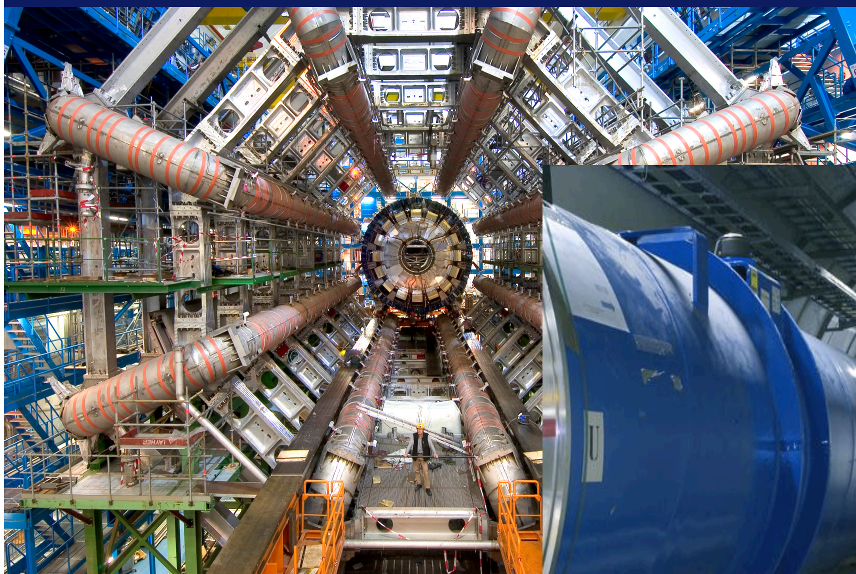
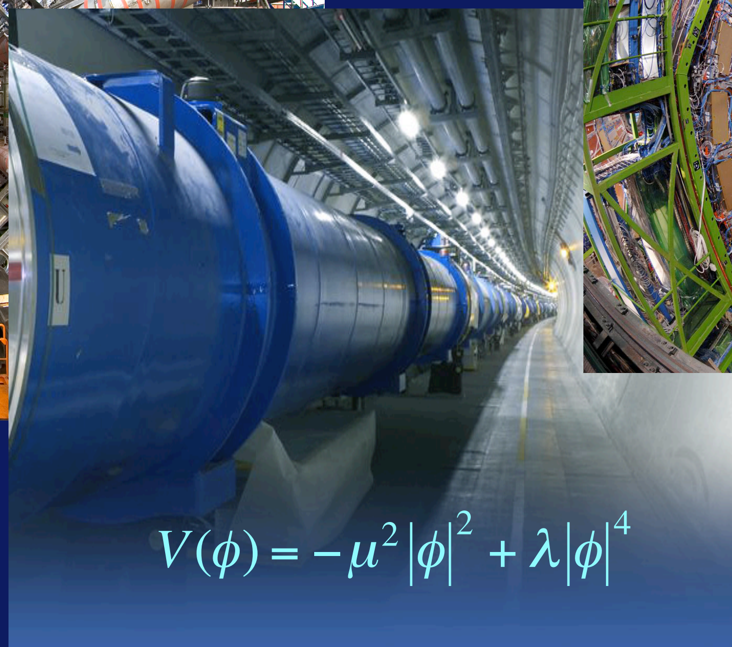
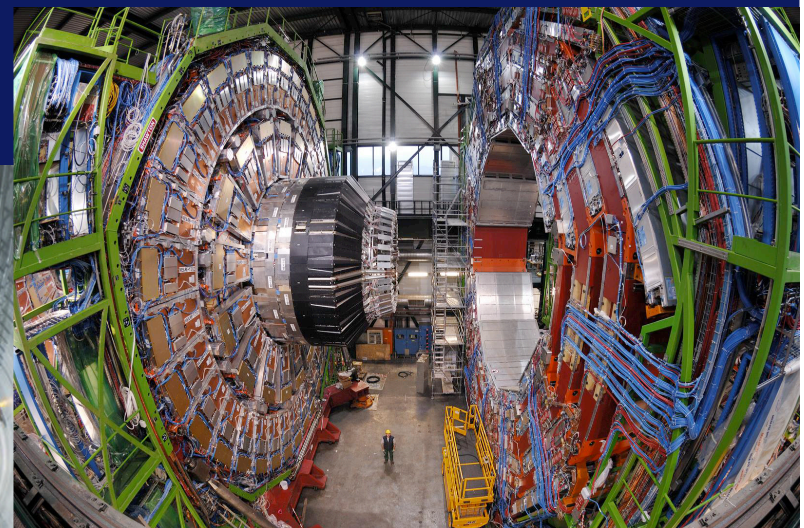
Lectures on Higgs Boson Physics
The Standard Model and Supersymmetry





$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$



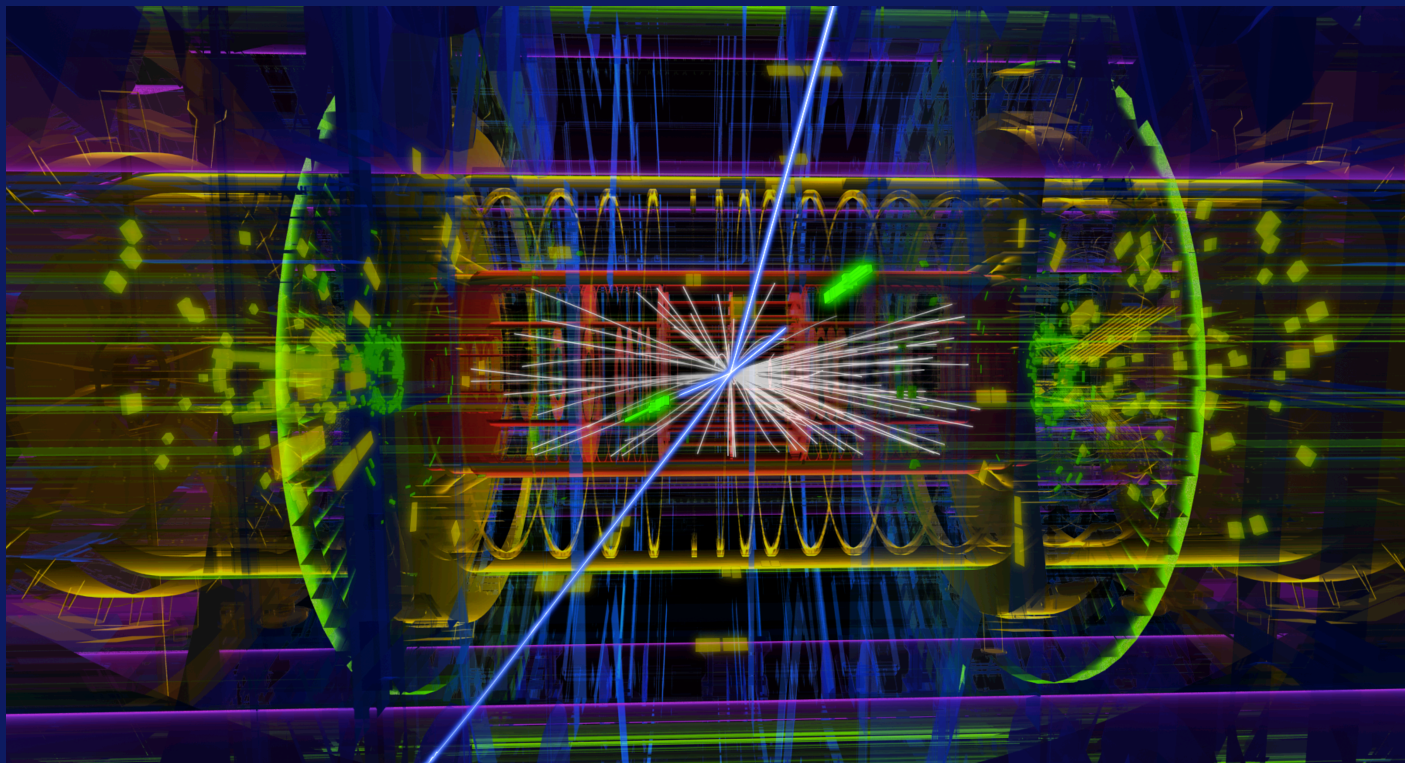
Marcela Carena

Fermilab and U. of Chicago

Pre-SUSY 2015

UC Davis, August 18, 2015

Fireworks on 4th July 2012



- Discovery of a new particle, of a type never seen before
- Confirmation of a new type of interaction among particles

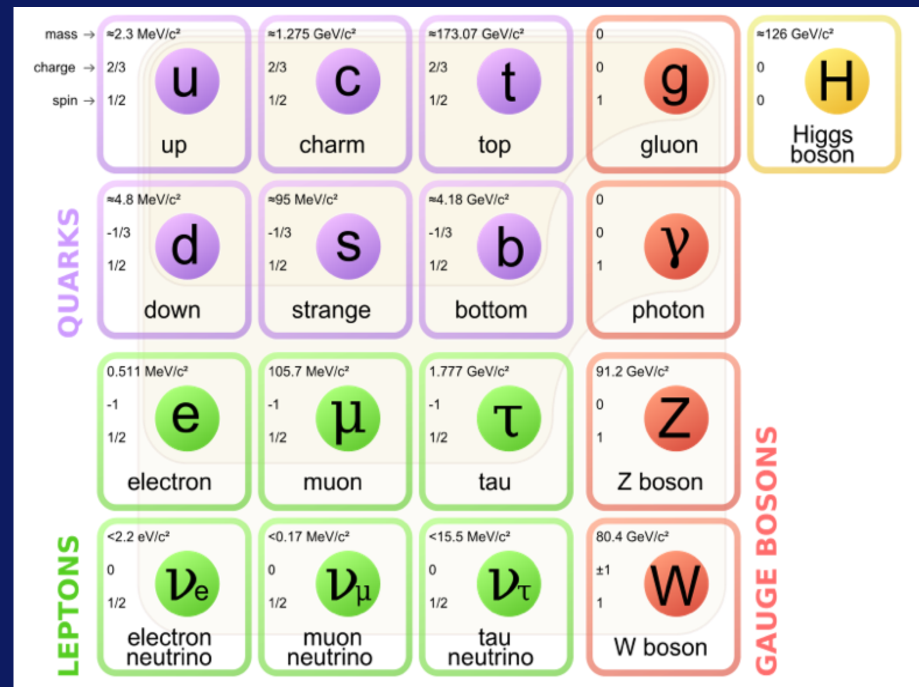
A new era of particle physics and cosmology

The Standard Model

A quantum theory that describes how all known fundamental particles interact via the strong, weak and electromagnetic forces

based on a gauge field theory
with a symmetry group

$$G = SU(3)_c \times SU(2)_L \times U(1)_Y$$



Force Carriers:

12 fundamental gauge fields:

8 gluons, 3 Wμ 's and Bμ

and 3 gauge couplings: g_3, g_2, g_1

Matter fields :

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

Quarks come in three colors ($SU(3)_C$)

The Standard Model Particles: Quantum Numbers

- Quarks transform in the fundamental representation of SU(3).
- Left-handed quarks Q_L in the fundamental representation of SU(2), carrying Y= 1/6
- Right-handed quarks u_R and d_R are singlets under SU(2) with Y = 2/3 and -1/3
- Left-handed leptons L_L transform in the fundamental of SU(2) with Y = -1/2
- Right-handed leptons l_R and ν_R are singlets under SU(2) with Y = -1 and 0
- The three generations of fermions have very different masses, provided by the Higgs field

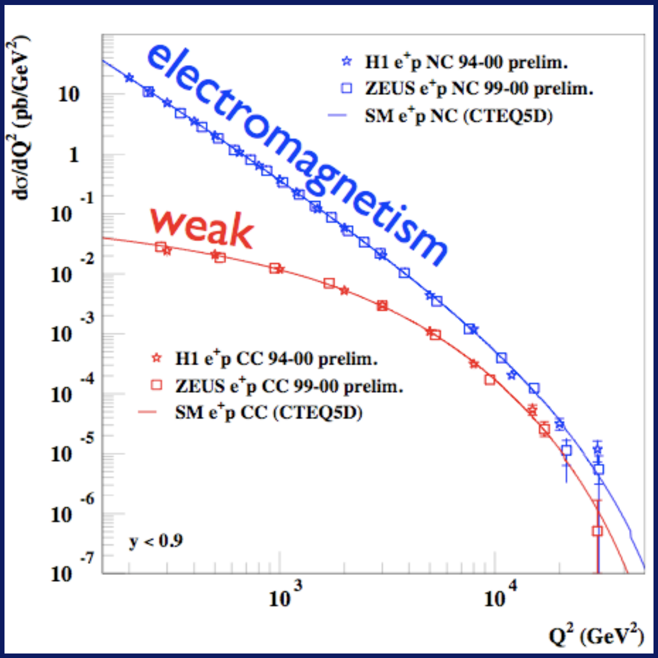
Fermions, with the possible exception of neutrinos, form Dirac particles, with equal charges for left and right-handed chiralities.

- Eight SU(3) gauge bosons ➔ gluons

A massive charge gauge boson, $W_\mu^\pm$ and a massive neutral gauge boson, Z_μ.

- A scalar field, with Y= 1/2 transforming in the fundamental representation of SU(2). Only one physical d.o.f., the neutral Higgs Boson.

The Standard Model



Electroweak gauge group ➔ $SU(2)_L \times U(1)_Y$

At low energies, only electromagnetic gauge symmetry is manifest:

$SU(2)_L \times U(1)_Y$ spontaneously broken to $U(1)_{em}$

3 $W\mu$'s + $B\mu$ → massive $W^{+-}$and Z, massless γ

Strong SU(3)c is unbroken ➔ massless gluons

At large distances: confinement (no free quarks in nature)

EW Symmetry Breaking occurs at a scale of O(100 GeV)

What breaks the symmetry?

And gives mass to W, Z ?

And to the fermions?

Mass Terms for the SM gauge bosons and matter fields

- Gluons and photons are massless and preserve gauge invariance

- Z and W bosons are not, but a term $L_M = m^2 V_\mu V^\mu$ is forbidden by gauge invariance

- Mass term for fermionic matter fields $\mathcal{L}_M = -m_D \; \bar{\psi}_L \psi_R + h.c.$

only possible for vector –like fermions, not for the SM *chiral* ones, *when Left and Right handed fields transform differently*

The symmetries of the model do not allow to generate mass at all!

SM gauge bosons and fermions should be massless,

THIS contradicts experience!

Why is the Higgs so important?

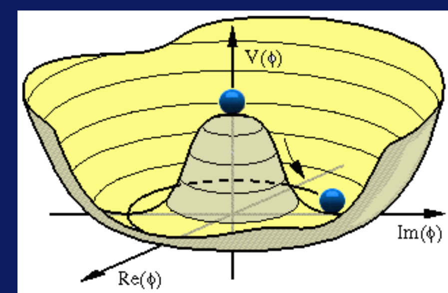
In the SM the Higgs Mechanism causes the fundamental particles to have mass

A fundamental scalar field with self interactions

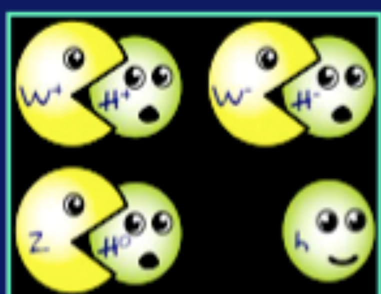
$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

can cause Spontaneous Symmetry Breaking (SSB) in the vacuum without picking a preferred frame or direction, and give mass to the gauge bosons

The global minimum defines the vacuum



Matter fields also get mass from new type of interactions with the Higgs field



A new massive scalar particle appears in the spectra
The Higgs Boson

Heavier particles interact more with the Higgs boson

Spontaneous Symmetry Breaking of Continuous Symmetries

- Occurs when the vacuum state is not invariant under a symmetry of the Hamiltonian

$$[S, H] = 0; \qquad S\,|\Omega\rangle \neq |\Omega\rangle$$

- Take a symmetry group with generators T_a and a set of real fields Φ^i transforming under some representation group G, with dimension d(G) = n; n generators

$$\phi_i(x) \to \phi_i(x) + i\,\epsilon^a T^a_{ij}\phi_j(x)$$

- Scalar potential such that the scalar fields acquire vacuum expectation value (ground state)

$$< \phi_i >= v_i$$

Once a given state is chosen, out of the infinite vacuum states associated to the symmetry, the continuous symmetry is spontaneously broken (the original symmetry is hidden)

- Since the potential is invariant under the transformations, for all the fields one has:

$$\delta \mathbf{V} = \frac{\partial \mathbf{V}}{\partial \phi_\mathbf{i}} \delta\phi_\mathbf{i} = \mathbf{i}\epsilon^\mathbf{a}\mathbf{T}^\mathbf{a}_\mathbf{ij}\phi_\mathbf{j} = \mathbf{0} \quad \longrightarrow \quad \frac{\partial^2 \mathbf{V}}{\partial\phi_\mathbf{i}\partial\phi_\mathbf{k}}\mathbf{T}^\mathbf{a}_\mathbf{ij}\phi_\mathbf{j} + \frac{\partial \mathbf{V}}{\partial \phi_\mathbf{i}}\mathbf{T}^\mathbf{a}_\mathbf{ik} = \mathbf{0}$$

- At the minimum, the second term vanishes & the first one is proportional to the mass matrix.

SSB and the Goldstone Theorem

- If the theory is invariant under a continuous symmetry the following condition must be fulfilled

$$\mathbf{M^2_{ki} T^a_{ij} v_j = 0}$$

- If $\delta\phi_i|_{v_j} = i\epsilon T^a_{ij} v_j = 0$ the symmetry is respected by the vacuum state since the transformation leaves $<\Phi_i>$ unchanged and the above condition is trivially fulfilled
- However, if there is SSB ➔ the vacuum state is not invariant, then the above condition implies the existence of massless Goldstone modes

More specifically:

Assume there is a subgroup G' with n' generators such that

$T^b_{ij}\, v_j = 0$ for b = 1,2,...n', hence the G' symmetry is respected

and $T^c_{ij}\, v_j \neq 0$ for c = n'=1, ….n ⟶ broken generators

Since the generators are linearly independent

$$\mathbf{M^2_{ki} T^a_{ij} v_j = 0 \to n - n'} \text{ massless modes}$$

- There will be n-n' massless Nambu-Goldstone Bosons, one per each generator of the spontaneously broken continuous symmetry of the group G.

We do not see such massless modes though

Gauge Theories

- Theorem no longer valid if there is a gauge symmetry
- The gauge symmetry defines the equivalency of all vacua related by gauge transformations. One can always fix the gauge, eliminating the massless Goldstone modes from the theory.
- Something else happens:

  A local gauge symmetry requires the existence of a massless vector field (gauge boson) per symmetry generator. BUT, in the presence of SSB, the gauge bosons associated with the broken generators acquire mass proportional to the gauge couplings and the vev.

The Higgs mechanism in action:

- Consider again a set of scalar fields transforming under some general representation of the group G, of dimension n, and again take a field that has a nontrivial v.e.v.
- Promote the symmetry group G to a local gauge symmetry, then

$$(\mathcal{D}\phi)^\dagger \mathcal{D}\phi \to \mathbf{g^2 A^a_\mu A^{\mu b}} (\mathbf{T^a}\phi^*)_\mathbf{i} (\mathbf{T^b}\phi)_\mathbf{i} = \mathbf{g^2 A^a_\mu A^{\mu b}} \phi^*_\mathbf{j} \mathbf{T^a_{ji} T^b_{ik}} \phi_\mathbf{k}$$

Taking for simplicity real v.e.v.'s, $<\Phi_i>= v_i/\sqrt{2}$, the above expression may be rewritten as

$$\frac{1}{2} A^a_\mu A^{\mu,b} \mathcal{M}^2_{ab} \quad \text{with} \quad \mathcal{M}^2_{ab} = g^2 \left(T^a_{ij} v_i\right) \left(T^b_{jk} v_k\right) \quad \rightarrow \quad \frac{\mathbf{g^2 v^2}}{\mathbf{8}} \mathbf{A^a_\mu A^{\mu a}}$$

There is precisely one massive gauge boson per "broken" generator! The Goldstone modes are replaced by the new, longitudinal degrees of freedom of the massive gauge fields.

The Glasgow-Weinberg-Salam Theory (SM) of EW interactions

- The Standard Model is an example of a theory invariant under a non-simple group, namely SU(3) x SU(2) x U(1). The SU(3) generators are not broken (the gluons remain massless).

- Consider SU(2) x $U(1)_Y$ => $\Phi \to e^{i\alpha^a T^a} e^{i\beta/2}\Phi$ with $T^a = \sigma^a/2$ and Y =1/2

  If $\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$, a transf. with $\alpha_1=\alpha_2=0$; $\alpha_3=\beta$ leaves <Φ> invariant

  and there will be a massless gauge boson

- Previous expressions can be generalized associating to each generator the corresponding gauge coupling.

$$\mathcal{D}_\mu \phi = \left(\partial_\mu - igA^a_\mu T^a - ig'YB_\mu\right)\phi$$

Using symmetry properties and $\{\sigma_a, \sigma_b\} = \delta_{ab},\ \{\sigma_a, I\} = 2\sigma_a,\ \{I, I\} = 2$

now the mass Matrix may be rewritten as

$$\mathcal{M}^2_{ab} = \frac{g^2v^2}{4}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -g'/g \\ 0 & 0 & -g'/g & g'^2/g^2 \end{pmatrix}$$

Det $M^2 = 0$ → one zero eigenvalue

2 eigenvalues $M^2_W = \frac{g^2v^2}{4}$

One eigenvalue $M^2_Z = \frac{(g'^2 + g^2)v^2}{4}$

Mass Eigenstates and Couplings

- The mass terms in the Lagrangian read: $\mathcal{L}_M = \frac{1}{2}\frac{v^2}{4}\left[g^2\left(A_\mu^1\right)^2 + \left(A_\mu^2\right)^2 + \left(gA_\mu^3 - g' B_\mu\right)^2\right]$
- Defining the states $W_\mu^\pm = \frac{1}{\sqrt{2}}\left(A_\mu^1 \mp iA_\mu^2\right), \quad Z_\mu = \frac{gA_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}}$
- The Lagrangian can now be written as: $\mathcal{L}_M = \frac{g^2 v^2}{4} W_\mu^+ W^{\mu,-} + \frac{1}{2}\frac{\left(g^2 + (g')^2\right)v^2}{4} Z_\mu Z^\mu$
- A massless mode, the photon, remains in the spectrum $A_\mu = \frac{g' A_\mu^3 + gB_\mu}{\sqrt{g^2 + (g')^2}}$
- It is useful to write the covariant derivative in term of mass eigenstates:

$$\mathcal{D}_\mu = \partial_\mu - i\frac{g}{\sqrt{2}}\left(W_\mu^+ T^+ + W_\mu^- T^-\right) - i\frac{\left(g^2 T_3 - (g')^2 Y\right)}{\sqrt{g^2 + (g')^2}} Z_\mu - i\frac{gg'}{\sqrt{g^2 + (g')^2}} A_\mu \left(T_3 + Y\right)$$

with $T^\pm = T_1 \pm iT_2$

Observe: A_μ couples to the generator $T_3 + Y$ which generates the symmetry operation $\alpha_1 = \alpha_2 = 0$; $\alpha_3 = \beta$

- One can identify the charge operator $Q = T_3 + Y$ & the em coupling $e = \frac{gg'}{\sqrt{g^2 + (g')^2}}$
- Defining the weak mixing angle relating the weak and mass eigenstates

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \Rightarrow e = g' \cos\theta_W = g \sin\theta_W$$

Hence: $\mathcal{D}_\mu = \partial_\mu - i\frac{g}{\sqrt{2}}\left(W_\mu^+ T^+ + W_\mu^- T^-\right) - i\sqrt{g^2 + (g')^2} Z^\mu \left(T_3 - Q\sin^2\theta_W\right) - ieQA_\mu$

All weak boson couplings given in terms of $\cos\theta_W$ and e, as well as $M_W = M_Z \cos\theta_W$

The SM Higgs Mechanism and the Higgs Boson

- So far we have studied the generation of gauge boson masses but we did not identify the Higgs degrees of freedom/2

Adding a self-interacting, complex scalar field Φ, doublet under SU(2) and with Y =1/2 with the potential

$$V(\Phi) = \mu^2 \Phi^+ \Phi + \lambda (\Phi^+ \Phi)^2 \qquad (\lambda > 0)$$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{h + v}{\sqrt{2}} + i \frac{G^0}{\sqrt{2}} \end{pmatrix}$$

$\mu^2 < 0$ ➔ non-trivial minimum

Of the four degrees of freedom of Φ, three are the Goldstone modes associated with the directions of the non-trivial transformations of the v.e.v. The additional one, is a massive mode, the Higgs boson

- This implies that the couplings of the Higgs H will be associated with the ones leading to mass generation.

Number of degrees of freedom : EWSB reshuffles the degrees of freedom of the theory

Before:

1 complex scalar double	= 4
1 massless SU(2) Wμ	= 6
1 massless U(1) Bμ	= 2
	12

After:

1 charged W+-	= 6
1 massive Z	= 3
1 massless photon	= 2
1 massive scalar	= 1
	12

Higgs neutral under strong and em interactions ==> massless photon and gluons
Massless gauge bosons ==> Exact symmetry:

Fermion Masses and Mixings

Higgs mechanism generates masses also for the fermions through Yukawa couplings of the Higgs doublet to two fermions:

-- Higgs couplings to quark doublets and either up or down-type fermions

-- Higgs couplings to lepton doublet and charged lepton singlets

Each term is parametrized by a 3x3 matrix in generation space

$$L_{Hf\bar{f}} = -(h_d)_{ij}\bar{q}_{L_i}\Phi\, d_{R_j} - (h_u)_{ij}\bar{q}_{L_i}\Phi^C u_{R_j} - (h_l)_{ij}\bar{l}_{L_i}\Phi\, e_{R_j} + h.c$$

$$\Phi^C = -i\sigma_2\Phi^*$$

Once the electroweak symmetry is spontaneously broken

$$L_{m_f} = (m_d)_{ij}\bar{d}_{L_i}\, d_{R_j} + (m_u)_{ij}\bar{u}_{L_i}\, u_{R_j} + (m_e)_{ij}\bar{e}_{L_i}\, e_{R_j} + h.c$$

with $m_f = h_f\ v/\sqrt{2}$ and u_L ,d_L and e_L the quark and lepton doublet components

Heavier fermions correspond to fields more strongly coupled to the Higgs boson

Fermion Masses and Mixings (cont'd)

Fermion mass matrices are arbitrary complex matrices. They are therefore diagonalized by bi-unitary transformations,

$$V^{u\dagger} m_u \tilde{V}^u = diag(m_u, m_c, m_t)$$
$$V^{d\dagger} m_d \tilde{V}^d = diag(m_d, m_s, m_b)$$
$$V^{e\dagger} m_e \tilde{V}^e = diag(m_e, m_\mu, m_\tau)$$

with unitary matrices V → $V^\dagger V = I$

We change the basis from weak eigenstates (i, j,...) to mass eigenstates (α,β,...)

$$u_{Li} = V^u_{i\alpha}\, u_{L\alpha}, \qquad d_{Li} = V^d_{i\alpha}\, d_{L\alpha}, \qquad u_{Ri} = \tilde{V}^u_{i\alpha}\, u_{R\alpha}, \qquad d_{Ri} = \tilde{V}^d_{i\alpha}\, d_{R\alpha}$$

The up and down matrices V^u and V^d are not identical, hence, the charged current couplings are no longer diagonal

$$L_{CC} = -\frac{g}{\sqrt{2}} V^{CKM}_{\alpha\beta}\; \bar{u}_{L\alpha} \gamma^\mu d_{L\beta} W^+_\mu + h.c.$$

with the CKM matrix $V^{CKM}_{\alpha\beta} = V^{u\,\dagger}_{\alpha i} V^d_{i\beta}$

- The CKM mass matrix is almost the identity ==> flavor changing transitions are suppressed
- Due to the unitarity of the transformations ==> no FCNC on the neutral gauge sector
- The Higgs fermion interactions are also flavor diagonal in the fermion mass eigenstate basis

given $\bar{d}_i\,(m_{ij} + h_{ij} H)\, d_j$, since $m_{ij} = h_i j v$ they are diagonalised together

Neutrino Masses

Experimental data shows that neutrinos are massive

In the SM, fermion masses are generated via the Higgs mechanism, since direct mass terms are not allowed by gauge invariance.

SM + 3 singlets: ν_{Ri} ==> *generate Dirac masses (L conserved)*

$$L_{\nu\ \mathrm{mass}} = \bar{l}_{L_i} h_{\nu_{ij}} \Phi^C \nu_{R_j} + h.\,c. \xrightarrow{\langle\Phi\rangle = v} \bar{\nu}_{L_i} m_{D_{ij}} \nu_{R_j}$$

$m_\nu \neq I$ *(mixing)!*

$$\bar{\nu}_{L_i} m_{D_{ij}} \nu_{R_j} \rightarrow \bar{\nu}_{L_\alpha} m^{diag}_{D_{\alpha\beta}} \nu_{R_\beta} \quad \Rightarrow \quad \mathrm{m}^{\mathrm{diag}}_{\nu} = V^{(\nu_L)\dagger} m_D \tilde{V}^{(\nu_R)}$$

α and β are mass eigenstates

Define $V_{MNS} \equiv V^{(\nu L)\dagger} V^{(l)}$ analogous to the CKM quark mixing mass matrix, but large mixings lepton sector.

Issue: since $m_\nu << eV \Rightarrow h_\nu / h_l << 1$

Majorana masses : an exceptional case

Right-handed neutrinos are singlets of the standard model gauge group

==> Majorana mass term involving the charge conjugate fermion

$$\psi^C = C\bar{\psi}^T \quad \text{with} \quad C = i\gamma^2\gamma^0 \text{ the charge conjugation matrix}$$

The charge conjugation spinor has opposite charge $\psi^C = C\bar{\psi}^T = i\gamma^2\psi^*$
and opposite chirality $P_L\psi_R^C = \psi_R^C$ to the original one

Thus we can write a mass term $\overline{\psi^C}\psi$ (mass term always requires both chiralities)

which is gauge invariant only for singlet fields

The R-handed neutrino can have the usual Higgs coupling and a Majorana mass term (i,j family indices)

$$L_{\nu\ \text{mass}} = h_{\nu_{ij}}\, v\, \bar{\nu}_{L_i}\nu_{R_j} + \frac{M_{ij}}{2}\underbrace{\nu_{R_i}^T i\sigma_2 \nu_R}_{\overline{\nu_{R_i}^C}\nu_R} +$$

The eigenvalues of the Majorana matrix M can be much larger tha the Dirac ones $m_D = h_\nu v$

Diagonalization of the (ν_L, ν_R) system ==> three light neutrino modes ν_i

$$m_\nu = -m_D M^{-1} m_D^T$$

For M~ 10^{15} GeV and m_D~100 GeV
==> m_ν ~10^{-2} eV: consistent with data

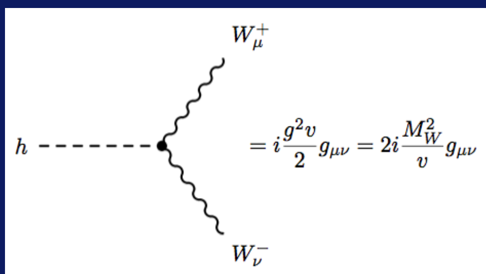
The see-saw mechanism: explains smallness of neutrino masses as a result of large Majorana masses as those appearing in many grand unified theories

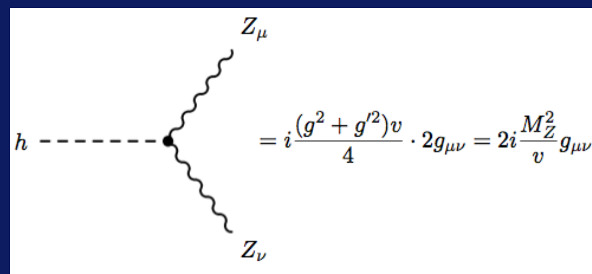
Higgs Couplings to Gauge Bosons and Fermions

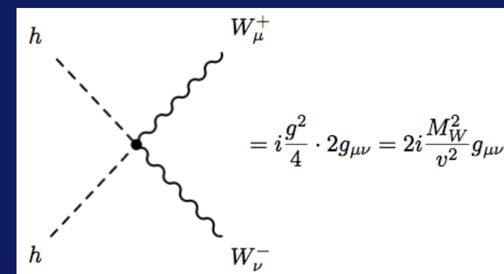
To gauge bosons from

$$\mathcal{L}_{H-W/Z} = \left(\frac{v}{\sqrt{2}} + \frac{H}{\sqrt{2}}\right)^2 \left[\frac{g_2^2}{2} W^+_\mu W^{-\mu} + \frac{g_1^2+g_2^2}{4} Z_\mu Z^\mu\right]$$

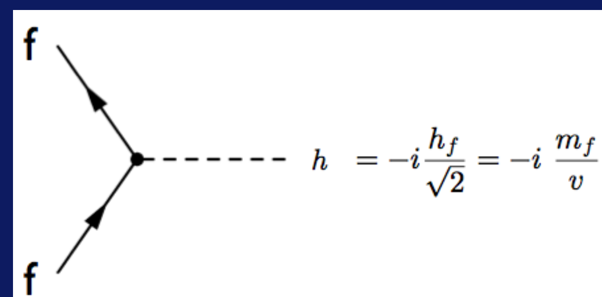
$g^2 = g$; $g^1 = g'$







Similarly from the Yukawa interactions



Tree level couplings are proportional to masses

These couplings govern the Higgs production and decay rates and LHC data provides evidence of their approximate realization in nature

There is still room for deviations from these SM couplings that can occur in many Beyond the SM realizations

Higgs Self Couplings

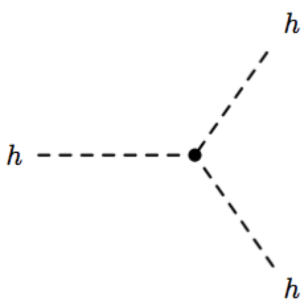
Recalling the form of the potential, restrict oneself to renormalizable couplings

$$V(\Phi) = -m^2|\Phi|^2 + \lambda\,(\Phi^{+}\Phi)^2$$

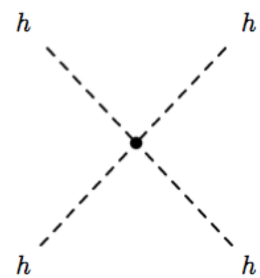
Keeping terms that depend on the physical Higgs field $\phi^\dagger \phi = \frac{(h+v)^2}{2}$

where $v^2 = m^2 / \lambda$ and $m_h^2 = 2\lambda\, v^2$

Then we have: $V = \lambda\, v^2 h^2 + \lambda\, v\, h^3 + \frac{\lambda}{4}\, h^4$



$$= -i\lambda v \cdot 3! = -6i\lambda v = -3i\frac{m_h^2}{v}$$



$$= -i\frac{\lambda}{4} \cdot 4! = -6i\lambda = -3i\frac{m_h^2}{v^2}$$

Higgs potential has two free parameters : m and λ, trade by v^2 and m_h^2

Stability Bounds and the Running Quartic Coupling

The Higgs mass is governed by the value of the quartic coupling at the weak scale. This coupling evolves with energy, affected mostly by top quark loops, self interactions and weak gauge couplings

$$16\pi^2 \frac{d\lambda}{dt} = 12(\lambda^2 + h_t^2\ \lambda - h_t^4) + \mathcal{O}(g^4, g^2\lambda) \qquad t = \log(Q^2)$$

•There is the usual situation of non-asymptotic freedom for sufficiently large Q^2

↓

λ becomes too large
(strongly interacting, close to Landau pole)

From requiring perturbative validity of the model up to scale Λ or M_{pl}

$$\lambda^{max}(\Lambda)/4\pi = 1 \Rightarrow m_h^{max} = 2\sqrt{\lambda^{max}}\,v$$

•The part of the β_λ independent of λ can drive $\lambda(Q)$ to negative values ==> destabilizing the electroweak minimum

↓

Lower bound on $\lambda(m_h)$ from stability requirement

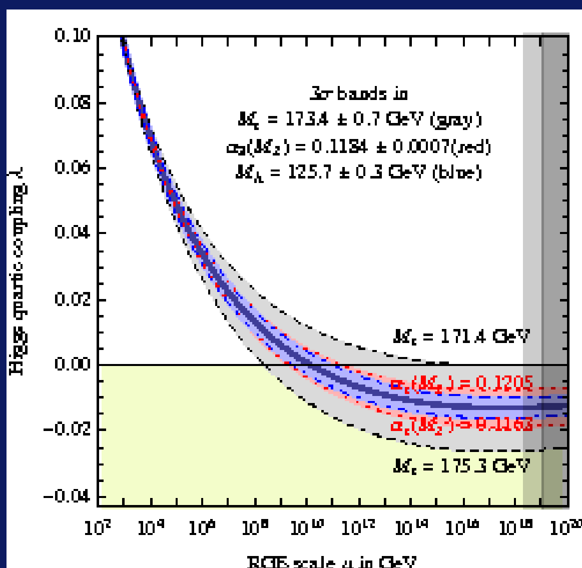
m_h^{min} strongly dependent on m_t

- If the Higgs mass were larger than the weak scale, the quartic coupling would be large and the theory could develop a Landau Pole. However, the observed Higgs mass leads to a value of $\lambda = 0.125$ and therefore the main effects are associated with the top loops.

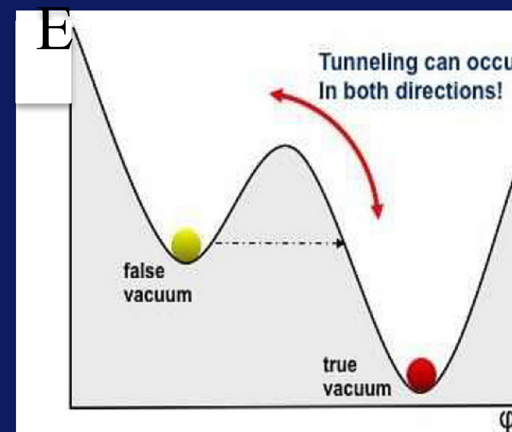
The Higgs and the fate of our universe in the SM

- The top quark loops tend to push the quartic coupling to negative values, inducing a possible instability of the electroweak symmetry breaking vacuum.

λ evolves with energy



The EW vacuum is metastable



A careful analysis, solving the coupled RG equations of the quartic and Yukawa couplings up to three loop order shows that the turning point would be at scales of order $10^{10\text{-}12}$ GeV. Therefore the electroweak symmetry breaking minimum is not stable.

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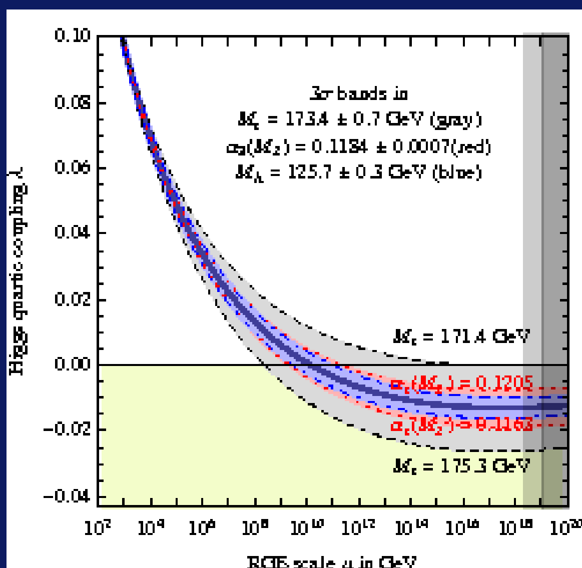

The EW vacuum is metastable

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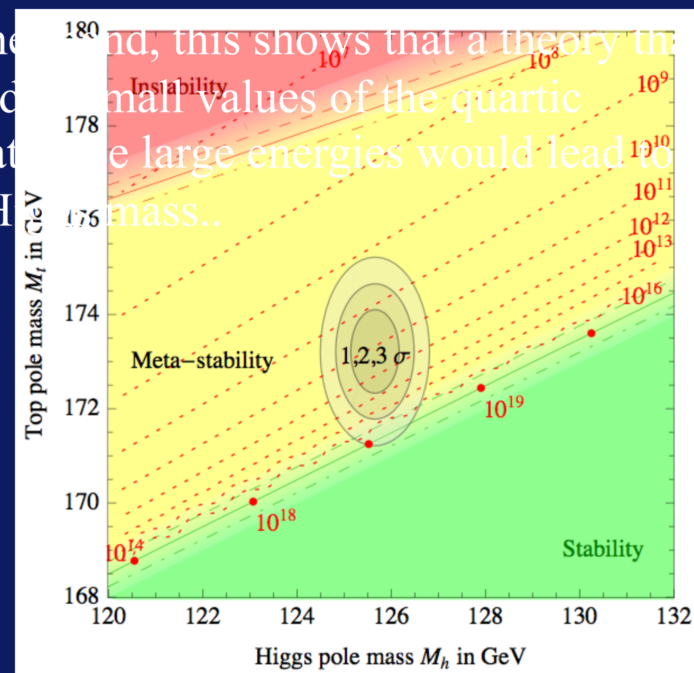
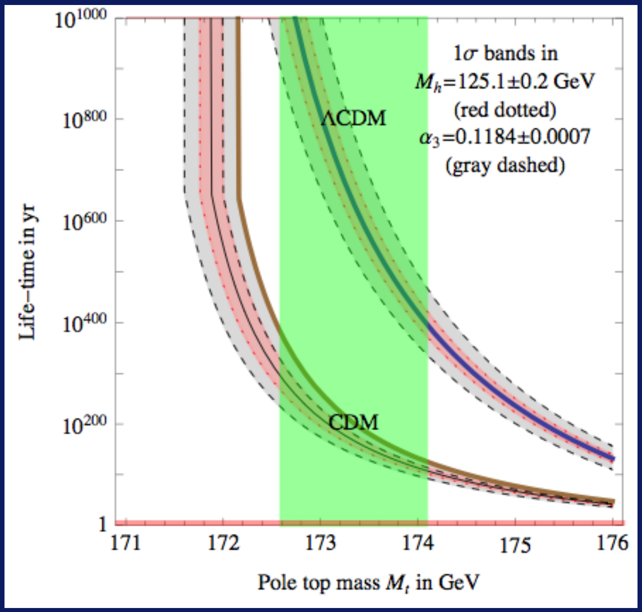


A careful analysis, solving the coupled RG equations of the quartic and Yukawa couplings up to three loop order shows that the turning point would be at scales of order $10^{10\text{-}12}$ GeV. Therefore the electroweak symmetry breaking minimum is not stable.

The Higgs and the fate of our universe in the SM

Within the SM framework, the relevant question is related to the lifetime of the EW metastable vacuum that is determined by the rate of quantum tunneling from this vacuum into the true vacuum of the theory



Careful analyses reveal that possible transitions to these new deep minima are suppressed and the lifetime of the electroweak symmetry breaking vacuum is much larger than the age of the Universe. **No need for New physics…**

On the other hand, this shows that a theory that would predict small values of the quartic coupling at these large energies would lead to the right Higgs mass.

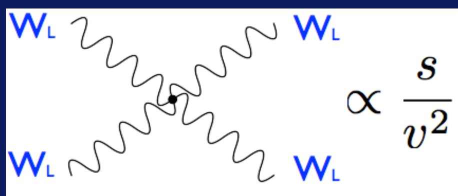
Slow evolution of λ at high energies saves the EW vacuum from early collapse

The peculiar behavior of λ:

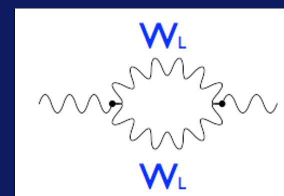
A coincidence, some special dynamics/new symmetry at high energies?
Or not there at all ? ➔ new physics at low energy scale

Indirect constraints on the Higgs Mass

Before the Higgs discovery, we knew that SOME new phenomena had to exist at the EW scale to restore the calculability power of the SM, otherwise

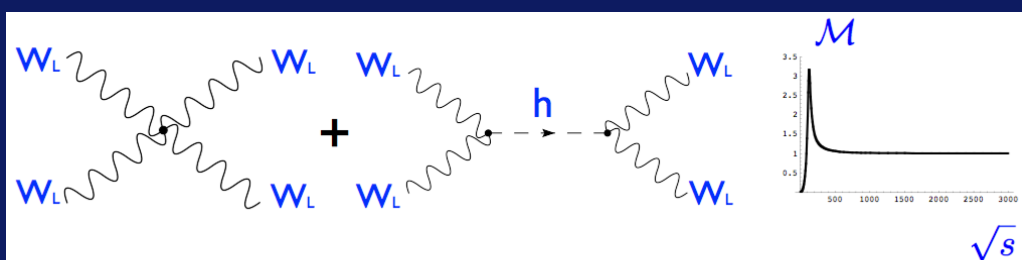


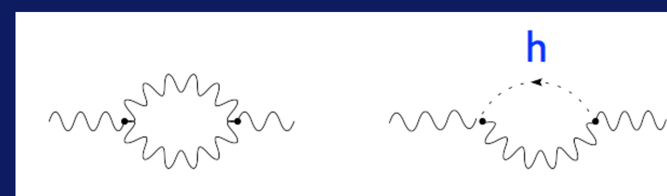
Unitarity lost at high energies



Loops are not finite

- **The Higgs restores the calculability power of the SM**





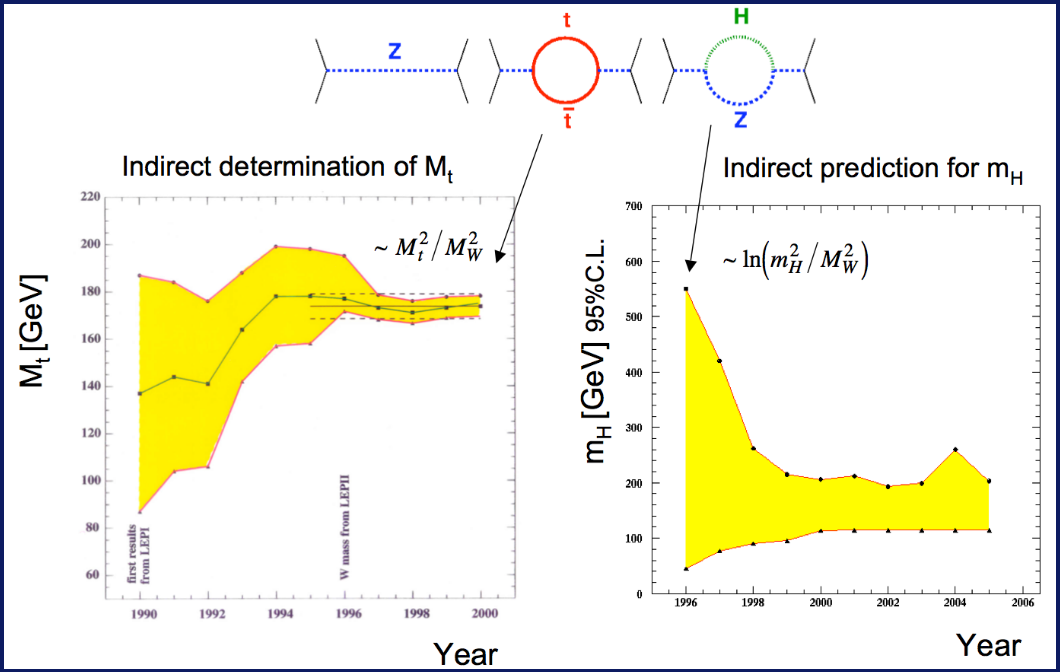
Loops are finite

To do to the job it is important that the couplings of the Higgs bosons to the gauge bosons are precisely the SM ones, otherwise additional new physics required

Indirect constraints on the Higgs Mass

The Higgs boson enters via virtual Higgs production in electroweak observables:
like the ratio of the W and Z masses, the Z partial and total width, and the lepton and quark forward-backward asymmetries
➔ they depend via radiative corrections, logarithmically on m_H

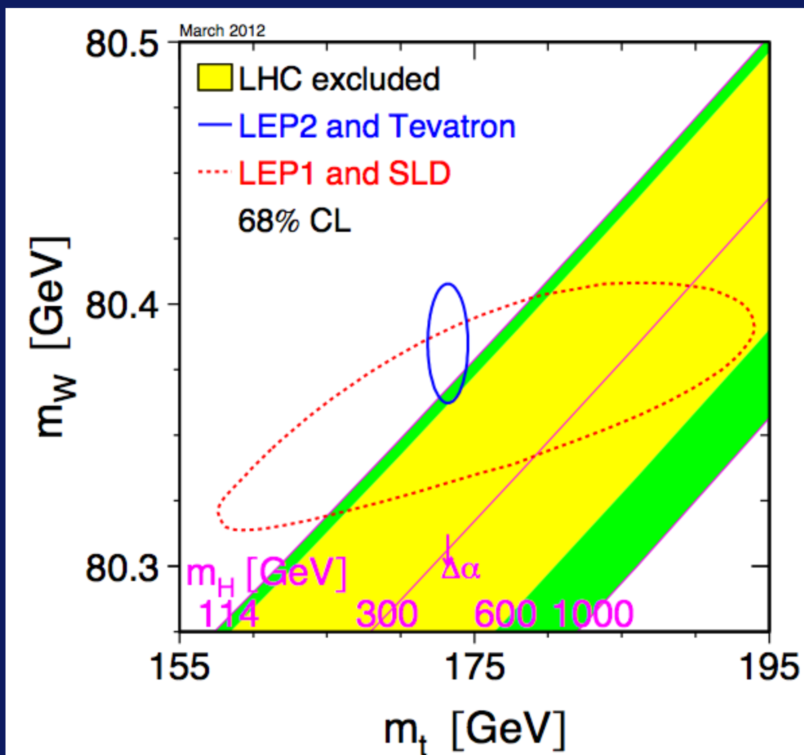
Indirect determination of SM particle masses proves high energy reach through virtual processes

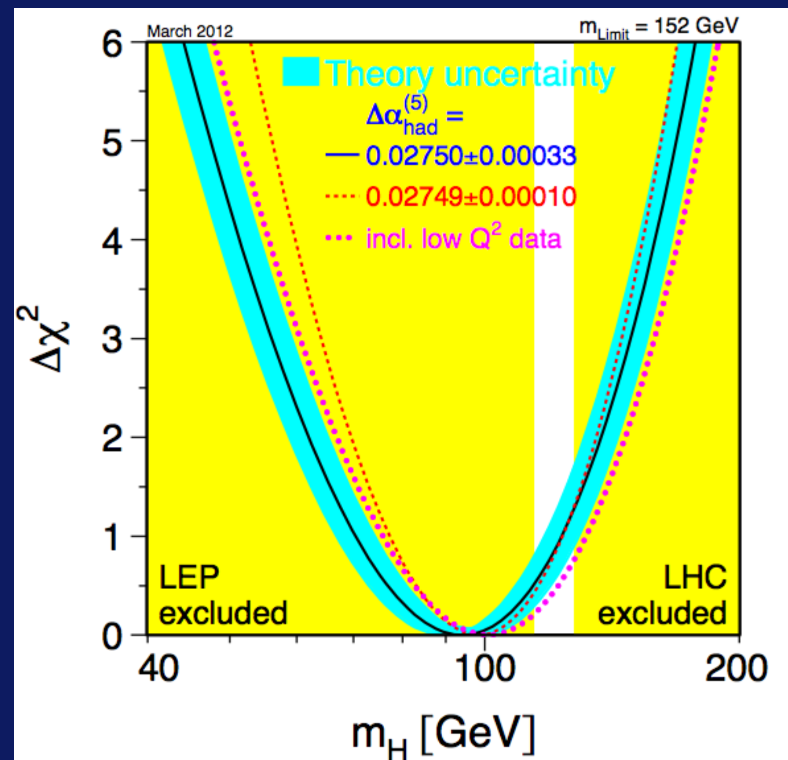


Departures of the Higgs couplings from their SM values demand the appearance of new states that tame the logarithmic divergences appearing in the computation of precision observables.

Precision Measurements prefer a light Higgs Boson

Assuming a Higgs like particle, one can obtain indirect information on the Higgs mass from a combination of the precision EW observables measured at LEP, SLC and the Tevatron colliders.





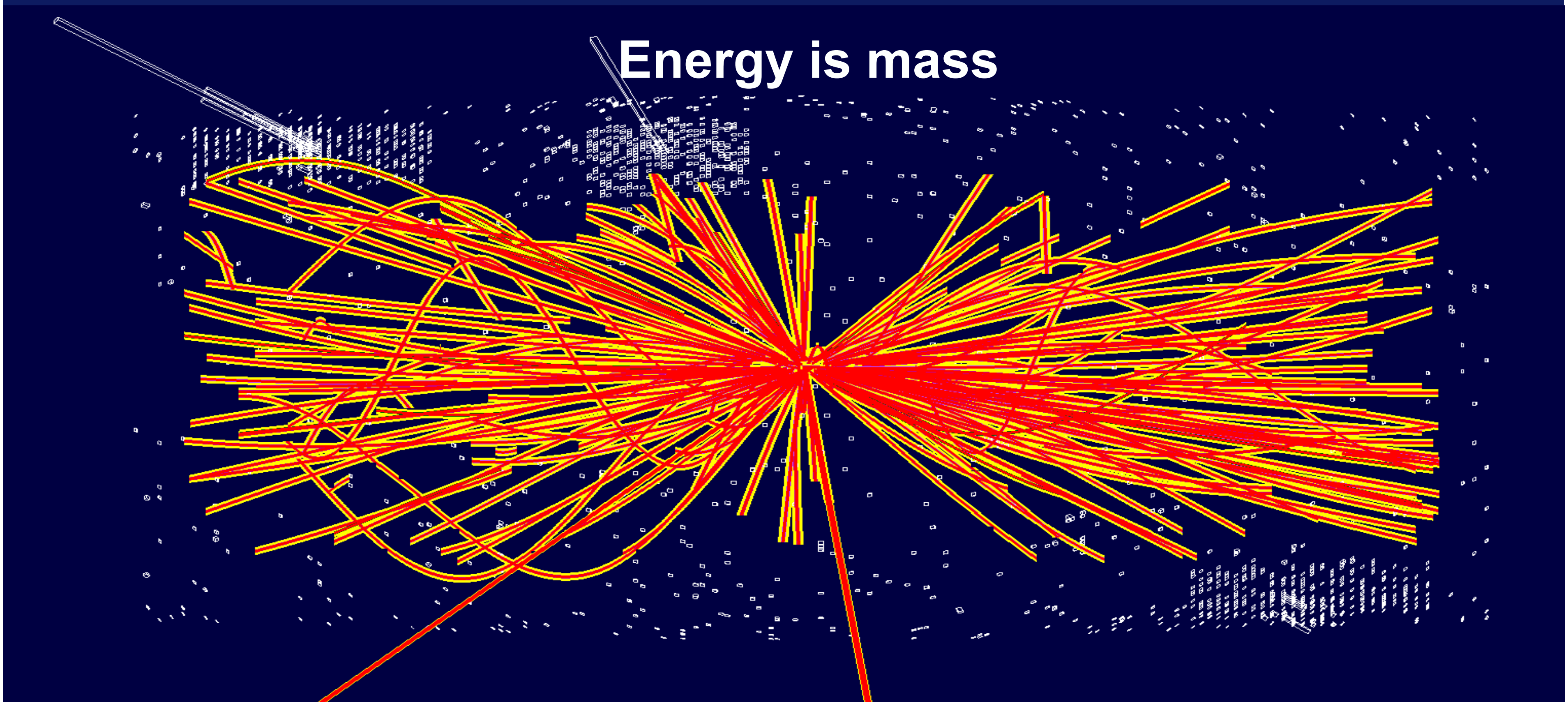
Precision measurements of the top quark and W boson:

SM correlation for M_t-M_w-m_{HSM}

From the LEP Electroweak Working Group
http://lepewwg.web.cern.ch/LEPEWWG/

How do we search for the Higgs?

Smashing Particles at High Energy Accelerators to create it



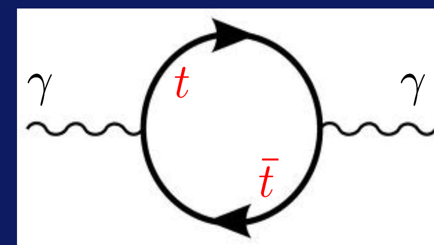
And searching for known particles into which the Higgs transforms (decays) almost instantly

How do we search for the Higgs Boson?

Quantum Fluctuations can produce the Higgs at the LHC

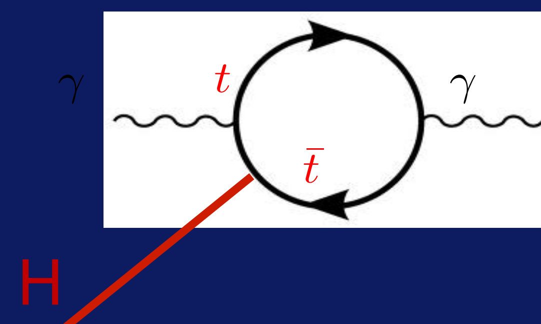
"Nothingness" is the most exciting medium in the cosmos!

Photon propagates in Quantum Vacuum

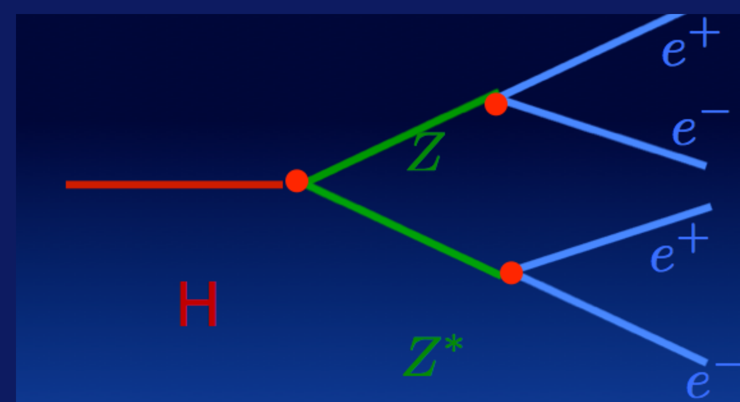


Quantum fluctuations create and annihilate "virtual particles" in the vacuum

Higgs decays into 2 Photons



Higgs decay into 4 leptons via virtual Z bosons



How do we search for the Higgs Boson?

Through its decays into gauge bosons and fermions

- Higgs couplings are proportional to fermion and gauge boson masses, and given that $m_H < 2\ M_{W/Z} < 2\ m_t$ ➔ Higgs decays should be dominated by its decay into the heavier fermions (excluding the top), namely bottoms and taus

$$\Gamma(h \to f\bar{f}) = m_h \frac{N_c}{8\pi} \frac{m_f^2}{v^2} \left(1 - \frac{4\ m_f^2}{m_h^2}\right)^{3/2}$$

Which fermion mass values should be used?

Using the running masses at the Higgs mass scale reduces in great part the size of the QCD corrections, which however remain relevant, but not sizable

$$\Gamma(h \to b\bar{b}) \simeq \frac{3M_h}{8\ v^2\ \pi} m_b(m_h)^2 \Delta_{\mathrm{QCD}}$$

$$\Delta_{\mathrm{QCD}} = 1 + 5.7\frac{\alpha_s(m_h)}{\pi} + 30\left(\frac{\alpha_s(m_h)}{\pi}\right)^2 + \ldots.$$

Similar for other quarks

Fermion decay widths affected by smallness of fermion masses that allow for competing effects, from 3 body decays mediated by gauge bosons and even top quark loop effects

- The three body decay width induced by the vector bosons is

$$\delta_W = 1,\ \ \delta_Z = 7/12 - 10/9 \sin^2\theta_W + 40/9 \sin^4\theta_W$$

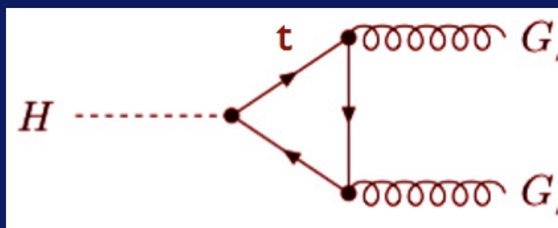
$$\Gamma(h \to V\ V^*) = \frac{3\ M_V^4}{32\pi^3 v^2} M_H\ \delta_V\ R(x)$$

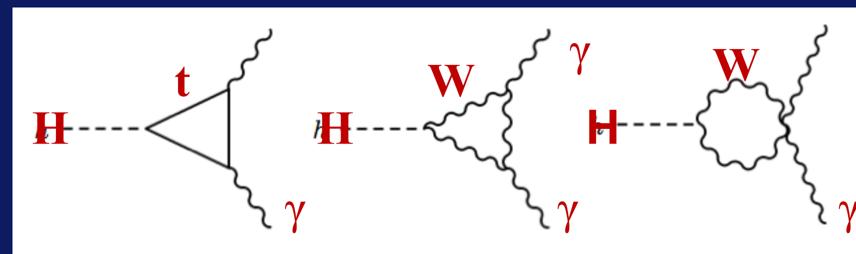
$$R_T(x) = \frac{3(1-8x+20x^2)}{(4x-1)^{1/2}} \arccos\left(\frac{3x-1}{2x^{3/2}}\right) - \frac{1-x}{2x}(2-13x+47x^2) - \frac{3}{2}(1-6x+4x^2)\log x$$

$$x = \frac{M_V^2}{M_H^2}$$

Higgs loop induced Couplings/Decays

The most important loop-induced decays are into massless gluons and photons.





The decay into gluons is mostly mediated by loops of top quarks

The decayinto photons also receive contributions from top quark loops, but the most important contribution comes from loops of W-bosons

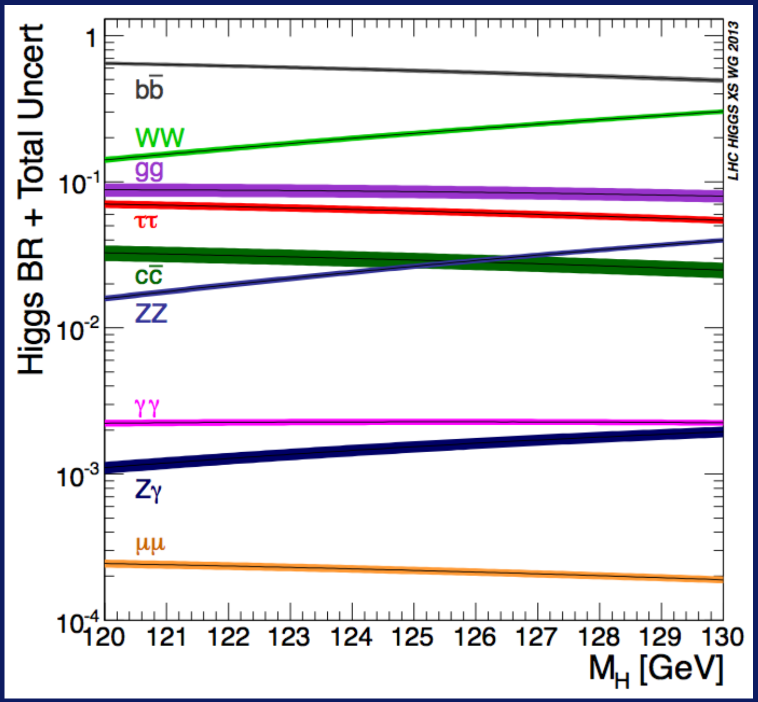
Both particles cannot produced on-shell from Higgs decays. Their contributions may be approximated by

$$\Gamma(h \to gg) \simeq \frac{\alpha_s^2\, m_h^3}{128\, \pi^3} |F_{1/2}|^2$$

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{256\pi^3 v^2} \left| \sum_i N_c^i\, Q_i^2\, F_i \right|^2$$

The factors $F_1 = -7$ and $F_{1/2} = 4/3$ are related to the contributions of the W bosons and the top quark to the electromagnetic coupling beta function

SM Higgs Boson branching ratios



$$BR(h \to XX) \equiv \frac{\Gamma(h \to XX)}{\sum_{X_i = \text{all particles}} \Gamma(h \to X_i X_i)}$$

- Uncertainties due to uncertainties in α_S, m_t, m_b and m_C
- Leading QCD corrections can be mapped into scale dependence of fermion masses $m_f(m_h)$
- Expected hierarchy of Higgs decays:

$$BR(\tau^+\tau^-) < 10^{-1} BR(b\bar{b}) \to O(m_b^2 / m_\tau^2) \times 3_{color}$$

$$BR(c\bar{c}) < BR(\tau^+\tau^-) \Longrightarrow \text{due to smallness of } m_c(m_h) \approx 0.6 \text{ GeV}$$

At m_H = 125 GeV

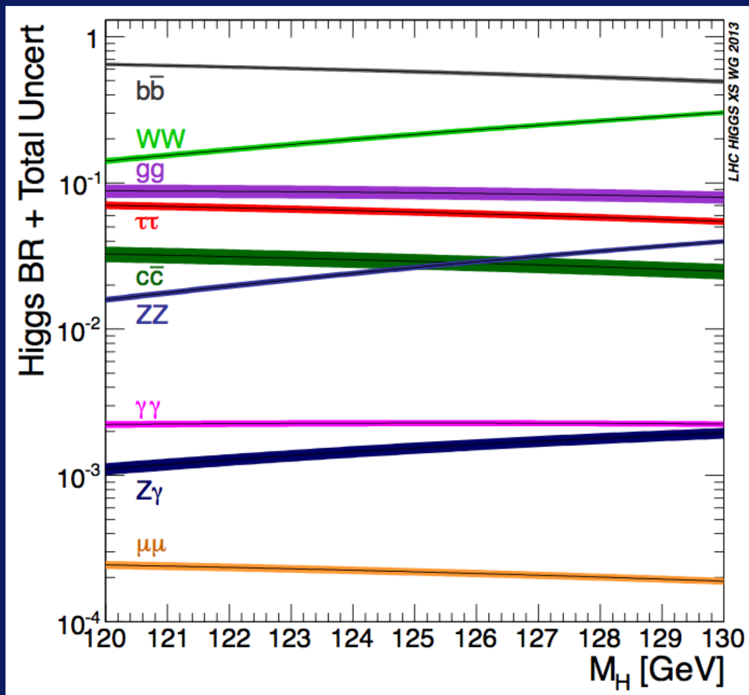
Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.54×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.19×10^{-4}	$^{+6.0\%}_{-5.9\%}$

$$h \to gg,\ Z\gamma,\ \gamma\gamma$$

generated only at one-loop, but due to heavy particles in the loop ==>relevant contributions to BR's

$\Gamma_H = 4.07 \times 10^{-3}$ GeV, with a relative uncertainty of $^{+4.0\%}_{-3.9\%}$.

SM Higgs Boson branching ratios



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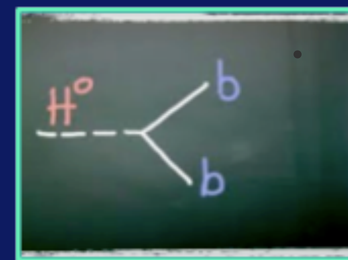
Higgs decays

after about

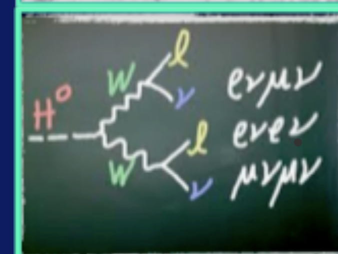
100 yocktoseconds

into various pairs

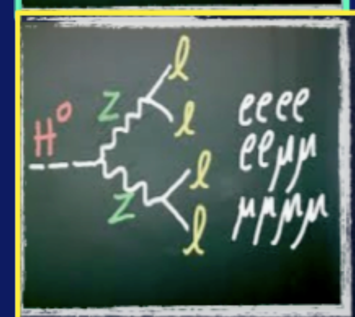
of lighter particles



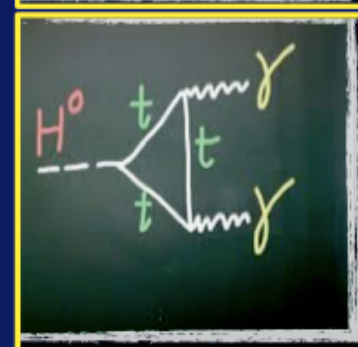
Lots of background



Neutrinos not detected



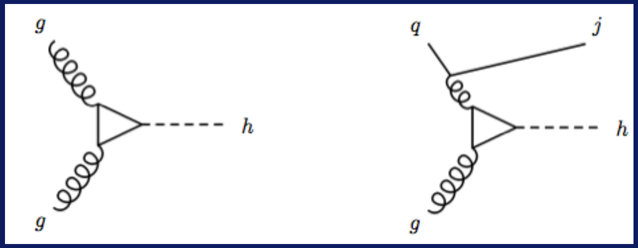
Rare but "Golden" channel



Rare but relatively clean

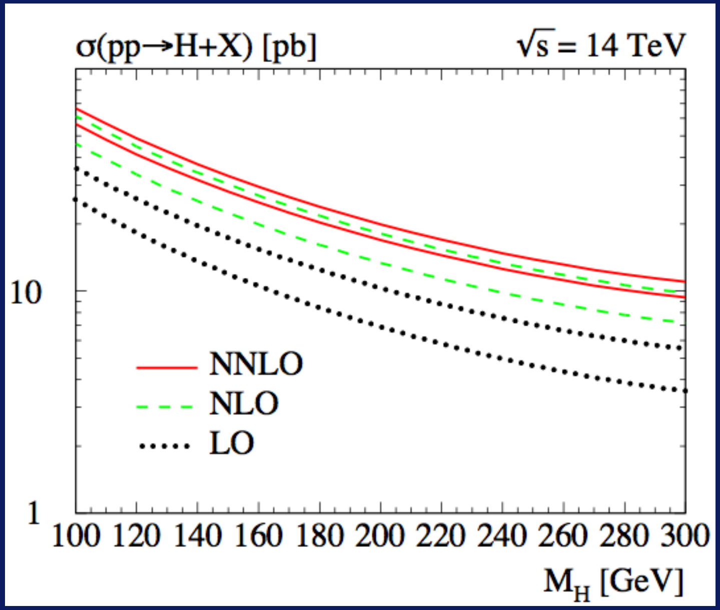
SM Higgs Boson Production at the LHC

The dominant Higgs Boson Production mode at the LHC is gluon fusion



$$\sigma_{LO} = \frac{\alpha_s(\mu)^2}{576\ v^2\ \pi} |F_{1/2}|^2$$

At LO can be computed using low energy effective theorems in the limit of infinite top quark mass, but NLO and NNLO corrections are sizable



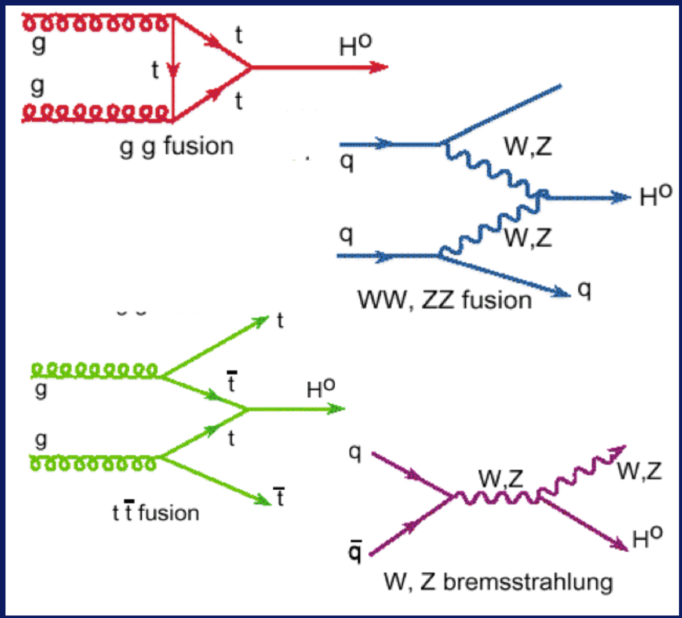
Convergence of the computed Higgs Cross section at LO, NLO, and NNLO in QCD

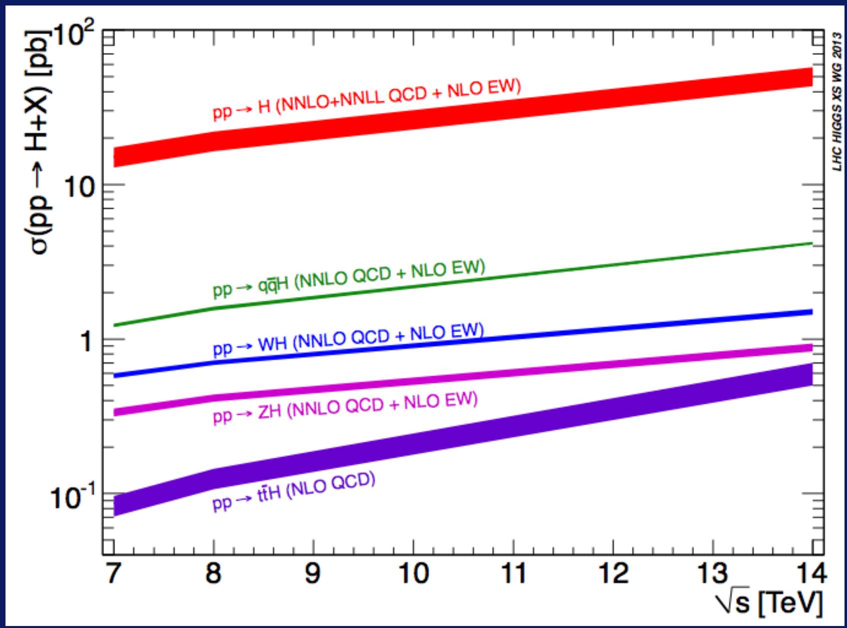
Bands show the renormalization/factorization Scale dependence varying up and down by a factor 2 with respect to a reference scale equal to ¼ of the Higgs mass

NNLO QCD corrections show a good degree of convergence and a small scale dependence

SM Higgs Boson Production at the LHC

Three additional production modes at the LHC:
significant hierarchy between dominant production cross section and subdominant ones



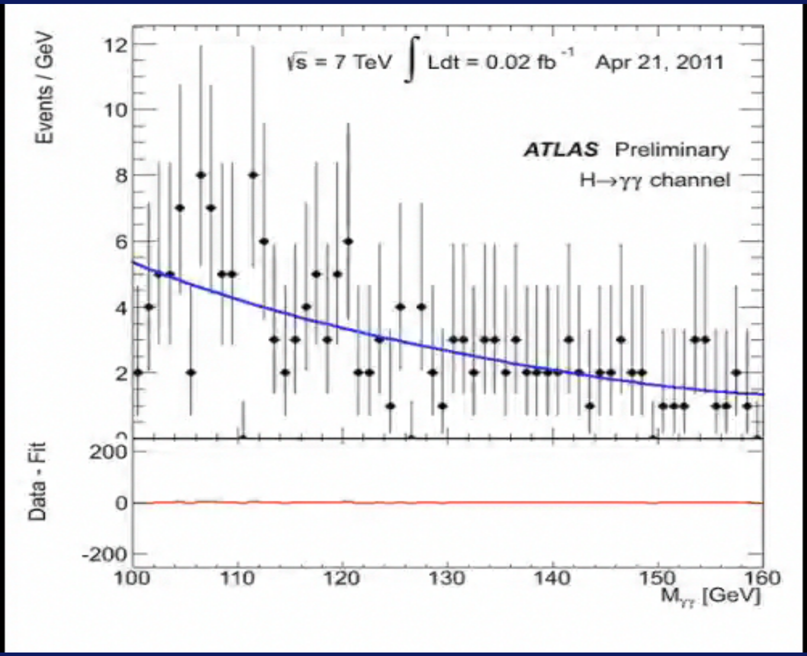


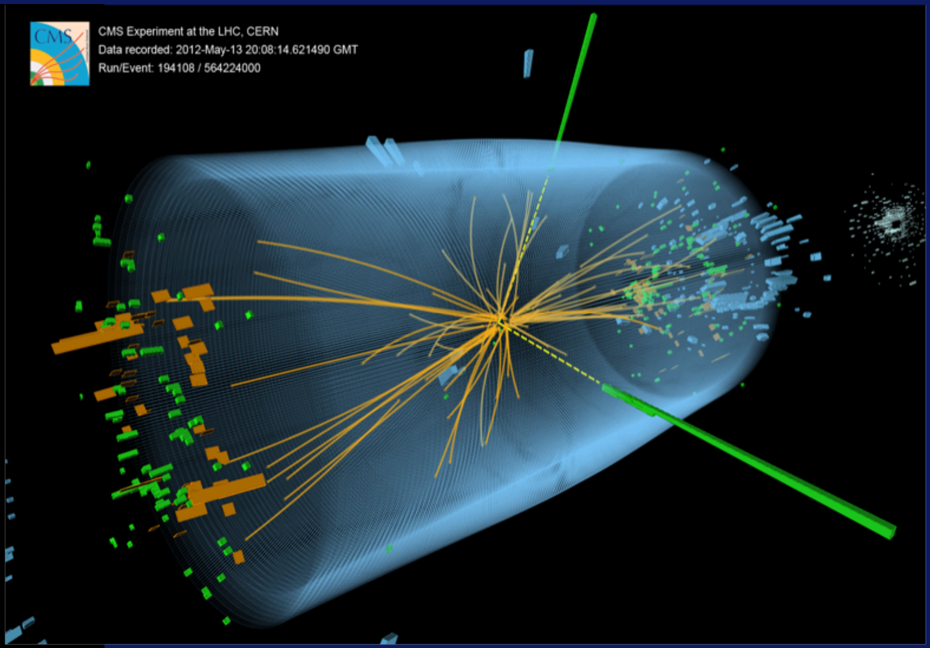
All these processes , together with the decay BR's are important to determine Higgs couplings

Discovery modes were mostly in the Higgs production via gluon fusion
with subsequent decay into ZZ and di-photons

The Higgs self couplings may be probed by double Higgs production, which is mediated by
Higgs and also by loops of top-quarks. Very challenging at the LHC

The Discovery: Higgs → two photons

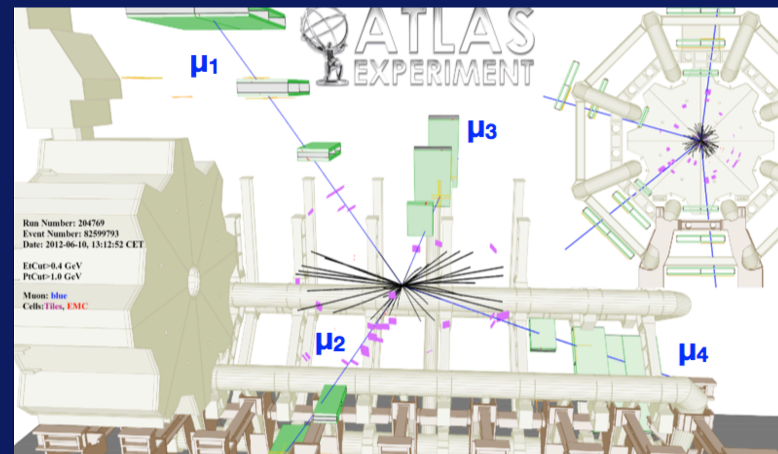


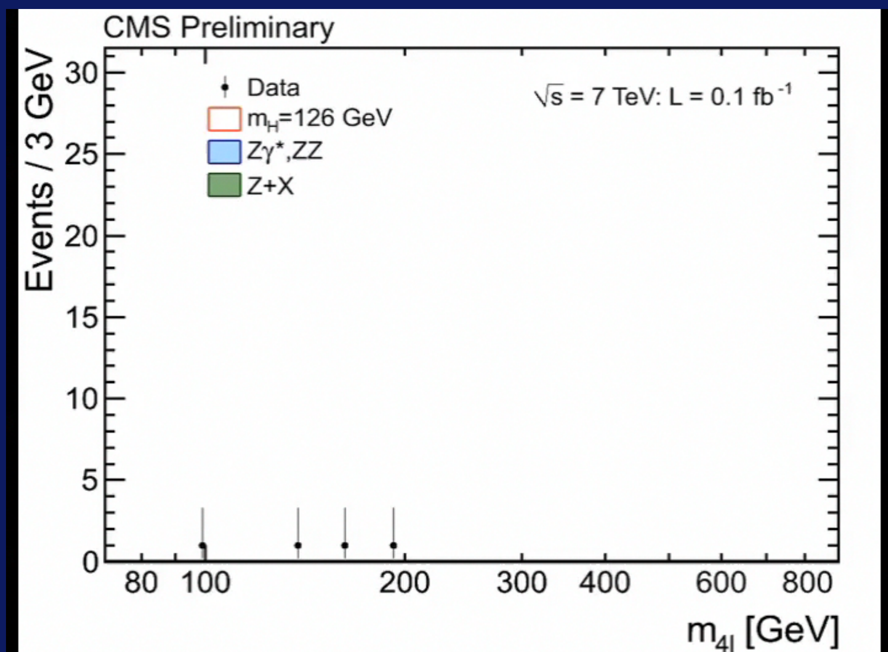


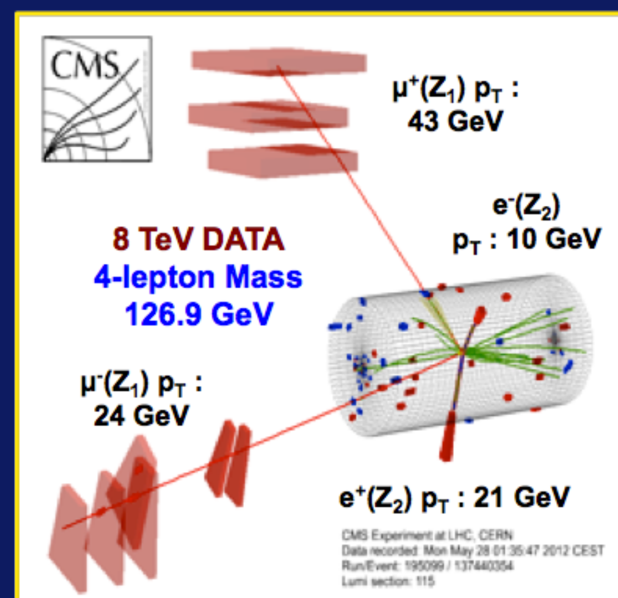
Search for a narrow mass peak with two isolated high E_T photons on a smoothly falling background

The Discovery: Higgs → 4 Leptons

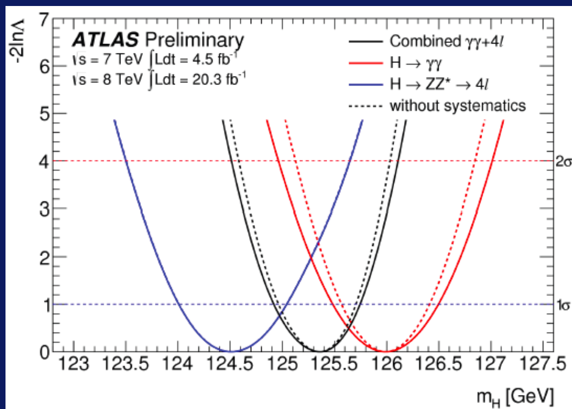
with virtual Z bosons: The Golden Channel







No doubt that a Higgs boson has been discovered

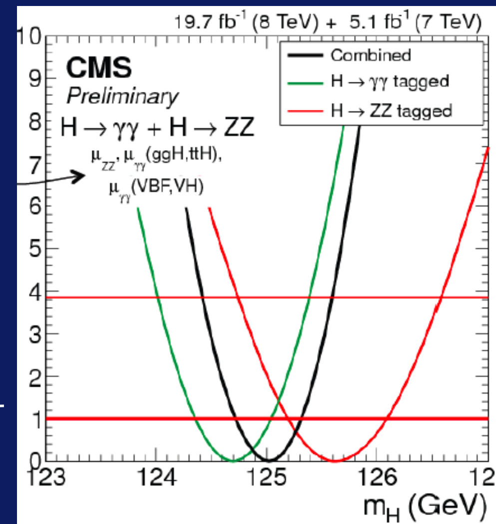


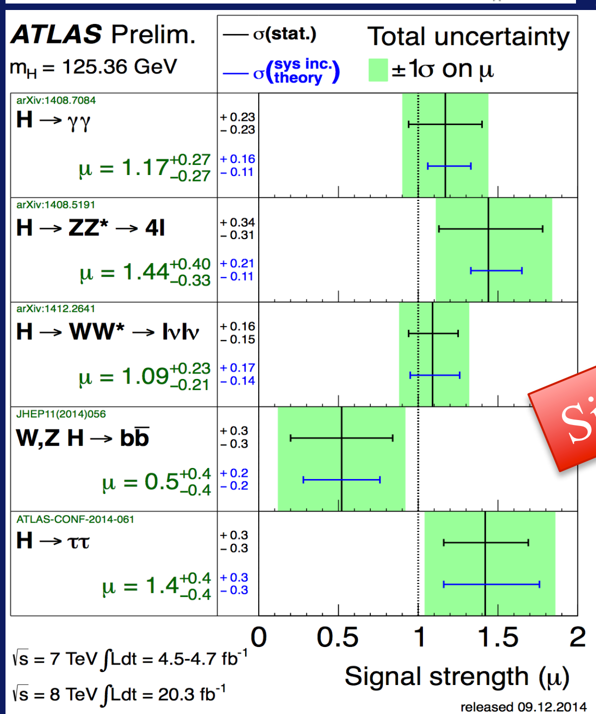
ATLAS:

$$m_H = [125.36 \pm 0.41]\,\mathrm{GeV}$$

CMS:

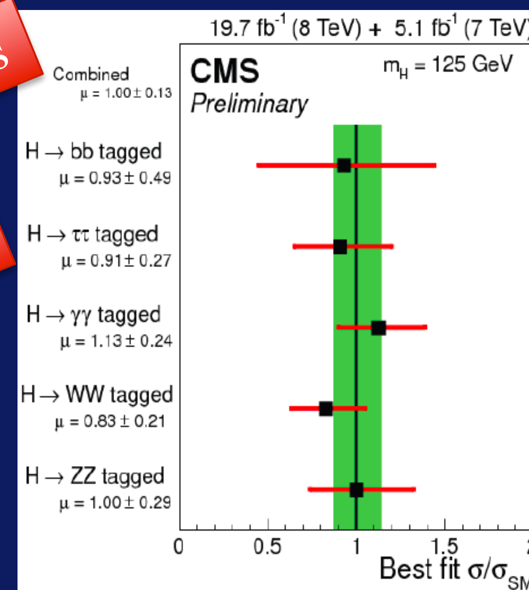
$$m_H = [125.03 \pm 0.30]\,\mathrm{GeV}$$





Signal compatible with SM Higgs

Also room for New Physics



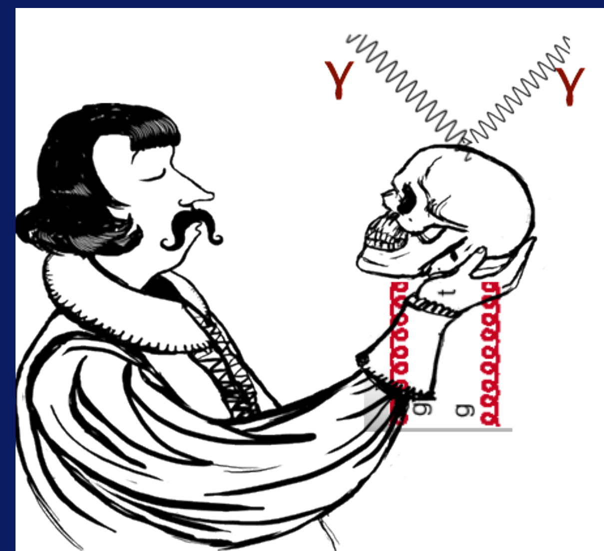
$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \; \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

What kind of Higgs?

- Is it THE Higgs boson that explains the mass of fundamental particles?

  ~1% of all the visible mass

" The" Standard Model Scalar Boson, or not ....



- Is it just THE STANDARD MODEL HIGGS ?

• **Spin 0**

• **Neutral CP even component of a complex $SU(2)_L$ doublet**

• **Couples to weak gauge bosons as**

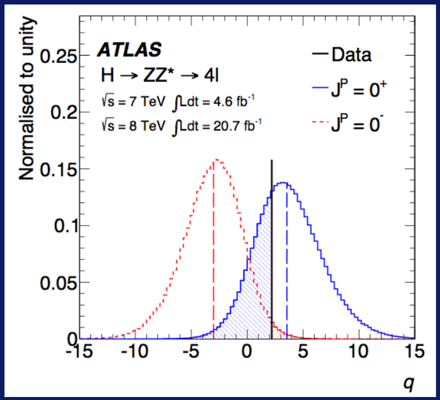
$$g_{WWH}/g_{ZZH} = m_W^2/m_Z^2$$

• **Couplings to SM fermions proportional to their masses**

• **Self-coupling strength determines its mass (and v = 246 GeV)**

- or just a close relative, or an impostor?

It could look SM-like but have some non-Standard properties and still partially do the job



- Could be a mixture of more than one Higgs
- Could be a mixture of CP even and CP odd states
- Could be a composite particle
- Could have enhanced/suppressed couplings to photons or gluons linked to the existence of new exotic charged or colored particles interacting with the Higgs
- Could decay to exotic particles, e.g. dark matter
- May not couple to matter particles proportional to their masses

The goal of the next LHC phase, that just started ! is to answer these questions and search for new physics