Higgs Bosons Decaying to Fermions in ATLAS and CMS

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on behalf of the ATLAS Collaboration
Higgs Couplings 2013, Freiburg
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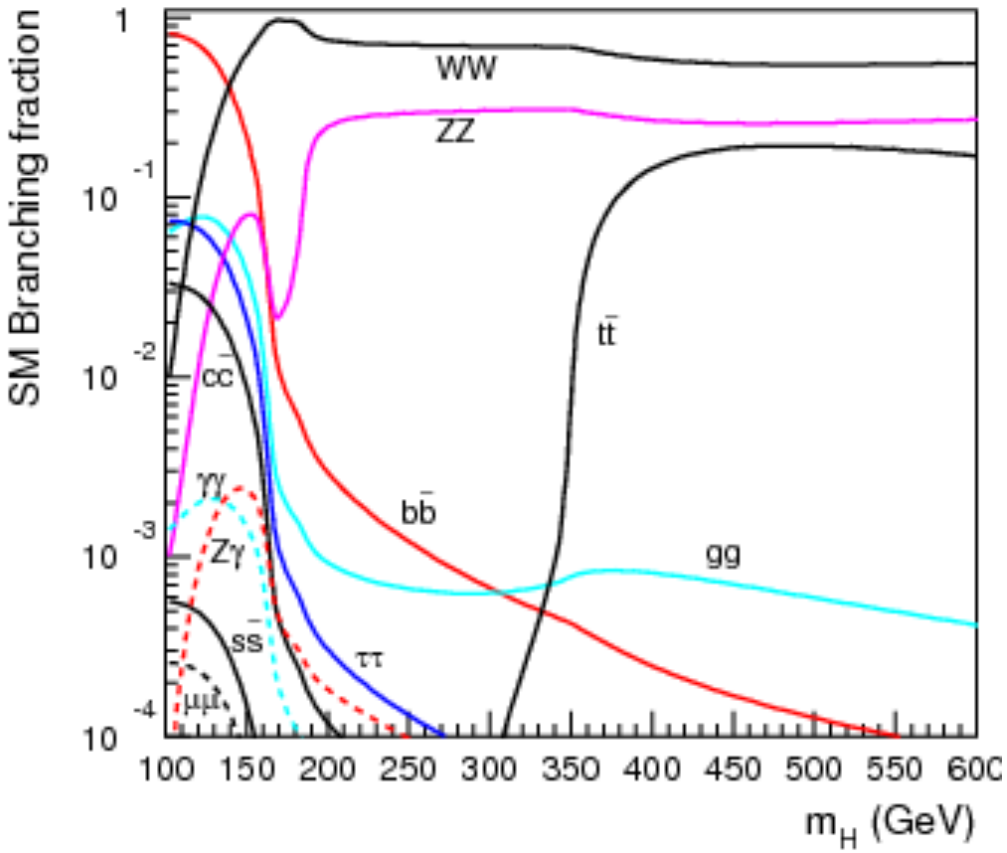
Background on this talk (this is not a real slide)

- Title: "Higgs boson decays to fermions at ATLAS and CMS"
- Conference: Higgs Couplings 2013 (Frieburg)
- Time: 30+5 minutes
- Audience: 80ish(?) experts, who are interested in the guts of the analyses (according to the organizers)
- 3rd talk of the conference, further talks will cover couplings, mass, BSM Higgs sector, etc. in more detail
  - Leading talk: "Electroweak Symmetry Breaking" (J. Iliopolous)
  - Second talk: "Higgs decays to bosons at ATLAS and CMS" (some CMS person)
  - Third talk: yours truly
- The slides shown today still need lots of formatting work–comments are more solicited on content and high-level stuff than details

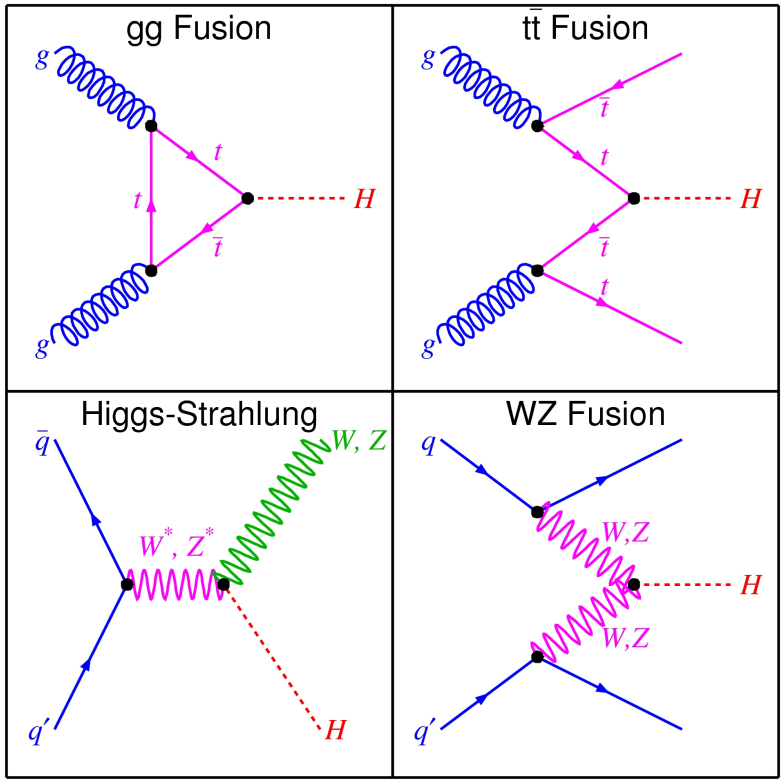
Introduction

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



Production Channels

gluon fusion:
- $\sigma \approx 15$ 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 (W) or 0.34 (Z) pb
- vector boson allows easier triggering and tagging

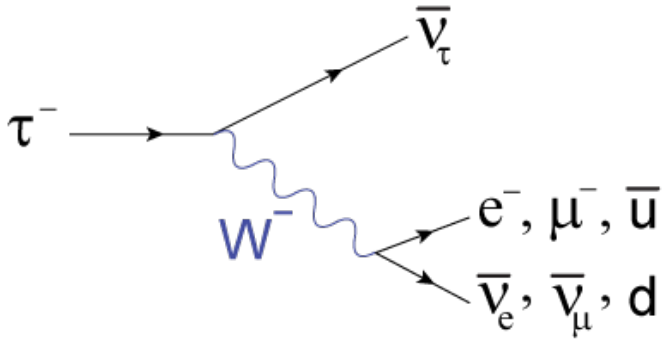
ttH:
- $\sigma \approx 0.086$ pb
- top quarks allow easier triggering and tagging

Vector Boson Fusion:
- $\sigma \approx$1.2 pb
- forward jets provide unique signature

$$H \rightarrow \tau\tau$$

$H \to \tau\tau$ 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

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

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

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

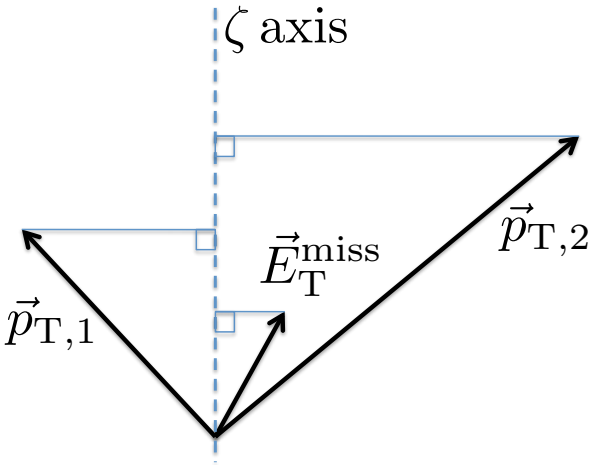
** ATLAS: 7 TeV only; CMS: control region only

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

ν Orientation Cuts and τ Embedding

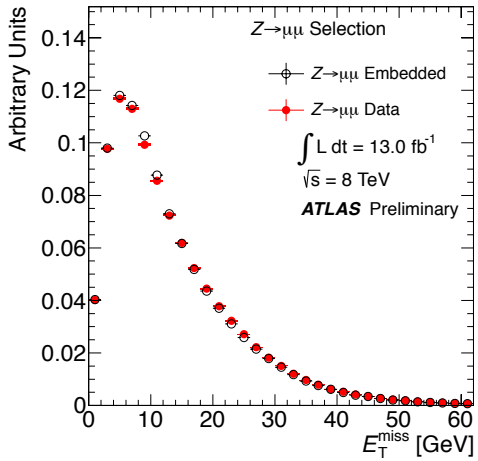
ν Direction Cuts

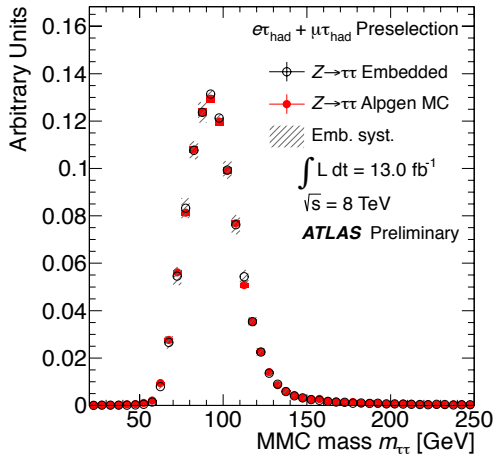
- τ from H decay highly boosted and decay products collimated
- Place cuts on how E_T^{miss} oriented relative to visible τ decay products



τ Embedding

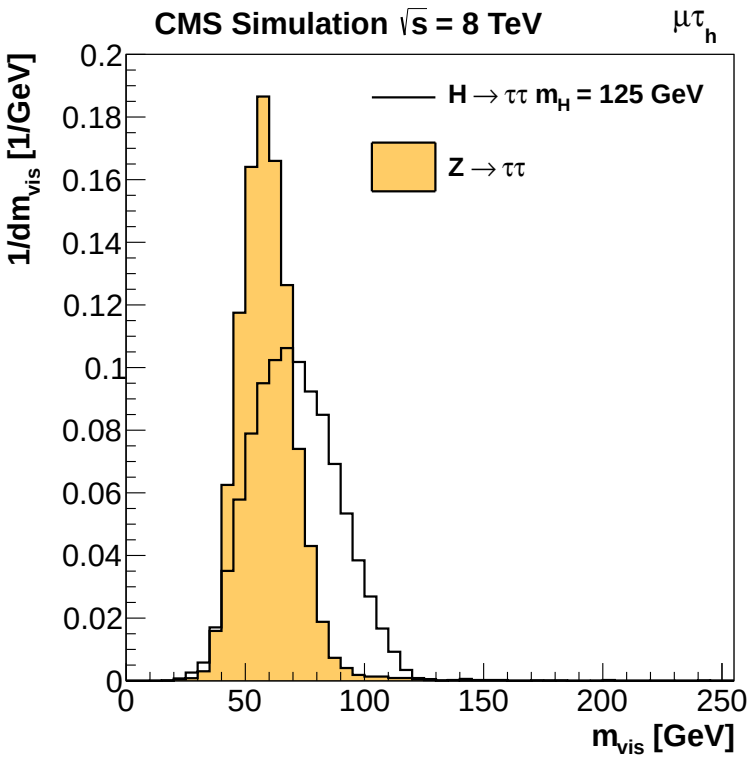
- Pure sample of $Z \rightarrow \tau\tau$ events difficult to get in data
- Embedding: get data-driven sample of $Z \rightarrow \mu\mu$ events, replace μ with simulated τ
- Gets Z kinematics, pileup, underlying event from data

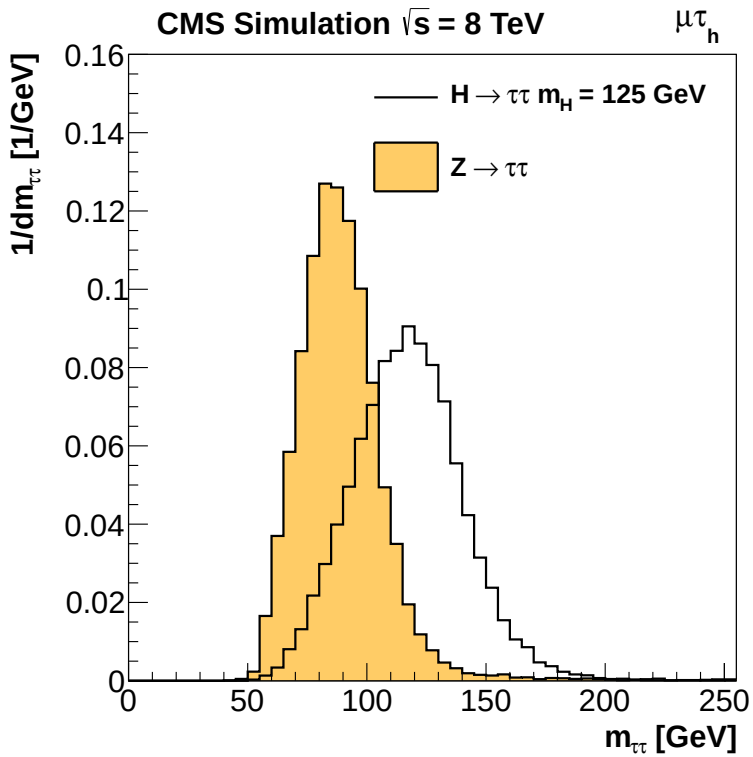




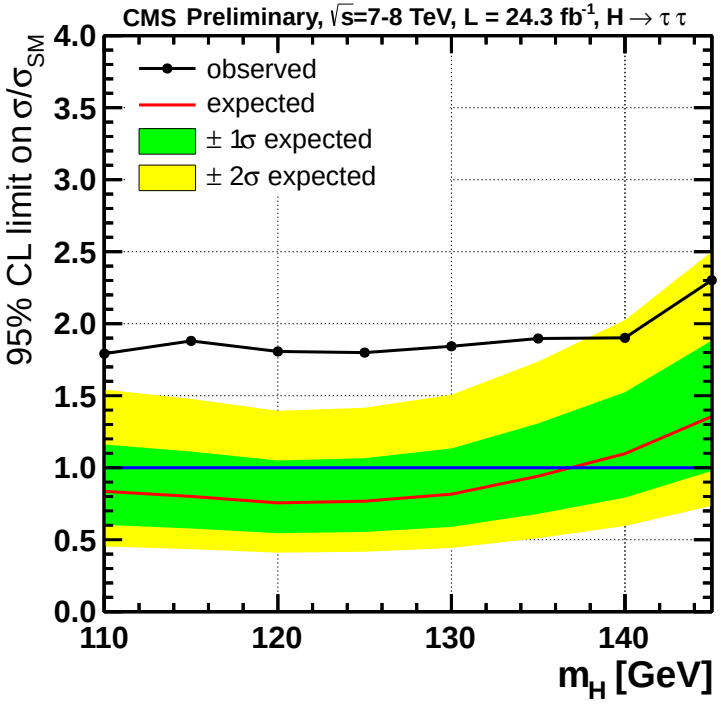
τ Invariant Mass Reconstruction

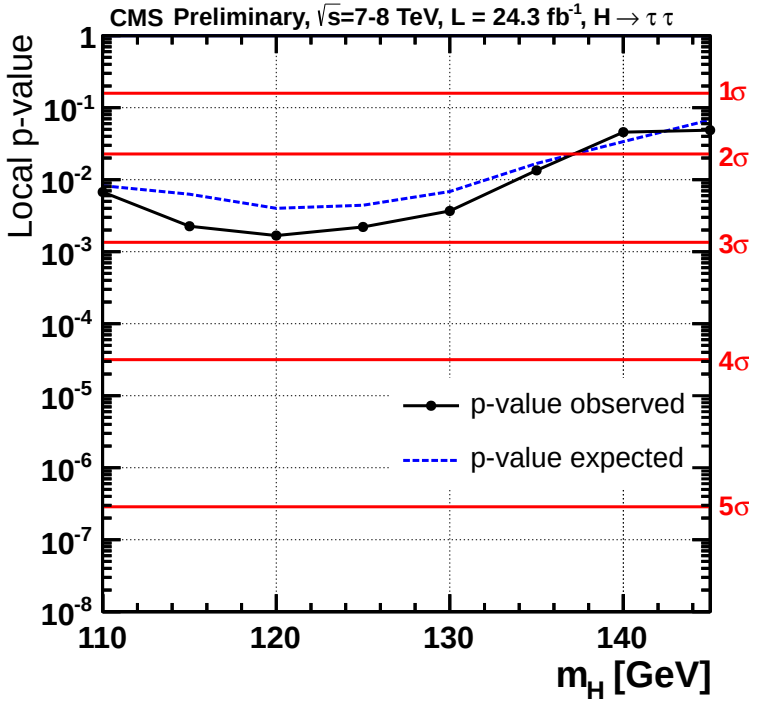
- Straightforward assumption of ν collinear with visible τ decay products gives an unphysical solution when doing τ reconstruction, especially when E_T^{miss} and boson parent mass are small
- ATLAS: Missing Mass Calculator (MMC) (Looking for an approved ATLAS plot or mass resolution number)
- CMS: SVFit Algorithm (20% mass resolution after applying algorithm)
- Idea: given the τ decay modes and the event kinematics, allocate the E_T^{miss} according to the maximization of a likelihood function





CMS $H \to \tau\tau$: Results



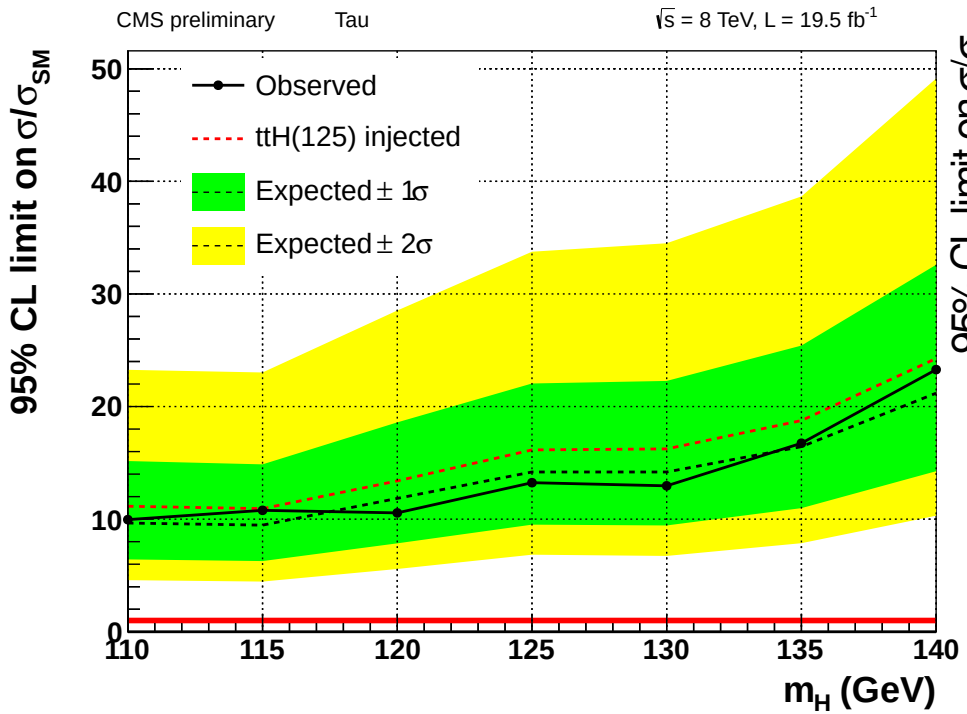


At m_H=125 GeV, observed (expected) 95% CL upper limit on cross section is 1.0 (1.63) $\times$ SM (background-only hypothesis)

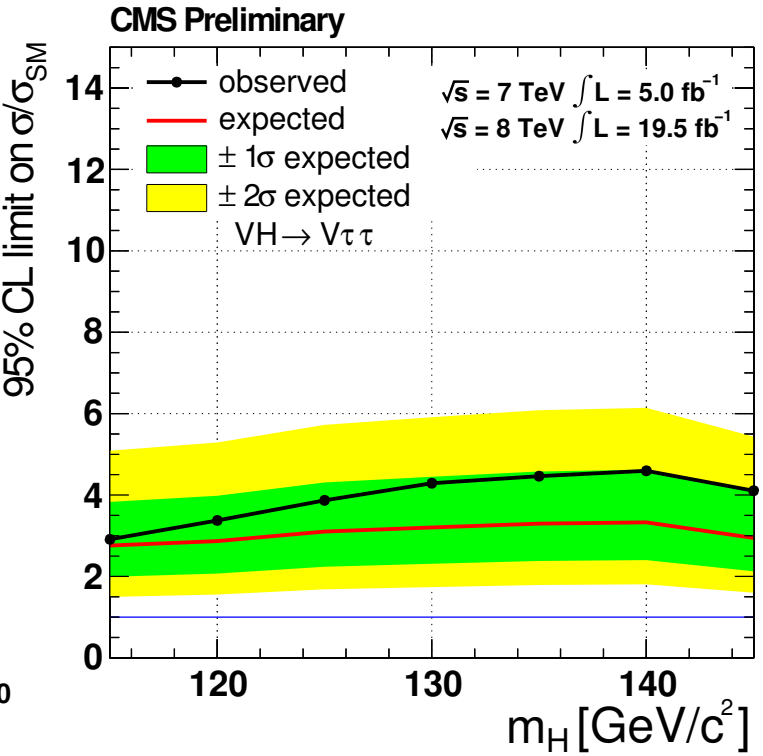
For m_H=125 GeV, observed (expected) p-value 2.85 (2.62) and best fit value μ=1.1$\pm$0.4

CMS: $ttH \to \tau\tau$ and $VH \to \tau\tau$

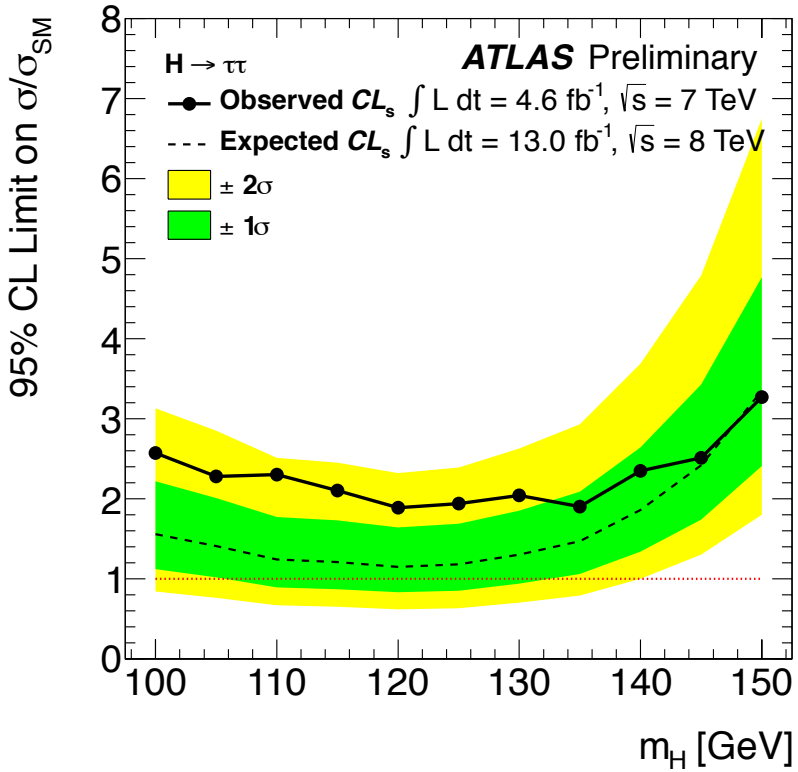
$ttH \to l\nu qqbb$



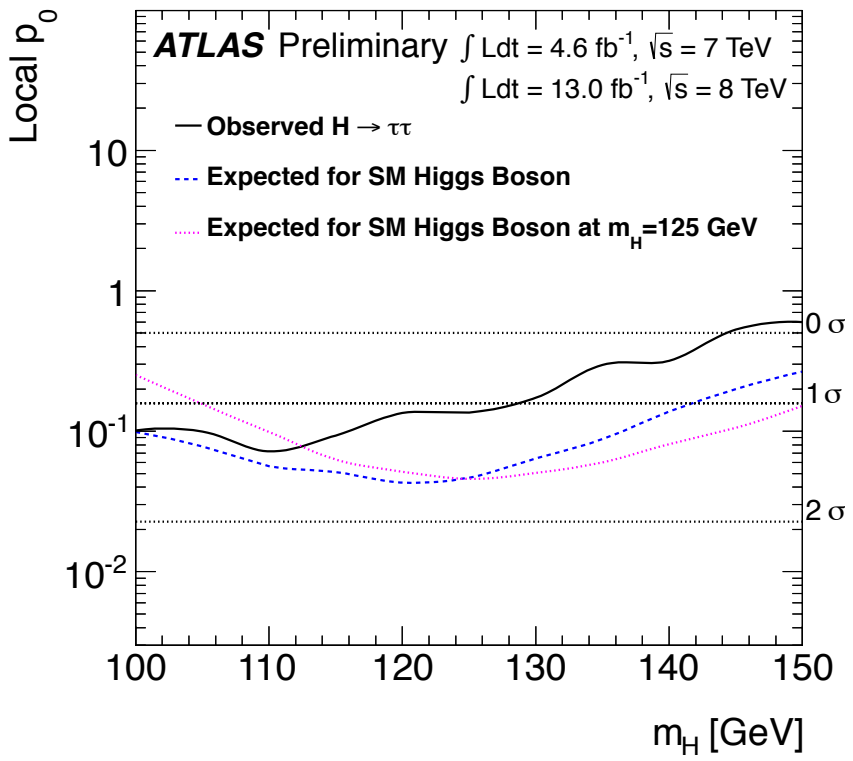
$VH \to \tau\tau$



ATLAS $H \to \tau\tau$: 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 μ=0.7$\pm$0.7

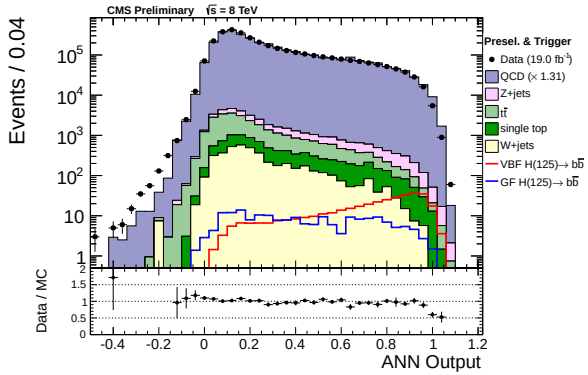
$$H \rightarrow bb$$

$H \to bb$ Motivation

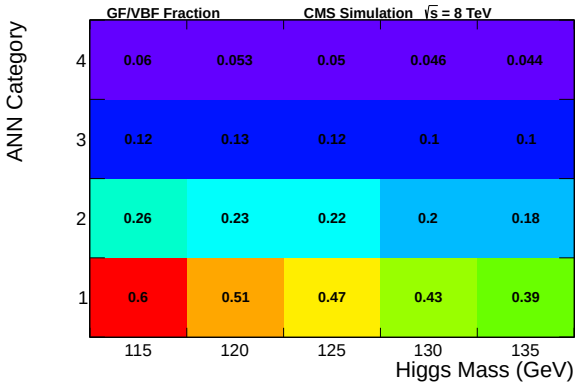
- Only experimentally visible decay mode to quarks
- Main way to probe couplings to down-type quarks
- Inclusive production (ggF) impossible to observe because of high QCD background
- Require extra particles or a unique topology
    - Forward jets: characteristic of VBF topology
    - Top quark pair: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

CMS VBF $H \to bb$

ANN discriminant based on event topology and b-tag values

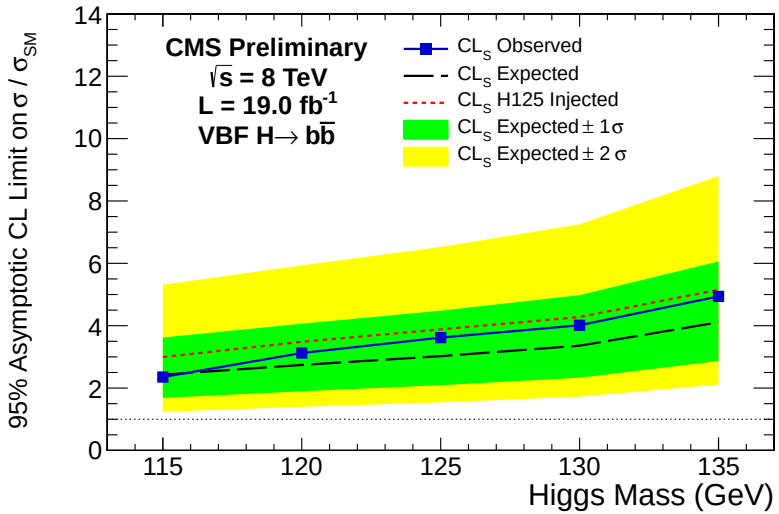


Highest categories of ANN heavily dominated by VBF production (vs. ggF)



Depending on the ANN category, the VBF channel can have up to 47% ggF Higgs signal

Yesterday's discovery ($gg \to H$) is today's measurement and tomorrow's background



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 μ=0.7$\pm$1.4

There is a 20-50% uncertainty on the $gg \to H$ normalization, which makes a precise measurement of VBF Higgs production difficult

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

$ttH,\ H \to bb$: ATLAS and CMS differences

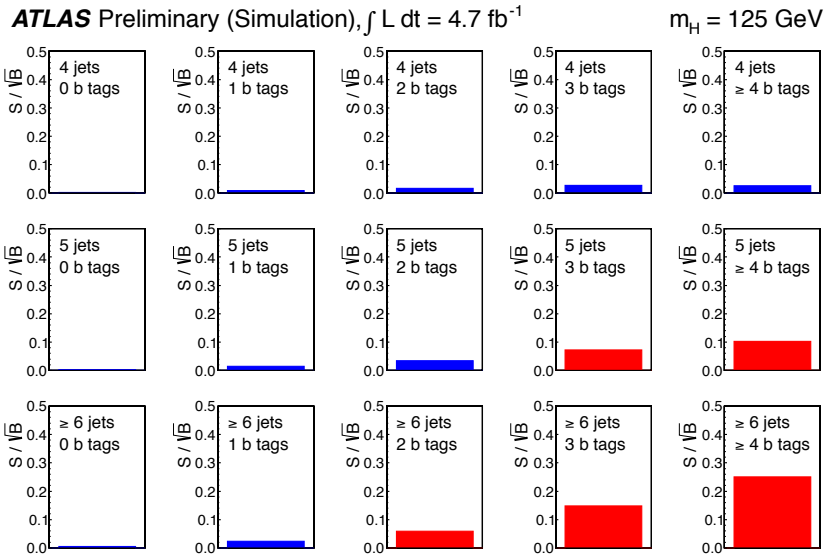
ATLAS

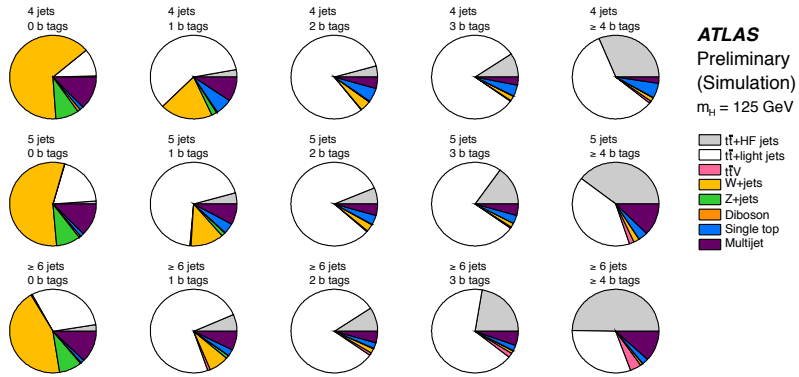
- Kinematic fit to reconstruct the top quarks, and determine which b quarks to use in Higgs reconstruction
- Final discriminant: m_{bb}
- Includes only $tt \to l\nu q\bar{q}$
- Result: observed (expected) sensitivity of 13.1 (10.5) $\times$ SM

CMS

- Result combined with $ttH,\ H \to \tau\tau$
- Final discriminant: output of BDT, look for excess in most Higgs-enriched categories
- Includes both $tt \to l\nu l\nu$ and $tt \to l\nu q\bar{q}$

$ttH,\ H \to bb$: ATLAS and CMS similarities

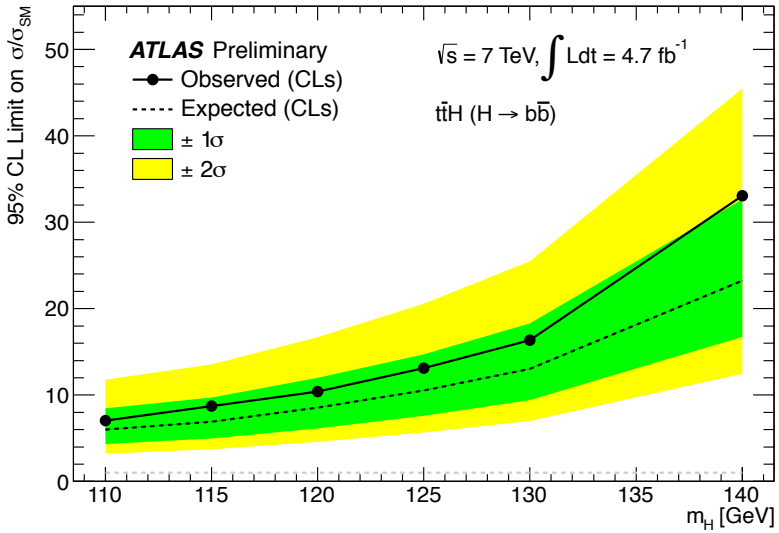




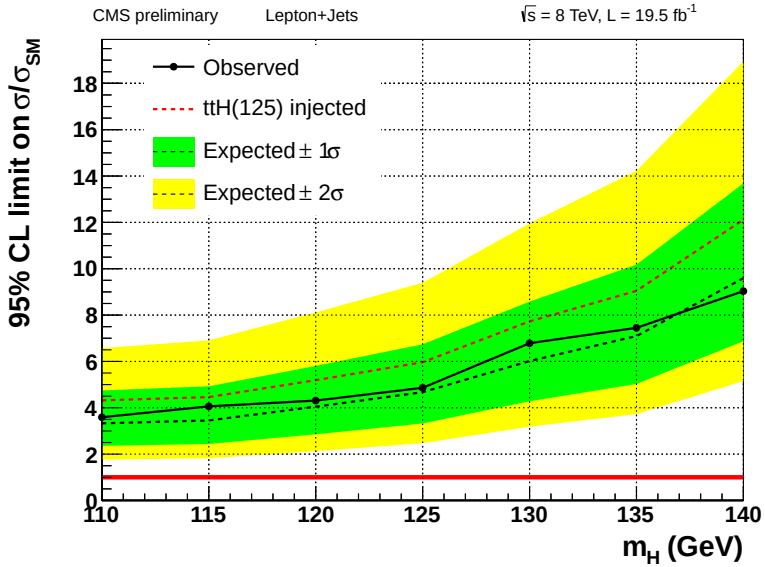
- Binning of analysis in njets, ntags
  - ATLAS: 4-6 jets, 0-4 b-tags
  - CMS varies by channel: 7 combinations ($tt \to l\nu qq$), 3 combinations ($tt \to l\nu l\nu$), 6 combinations ($H \to \tau\tau$)
- Also bins analysis in S/B
- Recently synchronized systematics on tt+HF background, leading to higher systematics (relative to 2011) for CMS

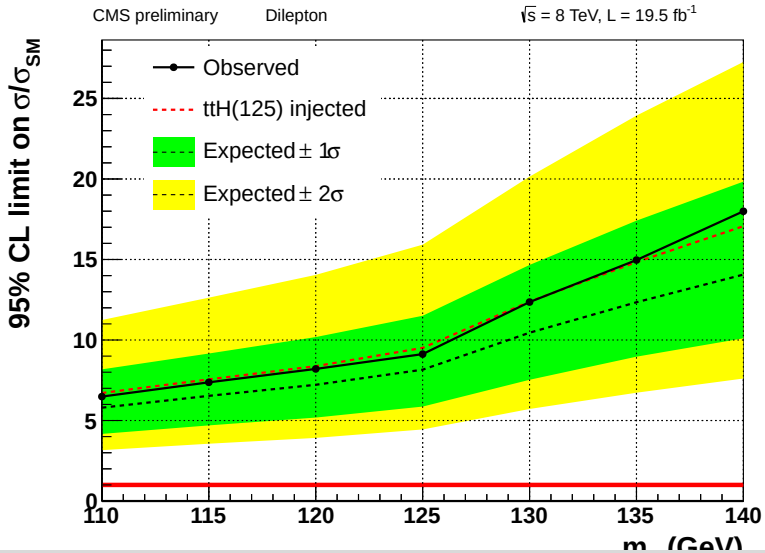
$ttH,\ H \to bb$: Results

ATLAS



CMS





top row: ATLAS and CMS results for $ttH \to l\nu qqbb$
bottom: CMS results for $ttH \to l\nu l\nu bb$

$VH \to bb$ at ATLAS and CMS: Similarities

- $Z \to \nu\nu$, $W \to l\nu$, $Z \to ll$ analyses
- Analyses binned in p_T^V to extract extra sensitivity from most powerful regions
  - Trigger on associated vector boson: higher p_T^V means higher efficiency
  - High p_T^V means harder Higgs, with better resolution of jets (and, by extension, m_{bb})
- Jet correction based on $H \to bb$ used to improve mass resolution
  - CMS: improves mass resolution by about 15%, overall sensitivity by 10-20%
  - ATLAS: improves mass resolution by about 10-12%
  - currently tracking down plot or two to show here
- Validated using $Z \to bb$ events
  - CMS: 7.5σ, $\mu = 1.19^{+0.28}_{-0.23}$
  - ATLAS: 4.8σ, $\mu = 0.9 \pm 0.2$

Tevatron results help round out the picture (link)

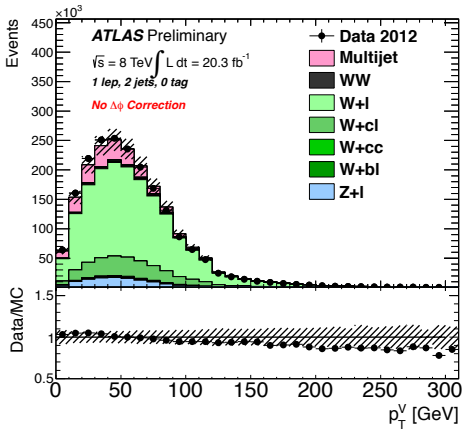
$VH \rightarrow bb$ at ATLAS and CMS: Differences

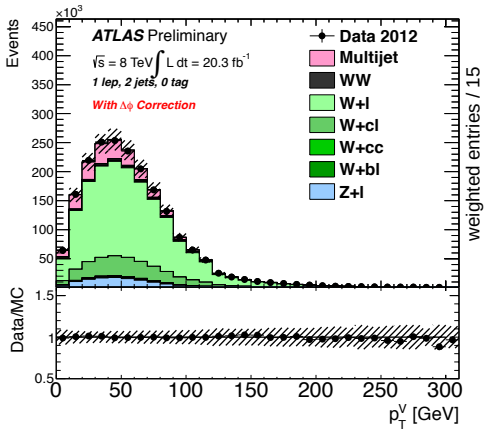
ATLAS

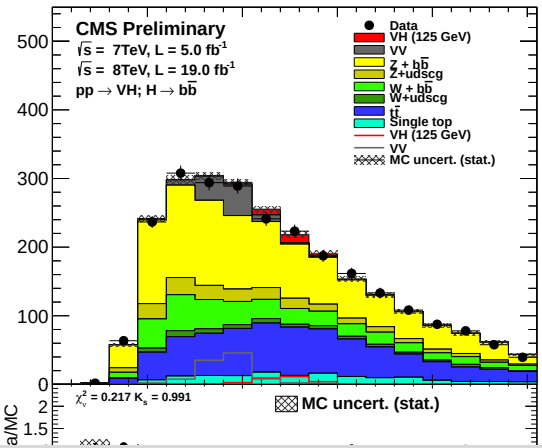
- Cut-based analysis
- Signal region has 2 b-tags applied, but use 1-tag and 0-tag regions for background control and validation
- 2-tag signal region further subdivided into 2-jet and 3-jet bins
- P_T^V-based reweighting of important backgrounds (W+jets, $t\bar{t}$) found to be mismodelled in MC

CMS

- B-tagging in trigger allows lower E_T^{miss} thresholds for $Z \rightarrow \nu\nu$ analysis
- BDTs trained to distinguish 4 main classes of events: $t\bar{t}$, diboson, Z+jets, VH
- Final discriminating variable is the BDT output–look for excess of event relative to background in the most signal-enriched BDT bins
- Validation cut-based analysis based on m_{bb} currently looking into whether there is a sensitivity computed for this analysis

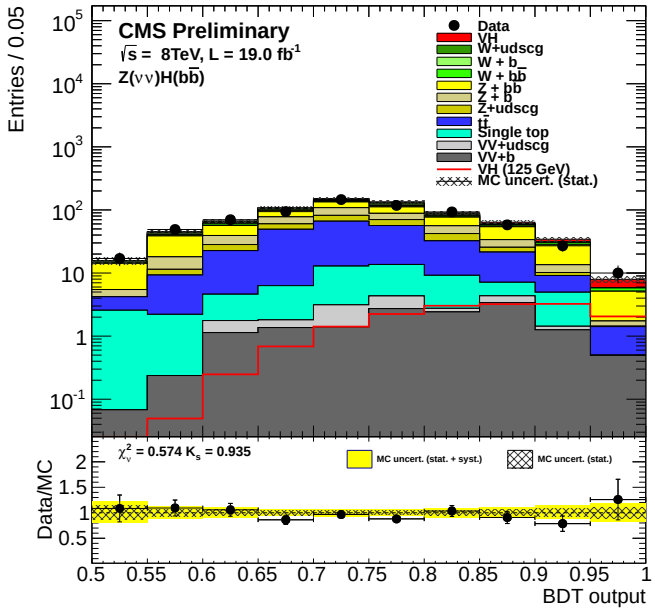


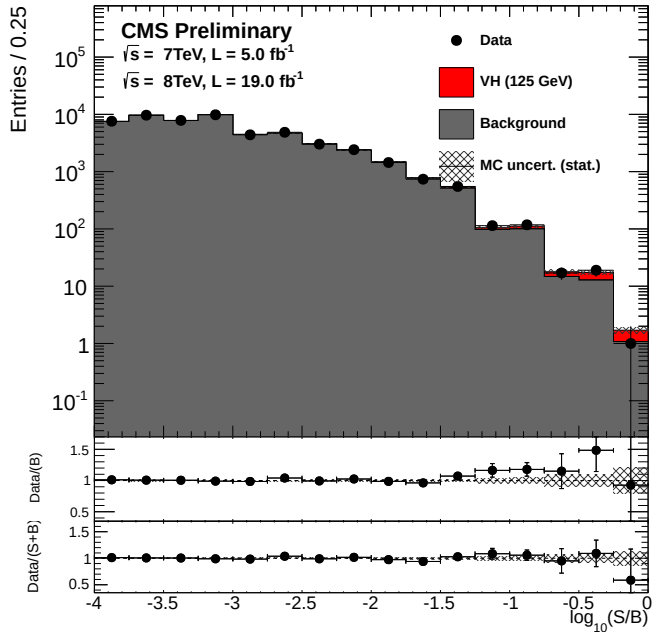




CMS $VH(H \to bb)$

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

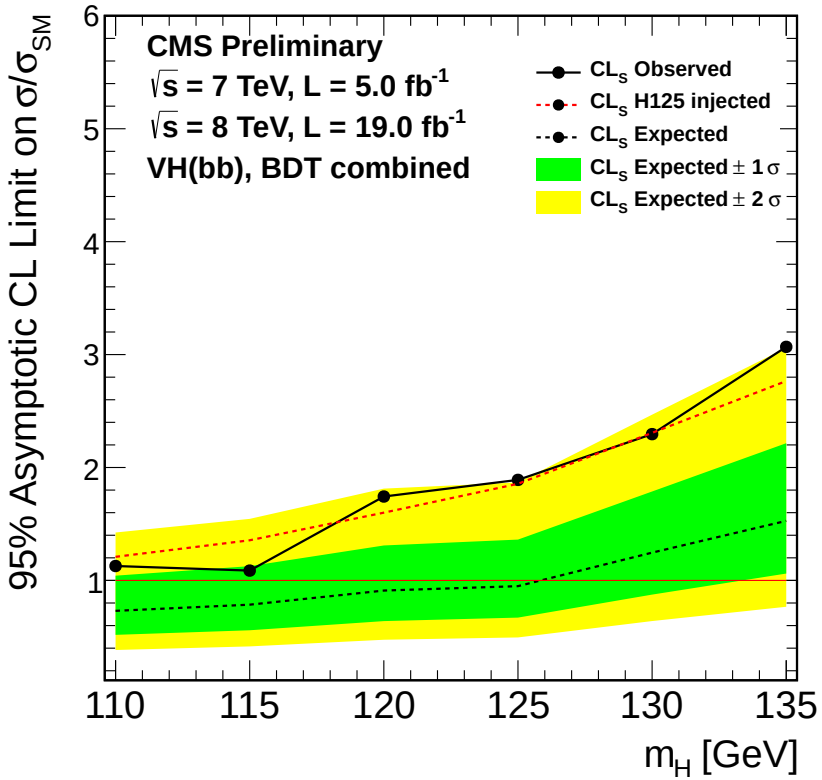




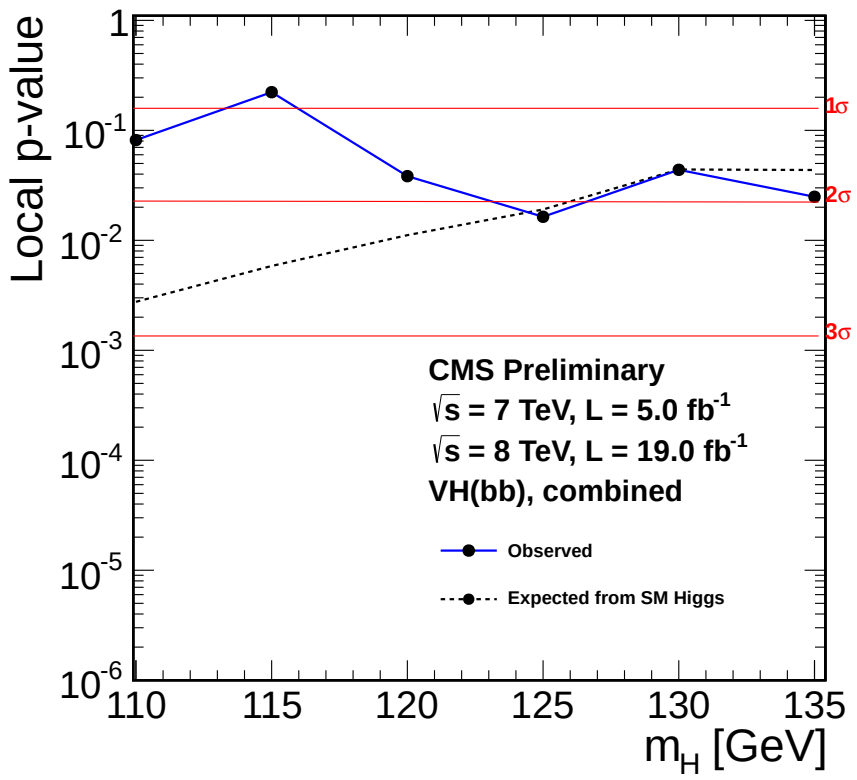
Example output of the BDT, focusing on the most signal-enriched component of the high-p_T Z($\nu\nu$) bin

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

$VH(H \to bb)$: 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)



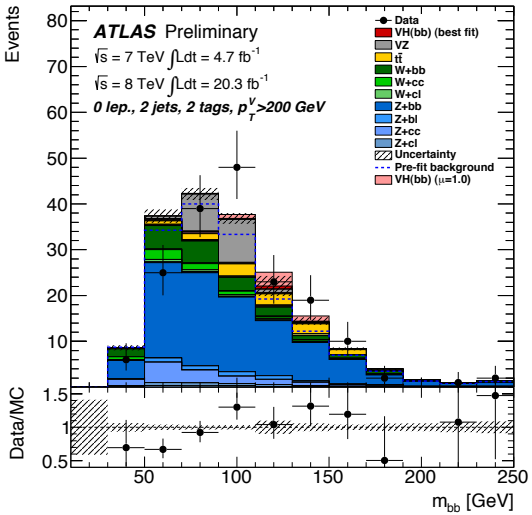
For m_H=125 GeV, BDT has observed p-value 2.1σ and best fit value μ=1.0$\pm$0.5

ATLAS $VH(H \to bb)$: Strategy

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× higher than 3-jet region for all categories
Below are the m_{bb} distributions from the 2-jet, 2-tag, p_T^V >200 GeV regions (which are the most signal-enriched)

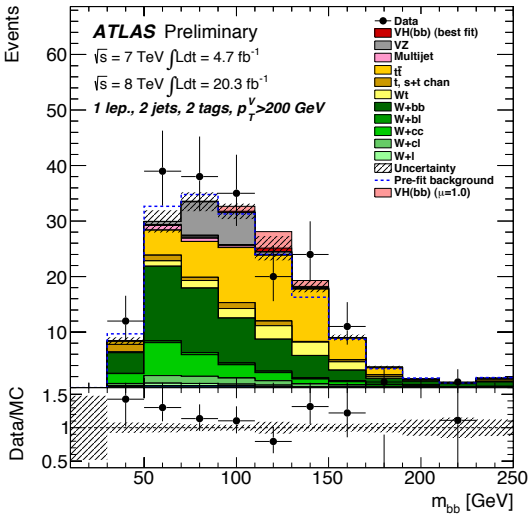
$Z \to \nu\nu$

0 leptons
2 b-tags, p_T^{jet1} >45 GeV, p_T^{jet2} >20 GeV
+ $\leq$ 1 extra jets
E_T^{miss} and p_T^{miss} cuts to minimize dijet QCD



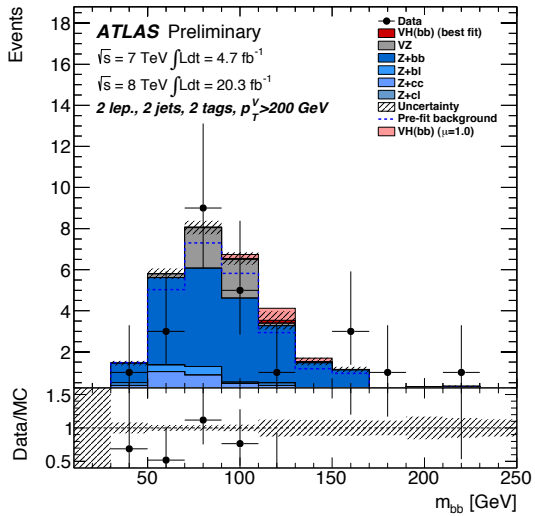
$W \to l\nu$

1 lepton
2 b-tags, p_T^{jet1} >45 GeV, p_T^{jet2} >20 GeV
+ $\leq$ 1 extra jets
E_T^{miss} > 25 GeV
m_T^W <120 GeV



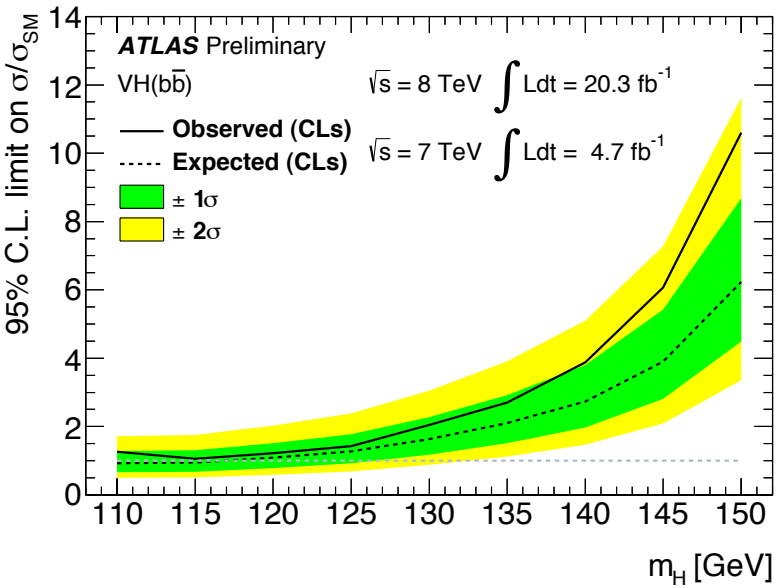
$Z \to ll$

2 leptons
2 b-tags, p_T^{jet1} >45 GeV, p_T^{jet2} >20 GeV
+ $\leq$ 1 extra jets
E_T^{miss} < 60 GeV
83< m_{ll} <99 GeV

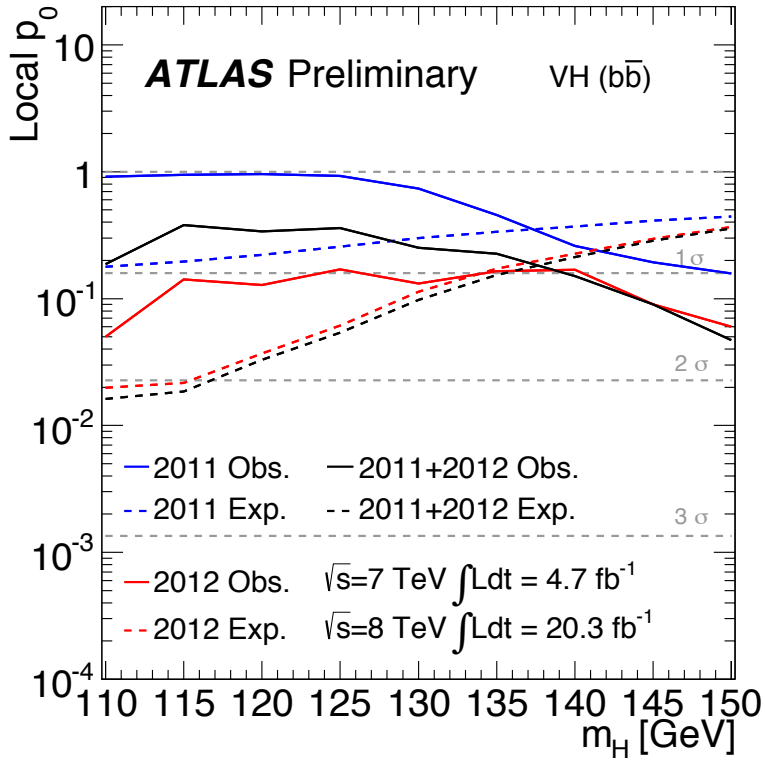


ATLAS is also actively investigating multivariate approaches for the $VH \to bb$ analysis, for possible inclusion in future results

ATLAS $VH(H \to bb)$: 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)

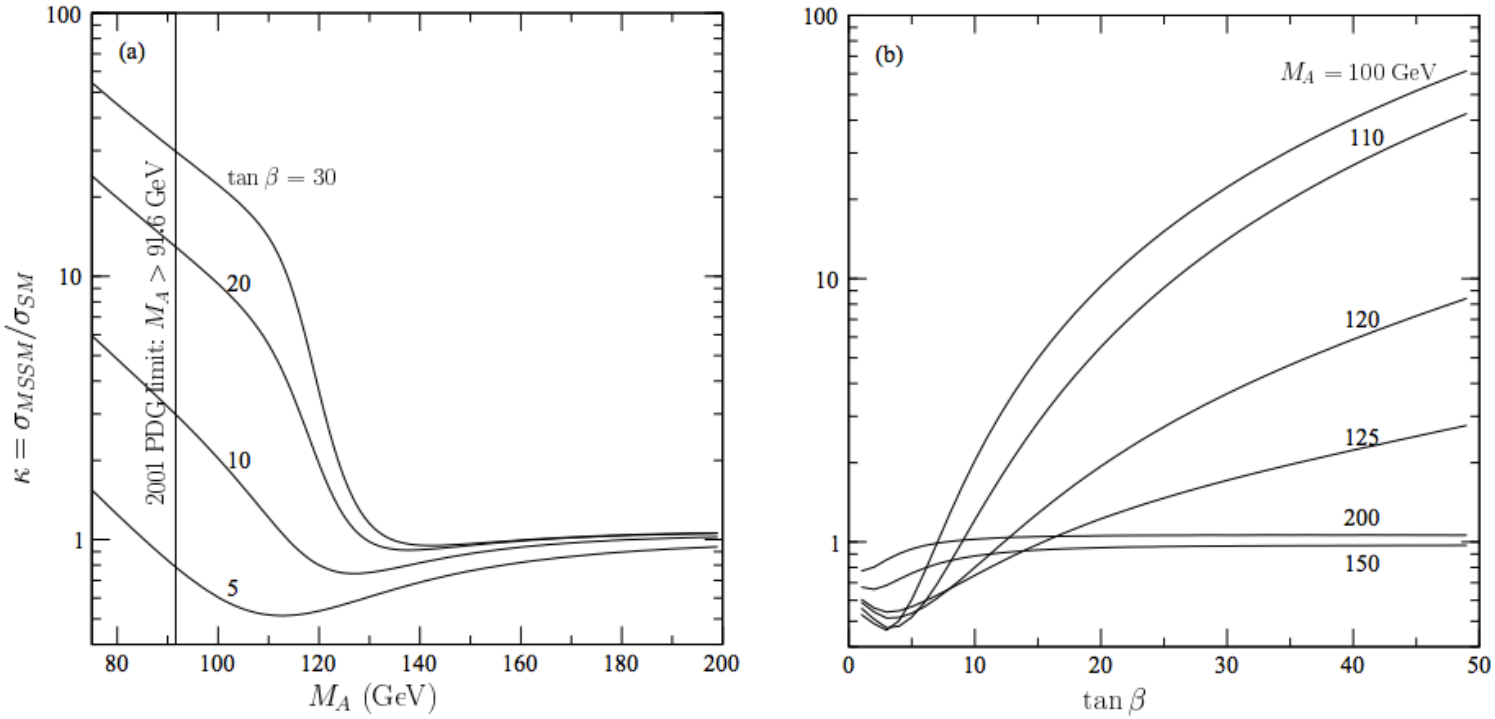


For m_H=125 GeV, observed (expected) p-value is 0.36 (0.05) and best fit value $\mu = 0.2 \pm 0.5(stat) \pm 0.4(syst)$

$$H \rightarrow \mu\mu$$

$H \to \mu\mu$ Motivation

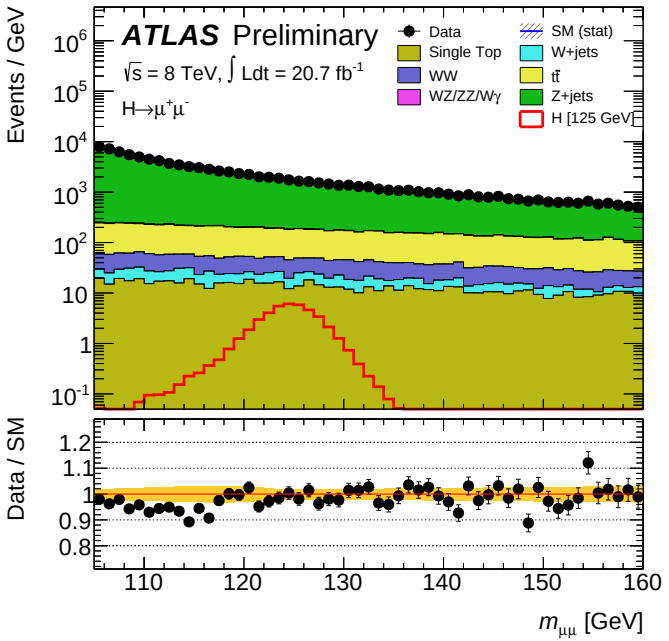
- Small cross section
- Clean final state signature
- Only channel for measuring coupling to second-generation fermions
- Large irreducible background of $Z/\gamma^* \to \mu\mu$
- Can have enhanced BF from non-SM contributions

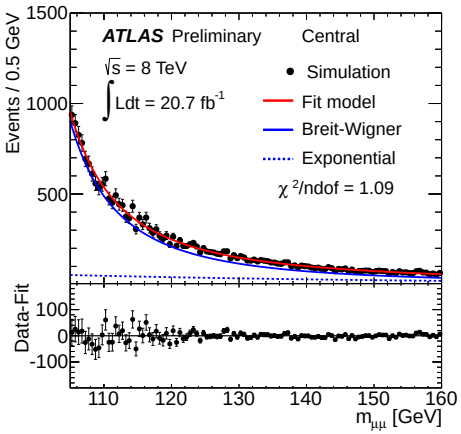


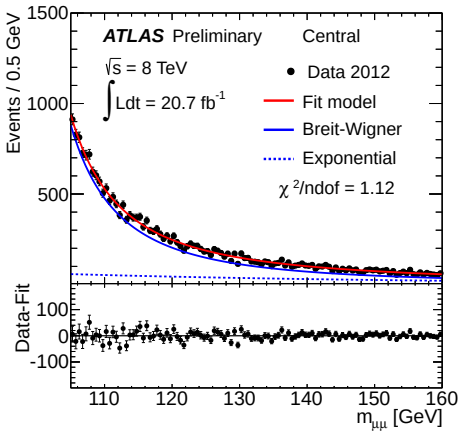
Plots from Tao Han and Bob McElrath showing MSSM enhancements to $H \to \mu\mu$ as a function of m_h and $\tan\beta$ (arXiv hep-ph 0201023)

$H \to \mu\mu$ at ATLAS

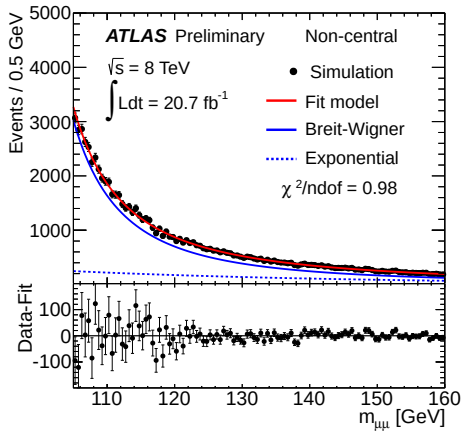
- Reconstruct invariant mass of 2 muons, $p_T^{\mu 1} > 25$ GeV and $p_T^{\mu 2} > 15$ GeV
- Remove 60% of Drell-Yan background events (and keeping 80% of signal) by requiring $p_T^{\mu+\mu-} > 15$ GeV (events failing this cut go into a background control region)
- Search for bump in the invariant mass spectrum, main background is Z+jets
- Background model: exponential plus Breit-Wigner, to capture Z tail

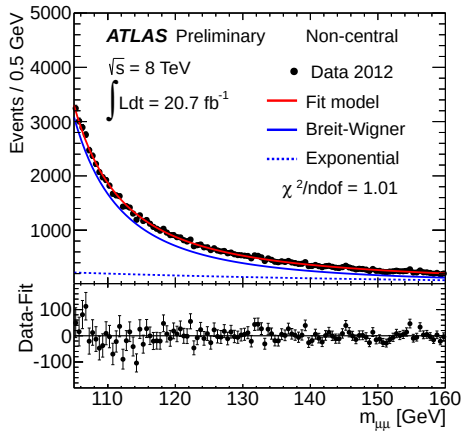






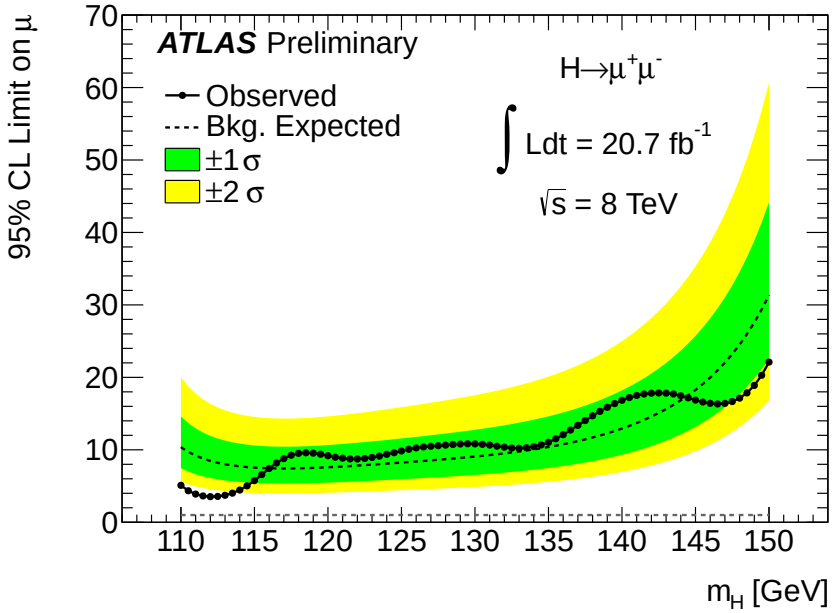
Simulation and data in central region ($|\eta(\mu_{1,2})| < 1.0$), fit with BW + exponential

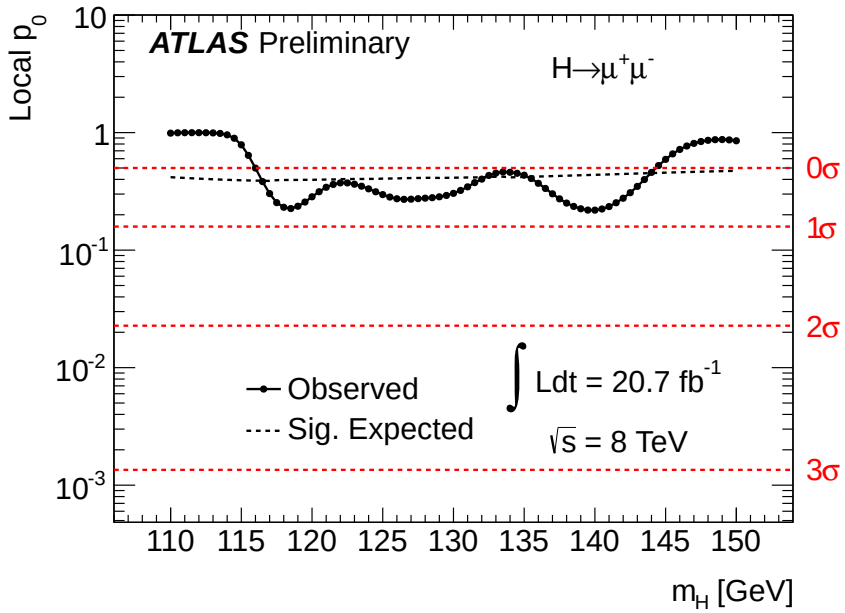




Simulation and data in non-central region ($|\eta(\mu_{1,2})| > 1.0$), fit with BW + exponential

$H \to \mu\mu$ Results at ATLAS





m_H	observed limits	exp. median	exp. $+2\sigma$	exp. $+1\sigma$	exp. -1σ	exp. -2σ
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

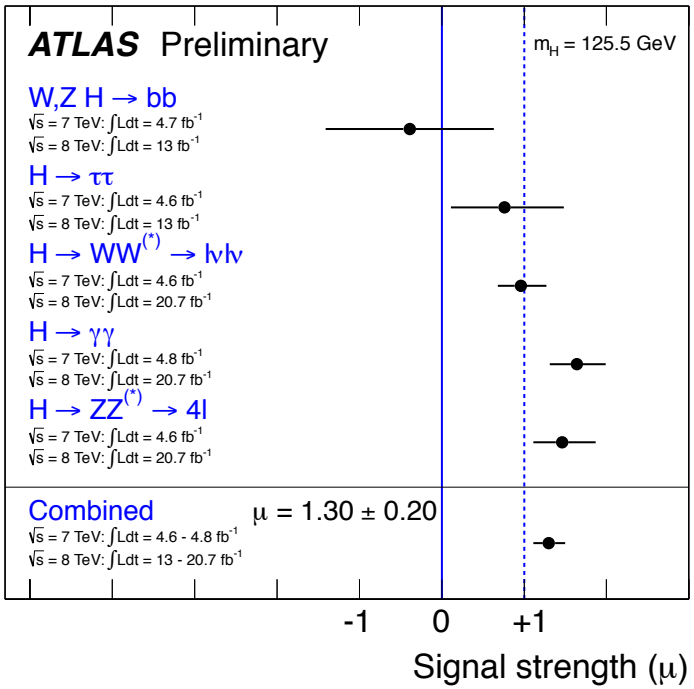
CMS analysis underway, with results planned for fall 2014

$H \to \mu\mu$ Results at CMS

to be included if approved

Summary of Channels

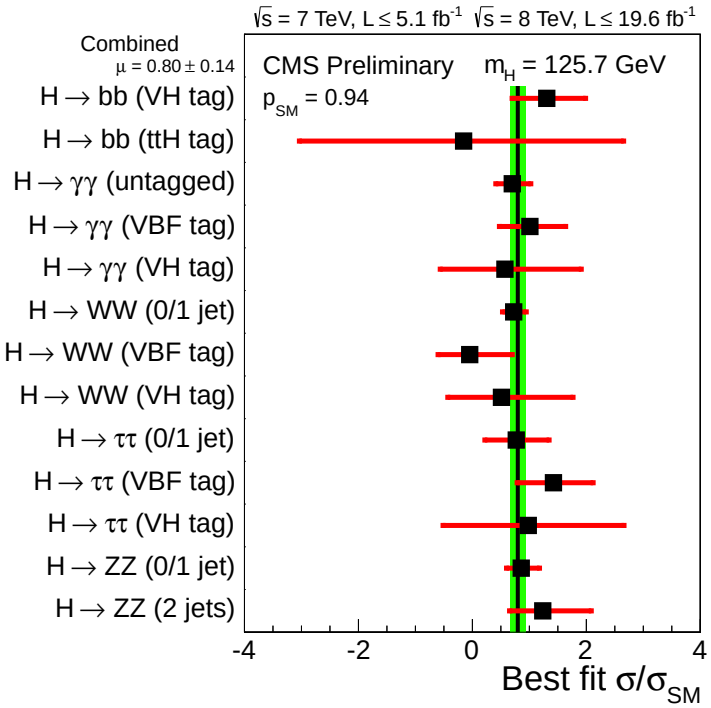
ATLAS



VH → *Vbb* coming into more consistency with SM μ expectation

Global best-fit signal strength: 1.30±0.13(stat)±0.14(sys) at 125.5 GeV

CMS



VH → *bb* slightly above $\mu = 1$

Global best-fit signal strength: 0.80±0.14 at 125.7 GeV

H → *bb* has largest error bar, so least effect on final fit value for μ

H → $\tau\tau$ consistent with SM for both collaborations

Implications of Fermionic Channels for Understanding the New Boson

- ATLAS Global fit of $\mu = 1.3 \pm 0.13(stat) \pm 0.14(syst)$ has p-value showing 9% consistency with SM
- However, when you vary QCD scale and PDF for the ggF production, consistency of observed signal strength with SM increases to about 40%
- Now that bb is on the scene, any first fits of the total width?

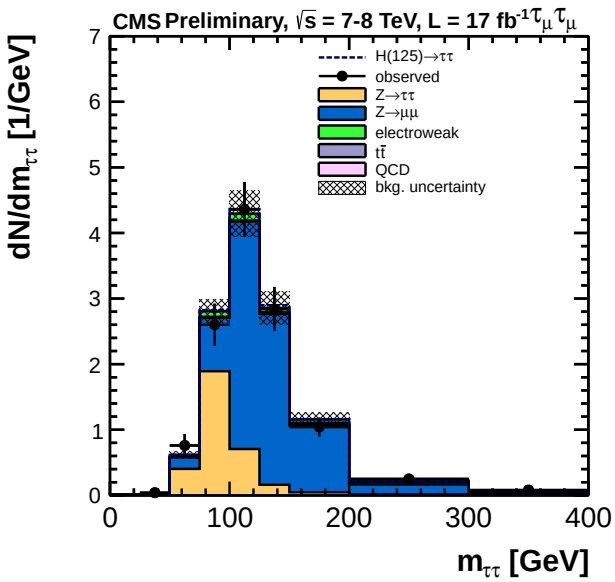
Prospects for 2015 and beyond

Additional Information

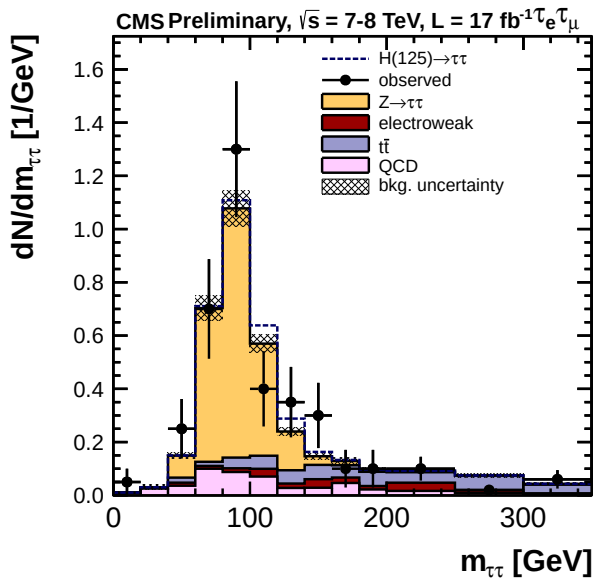
References

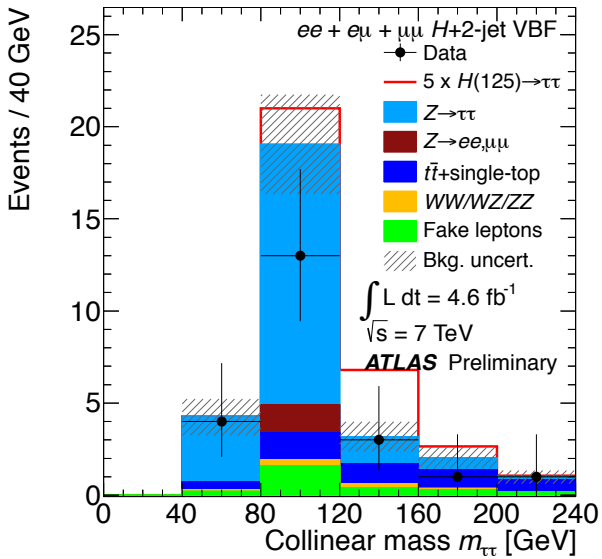
- ATLAS, *Search for the bb decay of the Standard Model Higgs boson in associated (W/Z)H production with the ATLAS detector*, 19 July 2013
- ATLAS, *Search for the Standard Model Higgs boson produced in association with top quarks in proton-proton collisions at $\sqrt{s}$=7 TeV using the ATLAS detector*, 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
- CMS, *Search for Higgs Boson Production in association with a top-quark pair and decaying to bottom quarks or tau leptons*, 26 July 2013
- ATLAS, *Search for the Standard Model Higgs boson in H to tau tau decays in proton-proton collisions with the ATLAS detector*, 13 November 2012
- CMS, *Search for the standard model Higgs boson decaying to tau pairs in proton-proton collisions at $\sqrt{s}$=7 and 8 TeV*, 15 March 2013
- CMS, *Search for the standard model Higgs boson decaying to tau pairs produced in association with a W or Z boson with the CMS experiment in pp collisions at $\sqrt{s}$ = 7 and 8 TeV*
- 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*

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

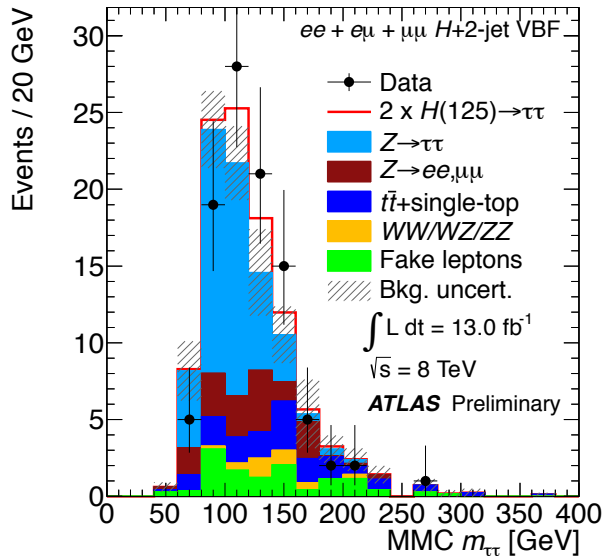


CMS breaks down results by final state of τ's ($\mu\mu$ vs. $e\mu$)
7 TeV and 8 TeV data combined

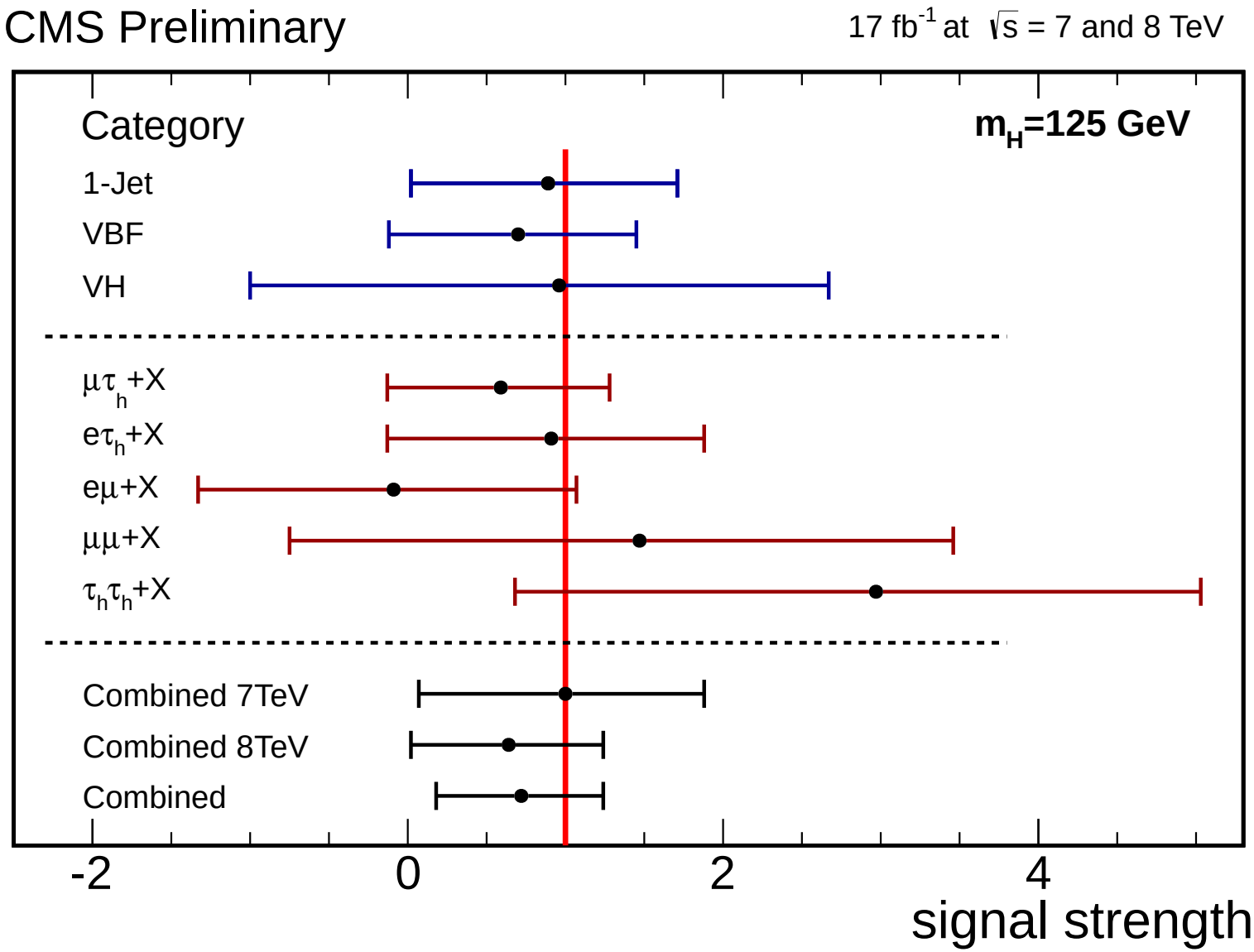




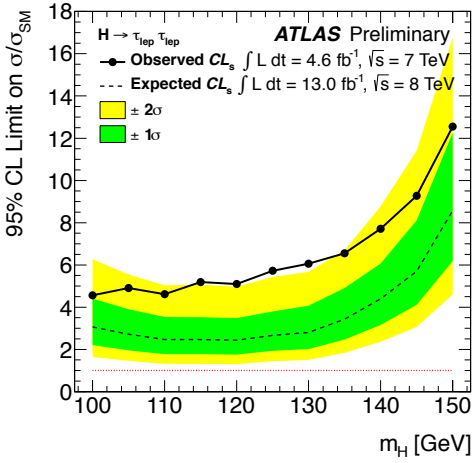
ATLAS breaks down results by energy (7 TeV vs. 8 TeV)
τ final states combined (ee, $e\mu$, $\mu\mu$)



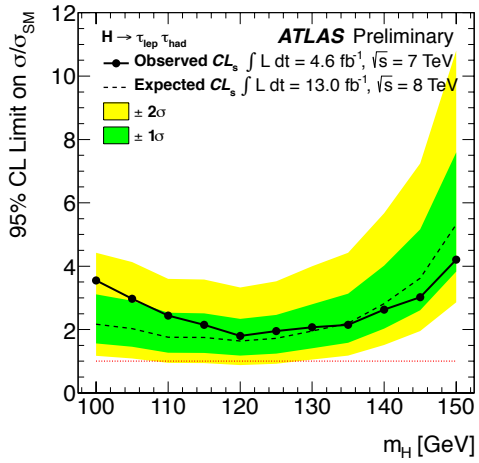
$H \to \tau\tau$: CMS Channel Breakdown



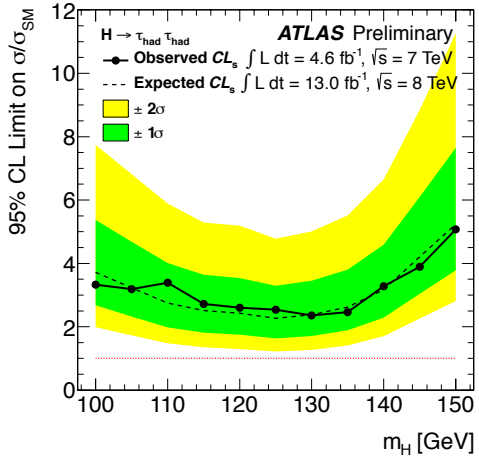
$H \to \tau\tau$: ATLAS Channel Breakdown



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



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



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

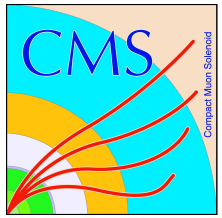
VBF channels

non-VBF channels

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(ll)	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(ll)	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