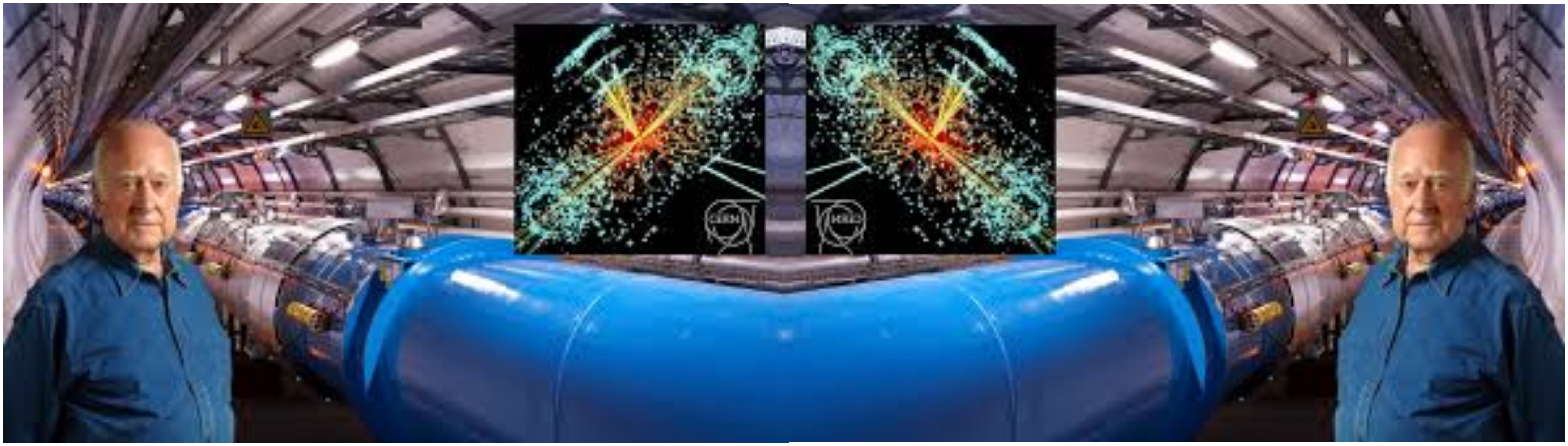
The Higgs Boson : From Theory to Experiment



Carlos E.M. Wagner
Phys. Dept., EFI and KICP, Univ. of Chicago
HEP Division, Argonne National Lab.

Workshop on Extended Scalar Sectors from all Angles
CERN, October 21—25, 2024.

ENRICO FERMI INSTITUTE

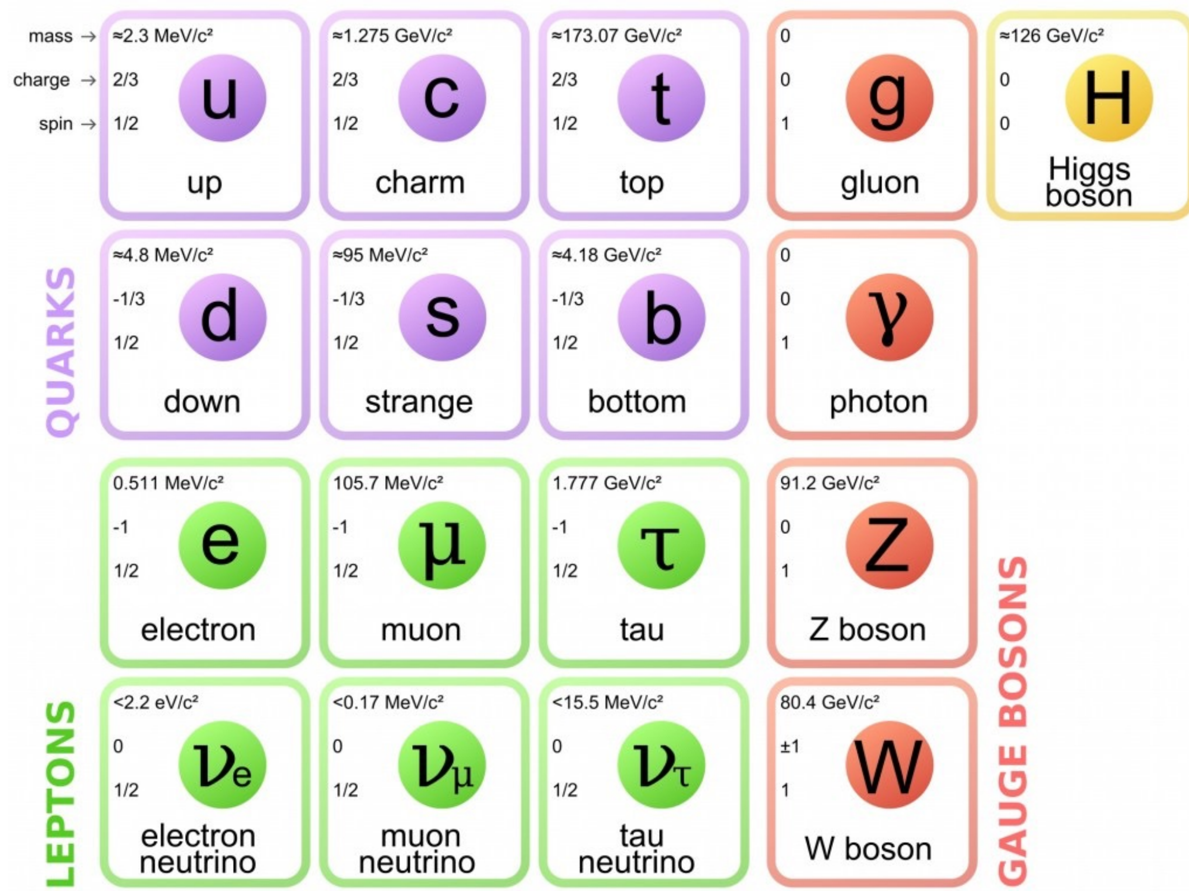
Argonne NATIONAL LABORATORY

The Standard Model

Is an extremely successful Theory that describes interactions between the known elementary particles.

3 generations of fermions (mattter)

Gauge and Higgs Fields



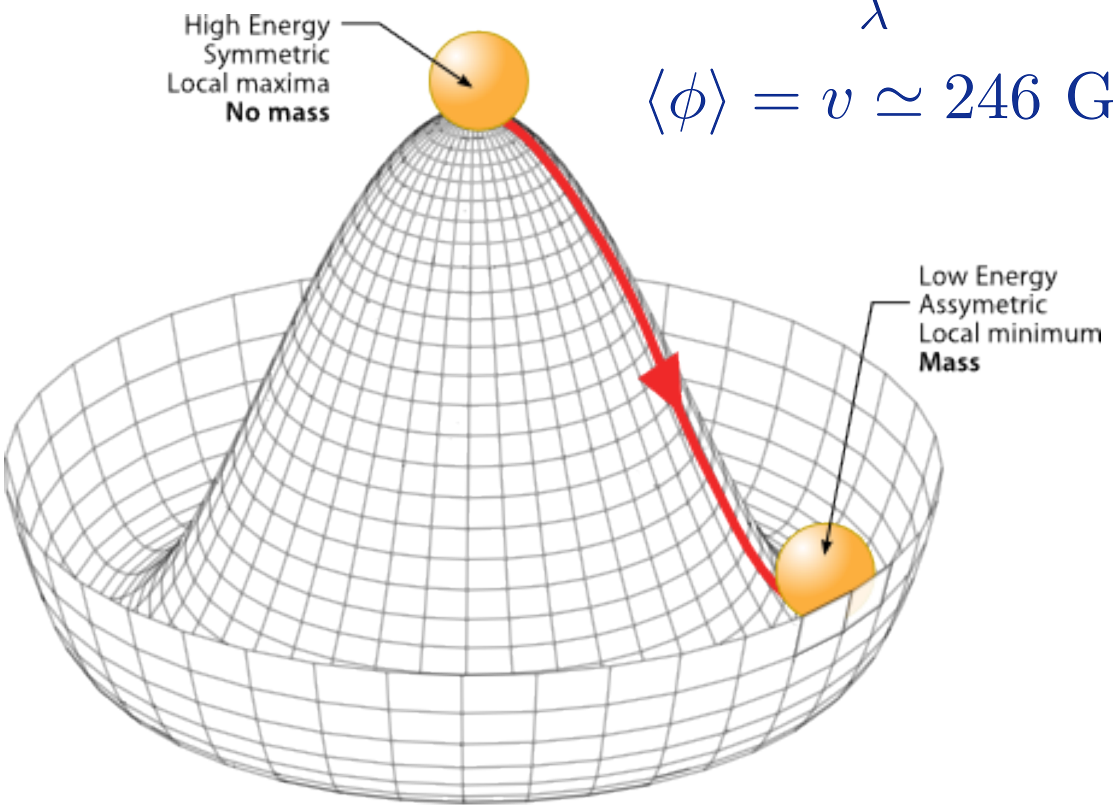
Higgs, Englert, Brout, Kibble, Guralnik, Hagen'64

Higgs vacuum : Elementary Particle Masses

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

$$v^2 = -\frac{m^2}{\lambda}$$

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



Particle acquire mass through interactions with Φ.

Couplings proportional to the ratio of mass to v

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

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

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

$$m_\gamma = m_g = 0$$

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

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

Amazing Properties of the SM Higgs sector

- The Higgs self interactions are described by a simple potential

$$V = -m_H^2 H^\dagger H + \frac{\lambda}{2}\left(H^\dagger H\right)^2$$

- This leads to the breakdown of the electroweak symmetry

$$v^2 = \frac{m_H^2}{\lambda}$$

- The interactions with gauge bosons are related to the mass generation mechanism

$$\frac{g^2}{2} H^\dagger H V_\mu V^\mu$$

- The linear interactions are therefore related to the insertion of a Higgs v.e.v. and if we add new doublets will be related to the projection of the particular Higgs field in the direction that acquires v.e.v.

$$g_{hVV} = \frac{m_V^2}{v}$$

- Higgs self interactions are also determined as a function of the Higgs mass

$$\lambda_3 = 3\frac{m_h^2}{v}$$

Amazing Properties of the SM Higgs sector

- The interactions with fermions an even more amazing story. We start with a completely arbitrary 3x3 Yukawa matrix interactions, where this three is related to generations

$$y_{ij}\bar{\psi}_L^i H \psi_R^j + h.c.$$

- Now, when you give the Higgs a v.e.v. this becomes a mass matrix that you must diagonalize when going to the physical states.

- But, due to the fact that mass and Yukawa matrices are proportional to each other, the interactions become flavor diagonal

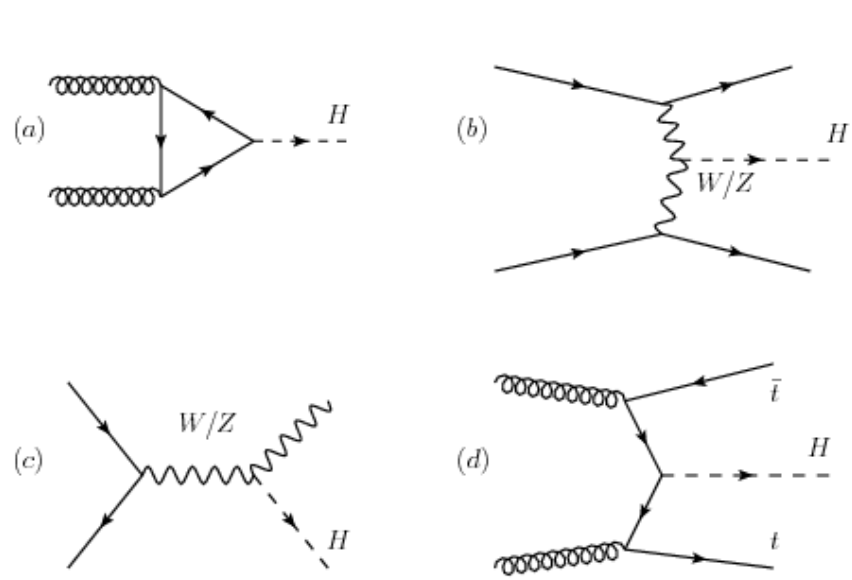
$$y_{hnm} = \frac{m_f}{v}\delta_{nm}$$

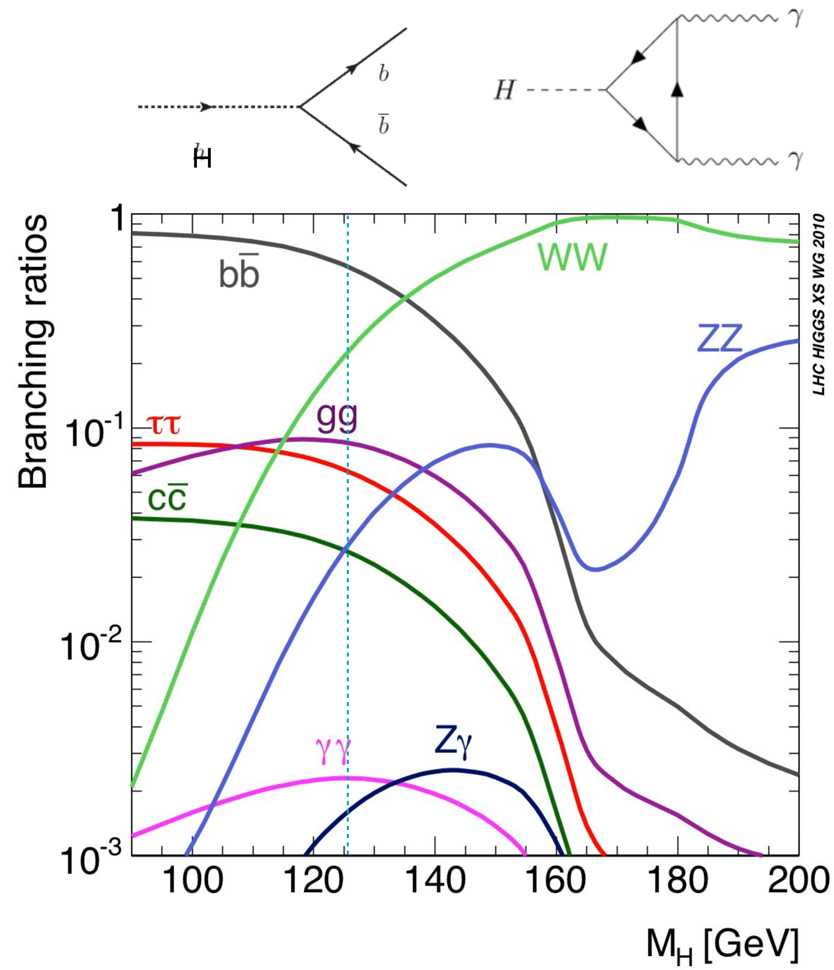
- In general, there are no tree-level Flavor Changing Neutral Currents ! No tree-level CP violation. All these effects occur at the loop-level, via the charged weak interactions, and are proportional to CKM matrix elements.

- I don't need to tell you how amazing this is ! Moreover, all available data is consistent with these predictions.

We collide two protons (quarks and gluons) at high energies :

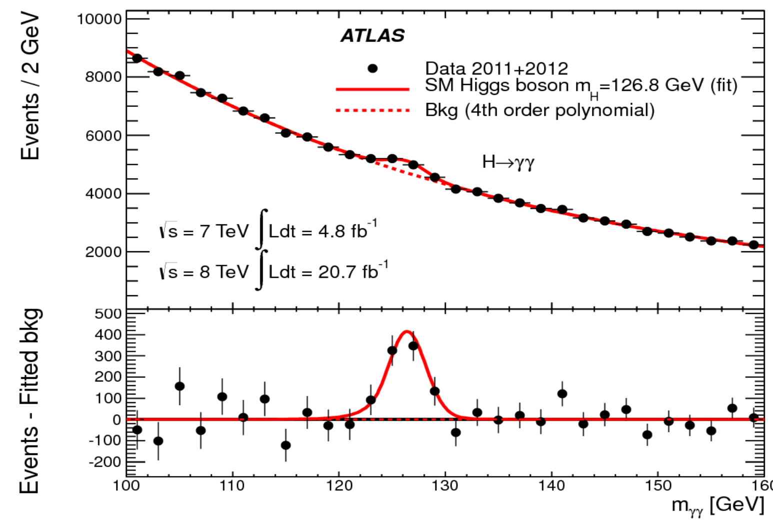
LHC Higgs Production Channels
and Decay Branching Ratios





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

The Higgs Discovery in July 2012 has established the Standard Model (SM) as the proper low energy theory describing all known particle interactions

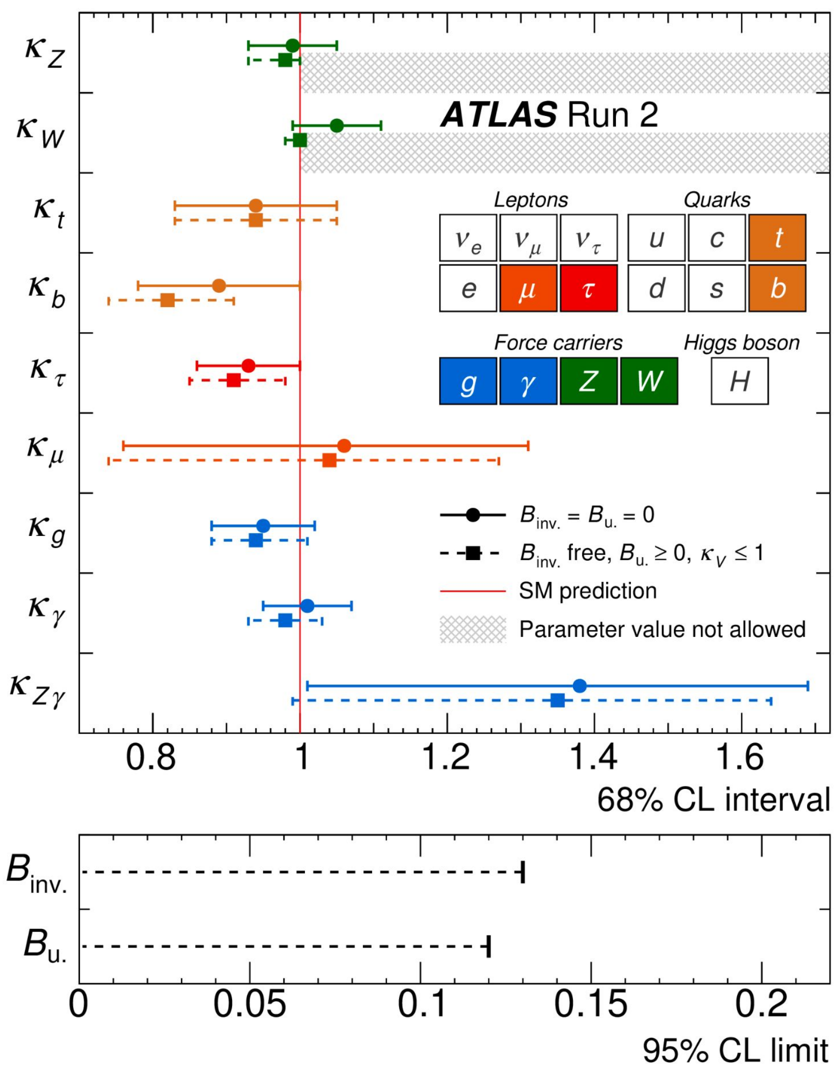


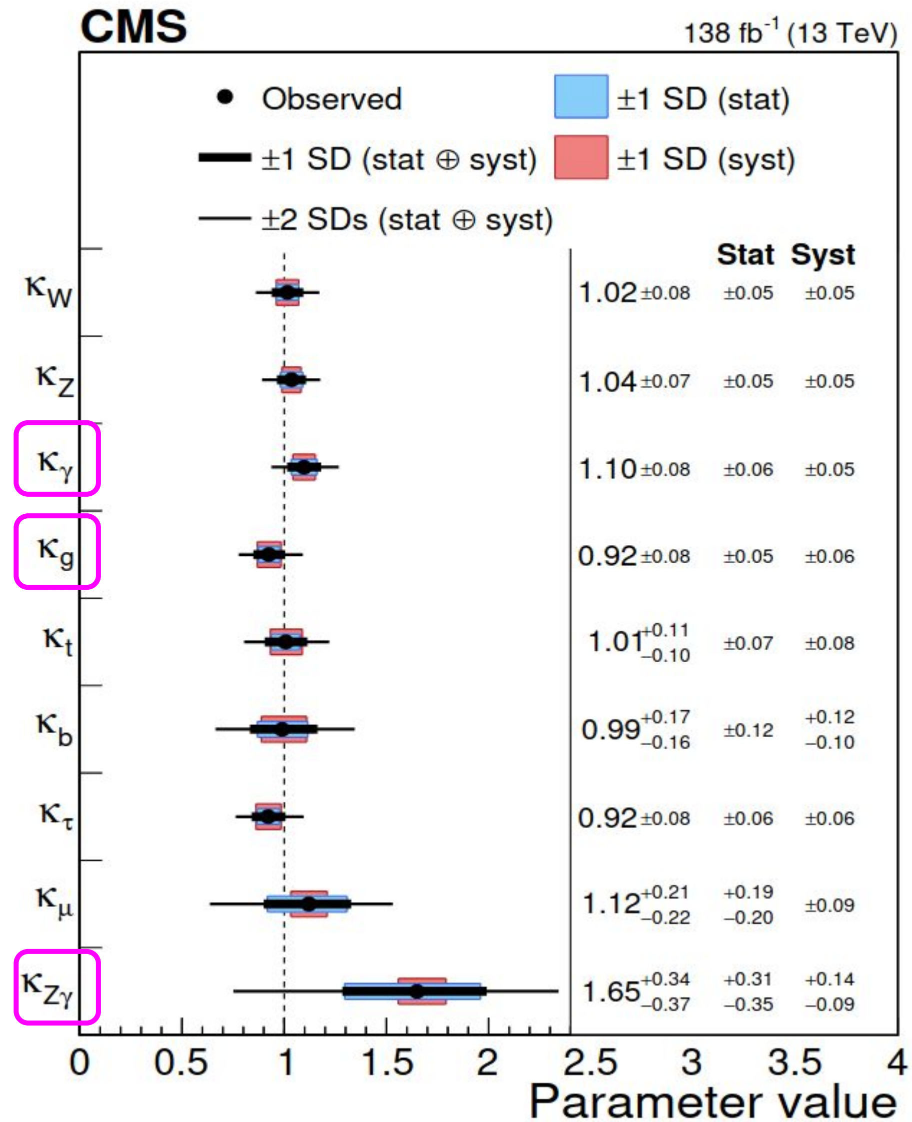
R. Brout ‘70

C. Wagner ‘13

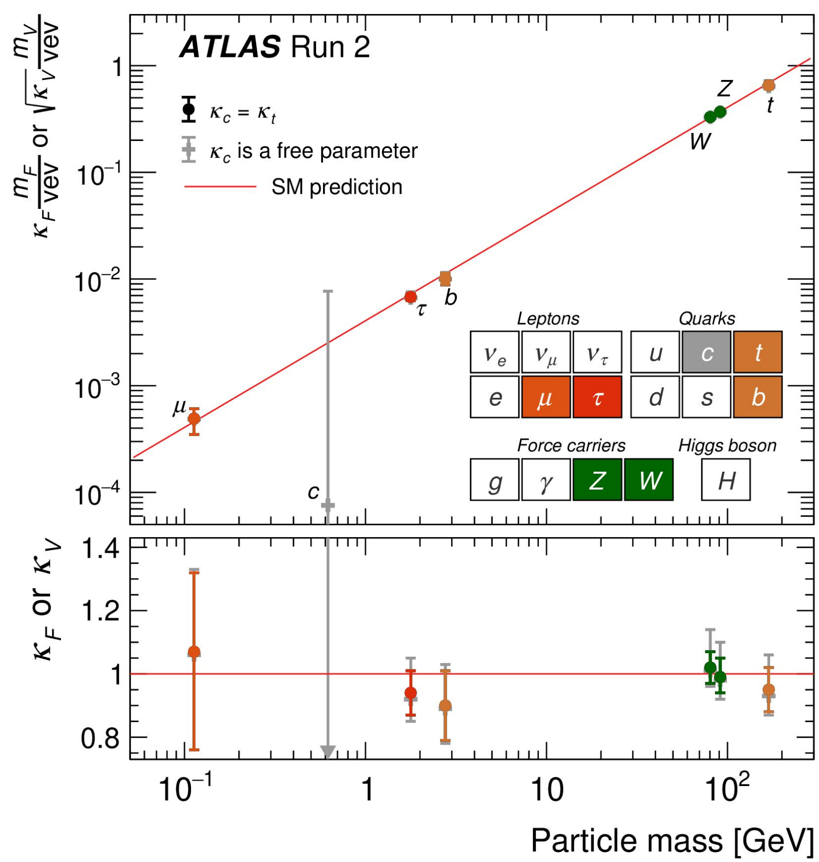
ATLAS and CMS Fit to Higgs Couplings

Departure from SM predictions of the order of few tens of percent allowed at this point.

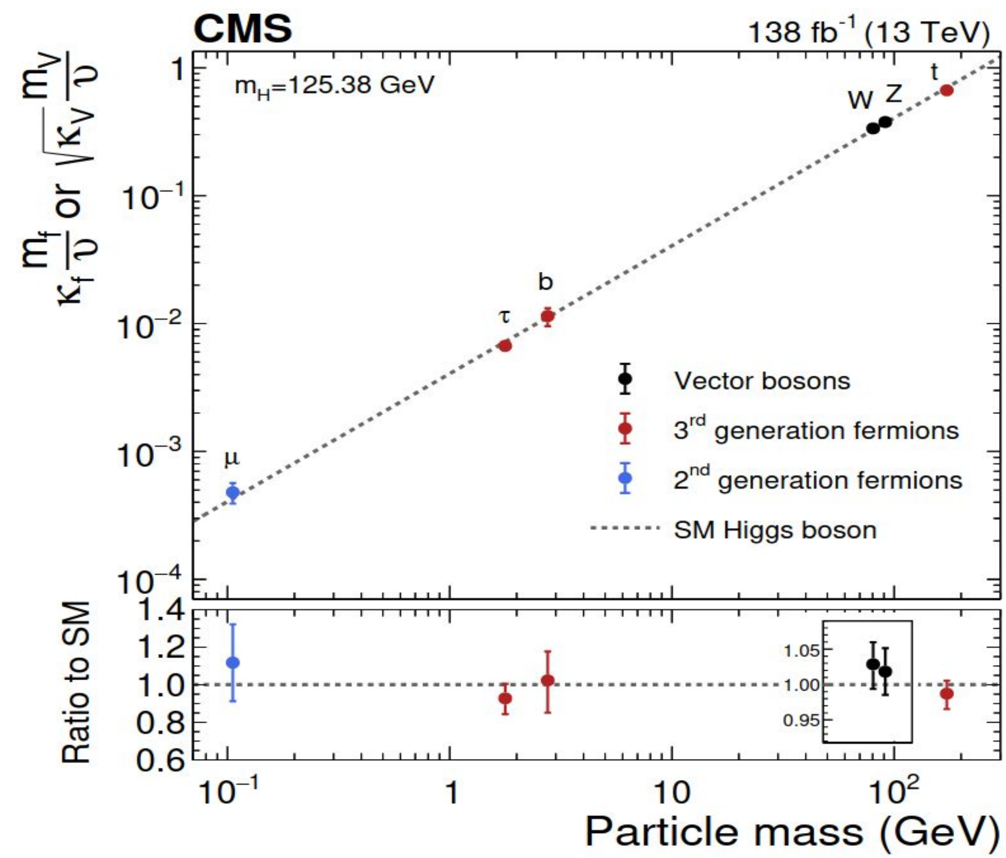




Correlation between masses and couplings consistent with the Standard Model expectations



H couplings vs particle mass



Why we should not be surprised

- There is another amazing property of the SM as an effective field theory
- Take any sector with gauge invariant mass terms, which do not involve the Higgs v.e.v.

$$\mathcal{L} = -m_\phi^2 \phi^\dagger \phi + (M_\Psi \bar{\Psi} \Psi)$$

- The Appelquist-Carrazonne decoupling theorem says that as we push these gauge invariant masses up, the low energy effective theory will reduce to the Standard Model !
- The speed of decoupling depends on how these sector couple to the SM. In general, for a coupling κ, decoupling occurs when

$$\frac{k^2}{m_{\rm new}^2} \ll \frac{1}{v^2}$$

- Obviously decoupling doesn't occur if the masses are proportional to the v.e.v.
- These properties are behind the EFT program.

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots .$$

Wilson coefficient and operator		Affected process group		
		LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		✓	
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$		✓	✓
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$		✓	✓
c_{HD}	$(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$		✓	✓
c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$		✓	
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		✓	
c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$		✓	
c_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	✓	✓	✓
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$		✓	
c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\widetilde{H})$		✓	
c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H}t)$		✓	
c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$		✓	
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	✓	✓	✓
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	✓	✓	
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{Q}\tau^I\gamma^\mu Q)$	✓	✓	
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	✓		
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	✓	✓	
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\, G_{\mu\nu}^A$		✓	
c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\widetilde{H}\, W_{\mu\nu}^I$		✓	
c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\widetilde{H}\, B_{\mu\nu}$		✓	
c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓		✓

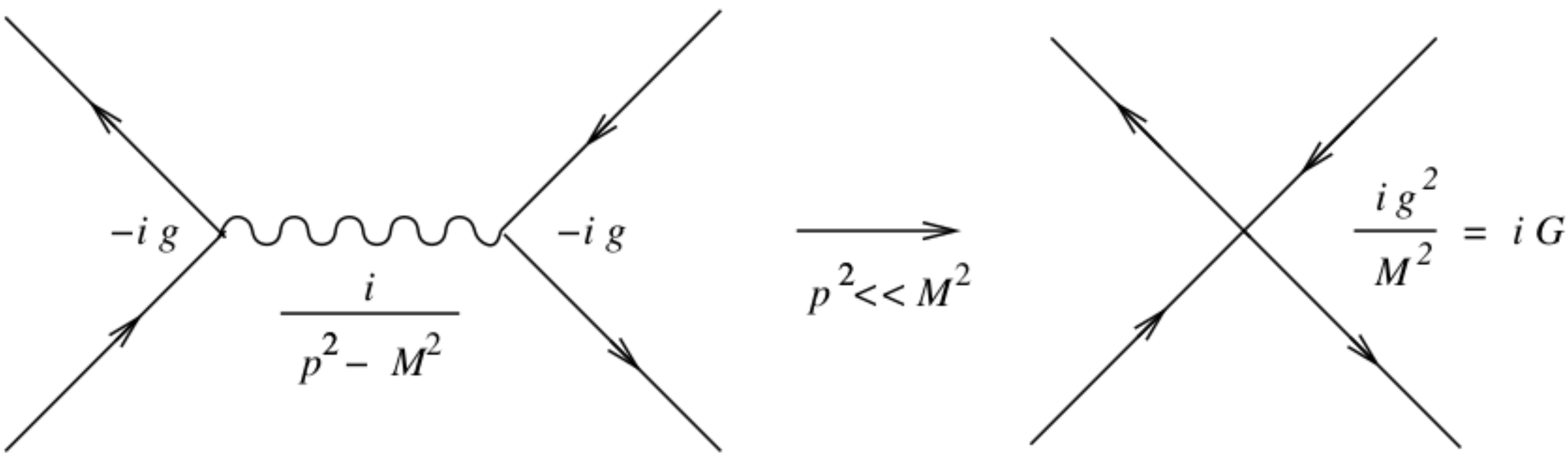
Some important Effective Field Theory Operators, and their experimental tests at LEP and the LHC.

Wilson coefficient and operator		Affected process group		
		LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$			✓
$c_{lq}^{(3)}$	$(\bar{l}\gamma_\mu\tau^I l)(\bar{q}\gamma^\mu\tau^I q)$			✓
c_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$			✓
c_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$			✓
c_{lu}	$(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$			✓
c_{ld}	$(\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)$			✓
c_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$			✓
$c_{qq}^{(1,1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$			✓
$c_{qq}^{(1,8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$			✓
$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$			✓
$c_{qq}^{(3,8)}$	$(\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$			✓
$c_{uu}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$			✓
$c_{uu}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$			✓
$c_{dd}^{(1)}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$			✓
$c_{dd}^{(8)}$	$(\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$			✓
$c_{ud}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$			✓
$c_{qu}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$			✓
$c_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$			✓
$c_{qd}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$		✓	
$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$		✓	
$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$		✓	
$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$		✓	
$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$		✓	
$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$		✓	
$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$		✓	
$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$		✓	
$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$		✓	
$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$		✓	
$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$		✓	

Subset of Effective Theory Operators for a given process
No clear deviation from SM predictions observed.

Reconstructing the fundamental Theory

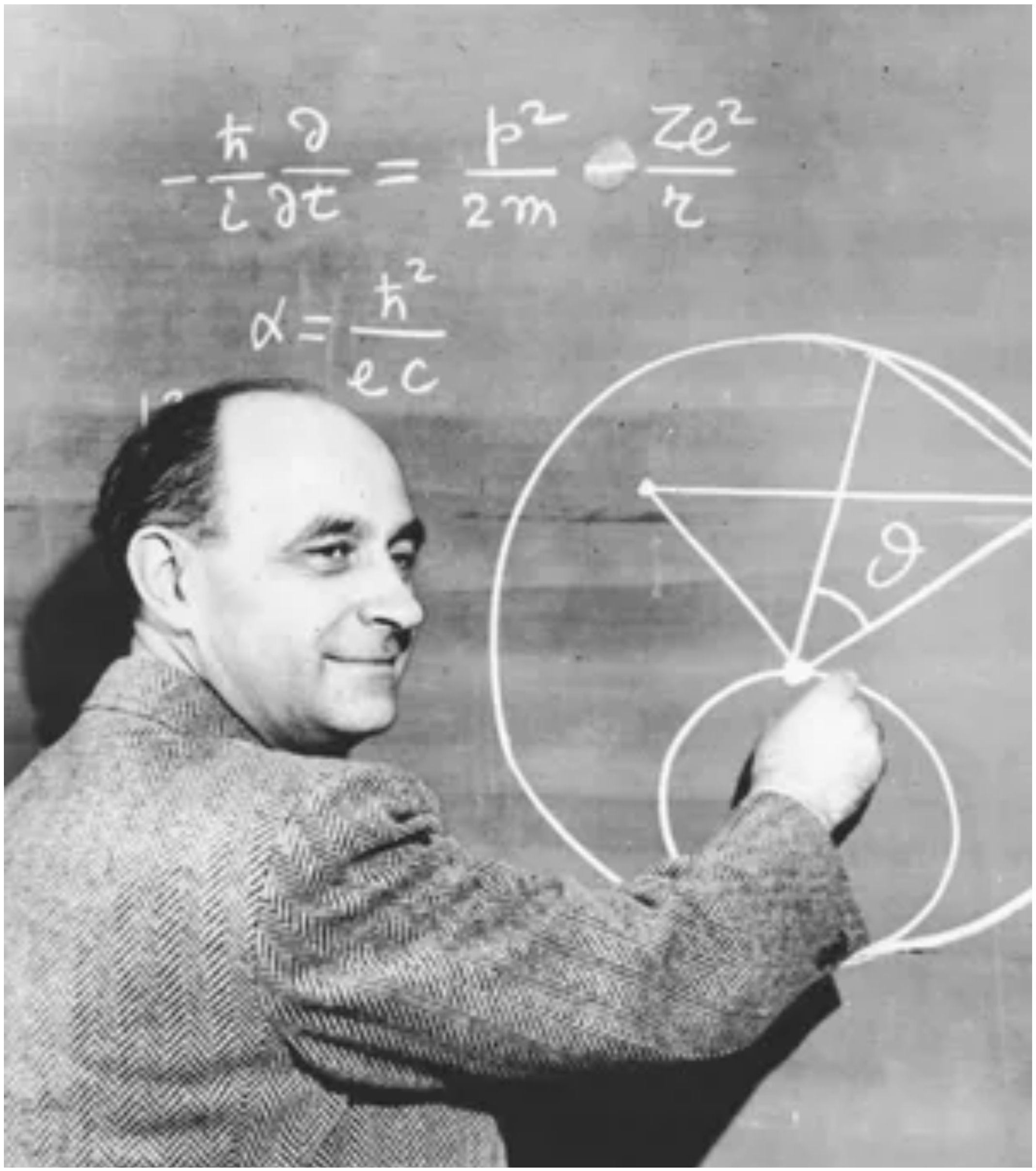
- Not an easy task. Let me mention a historical example, namely the Fermi constant, namely the strength of the four Fermi interactions governing beta and muon decays.



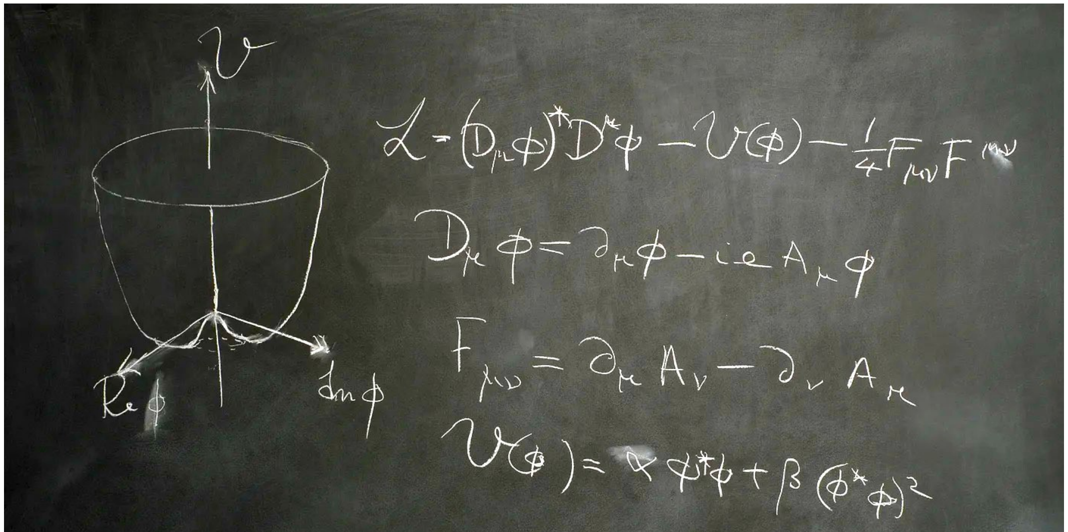
The relevant gauge bosons are the weak gauge bosons and hence, had Fermi known about the Higgs mechanism he would have find that G is nothing but the Higgs vev in disguise ! But of course, he didn't.

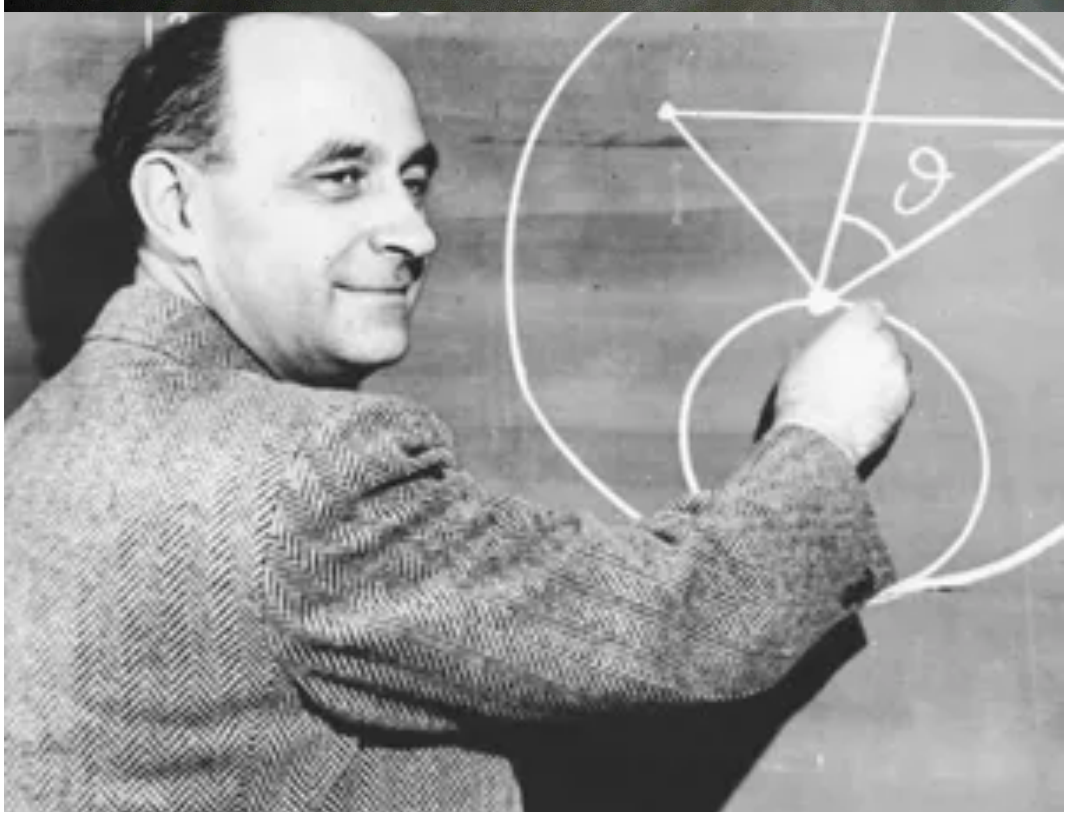
$$G \propto \frac{g^2}{g^2 v^2} = \frac{1}{v^2}$$

Reconstructing the Weak Interactions



Reconstructing the Weak Interactions





Fermi would have predicted correctly that the gauge bosons natural scale was of the order of 100 GeV.

He could have reconstructed a great part of the boson sector of the weak interactions from the four Fermi constant ! Needless to say, he would not have known about the neutral Z boson.

On the other hand, had he thought about the fermion masses, he would have predicted that the natural scale for the muon and electron mass was precisely 100 GeV !

He would have been puzzled about the fact that electron and muon masses are three and five orders of magnitudes below that scale !

He would have been even more puzzled about the reason why the neutrinos are so light.

Why we should be surprised

- The Higgs potential suffers from a problem of stability under ultraviolet corrections, namely, given any sector that couples to the Higgs sector with gauge invariant masses, the Higgs mass parameter will be affected

$$\Delta m_H^2 \propto (-1)^{2S} \frac{k^2 N_g}{16\pi^2} \; m_{\rm new}^2$$

- These are physical corrections, regularization independent and shows that unless the new physics is lighter than the few TeV scale or very weakly coupled to the Higgs sector, the presence of a weak scale mass parameter is hard to understand.

- This is particularly true in models that try to connect the Higgs with the ultraviolet physics, like Grand Unified Theories.

- To explain this, we need a delicate cancellation of corrections, that for instance an extension like Supersymmetry can provide.

Neutrino Masses : See-saw Mechanism

- The basic Lagrangian contains a Majorana mass for the right-handed neutrino

$$y\bar{L}_L H \nu_R + \frac{M}{2}\nu_R \nu_R + h.c.$$

- This leads to neutrino masses

$$m_\nu = \frac{m_D^2}{M} \equiv \frac{y^2 v^2}{M}$$

Dimension 5 operator

$$\mathcal{O}_5 = \frac{(LH)(LH)}{M}$$

- Corrections to the Higgs mass

$$\Delta m_H^2 \propto \frac{y^2}{16\pi^2} M^2 \equiv \frac{m_\nu M^3}{16\pi^2 v^2}$$

- Demanding this to be parametrically small compared to the SM Higgs mass parameter

$$M^3 < \frac{16\pi^2 v^4}{m_\nu} \Rightarrow M < 10^7 \text{ GeV}$$

- Minimal leptogenesis models demand larger values of M than this bound, and therefore generically imply a large fine tuning, unless you add supersymmetry.

Fermi and Majorana in the 1930's according to ChatGPT

Simple Framework for analysis of coupling deviations
2HDM : General Potential

- General, renormalizable potential has seven quartic couplings, with three of them, given in the last line, may be complex.

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

- In general, it is assumed that lambda 6 and 7 are zero, since this condition appears naturally in models with flavor conservation. However, this condition is basis dependent and it is not necessary.

- We will therefore concentrate on the general 2HDM, with all quartic couplings different from zero. As it is well known an important parameter in these models is

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

Higgs Basis

- An interesting basis for the phenomenological analyses of these models is the Higgs basis

$$H_1 = \Phi_1 \cos\beta + \Phi_2 \sin\beta$$
$$H_2 = \Phi_1 \sin\beta - \Phi_2 \cos\beta$$

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \phi_1^0 + iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\phi_2^0 + ia^0) \end{pmatrix}$$

- The field ϕ_1^0 is therefore associated with the field direction that acquires a vacuum expectation value and acts as a SM-like Higgs

- The behavior of the neutral mass eigenstates depend on the projection on the fields in this basis.

- Typically, it is the lightest neutral Higgs boson that behaves like the SM-like Higgs. The case in which one can identify the state ϕ_1^0 with the mass eigenstate is called alignment.

- In the alignment limit the tree-level couplings agree with the SM ones. Large departures from the alignment limit are heavily restricted by LHC measurements.

Quartic Couplings in the Higgs basis

Similar notation as in the generic basis, but changing lambdas by Z's

$$V \supset \frac{Z_1}{2}(H_1^\dagger H_1)^2 + \frac{Z_2}{2}(H_2^\dagger H_2)^2 + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4(H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \left[\frac{Z_5}{2}(H_1^\dagger H_2)^2 + Z_6(H_1^\dagger H_1)H_1^\dagger H_2 + Z_7(H_2^\dagger H_2)H_1^\dagger H_2 + h.c.\right]$$

Observe that since only H1 acquires vacuum expectation value in this basis, the mixing between the Higgs states of both doublets can only occur via Z6

Mass Matrix in the Higgs Basis

- The neutral Higgs mass matrix takes a particularly simple form in the Higgs basis

$$\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & Z_6^R & -Z_6^I \\ Z_6^R & \frac{M_{H^\pm}^2}{v^2} + \frac{1}{2}(Z_4 + Z_5^R) & -\frac{1}{2} Z_5^I \\ -Z_6^I & -\frac{1}{2} Z_5^I & \frac{M_{H^\pm}^2}{v^2} + \frac{1}{2}(Z_4 - Z_5^R) \end{pmatrix}$$

- Two things are obvious from here. First, in the CP-conserving case, the condition of alignment, $Z_6 \ll 1$ implying small mixing between the lightest and heavier eigenstates is given by

$$\cos(\beta - \alpha) = -\frac{Z_6 v^2}{m_H^2 - m_h^2} \qquad \text{Decoupling}: \quad Z_6 v^2 \ll m_H^2$$

- Second, while in the alignment limit the real part of Z_5 contributes to the splitting of the two heavier mass eigenstates, its imaginary part contributes to the splitting and their mixing.

$$M_{h_3,h_2}^2 = M_{H^\pm}^2 + \frac{1}{2}(Z_4 \pm |Z_5|)v^2 .$$

$$m_h^2 = Z_1 v^2, \qquad m_h = 125 \text{ GeV}$$

Mimicking the SM behavior

- In 2HDM, one can mimic the SM behavior by just allowing the fermions with a giving charge (up quarks, down quarks, charge leptons and neutrinos) to couple to only one of the Higgs fields.

- This leads to the so-called type I to IV 2HDM, depending on which couplings are allowed.

	Up-type	Down-type	Lepton
Type-I	Φ_1	Φ_1	Φ_1
Type-II	Φ_1	Φ_2	Φ_2
Type-LS	Φ_1	Φ_1	Φ_2
Type-F	Φ_1	Φ_2	Φ_1

- In type I, all fermions couple to the same Higgs. In type II, down quarks and charge leptons couple to one of the Higgs boson doublets and up quarks and neutrinos to the other. This is the scheme allowed at tree-level in SUSY theories.

- Let me emphasize that at the loop level in SUSY theories couplings to the

Generic case

- Although it is important to consider models that mimic the SM suppression of flavor violation, one should also analyze a more generic case, since it is what quite generally appears at low energies.

- So, let's write the coupling modifications in 2HDM for the case in which each type of fermions couple to both Higgs

$$\mathcal{L} \supset -(y_\alpha^{ij} \bar{F}_L \Phi_\alpha f_R + h.c.)$$

- The fermion mass matrix will then be given by

$$M^{ij} = (y_1^{ij} \cos\beta + y_2^{ij} \sin\beta) v$$

- We shall denote with a bar the Yukawas in the physical basis where the mass is diagonal. Hence

$$M_d^{ii} = (\bar{y}_1^{ij} \cos\beta + \bar{y}_2^{ij} \sin\beta) v$$

- Therefore, for $i \neq j$ $\quad \bar{y}_1^{ij} \cos\beta = -\bar{y}_2^{ij} \sin\beta$

Arbitrary Yukawas : $\mathcal{L} \supset -(y_\alpha^{ij} \bar{F}_L \Phi_\alpha f_R + h.c.)$ N. Coyle, D. Rocha, C.W. ' 24

General expression for neutral Higgs couplings

Mass term coming mainly from coupling to Φ_1

$$\mathcal{L}_{h_1^0} = -\frac{m_i}{v}\left[\sin(\beta-\alpha) - \frac{\cos(\beta-\alpha)}{(1+\Delta_i)}\left(\tan\beta - \frac{\Delta_i}{\tan\beta}\right)\right] h_1^0 \bar{f}_i f_i$$
$$+ \left[\left(\frac{\mathrm{Re}(\bar{y}_2^{ij})}{\cos\beta\sqrt{2}}\cos(\beta-\alpha)(1-\delta^{ij}) + i\frac{\mathrm{Im}(\bar{y}_2^{ij})}{\cos\beta\sqrt{2}}\cos(\beta-\alpha)\right) h_1^0 \bar{f}_L^i f_R^j + h.c.\right]$$

Mass term coming mainly from coupling to Φ_2

$$= -\frac{m_i}{v}\left[\sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{(1+\tilde{\Delta}_i)}\left(\frac{1}{\tan\beta} - \tilde{\Delta}_i \tan\beta\right)\right] h_1^0 \bar{f}_i f_i$$
$$- \left[\left(\frac{\mathrm{Re}(\bar{y}_1^{ij})}{\sin\beta\sqrt{2}}\cos(\beta-\alpha)(1-\delta^{ij}) + i\frac{\mathrm{Im}(\bar{y}_1^{ij})}{\sin\beta\sqrt{2}}\cos(\beta-\alpha)\right) h_1^0 \bar{f}_L^i f_R^j + h.c.\right]$$

$$M_d = U_L M U_R^\dagger \qquad \bar{y}_i = U_L y_i U_R^\dagger$$

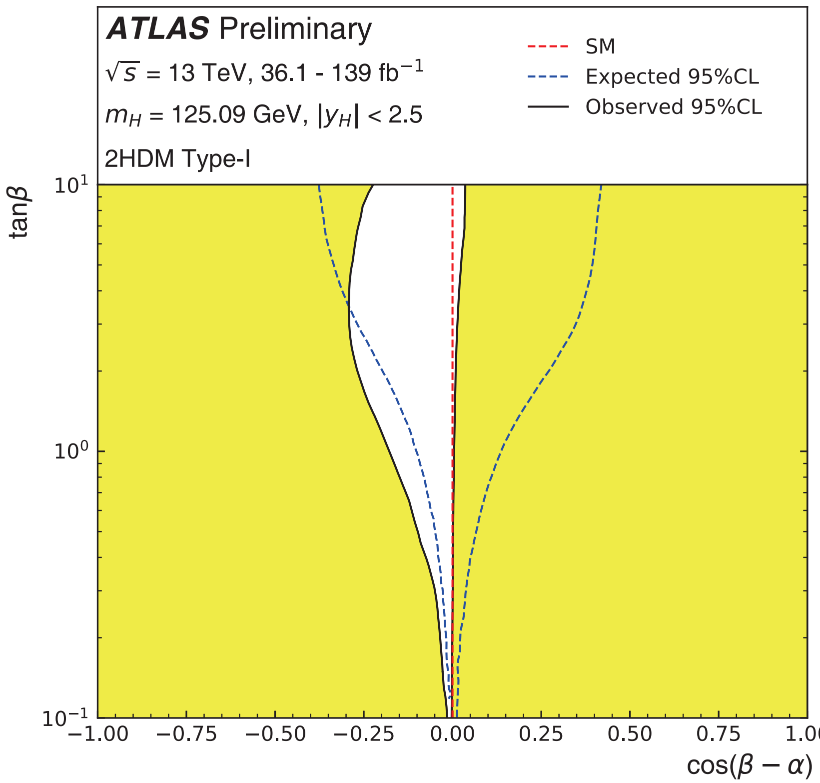
$$\Delta_i = \frac{\mathrm{Re}(\bar{y}_2^{ii})}{\mathrm{Re}(\bar{y}_1^{ii})}\tan\beta \qquad \tilde{\Delta}_i = \frac{1}{\Delta_i}$$

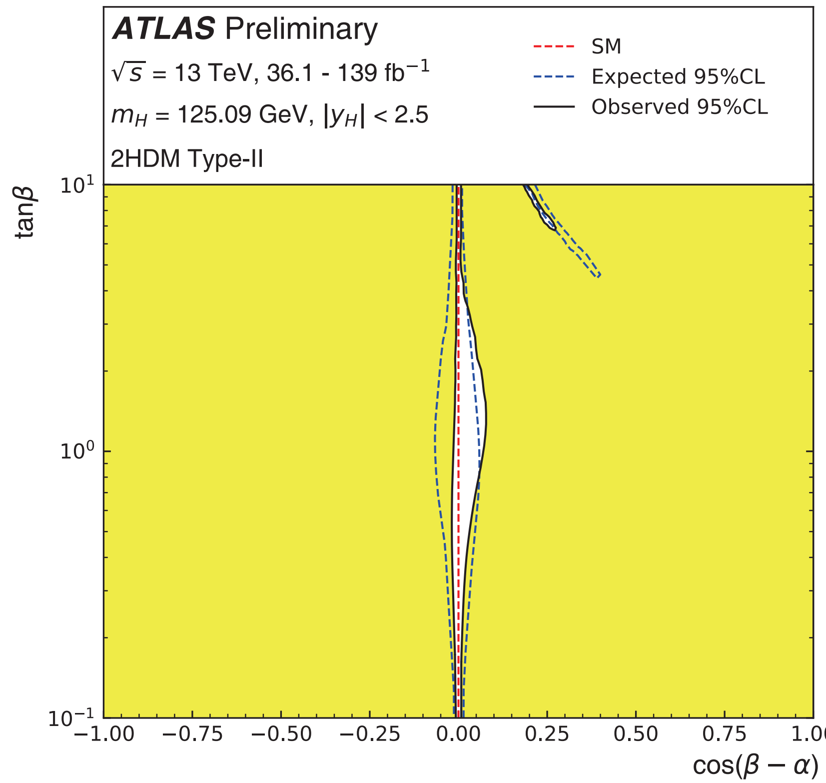
Higgs FCNC demands flavor as well as Higgs misalignment !

$$\bar{y}_1 v_1 + \bar{y}_2 v_2 = \mathrm{Diag}(m) \rightarrow \bar{y}_1 \cos\beta + \bar{y}_2 \sin\beta = \mathrm{Diag}(m/v)$$

We will keep in mind that the LHC favors and SM-like Higgs boson

LHC constraints on Higgs alignment in the 2HDM





Regions excluded by fits to the measured rates of the productions and decay of the Higgs boson (assumed to be h of the 2HDM). Contours at 95% CL. ATLAS-CONF-2021-053

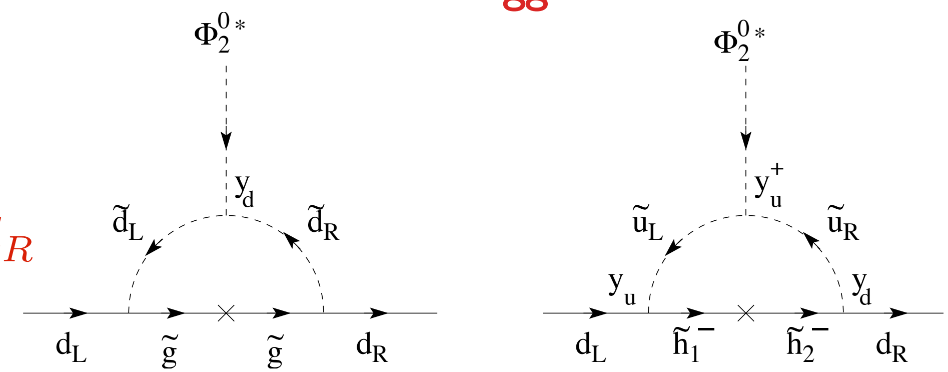
SUSY at Loop Level

Hempfling '93
Hall, Rattazzi, Sarid'93
Carena, Olechowski, Pokorski, C.W.'93

Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to both Higgs fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L (h_d H_1^0 + \Delta h_d H_2^0) d_R$$



- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

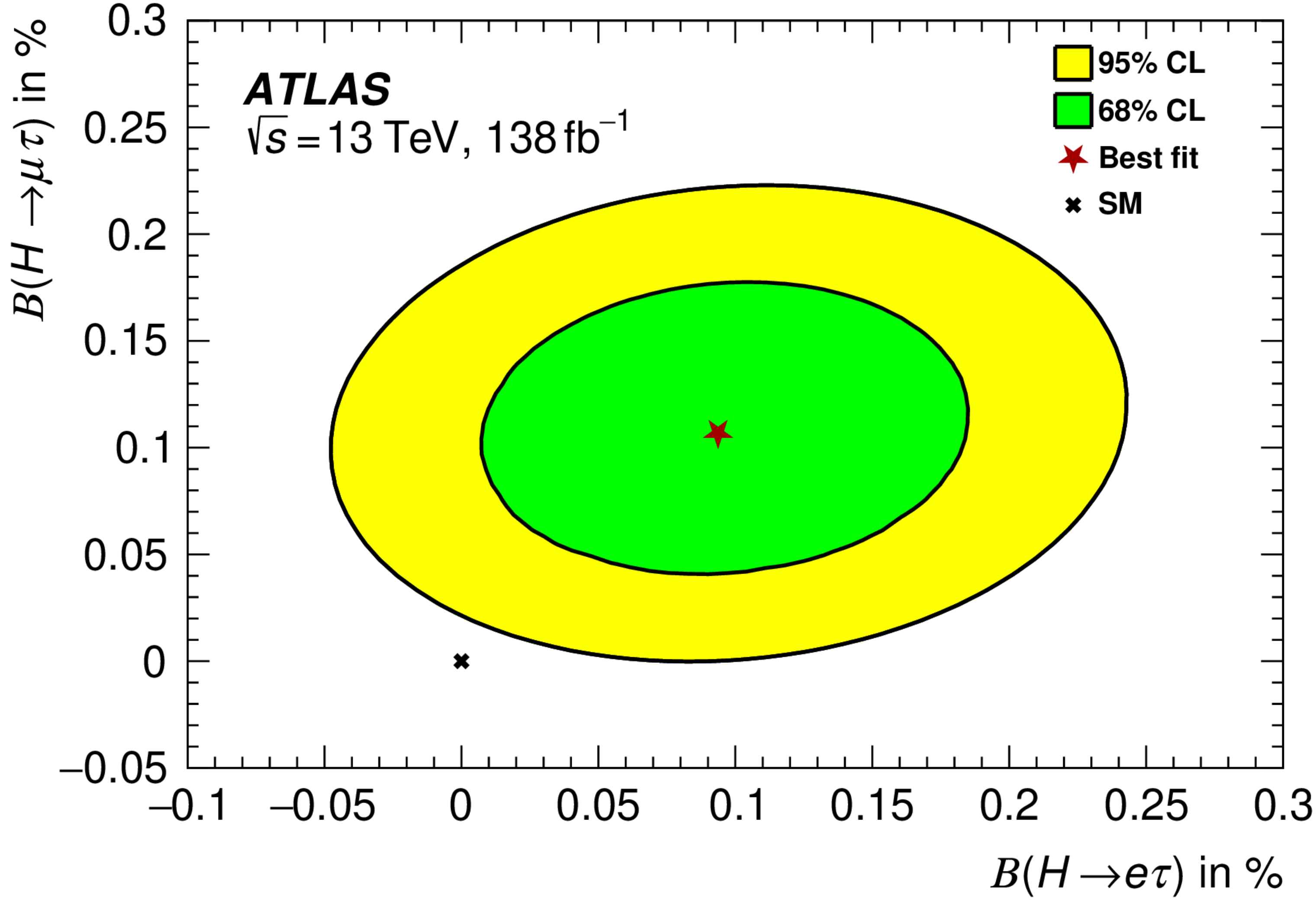
$$\tan\beta = \frac{v_2}{v_1}$$

$$\frac{\Delta_b}{\tan\beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

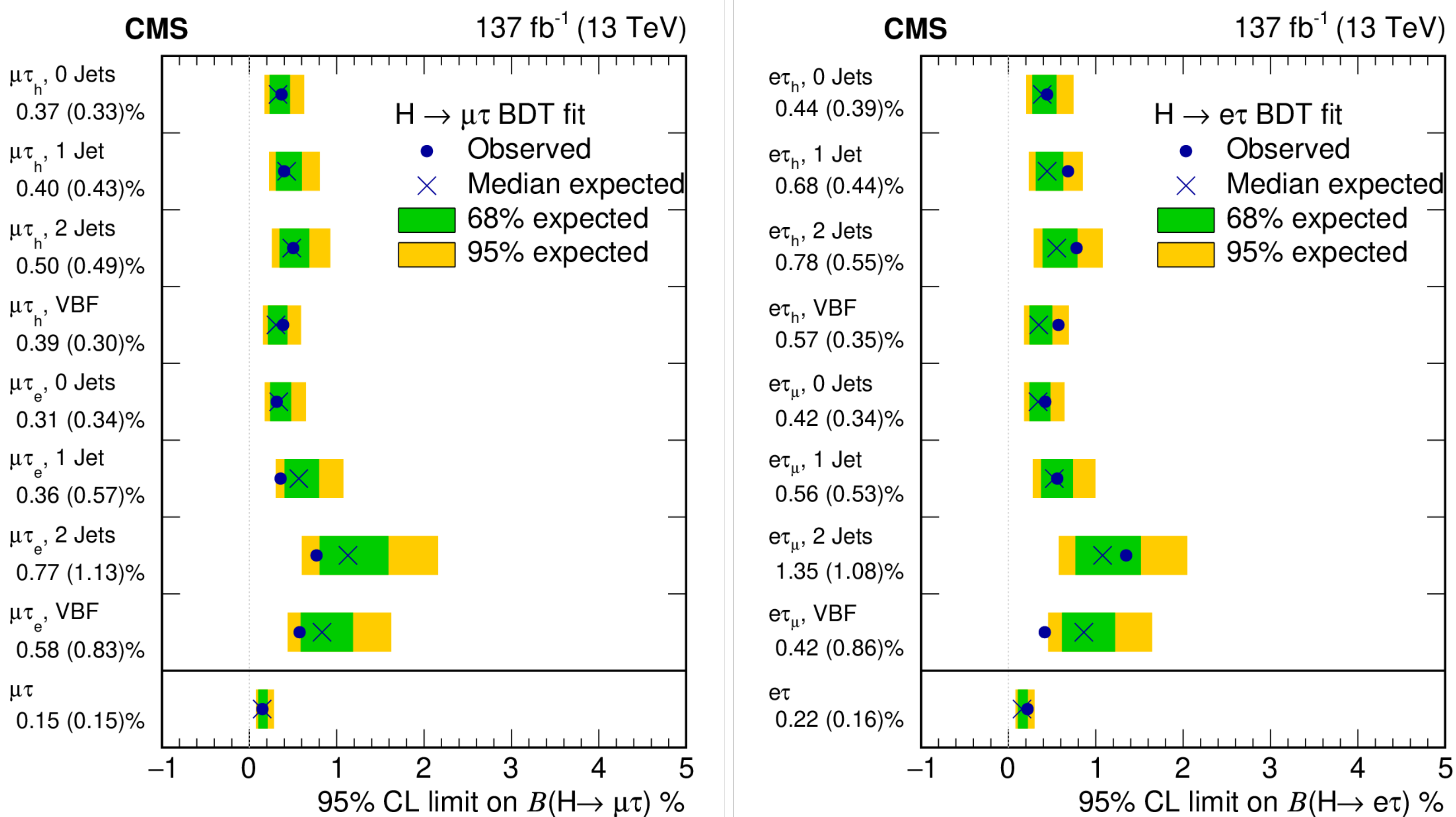
$$X_t = A_t - \mu/\tan\beta \simeq A_t \qquad \Delta_b = (E_g + E_t h_t^2) \tan\beta$$

Resummation : Carena, Garcia, Nierste, C.W.'00

Possible flavor violation in Higgs decays



No hint from CMS, though : $BR(H \to \tau\mu, e) < 0.15\%$



CMS
137 fb^{-1} (13 TeV)
$\mu\tau_h$, 0 Jets
0.37 (0.33)%
$\mu\tau_h$, 1 Jet
0.40 (0.43)%
$\mu\tau_h$, 2 Jets
0.50 (0.49)%
$\mu\tau_h$, VBF
0.39 (0.30)%
$\mu\tau_e$, 0 Jets
0.31 (0.34)%
$\mu\tau_e$, 1 Jet
0.36 (0.57)%
$\mu\tau_e$, 2 Jets
0.77 (1.13)%
$\mu\tau_e$, VBF
0.58 (0.83)%
$\mu\tau$
0.15 (0.15)%
H → $\mu\tau$ BDT fit
Observed
Median expected
68% expected
95% expected
95% CL limit on B(H→ $\mu\tau$) %
CMS
137 fb^{-1} (13 TeV)
$e\tau_h$, 0 Jets
0.44 (0.39)%
$e\tau_h$, 1 Jet
0.68 (0.44)%
$e\tau_h$, 2 Jets
0.78 (0.55)%
$e\tau_h$, VBF
0.57 (0.35)%
$e\tau_\mu$, 0 Jets
0.42 (0.34)%
$e\tau_\mu$, 1 Jet
0.56 (0.53)%
$e\tau_\mu$, 2 Jets
1.35 (1.08)%
$e\tau_\mu$, VBF
0.42 (0.86)%
$e\tau$
0.22 (0.16)%
H → $e\tau$ BDT fit
Observed
Median expected
68% expected
95% expected
95% CL limit on B(H→ $e\tau$) %

$$\mathcal{L} \supset -(y_\alpha^{ij} \bar{Q}_L H_\alpha f_R + h.c.)$$

N. Coyle, D. Rocha, C.W. ' 24

Non-SM Higgs Coupling

$$\begin{aligned}\mathcal{L}_{h_2^0} &= -\frac{m_i}{v}\delta^{ij}\left[\cos(\beta-\alpha) + \left(\frac{\tan\beta}{1+\Delta_i} - \frac{\Delta_i}{\tan\beta(1+\Delta_i)}\right)\sin(\beta-\alpha)\right] h_2^0 \bar{f}_i f_i \\ &+ \left[\left(\frac{\mathrm{Re}(\bar{y}_2^{ij})}{\sqrt{2}\cos\beta}(1-\delta^{ij})\sin(\beta-\alpha) + i\frac{\mathrm{Im}(\bar{y}_2^{ij})}{\sqrt{2}\cos\beta}\sin(\beta-\alpha)\right) h_2^0 \bar{f}_L^i f_R^j + h.c.\right]\end{aligned}$$

H_1-coupling

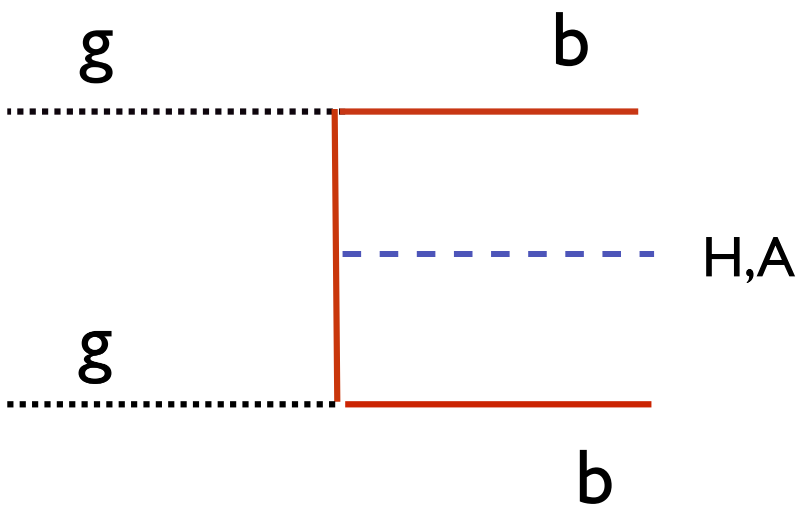
$$\begin{aligned}\mathcal{L}_{h_2^0} &= -\frac{m_i}{v}\delta^{ij}\left[\cos(\beta-\alpha) - \left(\frac{1}{\tan\beta(1+\tilde{\Delta}_i)} - \frac{\tilde{\Delta}_i\tan\beta}{(1+\tilde{\Delta}_i)}\right)\sin(\beta-\alpha)\right] h_2^0 \bar{f}_i f_i \\ &- \left[\left(\frac{\mathrm{Re}(\bar{y}_1^{ij})}{\sqrt{2}\sin\beta}(1-\delta^{ij})\sin(\beta-\alpha) + i\frac{\mathrm{Im}(\bar{y}_1^{ij})}{\sqrt{2}\sin\beta}\sin(\beta-\alpha)\right) h_2^0 \bar{f}_L^i f_R^j + h.c.\right]\end{aligned}$$

H_2-coupling

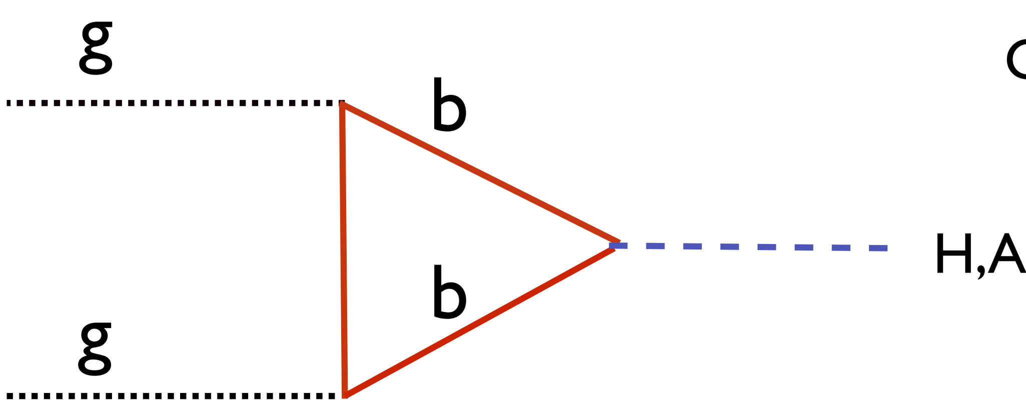
Higgs alignment, of course, does not ensure flavor alignment in the non-standard Higgs sector

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



Associated Production

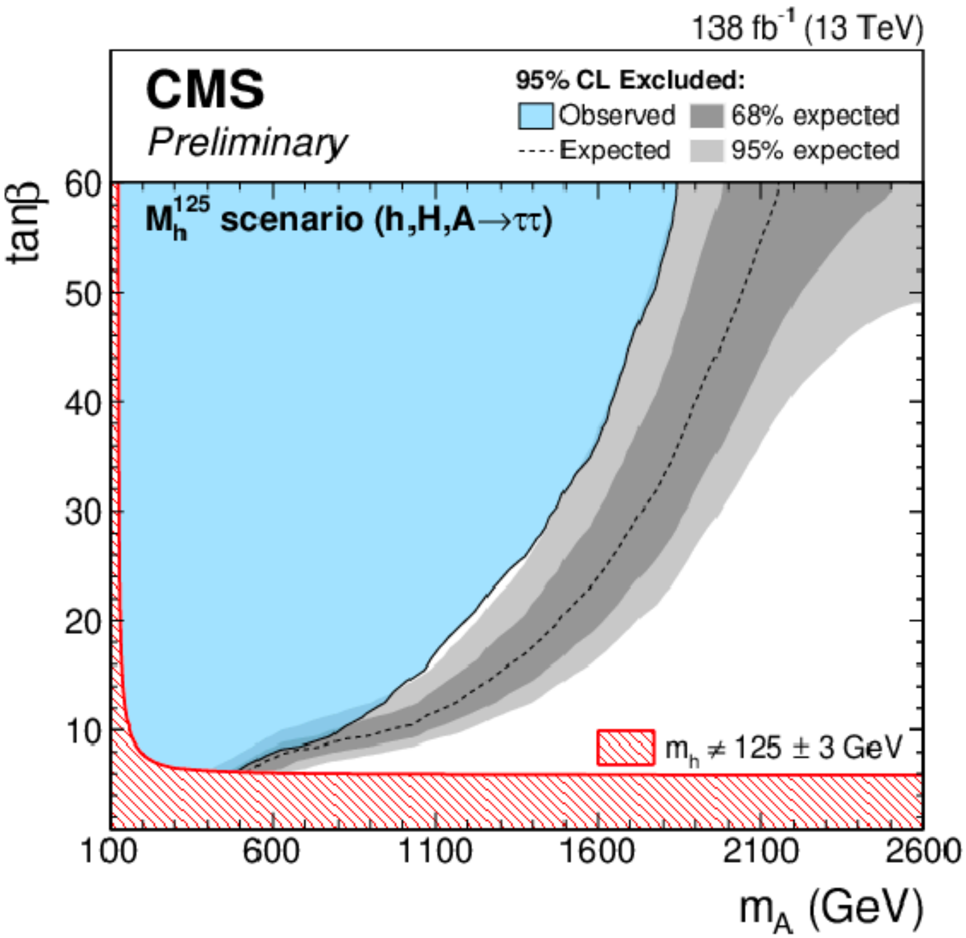


Gluon Fusion

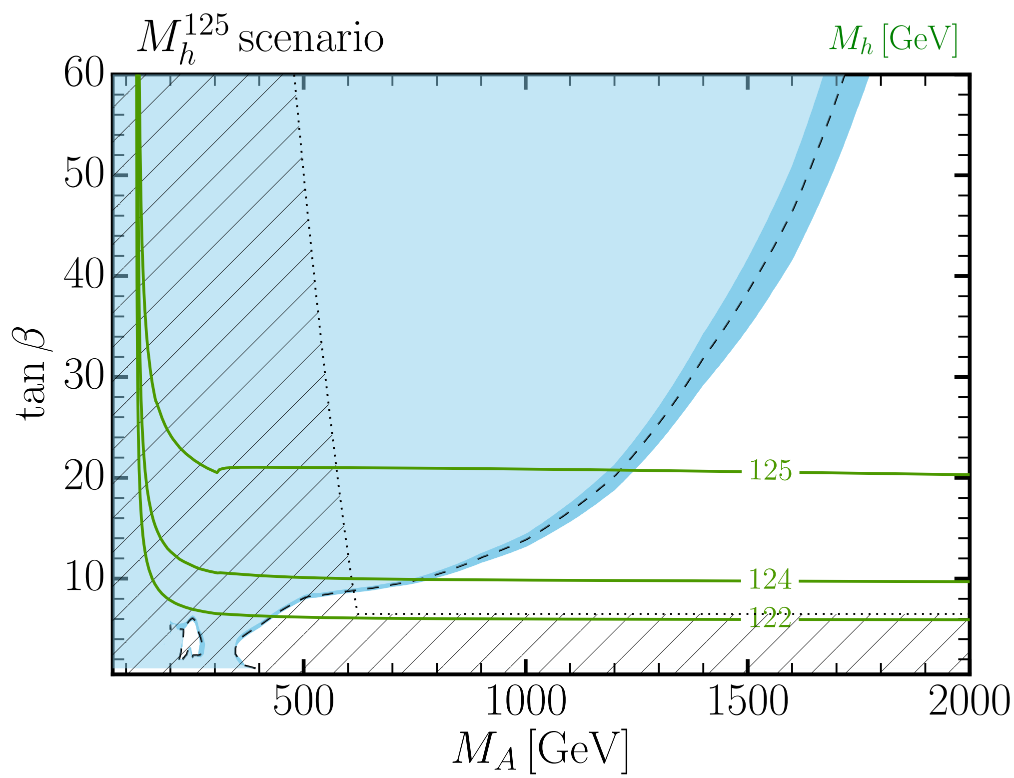
$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

Complementarity of Direct and Indirect Bounds

Bahl, Fuchs, Hahn, Heinemeyer, Liebler, Patel, Slavich, Stefaniak, Weiglein, C.W. arXiv:1808.07542



Dashed area, constrained by precision measurements.
Low values of the Higgsino Mass assumed in this Figure.



Interesting but not compelling excess appears at CMS.
No similar excess appears at ATLAS.

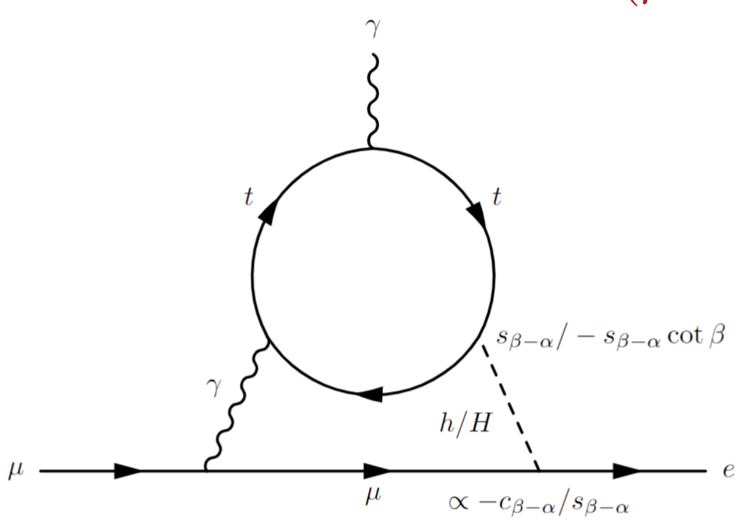
Higgs Flavor violation

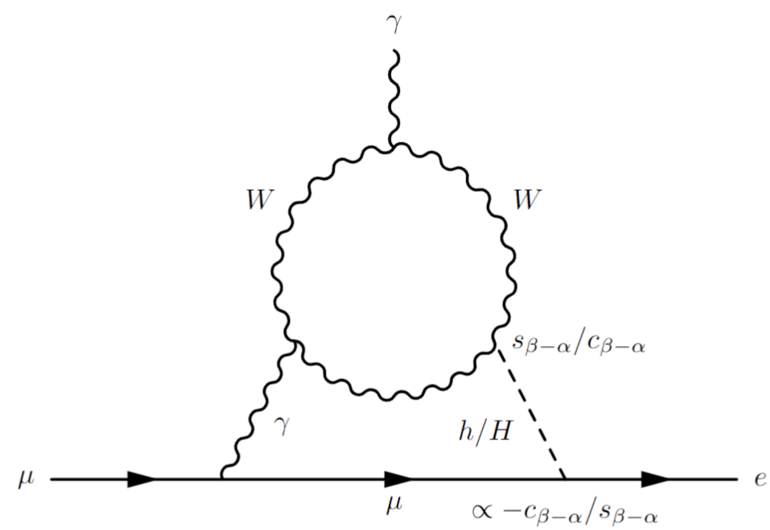
Induces flavor violating processes which do not involve the Higgs directly

One example is the radiative decay of heavy leptons into lighter ones

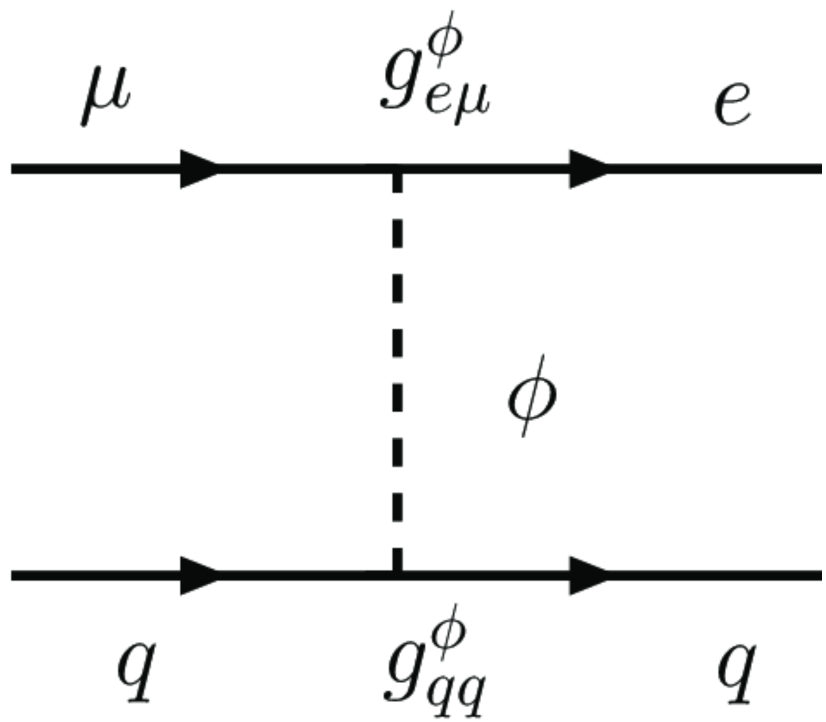
Here I assume that the top and leptons have dominant couplings like in type II scenarios

$$BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$$





μ to e Conversion



Less relevant interference

Harnik, Kopp, Zupan, arXiv:1209.1937

Flavor Conserving and Violating Processes

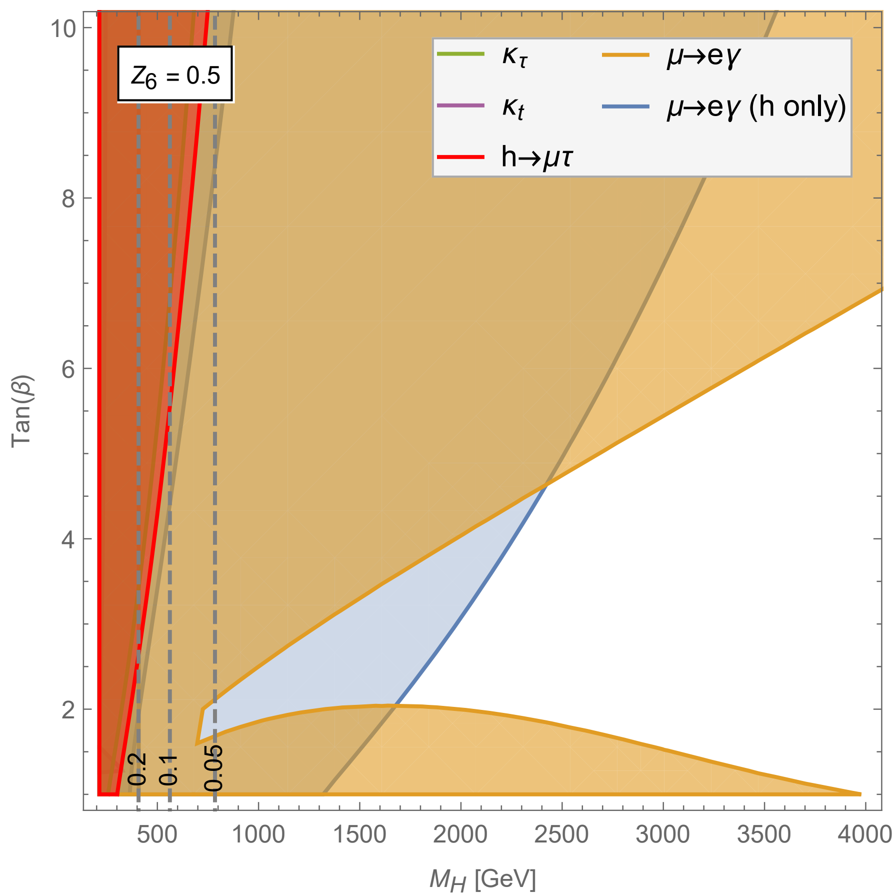
- There can be interesting cancellations between the flavor violating contributions of light and heavy Higgs bosons.
- The large hierarchy between the different generations can be explained in different ways.
- Generically, if we assume the dominant Yukawa to lead to the generation of the tau mass and the other to lead to the generation of the muon and electron masses, the off-diagonal elements are proportional to, for instance,

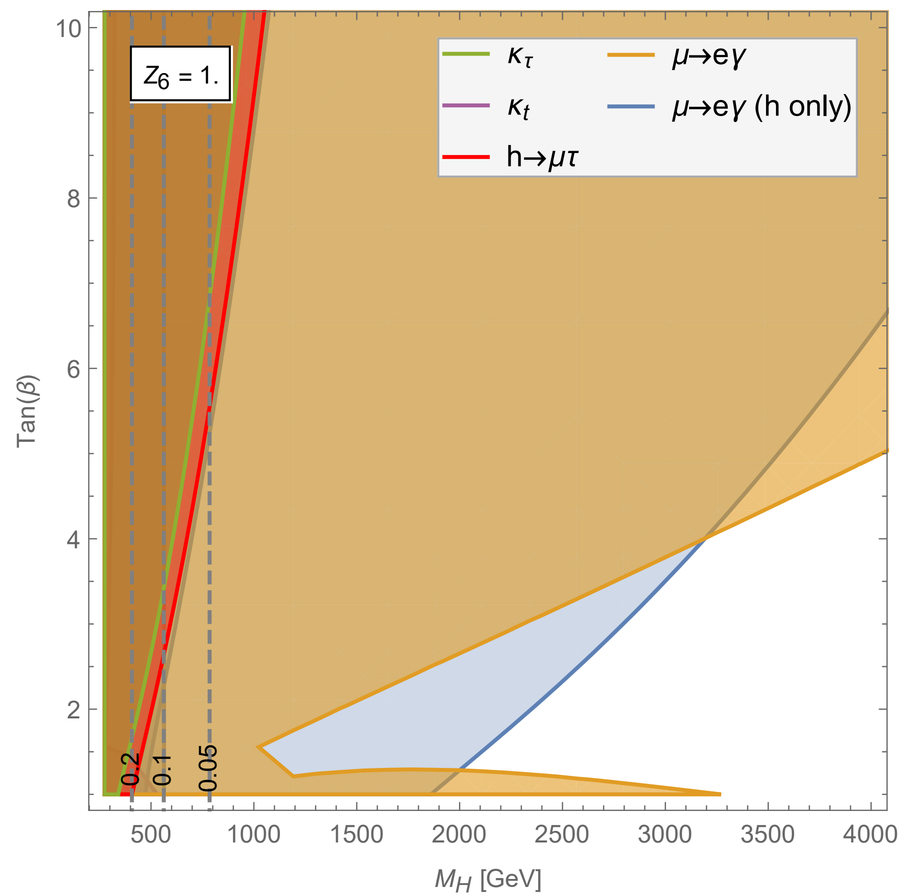
$$\bar{y}_{l_i l_j} \propto \frac{\sqrt{m_i m_j}}{v} \qquad \text{or} \qquad \bar{y}_{l_i l_j} \propto \frac{\mathrm{Min}(\mathrm{m_i}, \mathrm{m_j})}{v}$$

N. Coyle, D. Rocha, C.W. ' 24

Case in which $\bar{y}_{l_i l_j} \propto \frac{\sqrt{m_i m_j}}{v}$

$BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$ $k_\tau < 0.2$ $BR(h \to \tau\mu) < 0.002$

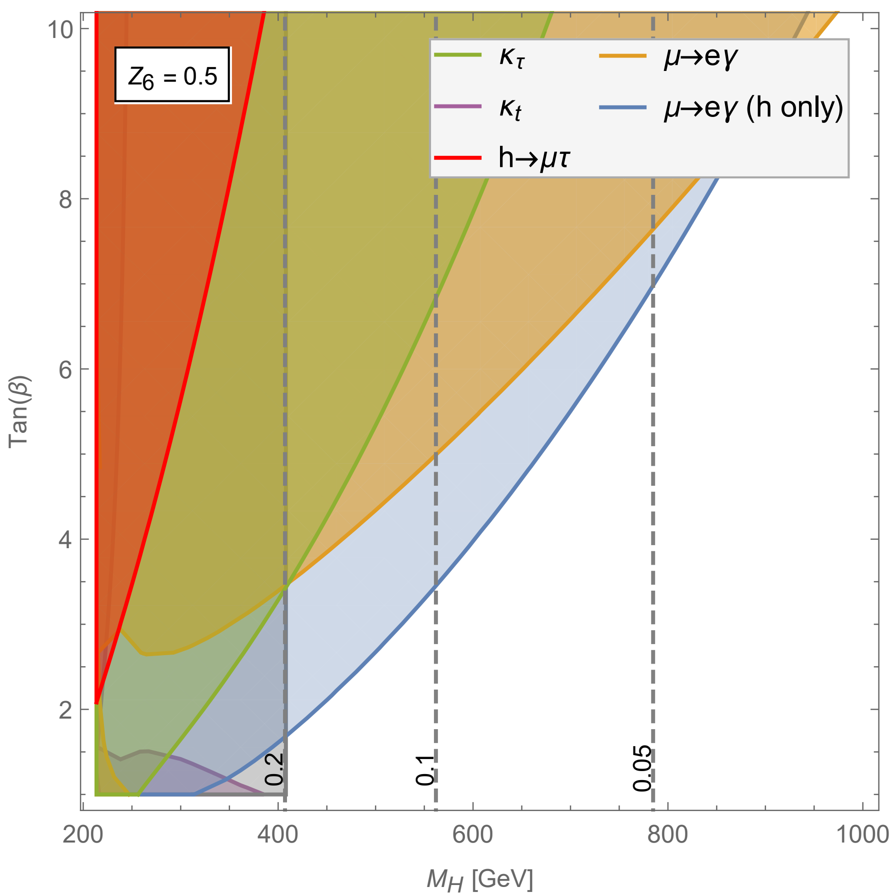


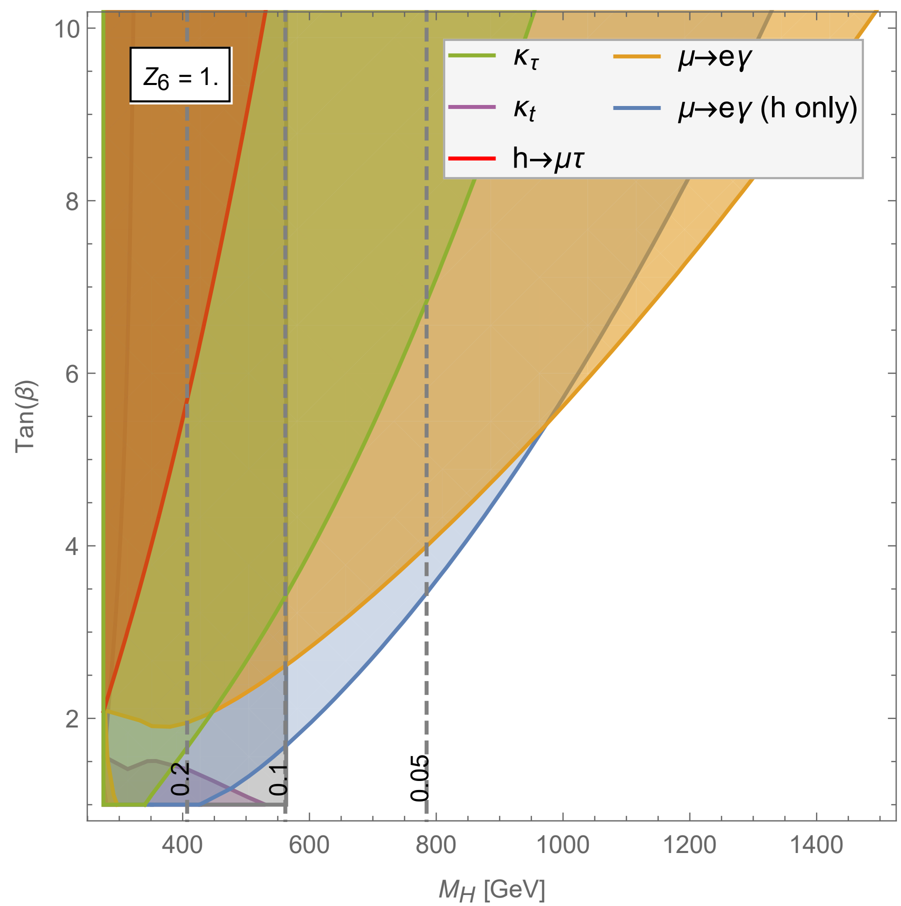


Visible interference between light and heavy Higgs contributions

N. Coyle, D. Rocha, C.W. ' 24

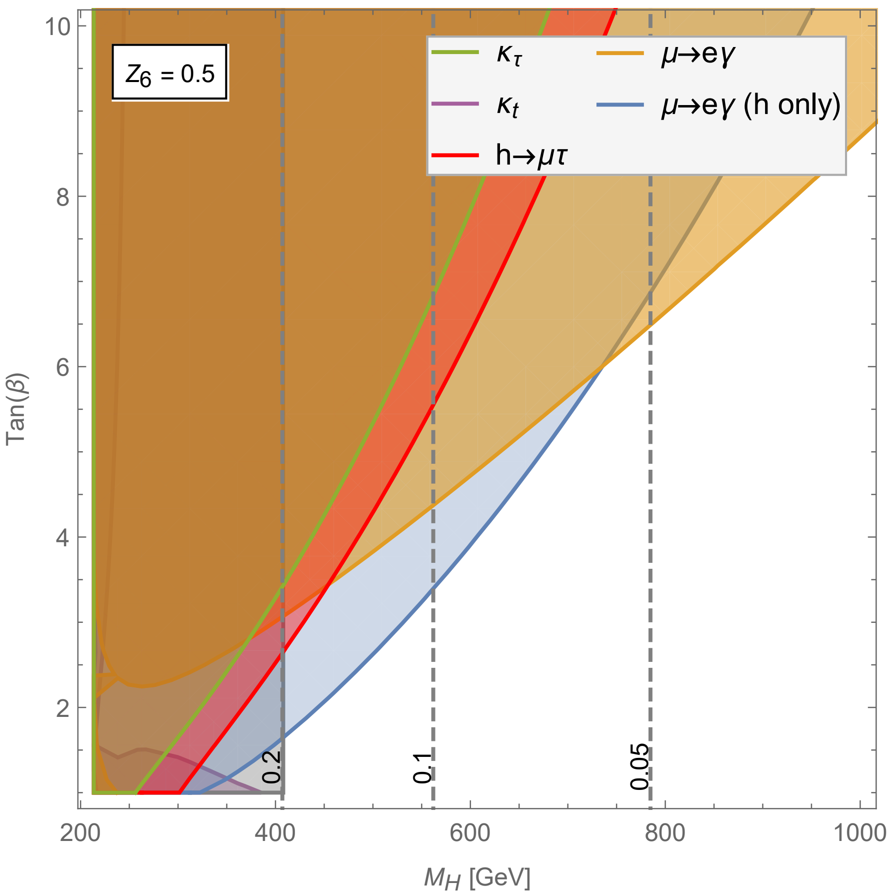
Case in which $\bar{y}_{l_i l_j} \propto \frac{\mathrm{Min(m_i, m_j)}}{v}$

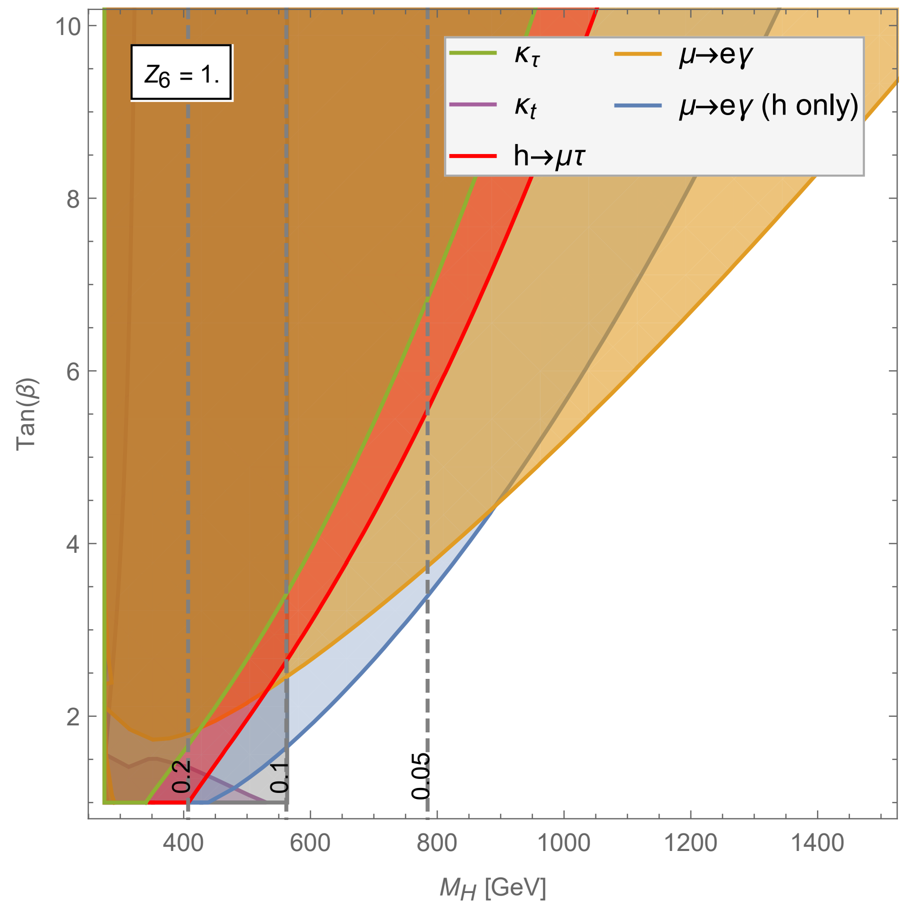




N. Coyle, D. Rocha, C.W. ' 24

Case in which $\bar{y}_{\mu\tau} \propto \frac{\sqrt{m_\tau m_\mu}}{v}, \quad \bar{y}_{\mu e} \propto \frac{m_e}{v}$

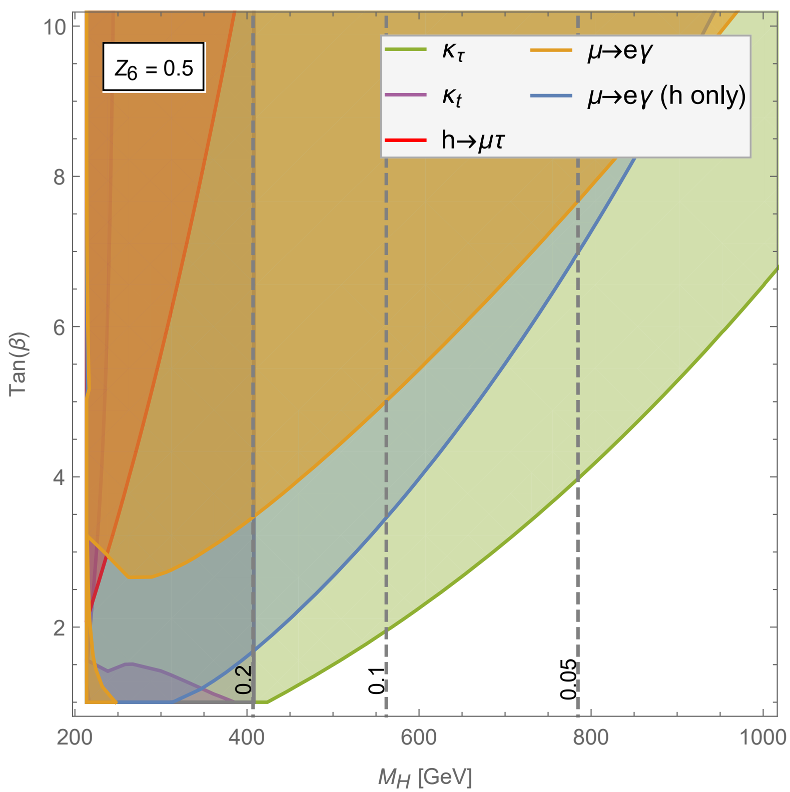




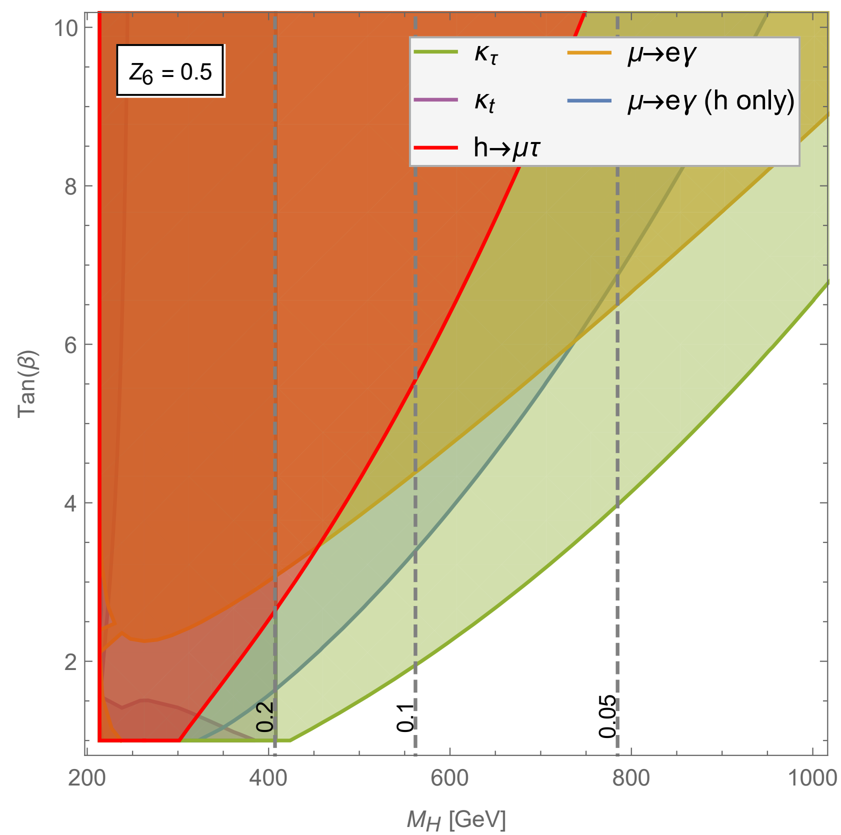
N. Coyle, D. Rocha, C.W. ' 24

Influence of Diagonal Couplings

$$\bar{y}_{l_i l_j} \propto \frac{\mathrm{Min}(\mathrm{m_i}, \mathrm{m_j})}{v}$$



$$\bar{y}_{\mu\tau} \propto \frac{\sqrt{m_\tau m_\mu}}{v}, \qquad \bar{y}_{\mu e} \propto \frac{m_e}{v}$$

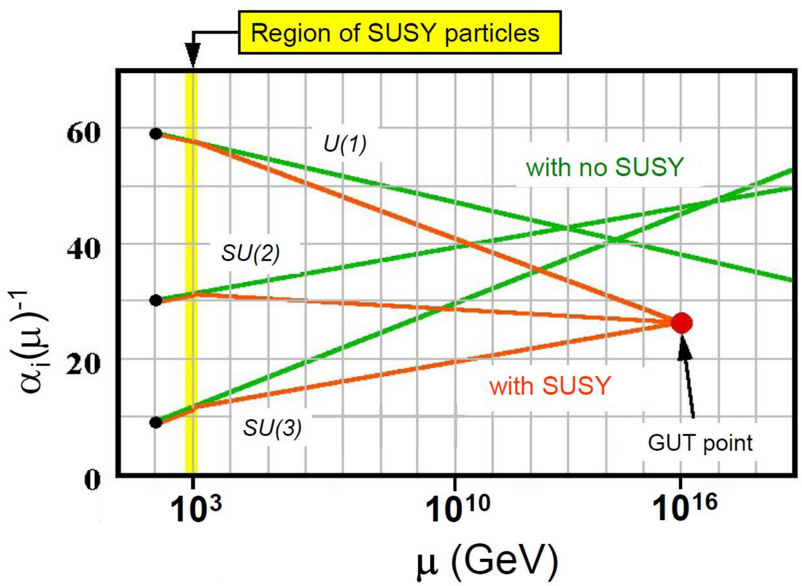


For Diagonal values $\bar{y}_2^{ii} = 0$ (impact of $\Delta_i = 0$).

Multiple Scalars

A well motivated example : Supersymmetry

Unification



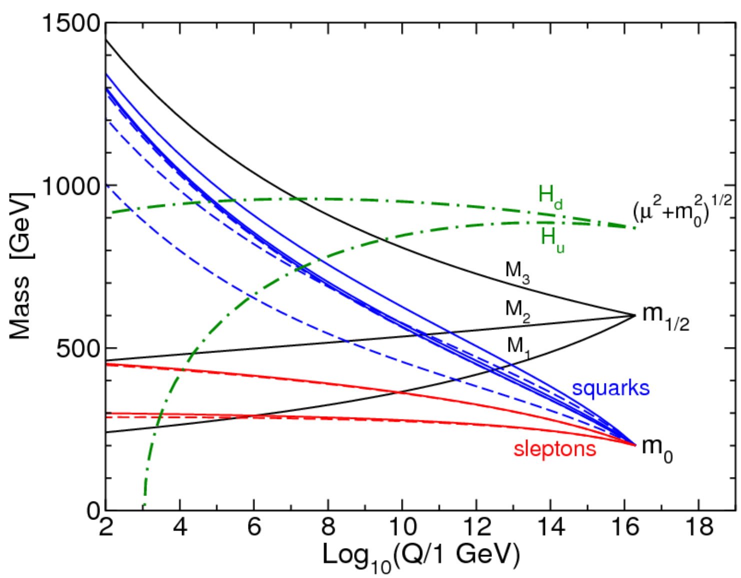
SUSY Algebra

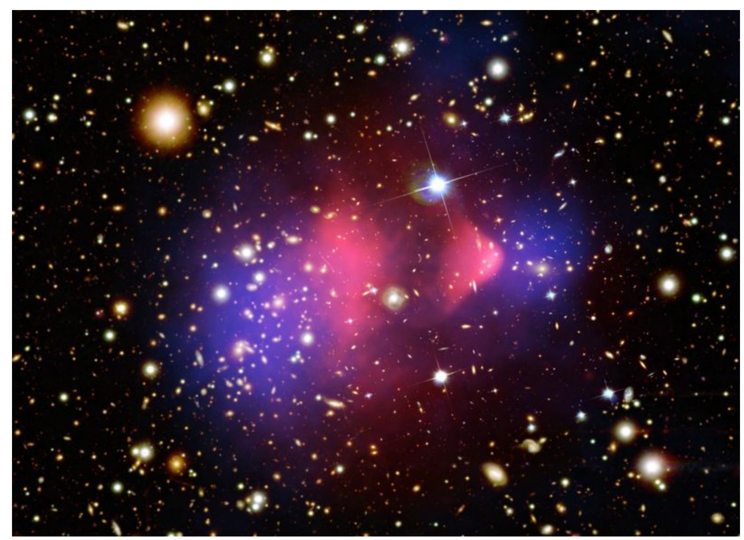
$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma^{\mu}_{\alpha\dot{\alpha}} P_\mu$$
$$[Q_\alpha, P_\mu] = [\bar{Q}_{\dot{\alpha}}, P_\mu] = 0$$

Quantum Gravity ?

Ultraviolet Insensitivity

Electroweak Symmetry Breaking





If R-Parity is Conserved the Lightest SUSY particle is a good Dark Matter candidate

Stop Searches : MSSM Guidance ?

Lightest SM-like Higgs mass strongly depends on:

- * CP-odd Higgs mass m_A
- * tan beta $= \frac{v_u}{v_d}$
- *the top quark mass
- * the stop masses and mixing

$$M^2_{\tilde{t}} = \begin{pmatrix} m^2_Q + m^2_t + D_L & m_t X_t \\ m_t X_t & m^2_U + m^2_t + D_R \end{pmatrix}$$

M_h depends logarithmically on the averaged stop mass scale M_{SUSY} and has a quadratic and quartic dep. on the stop mixing parameter X_t. [and on sbottom/stau sectors for large tan beta]

For moderate to large values of tan beta and large non-standard Higgs masses

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

$$t = \log(M^2_{SUSY}/m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M^2_{SUSY}}\left(1 - \frac{X_t^2}{12 M^2_{SUSY}}\right)$$

$X_t = A_t - \mu/\tan\beta \rightarrow$ LR stop mixing

Carena, Espinosa, Quiros, C.W.'95,96

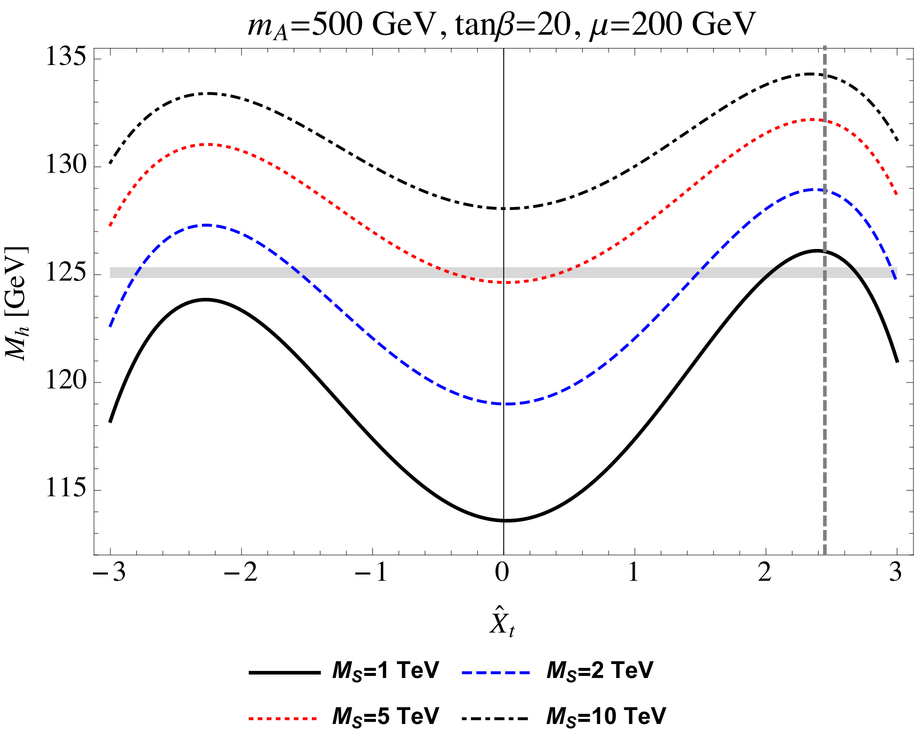
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

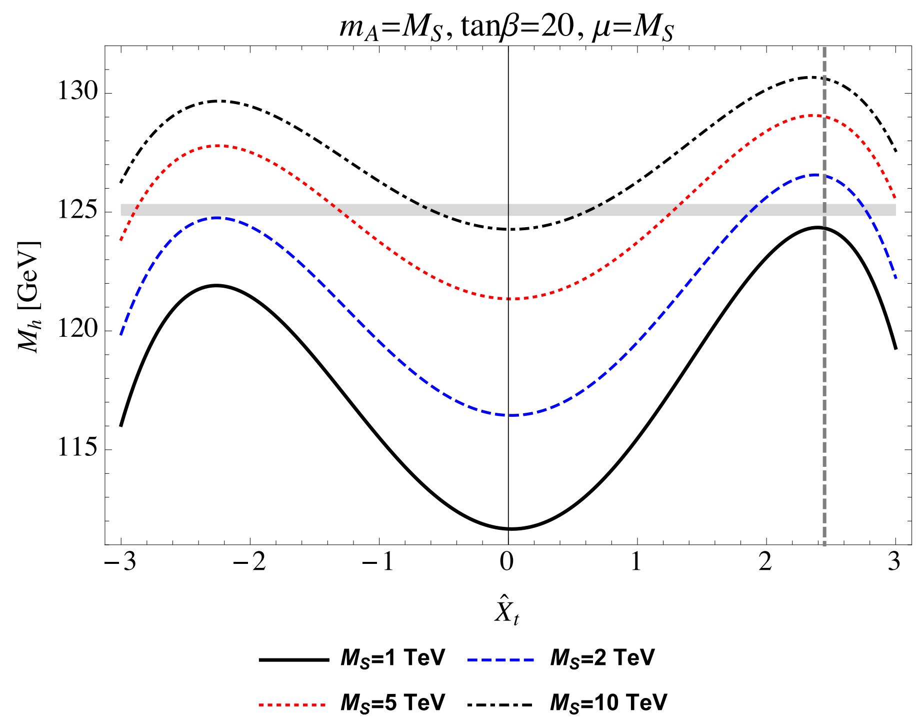
MSSM Guidance:
Stop Masses above about 1 TeV lead to the right Higgs Masss

P. Slavich, S. Heinemeyer et al, arXiv:2012.15629

P. Draper, G. Lee, C.W.'13, Bagnaschi et al' 14, Vega and Villadoro '14, Bahl et al'17

M. Carena, J. Ellis, J.S. Lee, A Pilaftsis, C.W.'16, G. Lee, C.W. arXiv:1508.00576

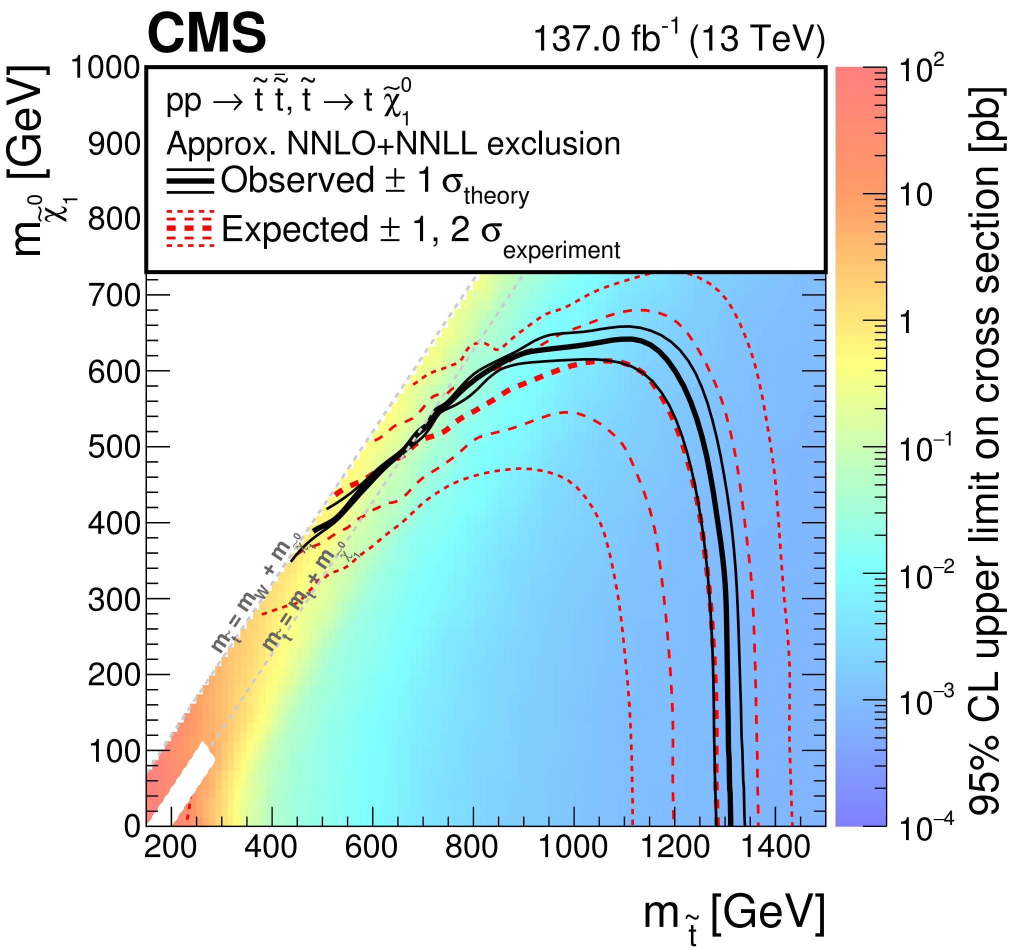


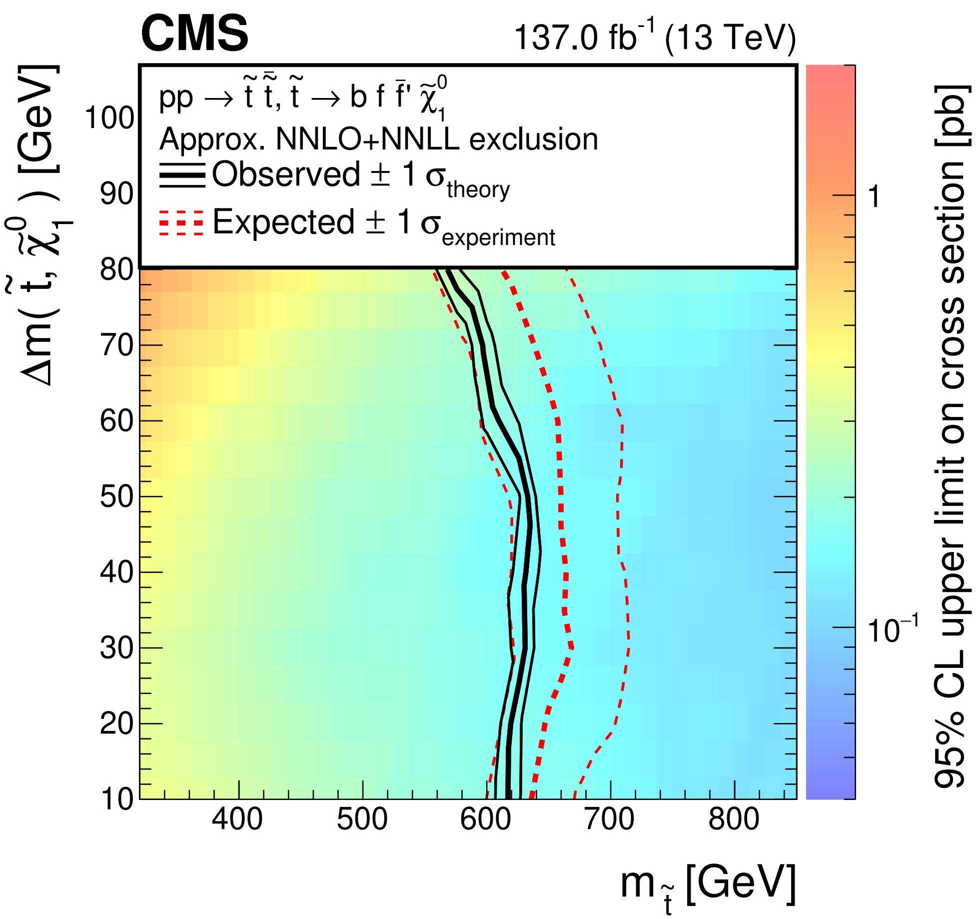


Necessary stop masses increase for lower values of tanβ, larger values of μ smaller values of the CP-odd Higgs mass or lower stop mixing values.

Lighter stops demand large splittings between left- and right-handed stop masses

Stop Searches





Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for sbottoms and 600 GeV for stops. Islands in one search are covered by other searches.

We are starting to explore the mass region suggested by the Higgs mass determination !

Carena, Haber, Low, Shah, C.W.'15

Stops don't need to be so heavy :

Naturalness and Alignment in the (N)MSSM

see also Kang, Li, Li,Liu, Shu'13, Agashe,Cui,Franceschini'13

- It is well known that in the NMSSM there are new contributions to the lightest CP-even Higgs mass,

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

- It is perhaps less known that it leads to sizable corrections to the mixing between the MSSM like CP-even states. In the Higgs basis, (correction to $\Delta\lambda_4 = \lambda^2$)

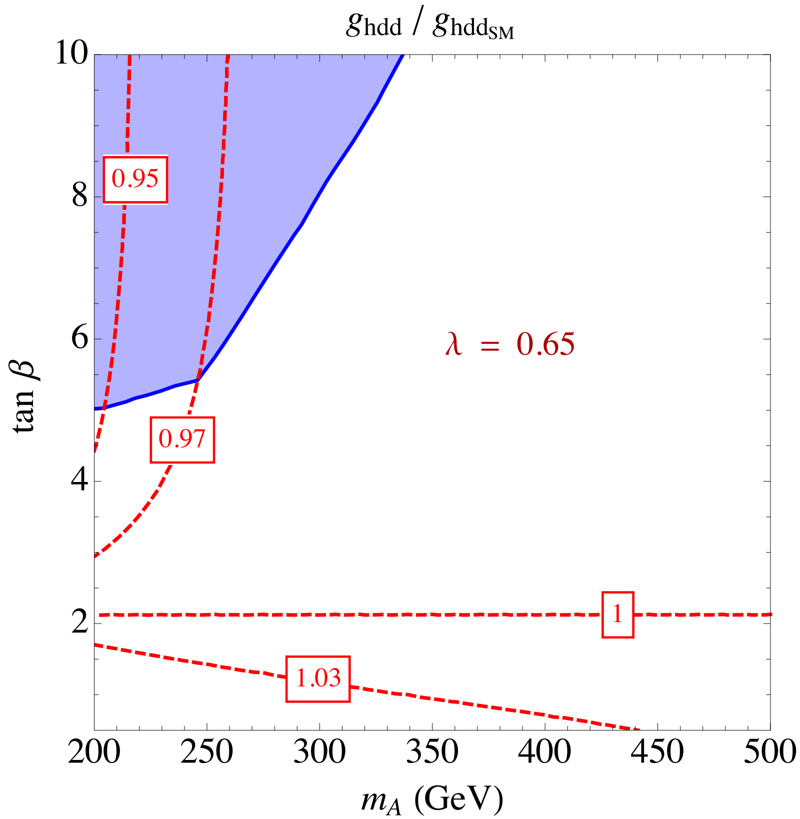
$$M_S^2(1,2) \simeq \frac{1}{\tan\beta} \left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2\beta + \delta_{\tilde{t}} \right) \equiv Z_6 v^2$$

- The values of lambda end up in a very narrow range, between 0.65 and 0.7 for all values of tan(beta), that are the values that lead to naturalness with perturbativity up to the GUT scale

$$\lambda^2 = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2\beta}$$

Alignment in the NMSSM (heavy or Aligned singlets)

Carena, Low, Shah, C.W.'13



It is clear from this plot that the NMSSM does an amazing job in aligning the MSSM-like CP-even sector, provided $\lambda \sim 0.65$

Very relevant phenomenological properties

This range of couplings, and the subsequent alignment, may appear as emergent properties in a theory with strong interactions at high energies

N. Coyle, C.W. arXiv:1912.01036

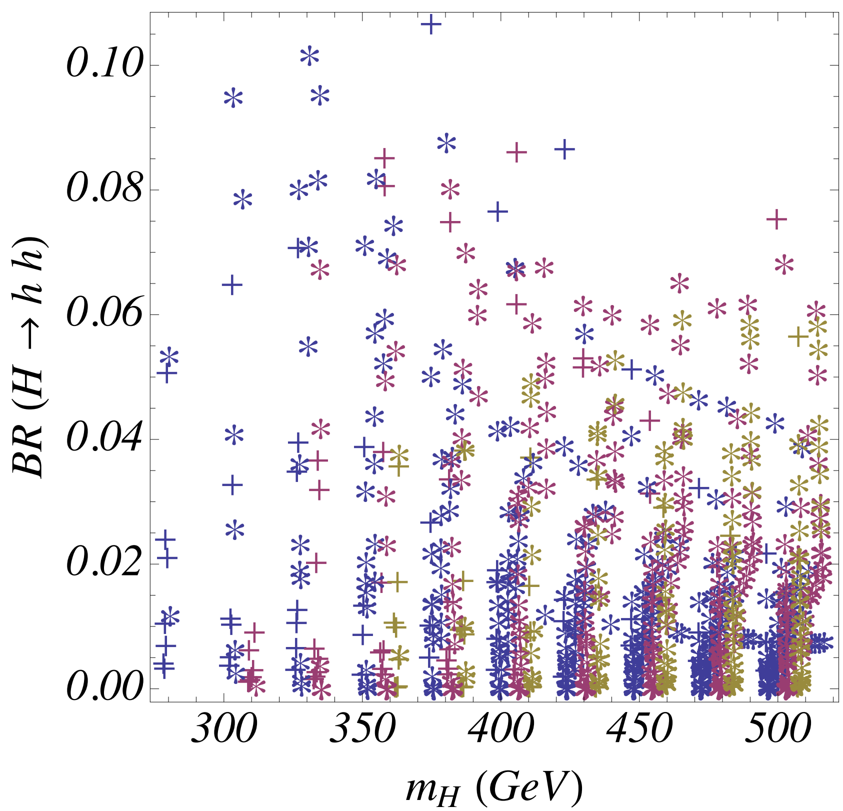
Decays into pairs of SM-like Higgs bosons suppressed by alignment

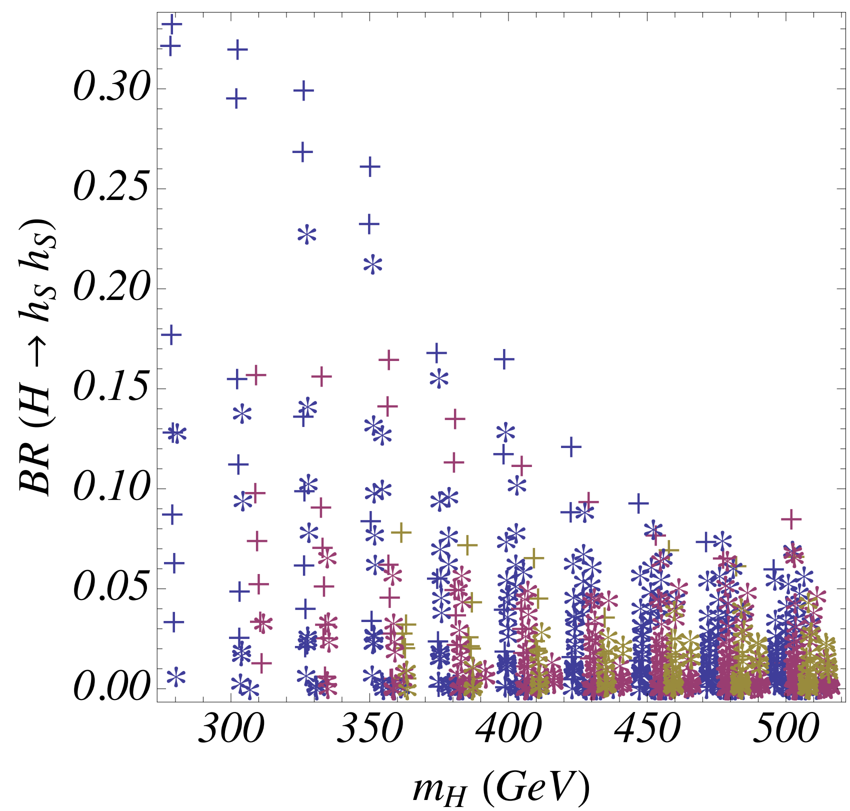
Carena, Haber, Low, Shah, C.W.'15

See also S. Su talk

Crosses : H1 singlet like
Asterix : H2 singlet like

Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow: $\tan\beta = 3$





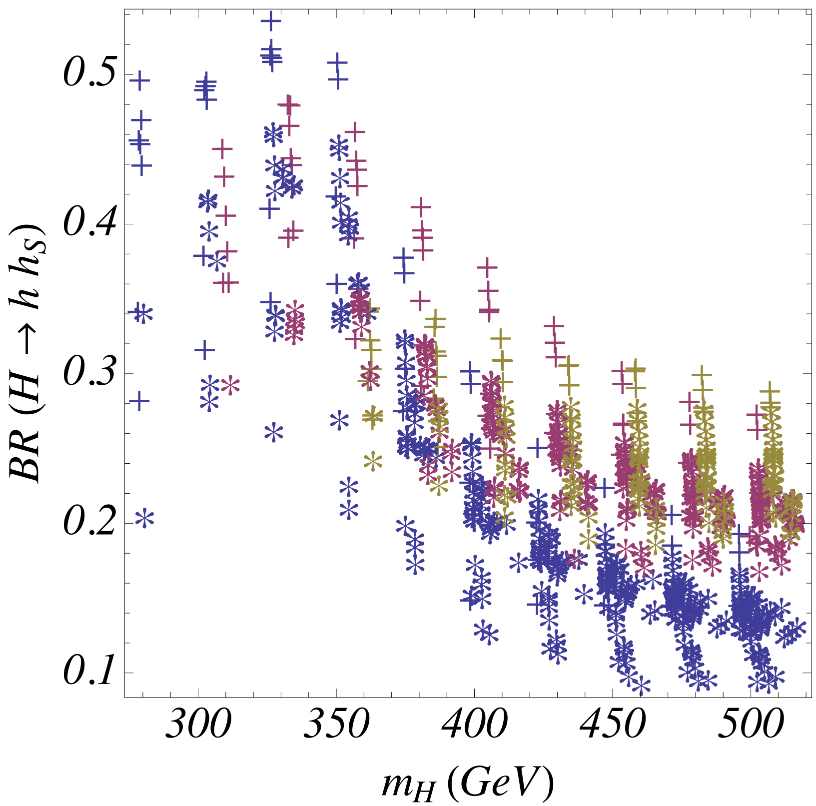
Significant decays of heavier Higgs Bosons into lighter ones and Z's

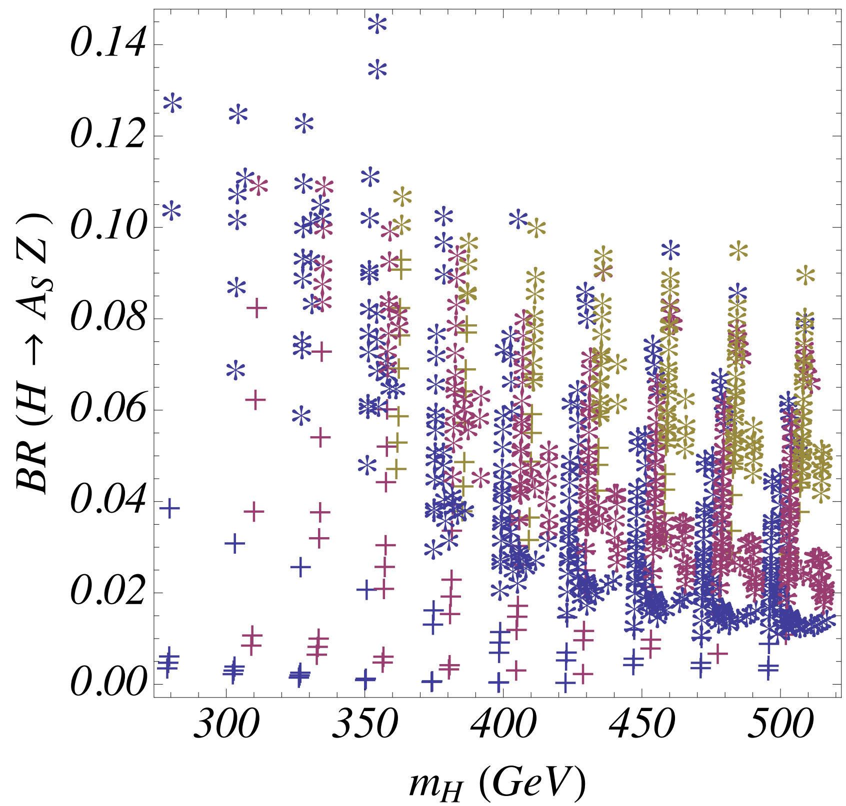
Relevant for searches for Higgs bosons

Crosses : H1 singlet like
Asterix : H2 singlet like

Blue : $\tan\beta = 2$
Red : $\tan\beta = 2.5$
Yellow: $\tan\beta = 3$

Carena, Haber, Low, Shah, C.W.'15

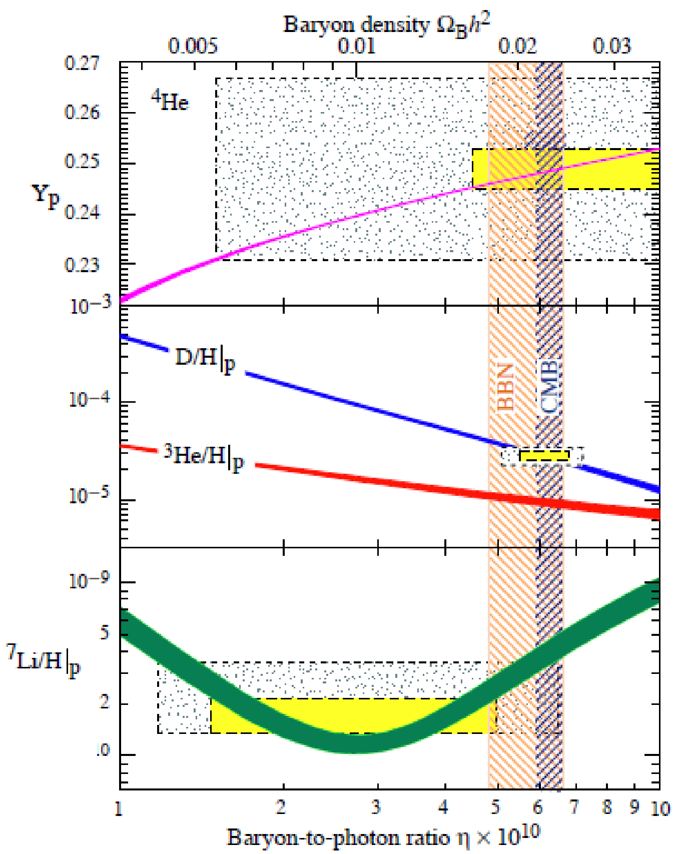




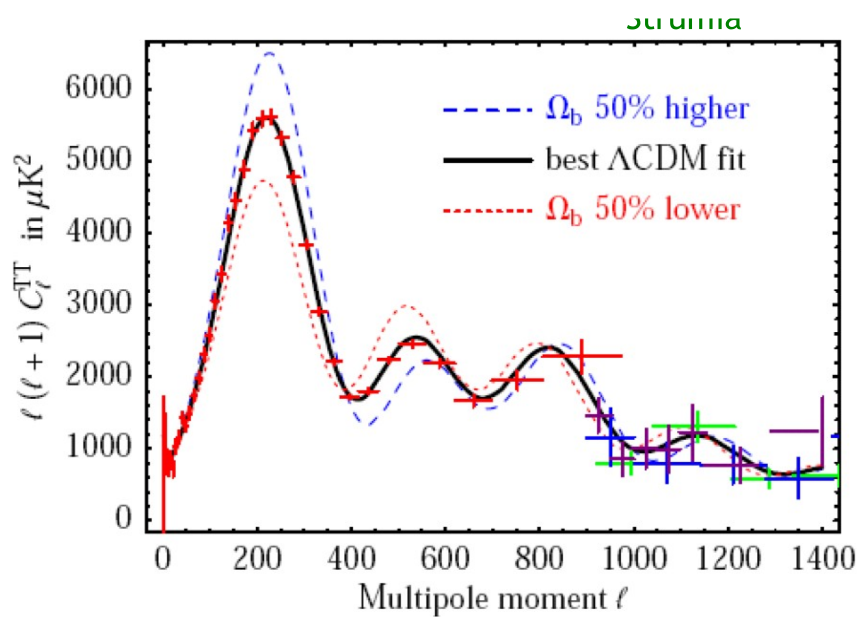
Origin of Ordinary Matter

Where is the Antimatter ?

Nucleosynthesis
Abundance of light elements



Peaks in CMB power spectrum



$$\eta_B = (6.11 \pm 0.19) \times 10^{-10}$$

$$\eta_B = \frac{n_B}{n_\gamma}$$

- How to explain the appearance of such a small quantity ?

Generating the Matter-Antimatter Asymmetry

Antimatter may have disappeared through annihilation processes in the early Universe

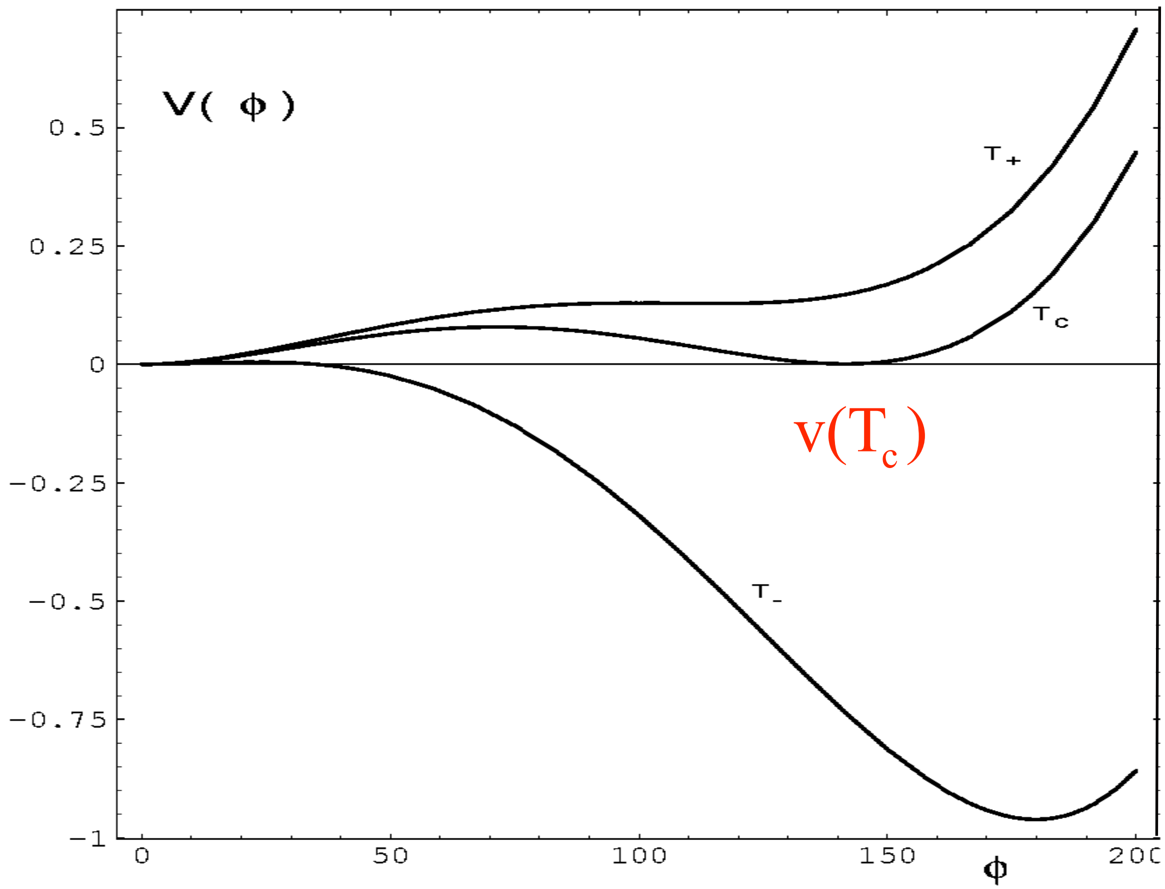
Sakharov's Conditions

- Baryon Number Violation (Quarks carry baryon number 1/3)
- C and CP Violation
- Non-Equilibrium Processes

These three conditions are fulfilled in the Standard Model

Electroweak Phase Transition

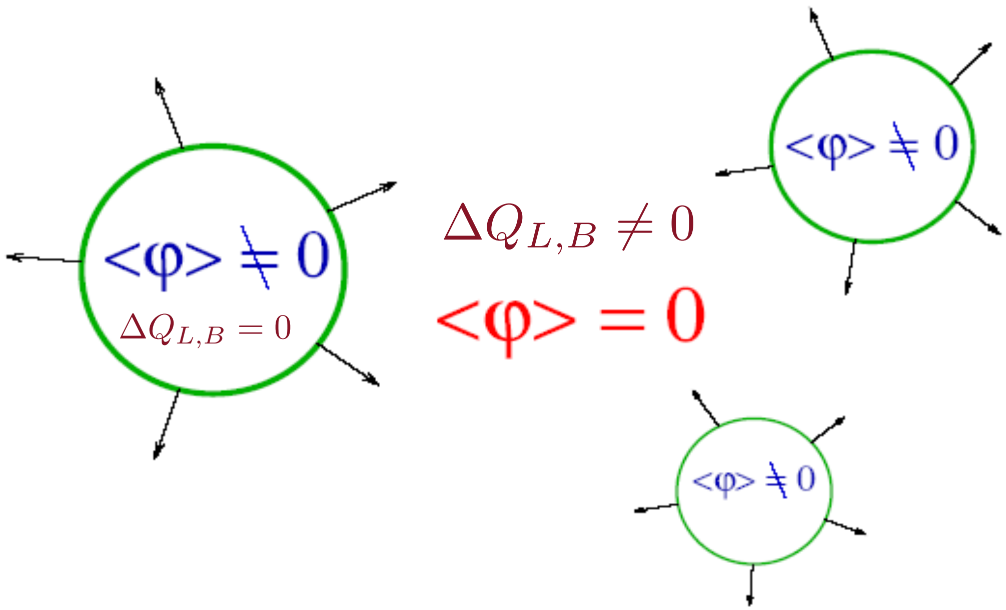
Higgs Potential Evolution in the case of a first order Phase Transition



Baryon Number Generation

First order phase transition :

Baryon number is generated by reactions in and around the bubble walls.



Morrissey '12

Condition for successful baryogengesis :
Suppression of baryon number violating processes inside the bubbles

$$\frac{v(T_c)}{T_c} > 1$$

Non-Equilibrium Processes :
Strongly First Order
Electroweak Phase Transition

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(- \frac{10^{16}}{\mathrm{T_c(GeV)}} \exp\left(- \frac{\mathrm{E_{sph}}(\mathrm{T_c})}{\mathrm{T_c}} \right)\right)$$

$$\mathbf{E_{sph}} \propto \frac{8\pi\ \mathbf{v}}{\mathbf{g}}$$

Kuzmin, Rubakov and Shaposhnikov, '85—'87

Klinkhamer and Manton '85, Arnold and Mc Lerran '88

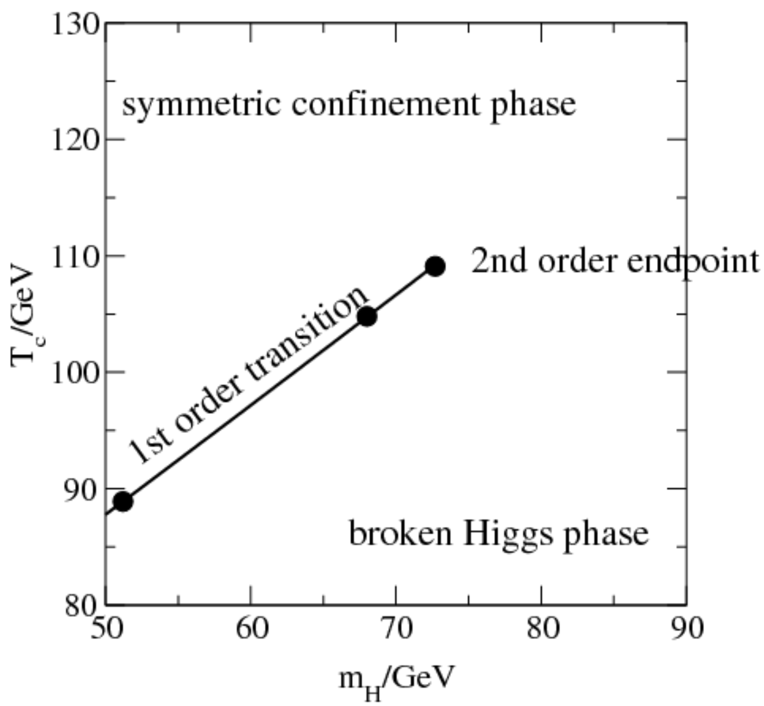
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry, a strongly first order phase transition is necessary:

$$\frac{\mathrm{v}(T_c)}{T_c} > 1$$

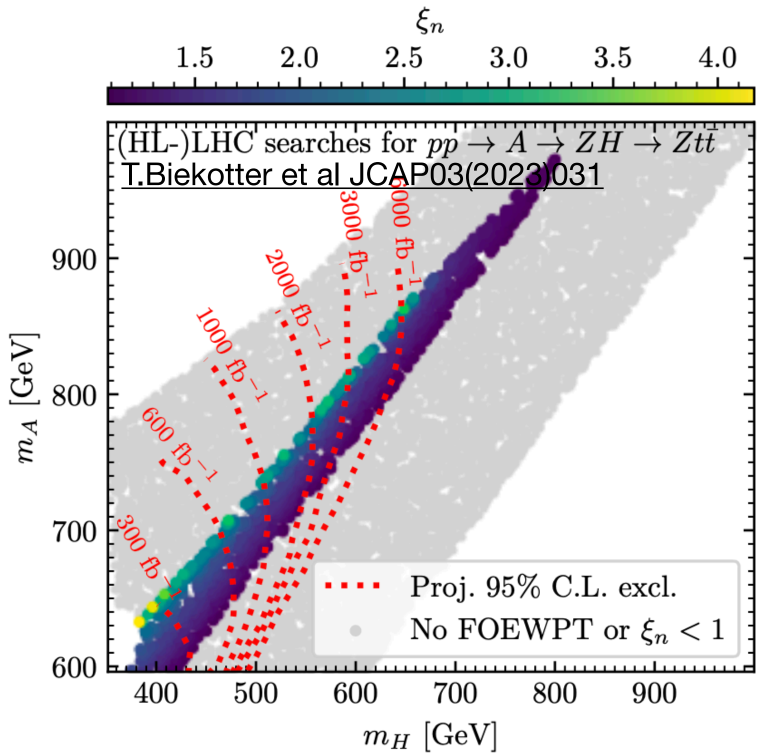
Is this the way the Standard Model generates the asymmetry ?

- It turns out that if the Higgs mass would have been lower than 70 GeV, the phase transition would have been first order

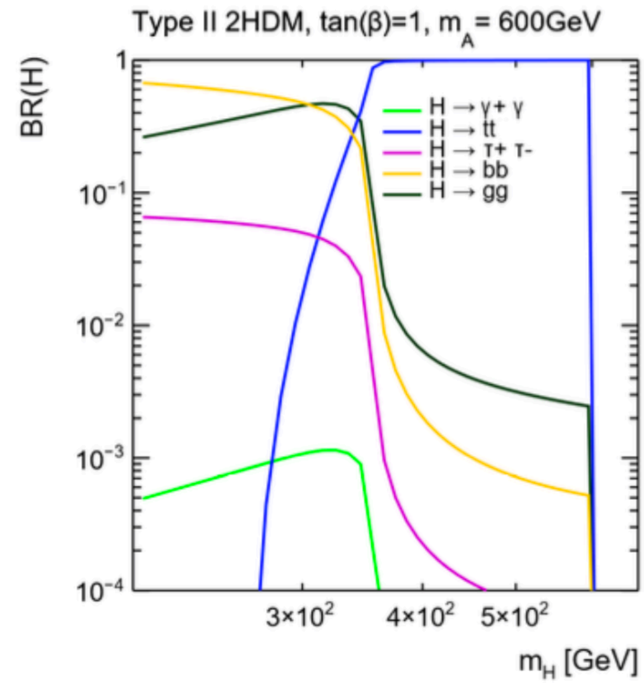


- But the Higgs mass is 125 GeV, and the electroweak phase transition is a simple cross-over transition. Making the phase transition strongly first order requires new physics.

Phase Transition in 2HDM



$$\xi = \frac{v}{T}$$



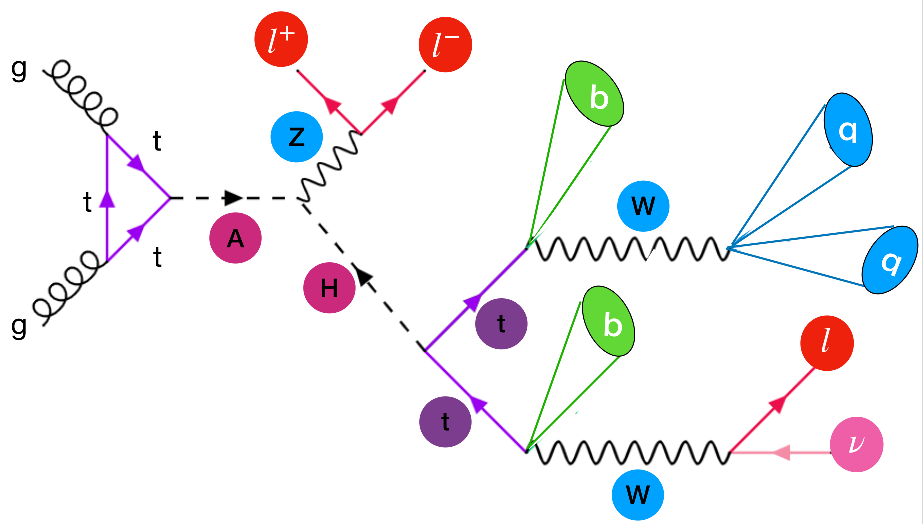
- "Smoking-gun" collider signature for FOEWPT in 2HDM
- Type-II 2HDM constraints pushes $m_H \geq 2m_t$ in parameter region featuring FOEWPT

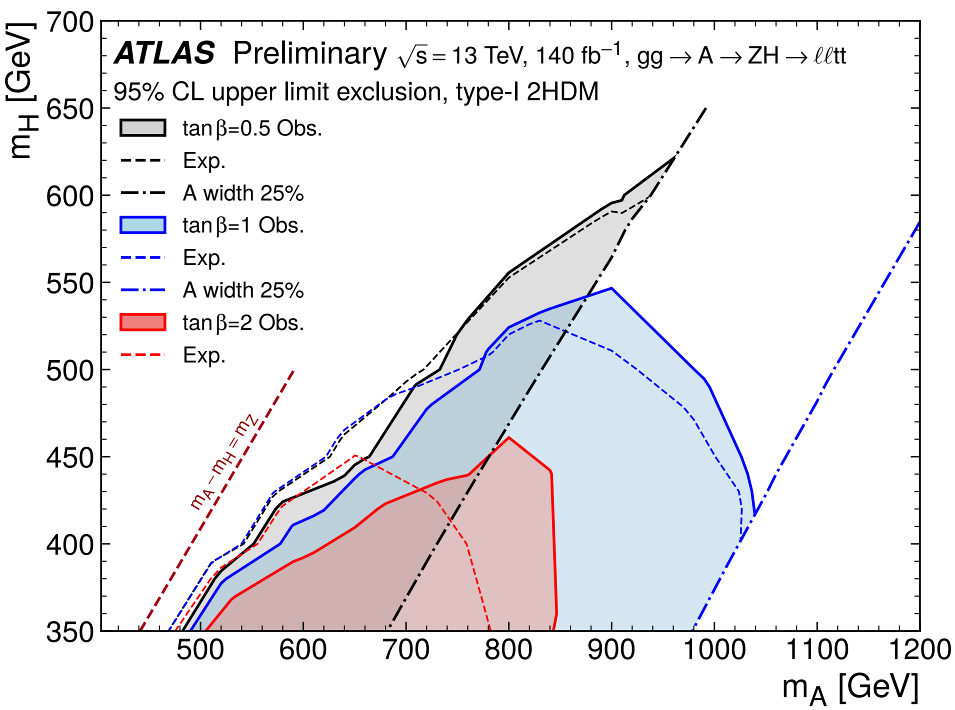
Baseler, Krause, Muhlleitner, Wittbrodt, Wlotzka '16
Basler, Muhlleitner, Wittbrodt '18

- BRs for H → bb and H → $\tau\tau$ become small
- H → tt much more promising

Some of these features depend on the resummation and should be double checked
P. Bittar, S. Roy, C.W. in preparation

Searches at the LHC





(a) $\ell^+\ell^- t\bar{t}$, type-I

Excess at ATLAS in region consistent with a FOPT

$$(m_A, n_H) = (650, 450) GeV$$

Not confirmed by CMS

ATLAS-CONF-2023-034

See M. Muhlleitner's talk

CP violation

- The general 2HDM allows for more sources of CP violation than in the case of $\lambda_6 = \lambda_7 = 0$
- This can be simply seen by the fact that in such a case, due to the minimization conditions, there is only one independent phase, and this phase must be zero in the alignment limit,

$$Z_6^I = Z_6^R = 0$$

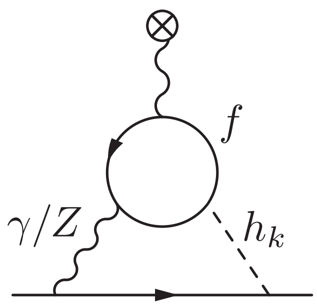
- On the contrary when the Z2 symmetry is not imposed one may still have a large CP-violation in the heavy Higgs sector, namely

$$Z_5^I \neq 0$$

- CP violating interactions are restricted by the search for electric dipole moment of the electron, which in the SM appears only a high loop levels and is quite suppressed.

SM-like Higgs Contribution

type II 2HDM

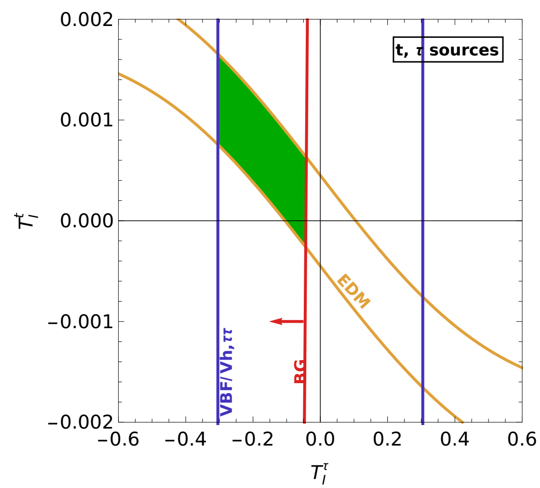


$$g^S_{H_1dd} \simeq O_{11} - \tan\beta\, O_{21}$$
$$g^P_{H_1dd} \simeq -O_{31}\tan\beta.$$

$$O_{11} \simeq 1$$
$$O_{21} \simeq -\frac{Z_6^R v^2}{m_H^2}$$
$$O_{31} \simeq -\frac{Z_6^I v^2}{m_H^2}$$

X_I^f : CP odd component of couplings

$$\frac{d_e^{(t)}}{e} \simeq -\frac{16}{3}\frac{e^2}{(16\pi^2)^2}\frac{m_e}{m_t}\frac{v}{\Lambda^2}X_I^t\left(2+\ln\frac{m_t^2}{m_h^2}\right),$$
$$\frac{d_e^{(b)}}{e} \simeq -4N_cQ_b^2\frac{e^2}{(16\pi^2)^2}\frac{m_em_b}{m_h^2}\frac{v}{\Lambda^2}X_I^b\left(\frac{\pi^2}{3}+\ln^2\frac{m_b^2}{m_h^2}\right),$$
$$\frac{d_e^{(\tau)}}{e} \simeq -4Q_\tau^2\frac{e^2}{(16\pi^2)^2}\frac{m_em_\tau}{m_h^2}\frac{v}{\Lambda^2}X_I^\tau\left(\frac{\pi^2}{3}+\ln^2\frac{m_\tau^2}{m_h^2}\right).$$



Altmannshofer, Gori, Hamer, Patel,'20
Fuchs, Losada, Nir, Viernik'20

In extensions of the SM, additional contributions from new particles are possible and should be included.

Cancellations between different contributions are possible.

Carena, Ellis, Lee, Pilaftsis, C.W. arXiv:1512.00437

Examples Scenarios for Higgs Exotic Decays

Higgs portals to new physics with suppressed SM couplings/ dark sector mediators

Portals	Couplings
Scalar (dark Higgs)	$(\kappa \mathbf{S} + \lambda_{\mathbf{SH}} \mathbf{S^2})\|\mathbf{H}\|^{\mathbf{2}}$
Fermion (sterile neutrino; SUSY neutralino)	$\mathbf{y_N NHL};\quad \frac{\kappa}{\mathbf{M}}(\mathbf{NN} + \mathbf{N^\dagger N^\dagger})\|\mathbf{H}\|^{\mathbf{2}}$
Vector (dark Z, dark photon)	$\frac{\epsilon}{\mathbf{2}\cos\theta_{\mathbf{W}}} \mathbf{B}_{\mu\nu}\mathbf{Z}_{\mathbf{D}}^{\mu\nu}$ (Higgs exotic decay through Z-Z_D mixing)
pseudoscalar (axion-like particles)	$\frac{c_{ah}}{f^2}\left(\partial_\mu a\right)(\partial^\mu a)H^\dagger H + \frac{c_{Zh}}{f^3}(\partial^\mu a)\left(H^\dagger\, iD_\mu\, H + \text{h.c.}\right)H^\dagger H$

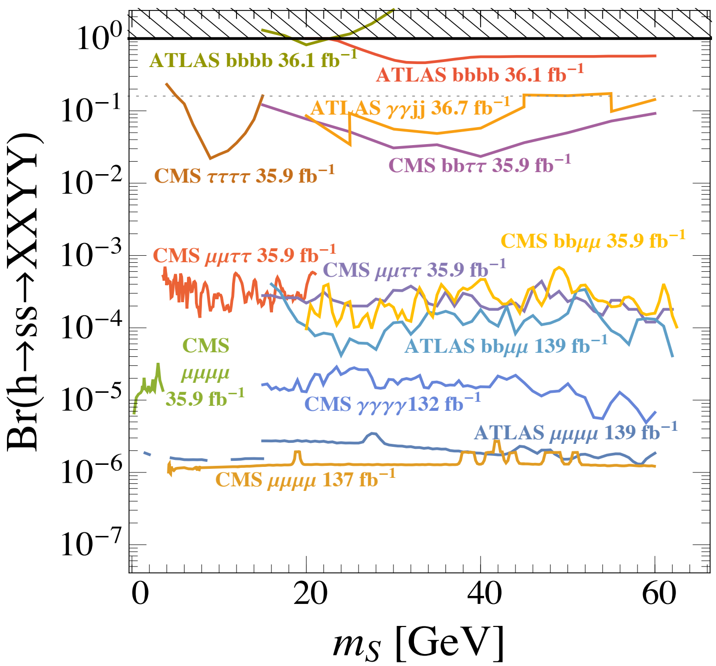
- One can also have some combinations of the above, e.g in 2HDM's or SUSY + scalars
- Beyond considering new particles with prompt decays also studies for long-lived new particles (displaced or invisible decays) are to be explored

--

Exotic Higgs decays as a potent probe of viable EW Baryogenesis

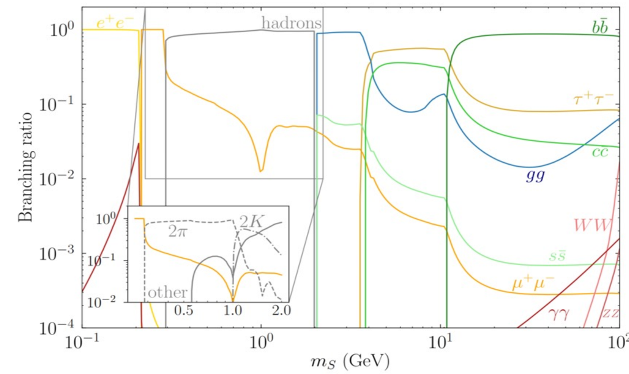
H→ SS can lead to many final states with S inheriting Higgs-like hierarchical BR's, mediated through mixing

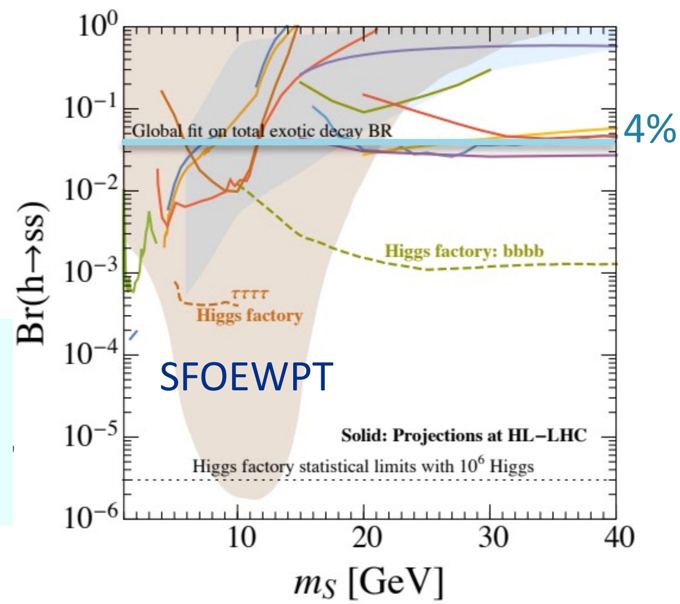
Considering LHC current bounds on exotic H decays:



Besides the 4b's final state, the rest involves at least a pair of EW states

Bounds on Br(h → ss) from Br(h → ss → XXYY) and updated for HL-LHC projections





Carena, Kozaczuk, Liu, Ou, Ramsey-Muself, Shelton, Wang, Xie, 2203.08206

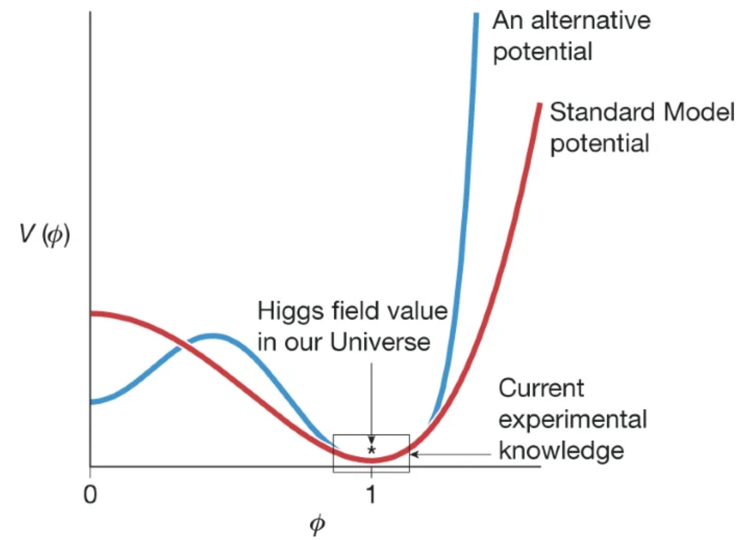
Additional signatures : Self-Coupling of the Higgs Boson

- In the Standard Model, the self couplings are completely determined by the Higgs mass and the vacuum expectation value

$$V_{SM}(h) = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h}{8v^2}h^4$$

- In particular, the trilinear coupling is given by

$$g_{hhh} = \frac{3m_h^2}{v}$$



- The Higgs potential can be quite different from the SM potential. So far, we have checked only the Higgs vev and the mass, related to the second derivative of the Higgs at the minimum.

- Therefore, it is important to measure the trilinear and quartic coupling to check its consistency with the SM predictions.

- Double Higgs production allows to probe the trilinear Higgs Coupling.

First Order Phase Transition

Grojean, Servant, Wells'06
Joglekar, Huang, Li, C.W.'15

- Simpler case

$$V(\phi, T) = \frac{m^2 + a_0 T^2}{2} \left(\phi^\dagger \phi\right) + \frac{\lambda}{4} \left(\phi^\dagger \phi\right)^2 + \frac{c_6}{8\Lambda^2} \left(\phi^\dagger \phi\right)^3$$

$$\lambda_3 = \frac{3m_h^2}{v} \left(1 + \frac{2c_6 v^4}{m_h^2 \Lambda^2}\right) \qquad \delta = \frac{\lambda_3 - \lambda_{3,SM}}{\lambda_{3,SM}}$$

- Demanding the minimum at the critical temperature to be degenerate with the trivial one, we obtain

$$\left(\phi_c^\dagger \phi_c\right) = v_c^2 = -\frac{\lambda \Lambda^2}{c_6}. \qquad \lambda + \frac{3c_6}{2\Lambda^2} v^2 = \frac{m_h^2}{2v^2}$$

- Negative values of the quartic coupling, together with positive corrections to the mass coming from non-renormalizable operators demanded.

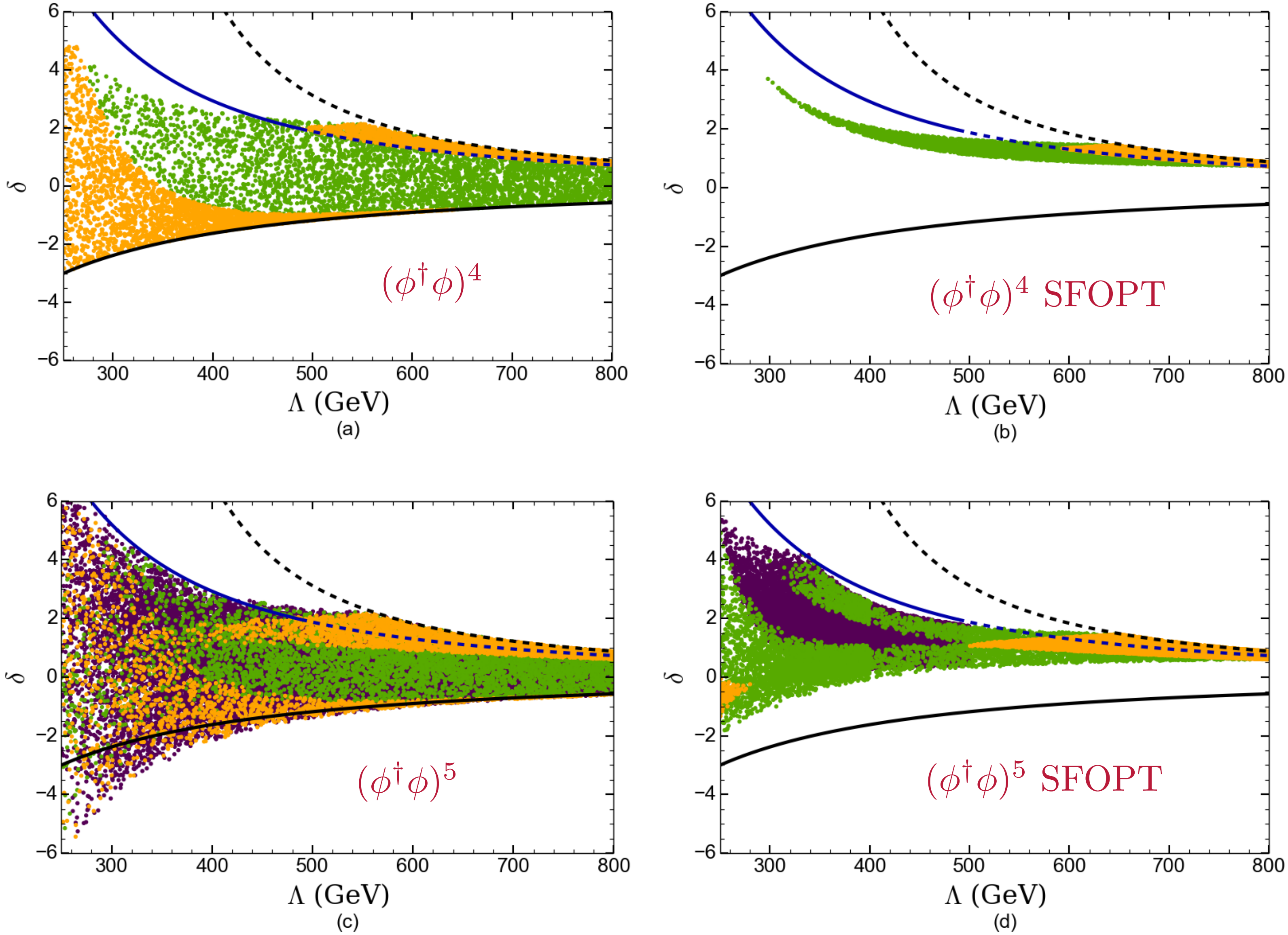
- It is simple algebra to demonstrate that, $T_c^2 = \frac{3c_6}{4\Lambda^2 a_0} \left(v^2 - v_c^2\right) \left(v^2 - \frac{v_c^2}{3}\right).$

$$\frac{v_c}{T_c} > 1 \Rightarrow \qquad \frac{2}{3} \leq \delta \leq 2.$$

- Now, in the two extremes, either vc or Tc go to zero, so in order to fulfill the baryogengesis conditions one would like to be somewhat in between.

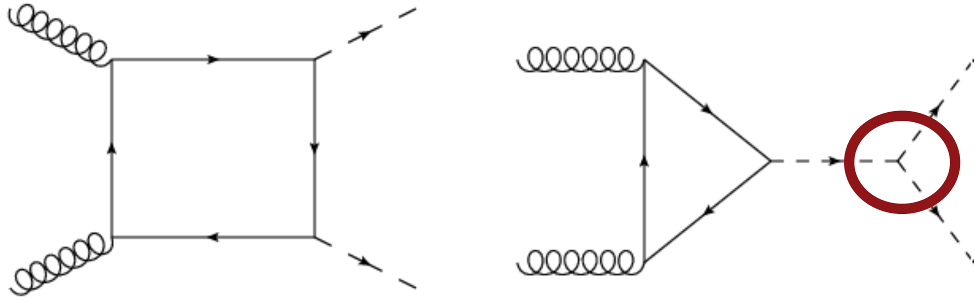
More General Modifications of the Potential

In general, it is difficult to obtain negative values of δ and at the same time a strongly first order phase transition (SFOPT)

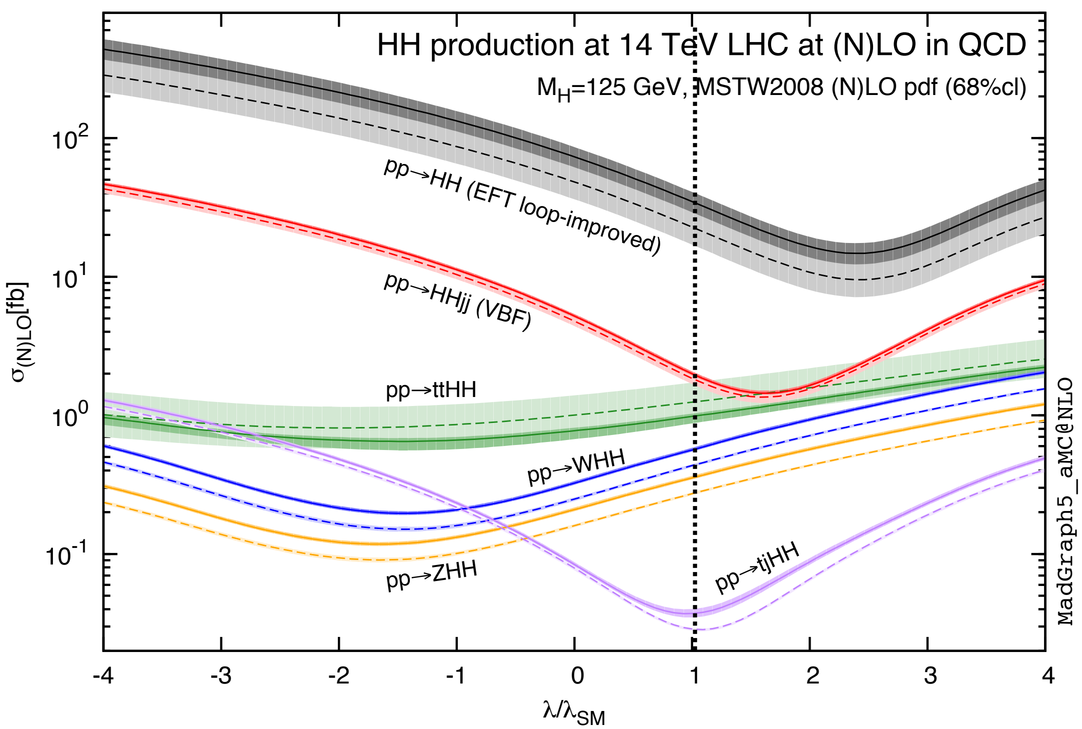


Joglekar, Huang, Li, C.W.'15

Di-Higgs Production dependence on the Higgs self coupling



Top Coupling Fixed to the SM value.

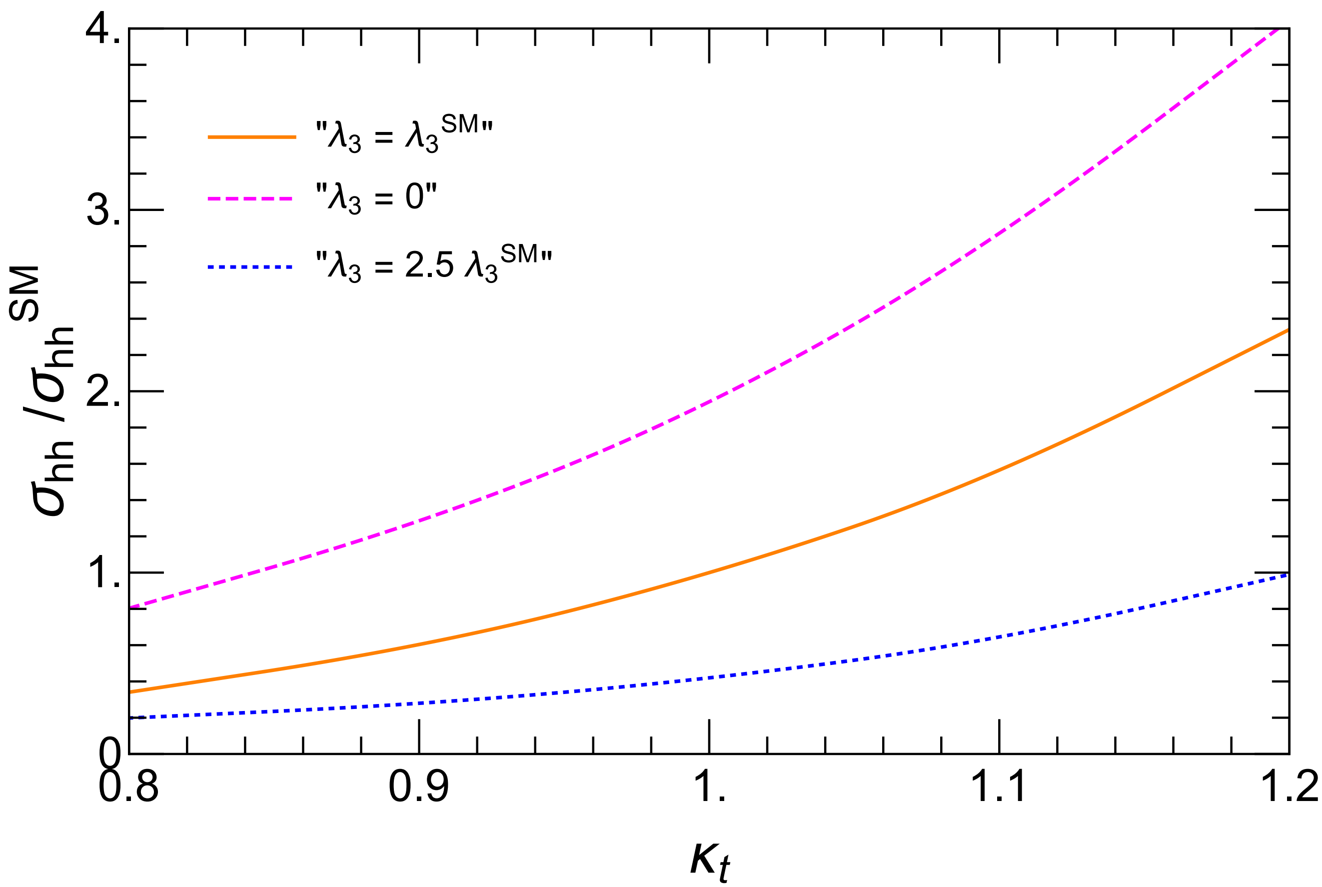


Frederix et al'14

Box Diagram is dominant, and hence interference in the gluon fusion channel tends to be enhanced for larger values of the coupling. At sufficiently large values of the coupling, or negative values, the production cross section is enhanced.

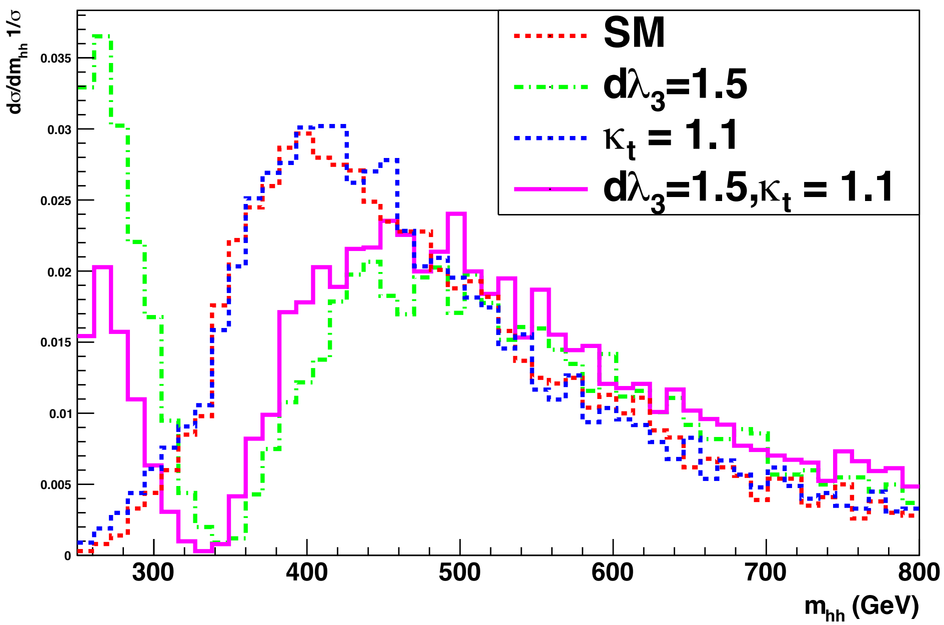
Variation of the Di-Higgs Cross Section with the Top Quark and Self Higgs Couplings

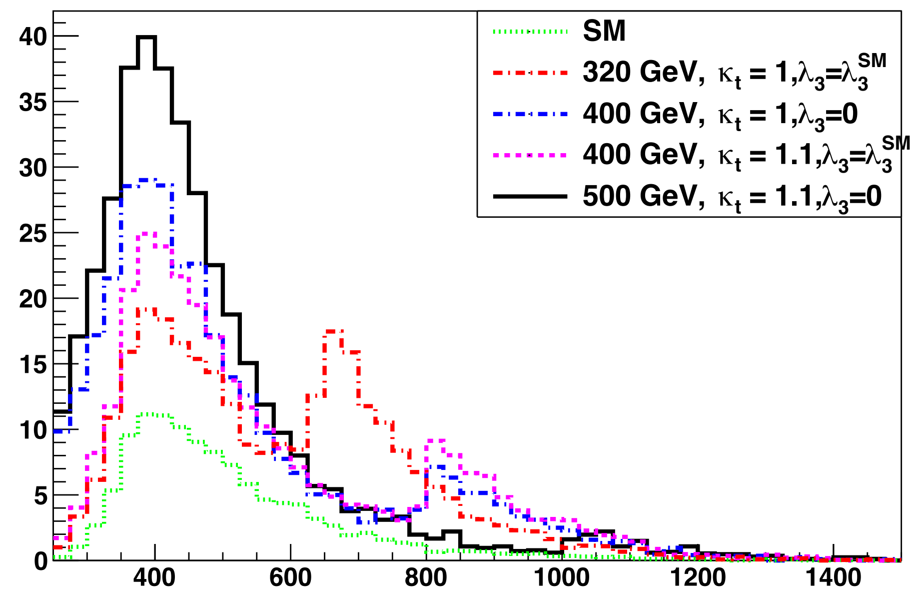
Huang, Joglekar, Li, C.W.'17



Strong dependence on the value of kt and λ3
Even small variations of kt can lead to 50 percent variations of the di-Higgs cross section

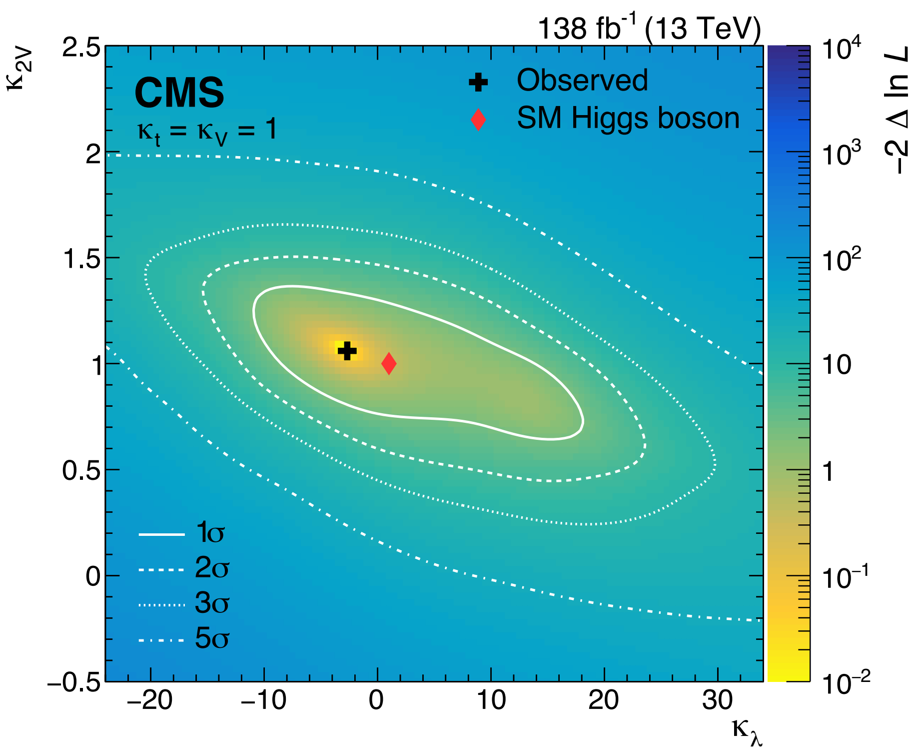
Invariant Mass Distributions

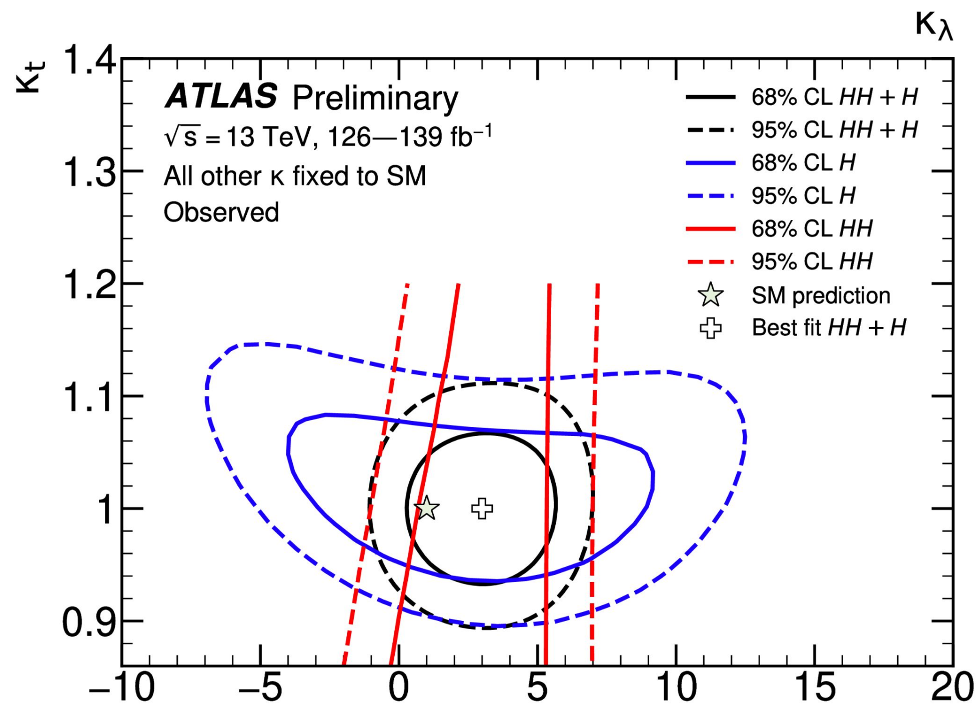




Provided lambda3 is not shifted to large values, acceptances similar as in the Standard Model

Amazing Experimental Progress





ATLAS-CONF-2022-050

HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination (2019)	$-2.3 < \kappa_\lambda < 10.3$	$-5.1 < \kappa_\lambda < 11.2$	$\kappa_\lambda = 4.6^{+3.2}_{-3.8}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$
HH+H combination (2019), κ_t, κ_V, κ_b, κ_ℓ floating	$-3.7 < \kappa_\lambda < 11.5$	$-6.2 < \kappa_\lambda < 11.6$	$\kappa_\lambda = 5.5^{+3.5}_{-5.2}$

Projected uncertainty of experiments at HL-LHC, of order 50 percent !

Great Times

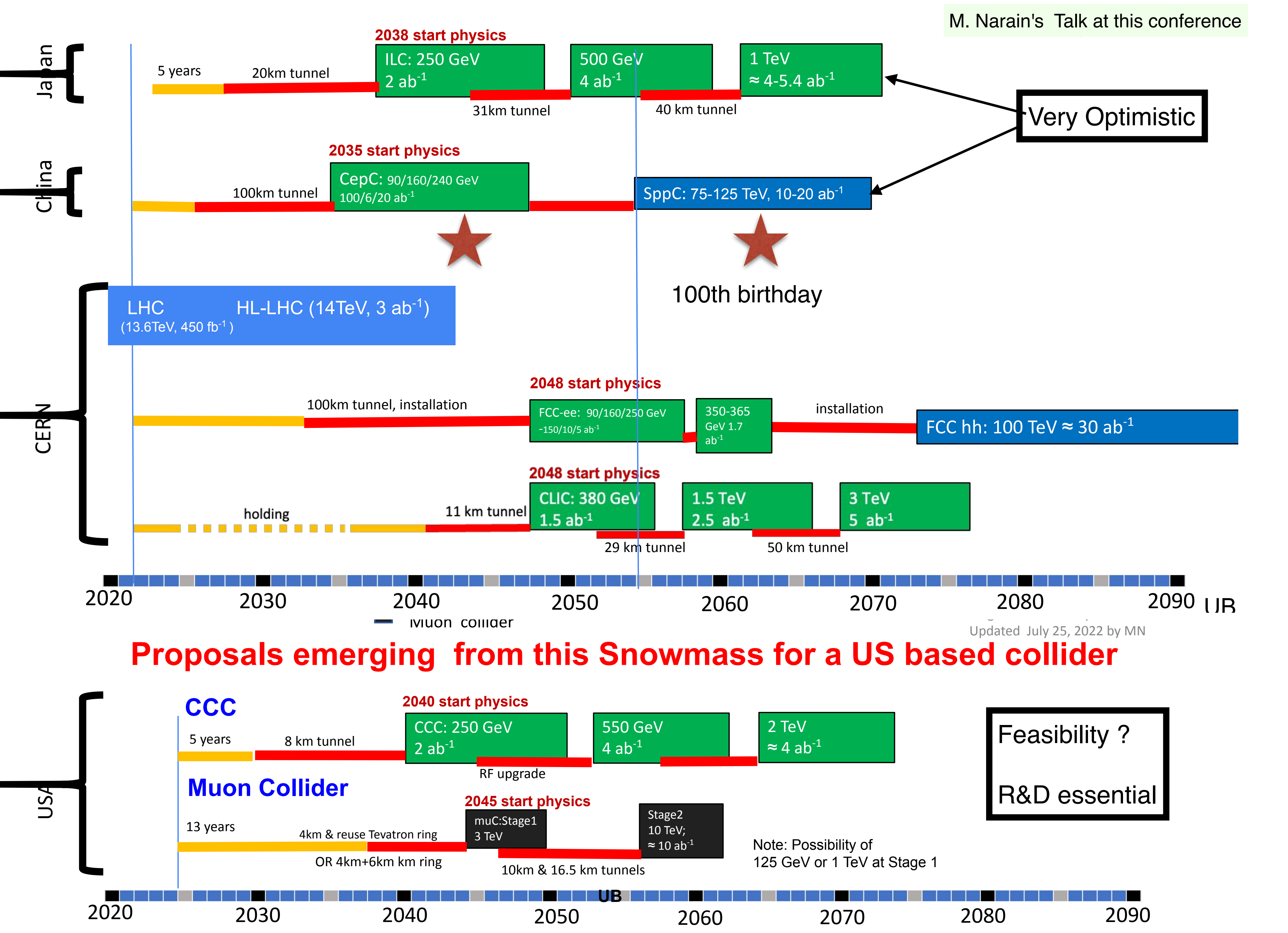
- We are living in great times. We have a set of working and near future experiments that are exploring all aspects of high energy physics, from neutrino physics to Dark Matter

- Never before we have seen such a marriage between the interests of particle physics and cosmologists, not only regarding Dark Matter, but also big bang nucleosynthesis, new light degrees of freedom and of course gravitational wave experiments.

- In the high energy frontier, we have the LHC. Let me emphasize how fantastic the LHC is. It is both a precision as well as a discovery machine.

- LHC is exploring the Higgs couplings at a great precision, and at the same time looking for new physics. It will be, most likely the only high energy collider for the next two decades and we should use its capabilities in the most efficient way possible.

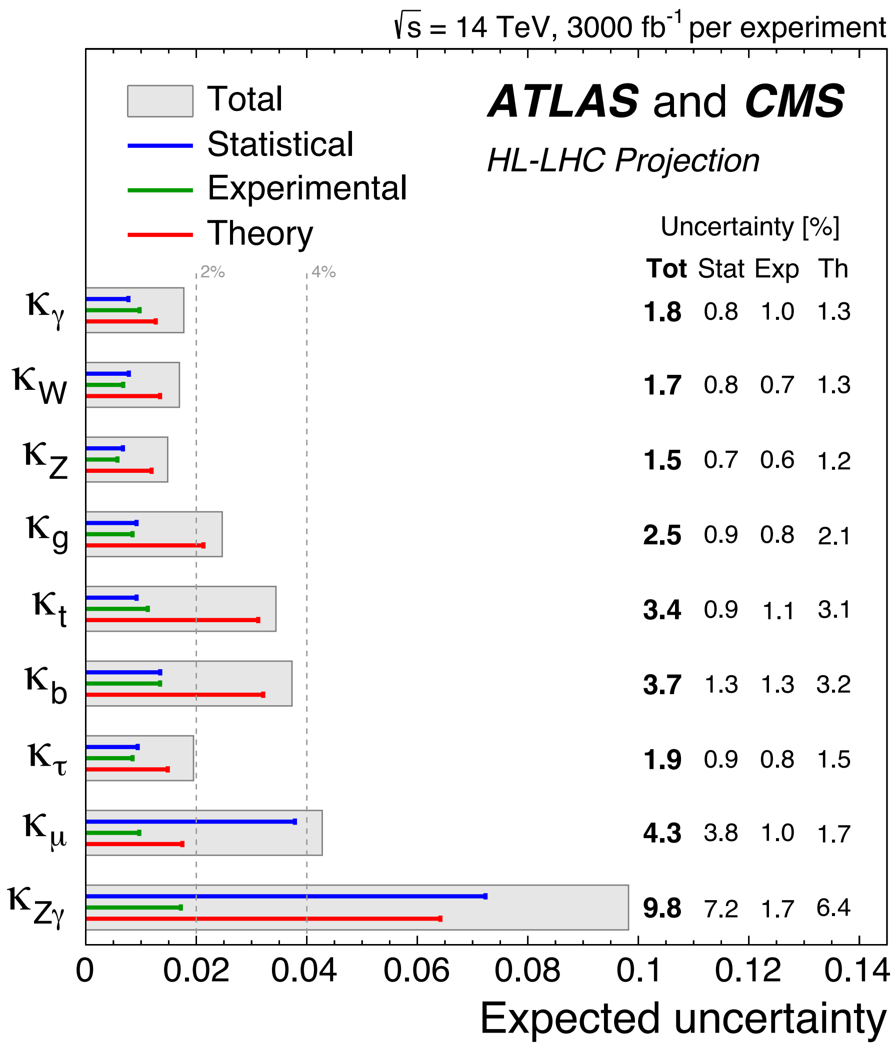
- I am persuaded that there are great times ahead and the LHC program will lead to the first convincing hints either by direct or indirect observations of what lies beyond the fantastic SM.



M. Narain's Talk at this conference
Japan
2038 start physics
5 years
20km tunnel
ILC: 250 GeV
2 ab-1
500 GeV
4 ab-1
1 TeV
≈ 4-5.4 ab-1
31km tunnel
40 km tunnel
Very Optimistic
China
2035 start physics
100km tunnel
CepC: 90/160/240 GeV
100/6/20 ab-1
SppC: 75-125 TeV, 10-20 ab-1
100th birthday
CERN
LHC
(13.6TeV, 450 fb-1)
HL-LHC (14TeV, 3 ab-1)
2048 start physics
100km tunnel, installation
FCC-ee: 90/160/250 GeV
-150/10/5 ab-1
350-365
GeV 1.7
ab-1
installation
FCC hh: 100 TeV ≈ 30 ab-1
2048 start physics
holding
11 km tunnel
CLIC: 380 GeV
1.5 ab-1
1.5 TeV
2.5 ab-1
3 TeV
5 ab-1
29 km tunnel
50 km tunnel
2020
2030
2040
2050
2060
2070
2080
2090
Updated July 25, 2022 by MN
Proposals emerging from this Snowmass for a US based collider
USA
CCC
2040 start physics
5 years
8 km tunnel
CCC: 250 GeV
2 ab-1
550 GeV
4 ab-1
2 TeV
≈ 4 ab-1
RF upgrade
Feasibility ?
R&D essential
Muon Collider
2045 start physics
13 years
4km & reuse Tevatron ring
OR 4km+6km km ring
muC:Stage1
3 TeV
Stage2
10 TeV;
≈ 10 ab-1
10km & 16.5 km tunnels
Note: Possibility of
125 GeV or 1 TeV at Stage 1
UB
2020
2030
2040
2050
2060
2070
2080
2090

Future collider : the High Luminosity LHC

Precision Higgs measurements at the HL-LHC:



Many relevant couplings will be tested at the few percent level.

The HL-LHC is both a discovery machine for particles with low production modes as well as a precision machine !

Higgs Measurements: an exploration tool at FCC-ee

- LHC and future HL-LHC measurements will probe SM expectations at the 2-4 % level for couplings to gauge bosons, 3rd gen. fermions plus 2nd gen. charged leptons
- FCC-ee programme:

-- can measure Higgs production inclusively as a recoil in e+e-→ HZ, yielding an absolute measurement of the HZZ coupling and a model independent extraction of Γ_H

Coupling	HL-LHC	linear colliders (250 or 380 GeV)	circular colliders (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.73	0.43 / 0.33
κ_Z [%]	1.3*	0.29	0.17 / 0.14
κ_g [%]	2*	1.4	0.90 / 0.77
κ_γ [%]	1.6*	1.4	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10	10 / 10
κ_c [%]	–	2.0	1.3 / 1.1
κ_t [%]	3.2*	3.1	3.1 / 3.1
κ_b [%]	2.5*	1.1	0.64 / 0.56
κ_μ [%]	4.4*	4.2	3.9 / 3.7
κ_τ [%]	1.6*	1.1	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.26	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.8	1.0 / 0.88

This assumes no flavor violation, what may be an important feature and should be analyzed.

Advances in the last thirty five years

- 1991 : LEP measures precisely the weak couplings, solidifying the SM description and confirming the idea of unification of gauge couplings (with Supersymmetry)
- 1995 : Tevatron discovers the top quark. Its mass consistent with the idea of unification of (bottom and top) Yukawa couplings.
- 1998 : Super-Kamiokande confirms neutrino oscillations, consistent with neutrino masses.
- 1998/1999 : Accelerated expansion of the Universe observed.
- 2003/2009 : Planck (2009) CMB measurements improves WMAP (2003) ones and lead to results that a high level of precision is consistent with the existence of DM, DE and with what is today the SM of cosmology.
- 2012 : Higgs Particle discovered at the LHC. Its properties are being explored by the CMS and ATLAS collaborations.
- 2015 : Gravitational Waves detected. GW detectors may one day not only measure mergers, but also waves from violent phase transitions in the early Universe.
- 2021 : Confirmation of muon g-2 anomaly ??
- 2023 : PTAs signals consistent with the ones of supermassive blackhole mergers.

Conclusions

- Precision Higgs measurement show a good agreement of all couplings with respect to the SM expectations
- Properties of the Higgs in the SM are highly rigid and therefore they must be probed experimentally with high precision.
- Higgs Flavor violating couplings may lead to the first hints of physics BSM.
- Light non-standard Higgs bosons demand alignment in field space of the mass eigenstates with the directions acquiring vev's.
- Higgs may play a role in our understanding of two relevant mysteries, the origin of the matter-antimatter asymmetry and the origin of Dark Matter.
- Higgs physics remains as the most vibrant field of particle physics, one in which many surprises may lay ahead, with profound implications for our understanding of Nature.

Backup

Comments

- Flavor or Higgs alignments are not guaranteed. Therefore, beyond the standard Higgs searches, there is a strong motivation to perform the following searches :

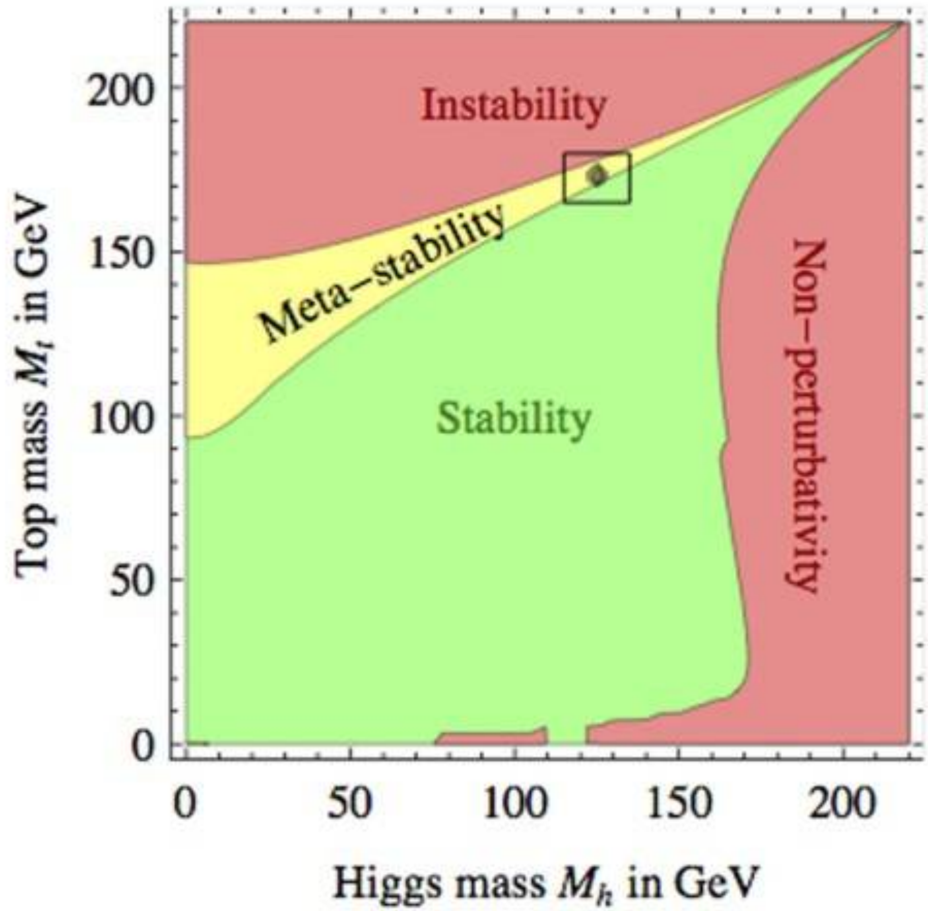
- Flavor violating decays of the Standard Higgs boson : modified diagonal couplings come usually together with flavor violating couplings. So, the simple kappa framework is not enough, for more than technical reasons $h \to \mu\tau, h \to \mu e, h \to e\tau, \mathrm{etc}$

- Flavor violating decays of non-standard Higgs bosons. They are unsuppressed $H \to tc, H \to \mu\tau, H \to \mu e, H \to e\tau, \mathrm{etc}$

- bs transitions are also of interest, although constrained by other processes

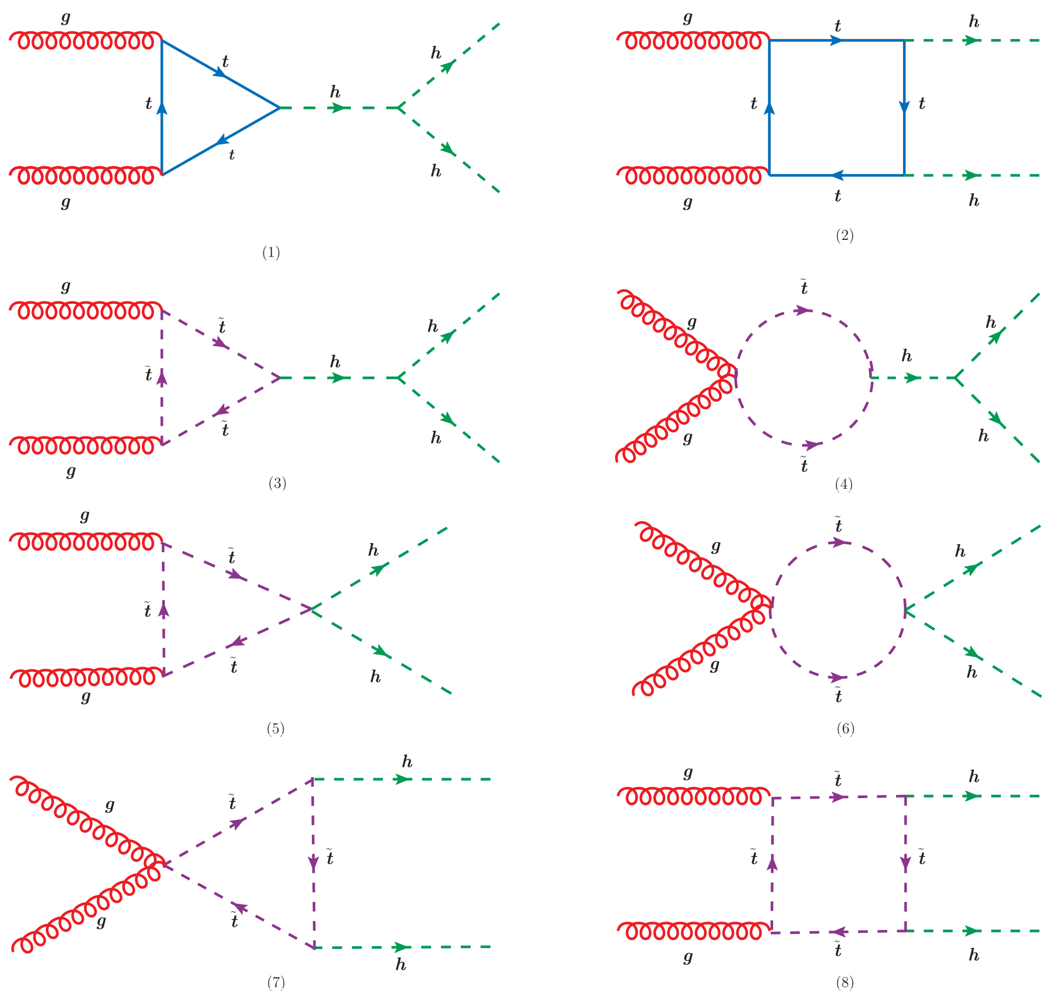
- Searches for heavy Higgs bosons decaying to other scalar states, non-necessarily SM Higgs bosons $H \to hX, H \to XY, etc.$

- I am aware that there are LHC groups working on these subjects. I would encourage more people to join these efforts.


Instability
Meta−stability
Stability
Non−perturbativity
Top mass M_t in GeV
Higgs mass M_h in GeV
0
50
100
150
200
0
50
100
150
200

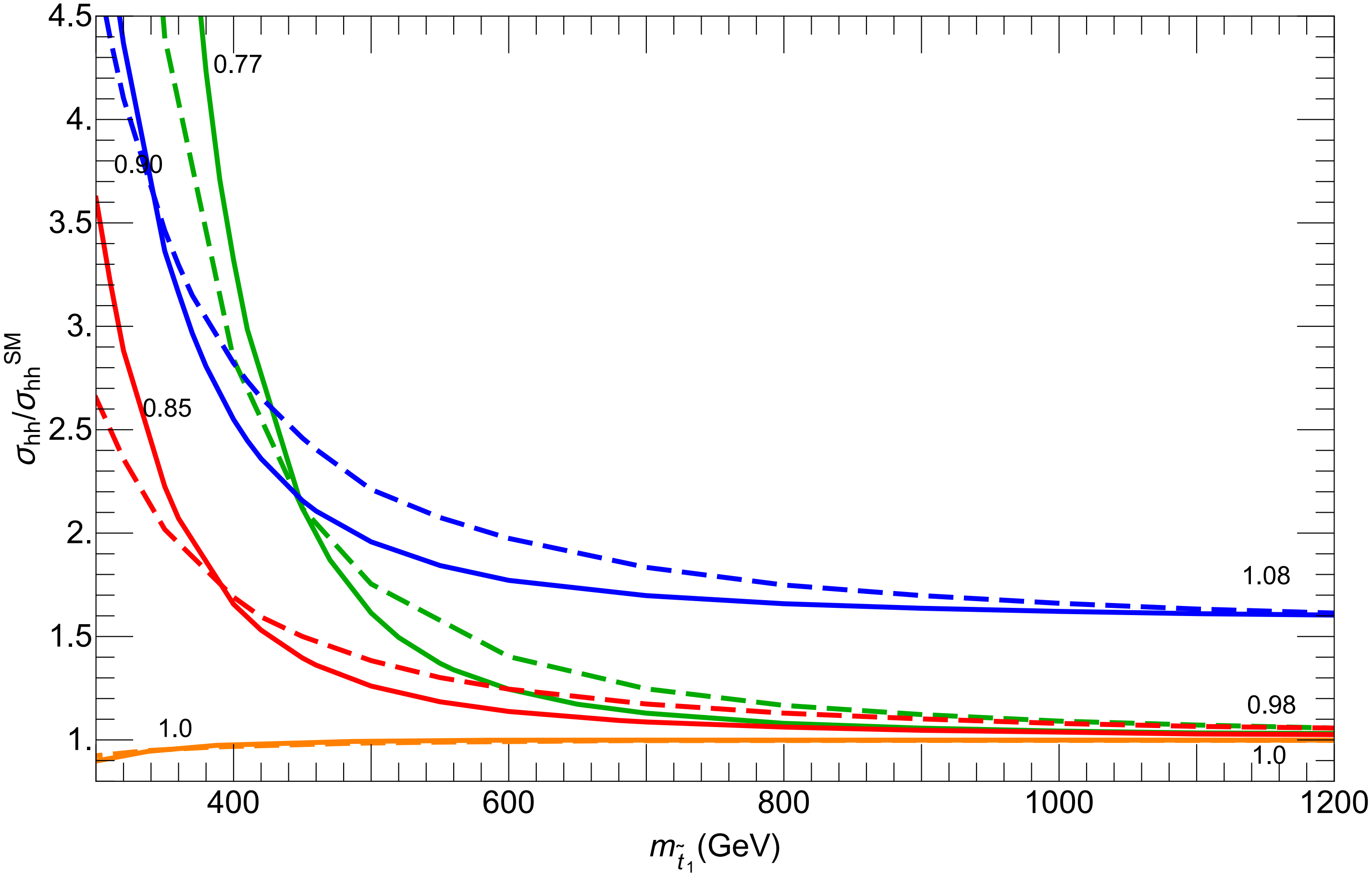
Huang, Joglekar, Li, C.W.'17

Stop Contributions



Stop Effects on Di-Higgs Production Cross Section

Huang, Joglekar, Li, C.W.'17



Orange : Stop corrections to kappa_g decoupled
Red : X_t fixed at color breaking vacuum boundary value, for light mA
Green : X_t fixed at color breaking boundary value, for mA = 1.5 TeV
Blue : Same as Red, but considering \kappa_t = 1.1

Couplings in the Higgs basis

- Let me emphasize that the Higgs basis is a convenient mathematical construction, and that the couplings can be derived by taking the limit of $\tan\beta = 0$ of the above expressions.

- It is simple to show that in this case the deviation of diagonal couplings as well as the flavor violating couplings are governed by the diagonal and off diagonal components of the Higgs that does not acquire vev (the Yukawa matrix to the Higgs that acquire vev is obviously diagonal in this case) (see Howie Haber's talk)

- Although in principle the Yukawa couplings to the second Higgs look arbitrary and not related to fermion masses, they must have a structure in the construction of the mass matrix in the original basis where both Higgs bosons acquire a vev. (otherwise the off-diagonal elements will look dangerously large in the non-decoupling limit).

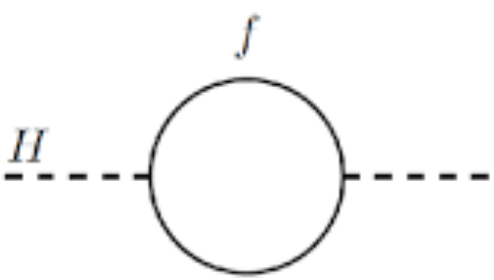
What sets the Higgs scale ?

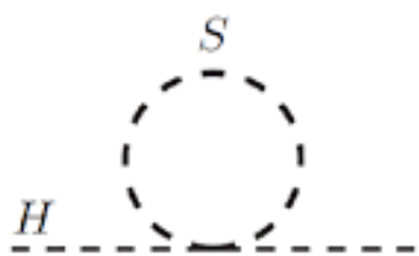
We don't understand why the Higgs mass parameter, which controls all elementary particle masses is so much smaller than the Planck scale.

$$G_N \frac{m_1 m_2}{r^2} \ll e^2/r^2$$

$$m_i \ll M_{\mathrm{Pl}}, \quad \text{where } M_{\mathrm{Pl}} = \sqrt{\frac{1}{G_N}} \simeq 10^{19} \text{ GeV}$$

This in spite of the fact that quantum corrections should bring this parameter to be of the order of any heavy particle that couples to the Higgs !





$$\Delta m_H^2 \simeq \lambda_f^2 \frac{M_f^2}{16\pi^2} - \lambda_S \frac{M_S^2}{16\pi^2}$$

In order to explain the weak scale, one would expect new physics at that scale.