Study of Higgs boson production in fermionic decay channels at the LHC

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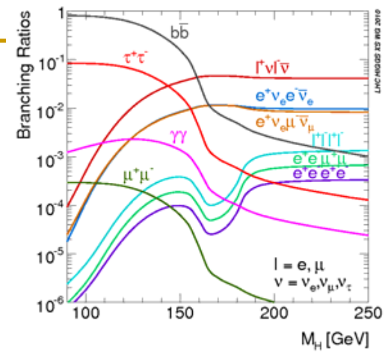
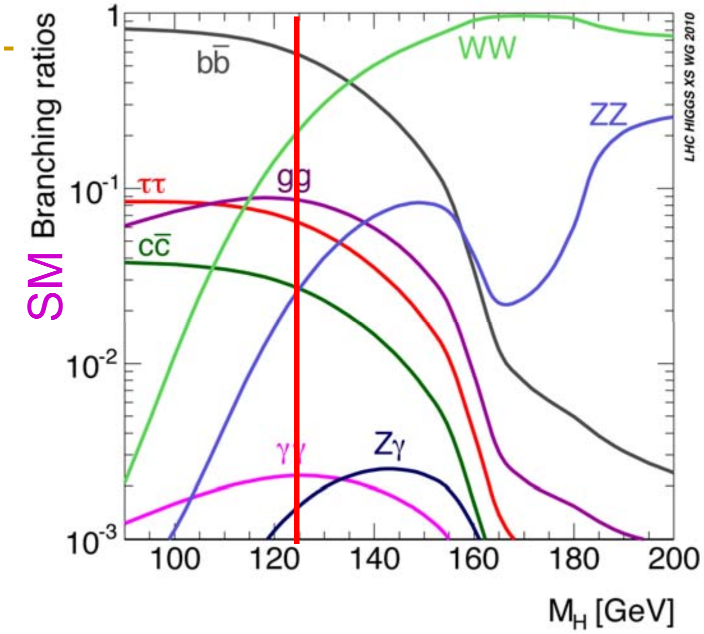
Outline





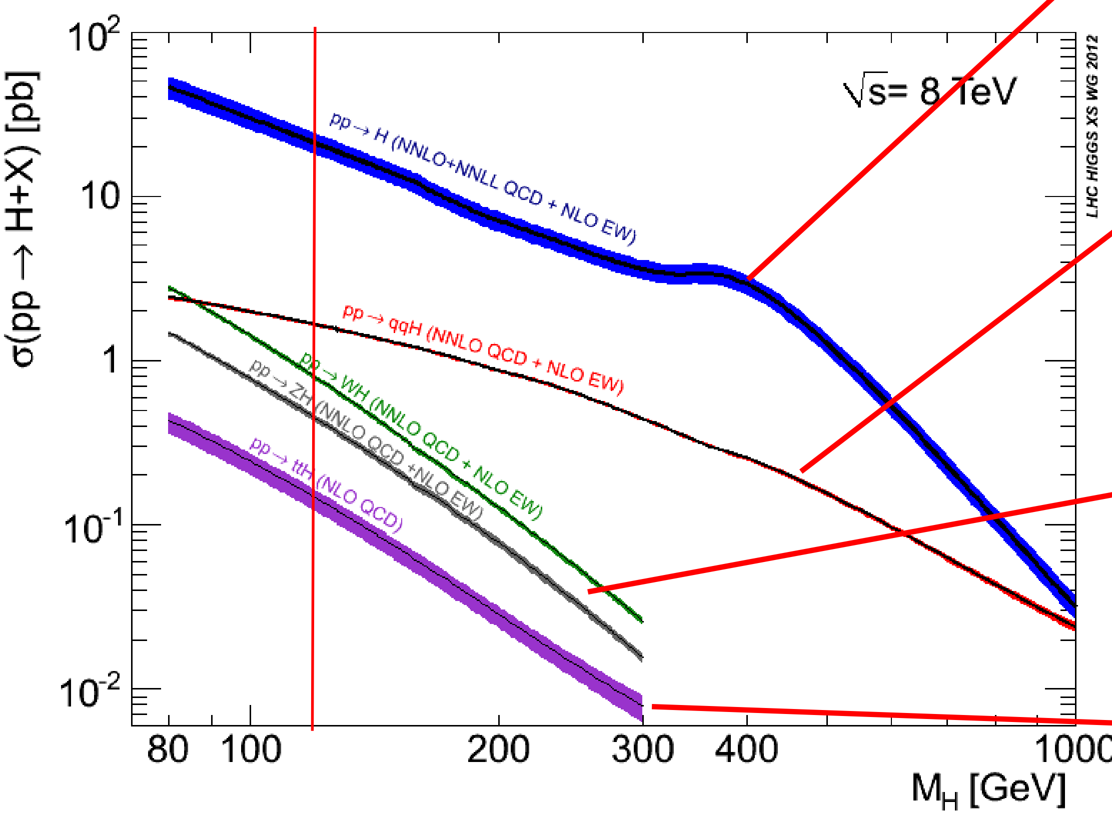
- Coupling to leptons
  - H → μμ
  - H → ττ

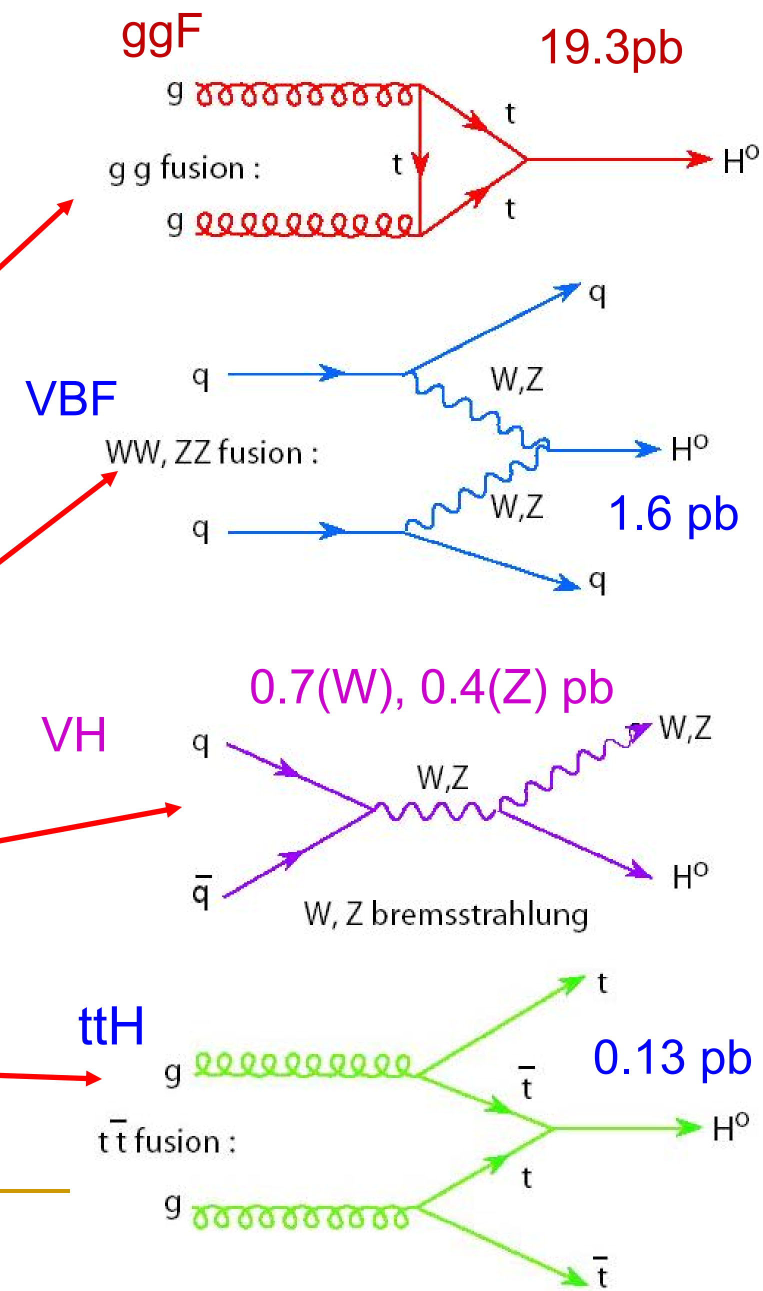
All results available at:

CMS ATLAS

- Coupling to quarks
  - VH (→ **bb),** where V = W/Z
  - Associated production of Higgs with **top quarks**
- Outlook

Analyses exploit details of various production channels to increase sensitivity





$H \rightarrow \mu\mu$

- BR($H \rightarrow \mu\mu$) for M_H = 125 GeV ~ $2.2*10^{-4}$
- Very clean, simple experimental signature
  - Two high pT muons with limited jet activity
- Data samples:
  - CMS: ~ 5, 20 fb^{-1} at 7, 8 TeV - (PAS-HIG-13-007)
  - ATLAS: ~ 21 fb^{-1} at 8 TeV – (CONF-2013-010)

- Basic Analysis Strategy:
  - CMS: Two analyses - one uses Particle Flow
    - Events categorized as 0, 1 and 2 jets (first two dominated by ggF, last by VBF)
    - Many η regions, pT(μμ) bins – leads to a 5% improvement in the limit
  - ATLAS: Two bins for $\eta(\mu_{1,2})$
    - $pT_{\mu\mu}$ > 15 GeV

$H \rightarrow \mu\mu$

- **Analysis details:**
  - CMS: Double Gaussian to fit M($\mu\mu$) signal: FWHM ~ 3.8 – 5.9 GeV
  - ATLAS: Crystal Ball + Gaussian fit: : FWHM ~ 4.9 – 6.0 GeV
  - Irreducible background for both is Z/γ* + jets.
    - Non-zero contributions from ttbar and WW

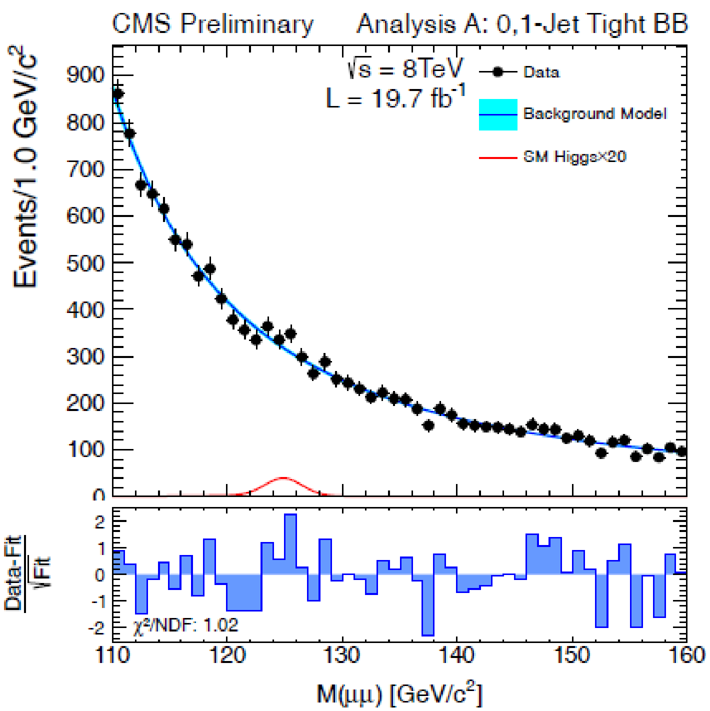
- **Systematic Uncertainties:**
  - Experimental systematics are small for both experiments
  - Luminosity uncertainty:
    - 2.7% (2.2%) for CMS (8/7 TeV)
    - 3.6% for ATLAS (in more recent analyses updated to 2.8% (1.8%))
  - Main theory: Higgs prod. x-section (~15%), Higgs BR (~ 6%)

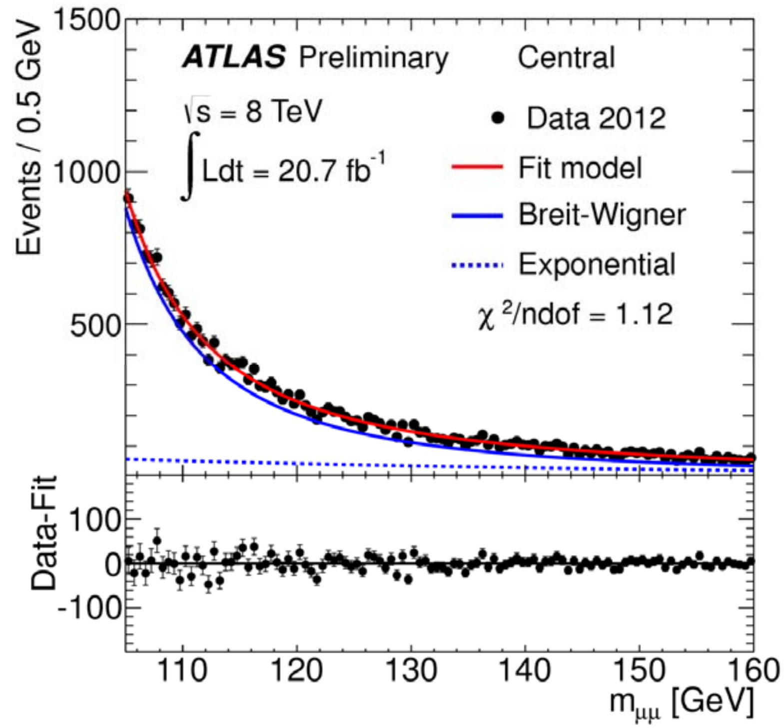
$H \to \mu\mu$

- Results: 95% CL for σ/σ_{SM} (M_H=125) : Observed (expected)

CMS: 7.4 (5.1)

ATLAS: 9.8 (8.2)





CMS also has Upper Limit (UL) on Br(H→ee) < 0.0017
(SM prediction is ~ $5*10^{-9}$)

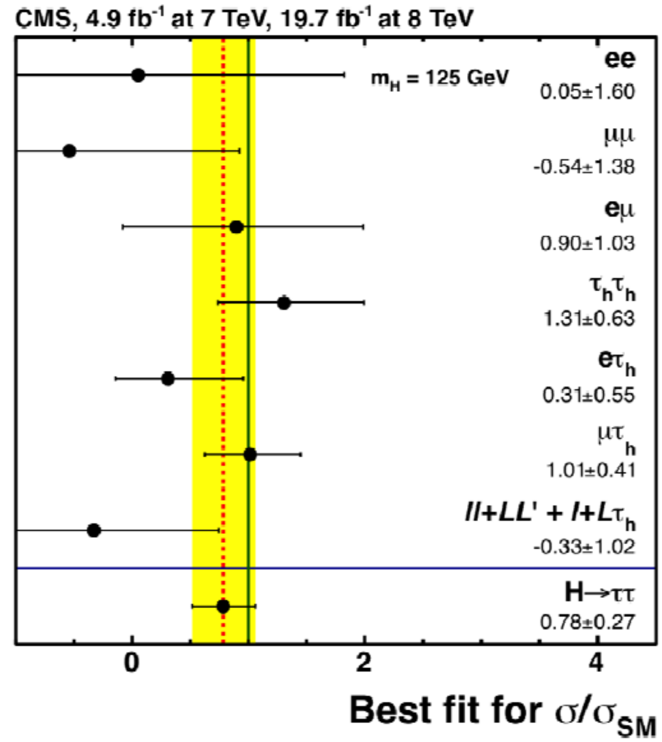
$H \rightarrow \tau\tau$

- BR($H \rightarrow \tau\tau$) for M_H = 125 GeV ~ 6.3% expected in the SM
- Data samples:
  - CMS: ~ 25 fb^{-1} at 7 and 8 TeV - (HIG-2013-004)
  - ATLAS: ~ 20 fb^{-1} at 8 TeV – (CONF-2013-108)

- τ detected in hadronic and leptonic channels leading to $\tau_h\tau_l$, $\tau_h\tau_h$, $\tau_l\tau_l$ final states:
  - Leptonic modes include both **e/μ** final states
  - Hadronic decays use calorimeter information (1/3-prongs)
- Both categorize events based on τ decay channels and Higgs production channel (ggF, VH and VBF), using # jets in event
  - Variety of triggers used to select events

$H \rightarrow \tau\tau$

- Analysis Strategy:
  - ATLAS: Separate BDTs are trained for each channel in each category
    - Many variables, including $M(\tau\tau)$
    - BDT score is simultaneously fit across all categories
  - CMS: Invariant mass of the tau pair is reconstructed and fitted
    - In ggF, VBF, ZH channels, ETmiss comes only from neutrinos in τ decays - use that to go from m_{vis} to $M(\tau\tau)$
    - In WH channel, Etmiss also from leptonic W decays. Use m_{vis}
  - Sensitivity in VBF better than in ggF production channel
- Backgrounds are channel dependent
  - Many sources – Z/γ^*, W/Z+jets, Single top/ttbar, WW/WZ/ZZ, gg2WW
- Systematic Uncertainties:
  - Since analysis strategy is different between the two experiments, different ones dominate, e.g., for ATLAS it is $Z \rightarrow \ell\ell$ normalization. For CMS it is τ_{had} energy scale



$H \rightarrow \tau\tau$

For M_H 125 GeV: Observed (expected) deviation from background only hypothesis:

ATLAS: 4.1 (3.2)σ

CMS: 3.2 (3.7)σ

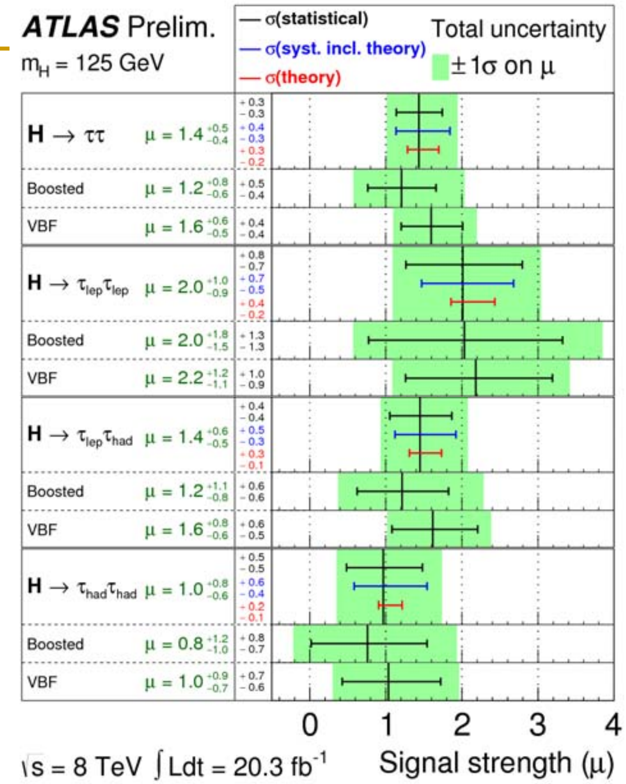
Evidence!

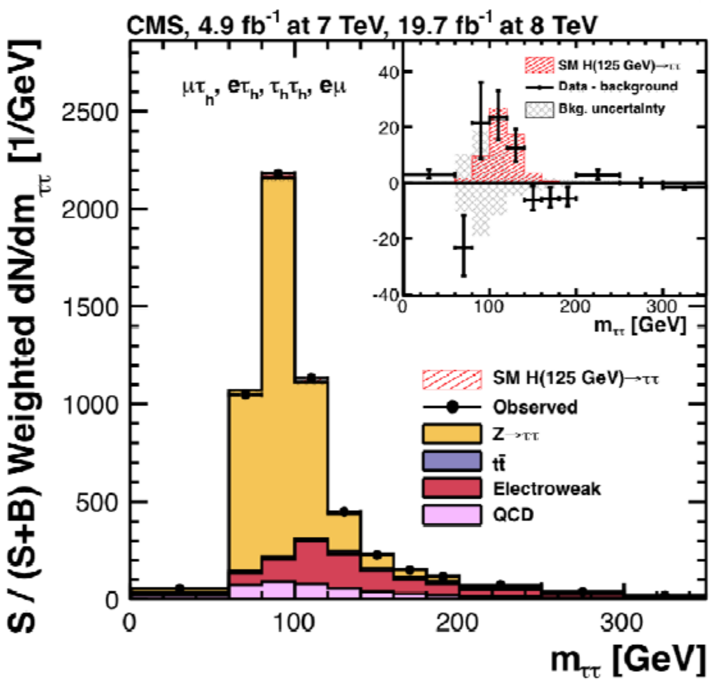
Best fit μ

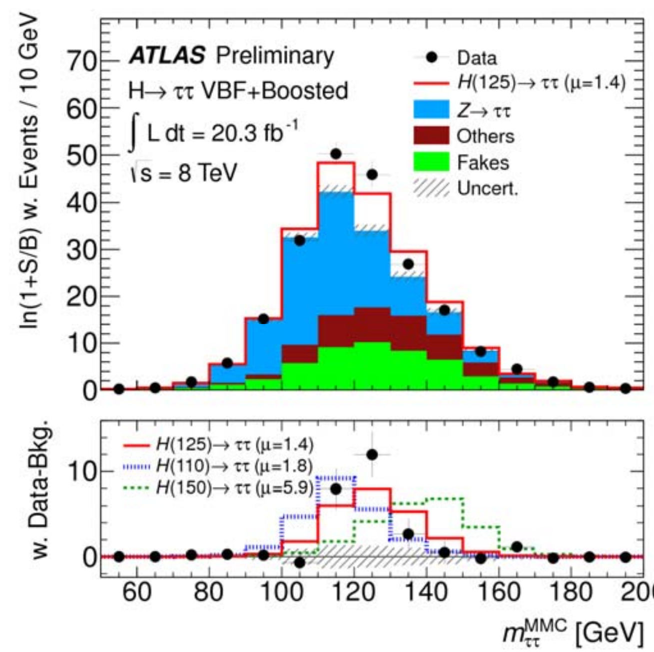
CMS: **0.78± 0.27**

ATLAS: **$1.4^{+0.5}_{-0.4}$**

Still statistics limited

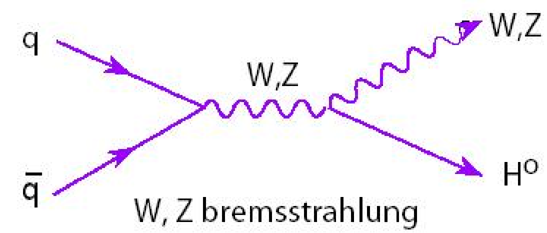






VH(bb) – Associated production

- $H \rightarrow bb$ has the largest BR (~58%) for M_H = 125 GeV, but detection is challenging in ggF mode
  - Use production with Vector bosons to reduce background

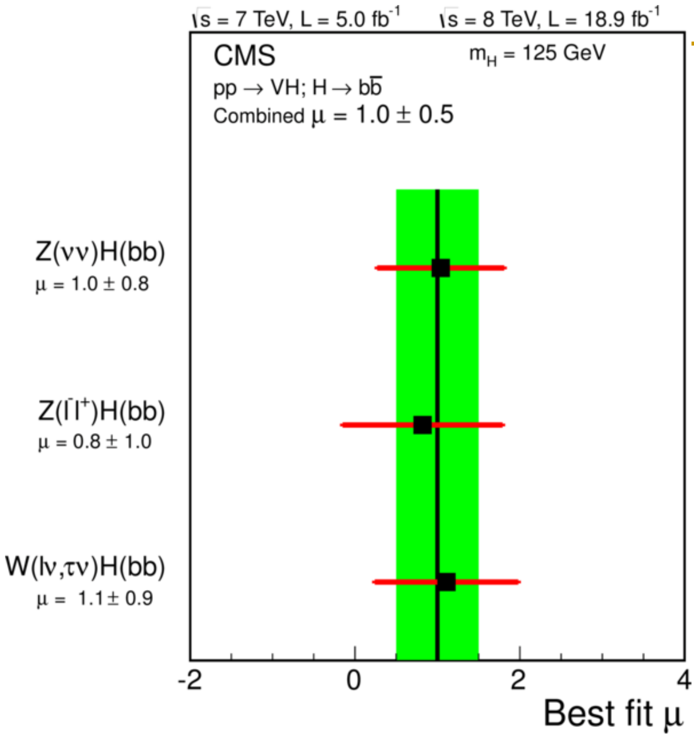


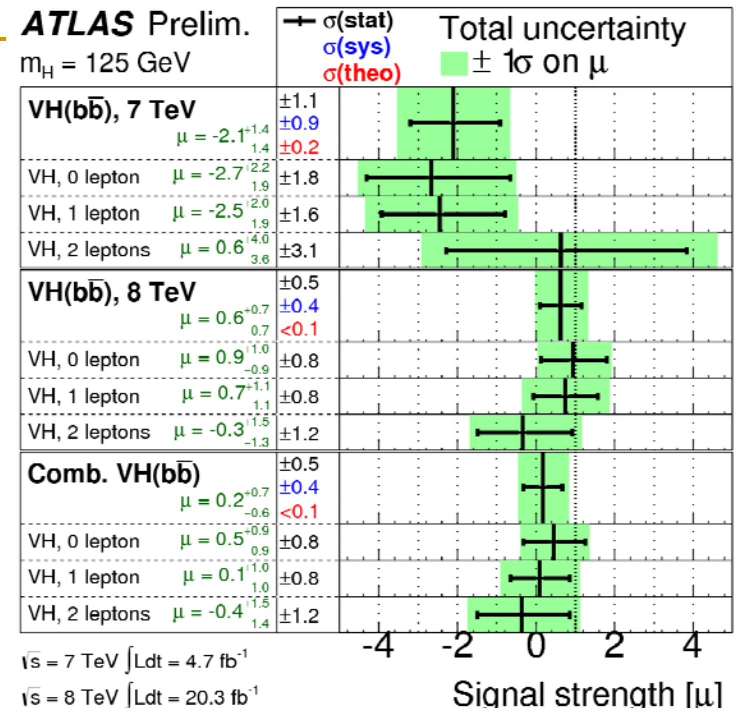
- Data:
  - CMS ~ 24 fb-1 (HIG-2013-012)
    - UL in VBF mode: (HIG-2013-011)
  - ATLAS ~ 25 fb-1 (CONF-2013-079)
- Analysis performed by categorizing events
  - With 0, 1, 2 leptons (from $Z\rightarrow\nu\nu$, $W\rightarrow e/\mu\nu$, $Z\rightarrow ee/\mu\mu$. τ incl. in MC)
  - Final state contains 2 b-jets
    - Also categorize events with 2 or 3 jets
    - Use bins of (W/Z) pT to boost sensitivity

- CMS uses BDT for each category and then does a simultaneous fit across all categories for the final result
  - BDT variables include di-jet mass/kinematics, b-tagging, etc.
  - Checked with analysis where M(bb) is fitted
- ATLAS does a simultaneous fit to M(bb) distributions in various categories

- Backgrounds vary with event category
  - Main sources: W/Z+jets, Single top/ttbar, diboson and multi-jet
- Systematics:
  - Modelling of ttbar and V+bb backgrounds, Jet energy scale, b-tagging, multi-jet background, theoretical uncert. on signal modelling, etc.

VH(bb) Results

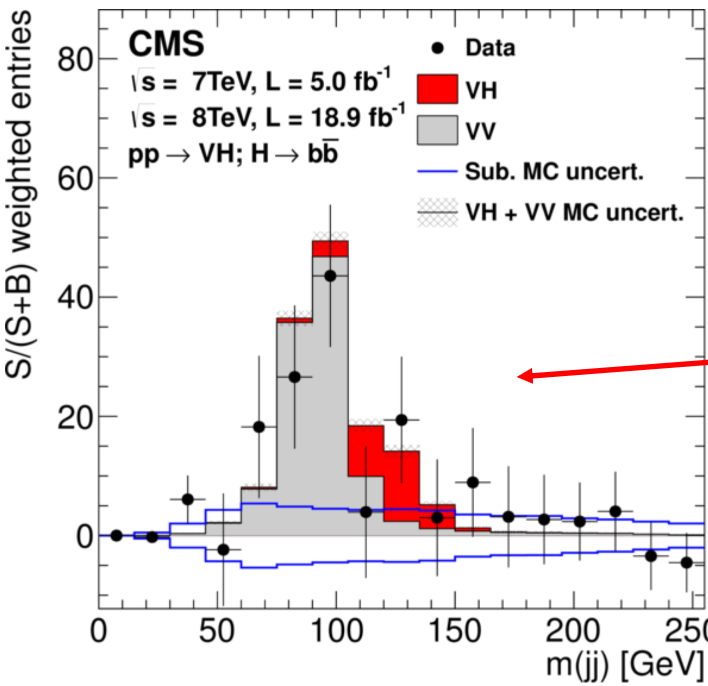




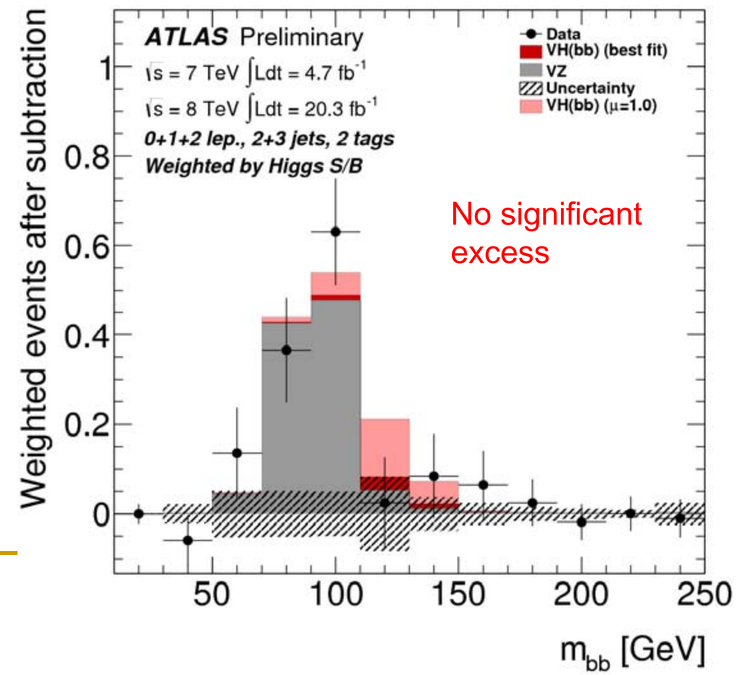
Best fit μ

CMS: **1.0± 0.5**

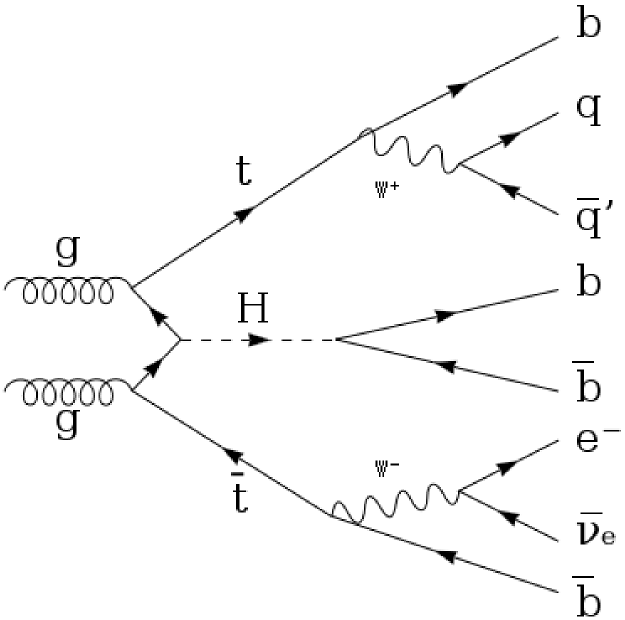
ATLAS: **0.2** $^{+0.7}_{-0.6}$

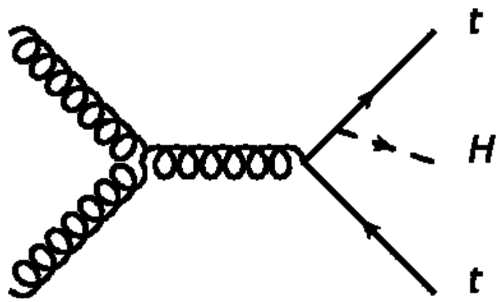


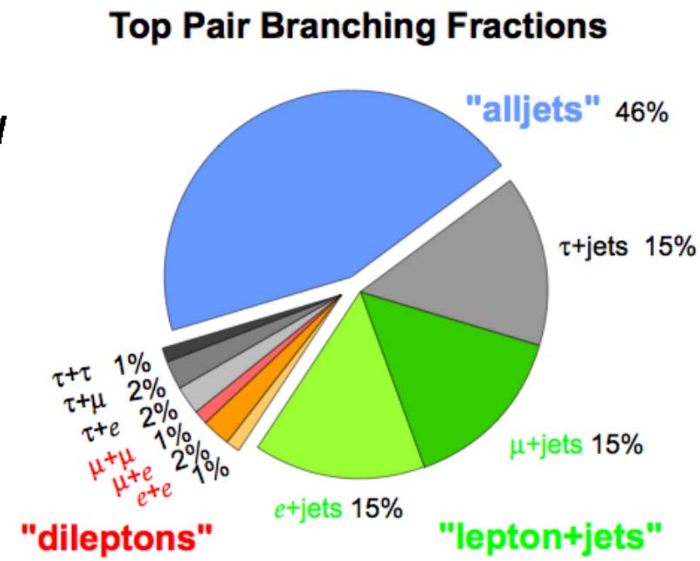
2.1σ excess consistent w/ SM



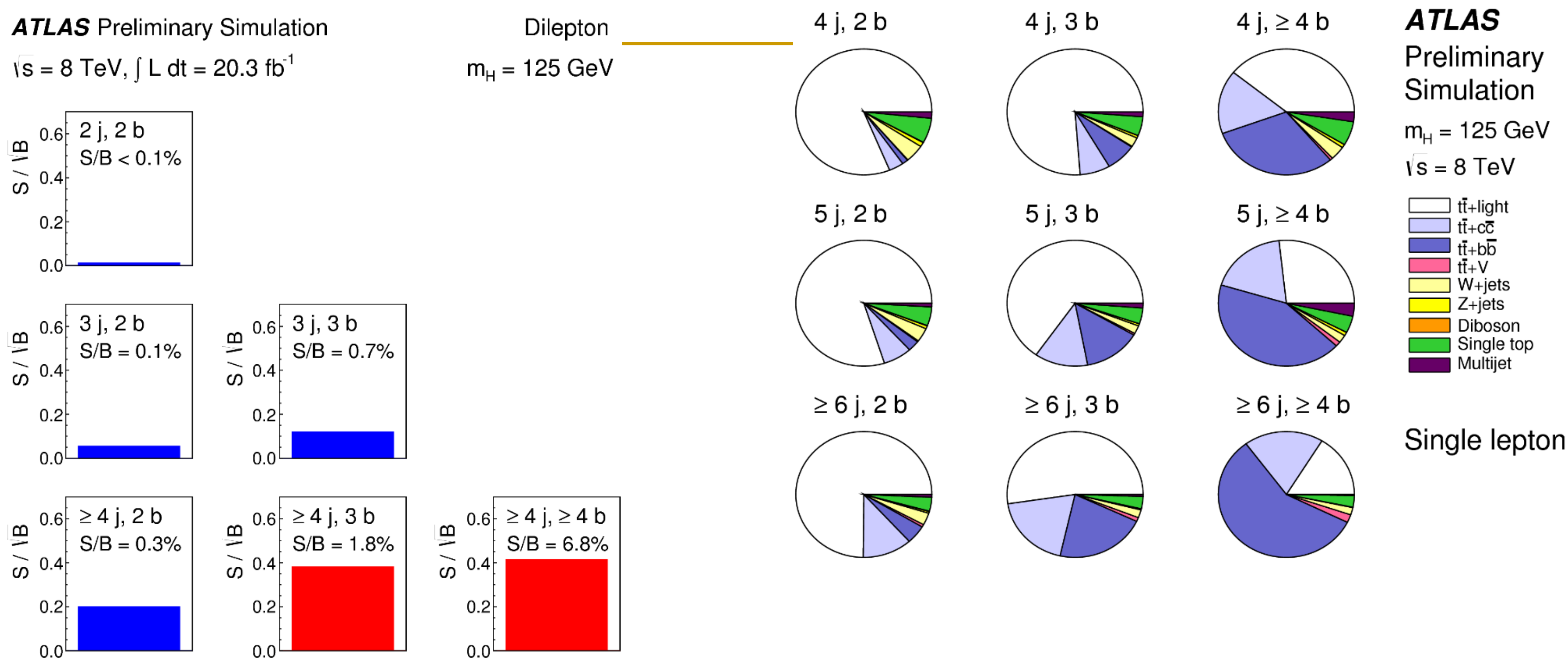
Associated production of Higgs with top quark pairs







- Event signature: 1 or 2 leptons from semi- and di-leptonic ttbar decays
  - Many jets (some of which are b-jets) + Missing Et
- Higgs can also be searched for in ($\gamma\gamma$, WW, $\tau\tau$)
  - In case of H$\rightarrow$ WW/$\tau\tau$, more than 2 leptons can be present



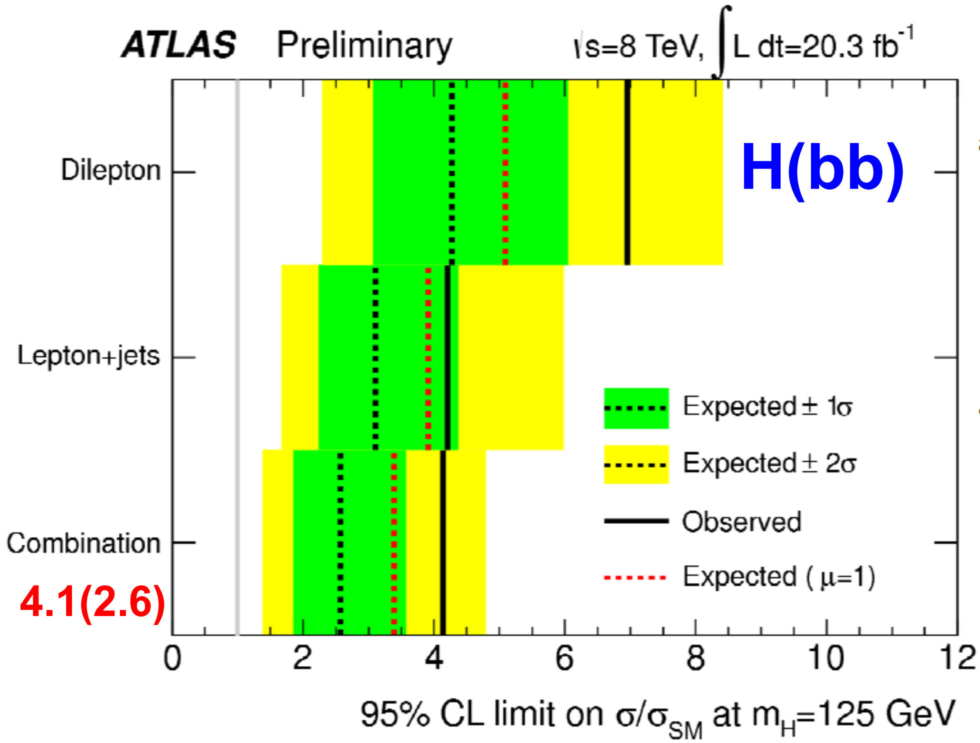
These are for **H → bb**, where the top decays semi (di-)leptonically

Data is fit in various bins of N_jet/N_btag

Complex analysis - relies on modelling of various background sources, e.g., ttbar+bb

ATLAS uses kinematic information in Neural Nets

CMS uses kinematics and b-tagging information in BDT



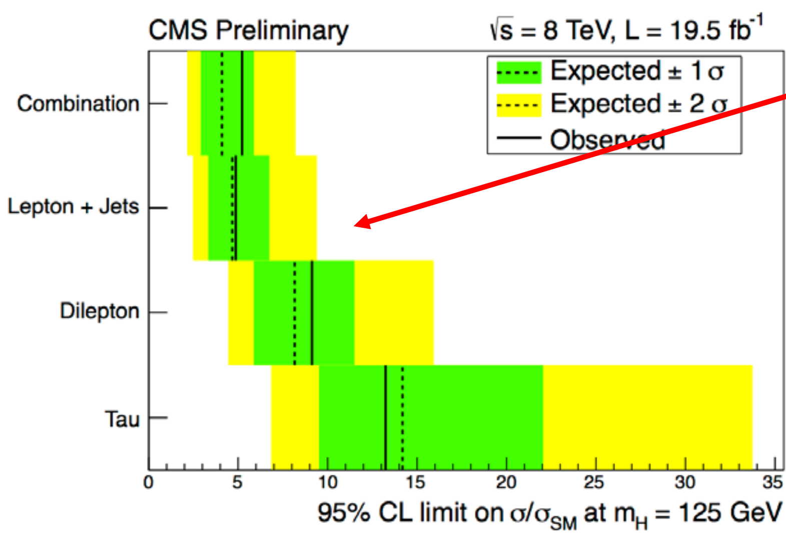
[ATLAS-CONF-2014-011]

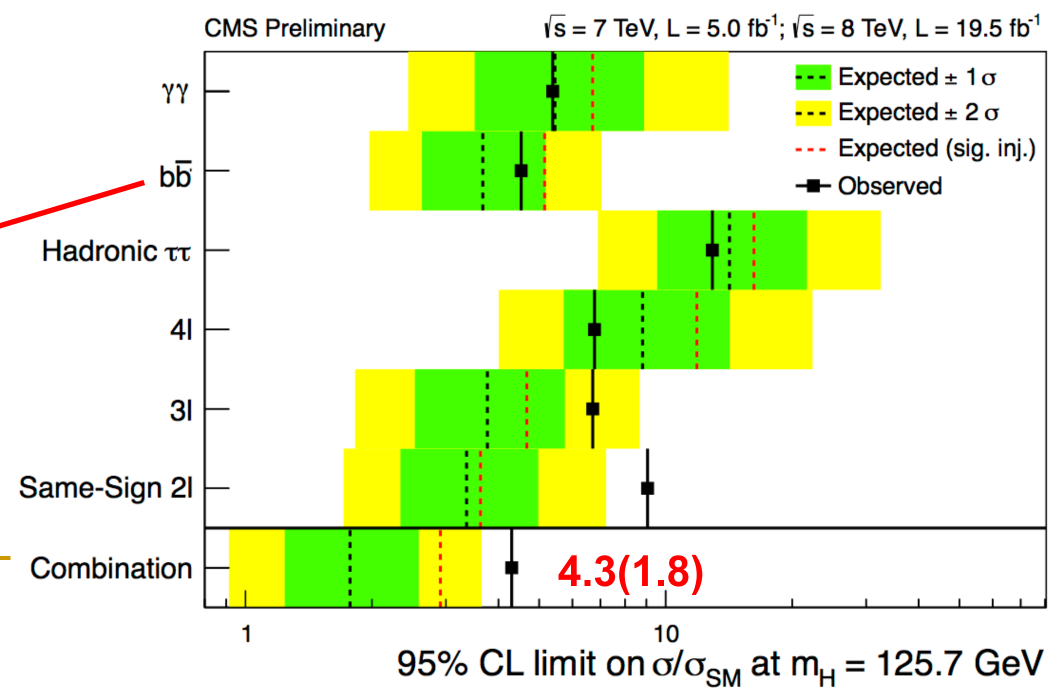
Other ATLAS 95% ULs on σ/σ_{SM}

[ttH(γγ) at 8 TeV]: 5.3 (6.4) (126.8 GeV)

[SL ttH(bb) at 7 TeV]: 13.1 (10.5)

[CMS ttH results:]

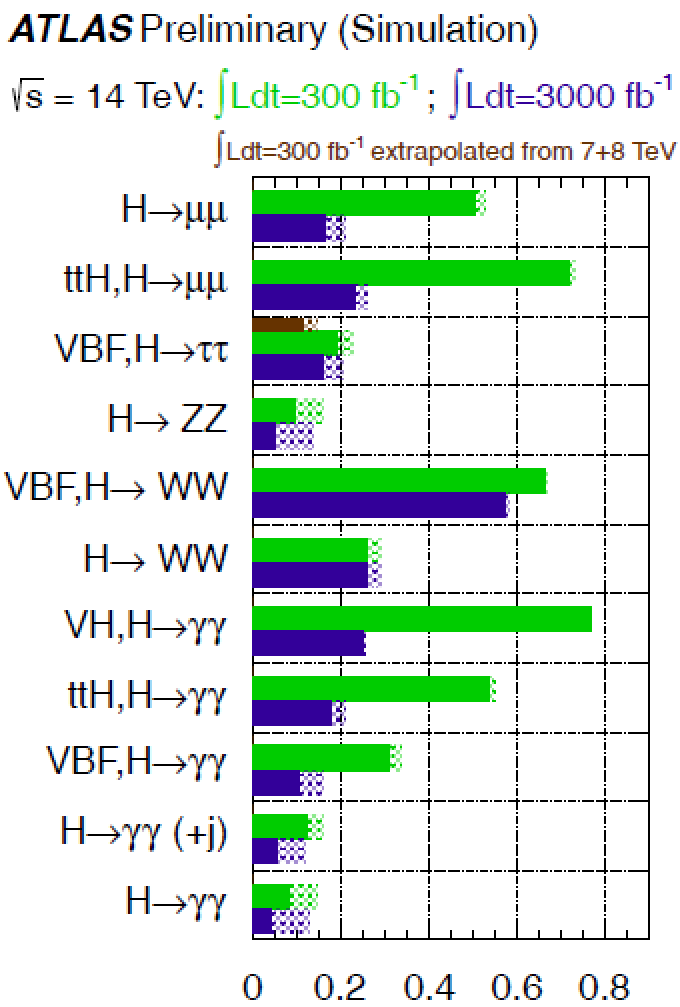




Outlook

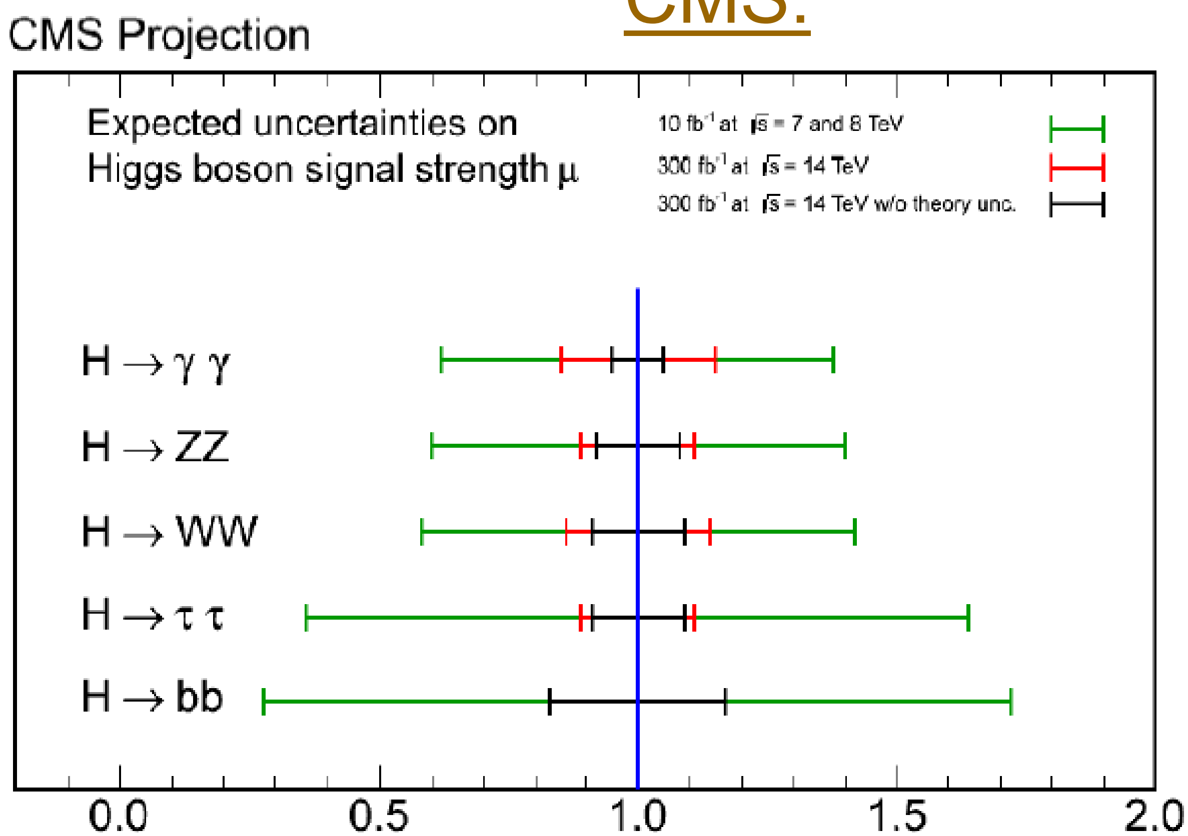
- Evidence for $H \rightarrow \tau\tau$ in both experiments
- $H \rightarrow bb$ around the corner!
- Improvements are underway, and new results based on Run-I should be available in the coming months
- In Run-II ($\sqrt{s}$ = 14 TeV) production cross-section for M_H (125) will increase by 2.6-4.7, as will the integrated luminosity
  - Largest increase is for ttH
- Stay tuned!

Projections: European Strategy – '12



ATLAS

CMS:



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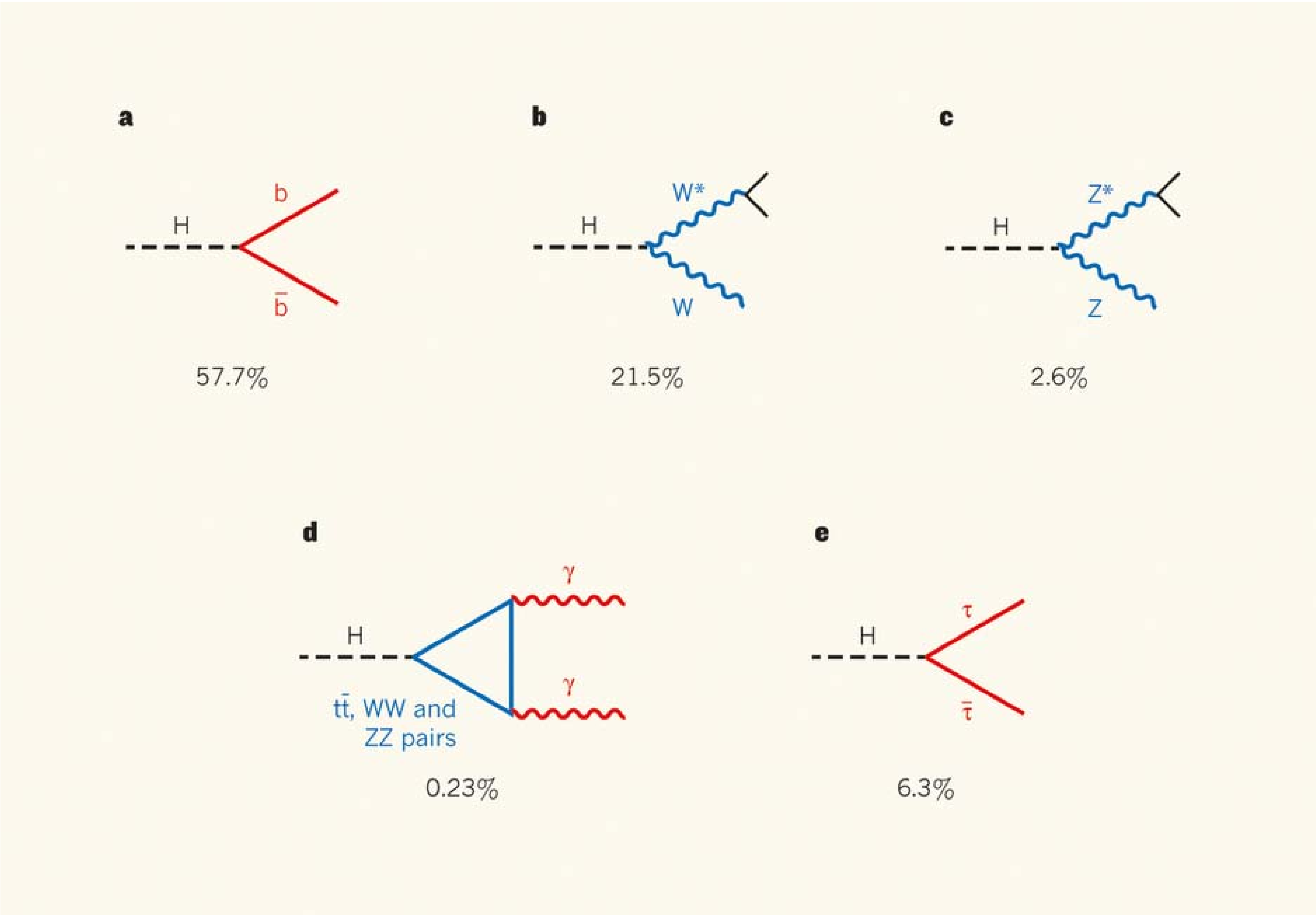


M_H (125)

H → μμ

CMS

Table 1: Optimized event categories used in Analysis A and Analysis B.

A	**0,1-Jet**	**Tight** $p_T(\mu\mu) \geq 10$ GeV/c	**BB** (Barrel-Barrel)
			BO (Barrel-Overlap)
			BE (Barrel-Endcap)
			OO (Overlap-Overlap)
			OE (Overlap-Endcap)
			EE (Endcap-Endcap)
		Loose $p_T(\mu\mu) < 10$ GeV/c	**BB**
			BO
			BE
			OO
			OE
			EE
	2-Jet	**VBF Tight** $M(jj) > 650$ GeV/c^2 and $\lvert\Delta\eta(jj)\rvert > 3.5$	
		GF Tight (not VBF Tight selected) $M(jj) > 250$ GeV/c^2 and $p_T(\mu\mu) > 50$ GeV/c	
		Loose (not VBF Tight and not GF Tight selected)	
B	**0-Jet**	**Tight** ($p_T(\mu\mu) \geq 15$ GeV/c)	
		Loose ($p_T(\mu\mu) < 15$ GeV/c)	
	1-Jet	no subcategories	
	2-Jet	**VBF Tight** $M(jj) > 500$ GeV/c^2 and $\lvert\Delta\eta(jj)\rvert > 4$, **for 7 TeV** $\lvert\Delta\eta(jj)\rvert > 3$	
		VBF Loose (not VBF Tight selected) $M(jj) > 300$ GeV/c^2 and $\lvert\Delta\eta(jj)\rvert > 3$ **category used only for** $\sqrt{s} = 8$ **TeV**	
		non-VBF (not VBF Tight and not VBF Loose selected)	

ATLAS

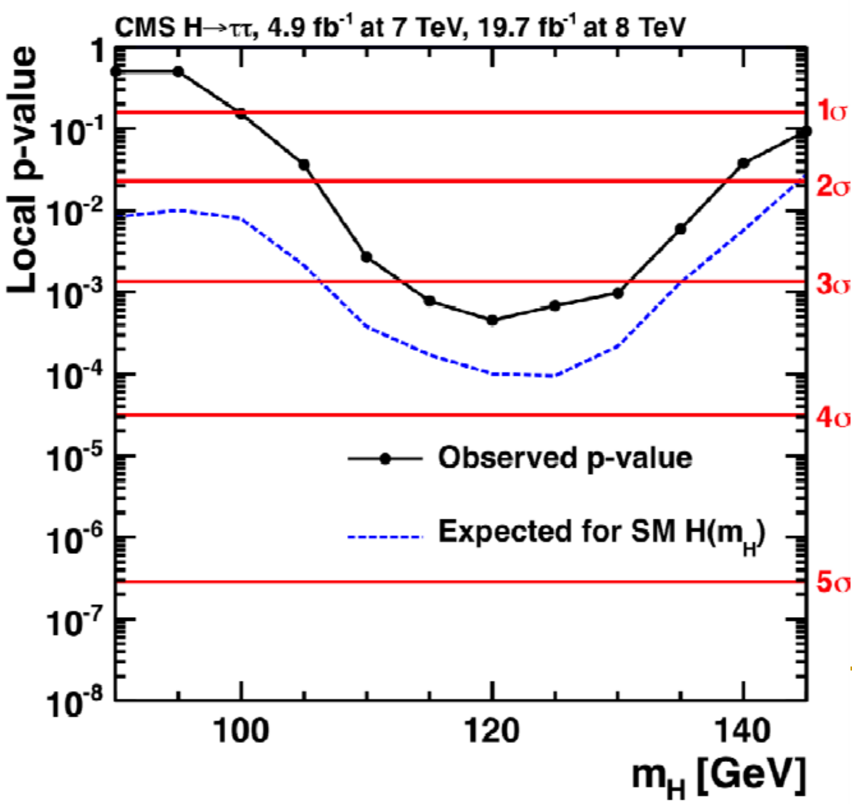
m_H [GeV]	observed limits	exp. median	exp. $+2\sigma$	exp. $+1\sigma$	exp. -1σ	exp. -2σ
110	5.1	10.4	20.0	14.6	7.5	5.6
115	5.7	7.5	14.5	10.6	5.4	4.0
120	9.2	7.6	14.6	10.7	5.5	4.1
125	9.8	8.2	15.9	11.6	5.9	4.4
130	10.8	9.1	17.5	12.8	6.5	4.9
135	11.0	10.4	20.1	14.6	7.5	5.6
140	16.8	12.9	25.0	18.2	9.3	6.9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

Table 5: Observed and expected 95% CL upper limits on the $H \to \mu^+\mu^-$ signal strength together with the upper and lower 1σ and 2σ uncertainties for different values of m_H.

$H \to \tau\tau$

Table 5: Predicted event yields in the $\tau_{lep}\tau_{had}$ channel for $m_H = 125$ GeV in the three highest bins of the BDT distributions. The background normalizations, signal normalization, and uncertainties reflect the preferred values from the global fit. The uncertainties on the total background and total signal reflect the full statistical+systematic uncertainty, while the uncertainties on the individual background components reflect the full systematic uncertainty only.

Process/Category	VBF			Boosted		
BDT score bin edges	0.5-0.667	0.667-0.833	0.833-1.0	0.6-0.733	0.733-0.867	0.867-1.0
ggF	2.2 ± 0.9	3.5 ± 1.5	1.2 ± 0.6	7.7 ± 2.9	6.3 ± 2.3	5.5 ± 2.1
VBF	4.1 ± 1.2	9.2 ± 2.7	7.5 ± 2.2	1.7 ± 0.5	1.5 ± 0.5	1.3 ± 0.4
WH	< 0.05	< 0.05	< 0.05	0.95 ± 0.29	0.85 ± 0.26	0.81 ± 0.25
ZH	< 0.05	< 0.05	< 0.05	0.42 ± 0.13	0.47 ± 0.14	0.41 ± 0.12
$Z \to \tau^+\tau^-$	28.6 ± 1.4	25.0 ± 1.6	2.41 ± 0.35	48.3 ± 3.4	26.1 ± 2.7	18.4 ± 2.0
Fake	37.7 ± 1.8	27.9 ± 2.1	3.5 ± 0.5	27 ± 4	10.8 ± 1.8	5.8 ± 1.4
Top	6.5 ± 0.7	4.1 ± 0.8	1.5 ± 0.4	7.0 ± 0.9	5.7 ± 0.8	2.23 ± 0.33
Diboson	2.9 ± 0.4	3.0 ± 0.5	0.23 ± 0.04	4.8 ± 0.5	4.0 ± 0.5	1.69 ± 0.23
$Z \to \ell\ell(j \to \tau_{had})$	8.7 ± 1.7	3.3 ± 0.5	0.40 ± 0.10	3.8 ± 0.5	0.71 ± 0.07	< 0.05
$Z \to \ell\ell(\ell \to \tau_{had})$	2.8 ± 1.2	1.9 ± 1.2	0.7 ± 0.6	9.4 ± 1.9	4.9 ± 1.1	3.8 ± 1.2
Total Background	87.2 ± 2.7	65 ± 5	8.7 ± 2.5	101 ± 6	52 ± 4	32 ± 4
Total Signal	6.3 ± 1.8	12.7 ± 3.5	8.7 ± 2.4	10.7 ± 3.3	9.2 ± 2.8	8.0 ± 2.5
S/B	0.07	0.20	1.0	0.11	0.18	0.25
Data	90	80	18	103	64	34



ATLAS: lep-had channel

$H \longrightarrow \tau\tau$

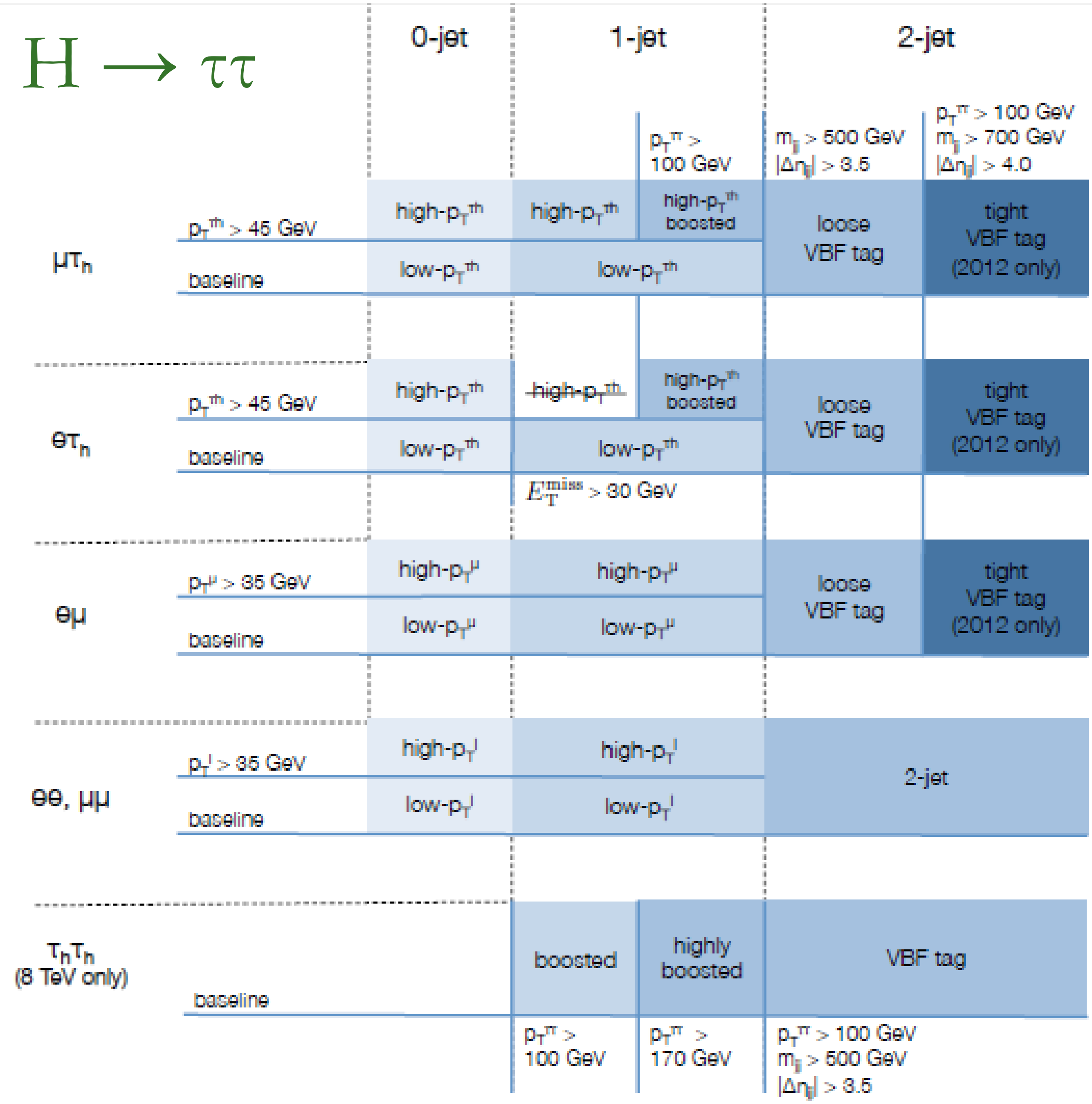


Figure 3: Event categories for the LL' channels. The $p_T^{\tau\tau}$ variable is the transverse momentum of the Higgs boson candidate. In the definition of the VBF-tagged categories, $|\Delta\eta_{jj}|$ is the dif-

CMS event categories

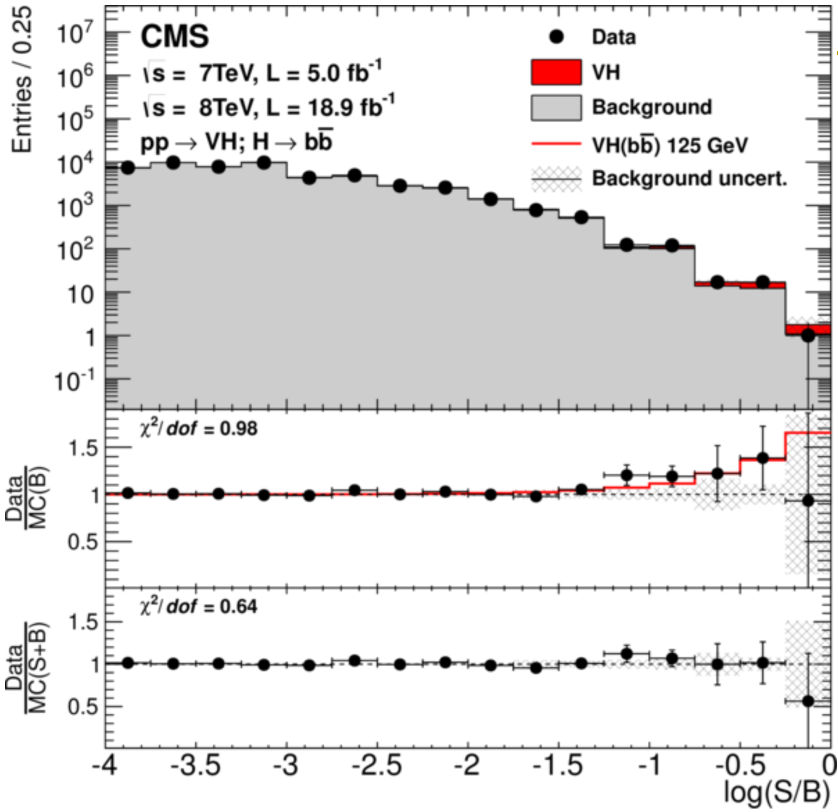
Variable	VBF			Boosted		
	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$m_{\tau\tau}^{\text{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau,\tau)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\text{T}}^{\text{Total}}$		•	•			
sum p_{T}					•	•
$p_{\text{T}}(\tau_1)/p_{\text{T}}(\tau_2)$					•	•
$E_{\text{T}}^{\text{miss}}\phi$ centrality		•	•	•	•	•
$x_{\tau 1}$ and $x_{\tau 2}$						•
$m_{\tau\tau,j_1}$				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi_{\ell_1,\ell_2}$				•		
sphericity				•		
$p_{\text{T}}^{\ell_1}$				•		
$p_{\text{T}}^{j_1}$				•		
$E_{\text{T}}^{\text{miss}}/p_{\text{T}}^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\text{jets}})$	•					
j_3 η centrality	•					
$\ell_1 \times \ell_2$ η centrality	•					
ℓ η centrality		•				
$\tau_{1,2}$ η centrality			•			

ggF

ATLAS

$H \to \tau\tau$

Table 3: Discriminating variables used for each channel and category. The filled circles identify which variables are used in each decay mode. Note that variables such as $\Delta R(\tau,\tau)$ are defined either between the two leptons, between the lepton and τ_{had}, or between the two τ_{had} candidates, depending on the decay



CMS VH(bb)

Table 10: The expected and observed 95% CL upper limits on the product of the VH production cross section times the $H \to b\bar{b}$ branching fraction, with respect to the expectations for the standard model Higgs boson, for partial combinations of channels and for all channels combined, for $m_H = 125\,GeV$. Also shown are the expected and observed local significances.

$m_H = 125\,GeV$	σ/σ_{SM} (95% CL) median expected	σ/σ_{SM} (95% CL) observed	Significance expected	Significance observed
$W(\ell\nu, \tau\nu)H$	1.6	2.3	1.3	1.4
$Z(\ell\ell)H$	1.9	2.8	1.1	0.8
$Z(\nu\nu)H$	1.6	2.6	1.3	1.3
All channels	0.95	1.89	2.1	2.1

CMS VH(bb)

Table 8: Information about each source of systematic uncertainty, including whether it affects the shape or normalization of the BDT output, the uncertainty in signal or background event yields, and the relative contribution to the expected uncertainty in the signal strength, μ (defined as the ratio of the best-fit value for the production cross section for a 125 GeV Higgs boson, relative to the standard model cross section). Due to correlations, the total systematic

Source	Type	Event yield uncertainty range (%)	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
Luminosity	norm.	2.2–2.6	<2	<0.1
Lepton efficiency and trigger (per lepton)	norm.	3	<2	<0.1
$Z(\nu\nu)$H triggers	shape	3	<2	<0.1
Jet energy scale	shape	2–3	5.0	0.5
Jet energy resolution	shape	3–6	5.9	0.7
Missing transverse energy	shape	3	3.2	0.2
b-tagging	shape	3–15	10.2	2.1
Signal cross section (scale and PDF)	norm.	4	3.9	0.3
Signal cross section (p_T boost, EW/QCD)	norm.	2/5	3.9	0.3
Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	norm.	10	15.9	5.2
Single-top-quark (simulation estimate)	norm.	15	5.0	0.5
Dibosons (simulation estimate)	norm.	15	5.0	0.5
MC modeling (V+jets and $t\bar{t}$)	shape	10	7.4	1.1

ATLAS: VH(bb)

Table 3: The cross section × branching ratio (BR) and acceptance for the three channels at both 7 and 8 TeV. The branching ratios are calculated considering only decays to muons and electrons for $Z \to \ell\ell$, decays to all three lepton flavours for $W \to \ell\nu$ and decays to neutrinos for $Z \to \nu\nu$. The acceptance is calculated as the fraction of events remaining in the 2-tag signal regions after the full event selection.

m_H = 125 GeV at 7 TeV				
$(W/Z)(H \to b\bar{b})$	Cross-section × BR [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$Z \to \ell\ell$	12.3	0.0	0.7	8.2
$W \to \ell\nu$	107.1	0.2	3.5	-
$Z \to \nu\nu$	36.4	2.2	-	-

m_H = 125 GeV at 8 TeV				
$(W/Z)(H \to b\bar{b})$	Cross-section × BR [fb]	Acceptance [%]		
		0-lepton	1-lepton	2-lepton
$Z \to \ell\ell$	15.3	0.0	0.9	8.4
$W \to \ell\nu$	130.2	0.2	3.3	-
$Z \to \nu\nu$	45.5	2.5	-	-

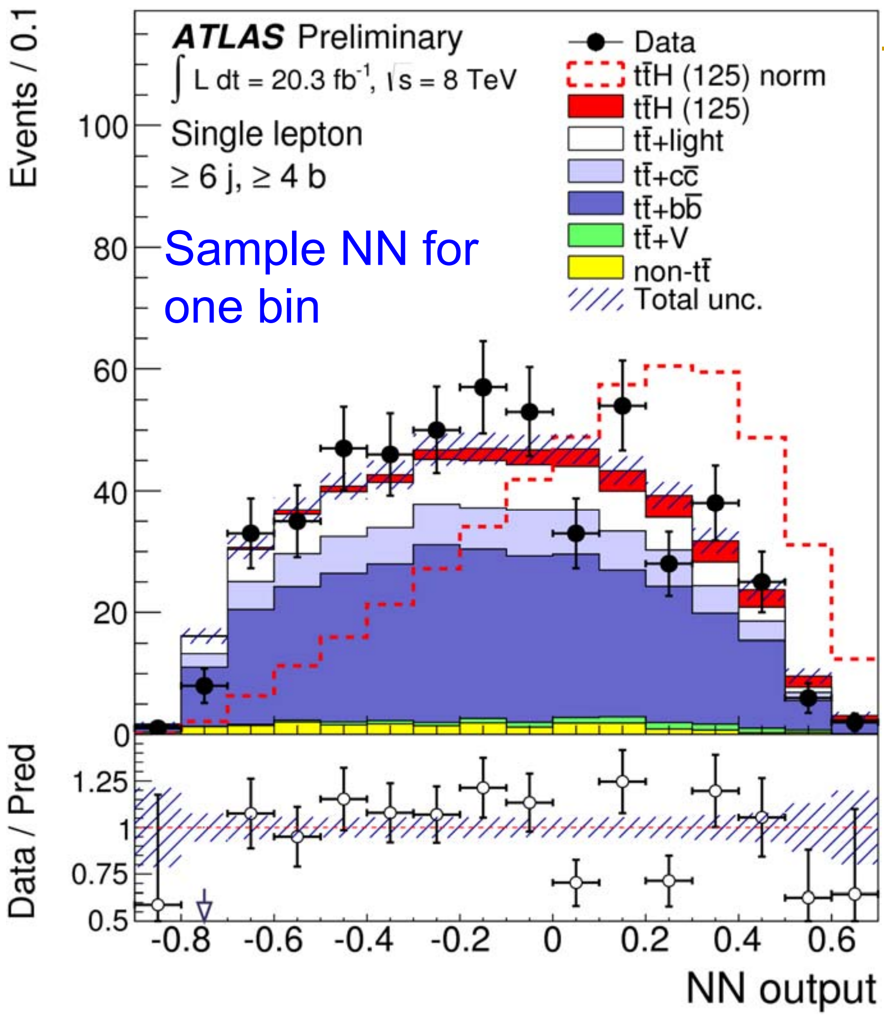
ttH Channel	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)				
CMS	Observed	Expected			
		Median Signal Injected	Median	68% CL Range	95% CL Range
$\gamma\gamma$	5.4	6.7	5.5	[3.5,8.9]	[2.4,14.1]
$b\bar{b}$	4.5	5.2	3.7	[2.6,5.2]	[2.0,7.0]
$\tau\tau$	12.9	16.2	14.2	[9.5,21.7]	[6.9,32.5]
4l	6.8	11.9	8.8	[5.7,14.2]	[4.0,22.4]
3l	6.7	4.7	3.8	[2.5,5.8]	[1.8,8.7]
Same-sign 2l	9.1	3.6	3.4	[2.3,5.0]	[1.7,7.2]
Combined	4.3	2.9	1.8	[1.2,2.6]	[0.9,3.6]

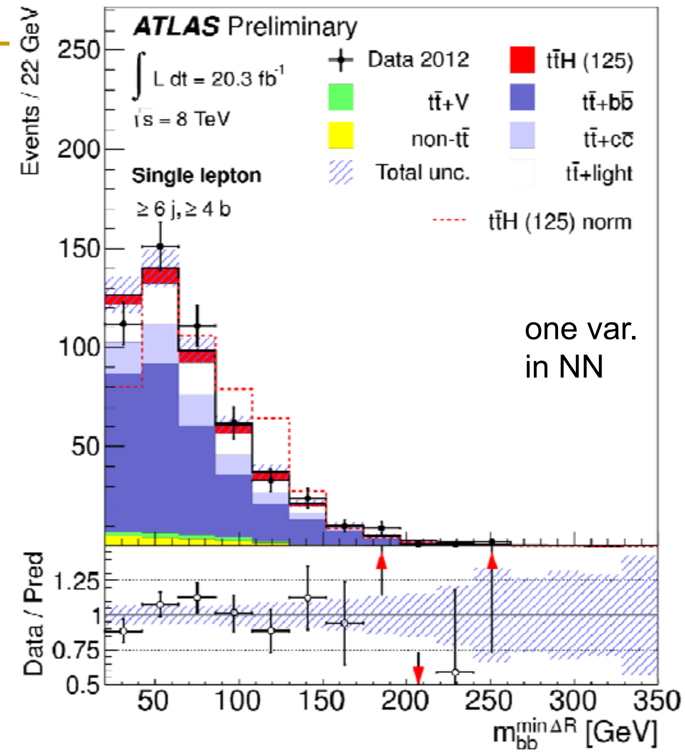
ttH

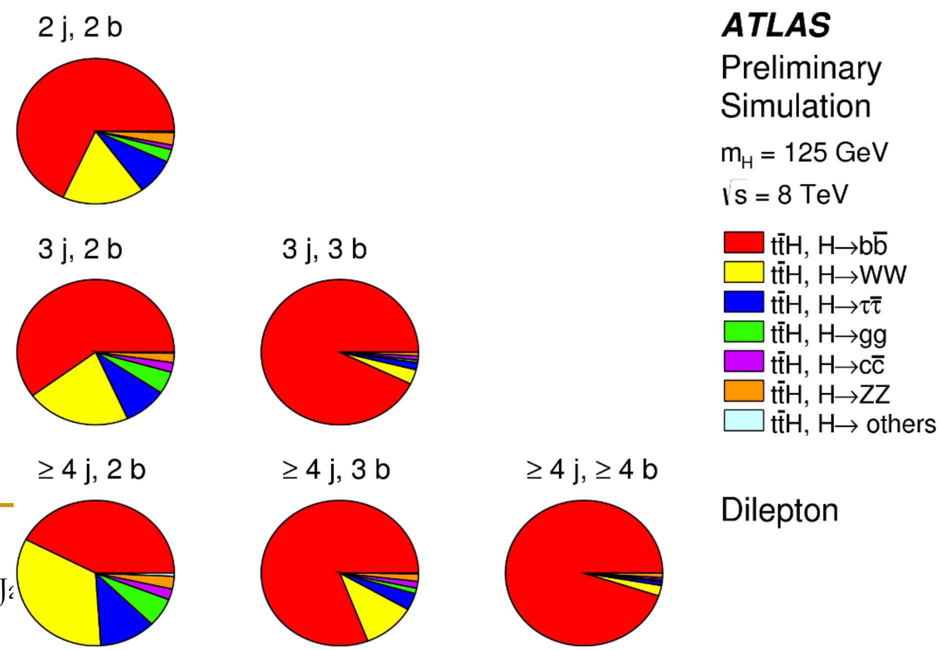
ATLAS:

95% CL upper limit on σ/σ_{SM}	observed	-2 σ	-1 σ	median	+1 σ	+2 σ	median ($\mu = 1$)
Single Lepton	4.2	1.7	2.2	3.1	4.4	6.0	3.9
Dilepton	7.0	2.3	3.1	4.3	6.1	8.4	5.1
Combination	4.1	1.4	1.9	2.6	3.6	5.0	3.4

Table 9: Observed and expected (median, for the background-only hypothesis) 95% CL upper limits on $\sigma(t\bar{t}H)$ relative to the SM prediction, for the individual channels as well as their combination, assuming $m_H = 125$ GeV. The $\pm1\sigma$ and $\pm2\sigma$ ranges around the expected limit are also provided. The expected (median) 95% CL upper limit assuming the SM prediction for $\sigma(t\bar{t}H)$ is shown in the last column.







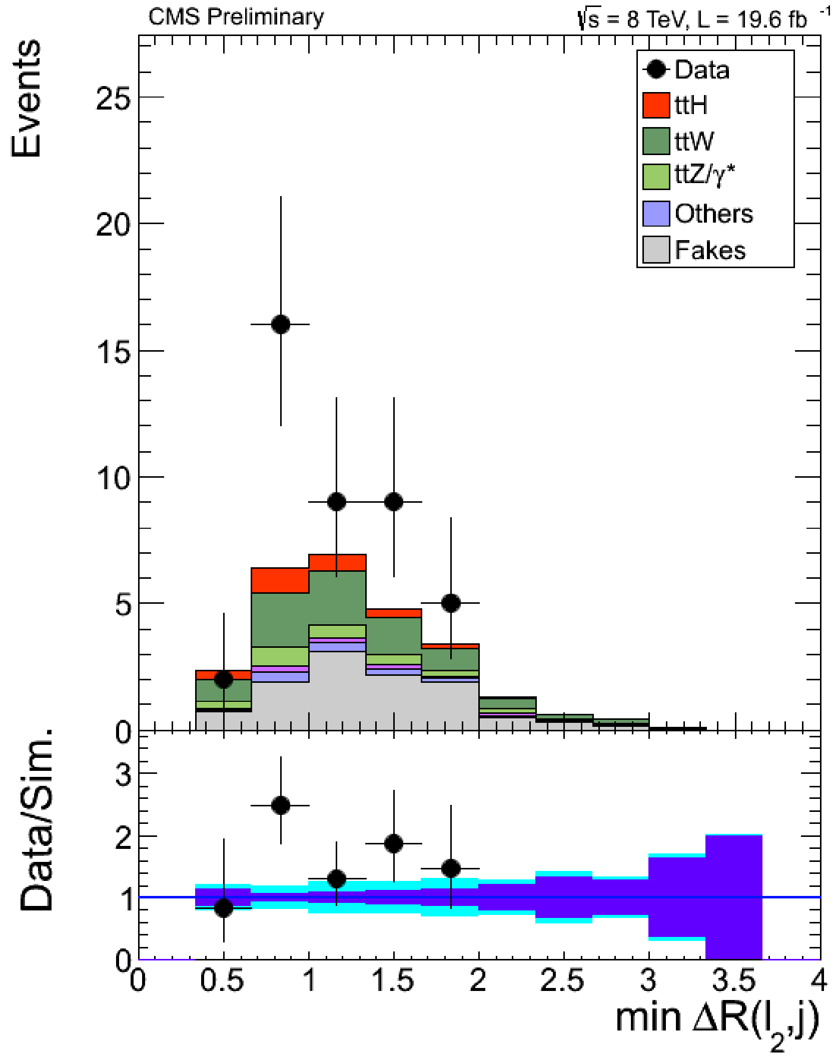
Sensitivity of the dileption ttH channel to various Higgs decays

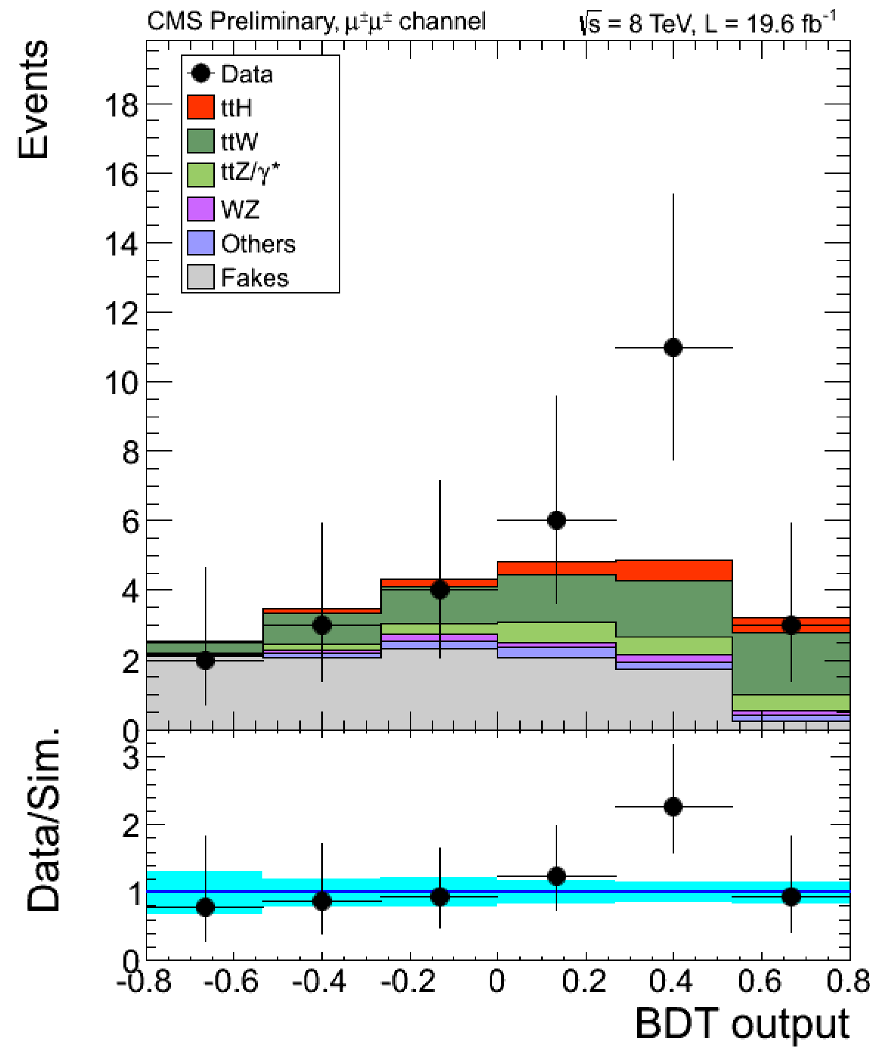
Yields in CMS and ATLAS

Publicly available numbers for ttH shown at the Collider Cross Talk

Semi-Lep	4 jets / 4 b-tags			5 jets / 4 b-tags			6 jets / 4 b-tags		
	CMS	ATLAS	Diff. (%)	CMS	ATLAS	Diff. (%)	CMS	ATLAS	Diff. (%)
ttH	1.8	1.8	0	5.2	5.8	-10	8.3	16	-48
tt+light	74	55	35	79	67	18	71	67	6
tt+cc	19	23	-17	32	47	-32	52	80	-35
tt+bb	34.1	43	-21	67	110	-39	111	240	-54

Di-Lep	≥ 3 jets / ≥ 3 b-tags			3 jets / 3 b-tags	4 jets / 3 b-tags	4 jets / 4 b-tags
	CMS	ATLAS	Diff. (%)	ATLAS	ATLAS	ATLAS
ttH	11.2	12.8	-13	2	8.3	2.5
tt+light	289	244.6	18.2	105	138	1.6
tt+cc	147	195	-25	70	120	5
tt+bb	229	309	-26	100	180	29





ttH: SS dileptons from CMS