Current Status of MSSM Higgs Sector and Future Prospects at the HL-LHC

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Supersymmetry: from M-theory to the LHC

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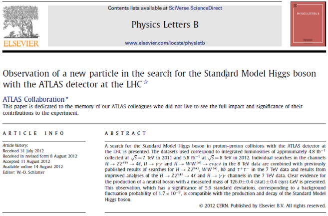
Plan of the Talk :

- Brief introduction to MSSM Higgs Sector.
- Global analysis and available pMSSM parameter space.
- Present status of MSSM from LHC 7/8 TeV data.
- Future reach at HL-LHC
- Conclusions.

Talk based on : B. Bhattacherjee, A. Chakraborty, A. Choudhury
Phys. Rev. D 92 (2015) 093007 [arXiv:1504.04308].

Higgs Discovery: July 4, 2012



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Physics Letters B

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ELSEVIER

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

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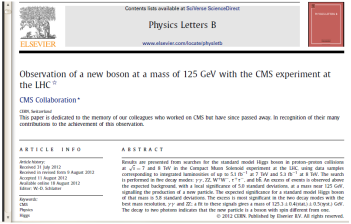
ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.



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Physics Letters B

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ELSEVIER

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

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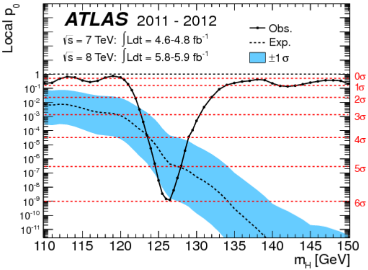
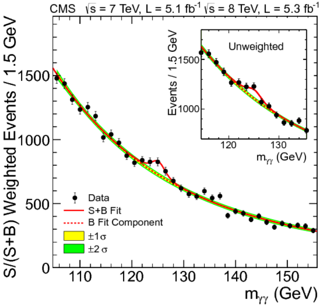
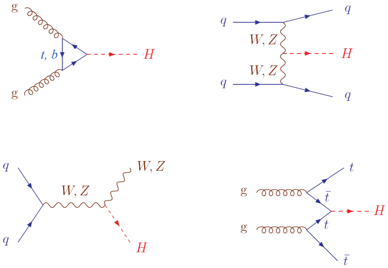
ABSTRACT

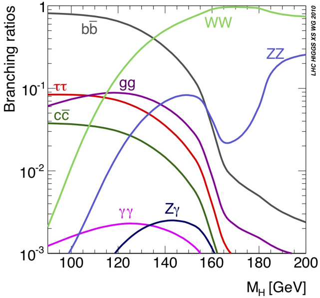
Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4(stat.) ± 0.5(syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.



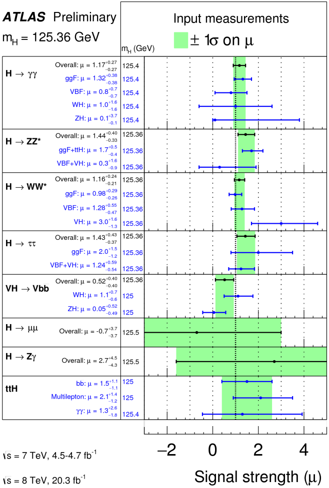


Higgs production and decay:



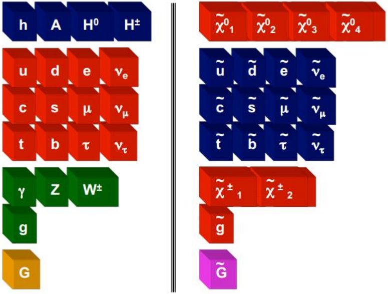


- Dominant Production Mode : gluon-gluon fusion.
- At $M_h = 125$ GeV, $h \to \gamma\gamma \sim 0.22\%$, $h \to WW^* \sim 21.5\%$, $h \to ZZ^* \sim 2.6\%$, $h \to b\bar{b} \sim 57.7\%$, $h \to gg \sim 8.6\%$, $h \to \tau\tau \sim 6.3\%$.



- Significance $\sim 10\ \sigma$
- Data consistent with SM hypothesis.
- Room for New Physics.
- Still 20 - 30 % deviation of Higgs coupling from SM is allowed.

A quick guide to SUPERSYMMETRY :



- In supersymmetric theories every boson has its fermionic counterpart and vice versa.
- In the limit of exact supersymmetry, each SUSY particle (sparticle) are identical to the corresponding particle except for their spin quantum number.
- Superpartners are yet to be observed. Therefore SUSY must be broken and one requires soft SUSY breaking mechanism.

- Experiments $\rightarrow$ A sparticle must be heavier than the corresponding particle.
- R-parity Conservation: The lightest sparticle (LSP) is stable.

Strong and EW sectors after 8/13 TeV:

In simplified model scenarios $\rightarrow$

- Gluino is excluded upto 1.5 - 1.8 TeV.
- Squark masses below 1 TeV are excluded.
- Stop masses upto 200 - 700 GeV are excluded.
- Also strong limit on EW sectors.

- See Overview talk by Alan Barr. Talk by Giuseppe Lerner & Dave Lewis for Third Generation Squarks. Talk by Yusufu Shehu for EW sectors.

Higgs sector of Minimal Supersymmetric SM (MSSM):

$$\mathcal{W}_{MSSM} = \widehat{U}^c Y_u \widehat{Q}\widehat{H}_u - \widehat{D}^c Y_d \widehat{Q}\widehat{H}_d - \widehat{E}^c Y_e \widehat{L}\widehat{H}_d + \mu \widehat{H}_d \widehat{H}_u .$$

Superfield	$SU(3)$	$SU(2)_L$	$U(1)_Y$	Particles
$\widehat{H}_d$	1	2	$-\frac{1}{2}$	$(H_d, \widetilde{H}_d)$
$\widehat{H}_u$	1	2	$\frac{1}{2}$	$(H_u, \widetilde{H}_u)$

$$H_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}, \quad \text{and} \quad H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix},$$

$$\widetilde{H}_d = \begin{pmatrix} \widetilde{h}_d^0 \\ \widetilde{h}_d^- \end{pmatrix}, \quad \text{and} \quad \widetilde{H}_u = \begin{pmatrix} \widetilde{h}_u^+ \\ \widetilde{h}_u^0 \end{pmatrix} .$$

- minimality signifies that this model contains only SM particles with their superpartners and the minimum number (two) of Higgs doublets.
- Higgsinos are chiral fermions. Second Higgs superfield with opposite hypercharge is needed to make the theory anomaly free.
- After the EW symmetry breaking $\rightarrow$ We are left with five physical Higgs bosons:
  - Two charged Higgs bosons : $H^{\pm}$,
  - Two CP-even Higgs bosons : h^0 (lighter) and H^0 (heavier),
  - One CP-odd Higgs boson : A^0.

MSSM Higgs sector:

At the tree level, the Higgs sector of MSSM is described by two parameters :

- the mixing angle α in the neutral CP even sector and and $\tan\beta$, where $\tan\beta$ is the ratio of the vacuum expectation values.
- Or by pseudoscalar mass M_A and $\tan\beta$.
- $tan2\alpha = \frac{M_h^2+M_H^2}{M_A^2-M_Z^2} tan2\beta$
- At the tree level $M_h \leq M_Z$.
- The higher order corrections $\rightarrow$ shift upper bound $\rightarrow$ $M_h \lesssim 135$ GeV.
- With dominant one loop correction from the top/stop sector: $m_h^2 \approx M_Z^2 \cos^2 2\beta \; + \frac{3g_2^2 m_t^4}{8\pi^2 M_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{(A_t - \mu cot\beta)^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right]$

MSSM Higgs sector:

At the tree level, the Higgs sector of MSSM is described by two parameters :

- the mixing angle α and $\tan\beta$,
- Or by pseudoscalar mass M_A and $\tan\beta$.
- $tan2\alpha = \frac{M_h^2+M_H^2}{M_A^2-M_Z^2} tan2\beta$
- Radiative corrections to the Higgs boson mass matrix involving various SUSY parameters can modify the tree level value of α significantly.
- $\tan 2\alpha = \frac{M_A^2+M_Z^2}{M_A^2-M_Z^2+\epsilon/\cos 2\beta} \tan 2\beta$, where $\epsilon = \frac{3G_F}{\sqrt{2}\pi^2}\frac{m_t^4}{\sin^2\beta} \log\left[1+\frac{{M_S}^2}{m_t^2}\right]$ (corrections in the leading ${m_t}^4$ - one-loop approximation)
- Global fit analysis considering various Higgs coupling measurements may constrain the MSSM parameter space.

Global fit analysis in MSSM, nMSSM, 2HDM, EFT..........

J. Ellis and T. You, [arXiv:1204.0464]. J. Ellis and T. You, [arXiv:1207.1693]. S. F. King et al., arXiv:1211.5074. J. Ellis and T. You, [arXiv:1303.3879]. K. J. de Vries, E. A. Bagnaschi, O. Buchmueller, R. Cavanaugh, M. Citron, A. De Roeck, M. J. Dolan and J. R. Ellis *et al.*, [arXiv:1504.03260]. M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, [arXiv:1205.2699]. T. Plehn and M. Rauch, [arXiv:1207.6108]. G. Cacciapaglia, A. Deandrea, G. D. La Rochelle and J. B. Flament, [arXiv:1210.8120]. T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia, [arXiv:1211.4580]. G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, [arXiv:1212.5244]. K. Cheung, J. S. Lee and P. Y. Tseng, [arXiv:1302.3794]. P. P. Giardino, K. Kannike, I. Masina, M. Raidal and A. Strumia, [arXiv:1303.3570]. A. Djouadi and G. Moreau, [arXiv:1303.6591]. K. Cheung, J. S. Lee, E. Senaha and P. Y. Tseng, [arXiv:1403.4775]. J. de Blas et al., [arXiv:1410.4204]. K. Cheung, J. S. Lee and P. Y. Tseng, [arXiv:1501.03552]. M. Endo, T. Moroi and M. M. Nojiri, [arXiv:1502.03959]. K. Cheung, J. S. Lee and P. Y. Tseng, [arXiv:1310.3937]. G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, [arXiv:1306.2941]. A. Celis, V. Ilisie and A. Pich, [arXiv:1302.4022]. W. Altmannshofer, S. Gori and G. D. Kribs, [arXiv:1210.2465 [hep-ph]]. Y. Bai, V. Barger [arXiv:1210.4922]. S. Chang, S. K. Kang, J. P. Lee, K. Y. Lee, S. C. Park and J. Song, [arXiv:1210.3439]. H. S. Cheon and S. K. Kang, [arXiv:1207.1083]. U. Ellwanger and C. Hugonie, [arXiv:1405.6647]. D. Carmi, A. Falkowski et al., [arXiv:1202.3144]. W. F. Chang, W. P. Pan and F. Xu, [arXiv:1303.7035]. S. Banerjee et al., [arXiv:1308.4860]. J. R. Espinosa etal., [arXiv:1207.7355]. J. Ellis, V. Sanz and T. You, [arXiv:1410.7703]. J. Ellis, V. Sanz and T. You, [arXiv:1404.3667].....

Experimental inputs from LHC and Tevatron

Channel	Signal strength (μ)		Production mode		
	ATLAS	*CMS*	ggF	VBF	Vh
$\mu(ggh)$	1.32 ± 0.38	$1.12^{+0.37}_{-0.32}$	100%	-	-
$\mu(VBF)$	0.8 ± 0.7	$1.58^{+0.77}_{-0.68}$	-	100%	-
$\mu(Wh)$	1.0 ± 1.6	$-0.16^{+1.16}_{-0.79}$	-	-	100%
$\mu(Zh)$	$0.1^{+3.7}_{-0.1}$	-	-	-	100%

- Signal strengths of $h \to \gamma\gamma$ channel by ATLAS (arXiv:1408.7084) and CMS (arXiv:1407.0558).

Channel	Signal strength (μ)		Production mode		
	ATLAS	*CMS*	ggF	VBF	Vh
$\mu(ggh + bbh + tth)$	$1.66^{+0.51}_{-0.44}$	$0.80^{+0.46}_{-0.36}$	100%	-	-
$\mu(VBF + Vh)$	$0.26^{+1.64}_{-0.94}$	$1.7^{+2.2}_{-2.1}$	-	60%	40%

- Signal strengths of $h \to ZZ^*$ channel by ATLAS (arXiv:1408.5191) and CMS (arXiv:1312.5353).

Channel	Signal strength (μ)		Production mode		
	ATLAS	*CMS*	ggF	VBF	Vh
$\mu(ggF)$	$1.02^{+0.29}_{-0.26}$	-	100%	-	-
$\mu(VBF)$	$1.27^{+0.53}_{-0.45}$	-	-	100%	-
$\mu(0/1\ jet)$	-	$0.74^{+0.22}_{-0.20}$	97%	3%	-
μ (VBF tag)	-	$0.60^{+0.57}_{-0.46}$	17%	83%	-
μ (Vh tag ($2l2\nu2j$))	-	$0.39^{+1.97}_{-1.87}$	-	-	100%
μ (Wh tag($3l3\nu$))	-	$0.56^{+1.27}_{-0.95}$	-	-	100%

- Signal strengths of $h \to WW^*$ channel by ATLAS (arXiv:1412.2641) and CMS (arXiv:1312.1129).

Channel	Signal strength (μ)		Production mode		
	ATLAS	*CMS*	ggF	VBF	Vh
μ(Vh tag)	$0.51^{+0.40}_{-0.37}$	1.0 ± 0.5	-	-	100%

- Signal strengths of $h \to b\bar{b}$ channel by ATLAS (arXiv:1409.6212) and CMS (arXiv:1310.3687).

Experimental inputs from LHC and Tevatron :

Channel	Signal strength (μ)		Production mode		
	ATLAS	*CMS*	ggF	VBF	Vh
$\mu(ggF)$	$1.93^{+1.45}_{-1.15}$	-	100 %	-	-
$\mu(VBF+Vh)$	$1.24^{+0.58}_{-0.54}$	-	-	60%	40%
μ (0-jet)	-	0.34 ± 1.09	96.9%	1.0%	2.1
μ (1-jet)	-	1.07 ± 0.46	75.7%	14%	10.3
μ (VBF tag)	-	0.94 ± 0.41	19.6	80.4	-
μ (Vh tag)	-	-0.33 ± 1.02	-	-	100%

- Signal strengths of $h \to \tau\tau$ channel by ATLAS (ATLAS-CONF-2014-06) and CMS (arXiv:1401.5041).

Channel	Signal strength (μ)	Production mode		
	Tevatron	ggF	VBF	Vh
$\mu(H \to \gamma\gamma)$	$6.14^{+3.25}_{-3.19}$	78%	5%	17%
$\mu(H \to WW^*)$	$0.85^{+0.88}_{-0.81}$	78%	5%	17%
$\mu(H \to b\bar{b})$	$1.59^{+0.69}_{-0.72}$	-	-	100%

- Signal strengths of $h \to \gamma\gamma$, WW^*, and $b\bar{b}$ channel by CDF and $D\emptyset$ collaborations (arXiv:1303.6346, 1409.5043).

Other Constraints:

- $2.82 \times 10^{-4} < \mathrm{Br}(\mathrm{B_s} \to \mathrm{X_s}\gamma) < 4.04 \times 10^{-4}$
- $1.57 \times 10^{-9} < \mathrm{Br}(\mathrm{B_s} \to \mu^+\mu^-) < 4.63 \times 10^{-9}$

Signal Strength:

For gluon-gluon fusion process and for a generic final state $h \to X\bar{X}$ ($\gamma\gamma$, WW^*, ZZ^*, etc.), then one can define the signal strength variable μ, assuming narrow-width approximation, as:

$$\mu_{ggF}(X\bar{X}) = \frac{\Gamma(h \to gg)}{\Gamma(h_{SM} \to gg)} \times \frac{Br(h \to X\bar{X})}{Br(h_{SM} \to X\bar{X})},$$

where h is a observed 125 GeV Higgs boson and h_{SM} is the SM Higgs boson. Similarly, if the Higgs boson is produced via VBF fusion process and it decays to $X\bar{X}$, then one can define,

$$\mu_{VBF}(X\bar{X}) = \frac{\Gamma(h \to WW)}{\Gamma(h_{SM} \to WW)} \times \frac{Br(h \to X\bar{X})}{Br(h_{SM} \to X\bar{X})}.$$

MSSM parameter space scan:

$$1 < \tan\beta < 50, \qquad 100\ \mathrm{GeV} < M_A < 600\ \mathrm{GeV},$$
$$-8000\ \mathrm{GeV} < A_\mathrm{t}, A_\mathrm{b} < 8000\ \mathrm{GeV}, \qquad 100\ \mathrm{GeV} < \mu < 8000\ \mathrm{GeV},$$
$$100\ \mathrm{GeV} < M_\mathrm{Q3},\ M_\mathrm{U3} < 8000\ \mathrm{GeV}, \qquad 100\ \mathrm{GeV} < M_\mathrm{D3} < 8000\ \mathrm{GeV},$$

while we fix the following parameters since they have little impact on our analysis,

$$M_1 = 100\ \mathrm{GeV}, \qquad M_2 = 2000\ \mathrm{GeV}, \qquad M_3 = 3000\ \mathrm{GeV},$$
$$M_{\mathrm{L}_{1,2,3}} = M_{\mathrm{E}_{1,2,3}} = 3000\ \mathrm{GeV}, \quad M_{\mathrm{Q}_{1,2}} = 3000\ \mathrm{GeV}, \quad M_{\mathrm{U}_{1,2}} = M_{\mathrm{D}_{1,2}} = 3000\ \mathrm{GeV},$$

- we compute χ^2 for all the scanned points, defined as:

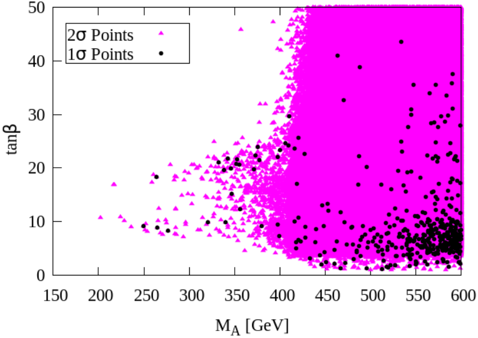
$$\chi^2 = \sum_i \frac{(\overline{\mu}_i - \mu_i)^2}{\Delta\mu_i^2}$$

- μ_i ($\overline{\mu}_i$) experimentally observed signal strength (MSSM) for a particular production/decay mode i. $\Delta\mu_i \to$ experimental error.
- contribution originating from different production mode: $\overline{\mu}_i = \sum T_i^j \widehat{\mu}_j$

Global χ^2 analysis:

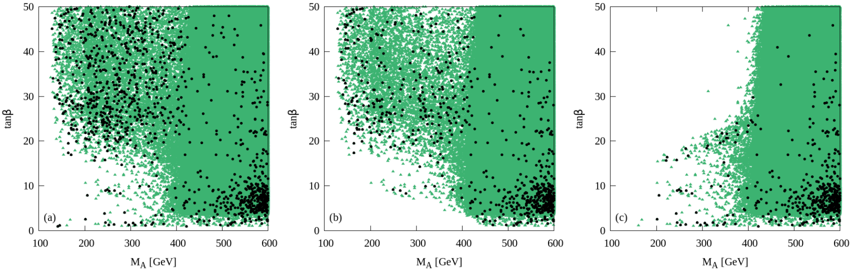
- Consider altogether 28 data points.
- A random scan for approximately 100 million points.
- The minimum value of χ^2 for SM is 15.744 with $\chi^2/\mathrm{d.o.f} = \chi^2/28 = 0.562$.
- For MSSM we obtain $\chi^2_{\mathrm{min}} = 15.013$ with $\chi^2/\mathrm{d.o.f} = \chi^2/20 = 0.75$.
- 1σ and 2σ allowed parameter in $M_A - \tan\beta$ plane $\rightarrow$ $\chi^2 = \chi^2_{\mathrm{min}} + 2.3$ and $\chi^2 = \chi^2_{\mathrm{min}} + 6.18$.

Parameter space allowed in M_A - tanβ plane:



- Allowed parameter space after global fit.
- Also satisfy the flavour physics constraints on Br(b $\rightarrow s\gamma$) and Br($B_s \rightarrow \mu^+\mu^-$).

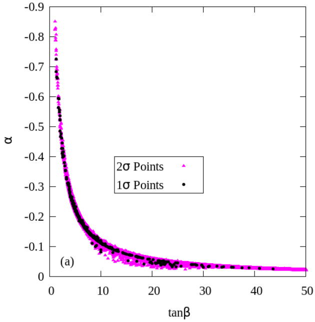
Effect of the flavour physics constraints:

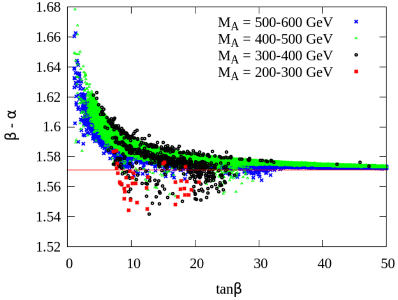


(a) without any flavor constraint (left panel).
(b) only after imposing Br(b $\rightarrow s\gamma$) constraint (middle panel).
(c) only after imposing Br($B_s \rightarrow \mu^+\mu^-$) constraint (right panel).

- $\mathrm{M_A} \leq 350$ GeV and tan $\beta \geq 25$ are excluded by $\mathrm{Br(B_s} \rightarrow \mu^+\mu^-)$.
- $\mathrm{M_A} \leq 350$ GeV with tan $\beta \leq 8$ are excluded by $\mathrm{Br(b} \rightarrow \mathrm{s}\gamma)$ constraint.

Alignment without decoupling:

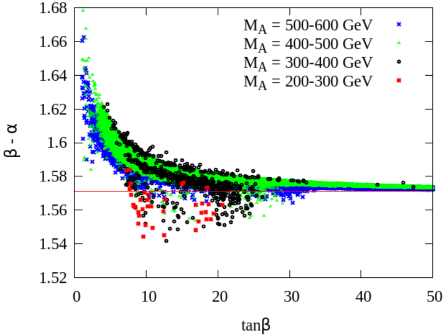




In the MSSM, the couplings (at the tree level) of the CP-even Higgs bosons (h, H) to SM gauge bosons/fermions are:

$$g_{hVV} = \sin(\beta - \alpha)\ g_V$$
$$g_{HVV} = \cos(\beta - \alpha)\ g_V$$
$$g_{hdd} = -\sin\alpha / \cos\beta g_f = (\sin(\beta - \alpha) - \tan\beta \cos(\beta - \alpha))\ g_f$$
$$g_{huu} = -\cos\alpha / \sin\beta g_f = (\sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha))\ g_f$$
$$g_{Hdd} = -\cos\alpha / \cos\beta g_f = (\cos(\beta - \alpha) + \tan\beta \sin(\beta - \alpha))\ g_f$$
$$g_{Huu} = -\sin\alpha / \sin\beta g_f = (\cos(\beta - \alpha) - \cot\beta \sin(\beta - \alpha))\ g_f$$

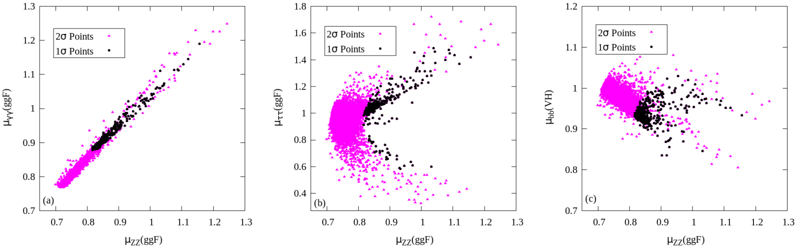
Alignment without decoupling:



- Alignment Limit : h is SM like i.e., $g_{hVV} \sim 1$ and $g_{HVV} \sim 0$.
- Heavier CP even Higgs boson couplings become highly suppressed.
- In decoupling region, $M_A >> M_Z$, $(\beta - \alpha) \sim \pi/2$

- Regions with light M_A ($\leq$ 400 GeV) satisfying the alignment limit is perfectly allowed by the current data.
- One is thus not always forced to be in the decoupling limit to comply with LHC data.

Correlations of various Higgs signal strength variables:

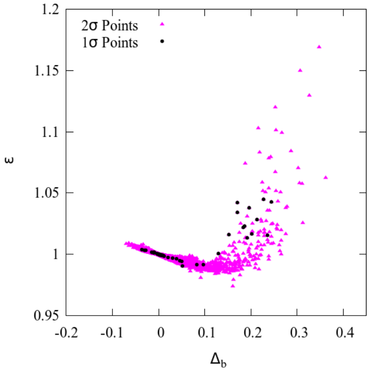


- the partial widths $\Gamma(h \to ZZ)$ and $\Gamma(h \to WW)$ remain almost unaltered w.r.t. SM.
- $\Gamma(h \to b\bar{b})$ and Γ_{tot} have increased while $\Gamma(h \to gg)$ has decreased for most of the scanned data points.

SUSY QCD corrections:

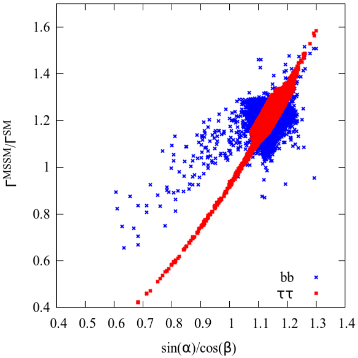
- In an effective Lagrangian approach :

$$L_{hb\bar{b}} = -\frac{m_b}{v_{SM}}\left(\frac{1}{1+\Delta_b}\right)\left(-\frac{\sin\alpha}{\cos\beta}\right)\left(1-\frac{\Delta_b}{\tan\beta\tan\alpha}\right)b\bar{b}h$$



- Loop corrections (in powers of $\alpha_s \tan\beta$) involving heavier sparticles can significantly modify the b quark mass and it's Yukawa coupling from its tree level predictions.
- $\epsilon = \left(\frac{1}{1+\Delta_b}\right) \times \left(1-\frac{\Delta_b}{\tan\beta\tan\alpha}\right)$
- Δ_b is mostly positive and varies within 10-15%.
- Effect of this variation of Δ_b on ϵ is small.

Partial widths and branching ratios for $b\bar{b}$ and $\tau^+\tau^-$:



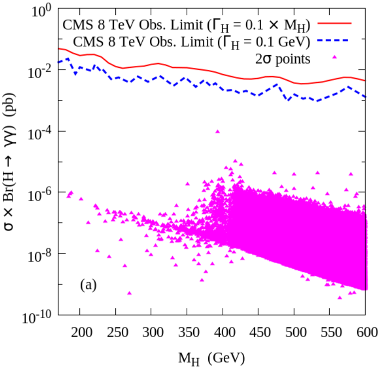
- Ratios of the partial decay widths (branching ratios) for $\tau^+\tau^-$ with the tree level Higgs Yukawa couplings $\frac{\sin\alpha}{\cos\beta}$ $\rightarrow$ 20-30% modifications.
- Being the dominant decay mode $\rightarrow$ change in $BR(h \rightarrow b\bar{b})$ is small.
- Interplay of the total Higgs decay width and individual Higgs branching ratios along with a mild dependence of Δ_b.

Bounds on MSSM heavy Higgses from LHC-8TeV direct searches:

- Neutral Higgs boson searches
  - Search for H with $\gamma\gamma$ final states. (CMS-PAS-HIG-14-006)
  - Search for H with WW final state. (CMS-PAS-HIG-13-027)
  - Search for H with hh ($b\bar{b}b\bar{b}$ and $b\bar{b}\gamma\gamma$) final states. (CMS-PAS-HIG-13-032,CMS-PAS-HIG-14-013)
  - Search for $H/A \to \tau^+\tau^-$ final states. (1409.6064, 1408.3316)
  - Search for A with Zh final states. (1502.04478, CMS-PAS-HIG-14-011)

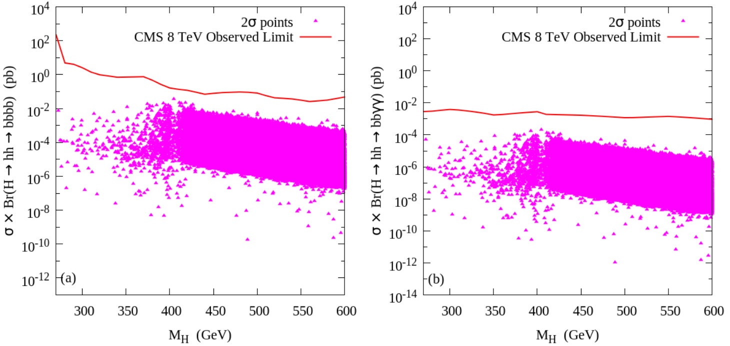
- Charged Higgs boson searches
  - Search for $H^{\pm}$ with $\tau\nu$ (1412.6663, CMS-PAS-HIG-14-020) and $c\bar{s}$ final states (1302.3694, CMS-PAS-HIG-13-035).
  - Search for $H^{\pm}$ with $t\bar{b}$ final states. (CMS-PAS-HIG-13-026)
- Bounds set by the ATLAS and CMS collaborations on the masses and BRs of the neutral and charged Higgs bosons from 8 TeV data.

Search for H with $\gamma\gamma$, WW final states.:



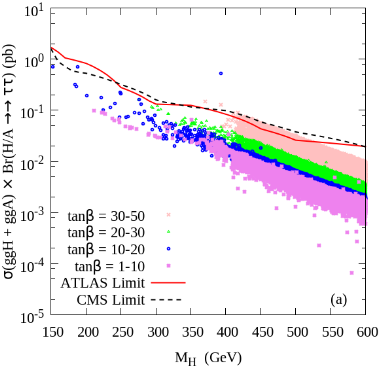
- $\mathrm{Br}(\mathrm{H} \to \gamma\gamma) \sim 10^{-6} - 10^{-7}$.
- Due to alignment limit (i.e. $(\beta - \alpha) \sim \frac{\pi}{2}) \to \mathrm{Br}(\mathrm{H} \to \mathrm{WW})$ highly suppressed.

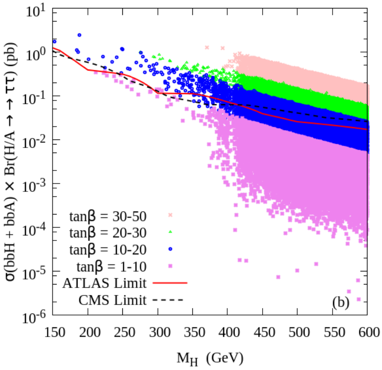
Search for H with hh ($b\bar{b}b\bar{b}$ and $b\bar{b}\gamma\gamma$) final state:



- $4b$ final state is experimentally challenging.
- $b\bar{b}\gamma\gamma$ channel has less background contamination and very good di-photon mass resolution.
- $\mathrm{Br(H \to hh)}$ sizable only for small $\tan\beta$ (≤ 5).
- For $M_A \geq 350$ GeV, $t\bar{t}$ opens up and dominates.

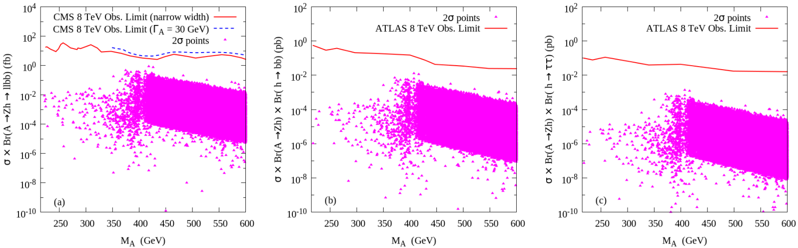
Search for H/A with $\tau^+\tau^-$ final states:





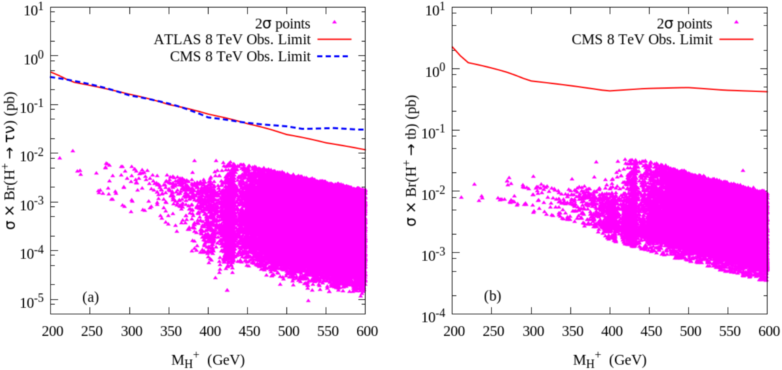
- $g_{Hf_df_d} = -\cos\alpha/\cos\beta g_{SM}$; $g_{Af_df_d} = -\tan\beta g_{SM}$.
- For fixed α, both the couplings $Hf_d\bar{f}_d$ and $Af_d\bar{f}_d$ increases with $\tan\beta$.
- $\tan\beta \geq 10$, H and A decays to $b\bar{b}$ ($\sim 90\%$) and $\tau^+\tau^-$ ($\sim 10\%$).
- Production of H/A is also primarily controlled by $\tan\beta$.
- Entire regions with $\tan\beta > 20$ are excluded.

Search for A with Zh final states:



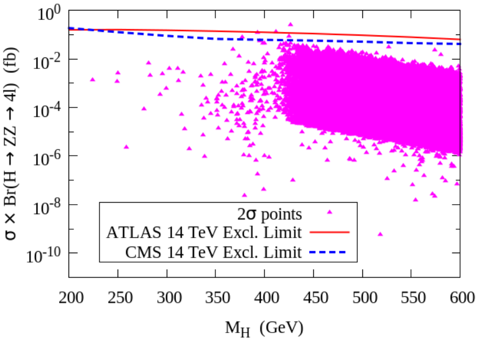
- $\mathrm{Br(A \to Zh)}$ sizable $\to$ with low $\tan\beta$ and $2M_t > M_A > (M_h + M_Z)$.
- One can fully reconstruct the mass of A.
- ATLAS and CMS data are not sensitive enough to impose any additional constraints.

Search for $H^{\pm}$ with $\tau\nu$ and $c\bar{s}$ final states:



- $g_{H^{\pm}\bar{u}d} \propto m_d \tan\beta(1+\gamma_5) + m_u \cot\beta(1-\gamma_5)$.
- For small $\tan\beta$, $H^{\pm}$ exclusively decays to $t\bar{b}$
- For large values of $\tan\beta$, $\mathrm{Br}(H^{\pm} \to \tau^{\pm}\nu_{\tau}) \sim 10\%$.
- Main production mechanism : $pp \to tbH^{\pm}$.

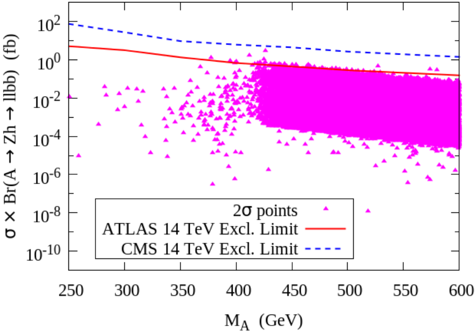
Future search limits for H with 4ℓ final states :



- Br($H \to ZZ$) is very small ($\sim 10^{-3}$ to 10^{-5}) $\to$ consistent with the alignment limit.
- Most of the parameter space points are beyond the reach of 14 TeV LHC with $\mathcal{L} = 3000\ \mathrm{fb}^{-1}$.

ATL-PHYS-PUB-2013-016; CMS-PAS-FTR-13-024

Search for $A \to Zh$ with $\ell^+\ell^- b\bar{b}$ final state:

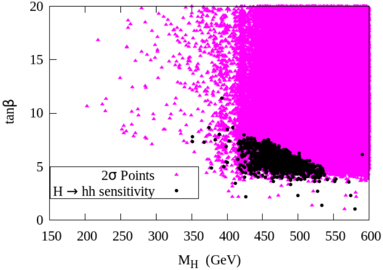


- Only a very small region of the parameter space will be excluded by the HL-LHC data.

ATL-PHYS-PUB-2013-016; CMS-PAS-FTR-13-024

Search for H with di-higgs ($H \to hh \to b\bar{b}\gamma\gamma$) final states:

- Single H production cross section can be up to two orders of magnitude larger compared to the direct h pair production.
- It can also have non-trivial effects on the self coupling measurement of the 125 GeV Higgs. B. Bhattacherjee, AC, Phys. Rev. D 91 (2015) 073015.



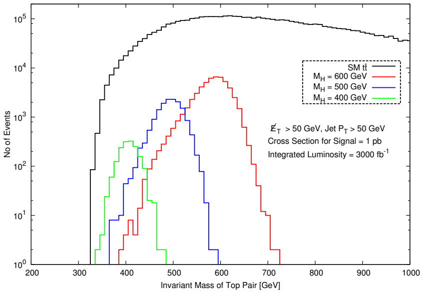
- $BR(H \to hh)$ is substantial only for smaller values of tan β.
- The most dominant production mechanism $\to$ ggF.
- Events with two b-jets, two photons and no isolated leptons are selected.
- Reconstruct two higgs from $b\bar{b}$ and $\gamma\gamma$.
- $M_{b\bar{b}\gamma\gamma} = M_H \pm 50$ GeV.
- Low tan β (< 10) regions are expected to be probed at the HL-LHC.

Search for H/A with $t\bar{t}$ final state :

- For $M_A > 350$ GeV and low-moderate $\tan\beta$, $H/A \to t\bar{t}$ dominates.
- Large cross section of the heavy Higgs H via ggF process.
- Extremely difficult to extract the $t\bar{t}$ resonance peak from the huge SM $t\bar{t}$ continuum background.
- We perform a detailed signal-background analysis.
- One top decays leptonically and one decays hadronically.
- Events with at least 4 jets with $p_T > 50$ GeV (two are $b-tagged$), one isolated leptons ($p_T > 30$ GeV) are selected.
- Select events with $t\bar{t}$ invariant mass between $M_H \pm$ 25 GeV.
- *SR-loose* $\to$ Missing energy ($\not{E}_T$) > 50 GeV.
- *SR-medium* $\to$ $\not{E}_T > 100$ GeV.
- *SR-tight* $\to$ $\not{E}_T > 100$ GeV, $(p_T)_{j_1,j_2} > 100$ GeV

Search for H/A with $t\bar{t}$ final state :

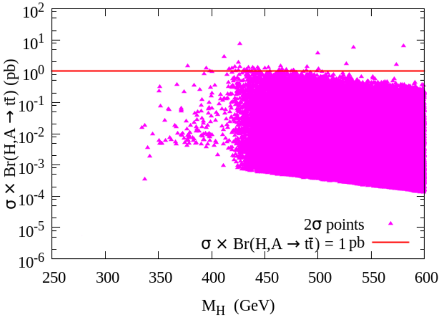
Channel	Number of Events at 3000 fb^{-1}					
	$M_H = 400$ GeV		$M_H = 500$ GeV		$M_H = 600$ GeV	
	Signal	$t\bar{t}$	Signal	$t\bar{t}$	Signal	$t\bar{t}$
$SR - loose$	1268	104612	9658	420572	26842	563452
$SR - medium$	8	1741	1584	69232	9656	194698
$SR - tight$	-	-	4	637	2296	44894



- $\sigma^{t\bar{t}}_{NNLO} = 966$ pb.
- $\sigma(pp \rightarrow H)_{NLO} \times Br(H \rightarrow t\bar{t}) = 1$ pb (assumption).

  - N_S/N_B ratio is very small for all the benchmark points.
  - Statistical significances $\mathcal{S}$ for $M_H = 600$ GeV are 36, 22 and 11 for *SR-loose*, *SR-medium* and *SR-tight* respectively.
  - However, even with 5% systematic uncertainty these numbers reduces to 0.95, 0.99, 1.02 respectively.

Search for H/A with $t\bar{t}$ final state :

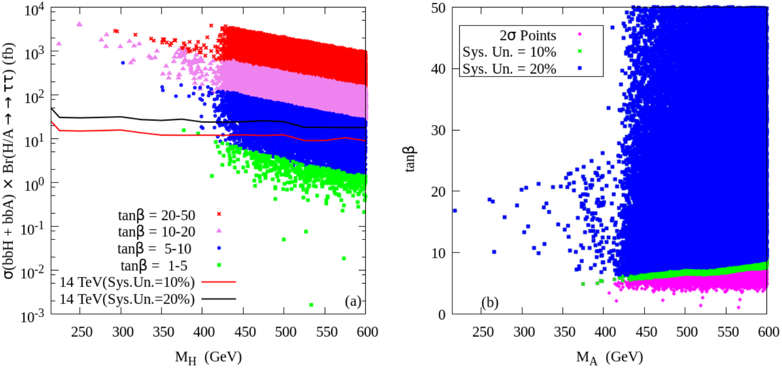


- Very challenging to observe a clear signal of heavy Higgs in the $t\bar{t}$ invariant mass distribution over the SM background.
- Using angular cuts, the signal significance can be improved. A. Djouadi et al. arXiv:1502.05653
- Inclusion of systematic uncertainties may change the significance drastically.
- $H \to t\bar{t} \to$ challenging task $\to$ needs more detailed studies.

Search for H/A with $\tau^+\tau^-$ final state :

- We assume that H/A are produced via the b-quark associated production process and decays to $\tau^+\tau^-$.
- A detailed signal-background analysis following ATLAS-8TeV $H/A \to \tau_{\rm lep}\tau_{\rm had}$ analysis.
- We identify taus through their one/three prong hadronic decays.
- Events are selected with: one lepton ($p_T > 50$ GeV), an oppositely charged τ-hadron with $p_T > 50$ GeV, at least one b-tagged jet with $p_T > 50$ GeV, $\Delta p_T \equiv p_T(\tau_{\rm had}) - p_T(\rm lepton) > 50$ GeV, $\sum \Delta\phi \equiv \Delta\phi(\tau_{\rm had}, \not{E}_T) + \Delta\phi(\tau_{\rm lep}, \not{E}_T) < 3.3$, $\Delta\phi(\tau_{\rm lep}, \tau_{\rm had}) > 2.4$.
- Reconstructed di-tau invariant mass ($m_{\tau\tau}$) is within $M_\Phi \pm$ 30 GeV ($\Phi = H/A$).
- The dominant SM background processes: $\rm Z$ +jets and $t\bar{t}$. Small contributions from $\rm W$ +jets, QCD multi-jets.
- Di-tau invariant mass $\to$ the "collinear approximation technique".

Search for H/A with $\tau^+\tau^-$ final state :



- Sensitivity at the HL-LHC with 3000 fb^{-1} of data assuming 20% and 10% systematic uncertainties.
- The regions with $\tan\beta > 20$ are already excluded by LHC-8 data.
- The regions with $\tan\beta$ down to 8 with any values of M_A can be probed at the HL-LHC.

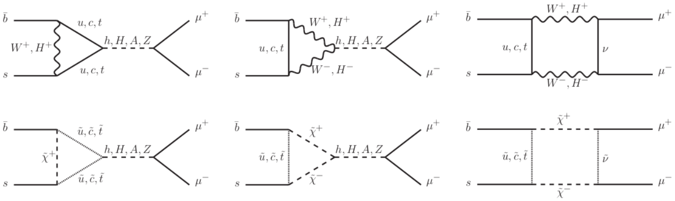
Conclusions:

- Global fit analysis using most updated data (till December 2014) from the LHC and Tevatron.
- The region with $\mathrm{M_A} \leq 350$ GeV and $\tan\beta \geq 25$ are excluded by the $\mathrm{Br}(\mathrm{B_s} \to \mu^+\mu^-)$ while $\mathrm{M_A} \leq 350$ GeV with $\tan\beta \leq 8$ is not favoured by the $\mathrm{Br}(\mathrm{b} \to \mathrm{s}\gamma)$ constraint.
- $200 < M_A < 400$ can have moderate $\alpha = 0.2$, while for relatively large values of M_A, α can be as large as ~ 0.8 with small $\tan\beta$.
- Not always forced to be in the decoupling limit.
- 10 - 20% deviations from the SM expectations are also observed for various Higgs signal strength variables.
- The 7+8 TeV LHC data for $\Phi(= H/A) \to \tau^+\tau^-$ put the most stringent bound $\to$ The entire region with $\tan\beta > 20$ is excluded.
- At the HL-LHC $\tan\beta$ down to 8 with low to moderate values of M_A can be probed with $\tau^+\tau^-$ mode.
- Below $\tan\beta < 8$, searches via $H \to hh$ at the HL-LHC can be very important to probe rest of the parameter space.

THANK YOU

Back Up

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



- dominant SM contribution from : Z penguin top loop & W box diagram.
- $\mathrm{Br}(B_s \to \mu^+\mu^-) = 3.1 \pm 0.7 \pm 0.31(\mathrm{theo.})$
- No room for large deviation.
- Susy contribution $\propto tan^6\beta/M_A^4$.

$Br(B_s \to X_s\gamma)$

- A very small room for any BSM contribution.
- $\mathrm{Br}(B_s \to X_s\gamma) = 3.43 \pm 0.22 \pm 0.21(\mathrm{theo.})$
- SM $t - W$ loop contribution almost saturates the experimental value.
- In the MSSM, the dominant contributions to $Br(B_s \to X_s\gamma)$ come from the $t - H^{\pm}$ and $\tilde{t}_{1,2} - \tilde{\chi}^{\pm}_{1,2}$.
- $Br(B_s \to X_s\gamma)|_{\chi^{\pm}} \propto \mu A_t \tan\beta f(m_{\tilde{t}}1, m_{\tilde{t}}2, m_{\tilde{\chi}^+}) \frac{m_b}{v(1+\Delta m_b)}$.
- $Br(B_s \to X_s\gamma)|_{H^+} \propto \frac{(h_t \cos\beta - \delta h_t \sin\beta)}{v\cos\beta}\, g(m_{H^+}, m_t) \frac{m_b}{(1+\Delta m_b)}$.
- $\delta h_t = h_t \frac{2\alpha_s}{3\pi} \mu M_{\tilde{g}} \left(\cos^2\theta_{\tilde{t}} I(m_{\tilde{s}_L}, m_{\tilde{t}_2}, M_{\tilde{g}}) + \sin^2\theta_{\tilde{t}} I(m_{\tilde{s}_L}, m_{\tilde{t}_1}, M_{\tilde{g}})\right)$.
- Typically, these NLO corrections are known to be important for large values of tanβ.
- NLO corrections are approximately proportional to $\mu M_{\tilde{g}} \tan\beta$

M. S. Carena, D. Garcia, U. Nierste and C. E. M. Wagner, hep-ph/0010003, hep-ph/9912516.

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