LHC Higgs boson results involving fermions

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on behalf of the ATLAS / CMS collaborations

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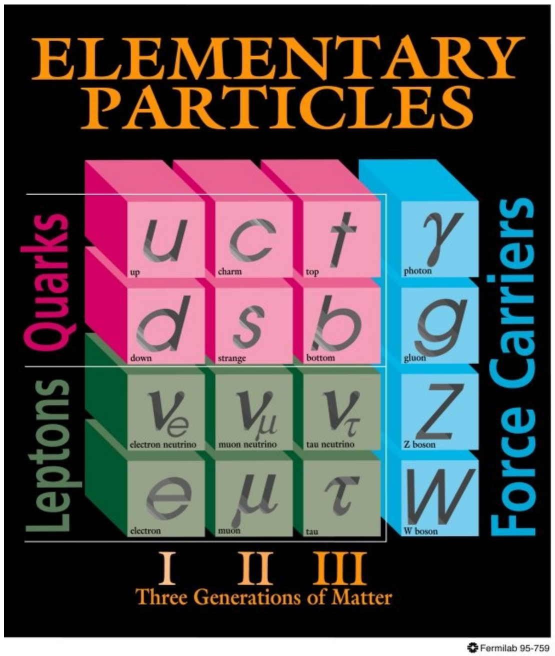
The Standard Model



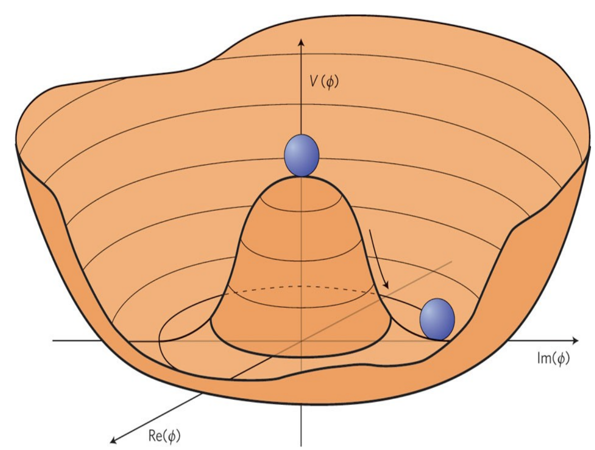
Force	**Carrier**
Strong	**Gluons (g)**
Electro-Weak	**Electro-weak bosons (γ,W,Z)**
Gravitation	**?**

✯ **Quarks and Leptons interact via the exchange of force carriers**

Interactions are controlled by symmetry:
$SU(3)\otimes SU(2)_L\otimes U(1)$

Gauge symmetry ⟺ **Particles massless**

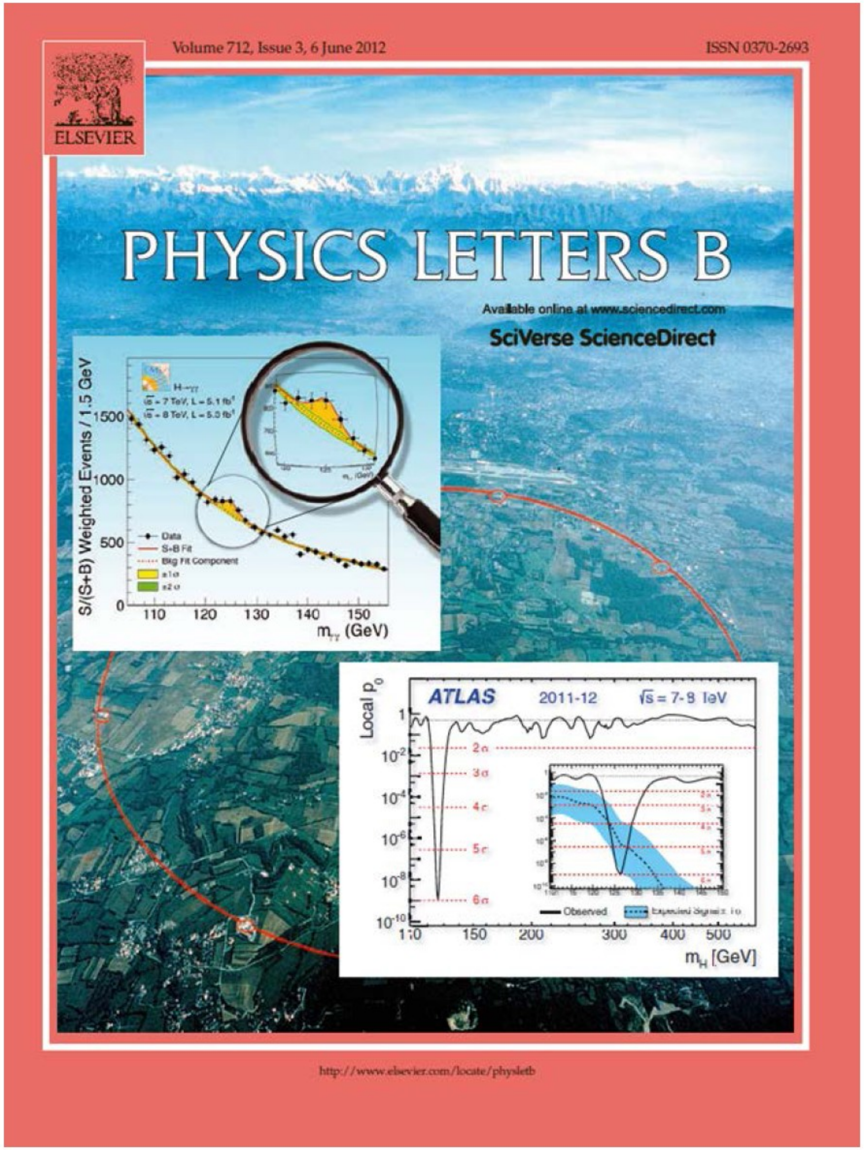
Gauge invariance is broken to generate particle mass – Higgs mechanism



$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

But the Higgs mass is not given by SM

The discovery of a Higgs-like particle

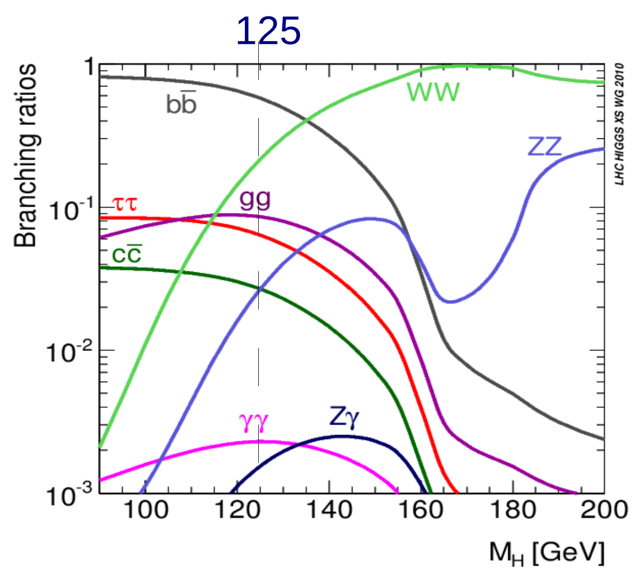


Phys. Lett. **B**716, 1-61 (2012)

The Higgs-like particle was observed in γγ, ZZ→4l and WW→2l2ν decays in the summer 2012 by both ATLAS and CMS

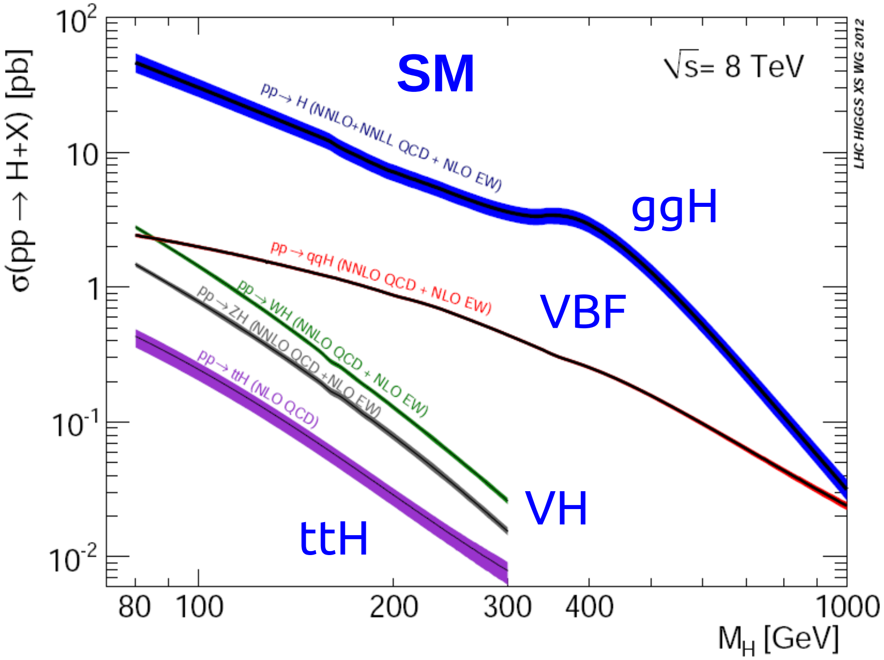
However, we need to see Higgs fermionic decay modes to prove that it is a SM Higgs!

Branching ratios for a Higgs mass of 125 GeV:



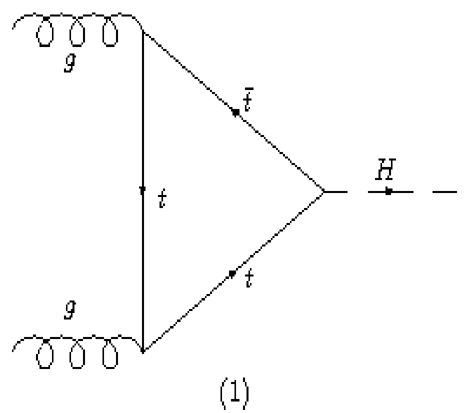
channel	BR
bb	57.7%
WW	21.5%
ττ	6.3%
ZZ	2.6%
γγ	0.23%

Higgs productions (SM and MSSM)

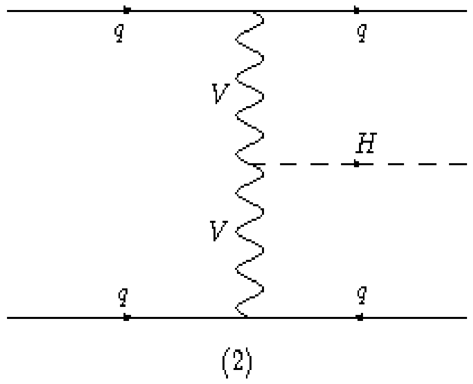


In the MSSM, Higgs couplings to down-type fermions can be enhanced with large tanβ: b-associated production and larger BR for H→ $b\bar{b}$ and H→ ττ

Main SM Higgs production modes:

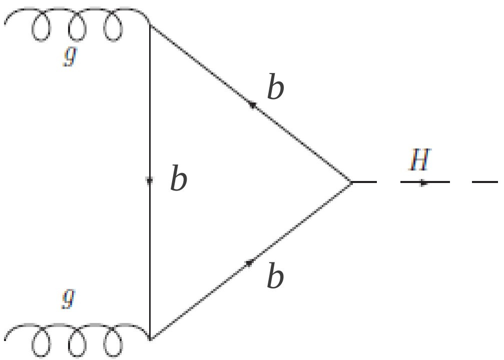


gg-fusion (top loop)

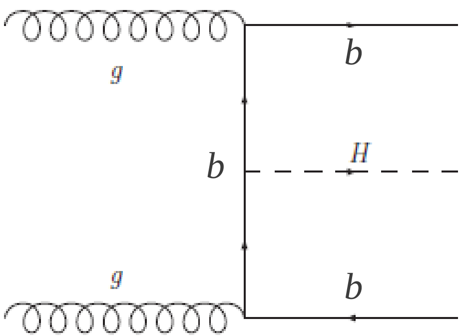


VBF

Important Higgs productions in MSSM:

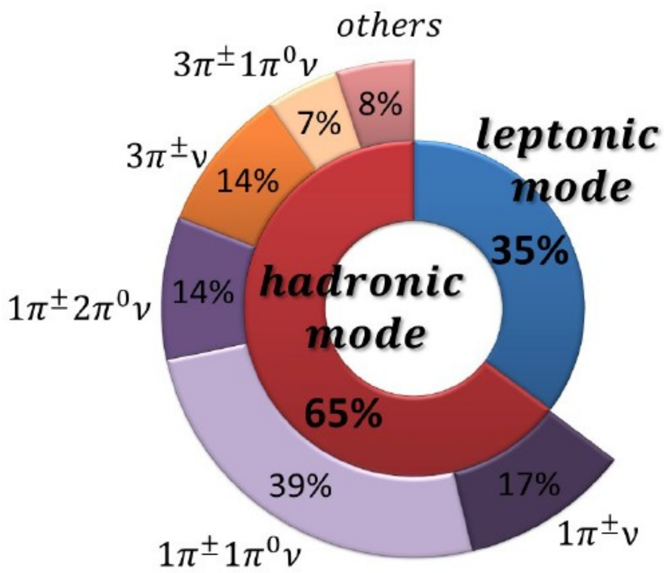


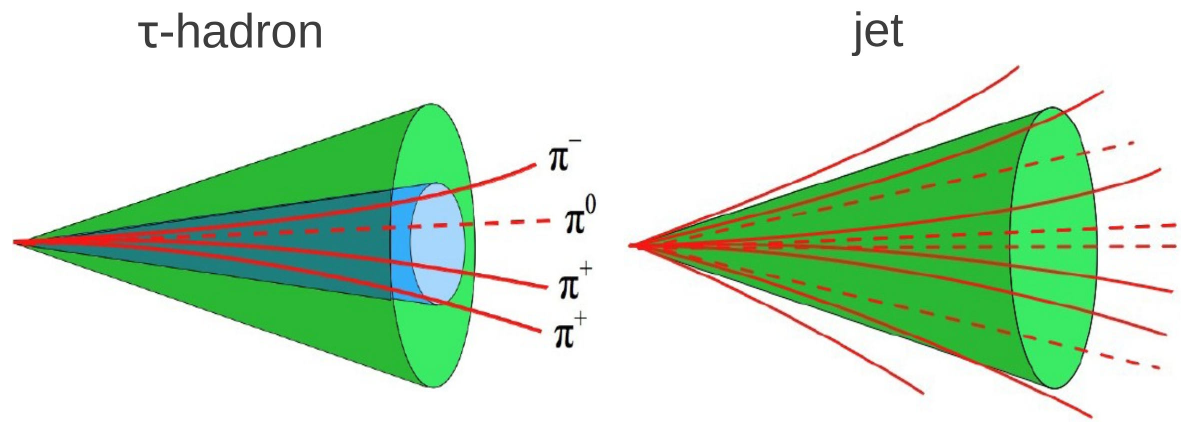
gg-fusion (b-loop)



b-associated

H → ττ



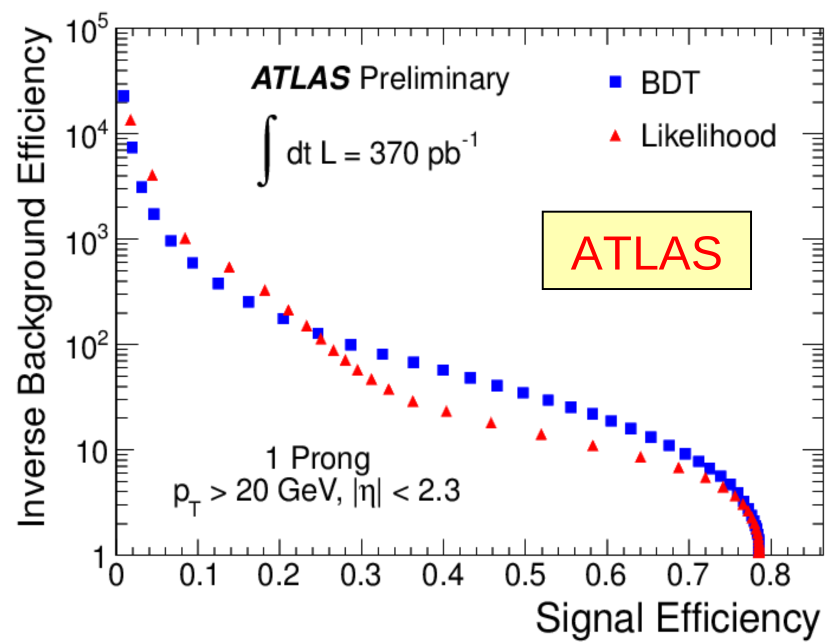


ATLAS channls:

ee, eμ, μμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

CMS channls:

eμ, μμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, VH



For a typical working point around 50% efficiency, about 2% fake rate is expected, for both ATLAS and CMS

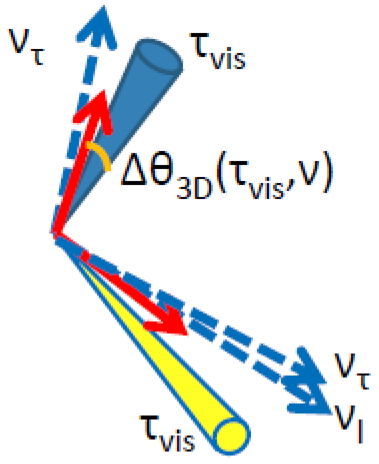
$H \to \tau\tau$

Categories used for the H→tautau analysis:

ATLAS	CMS
2-jet VBF, 2-jet VH ($\tau_{lep}\tau_{lep}$ only)	2-jet VBF
Boosted Higgs ($p_{T,H}$>100)	1-jet high p_T (τ_{lep},τ_h)
1-jet inclusive ($\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_h$ only)	1-jet low p_T (τ_{lep},τ_h)
0-jet ($\tau_{lep}\tau_h$ only)	0-jet (used as control sample only)

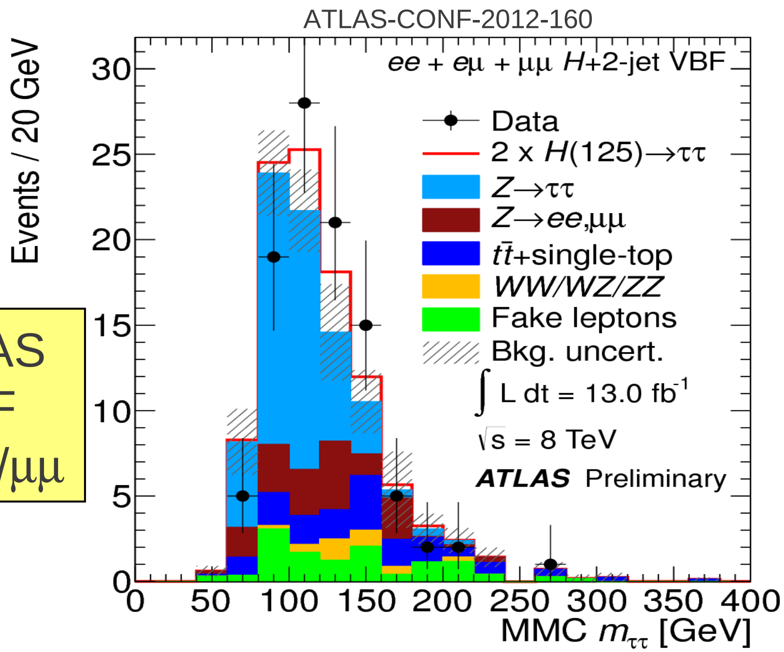
Higgs mass reconstruction:

- Take into account the tau decay kinematics and Missing E_T (MET) resolution
- The number of parameters is larger than the number of observables – maximum likelihood scan/fit
- The $m_{\tau\tau}$ that maximizes the likelihood is the final mass discriminant (ATLAS:MMC, CMS:SVFit)

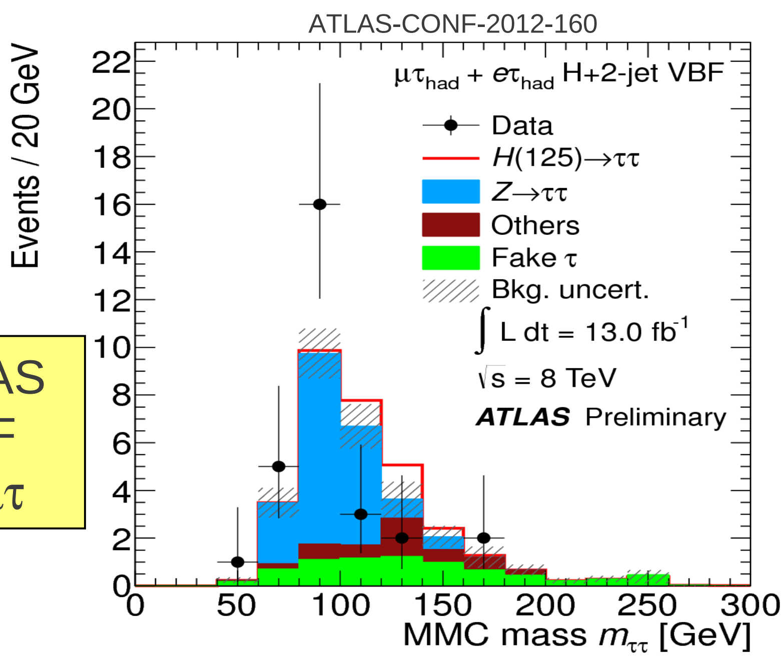


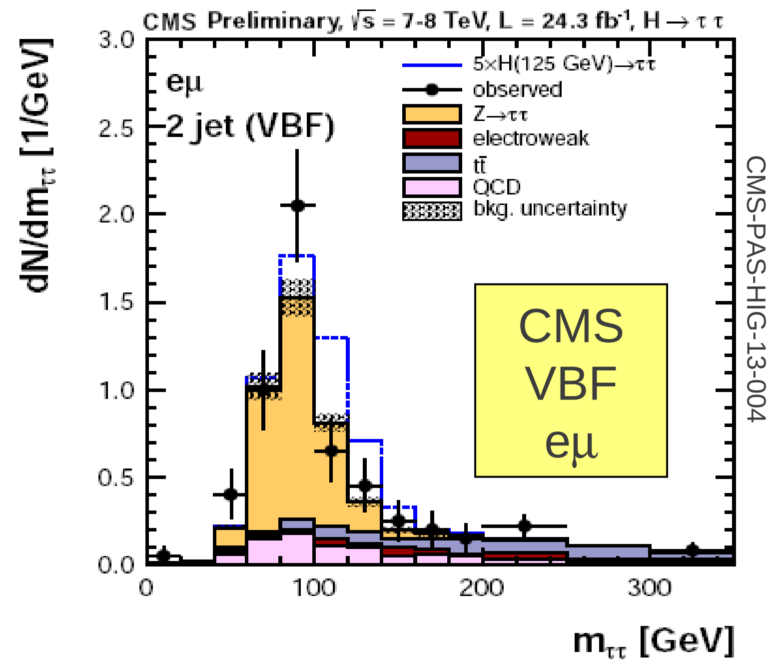
H → ττ

ATLAS VBF ee/eμ/μμ

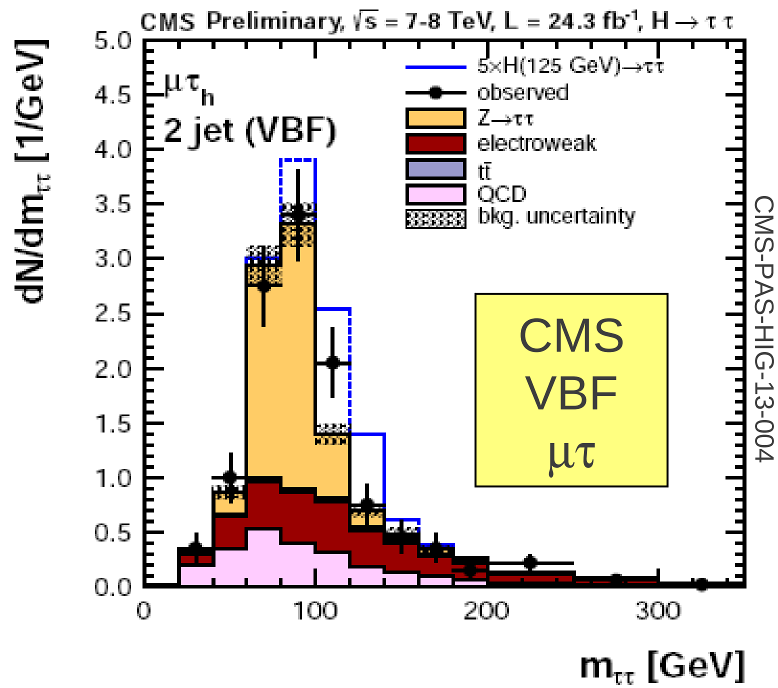


ATLAS VBF eτ/μτ





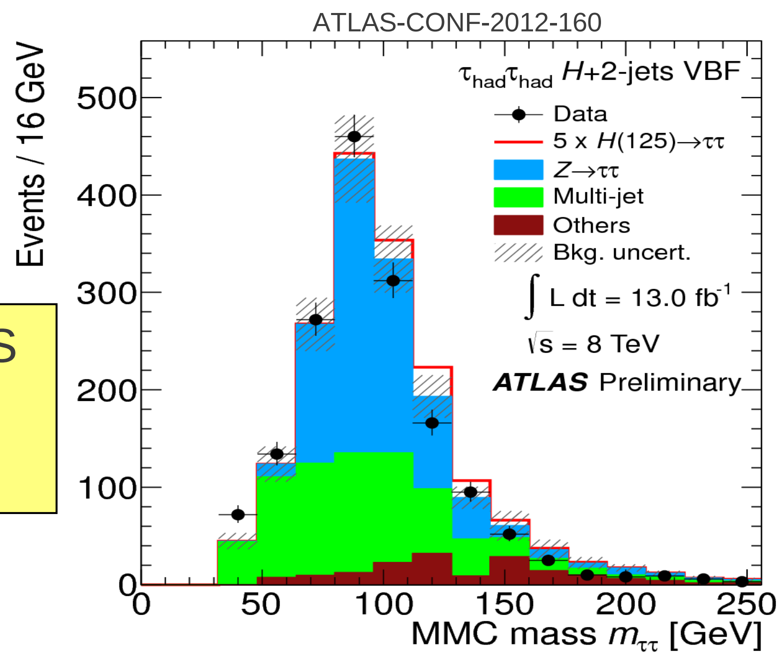
CMS VBF eμ



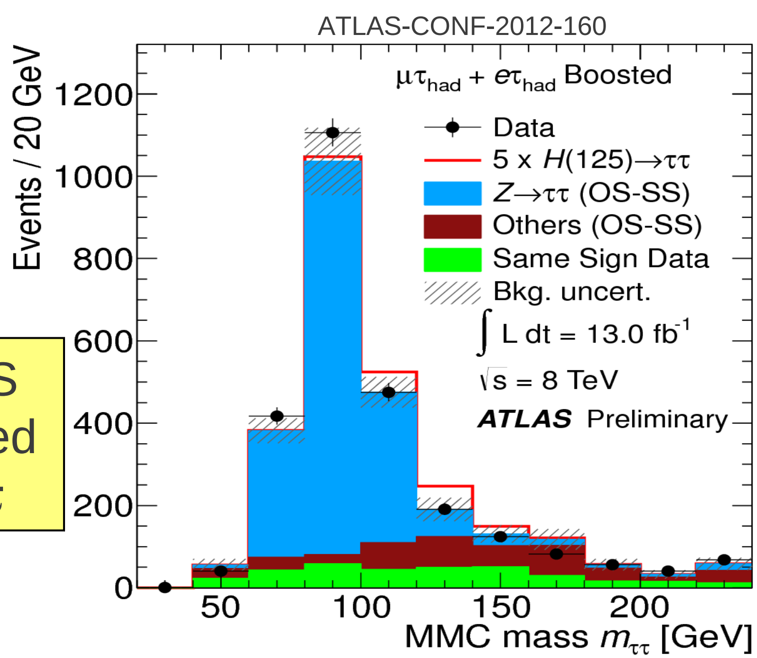
CMS VBF μτ

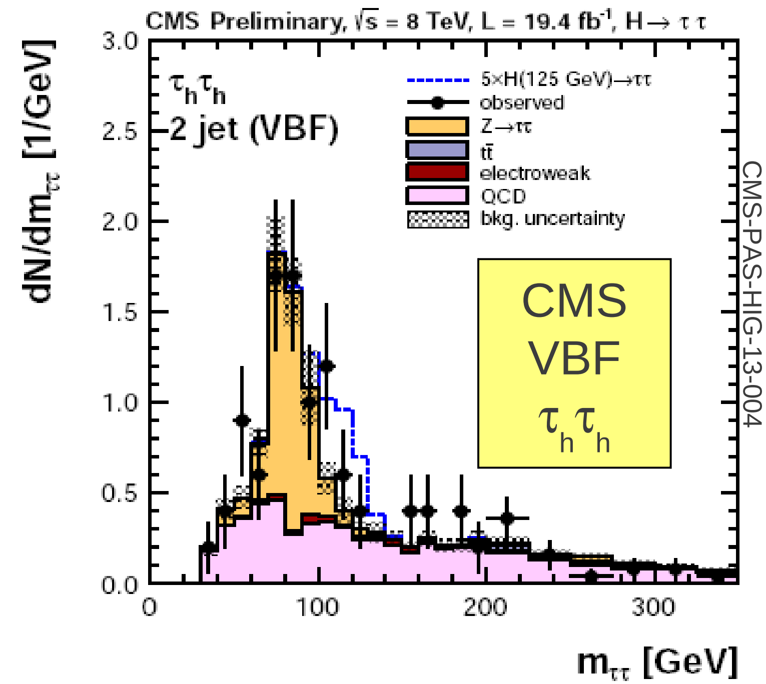
$H \to \tau\tau$

ATLAS
VBF
$\tau_h\tau_h$

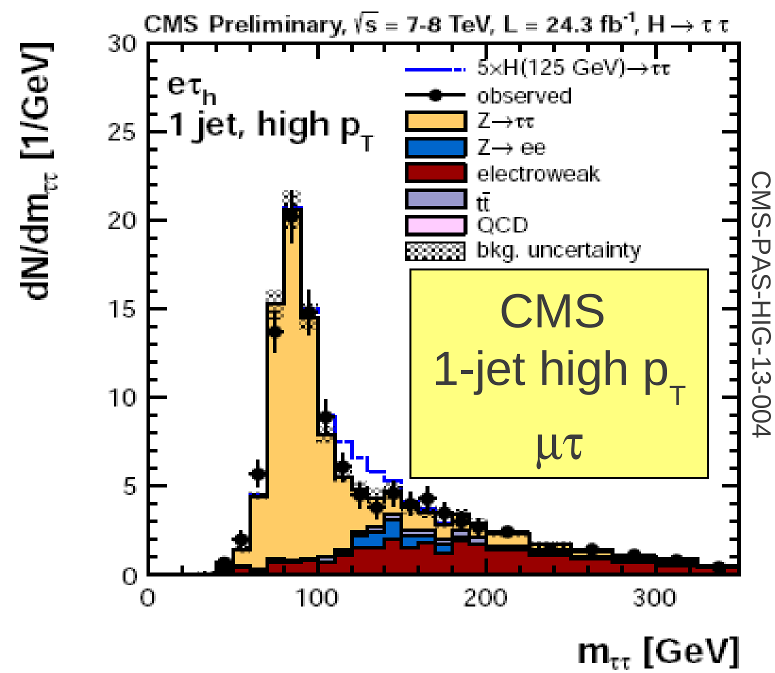


ATLAS
Boosted
$e\tau/\mu\tau$



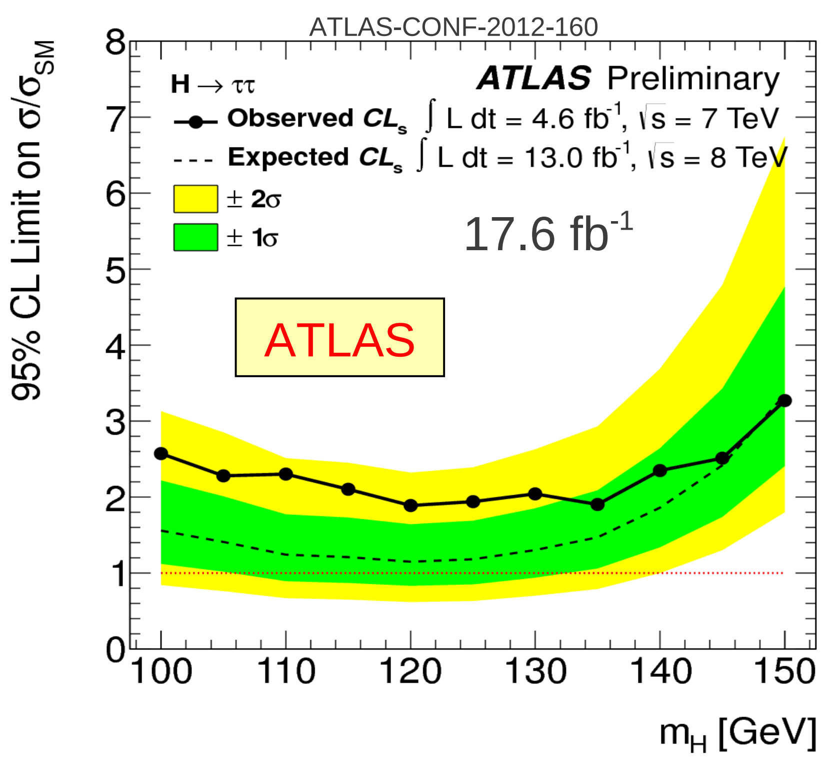


CMS
VBF
$\tau_h\tau_h$



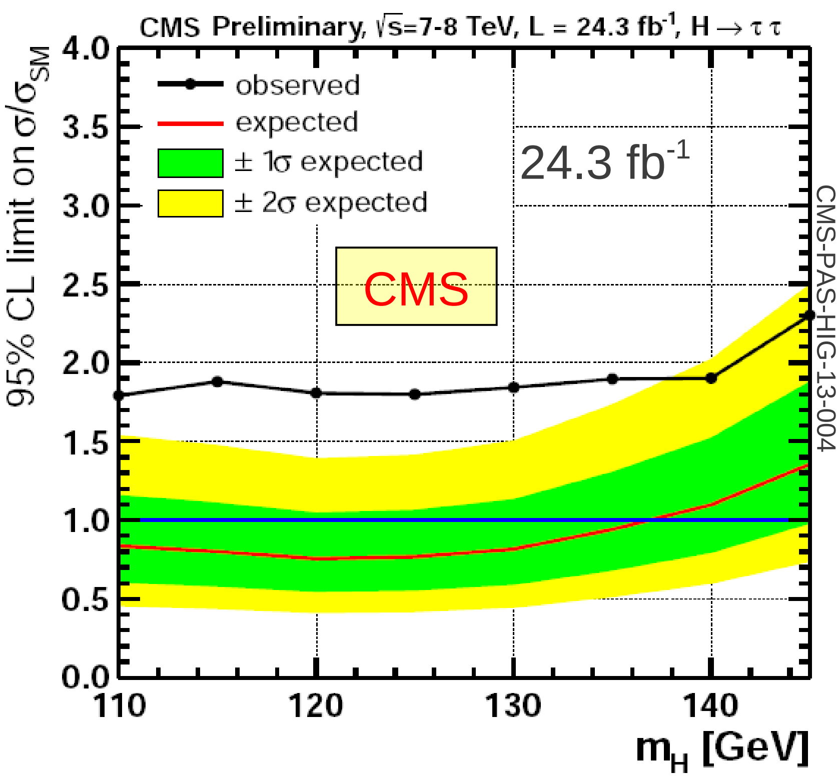
CMS
1-jet high p_T
$\mu\tau$

$H \rightarrow \tau\tau$



For mass at 125 GeV,
expected limit is 1.2xSM,
observed is 1.9xSM

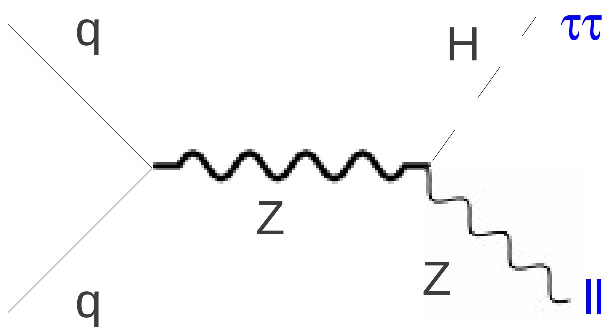
Best-fit μ = 0.7 ± 0.7
at m_H = 125 GeV

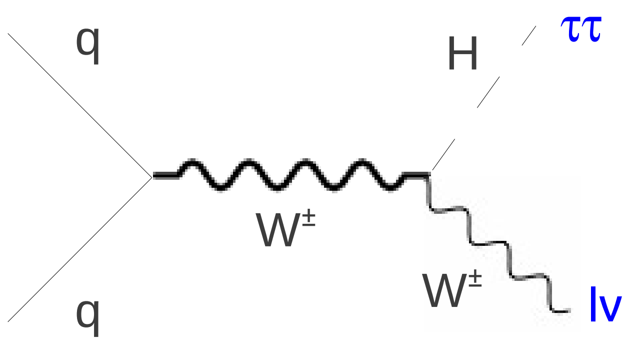


For mass at 125 GeV,
expected limit is 0.77xSM,
observed is 1.80xSM
VH is included (cf. next slide)

Best-fit μ = 1.1 ± 0.4
at m_H = 125 GeV

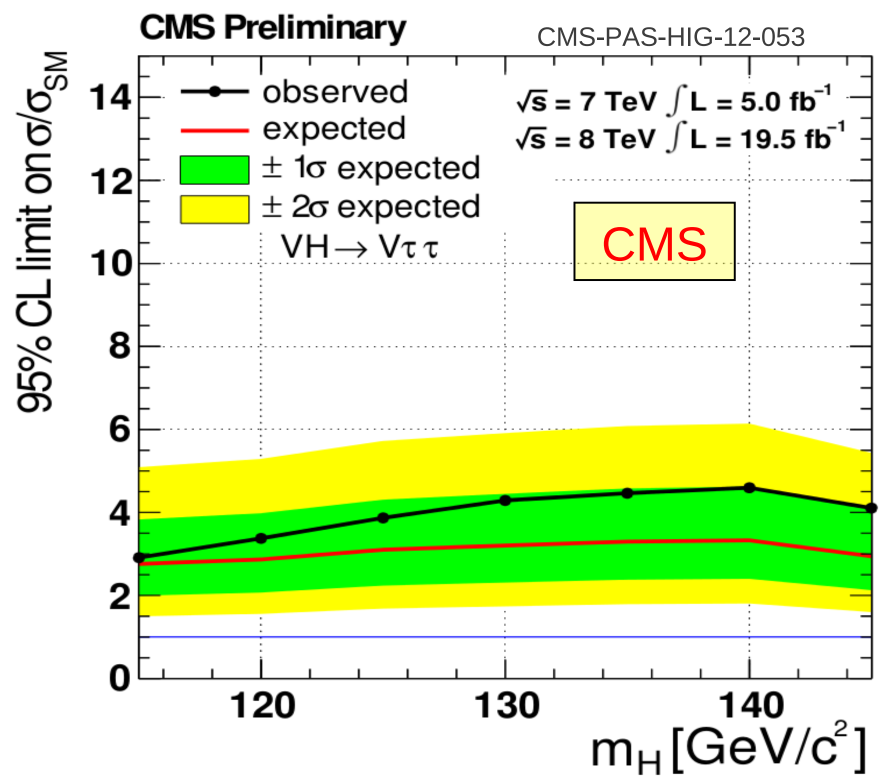
$VH \rightarrow (ll/l\nu)(\tau\tau)$



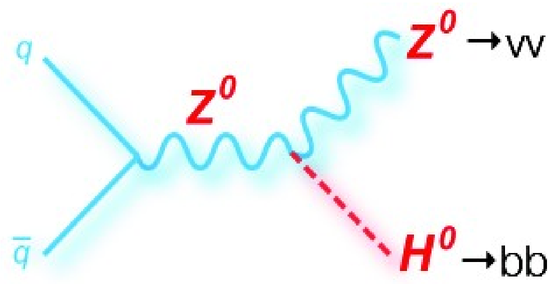


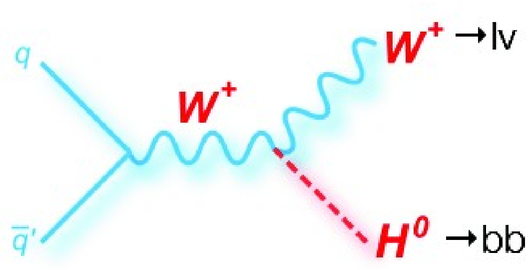
Process	$\ell\ell\tau_h$	$\ell\tau_h\tau_h$	$\ell\ell LL$
Reducible backgrounds	26.3 ± 4.7	20.8 ± 4.2	25.2 ± 10.0
WZ	35.3 ± 3.9	6.3 ± 0.9	
ZZ	2.5 ± 0.3	0.39 ± 0.08	27.2 ± 3.8
Total bkg.	64.1 ± 6.2	27.5 ± 4.3	52 ± 11
VH→V$\tau\tau$($m_H = 125\,\mathrm{GeV}/c^2$)	3.6 ± 0.4	1.2 ± 0.2	2.1 ± 0.2
VH→VWW ($m_H = 125\,\mathrm{GeV}/c^2$)	0.50 ± 0.05	0	1.13 ± 0.09
Observed	65	36	66

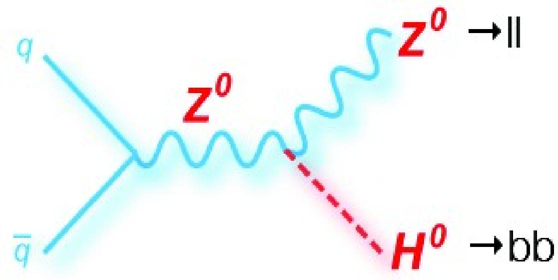
CMS	
$ll\tau_h$	$\mu\mu\tau_h,\ e\mu\tau_h$
$l\tau_h\tau_h$	$e\tau_h\tau_h,\ \mu\tau_h\tau_h$
$llLL$	$lle\mu,\ lle\tau_h,\ ll\mu\tau_h,\ ll\tau_h\tau_h$



$H \to b\bar{b}$







$ZH \to \nu\bar{\nu}b\bar{b}$ | $WH \to \ell\nu b\bar{b}$ | $ZH \to \ell^+\ell^- b\bar{b}$

Signal region:
0-lepton
large MET
2 b-tags

Signal region:
1-lepton
large MET
2 b-tags

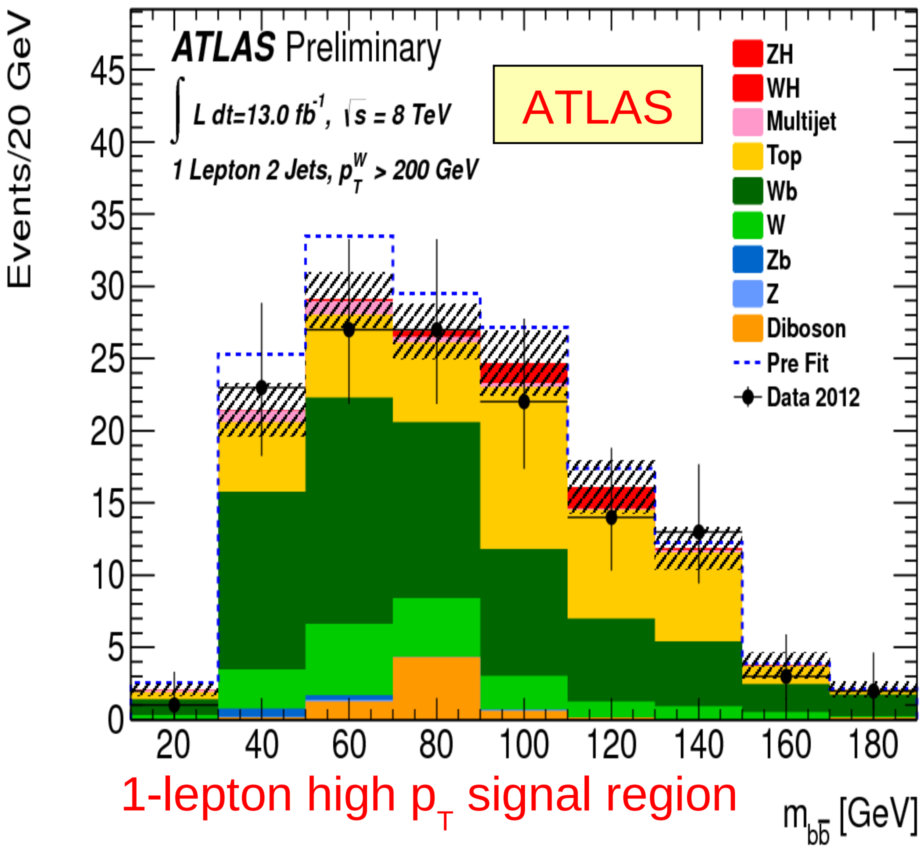
Signal region:
2-lepton, m_{LL} window
low MET
2 b-tags

Control samples for background estimation (by simultaneous fit):

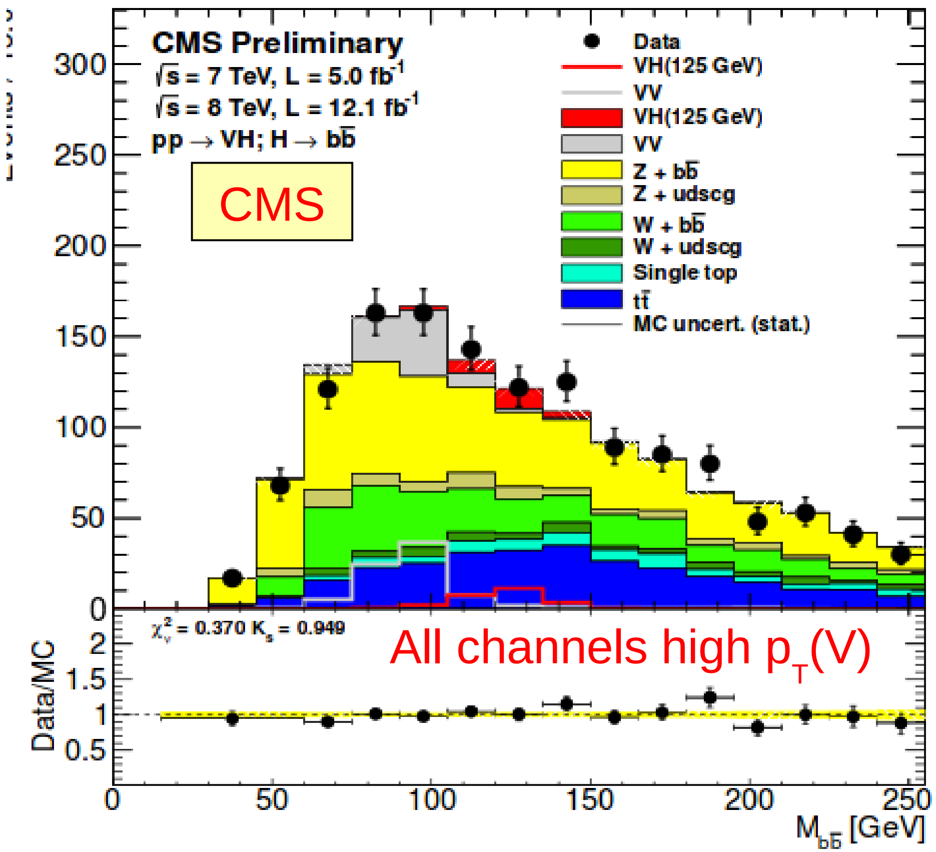
	Z(νν)H	W(lν)H	Z(ll)H
top ($t/t\bar{t}$)	1 b-tag, m($b\bar{b}$), or jet multiplicity		reverse m_{LL}/MET
W/Z+light jets	0/1 b-tag, m($b\bar{b}$)		
W/Z+b-jets	1/2 b-tag, m($b\bar{b}$)		
QCD	reverse the MET, MET-jet angle, or lepton isolation cuts		

$\mathrm{H} \rightarrow b\bar{b}$

ATLAS-CONF-2012-161



CMS-PAS-HIG-12-044

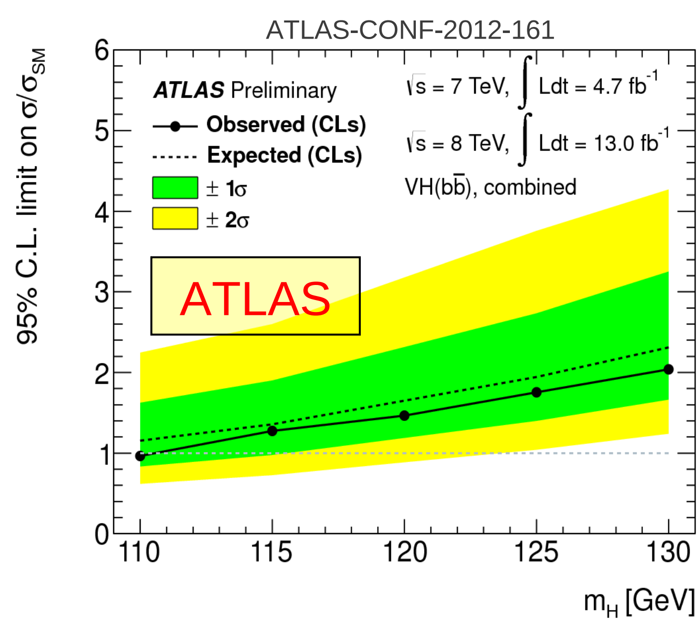


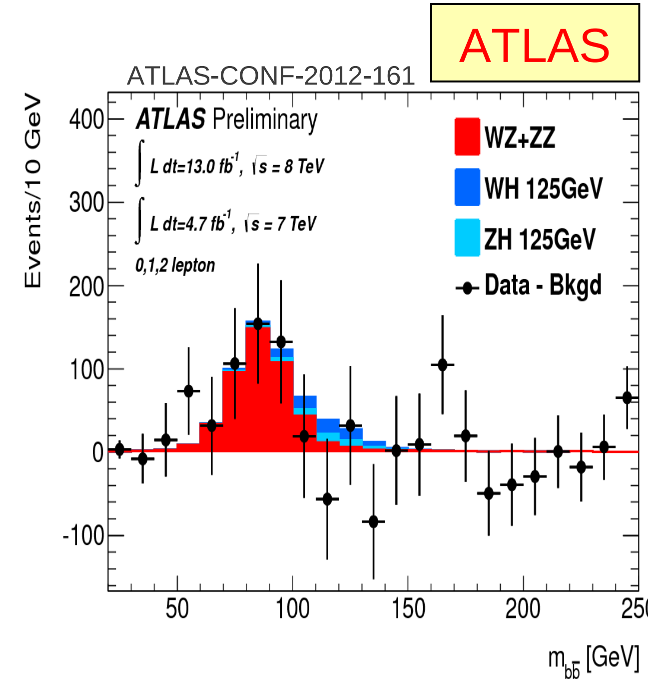
ATLAS:
Cut-based analysis
3-5 bins in $p_T(V)$
Separate V+c and V+udsg
One set of norm factors

CMS:
MVA-based analysis
2 bins in $p_T(V)$
merge V+c and V+udsg
Separate norms in bins

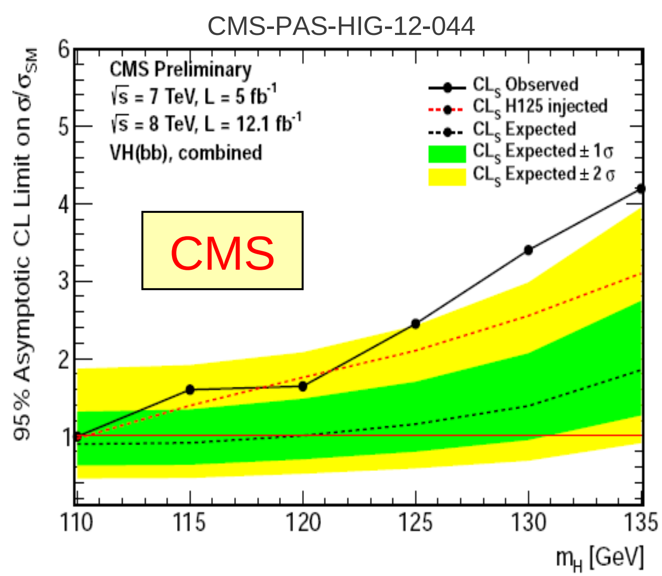
$\mathrm{H} \rightarrow b\bar{b}$

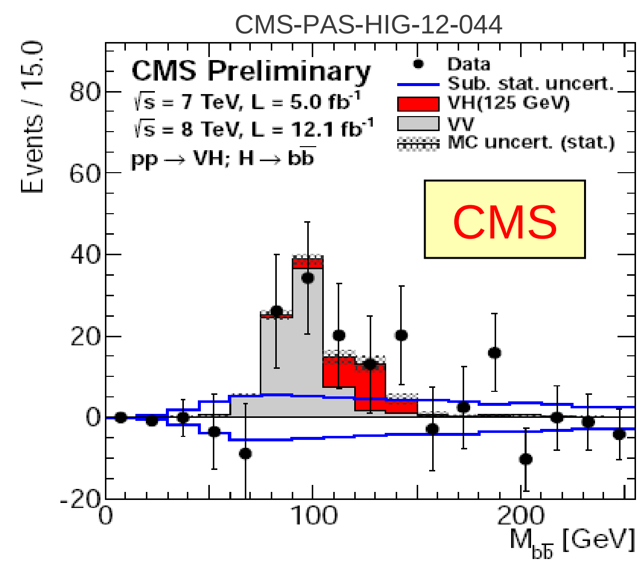
ATLAS:
Expected: 1.9xSM
Observed: 1.8xSM
Best-fit μ = -0.4 ± 1.1
at m_H = 125 GeV





CMS:
Expected: 1.2xSM
Observed: 2.5xSM
Best-fit μ = 1.3 $^{+0.7}_{-0.6}$
at m_H = 125 GeV



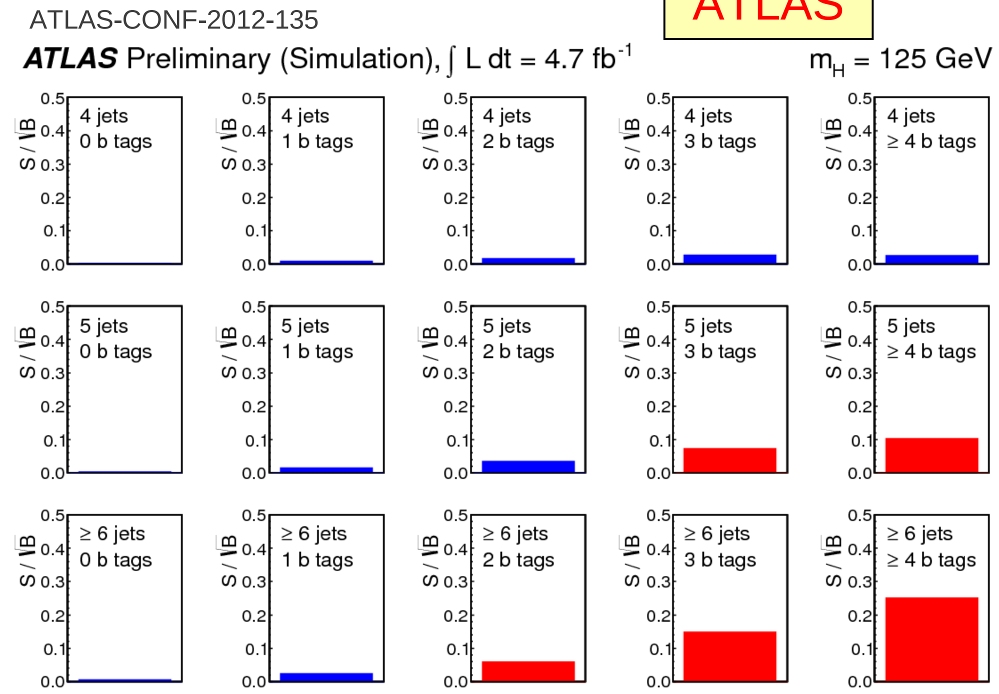


$t\bar{t}H \rightarrow b\bar{b}$

ATLAS: use m($b\bar{b}$) or H_T^{had} as discriminants, and use kinematic reconstruction for 6+ j, 3/4+ b topology
Only 1-lepton mode. Simultaneous fit

CMS: use MVA output (NN) as discriminants in each topology.
Both 1 and 2-lepton modes.
Simultaneous fit to NN

ATLAS

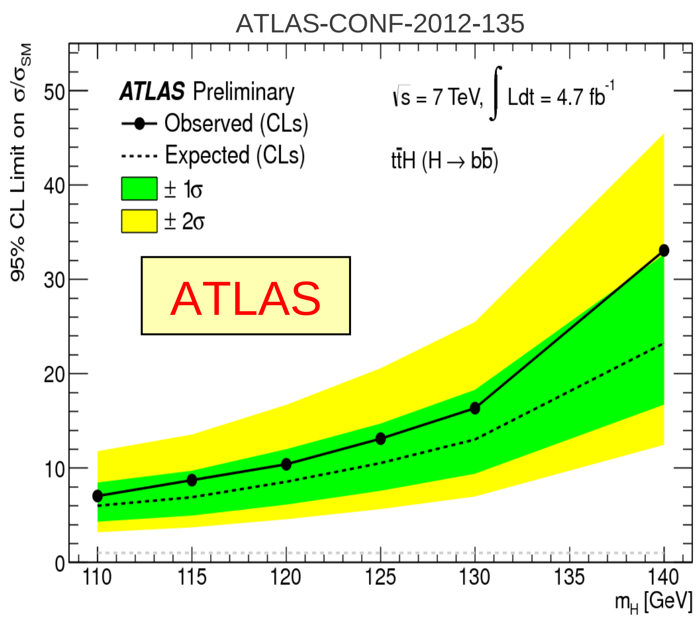


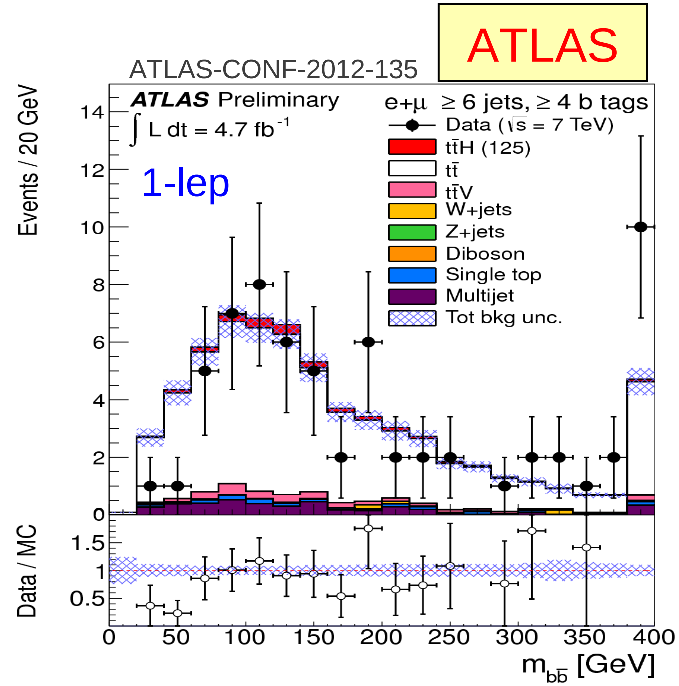
Topologies used (red ones are only used as control regions, not as signal regions) :

ATLAS				
1-lepton	5 j, 3/4+ b	6+ j, 3/4+ b	4 j, 0/1/2+ b	5/6+ j, 2 b
CMS				
1-lepton	4 j, 3/4+ b	5 j, 3/4+ b	6 j, 2/3/4+ b	
2-lepton	2 j, 2 b	3+ j, 3+ b		

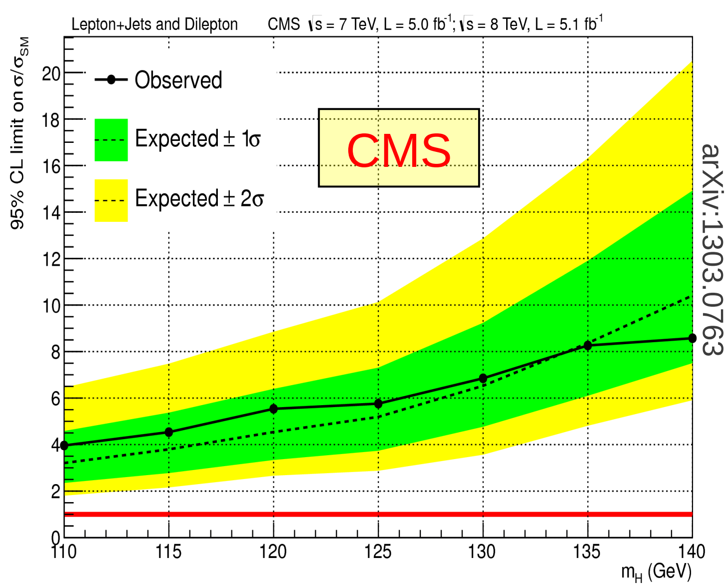
$t\bar{t}H \rightarrow b\bar{b}$

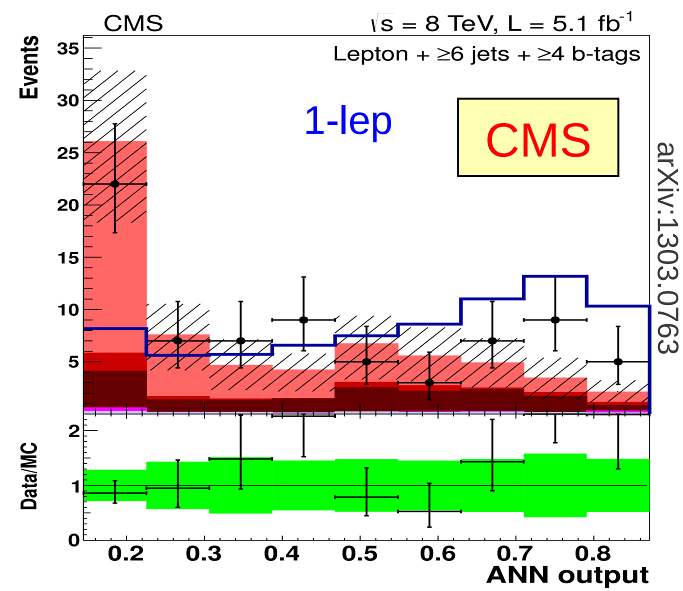
ATLAS:
Expected: 10.5xSM
Observed: 13.1xSM
at m_H = 125 GeV
1-lepton only



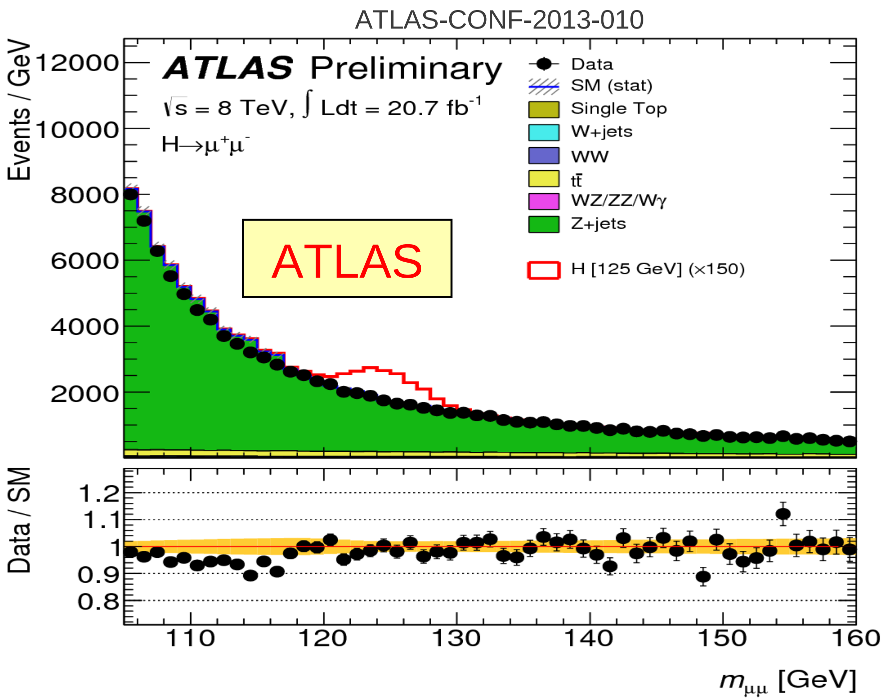


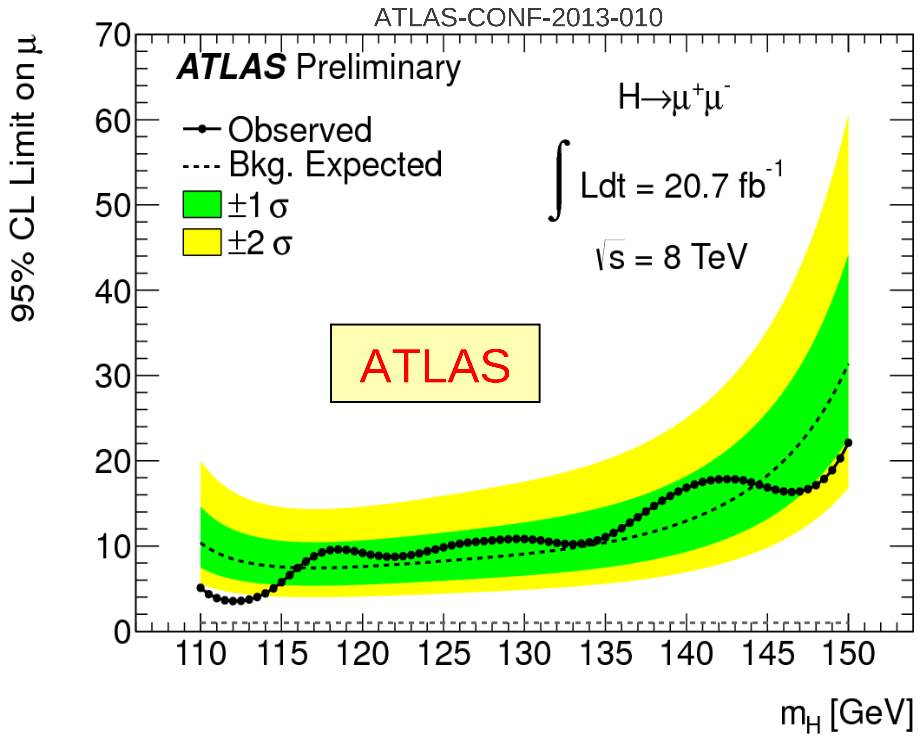
CMS:
Expected: 5.2xSM
Observed: 5.8xSM
at m_H = 125 GeV
1-lepton + dilepton





H → μμ





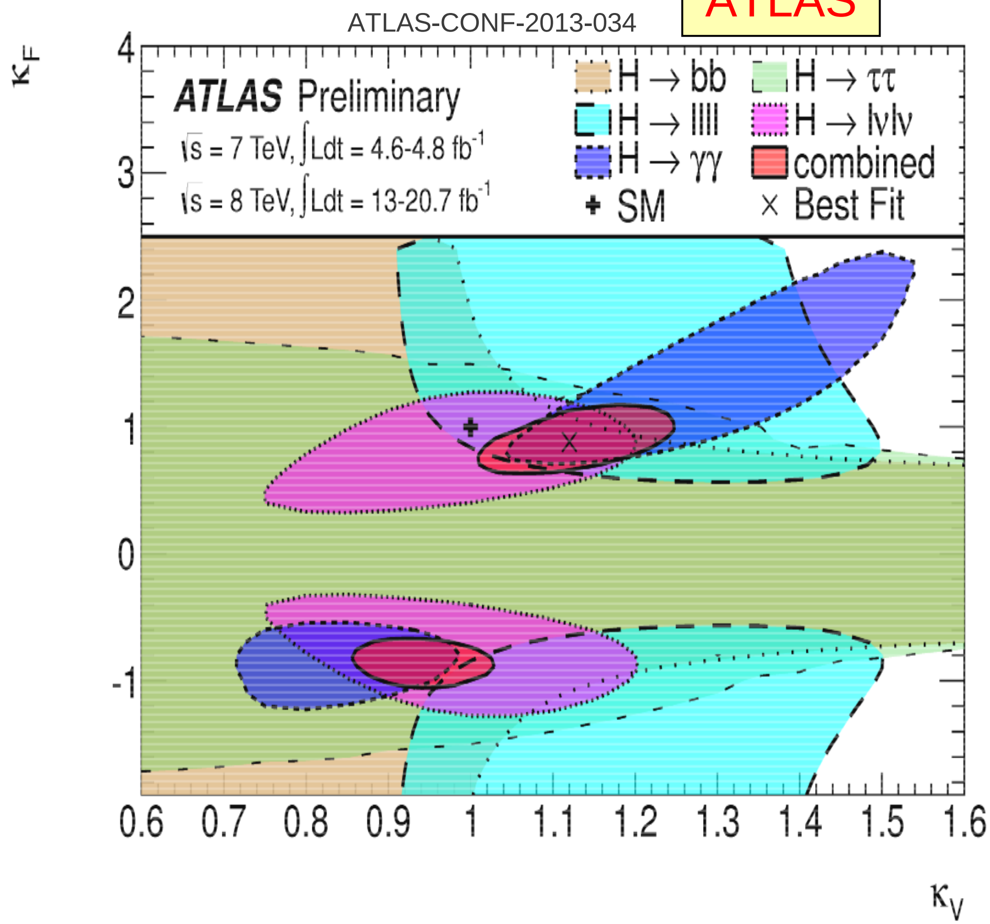
	$\|m_H - m_{\mu\mu}\| \leq 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
$WZ/ZZ/W\gamma$	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15810 ± 130
W+jets	88 ± 6
Total Bkg.	17700 ± 130
Observed	17442

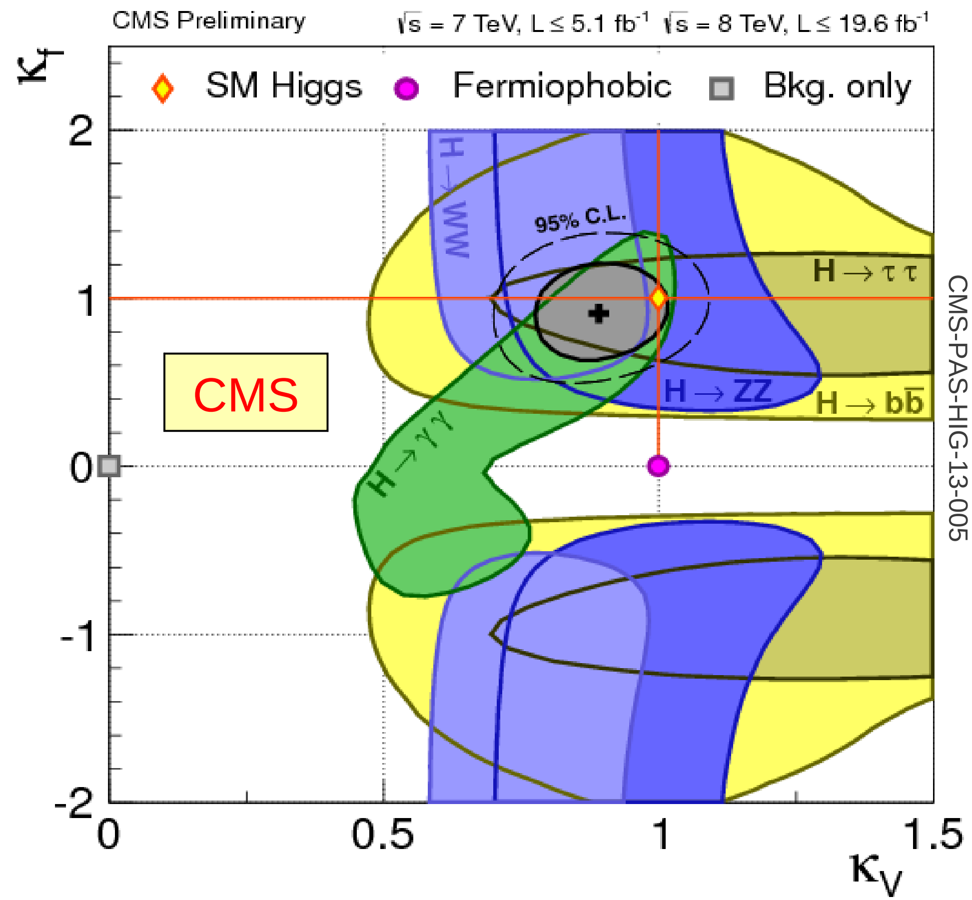
ATLAS SM H→μμ:
Expected: 8.2xSM
Observed: 9.8xSM
at m_H = 125 GeV

γγ-style bump hunting:
small rate, good resolution

SM couplings – boson vs fermion

ATLAS





K_F and K_V: coupling strength scale factors for fermions and bosons

Double minima are due to H → γγ : $K_\gamma^2 = |1.28\, K_W - 0.28\, K_t|^2$

H → μμ (MSSM)

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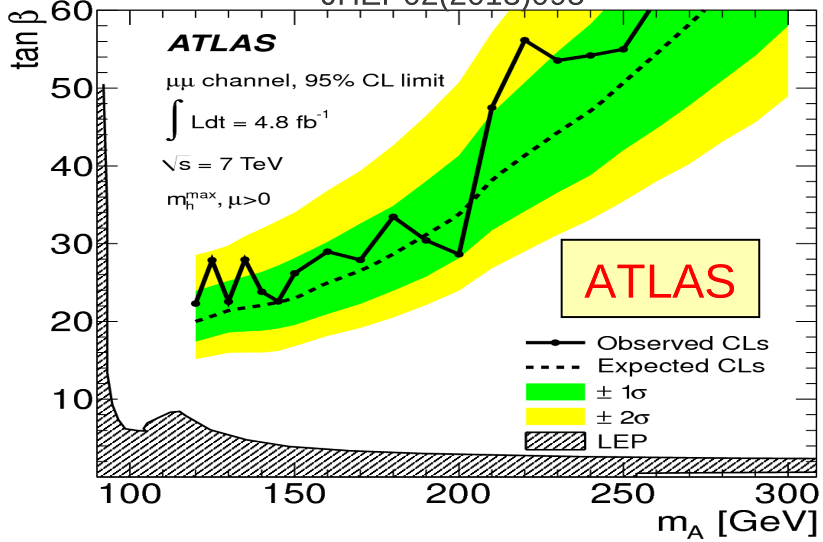

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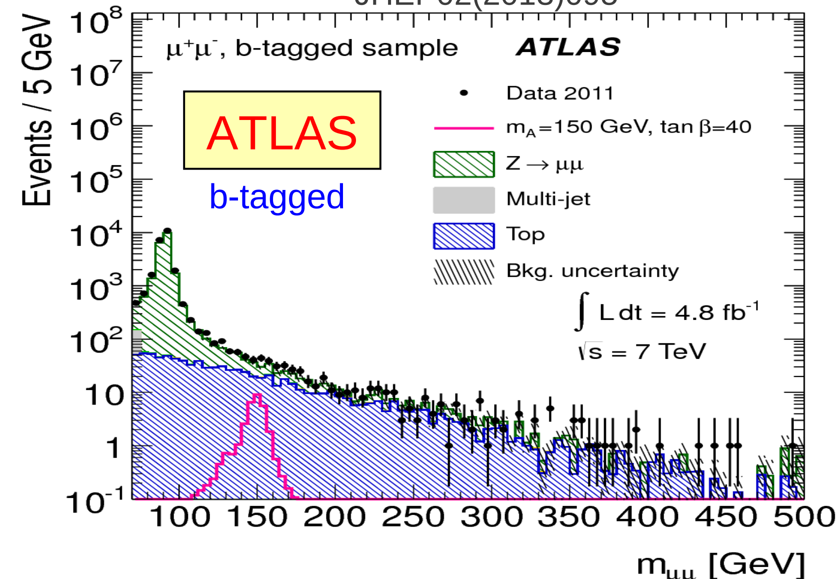
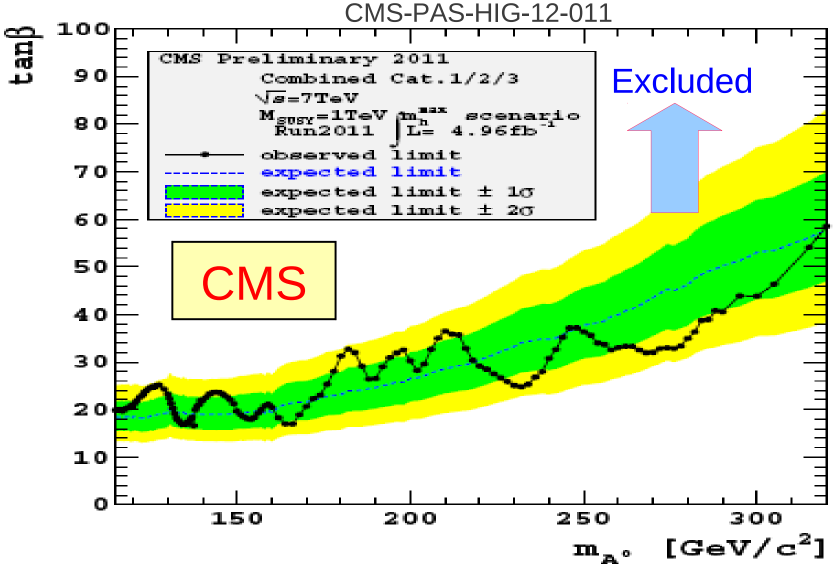
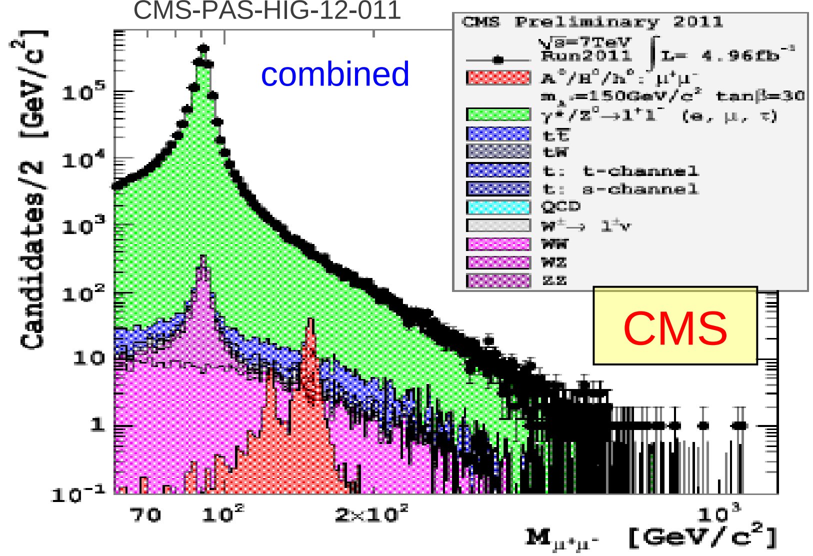


CMS-PAS-HIG-12-011

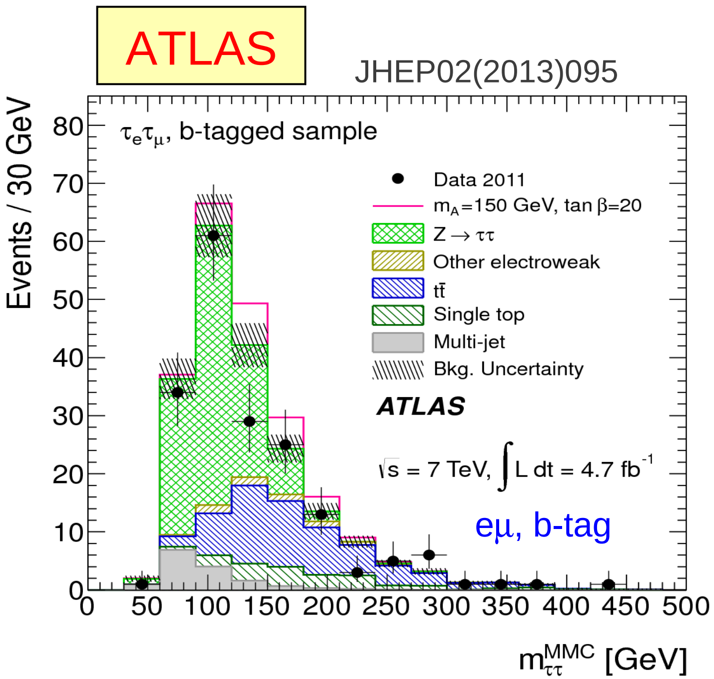


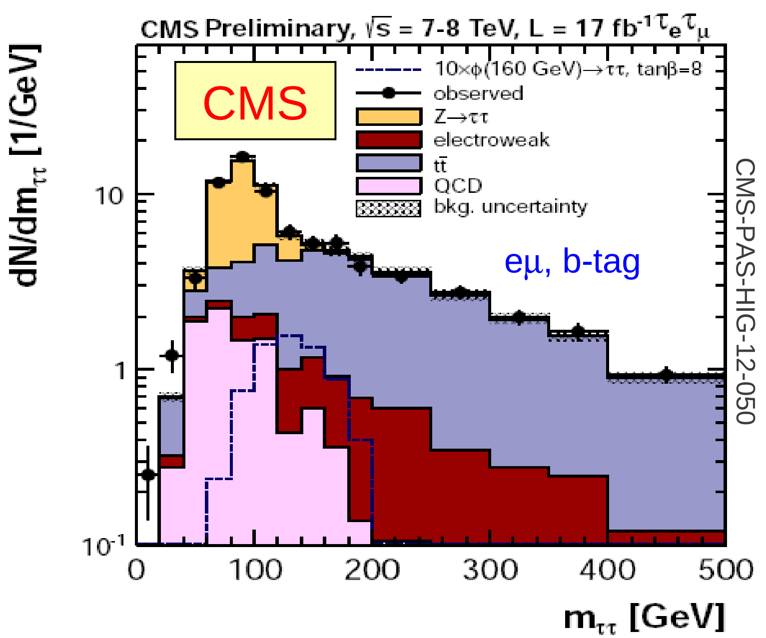
CMS-PAS-HIG-12-011



MSSM m_h^{max} scenario: the 3 contributions of h, H and A are considered together

$H \to \tau\tau$ (MSSM)



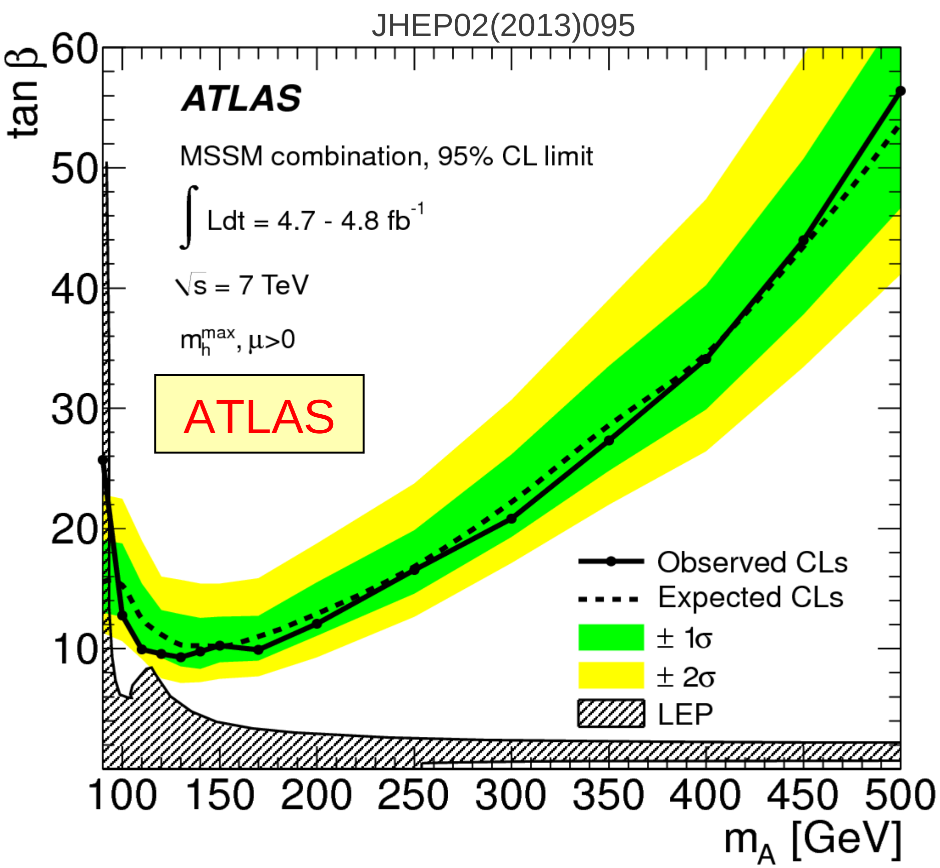


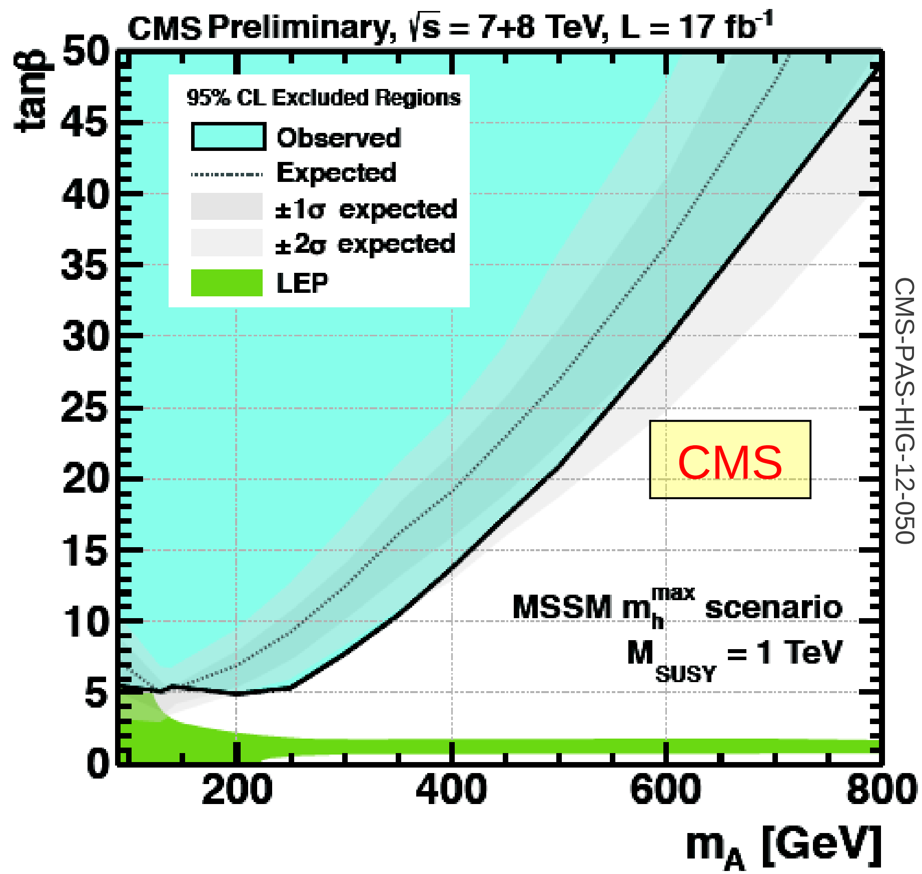
Events are generally divided into b-tagged and b-vetoed regions for $b\bar{b}H$ and ggH productions (the b-jets in $b\bar{b}H$ is soft in p_T)

Analysis techniques from SM ττ search can be largely re-used: background estimation and mass reconstruction

ATLAS		
eμ	exactly 1 b-tag	no b-tag
$e\tau_h$, $\mu\tau_h$	20<p_T(j1)<50 GeV, j1 is b-tagged	j1 is not b-tagged
$\tau_h\tau_h$		
CMS		
eμ, μμ, $e\tau_h$, $\mu\tau_h$	1+ b-tag, 1-jet exclusive	no b-tag

$H \rightarrow \tau\tau$ (MSSM)





With the discovery of a 125 GeV Higgs, MSSM is still compatible with either of the 2 CP-even Higgs (h, H) being the 125 GeV particle.

Both ATLAS and CMS used the MSSM m_h^{max} scenario: maximal mass for the lighter h

(refer to backup slide 28 for model independent limit on σxBR)

$H^+ \to \tau\nu$ (MSSM)

Light $H^{\pm}$ is most copiously produced in the $t \to H^+ b$ decay in the $t\bar{t}$ production. It alter the rate of taus in the final states, and/or distributions such as MET and m_T:

ATLAS

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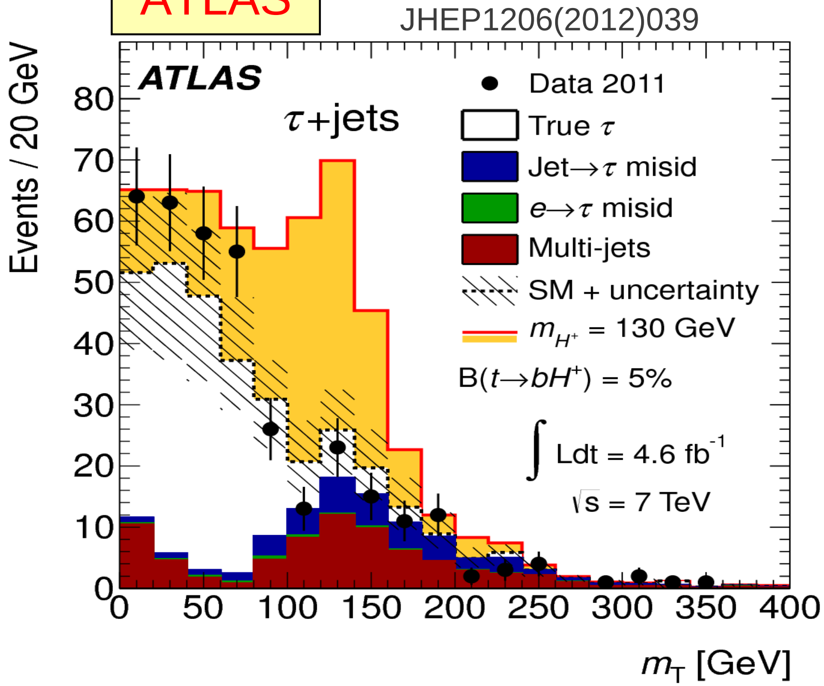
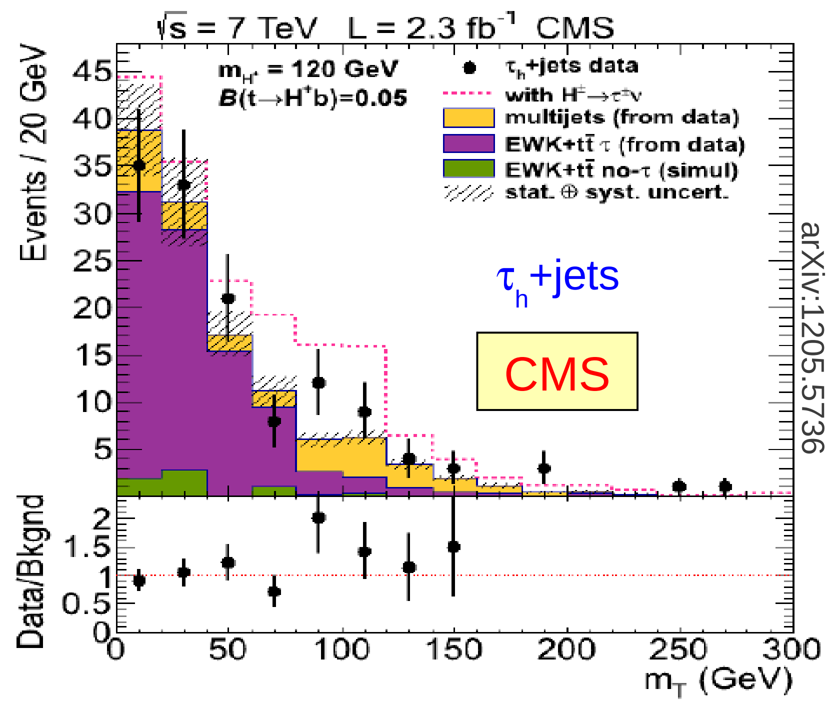
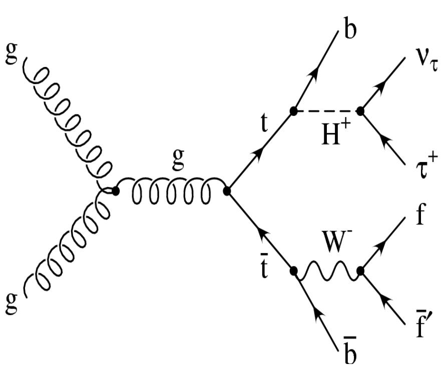




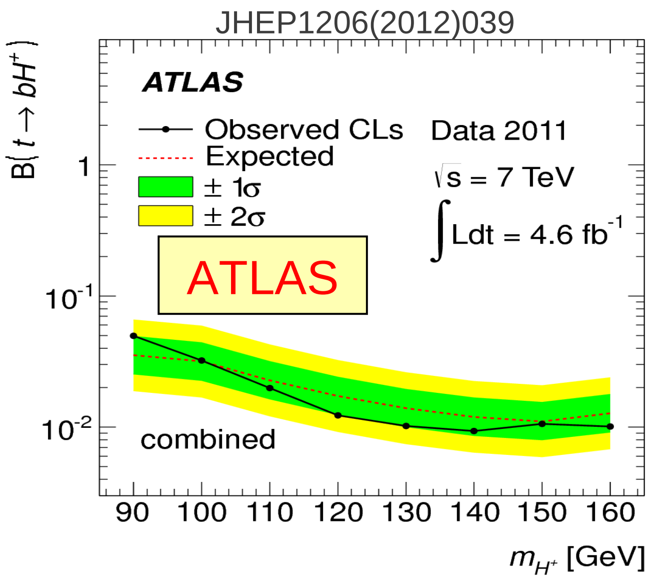
CMS

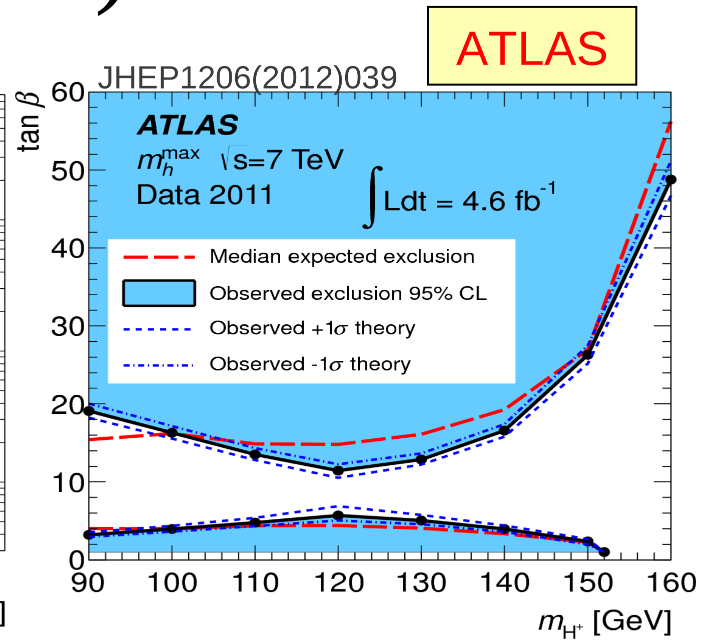


ATLAS	CMS
$t\bar{t} \to b\bar{b}WH \to b\bar{b}(q\bar{q}')(\tau_h \nu)$	$t\bar{t} \to b\bar{b}WH \to b\bar{b}(q\bar{q}')(\tau_h \nu)$
$t\bar{t} \to b\bar{b}WH \to b\bar{b}(l\nu)(\tau_h \nu)$	$t\bar{t} \to b\bar{b}WH \to b\bar{b}(l\nu)(\tau_h \nu)$
$t\bar{t} \to b\bar{b}WH \to b\bar{b}(q\bar{q}')(\tau_{lep} \nu)$	$t\bar{t} \to b\bar{b}WH \to b\bar{b}(l\nu)(\tau_{lep} \nu)$

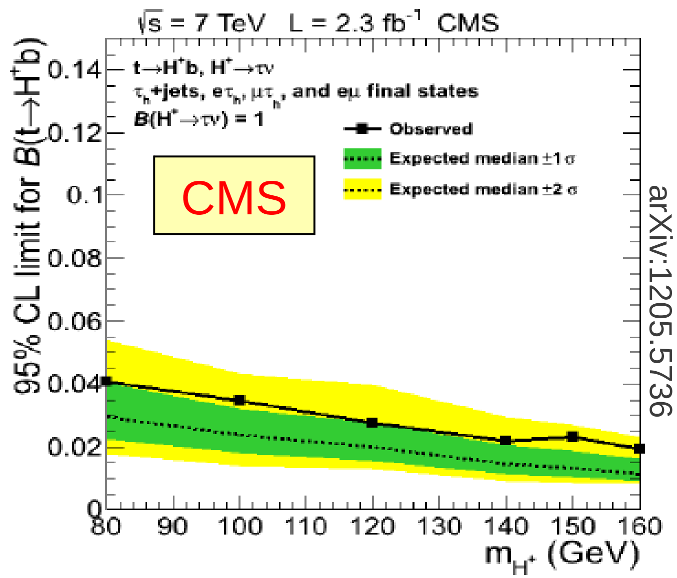
$H^+ \rightarrow \tau\nu$ (MSSM)

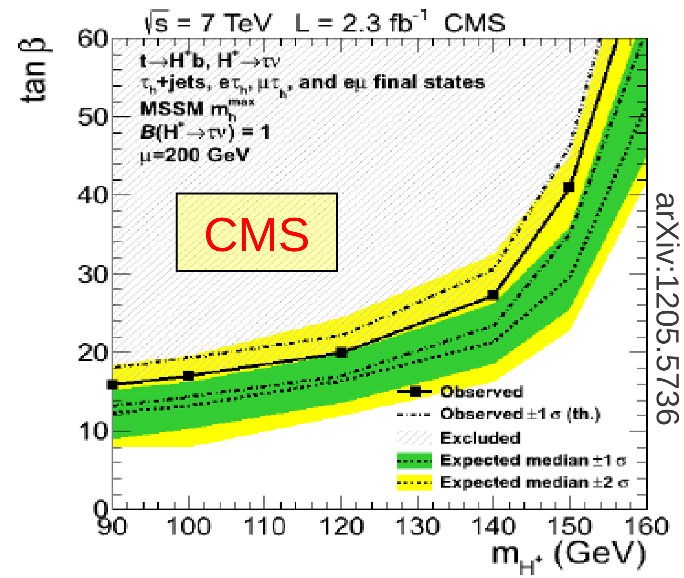
ATLAS:
Assuming $B(H \rightarrow \tau\nu)=1$,
limit on $B(t \rightarrow H^+ b)$ can be set at 1-5% in the mass range of [90-160] GeV





CMS:
Assuming $B(H \rightarrow \tau\nu)=1$,
limit on $B(t \rightarrow H^+ b)$ can be set at 2-4% in the mass range of [80-160] GeV





ATLAS: using a ratio method, better $B(t \rightarrow H^+ b)$ limits are achieved (backup slide 29)

Higgs fermionic decay summary

	ATLAS		CMS	
SM $H\to\tau\tau$	17.6 fb^{-1}	<1.9xSM μ=0.7±0.7	24.3 fb^{-1}	<1.8xSM μ=1.1±0.4
SM $VH\to(ll/l\nu)(\tau\tau)$	—		24.5 fb^{-1}	<3.9xSM
SM $H\to b\bar{b}$	17.6 fb^{-1}	<1.8xSM μ=-0.4±1.1	17.1 fb^{-1}	<2.5xSM $\mu=1.3^{+0.7}_{-0.6}$
SM $t\bar{t}H\to b\bar{b}$	4.7 fb^{-1}	<13.1xSM	10.1 fb^{-1}	<5.8xSM
SM $H\to\mu\mu$	20.7 fb^{-1}	<9.8xSM	—	
MSSM $H\to\mu\mu$	4.7 fb^{-1}	tanβ-m_A plane σxBR upper limit	5.0 fb^{-1}	tanβ-m_A plane σxBR upper limit
MSSM $H\to\tau\tau$	4.7 fb^{-1}		17 fb^{-1}	
MSSM $H^+\to\tau\nu$	4.6 fb^{-1}	$B(t\to H^+b)$<1-5% tanβ-m_{H^+} plane	2.3 fb^{-1}	$B(t\to H^+b)$<2-4% tanβ-m_{H^+} plane

Caveat: some search results are not covered in this talk: MSSM $H\to b\bar{b}$ (CMS), $H^+\to c\bar{s}$ (ATLAS), and the more exotic signatures such as $H^{++}\to l^+l^+$, $a_0\to\mu\mu$

Summary and outlook

- Following the discovery of a Higgs-like particle in the bosonic decay channels, it is very important to look for its fermionic decays to prove it is a SM Higgs, or something else such as MSSM Higgs

- No Higgs signal has been confirmed in any fermionic decay channels yet. This is partially because these modes are in general more complex in topology, involve MET, or have larger backgrounds. Consistent limits on these decays have been set by ATLAS and CMS (although data luminosities used are not)

- Prospects for the fermionic modes:

  - Not all channels have the full 2011+2012 data used. Several results will be updated with complete data analysis throughout 2013

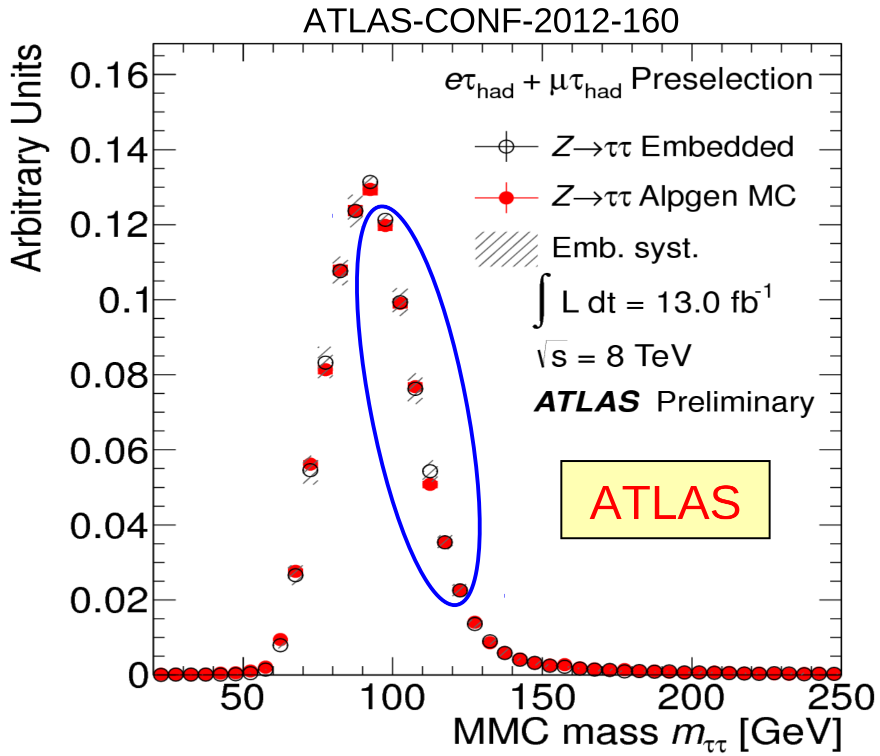
  - More precise measurements will be carried out in the 14 TeV collisions and the LHC high luminosity phase. They will be combined with the bosonic decays for the mapping of the coupling strengths across all decay modes

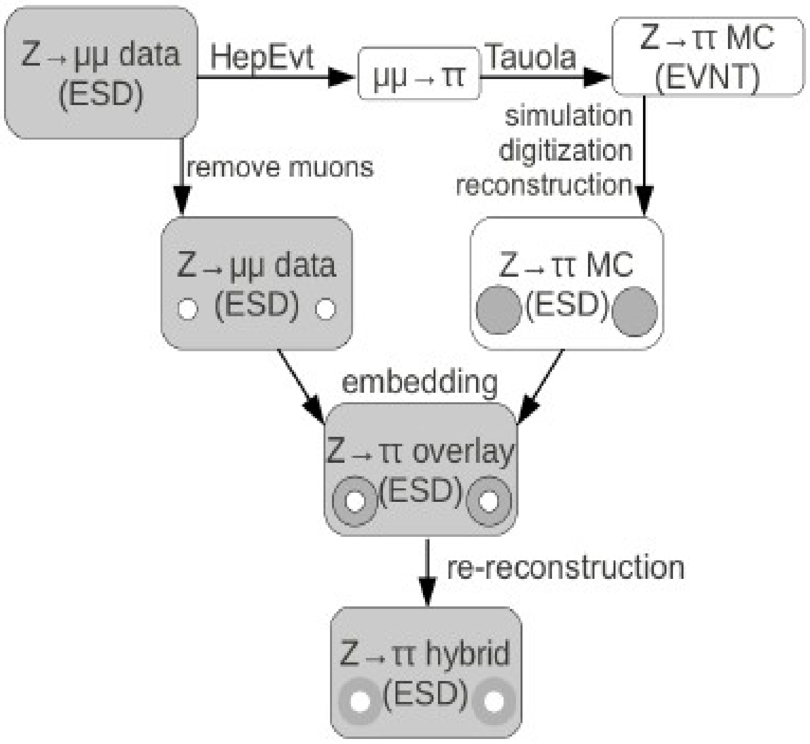
stay tuned for more exciting news from LHC !

Backup Slides

$Z \to \tau\tau$ background for $H \to \tau\tau$

- $Z \to \tau\tau$ (dominant background) is estimated from data using embedding:



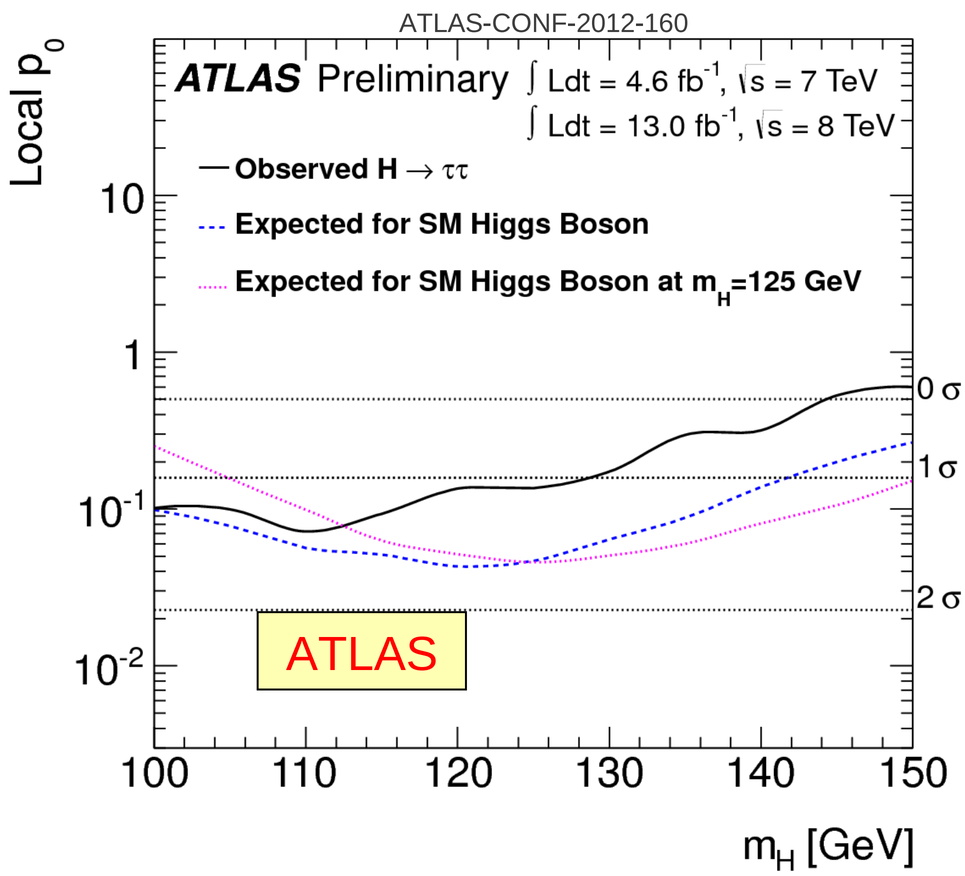


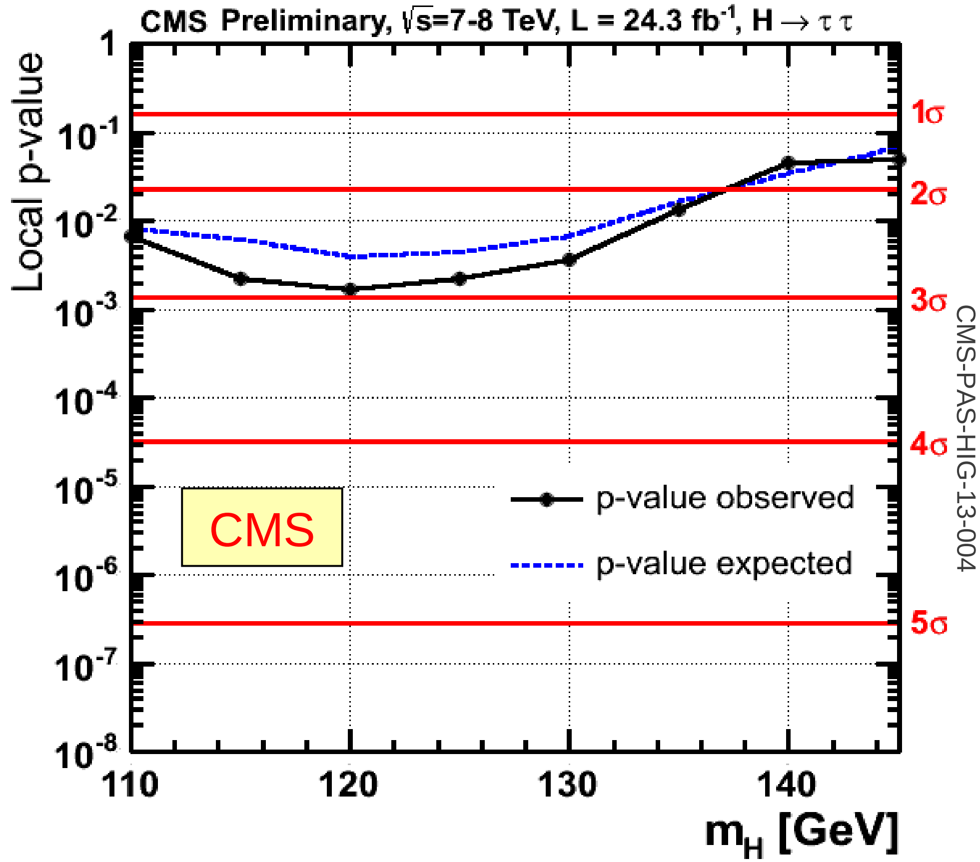
The Higgs signal is sitting on the right shoulder of the $Z \to \tau\tau$ peak. It is very important to use embedding to model this background well

1) Replace muons from $Z \to \mu\mu$ data by taus and decay the taus

2) Embed the simulated tau decay products into the original event

The local p-values for H → ττ





Some hints of H → ττ in both ATLAS and CMS in the local p-value or significance, but more data is needed for a better interpretation

H → ττ (MSSM)

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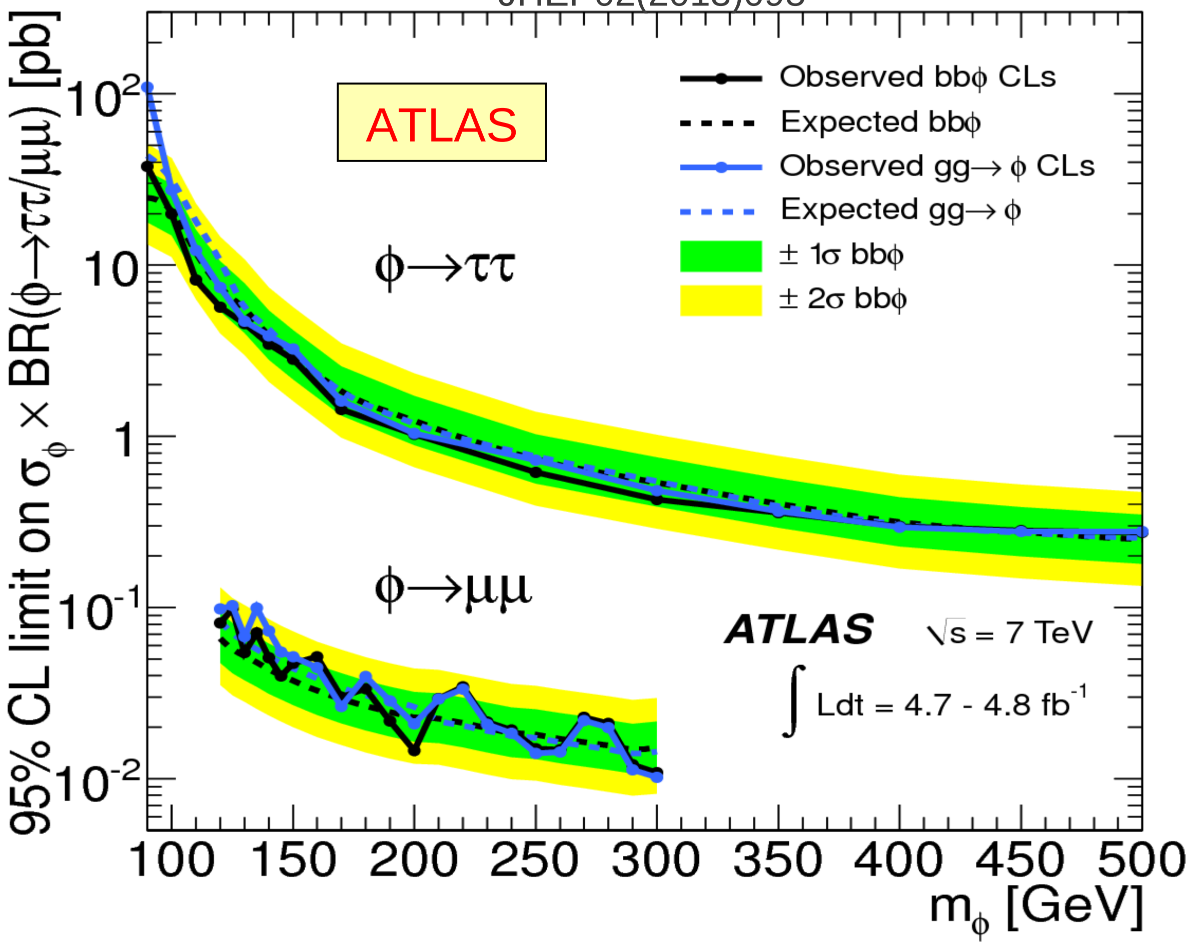
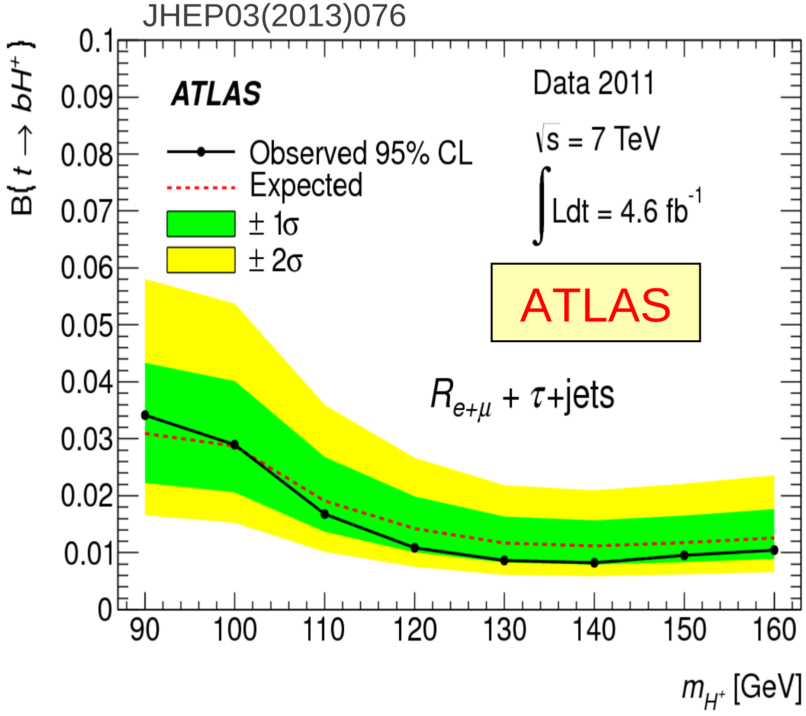
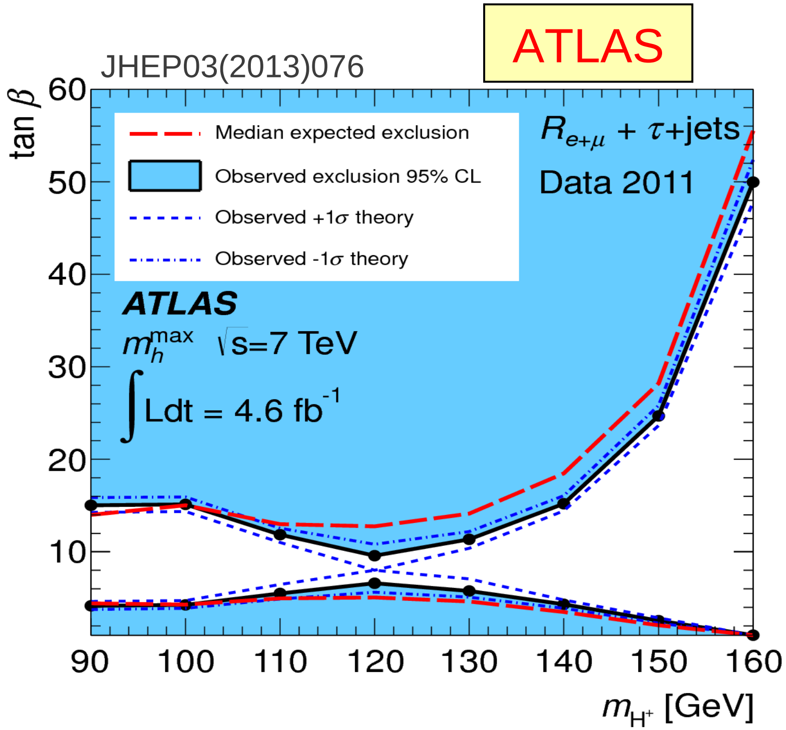


Model independent upper limit on σxBR(H → ττ,μμ) in MSSM

$H^+ \rightarrow \tau\nu$ (MSSM)





ATLAS: using a ratio method ($e\tau_h/e\mu$, $\mu\tau_h/\mu e$), the systematics is substantially reduced. If combined with τ_h+jets, better $B(t\rightarrow H^+b)$ limits of 0.8-3.4% are achieved