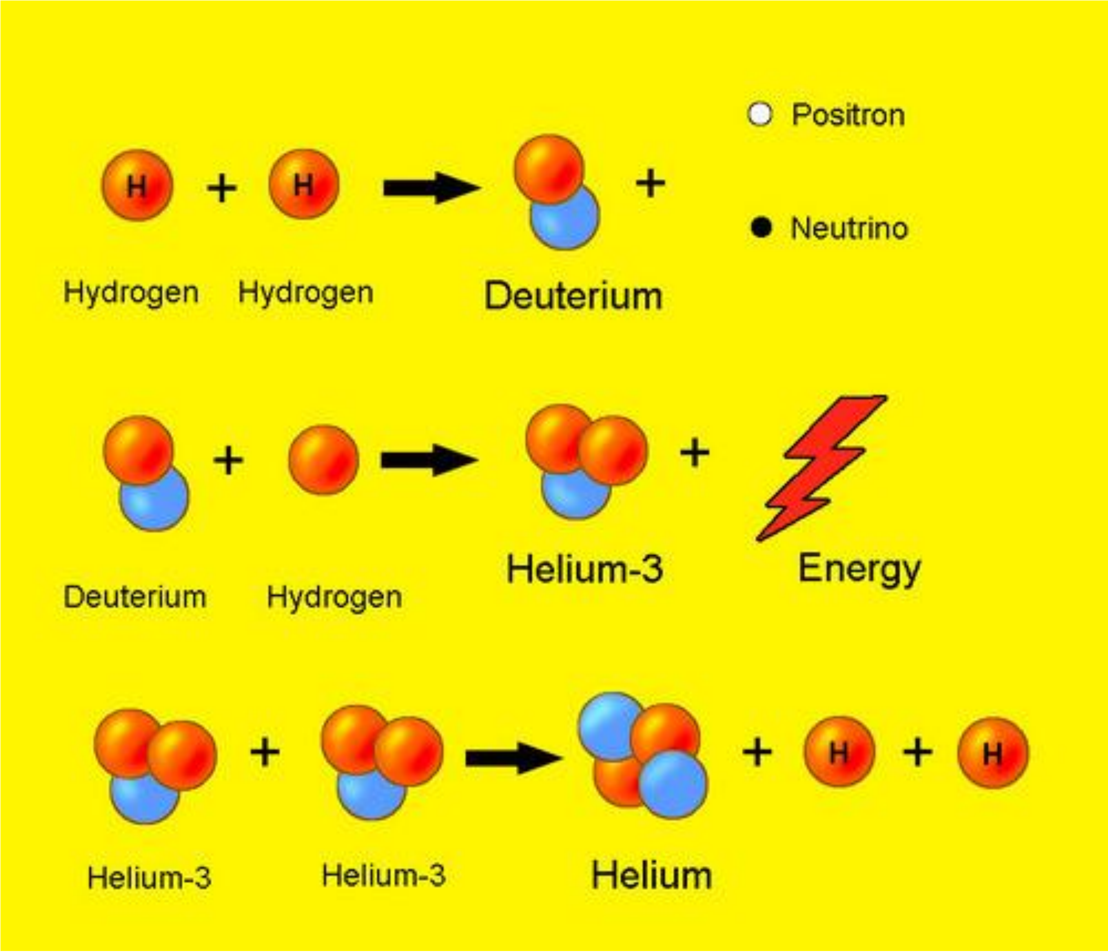
The Weak Interactions

The Weak Interactions

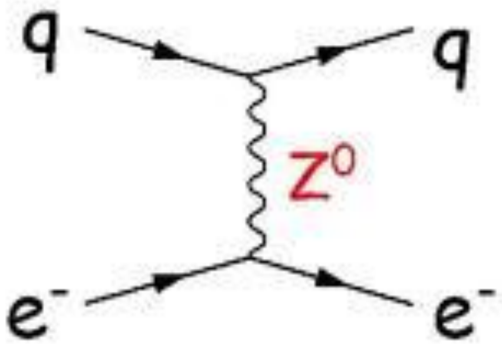
The Beta (electron) Decay of a neutron is really that of a down quark to an up quark with a virtual W^- creating an electron and an electron anti-neutrino. So the weak bosons W take us between up and down type quarks, and up and down type leptons in each generation.

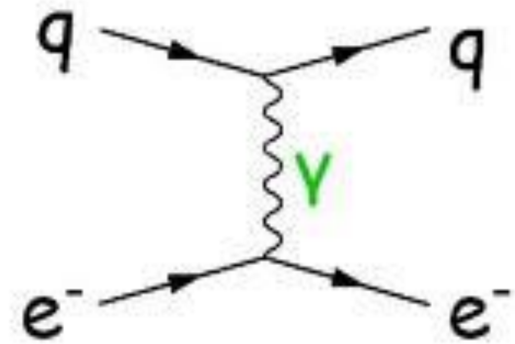


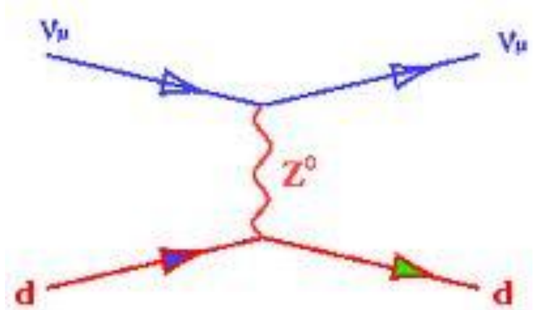
Protons Fuse to Deuterons via the Weak Interactions Then fuse to ^{3}He and then ^{4}He to power the sun. Source of all our food, and fossil fuels and renewable energy.

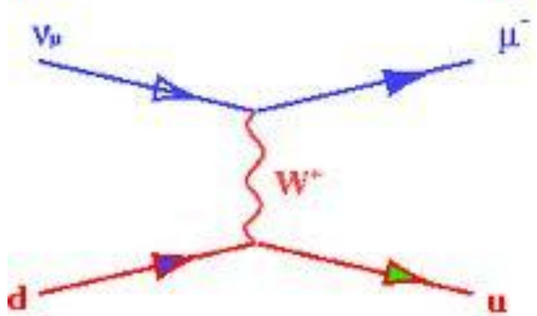


Charged W Bosons, Neutral Weak Interaction (Z^0) and Photon (γ) Exchanges



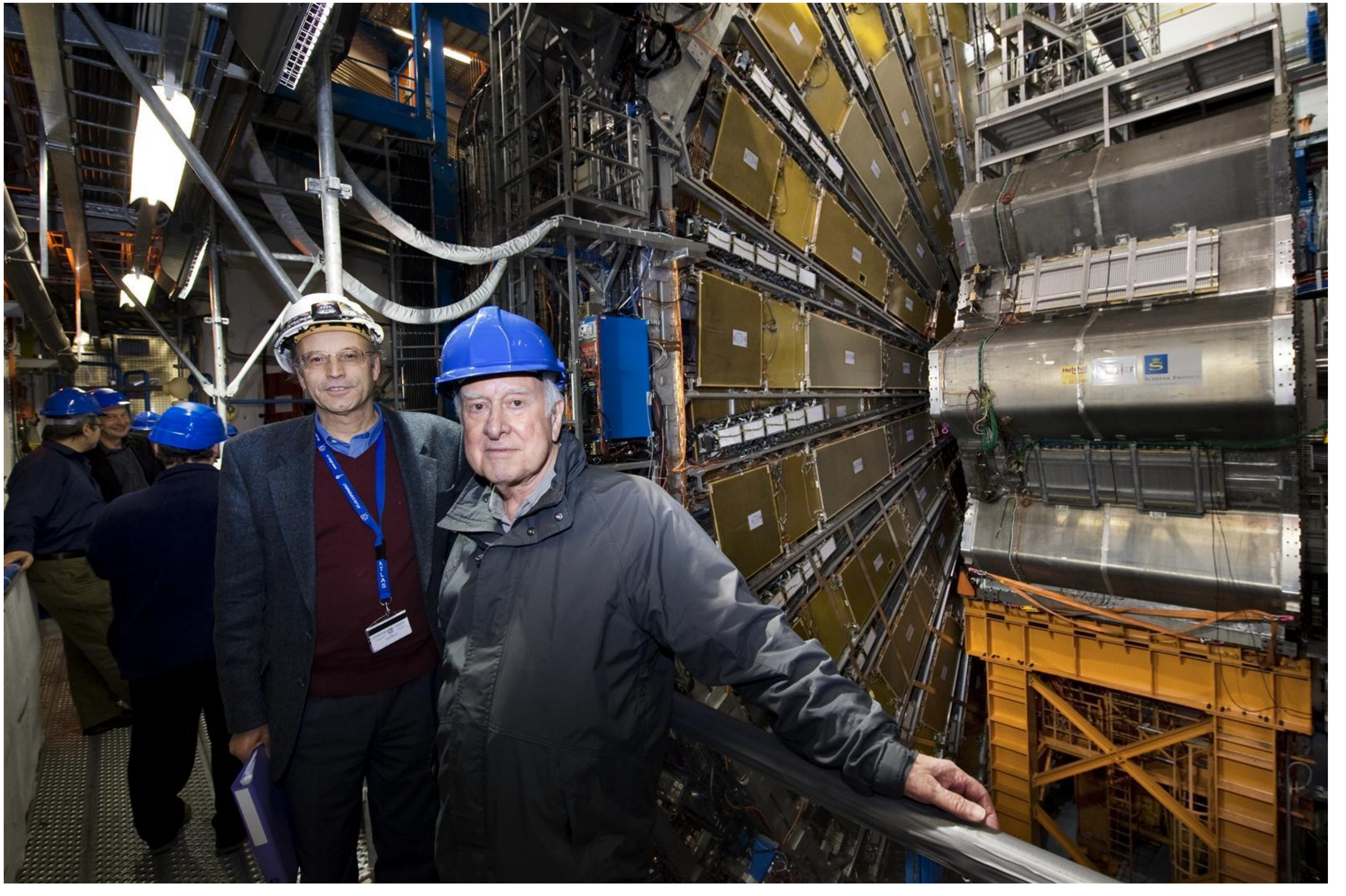






Photons couple with the charge.
Z^0 couples with $+1/2$ for up quarks or leptons, and $-1/2$ for down quarks or leptons, just like spin up or down with the magnetic field.
W^+ and W^- charged bosons change quarks and leptons between up and down.

Production and Decay of the Higgs Particle

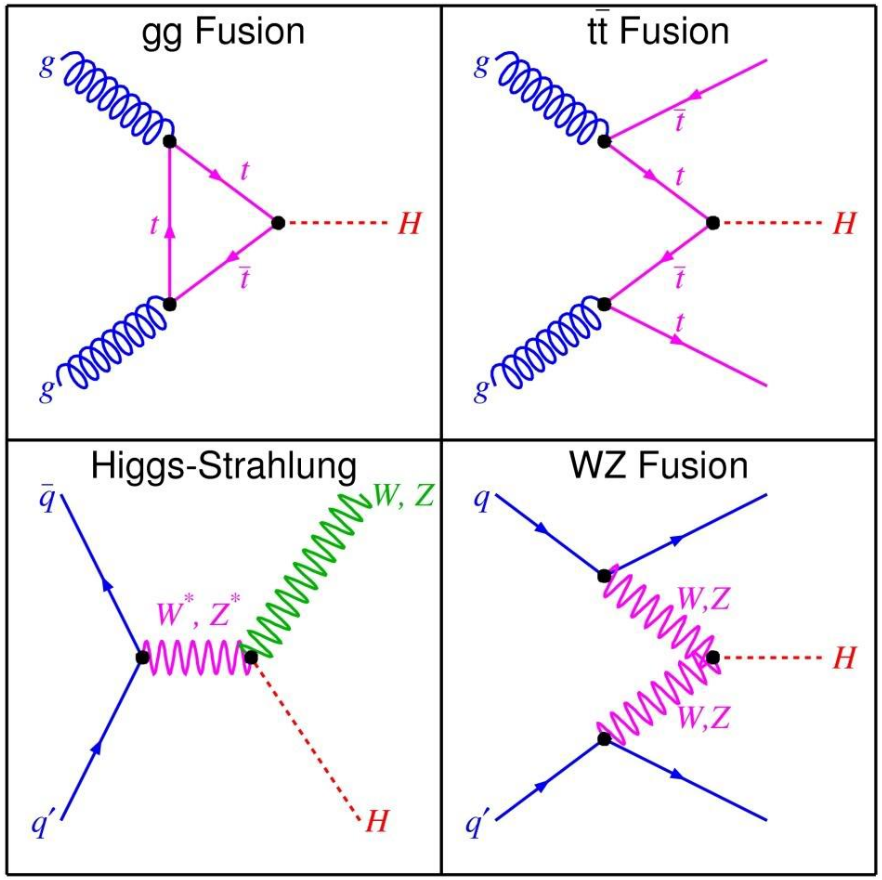


Peter Higgs at ATLAS. ATLAS Experiment @ 2013 CERN

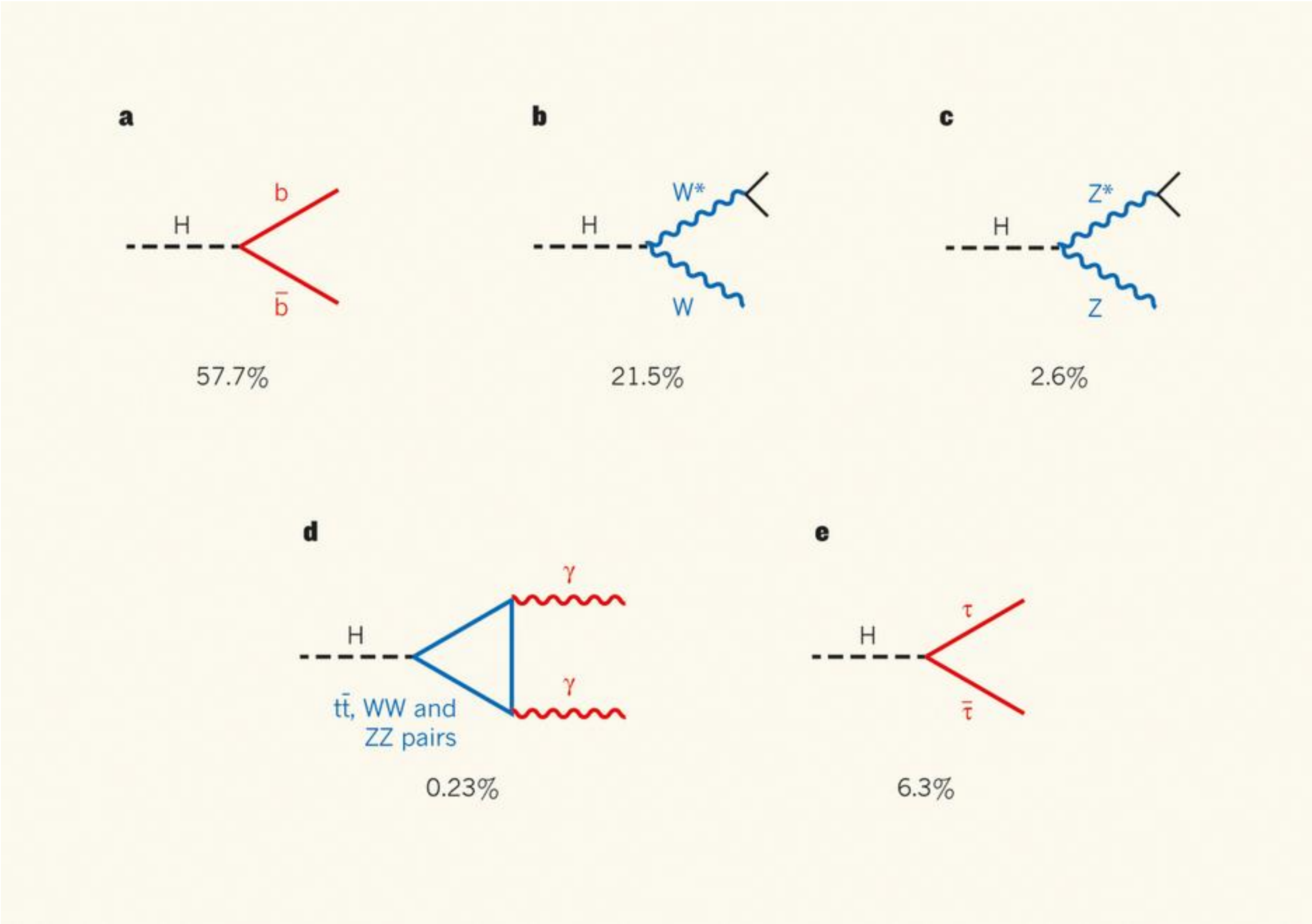
Higgs Creation and Decay

- The Higgs is a neutral particle.
- Higgs couples to particles essentially with the particle’s mass. So it couples best to the heavy top quark (175 GeV), W Bosons (80 GeV) and Z Boson (91 GeV).
- These can appear as real emitted particles, or virtual short distance excitations.

Higgs Creation
Pink Particles are Virtual
Beams come from the left



Higgs Decays
Intermediate Blue Particles are Virtual

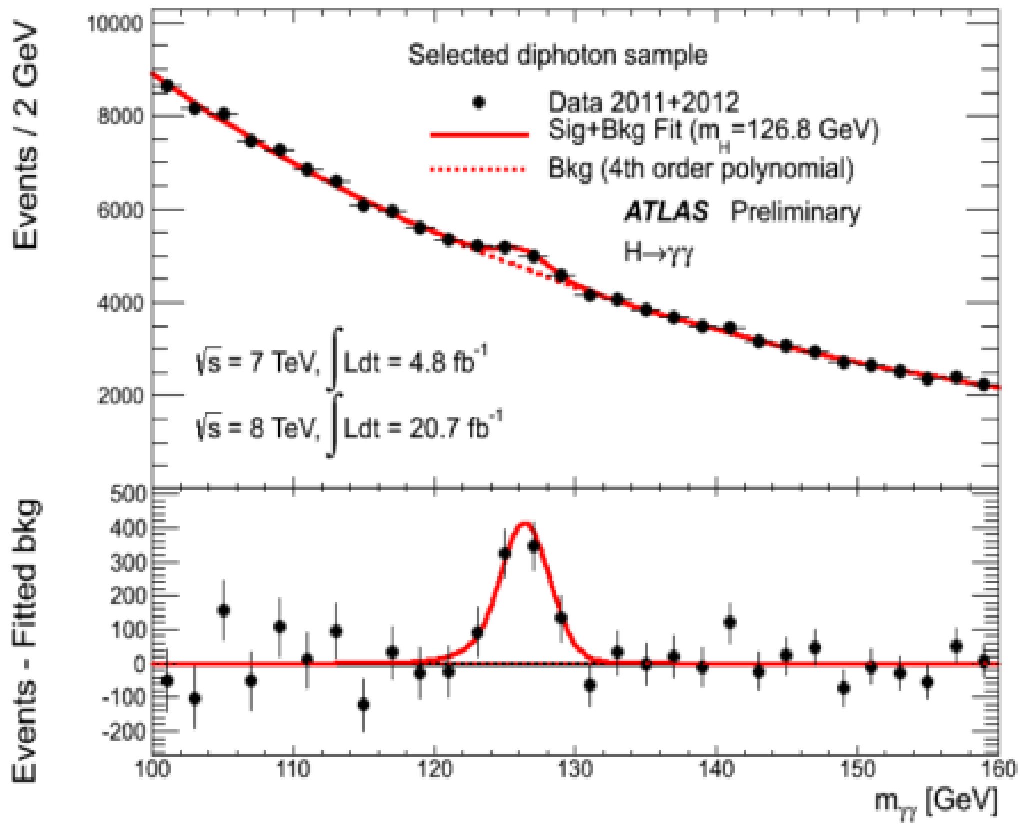


Higgs to Two Photons at 125 GeV

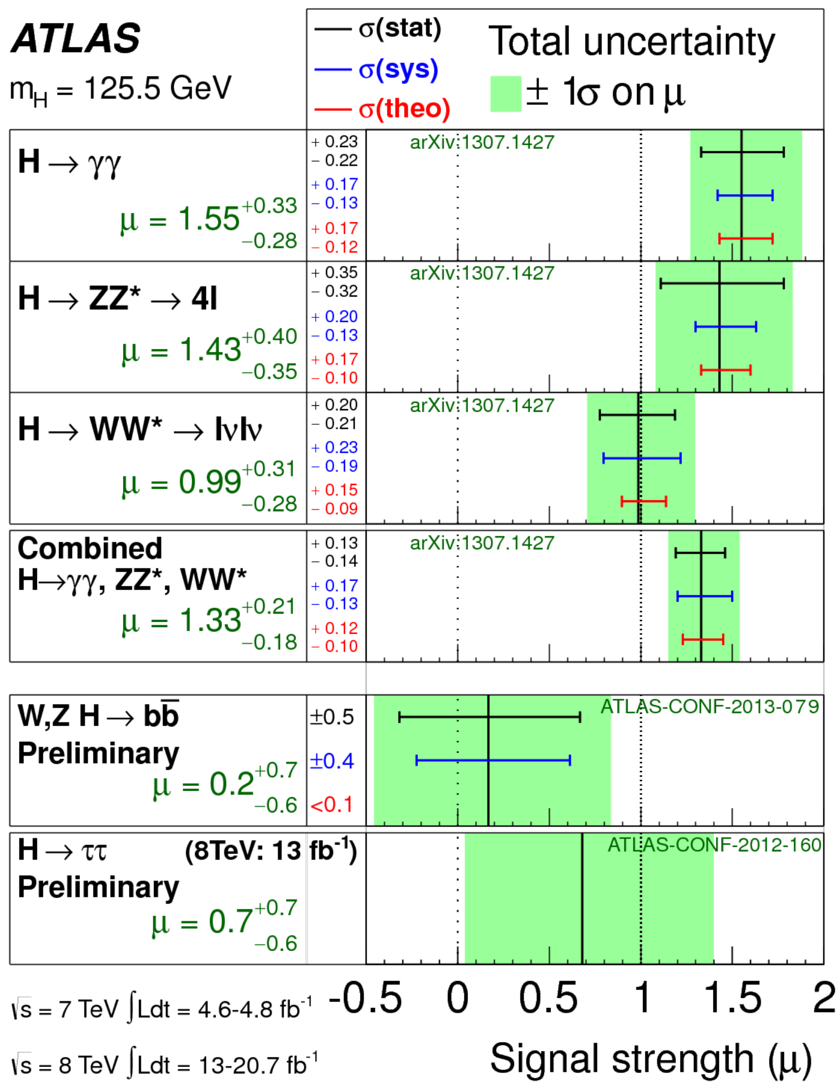
Upper Curve: Events with background.

Lower Curve: Events with background subtracted.

About 1,000 Higgs to two photons here.

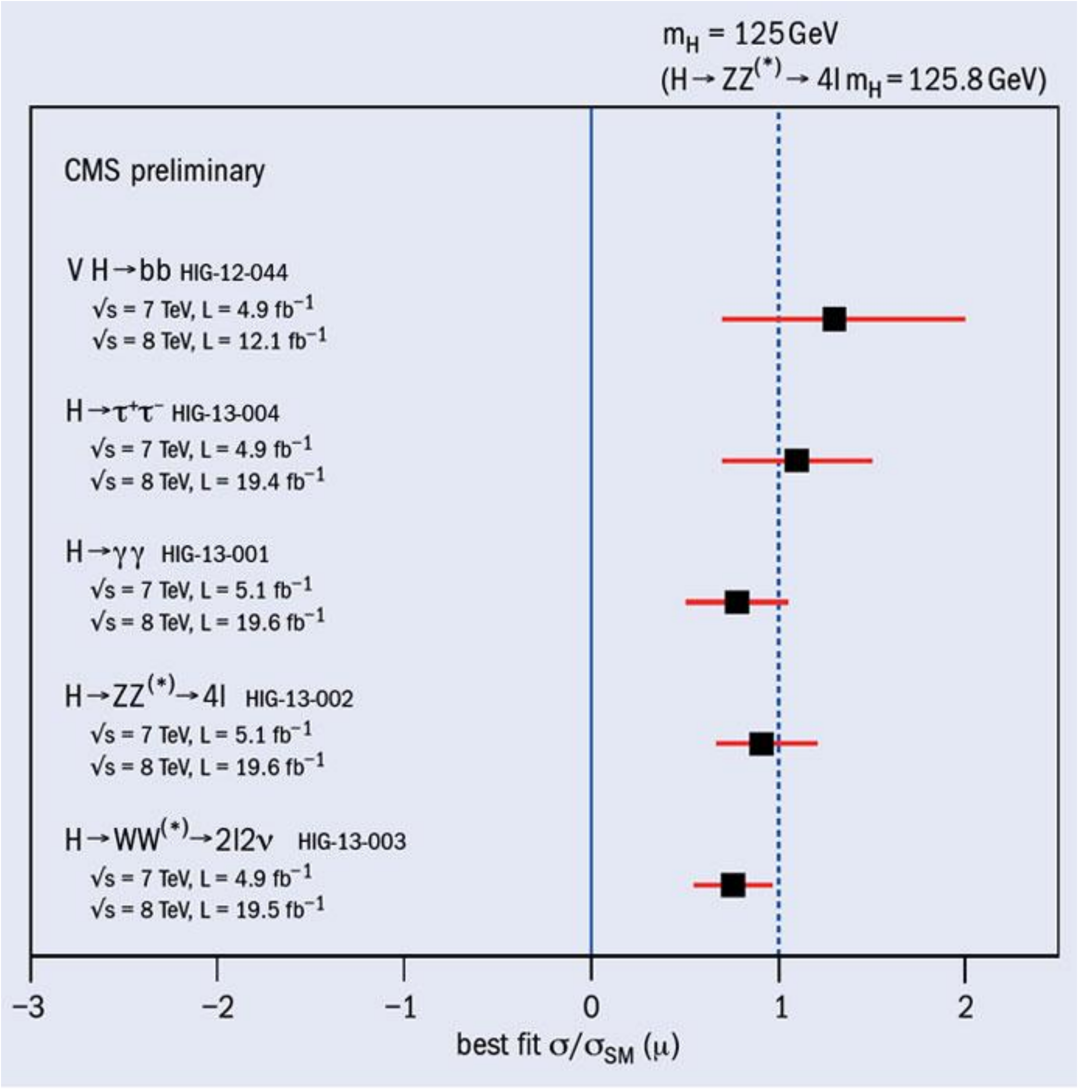


ATLAS Higgs Production Ratios to Standard Model Predictions Should Turn out to be 1; Combined Ratios = 1.33 $\pm$0.20



CMS Ratios of Higgs Production to the SM

Combined Ratios = 0.80 $\pm$ 0.14



Spin and Parity of the Higgs

- Other spin assignments for the Higgs than spin zero have been tested, since they would cause production and decay with different angular distributions.
- The Higgs is also supposed to be a positive parity particle under reflections through all three directions. If it were negative parity, angular distributions would also be affected.
- The produced "Higgs" has passed all these tests and is spin 0 with positive parity as a true Higgs would be.

Future of the LHC

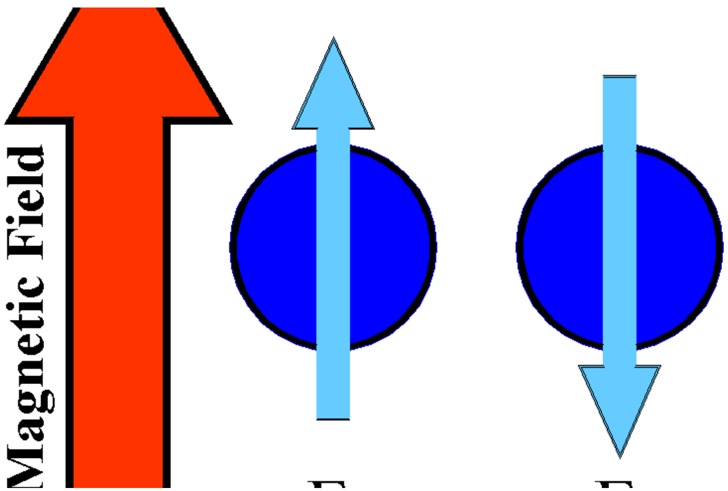
- The LHC is being prepared to run at planned energy, from 13 to 14 TeV, from 7 TeV protons colliding with 7 TeV protons.
- This will start in 2015.
- The LHC will run until 2022, generating 10 times as many collisions as they have so far. They should generate more than 10 times as many Higgs due to the increased energy, and hopefully new particles.
- After 2022, consideration will be given to the High Luminosity LHC, with upgrades to detectors to see events at five times the present rate. That will run from 2024 for ten years, and generate 100 times more events than at present.
- That should check Higgs couplings to a few percent, and allow Higgs self coupling to be seen and measured. It could also generate new particles.

The Theory of Electroweak Interactions
Spin and Weak Isospin

Spin and Magnetic Dipoles

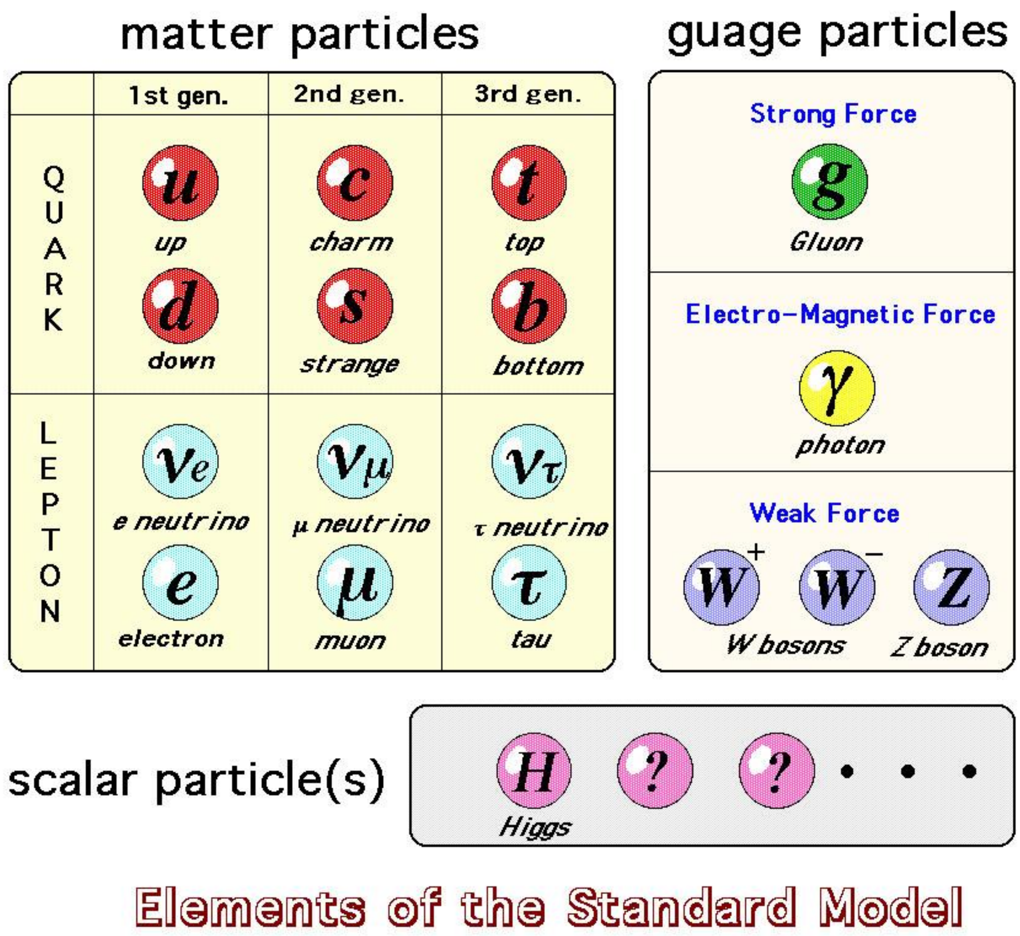
- Protons, Neutrons and Electrons all have spin ½ and are then Fermions. That gives each of them the property of being little magnets of different strengths μ.
- The spins or magnets can only be aligned up or down and only on one axis. The spins component on that axis only have values of Sz = $\pm$ ½ ħ (hbar).
- With no outside magnetic fields present, both up and down spin states have the same energy. So there is a symmetry between spin up and spin down.
- With an outside magnetic field, the spin up and down states now have opposite energies, and the up-down symmetry is broken.

B ↑

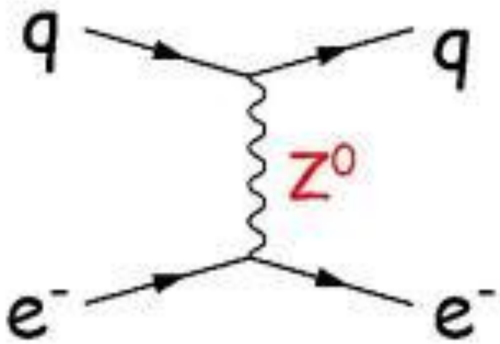


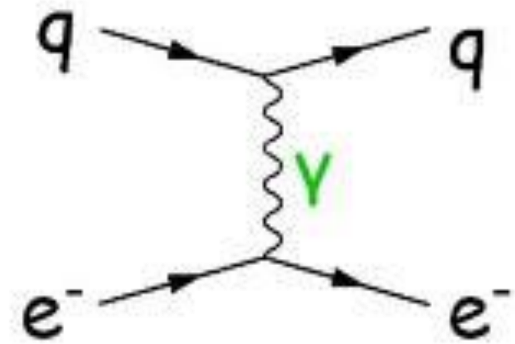
E = $-\mu$ B, E = $+\mu$ B

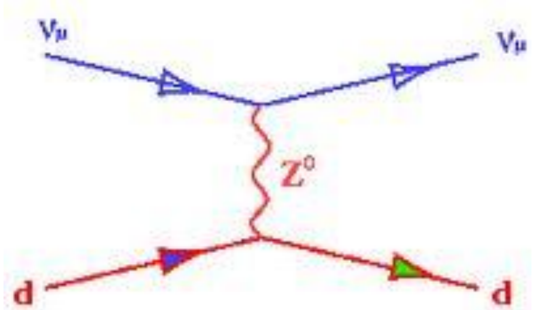
Charged Weak Interactions as Transitions between Up and Down Quarks or Up and Down Leptons

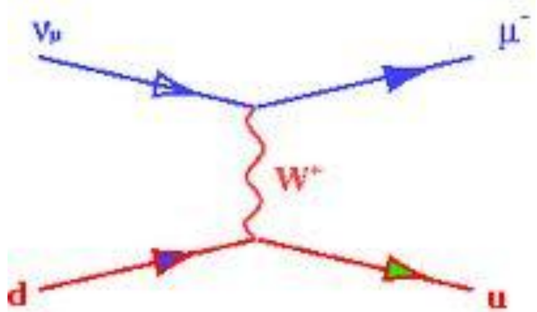


Charged W Bosons, Neutral Weak Interaction (Z^0) and Photon (γ) Exchanges





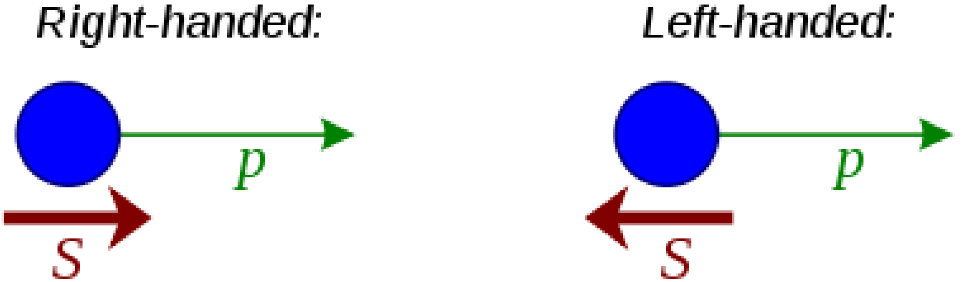




Photons couple with the charge.
Z^0 couples with $+1/2$ for up quarks or leptons, and $-1/2$ for down quarks or leptons, just like spin up or down with the magnetic field.
W^+ and W^- charged bosons change quarks and leptons between up and down.

Weak Isospin

- Weak Isospin is an analog of ordinary spin angular momentum.
- The weak interactions only involve the left handed quarks or leptons.
- The analog of the spin up and down states are the up and down left handed quark or lepton states with weak isospin 1/2 .
- The Weak Interactions (neglecting the charge) treats the up and down states with the same coupling strength, with the original W^0 partner to the W^+ and W^- just measuring the $\pm$ ½ weak isospin projection.
- The weak interactions then conserve weak isospin, by the theorem of Emily Noether.
- Then, in each interaction or process, the total incoming weak isospin component must equal the total outgoing sum.



Unified Electromagnetism and Weak Interactions

- The photon is massless, which means that it always travels at the maximum speed, that of light, and electric and magnetic fields that make it up have an infinite range.
- The W^+, W^-, and Z^0 can be unified with it into “electroweak theory” if they are also massless.
- Like the photon, they are spin one particles.
- In the massless theory, they start out as a triplet of a W^+, W^0, and W^-, and a singlet called B^0, to allow for the photon.
- The left handed quarks are also massless, and in doublets of up and down. The leptons are in doublets of neutrino and charged leptons.

Enter the Higgs

Finally, the Higgs Emerges

- The solution of how to keep the expression of a theory massless so that it has a beautiful and appropriate symmetry, but yet give mass to the particles is to first couple them to a spinless or scalar particle, the Higgs, called $\boldsymbol{\varphi}$, with a coupling proportional to their masses.
- The potential energy of a particle is

  $$V = \lambda\, \boldsymbol{\varphi} \bullet \text{(Density of the Particle)}$$

- Then give the Higgs field a non-zero, constant value $\boldsymbol{\varphi}=\mathrm{v}$ throughout space and time. This gives

  $$V = \lambda\, \mathrm{v} \bullet \text{(Density of the Particle)}$$

- Then $\mathbf{m} = \boldsymbol{\lambda}\, \mathbf{v}$ is the mass of the particle.
- The question of why all the masses m and λ's are different, and where they come from, is still an unsolved problem.

The Higgs Particle

- The Higgs field is not just the constant vacuum part v, but also has a particle part h: $\boldsymbol{\varphi} = \mathrm{v} + \mathrm{h}$.
- In the potential energy then, with λv=m

$$\mathrm{V}(\boldsymbol{\varphi}) = \lambda\, \boldsymbol{\varphi} \bullet \text{(Density of the Particle)}$$
$$= \lambda\, (\mathrm{v} + \mathrm{h}) \bullet \text{(Density of the Particle)}$$
$$= (\mathrm{m} + (\mathrm{m}/\mathrm{v})\, \mathrm{h}) \bullet \text{(Density of the Particle)}$$

- We see that the coupling strength to create the Higgs particle h is now (m/v), or always proportional to the mass of the particle.
- v = 246 GeV, and sets the scale for weak interaction boson masses of Mw = 80 GeV, and Mz = 91 GeV.

Electroweak Founders

- The unified electroweak theory was founded by Steven Weinberg, Sheldon Glashow, and Abdus Salam, shown below. They received the Noble Prize for Physics in 1979.

Peter Higgs, and other Higgs Theorists

T. W. B. Kibble, Gerald S. Guralnik, Carl R. Hagen, Francois Englert and Robert Brout, along with Peter Higgs, won the 2009 J. J. Sakurai Prize from the American Physical Society.
The theory of the Higgs was developed in 1964.

Subtleties of the Higgs

You Didn't Tell Me That You Had Relatives

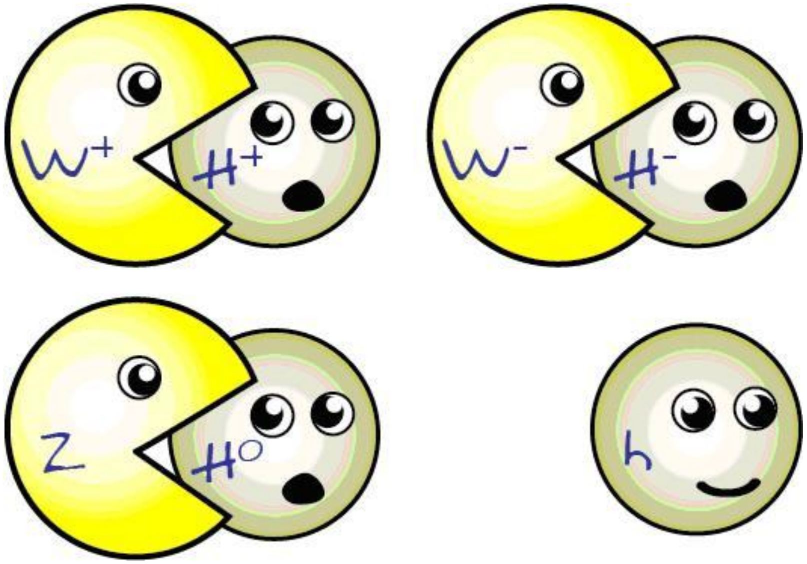
The More Complex Higgs and Electroweak Picture

- The W^0 and B^0 are both neutral and spin 1 bosons, and they mix to form the Z^0 and the massless photon.
- The W^+, W^-, and Z^0 start out as massless bosons, and as such can only have two components of spin, along or opposite their directions of motion. When they become massive, they must acquire a third component with zero spin projection for spin 1 particles in their rest frame.
- They get this from extra Higgs spinless components.
- So the real Higgs's come in weak isospin doublets: (H^+, H^0) and their anti-particles (H^{0*}, H^-), where H^{0*} is the anti-particle of H^0.

The Absorbed Higgs Fields

The lingo is that the three Higgs components are eaten to make the Weak bosons into massive spin one particles.

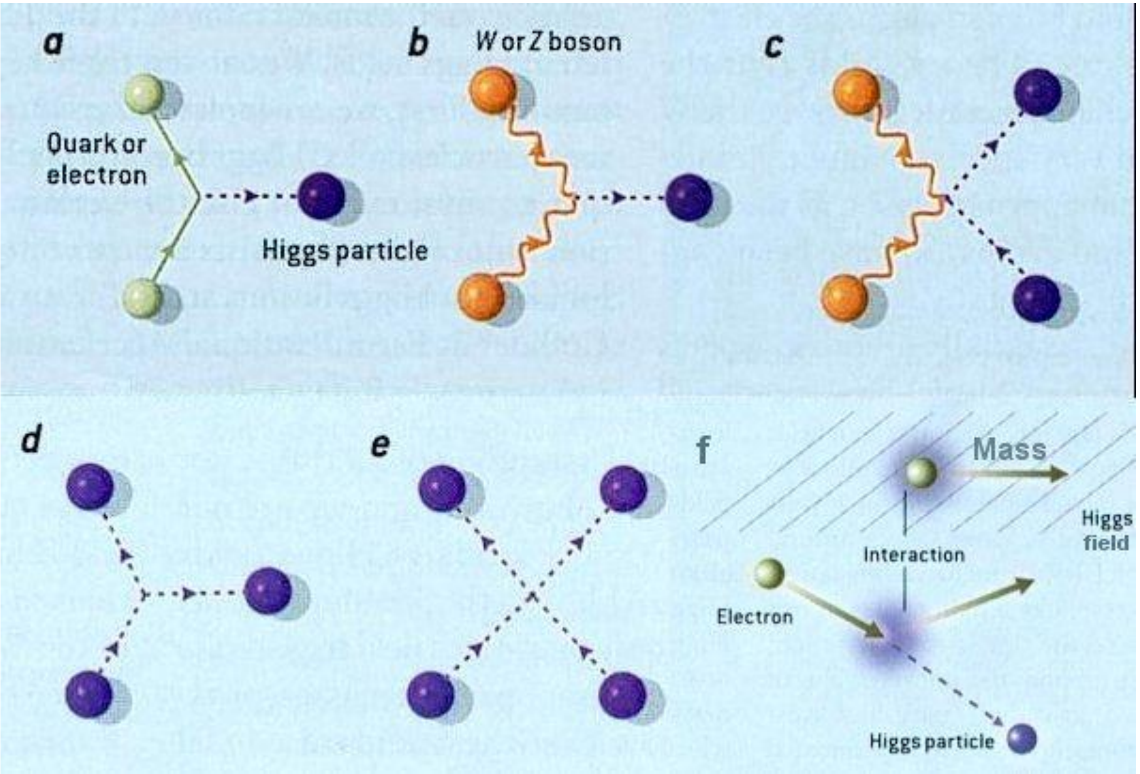
The remaining Higgs field $\boldsymbol{\varphi} = 1/\sqrt{2}(\mathrm{H}^0 + \mathrm{H}^0{}^*)$ is the one with the vacuum constant value. The rest of the field h is the excitable part that created the observed Higgs particle at 125 GeV. $\boldsymbol{\varphi}$ has to come from the neutral part of the weak isospin doublet, and it therefore breaks the weak isospin symmetry.



This illustration is by Flip Tanedo who runs an informative blog on particle physics and on the Higgs at http://www.quantumdiaries.org/author/flip-tanedo/)

The Full Higgs Couplings

The Higgs also couples to and gives mass to the W and Z bosons. Since the Higgs also has Weak Isospin, it couples to itself and gives itself mass.
Our world exists because the Higgs vacuum value gives mass to the electron, since a massless electron moves at the speed of light, and could not be bound into atoms.
If W's remained massless, they would be free particles like photons, but they would cause radioactive transformations continuously. They are weak forces because their high mass limits their range.



The Need for More Particles

- When the Higgs is coupled to a virtual top – anti-top pair, the calculation needs a cutoff at high virtual energy, and grows like the square of the cutoff energy. This behavior has to be canceled by new particles.
- While 5% of the energy of the universe is in ordinary matter, another 20% is in another form of matter which is neutral and therefore called **dark matter**. There is no reason that this is any different from other neutral particles, just that they are heavier so they haven't been seen yet. Dark matter forms halos about galaxies. Theories suggest that the dark matter particles are below 1 TeV, and can be discovered at the LHC.

Grand Unified Theories

- There are indications that there may be a Grand Unified Theory of extended symmetry that includes the symmetry of the strong color interactions along with the electroweak unification.
- But the GUT will be massless until it is broken by very massive Higgs particles, which could give masses around 10^{17} GeV.
- These GUT Higgs would couple to the light Higgs and drive its mass up toward the GUT mass scale. To keep the present Standard Model Higgs light, more virtual particles would have to be included at about 1 TeV to cancel the heavy Higg's effect.

Unsolved Particle Physics Problems

- Where are the new particles – Higg's, SUSY sparticles, etc.?
  - LHC Searches now go up to about 1 TeV
- What accounts for the different particle masses?
- Is the Higgs a composite particle?
- Why is there leftover matter (us) of one part in 10^8 from the initial matter – antimatter annihilation?
- Is there proton decay from a GUT, and will it be seen by our experiments?
- Why are there three generations?
  - Three generations may allow for particle – antiparticle asymmetry, and leftover matter (us).

Unsolved Cosmology Problems

- What is dark matter?
  - Will it be produced at the LHC?
  - Will it be directly detected in underground scattering experiments?
  - Will its annihilation products be detected from space?
- What is dark energy?
- What caused early inflation that made the universe uniform before the big bang?
- Is there a unified theory with gravity (a Theory of Everything)?
  - Is it string theory?
  - Are extra dimensions of string theory excitable at the LHC?

Particle Physics Blogs, Websites, and Books

- I have a blog section on the Higgs boson, where this lecture is posted, along with several elaborative posts.
  - My blog can be found by typing Dennis Silverman into Google search.
- The ATLAS website is atlas.ch.
- The CMS website is at cms.web.cern.ch/
- Lisa Randall has a new, inexpensive and short book (78 pages) on the Higgs discovery called *Higgs Discovery.*
- Sean Carroll has a book on the Higgs called *The Particle at the End of the Universe*.
- An up to date blog is Resonaances. (two a's, really)
- Matt Strassler has a comprehensive blog on the Higgs: profmattstrassler.com
- Matt Strassler's talk on the Higgs at the Aspen Center for Physics: http://www.youtube.com/watch?v=ZtaVs-4x6Qc
- A very well illustrated blog is by Flip Tanedo, now at UC Irvine, at www.quantumdiaries.org/author/flip-tanedo/
- The is a central list of all web articles in the press for particle physics at interactions.org
- Sean Carroll has a blog on physics at http://preposterousuniverse.com/
- An elementary introduction to particle physics at http://particleadventure.org

Other OLLI Particle Physics Lectures that I have given are on my blog

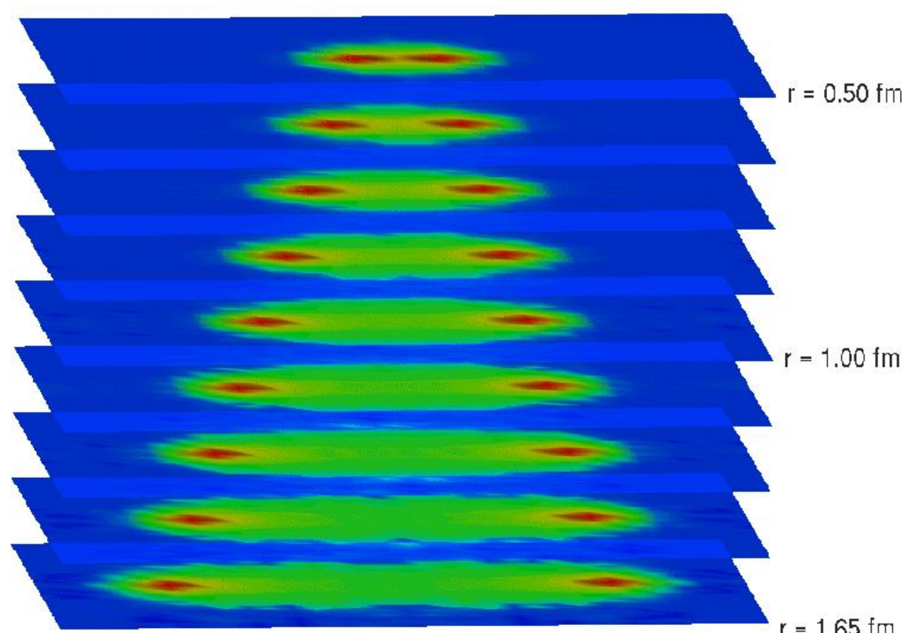
- I gave a lecture to UC Irvine OLLI on Murray Gell-Mann of Cal Tech and the invention of Chromodynamics, posted at that link on my blog.
- I also gave a lecture on Richard Feynman of Cal Tech and Feynman Diagrams on my blog at that link.

Where Our Mass Comes From – Color Confinement

•The matter that we are made of is protons, neutrons, and very light electrons. The nucleons are mostly made of up and down quarks of less than 1% of their mass, but there is a small amount of heavier strange quark and anti-quark virtual pairs that makes up about 3% of our mass.

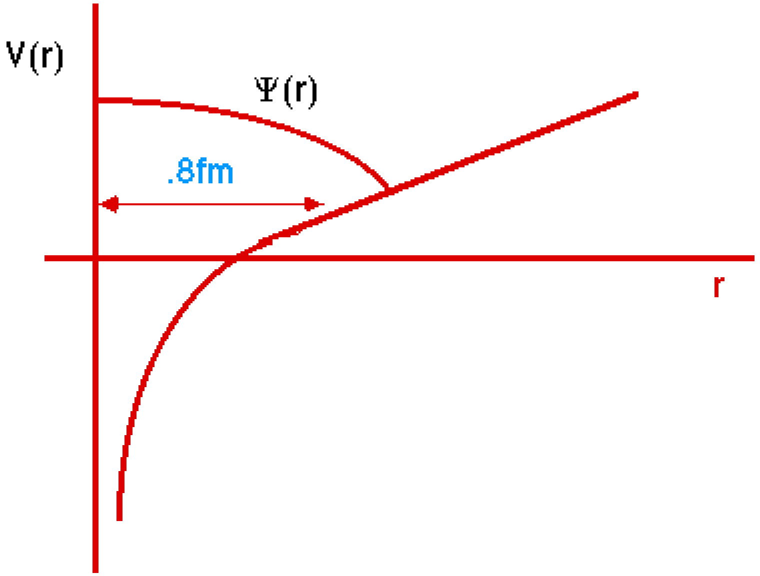
• Most of the energy and therefore mass of nucleons is from confinement of the colored quarks with color strings, much like the potential energy of stretched rubber bands.

•Whereas electromagnetic fields spread out, gluons are colored and attract each other into bands or strings.



Where **Our** Mass Comes From

- This produces a linearly increasing potential with radius at larger distances.
- There is also an attractive (negative) potential from gluon exchange at short distances
- By the uncertainty principle, the bound quarks cannot fall to small distances without increasing their momentum and therefore kinetic energy.
- The quarks end up with an effective energy or mass of about 0.300 GeV each, and that gives masses of about 0.938 GeV for the proton and neutron.
- $\boldsymbol{\Psi}(\mathrm{r})^2$ is the probability of finding the quark at a given radius.
- The electron mass does come from the Higgs, and without it, electrons would be massless and fly about at the speed of light, and could never form atoms.



Mixings of Neutral Bosons to form the Z^0 and Photon

- The charge Q of up and down has a unit difference, but it does not fit exactly with the weak isospin T_3 value.
  - This is corrected by adding in a hypercharge Y in the formula
  - $Q = T_3 + ½ Y$. For quarks, $Y = 1/3$. For leptons, $Y = -1$.
- To add this in to couple to the photon, the Isospin 0 B^0 is included.
- The mixings of the Weak Isospin 1 W^0 and Isospin 0 B^0 is
- $Z^0 = \cos(\theta)\, W^0 - \sin(\theta)\, B^0$
- $\gamma = \sin(\theta)\, W^0 + \cos(\theta)\, B^0$
- Where θ is the Weinberg angle, given by

  $\text{Cos}(\theta) = \text{Mass of } W^+ / \text{Mass of } Z^0 = .80/.91 = 0.88$
- This mass ratio shows the deviation of the Z^0 from the initial W^0 partner of W^+.

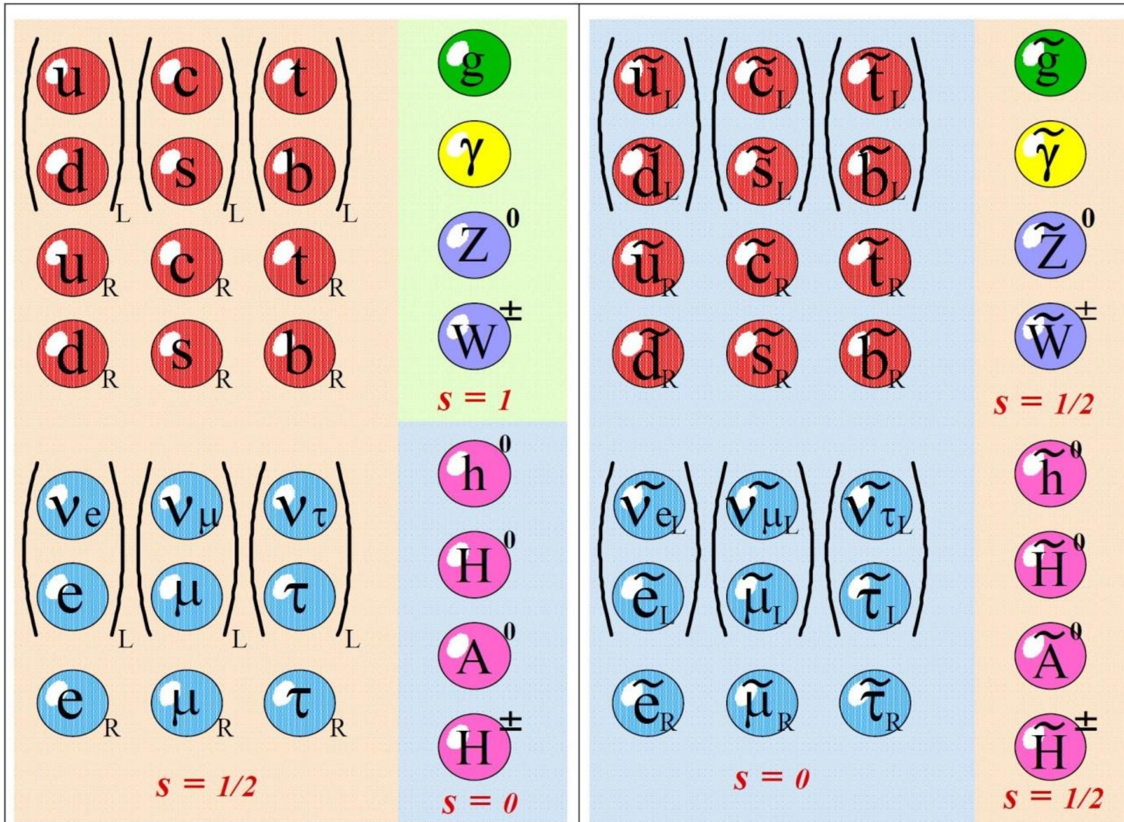
Super Symmetry as a Possible Future Scenario

SuperSymmetry (SUSY)

- Super Symmetry introduces new particles around 1 TeV to cause the electromagnetic, weak, and strong color couplings to come together to unify at 10^{17} GeV.
- It provides particle partners to cancel the virtual particles that would increase the new Higgs mass.
- It has stable, neutral candidates for dark matter.
- Since the reason for spin ½ and spin 1 particles is not well understood, except for providing chemistry and a livable universe, a dual universe of more massive SUSY particles is proposed by a symmetry that all real fermions are copied by SUSY bosons, and all real bosons are copied by SUSY fermions. They are all at higher mass to make them so far unseen.

The SUSY Spectrum of the MSSM (Minimal SUSY Model).

This is the popular two Higgs doublet model. One Higgs doublet Hu gives masses to the up quarks and leptons, and Hd gives masses to the down ones. While the original Higgs doublet had 3 of its four Higgs's "eaten", the new Higgs doublet adds four real Higgs's that could be seen in experiments.
One of the neutral SUSY (tilded) γ, Z^0, h^0, or H^0 could be the Dark Matter



Existing particles

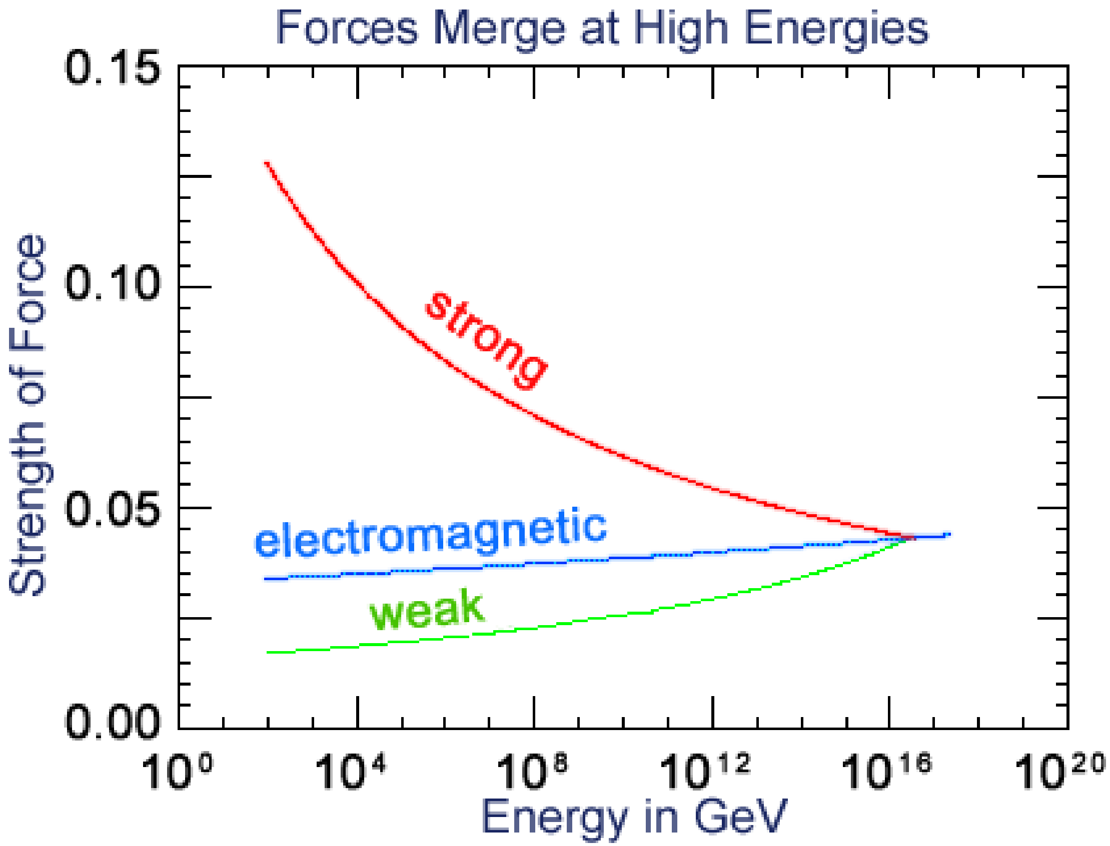
SUSY particles (MSSM model)

Grand Unified Theory and SUSY

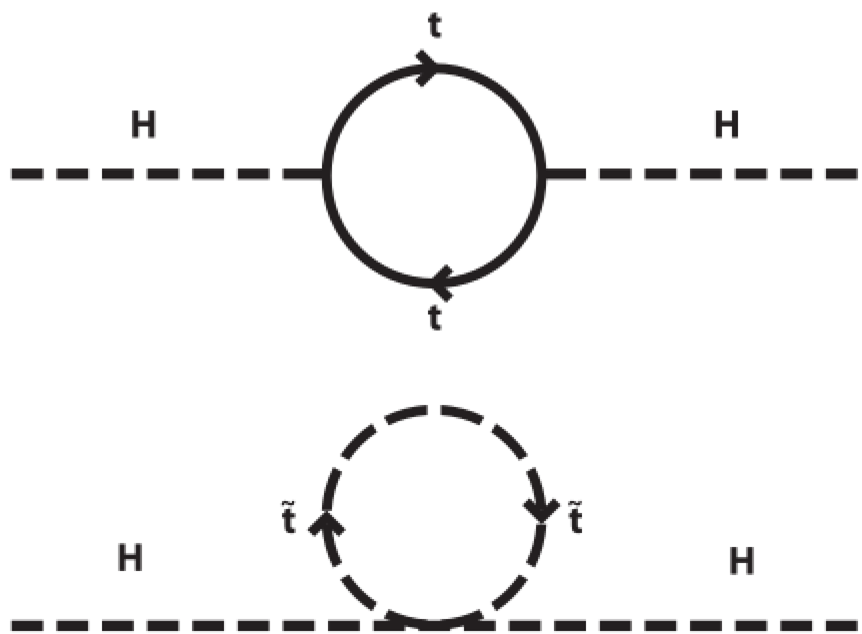
Merging of Coupling Strengths at 10^{17} GeV

Particles have clouds of virtual particles that change their effective charge as they are probed at shorter distances, which is the same as probing at higher energies.

The coupling strengths do not merge if just the standard model particles are used.



SUSY Cancellation of Higgs Loop Cutoff



Extra Topics – Read All About It

- Where **Our** Mass Comes From
- Benefits of the Particle Physics Program
- Neutrino Questions (Spring OLLI Class)
- Beauty of the Standard Model
- The Higgs Potential

Benefits of the Particle Physics Program

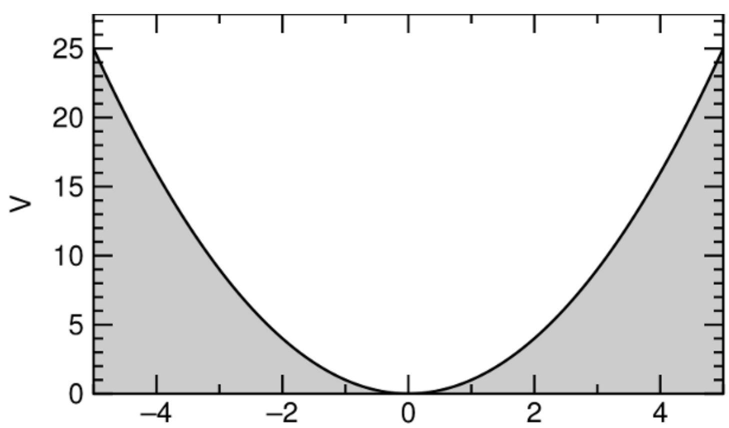
- The US particle physics program cost about \$750 million a year from DOE and \$100 million from the NSF.
- This averages out to \$3 per person per year in the US.
- It is a continuation of over 100 years of discoveries and technological development into the fundamental structure of matter, including atomic physics and nuclear physics.
- New technologies are created at the frontier of research, including nuclear power, medical detectors for X-rays, CAT scans, PET scans, and high energy photons for DNA analysis.
- The internet and the World-Wide-Web were created to handle multi-country and institution collaborations sharing the data.

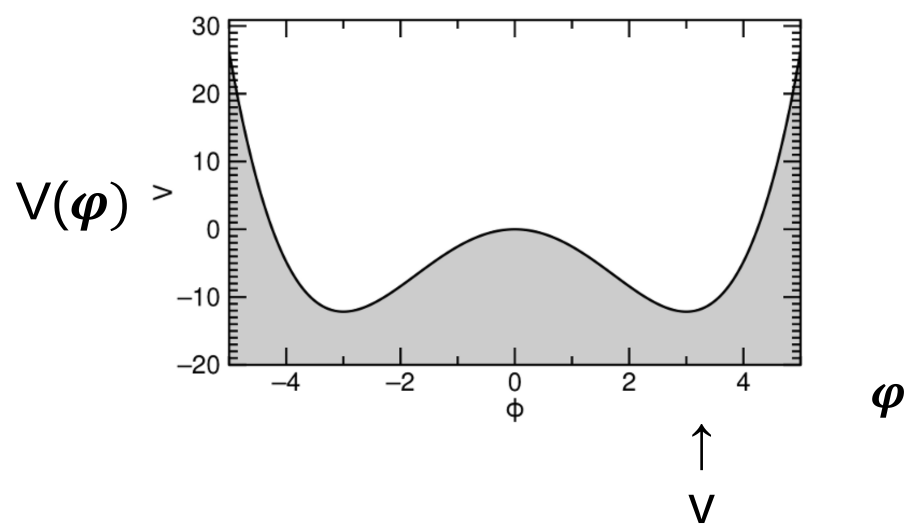
Local Benefits of Particle Physics

- The US participates in ATLAS, CMS, and most Neutrino Physics experiments.
- It also participates in dark matter detection experiments.
- Countries contribute in kind with new technological capabilities to make new devices
- Graduate students are trained with advanced new skills that will apply them in local businesses.
- In California, federal funding for research is a way to get back some of our federal tax payments.
- At UC Irvine, federal funding in all research fields, at 13% of our budget, now exceeds state funding.
- UC Irvine participates in ATLAS, in the SuperK neutrino experiment in Japan, in the ICECube neutrino detection in ice at the South Pole, in the Fermi gamma ray satellite, in the Large Synoptic Space Telescope, etc.
- UC Irvine Physics and Astronomy also has leading particle theory and cosmology groups.

The standard potential and The Higgs Potential

- The potential energy V depends on the value of the Higgs field ϕ.
- If V is linear in ϕ, then the potential becomes more negative as ϕ becomes negative, and ϕ is not finite. This would be true of ϕ^3 also.
- The next power is squared or ϕ^2, a standard potential, which is shown in the left hand figure. Here, the minimum energy is obtained for ϕ = o. This is not the desired result.
  - With a combination of negative ϕ^2 and positive ϕ^4, we obtain the desired Higgs Potential on the right. Here the desired non-zero value of **ϕ = v** is obtained. Choosing the positive value breaks the sign symmetry.

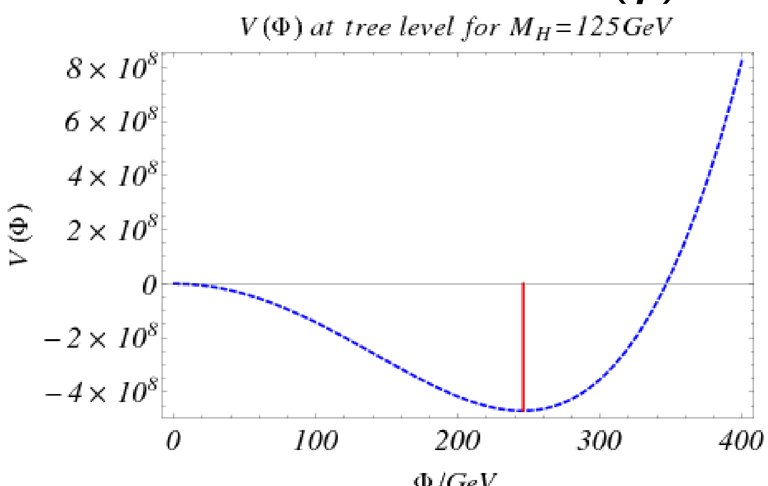




The Higgs Vacuum Value and the Higgs Mass

- The minimum value of ϕ is the Higgs vacuum expectation value v.
- Around the minimum the potential is quadratic in the deviation h, where $\boldsymbol{\phi} = \mathbf{v} + \mathbf{h}$. The value of v is 246 Gev.
- The potential is then $V(\boldsymbol{\varphi}) = \text{Vmin} + \frac{1}{2} M^2 h^2$, where M is now the mass of the Higgs particles created in the lab.
- Unfortunately, this is the one parameter which is not directly predicted by the theory.
- Hence the sequence of accelerators needed to search for it.

$\Downarrow \quad V(\boldsymbol{\varphi}) = \text{Vmin} + \frac{1}{2} M^2 h^2$



$\boldsymbol{\varphi}$

$\boldsymbol{\varphi} = \text{v} \uparrow$

$\leftarrow h \rightarrow$

Extra: The Higgs Potential in Detail

- The general potential energy for a spring or pendulum or any system oscillating about an equilibrium point, is the Harmonic Oscillator potential $V(x) = ½ k x^2$ (also known as Hooke's law).
- For any usual scalar field of compound scalars like pions, the potential is $V(\boldsymbol{\varphi}) = ½ \mathrm{m}^2 \boldsymbol{\varphi}^2$. The minimum of this is at $\boldsymbol{\varphi} = 0$.
- For the Higgs potential, where a non-zero result for $\boldsymbol{\varphi}$ is desired, the area around $\boldsymbol{\varphi} = 0$ must slope downward, so we take $\mathrm{m}^2 = -\mu^2$. Then to confine the result we add a positive $\boldsymbol{\varphi}^4$ term, giving
- $V(\boldsymbol{\varphi}) = -½\mu^2\boldsymbol{\varphi}^2 + ½\lambda\boldsymbol{\varphi}^4$.
- This has a minimum at $\boldsymbol{\varphi} = \mu / \sqrt{\lambda} = \mathrm{v}$, the Higgs field vacuum value of 246 GeV.
- Defining the particle Higgs field about the minimum as h: $\boldsymbol{\varphi} = \mathrm{v} + \mathrm{h}$
- Gives $V(\mathrm{h}) = \lambda\, \mathrm{v}^2\, \mathrm{h}^2 +$ terms in h^3 and h^4.
- Defining the Higgs particle mass M by $½\, \mathrm{M}^2\, \mathrm{h}^2 = \lambda\, \mathrm{v}^2\, \mathrm{h}^2$, we find
- $\mathrm{M} = \sqrt{(2\lambda)}\, \mathrm{v}$. But since λ wasn't known, the mass of the Higgs was unknown, which led to the sequence of accelerators to discover the Higgs particle.

Neutrino Questions

- Are neutrinos their own antiparticles, called Majorana neutrinos?
  - Are they Dirac fermions as leptons are, or mixtures of Dirac and Majorana?
- What are the real neutrino masses?
- What produces the neutrino's masses?
- Are there more neutrinos, such as very massive ones or sterile (non-interacting) ones?
- Are neutrino and antineutrino oscillations slightly different?
  - Test by Long Baseline Neutrino Experiment at Fermilab, if fully funded
  - If different, could allow "leptogenesis" or leftover matter.

The Beauty of the Standard Model

- The Standard Model is built of three theories in a sequence of charges.
- First, **electromagnetism** is built with one type of charge, the electric charge. It also has the only massless boson, the photon, which gives us light and the electromagnetic spectrum.
- Second, the **weak interactions**, are built on the two weak isospin charges for quarks and leptons of isospin up and isospin down. The theory has 3 weak isospin charged bosons, the W^+, W^-, and W^0. These also interact with themselves.
- Thirdly, the strong **chromodynamic interactions**, are built on the three colors of quarks, with eight gluons to make transitions between them. The gluons are also colored and interact with themselves.