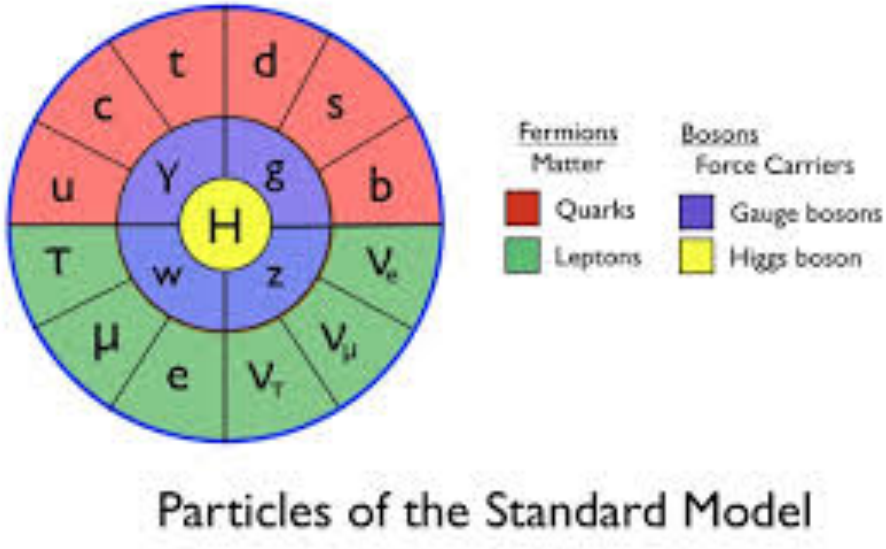
Open Questions in Particle Physics



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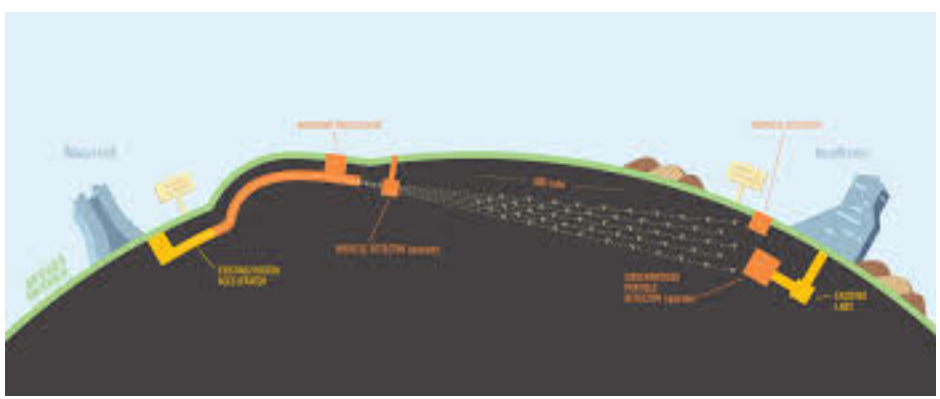
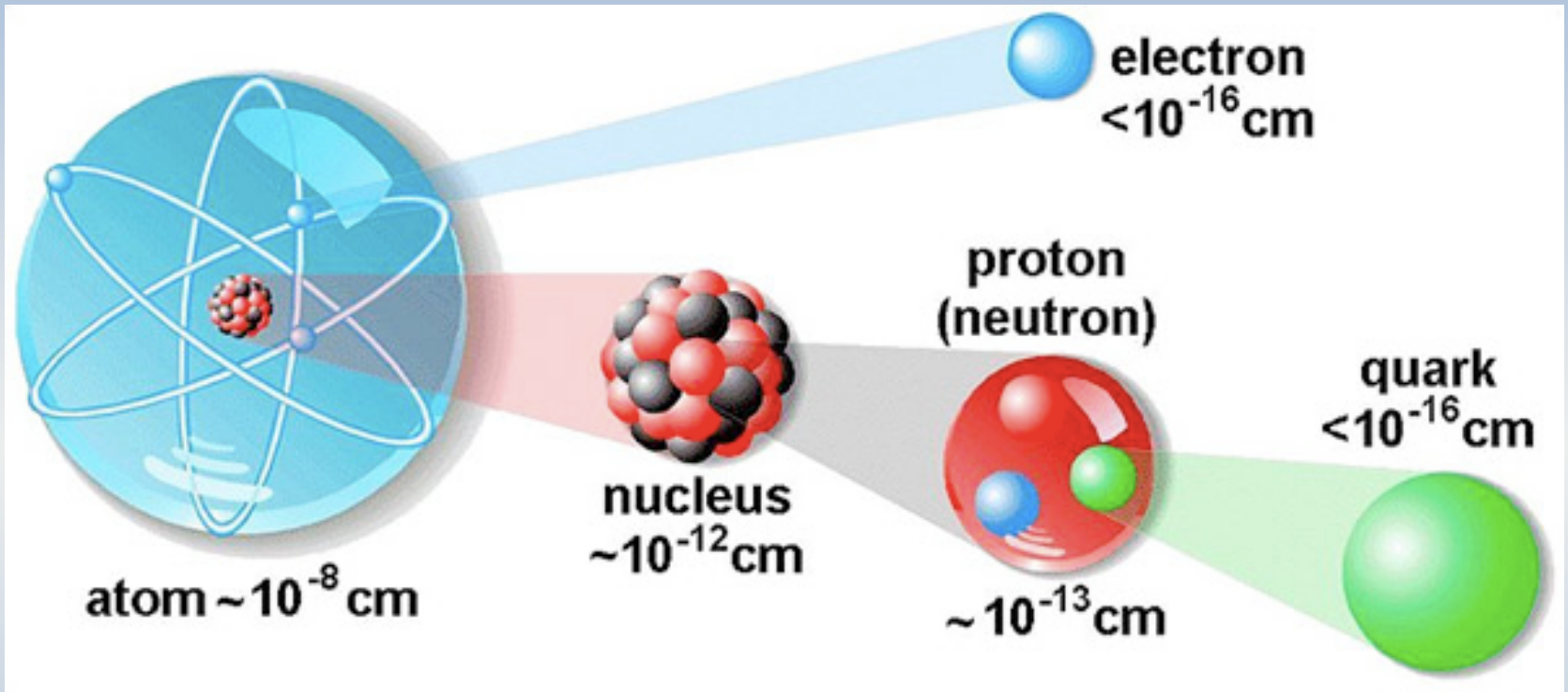


Society of Physics Students, Univ. of Chicago, Nov. 21, 2016

Particle Physics studies the smallest pieces of matter,



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and their interactions.

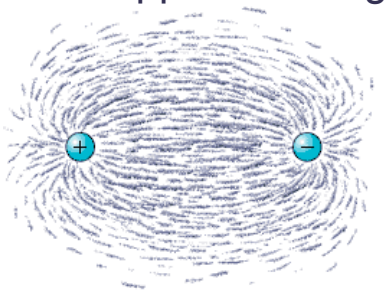
Forces and Particles in Nature

Gravitational Force

Attractive force between 2 massive objects:

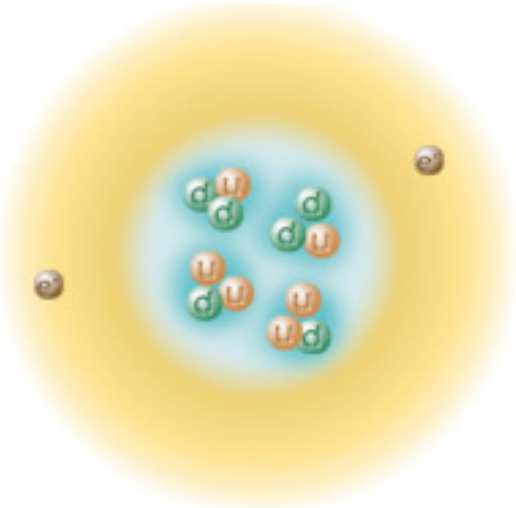
Electromagnetic Force

Attracts particles of opposite charge



Forces within atoms and between atoms

Strong Force

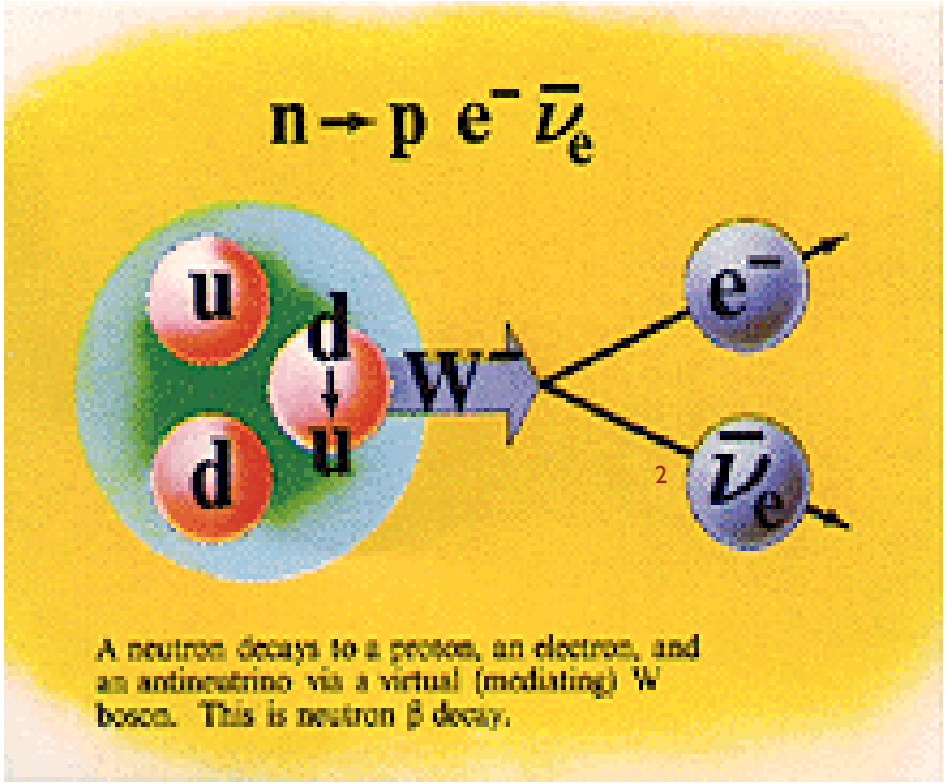


Strong nuclear force binds together protons and neutrons to form atoms nuclei

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

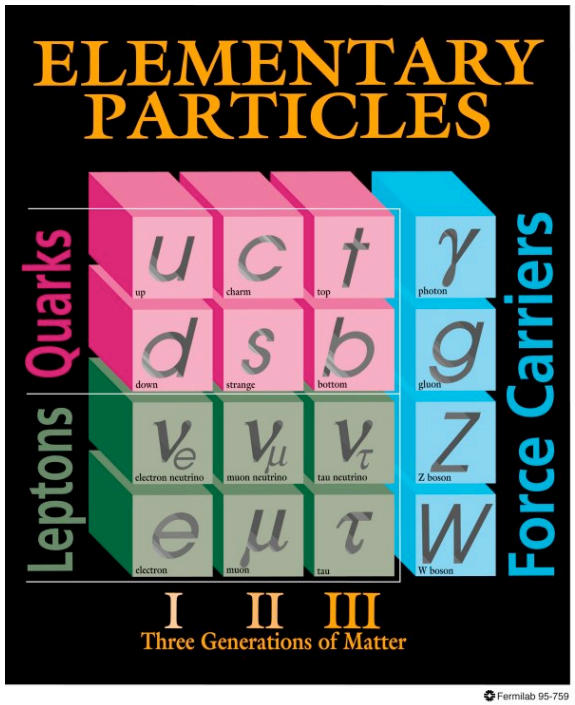
There are 12 fundamental gauge fields:

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

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

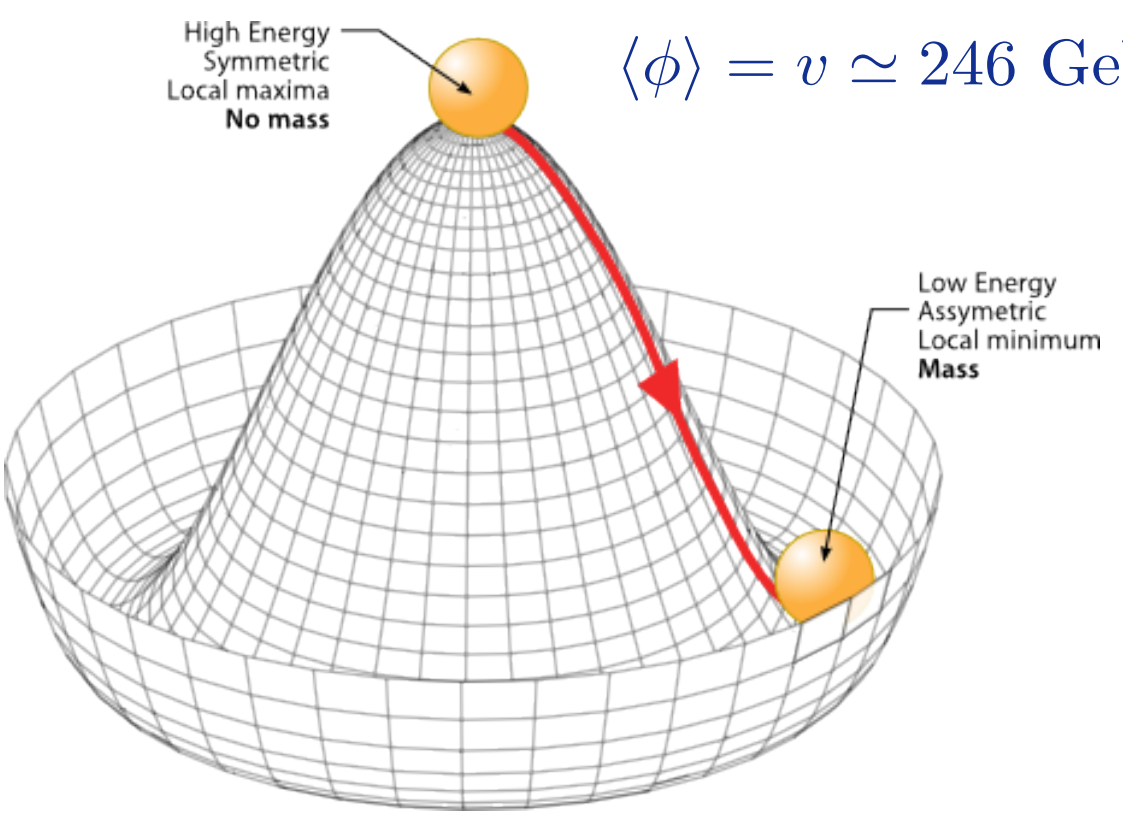
Only left handed fermions transform under the weak SM gauge group $SU(3) \times SU(2)_L \times U(1)_Y$

Fermion and gauge boson masses forbidden by symmetry

Higgs vacuum : Elementary Particle Masses

$$V(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4, \qquad m^2 < 0$$

$$\langle \phi \rangle = v \simeq 246 \text{ GeV}$$



Physical state h associated with fluctuations of ϕ, the radial mode of the Higgs field.

Higgs v.e.v. is a source of energy. Particle acquire mass through interactions with \phi.

Couplings proportional to the ratio of mass to v

$$m_f = h_f \frac{v}{\sqrt{2}}$$

$$m_W = g_2 \frac{v}{2}$$

$$m_Z = \sqrt{g_2^2 + g_1^2}\, \frac{v}{2}$$

$$m_\gamma = m_g = 0$$

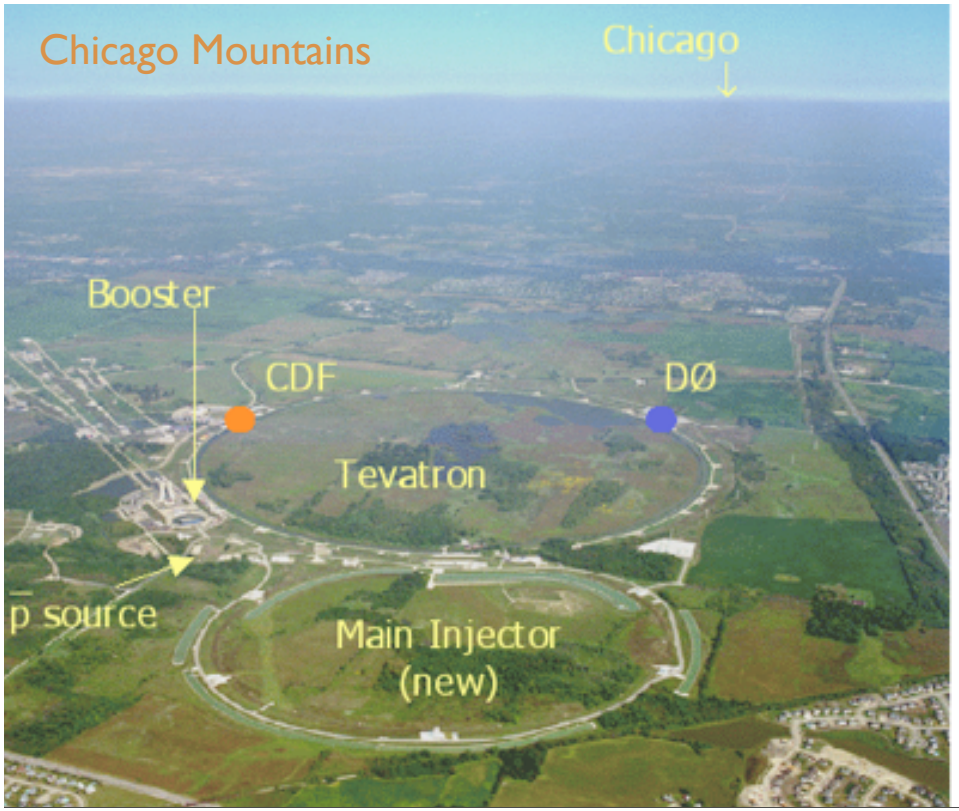
$$m_h^2 = \lambda v^2$$

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

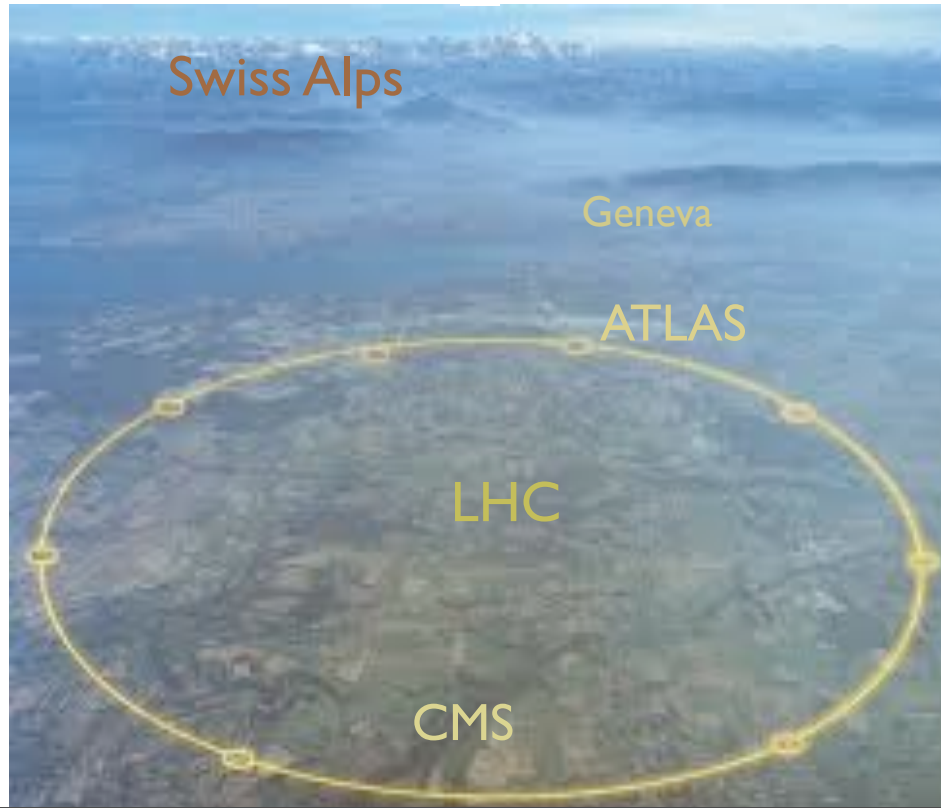
How did we search for the Higgs ?

Colliding particles at the Tevatron and the LHC

Tevatron Energy = 2,000 proton masses



LHC Energy = 8,000 proton masses



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

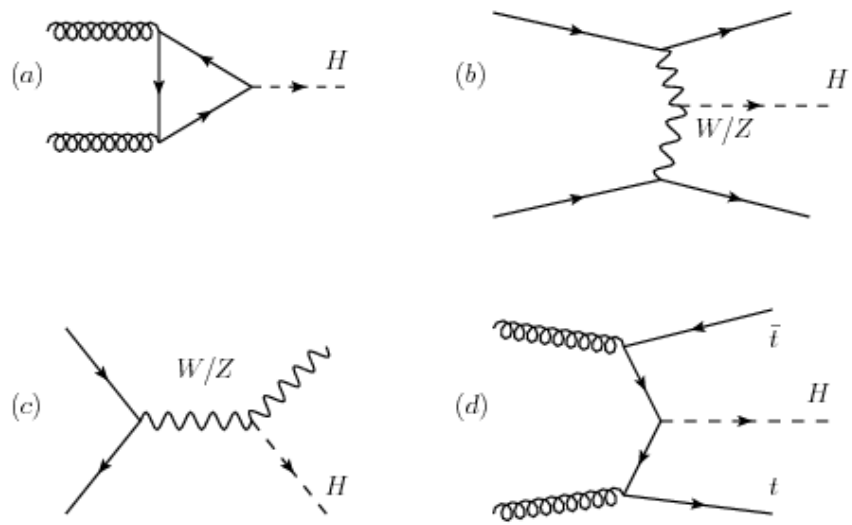
Received 7 November 1975

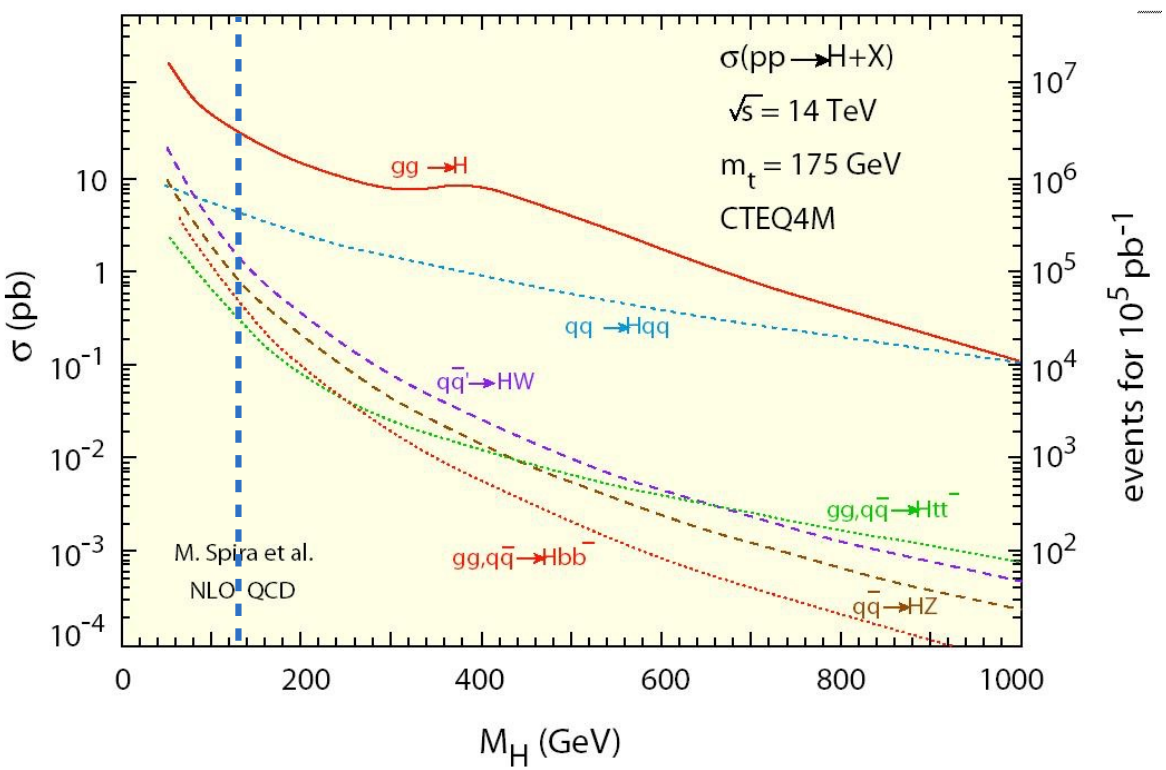
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.

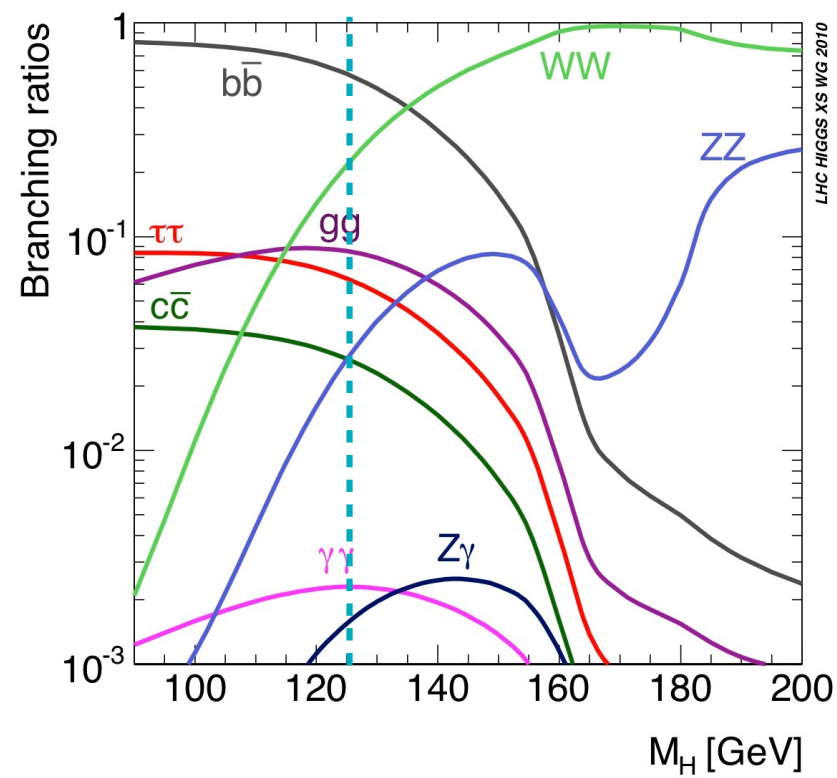
But the Higgs is not weakly coupled to all fundamental particles !

- 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 !

LHC Higgs Production Channels and Decay Branching Ratios

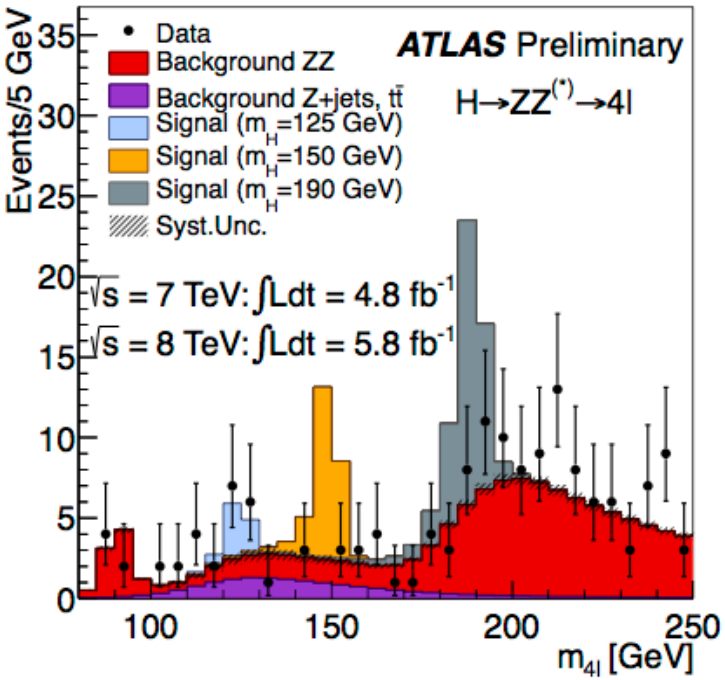


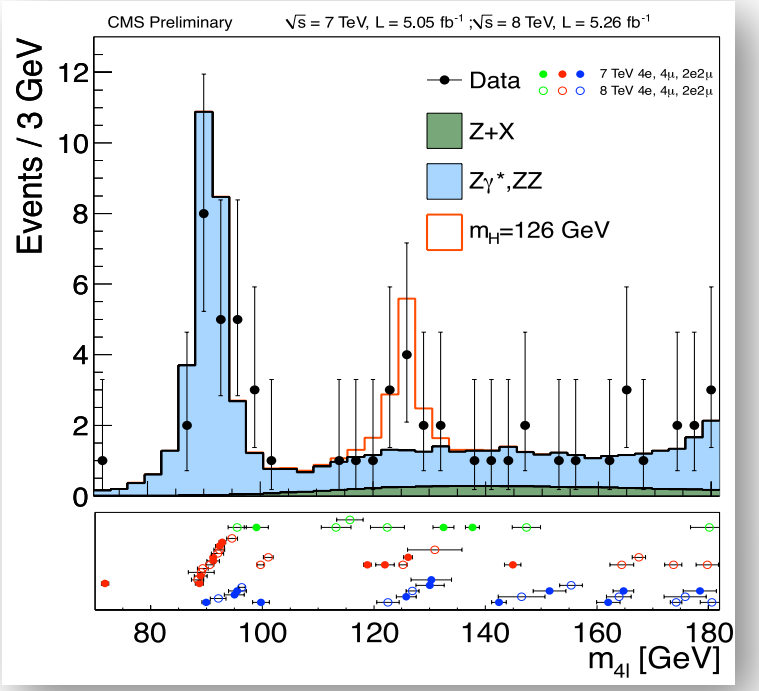




A Higgs with a mass of about 125 GeV allows to study many decay channels

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





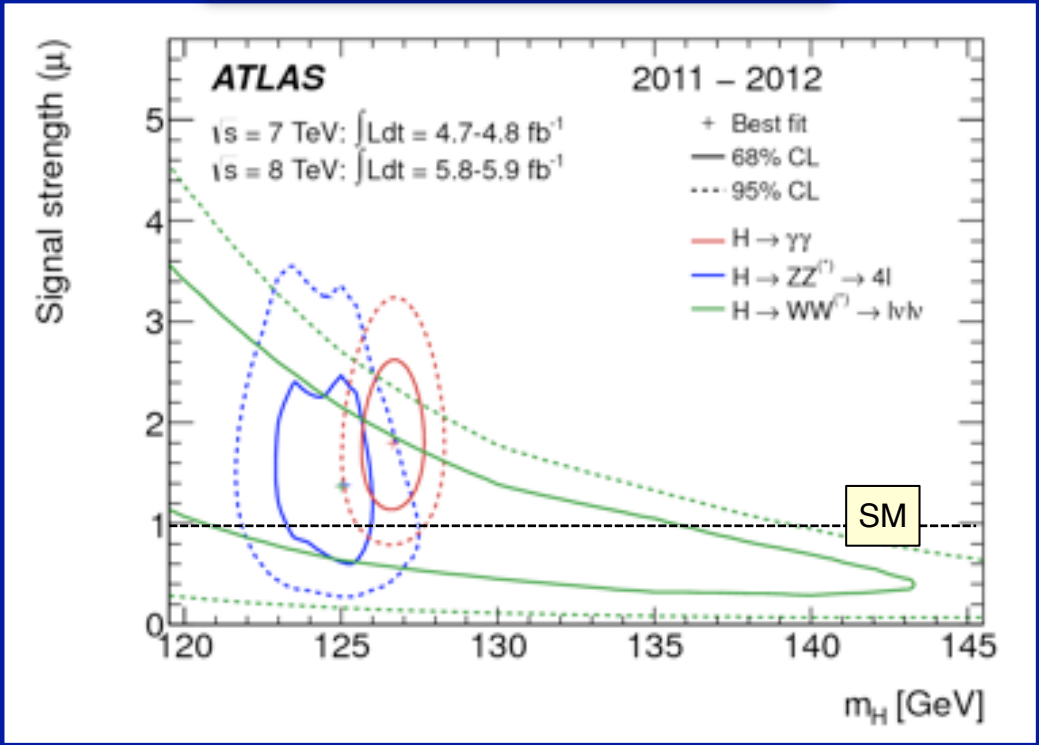
Both see an excess of ZZ events in the 125 GeV mass range. The production rate is consistent with the one expected for a 125 GeV mass Higgs.

Properties of the new state

Mass and signal strength

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

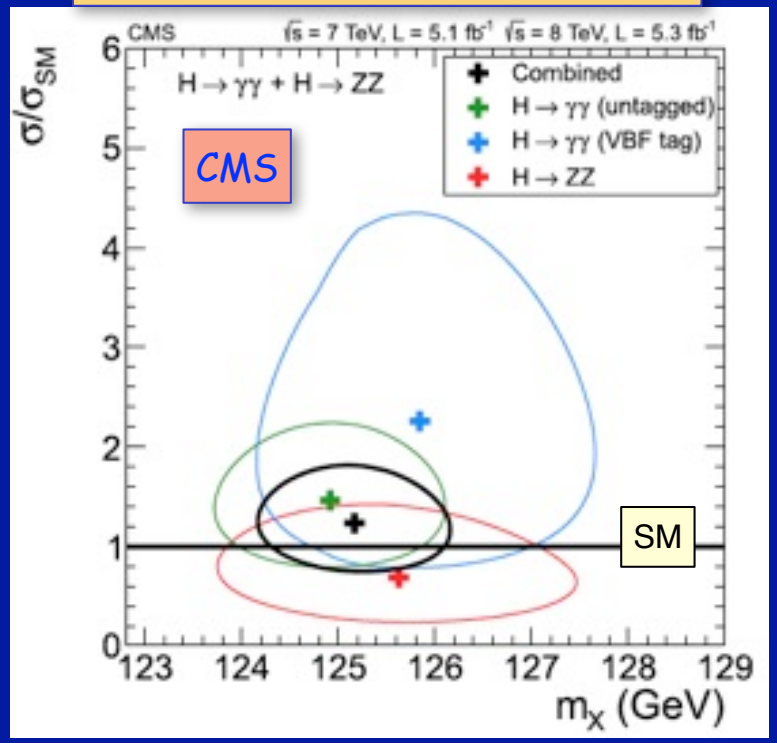
Mass = 126.0 ± 0.4 ± 0.4 GeV
σ/σ_{SM} = 1.4 ± 0.3



Observed width consistent with experimental resolution of ~ 2 GeV

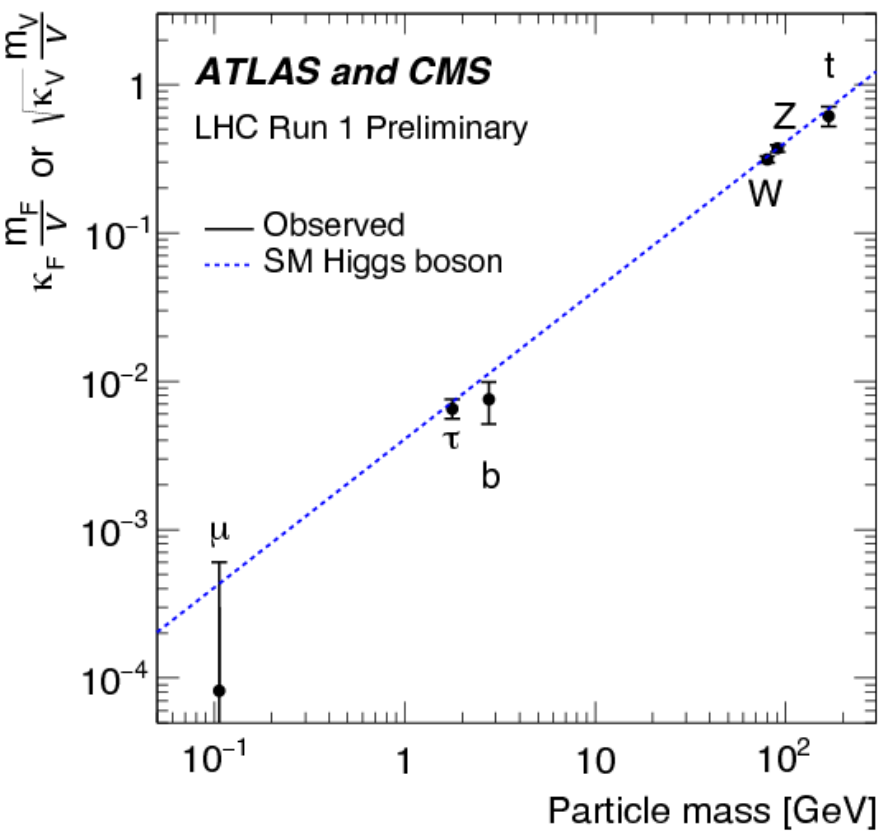
- expected width of SM Higgs ~ 4 MeV

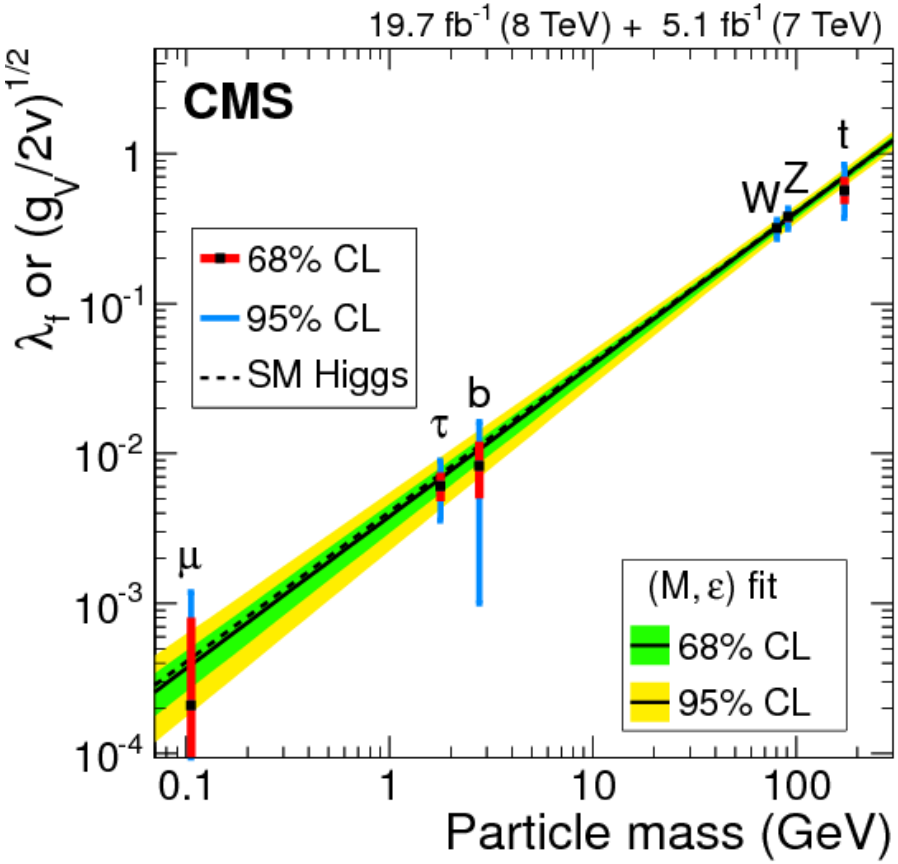
Mass = 125.3 ± 0.4 ± 0.5 GeV
σ/σ_{SM} = 0.87 ± 0.23



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

Assuming Standard Model induced couplings to photons and gluons

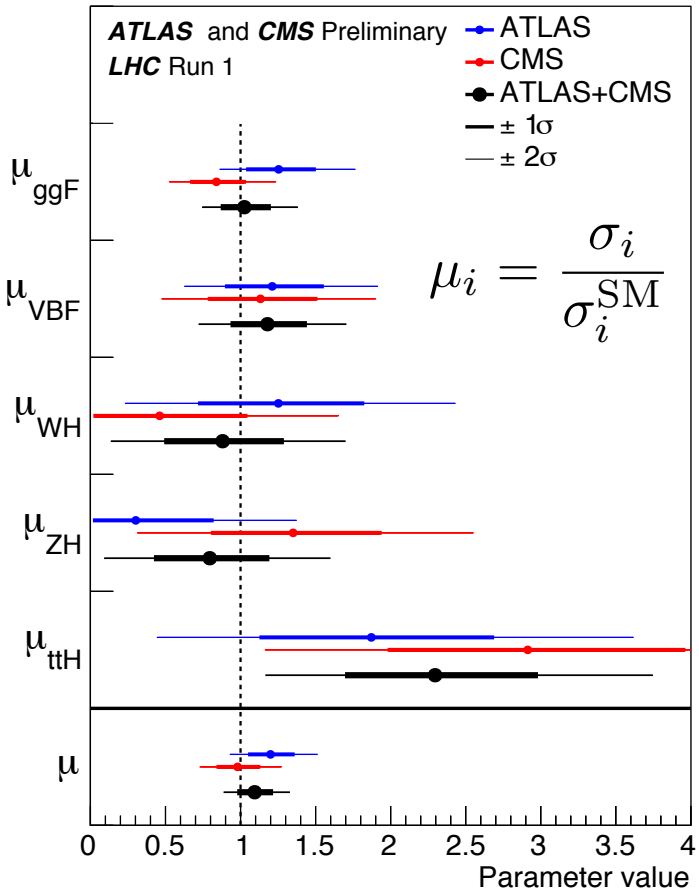


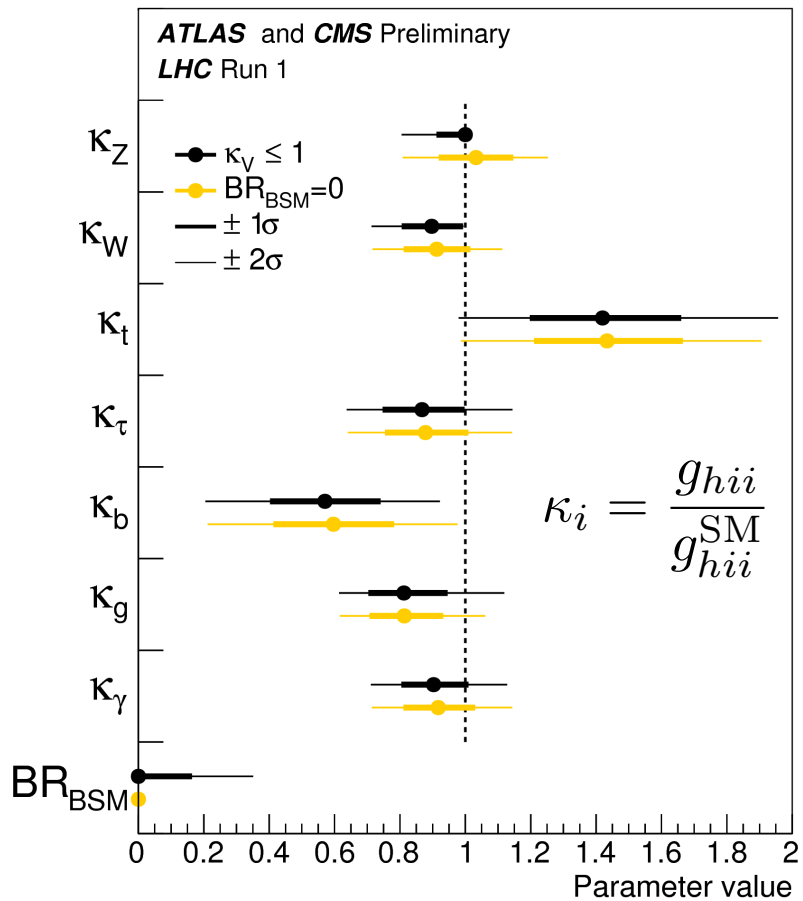


Linear correlation of masses and Higgs couplings established.
A Standard Model triumph

ATLAS and CMS Combination

Very good agreement of production rates with SM predictions





Assuming no strict correlation between gluon and top couplings

Direct Measurement of Bottom and Top Couplings subject to large uncertainties : 2σ deviations from SM predictions possible

Could this be a hint of new physics, beyond the SM ? In such a case, what ?


Now What?

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

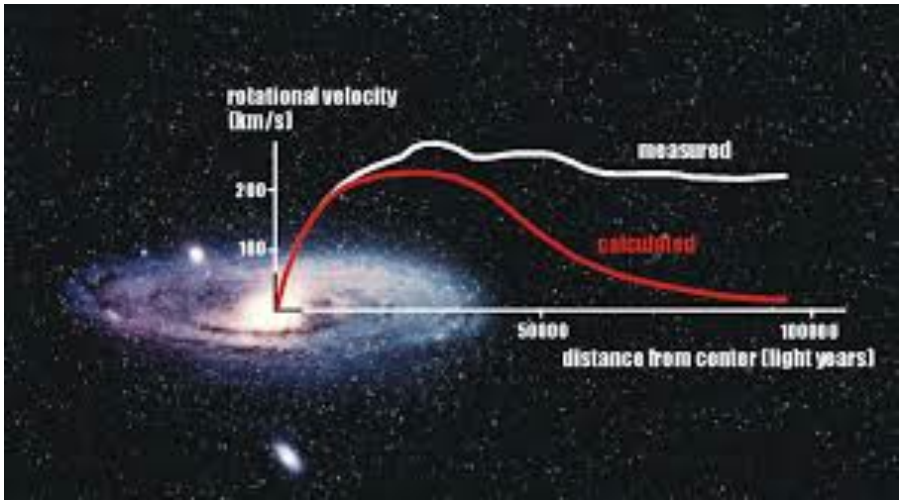
Many questions remain unanswered. Just to list some important ones :

- 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 ?

I talked about neutrinos and the matter-antimatter asymmetry in my colloquium. Let me emphasize other questions

Dark Matter and Electroweak Symmetry Breaking

Astrophysical Evidence of the Existence of Dark Matter



More mass in Galaxies than inferred from Stars and Dust

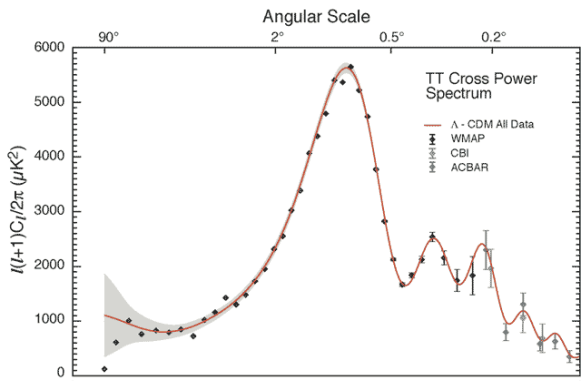
Collisionless form of Matter in Galaxies, carrying most of the Galaxies mass

Results from WMAP

Ω_i : Fraction of critical density

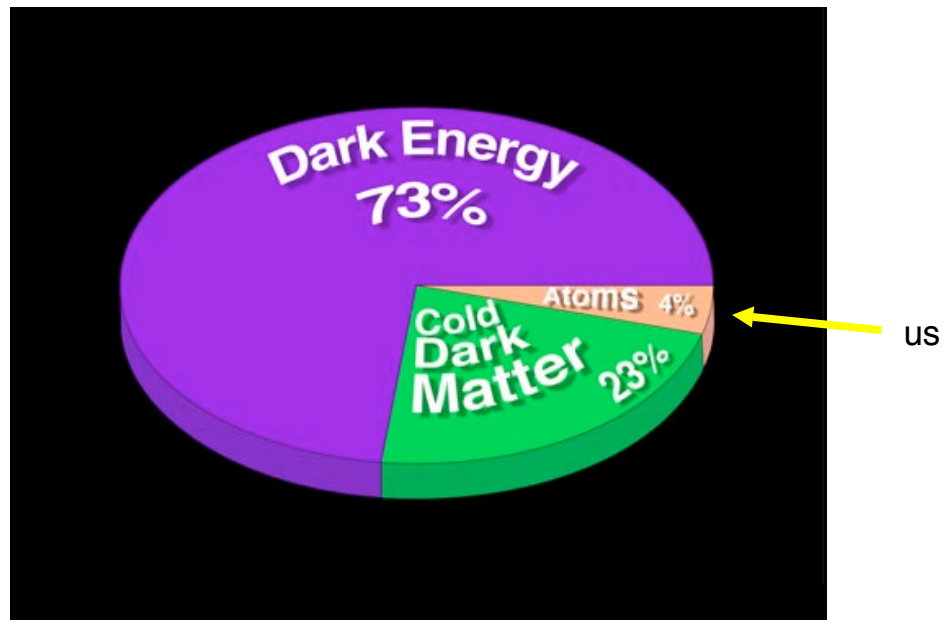
Universe density	$\Omega_0 = 1.02 \pm 0.02$
Dark energy density	$\Omega_\Lambda = 0.73 \pm 0.04$
Total matter density	$\Omega_M = 0.27 \pm 0.05$
Baryon matter density	$\Omega_b = 0.044 \pm 0.004$

→ 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:



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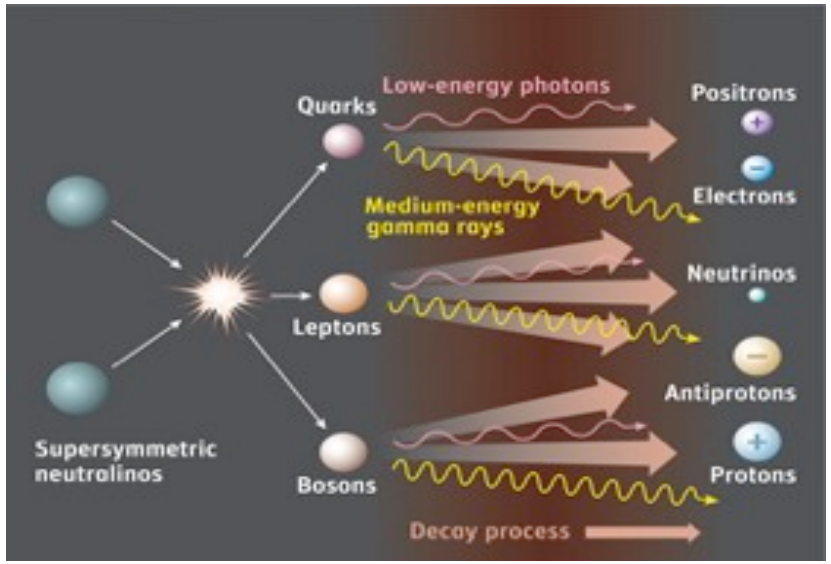
None of the SM particles satisfy the DM properties

- 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.

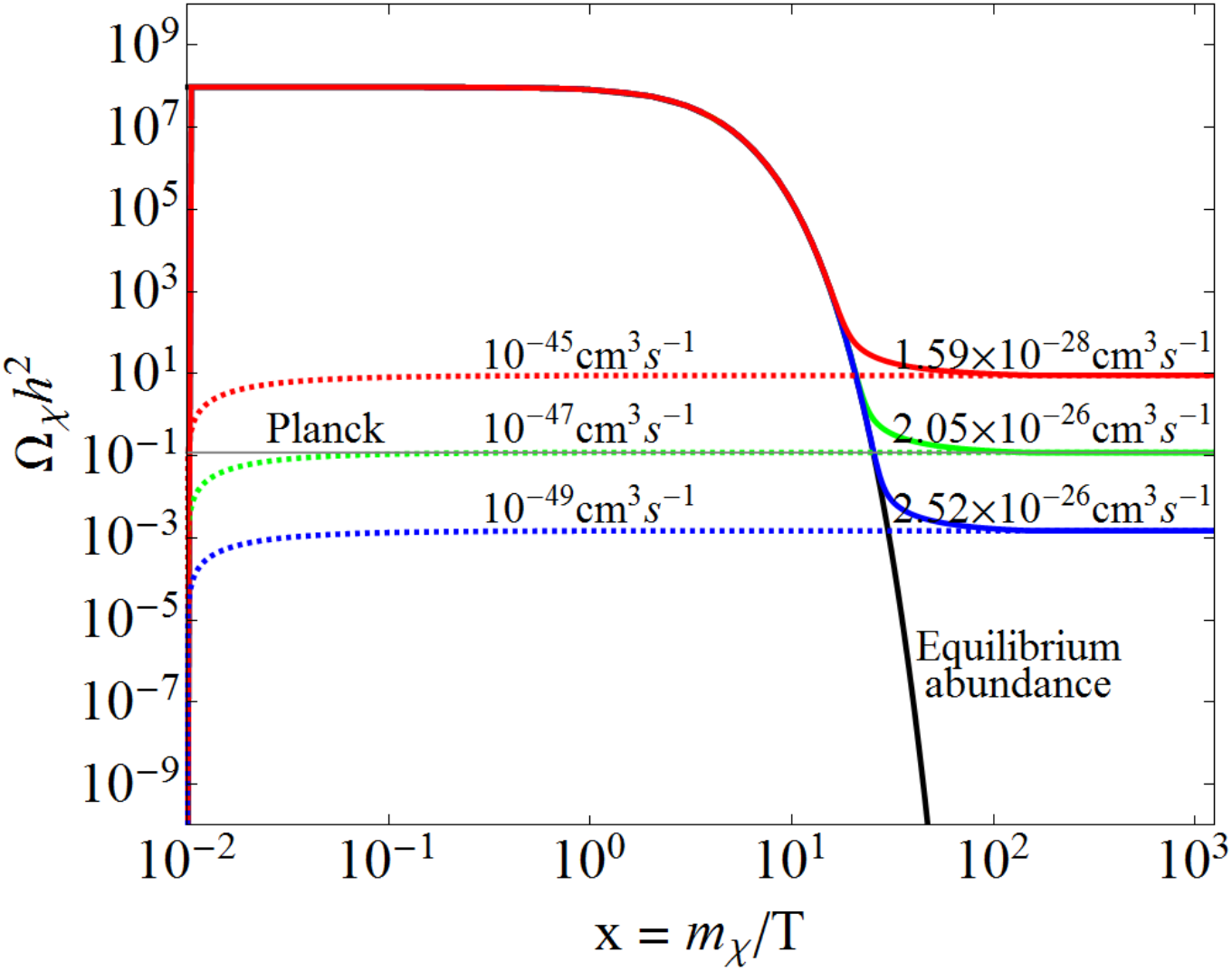
- Stable particles annihilate until the expansion of the Universe makes their encounter extremely rare

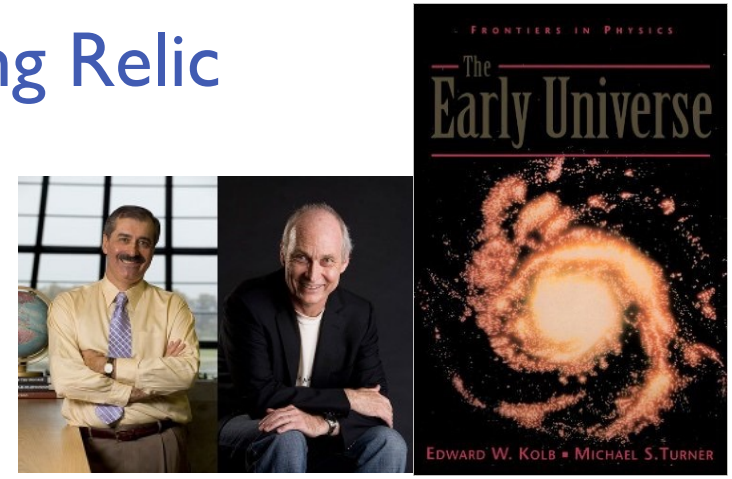


- Observed DM Density : DM are WIMPS (weakly interacting massive particles)

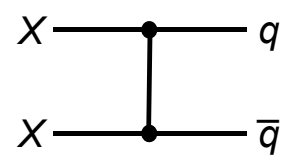
Kolb and Turner

Dark Matter as a Big Bang Relic





$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

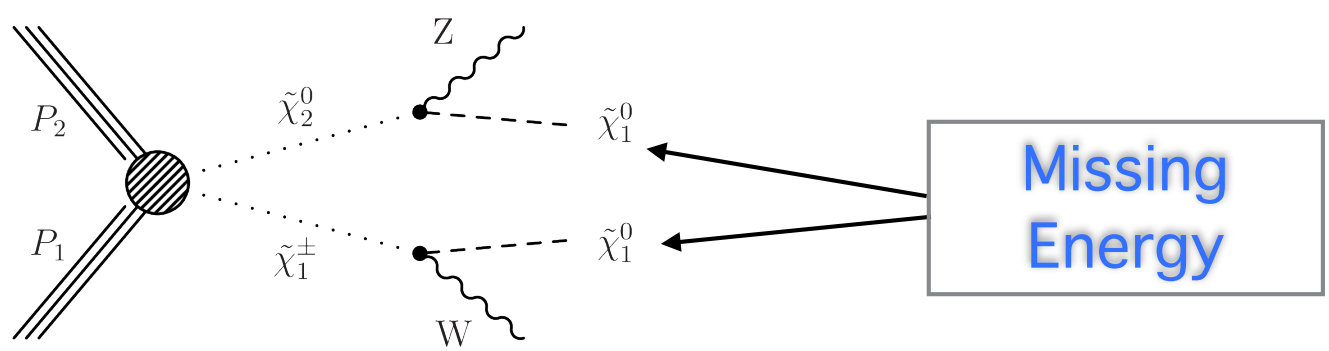


$m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

Weak scale size masses and couplings roughly consistent with Ω

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.



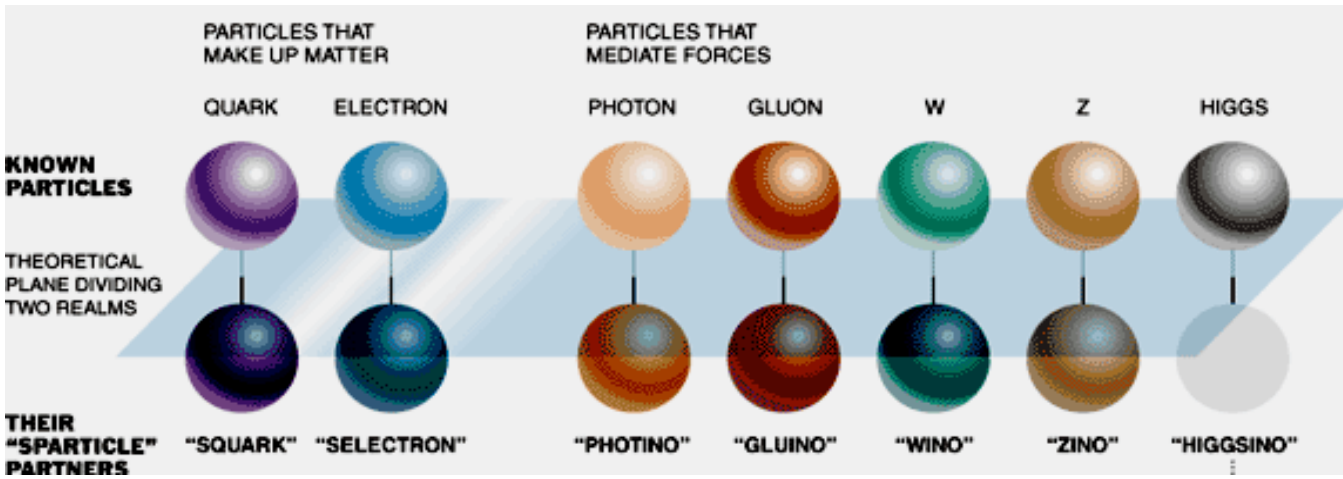
What lies ahead ?

- 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 ?
- Or should we modify gravity ?

Many alternatives proposed. None of them verified.
New ideas necessary ?

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: $\delta\, m_H^2 \approx (-1)^{2\,S_i}\, \frac{n_i\, g_i^2}{16\pi^2}\, \Lambda$

- 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.

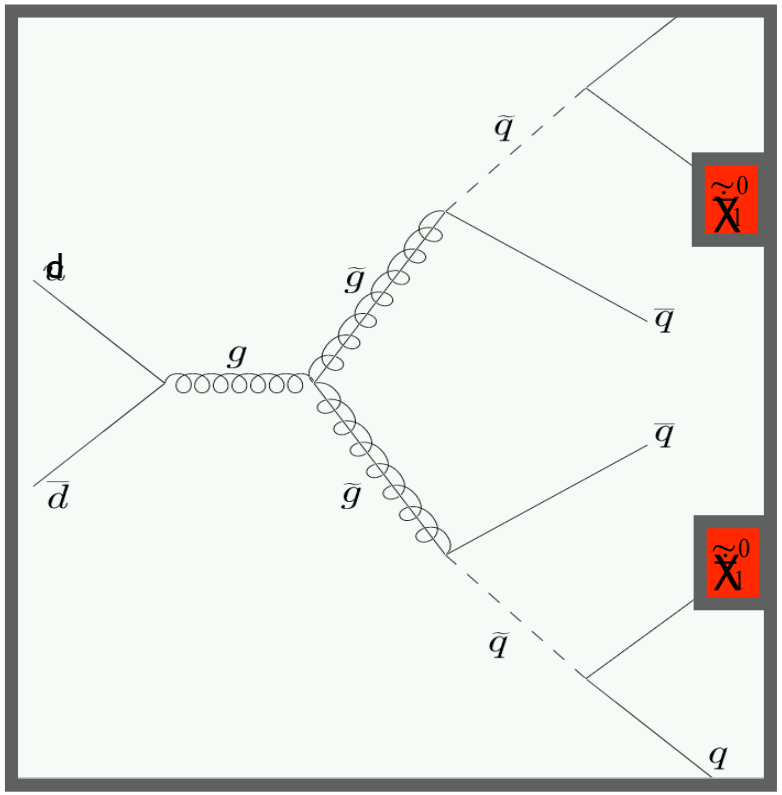
- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

- 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.

MOND
(Modified Newton Dynamics)

Modified gravity ?

- Milgrom discovered that, when you study the rotation curves of stars around the center of galaxies, Newton law started to be violated not at a given radius, but at a given acceleration

- He speculated that then the force of gravity should be the standard Newton law (GR) at large accelerations, but behave differently at small accelerations, namely

$$|\vec{F}| \propto \frac{1}{r^2}, \quad \text{at} \;\; |\vec{a}| \geq a_0$$

$$|\vec{F}| \propto \frac{1}{r} \quad \text{at} \;\; |\vec{a}| < a_0$$

- Hard to construct a consistent theory that incorporate this idea, which has some phenomenological successes, but does not replace DM as a successful description of all data.

- Interestingly enough, the value of $a_0 \simeq cH_0$

The weakness of gravity

Lowering the Planck Scale

- Idea: We live in a four dimensional wall, but there are extra dimensions and only gravity can penetrate into them.
- Problem: If gravity can penetrate intro the extra dimensions, Newton law will be modified

$$\vec{F} = \frac{m_1 m_2 \hat{r}}{\left(M_{Pl}^{\rm fund}\right)^{2+d} r^{2+d}}$$

- $M_{Pl}^{\rm fund}$ = Fundamental Planck Scale. Behaviour valid for $r \ll R$. For $r \gg R$, instead

$$\vec{F} = \frac{m_1 m_2 \hat{r}}{\left(M_{Pl}^{\rm fund}\right)^{2+d} r^2 R^d}$$

- Hence,

$$M_{Pl}^2 = \left(M_{Pl}^{\rm fund}\right)^{2+d} R^d$$

Arkani-Hamed, Dimopoulos, Dvali'98

Size of flat Extra Dimensions

- Let's assume that the fundamental Planck scale is of the order of 1 TeV, to solve the hierarchy problem.

$$M_{Pl}^2 = (1\text{TeV})^{2+d}\, R^d$$

- Then, the value of R is given by

$$R = 10^{32/d} 10^{-17}\text{cm}$$

- For $d = 1$ we get $R = 10^{15}$ cm $\rightarrow$ Excluded
- For $d = 2$ we get $R \simeq 1$ mm $\rightarrow$ Would demand somewhat larger fundamental Planck scale
- For $d = 6$ we get $R \simeq 10^{-12}$ cm.
- The scenario is allowed for $d \geq 2$

How can we probe ED from our 4D wall (brane)?

Flat case ($k = 0$) : 4-D effective theory:

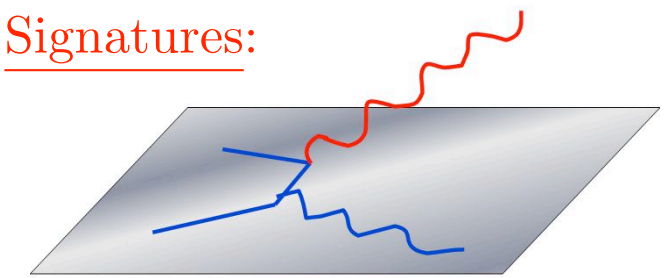
SM particles + gravitons + tower of new particles:

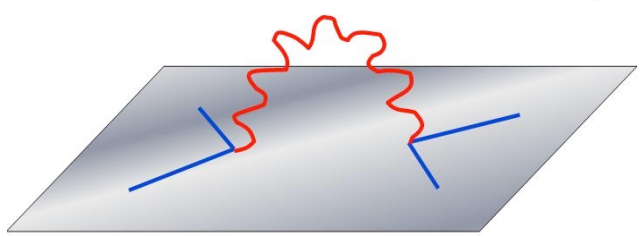
Kaluza Klein (KK) excited states with the same quantum numbers as the graviton and/or the SM particles

Mass of the KK modes $\Longrightarrow$ $E^2 - \vec{p}^2 = p_d^2 = \sum_{i=1,d} \frac{n_i^2}{R^2} = M^2_{G_{\vec{n}}}$

imbalance between measured energies and momentum in 4-D

Signatures:





- Coupling of gravitons to matter with $1/M_{Pl}$ strength
  $R^{-1} \simeq 10^{-2}$ GeV $(d = 6)$;
  $1/R \simeq 10^{-4}$ eV $(d = 2)$;

(a) Emission of KK graviton states: $G_n \Leftrightarrow \not{E}_T$
(gravitons appear as continuous mass distrib

(b) Graviton exchange $2 \to 2$ scattering
deviations from SM cross sections

Proton Stability

Grand Unified Theories: SU(5), SO(10), E_6…

<u>Explain</u>: Electric Charge-Color Quantization

$g^0_3 = g^0_2 = g^0_1 = g^0_{GUT}$ For $SU(3)_c x SU(2)_L x U(1)_Y$

$\sin^2\theta^0_W = 3/8$

<u>Quarks & Leptons</u>: 3 Mixed Families

10 + 5* + 1 of SU(5), 16 of SO(10), 27 of E_6

Provide a natural extension of the Standard Model

Easily include (suggest) supersymmetry

Superstring connection

<u>Part of the Particle Physics Vernacular</u>

Minimal SU(5) GUT

Quarks and leptons belong to

$$\{10 + \overline{5} + 1\}$$

$$\mathbf{10} : \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}$$

$$\overline{\mathbf{5}} : (d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

$$\mathbf{1} : \nu^c$$

24 gauge bosons of SU(5) contain the 8 gluo

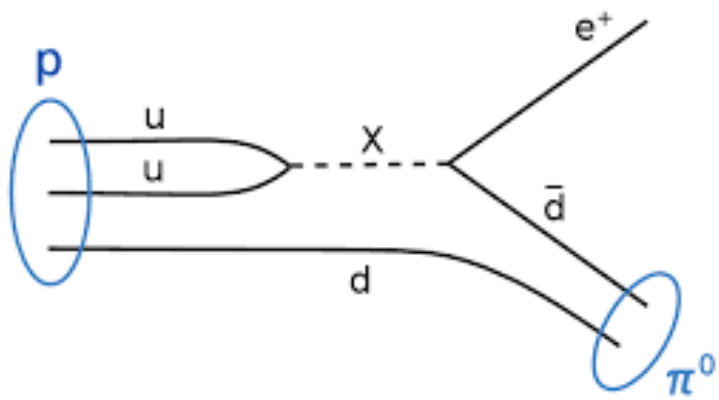
Z^0, γ, and two new sets of particles, (X, Y)

$(X, Y) \sim (3, 2, -5/6)$ under $SU(3)_c \times SU(2)_L \times U$

(X, Y) have diquark couplings and leptoquark c

$\Rightarrow$ proton decay induced by (X, Y)

$p \to e^+ \pi^0$



(X, Y) must be super-neavy

The Fate of the Hydrogen gas

- Hydrogen atom : P + e

- If proton decays into a pion and a positron

$$P \to \Pi^0 + e^+$$

- But then, the positron eventually annihilates with electrons and the pion decays into photons

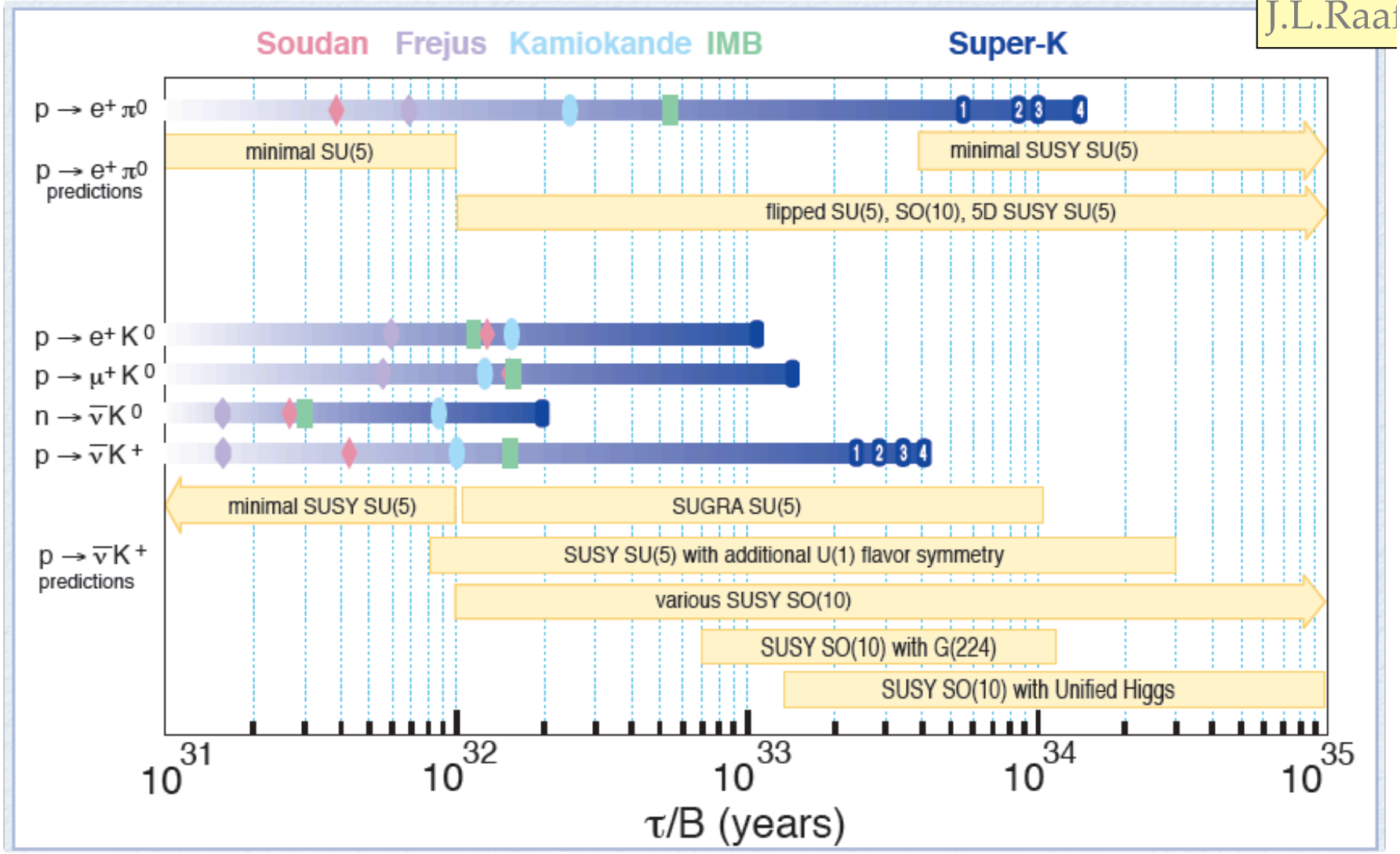
$$\Pi^0 \to \gamma\gamma\,, \qquad e^+ + e^- \to \gamma\gamma$$

- The whole gas is converted to photons !

- We came from radiation, and we will become it again !

EXPERIMENTS & PREDICTION

J.L.Raaf



Final Remarks

- In my talk I covered some of the open questions and proposed solutions.
- The question of unification includes the incorporation of gravity and its eventual quantization.
- Many theoretical ideas continuously proposed to solve phenomenological and conceptual problems. I mentioned some, like supersymmetry, extra dimensions and grand unification. Many other frameworks exist, but nothing beyond the Standard Model has been yet verified to exist.
- Some ideas, like the Higgs mechanism to generate particle masses seems to work, but generate other questions. For instance, what is the nature of the Higgs field ? How is it connected to Dark Energy ?
- Progress will be obtained by a combination of novel ideas with original experiments. Perhaps the proper marriage of quantum mechanics and general relativity is the clue.
- Do we need to understand better the physics of black holes ? Or is progress related to clues present in current data ?

Your help is welcome !