Higgs Boson Decays to Fermions in ATLAS and CMS

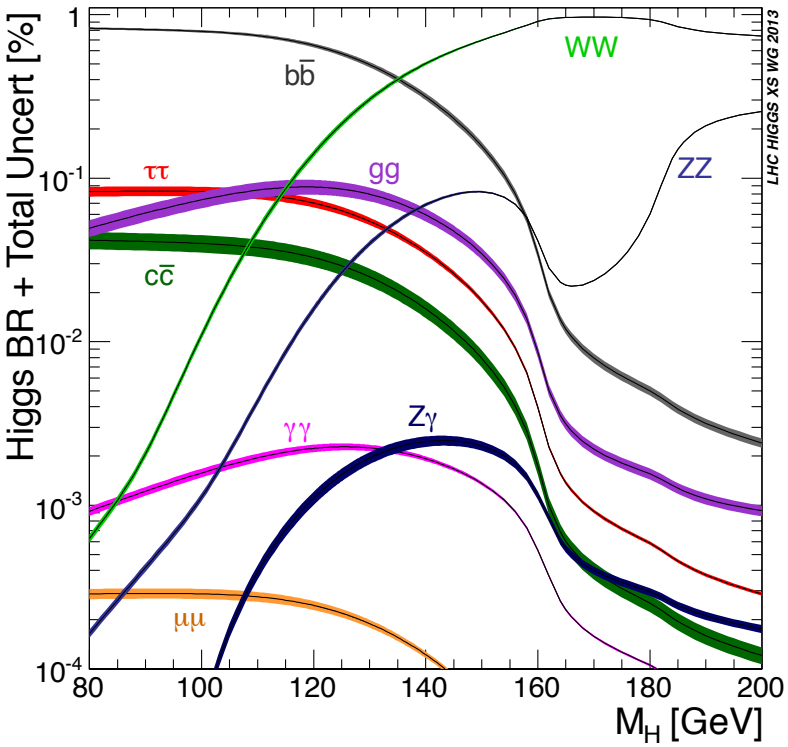
Caitlin Malone, SLAC

on behalf of the ATLAS and CMS Collaborations

Higgs Couplings 2013, Freiburg
14 October 2013

Introduction

- Higgs boson discovered near 125 GeV in bosonic channels, including $H \to \gamma\gamma$, $H \to ZZ \to 4l$, $H \to WW \to l\nu l\nu$
- At m_H =125 GeV, Higgs boson decays in many channels, including quarks and leptons $H \to bb$, $H \to \mu\mu$, $H \to \tau\tau$

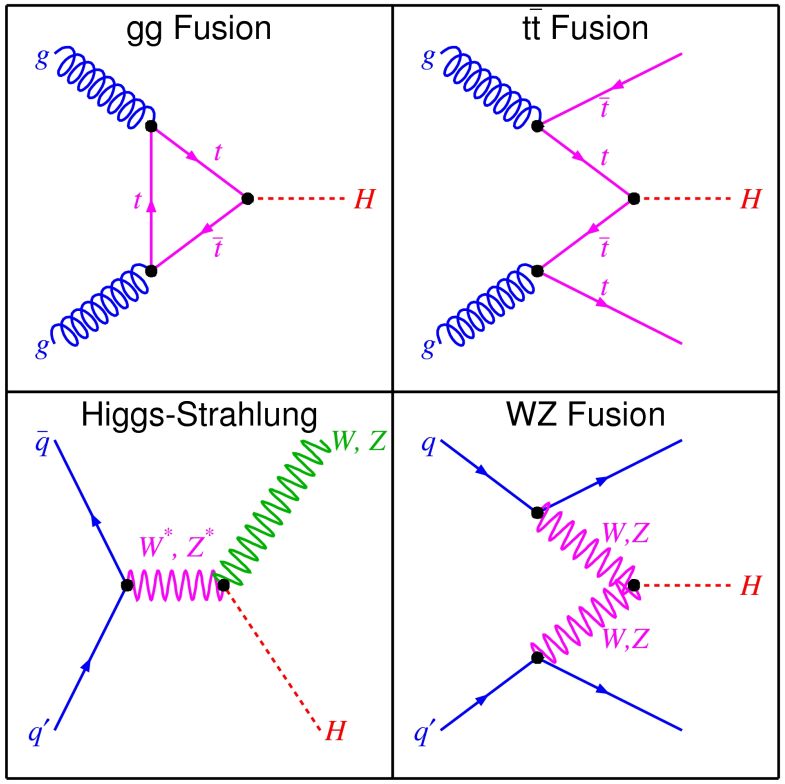


- bb
  - 58% SM branching ratio
  - Poor mass resolution
  - Important b-tagging and jet energy systematics
- $\mu\mu$
  - 2.2×10^{-4} SM branching ratio
  - Good resolution but signal dwarfed by background
- $\tau\tau$
  - 6.3% SM branching ratio
  - Important τ-tagging and energy scale systematics
  - First expected fermionic decay mode

Production Channels

gluon fusion:
- $\sigma \approx$ 15 (19) pb
- $\tau\tau$ and $\mu\mu$ analyses

W/Z associated production:
- $\sigma \approx$0.58 (0.70) (W) or 0.34 (0.42) (Z) pb
- leptons from W/Z allow easier event identification
- most powerful bb channel, also $\tau\tau$ channel



ttH:
- $\sigma \approx$ 0.086 (0.13) pb
- leptons from tt allow easier event identification
- bb and $\tau\tau$ analyses

Vector Boson Fusion:
- $\sigma \approx$1.2 (1.6) pb
- signature: forward jets
- most powerful $\tau\tau$ channel, also a bb channel

Cross sections are at 7 (8) TeV

Implications of Fermionic Channels for Understanding the New Boson

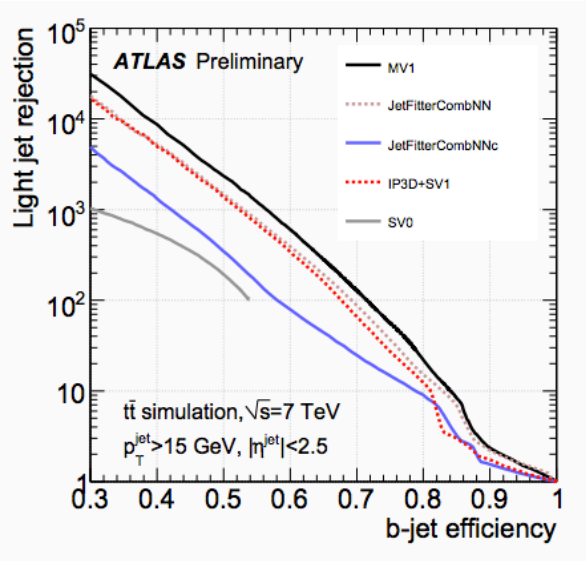
- Direct probe to fermionic couplings
- Since m_H <200 GeV or so, inherent width is $O(MeV)$ while experimental resolution is $O(GeV)$ (best case)
- Use decay ratios to constrain Higgs width
  - Ratio of widths $\gamma_{xx} = \Gamma_{h\to xx}/\Gamma_{h_{SM}\to xx}$
  - Total width $\Gamma_h^{tot}/\Gamma_{h_{SM}}^{tot} = 0.58\gamma_{bb} + 0.06\gamma_{\tau\tau} + 0.24\gamma_{VV} + 0.09\gamma_{gg} + 0.03\gamma_{cc}$
  - Contribution from bb dominates total width because BR($H \to bb$) =58%
  - Until BR($H \to bb$) constrained via measurement, major piece of puzzle is missing
- An SM Higgs will decay to fermions, particularly bb and $\tau\tau$ in a well-defined way–tests of the new Higgs boson must include studies of its decays to fermions in order to give us a full picture

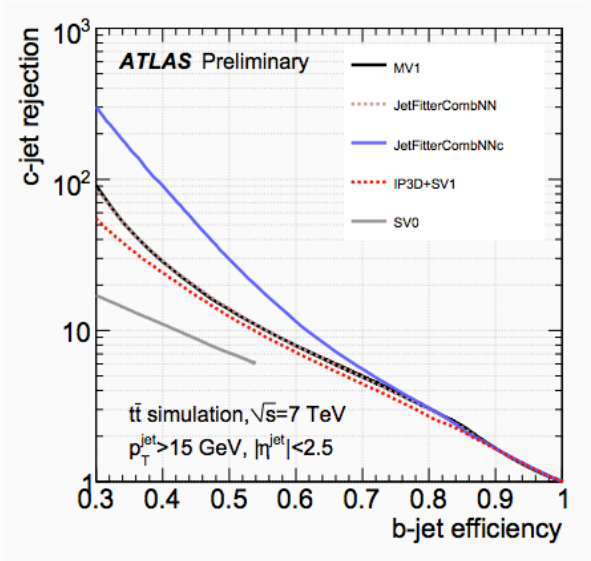
$H \rightarrow bb$

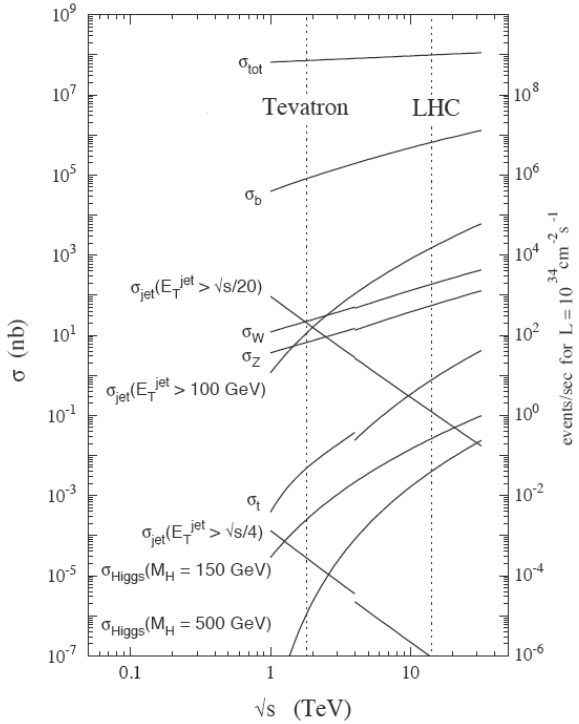
ATLAS: 4.6-4.7 fb^{-1} (2011) and 20.3(VH) fb^{-1} (2012)
CMS: 5.1 fb^{-1} (2011) and 12.1 (VH) or 19.5 (ttH) fb^{-1} (2012)

$H \to bb$ Motivation

- Inclusive production (ggF) impossible to observe because of high QCD background
- Require extra particles or a unique topology
  - Forward jets (VBF topology)
  - tt 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 production
- b-tagging and b-jet energy scale and resolution introduce substantial systematics

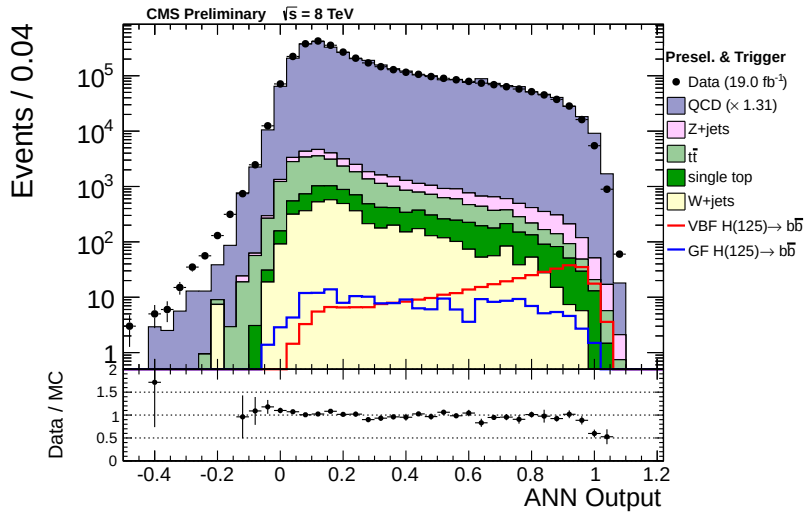




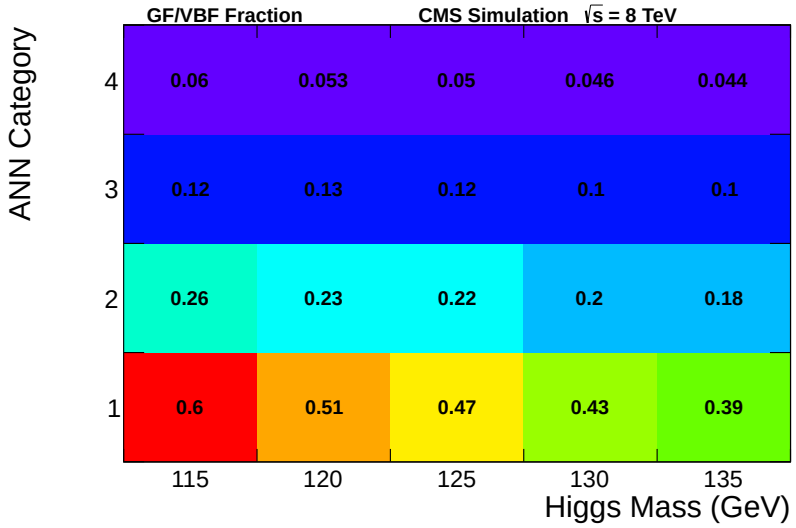


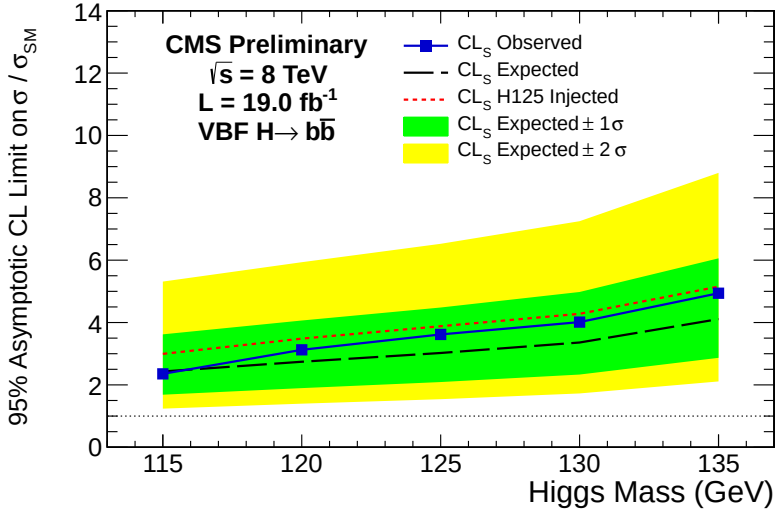
CMS VBF $H \to bb$

ANN discriminant based on event topology and b-tag values



Up to 47% ggF contamination at $m_H = 125$ GeV





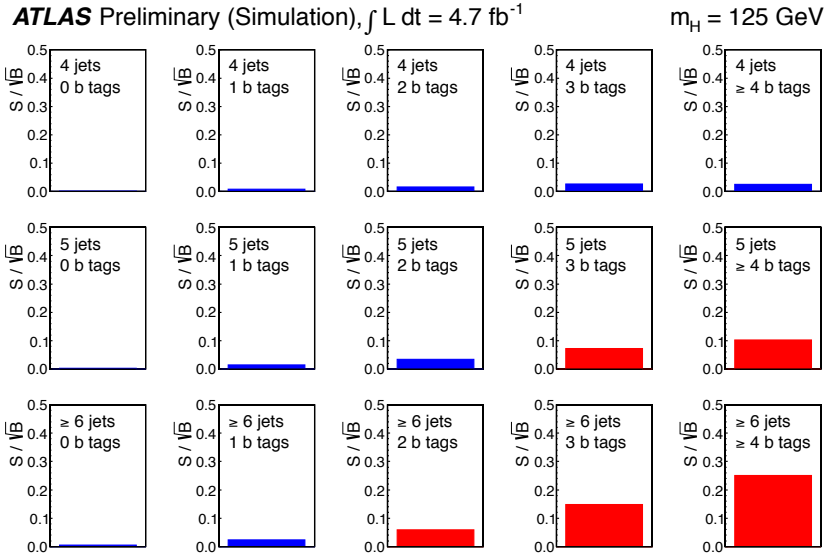
For m_H=125 GeV, 95% observed (expected) CL upper limits on cross section is 3.6 (3.0) $\times$ SM and observed signal strength μ=0.7$\pm$1.4

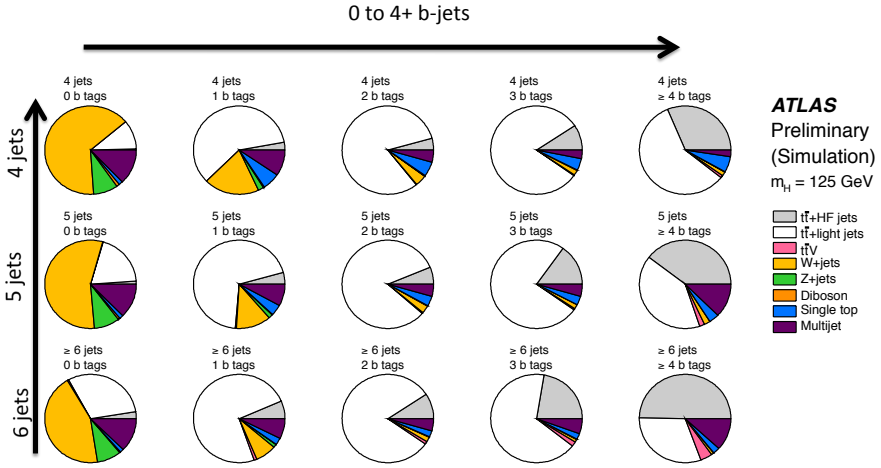
20-50% uncertainty on the $gg \to H$ normalization

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

ttH, $H \to bb$ at ATLAS and CMS: Similarities

$S/\sqrt{B} > 0.05$ or $S/\sqrt{B} < 0.05$



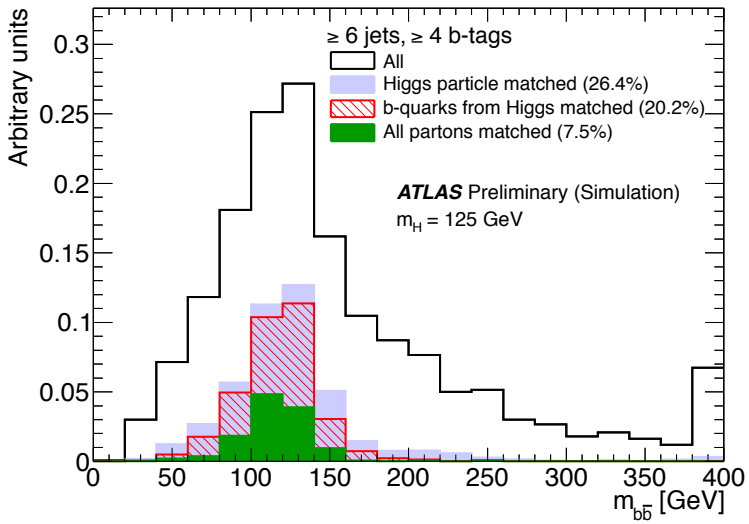


- Binning of analysis in number of jets and number of b-tags
  - ATLAS: 4-6 jets, 0-4 b-tags
  - CMS varies by channel: 7 combinations ($tt \to l\nu q\bar{q}b\bar{b}$, $H \to bb$), 3 combinations ($tt \to l\nu l\nu b\bar{b}$, $H \to bb$), 6 combinations ($H \to \tau\tau$)
- Kinematic fit to reconstruct the top quarks, and determine which b quarks to use in Higgs reconstruction
- Updated b-tagging systematics and correlations on tt+heavy flavor background, leading to higher systematics (relative to 2011) for CMS

$ttH,\ H \to bb$ at ATLAS and CMS: Distinctions

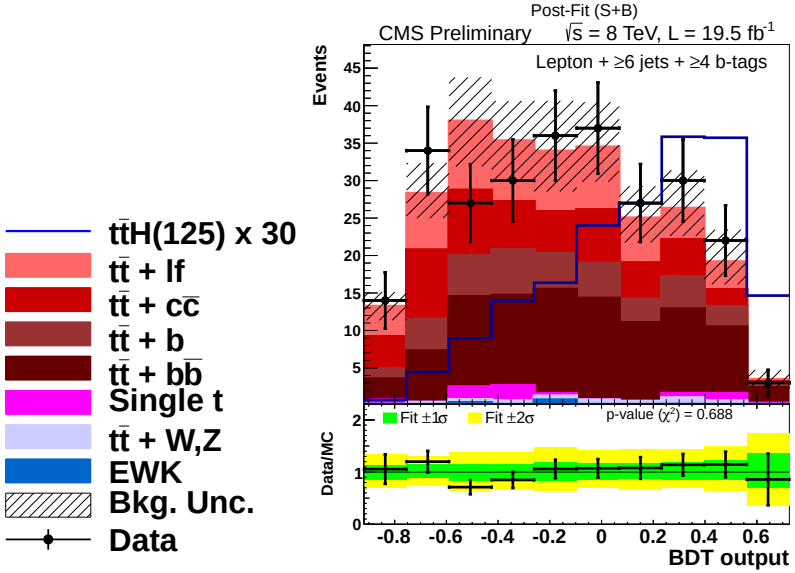
ATLAS

- Cut-based analysis, final discriminant: m_{bb} or H_T^{had}
- Includes only $tt \to l\nu q\bar{q}b\bar{b}$
- Below: kinematic fit results



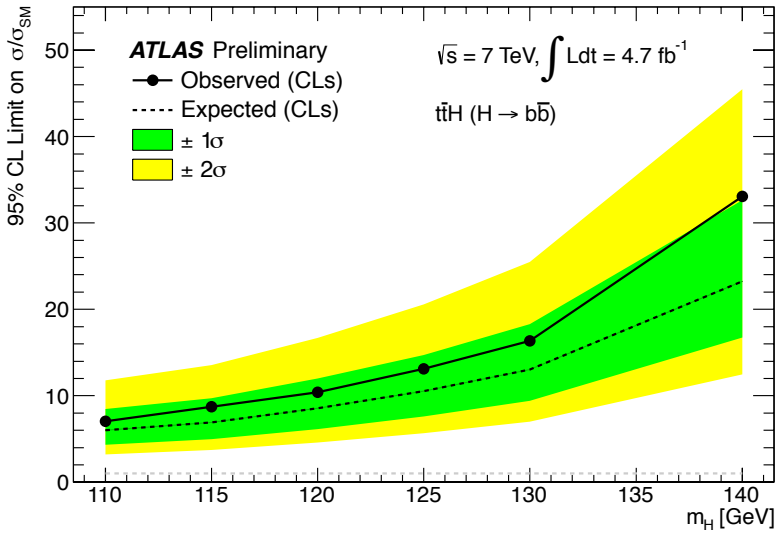
CMS

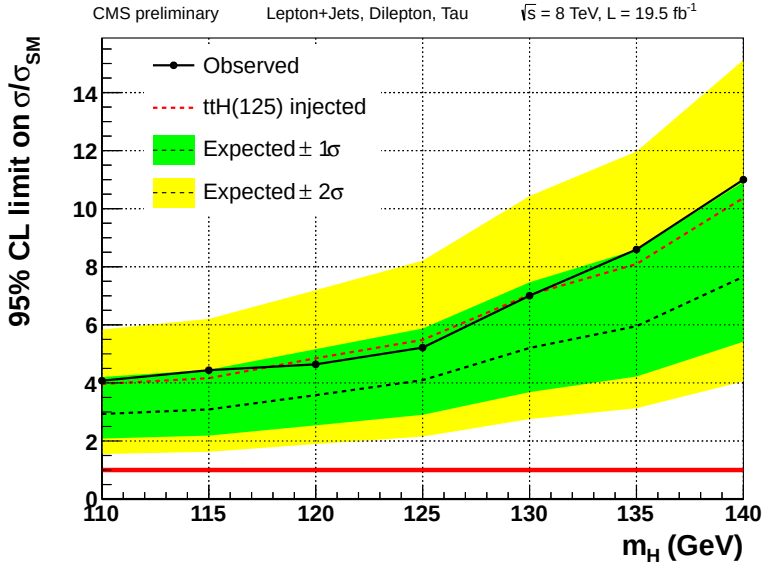
- BDT-based analysis, final discriminant: output of BDT
- Result combined with $ttH,\ H \to \tau\tau$
- Includes both $tt \to l\nu l\nu b\bar{b}$ and $tt \to l\nu q\bar{q}b\bar{b}$



ttH, $H \to bb$: Results

95% CL upper limit on cross section for m_H=125GeV





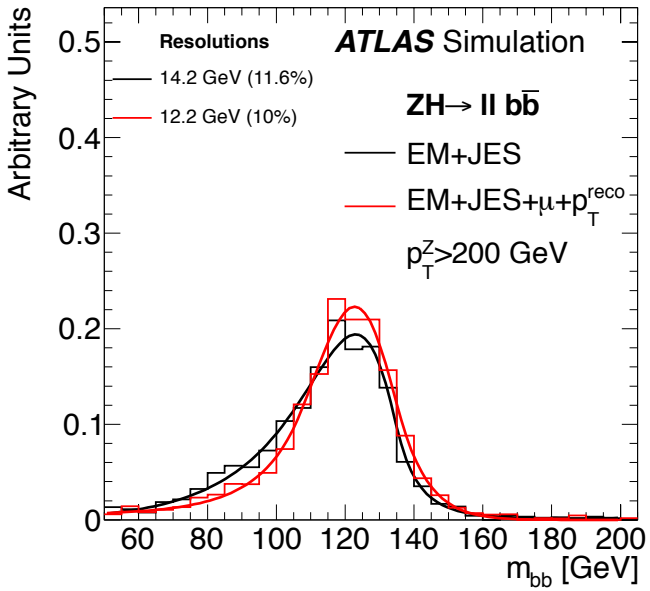
ATLAS: observed (expected) limit is 13.1 (10.5) $\times$ SM ($tt \to l\nu q\bar{q}b\bar{b}$)
note luminosity: 4.7 fb^{-1} at 7 TeV

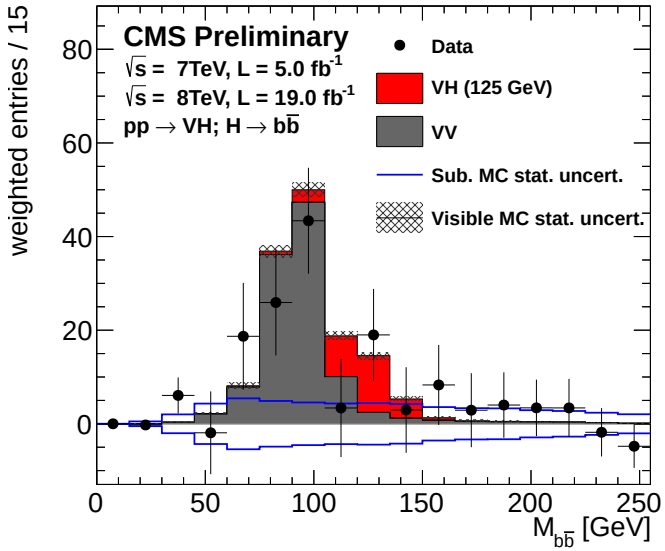
CMS: observed (expected) limit is 4.9 (4.7) $\times$ SM ($tt \to l\nu l\nu b\bar{b}$) and 9.1 (8.2) $\times$ SM ($tt \to l\nu q\bar{q}b\bar{b}$); combination with $ttH \to \tau\tau$ gives 5.2 (4.1) $\times$ SM

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

- 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})
  - Increasing S/B with increasing p_T^V

- Jet correction used to improve mass resolution
  - CMS: improves sensitivity by 10-20%
  - ATLAS: mass resolution improvement 10-12%





- Validated using $VZ, Z \to bb$ events
  - CMS: 7.5σ, $\mu = 1.19^{+0.28}_{-0.23}$
  - ATLAS: 4.8σ, $\mu = 0.9 \pm 0.2$

Tevatron also sees broad excess around 120 GeV (link)

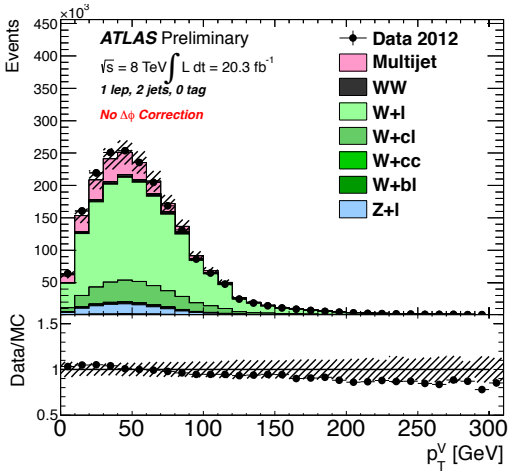
$VH \to bb$ at ATLAS and CMS: Distinctions

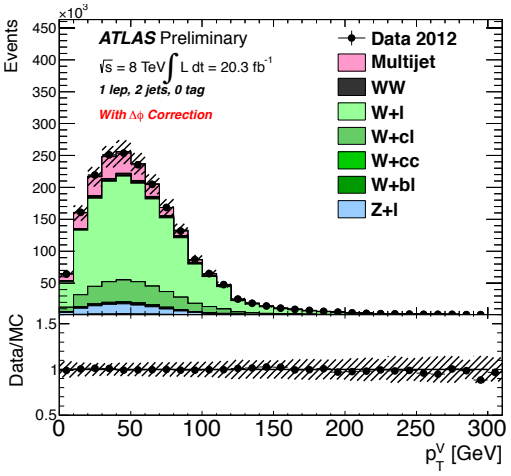
ATLAS

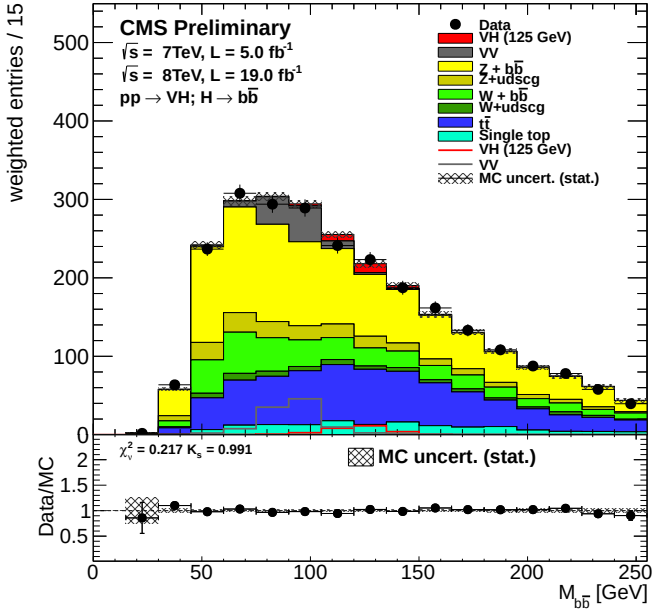
- Cut-based analysis
- 2-btag signal region, 1-tag and 0-tag regions for background validation
- $\Delta\phi(jet_1, jet_2)$ reweighting that improves p_T^V agreement between V+jets MC (Sherpa) and data

CMS

- BDT-based analysis
- 4 BDTs: $t\bar{t}$, diboson, Z+jets, VH
- Cut-based analysis: 1.1σ excess around 120 GeV
- $Z \to \nu\nu$ b-tag trigger $\to$ lower E_T^{miss} thresholds

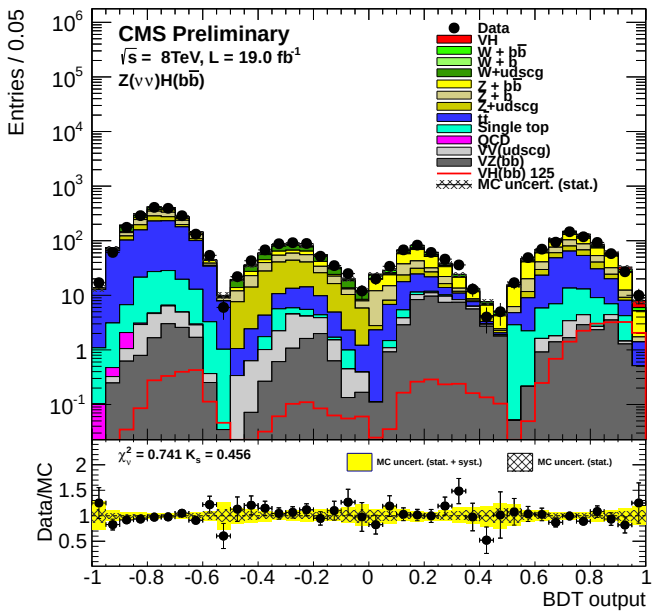


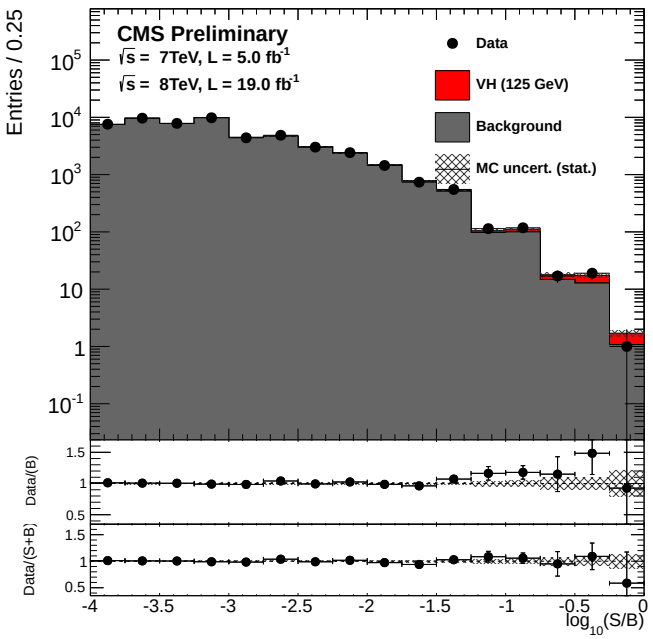




CMS $VH(H \to bb)$

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



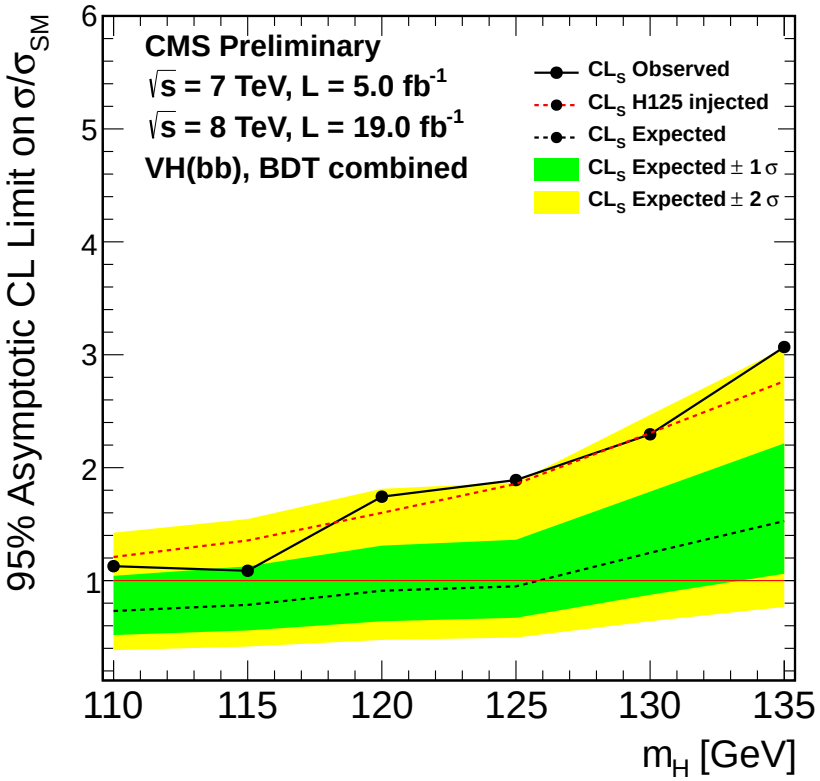


Example output of the BDT
4-hump structure because 4 BDTs trained, enriched in tt, Z+jets, diboson and signal

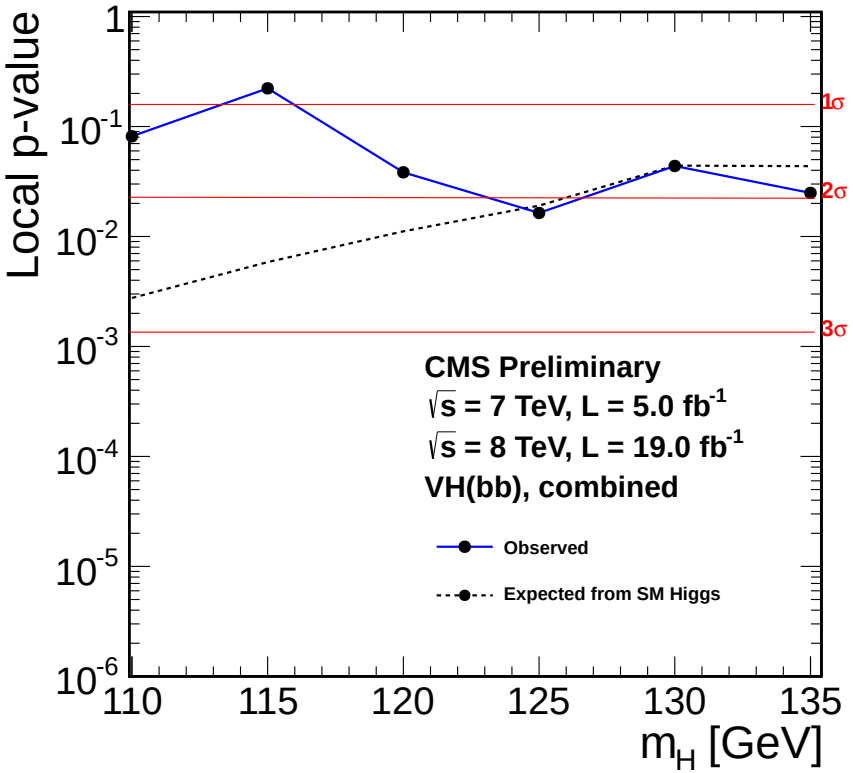
Combination of all BDT discriminants
Top ratio plot: data to the background-only prediction
Bottom ratio plot: data to signal+background prediction

$VH(H \to bb)$ at CMS: Results

95% CL upper limit on cross section and p-value for m_H=125GeV



observed (expected) limit of 1.89 (0.95) $\times$ SM



p-value corresponds to 2.1σ and signal strength μ=1.0$\pm$0.5

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

Each p_T^V category in ATLAS further divided into 2-jet and 3-jet signal regions

below: m_{bb} distributions from the 2-jet, 2-tag, p_T^V >200 GeV regions (most signal-enriched)

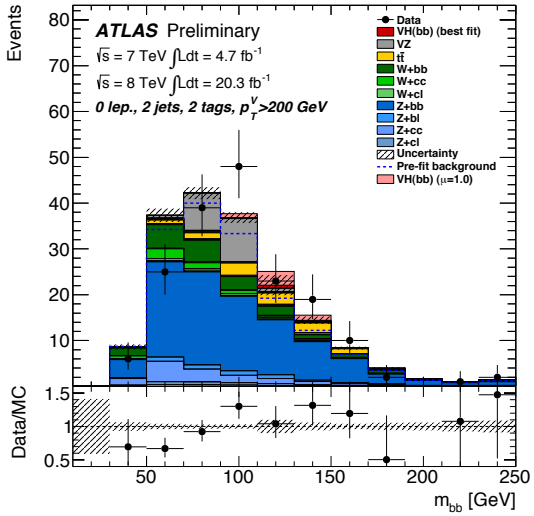
$Z \to \nu\nu$

0 leptons

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

+ $\leq$ 1 extra jets

angular cuts to minimize dijet QCD



$W \to l\nu$

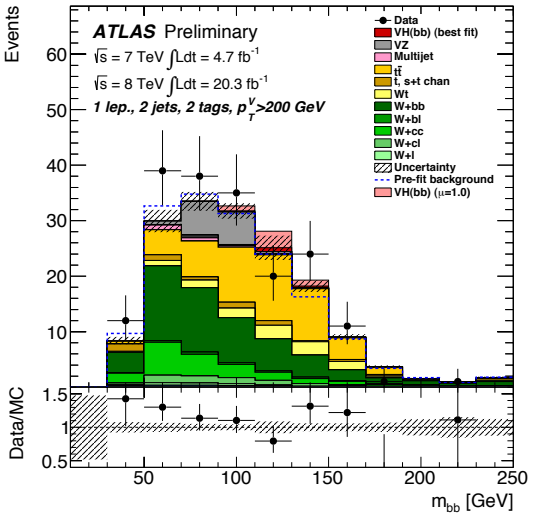
1 lepton

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



$Z \to ll$

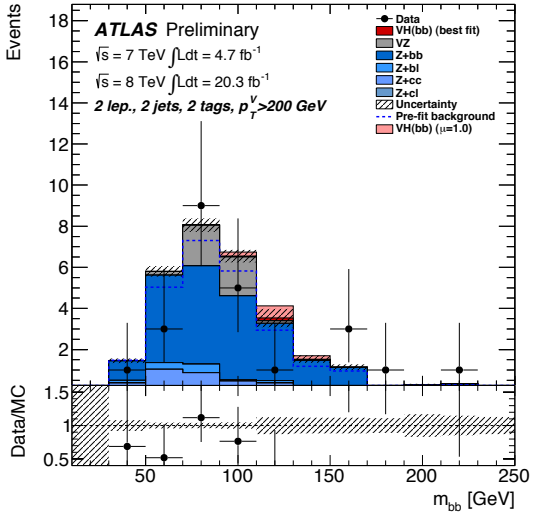
2 leptons

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

+ $\leq$ 1 extra jets

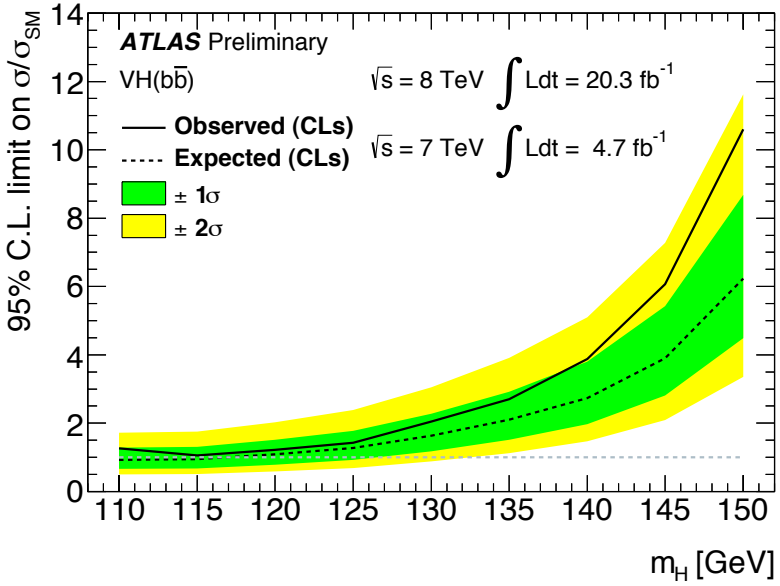
E_T^{miss} < 60 GeV

83< m_{ll} <99 GeV

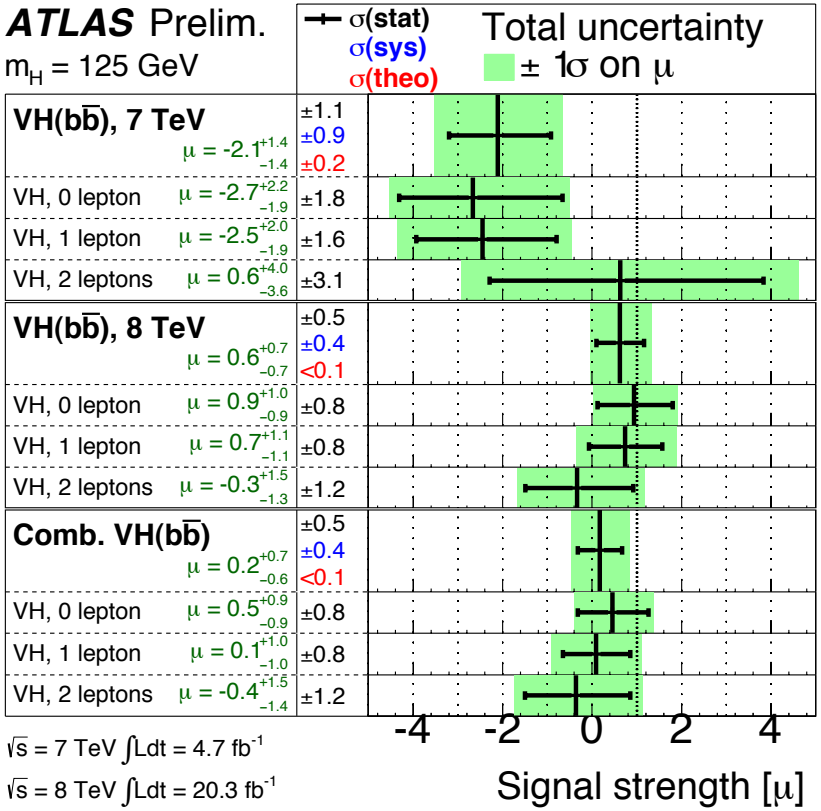


$VH(H \to bb)$ at ATLAS: Results

95% CL upper limit on cross section and μ for m_H=125GeV



observed (expected) limit is 1.4 (1.3) $\times$ SM



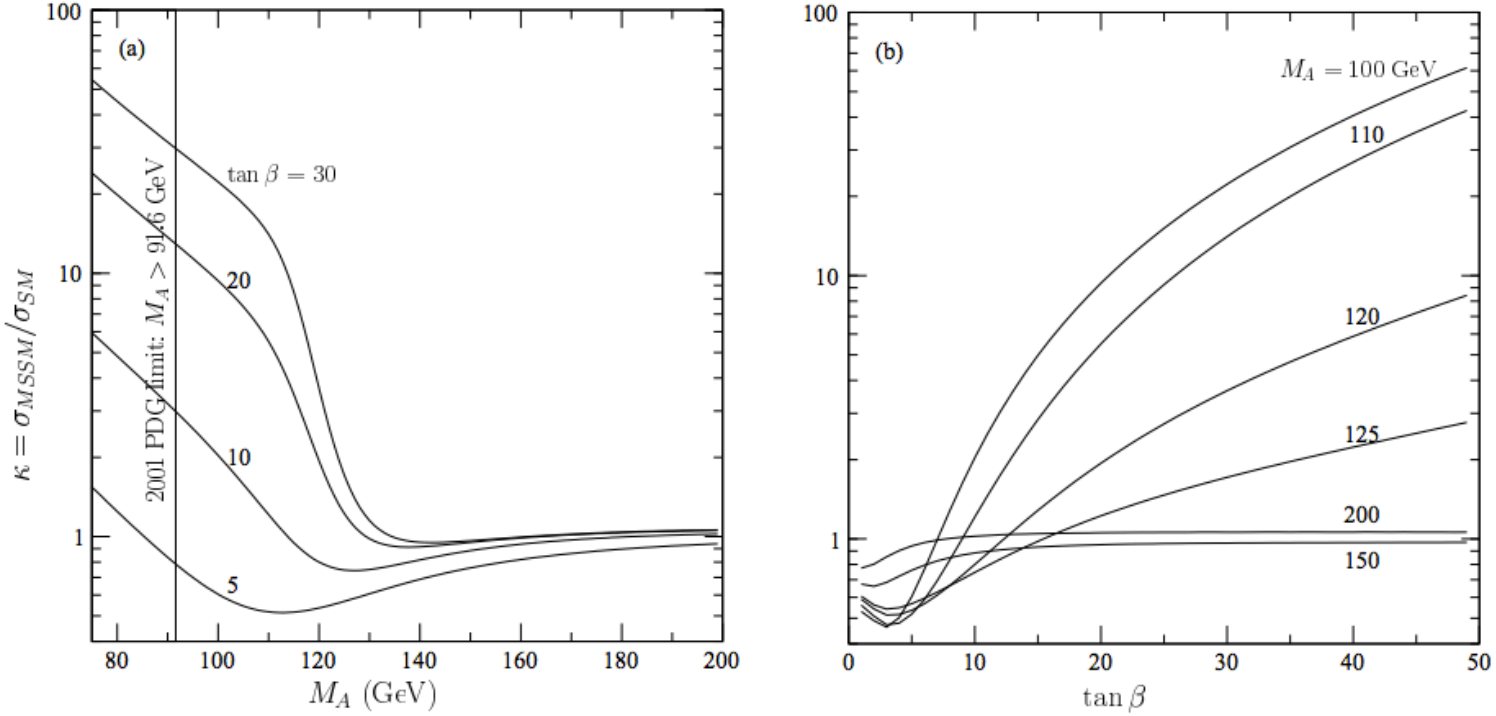
signal strength by channel and year

$H \rightarrow \mu\mu$

ATLAS: 20.7 fb^{-1} (2012)
CMS: 5.0 (2011) and 19.7 (2012) $fb{-}1$

$H \to \mu\mu$ Motivation

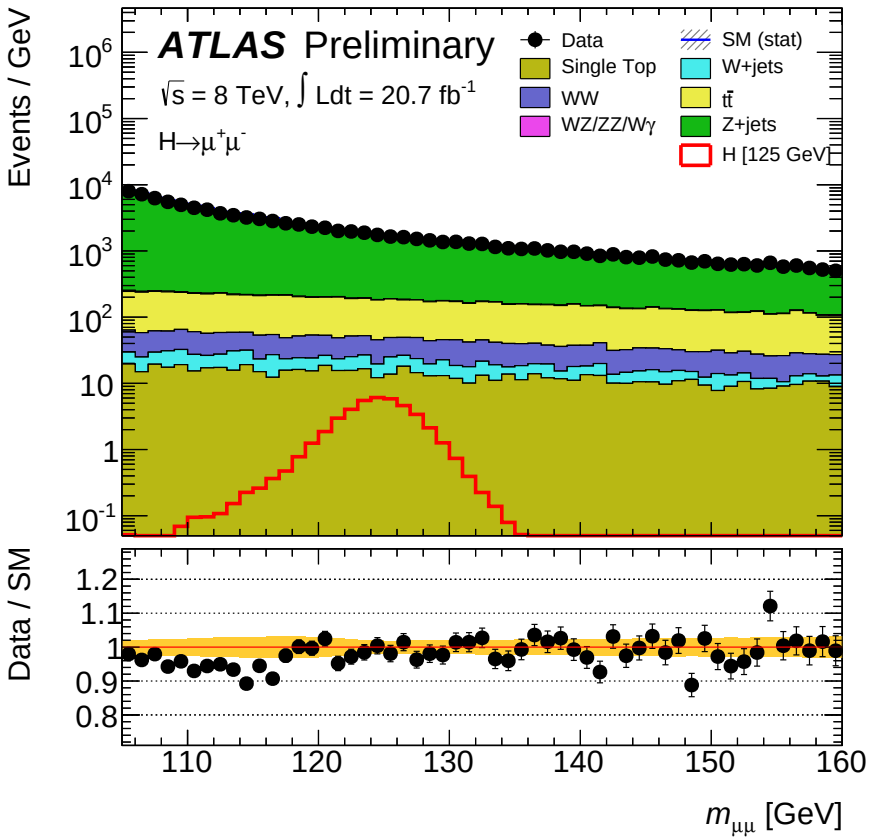
- Small branching fraction (2.2×10^{-4})
- Good mass resolution from muons
- Only channel for measuring coupling to second-generation fermions
- Substantial irreducible background of $Z/\gamma^* \to \mu\mu$
- Can have enhanced BF from non-SM contributions

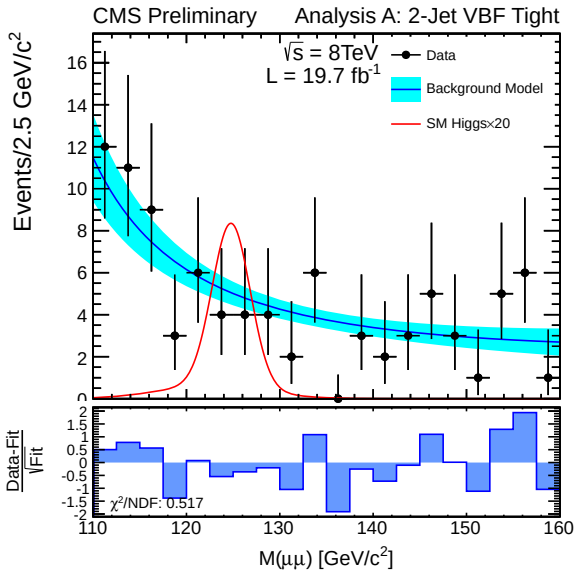


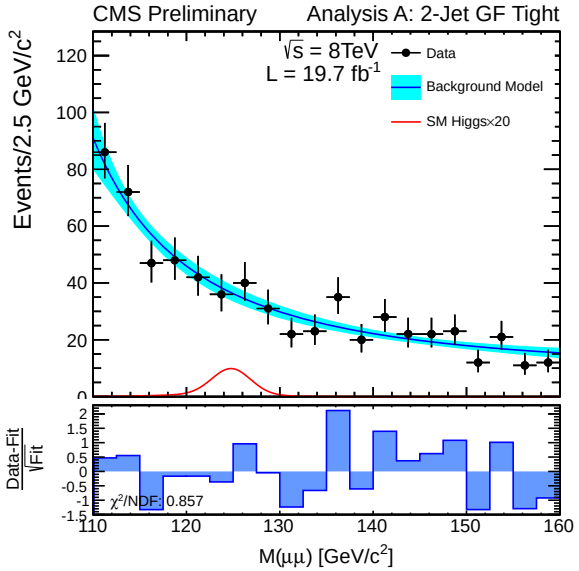
Plots from Tao Han and Bob McElrath showing MSSM enhancement factor to $gg \to h \to \mu\mu$ as a function of m_A and tanβ (arXiv hep-ph 0201023)

$H \to \mu\mu$

- Reconstruct invariant mass of 2 muons
- CMS: dedicated VBF search region, 2 independent analyses (inclusive vs. 125-GeV-oriented)
- Main background: Z+jets

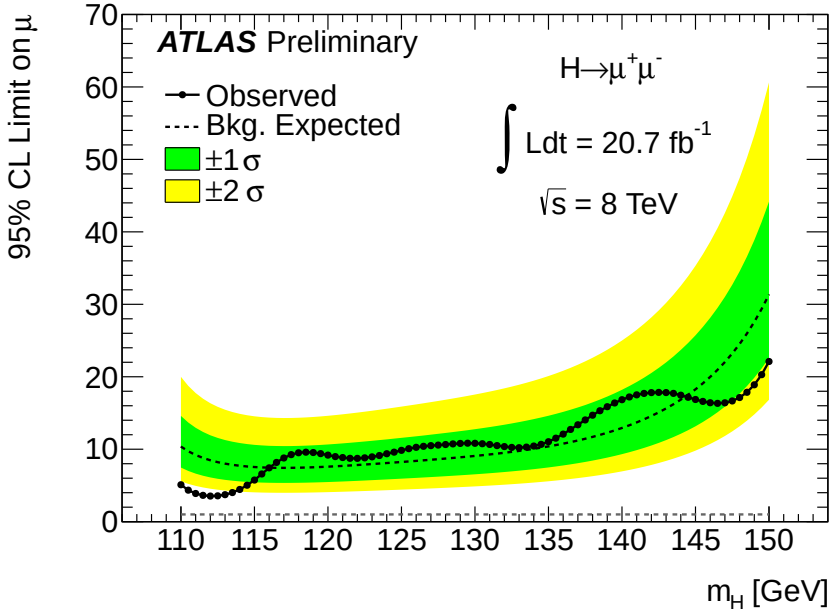




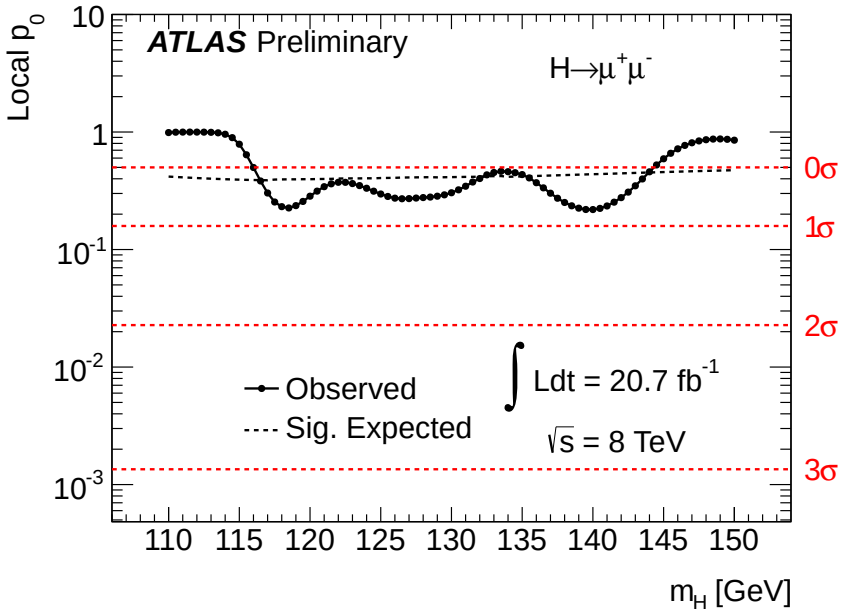


$H \to \mu\mu$ Results at ATLAS

95% CL upper limit on cross section and p-value for m_H=125GeV



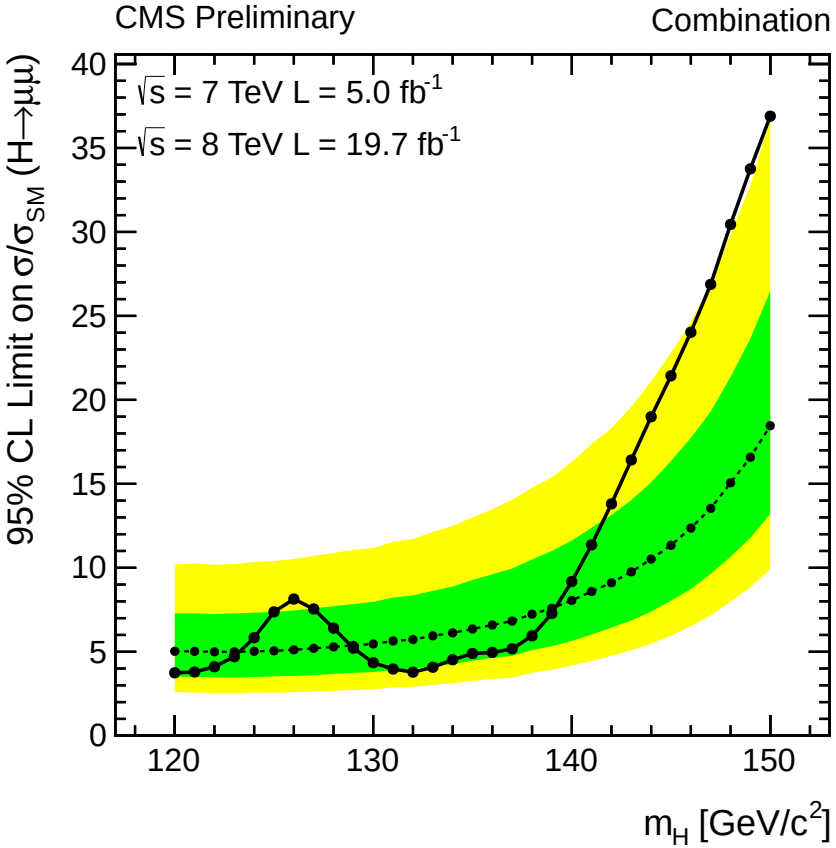
observed (expected) limit is 9.8 (8.2) × SM



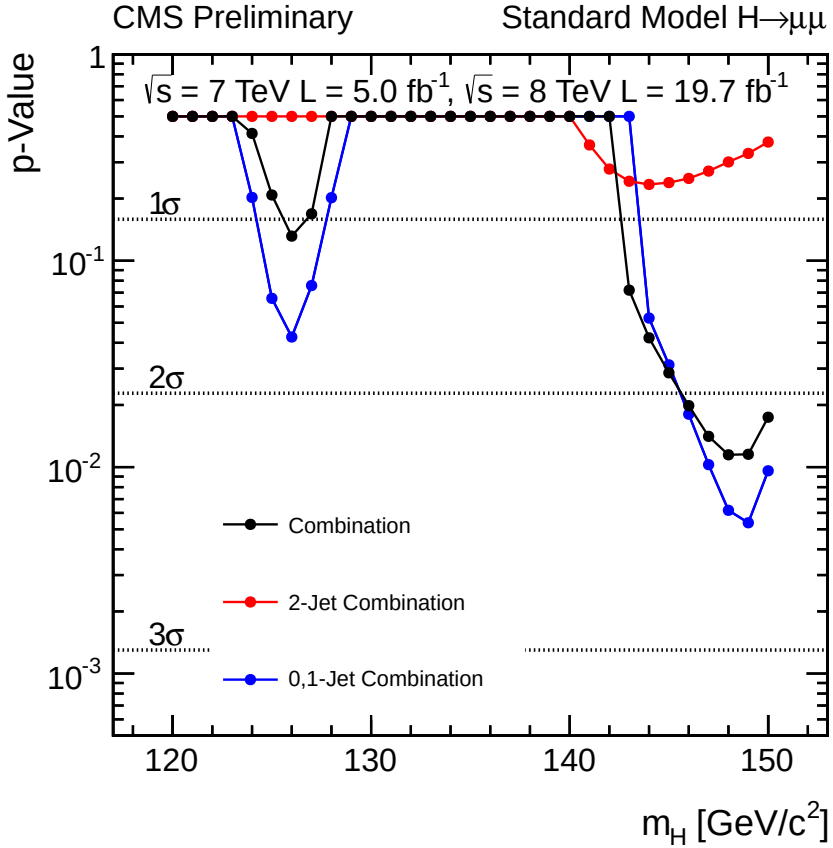
no significant deviation from SM seen

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

95% CL upper limit on cross section and p-value for m_H=125GeV



observed (expected) limit is 5.1 (7.4) $\times$ SM



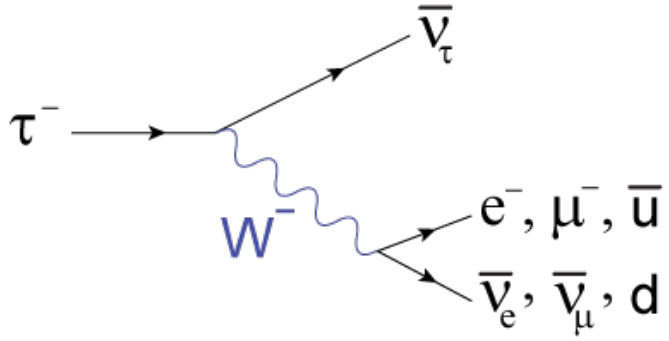
broad excess (2.3σ local/0.8σ global significance) around 140 GeV, signal strength at 127.5 GeV $\mu = 2.9^{+2.8}_{-2.7}$

$H \rightarrow \tau\tau$

ATLAS: 4.6 fb^{-1} (2011) and 13.0 fb^{-1} (2012)
CMS: 5.0 (VH) and 4.9 (0/1 jet and VBF) fb^{-1} (2011) and 19.5 (VH) and 19.6 (1 jet and VBF) and 19.5 (ttH) fb^{-1} (2012)

$H \to \tau\tau$ Motivation

- Direct coupling to lepton sector
- 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 $\mu\mu/ee$ background
- price: larger QCD jets background, τ 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, high-p_T category somewhat related to ATLAS boosted category

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

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

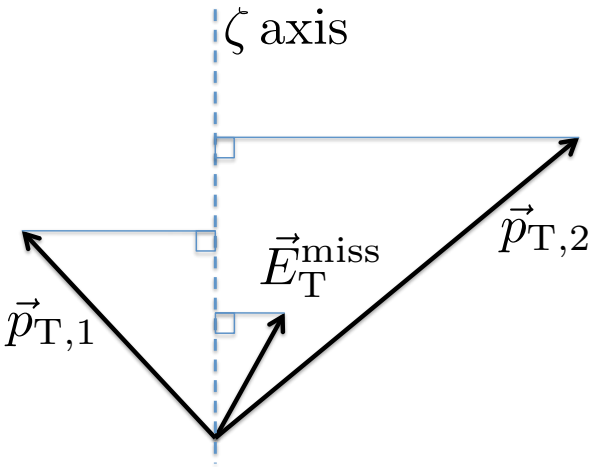
W+jets rejection by ν Orientation Cuts and $Z \to \tau\tau$ Estimate by Embedding

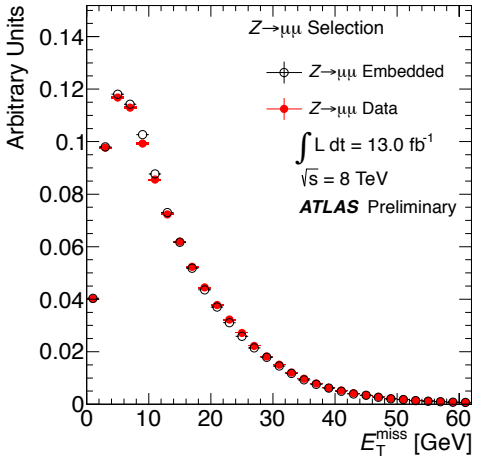
ν Direction Cuts

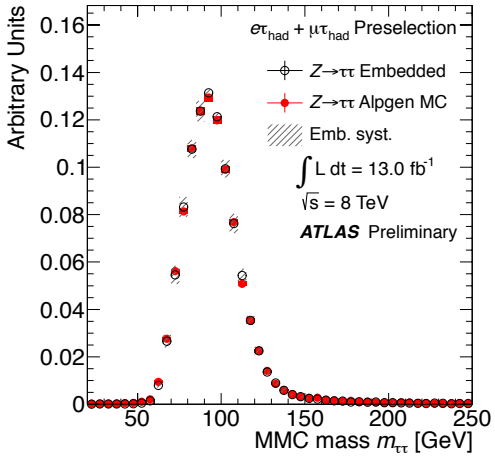
- τ from H decay highly boosted and decay products collimated
- E_T^{miss} from W+jets events more back-to-back with visible decay products

τ Embedding

- Pure data-driven $Z \to \tau\tau$ sample difficult
- Embedding: data-driven $Z \to \mu\mu$ sample, with μ replaced by simulated τ
- Gets Z kinematics, pileup, underlying event from data

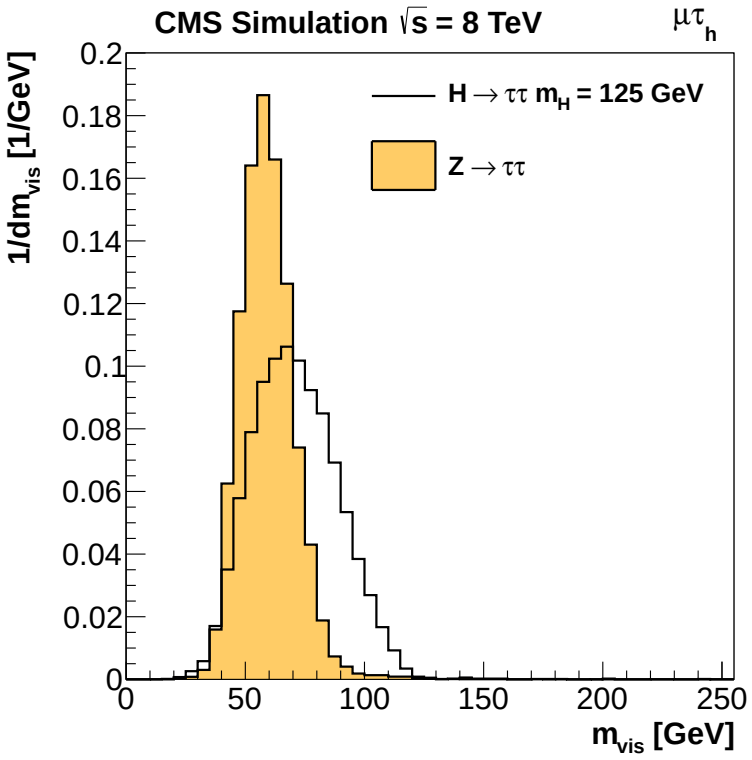


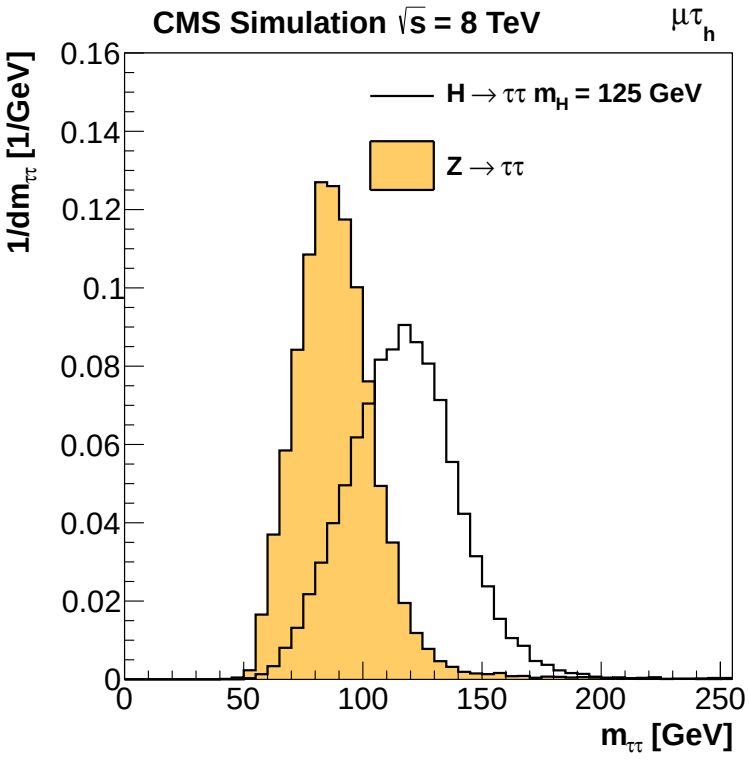




τ Invariant Mass Reconstruction

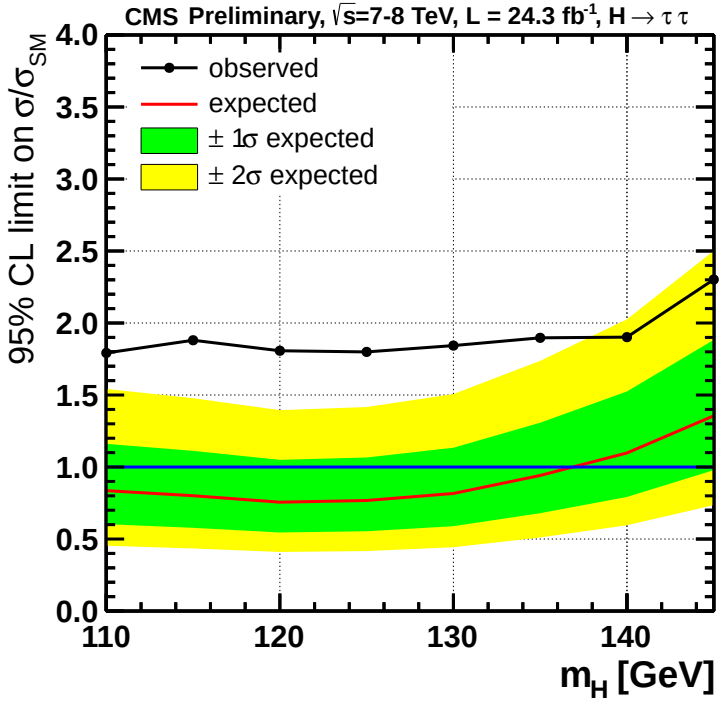
- Assumption of ν collinear with visible τ decay products gives an unphysical solution 20% of the time when reconstructing τ
- ATLAS: Missing Mass Calculator (MMC)
- CMS: SVFit Algorithm
- Idea: given the τ decay modes and the event kinematics, allocate the E_T^{miss} according to a likelihood function

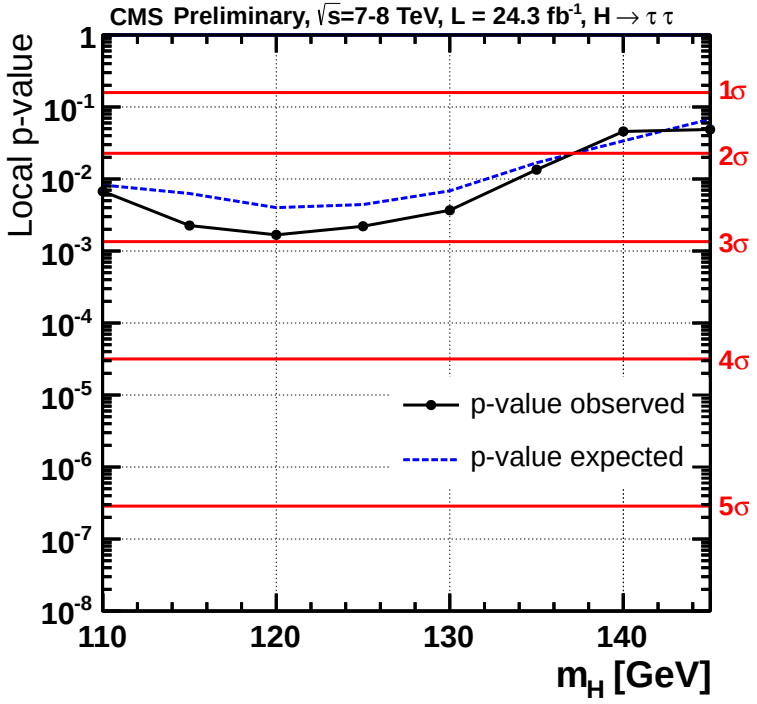




CMS $H \to \tau\tau$: Results

95% CL upper limit on cross section and p-value for m_H=125GeV



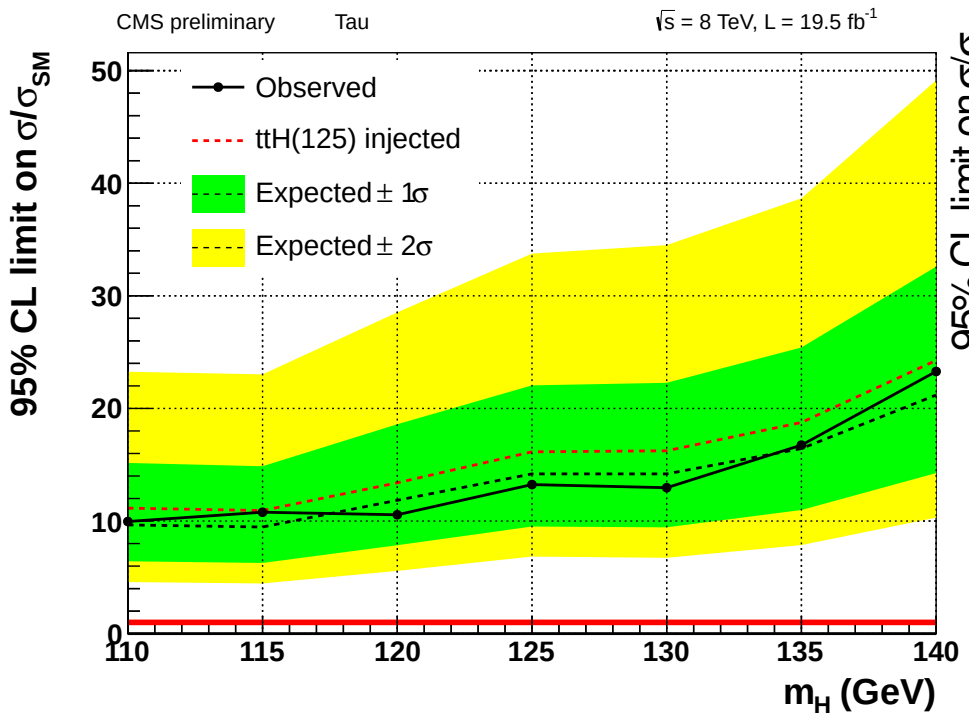


observed (expected) limit is 1.0 (1.63) $\times$ SM

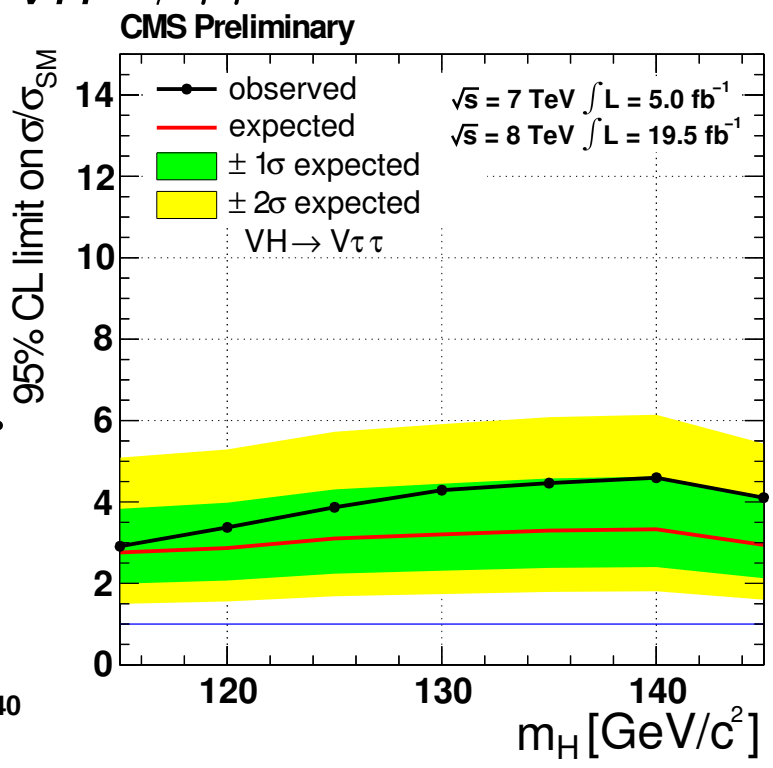
p-value corresponds to 2.85 (2.62) σ
signal strength μ=1.1$\pm$0.4

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

$ttH, tt \to l\nu q\bar{q}b\bar{b},\ H \to \tau\tau$



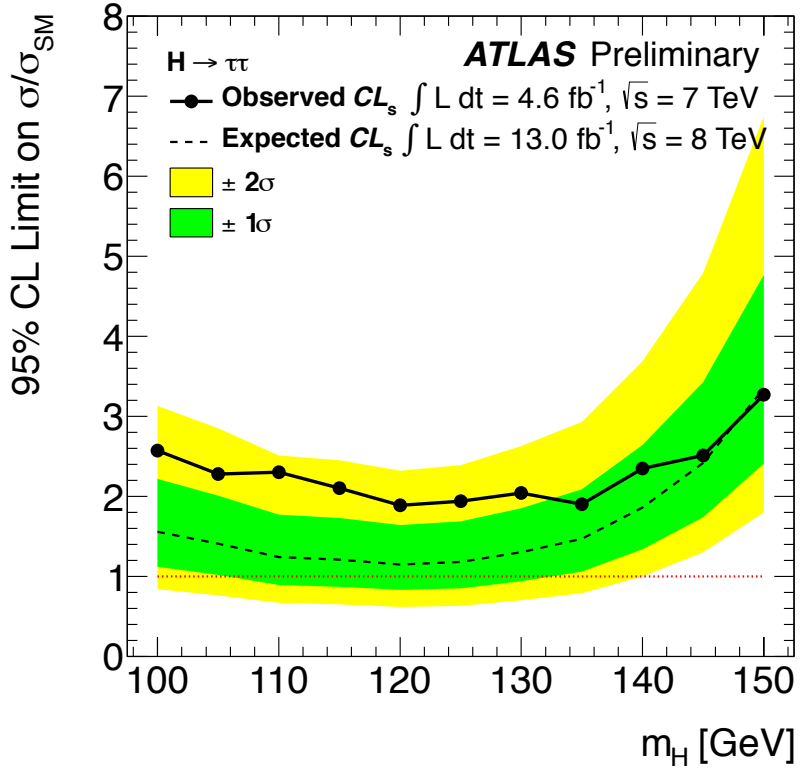
$VH \to \tau\tau$

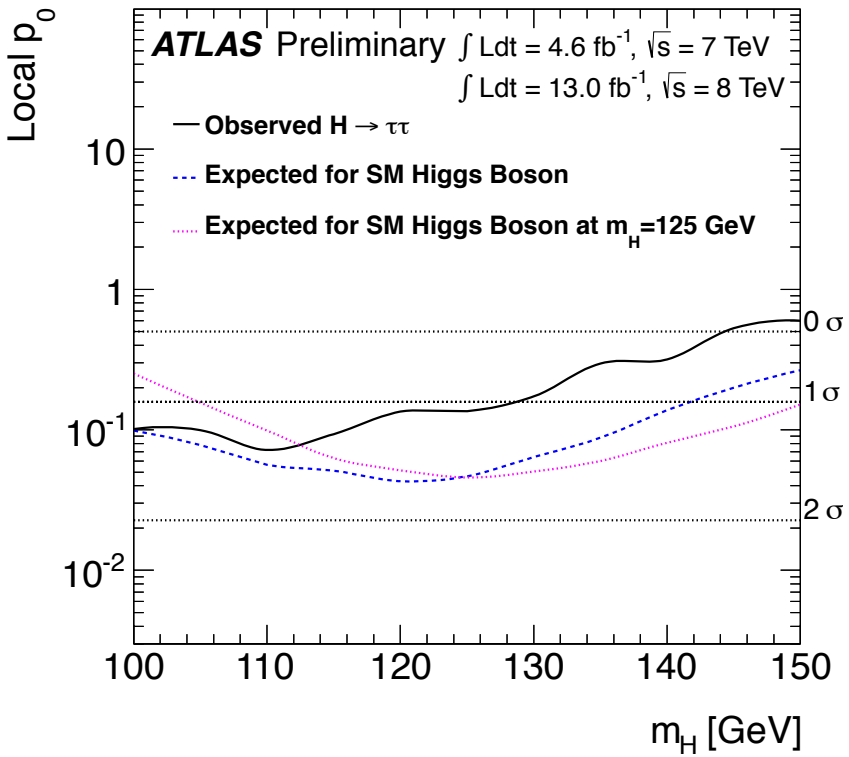


Neither ttH nor VH ($H \to \tau\tau$) is sensitive to SM production rates yet

ATLAS $H \to \tau\tau$: Results

95% CL upper limit on cross section and p-value for m_H=125GeV





observed (expected) limit is 1.9 (1.2) × SM

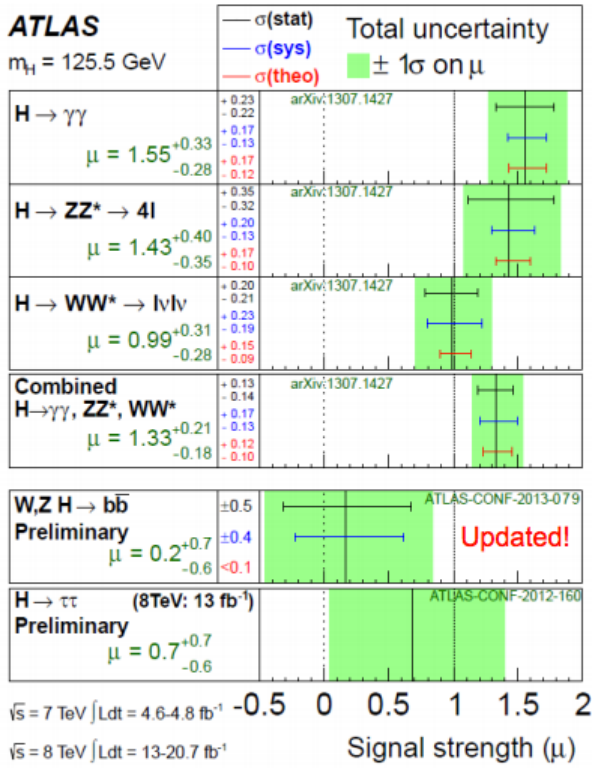
p-value corresponds to 1.1 (1.7)σ
signal strength μ=0.7±0.7

ATLAS update to $H \to \tau\tau$ analysis coming soon: analysis improvements and full 2012 dataset

Summary of Results, Future Prospects and Conclusions

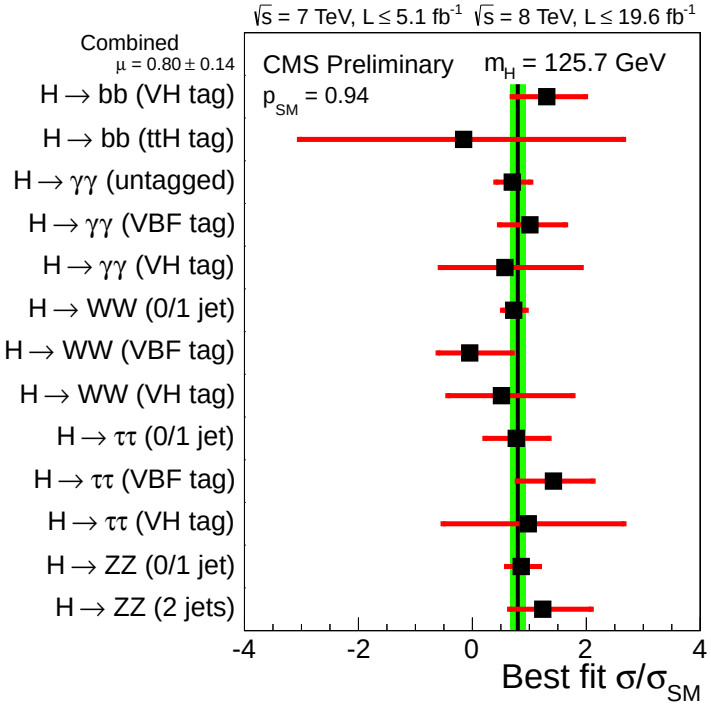
Summary of Channels

ATLAS



μ=1.23±0.18 at 125.5 GeV

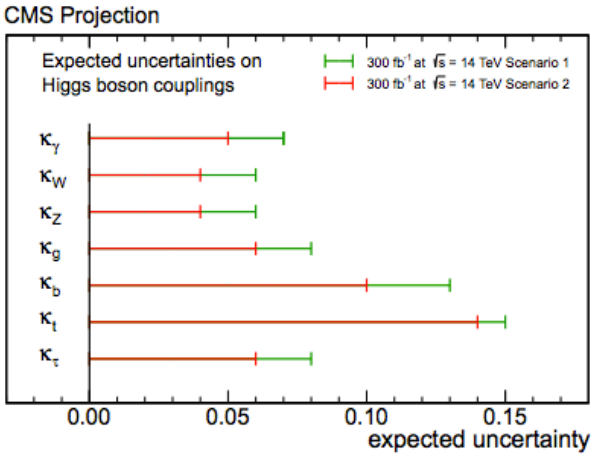
CMS

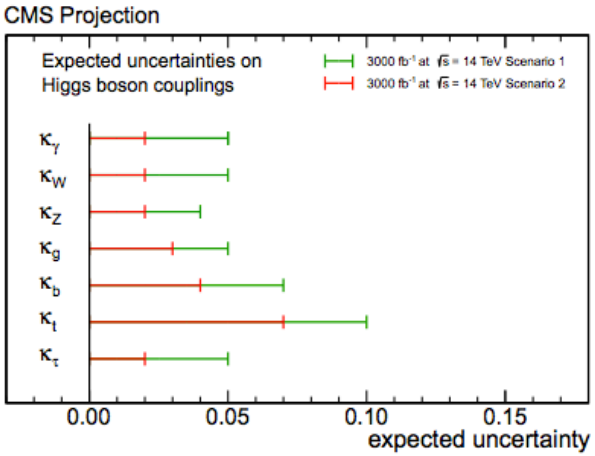


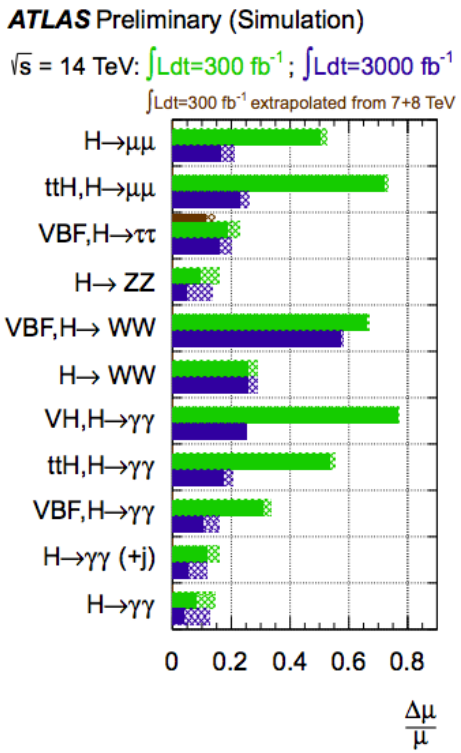
μ=0.80±0.14 at 125.7 GeV

$H \to bb$: largest error bar, least effect on final fit value for μ
$H \to \tau\tau$: consistent with SM for both collaborations

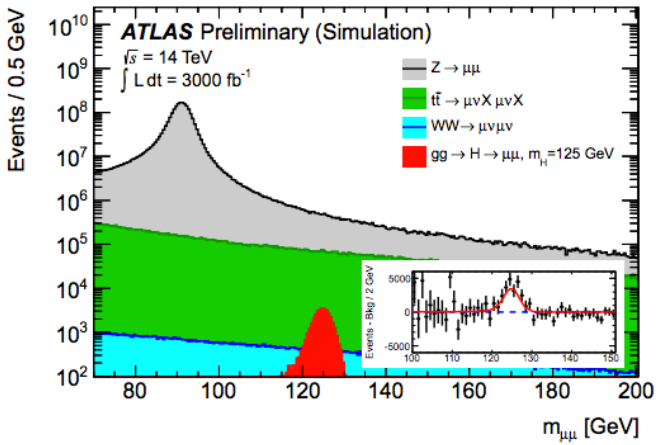
Prospects for 2015 and beyond







Two scenarios probed:
Assumes present systematic errors
Theoretical uncertainties scaled by 1/2, other systematics scaled by $\sqrt{integrated\ luminosity}$



higher center-of-mass energy → larger production cross sections and more data

5 σ signal in $H \to \mu\mu$ and 10-15% precision on $\mu = \sigma/\sigma_{SM}$ projected

Conclusions

- Fermionic channels are not for the weak of heart: poor resolution, large backgrounds, and/or low branching fractions
- However, great progress by ATLAS and CMS as fermionic channels are becoming sensitive
  - Up to about 3σ evidence from CMS of $H \to \tau\tau$, with ATLAS set to have an updated analysis very soon
  - First hints of $H \to bb$ signal, with many different analyses (VH, ttH, VBF) becoming mature
  - $H \to \mu\mu$ off to a strong start on ATLAS and CMS
- ATLAS and CMS analysis strategies complementary
  - CMS: many uses of multivariate classifiers, for performance and analysis
  - ATLAS: cut-based analyses for now, but MVA-based analyses under intense study for incorporation soon
  - Differences between analyses provide perspective–we have two collaborations because we expect them to do things a little differently, and to learn from those differences!
- Several analyses releasing updates before data-taking starts again in 2015
- Fermionic channels will be the place to watch in the next run, as we "discover" the Higgs decays to quarks and leptons

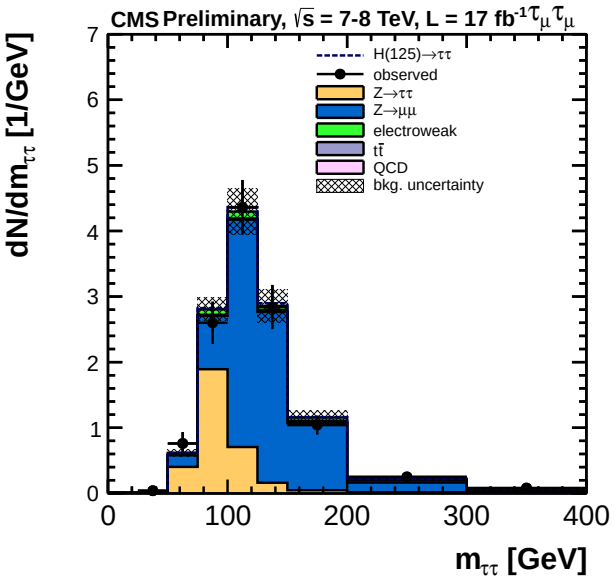
Thank you for your attention!

Additional Information

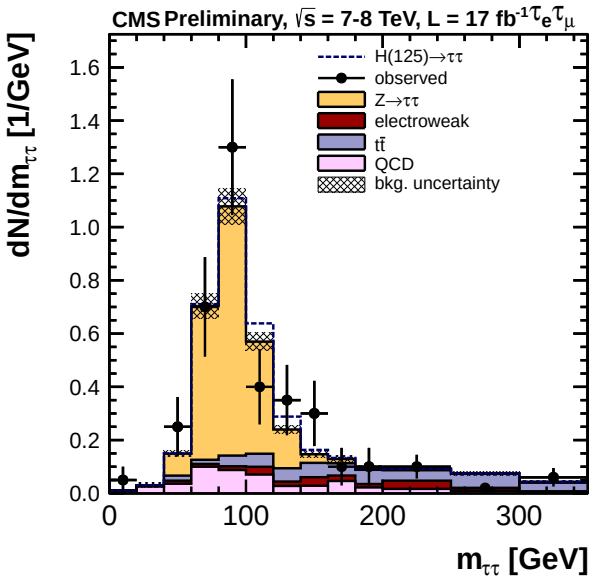
References

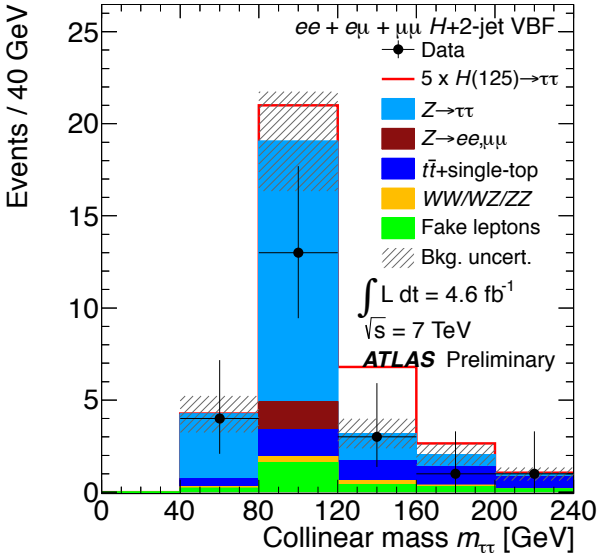
- ATLAS, *Search for the bb decay of the Standard Model Higgs boson in associated (W/Z)H production with the ATLAS detector*, 19 July 2013
- ATLAS, *Search for the Standard Model Higgs boson produced in association with top quarks in proton-proton collisions at $\sqrt{s}$=7 TeV using the ATLAS detector*, 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
- CMS, *Search for the Standard Model Higgs Boson in the $\mu\mu$ decay channel in pp collisions at $\sqrt{s}$ 7 and 8 TeV*, 8 October 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

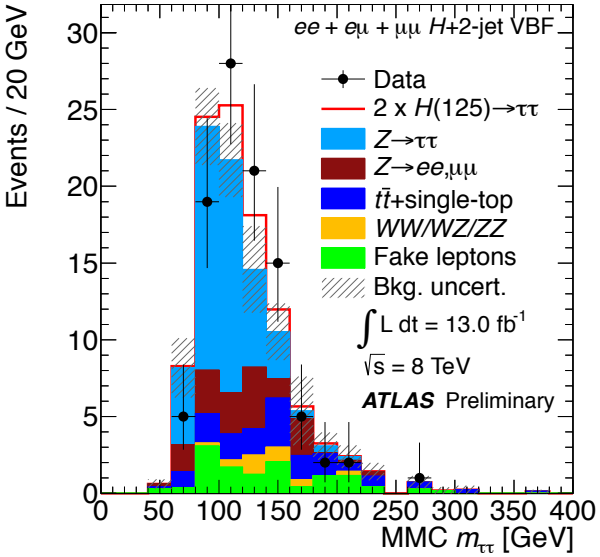


CMS breaks down results by final state of τ's ($\mu\mu$ vs. $e\mu$)
7 TeV and 8 TeV data combined

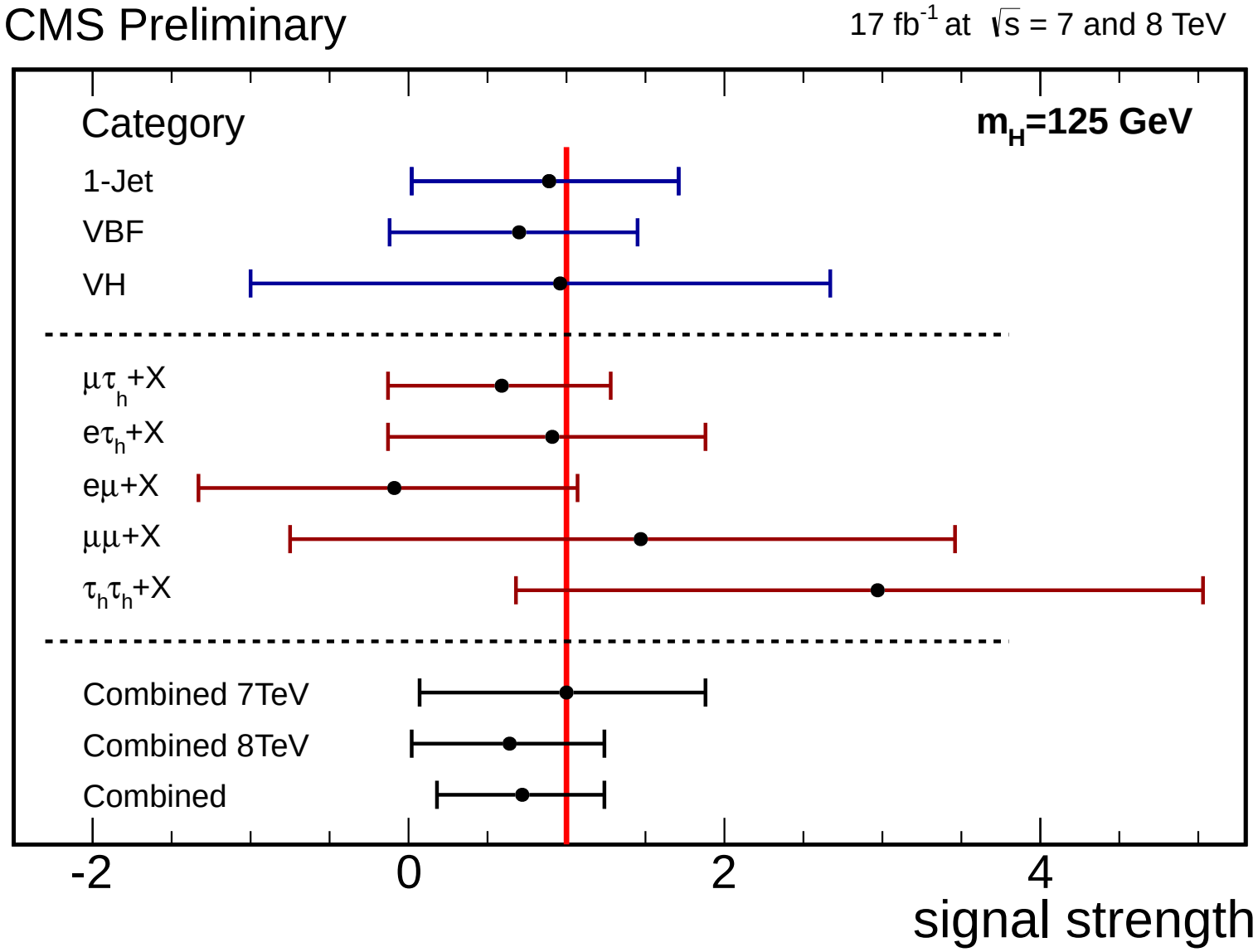




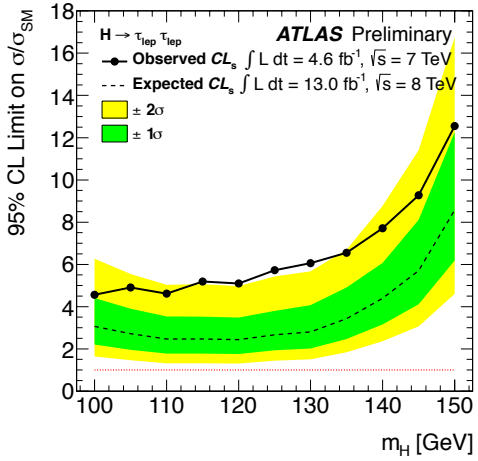
ATLAS breaks down results by energy (7 TeV vs. 8 TeV)
τ final states combined (ee, $e\mu$, $\mu\mu$)



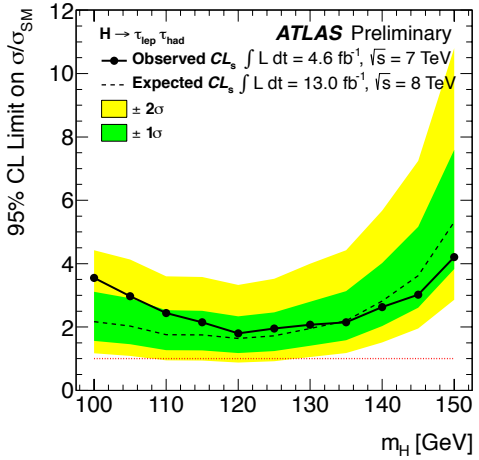
$H \to \tau\tau$: CMS Channel Breakdown



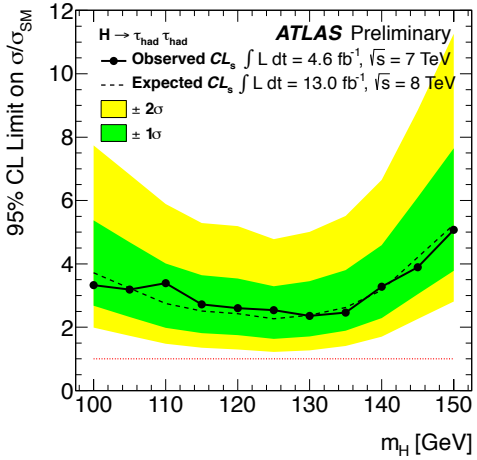
$H \to \tau\tau$: ATLAS Channel Breakdown



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



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



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

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

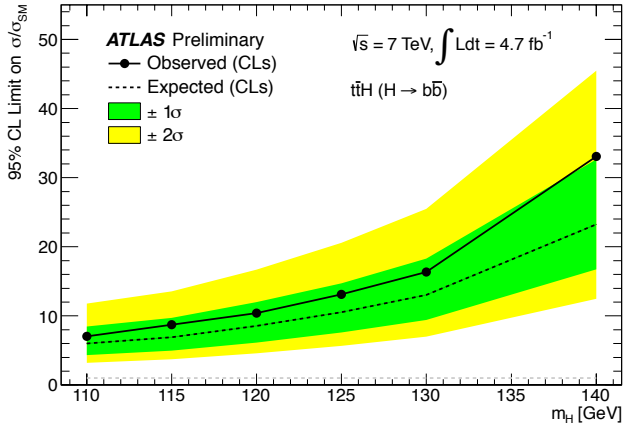
* E_T^{miss} trigger becomes 90% efficient at E_T^{miss}=120 GeV

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

ttH, $H \to bb$: Results

observed (expected) 95% CL upper limit on cross section and p-value for m_H=125GeV

ATLAS



ATLAS: sensitive to 13.1 (10.5) $\times$ SM ($tt \to l\nu q\bar{q}b\bar{b}$)
note luminosity: 4.7 fb^{-1} at 7 TeV

CMS: sensitive to 4.9 (4.7) $\times$ SM ($tt \to l\nu l\nu b\bar{b}$) and 9.1 (8.2) $\times$ SM ($tt \to l\nu q\bar{q}b\bar{b}$)

CMS