Higgs boson in the NMSSM

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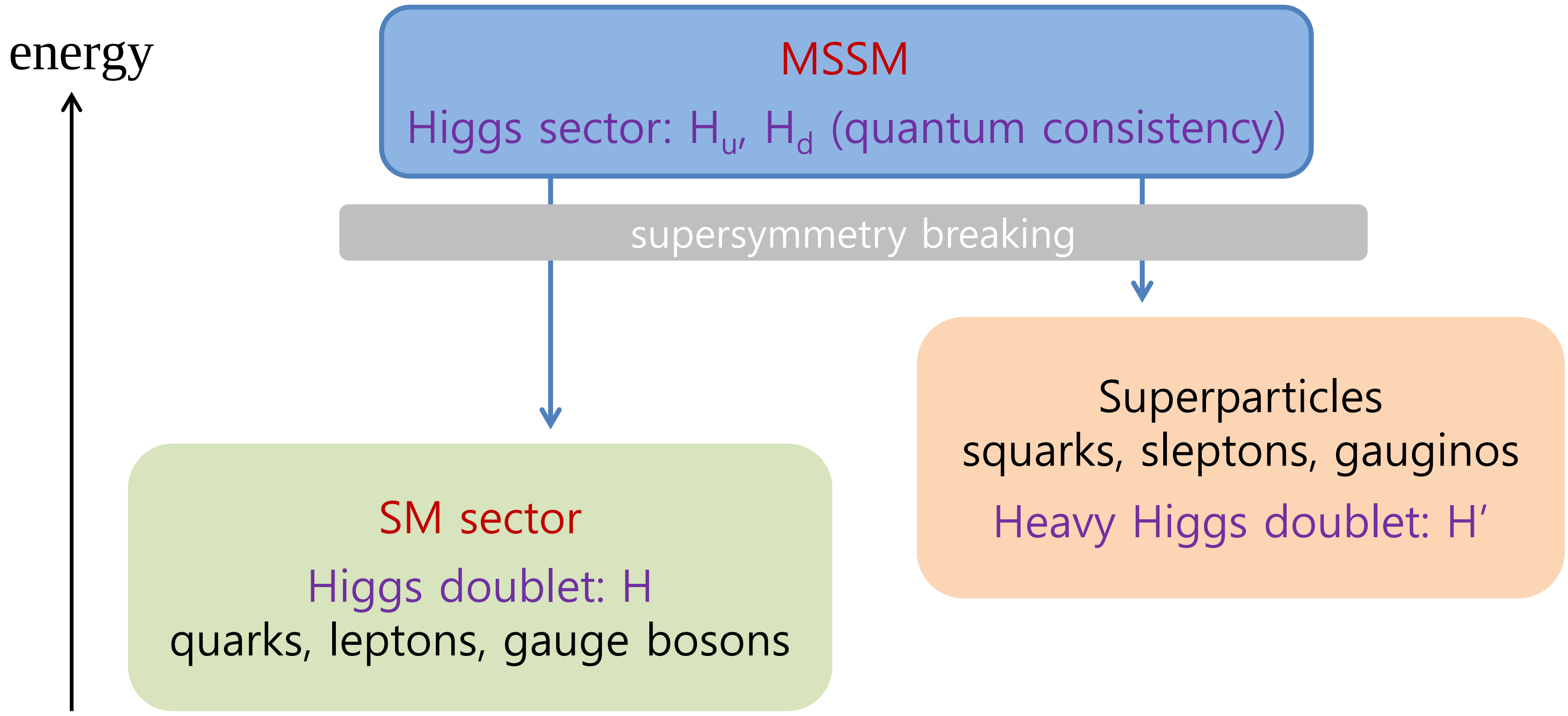
1. Supersymmetric SM

- Supersymmetric SM

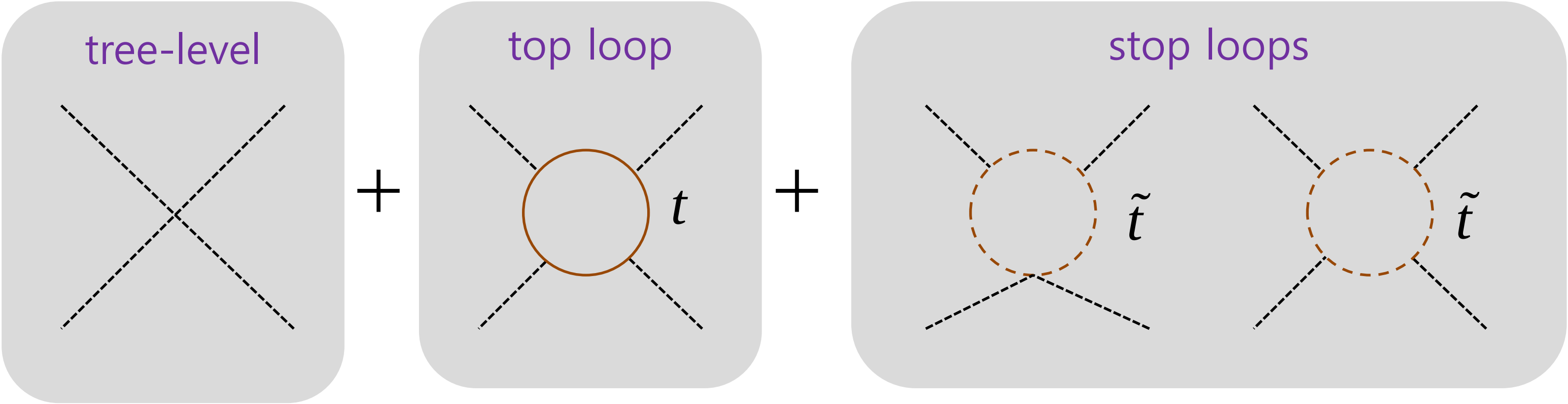


- The SM Higgs arises from MSSM in the decoupling limit.

▪ Supersymmetry at low energy scales

- solves the gauge hierarchy problem.
- leads to gauge coupling unification.
- offers a good dark matter candidate.
  (the lightest superparticle if neutral. w/ R-parity conservation)
- explains how electroweak symmetry breaking occurs.
- …
- gives a SM-like Higgs boson.

- Can the supersymmetric SM account for a SM-like Higgs boson around 125 GeV?
  - The Higgs quartic coupling is determined by gauge couplings at tree-level.



- Higgs boson mass in the MSSM

$$m_h^2 = \lambda_H \left\langle \left| H^0 \right| \right\rangle^2 = M_Z^2 \cos^2 2\beta + \Delta m^2$$

  - $\tan\beta$ is the ratio between VEVs of H_u and H_d.
  - Higgs mass around 125 GeV requires substantial loop contributions, Δm larger than 86 GeV.
  - Thus stops should have some mixing and masses above 1 TeV. (log dependence on stop mass)

→ More fine-tuning for EWSB.

2. NMSSM

- Next-to-minimal supersymmetric SM
- Extend the EWSB sector to include a SM singlet S s.t.

$$W = \mu H_u H_d \rightarrow \lambda S H_u H_d + f(S)$$

  - The Higgsino mass is dynamically generated by the VEV of S.

- Various models depending on f(S)
  - f(S) is needed to avoid a visible massless axion.
  - Approximate symmetry, e.g. Z_3 to suppress S and S^2 term.
  - Properties of SM-like Higgs boson are not sensitive to the details of f(S).

2. NMSSM

- NMSSM maintains most of the nice features of MSSM.
- In addition, it provides a richer physics in the Higgs scalar sector and the neutralino sector, both in collider and dark matter experiments.
  - Mixing between singlet and doublet Higgs bosons
    e.g. a light singlet-like Higgs boson may be present.
  - Mixing between singlino and neutral Higgsinos
    e.g. the lightest neutralino may have large singlino component.

2. NMSSM

- NMSSM contribution to the Higgs quartic coupling

$$m_h^2 = \lambda_H \left\langle \left| H^0 \right| \right\rangle^2 = M_Z^2 \cos^2 2\beta + \lambda^2 \left\langle \left| H^0 \right| \right\rangle^2 \sin^2 2\beta + \Delta m^2$$

  - $m_h > M_Z$ at tree-level for λ larger than 0.54.
  - NMSSM contribution becomes large at low tanβ and large λ.
  - Note that λ needs to be smaller than about 0.7 to remain perturbative up to the GUT scale.

- NMSSM requires less fine-tuning.
  - m_h=125 GeV does not require heavy stops.
  - For stops around 1 TeV, we need λ around or larger than 0.6.

3. Higgs boson in NMSSM

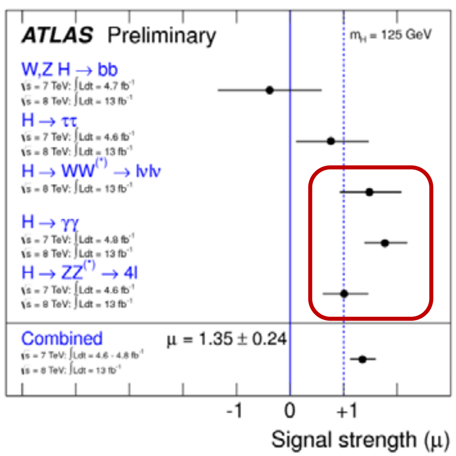
- Scalar mixing after EWSB
  - h= SM-like Higgs boson from Re(H^0) with small Re(S) and Re(H'^0) components.
- Deviation from the SM Higgs boson due to mixing
  - Higgs signal rate at LHC normalized by the SM value:

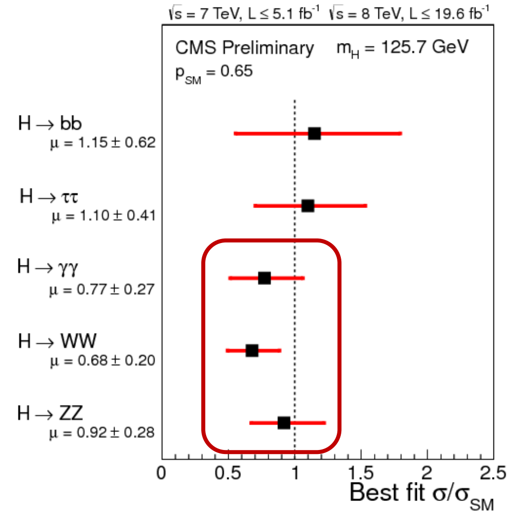
$$R_h^{ii} = \frac{\sigma(pp \to h) \times Br(h \to ii)}{\left[\sigma(pp \to h) \times Br(h \to ii)\right]_{\rm SM}} \approx C_{htt}^2 \times \frac{C_{hii}^2}{0.64 C_{hbb}^2 + 0.24 C_{hVV}^2 + 0.12 C_{htt}^2}$$

  - Higgs couplings $C_{hbb,htt,hVV}$, which are equal to one in the SM, are modified by the scalar mixing.

3. Higgs boson in NMSSM

- WW/ZZ channel
  - Experimental uncertainties are small compared other channels.
  - The measured rates in WW/ZZ (and in di-photon) are almost consistent with the SM prediction:



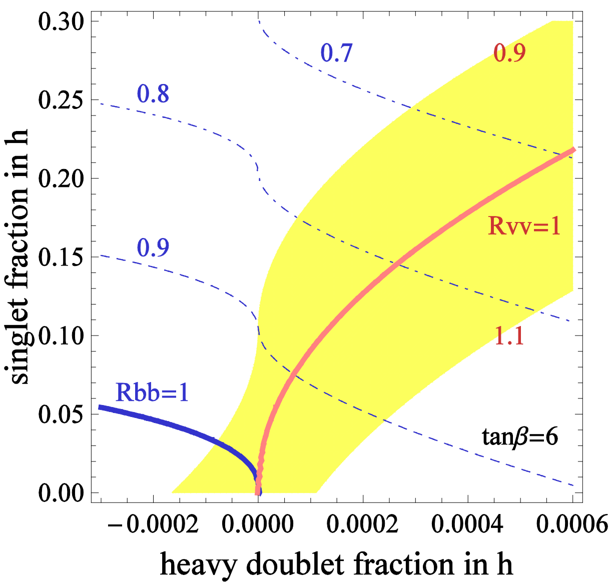


- This is the case when the H-H′ mixing is very small.

(also the case for sizable H - H' mixing if tanβ is larger than about 3.)

3. Higgs boson in NMSSM

- S-H mixing
  - A sizable S-H mixing can be consistent with the current data:



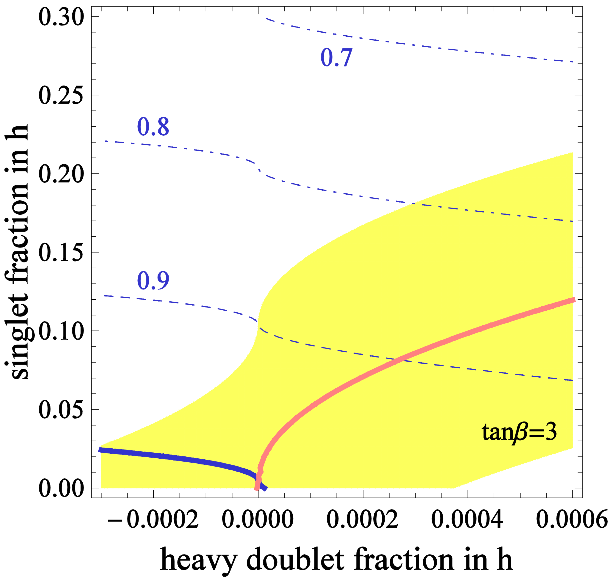
$* \ 0.9 \leq R_h^{VV} \leq 1.1$ in the yellow region.

$* \ R_h^{bb} \left(= R_h^{\tau\tau}\right)$ is shown by blue lines.

  - Rvv is close to the SM value even in the presence of mixing.

3. Higgs boson in NMSSM

- S-H mixing
  - For smaller tanβ, R^{VV} close to one requires small S-H mixing.



$*\ 0.9 \le R_h^{VV} \le 1.1$ in the yellow region.

$*\ R_h^{bb} \left(= R_h^{\tau\tau}\right)$ is shown by blue lines.

  - Singlet fraction in h giving $R^{VV}=1 \propto 1.4 \tan\beta + 1.7/\tan\beta$

- Di-photon signal rate

$$R_h^{\gamma\gamma} \simeq \left(1+\Delta C_{\rm SUSY}\right) R_h^{VV}$$

- In SM, hγγ coupling is radiatively induced with the dominant contribution coming from W and top loops.
- Sensitive to new physics: electric charged particles with mass around 100-200 GeV.

  e.g. stau with large left-right mixing, higgsino-like chargino, charged Higgs scalar.

- If $R^{\gamma\gamma} \neq R^{VV}$, we need light electric charged particles.

4. Implications of Higgs mixing

- Singlet-like Higgs boson
  - It interacts with the SM particles through its doublet Higgs component.
  - If it has a sizable doublet Higgs component, say 0.2, its mass would lie in the range between $m_h/2$ and about 200 GeV since otherwise it becomes difficult to arrange m_h=125 GeV:

$$\Delta m_h\big|_{\text{mixing}} \approx -(\text{singlet fraction in h})\times\frac{m_s^2-m_h^2}{2m_h}$$

the above holds when $|\Delta m_h| \ll m_h$.

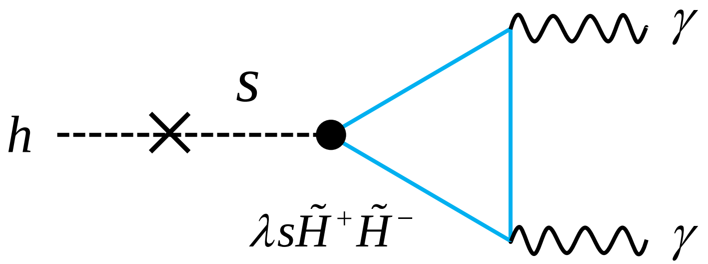
It can have a larger mass for stops above 1 TeV or λ>0.7.

4. Implications of Higgs mixing

- Singlet-like Higgs boson
  - If the singlet-like Higgs is lighter than m_h=125 GeV, the mixing increases m_h, independently of tanβ.

    Then moderate and large tanβ becomes viable in NMSSM.
  - Decay of the singlet-like Higgs boson into SM particles can be probed at the LHC or future collider experiments such as ILC, but with small deviation in Higgs signal rates in WW/ZZ.
  - Its decay into SM particles is dominated by that into bb if it is lighter than mh, while by that into WW otherwise. (C_{hbb}<C_{hVV}<1 in the situation under consideration)

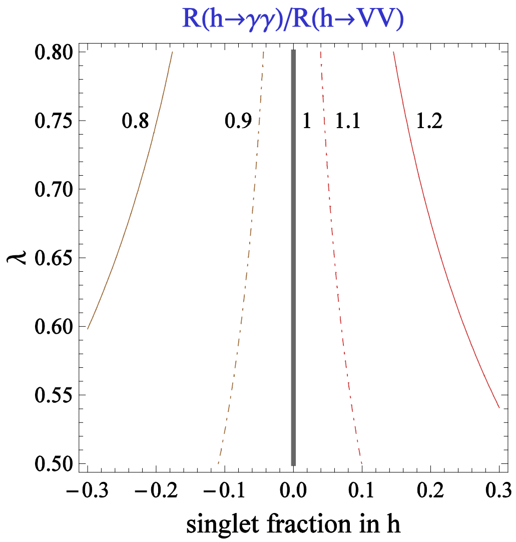
- Di-photon signal rate
  - In the presence of S-H mixing, the hγγ coupling can receive contribution from the charged Higgsino loop:



  - Sizable if μ is small (around the weak scale, as favored by naturalness) and λ is large.
  - LEP bound: the chargino mass > 104 GeV.

4. Implications of Higgs mixing

- Di-photon signal rate
  - For λ=0.7 and μ=120 GeV, Rγγ can be different from Rvv by about 25% if the singlet fraction in h is 0.3:



$$R_h^{\gamma\gamma} \approx \left(1 \pm 0.21 \frac{\lambda \langle |H^0| \rangle}{\mu} \sqrt{(\text{singlet fraction in h})}\right) R_h^{VV}$$

  - For small H-H′ mixing, the above result is insensitive to tanβ.

5. Implications of singlino-Higgsino mixing

- Lightest neutralino
  - Dark matter candidate.
  - It has different properties from the MSSM case if it has a sizable singlino component.
  - The coupling to h can be sizable when the singlino and Higgsino mass parameters are smaller than the supersymmetry breaking scale:

$$h\chi_1\chi_1 \text{ coupling from } H\text{-(singlino)-(Higgsino)}$$

If not much smaller than 0.1, it can be probed in near future via spin-independent DM-nucleon scattering.

5. Implications of singlino-Higgsino mixing

- Lightest neutralino
  - If it is lighter than $m_h/2$, the $h\chi_1\chi_1$ coupling leads to Higgs invisible decay.
  - Invisible Higgs decay rate can be sizable and thus be accessible at collider experiments, when the lightest neutralino is a mixture of singlino and neutral Higgsino.
  - $Br(h \to inv)$ should be smaller than about 20% to be consistent with the current LHC data.

6. Summary

- NMSSM can naturally accommodate a SM-like Higgs boson with mass around 125 GeV and signal rates consistent with the LHC data.
- NMSSM provides a rich (complicated but interesting) phenomenology in the Higgs and neutralino sector.
- The deviation from the SM Higgs properties, if survives, may imply a sizable singlet-doublet mixing.

  Then a relatively light singlet-like Higgs boson will be detected.