Higgs boson as a probe for physics beyond the SM at the LHC

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4th July 2012: Discovery of SM Higgs-like particle at CERN LHC

- Precision study, Higgs couplings, better fit ...
- Use as a *tool* for new physics.

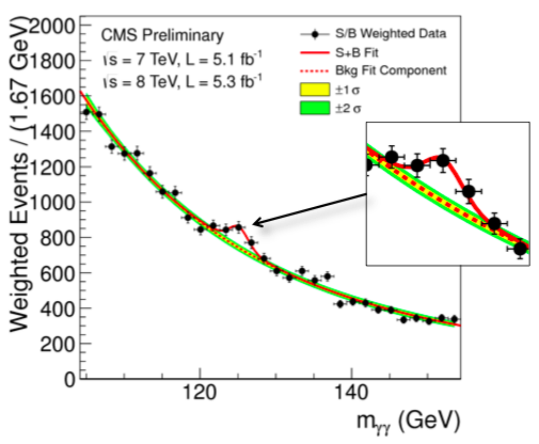
Could it be (say) one of the many Higgses predicted in SM extensions ?

- Higgs mixes with other scalars; How much mixing is allowed with present data ?
- Cascade decay of new physics particles; we understand Higgs decay objects, use the knowledge for BSM physics !
- Higgs as a *portal* for DM sector.

Higgs: best "probe" of new physics resonances !

Higgs Discovery !

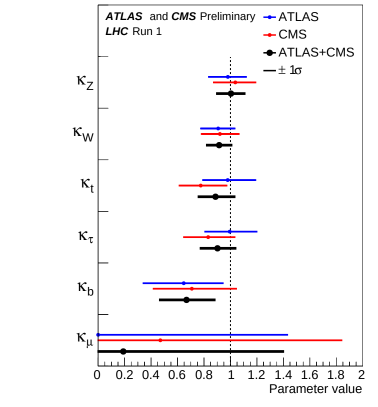
- **Mass**:
  $125.4 \pm 0.37(stat) \pm 0.18(sys)$ GeV [ATLAS]
  $125.7 \pm 0.3(stat) \pm 0.3(sys)$ GeV [CMS].
- **Spin** $= 0^+$ preferred (at 97.8% C.L. over 0^-)
- Decay width < 22 MeV [CMS-HIG-14-002]

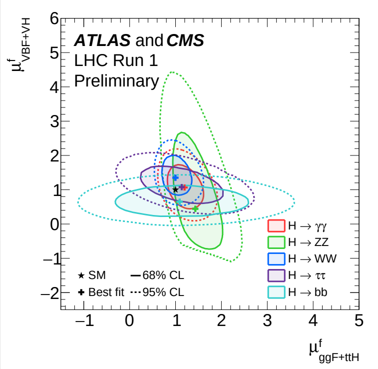


Does it behave as we expect in SM ?

[Phys. Lett. B **716**, 1 (2012) (ATLAS), Phys. Lett. B **716**, 30 (2012) (CMS)]

It's VERY SM-like





$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_{\rm SM}}, \qquad \mu_i^f = \frac{\sigma_i \times {\rm BR}^f}{(\sigma_i)_{\rm SM} \times ({\rm BR}^f)_{\rm SM}}$$

Uncertainties in Higgs coupling measurement

$\Rightarrow$ **Room for Beyond SM physics !**

Search Strategy

Direct search

- Direct production at LHC
- Cascade decay of new physics particles
- Highly suppressed SM processes

Indirect search

- Measure Higgs couplings precisely (ILC ?)
- Differential distributions

• **Many candidate new physics models e.g., SM+singlet, 2HDM, MSSM, NMSSM, Extra dimension models, ...**

• **Focus:**

  • **Minimal SUSY extension (MSSM)**
  • **Light Higgs ($\leq$ 100 GeV) & Heavy Higgs ($\geq$ 200 GeV)**

Disclaimer:

Impossible to cover all the results, Interesting subsets only !!

- Bosonic state transforms to fermionic state, and vice versa:

$$\text{Boson} \Longleftrightarrow \text{Fermion}$$

- Every SM particles $\Rightarrow$ its SUSY partners, called sparticles, differ by spin $\frac{1}{2}$.

SM:

- $\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} \nu \\ e \end{pmatrix}_L, u_R, d_R, e_R$
  quarks, leptons
- $W^{\pm}, Z, \gamma, g$
  W, Z, photon, gluon
- $\begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}, \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$
  Higgs

MSSM:

- $\begin{pmatrix} \widetilde{u} \\ \widetilde{d} \end{pmatrix}_L, \begin{pmatrix} \widetilde{\nu} \\ \widetilde{e} \end{pmatrix}_L, \widetilde{u}_R, \widetilde{d}_R, \widetilde{e}_R$
  squarks, sleptons
- $\widetilde{W}^{\pm}, \widetilde{Z}, \widetilde{\gamma}, \widetilde{g}$
  Wino, Zino, photino, gluino
- $\begin{pmatrix} \widetilde{H}_2^+ \\ \widetilde{H}_2^0 \end{pmatrix}, \begin{pmatrix} \widetilde{H}_1^0 \\ \widetilde{H}_1^- \end{pmatrix}$
  Higgsino

SUSY has several attractive features: Stabilization the Higgs boson mass, predicts light Higgs boson, provides DM candidate(s), Gauge coupling unification, ...

- Exact SUSY $\Longleftrightarrow m_e = m_{\tilde{e}} \Leftarrow$ NOT REALIZED IN NATURE, $\Longrightarrow$ SUSY must be broken
- Large number of free parameters (soft SUSY breaking) $\Longrightarrow$ **pheno. rich**

After SUSY breaking and EWSB,

Higgs: $h, H, A, H^{\pm}$

Neutralinos: $\widetilde{\chi}_1^0, \widetilde{\chi}_2^0, \widetilde{\chi}_3^0, \widetilde{\chi}_4^0$

Charginos: $\widetilde{\chi}_1^{\pm}, \widetilde{\chi}_2^{\pm}$

Squarks/Sleptons: $\widetilde{t}_{1,2}, \widetilde{b}_{1,2}, \widetilde{\tau}_{1,2}, ...$

Gluino: $\widetilde{g}$

MSSM Higgs sector

- Tree level: M_A and $\tan\beta = \frac{v_u}{v_d}$
- Higgs mixing: $\frac{\tan 2\alpha}{\tan 2\beta} = \left(\frac{M_A^2+M_Z^2}{M_A^2-M_Z^2}\right)$ OR, $\cos^2(\beta-\alpha) = \frac{M_h^2(M_Z^2-M_h^2)}{M_A^2(M_H^2-M_h^2)}$
- Physical masses:

$$
\begin{aligned}
M_{h,H}^2 &= \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2+M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right] \\
M_{H^\pm}^2 &= M_A^2 + M_Z^2
\end{aligned}
$$

- **Masses of A, H and $H^\pm$ can in principle be arbitrarily large !**

$\Rightarrow$ **Wide mass spectrum**

- **At tree level:** $M_h < M_Z|\cos 2\beta|$

(Enhancement due to large radiative corrections from stop loops)

Tree level couplings

Gauge bosons

$$hZZ, hW^+W^-, ZHA, W^{\pm}H^{\mp}H, \ldots \quad \propto \quad \sin(\beta-\alpha)$$
$$HZZ, HW^+W^-, ZhA, W^{\pm}H^{\mp}h, \ldots \quad \propto \quad \cos(\beta-\alpha)$$

Fermions

$$huu \sim \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha),$$

$$Huu \sim \frac{\sin\alpha}{\sin\beta}, \quad Auu \sim \cot\beta, \quad hdd \sim \frac{\sin\alpha}{\cos\beta}, \quad Hdd \sim \frac{\cos\alpha}{\cos\beta}, \quad Add \sim \tan\beta$$

$$H^{\pm}ud \sim [m_d \tan\beta(1-\gamma_5) + m_u \cot\beta(1+\gamma_5)]$$

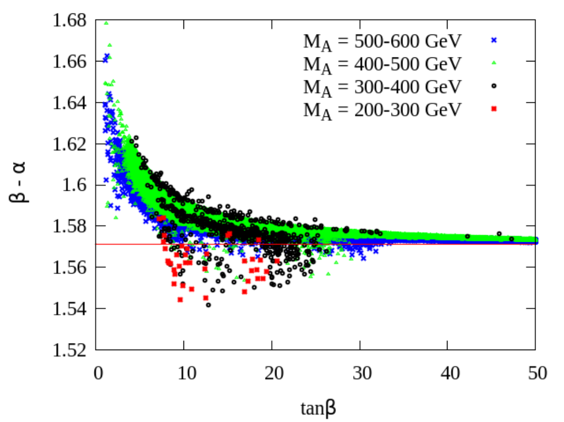
Lighter MSSM Higgs boson $\Longleftrightarrow$ SM Higgs

Decoupling limit:

$M_A >> M_Z$: $\cos(\beta - \alpha) \to 0 \Rightarrow hVV \sim 1, HVV \sim 0, \; hff \to 1$.
ONLY one light Higgs boson in the theory and all other Higgses are very heavy and degenerate
$M_H \sim M_{H^\pm} \sim M_A$.

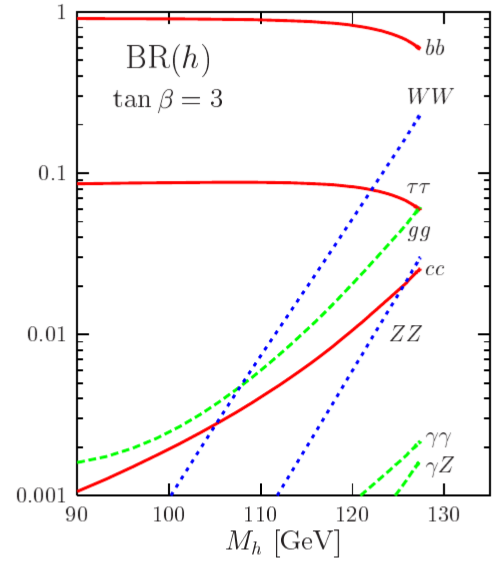
Alignment limit: $(\beta - \alpha) \sim \frac{\pi}{2}$
One SM state with SM tree-level couplings and self-couplings

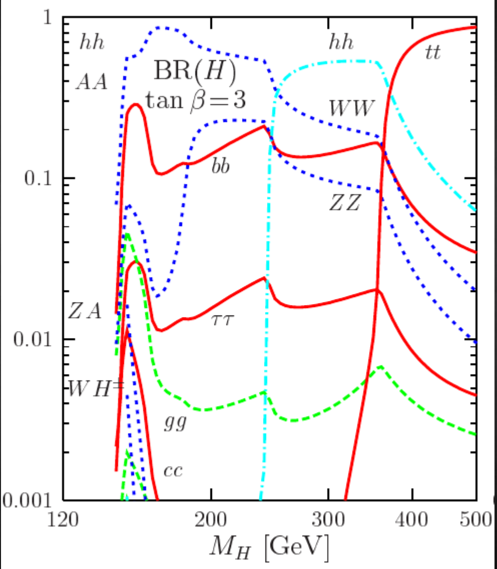
[arXiv: 1310.2248, 1507.00933]



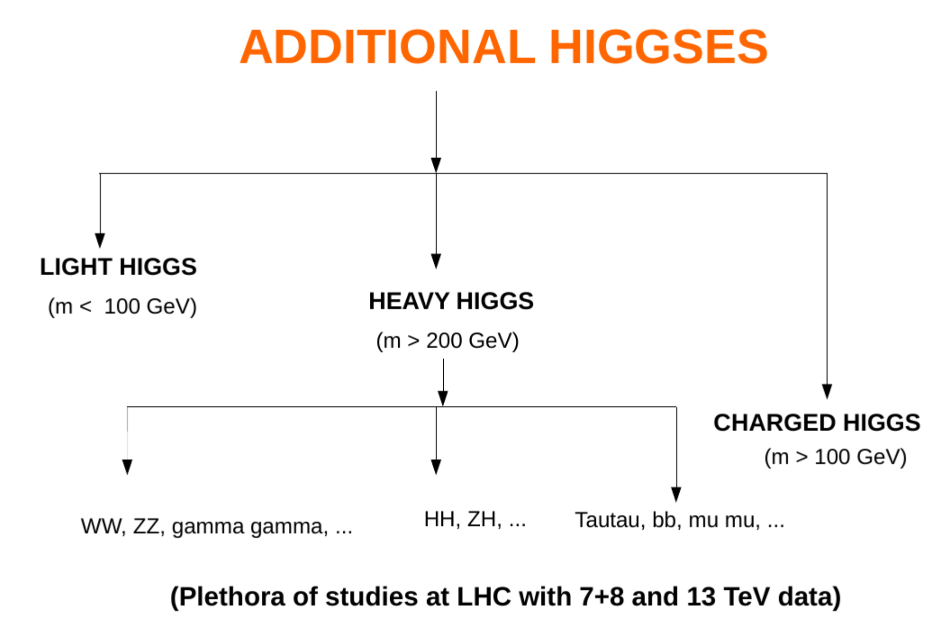
[AC, B. bhattacherjee, A, Choudhury, PRD92, 093007 (2015)]

MSSM Higgs Branching Ratios (BR)





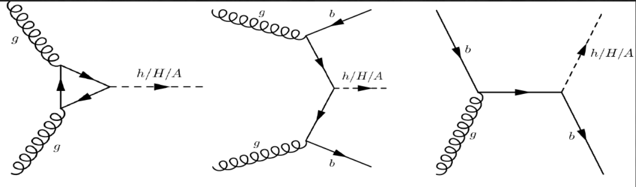
[Anatomy-II by A. Djouadi (hep-ph/0503173)]

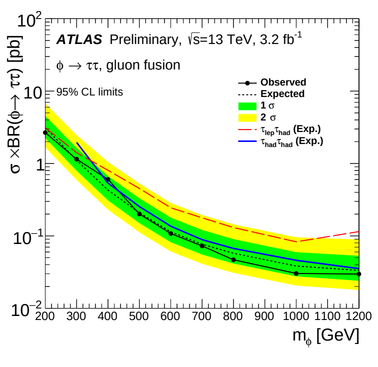


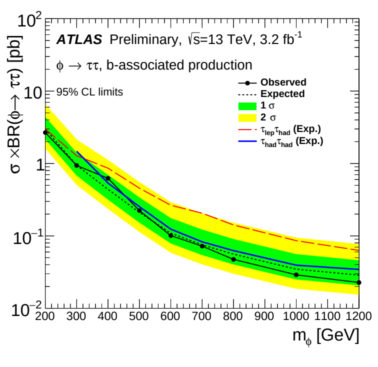
Let's now proceed, heavy neutral Higgs first ...

$H \to \tau^+\tau^-$ [ATLAS-CONF-2015-061]

$H\tau^+\tau^- \sim \frac{\cos\alpha}{\cos\beta}$
$A\tau^+\tau^- \sim \tan\beta$
$\phi b\bar{b} \sim \tan\beta$
Large Xsec, stronger bounds

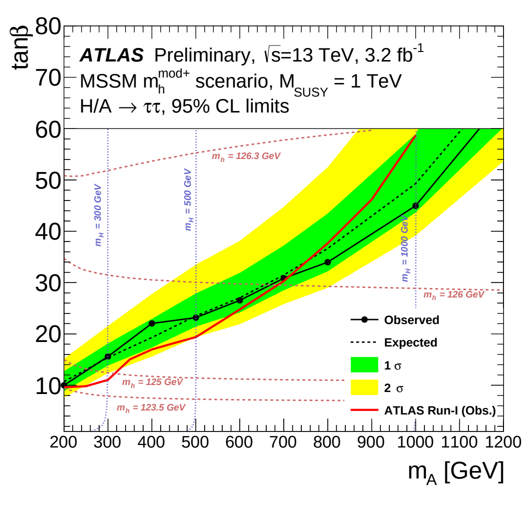






- Atleast one τ decays hadronically, 13 TeV analysis
- Upper limits: $\sigma \times BR$ for production of Φ decaying to $\tau\tau$.

Model interpretation: Inputs are important

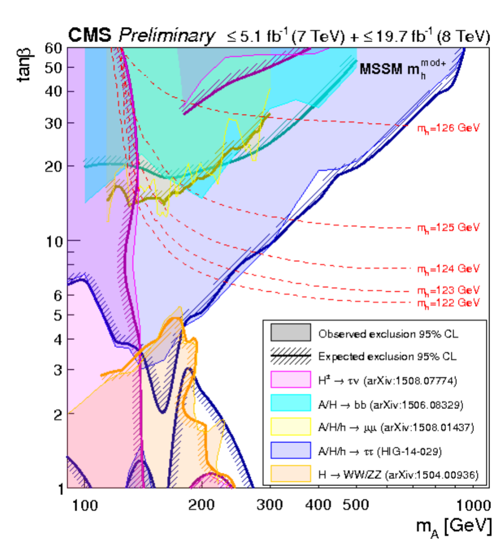


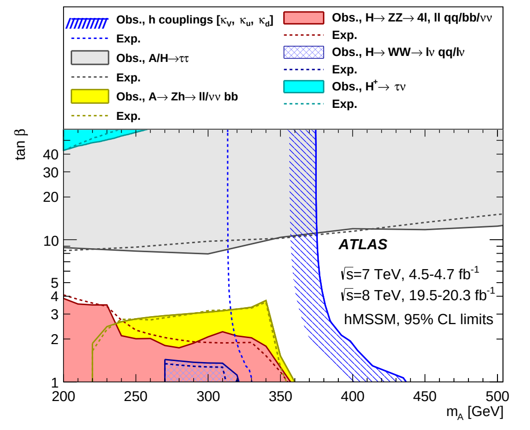
[ATLAS-CONF-2015-061]

Lessons:

- High $\tan\beta$ and small M_A regions are excluded !
- 13 TeV limits are already comparable with 8 TeV data.

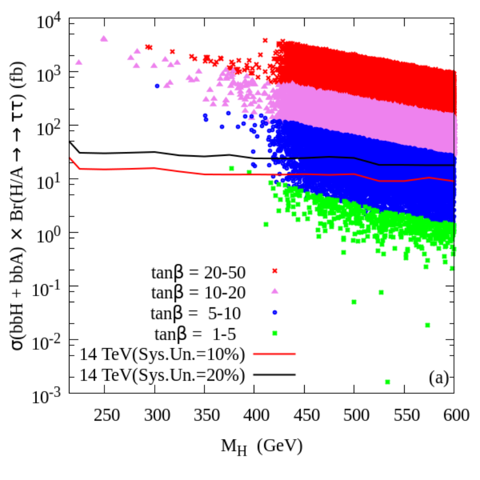
Combined Limits: Direct and Indirect searches

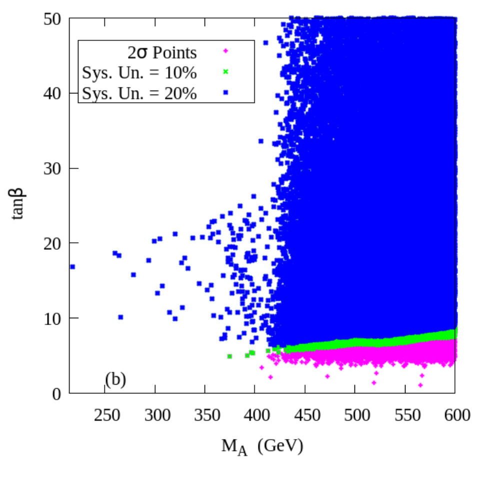




- **Higgs coupling, equally sensitive**
- $M_A > $ **350 GeV:** $t\bar{t}$ **study !**
- Di-Higgs: 250 - 350 GeV, already by $H \rightarrow ZZ$, $A \rightarrow Zh$

Sensitivity @HL-LHC





- Regions with $\tan\beta > 20$ are already excluded by LHC-8 data.
- Up to $\tan\beta \sim 8$ can be probed at the HL-LHC.

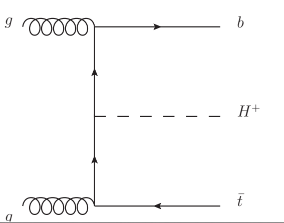
[AC, B. bhattacherjee, A, Choudhury, PRD92, 093007 (2015)]

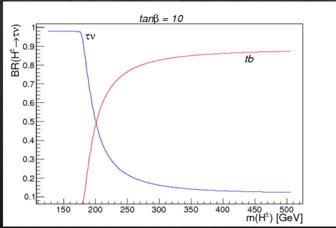
Charged Higgs

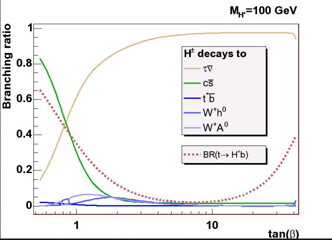
Light $H^{\pm}$: top decay, $t \to bH^{+}$.

Heavy $H^{\pm}$: Associated production with a top and bottom quark

$$H^{\pm}ud \quad \sim \quad [m_d \tan\beta(1-\gamma_5) + m_u \cot\beta(1+\gamma_5)]$$

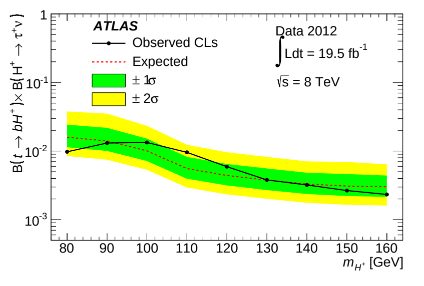


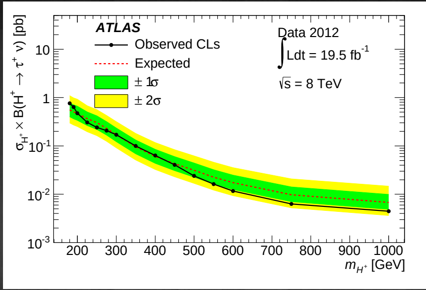


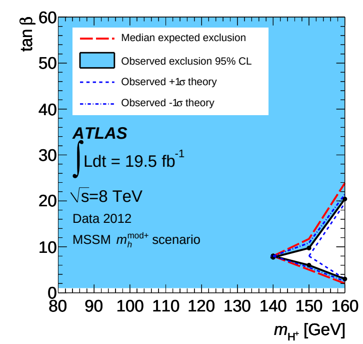


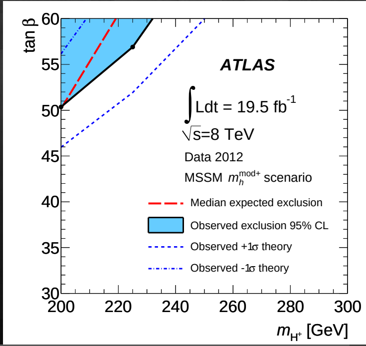
Decay: $\tau\nu_\tau$, $c\bar{s}$ and $t\bar{b}$, depends on $\tan\beta$ regime.

Charged Higgs: 1412.6663 (CMS), 1508.07774 (ATLAS)

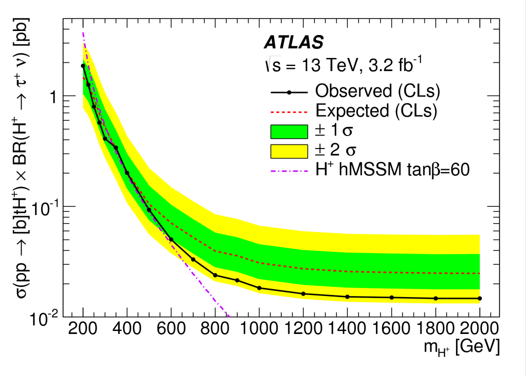


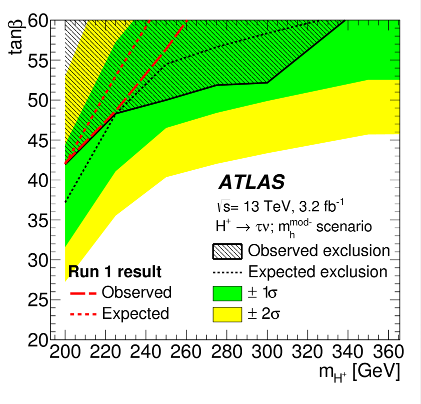






Charged Higgs: 13 TeV [arXiv:1603:09203]





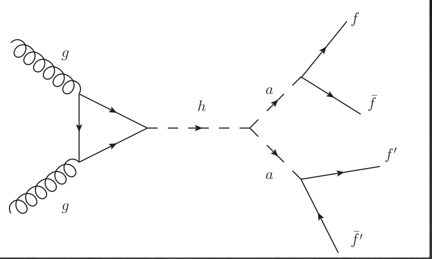
Already compareable with 8 TeV results, even better for large $\tan\beta$ **!**

Light Scalars

- **After LHC Run-1:**
  $\mathrm{BR}(h \to \mathrm{BSM}) < 34\%$.

  [CMS-PAS-HIG-15-002, ATLAS-CONF-2015-044 (ATLAS)]

- Room to fit **'Exotic'** Higgs decays !
- Example: NMSSM, 2HDM+S, ...



Many Possible final states:

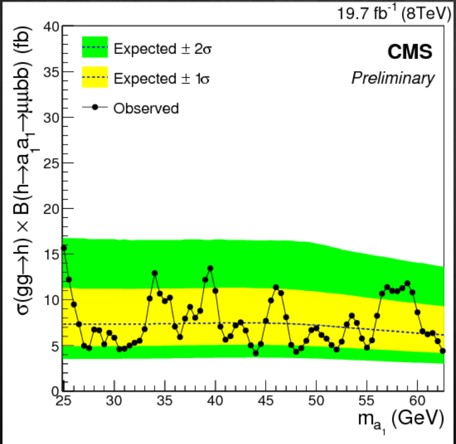
- $2\mu2\tau$ - 1505.01609 (ATLAS), CMS-PAS-HIG-15-011
- $2b2\mu$ - CMS-PAS-HIG-14-041 (CMS)
- 4μ - CMS PAS HIG-13-010 (CMS)
- 4τ - 1510.06534, CMS-PAS-HIG-14-022 (CMS)
- 4γ - 1509.05051 (ATLAS)

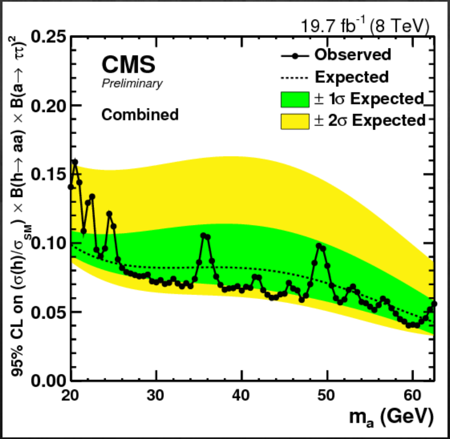
Note:

- FS with μ: stringent limits
- Fully hadronic: QCD dominated, weak bounds

Higgs decaying through $2b2\mu/\ 2\tau2\mu$: CMS 8 TeV

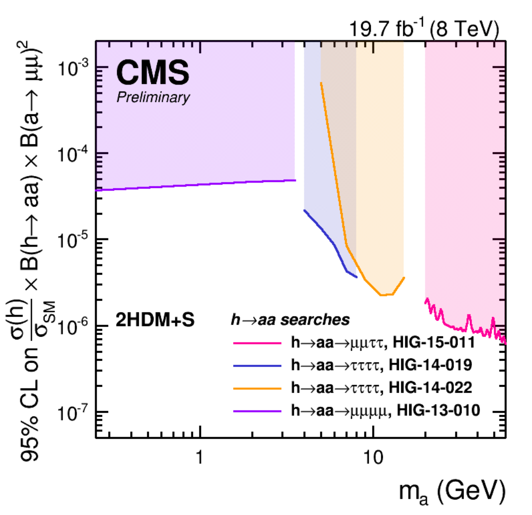
- Mass region: 20 - 62.5 GeV
- Upper limit on $\sigma_{ggF} \times \mathrm{BR}(h \to b\bar{b}\tau^+\tau^-) = 4$ - 12 fb.
- Upper limit on $\frac{\sigma_{ggF}}{\sigma_{SM}} \times \mathrm{BR}(h \to aa) \times \mathrm{BR}(a \to \tau^+\tau^-)^2 = 5$ - 20%.





[CMS-PAS-HIG-14-041, CMS-PAS-HIG-15-011]

CMS-PAS-HIG-15-011

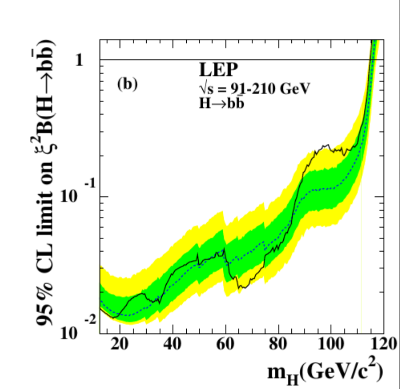


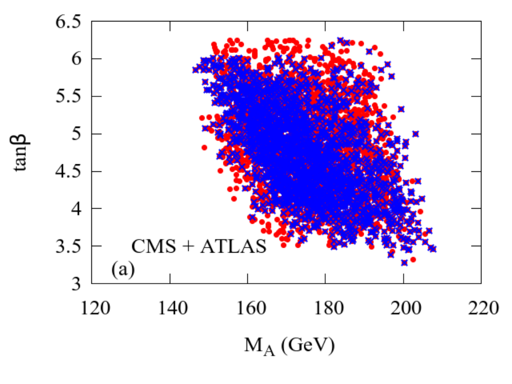
- Light (1 - 20 GeV) scalar via $\mu\mu\tau\tau$ [CERN-PH-EP-2015-057 (ATLAS)]

98-125 GeV Higgs scenario

- $95 \text{ GeV} < m_{H_1} < 101 \text{ GeV}$,
  $124 \text{ GeV} < m_{H_2} < 126 \text{ GeV}$
- $0.1 < \sin^2(\beta - \alpha) < 0.25$

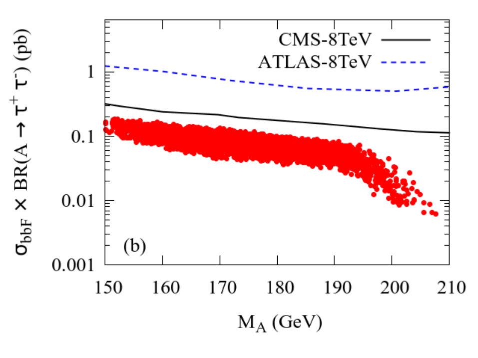
- LHC combined Higgs signal strengths
- Flavour data $Br(b \to s\gamma)$, $Br(B_s \to \mu^+\mu^-)$.

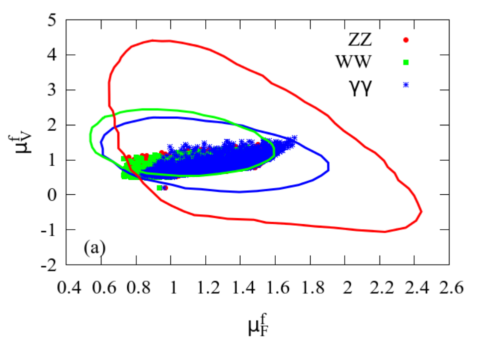




[AC, B. bhattacherjee, M. chakraborti, U. chattopadhyay, D. K. Ghosh, PRD93, 075004 (2016)]

Probing the 98-125 GeV



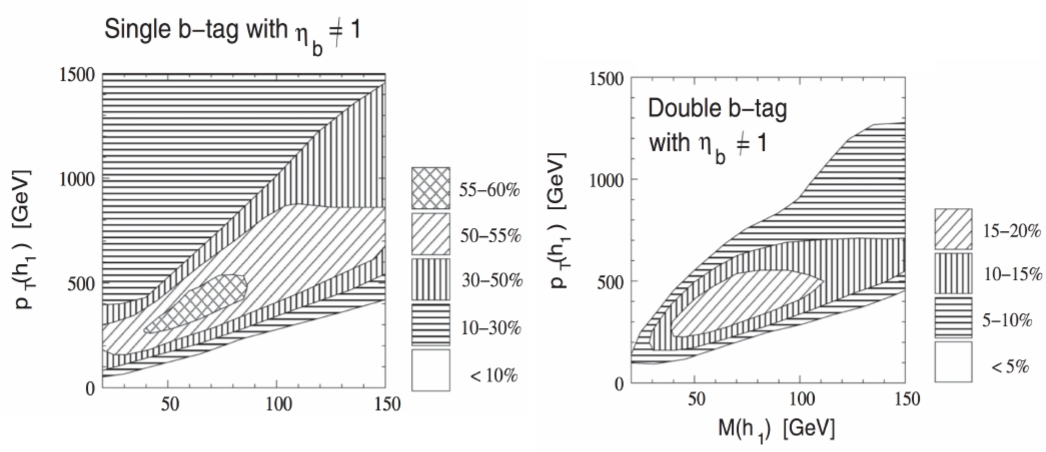


Note:

- Direct detection at LHC is extremely challenging ! (ILC easy)
- Indirect detection: Precise Higgs coupling measurements
- Extremely heavy sparticle spectrum: ample parameter space

[AC, B. bhattacherjee, M. chakraborti, U. chattopadhyay, D. K. Ghosh, PRD93, 075004 (2016)]

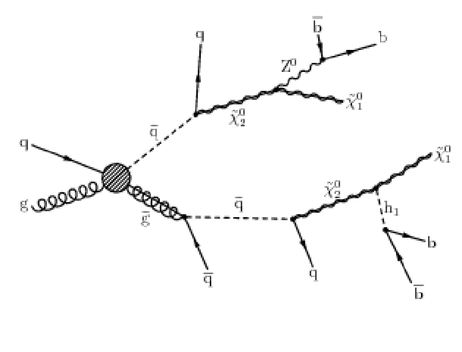
Boosted light BSM Higgs

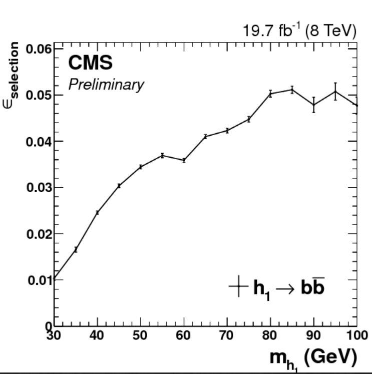


- Used default BDRS Higgs tagger
- Model independent analysis
- For $M \sim 20 - 100$ GeV and $p_T \sim 100 - 500$ GeV: efficiency 5 - 20%.

[AC, B. bhattacherjee, D. K. Ghosh, S. Raychaudhuri PRD86, 075012 (2012)]

Search for a light NMSSM Higgs boson produced in supersymmetric cascades and decaying into a b-quark pair [CMS PAS HIG-14-030]



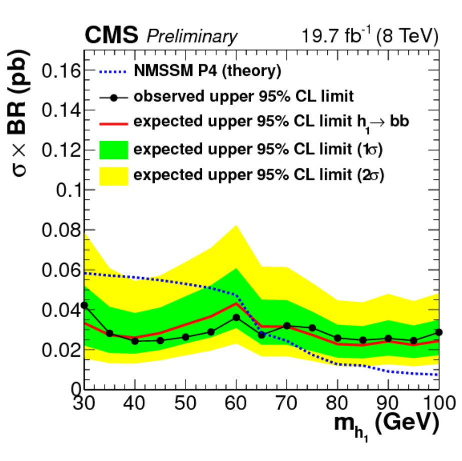


Selection:

- Two leading non b-jets are $p_T > 200$ and 100 GeV.
- $H_T > 600$ GeV.

Results

- Bound on $\sigma(pp \to h_1 + X) \times \mathrm{BR}(h_1 \to b\bar{b})$.
- No indication of a signal is observed.
- Near 60 GeV: transition from the region where $h_2 \to h_1 h_1$ is allowed or not.



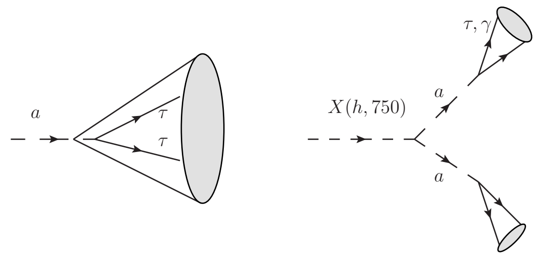
"The measured spectrum is found to be in very good agreement with the expected SM background within statistical and systematic uncertainties"

Universal framework of highly collimated objects

[AC, A. M. Iyer, T. S. Roy (in preparation)]

Goal:

- **Understand** the dominant SM backgrounds: γ, electron, τ and QCD
- **Discriminate** from Di-samples: di-photon, di-electron, di-tau, ...
- Originates from both Light and/or Heavy resonances.
- 750 GeV: collimated photons faking single photon ($R \sim \frac{2m}{p_T}$) !



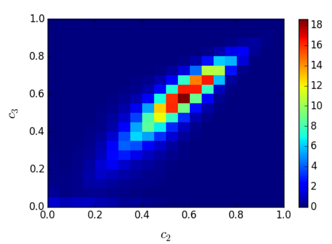
One of the most challenging tasks: QCD vs di-tau discrimination

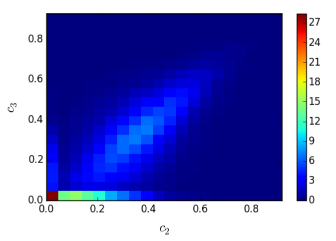
Earlier study “Ditau jets in Higgs searches" by Englart et. al. (Phys.Rev. D84 (2011) 075026)

Universal framework of highly collimated objects

[AC, A. M. Iyer, T. S. Roy (in preparation)]

- Conventional
  - **Number of charged tracks**
  - m_j/p_T^j: **angular scale**
  - θ_J: measure of **hadronic energy**
- Calorimetry based
  - N-subjettiness: τ_{21}, τ_{31}, ...
  - Energy correlation functions and their ratios: R_1, R_2, C_2, C_3, ...





$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k}\min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right\}$$

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\ldots<i_N\in j}\left(\prod_{a=1}^{N} p_{Ti_a}\right)\left(\prod_{b=1}^{N-1}\prod_{c=b+1}^{N}\Delta R_{i_b i_c}\right)^{\beta}$$

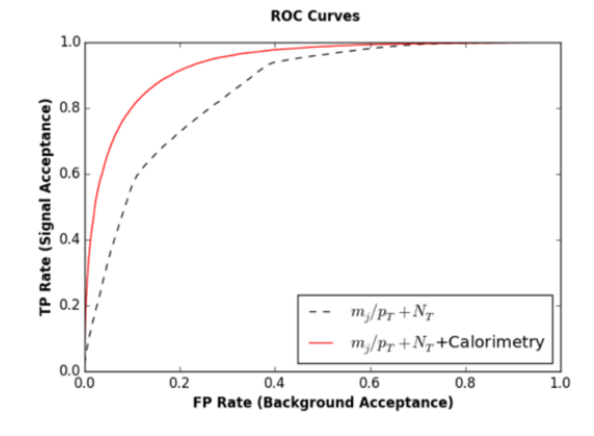
$$R_N^\beta = \frac{ECF(N+1,\beta)}{ECF(N,\beta)}, \qquad C_N^\beta = \frac{R_N^\beta}{R_{N-1}^\beta}$$

[J. Thaler and K. Van Tilburg [JHEP03(2011)015]; A. J. Larkoski, G. P. Salam and J. Thaler [JHEP06(2013)108]]

Universal framework of highly collimated objects

[AC, A. M. Iyer, T. S. Roy (in preparation)]

- **Signal:** $h \to a(\tau\tau)a(\tau\tau)$
- $m_a = 10$ **GeV, sufficient boost**
- **Background: QCD di-jet events**
- **PYTHIA + DELPHES framework**



Significant improvement in QCD-ditau discrimation using calorimetric variables

Summary

- BIG question after the LHC Higgs discovery:
Is the observed Higgs has some connection with BSM physics ? How ?

- Plethora of BSM Higgs searches by ATLAS and CMS:
Only a small subset has been covered.

- Continuous effort with LHC run-2 data.

Thank You