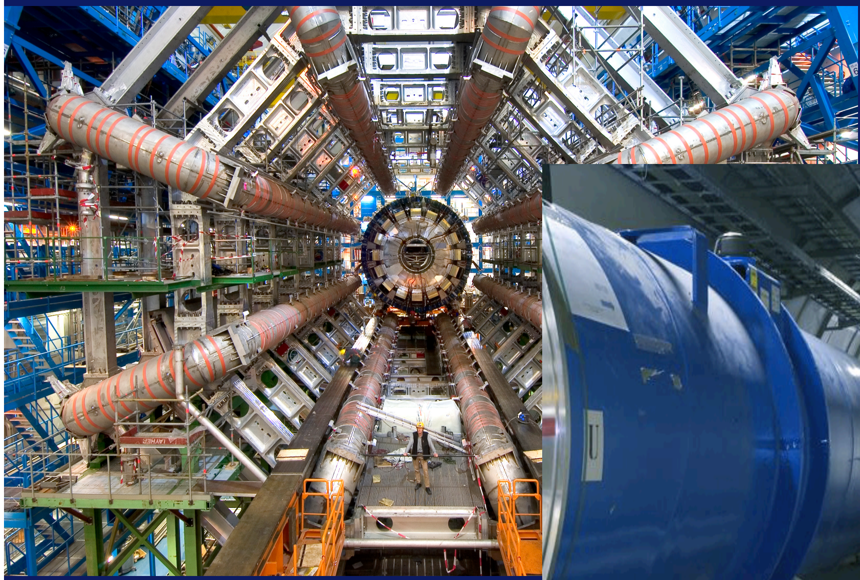
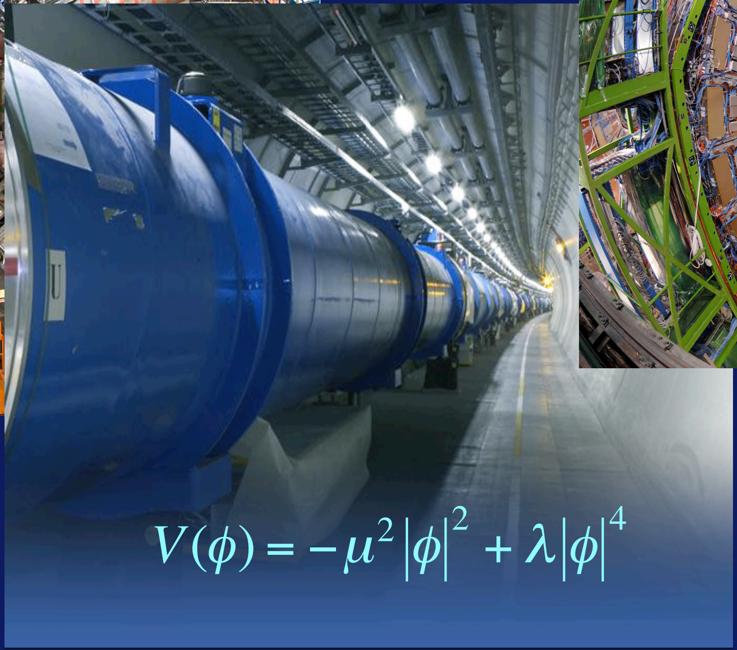
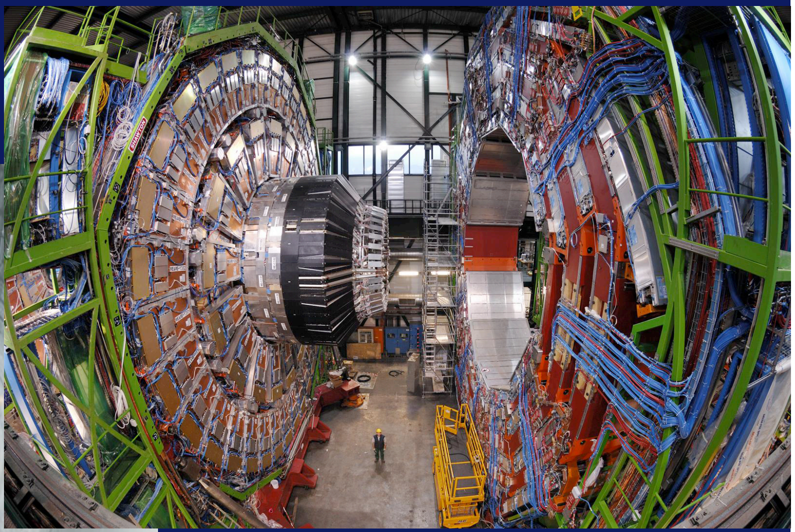
Lectures on Higgs Boson Physics
The Standard Model and Supersymmetry



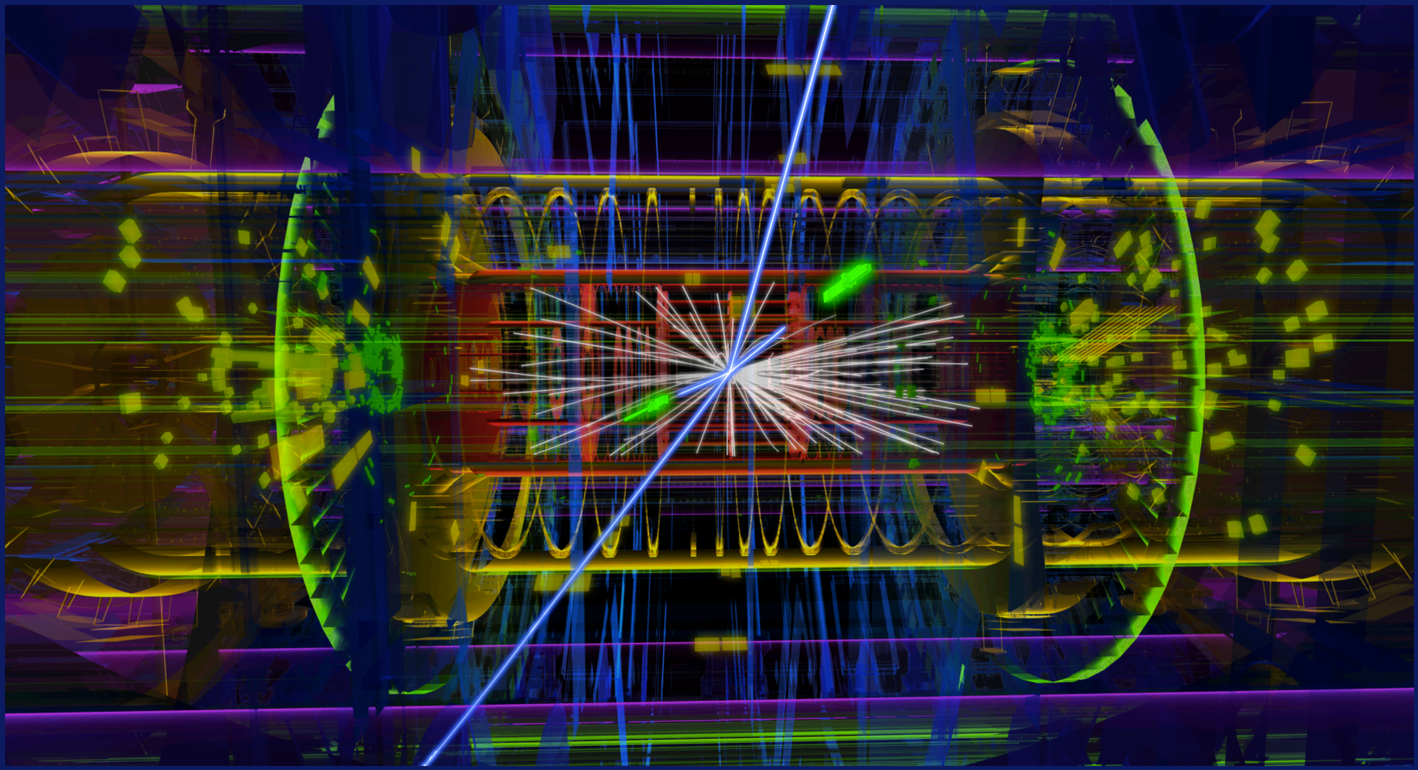




Marcela Carena
Fermilab and U. of Chicago

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

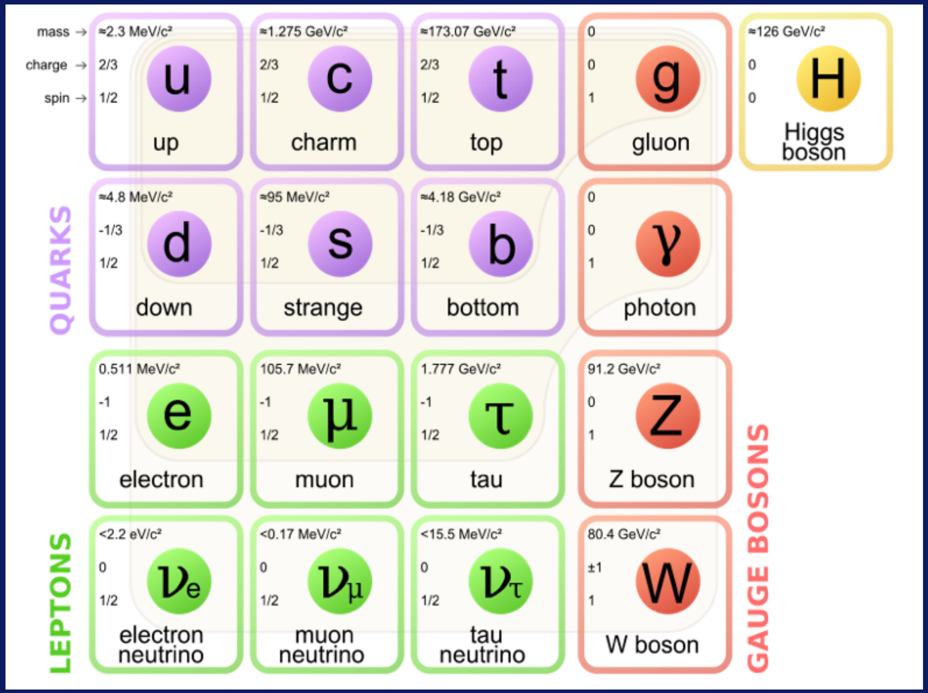
A new era of particle physics and cosmology

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.

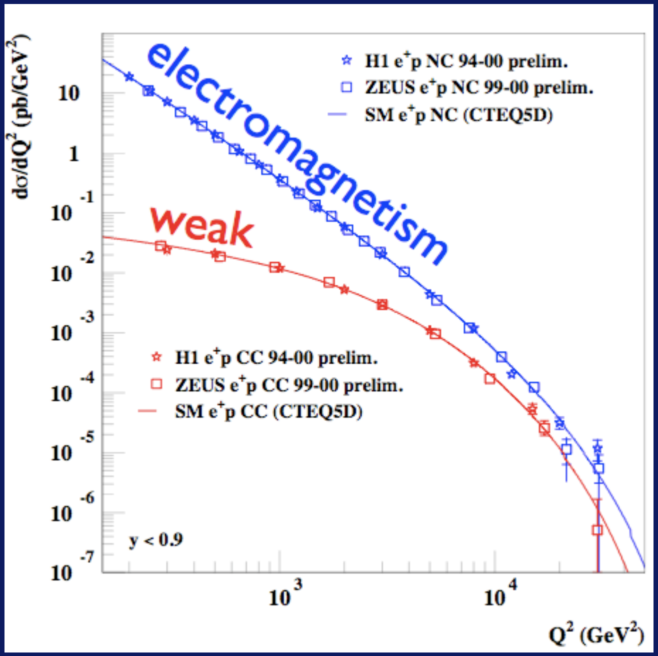
- Eight SU(3) gauge bosons → gluons

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?

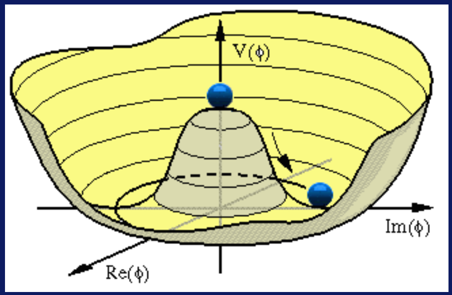
In the SM the Higgs Mechanism causes the fundamental particles to have mass

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:

$$\delta V = \frac{\partial V}{\partial \phi_i}\delta\phi_i = i\epsilon^a T^a_{ij}\phi_j = 0 \quad \longrightarrow \quad \frac{\partial^2 V}{\partial\phi_i \partial\phi_k} T^a_{ij}\phi_j + \frac{\partial V}{\partial \phi_i} T^a_{ik} = 0$$

- 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 $\delta\phi_\mathbf{i}|_{\mathbf{v_j}} = \mathbf{i}\epsilon\mathbf{T^a_{ij} v_j = 0}$ 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 $\longrightarrow$ broken generators

Since the generators are linearly independent

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

- 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

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

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 $\langle\Phi\rangle$ invariant

  and there will be a massless gauge boson

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

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

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

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

Det $M^2 = 0$ → one zero eigenvalue

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

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

Mass Eigenstates and Couplings

- The mass terms in the Lagrangian read: $\mathcal{L}_M = \frac{1}{2}\frac{v^2}{4}\left[g^2\left(A^1_\mu\right)^2 + \left(A^2_\mu\right)^2 + \left(gA^3_\mu - g' B_\mu\right)^2\right]$
- Defining the states $W^\pm_\mu = \frac{1}{\sqrt{2}}\left(A^1_\mu \mp i A^2_\mu\right), \quad Z_\mu = \frac{gA^3_\mu - g'B_\mu}{\sqrt{g^2 + g'^2}}$
- 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 $A_\mu = \frac{g' A^3_\mu + g B_\mu}{\sqrt{g^2 + (g')^2}}$
- It is useful to write the covariant derivative in term of mass eigenstates:

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

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

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

$\mu^2 < 0 \rightarrow$ 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:		After:	
1 complex scalar double	= 4	1 charged W+-	= 6
1 massless SU(2) Wμ	= 6	1 massive Z	= 3
1 massless U(1) Bμ	= 2	1 massless photon	= 2
		1 massive scalar	= 1
	12		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 ($i, j,\ldots$) to mass eigenstates ($\alpha,\beta,\ldots$)

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

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)!*

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

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

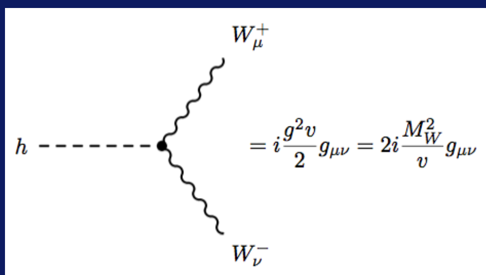
$$m_\nu = -m_D M^{-1} m_D^T$$

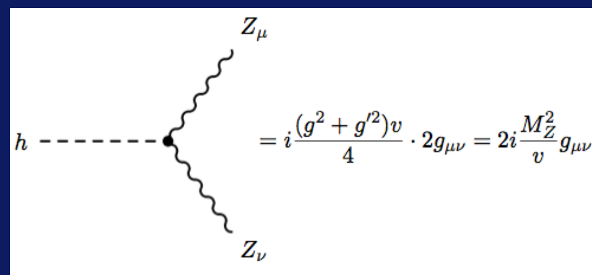
For M~ 10^{15} GeV and m_D~100 GeV
==> m_ν ~10^{-2} eV: consistent with data

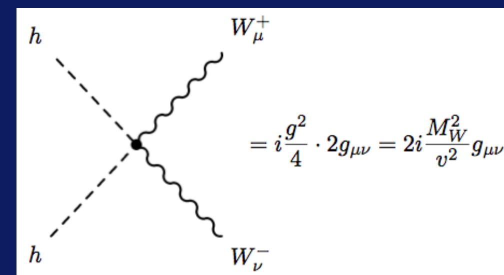
The see-saw mechanism: explains smallness of neutrino masses as a result of large Majorana masses as those appearing in many grand unified theories

Higgs Couplings to Gauge Bosons and Fermions

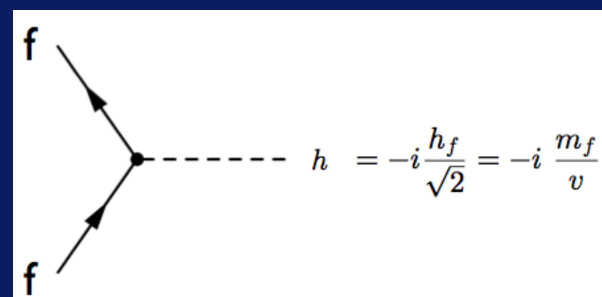
To gauge bosons from $\mathcal{L}_{H-W/Z} = \left(\frac{v}{\sqrt{2}} + \frac{H}{\sqrt{2}}\right)^2 \left[\frac{g_2^2}{2} W_\mu^+ W^{-\mu} + \frac{g_1^2+g_2^2}{4} Z_\mu Z^\mu\right]$ $g^2 = g$; $g^1 = g'$







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

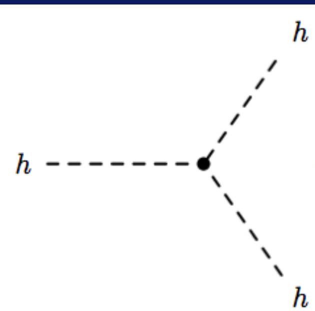
Recalling the form of the potential, restrict oneself to renormalizable couplings

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

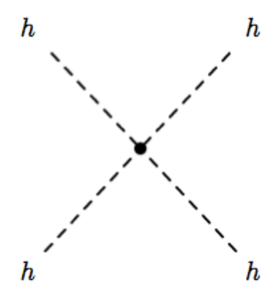
Keeping terms that depend on the physical Higgs field $\phi^\dagger \phi = \frac{(h+v)^2}{2}$

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

$\downarrow$

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

$\downarrow$

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

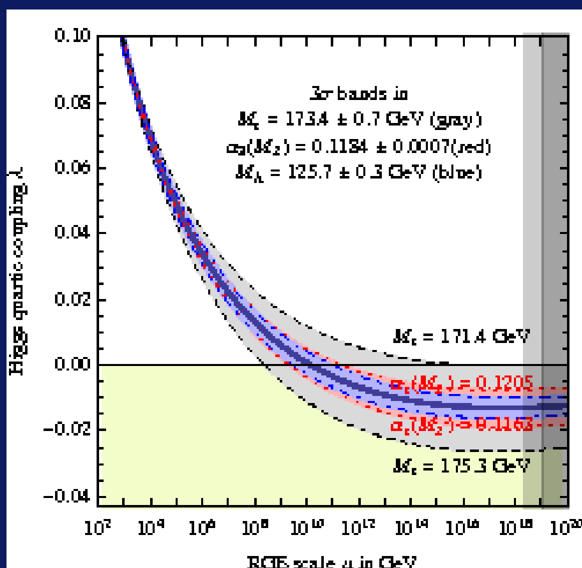
m_h^{min} strongly dependent on m_t

- 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.

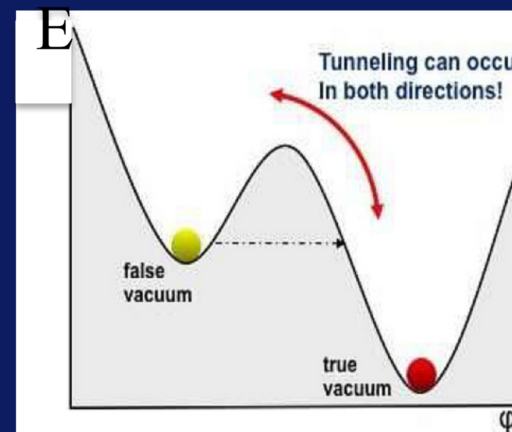
The Higgs and the fate of our universe in the SM

- 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

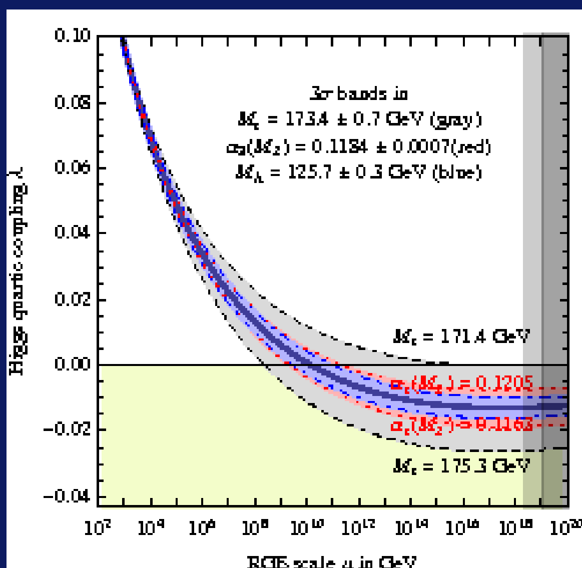


A careful analysis, solving the coupled RG equations of the quartic and Yukawa couplings up to three loop order shows that the turning point would be at scales of order $10^{10\text{-}12}$ GeV. Therefore the electroweak symmetry breaking minimum is not stable.

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.

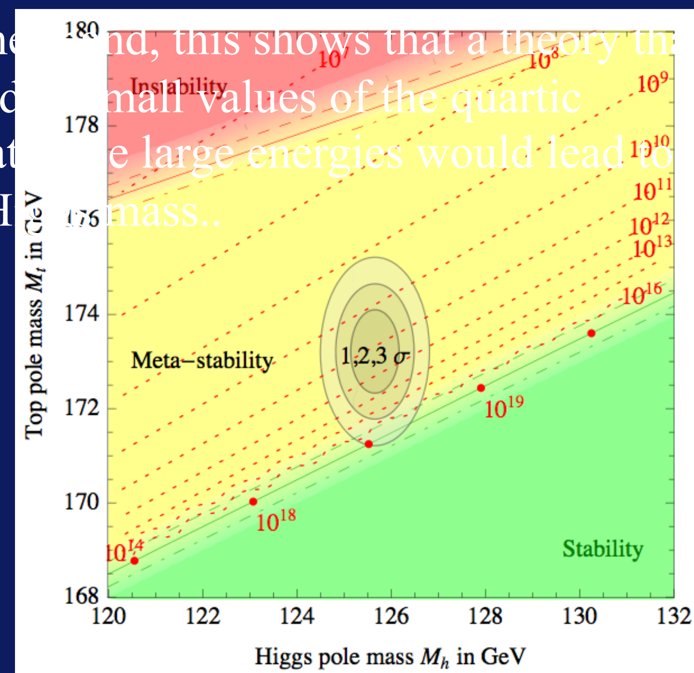
λ evolves with energy



The EW vacuum is metastable

On the othe
would pred
coupling at
the right H

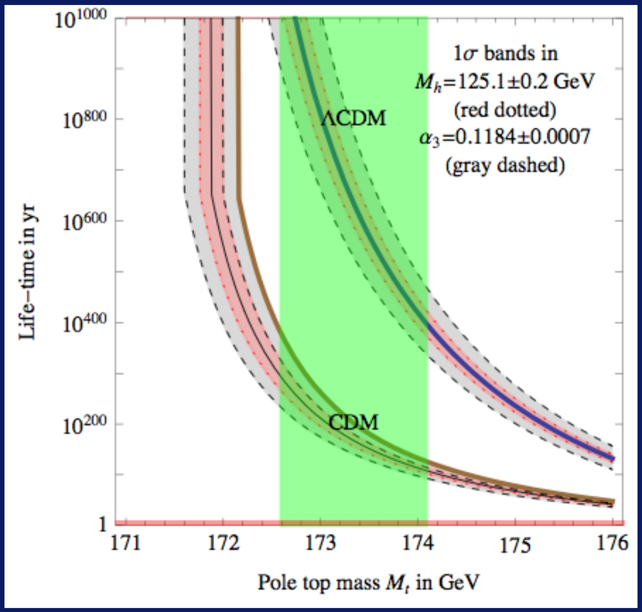
nd, this shows that a theory th
mall values of the quartic
e large energies would lead to
mass..



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.

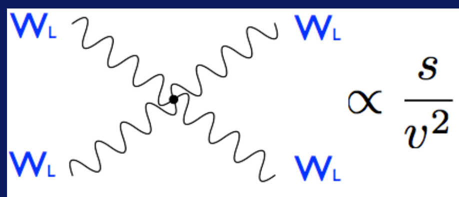
Slow evolution of λ at high energies saves the EW vacuum from early collapse

The peculiar behavior of λ:

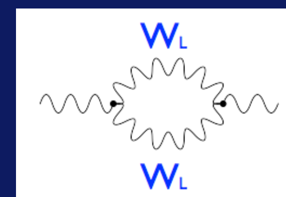
A coincidence, some special dynamics/new symmetry at high energies?
Or not there at all ? ➔ new physics at low energy scale

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

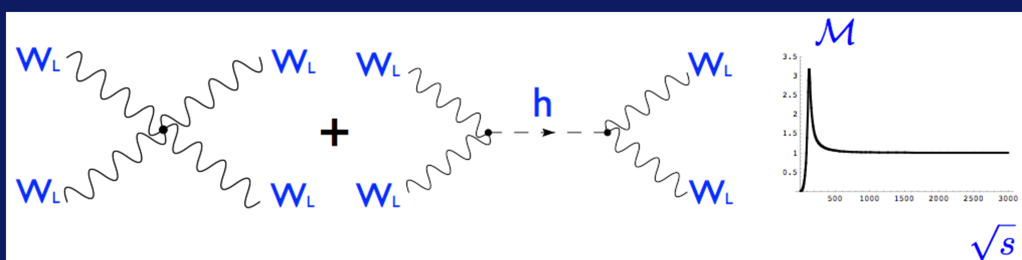


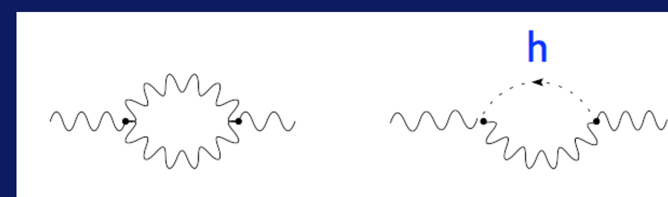
Unitarity lost at high energies



Loops are not finite

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





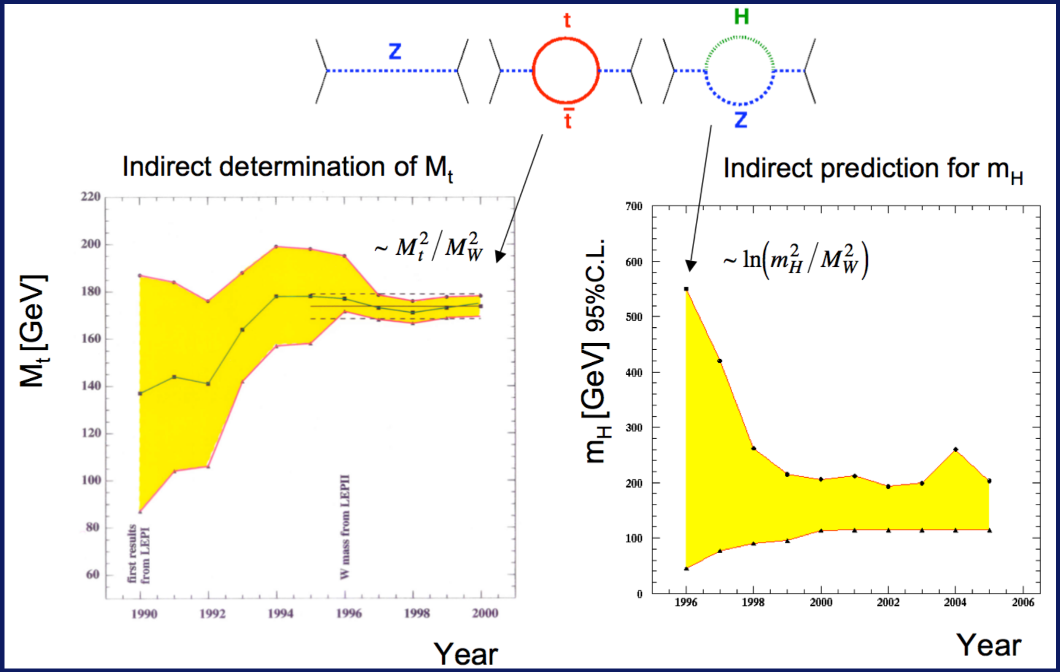
Loops are finite

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

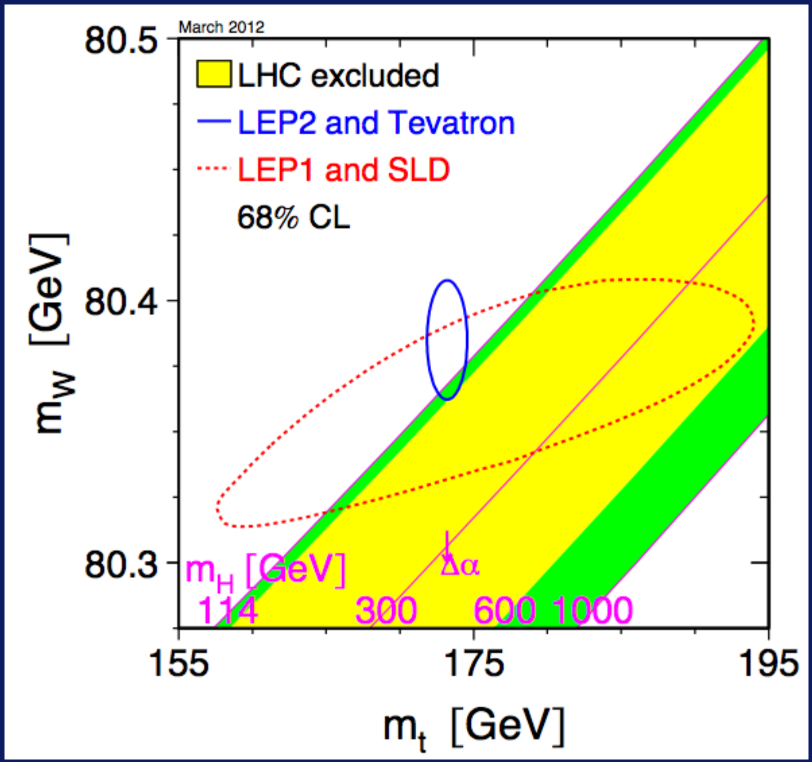
Indirect determination of SM particle masses proves high energy reach through virtual processes

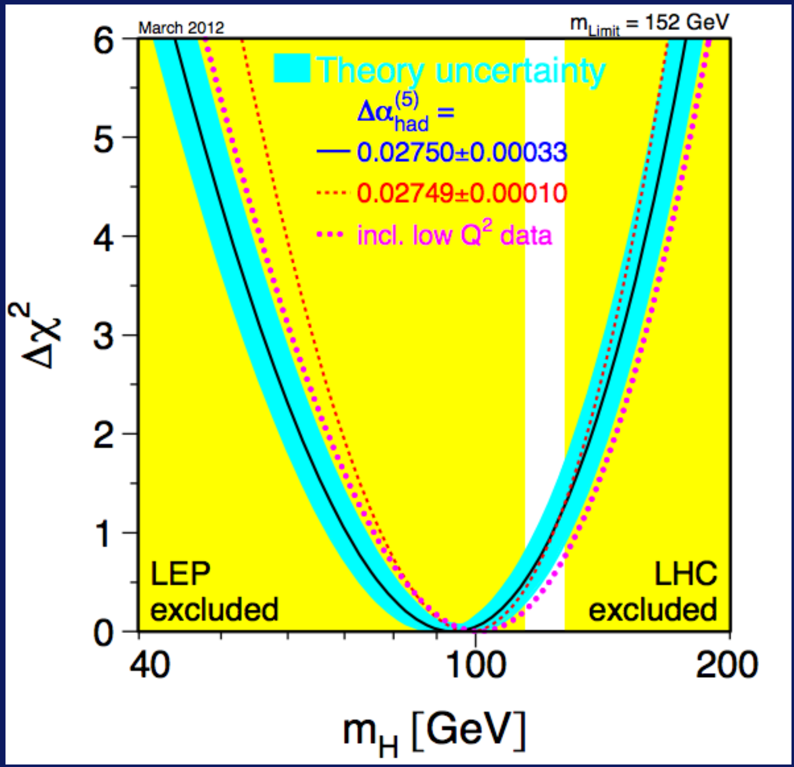


Departures of the Higgs couplings from their SM values demand the appearance of new states that tame the logarithmic divergences appearing in the computation of precision observables.

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.





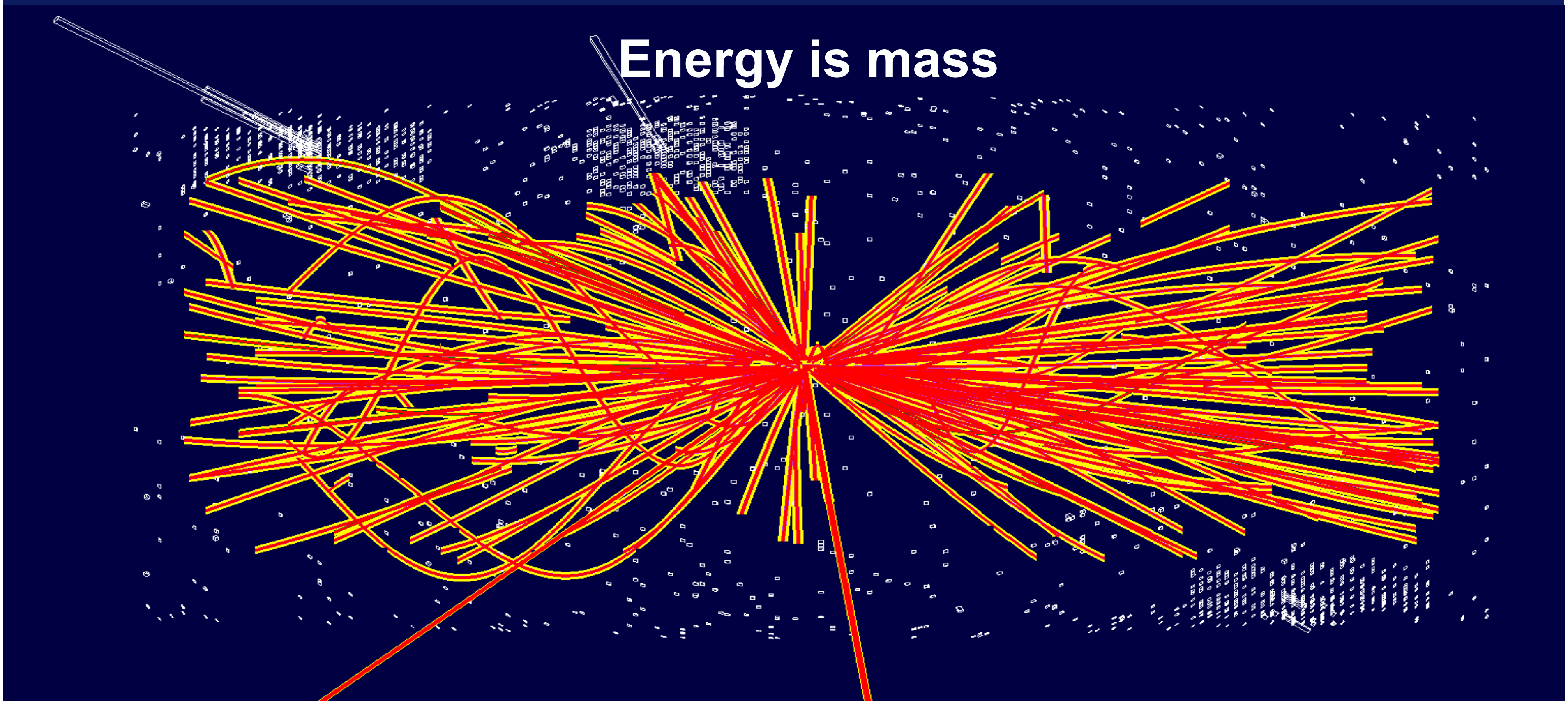
Precision measurements of the top quark and W boson:

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



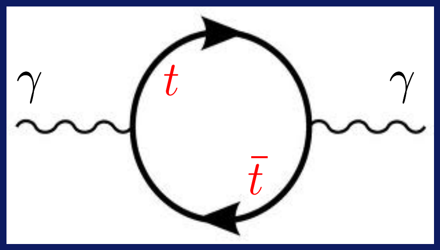
And searching for known particles into which the Higgs transforms (decays) almost instantly

How do we search for the Higgs Boson?

Quantum Fluctuations can produce the Higgs at the LHC

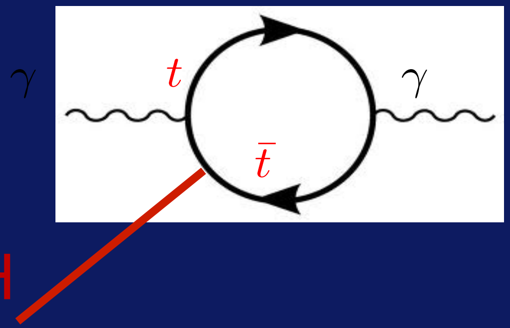
"Nothingness" is the most exciting medium in the cosmos!

Photon propagates in Quantum Vacuum

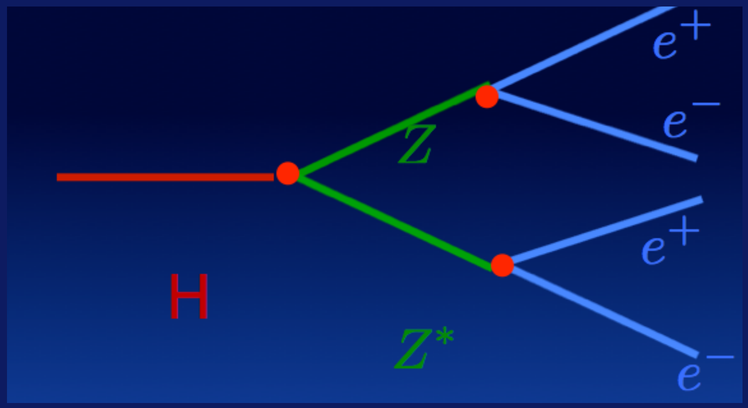


Quantum fluctuations create and annihilate "virtual particles" in the vacuum

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

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

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

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

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

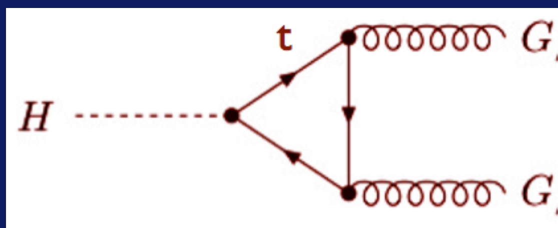
$$\delta_W = 1,\;\; \delta_Z = 7/12 - 10/9\sin^2\theta_W + 40/9\sin^4\theta_W$$

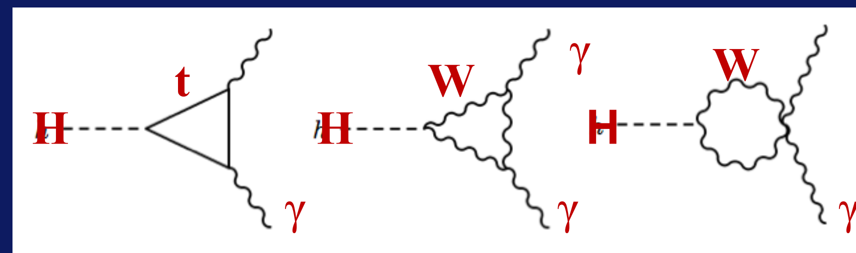
$$R_T(x) \;=\; \frac{3(1-8x+20x^2)}{(4x-1)^{1/2}} \arccos\left(\frac{3x-1}{2x^{3/2}}\right) - \frac{1-x}{2x}(2-13x+47x^2) - \frac{3}{2}(1-6x+4x^2)\log x$$

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

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

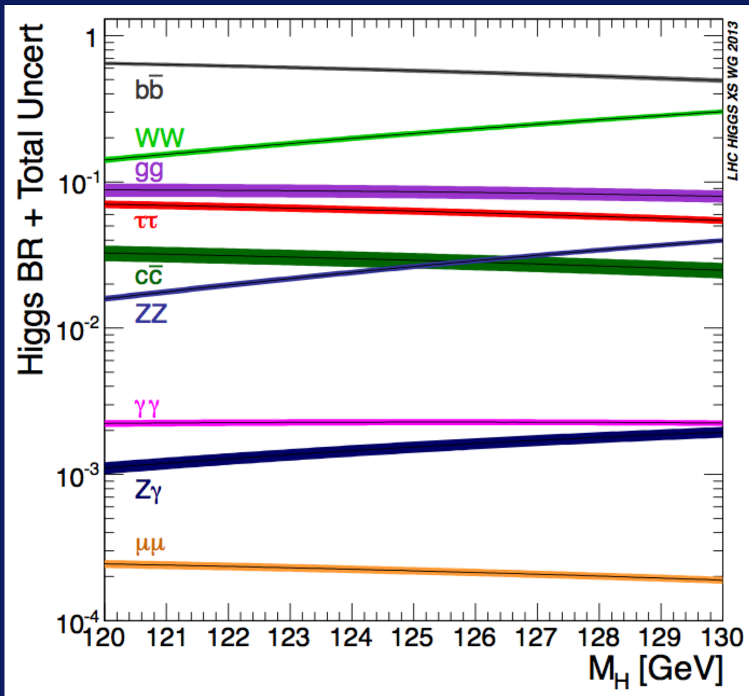
Both particles cannot produced on-shell from Higgs decays. Their contributions may be approximated by

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

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

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



$$BR(h \to XX) \equiv \frac{\Gamma(h \to XX)}{\sum\limits_{\substack{X_i = \\ all\ particles}} \Gamma(h \to X_i X_i)}$$

- 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

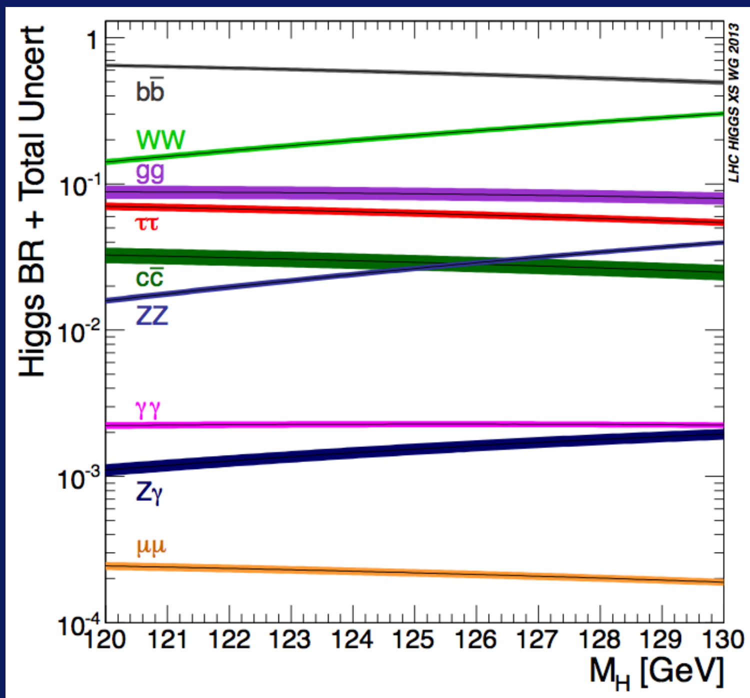
Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$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



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}	$^{+6.0\%}_{-5.9\%}$

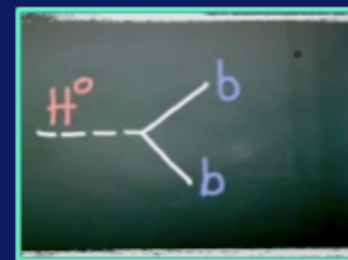
Higgs decays

after about

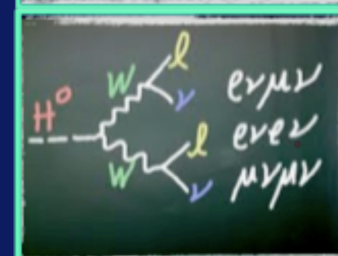
100 yocktoseconds

into various pairs

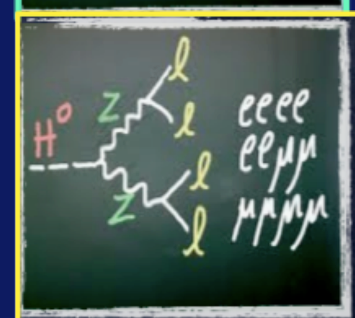
of lighter particles



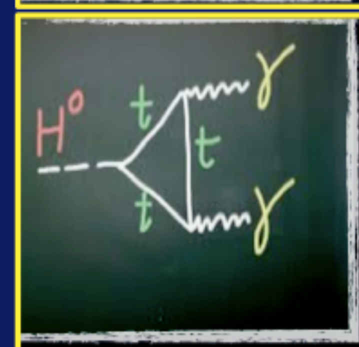
Lots of background



Neutrinos not detected



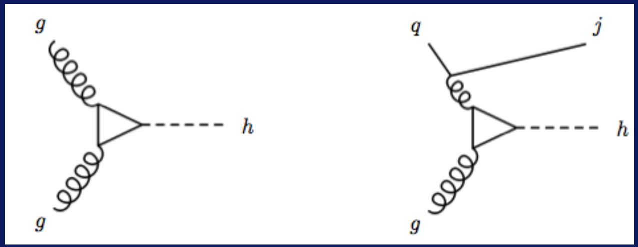
Rare but "Golden" channel



Rare but relatively clean

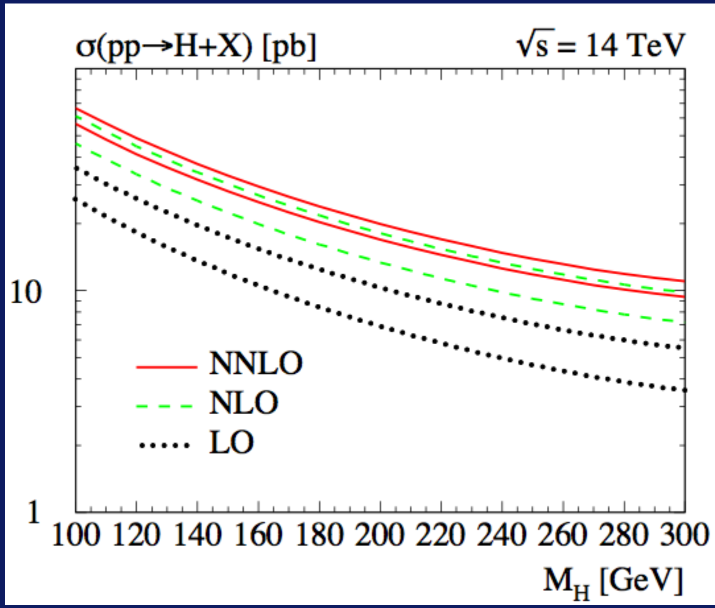
SM Higgs Boson Production at the LHC

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



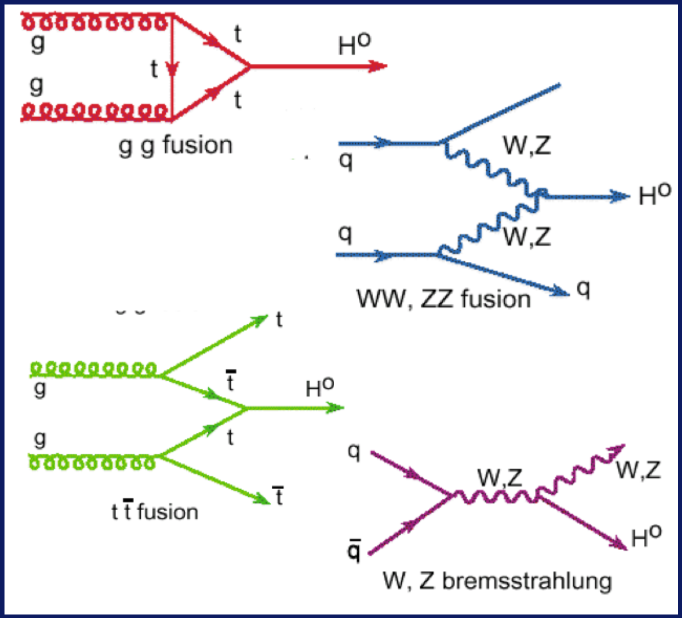
Convergence of the computed Higgs Cross section at LO, NLO, and NNLO in QCD

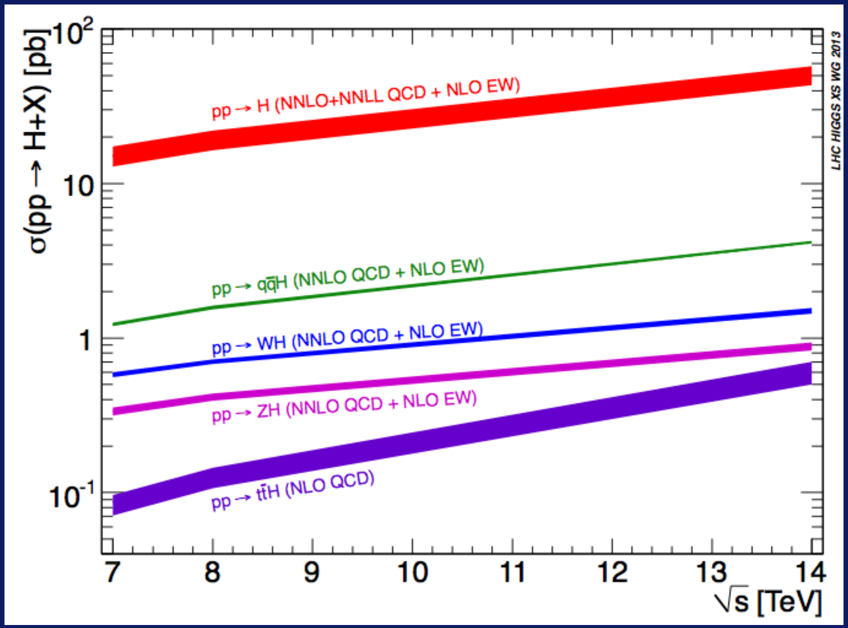
Bands show the renormalization/factorization Scale dependence varying up and down by a factor 2 with respect to a reference scale equal to ¼ of the Higgs mass

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



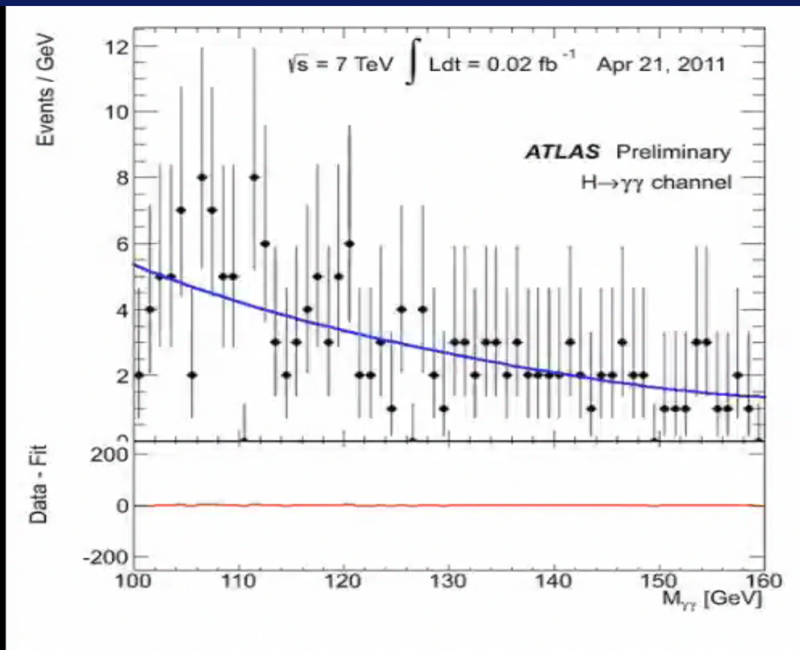


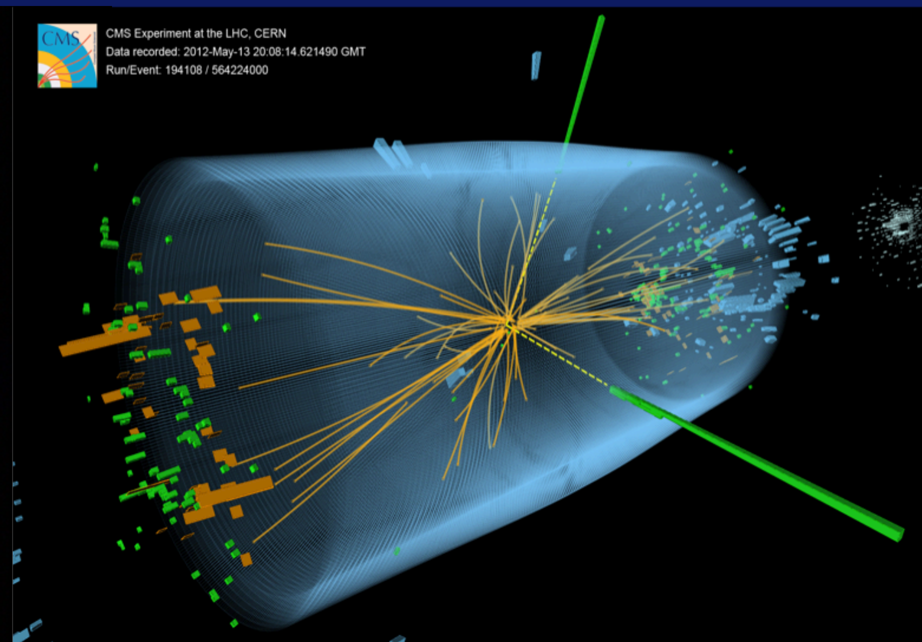
All these processes , together with the decay BR's are important to determine Higgs couplings

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

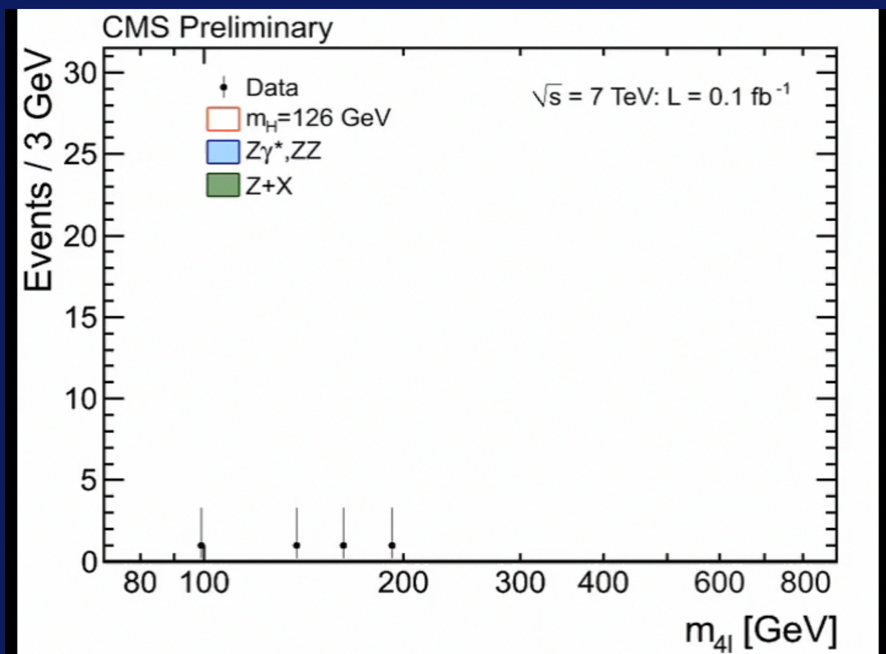


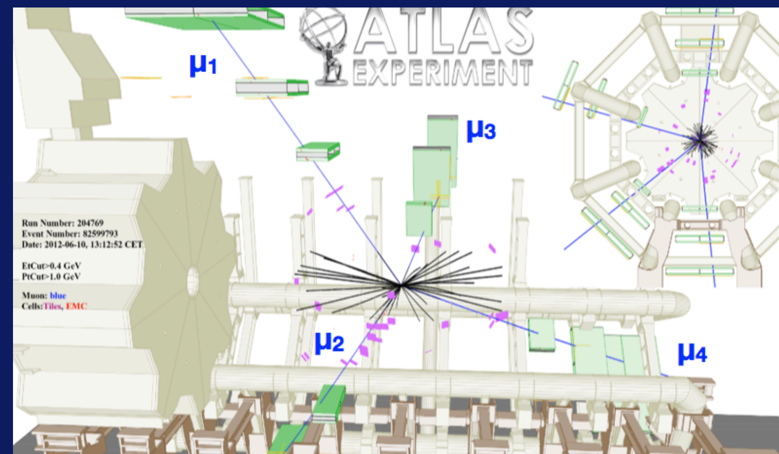


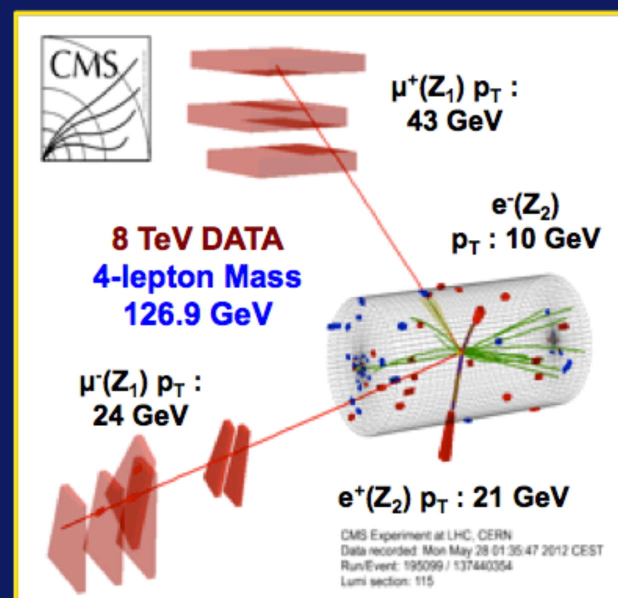
Search for a narrow mass peak
with two isolated high E_T photons
on a smoothly falling background

The Discovery: Higgs → 4 Leptons

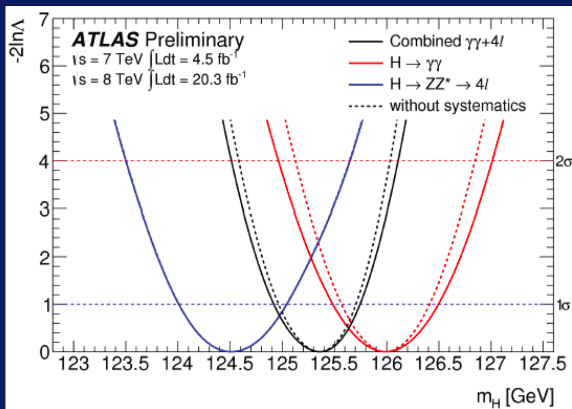
with virtual Z bosons: The Golden Channel

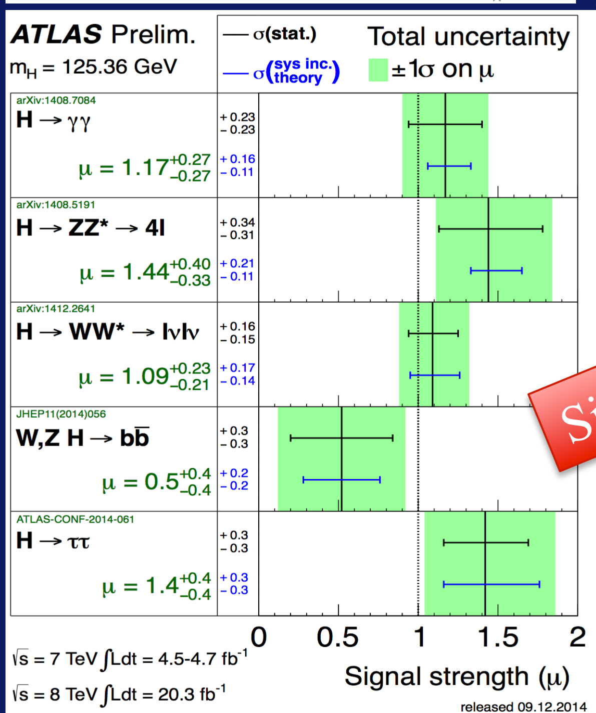






No doubt that a Higgs boson has been discovered



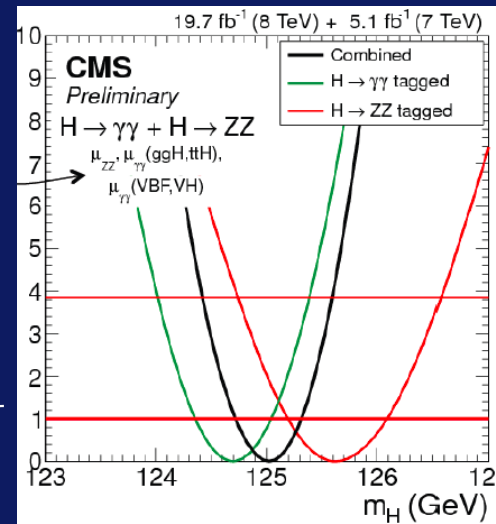


ATLAS:

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

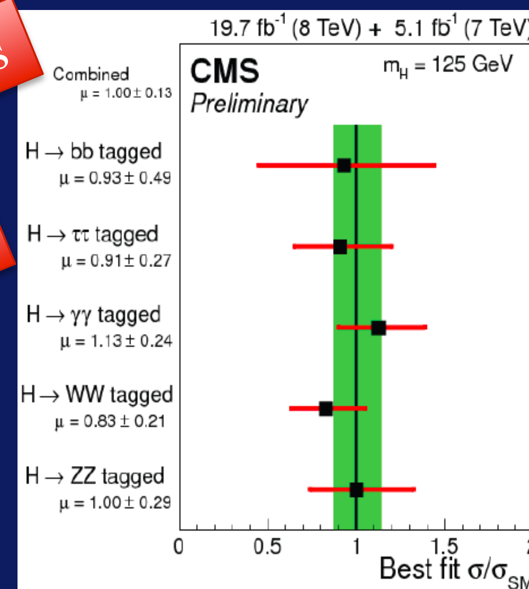
CMS:

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



Signal compatible with SM Higgs

Also room for New Physics



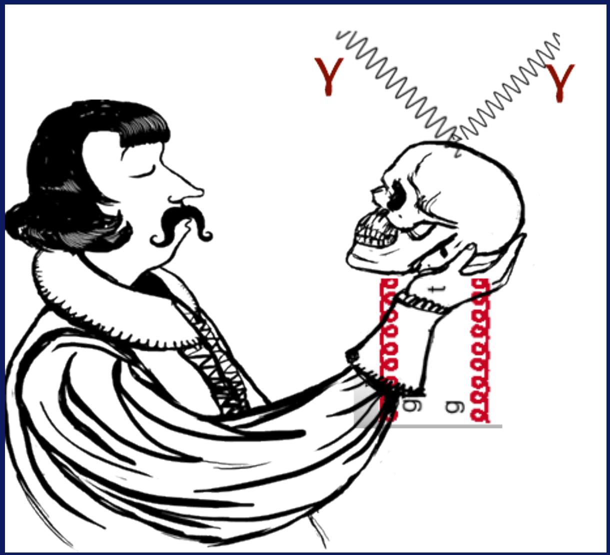
$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \;\left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

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**

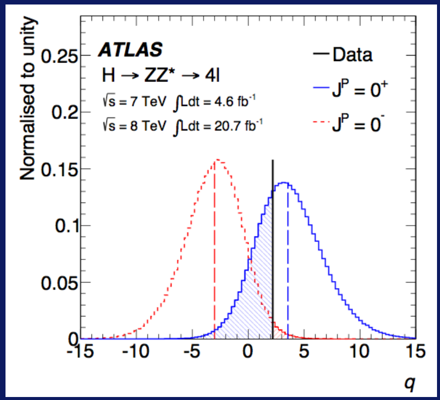
$$g_{WWH}/g_{ZZH} = m_W^2/m_Z^2$$

• **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

Lecture 2

Weakly Interacting Higgs Physics Beyond the SM

Why to expect New Physics?

To explain dark matter, baryogenesis, dynamical origin of fermion properties, tiny neutrino masses…

None of the above demands NP at the electroweak scale

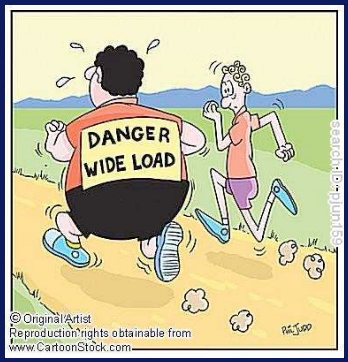
• The Higgs restores the calculability power of the SM

• The Higgs is special : it is a scalar

Scalar masses are not protected by gauge symmetries and at quantum level have quadratic sensitivity to the UV physics

$$\mathcal{L} \propto m^2 |\phi|^2 \qquad \delta \mathbf{m^2} = \sum_{\mathbf{B,F}} \mathbf{g_{B,F}} (-\mathbf{1})^{\mathbf{2S}} \frac{\lambda^{\mathbf{2}}_{\mathbf{B,F}} \mathbf{m^2_{B,F}}}{\mathbf{32}\pi^{\mathbf{2}}} \log(\frac{\mathbf{Q^2}}{\mu^{\mathbf{2}}})$$

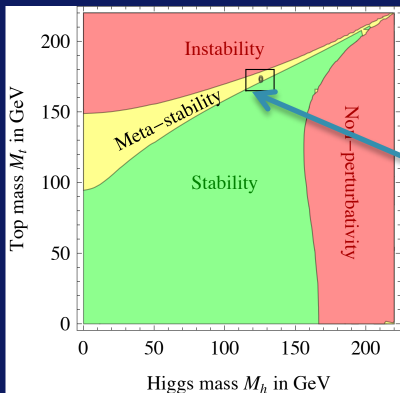
Although the SM with the Higgs is a consistent theory, light scalars like the Higgs cannot survive in the presence of heavy states at GUT/String/Planck scales

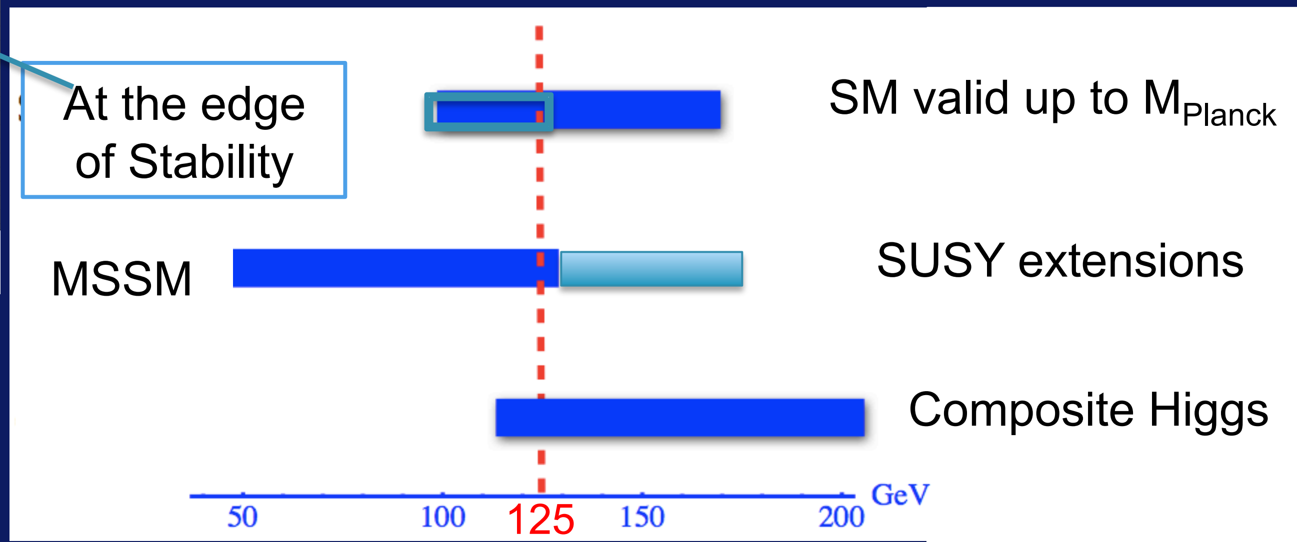


Fine tuning $\longleftrightarrow$ **Naturalness problem**

Looking under the Higgs lamp-post:

What type of Higgs have we seen?





Also, back in fashion:
Twin Higgs and Mirror Worlds

125 GeV is suspiciously light for a composite Higgs boson but it is suspiciously heavy for minimal SUSY

Additional option: Higgs as part of an extended sector (e.g. 2HDM) to explain flavor from the electroweak scale (a la Frogatt Nielsen)

Supersymmetry:

a fermion-boson symmetry :

The Higgs remains elementary but its mass is protected by SUSY ➔ $\delta m^2 = 0$

Composite Higgs Models

The Higgs does not exist above a certain scale, at which the new strong dynamics takes place

➔ dynamical origin of EWSB

New strong resonance masses constrained by Precision Electroweak data and direct searches

Higgs ➔ scalar resonance much lighter that other ones

2HDM's or Higgs Triplet models may induce EWSB and be well motivated from flavor or neutrino physics. Require a UV completion (a more fundamental theory)

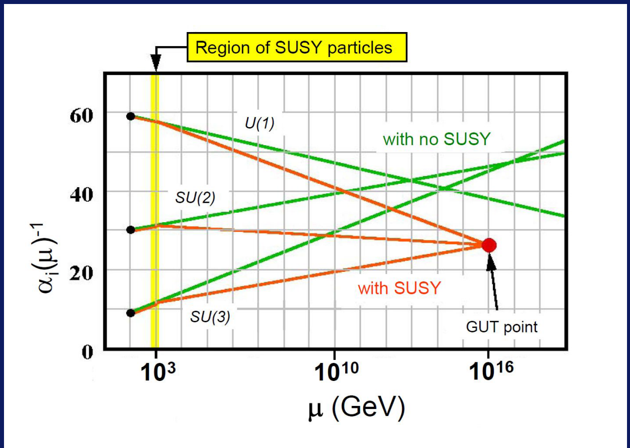
All options imply changes in the Higgs phenomenology and beyond

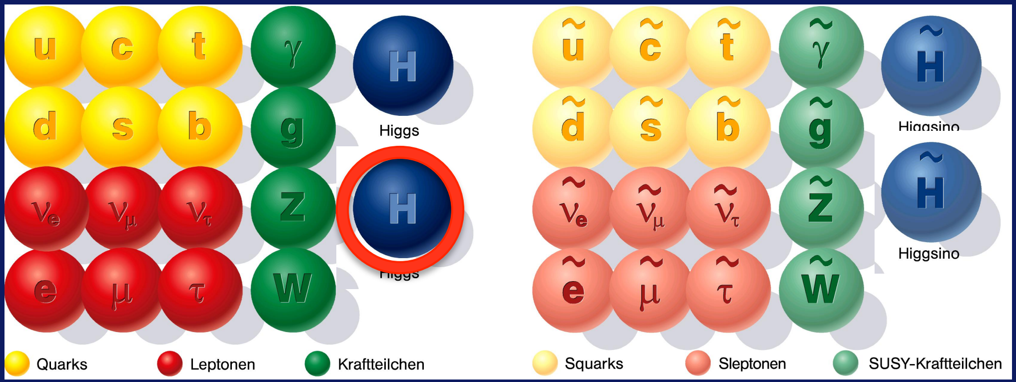
SUSY has many good properties

- **Allows a hierarchy between the electroweak scale and the Planck/unification scales**
- **Generates EWSB automatically from radiative corrections to the Higgs potential**
- Allows gauge coupling unification at ~10^{16} GeV
- Provides a good dark matter candidate:

    The Lightest SUSY Particle (LSP)

- Allows the possibility of electroweak baryogenesis
- String friendly





For every fermion there is a boson with equal mass & couplings

Extended Higgs sector at least a 2HDM (type II)

SUSY and Naturalness

• Higgs mass parameter protected by the fermion-boson symmetry: $\delta m^2 = 0$

In practice, no SUSY particles seen yet ➔ SUSY broken in nature:

$$\delta m^2 \propto M^2_{SUSY}$$

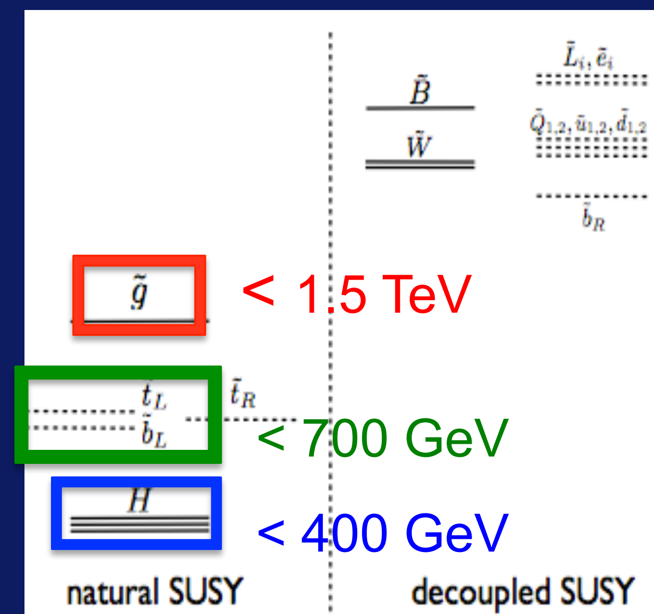
If $M_{SUSY} \sim M_{weak}$ $\longrightarrow$ Natural SUSY

If $M_{SUSY} \ll M_{GUT}$ $\longrightarrow$ big hierarchy problem solved

Where are the superpartners?

- **Not all SUSY particles play a role in the Higgs Naturalness issue**

Higgsinos, stops (sbottoms) and gluinos are special



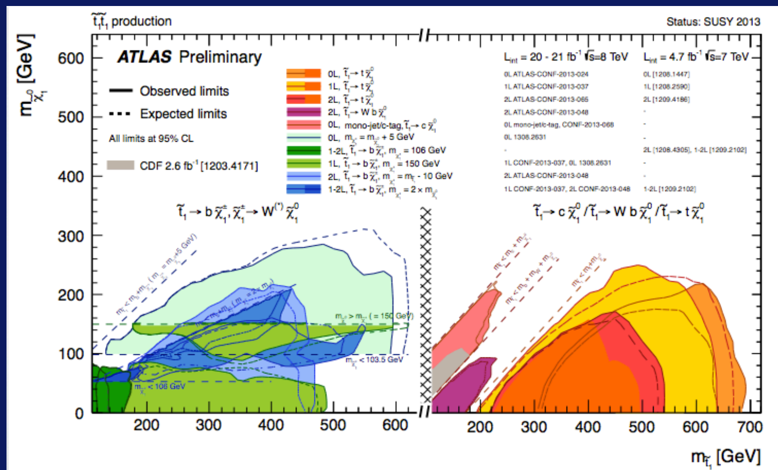
Papucci, Rudermann, Weiler '11

- So why didn't we discover any SUSY particle already at LEP, Tevatron, or LHC8?

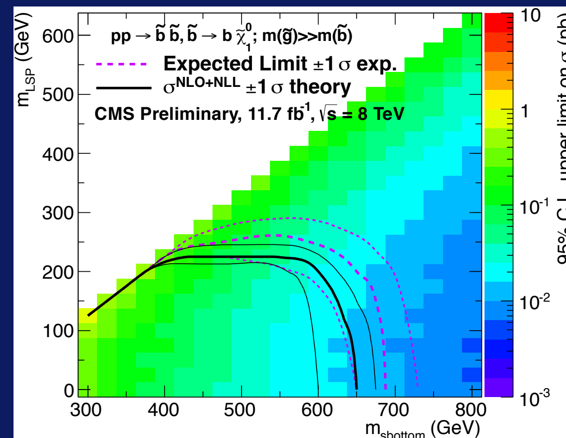
SUSY Weltschmerz*?

ATLAS/CMS are aggressively pursuing the signatures of "naturalness".

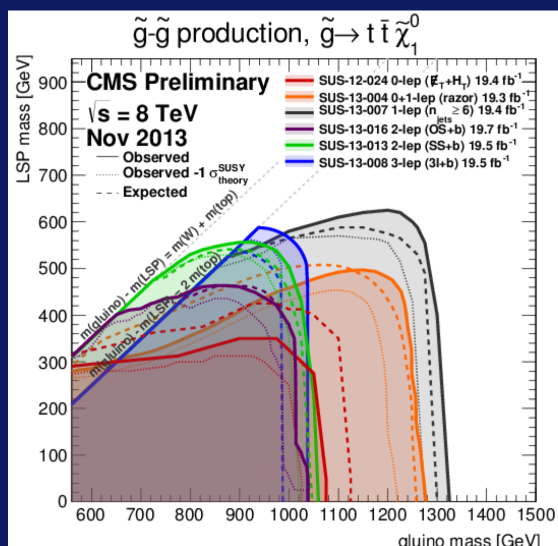
stops



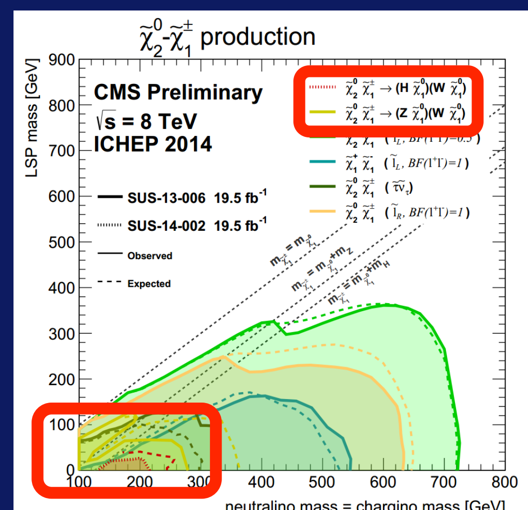
sbottoms



gluinos



Higgsinos



The feeling experienced by someone who understands that physical reality can never satisfy the demands of the mind

Is SUSY hiding?

It is possible to have SUSY models with super-partners well within LHC8 kinematic reach, but with ***degraded*** missing energy signatures or event activity

- Compressed spectra: e.g. stop mass ~ charm mass + LSP mass

M.C., Freitas, Wagner '08

- Stealth SUSY: long decay chains soften the spectrum of observed particles from SUSY decays
- The LSP is not the dark matter, but decays

ATLAS/CMS closing the gaps

Still many opportunities for non-minimal "Natural" SUSY models, not yet badly threaten by LHC:

• address flavor as part of the SUSY breaking mechanism

connect lightness of 3rd generation sfermions to heaviness of 3rd generation fermions

• alleviate the tension of a Higgs mass that needs sizeable radiative corrections from stop contributions, by raising its tree level value

additional SM singlets or triplets or models with enhanced weak gauge symmetries

General Features of 2HDM's (e.g. minimal SUSY)

The simplest extension of the SM is to add one Higgs doublet, with the same quantum numbers as the SM one.

Now, we will have contributions to the gauge boson masses coming from the vacuum expectation value of both fields

$$(\mathcal{D}\phi_i)^\dagger \mathcal{D}\phi_i \rightarrow g^2 \phi_i^\dagger T^a T^b \phi_i A_\mu^a A^{\mu,b}$$

Therefore, the gauge boson masses are obtained from the SM expressions by simply replacing

$$v^2 \rightarrow v_1^2 \ + \ v_2^2$$

There is then a free parameter, that is the ratio of the two vacuum expectation values, and this is usually denoted by

$$\tan\beta = \frac{v_2}{v_1}$$

The number of would-be Goldstone modes are the same as in the SM, namely 3. Therefore, there are still 5 physical degrees of freedom in the scalar sector which are a charged Higgs, a CP-odd Higgs and two CP-even Higgs bosons.

Goldstone Modes and Physical States

Since both Higgs fields carry the same quantum numbers, one can always define the combinations

$$\frac{H_2 v_2 + H_1 v_1}{\sqrt{v_1^2 + v_2^2}} \equiv H_2 \sin\beta + H_1 \cos\beta = H_v$$

$$\frac{H_2 v_1 - H_1 v_2}{\sqrt{v_1^2 + v_2^2}} \equiv H_2 \cos\beta - H_1 \sin\beta = H_{NS}$$

The first combination acquires vacuum expectation value v. The second does not acquire a vacuum expectation value.

Then, it is clear that the Goldstone modes will be the charged and the imaginary part of the neutral components of H_v

The charged and imaginary part of the neutral components of H_{NS} will be the physical charged and CP-odd Higgs bosons respectively.

$$G^{\pm} = H_2^{\pm} \sin\beta + H_1^{\pm} \cos\beta$$

$$H^{\pm} = -H_2^{\pm} \cos\beta + H_1^{\pm} \sin\beta$$

$$\sqrt{2}\ G^0 = \mathrm{Im} H_2^0 \sin\beta + \mathrm{Im} H_1^0 \cos\beta$$

$$\sqrt{2}\ A = -\mathrm{Im} H_2^0 \cos\beta + \mathrm{Im} H_1^0 \sin\beta$$

What about the CP-even states ? There is no symmetry argument and in principle both states could mix.

CP-even Higgs Bosons

There is no symmetry argument and in general these two Higgs boson states w
mix. The mass eigenvalues, in increasing order of mass, will be

$$\sqrt{2}\ h = -\sin\alpha\ \mathrm{Re}H_1^0 + \cos\alpha\ \mathrm{Re}H_2^0$$
$$\sqrt{2}\ H = \cos\alpha\ \mathrm{Re}H_1^0 + \sin\alpha\ \mathrm{Re}H_2^0$$

From here one can easily obtain the coupling to the gauge bosons. This is simpl
given by replacing in the mass contributions

$$v_i \to v_i + ReH_i^0$$

This leads to a coupling proportional to

$$v_i\ \mathrm{Re}H_i^0$$

Hence, the effective coupling of h is given by

$$hVV = (hVV)^{\mathrm{SM}}(-\cos\beta\sin\alpha + \sin\beta\cos\alpha) = (hVV)^{\mathrm{SM}}\sin(\beta-\alpha)$$
$$HVV = (hVV)^{\mathrm{SM}}(\cos\beta\cos\alpha + \sin\beta\sin\alpha) = (hVV)^{\mathrm{SM}}\cos(\beta-\alpha)$$

These proportionality factors are nothing but the projection of the Higgs mass
eigenstates into the one acquiring a vacuum expectation value.

CP-even Higgs Bosons

There is no symmetry argument and in general these two Higgs boson states w
mix. The mass eigenvalues, in increasing order of mass, will be

$$\sqrt{2}\ h = -\sin\alpha\ \mathrm{Re}H_1^0 + \cos\alpha\ \mathrm{Re}H_2^0$$
$$\sqrt{2}\ H = \cos\alpha\ \mathrm{Re}H_1^0 + \sin\alpha\ \mathrm{Re}H_2^0$$

From here one can easily obtain the coupling to the gauge bosons. This is simpl
given by replacing in the mass contributions

$$v_i \to v_i + ReH_i^0$$

This leads to a coupling proportional to

$$v_i\ \mathrm{Re}H_i^0$$

Hence, the effective coupling of h is given by

$$hVV = (hVV)^{\mathrm{SM}}(-\cos\beta\sin\alpha + \sin\beta\cos\alpha) = (hVV)^{\mathrm{SM}}\sin(\beta-\alpha)$$
$$HVV = (hVV)^{\mathrm{SM}}(\cos\beta\cos\alpha + \sin\beta\sin\alpha) = (hVV)^{\mathrm{SM}}\cos(\beta-\alpha)$$

These proportionality factors are nothing but the projection of the Higgs mass
eigenstates into the one acquiring a vacuum expectation value.

Fermion Masses and Flavor

Similarly to the gauge boson masses, the fermion masses are obtain from the sum of the contributions of both Higgs fields.

For instance, the down-quark mass matrix is given by

$$M_d^{ij} = h_{d,1}^{ij} \frac{v_1}{\sqrt{2}} + h_{d,2}^{ij} \frac{v_2}{\sqrt{2}}$$

The interaction of the two CP-even scalars with fermions is given, instead, by

$$g_{hd_id_j} \propto h_{d,1}^{ij}(-\sin\alpha) + h_{d,2}^{ij}(\cos\alpha)$$
$$g_{Hd_id_j} \propto h_{d,1}^{ij}(\cos\alpha) + h_{d,2}^{ij}(\sin\alpha)$$

So, contrary to the SM, the rotation that diagonalizes the mass matrix does not diagonalize the couplings. This in general leads to large Higgs mediated Flavor changing processes, that are in conflict with experiment.

One solution is to make the non-standard Higgs bosons very heavy, going close to the SM. Another natural solution is to restrict the couplings of each fermion sector to only one of the two Higgs doublets. This is what happens to a good approximation in supersymmetry.

Fermion-Higgs Couplings and Different Types of 2HDM's

Model	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

Add Symmetry transformations that determine the allowed Higgs boson couplings to up, down and charged lepton-type $SU(2)_L$ singlet fermions in four discrete types of 2HDM models

Low Energy Supersymmetry: 2HDM Type II

In Type II models, the Higgs H1 would couple to down-quarks and charge leptons, while the Higgs H2 couples to up quarks and neutrinos. Therefore,

$$g_{hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{(-\sin\alpha)}{\cos\beta}, \quad g_{Hff}^{dd,ll} = \frac{\mathcal{M}_{dd,ll}^{\rm diag}}{v} \frac{\cos\alpha}{\cos\beta} \quad g_{Aff}^{dd,ll} = \frac{\mathcal{M}_{\rm diag}^{\rm dd}}{v} \tan\beta$$

$$g_{hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{(\cos\alpha)}{\sin\beta}, \quad g_{Hff}^{uu} = \frac{\mathcal{M}_{uu}^{\rm diag}}{v} \frac{\sin\alpha}{\sin\beta} \quad g_{Aff}^{uu} = \frac{\mathcal{M}_{\rm diag}^{\rm uu}}{v\tan\beta}$$

If the mixing is such that $\cos(\beta-\alpha)=0$ $\longrightarrow$ **Decoupling limit obtained for large masses of non-standard Higgs bosons**

$$\sin\alpha = -\cos\beta,$$
$$\cos\alpha = \sin\beta$$

then the coupling of the lightest Higgs to fermions and gauge bosons is SM-like. This limit is called decoupling limit. Is it possible to obtain similar relations for lower values of the CP-odd Higgs mass ? We shall call this situation ALIGNMENT

The Higgs Potential

The most generic two Higgs doublet potential is given by

$$V = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} ,$$

One can minimize this potential and use the minimization conditions to derive the CP-odd and charged Higgs masses as a function of one mass parameter and the quartic couplings

$$m_A^2 = \frac{2m_{12}^2}{s_{2\beta}} - \frac{1}{2}v^2(2\lambda_5 + \lambda_6 t_\beta^{-1} + \lambda_7 t_\beta) \qquad m_H^{\pm} = m_A^2 + \frac{v^2}{2}(\lambda_5 - \lambda_4)$$

Using the minimization conditions one can also derive the masses in the CP-even sector, in terms of m_A and the quartic couplings

$$\mathcal{M} = \begin{pmatrix} \mathcal{M}_{11} & \mathcal{M}_{12} \\ \mathcal{M}_{12} & \mathcal{M}_{22} \end{pmatrix} \equiv m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}$$

$$L_{11} = \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 ,$$
$$L_{12} = (\lambda_3 + \lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2$$
$$L_{22} = \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 .$$

For large mA and perturbative quartics we can ignore the second term in the right hand side and one obtains that $m_H \sim m_A$, while m_h is of order an effective quartic coupling times v^2

Alignment without Decoupling

The eigenstate equation may be rewritten in the following way

$$\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} = -\frac{v^2}{m_A^2} \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} + \frac{m_h^2}{m_A^2} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

For large values of the CP-odd Higgs mass we obtain

$$\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} \approx 0 \qquad \cos(\beta - \alpha) = 0$$

Now, the idea would be to obtain this condition for lower CP-odd Higgs masses, independently of m_A

$$v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} = m_h^2 \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

Valid for any 2HDM

$$m_h^2 = v^2 L_{11} + t_\beta v^2 L_{12} = v^2 \left(\lambda_1 c_\beta^2 + 3\lambda_6 s_\beta c_\beta + \tilde{\lambda}_3 s_\beta^2 + \lambda_7 t_\beta s_\beta^2\right) \;,$$

$$m_h^2 = v^2 L_{22} + \frac{1}{t_\beta} v^2 L_{12} = v^2 \left(\lambda_2 s_\beta^2 + 3\lambda_7 s_\beta c_\beta + \tilde{\lambda}_3 c_\beta^2 + \lambda_6 t_\beta^{-1} c_\beta^2\right)$$

Alignment without Decoupling ➔ other light Higgs Bosons

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) \; ,$$
$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

Alignment conditions

If fulfilled not only alignment is obtained, but also the right Higgs mass, $m_h^2 = \lambda_{\rm SM} v^2$, with $\lambda_{\rm SM} \simeq 0.26$ and $\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$

$$\lambda_{\rm SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + \lambda_2 \sin^4\beta$$

- Case of $\lambda_{6,7} = 0$ (SUSY at tree level)

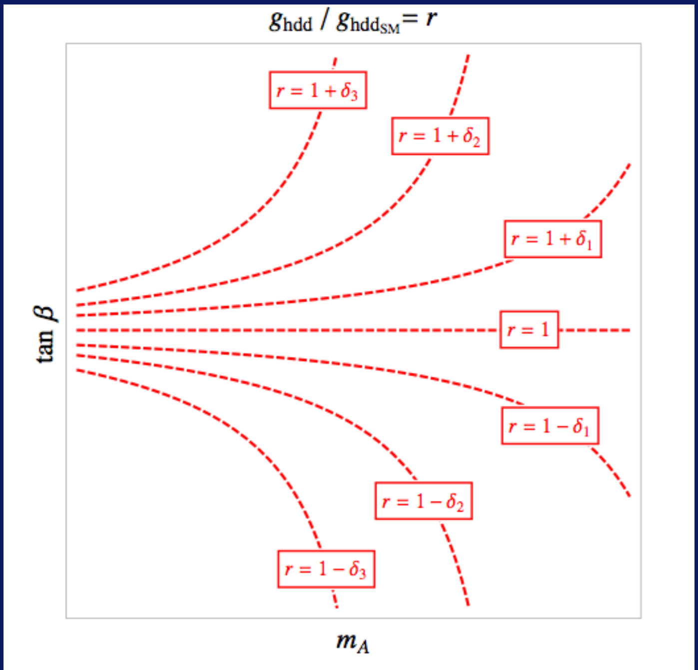
The additional condition is $\tan^2\beta = \dfrac{\lambda_1 - \lambda_{\rm SM}}{\lambda_{SM} - \tilde{\lambda}_3}$ and should be positive.

In the MSSM, this ratio tends to be negative, but tends to be positive in the NMSSM.

- Case of $\lambda_{6,7} \neq 0$

Alignment may occur at sizable tan beta

e.g in the MSSM $$t_\beta^{(1)} = \frac{\lambda_{\rm SM} - \tilde{\lambda}_3}{\lambda_7}$$



Down-quark coupling behavior for the lightest Higgs boson in the proximity of alignment

The Minimal SUSY Higgs Sector

2 Higgs doublets necessary to give mass to both up and down quarks and leptons in gauge/SUSY invariant way

2 Higgsino doublets necessary for anomaly cancellation

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
Higgs, higgsinos	H_u	$(H_u^+ \quad H_u^0)$	$(\widetilde{H}_u^+ \quad \widetilde{H}_u^0)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H_d^0 \quad H_d^-)$	$(\widetilde{H}_d^0 \quad \widetilde{H}_d^-)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$

- Both Higgs fields acquire v.e.v. New parameter, $\tan\beta = v_2/v_1$.

$$V_{SUSY}(H_u, H_d) = |\mu|^2(H_u^\dagger H_u + H_d^\dagger H_d) + \frac{(g_1^2+g_2^2)}{8}((H_u^\dagger H_u)^2 + (H_d^\dagger H_d)^2)$$
$$+ \frac{(g_1^2-g_2^2)}{4} H_u^\dagger H_u H_d^\dagger H_d - \frac{g_2^2}{2}|H_d^T i\tau_2 H_u|^2$$

$$H_1 = \begin{pmatrix} \mathrm{v}_1 + (H_1^0 + iA_1)/\sqrt{2} \\ H_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_2^+ \\ \mathrm{v}_2 + (H_2^0 + iA_2)/\sqrt{2} \end{pmatrix}$$

$$\boxed{\begin{array}{c} H_1 \equiv H_d \\ H_2 \equiv H_u \end{array}}$$

The supersymmetric parameter μ defines the higgsino masses and plays a relevant role in Higgs physics

SM-like Higgs boson mass in the Minimal SUSY SM extension

depends on: **CP-odd mass m_A, tanβ, M_t** **and Stop masses & mixing**

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

For large m_A

$$m_h^2 = \underbrace{M_Z^2 \cos^2 2\beta}_{< (91\ \text{GeV})^2} + \Delta m_h^2$$

$$\Delta m_h^2 = \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

m_h depends logarithmically on the averaged stop mass scale $\mathbf{M_{SUSY} \sim m_Q \sim m_U}$

$$t = \log(M_{SUSY}^2 / m_t^2)$$

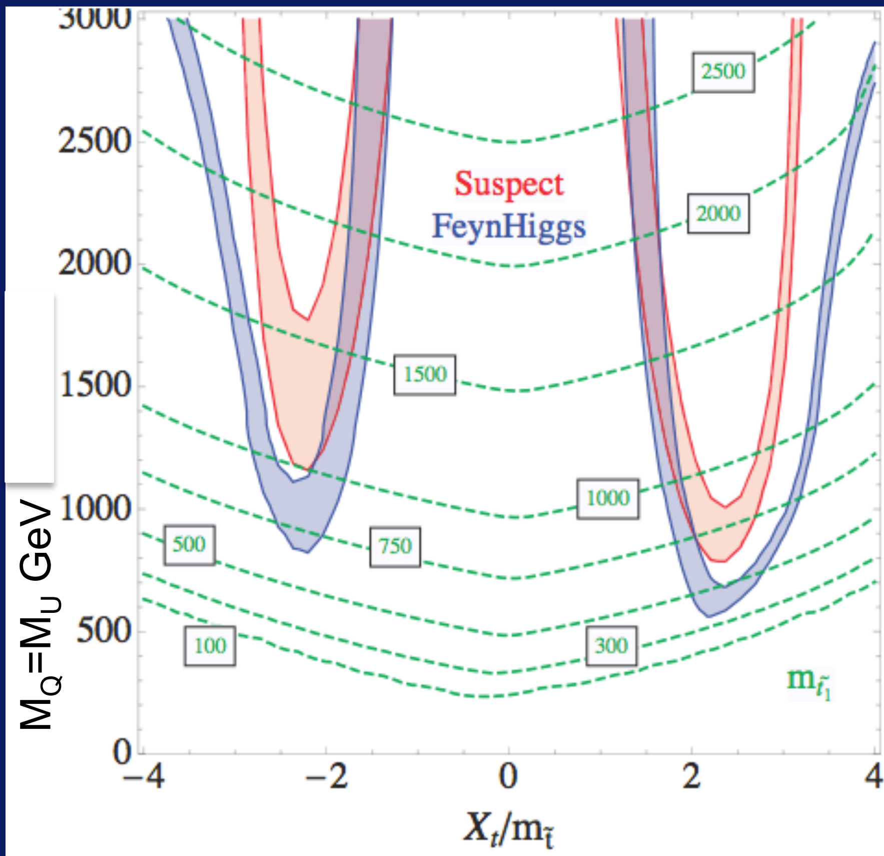
and has a quadratic and quartic dep. on the stop mixing parameter $X_t = A_t - \mu/\tan\beta$

$$\tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)$$

Also dependence on sbottoms/staus for large tanβ

Two-loop computations: Brignole, M.C, Degrassi, Diaz, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, Wagner,Weiglein, Zhang, Zwirner

Stop Spectra and the Higgs Mass in the MSSM



Hall, Pinner, Ruderman'11

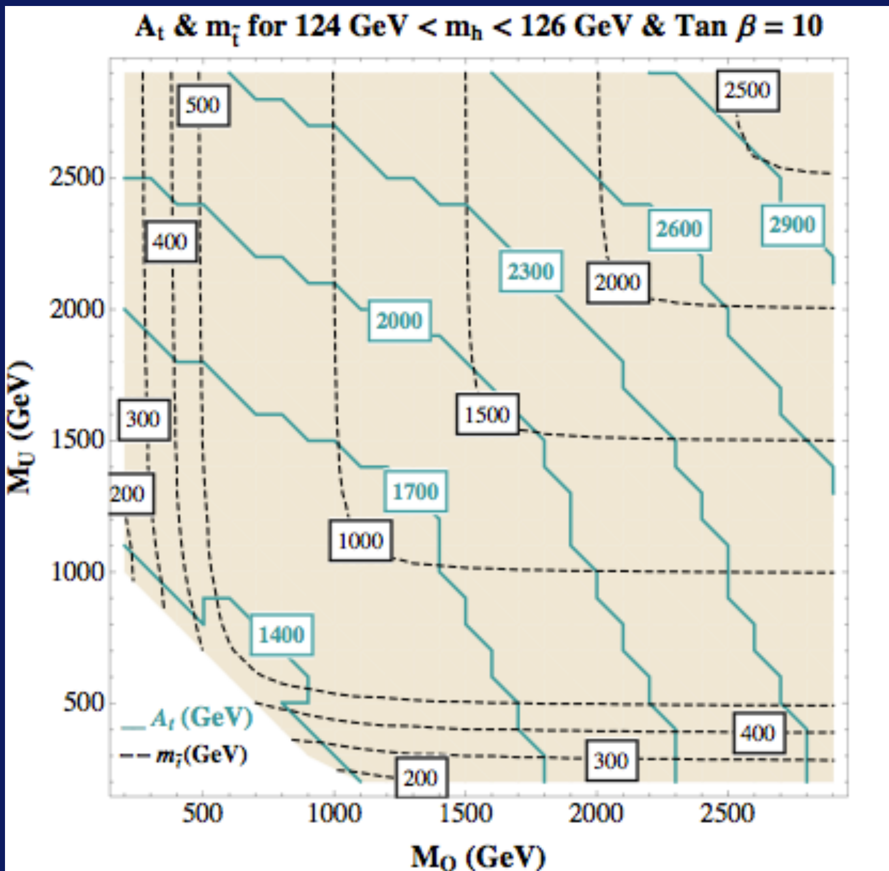
Large mixing in the stop sector
A_t > 1 TeV
[Unless stop very heavy (5-10 TeV)]

In the case of similar stop soft masses both stops should be > 500 GeV

Large mixing also constrains SUSY breaking model building

Similar results from
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon; Draper Meade, Reece, Shih
Heinemeyer, Stal, Weiglein'11; Ellwanger'11; Shirman et al.

Stop Spectra and the Higgs Mass in the MSSM



M. C., S. Gori, N. Shah, C. Wagner '11
+L.T.Wang '12

Large mixing in the stop sector
A_t > 1 TeV
[Unless stop very heavy (5-10 TeV)]

In the case of similar stop soft masses both stops should be > 500 GeV

For hierarchical stop soft masses, one stop can be light (~ few 100 GeV) and the other heavy (> 1 TeV)

Direct Stop searches at LHC are probing these mass regime

Similar results from
Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon; Draper Meade, Reece, Shih
Heinemeyer, Stal, Weiglein'11; Ellwanger'11; Shirman et al.

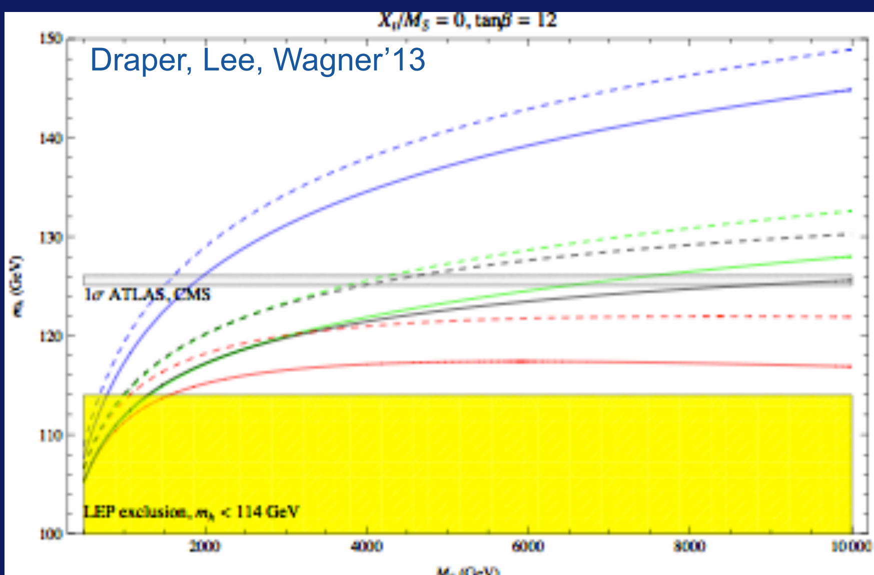
• A 125 GeV Higgs and light stops

Light stop coupling to the Higgs $$m_Q \gg m_U; \qquad m_{\tilde{t}_1}^2 \simeq m_U^2 + m_t^2 \left(1 - \frac{X_t^2}{m_Q^2}\right)$$

Lightest stop coupling to the Higgs approximately vanishes for Xt ~m_Q
Higgs mass pushes us in that direction
Modification of the gluon fusion rate mild due to this reason.

• A 125 GeV Higgs and very heavy stops

An upper bound on the SUSY scale [stop masses < 10 TeV]
if tanβ moderate or large (> 5-10)]



Recalculation of RG prediction with 4 loops in RG expansion:

The importance of higher order loop computations

See also: Martin'07; Strumia et al; Kant et al; *Feng, et al.;* G. Kane et al.: A.Arvanitaki et al.

Extensions of the MSSM

- MSSM with explicit CP violation (radiatively induced): no effect on m_h

Pilaftsis, Wagner '99

- Add new degrees of freedom that contribute at tree level to mh (new quartics)

new F term contributions ➔ e.g. additional SM singlets or triplets

Possible additional CP violation at tree level ➔ relevant for EW baryogenesis

and/or additional D terms ➔ models with enhanced weak gauge symmetries

New gauge bosons (~ a few TeV) at LHC reach?

- A more model-independent approach: (SUSY breaking as a perturbation)

SUSY 2HDM effective field theory with higher dimensional operators

Dine, Seiberg, Thomas; Antoniadis, Dudas, Ghilencea, Tziveloglou; M.C, Kong, Ponton, Zurita

look at specific examples singlet, triplets with Y =0 ; 1, and extra gauge bosons

Effects most relevant for small tanβ; for $M_A > 400$ GeV pheno very close to MSSM

Otherwise, new decay channels: H to AA/AZ, and H^+ to W^+A may be open (alignment?)

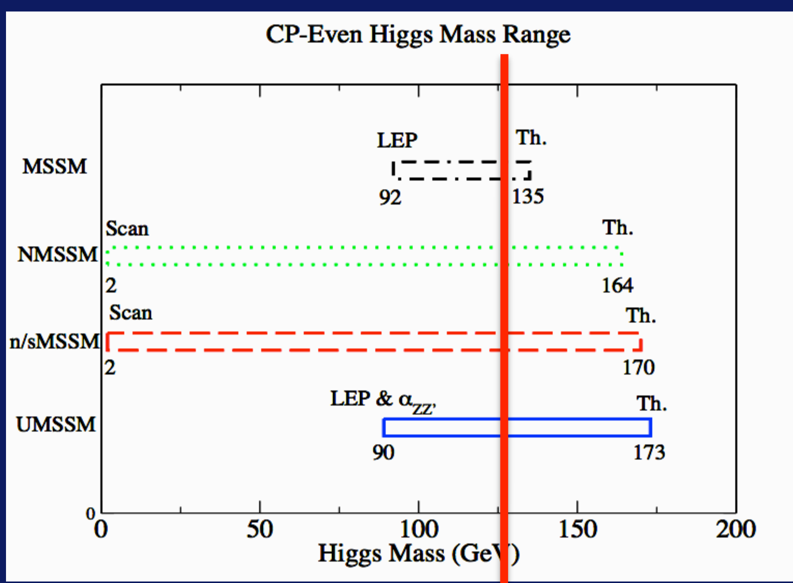
Singlet extensions of the MSSM

A solution to the μ problem: Superpotential ↄ $\lambda_s S H_u H_d$ ➔ $\mu_{eff} = \lambda_s \langle S \rangle$

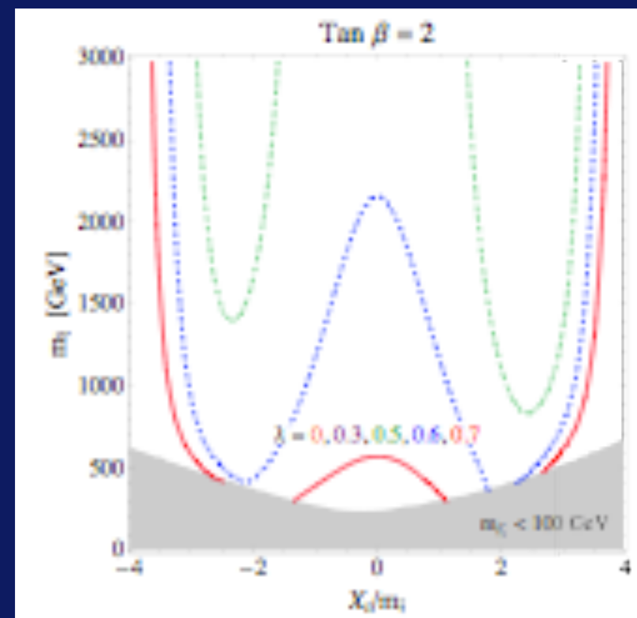
$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda_S^2 v^2 \sin^2 2\beta + \text{rad. corrections}$$

Main one-loop level contributions common with the MSSM

Model	MSSM	NMSSM	nMSSM	UMSSM
Symmetry	-	Z_3	Z_5^R, Z_7^R	$U(1)'$
Superpotential	$\mu \Phi_2 \cdot \Phi_1$	$\lambda_S S \Phi_2 \cdot \Phi_1 + \frac{\kappa}{3} S^3$	$\lambda_S S \Phi_2 \cdot \Phi_1 + t_F S$	$\lambda_S S \Phi_2 \cdot \Phi_1$
H_i^0	2	3	3	3
A_i^0	1	2	2	1



m_{H1} =125 GeV



Hall, Pinner, Ruderman'11

At low tan beta, trade requirement on large stop mixing by sizeable trilinear Higgs-Higgs singlet coupling λ_S
- more freedom on gluon fusion production -

SUSY with extended Gauge Sectors

TeV scale new gauge interactions, and MSSM Higgs bosons charged under them :

D term lifting of m_h^{tree}

requires extended gauge and Higgs sectors are integrated out in a non-SUSY way

Simplest example: extended $SU(2)_1 \times SU(2)_2$ sector spontaneously broken to $SU(2)_L$

bi-doublet Σ under the two SU(2) gauge groups acquires $\langle\Sigma\rangle = u$

Heavy gauge boson: $M_{W'}^2 = (g_1^2 + g_2^2)\, u^2/2$ $SU(2)_L$: $g^2 = g_1^2 g_2^2/(g_1^2 + g_2^2)$

Flavor option: 3rd gen. fermions and Higgs doublets charged under $SU(2)_1$,
while the 2nd and 1st gen. are charged under $SU(2)_2$.

$$\boxed{m_h^2|_{tree} = \frac{g^2\Delta + g'^2}{4} v^2 \cos^2 2\beta}$$ with $$\Delta = \left(1 + \frac{4m_\Sigma^2}{g_2^2 u^2}\right)\left(1 + \frac{4m_\Sigma^2}{(g_1^2 + g_2^2)u^2}\right)^{-1}$$

m_Σ

$\cancel{\text{SUSY}}$ mass

For $m_\Sigma \rightarrow 0$ one recovers the MSSM; for $m_\Sigma \gg M_{W'}$ the D term is that of $SU(2)_1$

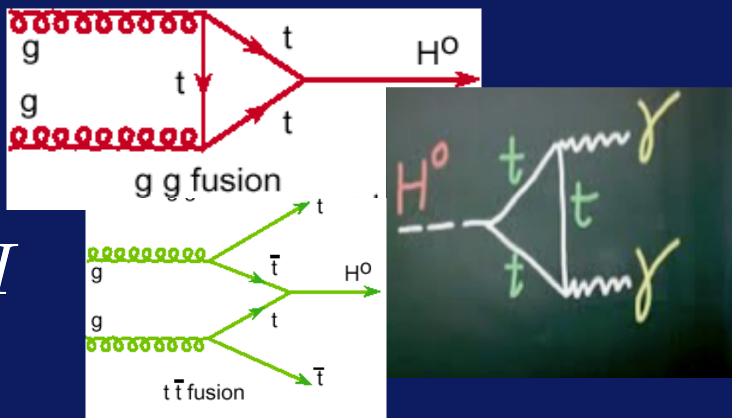
For $m_\Sigma \sim M_{W'}$ and $g_1 \sim g_2 \sim O(1)$ ➔ $m_h \sim 125$ GeV without heavy stops or large stop mixing

- In addition, in gauge extensions m_h can be increased due to RG evolution of the Higgs quartic couplings at low energies, in the presence of light strongly coupled gauginos

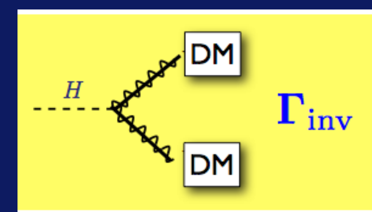
What do the Higgs Production and Decay rates tell us?

Many different pieces of information: $B\sigma(p\bar{p} \to h \to X_{\mathrm{SM}}) \equiv \sigma(p\bar{p} \to h)\dfrac{\Gamma(h \to X_{\mathrm{SM}})}{\Gamma_{\mathrm{total}}}$

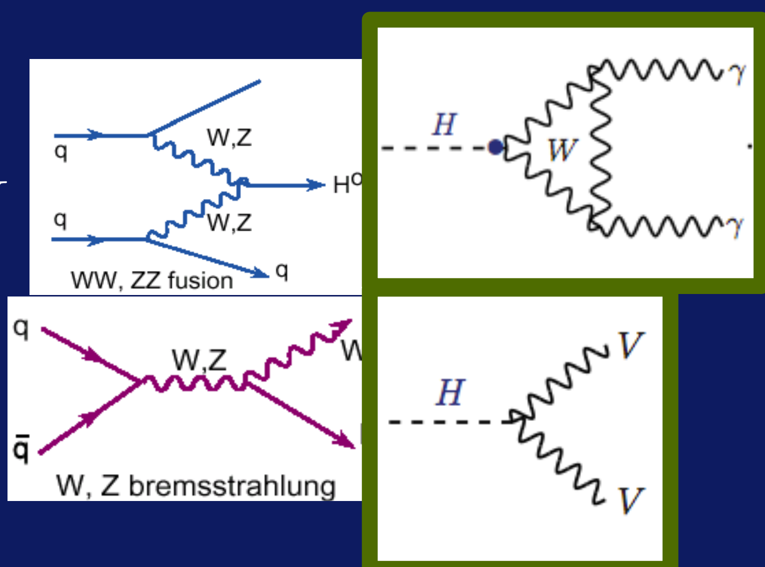
$t\bar{t}H$



also $H \to b\bar{b}, \tau^+\tau^-$



VVH



Different patterns of deviations from SM couplings if:

- New light charged or colored particles in loop-induced processes
- Modification of tree level couplings due to mixing effects
- Decays to new or invisible particles

crucial info on NP from Higgs precision measurements

Loop induced Couplings of the Higgs to Gauge Boson Pairs

Low energy effective theorems

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi}\frac{h}{v}\left[\sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{F,i}^{\dagger}\mathcal{M}_{F,i}\right) + \sum_i b_i \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{B,i}^{2}\right)\right] F_{\mu\nu}F^{\mu\nu}$$

Ellis, Gaillard, Nanopoulos'76, Shifman,Vainshtein,Voloshin, Zakharov'79, Kniehl and Spira '95
M. C, Low, Wagner '12

Similarly for the Higgs-gluon gluon coupling

Hence, W (gauge bosons) contribute negatively to Hγγ,
while top quarks (matter particles) contribute positively to Hgg and Hγγ

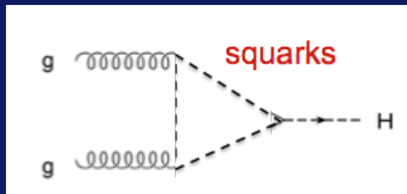
- New chiral fermions will enhance Hgg and suppress hγγ
- To reverse this behavior matter particles need to have negative values for

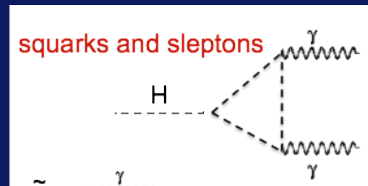
$$\frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{F,i}^{\dagger}\mathcal{M}_{F,i}\right) \qquad \frac{\partial}{\partial \log v}\log\left(\det \mathcal{M}_{B,i}^{2}\right)$$

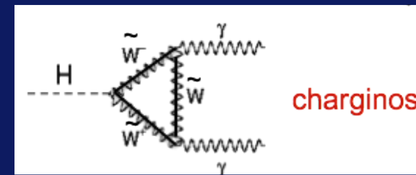
For a study considering CP violating effects and connection with EDM's and MDM's see Voloshin'12; Altmannshofer, Bauer, MC'13, Brod et al.; Primulando et al.

Possible departures in the production and decay rates at the LHC

- **Through SUSY particle effects in loop induced processes**







$$\delta A^{\tilde f}_{\gamma\gamma,gg} \propto \frac{m_f^2}{m^2_{\tilde f_1}\, m^2_{\tilde f_2}}\left[m^2_{\tilde f_1} + m^2_{\tilde f_2} - X_f^2\right]$$

$$\delta A^{\tilde\chi^\pm}_{\gamma\gamma} \propto -\frac{g^2 v^2 \sin 2\beta}{M_2\mu - \frac{1}{2} g^2 v^2 \sin 2\beta}$$

If a particle's mass is proportional to the Higgs vev, contributes with the same sign of the top loop. But mixing can alter the sign

- Light stops and gluon fusion production

MSSM➔ increase the gluon fusion rate but, for large stop mixing X_t required by m_h~125 GeV, mostly leads to moderate suppression

Singlet extensions at low tanβ ➔ no need for large X_t, hence more freedom in gluon fusion

- MSSM Light staus with large mixing (sizeable μ and tanβ) can enhance Higgs to di-photons without changing any other rates.

- Singlet extensions with light charginos, depending on sign of $M_2\mu$, can enhance Higgs to di-photon rate for small tanβ

- Gauge extensions with light charginos, enhance Higgs to di-photons for strong coupling

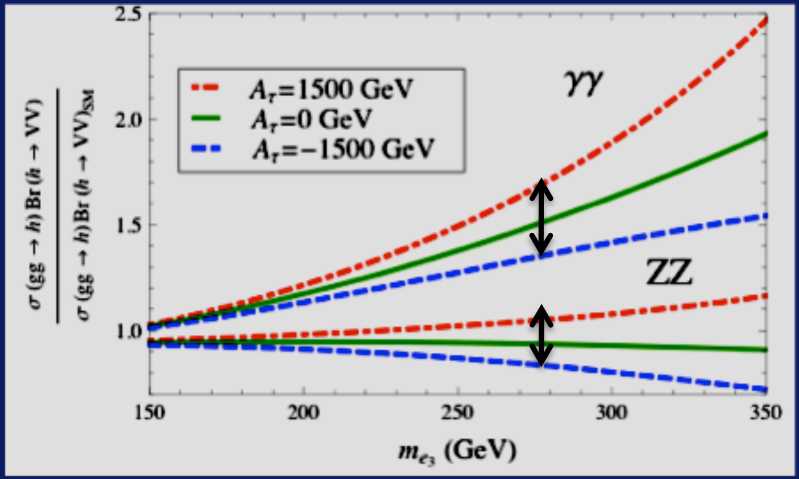
Possible departures in the production and decay rates at the LHC cont'd

•Through enhancement/suppression of the Hbb and Hττ coupling strength via mixing in the scalar sector

This affects in similar manner BR's into all other particles

MSSM: Additional modifications of the Higgs rates into gauge bosons via stau induced mixing effects in the Higgs sector

NMSSM : Wide range of WW/ZZ and γγ rates due to Higgs-singlet mixing (λ_S)



pMSSM/MSSM fits: Arbey, Battagllia, Djouadi, Mahmoudi '12
Benbrik, Gomez Bock, Heinemeyer, Stal, Weiglein, Zeune'12

•Through vertex corrections to Yukawa couplings: different for bottoms and taus

This destroys the SM relation BR(h→bb)/BR(h→ττ) ~ m_b^2/m_τ^2

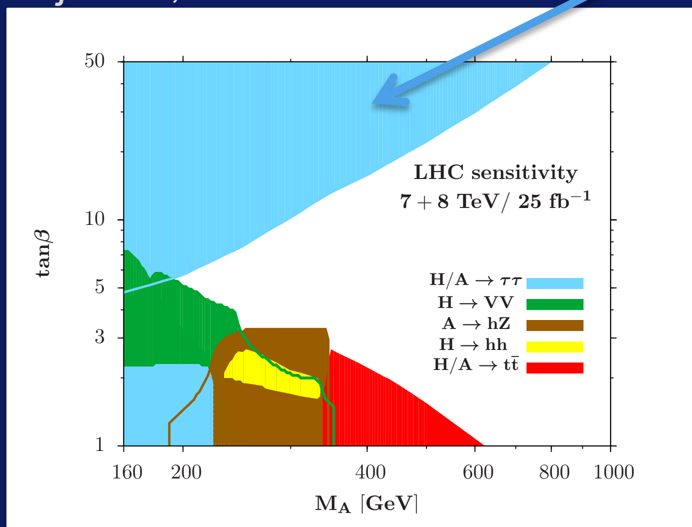
•Through decays to new particles (including invisible decays)

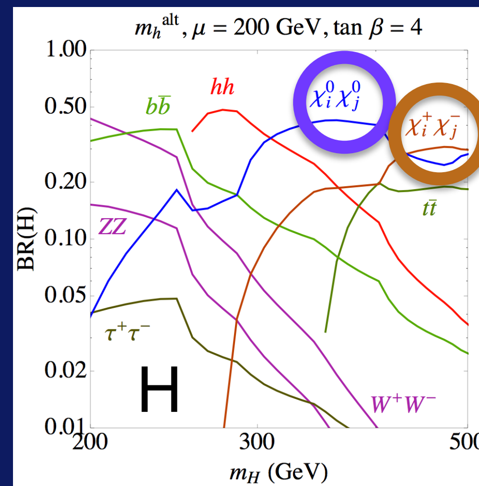
This affects in similar manner BR's to all SM particles

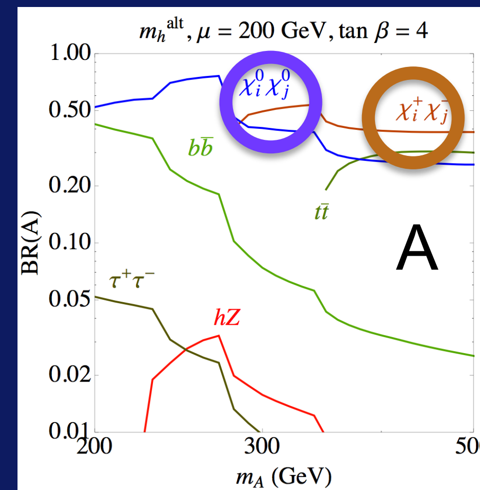
Additional Higgs boson Searches at the LHC

ATLAS/CMS strong limits in A/H → τ τ via gluon fusion and bbA/H production

Djouadi, Quevillon'13





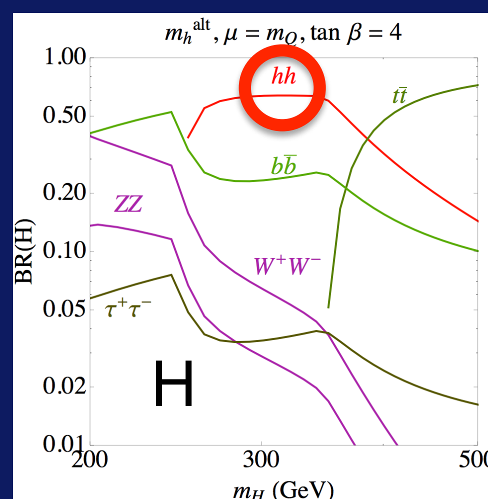


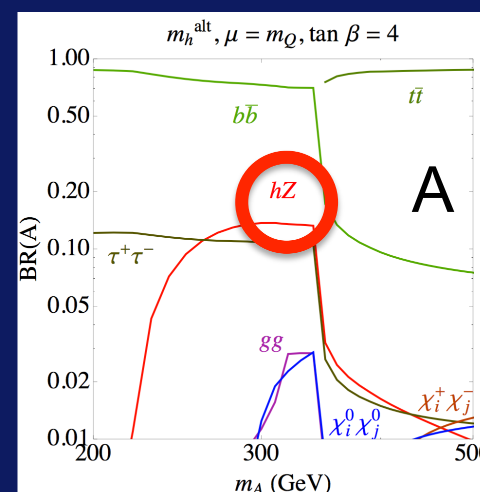
At low tanβ, it is important to search for

H → WW+ ZZ, hh, tt ; A → Zh, tt

If low mu, then chargino and neutralino channels open up

(stop masses > 10 TeV if tanb < 4)





M.C, Low, Shah, Wagner'13 + Haber'14

Alignment and Complementarity for A/H Searches

Haber, Gunion '03
MC, Low, Shah, Wagner '13

sinα = - cosβ ➔ h has SM like properties

Alignment Conditions:

Independent of m_A

$$\boxed{\begin{aligned}(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 &= v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3)\ ,\\ (m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} &= v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})\end{aligned}}$$

$$\lambda_3 + \lambda_4 + \lambda_5 = \tilde{\lambda}_3$$

also

$$m_h^2 = \lambda_{SM} v^2$$

$$\lambda_{SM} = \lambda_1 \cos^4\beta + 4\lambda_6 \cos^3\beta \sin\beta + 2\tilde{\lambda}_3 \sin^2\beta \cos^2\beta + 4\lambda_7 \sin^3\beta \cos\beta + + \lambda_2 \sin^4\beta$$

Alignment solutions for
- **MSSM: sizeable μ and intermediate tanβ**
- **NMSSM: small μ and tanβ**

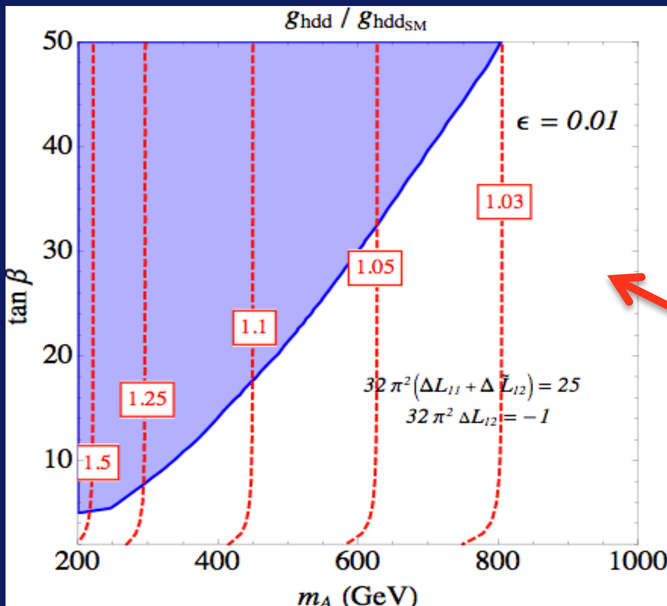
Is it more important to measure Higgs couplings with the highest precision possible

Or

Find new ways of searching for additional Higgs states?

Alignment and Complementarity for A/H Searches

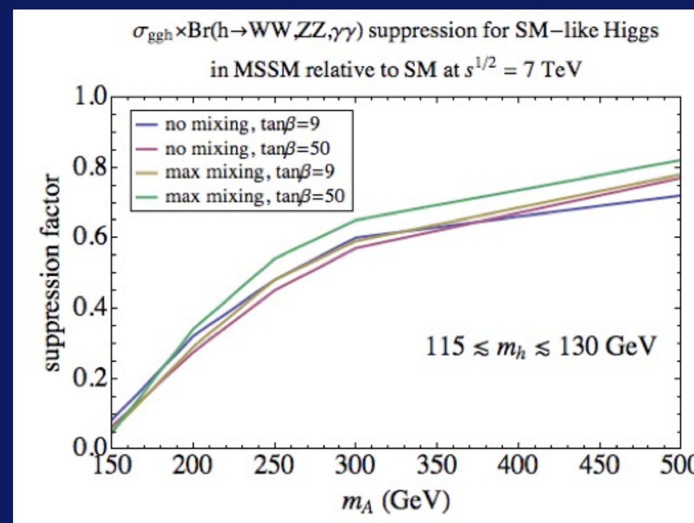
MC, Low, Shah, Wagner '13

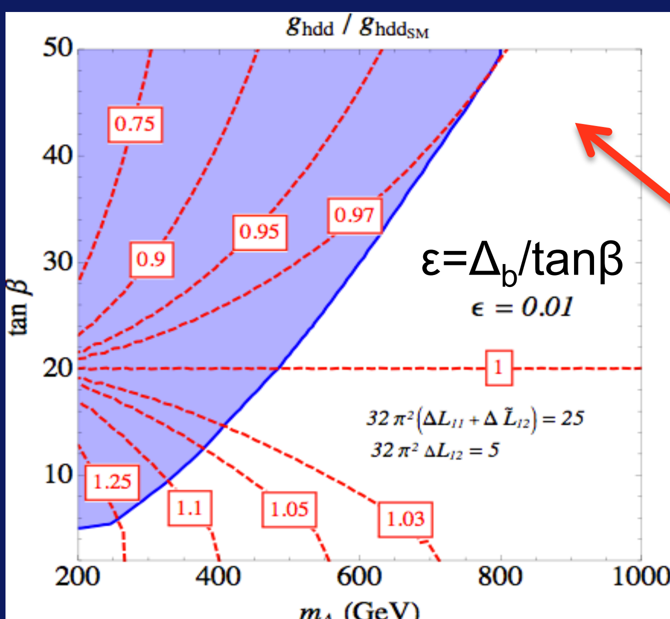


No alignment for small μ

Strong lower bounds on m_A from BR(h →WW/ZZ) variations due to enhancement in hbb coupling

All vector boson BRs suppressed indep. of tanβ





Alignment for large μ and tanβ ~O(10)

Weaker lower bounds on m_A, with strong tanβ dependence

e.g. Tauphobic Benchmark

MC, Heinemayer, Stal, Wagner, Weiglein'14

The new era of precision Higgs Physics (cont'd)

All other 3 Higgs bosons may be heavy ~ TeV range ~ (Decoupling)
Or as light as a few hundred GeV (Alignment)

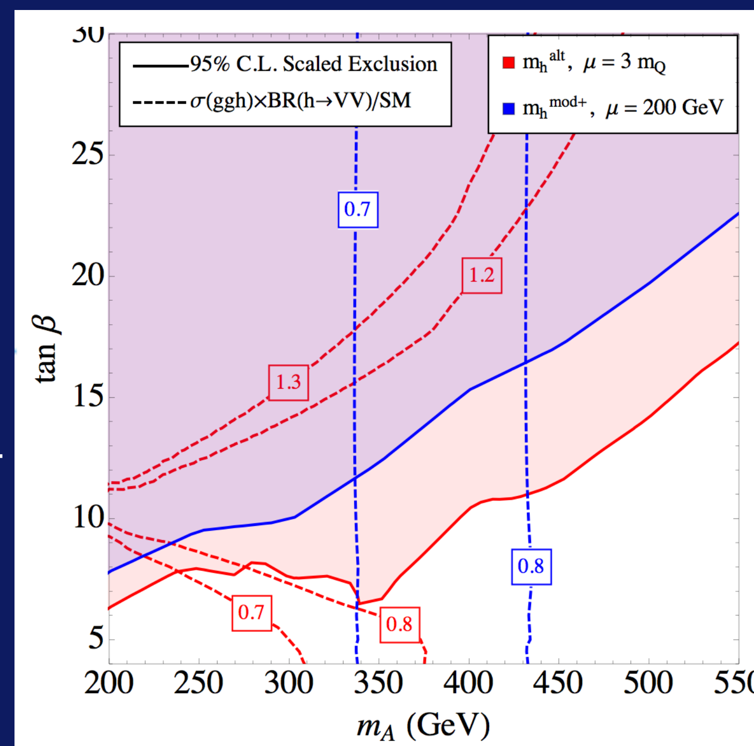
Additional Higgs Bosons Searches:
A/H → ττ (shaded)
Vs Precision Higgs Physics:
h → WW/ZZ (dashed lines)

Complementarity crucial to probe SUSY Higgs sector

Correlations between deviations may reveal underlying physics

At low tanβ: important to look for
H → WW+ ZZ, hh, tt ; A → Zh, tt

tanβ



m_A [GeV]

M.C., Haber, Low, Shah, Wagner'14

Similar effects in Extensions of the MSSM

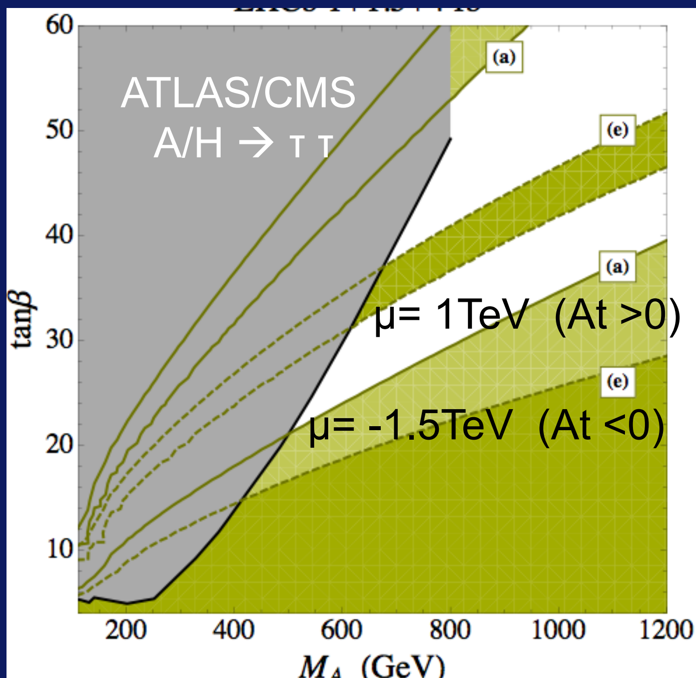
~ Add new degrees of freedom that contribute at tree level to m_h ~

e.g. additional SM singlets or triplets or models with enhanced weak gauge symmetries

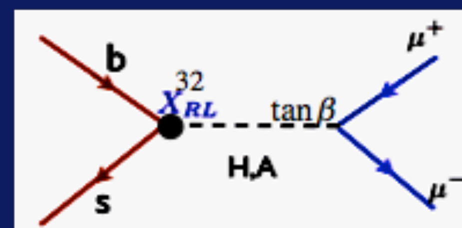
Indirect limits on the SUSY spectrum from rare processes

The Higgs-flavor connection in the MSSM with Minimal Flavor Violation

Altmannshofer, MC, Shah, Yu ’13



$B_s \to \mu^+\mu^-$



$$\frac{y_t^2}{16\pi^2}\,\frac{\mu A_t}{m_{\tilde t}^2}\,\frac{\tan\beta^3}{M_A^2}$$

mu = 1TeV (At >0)

LHCb Projections: 1 (7 TeV) +1.5 (8 TeV)+4 (13 TeV) fb^{-1}

SM central value with 30% effects of NP allowed

SUSY effects intimately connected to the structure of the squark mass matrices

Two Higgs Doublet models and a Theory of Flavor

- The Froggatt Nielsen mechanism: Effective Yukawa coupling

$$\mathcal{L}_{\rm Yuk} = y_t \bar{Q}_L \tilde{H} t_R + y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R + \cdots$$

$$m_t = y_t \frac{v}{\sqrt{2}} \qquad m_b = y_b \frac{v}{\sqrt{2}} \left(\frac{f}{\Lambda}\right)^{n_b}$$

$$y_{\rm eff} = \epsilon^n y \qquad \epsilon = f/\Lambda$$

- New scalar singlet S obtains a vev: <S> =f
  - Quarks & scalars are charged under a global $U(1)_F$ flavor symmetry
- Lighter quarks, more S insertions

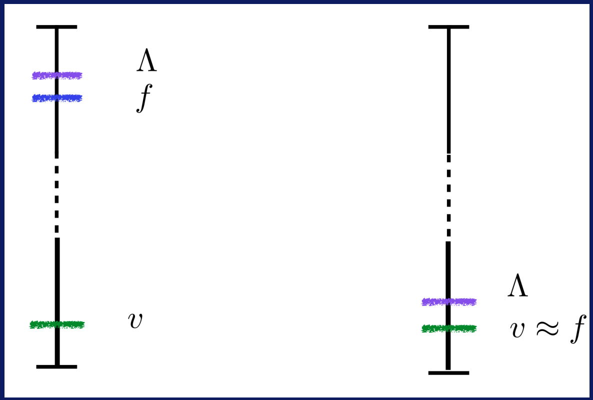
Issue: Scales undetermined

- How to define the scales? Can the Higgs play the role of the Flavon?

Babu '03, Giudice-Lebedev '08

$$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H b_R \to y_b \left(\frac{H^\dagger H}{\Lambda^2}\right)^{n_b} \bar{Q}_L H b_R$$

$$\epsilon = v^2/2\Lambda^2 \equiv m_b/m_t \to \Lambda \approx (5-6)v$$



Two Main Problems

- **The flavon is a flavor singlet**
- **The Higgs coupling to Bottom quarks is too large**

$$g_{hbb} \propto 3\, m_b/v$$

Two Higgs Doublet models and a Theory of Flavor (cont'd)

- Type II 2HDM with different flavor charges for H_u and H_d

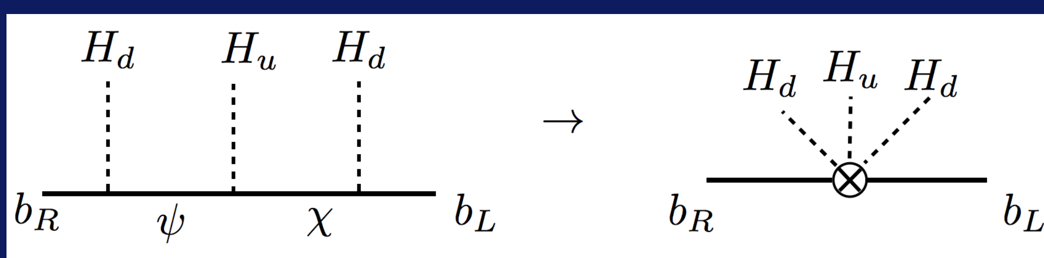
$$y_b \left(\frac{S}{\Lambda}\right)^{n_b} \bar{Q}_L H\, b_R \rightarrow y_b \left(\frac{H_u H_d}{\Lambda^2}\right)^{n_b} \bar{Q}_L H_d\, b_R$$

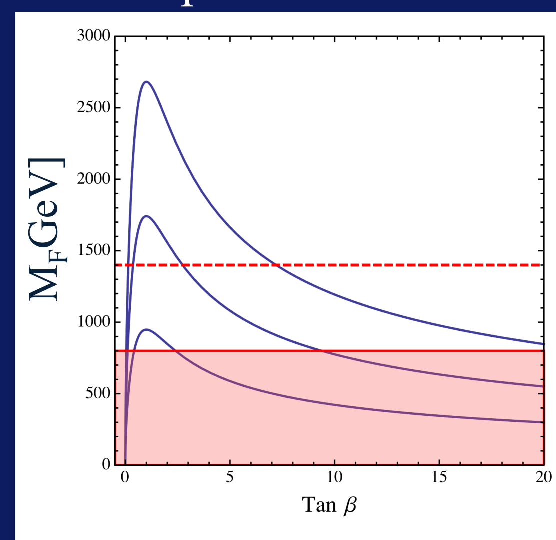
Bauer, MC, Gemmler '15

With effective Yukawa coupling suppression factor

$$\epsilon = \mathbf{v_u v_d / 2\Lambda^2 \equiv m_b/m_t \rightarrow \Lambda \approx (5-6)v} \left(\frac{\mathbf{tan}\beta}{\mathbf{1} + \tan^{\mathbf{2}}\beta}\right)^{\mathbf{1/2}}$$

The value of $\Lambda \sim 4$ v ~ 1TeV (maximizes for tan $\beta = 1$) and can be slightly larger depending on the specific UV completion





Flavor from the Electroweak Scale

- Flavor Structure by fixing flavor charges

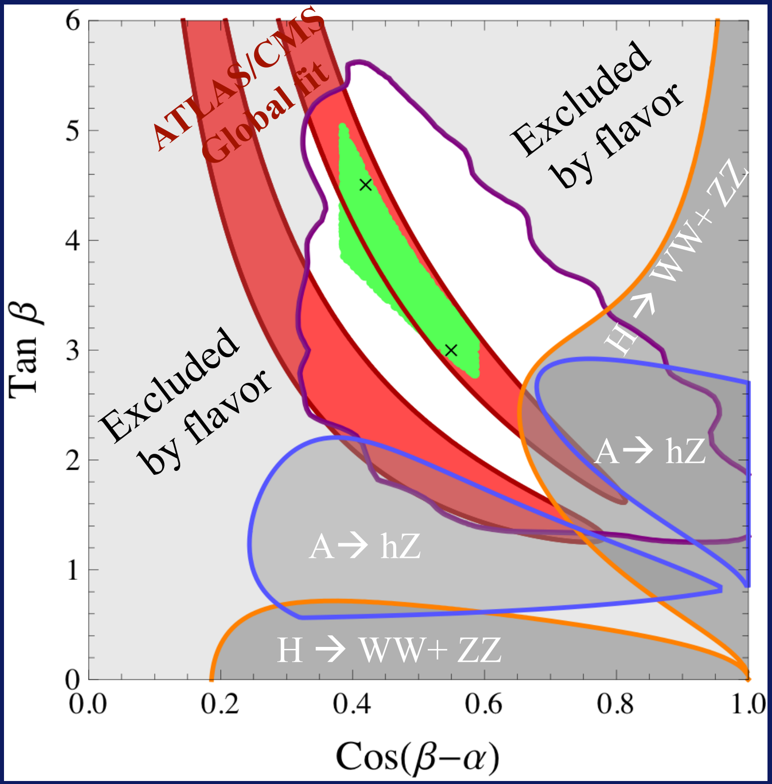
$$m_t \approx \frac{v_u}{\sqrt{2}}, \quad \frac{m_b}{m_t} \approx \frac{m_c}{m_t} \approx \varepsilon^1, \quad \frac{m_s}{m_t} \approx \varepsilon^2, \quad \frac{m_d}{m_t} \approx \frac{m_u}{m_t} \approx \varepsilon^3$$

$$(V_{\mathrm{CKM}})_{12} \approx \varepsilon^0, \qquad (V_{\mathrm{CKM}})_{13} \approx (V_{\mathrm{CKM}})_{23} \approx \varepsilon^1$$

- Higgs couplings to gauge bosons and top quark as in 2HDM
- Light quark coupling to Higgs special!

~ in particular Higgs-bottom coupling ~

A predictive model with new Physics at LHC reach (shaded green)



- Interplay of flavor phyiscs with precision Higgs global fit {ATLAS/CMS)
- Great possibilities for direct collider searches for additional Higgs bosons
- New particles in the few TeV range

SM Higgs

- Resolves the problem of consistency within the SM
- Is a scalar, sensitive to new physics at high scales

- **All current data is well compatible with SM expectations but there is room for small deviations**

- **Still many open questions that demand new physics**

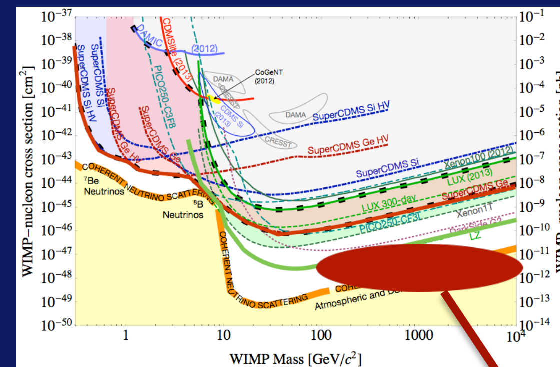
Extended Higgs and Natural SUSY models

- Being cornered by LHC data but still many places to hide

  (searches moving in those directions)

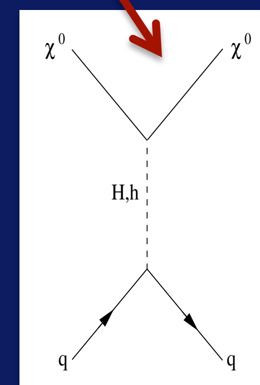
- Direct searches for additional Higgs bosons as important as precise measurements of Higgs properties
- Correlations among deviations in different Higgs signals may reveal underlying physics

We are exploring the Higgs connections



- In there a Higgs portal to dark matter

  and/or other dark sectors?



- Is Baryogenesis generated at the EWSB scale?
- How does the Higgs talk to neutrinos ?
- What are the implications of the Higgs sector for flavor?
- Is the Higgs a portal to new particles and new energy scales?
- Is the Higgs related to inflation or dark energy?
- What is the dynamical origin of the electroweak scale?