Status of MSSM in the light of 13 TeV LHC results

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What does Higgs discovery tell us?

- Higgs discovery in 2012 $\rightarrow$ prediction of Standard Model.
- Is it the SM Higgs(validation of SSB)?? Presion meaurements to the rescue!!
- Spin 0, CP even or CP-mixed? window for new physics.
- Precise mesurement of the couplings of gauge bosons and fermions to the Higgs required.
- Till then.....Let's concentrate on

And what it does not tell us....

- Issues with SM—- Naturalness or hierarchy problem(one of the issues!)
- DARK MATTER(a more severe one!)
- SUSY offers solution to both!!
- MSSM the simplest and most economical framework of SUSY- our favourite MSSM.
- Each SM particle has one superpartner.
- Additional Higgs doublet required $\rightarrow$ two neutral CP-even scalars(h^0,H^0), one CP-odd neutral scalar(A^0) and two charged Higgs states($H^\pm$).
- Did we discover the lightest Higgs boson (h^0) at 125 GeV?

Where is SUSY hiding?

- SUSY breaking scale $\lesssim 1$ TeV implies an upper limit on the neutral lightest Higgs mass to be 135 GeV. Really close!!
- SUSY breaking scale rather high?
- no sign of sparticles so far, hints towards higher SUSY-breaking scale.
- Higgs sector and EW sector can still be light!!! HOPE.
- Direct search of heavy Higgs states $\rightarrow$ new goal of LHC.
- Objective of our paper: The status of the parameter space of phenomenological MSSM (pMSSM) in the light of the new $13-15$ fb^{-1} data from Run-II of the LHC at 13 TeV, as reported by the CMS and ATLAS collaborations and concentrate on the Higgs sector.

Constraints on the MSSM Higgs sector so far

Let us discuss the constraints we take into account.

- Light Higgs mass within the range 125$\pm$ 3 GeV
- low-energy constraints from low-energy flavor observables through the bound from the rare-decays like $B \to X_s\gamma$, $B_s \to \mu^+\mu^-$, $B^+ \to \tau^+\nu_\tau$.
- Correlated SM-like Higgs signal strength in various production and decay modes from Run-I and second phase of Run-II.
- Heavy Higgs($H^0, A^0, H^\pm$) direct search limits from 8 and 13 TeV.

The scan

The framework: We perform a random scan over the MSSM parameter space, varying all the parameters related to the Higgs sector These input parameters are varied over the following ranges:

$$M_1 = 1 \text{ TeV}, M_2 = 1 \text{ TeV}, \; 500 \text{ GeV} < M_3 < 5 \text{ TeV},$$
$$3 < \tan\beta < 60, \quad 100 \text{ GeV} < M_A < 1 \text{ TeV}, \quad 100 \text{ GeV} < \mu < 5 \text{ TeV},$$
$$M_{\tilde{L}_{1,2,3}} = M_{\tilde{e}_{1,2,3}} = M_{\tilde{Q}_{1,2}} = M_{\tilde{u}_{1,2}} = M_{\tilde{d}_{1,2}} = 2 \text{ TeV},$$
$$A_{e,\mu,\tau} = A_{u,d,c,s} = 0, \quad -10 \text{ TeV} < A_{b,t} < 10 \text{ TeV},$$
$$200 \text{ GeV} < M_{\tilde{Q}_3,\tilde{u}_3,\tilde{d}_3} < 10 \text{ TeV}.$$

- Sample of 10^8 points

The calculation:

- The gluon fusion (ggF) for H/A and charged Higgs production($gb \rightarrow tH^+$) cross section are calculated using FeynHiggs.
- For vector boson fusion (qqH), associated production with vector bosons (VH), associated $t\bar{t}H$ and associated $b\bar{b}H$ we take the corresponding SM-like heavy Higgs cross section from LHC Higgs Cross section Working Group and scale them accordingly.

Current Bounds in detail:Higgs mass and flavor physics

- Higgs mass bound
- Current experimental results allow a window of 124.4-125.8 GeV at 3σ.
- The available calculation of Higgs mass in pMSSM is not exact.
- FeynHiggs-2.12.0 does complete diagrammatic on-shell results at the one-loop level, the leading diagrammatic two-loop QCD contributions and further improvements taking into account leading electroweak two-loop and leading higher-order QCD corrections.
- The uncertainty in the top mass measurement also goes into the Higgs mass calculation and adds to the theoretical uncertainty.
- All these taken together we allow a range of $\pm$ 3 GeV ie. 122.4-127.8 GeV.

- Low energy constraints

$$R_{bs\gamma} = \frac{\mathrm{Br}(B \to X_s\gamma)}{\mathrm{Br}(B \to X_s\gamma)_{\mathrm{SM}}} \tag{1}$$

- In the SM, the NNLO prediction for the branching ratio is $\mathrm{Br}(B \to X_s\gamma)_{\mathrm{SM}} = (3.36 \pm 0.23) \times 10^{-4}$
- Room for new physics in the $R_{bs\gamma}$ as the experimental value of this quantity

$$R_{bs\gamma} = 1.02 \pm 0.10 \tag{2}$$

$B_s \to \mu^+\mu^-$ gets contribution from H^0 and A^0 at one loop Combined result of LHCb and CMS gives $\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{expt.}} = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$.

- B^+ meson to $\tau^+\nu_\tau$,

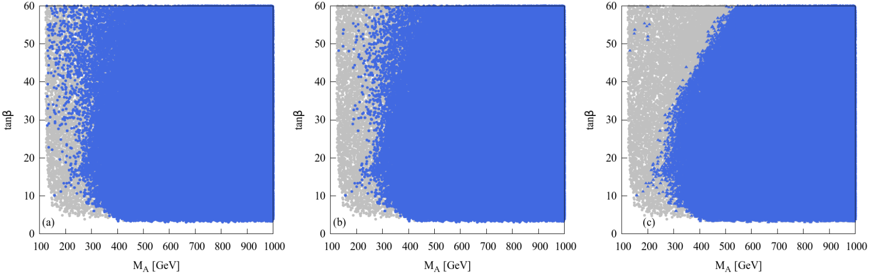
indirect fit prediction and the direct measurement for the semi-leptonic decay of B^+ meson to $\tau^+\nu_\tau$ final state, presently deviate by $1.4\sigma \rightarrow$ can be solved by a tree level mediation of charged Higgs in MSSM. The present world average of this branching fraction is
$\mathrm{Br}(B^+ \rightarrow \tau^+\nu_\tau) = (1.14 \pm 0.22) \times 10^{-4}$
We have taken the ratio of this branching with its SM value. The SUSY contribution to all the low energy flavor observables have been calculated using micrOmega 4.3.0.

$$\frac{\mathrm{Br}(B \rightarrow X_s\gamma)_{\mathrm{MSSM}}}{\mathrm{Br}(B \rightarrow X_s\gamma)_{\mathrm{SM}}} \in [0.82,\ 1.22]\ (2\sigma), \tag{3}$$

$$\mathrm{Br}(B_s \rightarrow \mu^+\mu^-) \in [1.6,\ 4.2] \times 10^{-9}\ (2\sigma), \tag{4}$$

$$\frac{\mathrm{Br}(B^+ \rightarrow \tau^+\nu_\tau)_{\mathrm{MSSM}}}{\mathrm{Br}(B^+ \rightarrow \tau^+\nu_\tau)_{\mathrm{SM}}} \in [0.48,\ 1.88]\ (2\sigma). \tag{5}$$

- Impact of Higgs mass and low energy constraints



Constraints from Higgs data(7+8 TeV)

- CMS and ATLAS have performed a combined analysis of the LHC data collected at $\sqrt{s} = 7(8)\ \mathrm{TeV}$ corresponding to an integrated luminosity of $\approx 5(20)\ \mathrm{fb}^{-1}$ and derived constraints on the couplings of the Higgs boson.
- The most significant production modes of Higgs boson at LHC, namely, ggF,VBF, associated production with top-quark pairs($t\bar{t}h$) and associated production with vector bosons(Vh), and for the decay modes, $h \to ZZ, W^+W^-, \gamma\gamma, \tau^+\tau^-, b\bar{b}$.

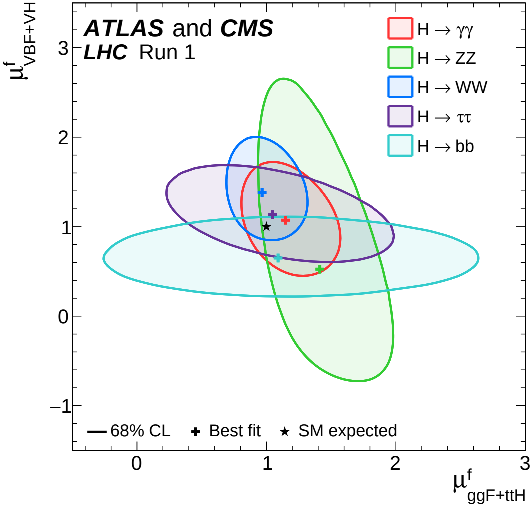
$$\mu_i^f = \frac{\sigma_i \cdot B^f}{\sigma_{i_{SM}} \cdot B^f_{SM}} \,. \tag{6}$$

	LHC Run-I (7+8 TeV)	
Production mode	VBF+Vh	ggF+$t\bar{t}h$
	ATLAS+CMS	
$\mu^{\gamma\gamma}$	$1.05^{+0.44}_{-0.41}$	$1.16^{+0.27}_{-0.24}$
μ^{ZZ}	$0.47^{+1.37}_{-0.92}$	$1.42^{+0.37}_{-0.33}$
μ^{WW}	$1.38^{+0.41}_{-0.37}$	$0.98^{+0.22}_{-0.20}$
$\mu^{b\bar{b}}$	$0.65^{+0.31}_{-0.29}$	$1.15^{+0.99}_{-0.94}$
$\mu^{\gamma\gamma}$	$1.16^{+0.27}_{-0.24}$	$1.06^{+0.60}_{-0.56}$

Table: Best fit values of μ^{f}_{VBF+Vh} and $\mu^{f}_{ggF+t\bar{t}h}$ along with their uncertainties at 68% C.L. corresponding to LHC Run-I data

But we do not use these best-fit values for our analysis

But we use the 2-dimensional signal strength correlations derived at 95% C.L.



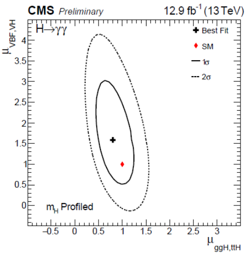
Constraints from Higgs data(13 TeV)

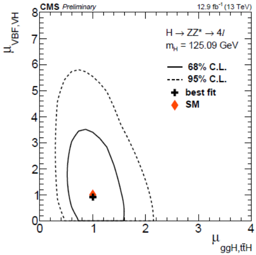
In addition to above mentioned 8 TeV Higgs bounds, we have also implemented some of the latest 13 TeV Higgs bounds, which were presented in ICHEP 2016.

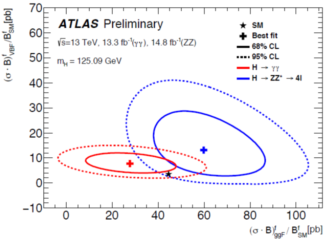
	ICHEP 2016 13 TeV limits
ATLAS	$\sigma_{ggF+t\bar{t}h+b\bar{b}h} \cdot B(h \to ZZ) = 1.80^{+0.49}_{-0.44}$ pb $\sigma_{VBF} \cdot B(h \to ZZ) = 0.37^{+0.28}_{-0.21}$ pb $\sigma_{Vh} \cdot B(h \to ZZ) = 0^{+0.15}$ pb $\mu^{b\bar{b}}_{Vh} = 0.21^{+0.51}_{-0.50}$
CMS	$\mu^{ZZ}_{VBF+Vh} = 0.91^{+1.56}_{-0.91}$, $\mu^{ZZ}_{ggh+t\bar{t}h} = 1.00^{+0.39}_{-0.32}$ $\mu^{\gamma\gamma}_{VBF+Vh} = 1.59^{+0.73}_{-0.45}$, $\mu^{\gamma\gamma}_{ggh+t\bar{t}h} = 0.80^{+0.14}_{-0.18}$ $\frac{\sigma}{\sigma_{SM}} = 0.3 \pm 0.5$ (WW channel)

Table: Best fit values for the corresponding channels along with uncertainties at 68% C.L., derived by CMS and ATLAS (presented at ICHEP 2016).

We have not used these limits for our analysis. We have implemented the 2-dimensional signal strength correlations derived by CMS and ATLAS at 95% C.L. for $\gamma\gamma/ZZ$ final states.







Higgs fit at 8 and 13 TeV

We examine the consequence of imposing the 8 and 13 TeV Higgs signal strength constraints on our parameter space on top of low energy flavor and Higgs mass bound.

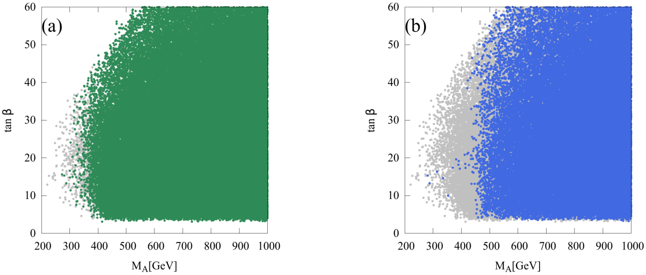
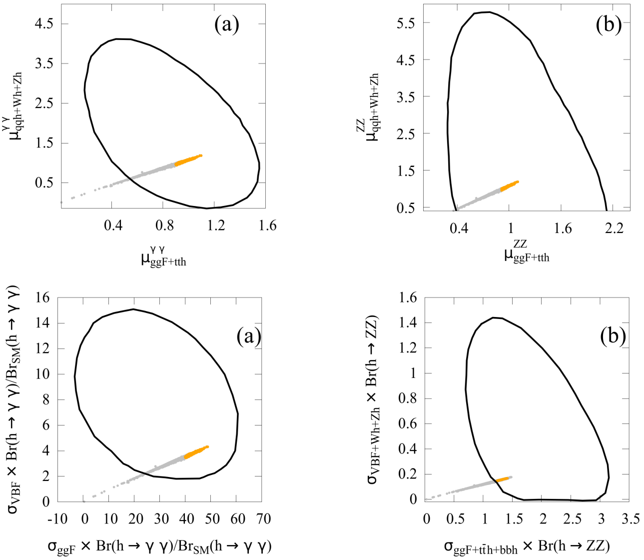


Figure: left panel: 7+8 TeV Higgs signal strengths and right panel: 7+8+13 TeV Higgs signal strength constraints


(a)
(b)
$\mu^{\gamma\gamma}_{qqh+Wh+Zh}$
$\mu^{\gamma\gamma}_{ggF+tth}$
$\mu^{ZZ}_{qqh+Wh+Zh}$
$\mu^{ZZ}_{ggF+tth}$
$\sigma_{VBF} \times Br(h \to \gamma\gamma)/Br_{SM}(h \to \gamma\gamma)$
$\sigma_{ggF} \times Br(h \to \gamma\gamma)/Br_{SM}(h \to \gamma\gamma)$
$\sigma_{VBF+Wh+Zh} \times Br(h \to ZZ)$
$\sigma_{ggF+t\bar{t}h+bbh} \times Br(h \to ZZ)$

μ_{ZZ} from the ATLAS 13 TeV puts the most severe constraint on the parameter space.

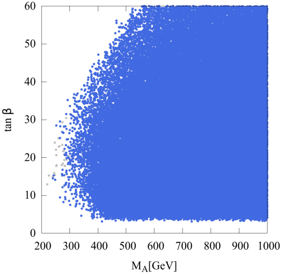


Figure: 7+8+13 TeV Higgs signal strength constraints without ATLAS μ_{ZZ} constraint.

Heavy Higgs direct search

Heavy Higgs decaying to WW,ZZ,$\gamma\gamma$,$b\bar{b}$, $\tau\tau$, hh and $t\bar{t}$ final states. All 8 TeV and 13 TeV upper limits by ATLAS and CMS are taken into account.

- $H \to WW$

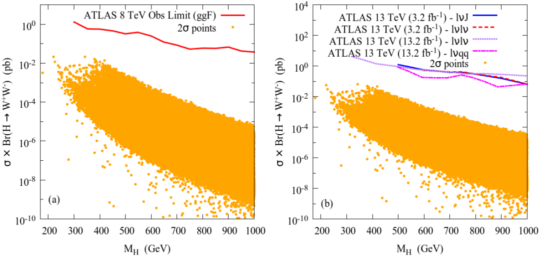


Figure: 95% C.L. upper limit on production cross section times branching ratio for WW final state at 8 TeV(left) and 13 TeV(right).

We have assumed ggF process for heavy Higgs production in this case.

- $H \to ZZ$

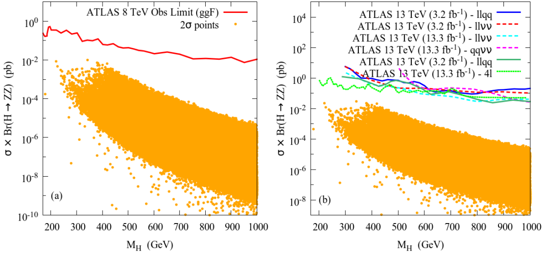


Figure: 95% C.L. upper limit on production cross section times branching ratio forZZ final state at 8 TeV(left) and 13 TeV(right).

ggF production process for heavy Higgs assumed.

- Being in the alignment limit ensures extremely small branching ratio for the processes $H \to WW or ZZ$. At least three orders of magnitude improvement in the upper limit is required to probe the region of interest through these channels.

- $H \to \gamma\gamma$

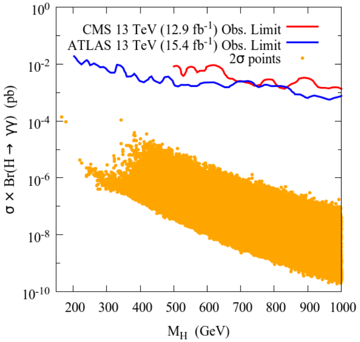


Figure: 95% C.L. upper limit on production cross section times branching ratio for$\gamma\gamma$ final state at 13 TeV.

As soon as the mass of neutral Higgs state increases the branching ratio $H \to \gamma\gamma$ decreases.

- $H \to hh$

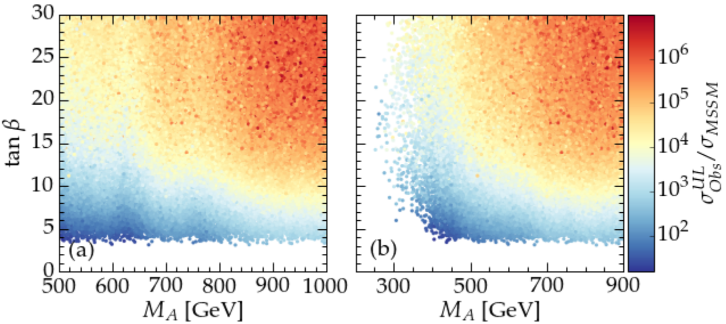
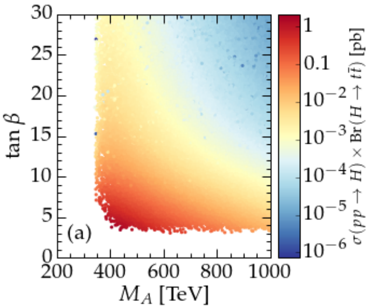


Figure: color palette plot of $\sigma^{UL}_{Obs}/\sigma_{MSSM}$ in the $M_A - \tan\beta$ plane. σ^{UL}_{Obs} represents the upper limits on $\sigma_H \times \mathrm{Br}(H \to hh \to b\bar{b}b\bar{b})$(left) and $H \to hh \to b\bar{b}\tau^+\tau^-$ channel (right) obtained by ATLAS at 95% C.L. using LHC Run-II data with luminosity 13.3 fb^{-1}. σ_{MSSM} represents the corresponding values calculated for our scanned data set.

- The branching ratio for the process $H \to hh$ is considerable for low $\tan\beta$, when $M_A < 350$ GeV ie. before the $t\bar{t}$ threshold is crossed.
- The production cross section $pp \to H \to hh$ is 2 orders of magnitude larger than the direct di-Higgs production in the SM.
- The quantity $\sigma^{UL}_{Obs}/\sigma_{MSSM} < 1$ indicates that the current LHC data has excluded that point.
- For all points the quantity is > 1, hence all the points are allowed by the current LHC results.
- In case the future limits are 100 times stronger, this search would be important to rule out low $\tan\beta$ and low M_A region.

- $H \to t\bar{t}$: The coupling to H to $t\bar{t}$ becomes large in low $\tan\beta$ region.
- At low $\tan\beta$ region the ggF production cross section becomes large due to enhanced heavy Higgs to top yukawa coupling.
- In the $t\bar{t}$ kinematical threshold and low $\tan\beta$ region, one would expect a resonance peak in the invariant mass distribution of $t\bar{t}$ pair.
- But this will be hidden behind the continuous SM $t\bar{t}$ background and the strong interference between the SM-QCD production and resonance production of $t\bar{t}$ makes it difficult to probe this channel at the current reach of LHC.



- $A \to hZ$: Important decay channel for A at low $\tan\beta$ and when $M_h + M_Z < M_A < 2m_t$.
- CMS searched for two same flavor opposite sign leptons(from Z) and $b\bar{b}$(from h)
- ATLAS looked at both $b\bar{b}$ and $\tau^+\tau^-$ final states for the light Higgs.
- For all the points of our parameter space $(\sigma^{UL}_{Obs}/\sigma_{MSSM} > 1)$.
- 100 times stonger limit may probe the pseudoscalar Higgs at low $\tan\beta$

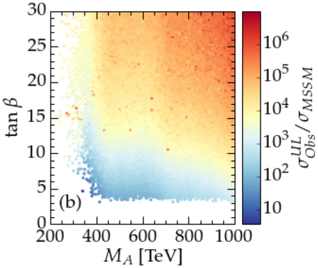


Figure: Using upper limit for $\sigma_{ggA} \times$ Br$(A \to hZ \to Zb\bar{b})$ from 3.2 fb^{-1}runII(ATLAS).

$H \to b\bar{b}$ and $\tau^+\tau^-$:

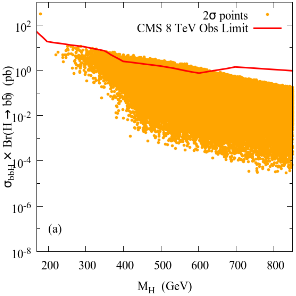
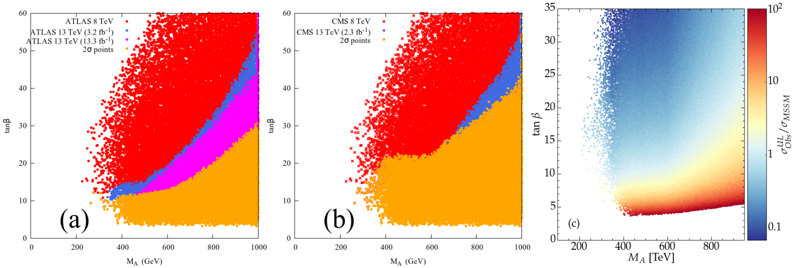


Figure: Using upper limit for $\sigma_{bbH} \times \mathrm{Br}(H \to b\bar{b})$ from 8 TeV CMS data.

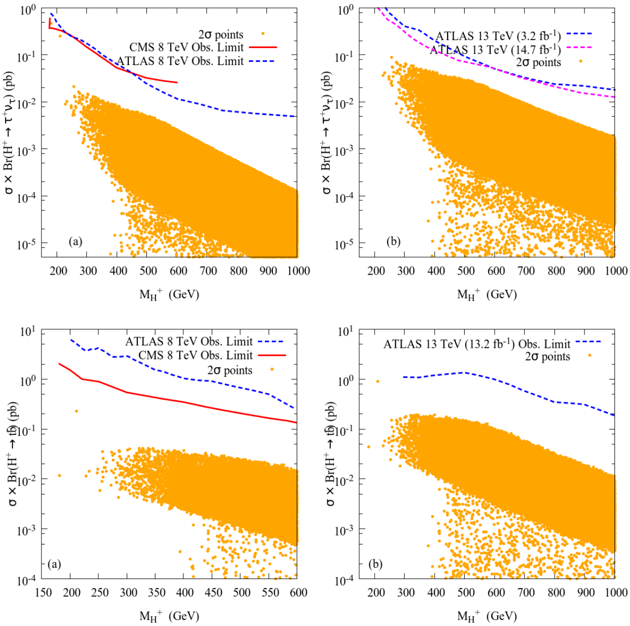
- The coupling of MSSM heavy Higgs and pseudoscalar Higgs with down type fermions (b quark and τ lepton) is proportional to $\cos\alpha/\cos\beta$ and $\tan\beta$ respectively.
- Both of them increase with $\tan\beta$.
- For large $\tan\beta(> 10)$ the dominant decay mode for H and A both are $b\bar{b}(90\%)$ and $\tau^+\tau^-(10\%)$.
- CMS and ATLAS have both presented their results for direct search of heavy Higgs to $b\bar{b}$ and $\tau^+\tau^-$ final states, for gluon fusion as well as in association with b-quark.
- Upper limit on cross section $\times$ branching ratio for $b\bar{b}$ final state from CMS 8 TeV data is able to exclude a small region of the parameter space.



- The $\tau^+\tau^-$ channel puts the most severe constraint on the MSSM parameter space among all the direct search channels of the heavy Higgs states.
- Production of heavy Higgs in association with *b* quark is most effective in this case as the production is also enhanced in the high $\tan\beta$ regime as well as decay.
- This channel can be effective to probe even moderate to low $\tan\beta$ with 100 times improvement in the upper bound.
- $\tau^+\tau^-$ is the most useful channel beyond any doubt.

Search for charged Higgs in $\tau^{\pm}\nu_{\tau}$ and tb final state:

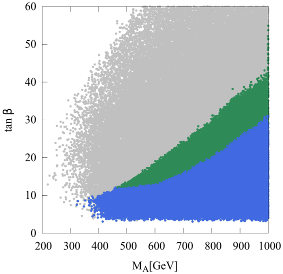
- Direct search by LEP puts an lower limit on charged Higgs mass of 78.6 GeV.
- When charged Higgs is lighter than top quark, it is mostly produced in $t\bar{t}$ events from the decay of top quark and decays into $\tau^{\pm}\nu_{\tau}$ or $c\bar{s}$ final state.
- In most parts of our allowed parameter space charged Higgs is heavier than the top quark and is hence produced in association with a top and bottom quark ie. $gb/gg \to tbH^{\pm}$.
- When $M_{H^{\pm}} > (m_t + m_b)$ the most dominat decay channel becomes $H^{\pm} \to tb$.
- Both of these final states look promising in terms of future direct search of charged Higgs at LHC.



2σ points
CMS 8 TeV Obs. Limit
ATLAS 8 TeV Obs. Limit
(a)
ATLAS 13 TeV (3.2 fb⁻¹)
ATLAS 13 TeV (14.7 fb⁻¹)
(b)
σ × Br(H⁺ → τ⁺ν_τ) (pb)
ATLAS 13 TeV (13.2 fb⁻¹) Obs. Limit
σ × Br(H⁺ → tb) (pb)
M_H⁺ (GeV)

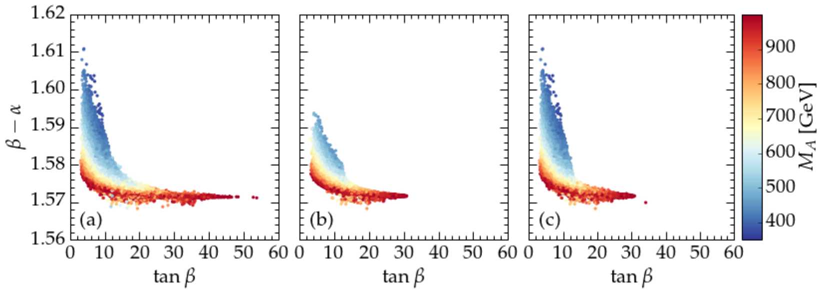
Status of the parameter space after the 13 TeV higher luminosity run

- $M_A - \tan\beta$ plane



grey region allowed by Higgs mass and low energy constraints. Green region allowed by Higgs signal strength and heavy Higgs direct search at 8 TeV and the blue region is allowed by all constraints + 8 TeV or 13 TeV Higgs signal strength correlation.

- Between α, β and M_A



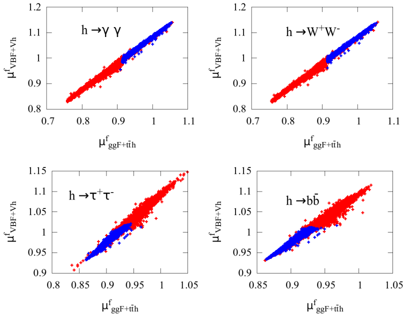
In MSSM

$g_{hVV} = \sin(\beta - \alpha) g_V$ and $g_{HVV} = \cos(\beta - \alpha) g_V$ where g_V is the SM gauge coupling.

- The lightest CP-even Higgs boson will mimic the SM Higgs boson in the limit $\beta - \alpha = \pi/2$(Alignment limit)
- All the experimental results so far indicates that we are indeed very close to the 'Alignment limit'.

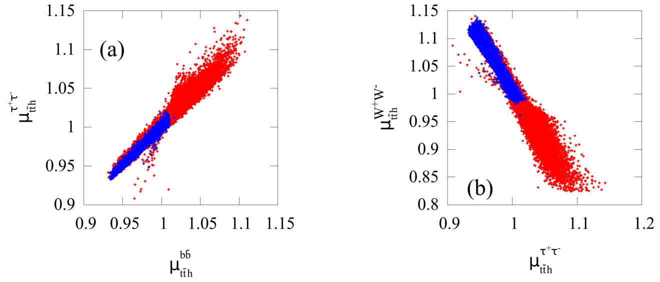
- Point to be noted- It is possible to be in the alignment limit with low $M_A \approx 200 - 400$ GeV, but only with low $\tan\beta$.(Alignment without decoupling).
- Fig.(left) 8 TeV Higgs signal strength+Heavy Higgs direct search , (middle) 8+13 TeV Higgs signal strength and heavy Higgs direct search, (right) without μ_{ZZ} correlated bound by ATLAS at 13 TeV.
- The reason behind this that ATLAS 13 TeV μ_{ZZ} favors more light Higgs coupling to the gauge bosons and consequently less heavy Higgs to gauge bosons coupling.

Signal-strength correlations



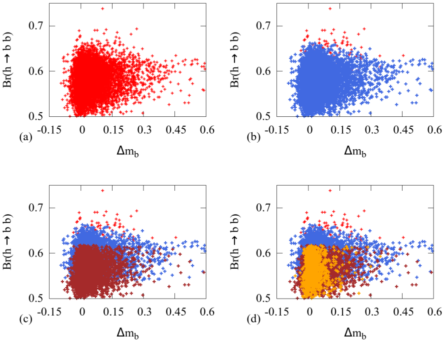
- In case of $\gamma\gamma$ and W^+W^-, points in which both the signal strengths $\mu_{ggF+t\bar{t}h} < 1$ and $\mu_{VBF+Vh} < 1$, and are disallowed by the post-ICHEP 2016 data.
- In case of $b\bar{b}$ and $\tau^+\tau^-$ final states, there is region in which both the signal strengths $\mu_{ggF+t\bar{t}h} > 1$ and $\mu_{VBF+Vh} > 1$, and that region is disfavored by the post-ICHEP 2016 data.

$t\bar{t}h$ correlations



- Where both $\mu^{\tau^+\tau^-}_{t\bar{t}h} > 1$ and $\mu^{b\bar{b}}_{t\bar{t}h} > 1$ are constrained by the signal strength correlation from the 13 TeV post-ICHEP 2016 data.
- The region with $\mu^{\tau^+\tau^-}_{t\bar{t}h} > 1$ and $\mu^{W^+W^-}_{t\bar{t}h} < 1$ are disfavored by the 13 TeV post-ICHEP 2016 data.

Correction to the bottom-yukawa coupling



- The loop corrections involving various supersymmetric particles can modify the bottom Yukawa coupling significantly.

$$\mathcal{L}_{eff} = h_b H_d^0 b\bar{b} + \Delta h_b H_u^0 b\bar{b}. \tag{7}$$

- The tree level $H_u^0 b\bar{b}$ coupling does not exist in MSSM, as H_u^0 couples only to the up type quarks at tree level. But a non-vanishing Δh_b can be generated dynamically at one loop level.
- Although Δh_b is loop suppressed, when H_u^0 and H_d^0 aquire vev a small Δh_b shift introduces a large modification to the tree level relation between the bottom mass and its Yukawa coupling.
- Fig.(a) Higgs mass and low energy constraints,
  Fig.(b) $\rightarrow$ Fig.(a)$+$ Higgs signal strength constraints (both 8 TeV and 13 TeV ATLAS and CMS without the constraints on the signal strength in ZZ channel given by ATLAS 13 TeV data)
  Fig.(c) $\rightarrow$ Fig.(b) $+$ ATLAS μ_{ZZ} 13 TeV.

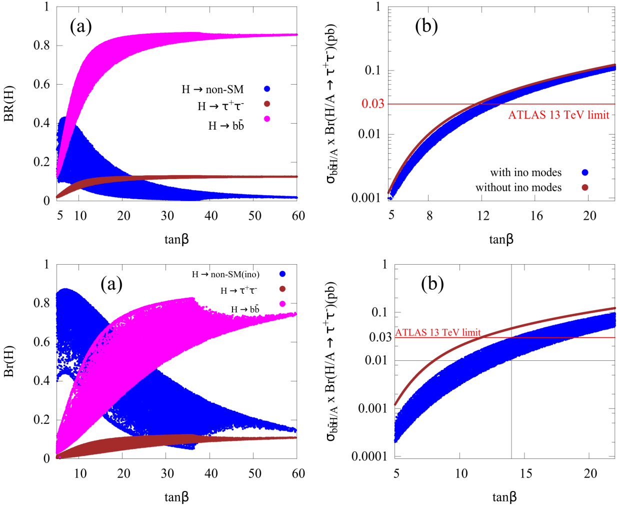
- Branching more than 62% or so, are disfavored by the ATLAS 13 TeV signal strength constraints in the ZZ channel.
- The points beyond which the signal strengths in the ZZ channel are disfavored by that particular constraint correspond to a specific value of the partial decay width of $h \to b\bar{b}$ and consequently a particular value of $\mathrm{Br}(h \to b\bar{b})$.
- But wait!!!
- Fig. (d)$\to$ Fig.(c) $+$ Heavy Higgs direct search (8 and 13 TeV)
- Heavy Higgs direct search in the $\tau^+\tau^-$ channel puts an upper limit on $\tan\beta$ and this limit gets translated into an upper limit on Δm_b.

Heavy Higgs decay to SUSY particles

We consider heavy Higgs decay to electroweakinos, 3rd gen squarks and sleptons. Gluino, first two gen squarks and sleptons are heavy.

- Heavy Higgs decaying to electroweakinos: Intermediate $\tan\beta$ region this decay dominates if kinematically allowed.
- This decay crucially depends on the gaugino-Higgsino mixing.
- There is lower limit on light electroweakinos from the direct search LEP and LHC run I.
- We perform a random scan on M_1, M_2 and $\tan\beta$ but fix the heavy Higgs mass at 600 GeV.
- We vary M_1 and μ so that $M_1 + \mu < M_A$ and both $M_1, \mu > 100$ GeV. In addition, $|M_{\chi_1^0} - M_{\chi_3^0, \chi_1^\pm}| < M_W$. Then Higgs to 'ino' branching fraction can reach up to 40% in the moderately low $\tan\beta$ region.The effect of this on $\tau^+\tau^-$ channel is striking.
- For an admixture of wino and higgsino and see that the branching to 'ino' states can reach upto 80%.

- The statistics in the $\tau^+\tau^-$ channel has to increase by an order of magnitude to maintain the same sensitivity of the 13 TeV results in the presence of 'ino' decay modes.



Heavy Higgs decay to sfermions

- First two gen squaks will have negligible coupling with the Higgs because of small fermion masses.
- Because of large mass and large mixing in the 3rd gen sfermion sector $H \rightarrow \tilde{t}_1 \tilde{t}_1$ and $\tilde{b}_1 \tilde{b}_1$ can be dominant decay modes.
- For large $\tan\beta$ and large A_τ the Heavy Higgs to staus will be large but in that limit $H \rightarrow b\bar{b}$ dominates over everything.

Heavy Higgs to stops

- Owing to the large mixing and large m_t the lightest stop can be really light and heavy Higgs can decay into a pair of stops.
- For not so heavy Higgs, small $\tan\beta$, and large mixing the partial decay width of heavy Higgs to stops can dominate over the $t\bar{t}$ decay mode.
- To probe such scenarios we scan the MSSM parameter space by fixing the masses of first two generation squarks and all three generation sleptons at 4 TeV.
- Must take into account of the lower limit on the stop masses from the direct stop search results by the LHC.
- Noteworthy is that these direct search limits depends on the particular decay mode of stop considered.
- We took the most conservative lower limit(≈ 350) on the stop mass and consequently a limit of 700 GeV on the heavy Higgs mass.
- For a specific B.P $M_1 \approx 300$GeV, $M_H \approx 800$ GeV the branching fraction of heavy Higgs to stops can reach 95%!!

Heavy Higgs to sbottoms

- LHC direct search puts severe constraints on sbottom mass(> 800) GeV), for $m_{\tilde{\chi}_1^0} \lesssim 250$ GeV.
- Only for degenerate sbottom case we can evade this limit, here we take sbottom mass to be greater than 300 GeV.
- Large A_b and large $\tan\beta$ heavy Higgs coupling to sbottom pair is large and because of large mixing one sbottom will be light and the decay will be kinematically feasible.
- We perform a general scan varying only the third gen squark masses, trilinear couplings and $\tan\beta$ and found that both $H \to \tilde{t}_1 \tilde{t}_1$ and $H \to \tilde{b}_1 \tilde{b}_1$ can be as large as 95%.
- The regions where 3rd gen sfermions are degenerate with the neutralino and hence allowed by the LHC direct search bound to have low enough mass for heavy Higgs to decay into them, needs special attention in terms of heavy Higgs direct search.

Summary

- Since the discovery of the new 125 GeV resonance CMS and ATLAS have performed various studies to match its properties with the SM template.
- Production and decay are both under scrutiny in terms of signal strength μ^i_f's.
- In addition direct searches for additional Higgs boson states have been performed in various channels.
- No positive conclusion so far on the existance of new states.
- 95% C.L. Upper limits on cross section times branching ratios have been given to constrain various new physics model parameter space.

- We try to understand the impact of all the LHC searches put together so far in the Higgs signal strength as well as heavy Higgs direct search on top of the Higgs mass and low energy flavor constraints on the MSSM parameter space.
- Key findings:
- Signal strength/cross-section measurement in $h \to \gamma\gamma$ channel by ATLAS and CMS with 13 TeV ($\sim$ 15 fb^{-1}) data has no significant impact in constraining the parameter space, compared to Run-I combined analysis.
- On the other hand ATLAS signal strength measurement on $h \to ZZ$ constraints/disfavors the parameter space with $M_A < 450$ GeV. The slight upward fluctuation in the ATLAS results for $h \to ZZ$ channel pushes us to the decoupling region.
- As the signal strength measurements are in favor of the alignment/decoupling limit, the direct searches with $H \to W^+W^-, ZZ$ final states are not effective to probe the relevant parameter space of our interest through the heavy Higgs direct search.

- Upper bounds derived on $H/A \to \tau^+\tau^-$ are found to impose the strongest constraints on the parameter space and rules out a significant region of parameter space in the high $\tan\beta$ and low M_A region. Compared to Run-I data, the very recent 13 TeV data is more stringent in the region with $\tan\beta > 10$.
- At least two orders of magnitude improvent in the upper limit is necessary to probe the MSSM parameter space through other decay channels of heavy Higgs.
- All the conclusions from the heavy Higgs direct search depends on the available decay channels of the heavy Higgs assumed.
- If heavy Higgs decays to non-SM states the branching ratios will change significantly.
- The additional decay modes will affect the most stringent constraints put by the $H \to \tau^+\tau^-$ final state.
- In principle these additional decay modes will weaken the bounds on the parameter space.
- Much improved measurements are required to achieve the same level of sensitivity in presence of the SUSY decay modes.