



Search for the Higgs boson in fermionic channels using the CMS detector

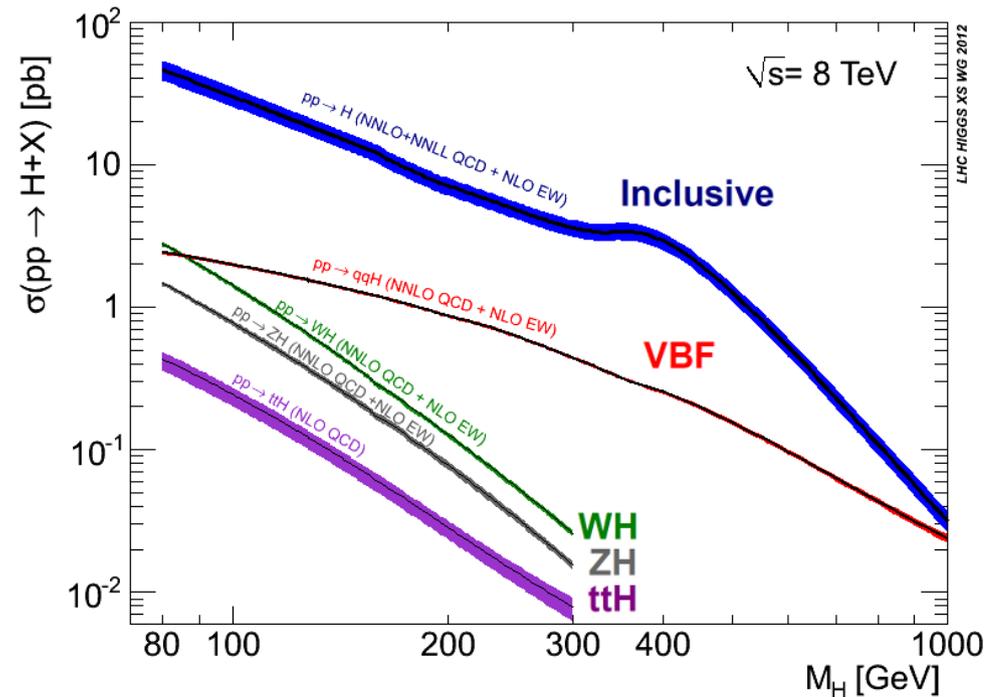
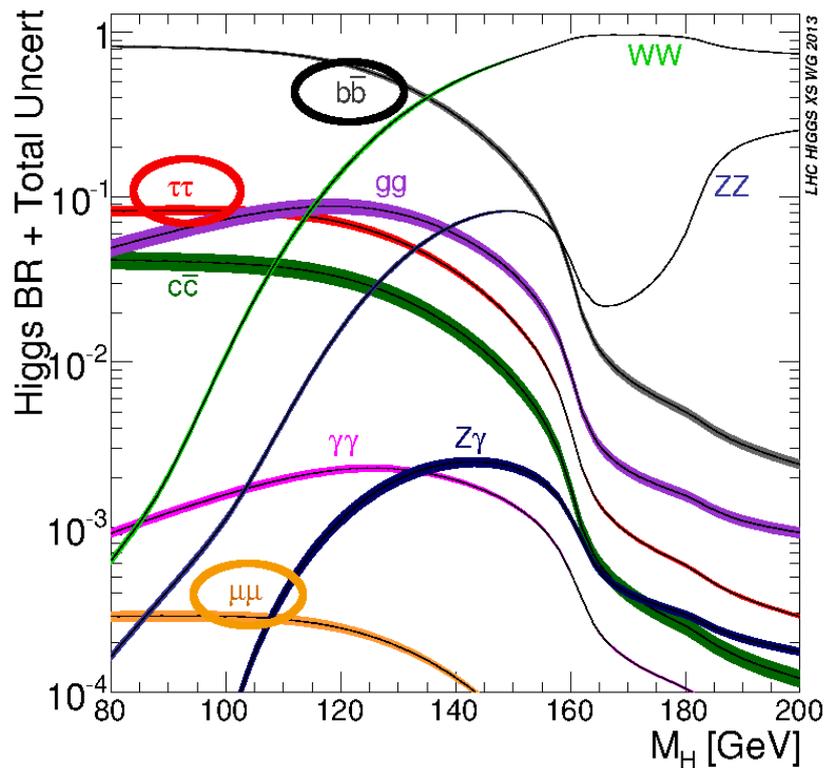


Jesus Vizan (on behalf of the CMS Collaboration)
Université catholique de Louvain

XXII International Workshop on Deep-Inelastic Scattering and Related Subjects
April 28th – May 2nd, 2014
Warsaw

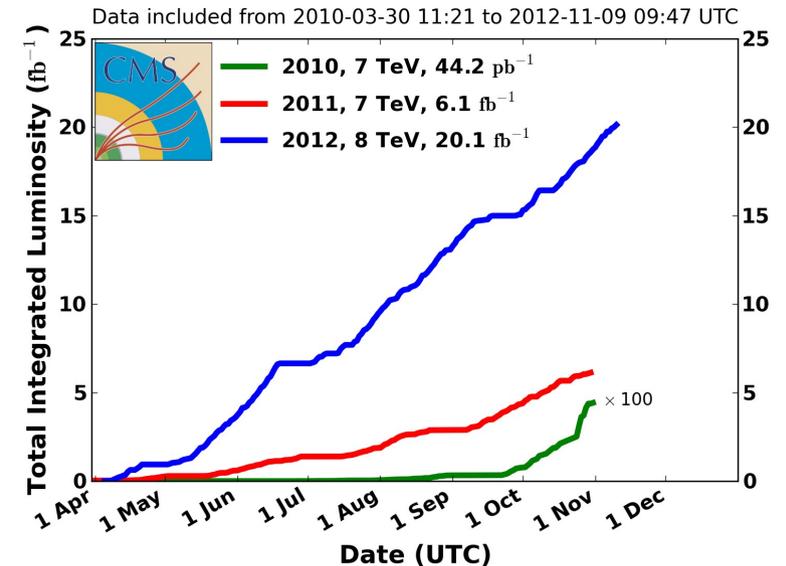
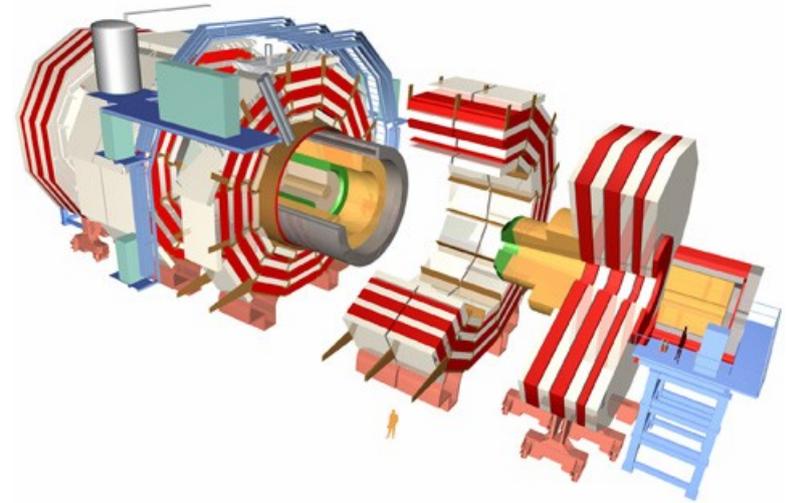
Motivation

- New ~ 125 GeV boson observation in July of 2012 driven by bosonic final states
- Increasing consistency with the SM predictions seen since then
- Couplings to bosons established: $\gamma\gamma$, ZZ , WW
- **Establishing Higgs couplings to fermions is essential to conclude if we are seeing the SM Higgs boson**
- Challenge: Fermionic decays are in general less sensitive to SM Higgs
 - ◊ Different fermionic decays are accessible at CMS for different production modes:
 - ◊ **bb**: high BR, very large backgrounds
 - ◊ **$\tau\tau$** : relatively high BR, large backgrounds
 - ◊ **$\mu\mu$** : Good resolution but very small BR



Outline

- ◉ **ttH** searches in fermionic decays:
H → bb/ττ
 - ◇ **ttH combination** also including bosonic decays
- ◉ **H → bb (VH)** search (legacy)
 - ◇ Also VBF H → bb search
- ◉ **H → ττ** (legacy)
- ◉ **Fermionic Combination** (H → bb and H → ττ)
- ◉ **H → μμ/ee** searches

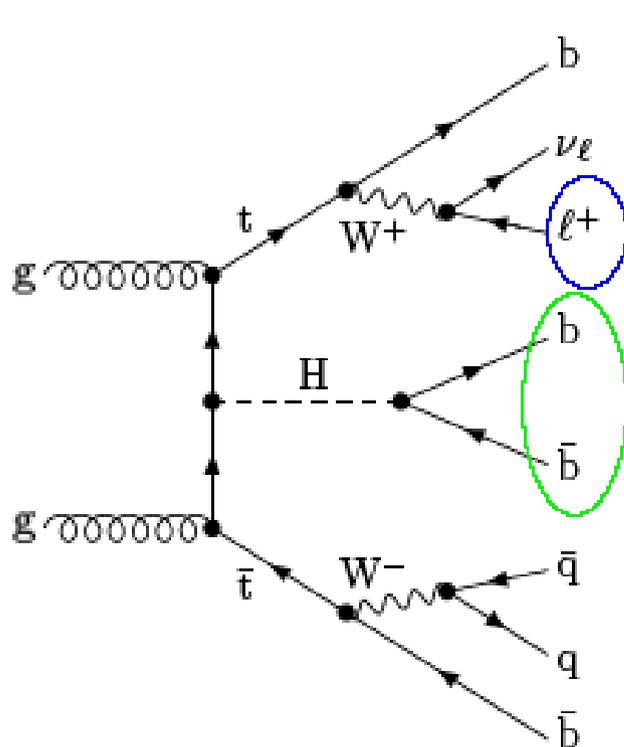


Most of the analysis use full 7 and 8 TeV datasets

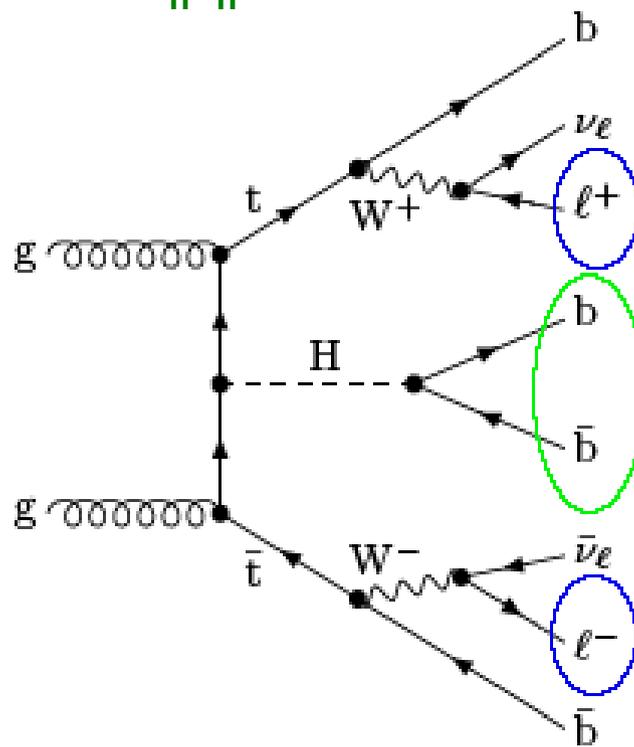
ttH: Overview

- Allows to **probe directly the top Yukawa coupling**
- Very small cross section (~ 130 fb for $m_H = 125$ GeV at 8 TeV), complex final states with jets, MET, leptons from tt
- Interest in ttH \rightarrow anything with large enough BR
 - ◊ **H \rightarrow bb is a very important channel** for this mode
 - ◊ Recently also included **H $\rightarrow \tau_h \tau_h$**

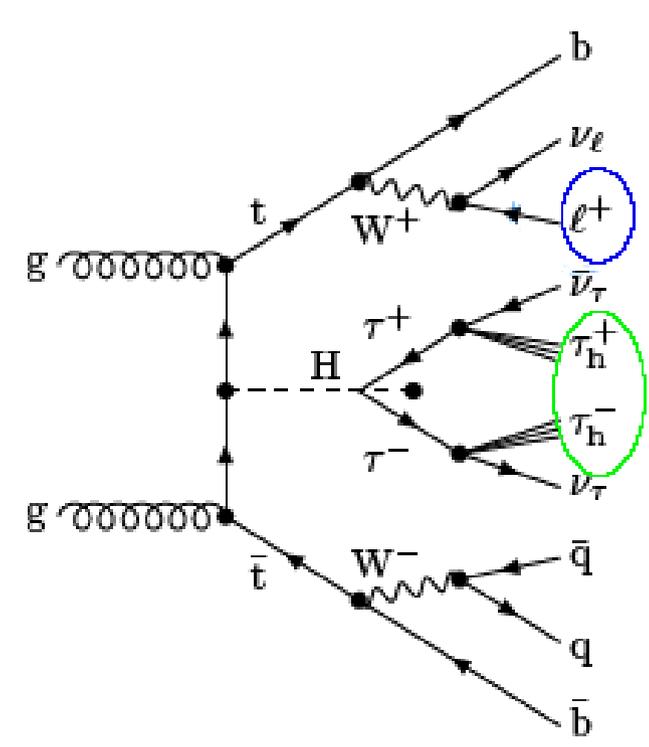
CMS-HIG-13-019



bb-semileptonic channel



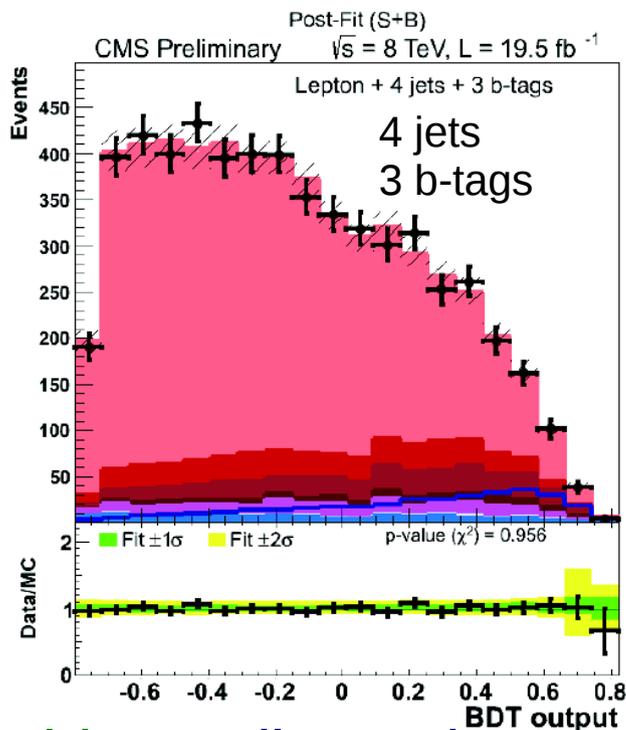
bb-dileptonic channel



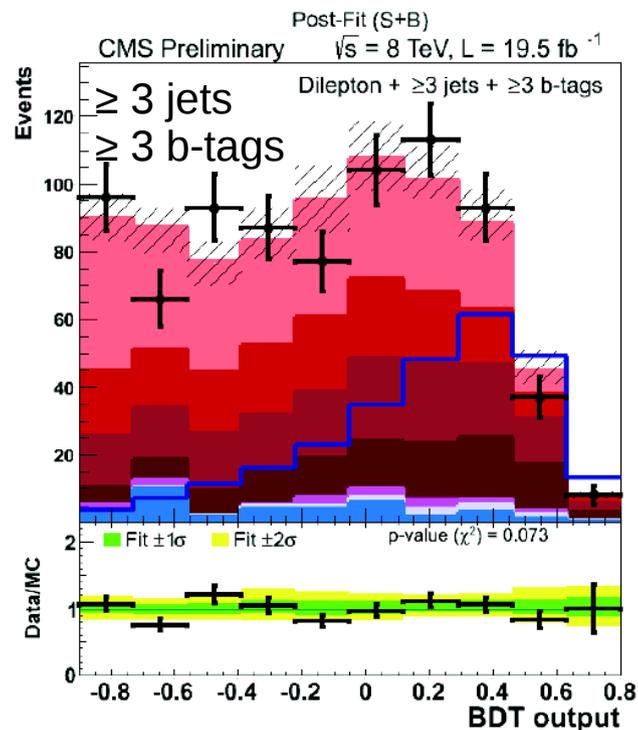
$\tau_h \tau_h$ -semileptonic channel

$t\bar{t}H, H \rightarrow b\bar{b} / \tau_h \tau_h$: Analysis Strategy

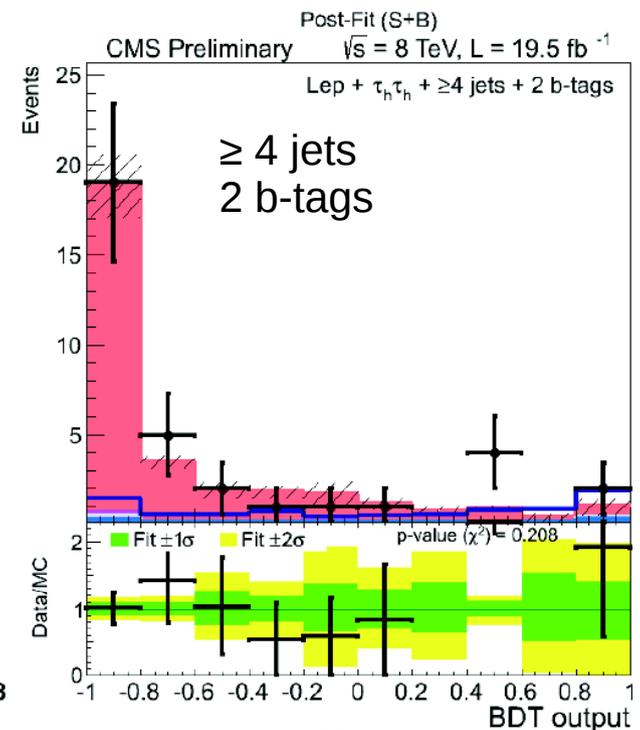
- Further categorization based on number of **jets** and **b-tags**
 - 16 categories, S/B increases with Njet, Nbtag
- Main background: **$t\bar{t}$ + jets**
 - Backgrounds are modeled using MC
 - Data in low S/B bins are used to constrained them
- Signal is extracted by fitting **BDT discriminators**
 - BDT inputs: **kinematic, b-tagging and event shape variables**



bb-semileptonic



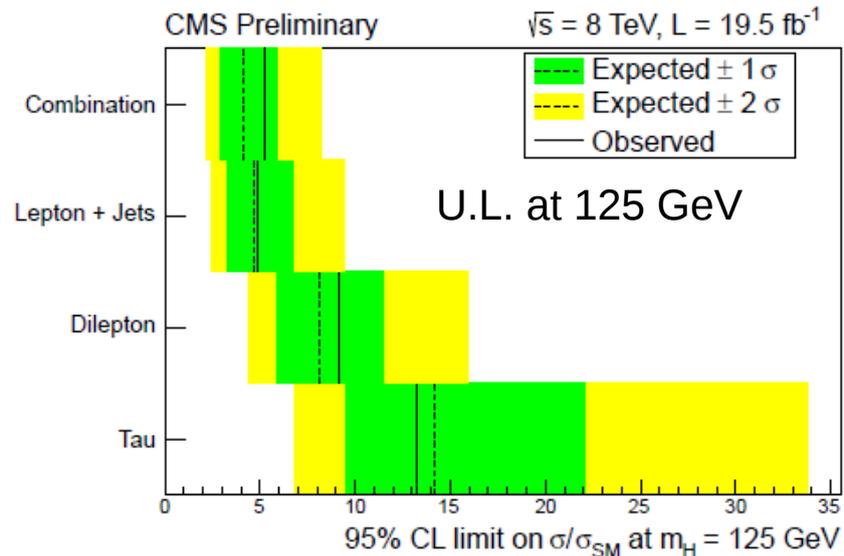
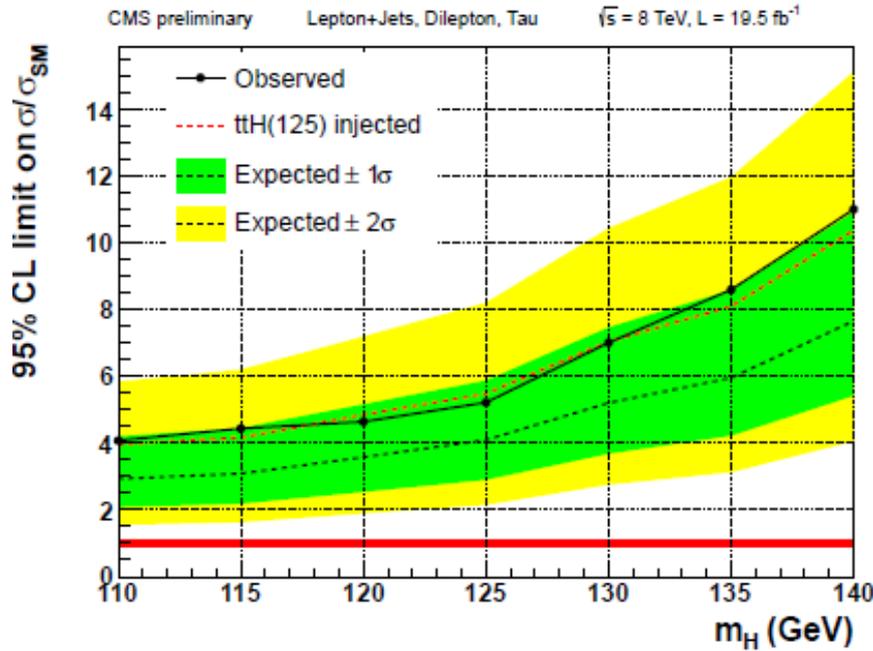
bb-dileptonic



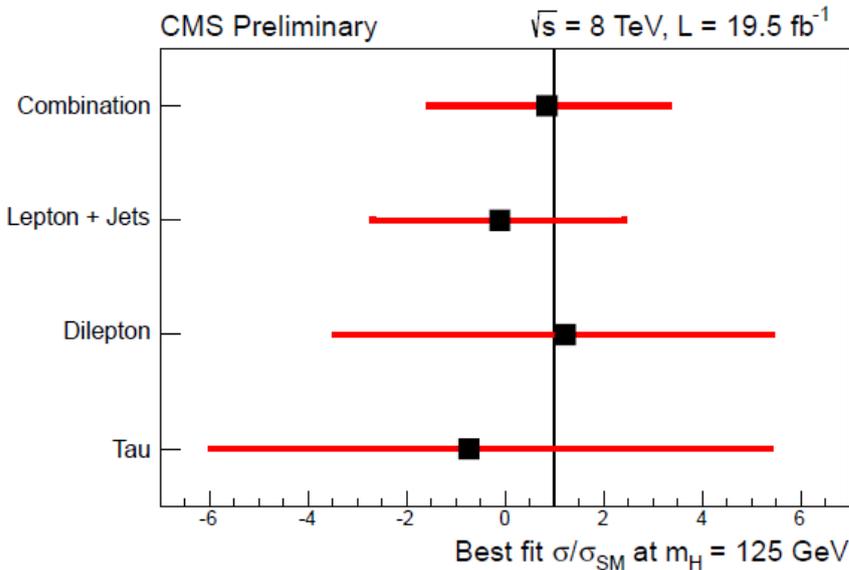
$\tau_h \tau_h$ -semileptonic

ttH, H → bb / τ_hτ_h: Results

Only 8 TeV



⊙ 95% CL Upper Limit on $\sigma/\sigma_{\text{SM}}$ at 125 GeV: **5.2 observed** (4.1 expected) for $\mu=0$



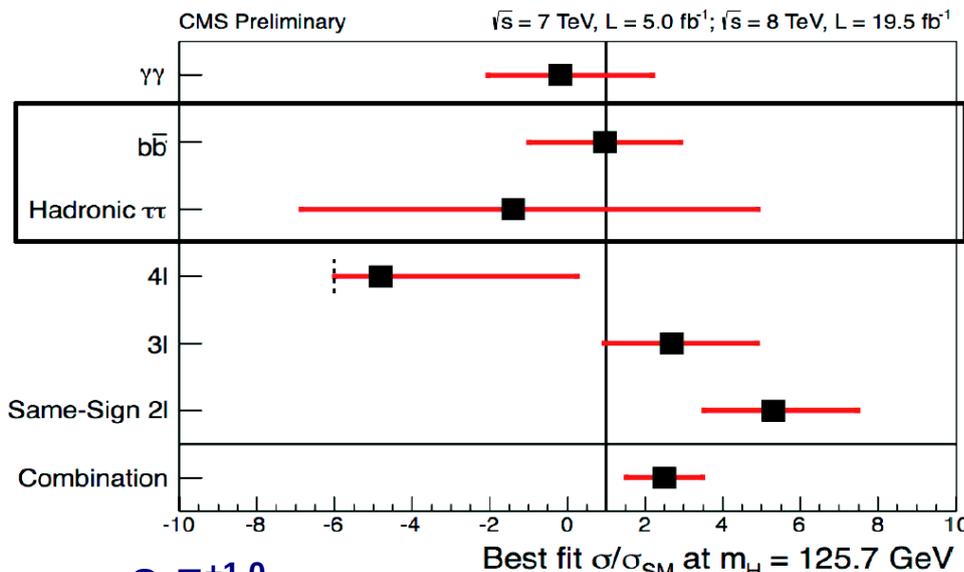
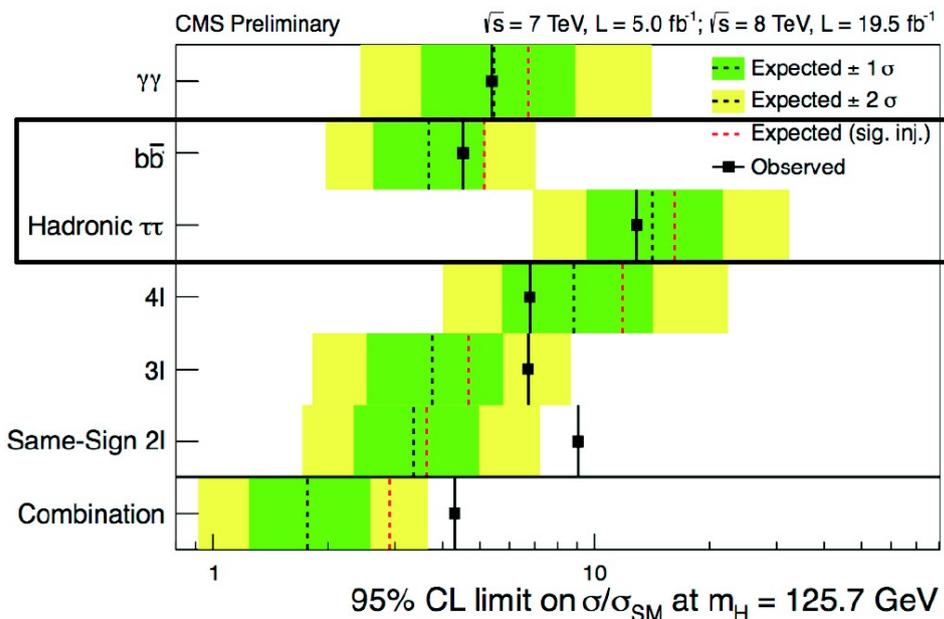
⊙ $\mu = 0.85^{+2.5}_{-2.4}$

- ◇ Using 19.5 fb⁻¹ at $\sqrt{s}=8 \text{ TeV}$
- ◇ $\sqrt{s}=7 \text{ TeV}$ ttH, H → bb analysis using 5.1 fb⁻¹ also used in ttH combination shown next

ttH, Combination

- ttH with $H \rightarrow \gamma\gamma$ or $H \rightarrow$ Multi-leptons (WW, ZZ, $\tau\tau$) analyses using full 8 TeV datasets included as well

$H \rightarrow b\bar{b}/\tau\tau$ @8 TeV **CMS-HIG-13-019**
 $H \rightarrow b\bar{b}$ @7 TeV **CMS-HIG-12-025**
 $H \rightarrow \gamma\gamma$ @8 TeV **CMS-HIG-13-015**
 $H \rightarrow$ Multi-leptons @8 TeV **CMS-HIG-13-020**

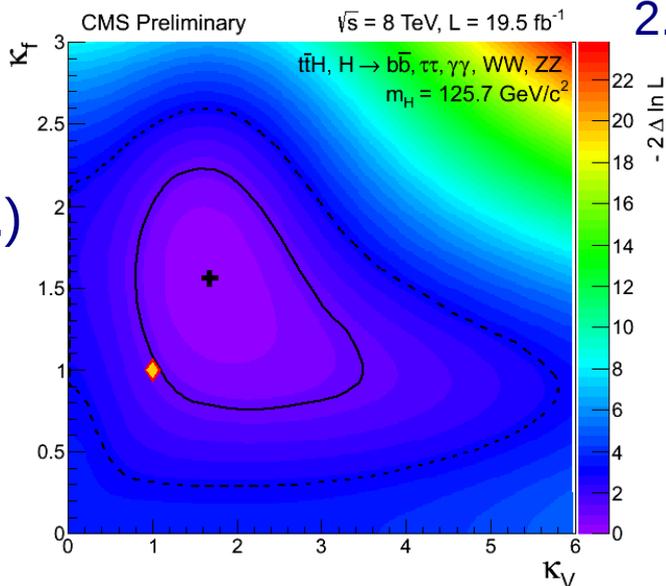


- 95% CL U.L. on $\sigma/\sigma_{\text{SM}}$ at 125.7 GeV: **4.3 observed** (1.8 expected for $\mu=0$)

$\mu = 2.5^{+1.0}_{-1.1}$

- Reached **1xSM sensitivity in $\mu(\text{ttH})$** (was 2.6 x SM at Moriond'13)

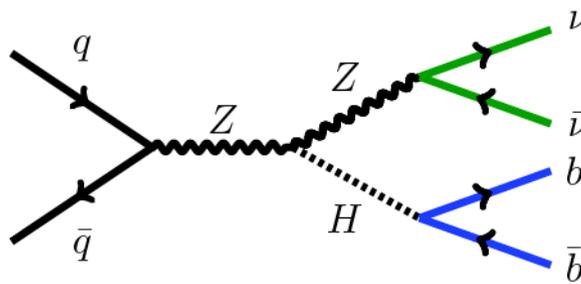
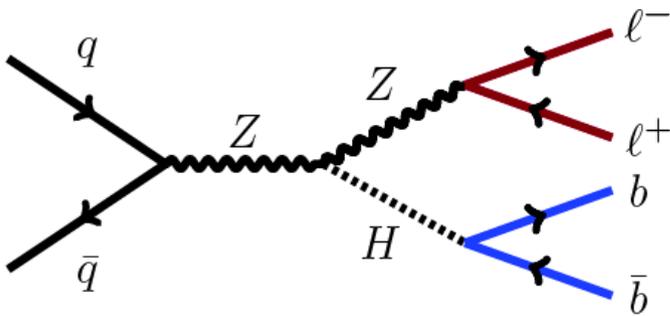
- Excess significance is **2.7σ** (1.2σ exp.)
- \diamond **1.6σ** relative to $\mu=1$



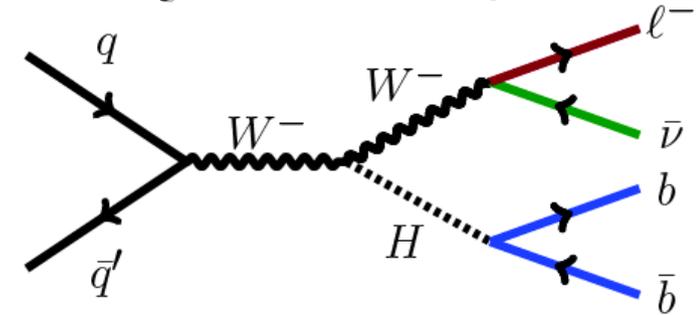
- couplings consistent with SM**

H → bb: Overview

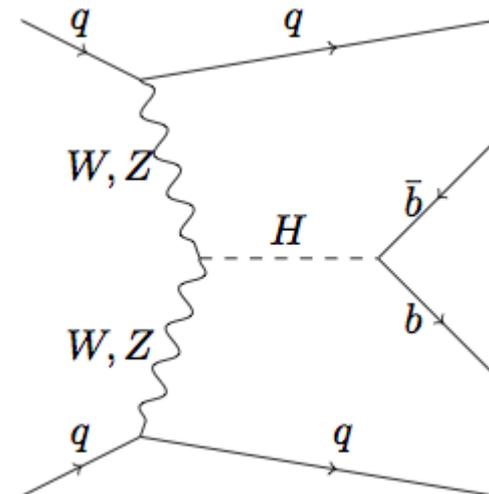
- Direct access to “down-type” fermion couplings
- Largest BR at low mass, but too large backgrounds to probe ggF
- “Legacy result” using full 7 and 8 TeV datasets for VH production
 - 6 channels: $ZH \rightarrow llbb$ ($l=e,\mu$), $ZH \rightarrow \nu\nu bb$, $WH \rightarrow l\nu bb$ ($l=e,\mu,\tau$)



Phys. Rev. D 89, 012003



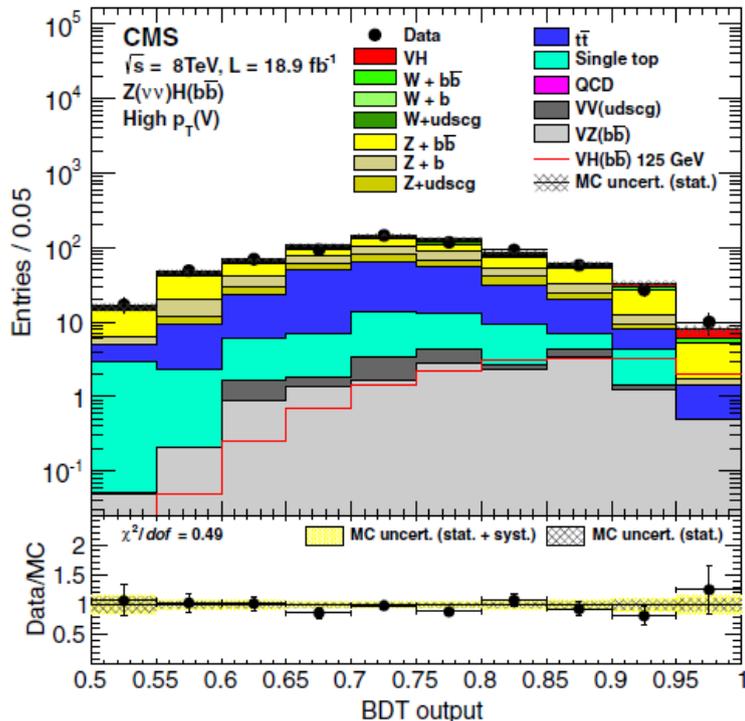
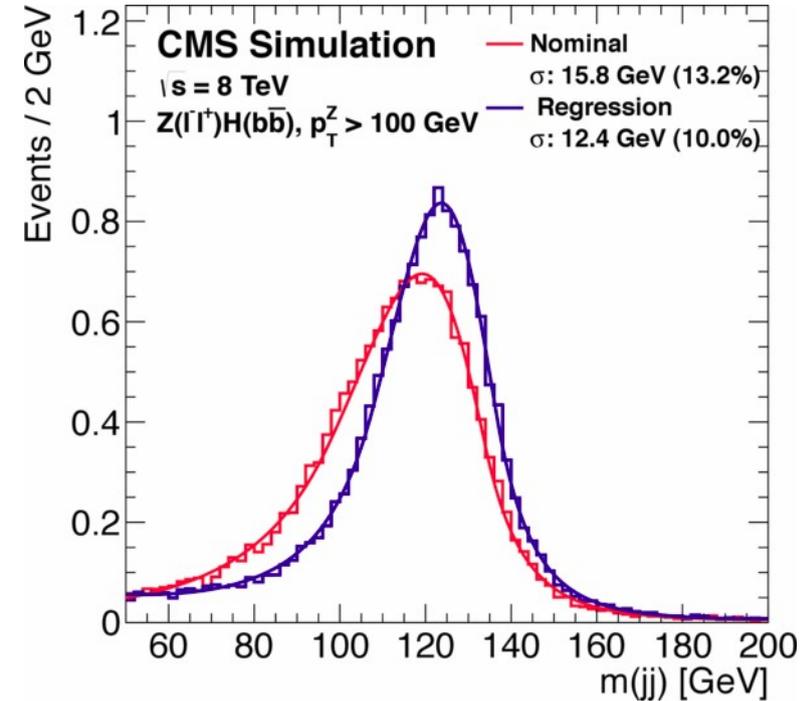
HIG-13-011



- Also VBF search using 8 TeV dataset
 - Brings additional sensitivity to $H \rightarrow bb$ despite large QCD background

VH \rightarrow bb: Analysis Strategy

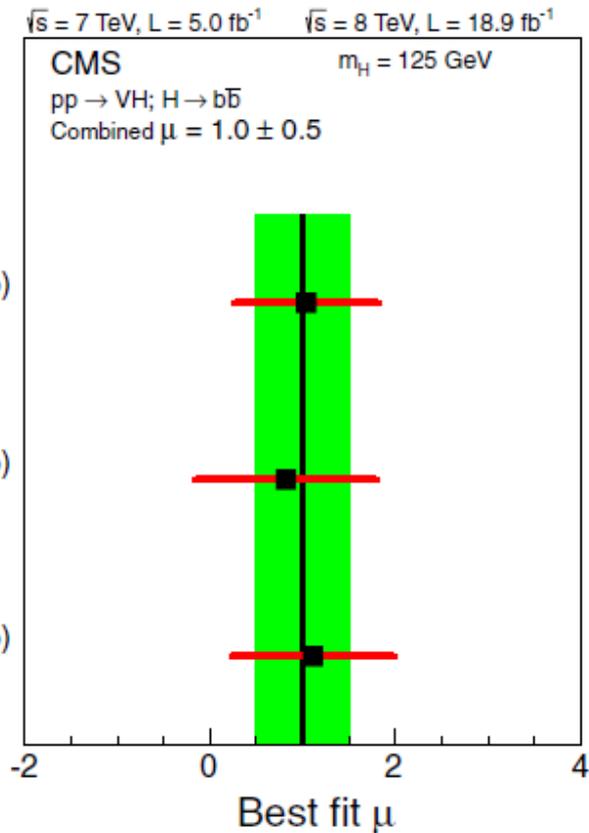
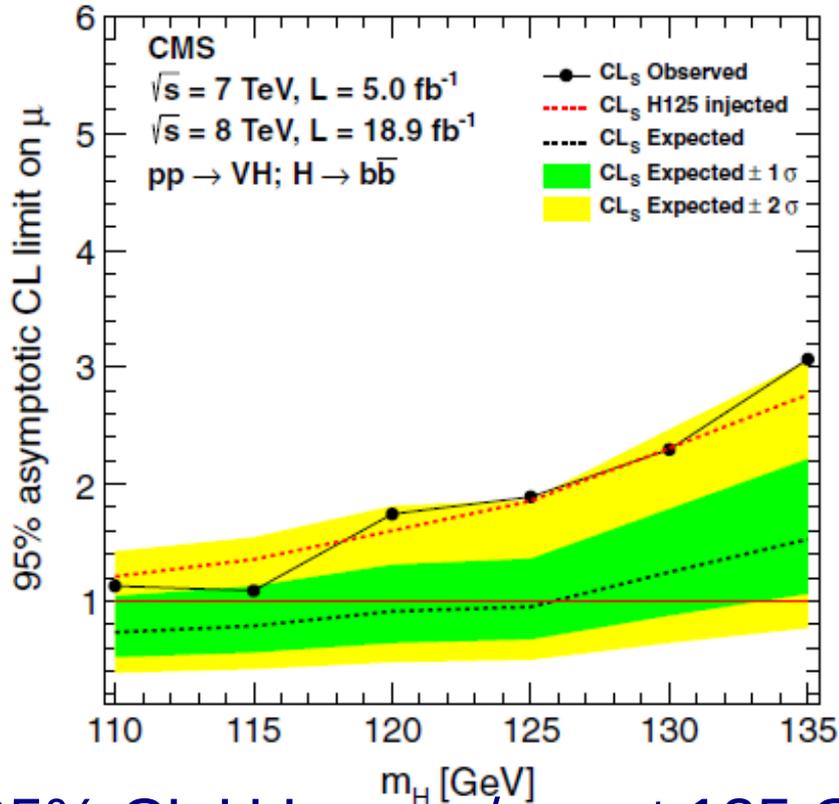
- Further categorization based on $P_T(V)$
- BDT based **b-jet regression** to improve bb mass resolution
- Use of **data control regions to normalize backgrounds**: V+jets, Top, VV
- Signal extraction from simultaneous fit to final **BDT discriminators** corresponding to 14 signal regions



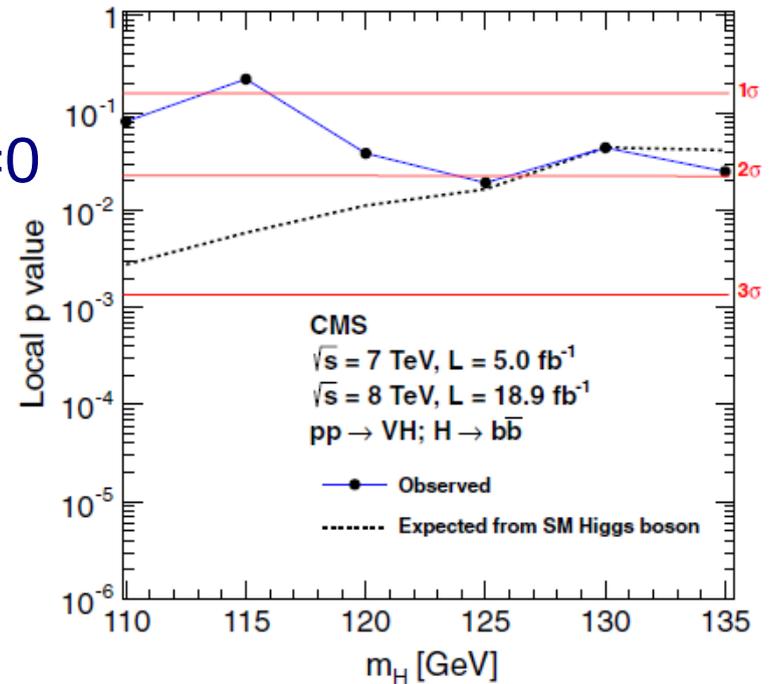
post-fit BDT $Z(vv)bb$
 (only VH enriched region)

- Main systematics from MC statistic, b-tagging and data driven background normalization
- Search validated with $VZ \rightarrow Vbb$ search
 - Result consistent with SM expectations

VH \rightarrow bb: Results

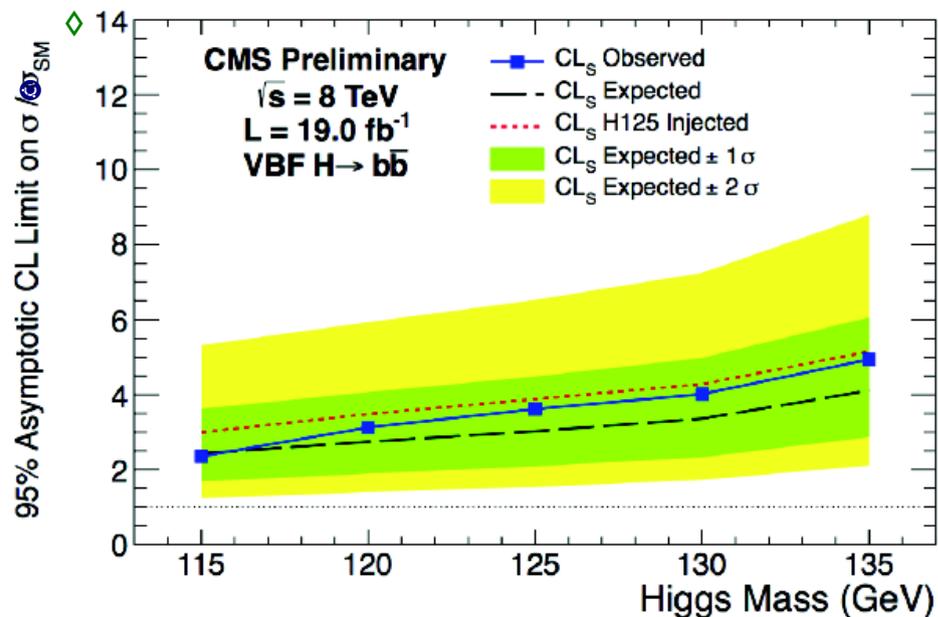
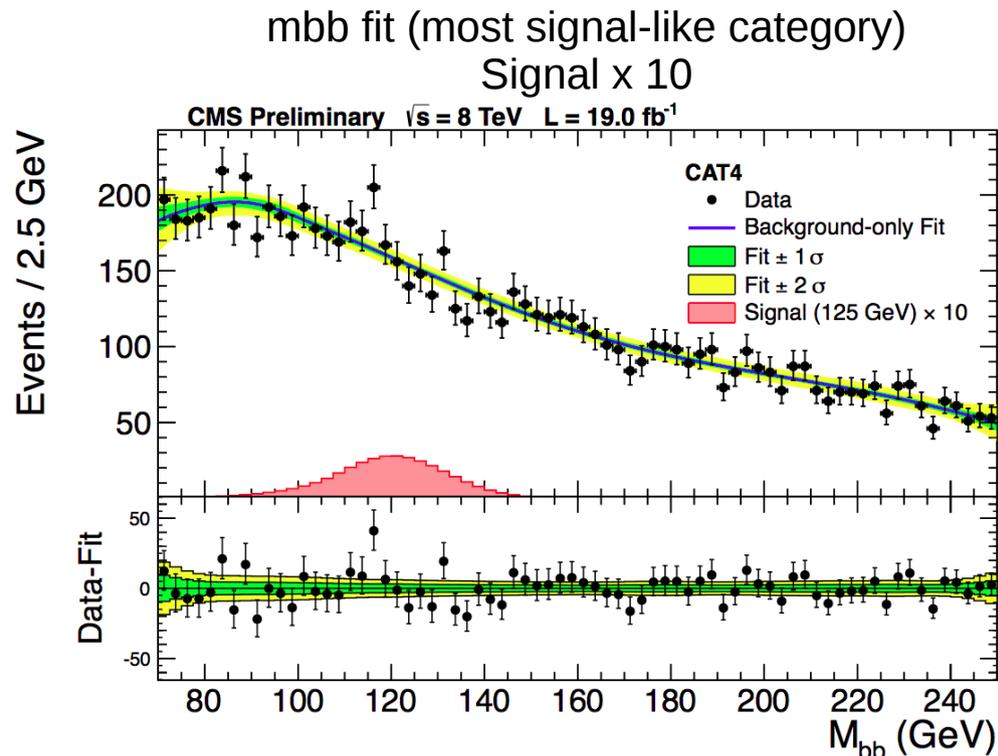


- 95% CL U.L. on σ/σ_{SM} at 125 GeV:
1.89 observed (0.95 expected) for $\mu=0$
- $\mu=1.0\pm 0.5$**
- 2.1 σ excess** seen at $m_H=125 \text{ GeV}$
 - Very good agreement with SM prediction (2.1 σ exp.)



VBF $H \rightarrow bb$ search

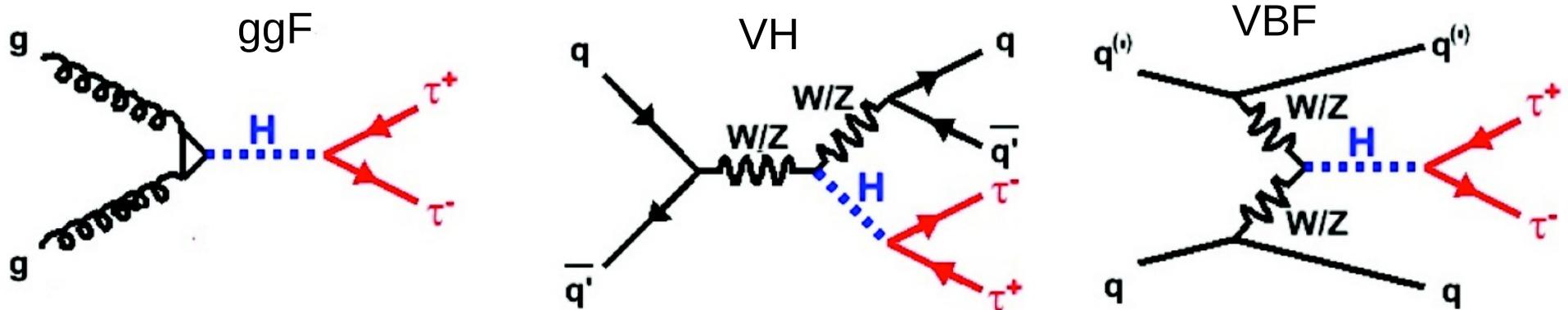
- Fully hadronic final state (and trigger)
 - ◊ 2 b-tagged and VBF light jets
 - ◊ High QCD background
- Likelihood fit for best b-pair mass to extract signal
 - ◊ Regression to improve resolution
 - ◊ Quark-gluon discriminant
 - ◊ 4 categories based on ANN (no strong correlation with m_{bb})



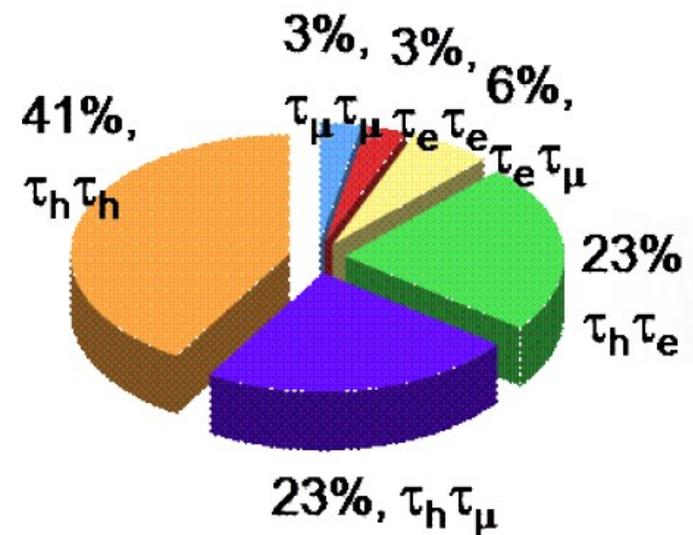
- 95% CL U.L. on σ/σ_{SM} at 125 GeV:
3.6 observed (3.0 expected) for $\mu=0$
- $\mu=0.7 \pm 1.4$
- Valuable contribution to $H \rightarrow bb$ CMS program

H → ττ: Overview

- “Legacy result” using full 7 and 8 TeV datasets
- Covers 3 leading production modes, ggF, VBF, VH

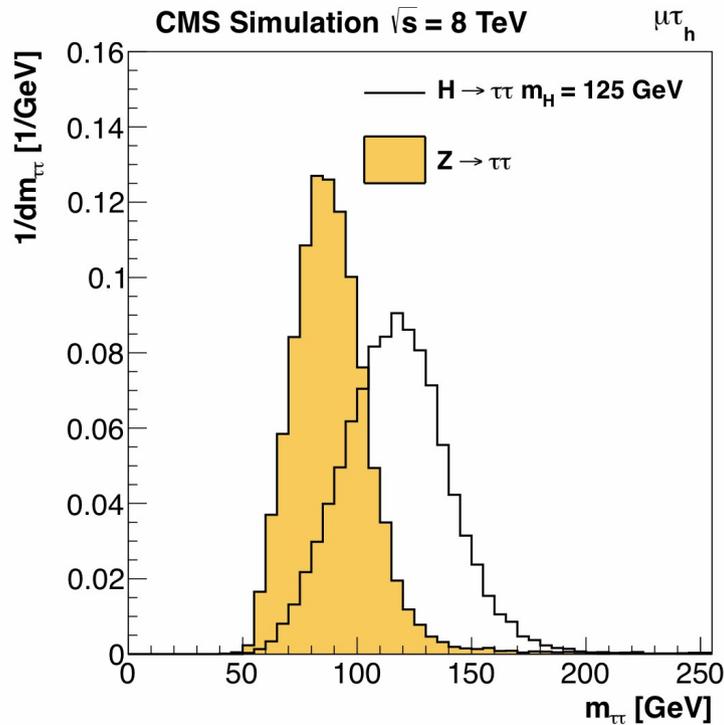


- All τ decay modes included, defining following 5 channels for non-VH analysis:
 - lep-had: $e\tau_h + \mu\tau_h$
 - lep-lep: $e\mu; \mu\mu + ee$
 - had-had: $\tau_h\tau_h$
- Combined with VH channels using dedicated analysis strategies

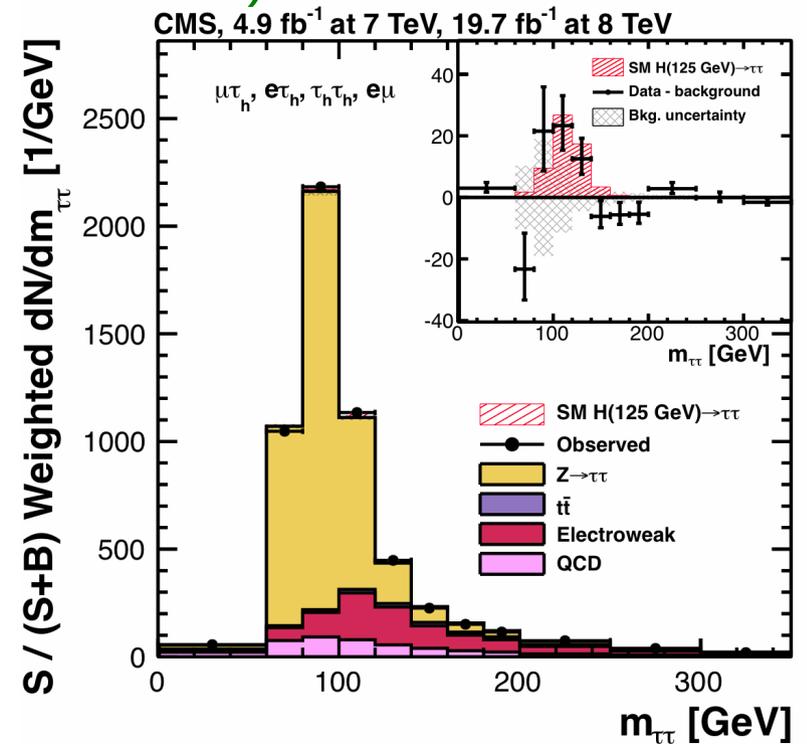


H → ττ: Analysis Strategy

- ◉ Further categorization based on Njet and boost of the system
 - ◇ **0-jet:** Use to constrain backgrounds
 - ◇ **1-jet:** Exploits boost of the Higgs system. Sensitive to **ggF**
 - ◇ **2-jet:** Low statistics but high S/B. Sensitive to **VBF**
- ◉ **Data-driven techniques** used to normalize and/or model dominant backgrounds when possible: **Z → ττ**, **Z → ll**, **W+jets**, **QCD**
- ◉ Di-τ mass reconstructions improved using likelihood-based method (SVFit)
 - ◇ Used for signal extraction (for most of the channels)

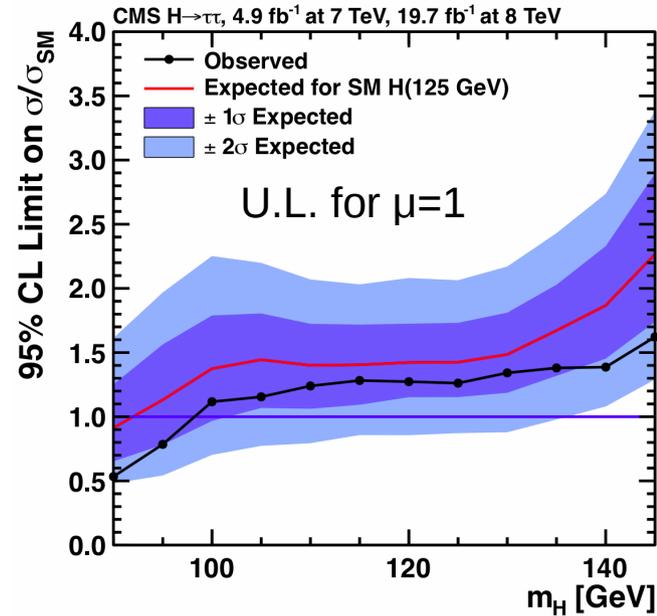
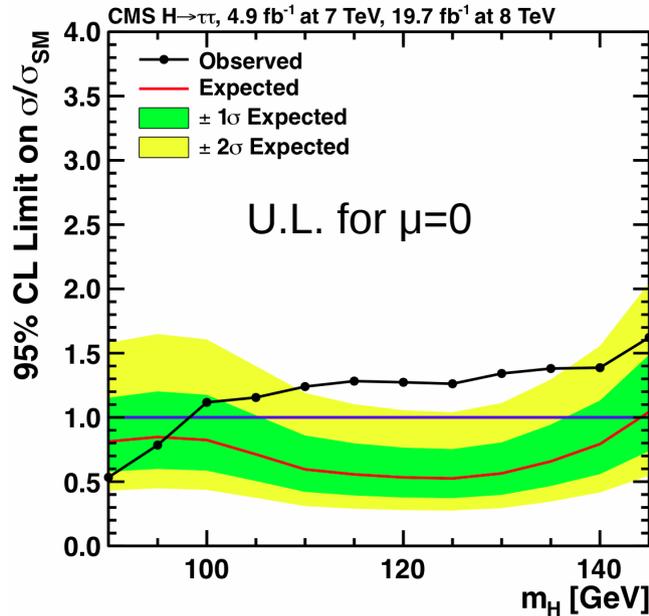


post-fit $m_{\tau\tau}$
 (different channels weighted)

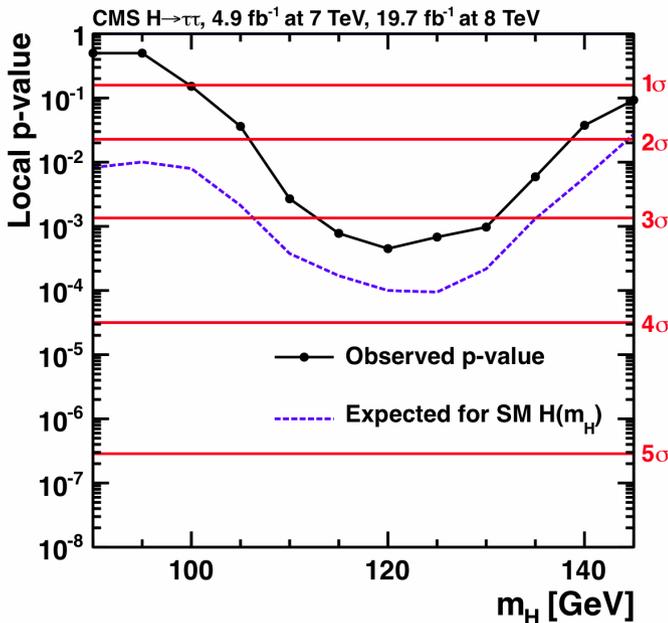


H → ττ: Results

background-only includes H → WW (for $m_H = 125$ GeV)



• Clear excess of events compatible with SM expectations



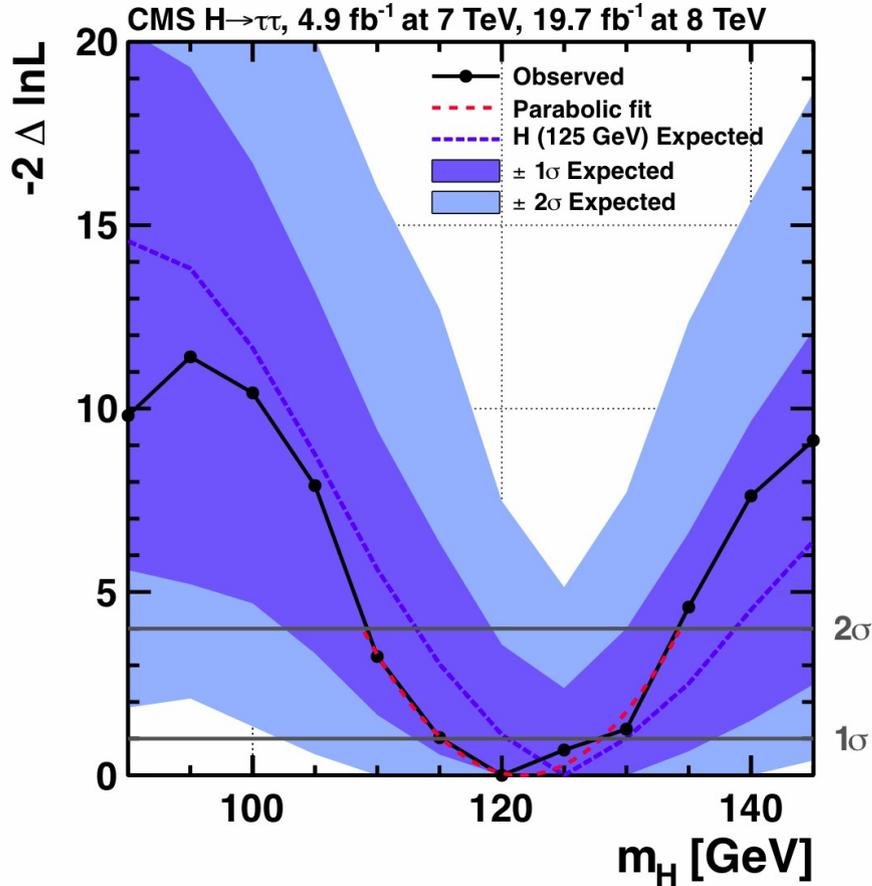
- $\mu = 0.78 \pm 0.27$ at 125 GeV
- 3.2σ observed (3.7σ exp.) at 125 GeV

Evidence for H → ττ

H → ττ: Results

Scan vs m_H

($H_{125} \rightarrow WW$ included as background)

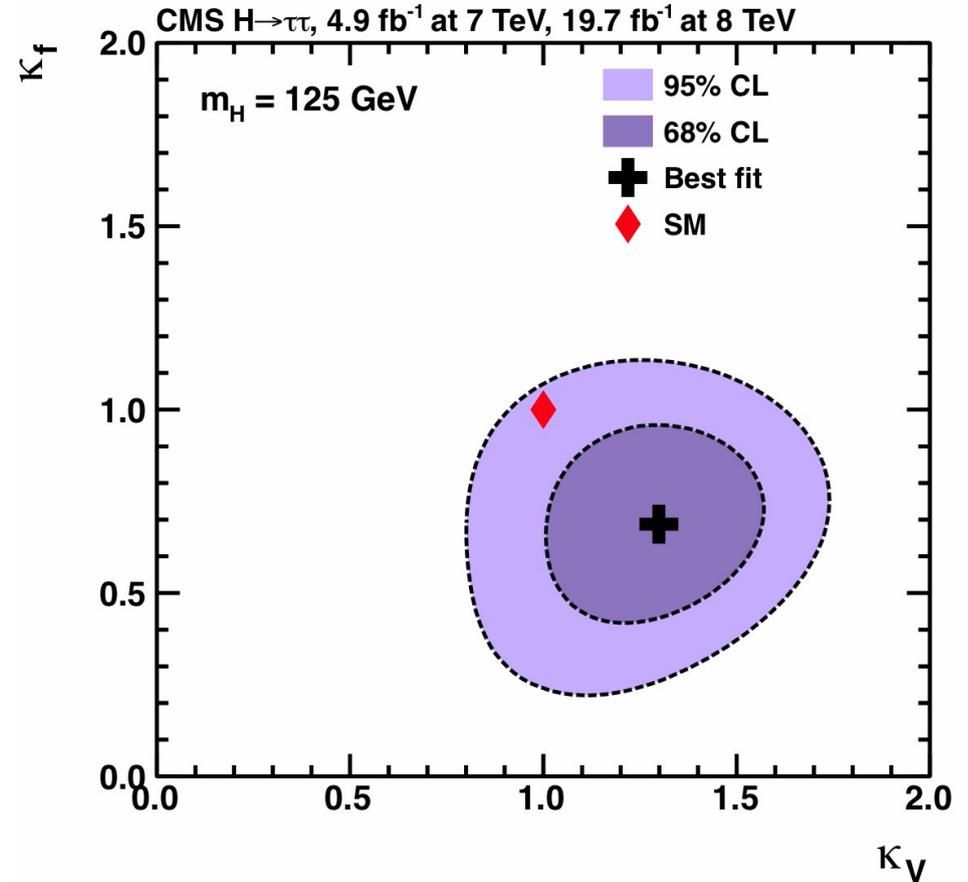


⊙ $m_H = 122 \pm 7$ GeV

◇ Compatible with ZZ/γγ results

Scan vs κ_f and κ_V

($H_{125} \rightarrow WW$ included as signal)

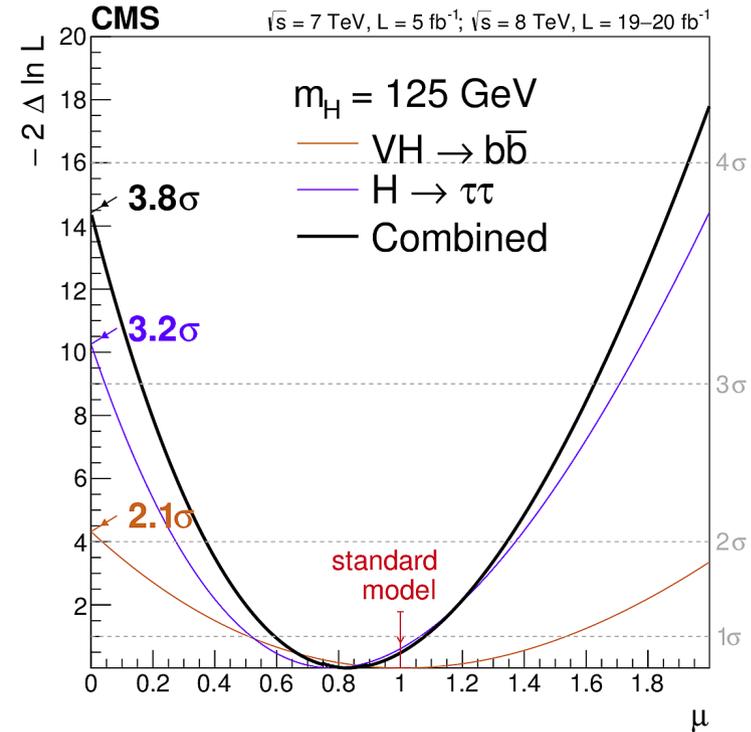
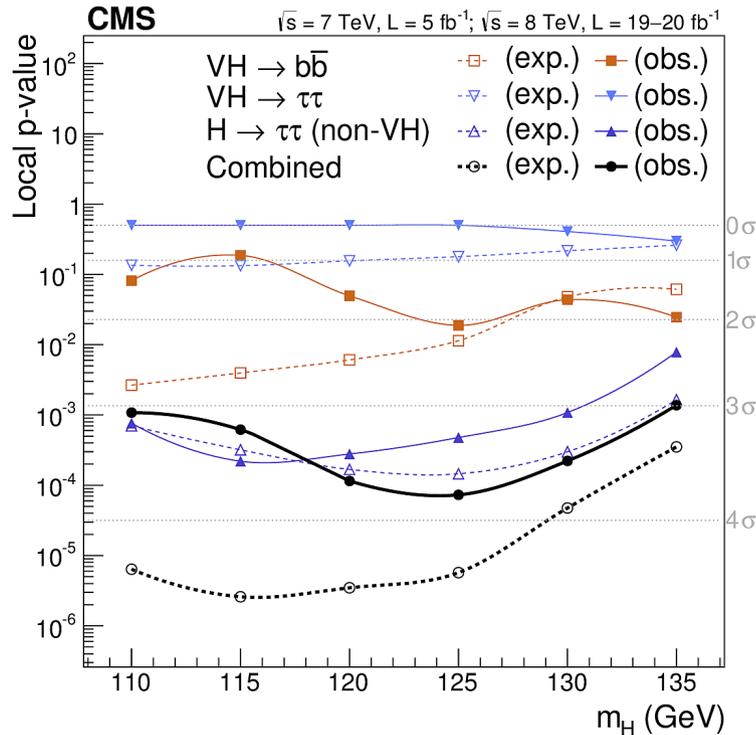


⊙ Compatible with SM expectation

H → bb/ττ Combination

arXiv:1401.6527
 Submitted to Nature Physics
 (Jan 2014)

◉ Combination of H → bb (VH only) and H → ττ



◊ Combined significance of **3.8σ** (4.4σ exp.)

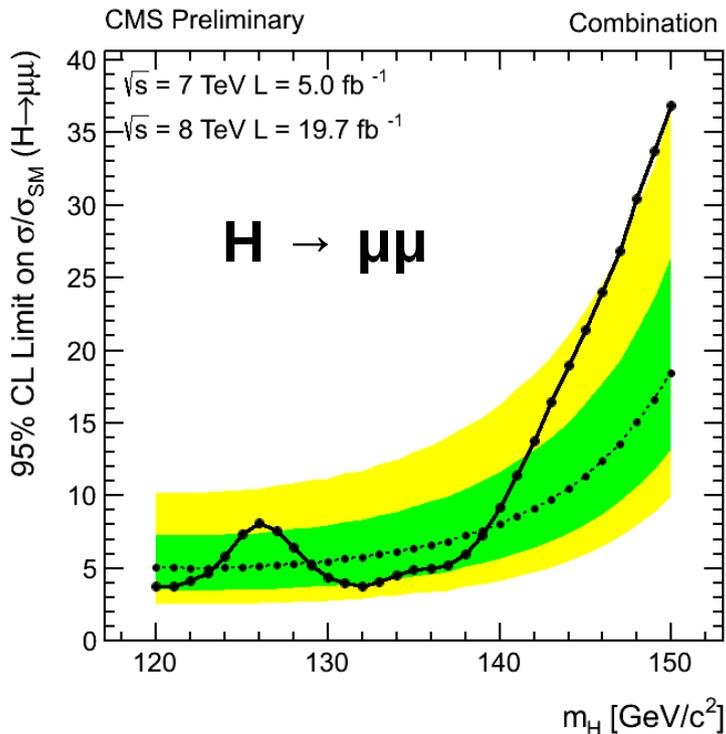
◊ **$\mu = 0.83 \pm 0.24$**

Channel ($m_H = 125 \text{ GeV}$)	Significance (σ)		Best-fit
	Expected	Observed	μ
$VH \rightarrow b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \rightarrow \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24

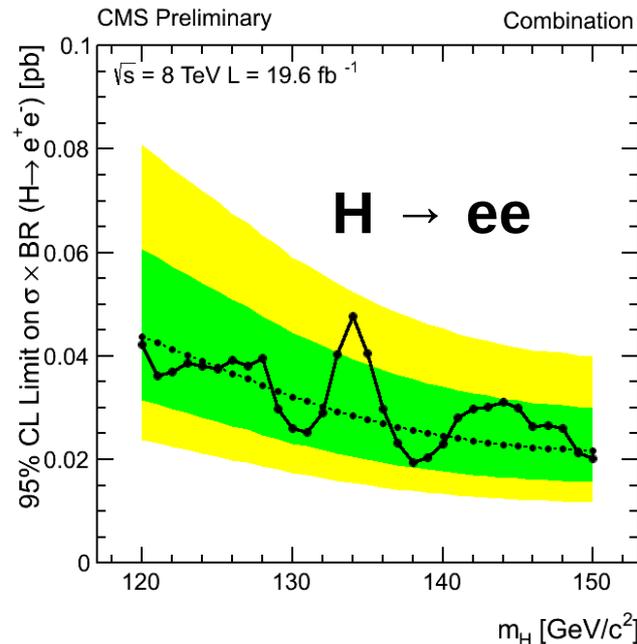
Evidence for H → fermions

H → μμ (and ee)

- BR for H → μμ is ~2x10⁻⁴ for 125 GeV (around 10 times smaller than γγ)
- Search using full 7 and 8 TeV datasets
 - ♦ Also performed H → ee search (BR around 2x10⁻⁵ smaller) for 8 TeV
- ggF and VBF categories (further categorization based on η^μ, p_T^{μμ})
- Fit m_{μμ} with signal and background shapes



- 7.4 σ_{SM} observed (5.1 σ_{SM} exp.) U.L. for H → μμ at 125 GeV
- Interesting channel for Run II and HL-LHC



- 0.038 pb observed U.L. for H → ee at 125 GeV

Summary

- **Very important progress in SM Higgs fermionic searches since July 2012**
- **ttH combination (2.7 σ excess, 1.6 σ for $\mu=1$), with important contribution to sensitivity from $H \rightarrow bb/\tau_h \tau_h$**
- **VH, $H \rightarrow bb$, 2.1 σ excess, $\mu=1 \pm 0.5$**
- **Evidence of $H \rightarrow \tau\tau$ of 3.2 σ , $\mu=0.78 \pm 0.27$**
- **Evidence of $H \rightarrow$ fermions of 3.8 σ , $\mu=0.83 \pm 0.24$**
- **First $H \rightarrow \mu\mu$ and $H \rightarrow ee$ searches. Interesting for the future**

BACK UP

ttH categories 8 TeV analysis

	≥ 6 jets 2 b-tags	4 jets 3 b-tags	5 jets 3 b-tags	≥ 6 jets 3 b-tags	4 jets 4 b-tags	5 jets ≥ 4 b-tags	≥ 6 jets ≥ 4 b-tags
ttH(125)	33.4 ± 8.1	14.0 ± 3.0	21.1 ± 4.5	23.1 ± 5.5	1.8 ± 0.5	5.2 ± 1.4	8.3 ± 2.3
t \bar{t} +lf	7650 ± 2000	4710 ± 820	2610 ± 530	1260 ± 340	74 ± 30	79 ± 34	71 ± 36
t \bar{t} +b	530 ± 300	350 ± 190	360 ± 200	280 ± 160	21 ± 12	29 ± 17	33 ± 20
t \bar{t} + b \bar{b}	220 ± 120	99 ± 52	158 ± 85	200 ± 110	13.1 ± 7.3	38 ± 21	78 ± 47
t \bar{t} + c \bar{c}	1710 ± 1110	440 ± 230	520 ± 290	470 ± 280	19 ± 11	32 ± 18	52 ± 31
t \bar{t} V	99 ± 27	16.2 ± 3.8	23.9 ± 5.7	28.8 ± 7.4	1.1 ± 0.4	2.5 ± 0.7	5.8 ± 1.8
Single t	264 ± 54	235 ± 41	116 ± 22	55 ± 14	3.4 ± 1.6	10.3 ± 5.3	7.3 ± 3.1
V+jets	160 ± 110	122 ± 95	44 ± 38	29 ± 27	2.1 ± 2.4	1.9 ± 1.7	1.2 ± 1.3
Diboson	5.9 ± 1.6	6.3 ± 1.4	2.4 ± 0.7	1.0 ± 0.4	0.3 ± 0.2	0.1 ± 0.1	0.2 ± 0.1
Total bkg	10630 ± 2790	5970 ± 1060	3830 ± 790	2310 ± 620	133 ± 44	193 ± 62	249 ± 90
Data	10724	5667	3983	2426	122	219	260

Table 1: Expected event yields in 19.5 fb^{-1} for signal and backgrounds in the lepton + jets channel.

	2 jets 1 b-tag	3 jets 1 b-tag	≥ 4 jets 1 b-tag	2 jets 2 b-tags	3 jets 2 b-tags	≥ 4 jets 2 b-tags
ttH(125)	0.4 ± 0.1	0.6 ± 0.1	0.6 ± 0.2	0.1 ± 0.0	0.2 ± 0.1	0.4 ± 0.1
t \bar{t}	225 ± 69	119 ± 38	64 ± 22	48 ± 15	38 ± 12	27.0 ± 9.1
t \bar{t} V	1.1 ± 0.3	1.3 ± 0.3	1.4 ± 0.4	0.4 ± 0.1	0.6 ± 0.2	1.1 ± 0.3
Single t	11.2 ± 4.0	3.0 ± 1.4	1.1 ± 1.0	1.9 ± 1.1	0.9 ± 0.6	0.6 ± 0.7
V+jets	33 ± 17	11.7 ± 6.8	3.8 ± 2.8	1.4 ± 0.9	0.4 ± 0.3	0.5 ± 0.6
Diboson	0.9 ± 0.2	0.7 ± 0.2	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.1 ± 0.1
Total bkg	271 ± 82	135 ± 41	71 ± 24	52 ± 16	40 ± 12	29.2 ± 9.4
Data	292	171	92	41	48	35

Table 3: Expected event yields in 19.5 fb^{-1} for signal and backgrounds in the tau channel. All events have two additional τ tagged jets.

	3 jets + 2 b-tags	≥ 4 jets + 2 b-tags	≥ 3 b-tags
ttH(125)	7.7 ± 1.4	16.1 ± 3.1	11.2 ± 2.5
t \bar{t} +lf	7460 ± 1060	3190 ± 680	289 ± 83
t \bar{t} +b	189 ± 97	172 ± 93	149 ± 82
t \bar{t} + b \bar{b}	38 ± 20	58 ± 31	80 ± 44
t \bar{t} + c \bar{c}	480 ± 260	510 ± 300	147 ± 79
t \bar{t} V	30.2 ± 6.3	54 ± 12	11.9 ± 2.9
Single t	229 ± 35	97 ± 16	17.3 ± 5.1
V+jets	350 ± 130	151 ± 66	40 ± 23
Diboson	10.4 ± 1.7	3.1 ± 0.6	0.7 ± 0.4
Total bkg	8770 ± 1250	4230 ± 850	740 ± 190
Data	9060	4616	774

Table 2: Expected event yields in 19.5 fb^{-1} for signal and backgrounds in the dilepton channel.

ttH systematics

Uncertainties of the sum of $t\bar{t}+lf$, $t\bar{t}+b$, $t\bar{t} + b\bar{b}$, and $t\bar{t} + c\bar{c}$ events with ≥ 6 jets and ≥ 4 b-tags

Source	Rate	Shape?
QCD Scale (all $t\bar{t}+hf$)	35%	No
QCD Scale ($t\bar{t} + b\bar{b}$)	17%	No
b-Tag bottom-flavor contamination	17%	Yes
QCD Scale ($t\bar{t} + c\bar{c}$)	11%	No
Jet Energy Scale	11%	Yes
b-Tag light-flavor contamination	9.6%	Yes
b-Tag bottom-flavor statistics (linear)	9.1%	Yes
QCD Scale ($t\bar{t}+b$)	7.1%	No
Madgraph Q^2 Scale ($t\bar{t} + b\bar{b}$)	6.8%	Yes
b-Tag Charm uncertainty (quadratic)	6.7%	Yes
Top p_T Correction	6.7%	Yes
b-Tag bottom-flavor statistics (quadratic)	6.4%	Yes
b-Tag light-flavor statistics (linear)	6.4%	Yes
Madgraph Q^2 Scale ($t\bar{t} + 2$ partons)	4.8%	Yes
b-Tag light-flavor statistics (quadratic)	4.8%	Yes
Luminosity	4.4%	No
Madgraph Q^2 Scale ($t\bar{t} + c\bar{c}$)	4.3%	Yes
Madgraph Q^2 Scale ($t\bar{t}+b$)	2.6%	Yes
QCD Scale ($t\bar{t}$)	3%	No
pdf (gg)	2.6%	No
Jet Energy Resolution	1.5%	No
Lepton ID/Trigger efficiency	1.4%	No
Pileup	1%	No
b-Tag Charm uncertainty (linear)	0.6%	Yes

Source	Shape	Remarks
Luminosity	No	Signal and all back
Lepton ID/Trigger efficiency	No	Signal and all back
Pileup	No	Signal and all back
Top p_T reweighting	Yes	Only $t\bar{t}$ background
Jet Energy Resolution	No	Signal and all back
Jet Energy Scale	Yes	Signal and all back
b-Tag bottom-flavor contamination	Yes	Signal and all back
b-Tag bottom-flavor statistics (linear)	Yes	Signal and all back
b-Tag bottom-flavor statistics (quadratic)	Yes	Signal and all back
b-Tag light-flavor contamination	Yes	Signal and all back
b-Tag light-flavor statistics (linear)	Yes	Signal and all back
b-Tag light-flavor statistics (quadratic)	Yes	Signal and all back
b-Tag Charm uncertainty (linear)	Yes	Signal and all back
b-Tag Charm uncertainty (quadratic)	Yes	Signal and all backgrounds
QCD Scale ($t\bar{t}H$)	No	Scale uncertainty for NLO $t\bar{t}H$ prediction
QCD Scale ($t\bar{t}$)	No	Scale uncertainty for NLO $t\bar{t}$ and single top predictions
QCD Scale (V)	No	Scale uncertainty for NNLO W and Z prediction
QCD Scale (VV)	No	Scale uncertainty for NLO diboson prediction
PDF (gg)	No	Parton distribution function (PDF) uncertainty for gg initiated processes ($t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$)
PDF ($q\bar{q}$)	No	PDF uncertainty for $q\bar{q}$ initiated processes ($t\bar{t}W$, W , Z).
PDF (qg)	No	PDF uncertainty for qg initiated processes (single top)
Madgraph Q^2 Scale ($t\bar{t}+0p,1p,2p$)	Yes	Madgraph Q^2 scale uncertainty for $t\bar{t}$ +jets split by parton number. There is one nuisance parameter per parton multiplicity and they are uncorrelated.
Madgraph Q^2 Scale ($t\bar{t}+b/b\bar{b}/c\bar{c}$)	Yes	Madgraph Q^2 scale uncertainty for $t\bar{t}+b/b\bar{b}/c\bar{c}$.
Madgraph Q^2 Scale (V)	No	Varies by jet bin.
Extra $t\bar{t}+hf$ rate uncertainty	No	A 50% uncertainty in the rate of $t\bar{t}+b$, $t\bar{t} + b\bar{b}$, $t\bar{t} + c\bar{c}$.
τ Energy Scale	Yes	Tau signal and background
τ ID efficiency	Yes	Tau signal and background
τ Jet Fake Rate	Yes	Tau signal and background
τ Electron Fake Rate	Yes	Tau signal and background

ttH individual channel 8 TeV analysis

Higgs Mass	Observed	Expected		
		Median	68% C.L. Range	95% C.L. Range
110 GeV	3.6	3.3	[2.4,4.7]	[1.8,6.6]
115 GeV	4.1	3.5	[2.4,4.9]	[1.8,6.9]
120 GeV	4.3	4.0	[2.9,5.8]	[2.1,8.1]
125 GeV	4.9	4.7	[3.3,6.7]	[2.5,9.4]
130 GeV	6.8	6.0	[4.3,8.6]	[3.2,12.0]
135 GeV	7.4	7.1	[5.0,10.2]	[3.7,14.2]
140 GeV	9.0	9.6	[6.9,13.7]	[5.2,18.9]

ttH, H → bb lep + jet

Higgs Mass	Observed	Expected		
		Median	68% C.L. Range	95% C.L. Range
110 GeV	6.5	5.8	[4.2,8.2]	[3.2,11.2]
115 GeV	7.4	6.5	[4.7,9.2]	[3.6,12.6]
120 GeV	8.2	7.2	[5.2,10.2]	[3.9,14.0]
125 GeV	9.1	8.2	[5.9,11.5]	[4.4,15.9]
130 GeV	12.4	10.5	[7.5,14.7]	[5.7,20.1]
135 GeV	15.0	12.3	[9.0,17.4]	[6.7,23.9]
140 GeV	18.0	14.1	[10.1,19.8]	[7.6,27.3]

ttH, H → bb dilepton

Higgs Mass	Observed	Expected		
		Median	68% C.L. Range	95% C.L. Range
110 GeV	10.0	9.7	[6.4,15.2]	[4.6,23.3]
115 GeV	10.8	9.5	[6.3,14.9]	[4.5,23.0]
120 GeV	10.6	11.8	[7.9,18.6]	[5.6,28.5]
125 GeV	13.2	14.2	[9.5,22.0]	[6.8,33.7]
130 GeV	13.0	14.2	[9.4,22.3]	[6.7,34.5]
135 GeV	16.7	16.4	[11.0,25.4]	[7.9,38.7]
140 GeV	23.3	21.2	[14.3,32.6]	[10.3,49.1]

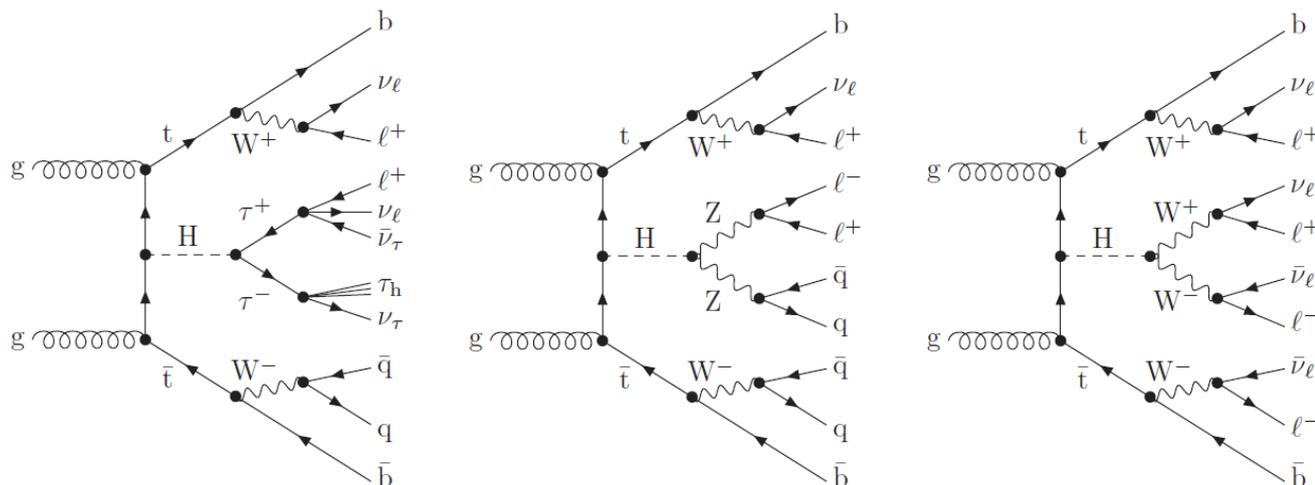
ttH, H → tau tau

ttH, multileptons

ttH, H → multileptons categories

	$\mu\mu$	ee	$e\mu$	3ℓ	4ℓ
$t\bar{t}H, H \rightarrow WW$	2.0 ± 0.3	0.9 ± 0.1	2.7 ± 0.4	3.2 ± 0.6	0.28 ± 0.05
$t\bar{t}H, H \rightarrow ZZ$	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H, H \rightarrow \tau\tau$	0.6 ± 0.1	0.3 ± 0.0	0.9 ± 0.1	1.0 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	8.2 ± 1.5	3.4 ± 0.6	13.0 ± 2.2	9.2 ± 1.9	-
$t\bar{t}Z/\gamma^*$	2.5 ± 0.5	1.6 ± 0.3	4.2 ± 0.9	7.9 ± 1.7	1.25 ± 0.88
$t\bar{t}WW$	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	-	1.3 ± 0.3	1.9 ± 0.5	2.9 ± 0.8	-
WZ	0.8 ± 0.9	0.5 ± 0.5	1.2 ± 1.3	4.2 ± 0.9	-
ZZ	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.4 ± 0.1	0.45 ± 0.09
rare SM bkg.	1.1 ± 0.0	0.4 ± 0.0	1.5 ± 0.0	0.8 ± 0.0	0.01 ± 0.00
non-prompt	10.8 ± 4.8	8.9 ± 4.5	21.2 ± 8.1	33.2 ± 12.3	0.53 ± 0.32
charge flip	-	1.9 ± 0.6	2.4 ± 0.8	-	-
all signals	2.7 ± 0.4	1.2 ± 0.2	3.7 ± 0.6	4.4 ± 0.8	0.52 ± 0.09
all backgrounds	23.7 ± 5.2	18.0 ± 4.7	45.9 ± 8.6	58.9 ± 12.7	2.28 ± 0.94
data	41	19	51	68	1

Table 1: Expected and observed yields after the selection in all five final states. The rare SM backgrounds include triboson production, $t\bar{t}Z, W^\pm W^\pm qq$, and WW produced in double-parton interactions. A '-' indicates a negligible yield. Non-prompt and charge-flip backgrounds are described in Sec. 8.



ttH, combination

ttH, limits for each channel

ttH Channel	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)				
	Observed	Median Signal Injected	Expected		
			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]

H → tautau channels

the $l\bar{l}LL'$ channels

Resonance	HLT requirement	Lepton selection		
$Z \rightarrow \mu\mu$	$\mu(17) \& \mu(8)$	$p_T^{\mu_1} > 20$ $p_T^{\mu_2} > 10$	$ \eta^\mu < 2.4$	$R^\mu < 0.3$
$Z \rightarrow ee$	$e(17) \& e(8)$	$p_T^{e_1} > 20$ $p_T^{e_2} > 10$	$ \eta^e < 2.5$	$R^e < 0.3$
$H \rightarrow \mu\tau_h$		$p_T^\mu > 10$ $p_T^{\tau_h} > 15$	$ \eta^\mu < 2.4$ $ \eta^{\tau_h} < 2.3$	$R^\mu < 0.3$ $I^{\tau_h} < 2$
$H \rightarrow e\tau_h$		$p_T^e > 10$ $p_T^{\tau_h} > 15$	$ \eta^e < 2.5$ $ \eta^{\tau_h} < 2.3$	$R^e < 0.2$ $I^{\tau_h} < 2$
$H \rightarrow \tau_h\tau_h$		$p_T^{\tau_h} > 15$	$ \eta^{\tau_h} < 2.3$	$I^{\tau_h} < 1$
$H \rightarrow e\mu$		$p_T^\ell > 10$	$ \eta^e < 2.5$ $ \eta^\mu < 2.4$	$R^\ell < 0.3$

the LL' and $l\bar{l}l\tau_h$ channels

Channel	HLT requirement	Lepton selection		
$\mu\tau_h$	$\mu(12-18) \& \tau_h(10-20)$	$p_T^\mu > 17-20$ $p_T^{\tau_h} > 30$	$ \eta^\mu < 2.1$ $ \eta^{\tau_h} < 2.4$	$R^\mu < 0.1$ $I^{\tau_h} < 1.5$
$e\tau_h$	$e(15-22) \& \tau_h(15-20)$	$p_T^e > 20-24$ $p_T^{\tau_h} > 30$	$ \eta^e < 2.1$ $ \eta^{\tau_h} < 2.4$	$R^e < 0.1$ $I^{\tau_h} < 1.5$
$\tau_h\tau_h$ (2012 only)	$\tau_h(35) \& \tau_h(35)$ $\tau_h(30) \& \tau_h(30) \& \text{jet}(30)$	$p_T^{\tau_h} > 45$	$ \eta^{\tau_h} < 2.1$	$I^{\tau_h} < 1$
$e\mu$	$e(17) \& \mu(8)$ $e(8) \& \mu(17)$	$p_T^{\ell_1} > 20$ $p_T^{\ell_2} > 10$	$ \eta^\mu < 2.1$ $ \eta^e < 2.3$	$R^\ell < 0.1-0.15$
$\mu\mu$	$\mu(17) \& \mu(8)$	$p_T^{\mu_1} > 20$ $p_T^{\mu_2} > 10$	$ \eta^{\mu_1} < 2.1$ $ \eta^{\mu_2} < 2.4$	$R^\mu < 0.1$
ee	$e(17) \& e(8)$	$p_T^{e_1} > 20$ $p_T^{e_2} > 10$	$ \eta^e < 2.3$	$R^e < 0.1-0.15$
$\mu + \mu\tau_h$	$\mu(17) \& \mu(8)$	$p_T^{\mu_1} > 20$ $p_T^{\mu_2} > 10$ $p_T^{\tau_h} > 20$	$ \eta^\mu < 2.4$ $ \eta^{\tau_h} < 2.3$	$R^\mu < 0.1-0.2$ $I^{\tau_h} < 2$
$e + \mu\tau_h /$ $\mu + e\tau_h$	$e(17) \& \mu(8)$ $e(8) \& \mu(17)$	$p_T^{\ell_1} > 20$ $p_T^{\ell_2} > 10$ $p_T^{\tau_h} > 20$	$ \eta^e < 2.5$ $ \eta^\mu < 2.4$ $ \eta^{\tau_h} < 2.3$	$R^\ell < 0.1-0.2$ $I^{\tau_h} < 2$
$\mu + \tau_h\tau_h$	$\mu(24)$	$p_T^\mu > 24$ $p_T^{\tau_{h,1}} > 25$ $p_T^{\tau_{h,2}} > 20$	$ \eta^\mu < 2.1$ $ \eta^{\tau_h} < 2.3$	$R^\mu < 0.1$ $I^{\tau_h} < 2-3$
$e + \tau_h\tau_h$	$e(20) \& \tau_h(20)$ $e(22) \& \tau_h(20)$	$p_T^e > 24$ $p_T^{\tau_{h,1}} > 25$ $p_T^{\tau_{h,2}} > 20$	$ \eta^e < 2.1$ $ \eta^{\tau_h} < 2.3$	$R^e < 0.1-0.15$ $I^{\tau_h} < 2$

H → tautau categories

		0-jet	1-jet	2-jet
$\mu\tau_h$	$p_T(\tau_h) > 45 \text{ GeV}$	high $p_T(\tau_h)$	high $p_T(\tau_h)$	high $p_T(\tau_h)$ boost $p_{T^{\tau\tau}} > 100 \text{ GeV}$
	baseline	low $p_T(\tau_h)$	low $p_T(\tau_h)$	loose VBF tag $m_{jj} > 500 \text{ GeV}$ $ \Delta\eta_{jj} > 3.5$
$e\tau_h$	$p_T(\tau_h) > 45 \text{ GeV}$	high $p_T(\tau_h)$	high $p_T(\tau_h)$	high $p_T(\tau_h)$ boost $p_{T^{\tau\tau}} > 100 \text{ GeV}$ $m_{jj} > 700 \text{ GeV}$ $ \Delta\eta_{jj} > 4.0$
	baseline	low $p_T(\tau_h)$	low $p_T(\tau_h)$	loose VBF tag
$e\mu$	$p_T(\mu) > 35 \text{ GeV}$	high $p_T(\mu)$	high $p_T(\mu)$	loose VBF tag
	baseline	low $p_T(\mu)$	low $p_T(\mu)$	tight VBF tag (2012 only)
$ee, \mu\mu$	$p_T(l) > 35 \text{ GeV}$	high $p_T(l)$	high $p_T(l)$	2-jet
	baseline	low $p_T(l)$	low $p_T(l)$	
$\tau_h\tau_h$			boost	VBF tag
	baseline		large boost $p_{T^{\tau\tau}} > 170 \text{ GeV}$	VBF tag $p_{T^{\tau\tau}} > 100 \text{ GeV}$ $m_{jj} > 500 \text{ GeV}$ $ \Delta\eta_{jj} > 3.5$

- Events split into categories

- Boost Significance

- Enhance production modes

- High sensitivity VBF Modes

- Boosted modes

- Initial state gluon radiates a jet

H → tautau systematics

Uncertainty	Affected processes	Change in acceptance
Tau energy scale	signal & sim. backgrounds	1–29%
Tau ID (& trigger)	signal & sim. backgrounds	6–19%
e misidentified as τ_h	Z → ee	20–74%
μ misidentified as τ_h	Z → $\mu\mu$	30%
Jet misidentified as τ_h	Z + jets	20–80%
Electron ID & trigger	signal & sim. backgrounds	2–6%
Muon ID & trigger	signal & sim. backgrounds	2–4%
Electron energy scale	signal & sim. backgrounds	up to 13%
Jet energy scale	signal & sim. backgrounds	up to 20%
E_T^{miss} scale	signal & sim. backgrounds	1–12%
$\epsilon_{\text{b-tag}}$ b jets	signal & sim. backgrounds	up to 8%
$\epsilon_{\text{b-tag}}$ light-flavoured jets	signal & sim. backgrounds	1–3%
Norm. Z production	Z	3%
Z → $\tau\tau$ category	Z → $\tau\tau$	2–14%
Norm. W + jets	W + jets	10–100%
Norm. $t\bar{t}$	$t\bar{t}$	8–35%
Norm. diboson	diboson	6–45%
Norm. QCD multijet	QCD multijet	6–70%
Shape QCD multijet	QCD multijet	shape only
Norm. reducible background	Reducible bkg.	15–30%
Shape reducible background	Reducible bkg.	shape only
Luminosity 7 TeV (8 TeV)	signal & sim. backgrounds	2.2% (2.6%)
PDF (qq)	signal & sim. backgrounds	4–5%
PDF (gg)	signal & sim. backgrounds	10%
Norm. ZZ/WZ	ZZ/WZ	4–8%
Norm. $t\bar{t}$ + Z	$t\bar{t}$ + Z	50%
Scale variation	signal	3–41%
Underlying event & parton shower	signal	2–10%
Limited number of events	all	shape only

H → μμ categories

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

H \rightarrow $\mu\mu$ 14 TeV projections

