

BSM Higgs: Experimental results, ATLAS+CMS

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on behalf of the ATLAS and CMS collaborations
LHCb Barcelona,
May 13, 2013

Albert-Ludwigs-Universität Freiburg



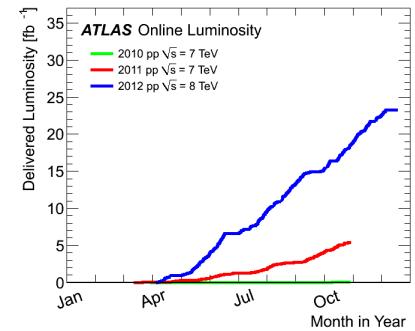
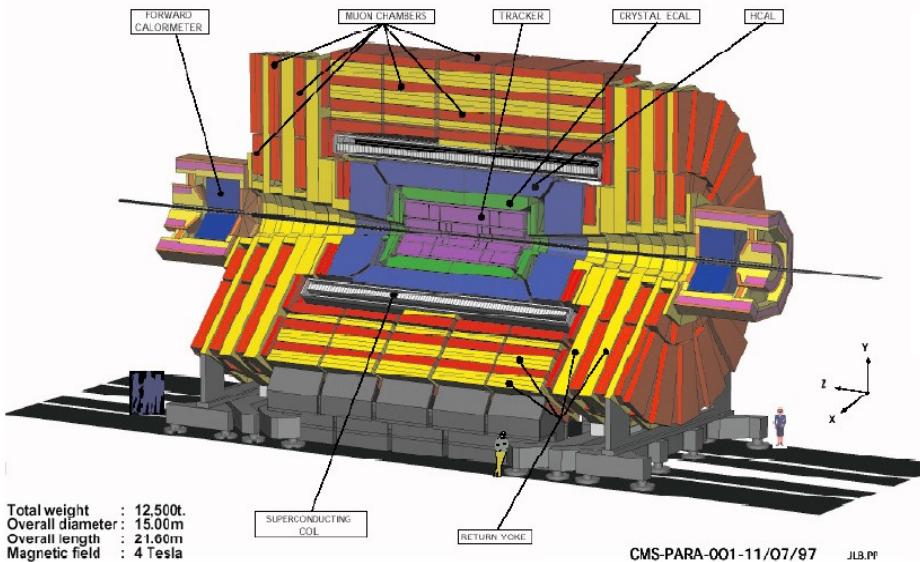
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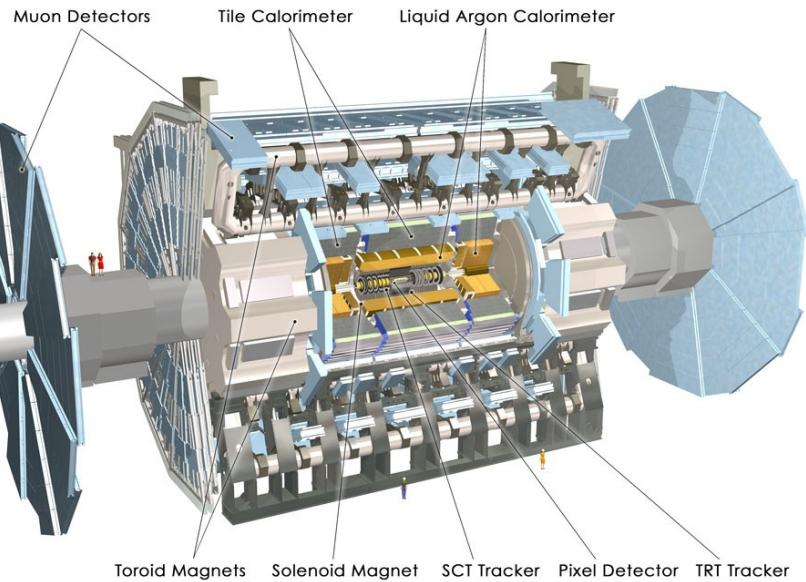
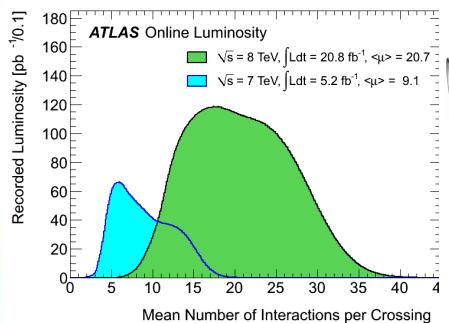


CMS & ATLAS



ATLAS & CMS:

- high data-taking efficiency
- excellent data quality

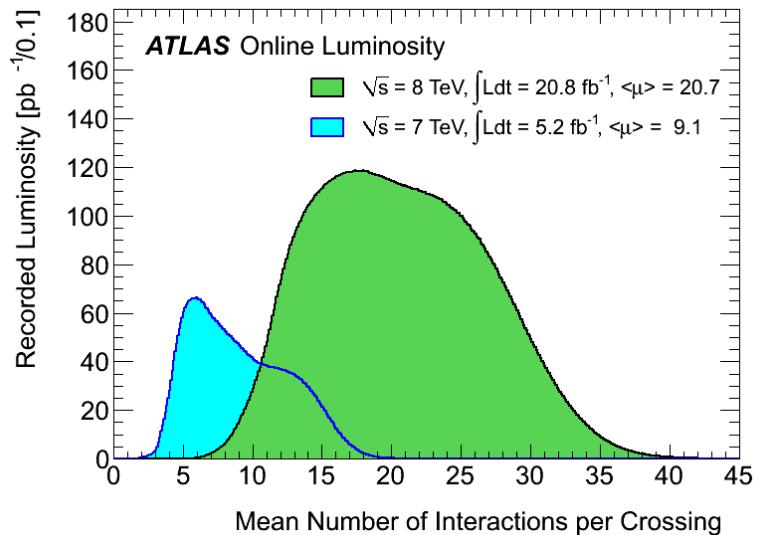


The mission

- Last year's discovery is probably the most important event in HEP in the last 30 years
- It looks like a Higgs boson... how will the story continue?
- ... could turn out to be one of the most boring HEP discoveries
 - Another disappointing triumph of the Standard Model?
 - Time to look for a new job?
- ... or it could be the gateway to new physics
 - Which models are compatible with a 125-GeV boson with fairly SM-Higgs-like properties?
 - To which of these models are we sensitive at the LHC?
 - If more Higgs bosons are around the corner:
are we watching the right corners?

Outline

- MSSM-inspired searches
 - $H^+ \rightarrow c\bar{s}b\bar{b}$, $H^+ \rightarrow \tau\nu$
 - $H \rightarrow WW$, $H \rightarrow bb$, $H \rightarrow \tau\tau/\mu\mu$
- NMSSM-inspired searches
 - $a_1 \rightarrow \gamma\gamma$
- Generic / exotic Higgs searches
 - Heavy Higgs $\rightarrow WW/ZZ$
 - Invisible Higgs, ZH
 - Doubly charged Higgs
 - Fermiophobic Higgs
 - 4th generation
- Not covered: mX125 properties => see SM Higgs talks
 - Indirect search for BSM physics in the Higgs sector

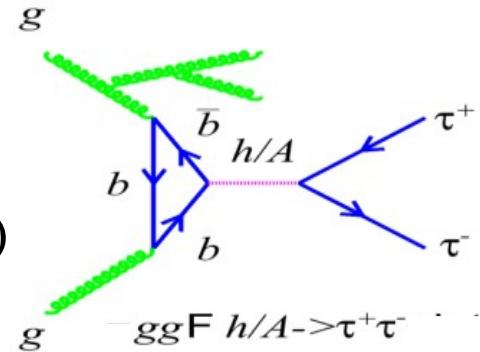


Not covered ($L < 5/\text{fb}$):

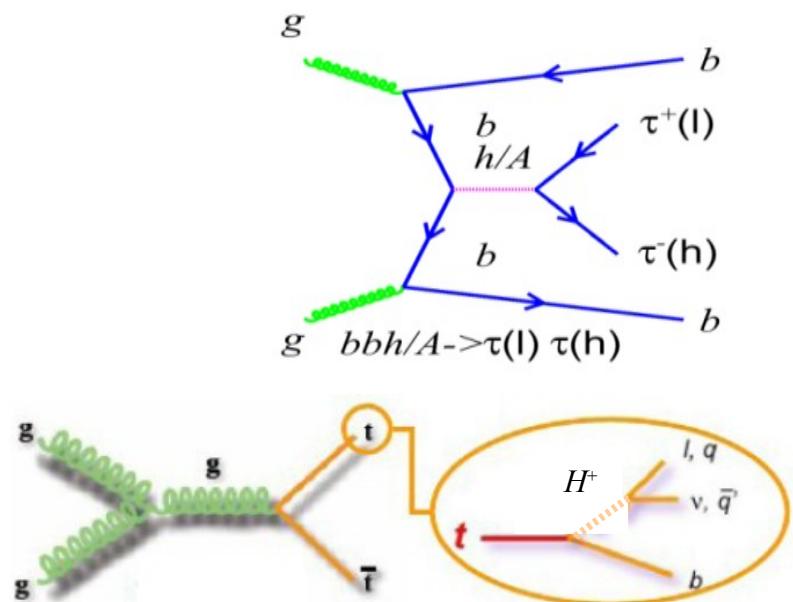
- Higgs to long-lived particles
- Higgs to electron jets
- Higgs to displaced muon jets
- $a_1 \rightarrow \mu\mu$

Overview: MSSM Higgs sector

- Higgs sector of the MSSM: 2HDM (type II)
 - 5 Higgs bosons $h/H/A$, H^+ , H^-
 - Higgs sector: at tree level, determined by two (add.) parameters: $\tan \beta = v_1/v_2$ and m_A (or m_{H^\pm})

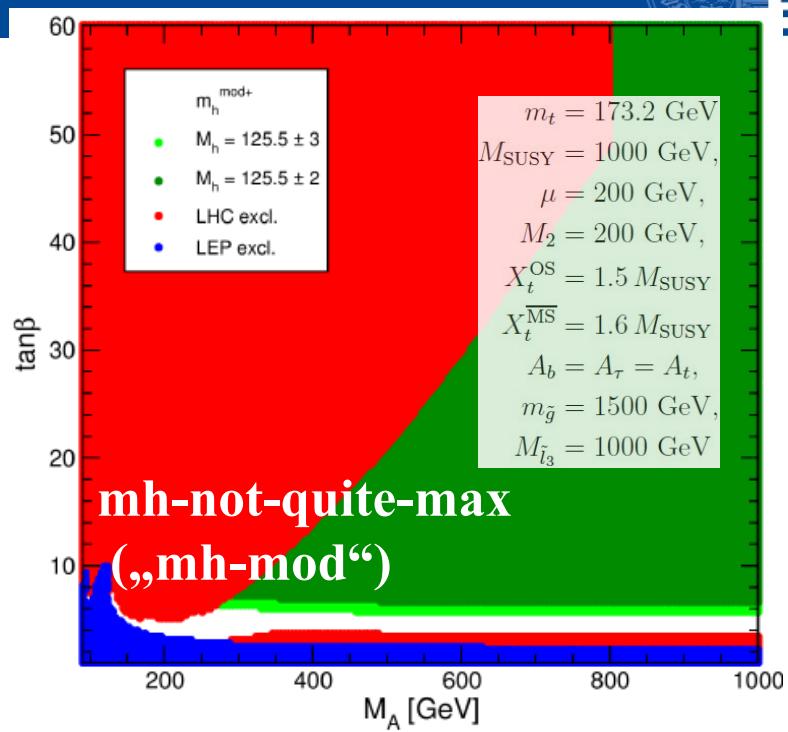
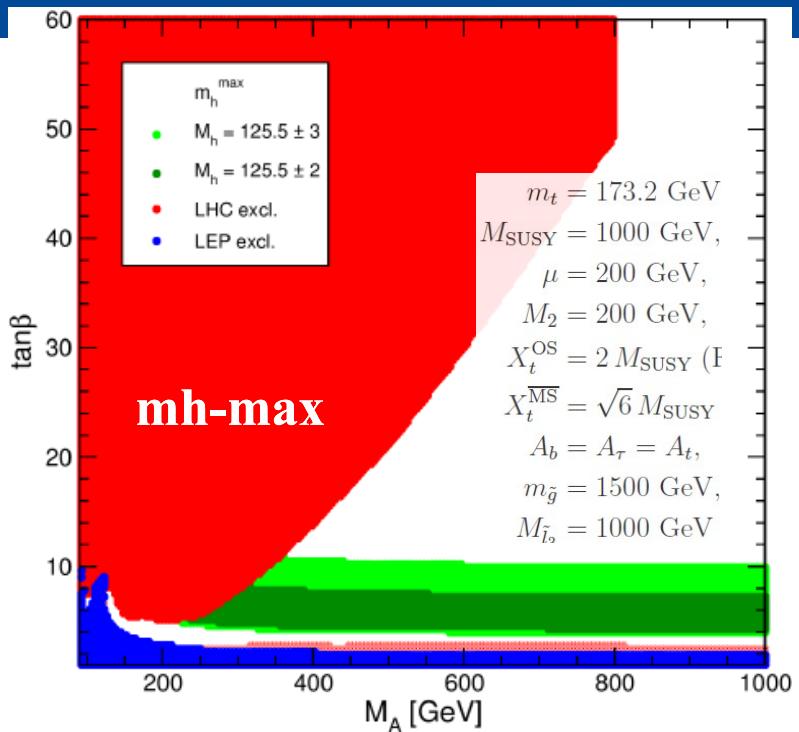


- Major Higgs production modes:
 - $h/H/A$: gg-fusion, b -associated
 - Light H^+ : top quark decays
 - [Heavy H^+ : gg/gb -fusion]
- Dominant decay modes
 - $h/H/A \rightarrow b\bar{b}$, $\tau\tau$
 - Light $H^+ \rightarrow \tau\nu$, small $\tan \beta$: $H^+ \rightarrow c\bar{s}$



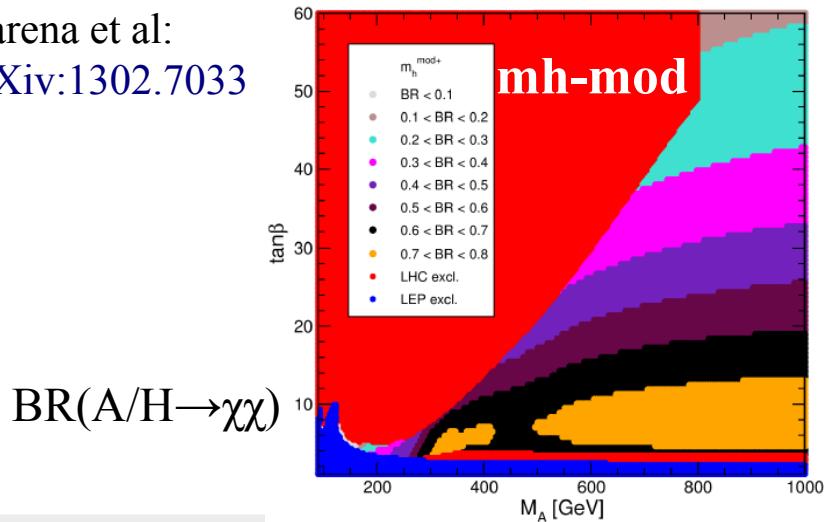
Couplings to b , τ enhanced wrt SM for large $\tan \beta$

MSSM and $m_h=125.5$ GeV?



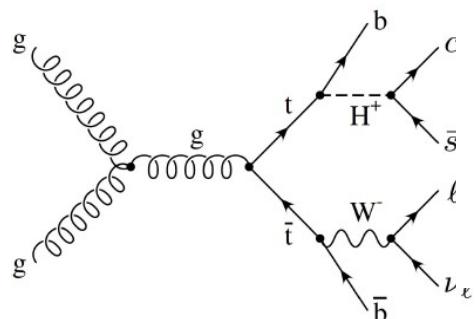
- Most of m_A - $\tan\beta$ parameter space compatible with $m_h=125.5$ GeV.
- Small region still allowed also for $m_H=125.5$ GeV. H^+ searches can access this region.

Carena et al:
[arXiv:1302.7033](https://arxiv.org/abs/1302.7033)



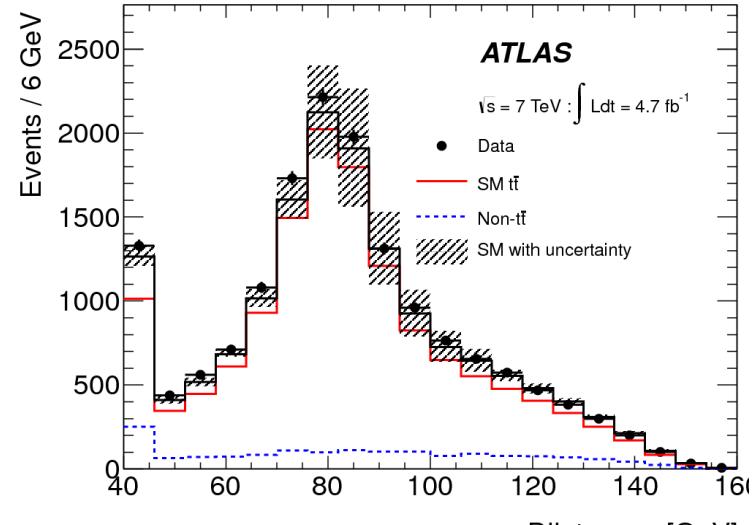
H⁺ → csbar

- Idea: find 2nd mass peak in dijet distribution of ttbar lep+jets events
MSSM: Sizable for $\tan \beta < 1$

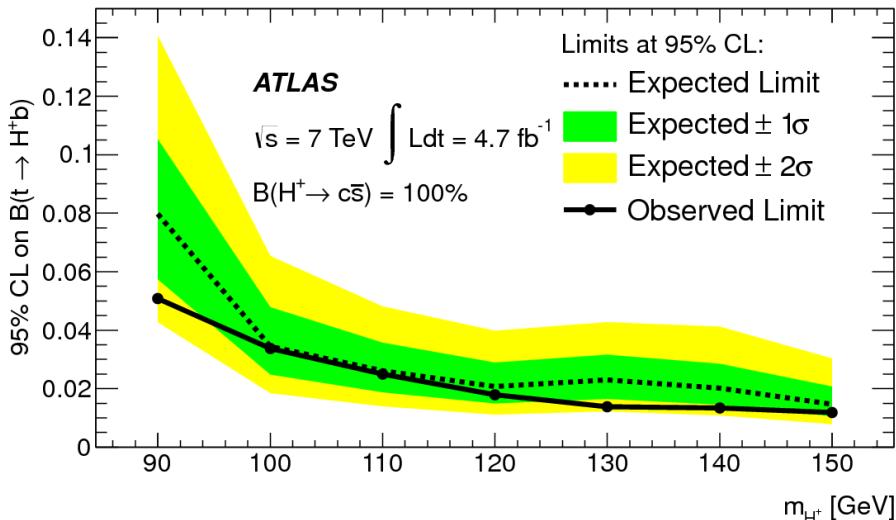


- Event selection:
 - isolated lepton
 - 4 jets (2 b-tagged)
 - MET, mT(lep+MET)
 - Kinematic fit of the whole event

- Agreement with SM expectation
 - Limit on $B(t \rightarrow bH^+) = (5-1)\%$ for $m_{H^+} = 90-150$ GeV, assuming $B(H^+ \rightarrow c\bar{s}) = 100\%$



arXiv:1302.3694

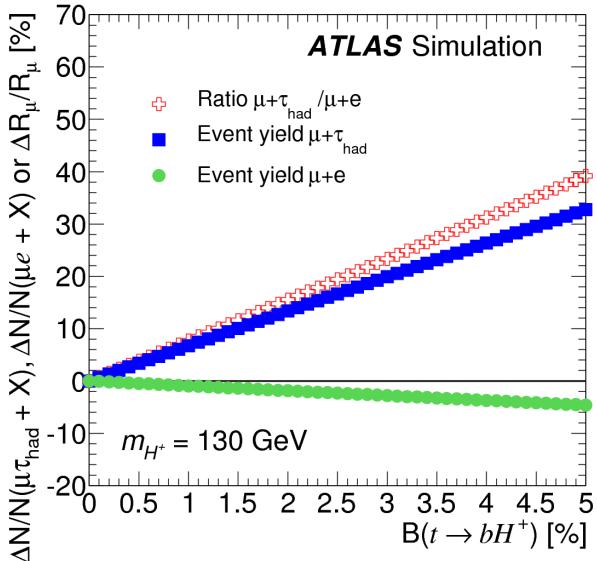


Light H⁺ → τν

- Production in ttbar decays $t\bar{t} \rightarrow bH^+ + bW$, $H^+ \rightarrow \tau\nu$

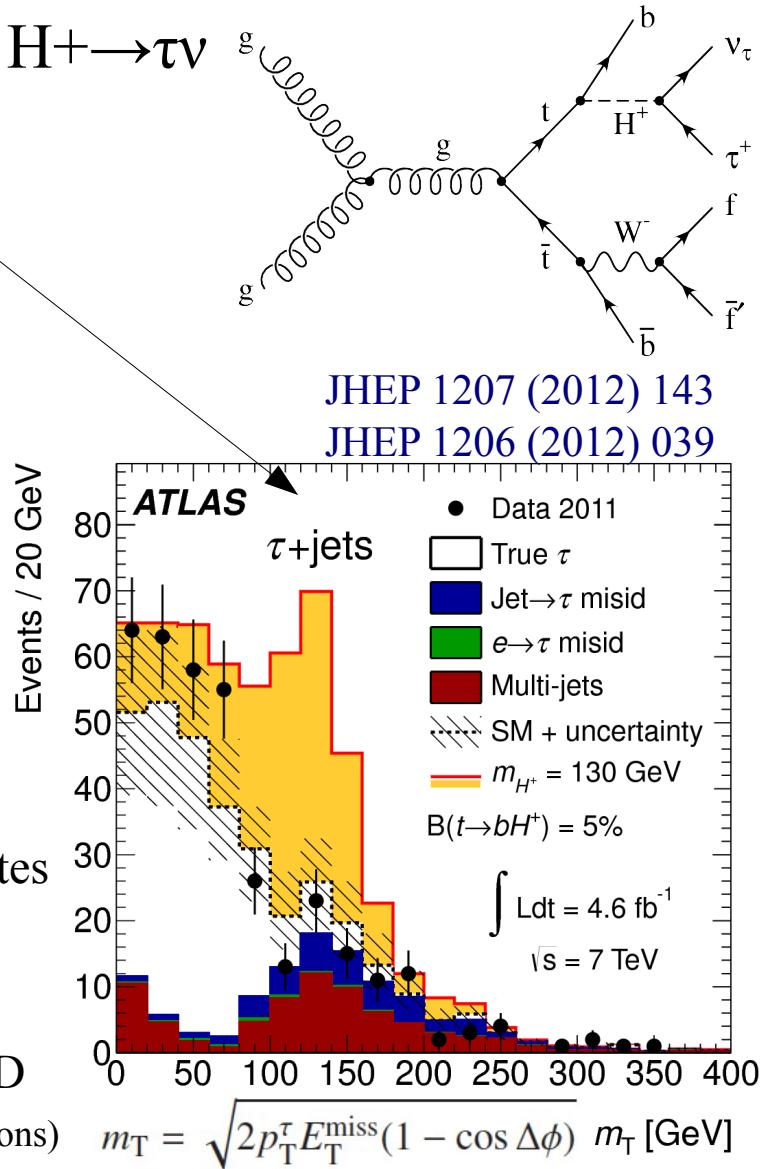
- $\tau_{\text{had}} + \text{jets}$: mT as final discriminant
- $\tau_{\text{had}} + \text{lep}$: measure ratio ($\tau + \text{lep}/\text{dilep}$), assuming lepton universality for SM

Ratio	R_e	R_μ
SM value	0.105 ± 0.012	0.166 ± 0.017
Measured value	$0.115 \pm 0.010 \text{ (stat)}$	$0.165 \pm 0.015 \text{ (stat)}$



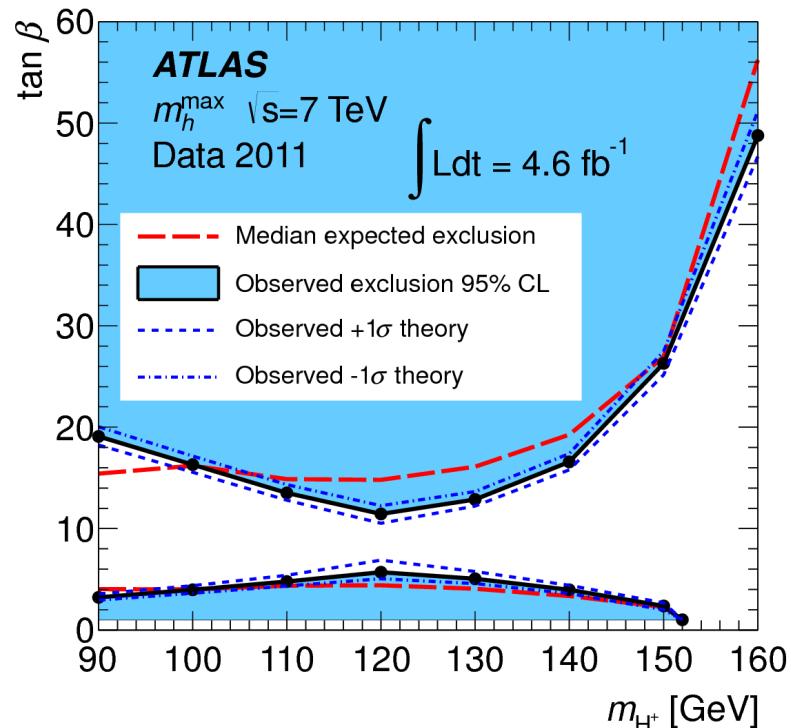
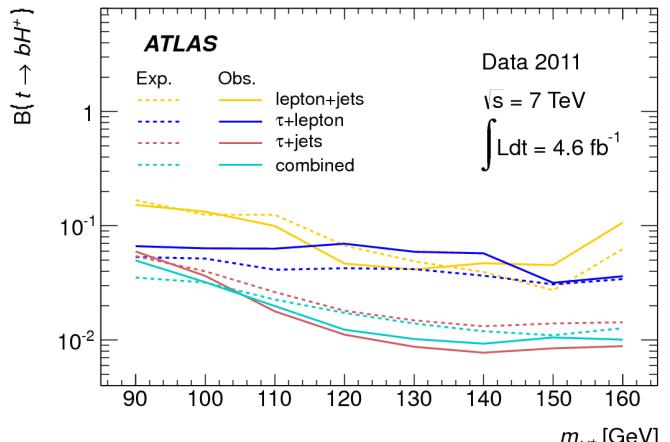
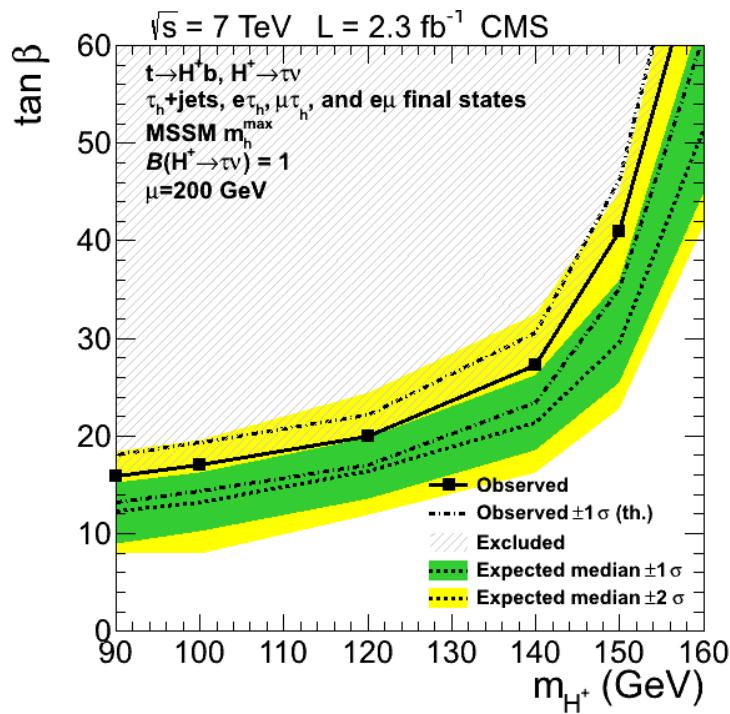
ratio: changes by 40%
for $B(t \rightarrow bH^+) = 5\%$;
systematics cancel

- all background estimates data-driven:
- embedding (true τ)
 - correct MC for MisID prob measured (τ ; leptons)



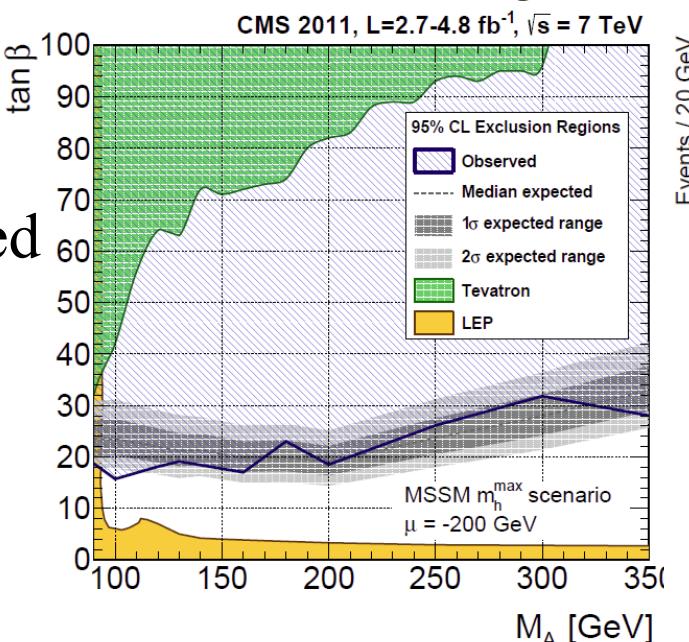
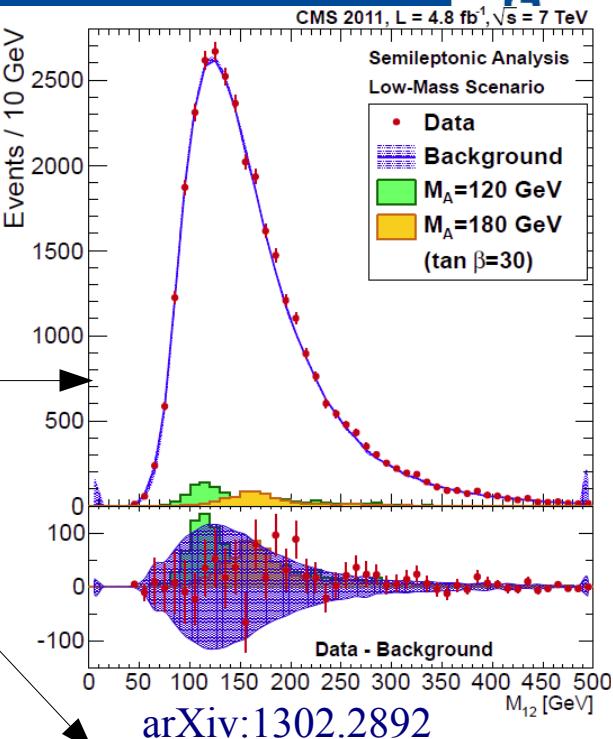
$H^+ \rightarrow \tau\nu$: Limits

- Limit on $\text{BR}(t \rightarrow bH^+)$:
 - 1% for $120 < m_{H^+} [\text{GeV}] < 160$ ($< 5\%$ below)
- MSSM, m_h -max
 - Only small region for low-mass H^+ survives, around minimum of $\tan \beta \approx 8$



MSSM bH \rightarrow bbb

- Selection – two channels:
 - All-hadronic channel: 3 tight b-tagged jets
 - Search split in mH smaller/greater 180 GeV
 - Semileptonic: 2 medium b-tags (pT-leading jets) / 1 loose b-tag; muon overlap with a leading jet
 - Discriminant: Invariant mass of 2 leading b-jets
- Background estimated from data, using 2b-tag /1-btag samples

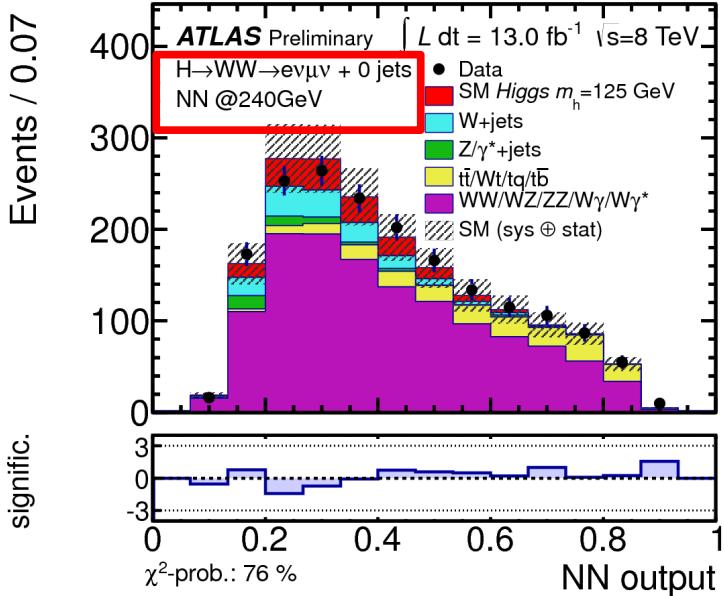


2HDM WW

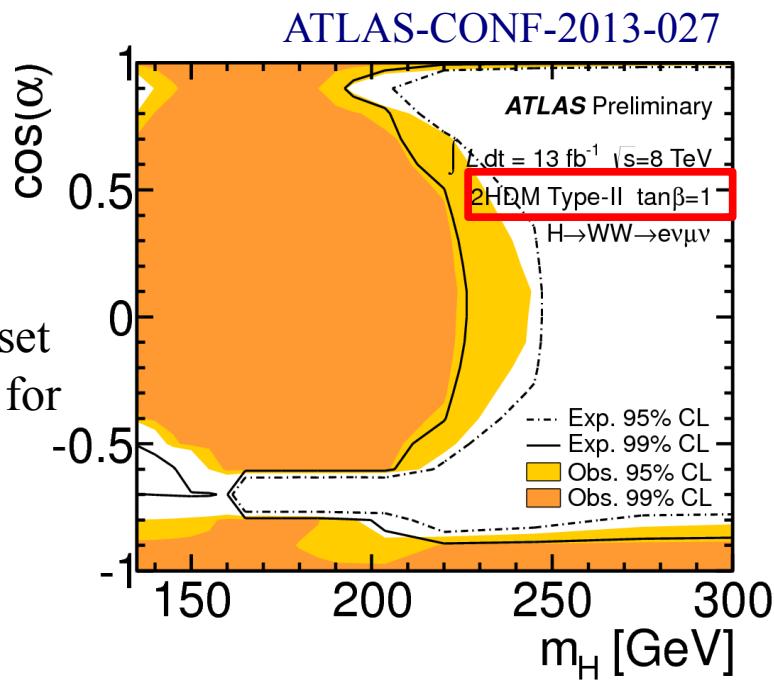
- Search for additional heavier Higgs decaying to WW
 - Using $e\nu\mu\nu+0$ and $+2$ jets, for $m_H=135-300$ GeV
- Preselection in common with SM $H \rightarrow WW$ search; then employs a neural net using kinematic information
- Type-I and type-II 2HDM investigated; signal rates depend on m_H , $\tan\beta$, $\cos\alpha$
 - Assuming other Higgses are too heavy to interfere

Yukawa couplings to right-handed fermions

	Type I	Type II
u	H_u	H_u
d	H_u	H_d
ℓ	H_u	H_d



No excess observed.
 \Rightarrow Produce set of 2D limits for fixed $\tan\beta$



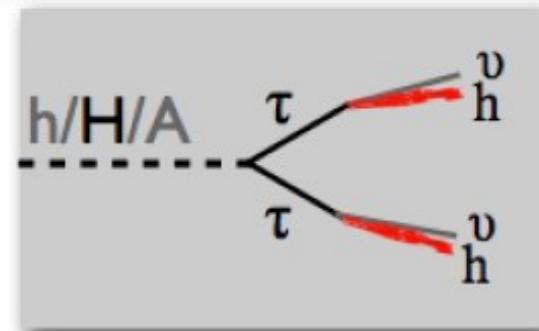
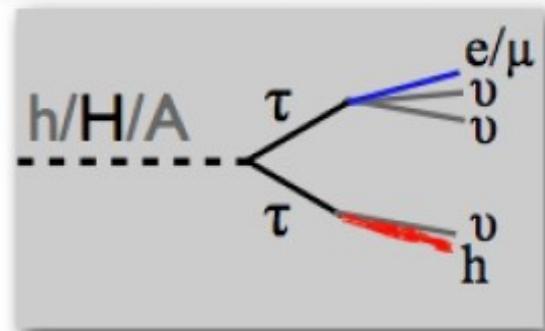
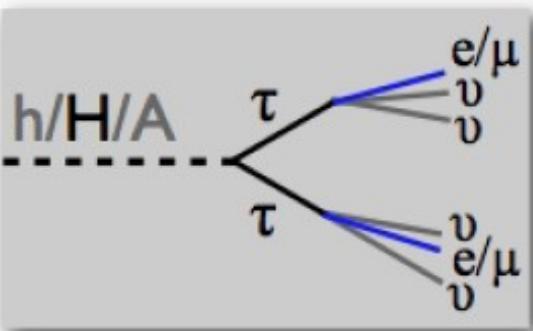
H → ττ / μμ

- CMS: $\tau_\mu \tau_h$, $\tau_e \tau_h$, $\tau_e \tau_\mu$, $\tau_\mu \tau_\mu$; L=17/fb analyzed [μμ: 5/fb, not combined]
 - Di-tau mass: max-likelihood technique („SVFit“) CMS-PAS-HIG-12-050 CMS-PAS-HIG-12-011
- ATLAS: in addition: $\tau_h \tau_h$, μμ, but no $\tau_\mu \tau_\mu$; L= 5/fb analyzed JHEP02(2013)095
 - Di-tau mass: Missing Mass calculator („MMC“) [except μμ]
- Main background: Z → ττ [except μμ]
 - Estimated by replacing muons in Z → μμ -enhanced data by simulated tau leptons („embedding“)
 - Most other backgrounds normalized in data control regions

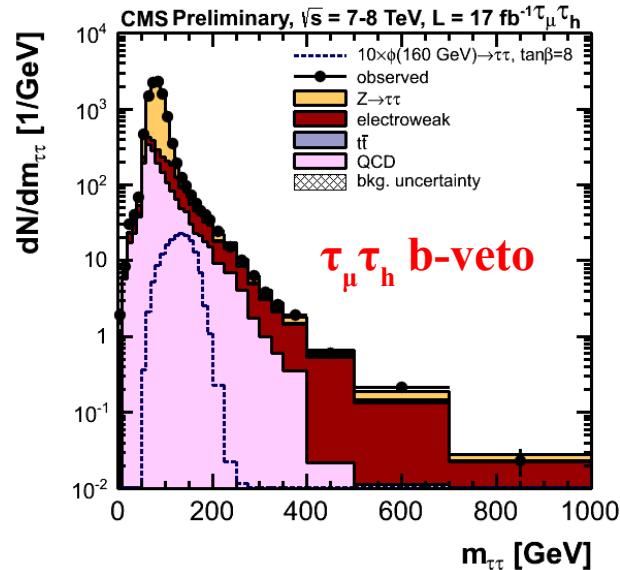
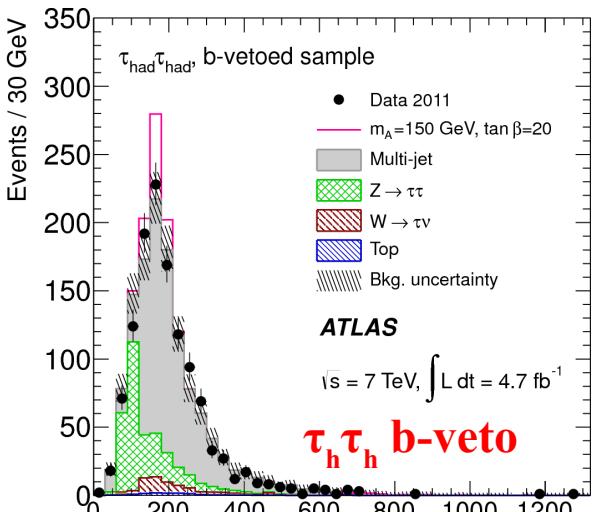
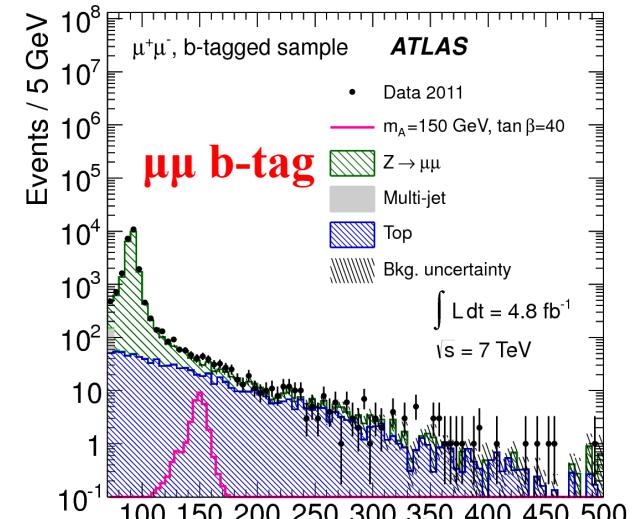
lep-lep: 12.4%

lep-had: 45.6%

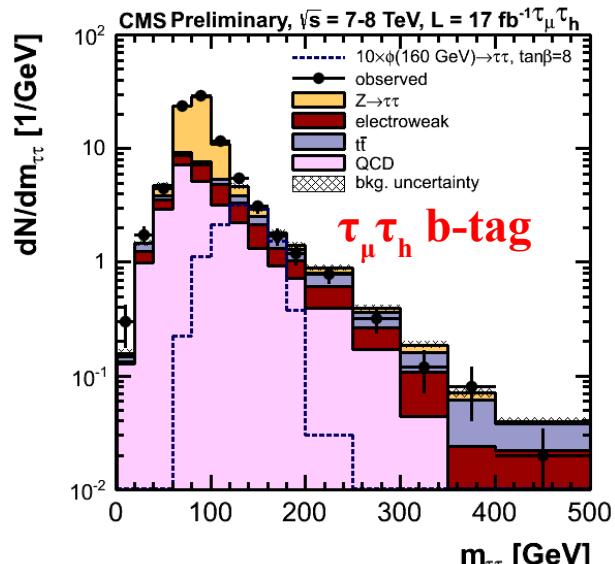
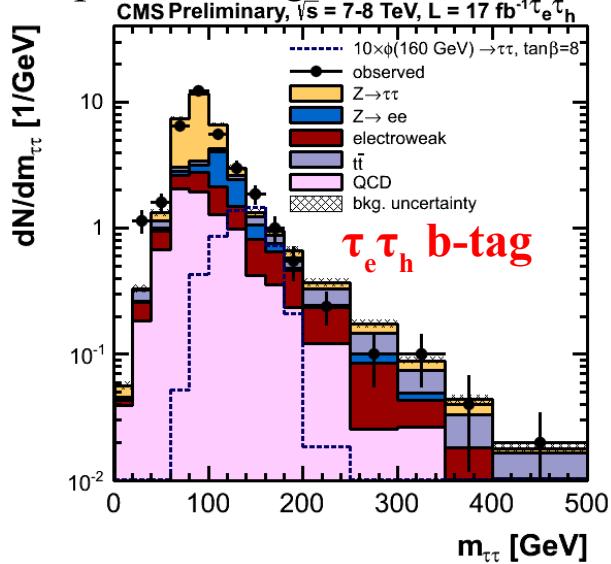
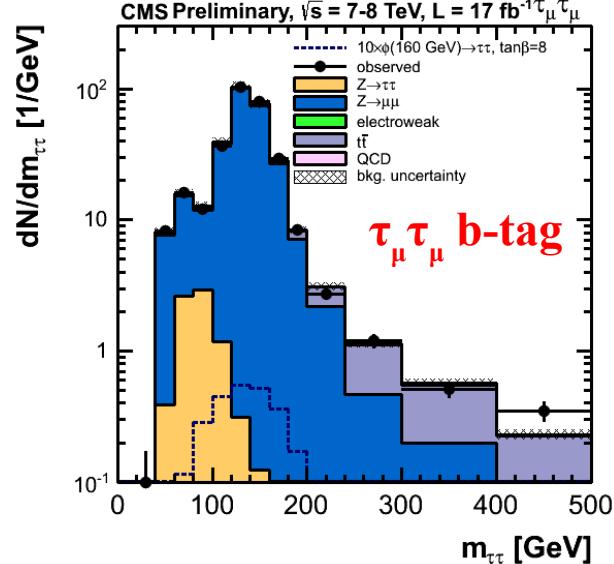
had-had: 42.0%



$H \rightarrow \tau\tau / \mu\mu$: Mass distributions

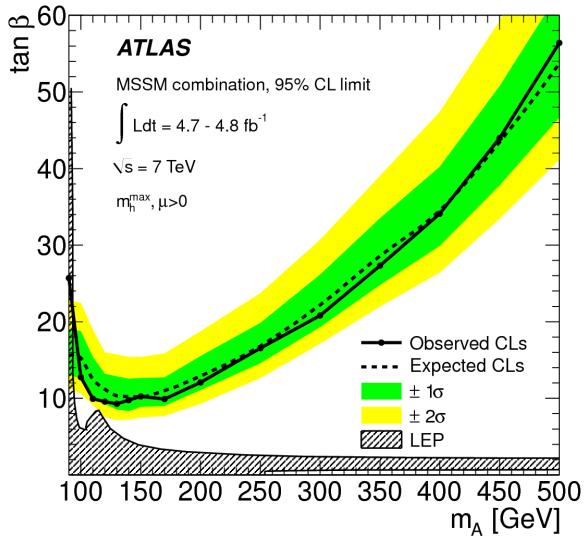
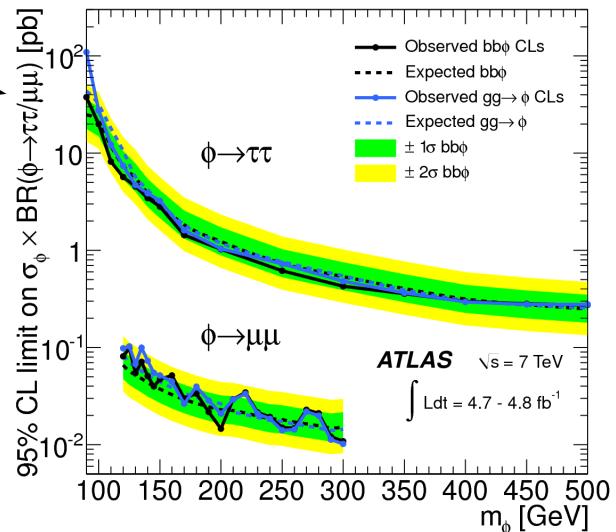
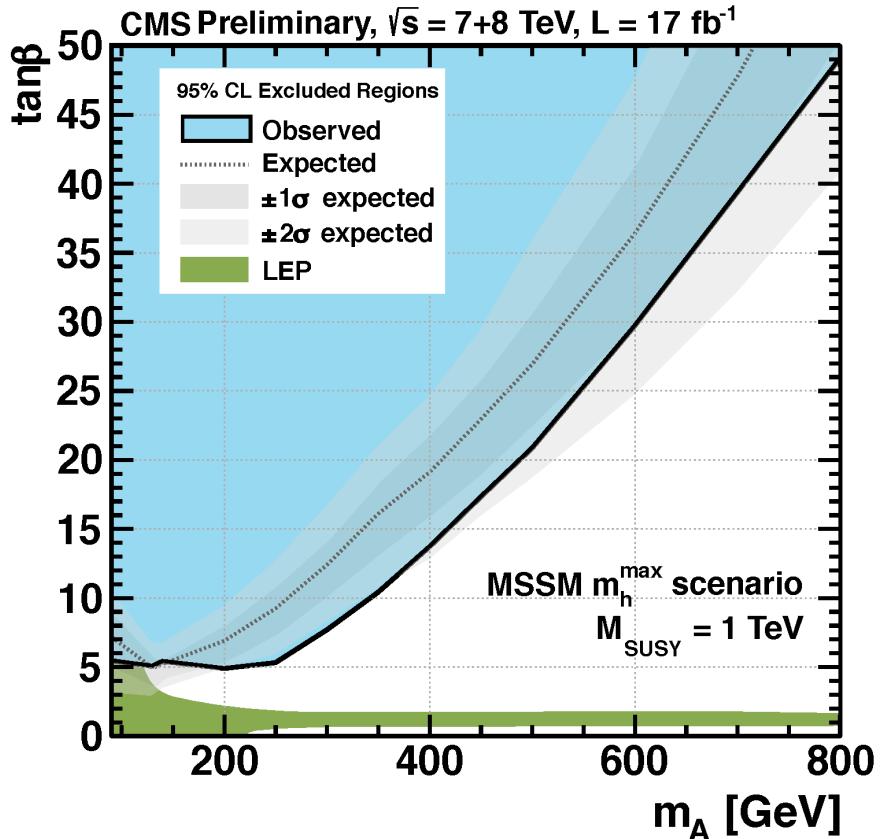


Data / SM expectation agree



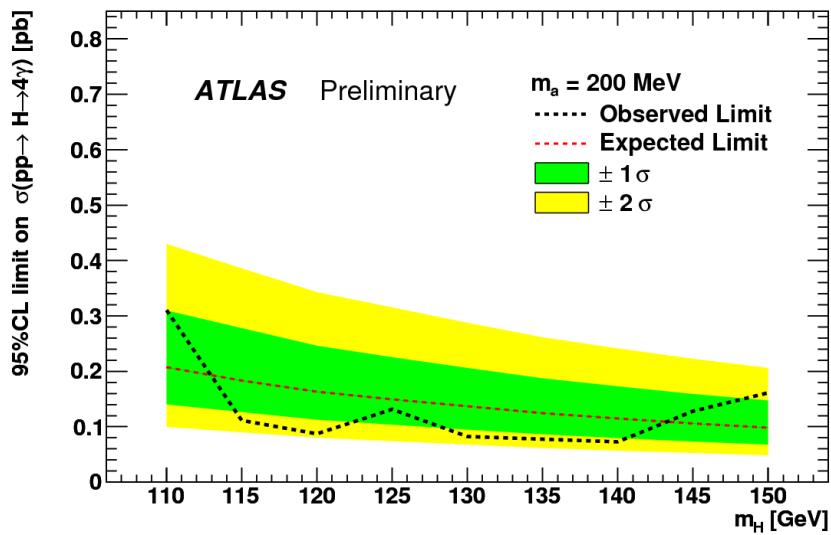
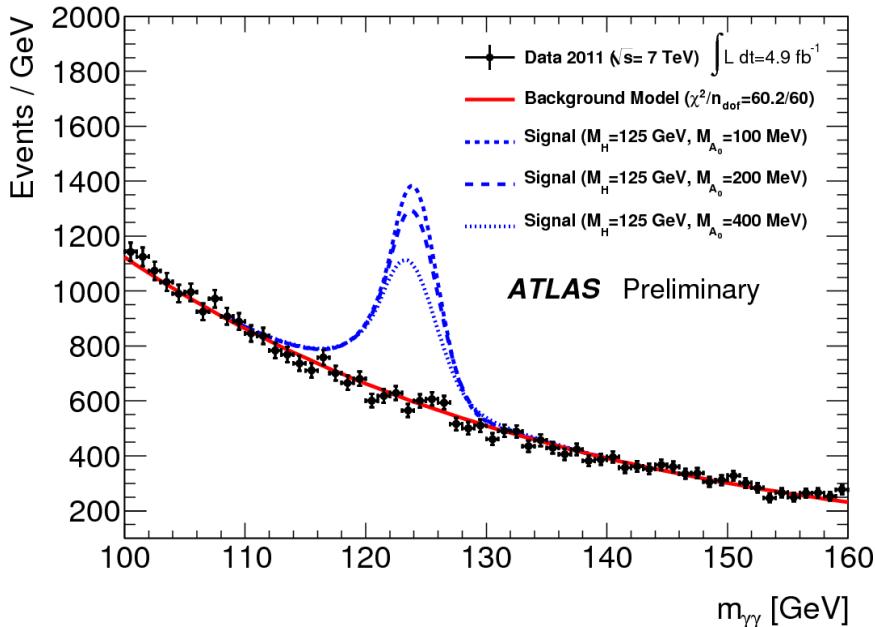
$H \rightarrow \tau\tau / \mu\mu$: Limits

- Independent limits for $bb\Phi/gg\rightarrow\Phi$
- MSSM m_h -max limits
 - $m_A < 125$ GeV excluded (CMS+LEP)
 - $\tan\beta > 5$ excluded for $m_A < 225$ GeV



$h \rightarrow a_0 a_0 \rightarrow \gamma\gamma \gamma\gamma$

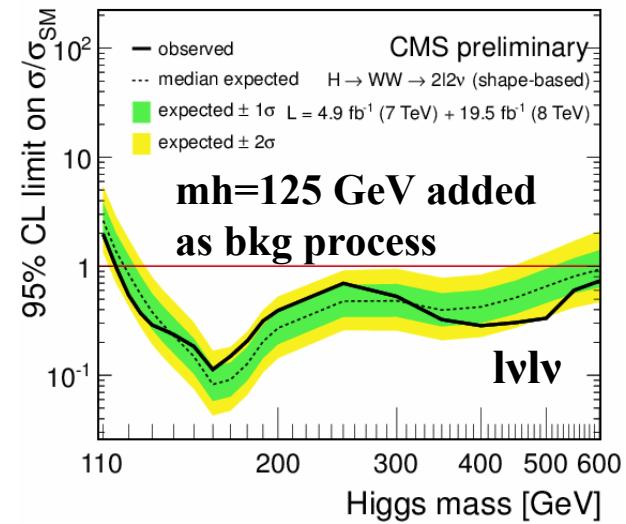
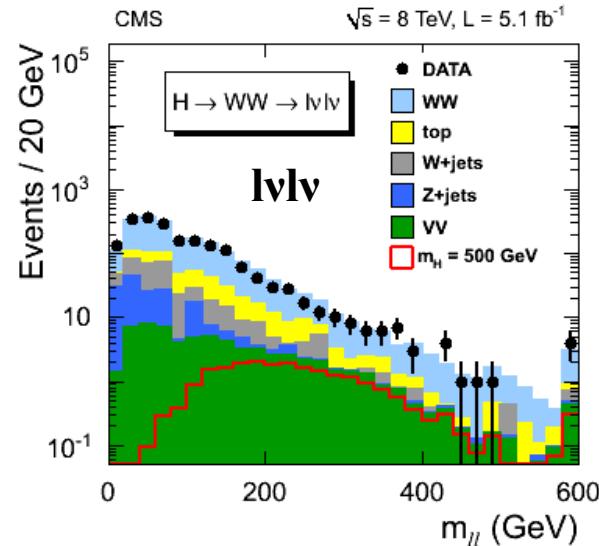
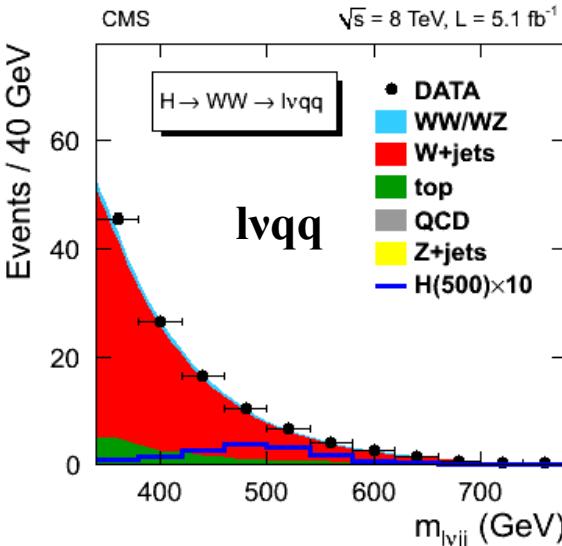
- Model-independent search
 - NMSSM/composite-Higgs-inspired
- Tested: a_0 with $m=O(100 \text{ MeV})$
 - Collimated $a_0 \rightarrow \gamma\gamma$ decays, process can mimick diphoton events
- Selection
 - Two photons, with loosened shower shape requirements wrt SM search ($\Rightarrow \gamma\gamma$ merging)
- No excess observed
 - Set limit on cross section:
Excluded: σ greater than a few 0.1 pb for $m_h=110-150 \text{ GeV}$ and $a_0=100/200/400 \text{ GeV}$



Generic / exotic searches

Heavy Higgs: $H \rightarrow WW$

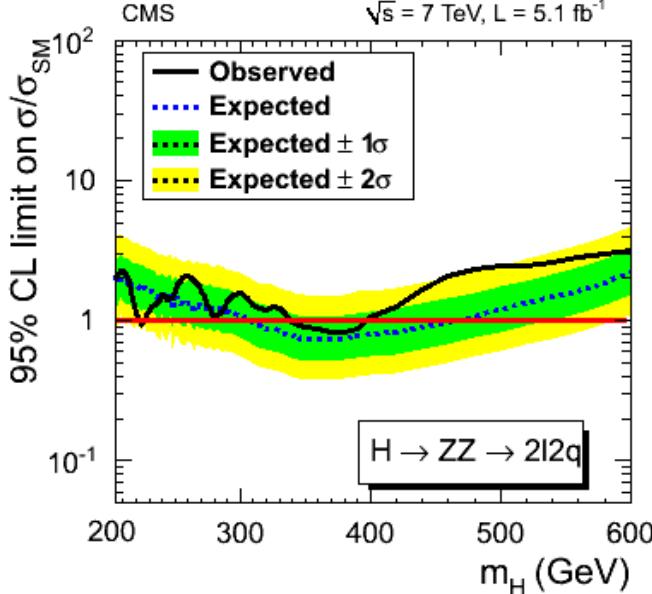
- Several BSM models are consistent with $m_H=125$ GeV and additional heavy Higgs bosons (e.g. MSSM) [arXiv:1112.5517](#) [arXiv:1112.1964](#)
- Some models even require a 2nd SM-like heavy Higgs boson
- $H \rightarrow WW$:
 - CMS: lvqq and lvlv, up to 25/fb [arXiv:1304.0213](#) [CMS-HIG-13-003](#)
 - ATLAS: lvlv, 5/fb [Phys. Lett. B 718 \(2012\) 391-410](#)
- 2nd heavy Higgs boson with SM couplings: excluded: $m_H < 600$ GeV



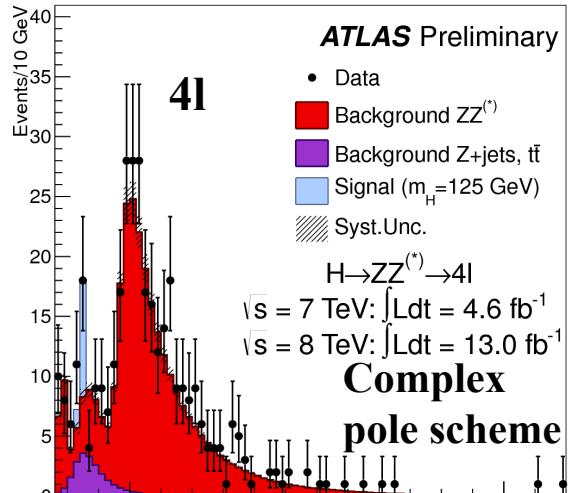
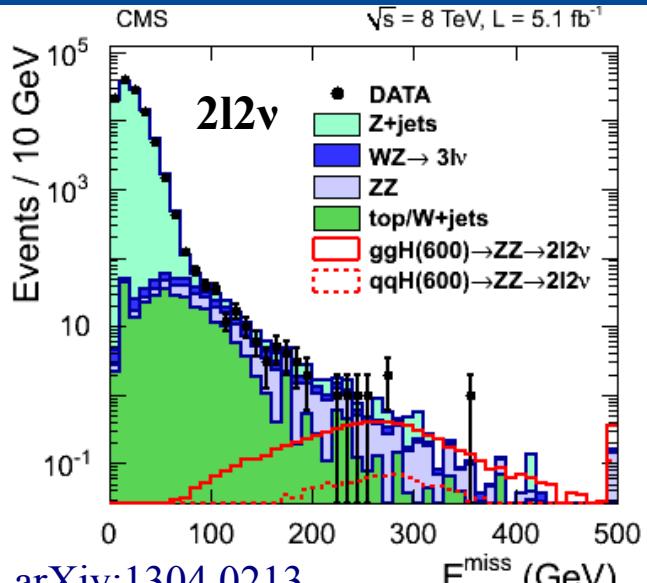
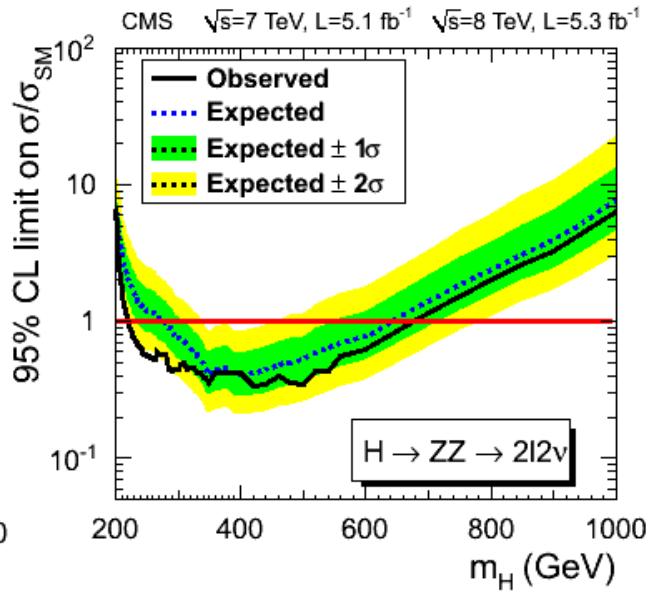
Heavy Higgs: $H \rightarrow ZZ$

- Second SM-like Higgs boson
95% CL excluded for 130-827 GeV
- For 150-400 GeV:
 σ limit $O(0.1 \times \text{SM})$

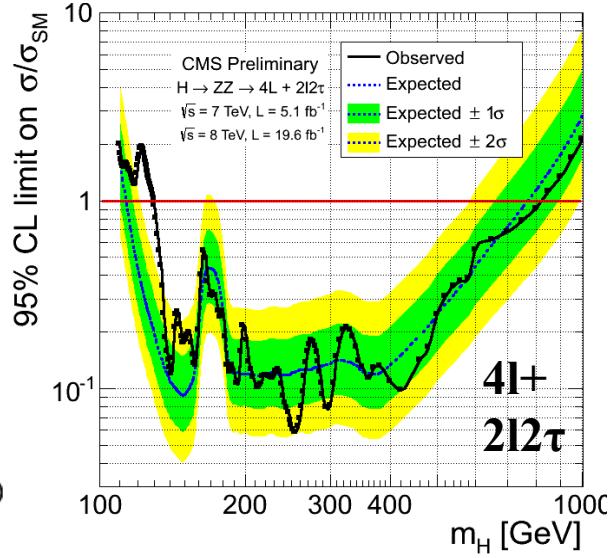
Phys.Lett. B 717 (2012) 70-88



arXiv:1304.0213



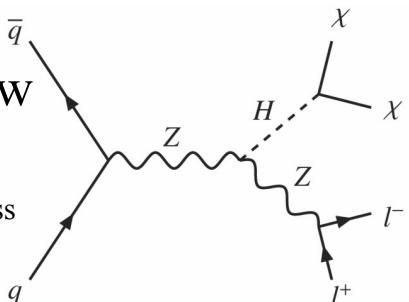
ATLAS-CONF-2013-013
CMS-PAS-HIG-13-002



Invisible Higgs, $ZH \rightarrow ll + \text{inv}$

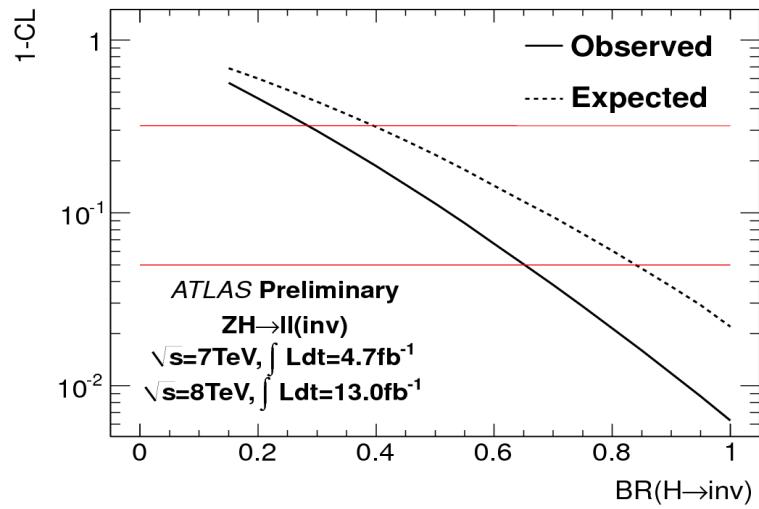
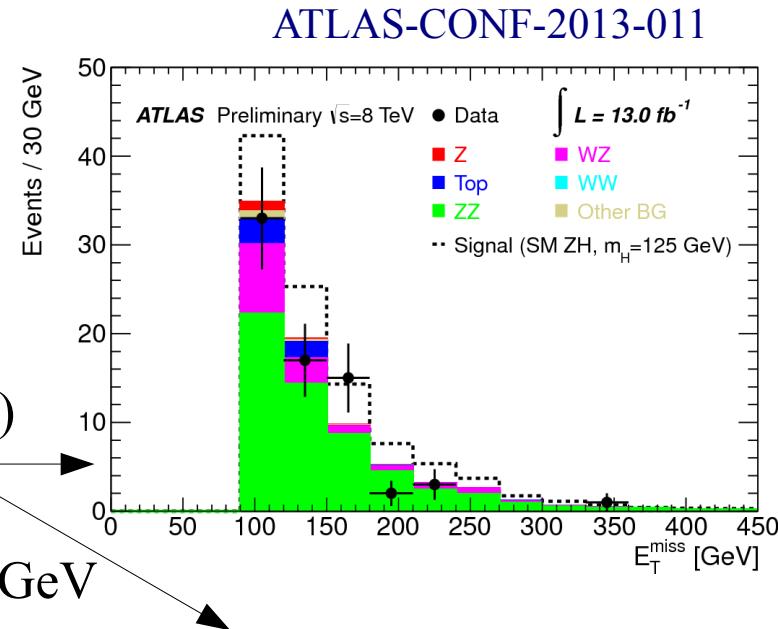
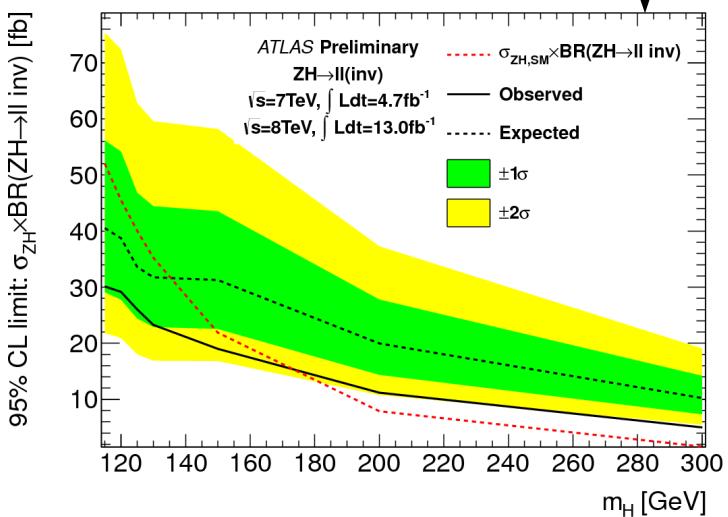
Selection:

- ee/ $\mu\mu$ pair in mZ window
- No additional lepton/jet
- Final discriminant: E_T^{miss}



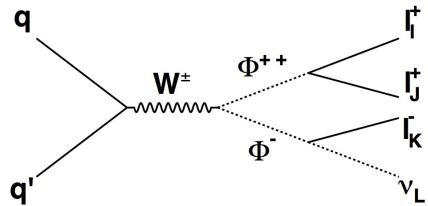
Interpretation

1. assuming $m_H=125$ GeV, limit on $B(H \rightarrow \text{inv})$
 $B(H \rightarrow \text{inv}) > 65\%$ excluded at 95% C.L.
2. Limit on additional Higgs-like state,
 $\sigma(ZH)\times B(Z \rightarrow ll)\times B(H \rightarrow \text{inv})$, $m_H=115-300$ GeV

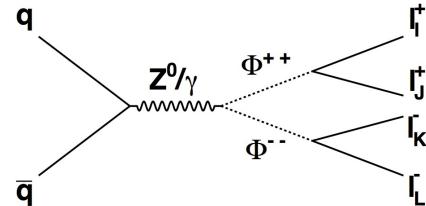


Doubly charged Higgs

Associated production ($l^+ l^+ l^- \nu$)

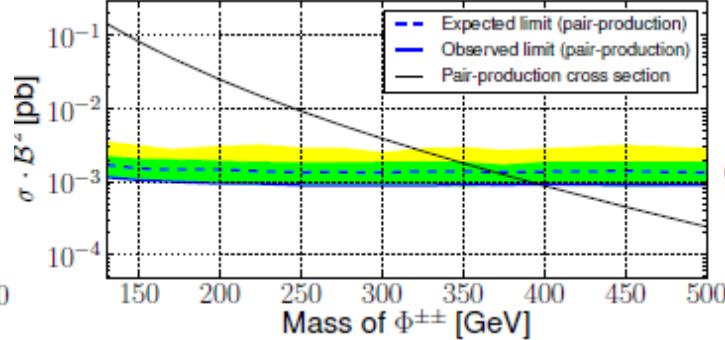
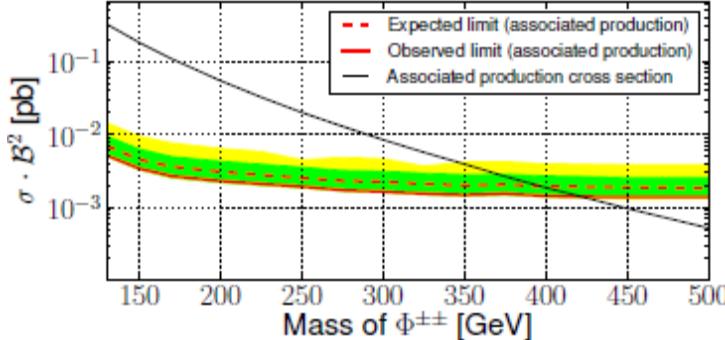


Pair production ($l^+ l^+ l^- l^-$)



- Search for excess of events with same-sign lepton pairs

- SU(2)_L scalar triplet, model-independent & type-II seesaw mechanism



- Lower bound on $m_{\Phi^{++}}$ of 204-444 GeV is set

Final State	pair prod.		combined
	ATLAS ¹	CMS	
$\mathcal{B}(\Phi^{++} \rightarrow e^+ e^+) = 100\%$	409	382	444
$\mathcal{B}(\Phi^{++} \rightarrow e^+ \mu^+) = 100\%$	409	391	453
$\mathcal{B}(\Phi^{++} \rightarrow \mu^+ \mu^+) = 100\%$	398	395	459
$\mathcal{B}(\Phi^{++} \rightarrow e^+ \tau^+) = 100\%$	-	293	373
$\mathcal{B}(\Phi^{++} \rightarrow \mu^+ \tau^+) = 100\%$	-	300	375
$\mathcal{B}(\Phi^{++} \rightarrow \tau^+ \tau^+) = 100\%$	-	169	204

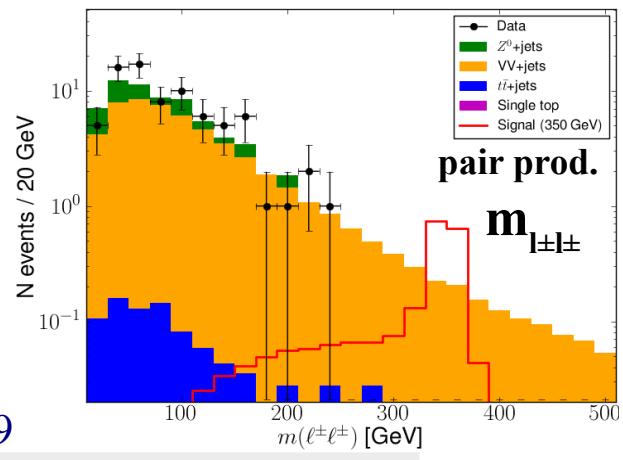
+limits for 4 benchmark points EPJC 72 (2012) 2244

EPJ C 72 (2012) 2189

$\mathcal{B}(\Phi^{\pm\pm} \rightarrow \mu^\pm \mu^\pm) = 100\%$
CMS $\sqrt{s} = 7$ TeV, $\int \mathcal{L} dt = 4.9 \text{ fb}^{-1}$

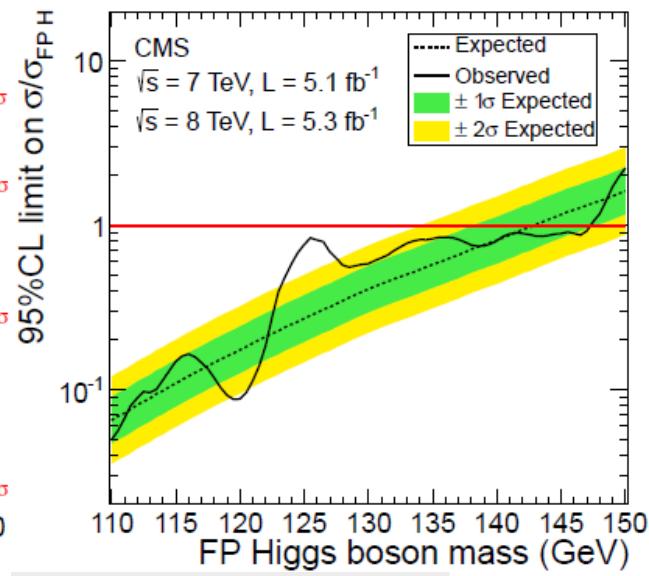
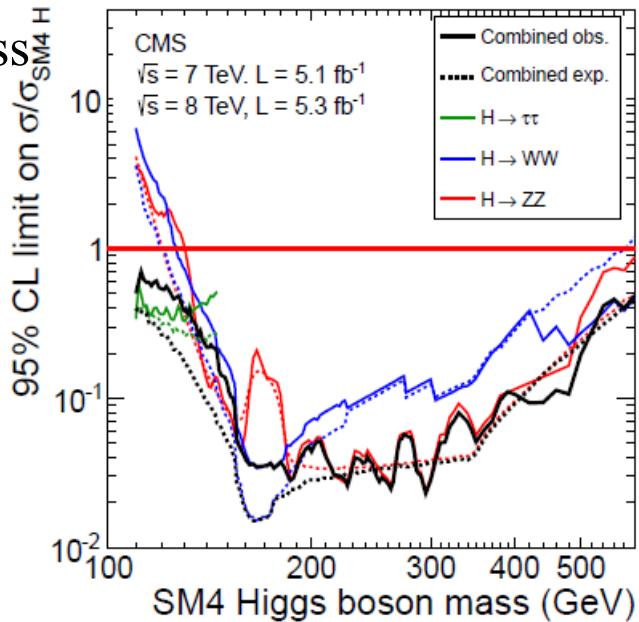
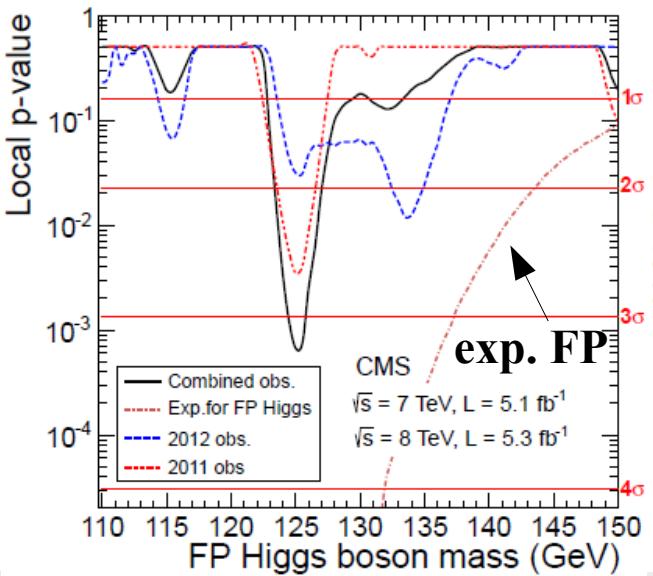
Limit: O(1 fb)

CMS Preliminary $\sqrt{s} = 7$ TeV, $\int \mathcal{L} = 4.6 \text{ fb}^{-1}$



4th generation / fermiophobic Higgs

- Main goal: Establish inconsistency with 125-GeV excess arXiv:1302.1764
- 4th generation (SM4)
 - Use LHCHXSWG benchmark
 - gg-fusion strongly enhanced (factor 4-9)
 - $\gamma\gamma$ almost entirely suppressed (factor 100)
 - Channels: WW, ZZ, $\tau\tau$; only in gg (no VBF/VH)
 - mH from 110-660 GeV excluded at 99% C.L.
- Fermiophobic (FP)
 - gg fusion suppressed
 - Channels: $\gamma\gamma$;
 - 9 categories
 - mH: 110-147 GeV excluded at 95% C.L.



Conclusions

- Large number of BSM Higgs searches at ATLAS+CMS
 - No significant excess observed
- Sizable regions of parameter space have been excluded
 - In particular, the MSSM is getting heavily constrained:
 - $m_A < 125$ GeV excluded (m_h -max)
 - $m_A < 225$ GeV excluded for $\tan \beta < 5$ (m_h -max)
 - Further constraints up to $m_A = 800$ GeV / $\tan \beta = 50$
- Very few analyses have analysed full 2011+2012 dataset yet
 - Interesting final states of several well-motivated models have not seen any publication yet
- 2015 and $\sqrt{s} = 13$ TeV will greatly enhance our sensitivity
 - BSM Higgses might be just around the corner...

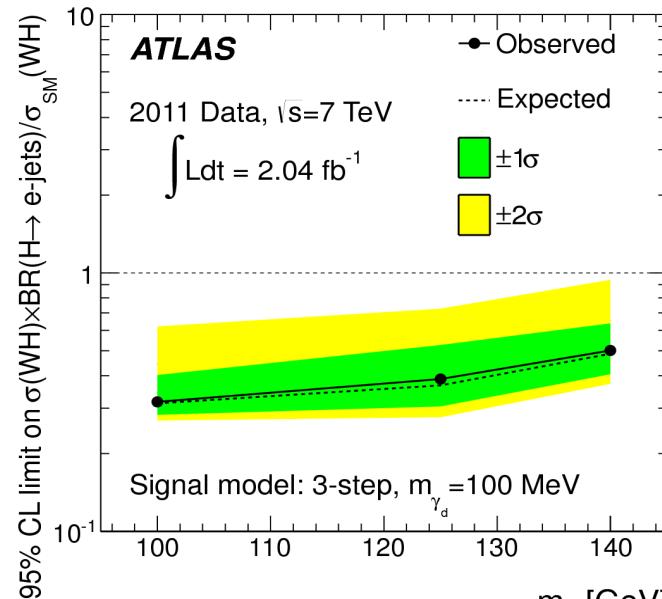
Backup slides

Less recent results

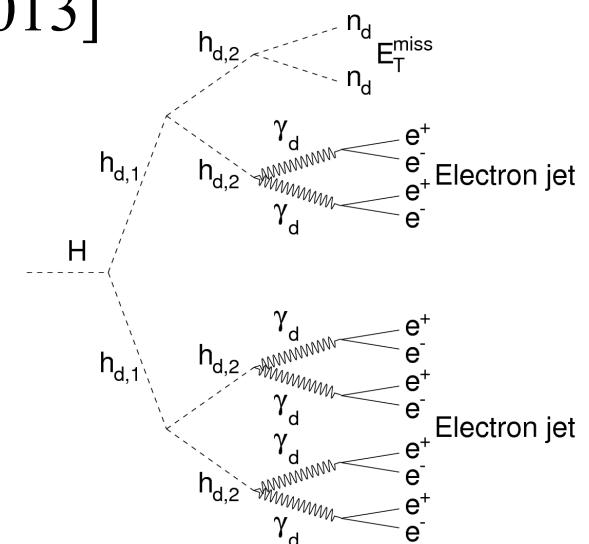
More BSM Higgs...

- Higgs decays to long-lived particles [1.9/fb, Mar 2012]
 - e.g. Hidden valley
- Higgs decays to electron jets [2.0/fb, Feb 2013]
 - Hidden sector

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- Higgs decays to displaced muonic lepton jets
[1.9/fb, Sep 2012]

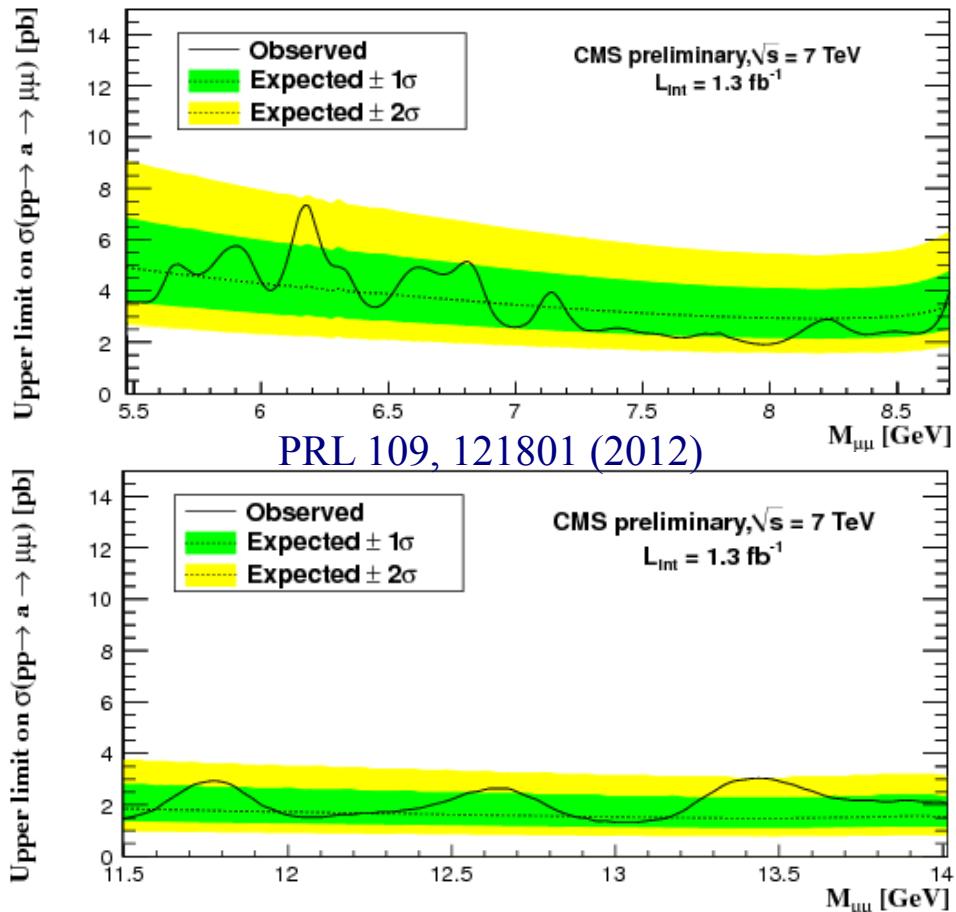
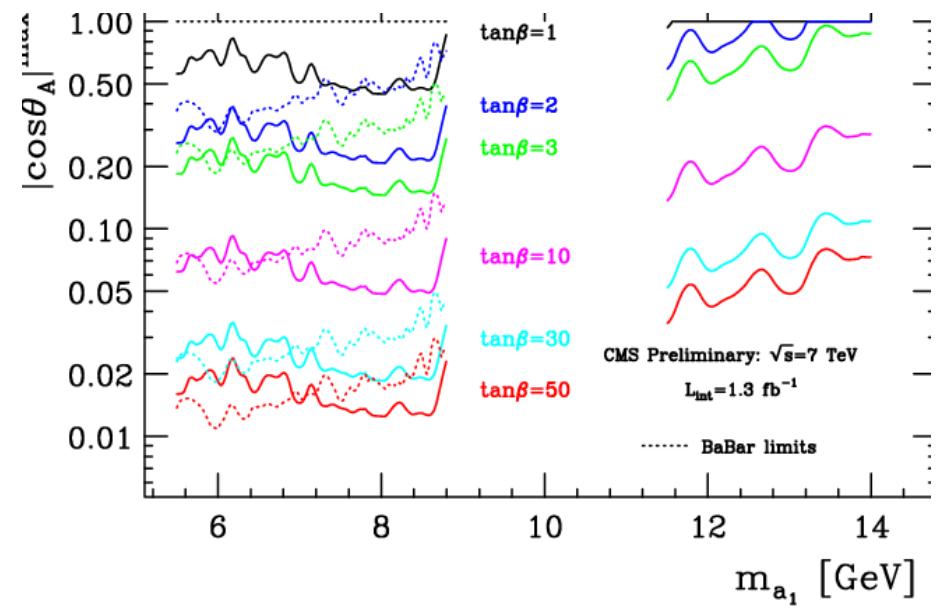
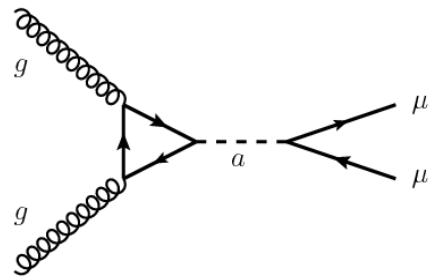


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$a_1 \rightarrow \mu\mu$



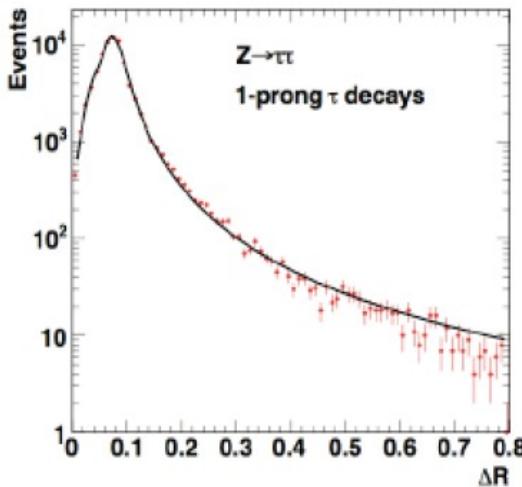
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More info

MSSM A/H $\rightarrow\tau\tau$: MMC

The Missing Mass Calculator (MMC) is used to estimate the di-tau mass



$$\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$$

- **Basic idea**
 - $M_\tau \ll M_Z$ or $M_H \Rightarrow \tau$'s are heavily boosted
 - $dR(\nu-\tau_{vis})$ is very small, but non-zero !!
 - $dR(\nu-\tau_{vis})$ distribution depends only τ -type and $P(\tau)$

$$E_{\Gamma_x} = p_{mis_1} \sin \theta_{mis_1} \cos \phi_{mis_1} + p_{mis_2} \sin \theta_{mis_2} \cos \phi_{mis_2}$$

$$E_{\Gamma_y} = p_{mis_1} \sin \theta_{mis_1} \sin \phi_{mis_1} + p_{mis_2} \sin \theta_{mis_2} \sin \phi_{mis_2}$$

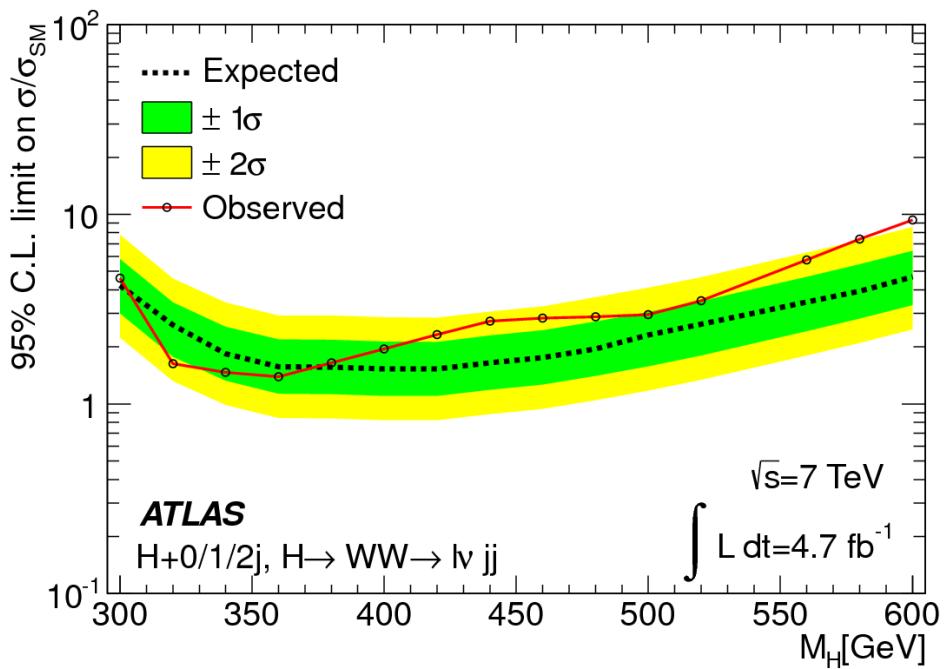
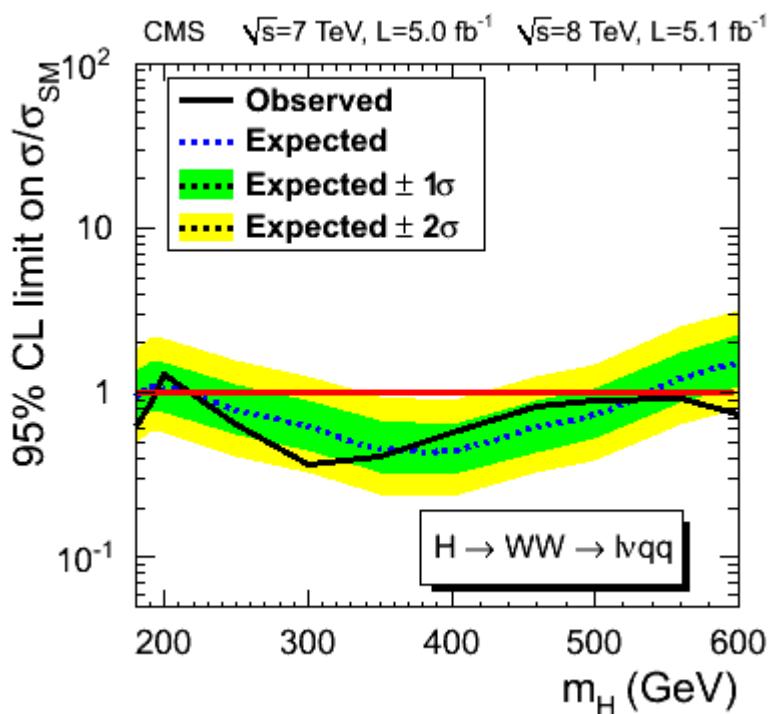
$$M_{\tau_1}^2 = m_{mis_1}^2 + m_{vis_1}^2 + 2\sqrt{p_{vis_1}^2 + m_{vis_1}^2} \sqrt{p_{mis_1}^2 + m_{mis_1}^2} - 2p_{vis_1}p_{mis_1} \cos \Delta\theta_{vm_1}$$

$$M_{\tau_2}^2 = m_{mis_2}^2 + m_{vis_2}^2 + 2\sqrt{p_{vis_2}^2 + m_{vis_2}^2} \sqrt{p_{mis_2}^2 + m_{mis_2}^2} - 2p_{vis_2}p_{mis_2} \cos \Delta\theta_{vm_2}$$

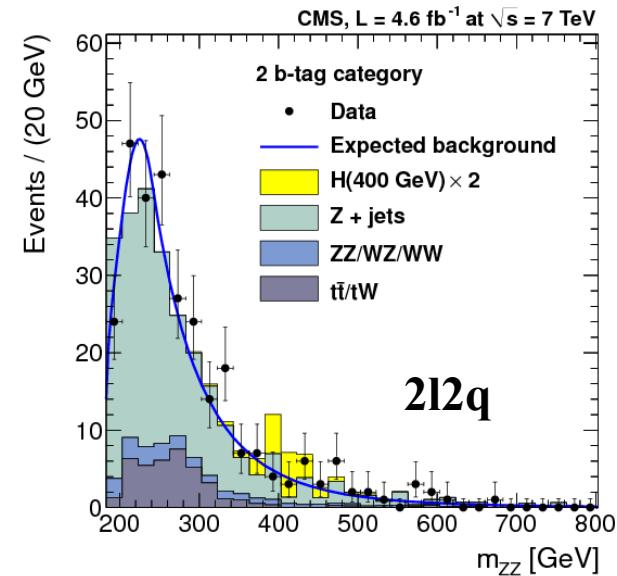
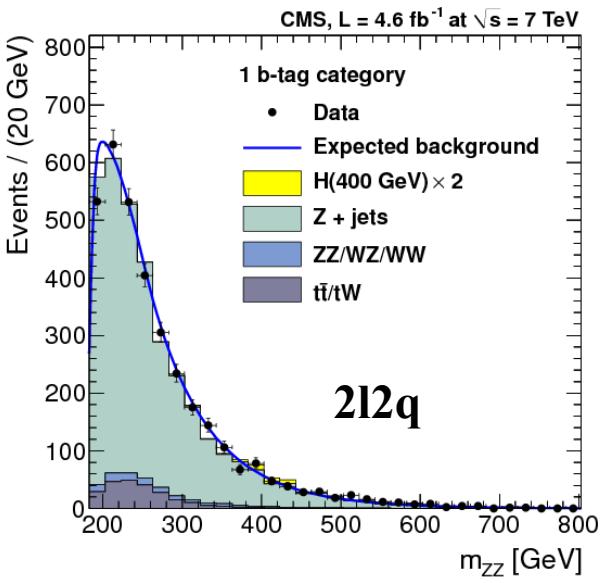
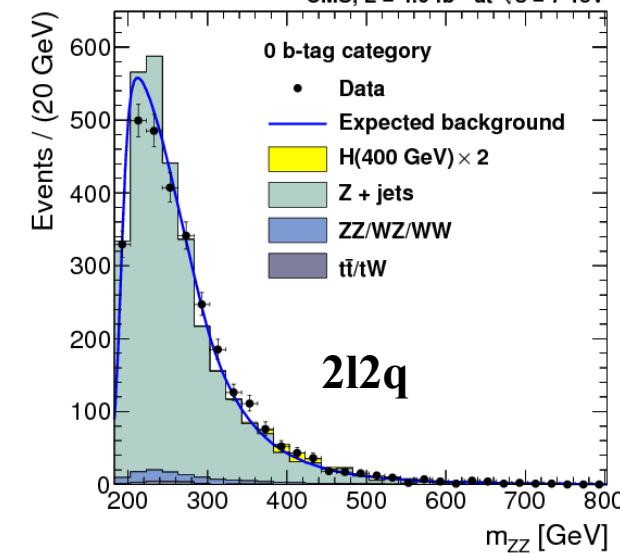
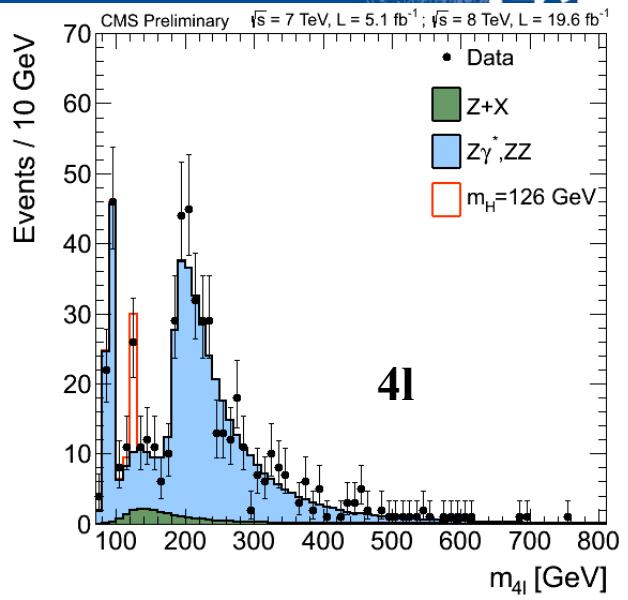
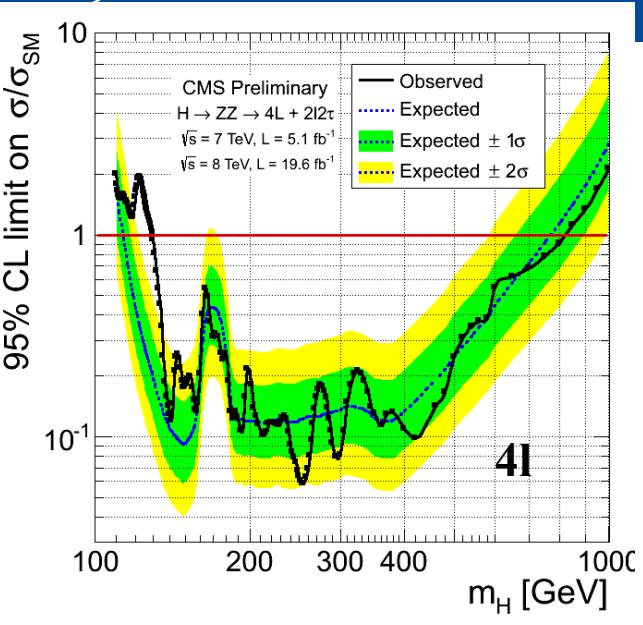
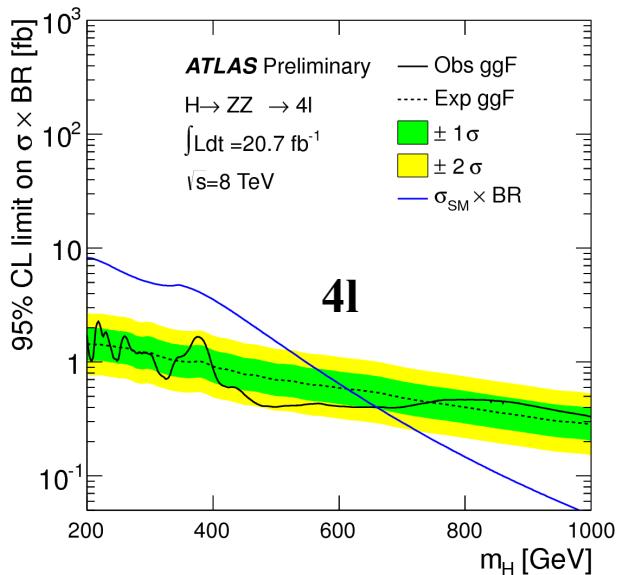
6-8 unknowns (neutrino 4-momenta), 4 constraints (METx, METy, M_{τ_1} , M_{τ_2}).
 need to vary METx, METy as well \Rightarrow 4-6 dimensions, O(100M) scan points
 \Rightarrow scan points weighed e.g. by ΔR and distance to reconstructed METx, METy

- One additional scalar singlet (wrt MSSM)
 - 3 cp-even (h_1, h_2, h_3), 2 cp-odd (a_1, a_2), 2 charged (h^+, h^-) Higgs bosons
 -
- Very light a_1 is not excluded
 - $m(a_1) < 2m(b)$: typically $a_1 \rightarrow \tau\tau$ dominant; $a_1 \rightarrow \mu\mu$ still important
- If a_1 is very light ($a_1 \rightarrow \pi_0 \pi_0 \pi_0$ suppressed) then $a_1 \rightarrow \gamma\gamma$ can be dominant

Heavy H \rightarrow WW, more:



Heavy H \rightarrow ZZ, more:

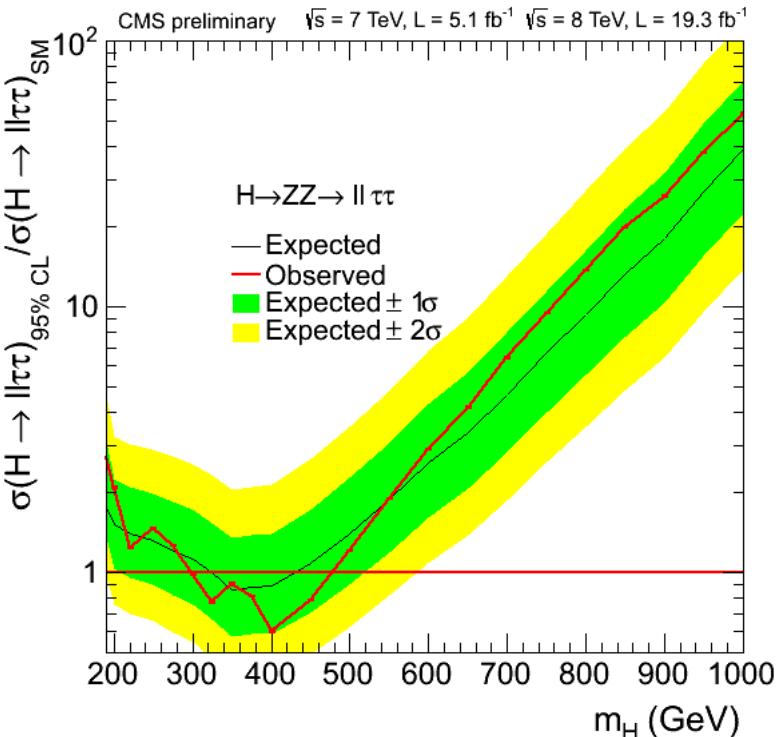
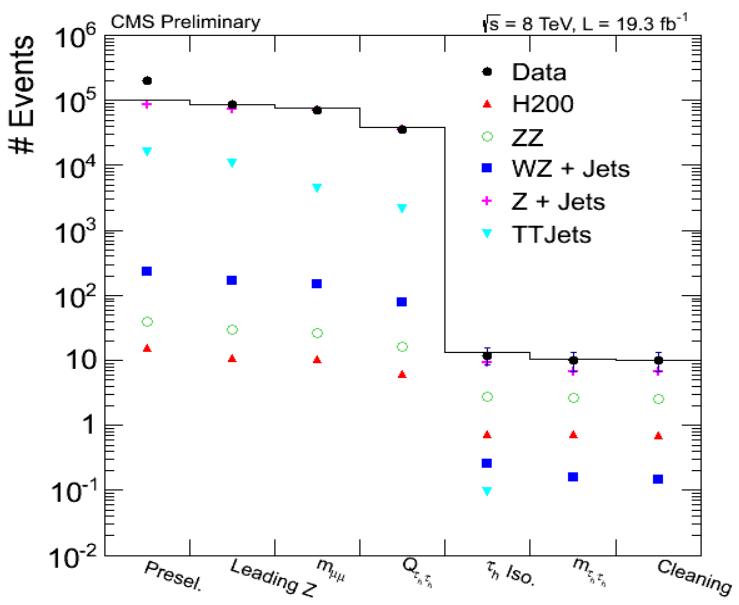


Heavy H \rightarrow ZZ \rightarrow 4l CMS:

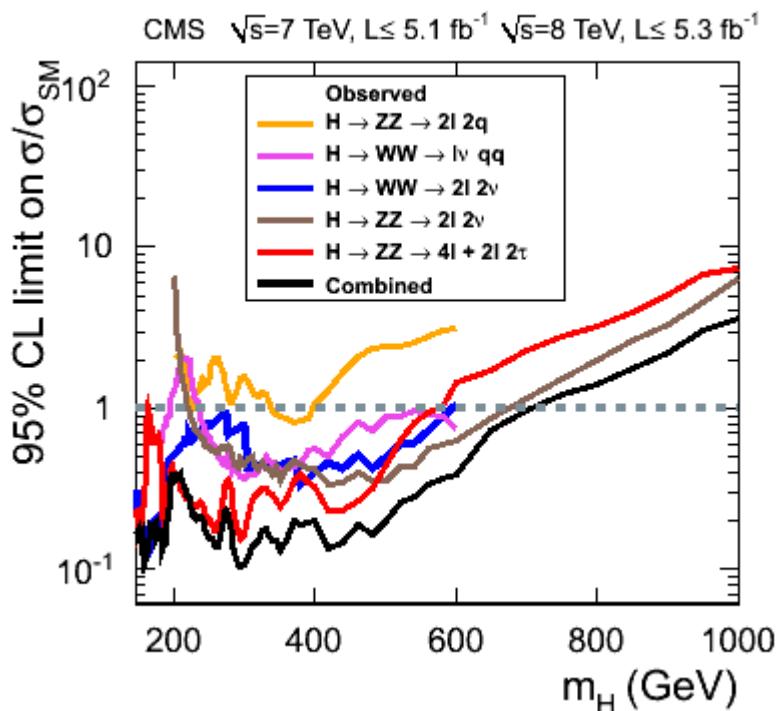
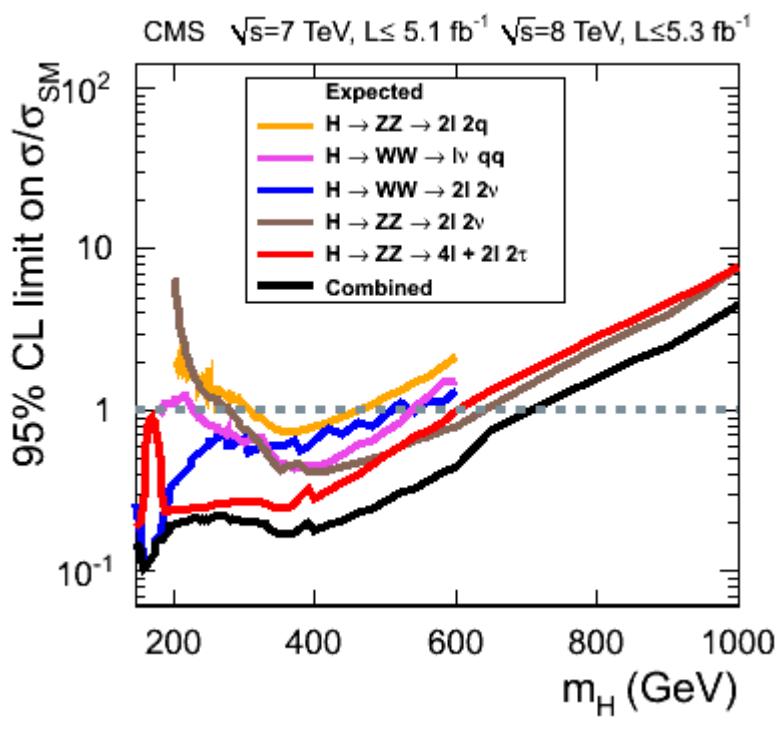
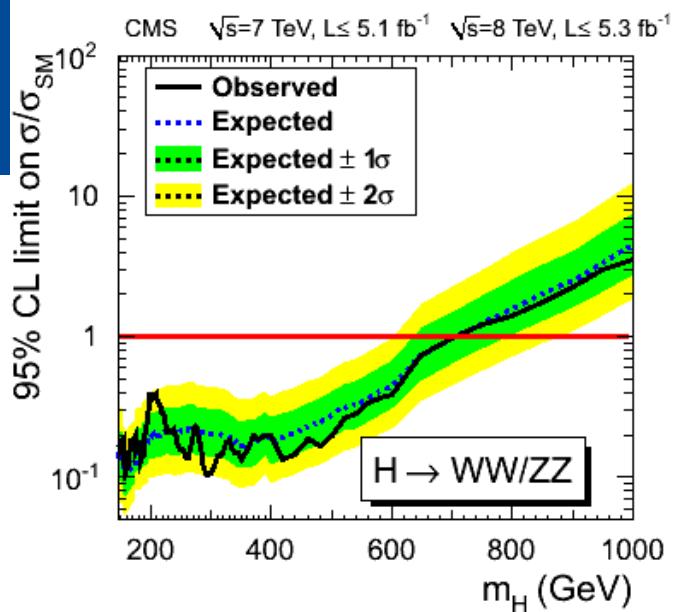
- mH=100-1000 GeV,
2011+2012
combined:

Channel	4e	4 μ	2e2 μ	2 ℓ 2 τ
ZZ background	78.9 ± 10.9	118.9 ± 15.5	192.8 ± 24.8	27.4 ± 3.6
Z + X	6.5 ± 2.6	3.8 ± 1.5	9.9 ± 4.0	22.9 ± 7.8
All background expected	85.5 ± 11.2	122.6 ± 15.5	202.7 ± 25.2	50.3 ± 8.6
$m_H = 125$ GeV	3.5 ± 0.5	6.8 ± 0.8	8.9 ± 1.0	—
$m_H = 126$ GeV	3.9 ± 0.6	7.4 ± 0.9	9.8 ± 1.1	—
$m_H = 500$ GeV	5.1 ± 0.6	6.8 ± 0.8	12.0 ± 1.3	3.7 ± 0.4
$m_H = 800$ GeV	0.7 ± 0.1	0.9 ± 0.1	1.6 ± 0.2	0.4 ± 0.1
Observed	86	125	240	57

- 2l2tau



Heavy Higgs: combination



Heavy Higgs: line shape & CPS

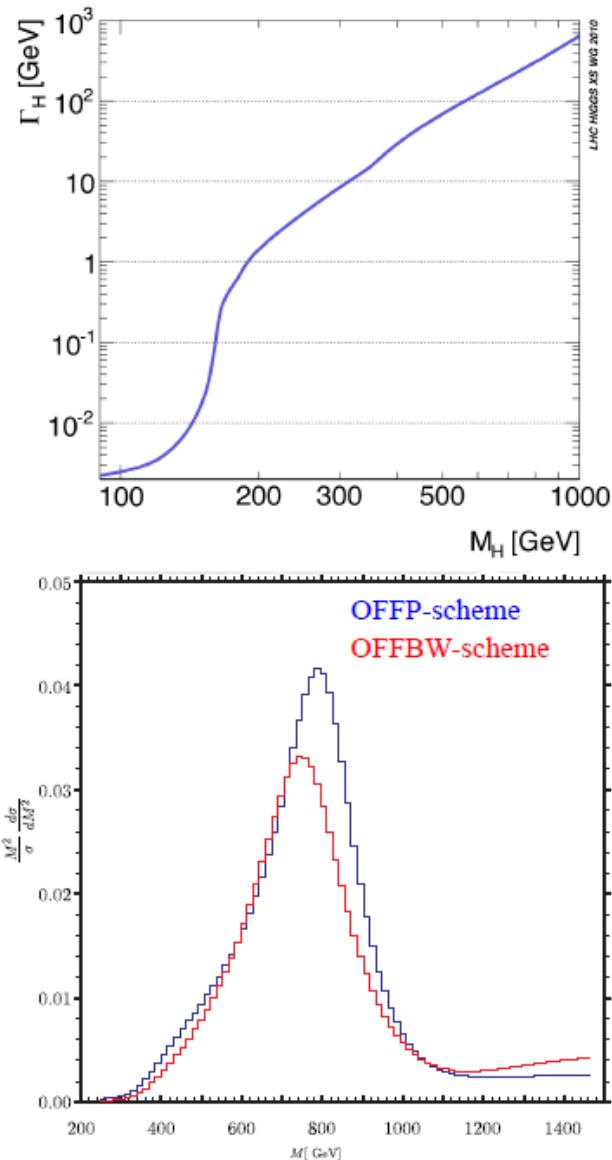


There are BSM models compatible with the observed ~ 125 GeV resonance and EWK fit that predict a second SM-like heavy Higgs state to complete the unitarization of scattering amplitudes.

Heavy Higgs region must account for:

- ▶ Lineshape effect
- ▶ Signal – Background interference effect

Ongoing discussions in the LHC xsec working group on these topics.



arXiv:1112.5517v1

The square of the effective coupling of an SM4 Higgs boson to gluons (g) is increased by a factor $K_{gg}(m_H)$ that ranges between nine and four for a Higgs boson mass that ranges from 110 to 600 GeV. This enhancement results from the inclusion of u_4 and d_4 quarks in the quark loop diagrams associated with the $H \rightarrow gg$ and $gg \rightarrow H$ processes. The square of the effective coupling of an SM4 Higgs boson to W and Z vector bosons (henceforth referred to collectively as V bosons) becomes about three times smaller, $K_{VV}(m_H) \sim 0.3$, as the amplitudes of the NLO and leading order contributions are of opposite signs in this case. A coincidental cancellation of the contributions from W bosons and heavy fermions (top, u_4 , d_4 , ℓ_4) to the loop diagrams responsible for the $H \rightarrow \gamma\gamma$ decay suppresses the square of the effective coupling to photons by $\mathcal{O}(100)$. The squares of the fermionic (f) couplings are enhanced by a factor $K_{ff}(m_H) \sim 1.6$.

The enhancement in the effective couplings to gluons and the suppression of couplings to vector bosons causes gluon fusion production to dominate over the vector boson fusion (VBF) and associated (VH) production mechanisms. Hence, the last two processes can be neglected in searches for SM4 Higgs bosons, and are ignored in the search presented in this paper. The contribution from gluon fusion is rescaled by the SM4/SM m_H -dependent factor $K_{gg}(m_H)$ mentioned above. The $H \rightarrow bb$ search channel that fully relies on associated production is not included in this combination. (For simplicity, $H \rightarrow bb$ is denoted as $H \rightarrow bb$, $H \rightarrow \tau^+\tau^-$ as $H \rightarrow \tau\tau$, etc.) Following Ref. [37], the uncertainties on the gluon fusion cross section for the SM4 model are assumed to be the same as for the SM Higgs boson and are taken from Ref. [45]. The change in the Higgs boson decay partial widths modifies the decay branching fractions as follows. The branching fraction $\mathcal{B}(H \rightarrow \gamma\gamma)$ is suppressed by $\mathcal{O}(100)$ with respect to the standard model. The branching fractions $\mathcal{B}(H \rightarrow WW)$ and $\mathcal{B}(H \rightarrow ZZ)$ are suppressed by approximately a factor of five for low Higgs boson masses for which the WW and ZZ partial widths are not dominant, remain almost unchanged in the mid-range around $m_H \sim 200$ GeV, where vector boson partial widths are the main contributors to the total width Γ_{tot} , and are about 60% of the SM Higgs boson values above $m_H \sim 350$ GeV after the $H \rightarrow tt$ decay channel opens up. The branching fraction $\mathcal{B}(H \rightarrow \tau\tau)$ is affected only slightly in the mass range where this decay mode is used. The total width of the SM4 Higgs boson at high masses, where it is relevant for the $H \rightarrow ZZ \rightarrow 4\ell$ (where ℓ denotes an electron or a muon) search, is about 30–50% of the SM Higgs width, depending on the Higgs boson mass.

As a fermiophobic Higgs boson does not couple to fermions, gluon fusion production becomes negligible, while the VBF and VH production cross sections remain unchanged. Direct decays to fermion pairs become impossible, which significantly increases the branching fractions $\mathcal{B}(H \rightarrow \gamma\gamma)$, $\mathcal{B}(H \rightarrow WW)$ and $\mathcal{B}(H \rightarrow ZZ)$. The diphoton decays are enhanced further as the negative interference between the W and top loops responsible for this decay in the SM is no longer present. For a low mass FP Higgs boson ($m_H \approx 125$ GeV) the decay to two photons is enhanced by an order of magnitude with respect to the SM [23–25]. Production cross sections and decay branching fractions, together with their uncertainties, are taken from Ref. [45] and are derived from Refs. [46–51].