Implications of 98 GeV and 125 GeV Higgs scenario in non-decoupling SUSY

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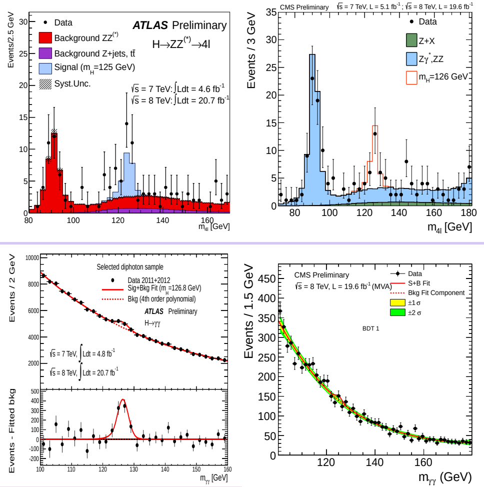
Ref: [Phys. Rev. D 88 (2013) 035011]

Plan of the talk

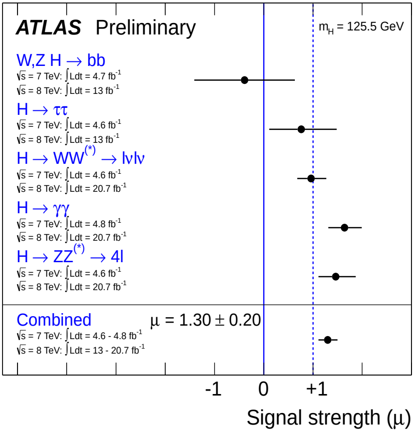
- Introduction
- Inclusive LEP-LHC Higgs (ILLH) scenario
- ILLH @MSSM and NMSSM
- Collider analysis and results
- Updated analysis (in progress)
- Summary

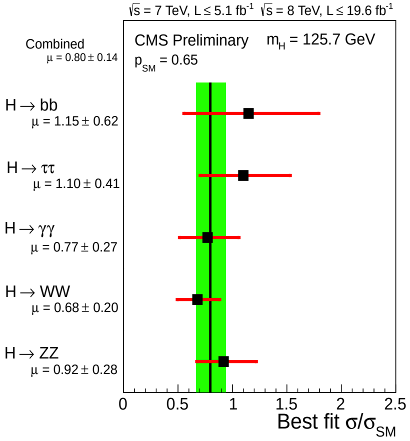
Introduction



- A Standard Model like Higgs particle has been found by the ATLAS & CMS collaboration of the LHC experiment with $m_h \simeq 125$ GeV.
- Evidence of this particle in multiple channels.
- The observed rates of this particle are compatible with the SM prediction.

- Higgs couplings are not yet measured very precisely
- With future LHC run and possibly at ILC the couplings will be measured more precisely $\Longrightarrow$ constrain several scenarios beyond the SM / or give a possible direction to new physics.



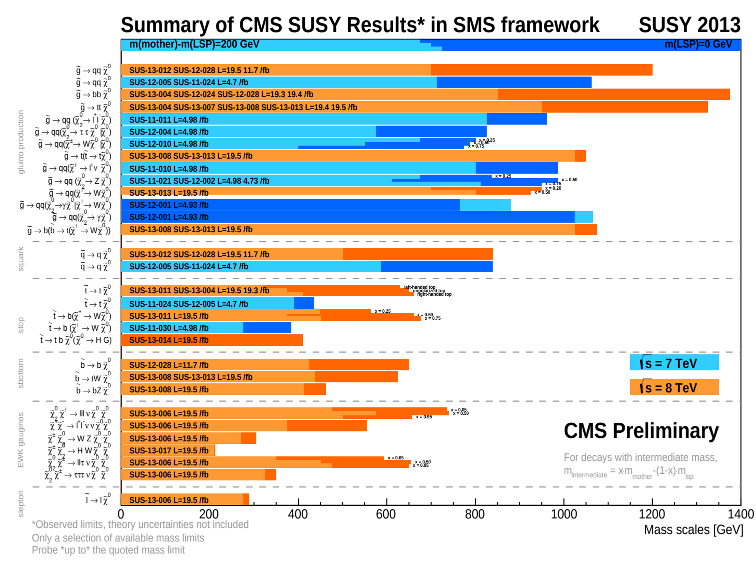


Can MSSM accommodate 125 GeV Higgs boson ?

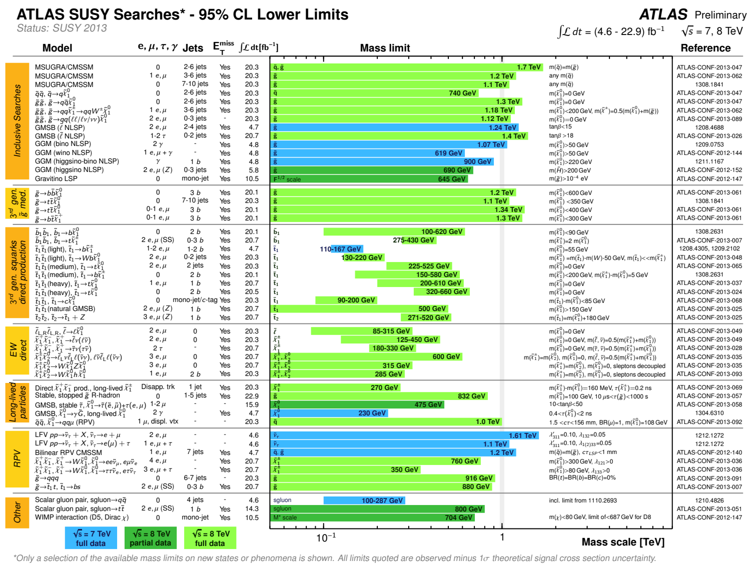
125 GeV Higgs and MSSM

- It seems that the observed 125 GeV Higgs like particle agrees well with prediction of MSSM.
- In MSSM, the large quadratic divergence in m_h^2 due to top quark loop is cancelled by the scalar partner of top quarks (called stop $\tilde{t}_i$, with $i = 1, 2$).
- Stop sector plays a crucial role in determining the Higgs mass $\Longrightarrow$ the experimental determination of the stop properties is crucial to understand the nature of SUSY protecting the Higgs mass at EW scale.
- So far LHC has not seen any evidence of SUSY particles, only lower bounds have been put on different SUSY particles.
- Limits on gluino ($\tilde{g}$) and squarks ($\tilde{q}$) currently stands at about 1.5 TeV for $\mathrm{m}_{\tilde{\mathrm{g}}} \simeq \mathrm{m}_{\tilde{\mathrm{q}}}$ and about 1.2 TeV for $\mathrm{m}_{\tilde{\mathrm{g}}} \ll \mathrm{m}_{\tilde{\mathrm{q}}}$.

CMS SUSY exclusion



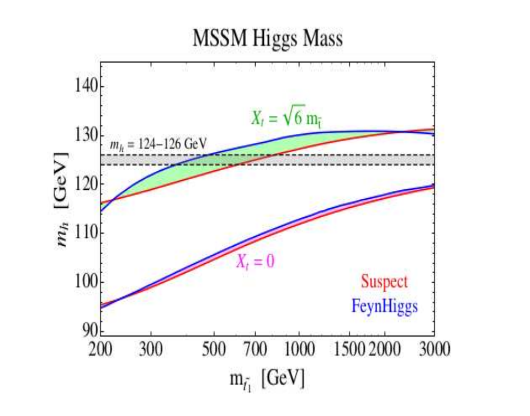
ATLAS SUSY exclusion



- superparticles responsible for cancellation of quadratic divergence in Higgs mass are the third generation squarks, can be comparatively light to cure the fine-tuning problem of SM.

$$
\begin{aligned}
m_h^2 &\simeq m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left(\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}(1 - \frac{X_t^2}{12M_S^2})\right) \\
M_S &= \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \\
X_t &\equiv A_t - \mu \cot\beta
\end{aligned}
$$

- A_t : the trilinear Higgs-stop coupling.
- $m_h \Longrightarrow$ heavier for larger $\tan\beta$ or M_S.
- For a given M_S, m_h reaches maximum when $X_t = \sqrt{6}M_S$ so-called $m_h^{\max}$ scenario.
- Lighter stop/sbottom : large stop/sbottom tri-linear couplings.



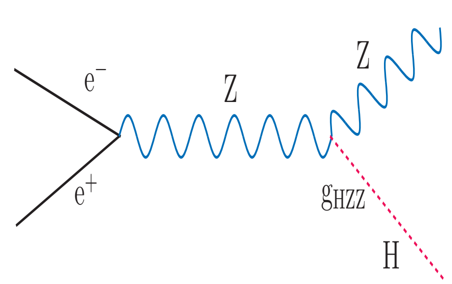
[L.J.Hall et.al, JHEP 04, 131 (2012)]

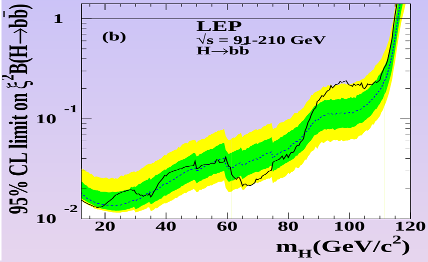
- Light third generation scenario has an extremely attractive prospect for both the theorists and the experimentalists

Did LEP give us any hint about Higgs ?

Higgs@LEP ?

- At LEP, Higgs boson is searched in $e^+e^- \to ZH$ channel.
- Combined analysis of four LEP experiments: $M_h > 114.4$ GeV @ 95% C.L.





- Parameter: $\zeta \equiv \left(\frac{g_{HZZ}^{BSM}}{g_{HZZ}^{SM}}\right) = \sin(\beta - \alpha)$

  (α: Higgs mixing angle, $\tan\beta$: ratio of VEVs)
- A mild excess $(\sim 2.3\sigma)$ of Higgs-like events $e^+e^- \to Zh$ with a mass near 98 GeV.

- Both LEP and LHC events can be explained simultaneously in MSSM, and NMSSM.
- MSSM: Five Higgses : $h^0, H^0, A^0, H^\pm$.
- At tree level, M_A and $\tan\beta$ controls the MSSM Higgs sector.
- Higgs couplings to gauge bosons and fermions are functions of β and α.
- W^+W^-H, HZZ, ZAh, $W^\pm H^\mp h$, $ZW^\pm H^\mp h$ and $\gamma W^\pm H^\mp h \propto \cos(\beta-\alpha)$.
- W^+W^-h, hZZ, ZAH, $W^\pm H^\mp H$, $ZW^\pm H^\mp H$ and $\gamma W^\pm H^\mp H \propto \sin(\beta-\alpha)$.

- decoupling : $M_A \geq 300$ GeV and $\cos^2(\beta-\alpha) \to 0 \implies \sin^2(\beta-\alpha) \to 1$.
- In decoupling limit : One can interpret the newly observed state at 125 GeV as the light CP even Higgs boson with SM like couplings.
- non-decoupling : $M_h \sim M_A \sim M_H \sim M_Z$ or $\sin^2(\beta-\alpha) \to 0 \implies \cos^2(\beta-\alpha) \to 1$.
- This would mean larger coupling strength of H with the SM gauge bosons.
- We may explore the possibility of $M_H \sim 125$ GeV, instead of h as the discovered new resonance.
- H behaves like $h_{\rm SM}$ and h has weaker couplings to W/Z.

MSSM parameter space scan

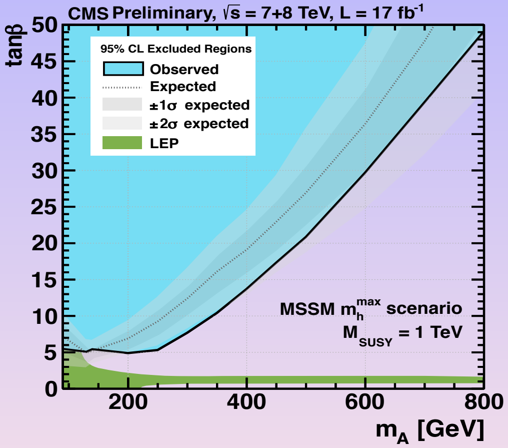
- We generate approximately 70 million random points in the following combined range of parameters:
- We consider $m_t^{\rm pole} = 173.3 \pm 2.8$ GeV.

$$
\begin{aligned}
3 < \tan\beta < 5.5,\ 0.085 < M_A < 0.2\ \text{TeV},\ 0.3\ \text{TeV} < \mu < 12\ \text{TeV}, \\
0.05\ \text{TeV} < M_1, M_2 < 1.5\ \text{TeV},\ 0.9\ \text{TeV} < M_3 < 3\ \text{TeV}, \\
-8\ \text{TeV} < A_t < 8\ \text{TeV},\ -3\ \text{TeV} < A_b,\ A_\tau < 3\ \text{TeV},\ A_u = A_d = A_e = 0, \\
0.3\ \text{TeV} < M_{\tilde{q}_3} < 5\ \text{TeV},\ \text{where},\ \tilde{q}_3 \equiv \tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R \\
M_{\tilde{q}_i} = 3\ \text{TeV}, \text{for } i = 1,2\ \text{ and }\ M_{\tilde{\ell}_i} = 3\ \text{TeV}, \text{for } i = 1,2,3.
\end{aligned}
$$

- CMS has constrained $\tan\beta - M_A$ plane from $H/A \to \tau^+\tau^-$ decay.
- ATLAS has constrained $\tan\beta - M_{H^\pm}$ plane from $H^+ \to \tau^+\nu_\tau$ in $t\bar{t}$ events, where one $t \to bH^+$.

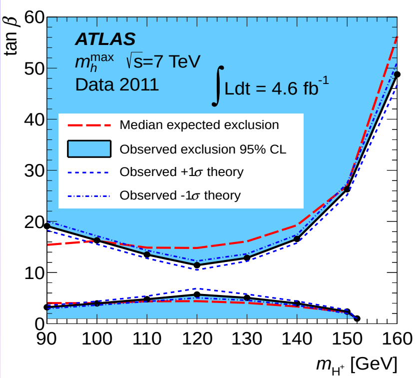
[CMS-PAS-HIG-2012-050],[ATLAS Collaboration, JHEP 06 (2012),039]

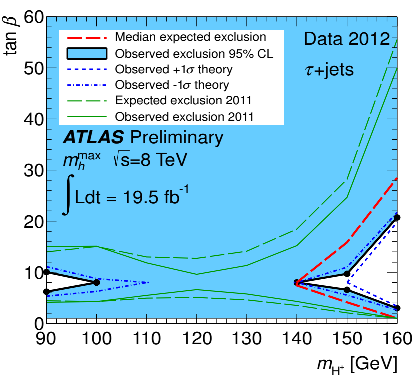
CMS exclusion in $\tan\beta - M_A$ plane



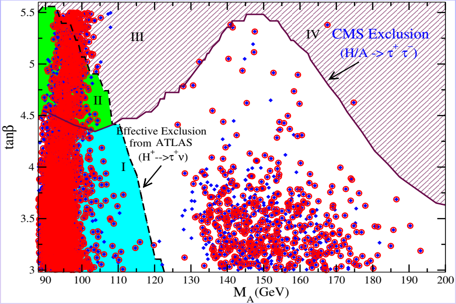
- $90 < M_A < 250$ GeV for $\tan\beta > 5.5$ is excluded.

ATLAS exclusion in $\tan\beta - M_{H^\pm}$ plane



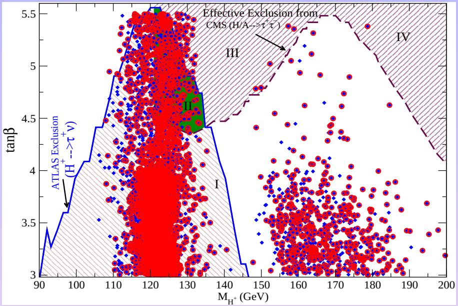


- $90 < M_{H^\pm} < 150$ GeV for $2 < \tan\beta < 6$ is excluded.



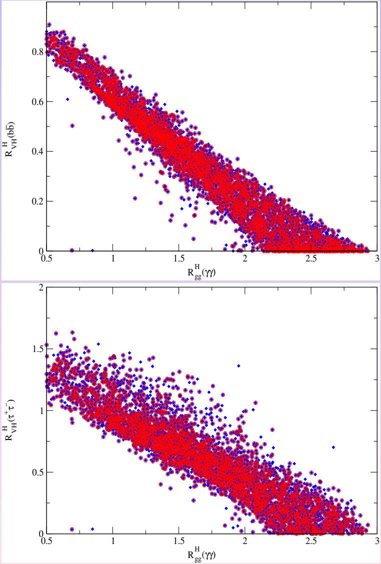
- The blue points satisfy following constraints:
  - Lower limits on SUSY particles
  - $95\ \mathrm{GeV} < m_h < 101\ \mathrm{GeV}$; $122\ \mathrm{GeV} < m_H < 128\ \mathrm{GeV}$.
  - $0.1 < \sin^2(\beta - \alpha) < 0.25$.
  - $R_{gg}^{H_2}(\gamma\gamma)_{\mathrm{min}} > 0.5$, [CMS : $\hat{\mu} = 0.78^{+0.28}_{-0.26}$].
  - $2.77 \times 10^{-4} < \mathrm{Br}(b \to s\gamma) < 4.09 \times 10^{-4}$ at 3σ level.
    $[\mathrm{Br}(b \to s\gamma)(\mathrm{exp}) = (3.43 \pm 0.22) \times 10^{-4}]$. [arXiv:1207.1158].
  - $0.67 \times 10^{-9} < \mathrm{Br}(B_s \to \mu^+\mu^-) < 6.22 \times 10^{-9}$ at 2σ level.
- The red circles (enclosing blue points) shows points satisfy the DM relic density constraint (only upper limit): $0.112 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.128$.

ILLH in MSSM



- From our previous figure : 130 GeV$< M_A <$200 GeV for $3 < \tan\beta < 5.5$.
- Direct constraint from $H^{\pm} \to \tau^{+}\nu_{\tau}$ (ATLAS) : blue solid line.
- Exclusion from $H/A \to \tau^{+}\tau^{-}$: maroon line
- The region of $M_{H^{\pm}} < 145$ GeV becomes entirely disallowed via $H^{+} \to \tau^{+}\nu_{\tau}$ from ATLAS.
- $150 < M_{H^{\pm}} < 200$ GeV.

- Anti-correlation behavior between primary signal strength observables.
- Total Higgs decay width is primarily determined by $h \to b\bar{b}$ decay width.
- QCD and SUSY QCD corrections to m_b (Δ_b) play important roles in modifying the total decay width/ relevant branching ratios.
- A reduction (enhancement) of $h, H \to b\bar{b}$ couplings decreases (increases) the total decay width of Higgs.
- Enhances (reduces) the branching ratios to $h, H \to \gamma\gamma$ increasing (decreasing) $R^h_{gg}(\gamma\gamma)$ or $R^H_{gg}(\gamma\gamma)$.



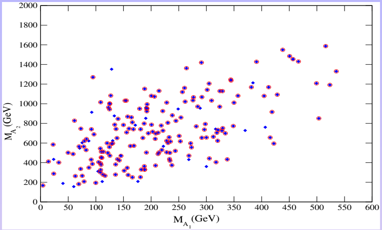
Sample benchmark point in MSSM parameter space

M_t	M_A	$\tan\beta$	μ	M_1	M_2	M_3	A_t	A_b
173.6	167.5	5.0	5429.8	527.9	119.2	1416.6	5729.2	-217.1
A_τ	$M_{\tilde{q}_{3L}}$	$M_{\tilde{t}_R}$	$M_{\tilde{b}_R}$	M_h	M_H	$M(H^\pm)$	$M_{\tilde{t}_1}$	$M_{\tilde{b}_1}$
-115.2	1712.6	1602.2	426.7	97.7	125.1	182.1	999.2	539.1
$M_{\tilde{g}}$	BR($B_s \to \mu^+\mu^-$)	BR($b \to s\gamma$)	Ωh^2	$\zeta\sigma^{SI}_{(p-\chi)}$				
1608.9	2.8×10^{-9}	3.8×10^{-4}	4.5×10^{-4}	5.5×10^{-11}				

- All masses are in GeV unit
- cross-section is pb unit.

- Main issues of our analysis in MSSM :

- In MSSM one can have 98 GeV and 125 GeV Higgs bosons.
- This restrict : $3 < \tan\beta < 5.5$, $130\ \mathrm{GeV} < M_A < 200\ \mathrm{GeV}$ and $150\ \mathrm{GeV} < M_{H^\pm} < 200\ \mathrm{GeV}$



- $\lambda \hat{S}\hat{H}_u\hat{H}_d + \frac{\kappa}{3}\hat{S}^3$.
- 3 (2) CP even (odd) neutral Higgses, $H_i, i = 1, 2, 3$ and $A_i, i = 1, 2$, and $H^{\pm}$.
- We vary λ, κ, A_λ, A_κ, A_0, m_0, $m_{1/2}$, $\tan\beta$, $\mu_{\rm eff}$ using NMSSMTools3.2.4.
- In this parameter (figure) space of interest, $M_{A_2} \sim M_{H_3} \sim M_{H^{\pm}}$.
- Heavy mass scale ($M_A > 200$ GeV) $\Longrightarrow$ can accommodate $m_h \sim 98$ GeV (not possible in MSSM with $M_A > 200$ GeV.)
- Indirect exclusion: A bit tough, particle masses relatively heavy, so less sensitive at the LHC.
- Exclusion is Model dependent.
- Can we discover/exclude this at LHC in a model independent way ?

Prospect of observing 98 GeV Higgs @ Colliders

Can we find this 98 GeV Higgs @LHC ?

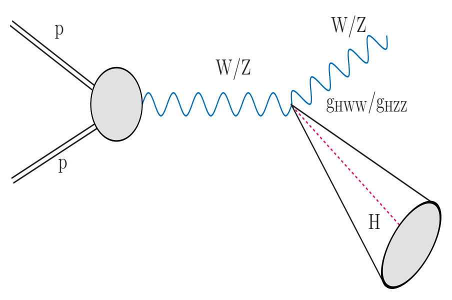
- A combination of a 98 GeV & a 125 GeV Higgs boson in the nondecoupling limit of MSSM and in NMSSM.
- Nondecoupling limit of MSSM: $\Longrightarrow$ relatively light Higgs bosons $\Longrightarrow$ can be probed at the early run of the LHC.
- Non observation of such light Higgs bosons will indirectly exclude the possibility of scenario with a 98 GeV Higgs boson.

- Previous attempts :
- At 8 TeV LHC, 5σ signal for $pp \to H^{\pm}A^0, H^{\pm}h^0 \to \tau^{\pm}\nu b\bar{b}$ and $pp \to H^+H^- \to \tau^+\nu\tau^-\bar{\nu}$ can be observed with an integrated luminosity of $7(11)\ \mathrm{fb}^{-1}$ and $24(48)\ \mathrm{fb}^{-1}$, respectively for $M_A = 95(130)$ GeV.
- At the 14 TeV energy : 5σ signal can be observed with an integrated luminosity of $4(7)\ \mathrm{fb}^{-1}$ and $10(19)\ \mathrm{fb}^{-1}$ respectively. [N.D.Christensen etal. 2012]
- ATLAS search : $130 < M_A < 200$ GeV for $\tan\beta \sim 3 - 5.5$ ruled out the above analysis and some others.

[M. Drees, PRD (2005) & (2012), N.D.Christensen etal. 2012, M. Asano etal. PRD (2012), S. Scopel etal. PRD (2013)].

Can we find this 98 GeV Higgs @LHC ?

- Gluon fusion: g g $\rightarrow$ H $\rightarrow$ $b\bar{b}$ for 98 GeV Higgs boson, large QCD jet background, difficult to prove.
- Di-photon via Gluon fusion: Heavily suppressed BR(H $\rightarrow \gamma\gamma$) for a 98 GeV Higgs, hard to distinguish from the continuous backgrounds.
- VBF production: not so sensitive for a 98 GeV Higgs boson.
- Higgs-strahlung process (VH): H is produced along with a gauge boson W/Z, may have sufficient boost (large p_T of Higgs)



- 2.3σ excess in the LEP constrains the effective coupling :
  $g^{BSM}_{ZZh}/g^{SM}_{ZZh} \simeq 0.3 - 0.5$
  $\Rightarrow$ controls the 98 GeV Higgs production cross-section in Vh at LHC
  $\Rightarrow$ A Model independent input parameter.
- We follow ATLAS simulation considering 20% LEP excess and apply the Jet Substructure technique.

- $\not{E}_T > 30$ GeV and $p_T^{e/\mu} > 30$ GeV [hW, $W \to \mu\nu, e\nu$]
- $80 < m_{\ell\ell} < 100$ GeV, [$hZ, Z \to e^+e^-/\mu^+\mu^-$]
- $\not{E}_T > p_T^{\rm min}$, with $p_T^{\rm min} = 200$ GeV [$hZ, Z \to \nu\bar{\nu}$ and hW, $W \to \ell\nu$, ℓ is missing.]

Process	Significance ($\frac{S}{\sqrt{B}}$)	Combined
$\ell\nu b\bar{b}$	1.7	
$\ell^+\ell^- b\bar{b}$	0.9	2.5
$\not{E}_T b\bar{b}$	1.6	

1. 98 GeV Higgs at the 14 TeV LHC with 300 $\rm fb^{-1}$ luminosity is $\sim 2.5\sigma$.
2. This signal significance may be reduced further if systematic uncertainties in the SM background estimations are considered.

[ATLAS Collaboration, Report No. ATL-PHYS-PUB-2009-008]

Associated production with top quarks

- Associated production of 98 GeV Higgs boson with top quarks:

$$pp \to t\bar{t}h(h \to b\bar{b})$$

- $\sigma(pp \to t\bar{t}h) \sim 1$ pb for $m_h \sim 100$ GeV. at 14 TeV run of LHC. [CERN Yellow Report Page At 14TeV]
- Translated the results already performed by Tilman Plehn et. al. for $\sim$ 115 GeV Standard Model Higgs boson at 14 TeV LHC. [T. Plehn et.al. PRL 104, 111801 (2010)]
- While translating the results of Tilman Plehn for our choice of Higgs mass, we expect enhancements of 60% and 20% in Higgs production rate and background estimation.
- In our analysis, we scale the signal and background by 1.6 and 1.2, respectively for $h(m_h = 98\ \mathrm{GeV}) \to b\bar{b})$.
- For an integrated luminosity of 300 fb^{-1} with two tagged b-jets the significance $\sim$ 3.1σ, while for three b-tag sample $\sim$ 2.6σ.
- Jet Substructure may marginally exclude the 98 GeV Higgs: experimental collaborations need to perform further detailed analysis.
- In NMSSM A 98 GeV Higgs production from the decay of heavy Higgs bosons as well as from the cascade decays of other sparticles may play an important role at the LHC. [S.F. King et.al. NPB 870,323 (2013); Z.Kang et.al. PRD 88,015006 (2013)]

ILC

- There has been a plan to build e^+e^- linear collider (ILC) with $\sqrt{s} \sim 250$ GeV - 1000 GeV.
- Like LEP, the Higgs boson will be produced in $e^+e^- \to Zh$ channel.
- ILC will be an ideal machine for the Higgs precision study.
- In our analysis, we assume $h \to b\bar{b}$ decay mode, while Z can decay leptonically or hadronically.
- We use MadGraph5 to estimate the signal as well as SM background cross-section for the 98 GeV Higgs boson.
- For $\sqrt{s} = 250$ GeV, $\sigma(e^+e^- \to Zh) = 350$ fb, whereas $\sigma(e^+e^- \to ZZ) \sim 1.1$ pb.
- We find that a 98 GeV Higgs boson can be easily discovered / excluded at the 250 GeV ILC with a $100\ \mathrm{fb}^{-1}$ luminosity.
- Discovery potential at the LHC is marginal.
- ILC is an ideal machine to study this scenario.

Updated analysis (work in progress)

- We relook the MSSM parameter space in the light of updated Higgs data:

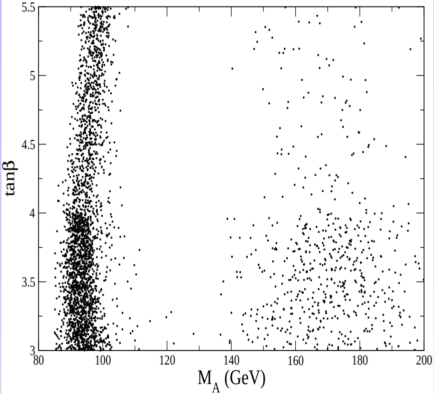
- ATLAS limits :

$$R_{\gamma\gamma} \;:\; 1.55^{+0.33}_{-0.28} @ [7 \text{ TeV}(4.8) + 8 \text{ TeV}(20.7)]$$
$$R_{ZZ^*} \;:\; 1.43^{+0.40}_{-0.35} @ [7 \text{ TeV}(4.6) + 8 \text{ TeV}(20.7)]$$
$$R_{b\bar{b}} \;:\; 0.2^{+0.7}_{-0.6} @ [7 \text{ TeV}(4.7) + 8 \text{ TeV}(20.3)]$$
$$R_{\tau^+\tau^-} \;:\; 1.4^{+0.5}_{-0.4} @ [8 \text{ TeV}(20.3)]$$

- CMS limits :

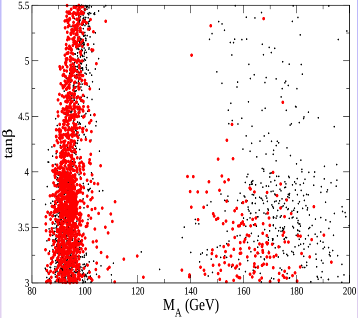
$$R_{\gamma\gamma} \;:\; 0.78^{+0.28}_{-0.26} @ [7 \text{ TeV}(5.1) + 8 \text{ TeV}(19.6)]$$
$$R_{ZZ^*} \;:\; 0.93^{+0.29}_{-0.25} @ [7 \text{ TeV}(5.1) + 8 \text{ TeV}(19.7)]$$
$$R_{b\bar{b}} \;:\; 1.0^{+0.5}_{-0.5} @ [7 \text{ TeV}(5.1) + 8 \text{ TeV}(18.9)]$$
$$R_{\tau^+\tau^-} \;:\; 0.87^{+0.29}_{-0.29} @ [7 \text{ TeV}(4.9) + 8 \text{ TeV}(19.7)]$$

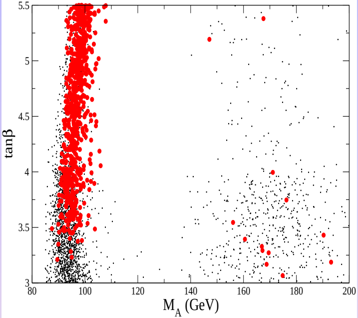
Updated analysis



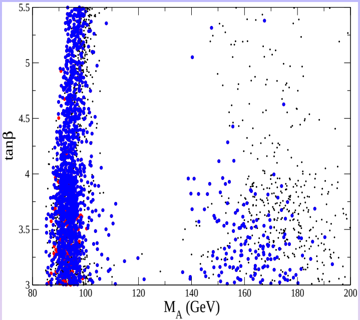
- All points satisfy following constraints :
  - $95\ \mathrm{GeV} < m_h < 101\ \mathrm{GeV}$ and $122\ \mathrm{GeV} < m_H < 128\ \mathrm{GeV}$
  - $0.1 < \sin^2(\beta - \alpha) < 0.25$
  - $2.77 \times 10^{-4} < \mathrm{Br}(b \to s\gamma) < 4.09 \times 10^{-4}$
  - $0.67 \times 10^{-9} < \mathrm{Br}(B_s \to \mu^+\mu^-) < 6.22 \times 10^{-9}$

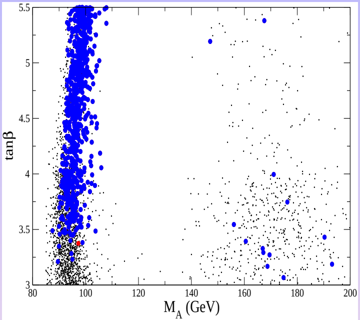
Limits from the ATLAS and CMS Higgs search data



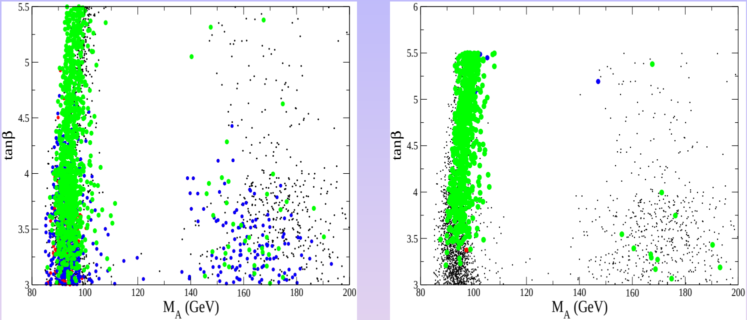


- All points satisy previous constraints and $R_{\gamma\gamma}$ @2σ level .
- ATLAS left figure and CMS right figure
- Point to note : $130~\mathrm{GeV} < M_A < 200~\mathrm{GeV}$ is allowed from CMS analysis of $H/A \to \tau^+\tau^-$.





- Previous constraints plus R_{ZZ^*} and $R_{b\bar{b}}$ @2σ level



- Previous constraints plus $R_{\tau^+\tau^-}$ @2σ level .

Conclusions

- We studied the possibility that both the LEP excess in the $b\bar{b}$ final state with a 98 GeV Higgs boson and the LHC signal for a 125 GeV Higgs like object can be simultaneously explained in the most general MSSM framework.
- This can happen in nondecoupling zone of MSSM Higgs sector, where, $M_h \sim M_A \sim M_H \sim M_Z$ or $\sin^2(\beta - \alpha) \to 0 \Longrightarrow \cos^2(\beta - \alpha) \to 1$.
- We have found a region of parameter space in MSSM allowed by heavy flavour physics, CDM constraints, constraints from the XENON100 experiment on the DM direct detection cross-section.
- Both ATLAS & CMS searches on $H/A \to \tau^+\tau^-$ and $H^\pm \to \tau^+\nu_\tau$ from ATLAS collaboration severely constraint the parameter space : $130~\mathrm{GeV} < M_A < 200~\mathrm{GeV}$ and $150~\mathrm{GeV} < M_{H^\pm} < 200~\mathrm{GeV}$.
- For these ranges of M_A and $M_{H^\pm}$, $\tan\beta \sim 3 - 5.5$.
- We have shown that at the LHC it will be difficult to probe directly 98 GeV Higgs boson scenario, due low signal significance.

Work in progress..

- The most recent data (at 2σ) on Higgs search still allow MSSM parameter space where one can have simultaneously 98 GeV and 125 GeV Higgs boson.
- More precise measurement on Higgs may be able to rule out this scenario indirectly.
- ILC is an ideal machine to explore this possibility.

Thank You!

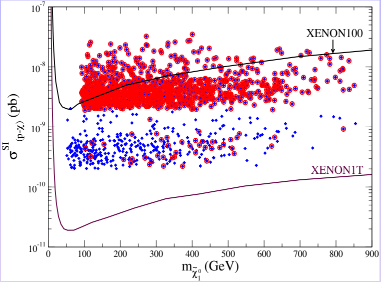
References

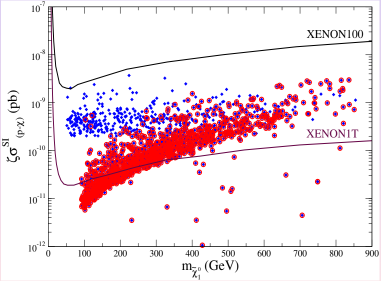
1. B. Bhattacherjee et. al., arXiv:1305.4020 [hep-ph].
2. R. Barate *et al.* [LEP Higgs WG], Phys. Lett. B **565**, 61 (2003).
3. T. Plehn et. al., Phys. Rev. Lett. **104**, 111801 (2010).
4. J. Butterworth et. al., Phys. Rev. Lett. **100**, 242001 (2008).
5. ATLAS Public NOTE: ATL-PHYS-PUB-2009-088

Backup slides

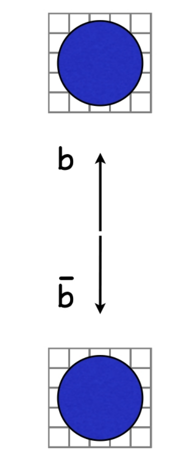
Dark matter direct detection

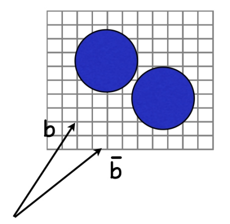
- Exclude points with over-abundant relic densities, include the possibility of multi-component dark matter.
- $\tilde{\chi}_1^0$-$\tilde{\chi}_1^\pm$ coannihilation: $\tilde{\chi}_1^0$ a pure bino & $\tilde{\chi}_1^\pm$ is pure wino.
- Heavy sleptons: no coannihilation with LSPs.
- spin-independent direct detection $\tilde{\chi}_1^0 - p$: Region above the solid (black) line discarded via XENON100 data
- Scaled cross-section ($\zeta\sigma^{SI}_{p\tilde{\chi}_1^0}$): under-abundant relic densities. $\zeta = \min\{1, \Omega_{\tilde{\chi}_1^0} h^2/(\Omega_{CDM}h^2)_{\min}\}$, where $(\Omega_{CDM}h^2)_{\min} = 0.112$
- Possibility at future direct-detection experiment XENON-1T





No Boost vs Boost

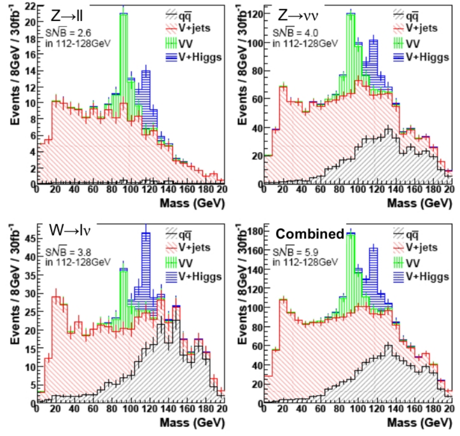




$m_H = 120$ GeV, $p_T \gtrsim 200 - 300$ GeV $\Longrightarrow$
large boost $\Longrightarrow$ $\Delta R \approx 2m_H/p_T \approx 1.2 - 0.8$
$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

$H \to b\bar{b}$ at rest $\Longrightarrow$ Two back to back jets

G. Kribs talk @ Fermilab (2011)



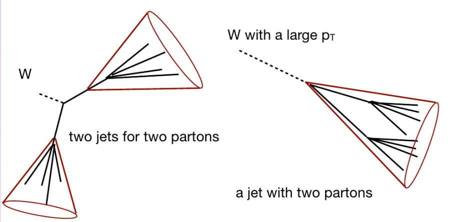
- $pp \to VH$, with $V = W^{\pm}, Z \Longrightarrow$
- $\ell\nu b\bar{b}$, $\ell\ell b\bar{b}$, $\nu\bar{\nu}b\bar{b}$ final state
- For Higgs to be boosted $p_T(H) > 200$ GeV
- Such a high $p_T(H) \Longrightarrow$ $\sigma_{\rm boosted}(WH/ZH) \sim 5\%$ of $\sigma_{\rm tot}(WH/ZH)$ @ 14 TeV

- ATLAS simulation @14 TeV with 30fb^{-1} luminosity : $N_S(m_H \sim 120~\mathrm{GeV}) \sim 13.5$ and $N_B \sim 20.3 \Longrightarrow \frac{S}{\sqrt{B}} = 3$

[J.Butterworth *etal.*, PRL (2008)], ATL-PHYS-PUB-2009-088, G. Kribs talk @ Fermilab (2011)

Fat jets

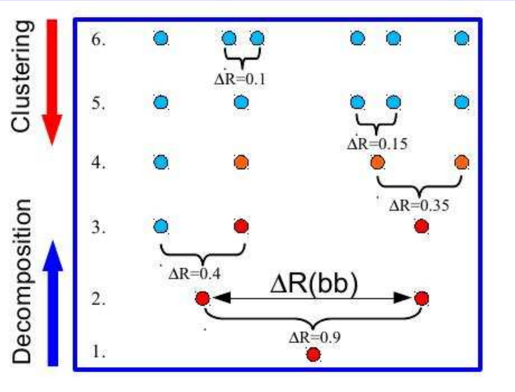
- Quantitatively, consider the following thumb rule for a two-body decay: To resolve the two partons of a $X \to q\ \bar{q}$ decay,choose a radius (or more generally a jet size) of $R < 2M_X / P_T$
- For $P_T \gg M_h$ $R \to$ very small (Overlap of Jet areas !)
- **These highly boosted jets are called "Fat Jets"**
- Example: Consider a hadronically decaying W Boson..



- Question : How do I see the inside of this fat jet ?

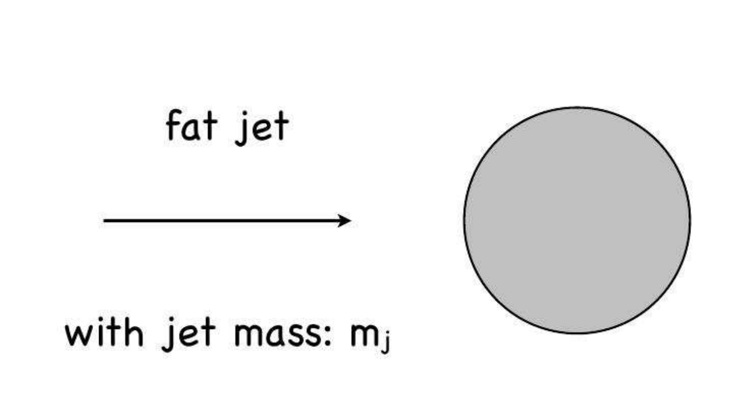
Jet Substructure

The basis of this technique involves an iterative jet clustering algorithm (e.g C/A), examining subjet kinematics step-by-step, and finally choosing the "best" subjets to form the fat-jet mass.



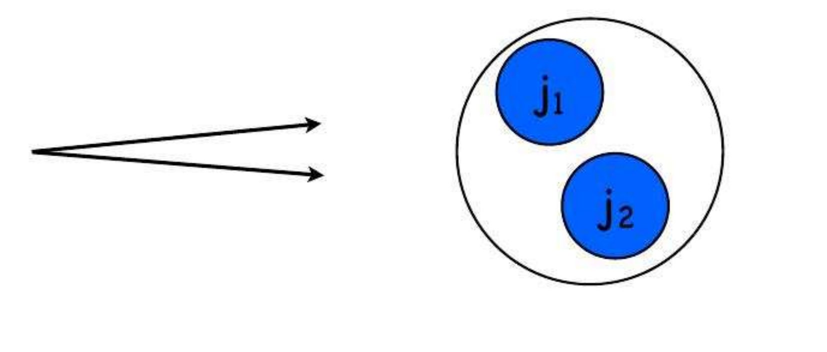
**Ref: Phys. Rev. Lett. 100.242001, Butterworth, Davison, Rubin & Salam

Jet Decomposition 1



Jet Decomposition 2

Step 1: Break the jet j into two subjets(j_1,j_2) by undoing its last stage of clustering s.t $m_{j_1} > m_{j_2}$.



Jet Decomposition 3

Step 2: a) Significant mass drop (MD),

$$m_{j_1} < \mu m_j$$

b) Splitting is nearly Symmetric

$$y = [min(P^2_{T_{j_1}}, P^2_{T_{j_2}})/m^2_j]\Delta R^2_{j_1,j_2} > y_{cut}$$

- Two parameters μ and y_{cut} are independent of Higgs mass and Higgs p_t.
- $$\mu = 0.667$$ $$y_{cut} = (0.3)^2$$

$\Rightarrow$ Helps to reject/minimize QCD contamination.

Jet Decomposition 4

Step 3: If y$>$ y_{cut}, consider j as heavy particle neighborhood and exit the loop.

Otherwise

Redefine j to be j_1 and go back to Step 1.

In practice, above procedure is not optimal for LHC, when the transverse momentum can be around 250-300 GeV.
Since,

$$m_x \sim 150 \text{ GeV} \quad \Rightarrow \quad R_{j_1,j_2} \sim 1.0 \rightarrow \text{Large}$$

$\Rightarrow$ Significant degradation due the Underlying Events (UE)

$\rightarrow$ UE $\propto R^4_{j_1,j_2}$

Filtering

- To minimize UE contamination $\Rightarrow$ Filter the subjets j_1, j_2 within a finer angular region, $R_{filt} < R_{j_1,j_2}$
- Consider 3 hardest p_T subjets 2b & gluon
- Most Effective result (In the context of Higgs search) $\Rightarrow$ $R_{filt} = min(R_{j_1,j_2}/2, 0.3)$
- (provided, both the subjets have tagged b's)