

**University of  
Zurich<sup>UZH</sup>**

# Study of Higgs Production in Fermionic Decay Channels at CMS

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on behalf of the CMS Collaboration

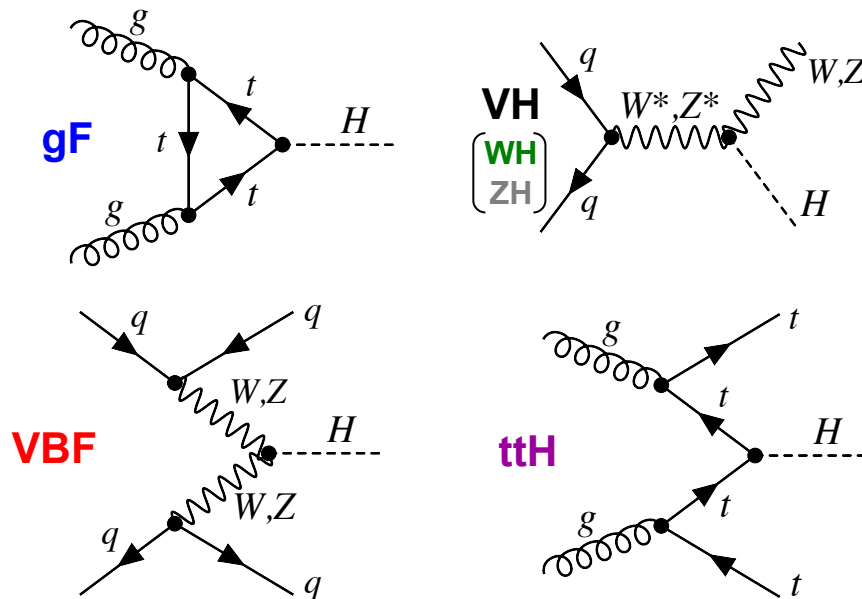
SUSY 2016

*5 July 2016, The University of Melbourne, Australia*

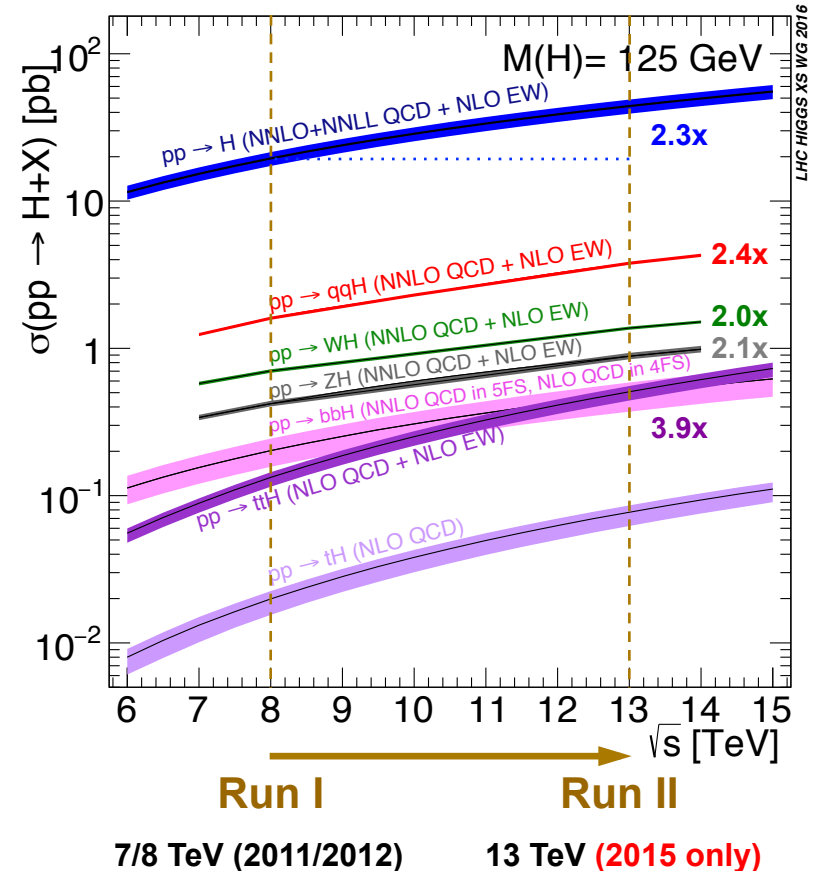
# SM Higgs boson production

## Introduction

- Higgs boson with 125 GeV mass discovered by CMS and ATLAS
- 4 main production mechanisms at the LHC



## Production cross section at LHC



# Higgs boson decay

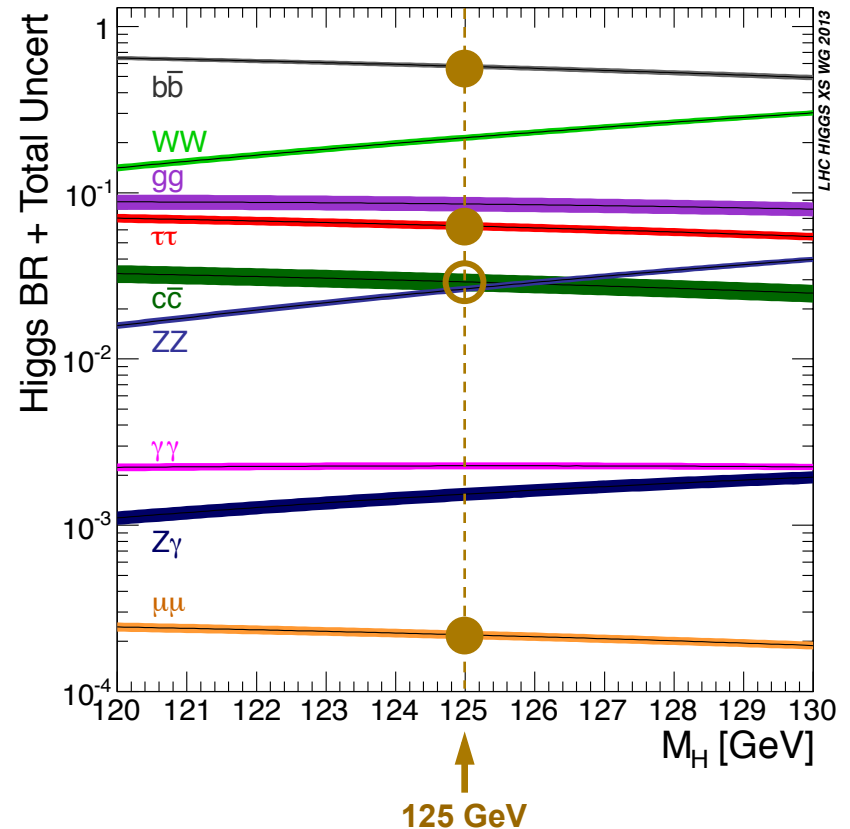
## Comments

- Observation of fermionic decays would be a test of the Yukawa couplings
  - ▶ Generate fermion masses
- Fermionic decay channels less sensitive than bosonic channels
  - ▶ Suffer from large backgrounds
- Could provide insight into possible new physics
  - ▶ BSM searches not considered

## Searches presented

Hbb      ttH      Hττ      Hμμ

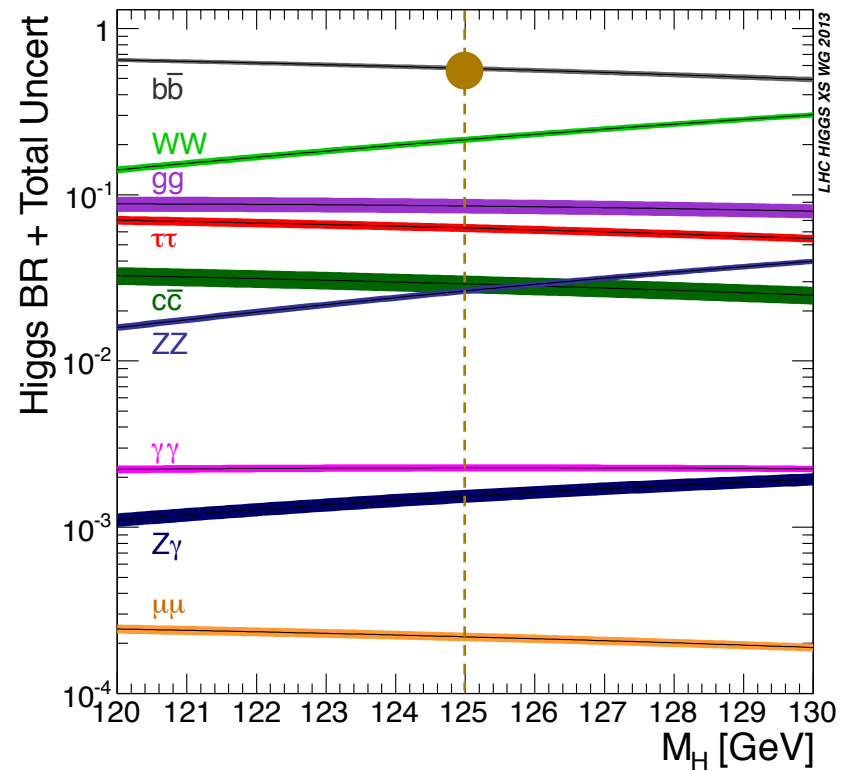
## Decay branching ratios



# $H \rightarrow bb$

**Searches presented**

**Hbb**      **ttH**      **H $\tau\tau$**       **H $\mu\mu$**



# H $\rightarrow$ bb: Reconstructing $m_{bb}$

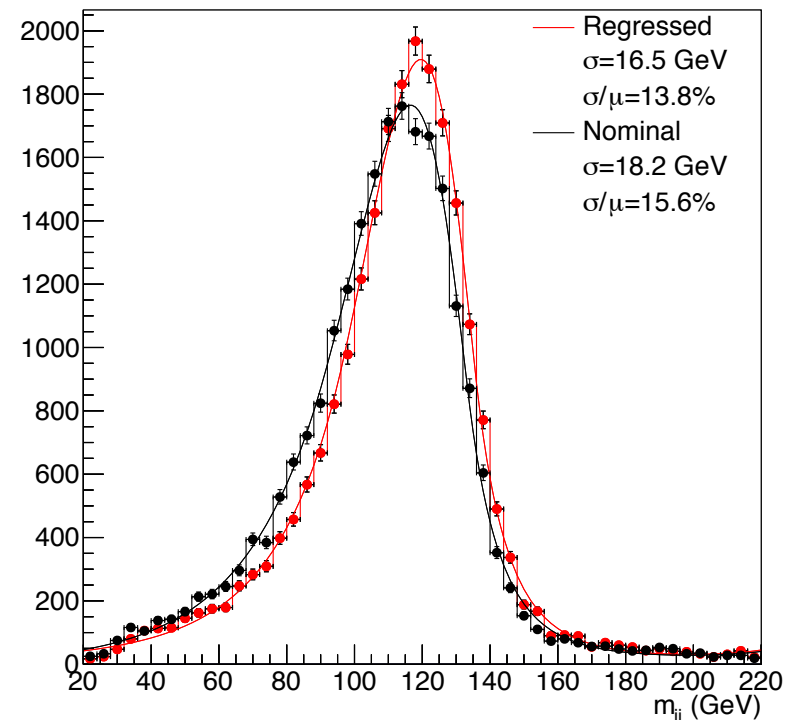
VH, H $\rightarrow$ bb Dec 15

## Regression method (VH & VBF)

- Applied to b-tagged jets
- Improves the standard CMS jet calibration to better extract the true b-quark energy
- Uses a multivariate BDT
  - ▶ Several input variables related to the jet structure and nearby leptons
    - Targeting semi-leptonic b decays
  - ▶ Output is the corrected jet  $p_T$
- Improves the di-jet invariant mass resolution by  $\sim 15\%$ 
  - ▶ Improves VH analysis sensitivity by 10-20%

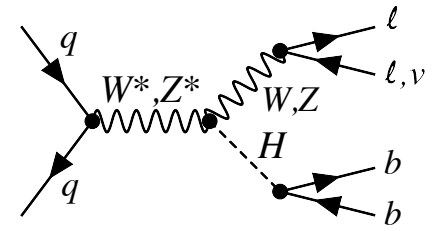
## Higgs mass – Run II

CMS Simulation (13 TeV)



H $\rightarrow$ bb candidate invariant mass  
without (black) and with (red) b-jet regression

# VH, H → bb

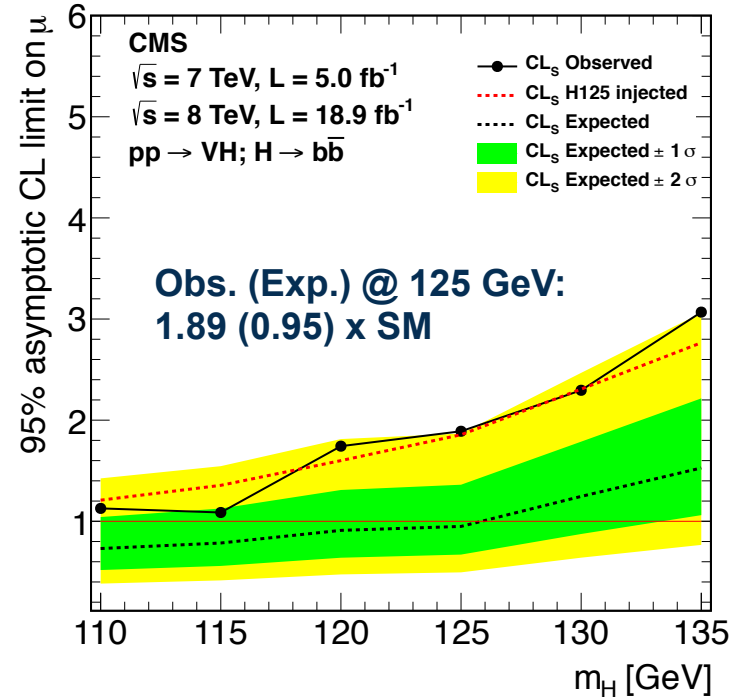


PRD 89 (2014) 012003

## Analysis overview

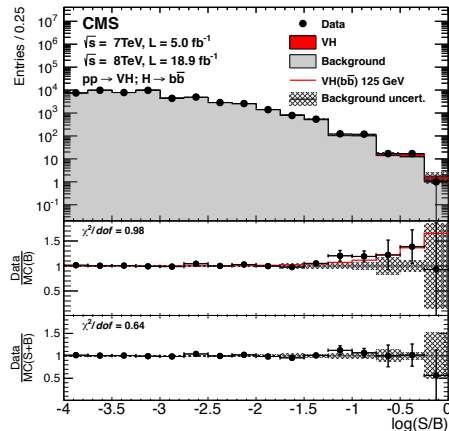
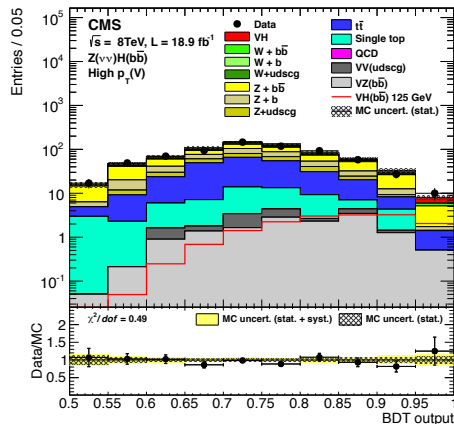
- Event triggered by leptonic decay of vector boson
- b-jet energy regression
  - ▶ Improves  $m_{bb}$  resolution
- BDT final discriminant
  - ▶ 18 input variables, best discrimination:  $m_{jj}$ ,  $N_{aj}$ ,  $CSV_{min}$ ,  $\Delta R_{jj}$

## Results – Run I



2.1 (2.1) sigma excess observed (expected)  
 @125 GeV

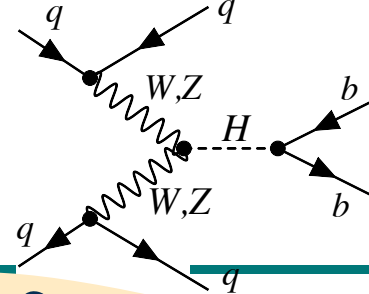
Best fit  $\mu = \sigma/\sigma_{SM} = 1.0 \pm 0.5$



Fully  
Hadronic

13 TeV

VBF,  $H \rightarrow bb$

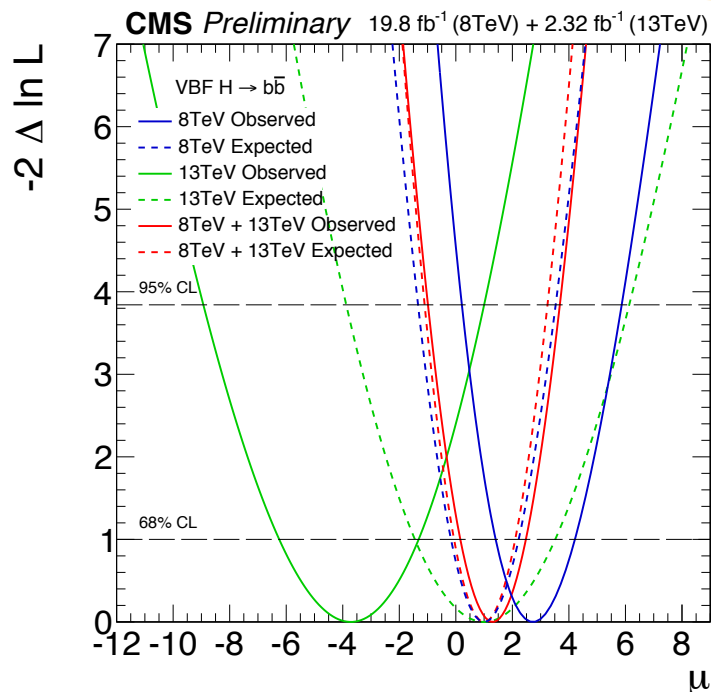


CMS-HIG-16-003

## Analysis overview

- 2 scattered light jets
  - ▶ Expected to be close to beam line
  - ▶ EWK process  $\Rightarrow$  little QCD activity
- 2 b-jets from Higgs
  - ▶ Regression method reconstruction
  - ▶  $m_{bb}$  final discriminant

## Results – Run II

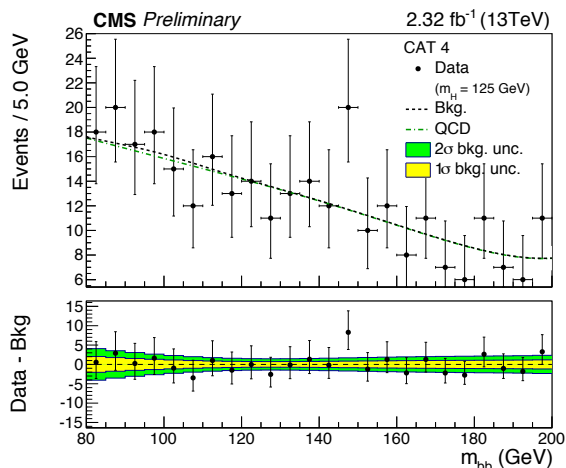


Combined Run I & Run II results:  
Obs. (Exp.) limit: 3.4 (2.3) x SM  
Best fit  $\mu = \sigma/\sigma_{SM} = 1.3 +1.2/-1.1$

## Hadronic triggers

QuadJet92,76,64,15, 1xCSV  
 $\Delta\eta_{qq} > 4.1$ ,  $m_{qq} > 460$ ,  $\Delta\phi_{bb} < 1.6$

QuadJet92,76,64,15, 2xCSV  
 $\Delta\eta_{qq} > 1.2$ ,  $m_{qq} > 200$



# ttH

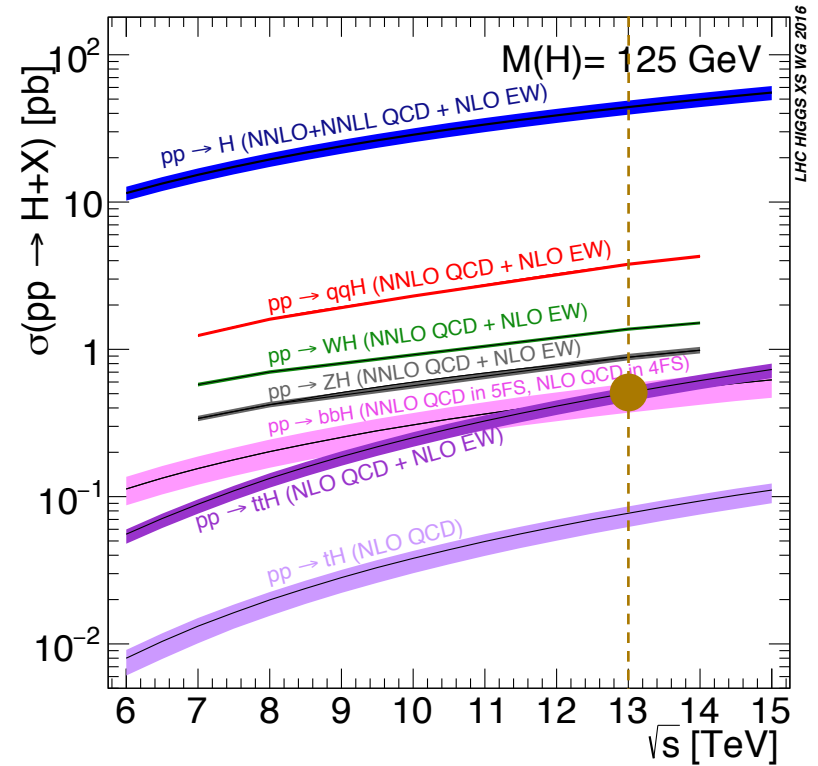
## Searches presented

Hbb

ttH

H $\tau\tau$

H $\mu\mu$



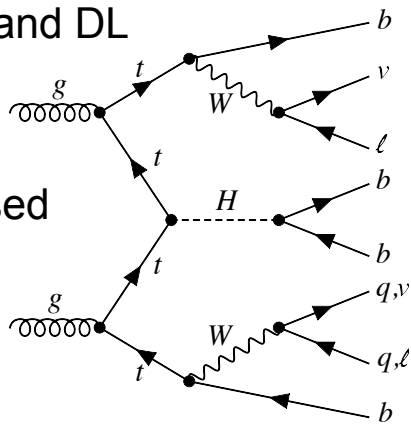
13 TeV

# ttH, H → bb

CMS-HIG-16-004

## Analysis overview

- Small cross section, but direct probe of the Higgs/top Yukawa coupling  $y_t$
- 2 channels: SL and DL
- BDT and Matrix Element discriminants used



Run I results at 8 TeV:

Obs. (Exp.) limit

BDT: 5.2 (4.1) CMS-PAS-HIG-13-019

Matrix Element: 4.2 (3.3) EPJC 75 (2015) 251

Run II results at 13 TeV:

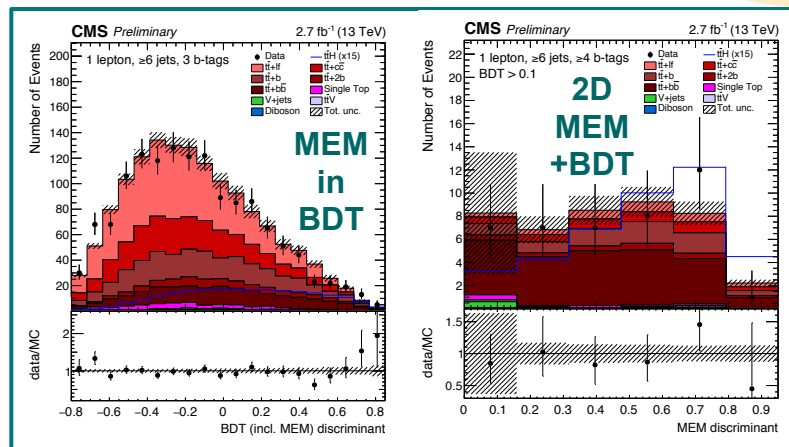
Obs. (Exp.) limit: 2.6 (3.6) x SM

Best fit  $\mu = \sigma/\sigma_{SM} = -2.0 \pm 1.8$

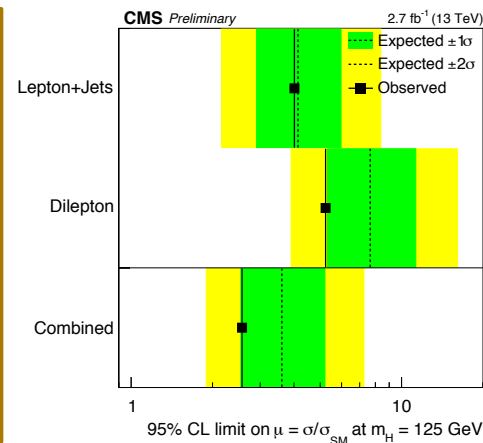
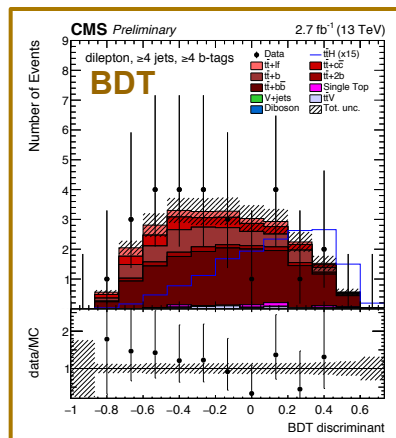
1.7 sigma below SM expectation

## Results – Run II

single lepton



dilepton





# ttH, multileptons

CMS-HIG-15-008

## Analysis overview

- 3 channels:  $H \rightarrow ZZ^*, WW^*, \tau\tau$ 
  - 2 same sign leptons, or 3 leptons
  - 1 hadronic top and Z,W, $\tau$  allowed
- S/B binned final discriminant
  - Based on two BDTs: vs. tt and ttV
    - 7 input variables each

Run I results at 8 TeV:

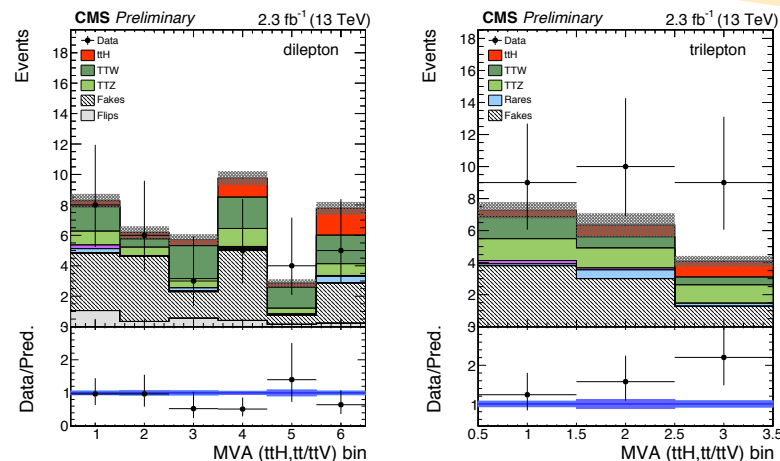
Obs. (Exp.) limit: 6.6 (2.4)

Excess observed in di-muon channel

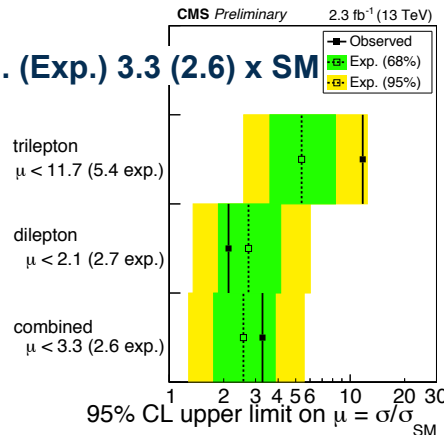
CMS-PAS-HIG-13-020

No di-muon excess observed in Run II

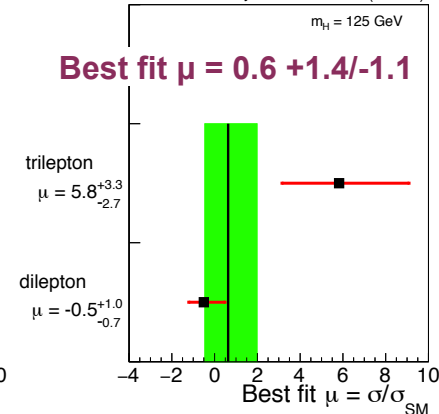
## Results – Run II



Obs. (Exp.) 3.3 (2.6) x SM



Best fit  $\mu = 0.6 +1.4/-1.1$



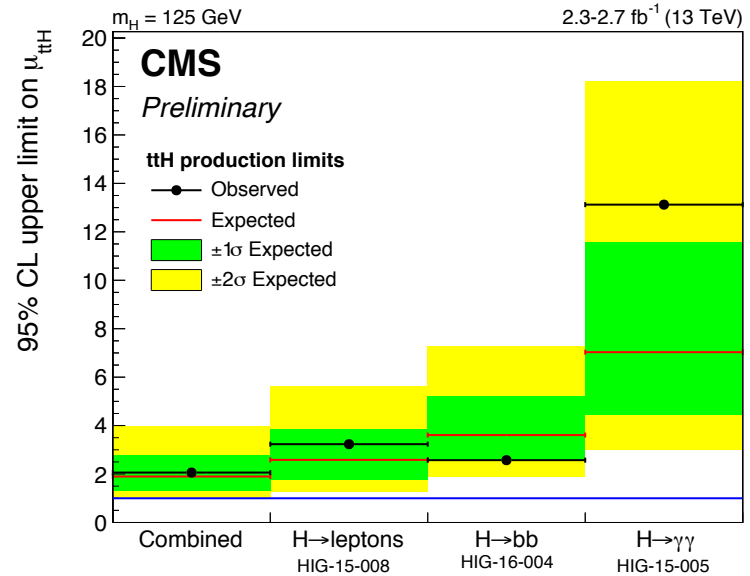


# ttH, combination

CMS-HIG-15-005  
 CMS-HIG-15-008  
 CMS-HIG-16-004

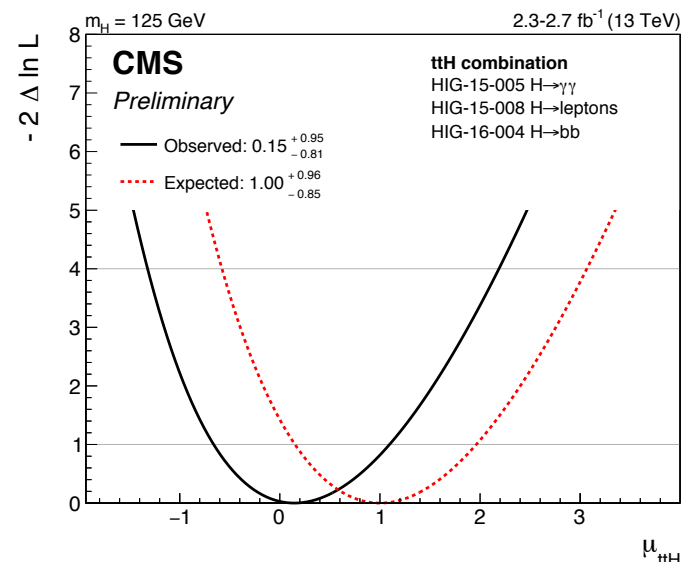
Combines: **ttH, H→γγ**    **ttH, multileptons**    **ttH, H→bb**

## 95% CL upper limit on $\mu_{ttH}$



**Observed limit on  $\mu_{ttH} = 2.1 \times \text{SM}$**   
**Expected limit on  $\mu_{ttH} = 1.9 \times \text{SM}$**

## ttH signal strength



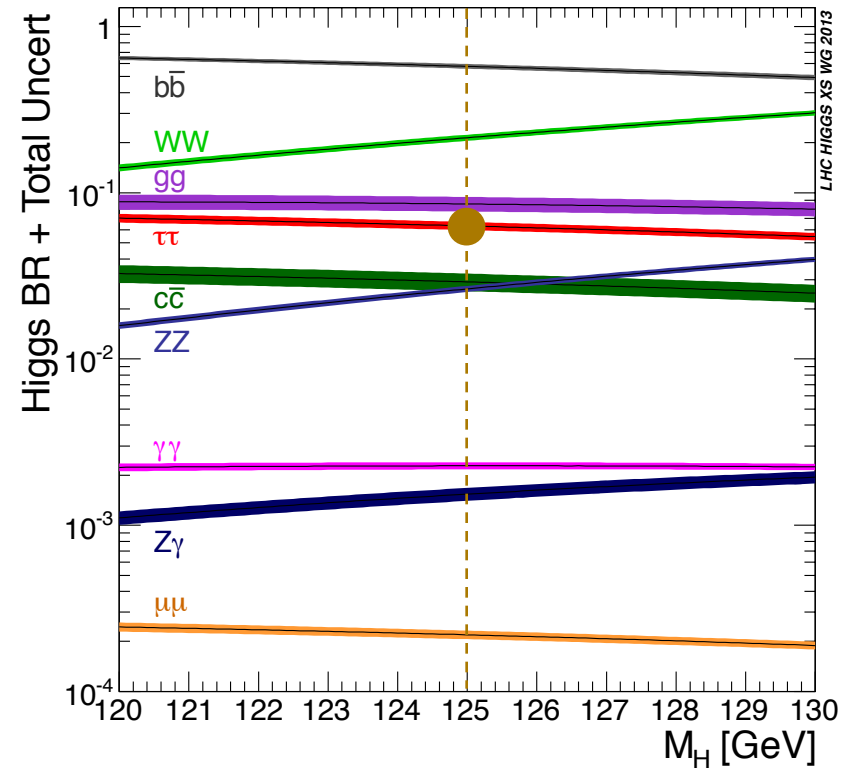
**Observed  $\mu_{ttH} = 0.15^{+0.95/-0.81}$**   
**Expected  $\mu_{ttH} = 1.00^{+0.96/-0.85}$**   
 Other SM signal processes fixed to SM rates

**Run I results at 8 TeV:    Obs. (Exp.) limit: 4.5 (2.7)    Best fit  $\mu = 2.8^{+1.0/-0.9}$     JHEP 09 (214) 087**

# $H \rightarrow \tau\tau$

Searches presented

Hbb    ttH    **H $\tau\tau$**     H $\mu\mu$



# H → ττ: Reconstructing $m_{\tau\tau}$

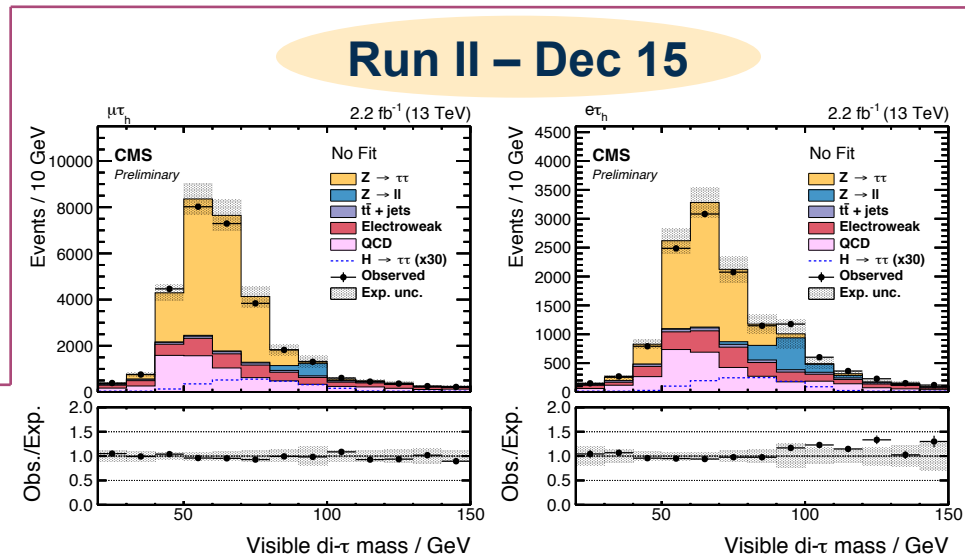
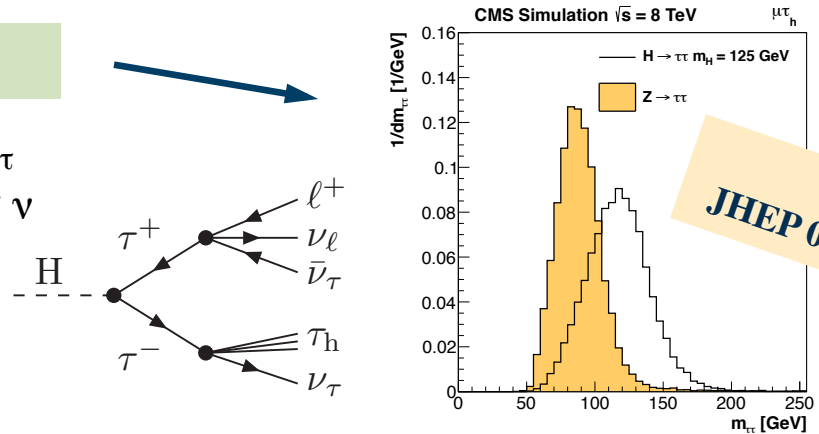
## Likelihood method

- Tau decay produces invisible  $\nu_\tau$ 
  - ▶ Leptonic decay produces further  $\nu$
  - ▶  $m_{\tau\tau}$  is left unconstrained
- If no other source of neutrino, construct a likelihood  $f(\mathbf{z}, \mathbf{y}, \mathbf{x})$ 
  - ▶  $E_T^{\text{miss}}$ :  $\mathbf{z}$
  - ▶ Visible decay kinematics:  $\mathbf{y}$
  - ▶ True tau-tau kinematics:  $\mathbf{x}$

$$P(m_{\tau\tau}^*) = \int \delta(m_{\tau\tau}^* - m_{\tau\tau}(\mathbf{x})) f(\mathbf{z}, \mathbf{y}, \mathbf{x}) d\mathbf{x}$$

- Take  $m_{\tau\tau}$  that maximises  $P(m_{\tau\tau}^*)$

If another source of  $\nu$  (i.e. WH production), take visible  $m_{\tau\tau}^{\text{vis}}$



# $H \rightarrow \tau\tau$

JHEP 05 (2014) 104

## Analysis overview

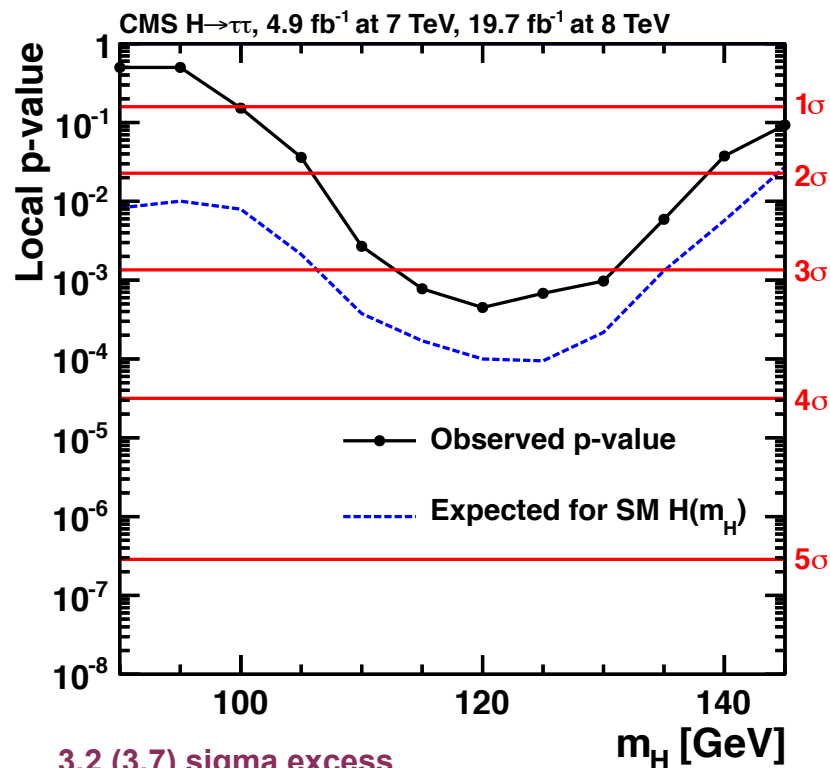
- Includes 3 main production channels
- All tau decay modes allowed
- ATLAS + CMS combined **observation** in Run I
  - ▶ No single experiment has yet made an observation
    - More data needed

Run I ATLAS+CMS combined  $H \rightarrow \tau\tau$ :

**5.5 (5.0) sigma observed (expected) significance**

ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002

## Results – Run I



3.2 (3.7) sigma excess  
observed (expected)  
@ 125 GeV

Best fit  $\mu = 0.78 \pm 0.27$

# $H \rightarrow \mu\mu$

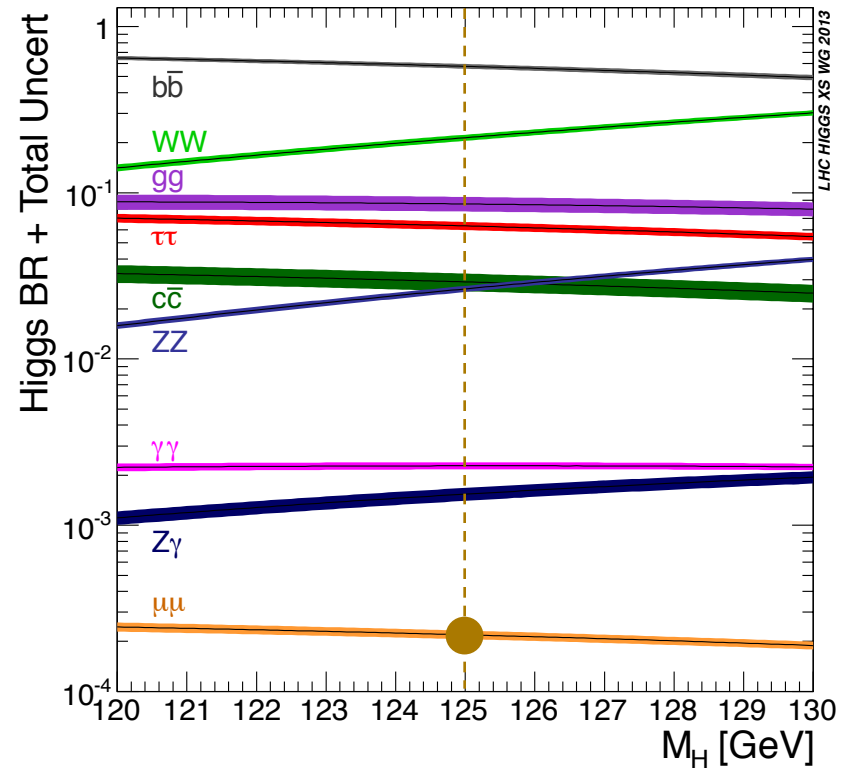
## Searches presented

Hbb

ttH

H $\tau\tau$

H $\mu\mu$



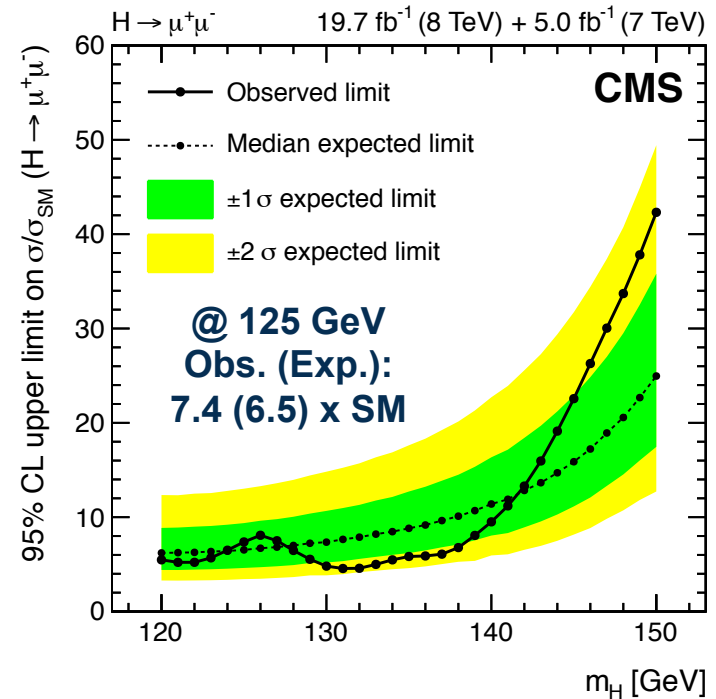
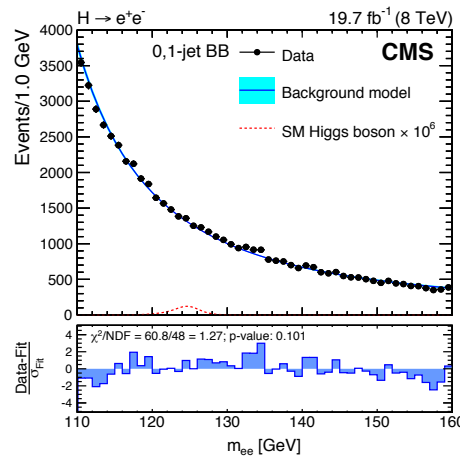
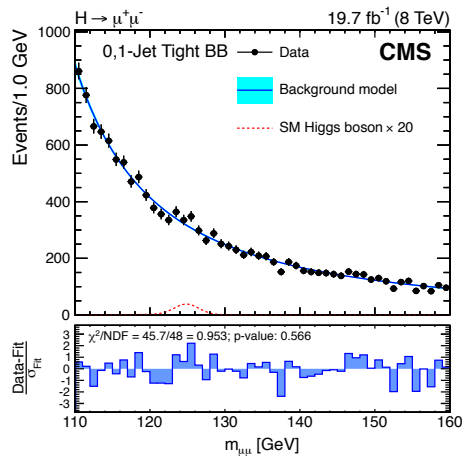
# H → μμ/ee

PLB 744 (2015) 184

## Analysis overview

- Small branching ratio
  - ▶ Cleanest of fermionic decays
  - ▶ Test of Yukawa coupling to second/first generation fermions
- Search for peak in  $m_{\ell\ell}$  spectrum
  - ▶ Over smoothly falling background

## Results – Run I



Best fit  $\mu = \sigma/\sigma_{SM} = 0.8 +3.5/-3.4$

For H → ee:

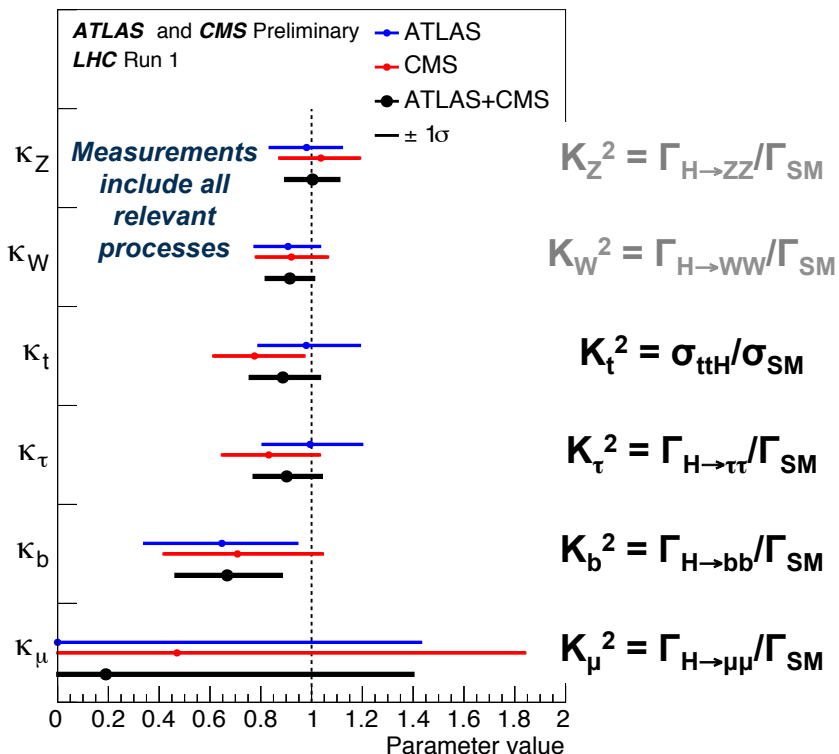
95% CL limit on  $\mu = \sigma/\sigma_{SM} \sim 4 \times 10^5$

# ATLAS+CMS combination

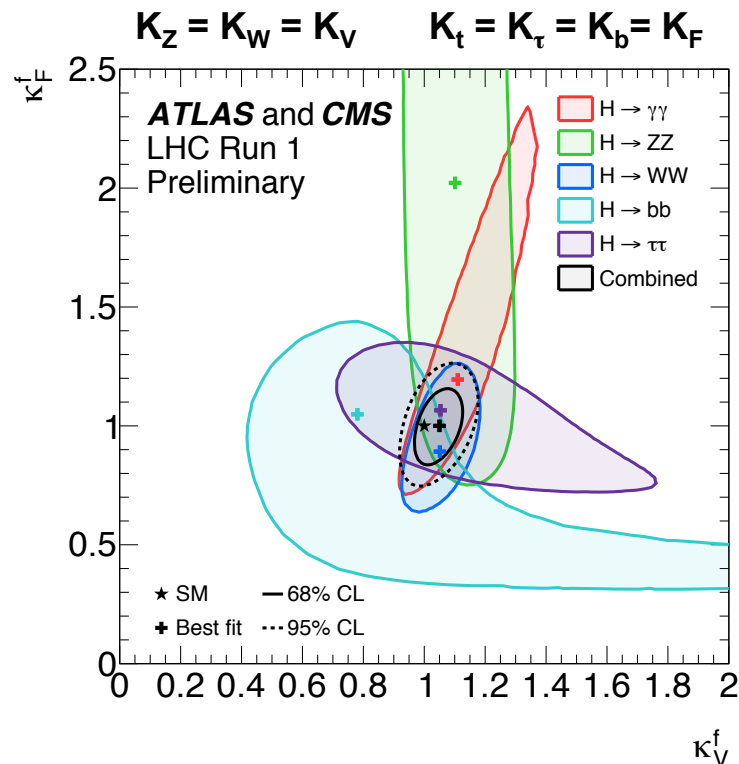
ATLAS-CONF-2015-044  
CMS-PAS-HIG-15-002

Run I:  $\sim 5 \text{ fb}^{-1}$  @ 7 TeV,  $\sim 20 \text{ fb}^{-1}$  @ 8 TeV

## Coupling modifiers



## Vector – fermion CM contours



**Data consistent with Standard Model predictions for all parameterisations**  
**However, more data needed to better constrain these parameters**

# Summary

## Summary

- Strong Run I results for CMS and ATLAS:
  - ▶ **Significance ( $\sigma$ )**

	<b>CMS Obs. (Exp.)</b>	<b>ATLAS+CMS Obs. (Exp.)</b>
ttH production	3.6 (1.3)	4.4 (2.0)
H $\rightarrow$ bb	2.0 (2.5)	2.6 (3.7)
H $\rightarrow$ $\tau\tau$	3.2 (3.7)	5.5 (5.0)

  - ▶ H $\rightarrow$  $\mu\mu$ /ee low sensitivity – still needs more data- Early Run II results show good sensitivity

## What's next?

- More data in 2016
  - ▶ Expect  $\sim 30 \text{ fb}^{-1}$  by year end
  - ▶ All analyses will reach higher sensitivities than Run I
- First results for VH, H $\rightarrow$ bb, H $\rightarrow$  $\tau\tau$ , & H $\rightarrow$  $\mu\mu$ /ee in Run II
- Updated ttH, H $\rightarrow$ bb results – including fully hadronic channel
- Observations of new physics?

# Backup



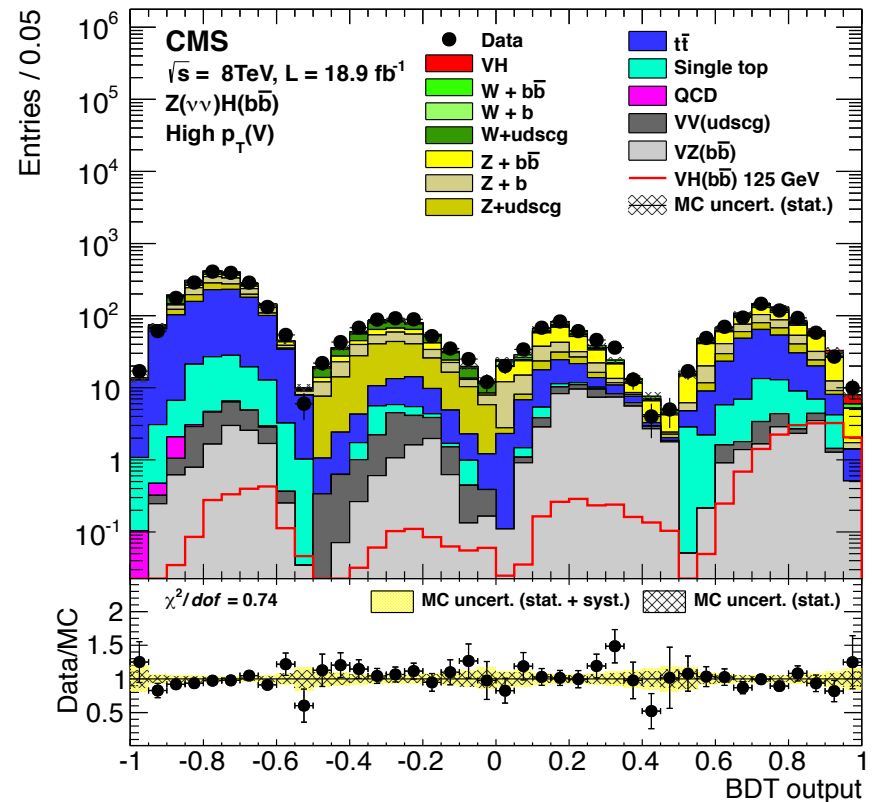
# VH, H → bb

PRD 89 (2014) 012003

## Analysis overview

- Channels include:  $W(\mu\nu)H$ ,  $W(e\nu)H$ ,  $W(\tau\nu)H$ ,  $Z(\mu\mu)H$ ,  $Z(ee)H$ ,  $Z(\nu\nu)H$
- Major backgrounds:  $V$ +jets,  $t\bar{t}$ , single-top,  $VV$  (simulated)
- Associated vector boson triggered using leptonic or tau decay
- $H \rightarrow b\bar{b}$  reconstructed from pair of  $b$ -tagged jets with highest  $p_T(jj)$ 
  - ▶ B-jet energy regression to improve  $m_{jj}$  resolution
- Boosted  $p_T$  of  $V$  or  $H$  required
- Major systematics:  $b$ -tagging scale factors, MC statistics, data estimate of background yields
- BDT discriminant

## Results – Run I



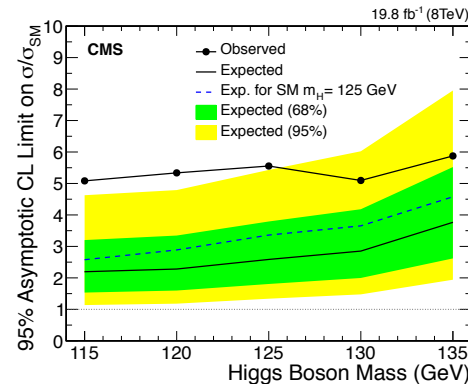
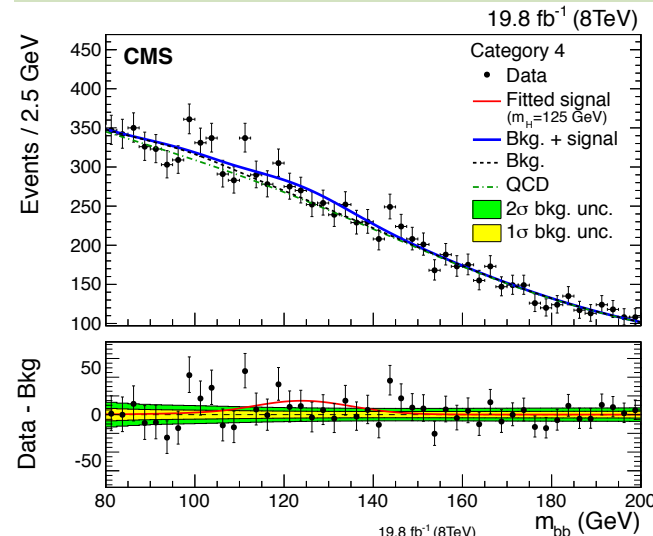
# VBF $H \rightarrow bb$

## Analysis overview

- Major backgrounds: QCD multijet (polynomial), V+jets, tt, single-top (simulated)
- 2 forward light quarks
  - $|\Delta\eta_{qq}| > 1.2, 4.1$  (trigger dependant)
  - $m_{qq} > 200, 460$  GeV
- $H \rightarrow bb$  reconstructed from pair of b-tagged jets with  $\Delta\phi_{bb} < 2.0$ 
  - B-jet energy regression to improve  $m_{jj}$  resolution
- BDT discriminant for signal/QCD separation and categorisation
- Major systematics: QCD description, JEC, b-tagging, trigger scale factor
- Invariant mass final distribution

## Results – Run I

PRD 92 (2015) 032008



**Obs. (Exp.) @ 125 GeV:  
5.5 (2.5)**

**2.2 (0.8) sigma excess  
observed (expected)  
@ 125 GeV**

**Best fit  $\mu = \sigma/\sigma_{SM} =$   
2.8 +1.6/-1.4**

# ttH, H → bb

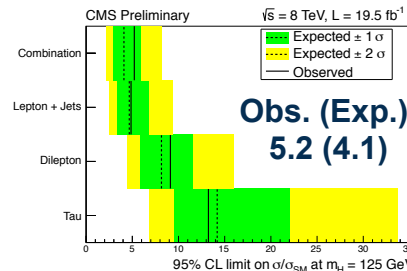
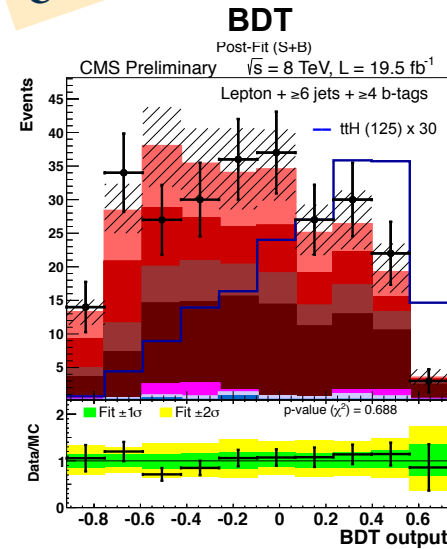
## Analysis overview

- Major backgrounds: tt+jets (including tt+bb), single-top, V+jets, VV, tt+V (simulated)
- 1 or 2 opposite sign leptons
- At least 4 (l+jets) or 3 (DL) jets
  - Including at least 2 b-tags
  - Boosted top and Higgs in Run II
- Several event categories
  - Based on  $N_{\text{jets}}$  and  $N_{\text{b-jets}}$
- Major systematics: JES, b-tagging, theory uncertainty on tt+hf
- BDT and Matrix Element discriminants used

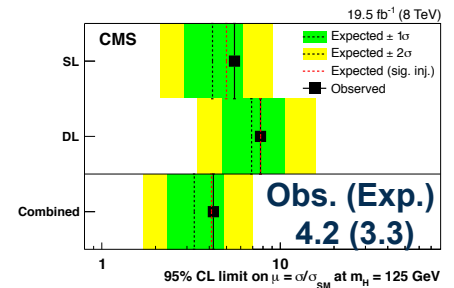
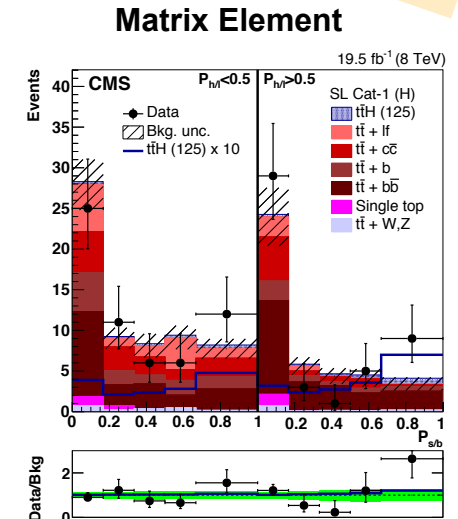
CMS-PAS-HIG-13-019

## Results – Run I

EPJC 75 (2015) 251



Best fit  $\mu = 0.9 +2.5/-2.4$



Best fit  $\mu = 1.2 +1.6/-1.5$



13 TeV

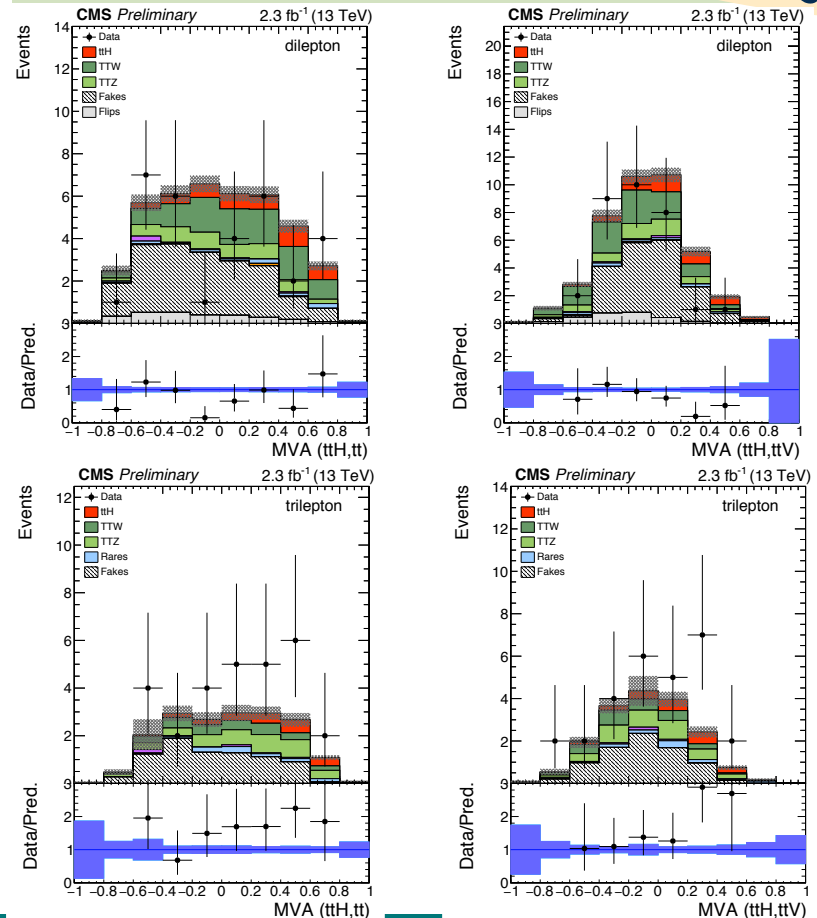
# ttH, multileptons

CMS-HIG-15-008

## Analysis overview

- Channels include: ttH(ZZ\*), ttH(WW\*), ttH( $\tau\tau$ )
  - ▶ Leptonic top and Z,W, $\tau$  decays
  - ▶ 1 hadronic top and Z,W, $\tau$  allowed
- Major backgrounds: ttV, VV (simulated), QCD (fake leptons, data estimated)
- At least 4 or 2 jets (2SSL, 3L)
  - ▶ Including at least 1 b-tag
- Cut on ETmissLD > 45 GeV
- BDT variables
  - ▶ tt: Maxeta(l1,l2), nj,  $\Delta R_{\min}(l1,j)$ ,  $\Delta R_{\min}(l2,j)$ , ETmiss,  $\Delta R_{\text{ave}}(j,j)$ , MT(l,ET)
  - ▶ ttV: Maxeta(l1,l2), nj,  $\Delta R_{\min}(l1,j)$ ,  $\Delta R_{\min}(l2,j)$ , l1pT, l2pT, MT(l,ET)

## Results – Run II



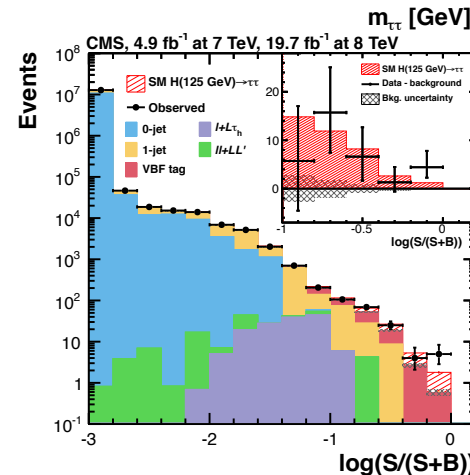
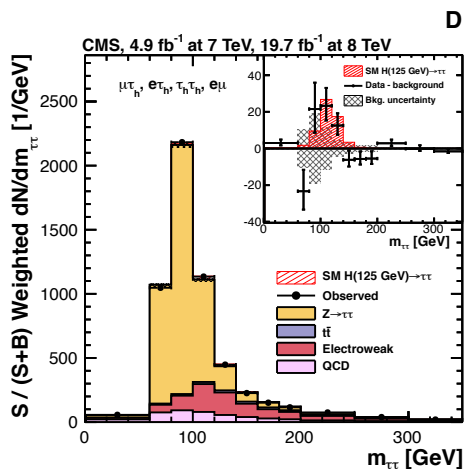
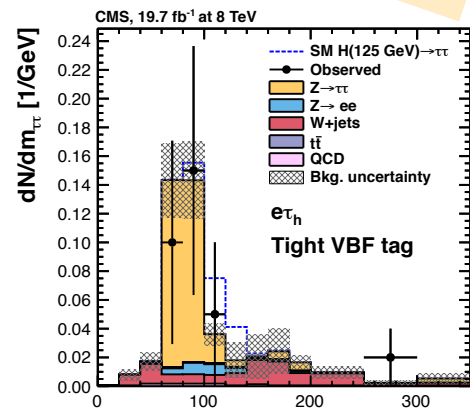
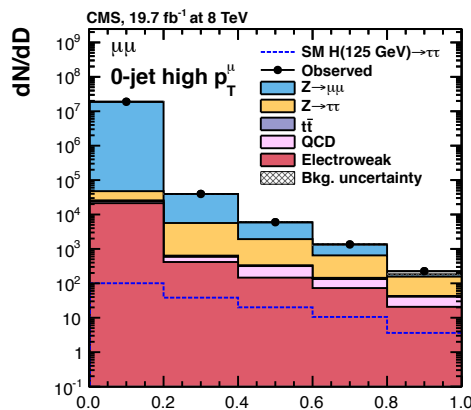
# H $\rightarrow$ $\tau\tau$

JHEP 05 (2014) 104

## Analysis overview

- Production: gF, VBF, VH
- 3 channels: LL',  $l+L\tau_h$ ,  $ll+LL'$ 
  - $ee, \mu\mu, e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$
  - $\mu+\mu\tau_h, e+\mu\tau_h/\mu+e\tau_h, e+\tau_h\tau_h, \mu+\tau_h\tau_h$
  - $ll + \mu\tau_h, e\tau_h, e\mu, \tau_h\tau_h$
- Muon, lepton+ $\tau_h$ , di- $\tau_h$  triggers
- Major backgrounds: DY  $Z\rightarrow\tau\tau/ll$ , QCD multijet (data estimated), W+jets, tt, (simulated)
- Several event categories
  - Based on  $N_{\text{jets}}, N_{\text{leps}}$  and  $p_T$  of  $l, \tau, H$
- Major systematics: QCD norm., false e/u/jet  $\rightarrow \tau_h$  id, tau/JES
- BDT (ee or  $\mu\mu$  channels) or  $m_{\tau\tau}$  or  $m_{\text{vis}}$  discriminant

## Results – Run I



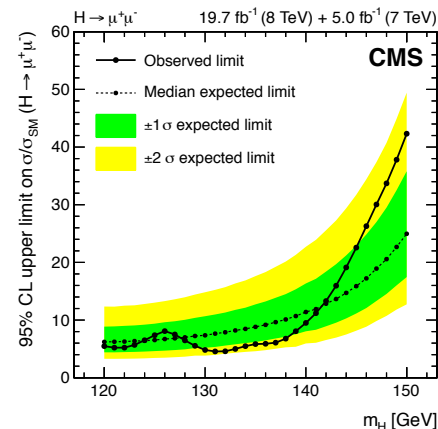
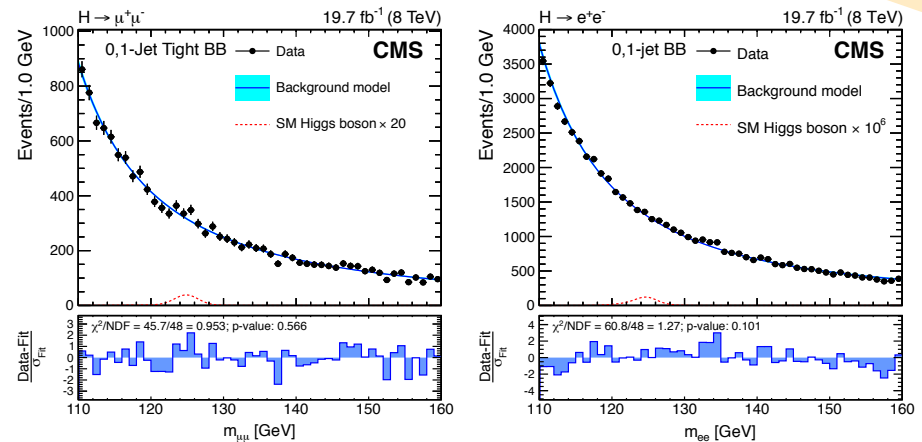
# H → μμ/ee

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## Analysis overview

- Single-μ (24), double-e (17,8) trigger
- 2 OS μ,  $p_T > 25/15$ ,  $|\eta| \leq 2.1$
- 2 electrons,  $p_T > 25$ ,  $|\eta| < 2.5$
- Major backgrounds: DY  $Z/\gamma \rightarrow \ell\ell$ ,  $t\bar{t}$ ,  $VV$  (fitted from data)
- Several event categories
  - ▶ Based on  $N_{\text{jets}}$  and  $p_T(\mu\mu) / m_{ee}$
  - ▶ 0, 1,  $\geq 2$  jets, split in two sub-cat.
- Major systematics:  $\mu$ - $p_T$  scale/res., background parameterization
- Signal extracted by fitting  $m_{\ell\ell}$  with parameterized bkg+signal in all categories simultaneously

## Results – Run I



Obs. (Exp.) @ 125 GeV:  
7.4 (6.5)

Best fit  $\mu = \sigma/\sigma_{\text{SM}} =$   
0.8 +3.5/-3.4

For  $H \rightarrow ee$ :

95% CL limit on  
 $\mu = \sigma/\sigma_{\text{SM}}$   
 $\sim 4 \times 10^5$