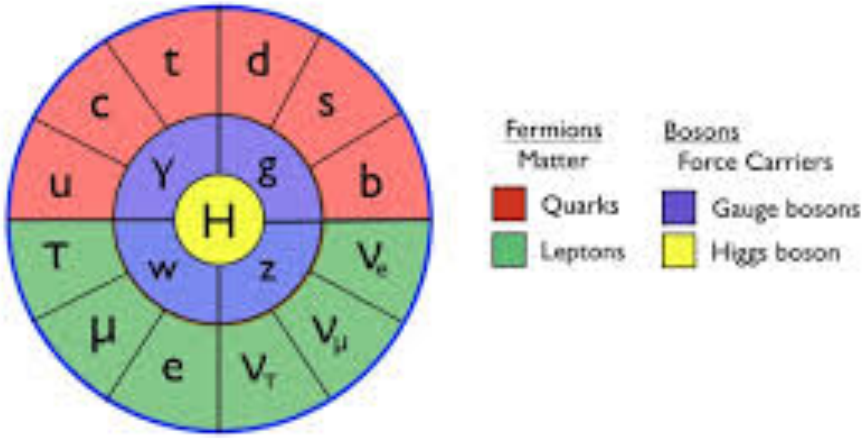
Elementary Particle Physics
From Theory to Experiment



Particles of the Standard Model

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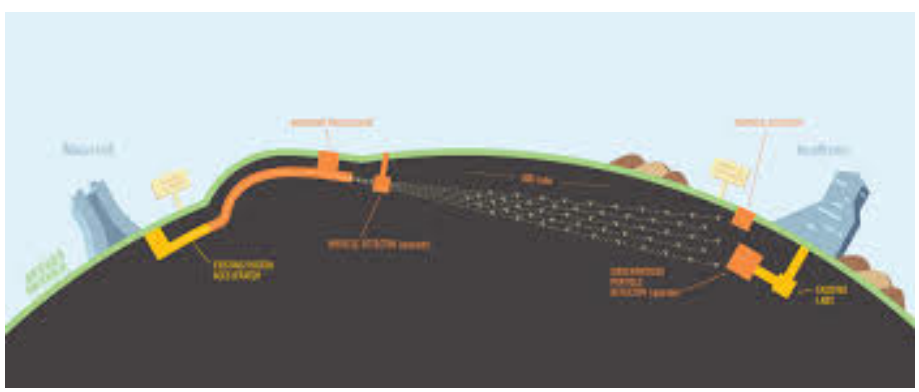
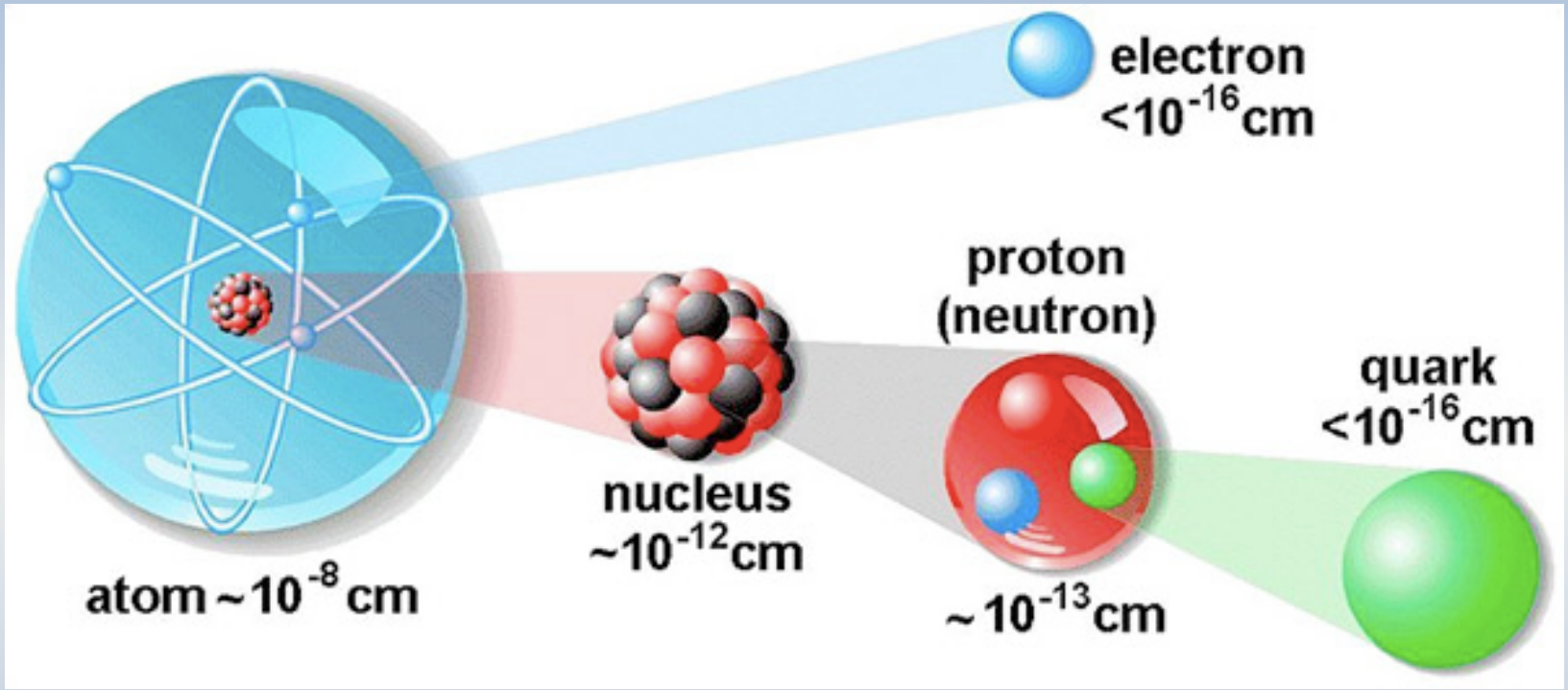
HEP Division, Argonne National Laboratory



Society of Physics Students, Univ. of Chicago, Nov. 10, 2014

Particle Physics studies the smallest pieces of matter,



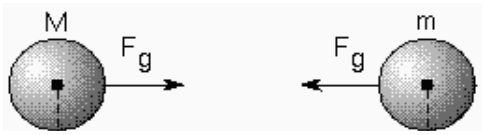
1 1/10.000 1/100.000 1/100.000.000

and their interactions.

Forces and Particles in Nature

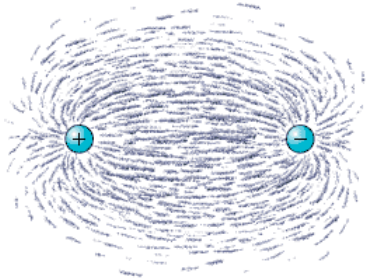
Gravitational Force

Attractive force between 2 massive objects:



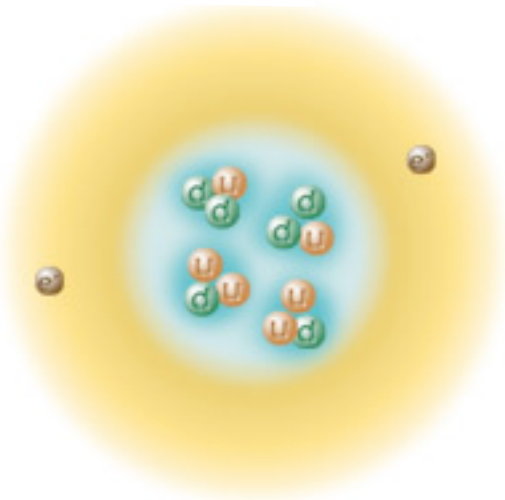
Electromagnetic Force

Attracts particles of opposite charge



Forces within atoms and between atoms

Strong Force

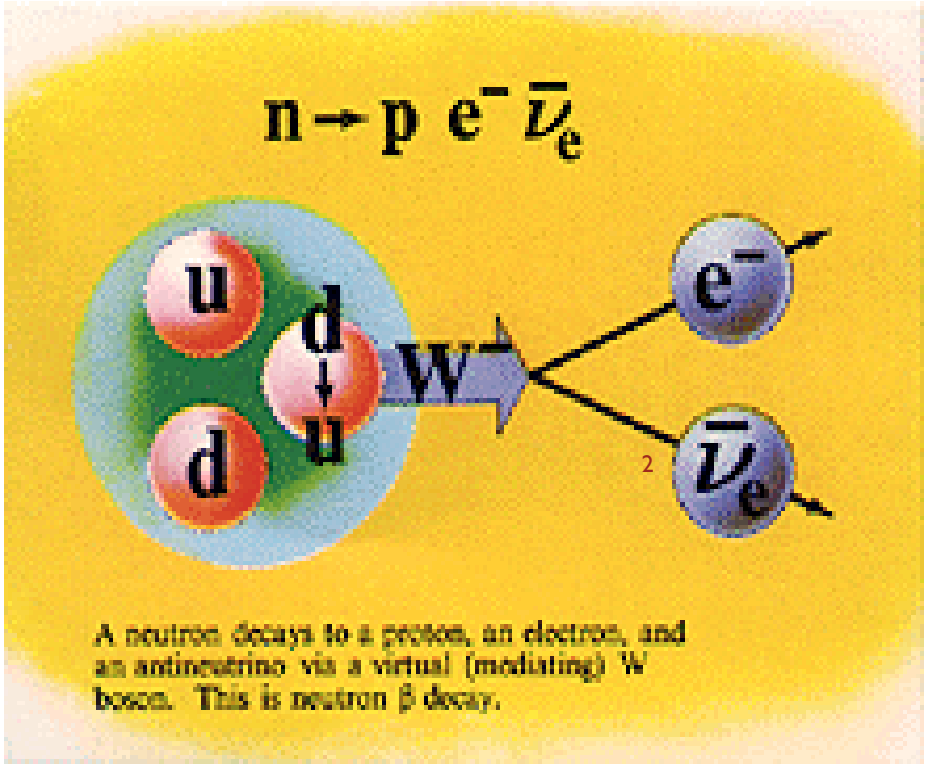


Strong nuclear force binds together protons and neutrons to form atoms nuclei

proton → uud
neutron → udd

formed by three quarks, bound together by the gluons of the strong interactions

Force Mediating particle transformations



Weak Force

Similar transformations explain the non-observation of heavier elementary particles in our everyday experience.

Standard Model Particles

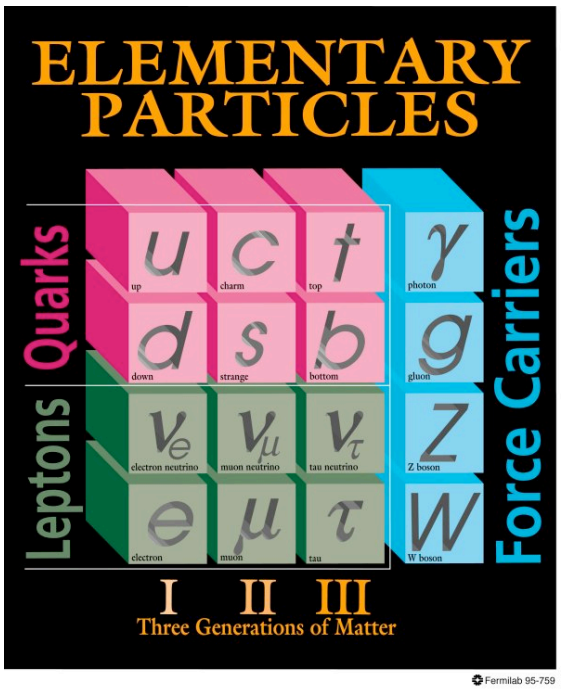
There are 12 fundamental gauge fields:

8 gluons, 3 W_μ's and B_μ

and 3 gauge couplings g_1, g_2, g_3

The matter fields:

3 families of quarks and leptons with same quantum numbers under gauge groups



But very different masses!

m_3/m_2 and $m_2/m_1 \simeq$ a few tens or hundreds

$m_e = 0.5\ 10^{-3}$ GeV, $\frac{m_\mu}{m_e} \simeq 200$, $\frac{m_\tau}{m_\mu} \simeq 20$

Largest hierarchies

$m_t \simeq 175$ GeV $\qquad m_t/m_e \propto 10^5$

neutrino masses smaller than as 10^{-9} GeV!

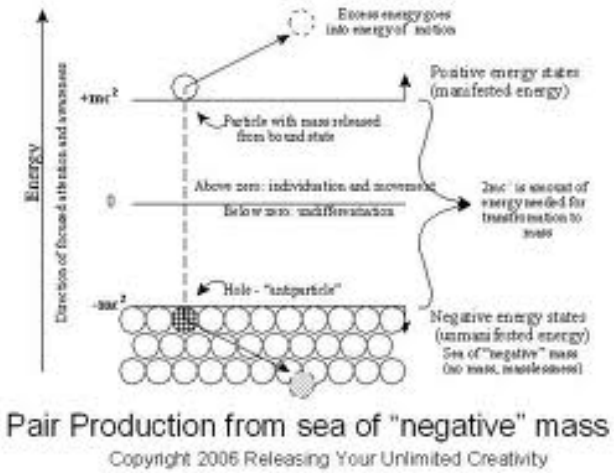
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

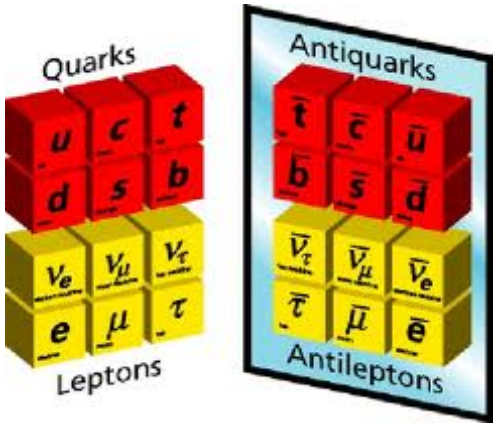
Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c²	Electric charge	Flavor	Approx. Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

Only left handed fermions transform under the weak SM gauge group $SU(3) \times SU(2)_L \times U(1)_Y$

Fermion and gauge boson masses forbidden by symmetry

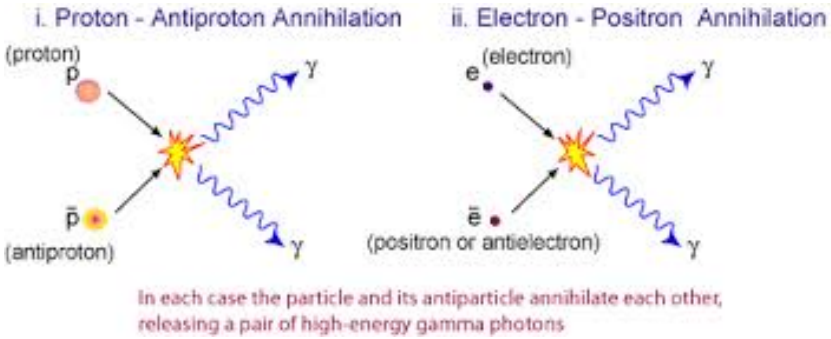
Antiparticles

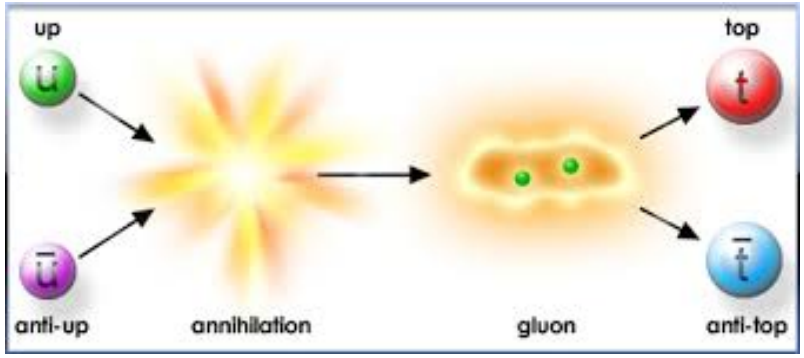




Dirac equation leads to negative energy states

Solution to this problem : States filled (the Dirac sea)





Holes in the Dirac sea : Antiparticles

Positron discovered a few years later

Particle Physics Property : When two particles collide, they may be converted into other forms of energy (particles energetically accessible)

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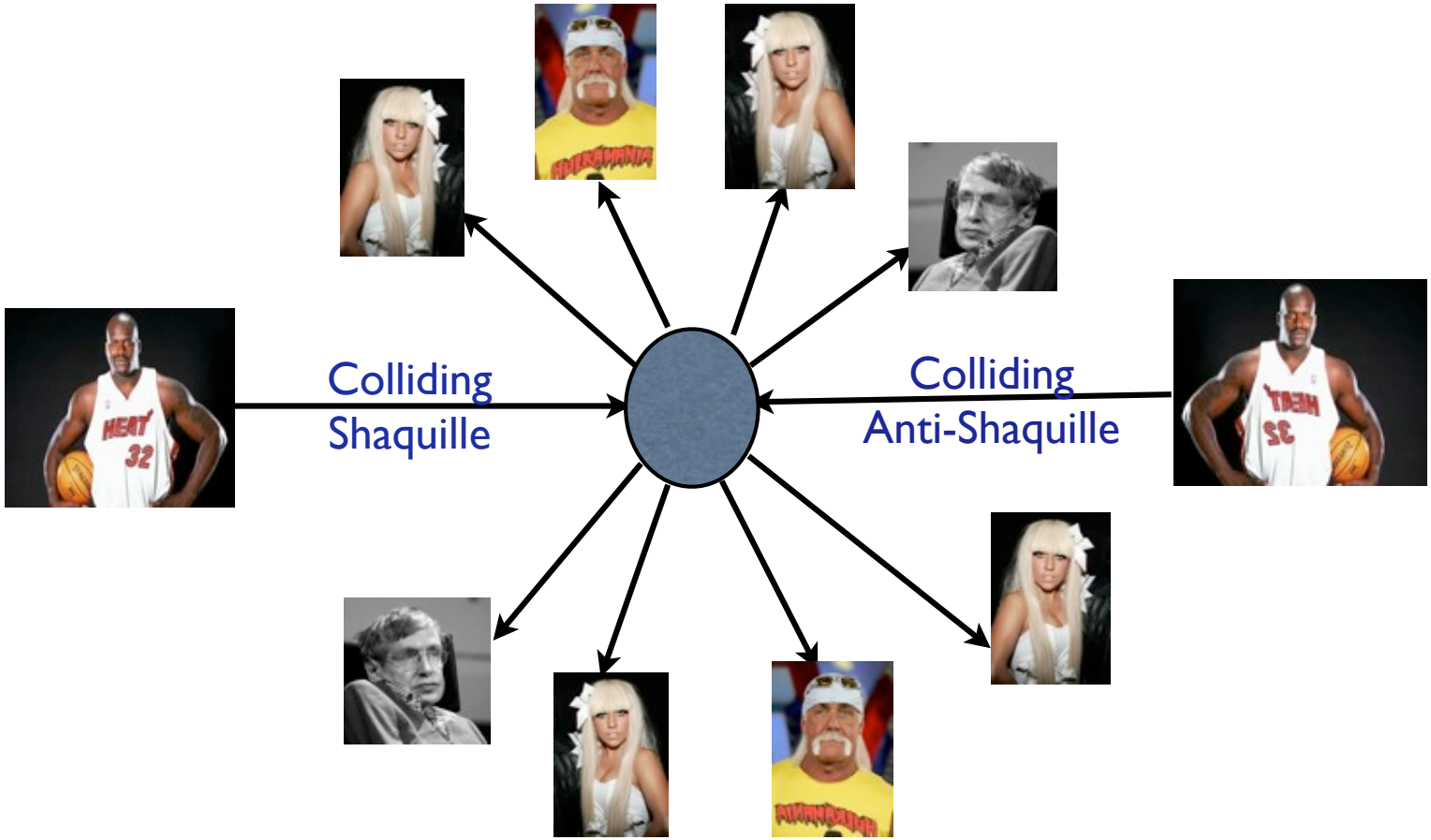
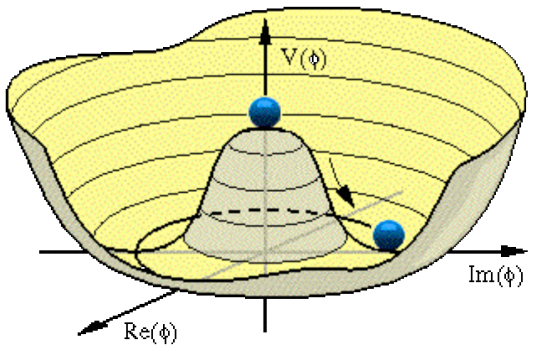


Rate of production of a given particle depends on its strength of interactions with colliding particles. Hulk Hogan (and anti-Hogan) produced more frequently than Hawking

In the Standard Model, explicit masses are forbidden by symmetry

The Higgs Mechanism and the Origin of Mass

A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy



Spontaneous Breakdown of the symmetry : $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\mathrm{em}}$

Vacuum becomes a source of energy = a source of mass

$$\langle H^0 \rangle = \mathrm{v}$$

A physical state (Higgs boson) appear associated to fluctuations in the radial direction . Goldstone modes: Longitudinal component of massive Gauge fields.

Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

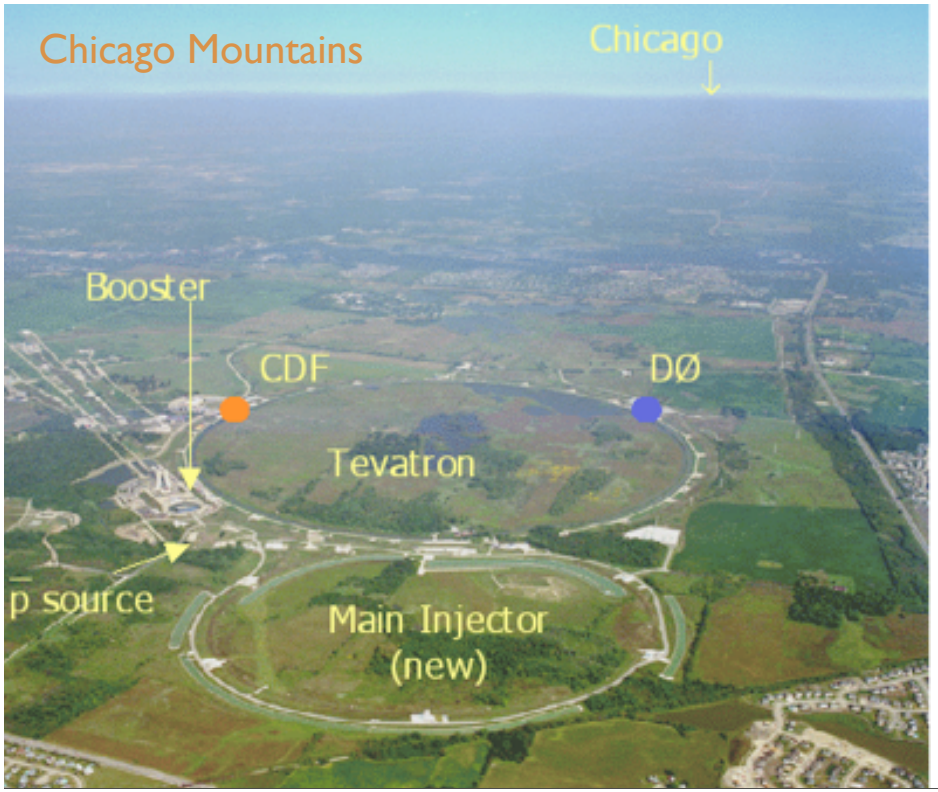
$M_{w,z} = g_{w,z}\, v$ $\qquad$ $m_{top} = h_{top}\, v$ $\qquad$ $m_H^2 = \lambda\, v^2$

The Discovery of the Higgs puts the last piece of the Standard Model in place

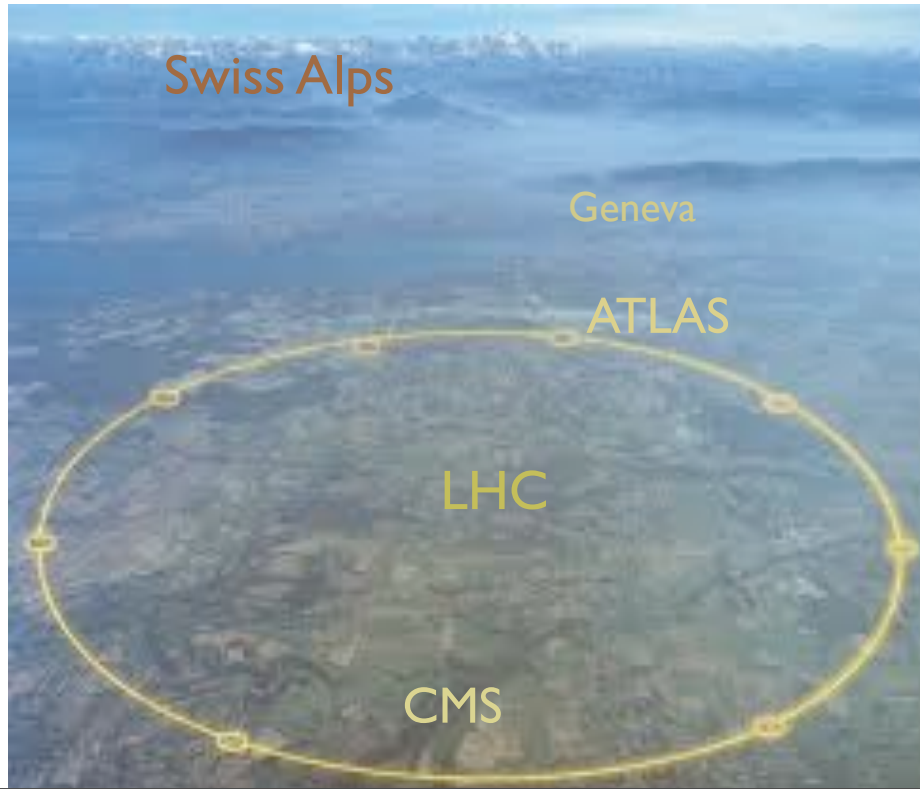
How did we search for the Higgs ?

Colliding particles at the Tevatron and the LHC

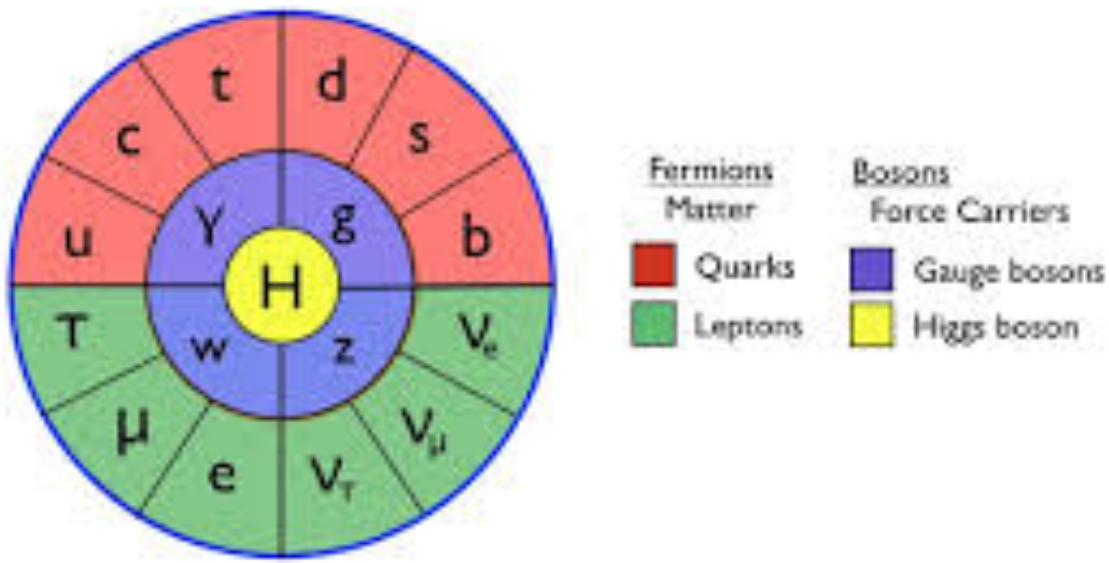
Tevatron Energy = 2,000 proton masses



LHC Energy = 8,000 proton masses



The complete set of Standard Model particles



Particles of the Standard Model

Progress in developing the SM has been
the result of collaboration of theory and experiment

Reasons for Proposal and Later Solutions to 4 Puzzles (1932)

- 1) Klein Paradox --apparent violation of unitarity (solution:positron existence- pair production possible)
- 2) Wrong Statistics in Nuclei--N-14 nucleus appeared to be bosonic--(solution: neutron not a proton-electron bound state)
- 3) Beta Ray Emission-apparent Energy non conservation (solution:neutrino)
- 4) Energy Generation in Stars (solution: nuclear forces, pep chain, carbon cycle etc.----pion)

Higgs Discovery
Historical Perspective

- In order to reflect on the future, it is useful to look at the lessons of the past.
- I will give a few interesting examples, and then speculate on the future.
- Higgs mechanism was proposed back in 1964, by several authors, including Higgs, and implemented in the SM by Weinberg, in 1967.
- What were the prospects of finding the Higgs Boson ten years after its proposal ?

A Phenomenological Profile of the Higgs Boson

1976

Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

The situation with regard to Higgs bosons is unsatisfactory. First it should be stressed that they may well not exist. Higgs bosons are introduced to give intermediate vector bosons masses through spontaneous symmetry breaking. However, this symmetry breaking could be achieved dynamically [10] without elementary Higgs bosons. Thus the confirmation or exclusion of their existence would be an important constraint on gauge theory model building. Unfortunately, no way is known to calculate the mass of a Higgs boson, at least in the context of the popular Weinberg-Salam [11]

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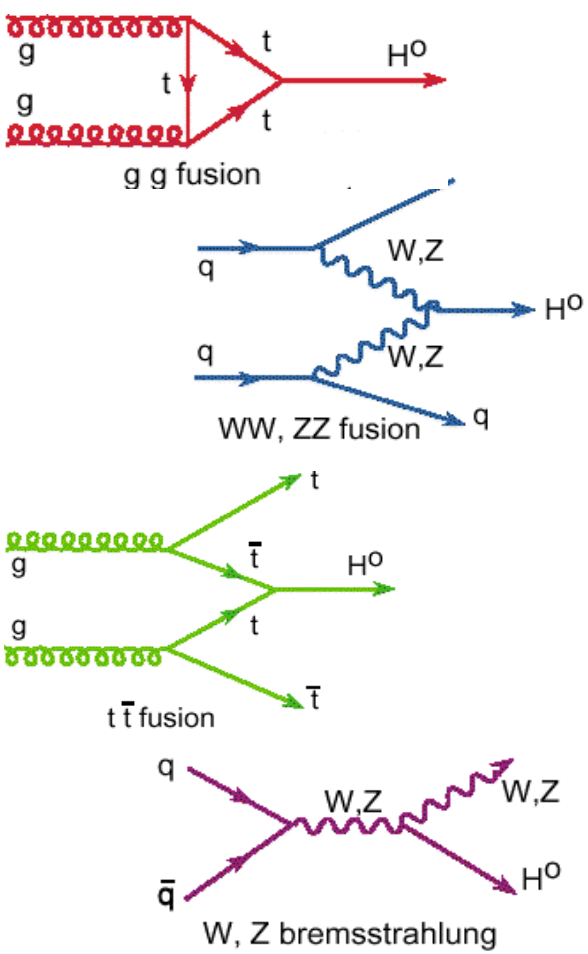
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

But the Higgs is not weakly coupled to all fundamental particles !

- It is relatively strongly coupled to those particles which had not been discovered at that time
- Indeed, the W mass, the Z mass and the top quark masses are all of the order of 100 times the proton mass
- Some of the authors soon realized that these could be used to produce Higgs bosons
- It is in processes mediated by these particles that we have searched for, and eventually found the Higgs boson !

Search for the Standard Model Higgs at Proton Colliders

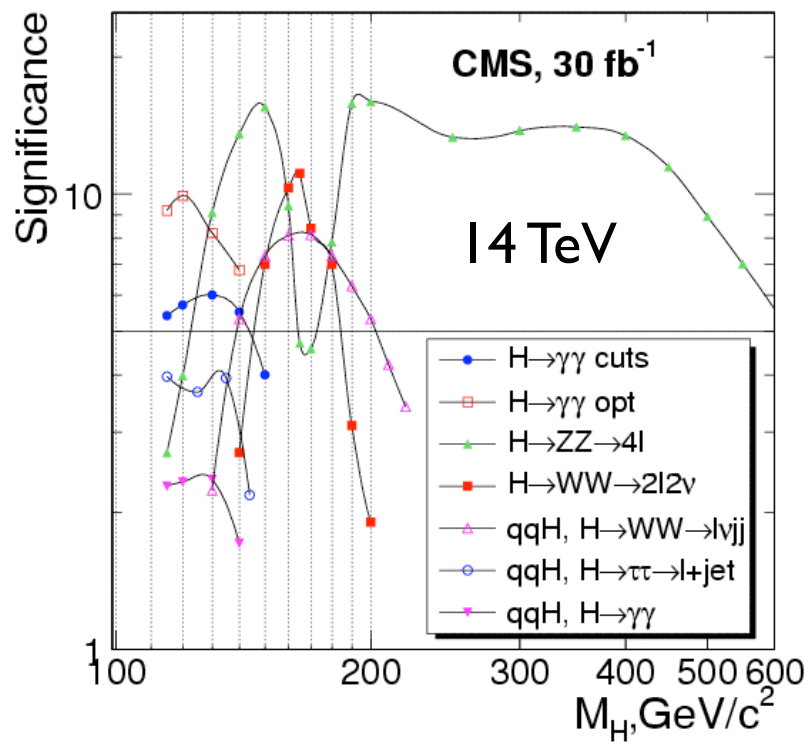


- **Low mass range** $m_{H_{SM}} < 200$ GeV

$$H \to \gamma\gamma, \tau\tau, bb, WW, ZZ$$

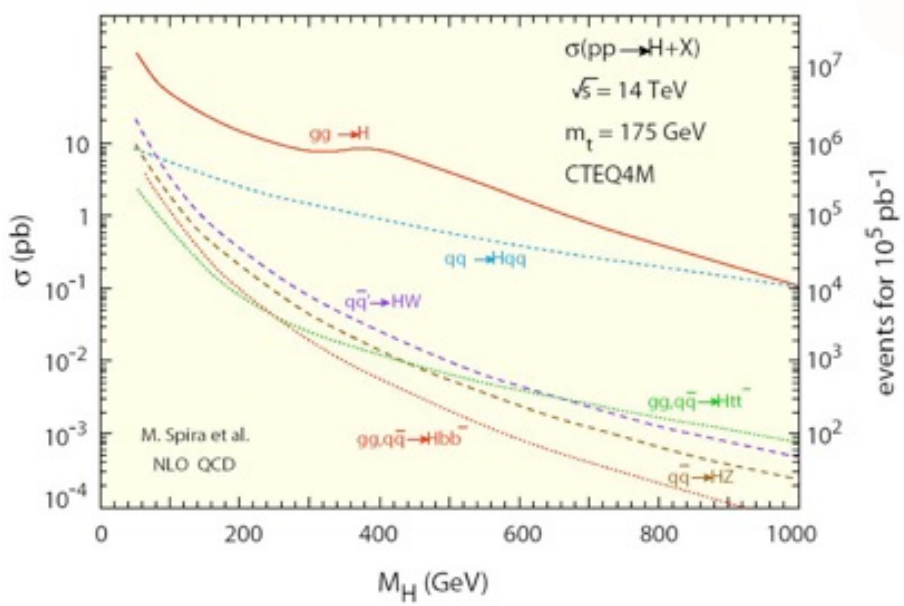
- **High mass range** $m_{H_{SM}} > 200$ GeV

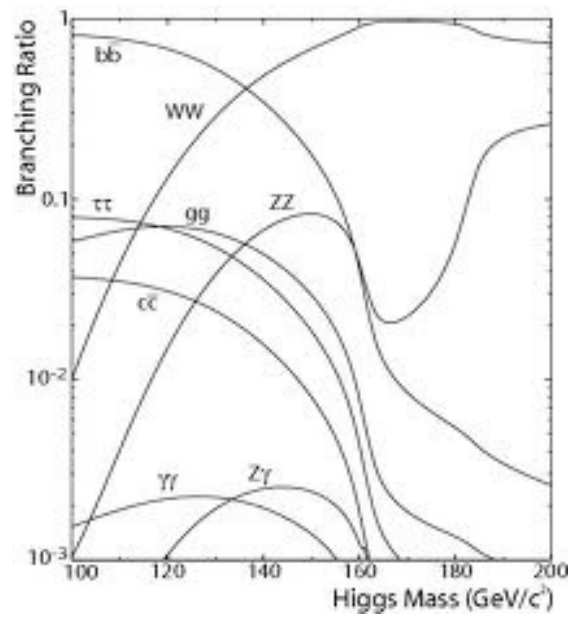
$$H \to WW,\ ZZ$$



SM Higgs LHC Cross Sections and Decay Branching Ratios

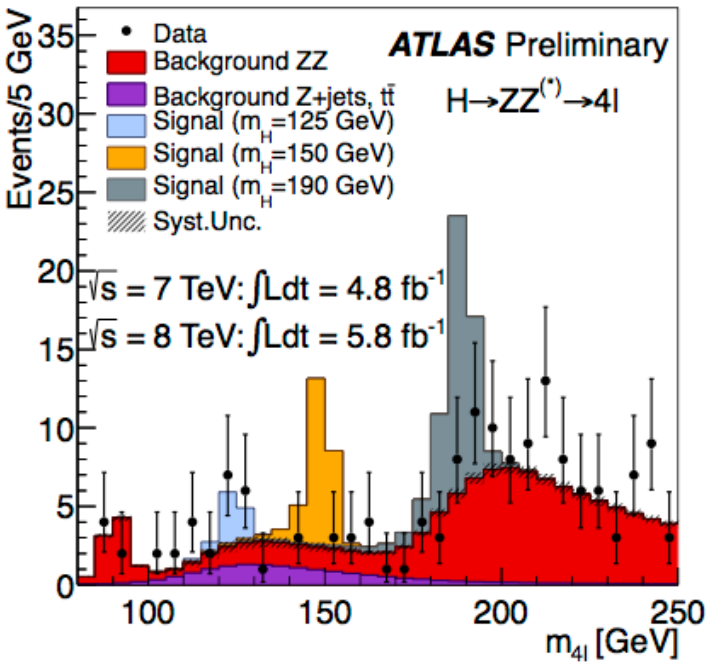
$$1 \text{ barn} : 10^{-24} \text{ cm}^2$$
$$1 \text{ pb} = 10^{-12} \text{ barn}$$
$$1 \text{ fb} = 10^{-15} \text{ barn}$$
$$L \times \sigma = \text{Number of events}$$

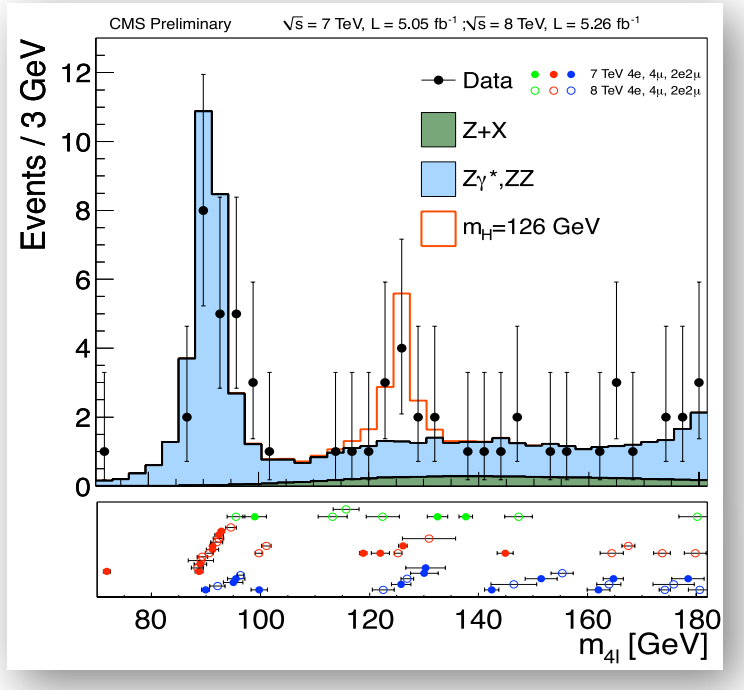




Higgs tends to decay into heavier SM particle kinematically available

Both Experiments look for a Higgs decaying into two Z's through four lepton channels





Both see an excess of ZZ events in the 125 GeV mass range. The production rate is consistent with the one expected for a 125 GeV mass Higgs.

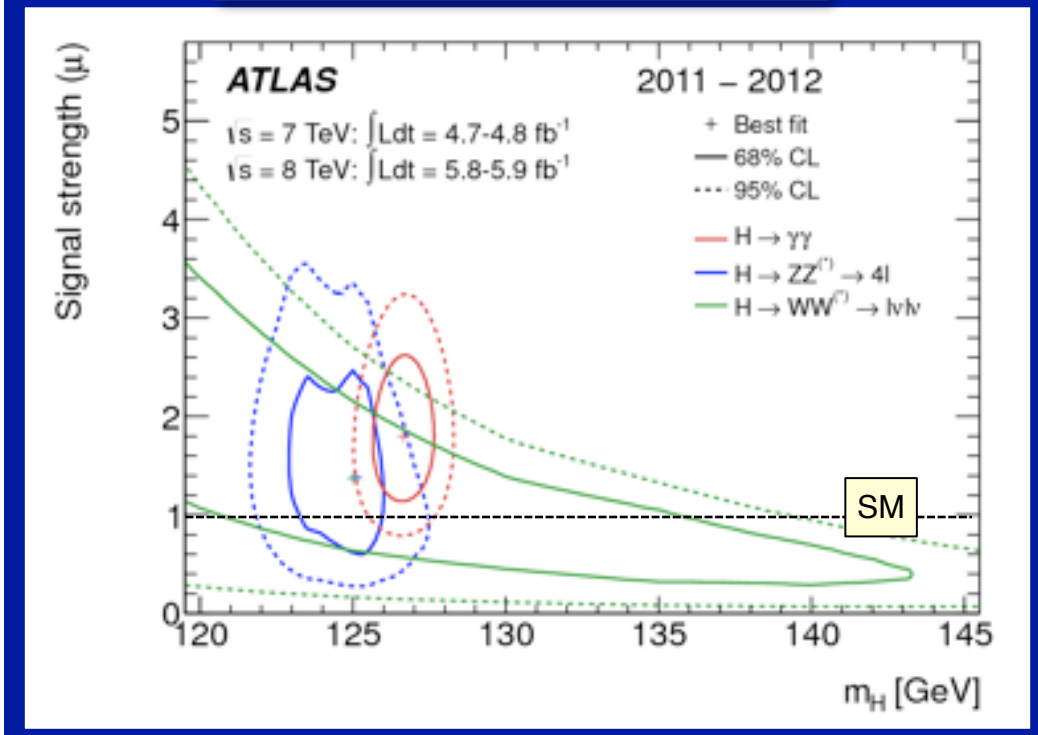
Properties of the new state

Mass and signal strength

- From a 2-D fit to ZZ* and γγ channels

Mass = 126.0 ± 0.4 ± 0.4 GeV

σ/σ_{SM} = 1.4 ± 0.3

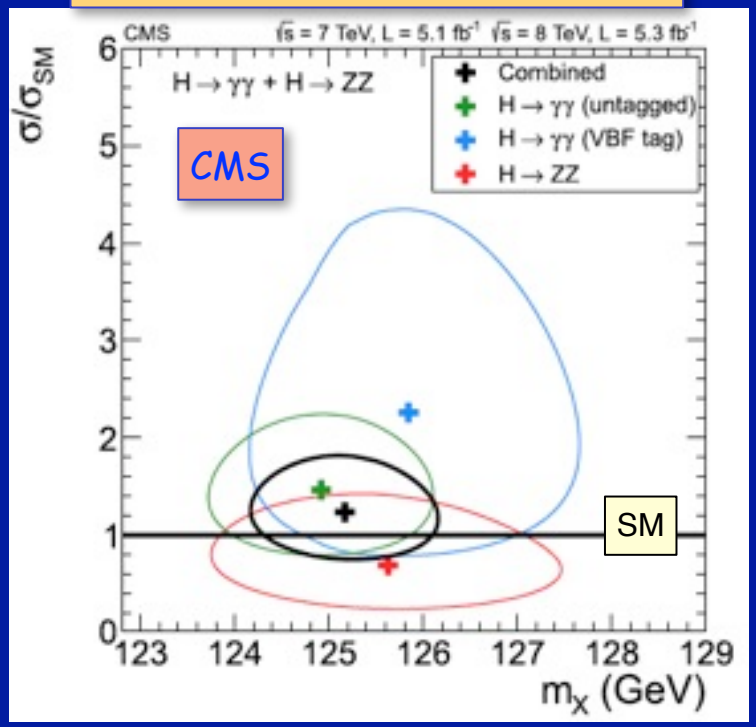


Observed width consistent with experimental resolution of ~ 2 GeV

- expected width of SM Higgs ~ 4 MeV

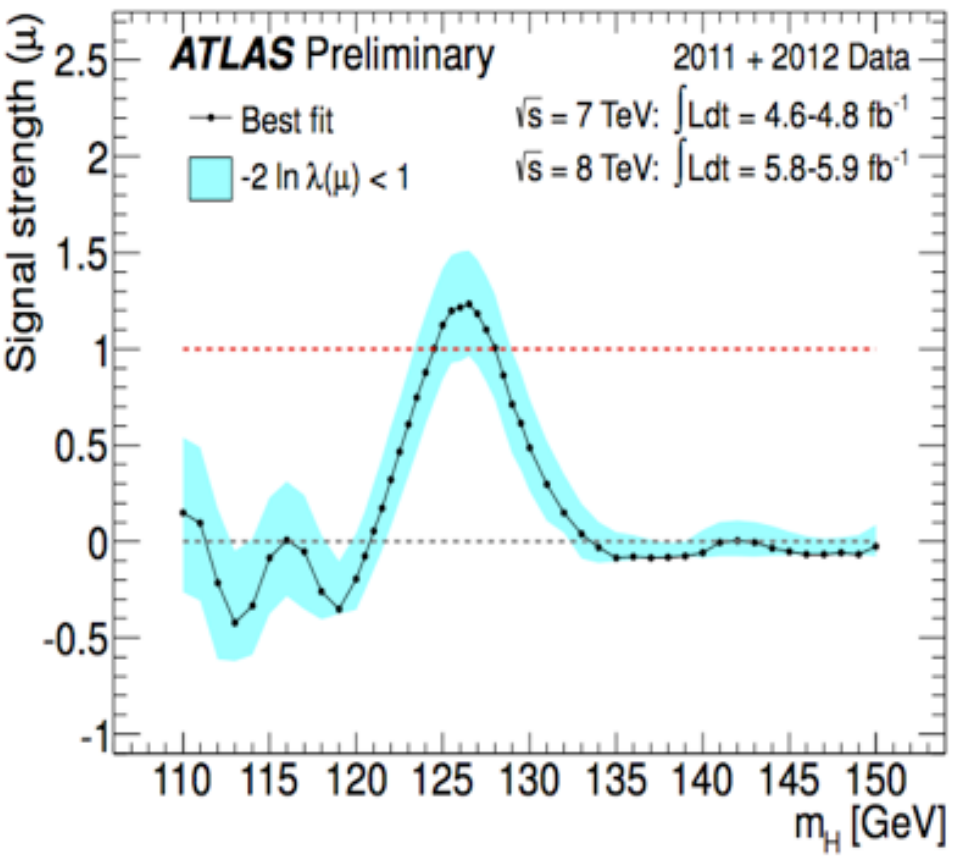
Mass = 125.3 ± 0.4 ± 0.5 GeV

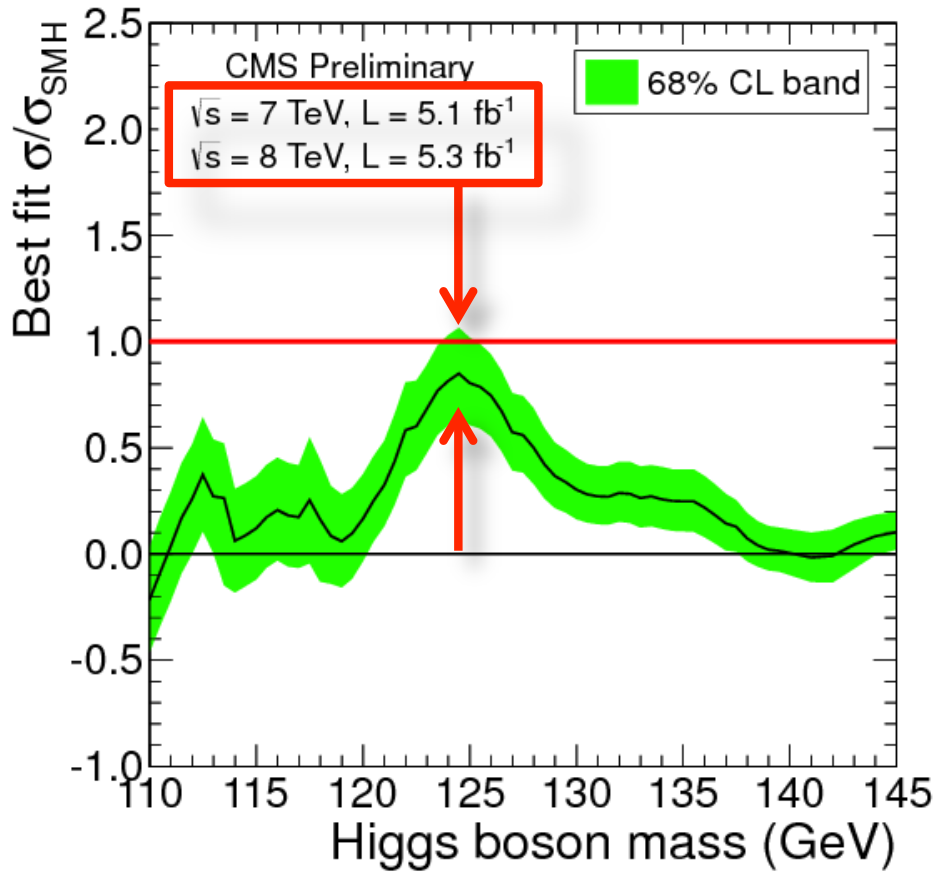
σ/σ_{SM} = 0.87 ± 0.23



Strengths in good agreement with prediction for SM Higgs at current precision.

Combining all channels the LHC experiments found a best fit to the Higgs production rate consistent with that one of a SM Higgs of mass close to 125 GeV






Now What?

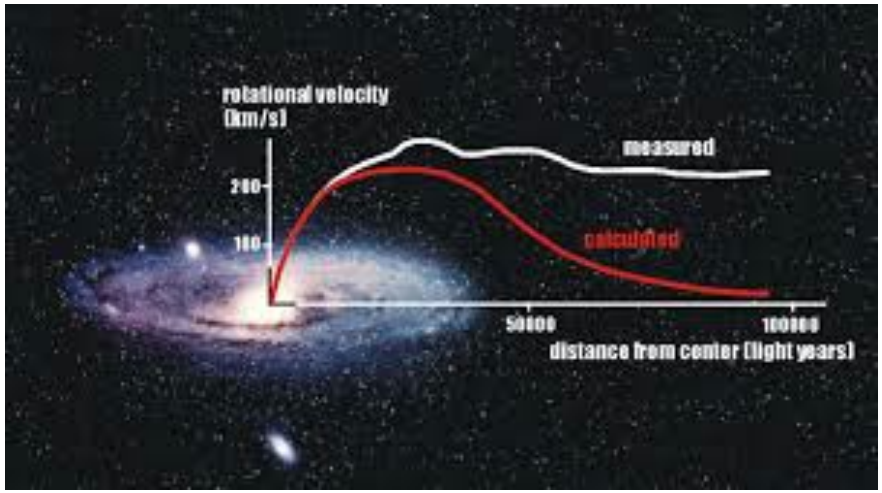
Assume Resonance behaves like a SM Higgs:
What are the implications for the future of High Energy Physics?

Many questions remain unanswered. Just to list some important ones :

- Why is gravity so weak or, equivalently, why is the Planck scale so high compared to the weak scale ? (hierarchy problem)
- What is the origin of the matter-antimatter asymmetry
- What is the origin of Dark Matter ?
- Are neutrinos their own antiparticle ?
- Why are there three generations of fermions ?
- What is the origin of the hierarchy of fermion masses ?
- Do forces unify ? Is the proton (ordinary matter) stable ?
- What about Dark Energy ?

Dark Matter and Electroweak Symmetry Breaking

Astrophysical Evidence of the Existence of Dark Matter



More mass in Galaxies than inferred from Stars and Dust

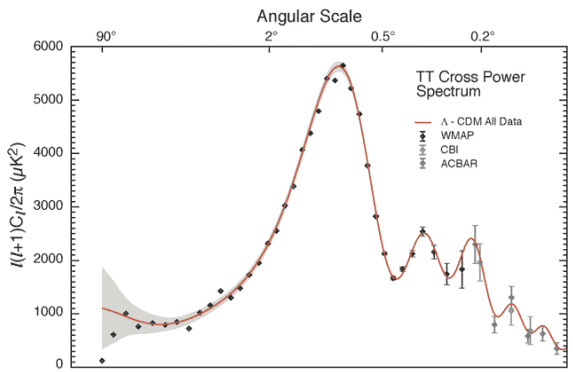
Collisionless form of Matter in Galaxies, carrying most of the Galaxies mass

Results from WMAP

Ω_i : Fraction of critical density

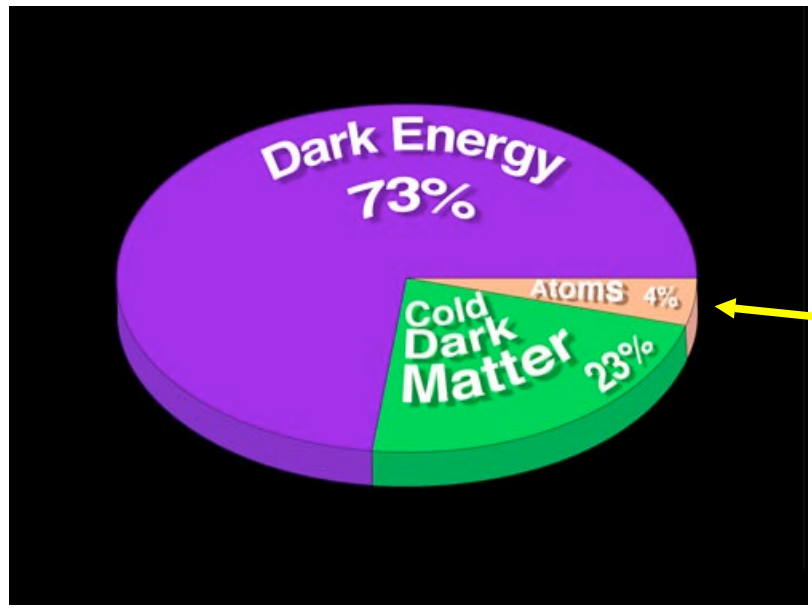
Universe density	$\Omega_0 = 1.02 \pm 0.02$
Dark energy density	$\Omega_\Lambda = 0.73 \pm 0.04$
Total matter density	$\Omega_M = 0.27 \pm 0.05$
Baryon matter density	$\Omega_b = 0.044 \pm 0.004$

→ Dark matter is non-baryonic



If Dark Matter is a neutral particle proceeding from the thermal bath, its density fraction is inversely proportional to its annihilation rate.

Our Universe:



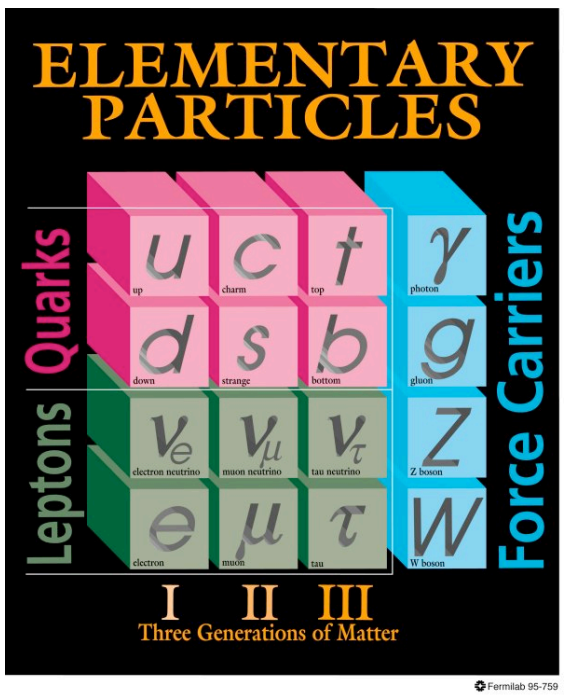
← us

Standard Model Particles

Three families of quarks and leptons. Second and third family heavy and unstable.

Force carriers W and Z are unstable and have mass of order 100 GeV

"Scalar Higgs" particle is necessary to explain mass generation. Collider experiments searching for it.



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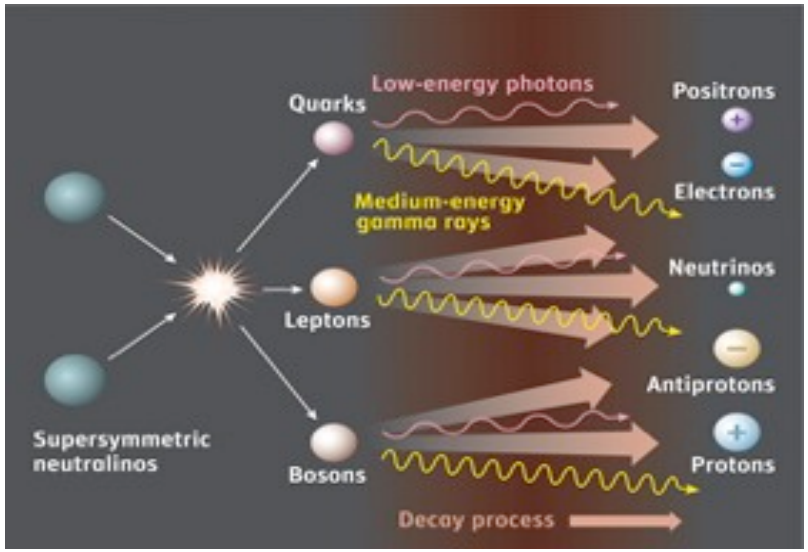
None of these particles is a good DM candidate !

- In the early Universe, particles are created and annihilated in collisions. Average particle energy is given by the Universe temperature.

- When the temperature drops below a particle mass, it can no longer be created, and it decays or annihilates.

- Stable particles annihilate until the expansion of the Universe makes their encounter extremely rare



- Observed DM Density : DM are WIMPS (weakly interacting massive particles)

Dark Matter : Missing Energy at Colliders

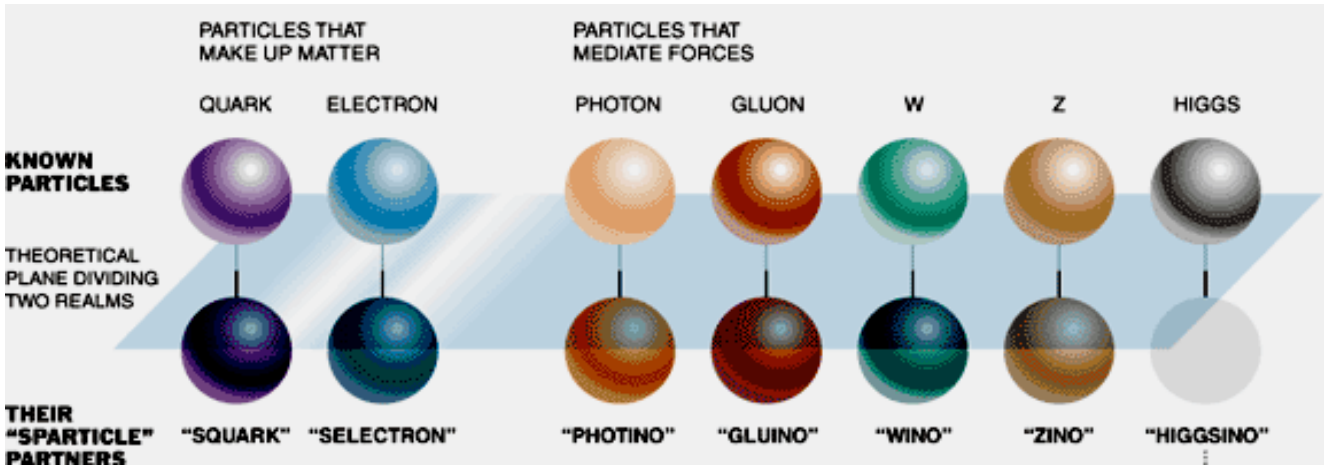
- In general, if the dark matter particle is neutral and weakly interacting, it will not be detected at current colliders.
- Just like when the neutrino was discovered, evidence of the production of such a particle will come from an apparent lack of conservation of the energy and momentum in the process.
- Missing Energy and (transverse) momentum signatures, beyond the ones expected in the Standard Model, should be sizable and will be the characteristic signatures of theories with a thermal WIMP as a Dark Matter Candidate.

What lies ahead ?

- Is Dark Matter isolated or is part of a new set of particles, soon to be discovered ?
- In the second case, are these particles related in some way to the Higgs ?
- Do they lead to an explanation of other puzzles ?
- Supersymmetry is an example of an extension of the SM that may solve several of these puzzles.
- It also leads to the unification of fermions (matter fields) and bosons (force fields)

Supersymmetry

fermions bosons



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

$$\text{Two Higgs doublets necessary} \rightarrow \tan\beta = \frac{v_2}{v_1}$$

Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy: $\delta m_H^2 \approx (-1)^{2S_i} \frac{n_i g_i^2}{16\pi^2} \Lambda$

- Supersymmetry algebra contains the generator of space-time translations.
  Possible ingredient of theory of quantum gravity.

- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.

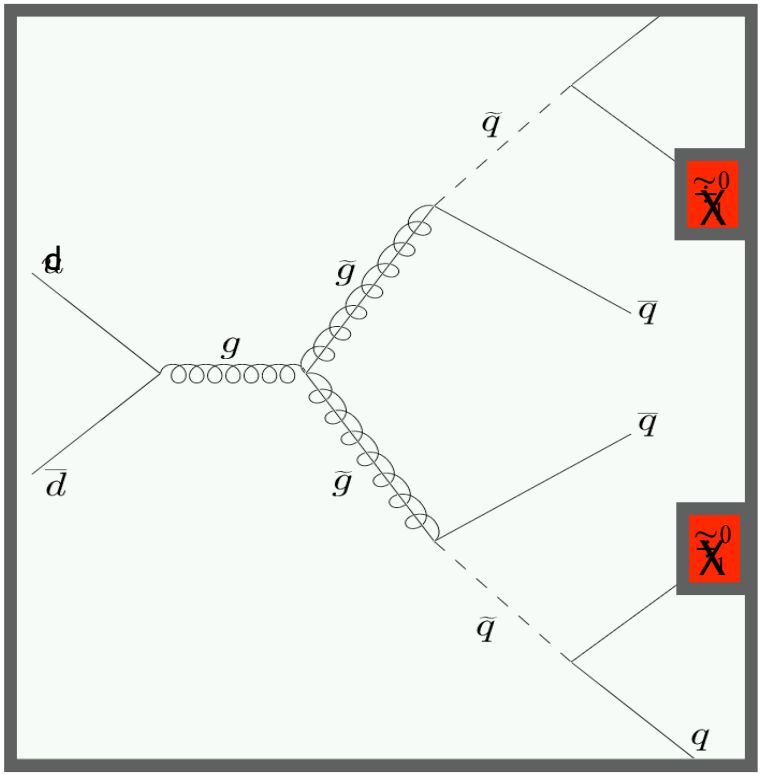
- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

- If discrete symmetry, $P = (-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Gluino production and decay: Missing Energy Signature

Supersymmetric Particles tend to be heavier if they carry color charges.

Charge-less particles tend to be the lightest ones.



Lightest Supersymmetric Particle: Excellent cold dark matter candidate

- Is Supersymmetry really there ?
- There are many alternatives, but none as compelling as SUSY.
- There may be extra dimensions of space time, that cannot be seen with the present resolution.
- There may be new gauge forces, or new, heavy fermions with masses not proceeding from the Higgs.
- The future will tell. But it will still be a joint effort between theory and experiment.