Rare Top quark decays in the SM and Beyond

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Talk at Blois (2014)

1. Motivation,
2. Top quark decays in the SM,
3. Top, Higgs and BSM,
4. The decay $t \to c + h$ in 3+1 HDM
5. Conclusions.

The top quark

- The heaviest SM particle, with $m_t = 173$ GeV $\simeq v = 246$ GeV, which, as is often said, could give some clues to understand EWSB,
- Its decays are dominated by the 2-body (CKM-favored) decay: $t \to Wb$, with $\Gamma(t \to bW) \simeq 1.55$ GeV,
- Possible to consider decays into new particles $t \to X + Y$, where X and/or Y could be new particles BSM, e.g. $t \to b + H^+$,
- Rare decays could also be relevant, e.g. $t \to c + X$ (FCNC), but they have very small BR's in SM ($BR < 10^{-11}$),
- FCNC decays could be greatly enhanced with physics BSM, and thus could provide new tests of such Physics BSM.

PDG on top quark: 1998

t-Quark Mass in $p\bar{p}$ Collisions

The t quark has now been observed. Its mass is sufficiently high that decay is expected to occur before hadronization. OUR EVALUATION is an AVERAGE which incorporates correlations as described in the note "The Top Quark"' above.

For earlier search limits see the *Review of Particle Physics*, Phys. Rev. **D54**,1 (1996).

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
173.8± 5.2 OUR EVALUATION				
168.4±12.3± 3.6	[1] ABBOTT	98D	D0	$\ell\ell$ + jets
173.3± 5.6± 5.5	[1] ABBOTT	98F	D0	ℓ + jets
175.9± 4.8± 4.9	[2] ABE	98E	CDF	ℓ + jets
161 ±17 ±10	[2] ABE	98F	CDF	$\ell\ell$ + jets

t-Quark Decay Branching Fractions

VALUE (%)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[4] ABE	97V	CDF	$\ell\tau$ + jets

[4] ABE 97V searched for $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$ events in 109 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. They observed 4 candidate events where one expects ~ 1 signal and ~ 2 background events. Three of the four observed events have jets identified as b candidates.

PDG on top quark: 2014

t $I(J^P) = 0(\frac{1}{2}^+)$

Charge $= \frac{2}{3}\,e$ Top $= +1$

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t-QUARK MASS

We first list the direct measurements of the top quark mass which employ the event kinematics and then list the measurements which extract a top quark mass from the measured $t\bar{t}$ cross-section using theory calculations. A discussion of the definition of the top quark mass in these measurements can be found in the review "The Top Quark."

OUR EVALUATION of $173.07 \pm 0.52 \pm 0.72$ GeV is an average of published top mass measurements from Tevatron Runs. The LHC experiments are working on a combined average that should appear in the 2014 PDG edition once the correlated uncertainties between experiments are understood. The Tevatron average was provided by the Tevatron Electroweak Working Group (TEVEWWG). It takes correlated uncertainties into account and has a χ^2 of 8.4 for 11 degrees of freedom.

t BRANCHING RATIOS

$\Gamma(Wb)/\Gamma(Wq(q=b,s,d))$ **Γ_2/Γ_1**

OUR AVERAGE assumes that the systematic uncertainties are uncorrelated.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
0.91±0.04 OUR AVERAGE				
0.90 ± 0.04	[1] ABAZOV	11X	D0	
$1.12^{+0.21}_{-0.19}{}^{+0.17}_{-0.13}$	[2] ACOSTA	05A	CDF	

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PDG on top quark: 2014

$m_t - m_{\bar{t}}$

Test of CPT conservation. OUR AVERAGE assumes that the systematic uncertainties are uncorrelated.

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
−0.6 ±0.6 OUR AVERAGE	Error includes scale factor of 1.2.			
−0.44±0.46±0.27	[1] CHATRCHYAN	12Y	CMS	$\ell + \geq 4$j
−3.3 ±1.4 ±1.0	[2] AALTONEN	11K	CDF	$\ell + \not{E}_T + 4$ jets
0.8 ±1.8 ±0.5	[3] ABAZOV	11T	D0	$\ell + \not{E}_T + 4$ jets (≥ 1 b-tag)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.8 ±3.4 ±1.2	[4] ABAZOV	09AA	D0	$\ell + \not{E}_T + 4$ jets (≥ 1 b-tag)

[1] Based on 4.96 fb^{-1} of data at LHC7. Based on the fitted m_t for ℓ^+ and ℓ^- events using the Ideogram method.
[2] Based on a template likelihood technique which employs 5.6 fb^{-1} in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV.
[3] Based on a matrix-element method which employs 3.6 fb^{-1} in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV.
[4] Based on 1 fb^{-1} of data in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV.

t-quark DECAY WIDTH

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
$\mathbf{2.00^{+0.47}_{-0.43}}$		[1] ABAZOV	12T	D0	$\Gamma(t \to bW)/B(t \to bW)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.99^{+0.69}_{-0.55}$		[2] ABAZOV	11B	D0	Repl. by ABAZOV 12T
> 1.21	95	[2] ABAZOV	11B	D0	$\Gamma(t \to Wb)$
< 7.6	95	[3] AALTONEN	10AC	CDF	ℓ + jets, direct
<13.1	95	[4] AALTONEN	09M	CDF	m_t(rec) distribution

The top quark decays in the SM

- 2-body (CKM-favored) decay: $t \to Wb$, with $BR \simeq 1$,
- 2-body (CKM-suppressed) decay: $t \to Wq$, $q = s, d$,
- 3-body (Radiative modes): $t \to Wb\gamma(g)$, $t \to Wbe^+e^-$,
- FCNC decay into vector bosons: $t \to q + X$, $X = \gamma, Z, g$, $q = u, c$,
- FCNC decay into Higgs: $t \to qh$, $q = u, c$, $m_h = 125 - 126$ GeV,

Rare Top Decays in SM

Mode	SM BR	Refs.
$BR(t \to sW)$	1.6×10^{-3}	B. Mele, hep-ph/0003064
$BR(t \to cWW)$	1.3×10^{-13}	E. Jenkins et al. PRD56 (97)
$BR(t \to bWZ)_{res}$	2×10^{-6} ($m_t = 175$ GeV)	G. Altarelli et al. PLB502 (2001)
$BR(t \to bW\gamma)$	3.5×10^{-3}	Decker et al. ZPhys.C57 (93)
$BR(t \to bWe^+e^-)$	$10^{-5} - 10^{-6}$	N. Quintero et al. PRD (2014)

Table : Branching ratios rare top decays

FCNC Top Decays in SM

Mode	SM BR	Refs	Refs
$BR(t \to c + \gamma)$	5×10^{-13}	Diaz-Cruz etal PRD41(90)	Eilam etal PRD44(91)
$BR(t \to c + Z)$	1.3×10^{-13}	PRD44(91)	
$BR(t \to c + g)$	5×10^{-11}	PRD44(91)	
$BR(t \to c + h)$	5×10^{-14}	PRD44(91) Errat. D59 (99)	Mele et al. PLB 435 (98)

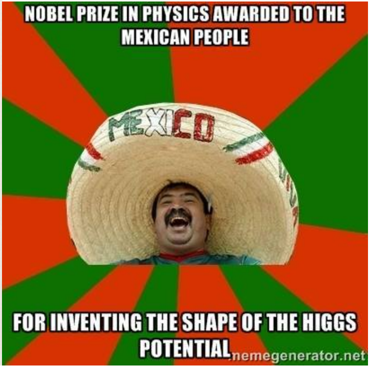
Table : Branching ratios for FCNC top decays

LHC limits on FCNC top decays

- FCNC decay: $t \to q + \gamma$ (from assoc. production $t + \gamma$),
  CMS (TOP-14-003): $BR(t \to u + \gamma) < 1.61 \times 10^{-4}$,
  $BR(t \to c + \gamma) < 1.82 \times 10^{-3}$,
- FCNC decay: $t \to q + Z$,
  CMS (arXive 1208.0957): $BR(t \to q + Z) < 2.1 \times 10^{-3}$,
- FCNC decay into Higgs: $t \to qh$ $q = u, c$, $m_h = 125 - 126$ GeV,
  CMS (arXive 1207.6794): $BR(t \to c + h) < 5.6 \times 10^{-3}$,
  ATLAS (JHEP 2012:139): $BR(t \to c + h) < 7.9 \times 10^{-3}$,

  (Recent re-analysis by A. Greljo et al, arXive 1404.1278)

BEH, Nobel Prize and Mexican Hat.



What is the nature of EWSB?

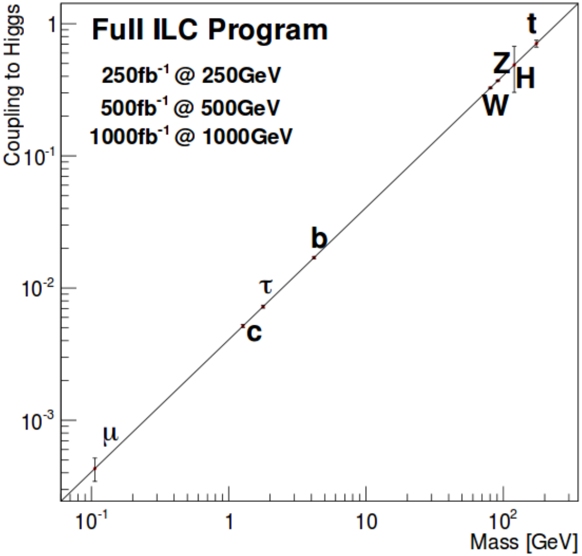
Questions:

1. Is there only one Higgs doublet that generates the masses of all particles?
2. Will we be able to test Higgs couplings with light fermions?
3. Are the Higgs couplings diagonal in flavor space?
4. Why W-mass << Planck mass? ((Hierarchy problem))

Answers:

- Strongly Interacting -Higgsless world - DECEASED!
- Strongly Interacting - Composite Higgs - pNGB,
- Weakly interacting- SM valid up to Planck Scale,
- Weakly interacting- Multi-Higgs model (SUSY, THDM, etc),

SM Higgs identity: $g_{hXX}^{sm} = \frac{M_X}{v}$



Beyond the SM

- Models with new fermions (4ta family, etc)
- Models with new gauge forces ($U(1)'$, Left-Right, ..)
- Models with extra Higgs multiplets (2HDM, triplets,..)
- Models with Grand Unification (ex. $SU(5), SO(10), E_6$,..)
- Models with new symmetries (SUSY),
- Models with extra dimensions extra.
- etc.

Arkani-Hamed/Dimopoulos:
Theories should be consistent, Theoreticians... not neccesarily

Multi-Higgs models-

- The SM Higgs boson knows about flavor but only to a certain extent, i.e. it distinguish the generations through the diagonal fermion masses,
- But in extentions of the SM one could get a ”more flavored Higgs sector”, where the Higgs couples with fermions of different families.
- In fact, adding another Higgs doublet could induce plenty of flavor signals,
  Glashow-Weinberg: When the mass of a fermion type (u,d,l) comes from more than one Higgs doublet, FCNC are induced at tree-level,
- Example of viable model: 2HDM with textures (2HDM-III or 2HDM-Tx), $M_q = v_1 Y_1^q + v_2 Y_2^q$,
- Bi-unitary transformation that diagonalizes M_q does not do the same for each $Y_{1,2}^q$, thus → FCNC Higgs interactions,

The texturized 2HDM-Tx

- In 2HDM-Tx, one assumes Mass matrices with 4-texture zeroes:

$$M_q = \begin{pmatrix} 0 & C_q & 0 \\ C_q^* & \tilde{B}_q & B_q \\ 0 & B_q^* & A_q \end{pmatrix}.$$

- $\bar{Y}_1^q = \frac{\sqrt{2}}{v_1}\bar{M}_q - \frac{v_2}{v_1}\bar{Y}_2^q$,

- $Y_{1,2}$ could have the same texture (Parallel) or different textures, but in such a way that form a mass matrix with certain texture (Complementary),
- In both cases, the Higgs-fermion couplings simplify as:

$$\bar{Y}_{2ij}^q = \chi_{ij}\frac{\sqrt{m_i m_j}}{v} \qquad (1)$$

(Cheng-Sher ansazt)

Hff Couplings with CPC Higgs potential

- For CPC Higgs potential, h, H are CP-even, while A is CP-odd,
- The corresponding coefficient for interactions of h^0 with up-quarks are

$$
\begin{aligned}
S^u_{ij1} &= \frac{1}{v} M^U_{ij} \left[\sin(\beta-\alpha) - \tan\beta \cos(\beta-\alpha) \right] \\
&\quad + \frac{\sqrt{m_i m_j}}{2\sqrt{2}v} \frac{\cos(\beta-\alpha)}{\cos\beta} \left(\chi_{ij} + \chi^\dagger_{ij} \right) \\
&. \\
P^u_{ij1} &= \frac{\sqrt{m_i m_j}}{2\sqrt{2}v} \frac{\cos(\beta-\alpha)}{\cos\beta} \left(\chi_{ij} - \chi^\dagger_{ij} \right)
\end{aligned}
$$

- $\tan\beta = v_2/v_1$ and α is the angle that diagonalizes the neutral CP-even Higgs sector,
- Low-energy FCNC processes imposse strong constraints on the possible Higgs-fermion couplings.

FCNC Top Decays in SM, 2HDM-Tx and MSSM (SUSY)

Mode	SM	2HDM-Tx	SUSY MSSM
$BR(t \to c + \gamma)$	5×10^{-13}	$\simeq 10^{-7}$	$\simeq 10^{-8}$
$BR(t \to c + Z)$	1.3×10^{-13}	$\simeq 10^{-6}$	$\simeq 10^{-8}$
$BR(t \to c + g)$	5×10^{-11}	$\simeq 10^{-5}$	$\simeq 10^{-6}$
$BR(t \to c + h)$	5×10^{-14}	2×10^{-2}	$\simeq 10^{-4} - 10^{-5}$

Table : Branching ratios for FCNC top decays

We find $BR(t \to ch) \simeq 10^{-4}$, with large trilinear terms, Diaz-Cruz, He, Yuan, PLB (2003)

The MSSM particle content

	SM	Superpartners
SM Bosons	$W^{\pm}, Z, \gamma$ gluon Higgs bosons	Wino,Zino, Photino gluino Higgsinos
SM Fermions	quarks leptons neutrinos	squarks sleptons sneutrinos

Mixing of gauginos and Higgsinos $\rightarrow$
Charginos ($\chi_i^{\pm}$, $i = 1, 2$) and Neutralinos (χ_j^0, $j = 1, 4$),

Gravitino is also part of the spectrum.

Mass matrix of sfermions

- In the MSSM the (6x6) mass matrix for squarks is:

$$M_{\tilde{q}}^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^2 \\ M_{RL}^2 & M_{RR}^2 \end{pmatrix}.$$

- For instance: $M_{LR}^2 = (x_\beta) v A_{\tilde{f}} - (y_\beta) \mu m_f,$
- In general, all entries are allowed $\rightarrow$ FCNC quark-squark-gluino vertex,

A 3+1 Higgs doublets model

- To study possible deviations from the SM predictions, we shall work with a 3+1 - Higgs doublet model (Φ_1, Φ_2, Φ_3 and Φ_0)
- The Higgs doublets only couple to one fermion type each, and do not induce FCNC, $\Phi_1 \rightarrow$ up-, $\Phi_2 \rightarrow$ down- and $\Phi_3 \rightarrow$ l,
- The model also includes one Froggart-Nielsen singlet, which reproduces the fermion masses and CKM,
- Through Higgs-Flavon mixing, it is possible to induce FV Higgs interactions,
- Φ_0 is odd under a discrete symmetry, and therefore its ligtest state is stable and a possible DM candidate,
- d. of f. (Real) = 3+1=4 , and when CP is conserved $\rightarrow$ 4 CP-even Higgs bosons, one (h_1) should have $m_h = 125$ GeV,

A 3+1 Higgs doublets model

- To go from weak to mass-eigenstates: $\phi_i^0 = O_{ij}^T h_j$
- The Higgs couplings of the lightest Higgs state ($h^0 = h_1^0$) with vector bosons are written as $g_{hVV} = g_{hVV}^{sm}\chi_V$, with χ_V:

$$\begin{aligned} \chi_V &= \frac{v_1}{v}O_{11}^T + \frac{v_2}{v}O_{21}^T + \frac{v_3}{v}O_{31}^T \\ &= \cos\theta\, O_{11}^T + \sin\theta\cos\phi\, O_{21}^T + \sin\theta\sin\phi\, O_{31}^T \end{aligned} \quad (2)$$

- In spherical coord. : $v_1 = v\cos\theta$, $v_2 = v\sin\theta\cos\phi$ and $v_3 = v\sin\theta\sin\phi$.

Lagrangian for 3+1 Higgs doublets model

The lagrangian for the Higgs-fermion couplings is,

$$\mathcal{L}_Y = [\frac{\eta^u}{v}\bar{U}M_u U + \frac{\eta^d}{v}\bar{D}M_d D + \frac{\eta^l}{v}\bar{L}M_l L + \kappa^u \bar{U}_i \tilde{Z}^u U_j + \kappa^d \bar{D}_i \tilde{Z}^d D_j + \kappa^l \bar{L}_i \tilde{Z}^l L_j] h^0 \quad (3)$$

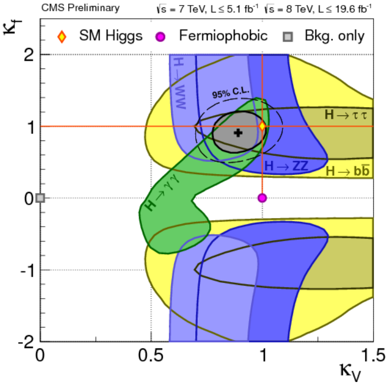
For FC Higgs couplings:

$\eta^u = O^T_{11}/\cos\theta, \quad \eta^d = O^T_{21}/\sin\theta\cos\phi, \quad \eta^l = O^T_{31}/\sin\theta\sin\phi,$

For FV Higgs couplings:

$\kappa^u = \frac{v}{u}O^T_{41}\cos\theta, \quad \kappa^d = \frac{v}{u}O^T_{41}\sin\theta\cos\phi, \quad \kappa^l = \frac{v}{u}O^T_{41}\cos\theta\sin\phi.$

Higgs identity: $g_{hXX} = c_X \, g^{sm}_{hXX}$



The Universal Higgs fit - P. Giardino et al., arXiv:1303.3570 [hep-ph]

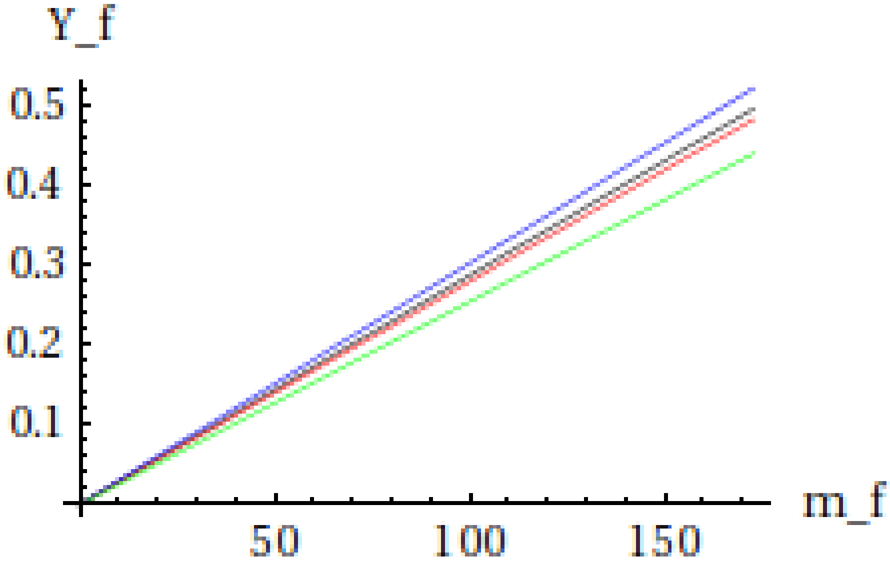
Under the small deviations approximation:

$$c_X = (1 + \epsilon_X) \tag{4}$$

From a fit to all observables (signal strengths), and assuming no new particles contribute to the loop decays hgg and $h\gamma\gamma$, they get:

- hZZ (hWW): $\epsilon_Z = -0.01 \pm 0.13$ $(\epsilon_W = -0.15 \pm 0.14)$,
- hbb: $\epsilon_b = -0.19 \pm 0.3$,
- $h\tau\tau$: $\epsilon_\tau = 0 \pm 0.18$
- htt (from hgg): $\epsilon_t = -0.21 \pm 0.23$

Higgs couplings in 3+1 HDM



Top FCNC Decay in 3+1 HDM

Scenario	u[TeV]	$\kappa^u \times \tilde{Z}_{23}$	$B.R.(t \to ch)$
X1	0.5	1.2×10^{-4}	8.6×10^{-9}
X2	1	6.1×10^{-5}	2.2×10^{-9}
X3	10	6.1×10^{-6}	2.2×10^{-11}
Y1	0.5	6.9×10^{-3}	2.7×10^{-5}
Y2	1	3.4×10^{-3}	6.8×10^{-6}
Y3	10	3.4×10^{-4}	6.8×10^{-8}
Z1	0.5	2.9×10^{-2}	4.8×10^{-4}
Z2	1	1.4×10^{-2}	1.2×10^{-4}
Z3	10	1.4×10^{-3}	1.2×10^{-6}

Table : The factor $\kappa^u \times \tilde{Z}^u_{23}$ and Branching ratios for $t \to ch$

Conclusions.

- LHC is already giving great results,
- Evidence for a SM-like Higgs with $m_h = 125$ GeV,
- Tests of Higgs couplings at LHC could show deviations from SM,
- FCNC decays of top quark could also provide another window into PBSM,
- Limits on top FCNC decays are starting to appear at LHC ,
- No evidence at LHC, so far, of new phyics,
- If no signal of BSM physics shows up at LHC, then what?
  Super-split SUSY

Interesting times!

The parameters of the MSSM

In addition to SM parameters, the MSSM includes O(100) new ones:

- Scalar masses (Sleptons, squarks, Higgs),
- Gaugino masses $(\tilde{M}_G, \tilde{M}_W, \tilde{M}_B)$,
- Trilinear terms ($A_{\tilde{f}}$ for squarks and sleptons),
- From Higgs sector: $\tan\beta = v_2/v_1$ and μ,
- The masses of superpartners have important implications for EWSB,
- Spectrum of superpartners depends on mechanism of SUSY breaking,

The MSSM Higgs sector

At tree-level MSSM Higgs sector is a 2HDM of type-II, i.e. it contains two Higgs doublets, with:

- CP-even neutral Higgs bosons h^0, H^0, at tree-level $m_h < m_Z$,
- CP-odd neutral Higgs A^0 with $m_H^2 = m_A^2 + m_Z^2 \sin^2 2\beta$,
- Charged Higgs $H^\pm$, with $m_{H^+}^2 = m_A^2 + m_W^2$,
- Masses and mixing angles fixed with: m_A and $tan\beta = v_2/v_1$,
- When $m_A \leq \tilde{m}$, Higgs search uses SM techniques.
- But $H^0, A^0, H^\pm$ may decay into SUSY modes; LHC search gets more complicated!,

The MSSM Higgs mass

Radiative effects of Stop-top loops can make: $m_h > m_Z$

$$m_h^2 = m_Z^2[1 + \frac{3m_t^2}{2\pi^2 m_Z^2} log(\frac{m_{stop}}{m_t})] \tag{5}$$

But to get $m_h = 125$ GeV, with SM-like couplings, need:

- Large superpartner masses O(1) TeV,
- Only a few superpartners could be at the reach of LHC,
- Split SUSY? High Scale SUSY?
- O(1) or large $tan\beta$ allowed,
- Large $tan\beta \rightarrow$ enhanced production of $H + bb$ at LHC,

MSSM Higgs and Dark matter

For heavy sfermions the DM relic density is:

$$\Omega_X h^2 = C_X (\frac{m_X}{TeV})^2 \tag{6}$$

- For DM $X =$ pure Bino, no aceptable solution,
- For DM $X = \tilde{H}$ pure Higgsino, $C_{\tilde{H}} = 0.09$ and an aceptable solution is obtained for $1 < M_{\tilde{H}} < 1.2$ TeV,
- For DM $X = \tilde{W}$ pure Wino, $C_{\tilde{H}} = 0.02$ and an aceptable solution is otained for $2 < M_{\tilde{W}} < 2.5$ TeV,

In such case detection at LHC may be harder,

MSSM Higgs couplings:

- $(hVV):\quad \frac{2m_V^2}{v}\cos(\beta-\alpha),\quad v^2=v_1^2+v_2^2,$
- $(huu):\quad \frac{m_u}{v}(\frac{\cos\alpha}{\sin\beta}),$
- $(hdd):\quad \frac{m_d}{v}(\frac{\sin\alpha}{\cos\beta}),$
- $(hll):\quad \frac{m_l}{v}(\frac{\sin\alpha}{\cos\beta}),$
- $(hhh):\quad \simeq \lambda v,\quad \lambda=\frac{g^2+g'^2}{8},$
- $(hhhh):\quad \simeq \lambda.$

Similar expressions hold for H^0, A^0 and $H^{\pm}$.

Holographic Dark matter

- Composite Higgs can have a "baryon" partner,
- This composite state can be (Holographic) Dark matter (J.L. Diaz-Cruz, PRL81, 2008),
- Deviations from SM Higgs properties can show evidence of dark matter,