Discriminating between SUSY and Non-SUSY Higgs Sectors through the Ratio $H \to b\bar{b}/H \to \tau\bar{\tau}$

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From work in collaboration with:
E.Arganda, J.Guasch, W.Hollik, S.P., **arXiv:1506.08462 [hep-ph]**
J.Guasch, W.Hollik, S.P., PLB515 (2001) 367, hep-ph/0106027

Outline

1. Motivations
2. Neutral Higgs bosons decays
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   - Leading corrections to the quark masses
   - One-loop Effective couplings
3. Results
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   - Corrections for the lightest CP-even Higgs boson
   - Results for Heavy Higgses, H^0 and A^0
4. Conclusions

Motivations

New scalar particle discovered at the LHC with mass
$m_H = 125.09 \pm 0.21$ (stat.) $\pm$ 0.11 (syst.) GeV [ATLAS+CMS, 2015]
seems to behave as SM Higgs boson.

Is there new physics (NP) behind the Higgs boson?

- Many SM extensions enlarge Higgs sector, including a SM-like Higgs boson.
- In Two-Higgs-Doublet models (2HDM) there are 5 physical states: 2 charged ($H^{\pm}$) and 3 neutral (h, H, A).
- MSSM also contains 2 Higgs doublets with a light neutral scalar (h) compatible with discovered SM-like Higgs boson.

The Large Hadron Collider: pp @ $\sqrt{S} = 13\,TeV$

- Running and providing interesting results !? ...

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Is there new physics (NP) behind the Higgs boson?

- If new particles are found: what are they? (which model do they belong?)
  - $\Rightarrow$ Check model predictions at the same level as SM
  - $\Rightarrow$ Provide specific observables of the extensions of the SM

Possibility of probing (non-)SUSY nature of Higgs bosons at the LHC through the observable

$$R = \frac{\mathrm{BR}(H \to b\bar{b})}{\mathrm{BR}(H \to \tau\bar{\tau})}$$

.

Neutral Higgs bosons decays: $H \to b\bar{b} / H \to \tau^+\tau^-$

E.Arganda, J.Guasch, W.Hollik, S.P., **arXiv:1506.08462 [hep-ph]**

J.Guasch, W. Hollik, S. P., PLB515 (2001) 367, hep-ph/0106027, hep-ph/0307012

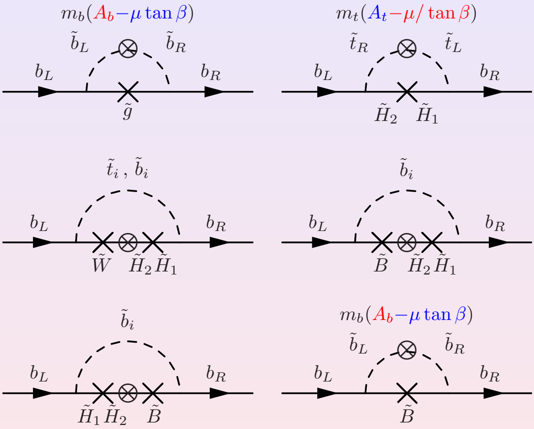
In the SM, after accounting for the leading QCD corrections:

$$R = \frac{BR(H \to b\bar{b})}{BR(H \to \tau^+\tau^-)} = \frac{3m_b^2(M_H)}{m_\tau^2} \simeq 7.45(M_{h^0} = 125\,GeV)$$

- Same leading expression in *any* Higgs model in which the Higgs sector follows the family structure of the SM
- Receives large SUSY corrections at large $\tan\beta$ due to Δm_b, Δm_τ
  - are non-decoupling ($M_{\rm SUSY}$)
  - CAN NOT be absorbed by a parameter redefinition
  - 2HDM CAN NOT give large corrections $\Rightarrow$ allow to distinguish between SUSY and THDM
- Systematics on Higgs production cancel in the ratio
  - NLO corrections, Luminosity, ...
- The only surviving systematic effect results from the efficiency of τ- and b-tagging

Leading corrections to the quark masses

Diagrams contributing to Δm_b: Leading $\tan\beta$ terms



The cross means a mass insertion, the cross with a circle coupling with H_1 (blue); H_2 (red).

τ-leptons have similar corrections: Δm_τ ($b \to \tau$, $\tilde{b} \to \tilde{\tau}$, $\tilde{t} \to \tilde{\nu_\tau}$)

Leading corrections to the quark masses

- Leading effects can be described through the finite threshold corrections to the bottom quark mass

$$
\begin{aligned}
\Delta m_b \;=\;& \Delta_b \tan\beta \simeq \mu \tan\beta \left\{ \frac{2\alpha_S}{3\pi} M_{\tilde g}\, I(M_{\tilde b_1}, M_{\tilde b_2}, M_{\tilde g}) + \frac{Y_t}{4\pi} A_t\, I(M_{\tilde t_1}, M_{\tilde t_2}, \mu) \right.\\
&+ \frac{\alpha}{4\pi} \left(-\frac{M_2}{s_W^2} \left(\left[c_t^2\, I(M_{\tilde t_1}, M_2, \mu) + s_t^2\, I(M_{\tilde t_2}, M_2, \mu) \right] \right.\right.\\
&\left. + \frac{1}{2} \left[c_b^2\, I(M_{\tilde b_1}, M_2, \mu) + s_b^2\, I(M_{\tilde b_2}, M_2, \mu) \right] \right)\\
&- \frac{M_1}{3\, c_W^2} \left(\frac{1}{3} I(M_{\tilde b_1}, M_{\tilde b_2}, M_1) + \frac{1}{2} \left[c_b^2\, I(M_{\tilde b_1}, M_1, \mu) + s_b^2\, I(M_{\tilde b_2}, M_1, \mu) \right] \right.\\
&\left.\left.\left. + \left[s_b^2\, I(M_{\tilde b_1}, M_1, \mu) + c_b^2\, I(M_{\tilde b_2}, M_1, \mu) \right] \right) \right) \right\} .
\end{aligned}
$$

$$
I(a,b,c) \;=\; \frac{a^2 b^2 \ln(a^2/b^2) + b^2 c^2 \ln(b^2/c^2) + c^2 a^2 \ln(c^2/a^2)}{(a^2-b^2)(b^2-c^2)(a^2-c^2)} \rightarrow \frac{1}{max(a^2, b^2, c^2)}
$$

$$
Y_t \equiv \frac{h_t^2}{4\pi} = \frac{g^2 m_t^2}{8\pi m_W^2 \sin\beta^2}
$$

Leading corrections to the quark masses

- Special Limit: All SUSY masses are equal to M_{SUSY}:

$$\Delta m_b \simeq \mathrm{sign}(\mu)\tan\beta\left\{\frac{\alpha_S}{3\pi}-\frac{\alpha}{16\pi s_W^2}\left(3+\frac{11}{9}\frac{s_W^2}{c_W^2}\right)+\frac{Y_t}{8\pi}\frac{A_t}{M_{SUSY}}\right\},$$

$$\Delta m_\tau \simeq -\mathrm{sign}(\mu)\tan\beta\,\frac{\alpha}{16\pi s_W^2}\left(3-\frac{s_W^2}{c_W^2}\right).$$

- Δm_b and Δm_τ:
  - grow with $\tan\beta$
  - The corrections are independent of the SUSY scale
  - non-decoupling ($\Delta m_b \neq 0$ if $M_{SUSY}\to\infty$)

  Large SUSY masses do not decouple from the Higgs sector!

One-loop Effective couplings

$$h^0 b\bar{b} \quad : \quad C_{hbb} = h_b \sin\alpha \left(1 - \frac{\Delta m_b}{\tan\beta \tan\alpha}\right)$$

$$H^0 b\bar{b} \quad : \quad C_{Hbb} = -h_b \cos\alpha \left(1 + \frac{\Delta m_b \tan\alpha}{\tan\beta}\right)$$

$$A^0 b\bar{b}/H^+ t\bar{b} \quad : \quad C_{Abb/H^- tb} = -h_b \sin\beta \left(1 - \frac{\Delta m_b}{\tan\beta^2}\right)$$

- Large M_{A^0} limit: $M_{A^0} \gg M_Z \Rightarrow \alpha \to \beta - \pi/2\,,\ \tan\alpha \to -1/\tan\beta$

  Haber *et al.* PRD63 (2001) 055004, hep-ph/0007006 (one-loop analysis)

$$\Rightarrow C_{hbb} \to \frac{m_b}{v\cos\beta(1+\Delta m_b)} \cos\beta(1+\Delta m_b) = C_{hbb}^{SM}$$

  $\Rightarrow$ The light Higgs behaves as SM!

- BUT: The heavy Higgs retain the non-decoupling effect!

$$C_{heavy} \to \frac{m_b}{v(1+\Delta m_b)} \tan\beta(1 - \frac{\Delta m_b}{\tan\beta^2})$$

Resummation and effective Lagrangian

J. Guasch, W. Hollik, S. P., PLB515 (2001) 367; J. Guasch, P. Häfliger, M. Spira, PRD68, 115001 (2003)

- Resum leading terms
- Matching conditions with the low energy effective theory
- Find effective couplings

$$h_b = \frac{m_b(Q)}{v_1}\frac{1}{1+\frac{h_b^s}{h_b}\Delta m_b} \quad , \quad \frac{h_b^s}{h_b} = \frac{1}{1+\Delta_2}$$

One-loop effective couplings:

$$h^0 b\bar{b} \quad : \quad C_{hbb} = h_b \sin\alpha \left(1 - \frac{h_b^s}{h_b}\frac{\Delta m_b}{\tan\beta\tan\alpha}\right)$$

$$H^0 b\bar{b} \quad : \quad C_{Hbb} = -h_b \cos\alpha \left(1 + \frac{h_b^s}{h_b}\frac{\Delta m_b \tan\alpha}{\tan\beta}\right)$$

$$A^0 b\bar{b}/H^- t\bar{b} \quad : \quad C_{Abb/H^-tb} = -h_b \sin\beta \left(1 - \frac{h_b^s}{h_b}\frac{\Delta m_b}{\tan\beta^2}\right)$$

$H \to b\bar{b} / H \to \tau^+\tau^-$: Numerical Analysis

- We consider different SUSY scenarios:
  $m_h^{\text{mod+}}$, $m_h^{\text{mod-}}$, light-stop, light-stau and pMSSM.

  M. Carena et al., Eur.Phys.J. C **73** (2013) 9, 2552, arXiv:1302.7033 [hep-ph].

  M.W. Cahill-Rowley et al., arXiv:1305.2419 [hep-ph].
- We check that these scenarios are compatible with the present experimental value of the Higgs boson mass.
  - The Higgs boson mass is computed by using `FeynHiggs 2.11`.

    S. Heinemeyer et al., Comput. Phys. Commun. **124** (2000) 76, hep-ph/9812320.
- The branching ratios of Higgs boson decays into $b\bar{b}$ and $\tau^+\tau^-$ have been also computed with `FeynHiggs 2.11` and we find a perfect agreement with our results.

MSSM scenarios: Numerical Analysis

- $\mu < 0$ $A_t > 0$ scenario [Guasch *et al.*, 2001]:
  $m_{\tilde{g}} = M_{\tilde{b}_1} = M_{\tilde{t}_1} = M_{\tilde{\tau}_1} = M_2 = |\mu| = A_b = A_\tau = |A_t| = 1.5$ TeV.
- Benchmark scenarios [Carena *et al.*, 2013]:
  $M_{\tilde{t}_L} = M_{\tilde{b}_L} = M_{\tilde{t}_R} = M_{\tilde{b}_R} = M_{\text{SUSY}}$; $M_1 = \frac{5}{3}\frac{s_W^2}{c_W^2} M_2$;
  $M_{\tilde{q}_{1,2}} = 1500$ GeV, $M_{\tilde{l}_{1,2}} = 500$ GeV; $A_f = 0$ $(f = c, s, d, u, \mu, e)$.

Parameter	$m_h^{\text{mod+}}$	$m_h^{\text{mod-}}$	light-stop	light-stau
M_{SUSY}	1000 GeV	1000 GeV	500 GeV	1000 GeV
μ	200 GeV	200 GeV	350 GeV	500 GeV
M_2	200 GeV	200 GeV	350 GeV	200 GeV
X_t	1.6 M_{SUSY}	-1.9 M_{SUSY}	2 M_{SUSY}	1.6 M_{SUSY}
A_b	$= A_\tau = A_t$	$= A_\tau = A_t$	$= A_\tau = A_t$	$= A_t$, $A_\tau = 0$
$m_{\tilde{g}}$	1500 GeV	1500 GeV	1500 GeV	1500 GeV
$M_{\tilde{l}_3}$	1000 GeV	1000 GeV	1000 GeV	245 GeV

- pMSSM 2392587 [Cahill-Rowley *et al.*, 2013]:
  $\mu = 3955$ GeV, $M_2 = 1606$ GeV, $M3 = 313$ GeV, $M_{\tilde{t}_L} = 2493$ GeV, $M_{\tilde{t}_R} = 2154$ GeV, $M_{\tilde{b}_R} = 2009$ GeV, $A_b = 2067$ GeV, $A_t = -3905$ GeV, $M_{\tilde{\tau}_L} = 3167$ GeV, $M_{\tilde{\tau}_R} = 2319$ GeV, $A_\tau = 2223$ GeV.

LHC data and constraints

ATLAS and CMS generic fits to Higgs coupling ratios

- CMS: $\lambda_{bZ}^{\mathrm{CMS}} = 0.59^{+0.22}_{-0.23}$, $\lambda_{\tau Z}^{\mathrm{CMS}} = 0.79^{+0.19}_{-0.17} \Rightarrow R^{\mathrm{CMS}} = 0.56^{+0.48}_{-0.52}$.
  [CMS Collaboration], Eur.Phys.J. C **75** (2015) 5, 212, arXiv:1412.8662 [hep-ex].
- ATLAS: $\lambda_{bZ}^{\mathrm{ATLAS}} = 0.60 \pm 0.27$, $\lambda_{\tau Z}^{\mathrm{ATLAS}} = 0.99^{+0.23}_{-0.19} \Rightarrow R^{\mathrm{ATLAS}} = 0.37^{+0.36}_{-0.37}$.
  [ATLAS Collaboration], ATLAS-CONF-2015-007.
- Combined (R. Barlow, physics/0406120.):
  $\lambda_{bZ} = 0.59 \pm 0.17$, $\lambda_{\tau Z} = 0.89^{+0.14}_{-0.13} \Rightarrow R^{\mathrm{Combined}} = R^{\mathrm{exp}}/R^{\mathrm{SM}} = 0.45^{+0.29}_{-0.30}$

$\Rightarrow$ The one-standard deviation (68% C.L.) favored bands are:

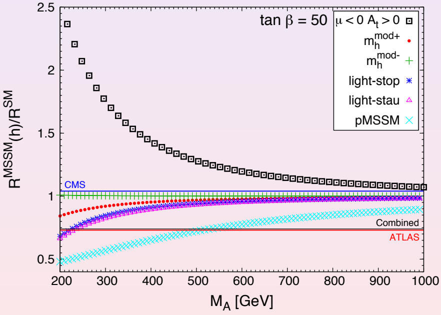
$$0.04 < R^{\mathrm{CMS}} < 1.04 \ , \ 0 < R^{\mathrm{ATLAS}} < 0.73 \ , \ 0.15 < R^{\mathrm{Combined}} < 0.74 \,.$$

- The CMS result includes the SM value ($R = 1$) in its favored region.
- The ATLAS and combined results disfavor the SM (at 68% C.L.).
- SUSY can provide the necessary corrections to bring the predicted theoretical value of R inside the ATLAS favored band.

Corrections for the lightest CP-even Higgs boson, h^0

$$\frac{R^{\rm MSSM}(h)}{R^{\rm SM}} = \frac{(1+\Delta m_\tau)^2\,(-\cot\alpha\,\Delta m_b + \tan\beta)^2}{(1+\Delta m_b)^2\,(-\cot\alpha\,\Delta m_\tau + \tan\beta)^2}\,.$$

Deviation of $R^{\rm MSSM}(h)$ with respect to the SM value



The horizontal lines show the one-standard deviation experimental upper limit.

- Decoupling behavior with M_A in all scenarios.
- $\mu < 0$ $A_t > 0$: largest deviations but excluded by ATLAS, CMS, and Combined, and also disfavored by BR($B_s \to \mu^+\mu^-$).
- $m_h^{\rm mod-}$: allowed by CMS, indistinguishable from SM.
- $m_h^{\rm mod+}$: allowed by CMS, deviations around 20% (disfavored by ATLAS).
- light-stop, light-stau: larger deviations up to 40% for small M_A, also allowed by ATLAS.
- pMSSM: 50% deviations, allowed by data if $M_A \lesssim 500$ GeV.

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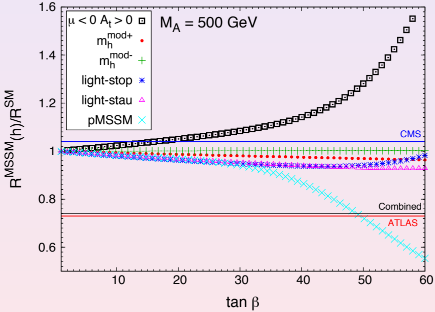
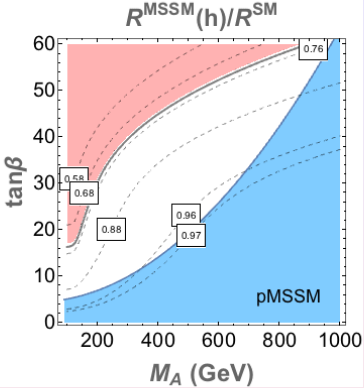


- Predictions allowed by CMS.
- No significant deviations in $m_h^{\rm mod+}$, $m_h^{\rm mod-}$, light-stop, and light-stau scenarios, up to 10%.
- pMSSM: predictions allowed by CMS for any value of $\tan\beta$, and by ATLAS and the combined analysis if $\tan\beta \gtrsim 50$ (up to 50%).

Potential discrimination I



- The black curve shows the upper (one-standard deviation) limit from ATLAS [combined].
- The favored region is shown in red.
- The blue area is the 95% C.L. allowed regions by the negative searches by ATLAS and CMS for neutral MSSM Higgs bosons decaying to a pair of τ leptons.
  ATLAS Collaboration, arXiv:1409.6064 [hep-ex]; CMS Collaboration, arXiv:1408.3316 [hep-ex].

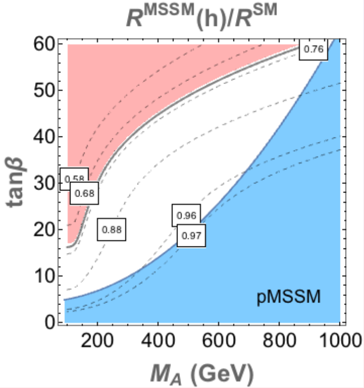
- The favored region is much larger than in the other scenarios, allowing large values of M_A with large tan β.
- The favored region fall completely inside the excluded region for the CMS and ATLAS direct searches for Higgs bosons decaying into τ-lepton pairs.

Potential discrimination II - Future prospects

Expected accuracies for the measurements of the Higgs boson couplings

C. Englert et al. J. Phys. G **41** (2014) 113001, [arXiv:1403.7191 [hep-ph]]

Observable	LHC	HL-LHC	LC	HL-LHC+LC
$Hb\bar{b}$	10-13%	4-7%	0.6%	0.6%
$H\tau^+\tau^-$	6-8%	2-5%	1.3%	1.2%
R	32-42%	12-24%	4%	3%



- The sensitivity regions are the ones above and to the left of the corresponding curve.
- Unfortunately the sensitivity regions lie mainly outside the shaded blue areas and are excluded by the ATLAS and CMS direct searches.
- HL-LHC only sensitive to SUSY nature of h for large values of M_A and $\tan\beta$ (allowed by direct search for Higgs boson decaying into τ-lepton pairs).
- LC can probe SUSY nature of h for any value of M_A and $\tan\beta$.
- able to observe deviations with respect the SM predictions at a future LC.

Results for Heavy Higgses: H^0 and A^0

For H^0 and A^0

Deviation of $R^{\rm MSSM}(H/A)$ with respect to the SM value

$$\frac{R^{\rm MSSM}(h)}{R^{\rm SM}} = \frac{(1+\Delta m_\tau)^2\,(-\cot\alpha\Delta m_b+\tan\beta)^2}{(1+\Delta m_b)^2\,(-\cot\alpha\Delta m_\tau+\tan\beta)^2}\,,$$

$$\frac{R^{\rm MSSM}(H)}{R^{\rm SM}} = \frac{(1+\Delta m_\tau)^2\,(\tan\alpha\Delta m_b+\tan\beta)^2}{(1+\Delta m_b)^2\,(\tan\alpha\Delta m_\tau+\tan\beta)^2}\,,$$

$$\frac{R^{\rm MSSM}(A)}{R^{\rm SM}} = \frac{(1+\Delta m_\tau)^2\,(\tan\beta^2-\Delta m_b)^2}{(1+\Delta m_b)^2\,(\tan\beta^2-\Delta m_\tau)^2}\,.$$

- Normalized $R^{\rm MSSM}(\phi)/R^{\rm SM}$ dependent only on $\tan\beta$, $\tan\alpha$, Δm_b and Δm_τ, encoding all the genuine SUSY corrections.
- Δm_b and Δm_τ independent of the SUSY mass scale $M_{\rm SUSY}$, only depend on $\tan\beta$ and the ratio $A_t/M_{\rm SUSY}$.

For H^0 and A^0

Deviation of $R^{\rm MSSM}(H/A)$ with respect to the SM value

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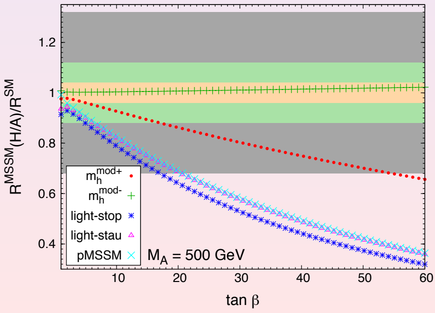


We could be sensitive to SUSY for...

- 32%: $m_h^{\rm mod+}$ for $\tan\beta \gtrsim 55$, rest of scenarios for $\tan\beta \gtrsim 20$.
- 12%: $m_h^{\rm mod+}$ for $\tan\beta \gtrsim 20$, rest of scenarios for $\tan\beta \gtrsim 5$.
- 4%: guaranteed for any of these 4 scenarios with $\tan\beta \gtrsim 5$.

$\Rightarrow$ A moderate level of precision would be neccesary.

CONCLUSIONS

$R = BR(H \to b\bar{b})/BR(H \to \tau^+\tau^-)$

- One could distinguish between MSSM and SM (2HDM) in some scenarious with moderate accuracy
- Update of the analysis of $R = \mathrm{BR}(H \to b\bar{b})/\mathrm{BR}(H \to \tau\bar{\tau})$ to look for a strong evidence for SUSY nature of Higgs bosons.
- MSSM scenarios with m_h compatible with $m_{H^{\mathrm{SM}}} \simeq 125$ GeV.
- Taken into account constraints by LHC data on $Hb\bar{b}$ and $H\tau\bar{\tau}$ couplings and the expected accuracy for these couplings at the HL-LHC and the future LC.

CONCLUSIONS

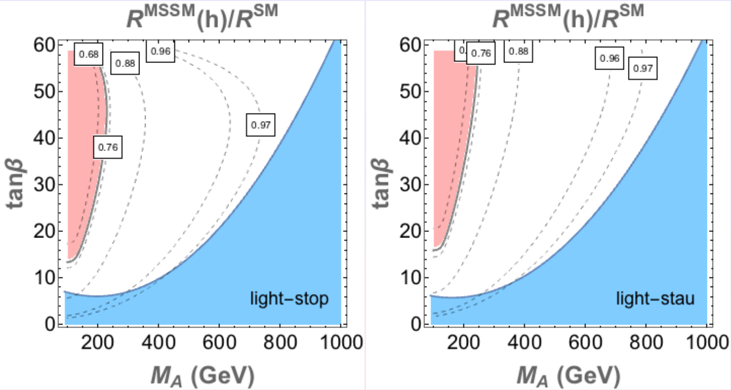
Results for $R = BR(H \to b\bar{b})/BR(H \to \tau^+\tau^-)$

- The SM prediction for R agrees with current CMS data, but using ATLAS data we obtain a (one-standard deviation) upper limit below the SM prediction.
- SUSY contributions can provide a prediction that agrees with the experiment at the one-standard deviation level.
- Current accuracy already allows to exclude portions of the parameter space, showing the potential of the observable R to discriminate among different models of new physics.
- To be sensitive to SUSY nature of h, a $3-4\%$ measurement required, to be performed at a future LC.
- For the heavy higgses, a moderate level of accuracy would be sufficient to discern the SUSY nature of H/A.

THANKS !!!!!!

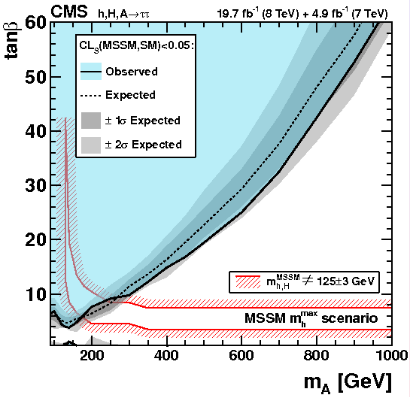
BACKUP

Potential discrimination with $R^{MSSM}(h)$

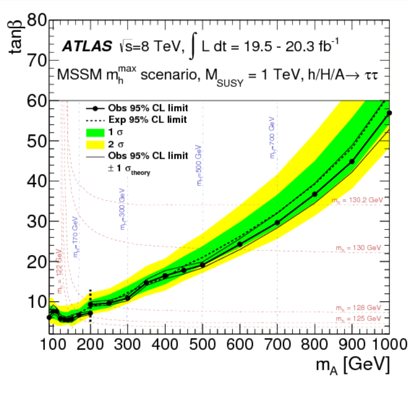


- HL-LHC only sensitive to SUSY nature of h for large values of M_A and $\tan\beta$.
- LC can probe h SUSY nature for any value of M_A and $\tan\beta$.

Searches for neutral MSSM Higgs bosons decaying to $\tau\bar{\tau}$



[CMS, 2014]



[ATLAS, 2014]