

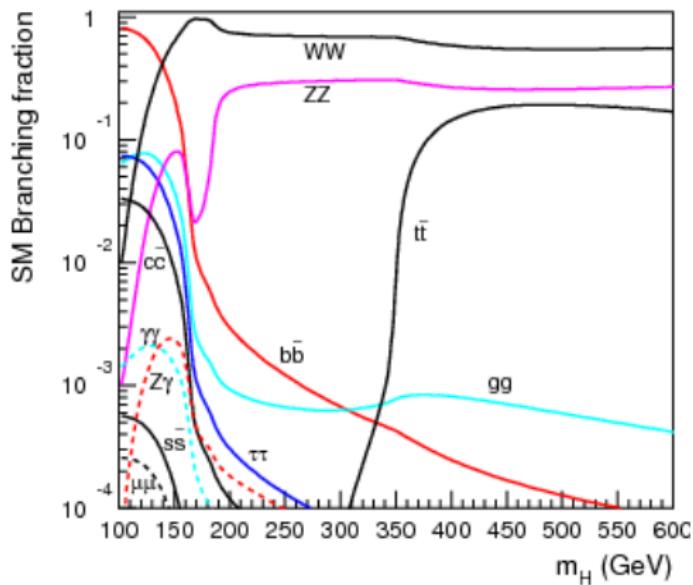
Higgs Bosons Decaying to Fermions in ATLAS and CMS

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on behalf of the ATLAS Collaboration
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Introduction

- New Higgs boson discovered near 125 GeV first seen and studied in bosonic channels ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow l\nu l\nu$)
- At a mass of 125 GeV, Higgs boson decays in many channels, including quarks and leptons $H \rightarrow bb$, $H \rightarrow \tau\tau$, $H \rightarrow \mu\mu$



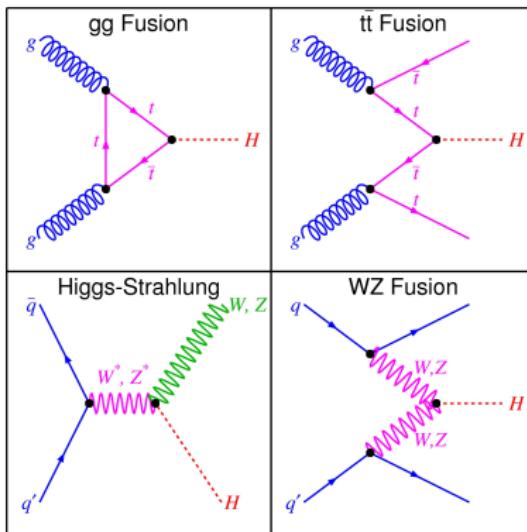
Production Channels

gluon fusion:

- $\sigma \approx 15 \text{ pb}$
- can get additional jets or high- p_T Higgs
- top quark loop provides main constraint on Higgs couplings to quarks

W/Z associated production:

- $\sigma \approx 0.58 \text{ (W) or } 0.34 \text{ (Z) pb}$
- vector boson allows easier triggering and tagging



ttH:

- $\sigma \approx 0.086 \text{ pb}$
- top quarks allow easier triggering and tagging

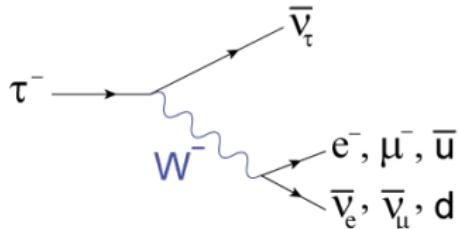
Vector Boson Fusion:

- $\sigma \approx 1.2 \text{ pb}$
- forward jets provide unique signature

$$H \rightarrow \tau\tau$$

$H \rightarrow \tau\tau$ Motivation

- Direct coupling to lepton sector
- 4th channel for observation, after vector bosons and $\gamma\gamma$
- 6.3% branching ratio at $m_H=125$ GeV
- Analyses categorized by decay mode, to allow optimization to different backgrounds



$\tau_{lep}\tau_{lep}$

- lep= μ, e
- cleanest channel
- μ generally cleaner than e in detector, lower backgrounds
- price: 12% branching fraction, Drell-Yan backgrounds

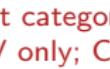
$\tau_{had}\tau_{had}$

- 42% branching ratio, small Drell-Yan background
- price: larger QCD jets background, jet energy scale/resolution

$\tau_{lep}\tau_{had}$

- best of both worlds: clean lepton tag, 46% branching ratio
- generally channel with most power

$H \rightarrow \tau\tau$: Overview of Analyses

	VBF	Boosted	VH	1-jet*	ttH	0-jet**
$\mu\tau_{had}$						
						
$e\tau_{had}$						
						
μe						
						
$\mu\mu$						
						
ee						
						

* CMS splits 1-jet category based on p_T of lepton or τ

** ATLAS: 7 TeV only; CMS: control region only

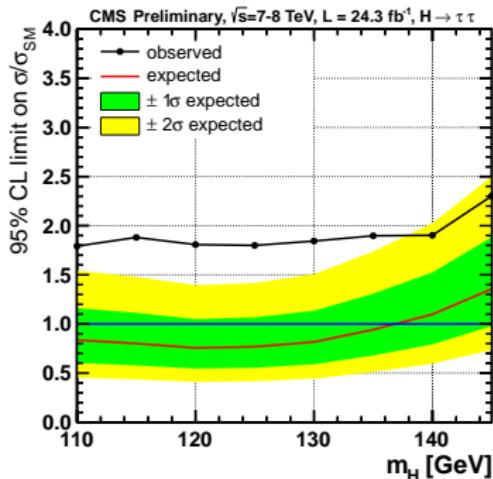
NB: Analysis definitions not identical between collaborations! See notes for more detail

τ Reconstruction and Embedding

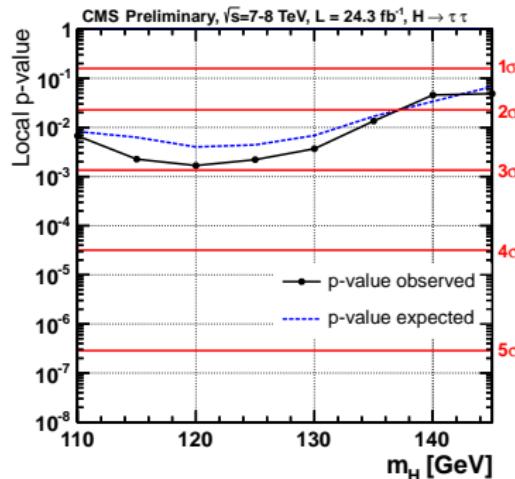
CMS Analysis



CMS $H \rightarrow \tau\tau$: Results



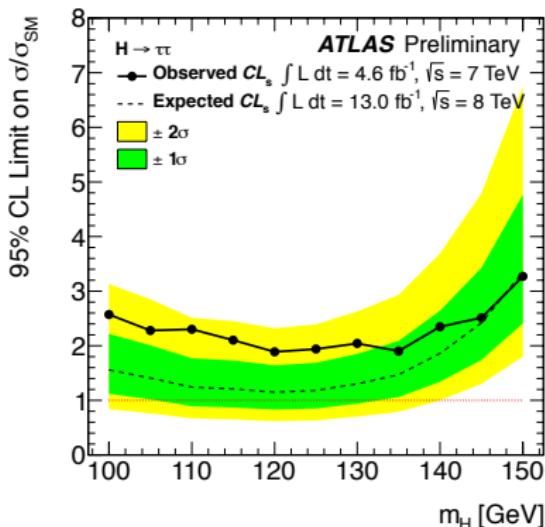
At $m_H=125$ GeV, observed (expected)
 95% CL upper limit on cross section is 1.0 (1.63) \times SM (background-only hypothesis)



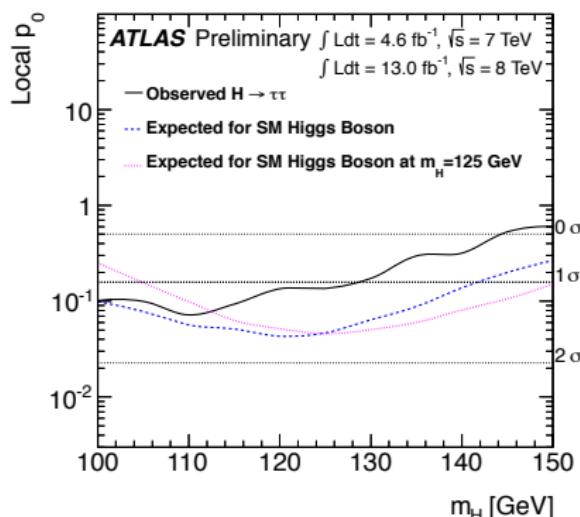
For $m_H=125$ GeV, observed (expected)
 p-value 2.85 (2.62) and best fit value
 $\mu=1.1 \pm 0.4$

ATLAS Analysis and MMC

ATLAS $H \rightarrow \tau\tau$: Results



For $m_H=125$ GeV, observed (expected) 95% CL upper limits on cross section is 1.9 (1.2) \times SM (background-only hypothesis)

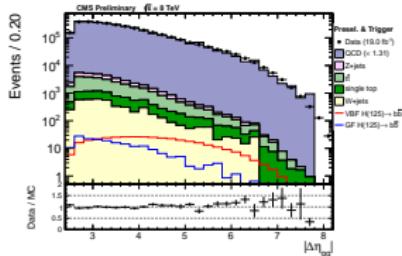


For $m_H=125$ GeV, observed (expected) p-value 1.1 (1.7) σ and best fit value $\mu=0.7 \pm 0.7$

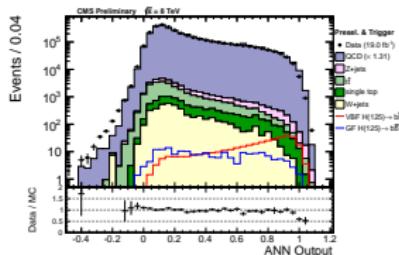
$$H \rightarrow bb$$

- Only experimentally visible decay mode to quarks
- Main way to probe couplings to down-type quarks
- Inclusive production (ggF) impossible to observe because of high QCD background
- Require extra particles or a unique topology
 - Forward jets: characteristic of VBF topology
 - Top quark pair:
 - Vector bosons: $Z \rightarrow \nu\nu$, $W \rightarrow l\nu$, $Z \rightarrow ll$
- High branching ratio (about 58%) means that observation is crucial to constrain the overall Higgs width

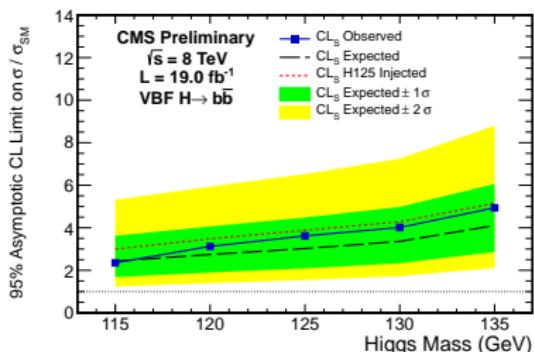
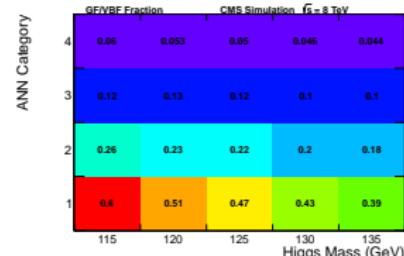
Event topology
characterized by large $\Delta\eta$
between non-b-tagged jets



ANN discriminant based on
event topology and b-tag
values



Highest categories of ANN
heavily dominated
by VBF production (vs. ggF)



For $m_H=125$ GeV, 95% CL upper limits on cross section is 3.6 (3.0) \times SM
(background-only hypothesis) and observed signal strength $\mu=0.7\pm1.4$

ATLAS VBF results still in progress, with result planned for winter 2014

Binning in p_T^V

Backgrounds are substantially reduced by requiring a significant boost of the p_T of the vector boson, p_T^V .

The boost categories (all numbers in GeV) below are for CMS and ATLAS.

	low	medium	high
$W(l\nu)$	100-130	130-180	>180
$W(\tau\nu)$			>120
$Z(\nu\nu)$	100-130	130-170	>170
$Z(II)$	50-100		>100



	low	med-low	medium	med-high	high
$W(l\nu)$	0-90	90-120	120-160	160-200	>200
$Z(\nu\nu)$	*	*	120-160	160-200	>200
$Z(II)$	0-90	90-120	120-160	160-200	>200

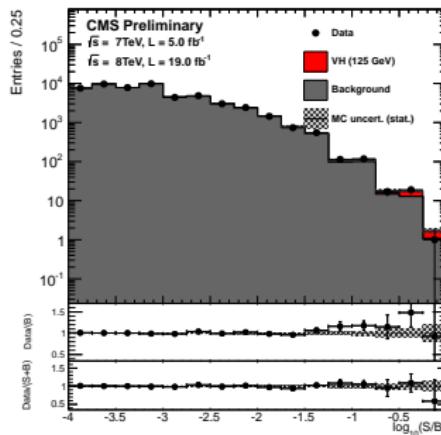
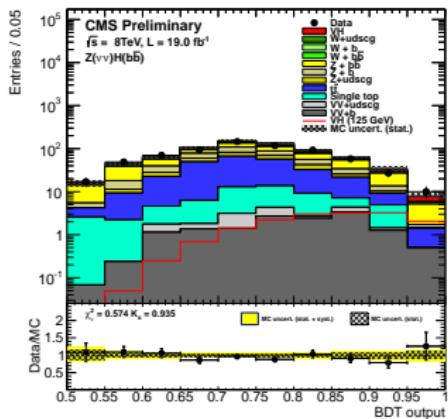


* E_T^{miss} trigger becomes 90% efficient at $E_T^{miss}=120$ GeV

Each vector boson final state and p_T category is further subdivided into 2-jet and 3-jet signal regions

CMS $VH(H \rightarrow bb)$

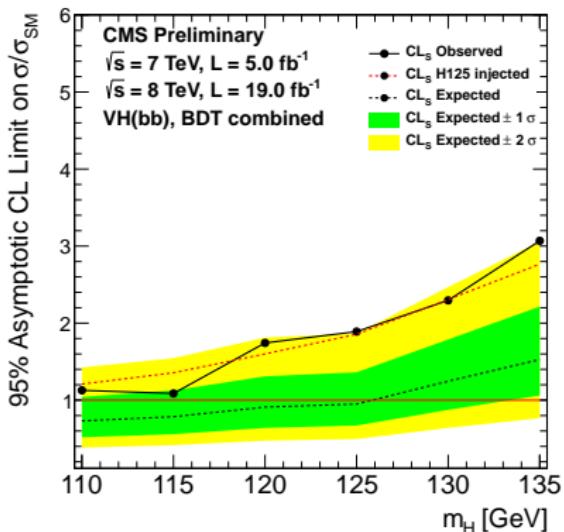
BDT-based analysis, where separate BDT trained for each channel $W(l\nu)H$, $W(\tau\nu)H$, $Z(l\bar{l})H$, $Z(\nu\nu)H$



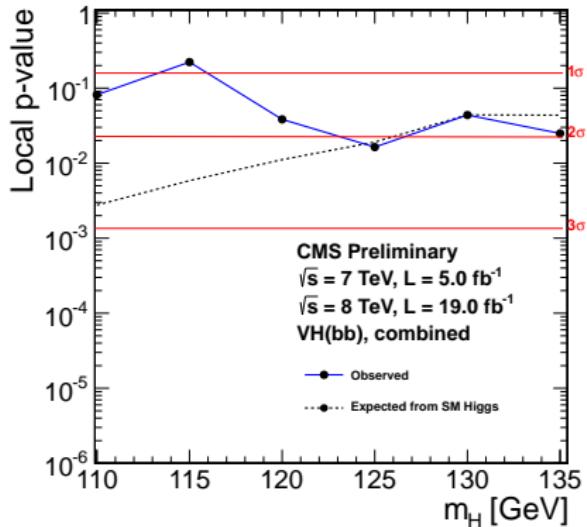
Example output of the BDT, focusing on the most signal-enriched component of the high- p_T $Z(\nu\nu)$ bin

Combination of all BDT discriminants.
 The two bottom insets show the ratio of the data to the background-only prediction (above) and to the predicted sum of signal plus background (below).

$VH(H \rightarrow bb)$: CMS Results



For $m_H=125$ GeV, observed (expected)
95% CL upper limits on cross section is
 1.89 (0.95) \times SM (background-only
hypothesis)



For $m_H=125$ GeV, BDT has observed
p-value 2.1σ and best fit value $\mu=1.0\pm 0.5$

ATLAS $VH(H \rightarrow bb)$: Analysis Strategy



ATLAS $VH(H \rightarrow bb)$: m_{bb} for $p_T^V > 200$ GeV

Each p_T^V category in ATLAS further divided into 2-jet and 3-jet signal regions
 2-jet signal region has S/B about $2\times$ higher than 3-jet region for all categories

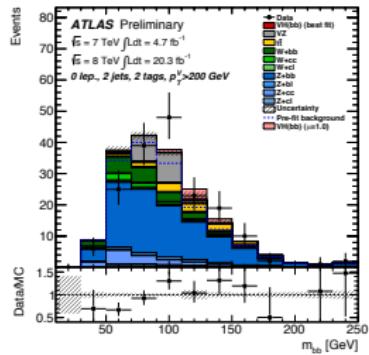
$Z \rightarrow \nu\nu$

0 leptons

2 b-tags, $p_T^{jet1} > 45$ GeV, $p_T^{jet2} > 20$ GeV

+ ≤ 1 extra jets

E_T^{miss} and p_T^{miss} cuts to minimize dijet QCD



$W \rightarrow l\nu$

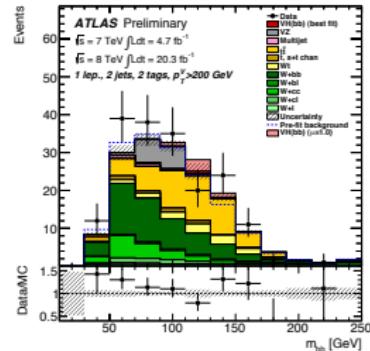
1 lepton

2 b-tags, $p_T^{jet1} > 45$ GeV, $p_T^{jet2} > 20$ GeV

+ ≤ 1 extra jets

$E_T^{\text{miss}} > 25$ GeV

$m_T^W < 120$ GeV



$Z \rightarrow ll$

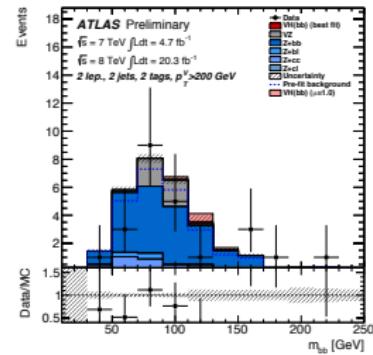
2 leptons

2 b-tags, $p_T^{jet1} > 45$ GeV, $p_T^{jet2} > 20$ GeV

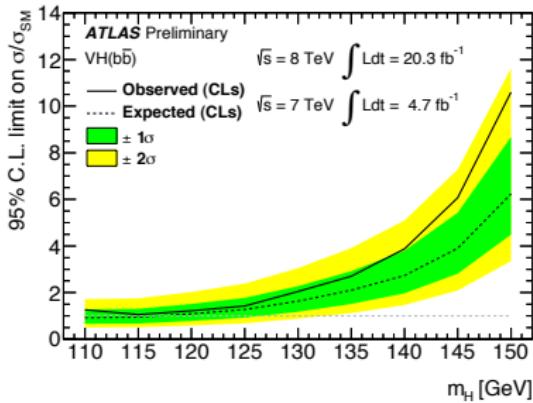
+ ≤ 1 extra jets

$E_T^{\text{miss}} < 60$ GeV

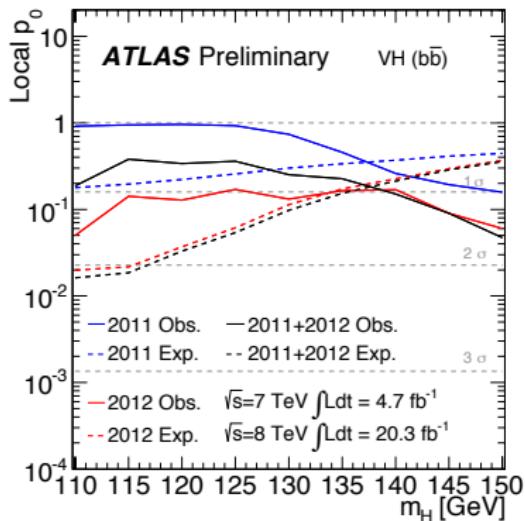
$83 < m_{ll} < 99$ GeV



ATLAS $VH(H \rightarrow bb)$: Results



For $m_H=125$ GeV, observed (expected) 95% CL upper limits on cross section is 1.4 (1.3) \times SM (background-only hypothesis)



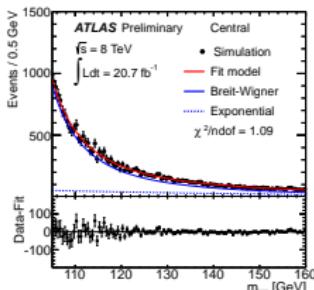
For $m_H=125$ GeV, observed (expected) p -value is 0.36 (0.05) and best fit value $\mu = 0.2 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})$

$H \rightarrow \mu\mu$ Motivation

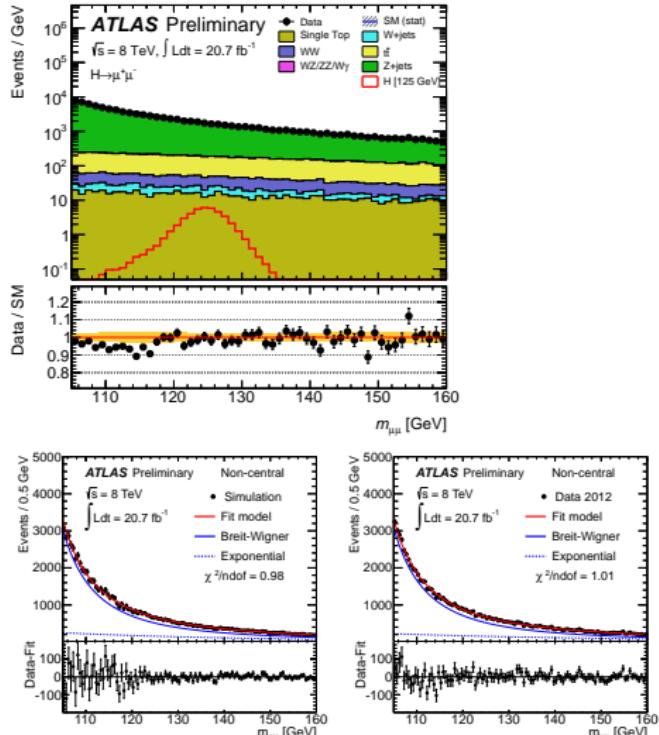
- Small cross section
- Clean final state signature
- Only channel for measuring coupling to second-generation fermions
- Large irreducible background of $Z/\gamma^* \rightarrow \mu\mu$
- Can have enhanced BF from non-SM contributions

$H \rightarrow \mu\mu$ at ATLAS

- Reconstruct invariant mass of 2 muons, $p_T^{\mu_1} > 25$ GeV and $p_T^{\mu_2} > 15$ GeV
- Remove 60% of Drell-Yan background events (and keeping 80% of signal) by requiring $p_T^{\mu_1+\mu_2} > 15$ GeV (events failing this cut go into a background control region)
- Search for bump in the invariant mass spectrum, main background is Z+jets
- Background model: exponential plus Breit-Wigner, to capture Z tail

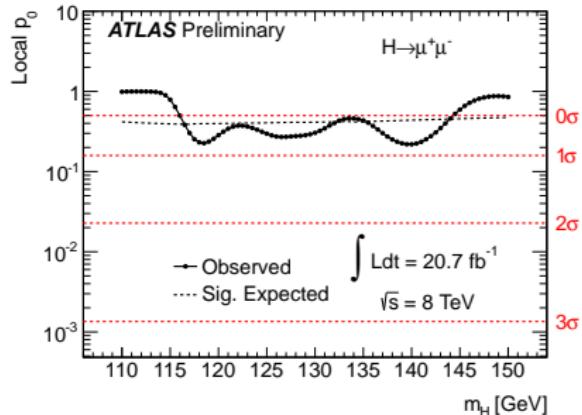
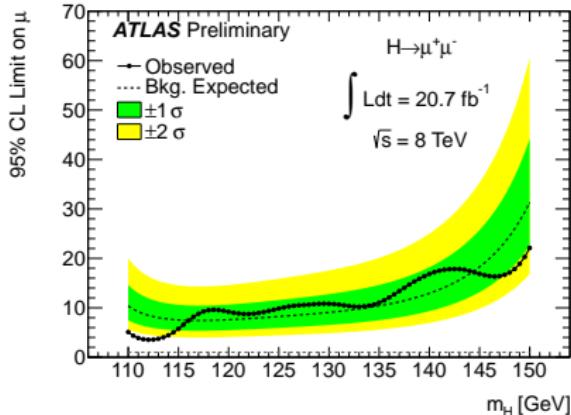


Simulation and data in central region ($|\eta(\mu_{1,2})| < 1.0$), fit with BW + exponential



Simulation and data in non-central region ($|\eta(\mu_{1,2})| > 1.0$), fit with BW + exponential

$H \rightarrow \mu\mu$ Results at ATLAS



m_H	observed limits	exp. median	exp. + 2 σ	exp. + 1 σ	exp. - 1 σ	exp. - 2 σ
110	5.1	10.4	20.0	14.6	7.5	5.6
115	5.7	7.5	14.5	10.6	5.4	4.0
120	9.2	7.6	14.6	10.7	5.5	4.1
125	9.8	8.2	15.9	11.6	5.9	4.4
130	10.8	9.1	17.5	12.8	6.5	4.9
135	11.0	10.4	20.1	14.6	7.5	5.6
140	16.8	12.9	25.0	18.2	9.3	6.9
145	16.9	18.3	35.3	25.7	13.2	9.8
150	22.1	31.3	60.6	44.2	22.6	16.8

$H \rightarrow \mu\mu$ Results at CMS



to be included if approved

Summary of Fermionic Channels

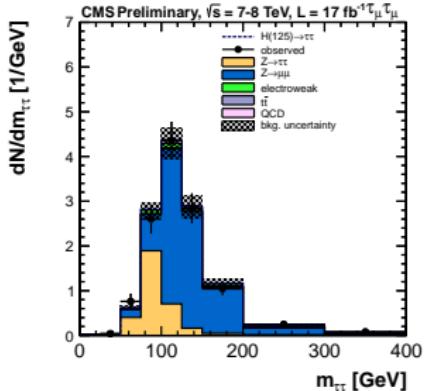
Prospects for 2015 and beyond

Additional Information

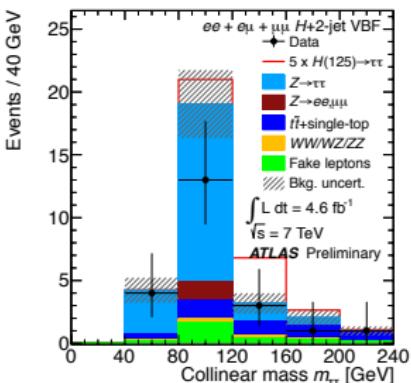
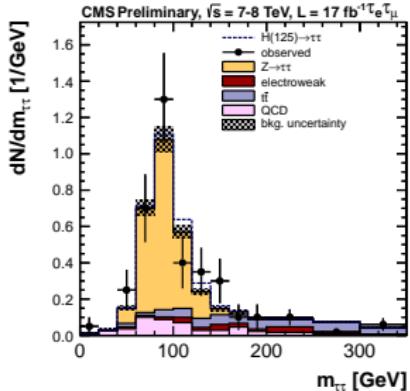
References

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- ATLAS, *Search for the Standard Model Higgs boson produced in association with top quarks in proton-proton collisions at $\sqrt{s}=7$ TeV using the ATLAS detector*, 15 September 2012
- CMS, *Search for the SM Higgs boson produced in association with W or Z bosons, and decaying to bottom quarks*, 14 May 2013
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- ATLAS, *Search for the SM Higgs boson in H to mu mu decays with the ATLAS detector*, 5 March 2013
- LHC Higgs Cross Section Working Group, <http://arxiv.org/abs/1101.0593>, 20 May 2011
- LHC Higgs Cross Section Working Group, *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*

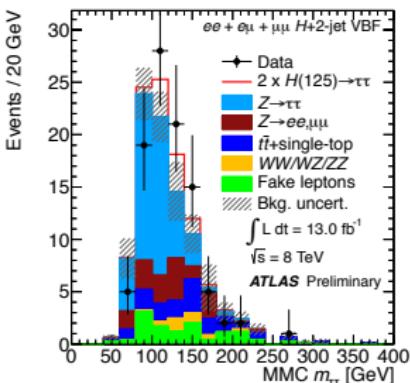
$H \rightarrow \tau\tau$: $\tau_{lep}\tau_{lep}$ VBF



CMS breaks
down results by
final state of τ 's
($\mu\mu$ vs. $e\mu$)
7 TeV and 8 TeV
data combined



ATLAS breaks
down results by
energy (7 TeV
vs. 8 TeV)
 τ final states
combined (ee ,
 $e\mu$, $\mu\mu$)

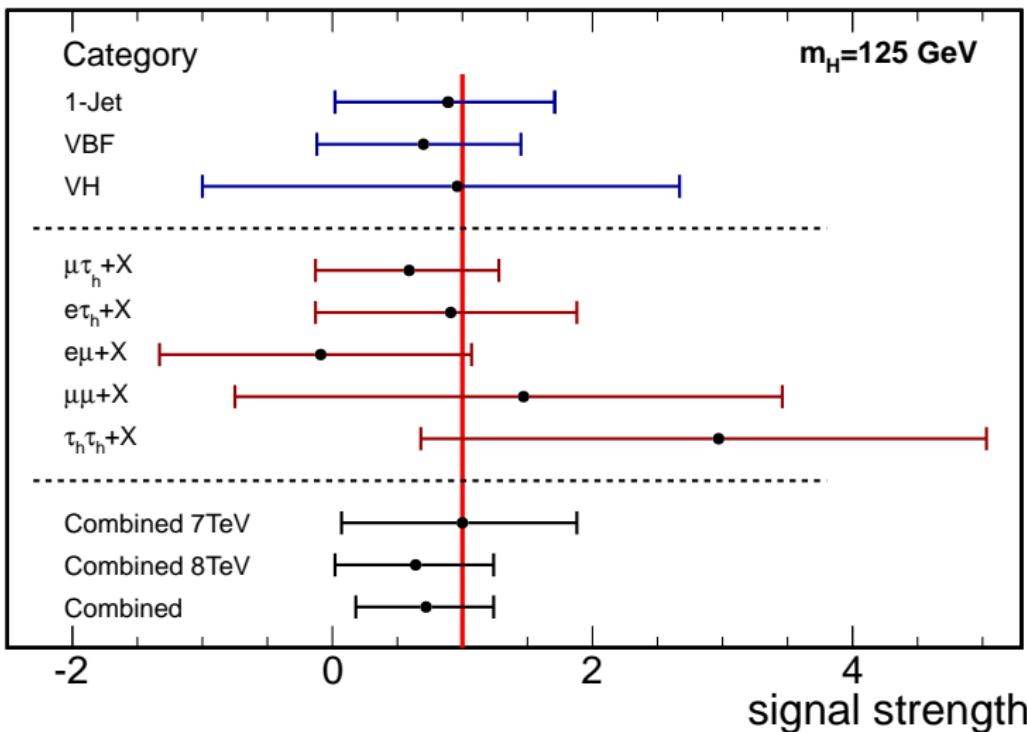


$H \rightarrow \tau\tau$: CMS Channel Breakdown

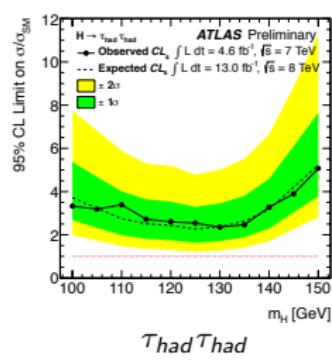
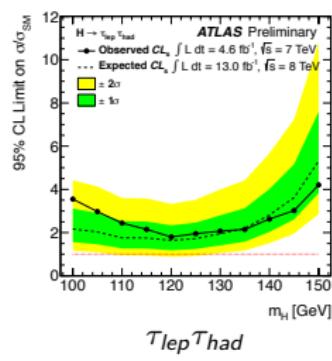
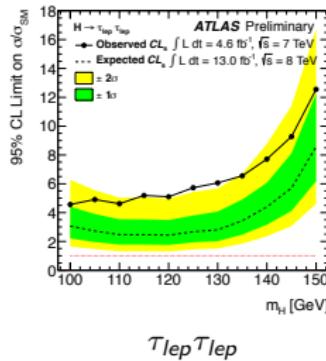
CMS Preliminary

17 fb^{-1} at $\sqrt{s} = 7$ and 8 TeV

$m_H = 125 \text{ GeV}$



$H \rightarrow \tau\tau$: ATLAS Channel Breakdown



VBF channels

non-VBF channels