Studies of Higgs bosons decaying to fermions with CMS

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on behalf of the CMS Collaboration

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Outline

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     - VBF
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   - ttH combination
   - $H \to \tau\tau$
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3. Standard Model ATLAS+CMS combination
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   - Run I $X \to HH$ comparison
   - $X \to H(bb)H(bb)$
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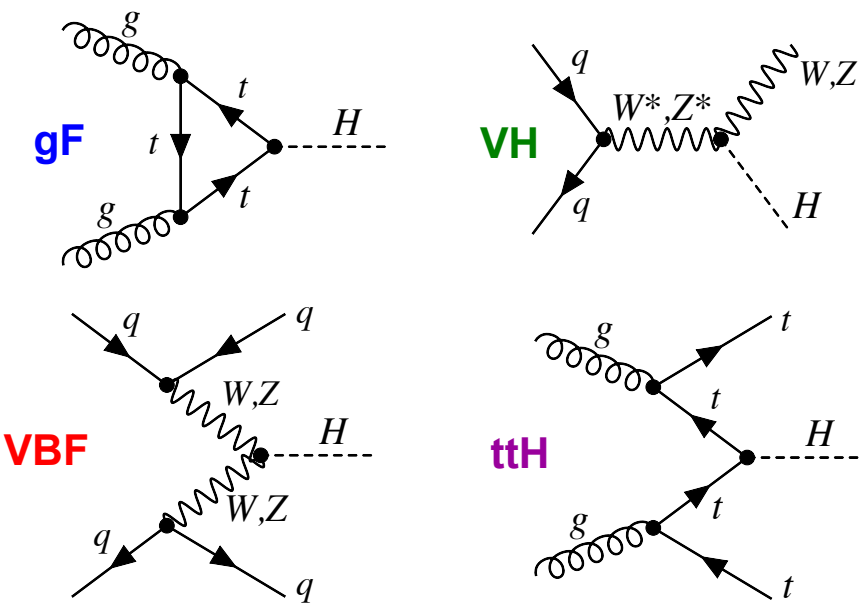
   - $X \to H(bb)H(\tau\tau)$
   - Non resonant $H(bb)H(\tau\tau)$
5. Summary

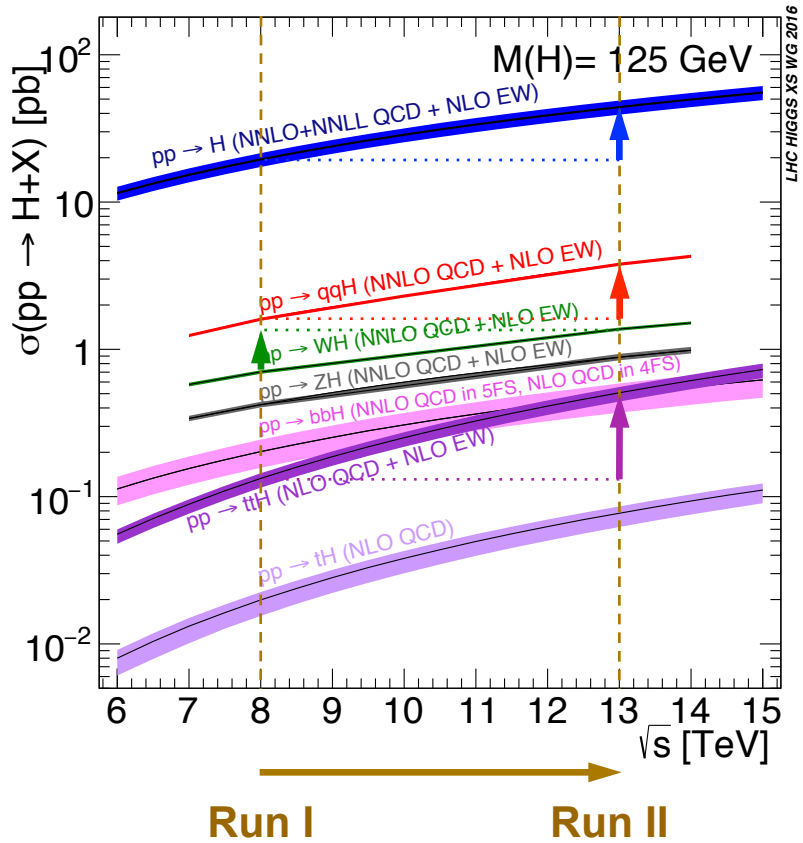
SM Higgs boson production

Introduction

- Higgs boson with 125 GeV mass discovered by CMS and ATLAS
- Number of different production mechanisms



Production cross section at LHC

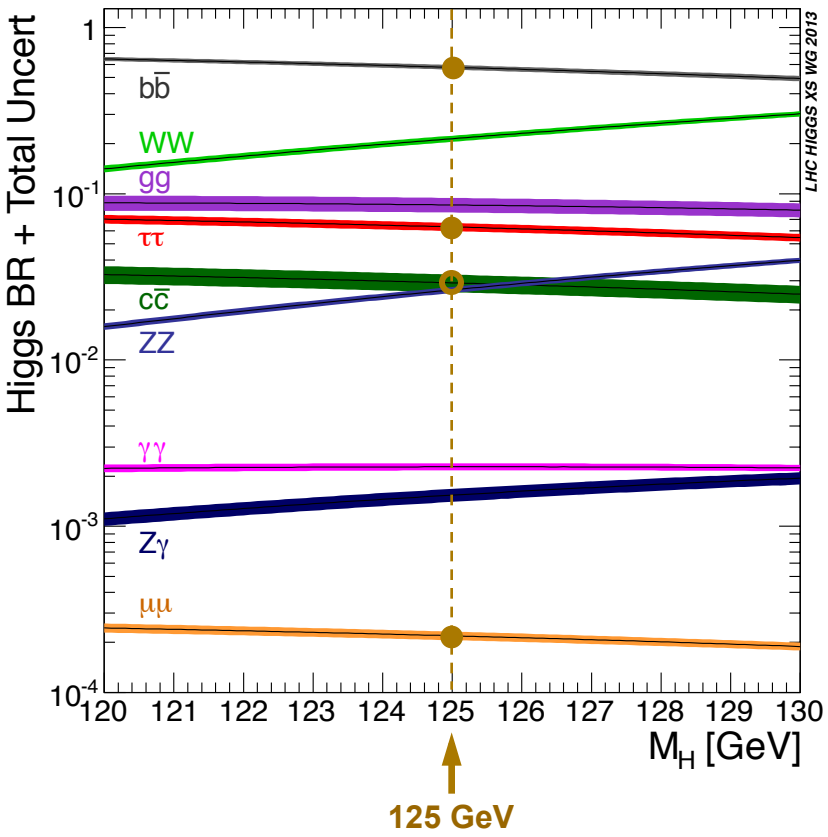


Higgs boson decay

Comments

- Fermionic decay channels offer good prospects
  - Large branching ratios for $H \rightarrow bb, \tau\tau, cc$
    - Analyses less sensitive due to large backgrounds (too large for cc)
- Observation of fermionic decays would be a test of the Yukawa couplings
- Provide insight into possible new physics

Decay branching ratios



Standard model searches

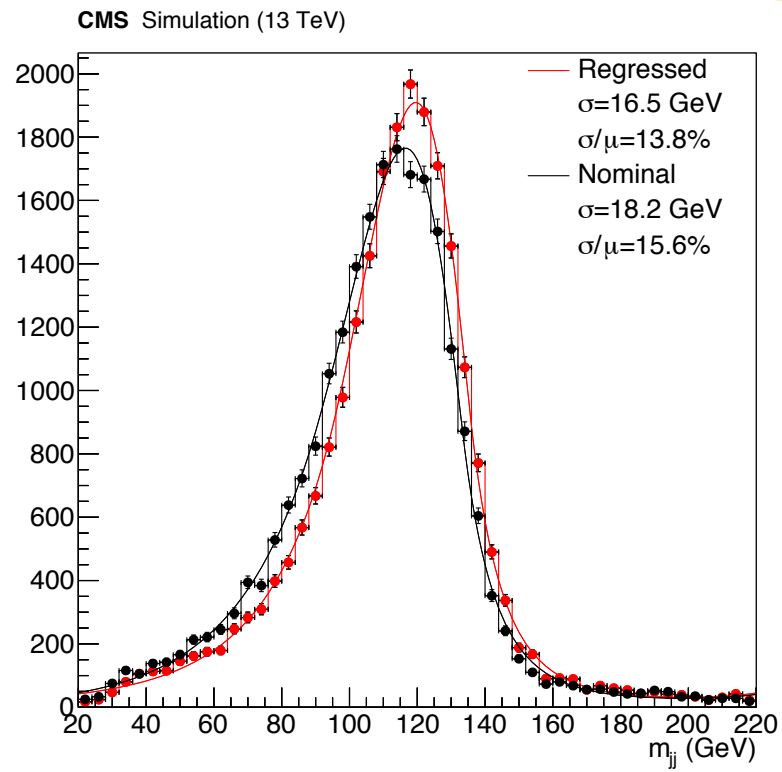
H→bb: Reconstructing m_{bb}

VH, H→bb Dec 15

Regression method (VH & VBF)

- Applied to b-tagged jets
- Aims to improve the standard CMS jet calibration to 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 ~ 15%
  - Improves VH analysis sensitivity by 10-20%

Higgs mass – Run II

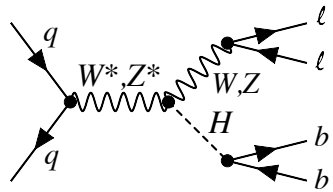


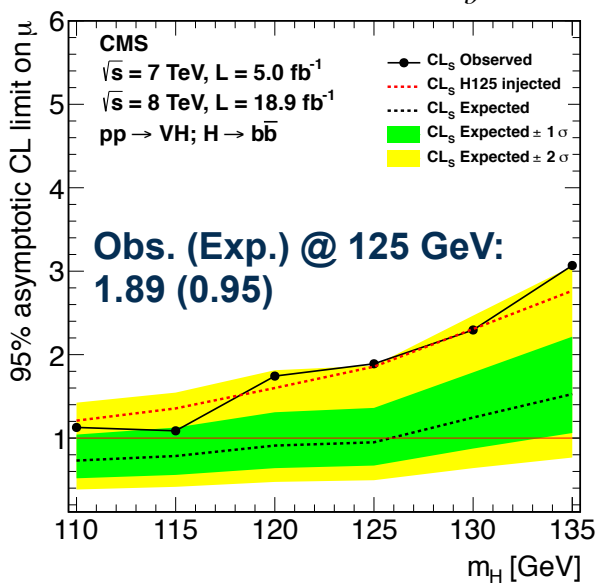
H→bb candidate invariant mass without (black) and with (red) b-jet regression fitted with the Bukin function.

H→bb

VH, H→bb – Run I

PRD 89 (2014) 012003





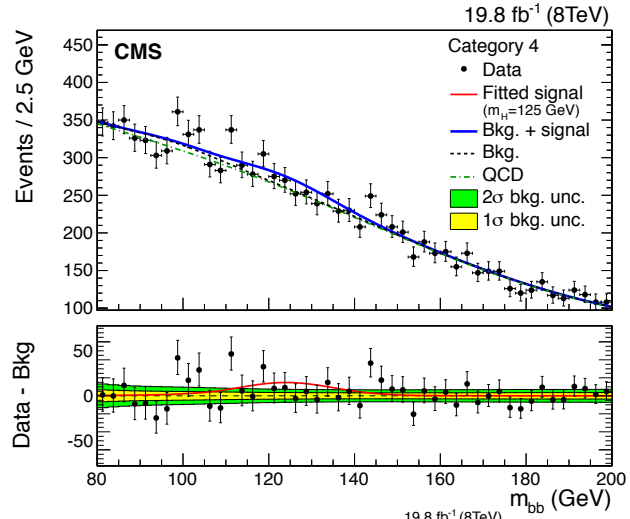
Obs. (Exp.) @ 125 GeV: 1.89 (0.95)

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

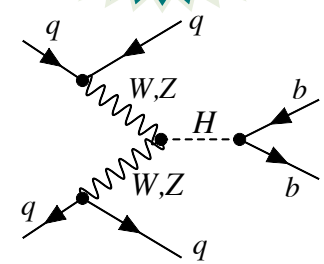
Best fit $\mu = \sigma/\sigma_{SM}$ = 1.0 ± 0.5

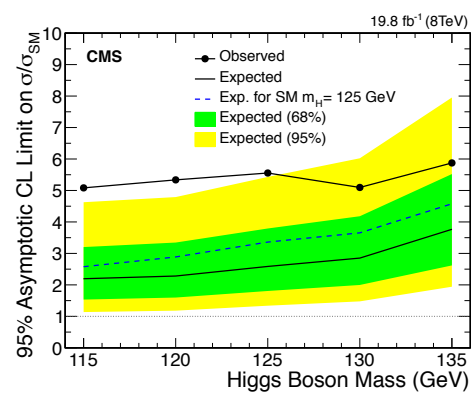
VBF, H→bb – Run I

PRD 92 (2015) 032008



Fully Hadronic





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

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

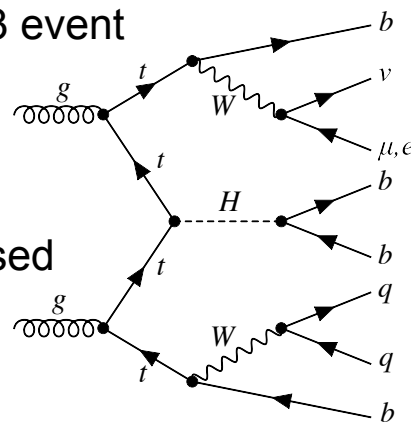
Best fit $\mu = \sigma/\sigma_{SM}$ = 2.8 +1.6/-1.4

13 TeV

ttH, H→bb

Analysis overview

- Small cross section, but direct probe of the Higgs/top Yukawa coupling y_t
- 2 channels & 13 event categories
- 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)

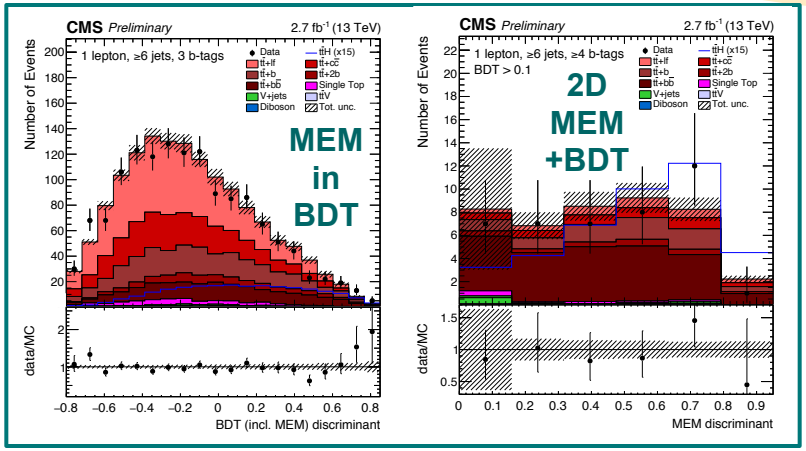
Best fit $\mu = \sigma/\sigma_{SM}$ = –2.0 ± 1.8

1.7 sigma below SM expectation

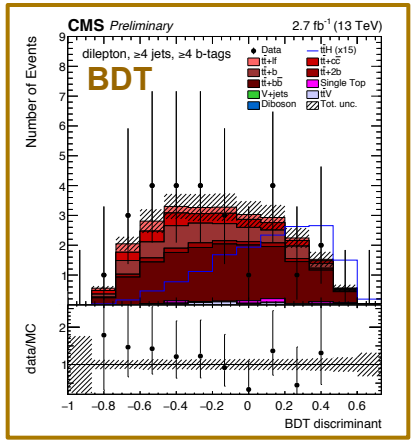
Results – Run II

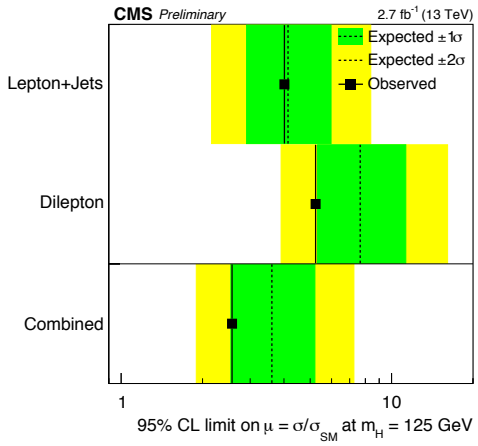
CMS-HIG-16-004

lepton + jets



dilepton





13 TeV

ttH, multileptons

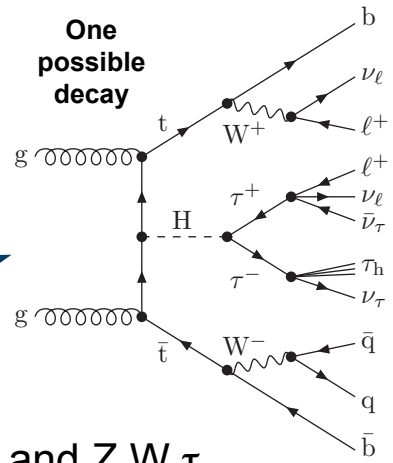
CMS-HIG-15-008

Analysis overview

Channels:

- ttH(ZZ*)
- ttH(WW*)
- ttH(ττ)
  - 1 hadronic top and Z,W,τ allowed
- BDT final discriminant

One possible decay



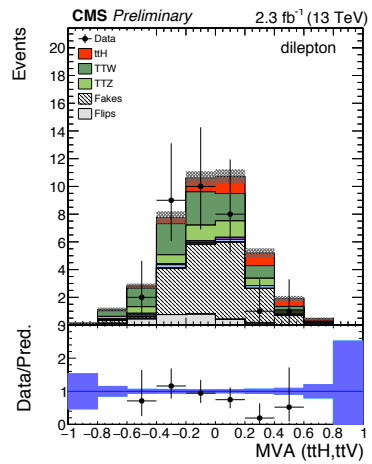
Run I results at 8 TeV:

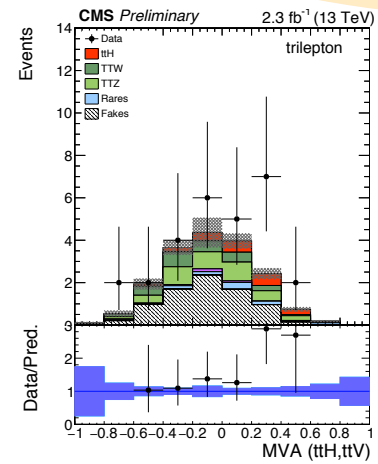
Obs. (Exp.) limit: 6.6 (2.4)

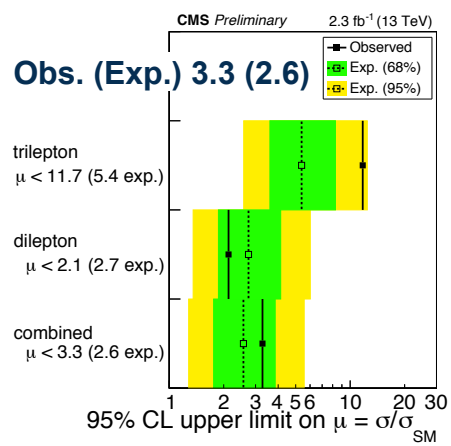
Excess observed in di-muon channel

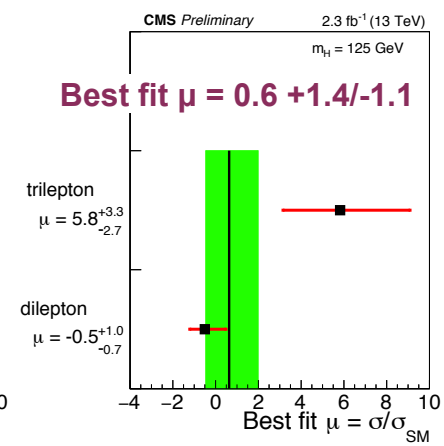
CMS-PAS-HIG-13-020

Results – Run II









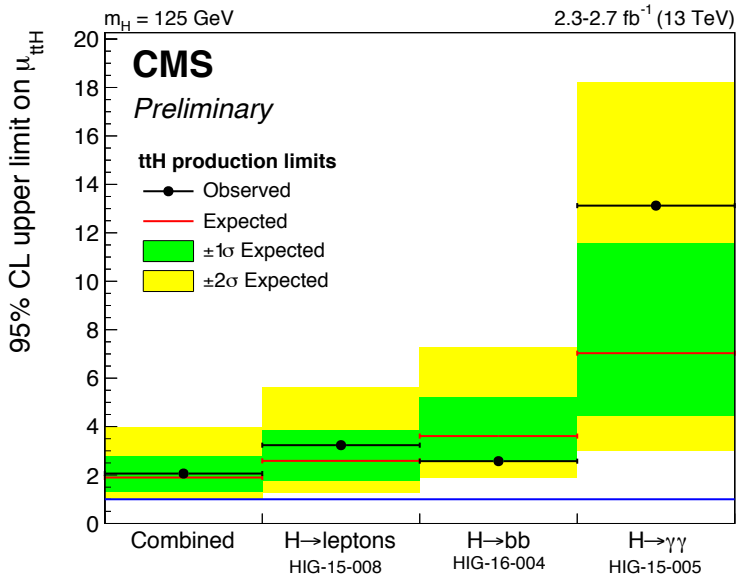
13 TeV

ttH, combination

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

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

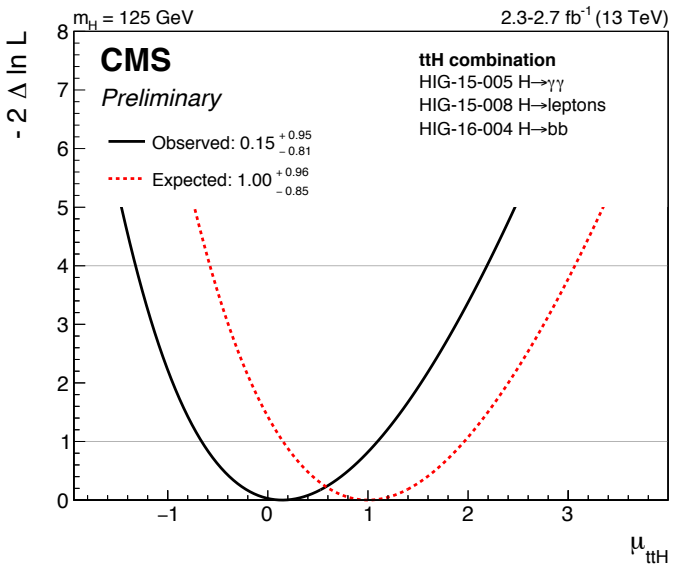
95% CL upper limit on μ_{ttH}



Observed limit on μ_{ttH} = 2.1

Expected limit on μ_{ttH} = 1.9

ttH signal strength



Observed μ_{ttH} = 0.15 +0.95/-0.81

Expected μ_{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 μ = 2.8 +1.0/-0.9** JHEP 09 (214) 087

$H \to \tau\tau$: Reconstructing $m_{\tau\tau}$

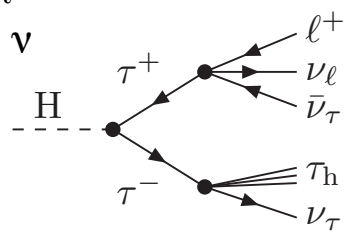
Likelihood method

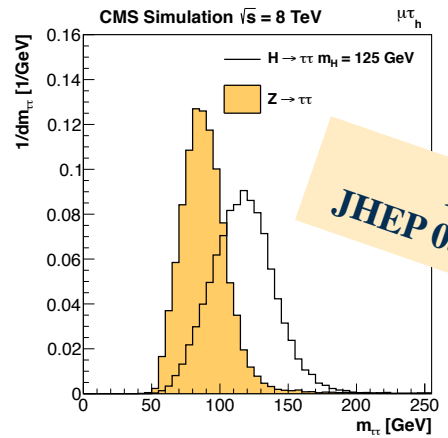
- Tau decay produces invisible ν_τ
  - Leptonic decay produces further ν
  - $m_{\tau\tau}$ is left unconstrained
- If no other source of neutrino, construct a likelihood f(**z**,**y**,**x**)
  - E_T^{miss}: **z**
  - Visible decay kinematics: **y**
  - True tau-tau kinematics: **x**

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

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

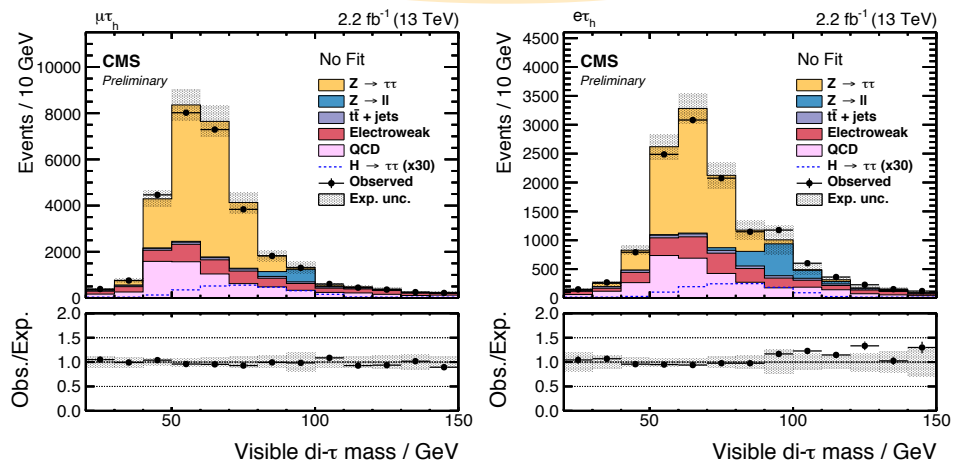
If another source of ν (i.e. WH production), take visible $m_{\tau\tau}^{vis}$





Run I
JHEP 05 (2014) 104

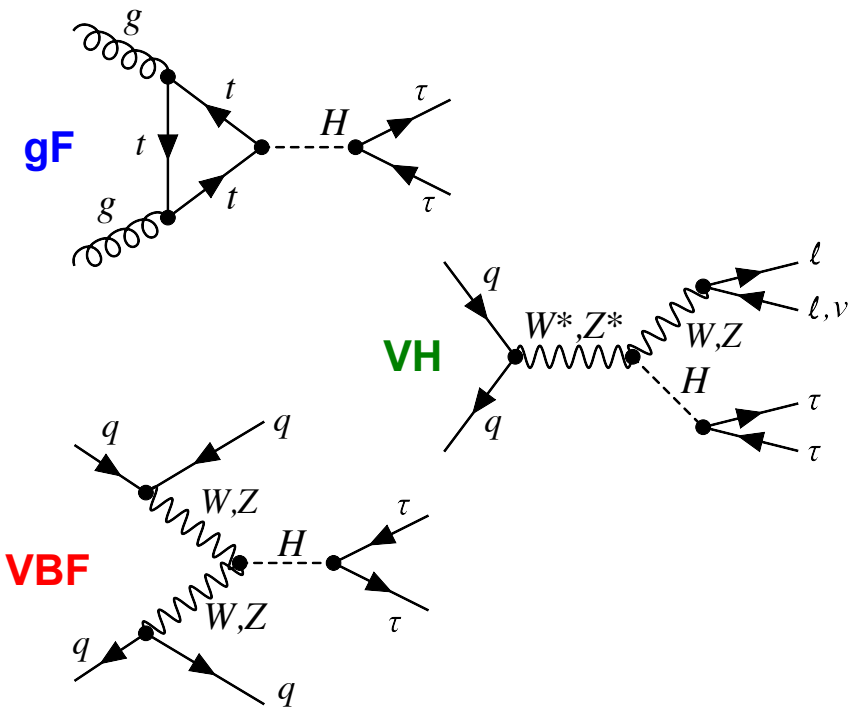
Run II – Dec 15



H→ττ

JHEP 05 (2014) 104

Production channels

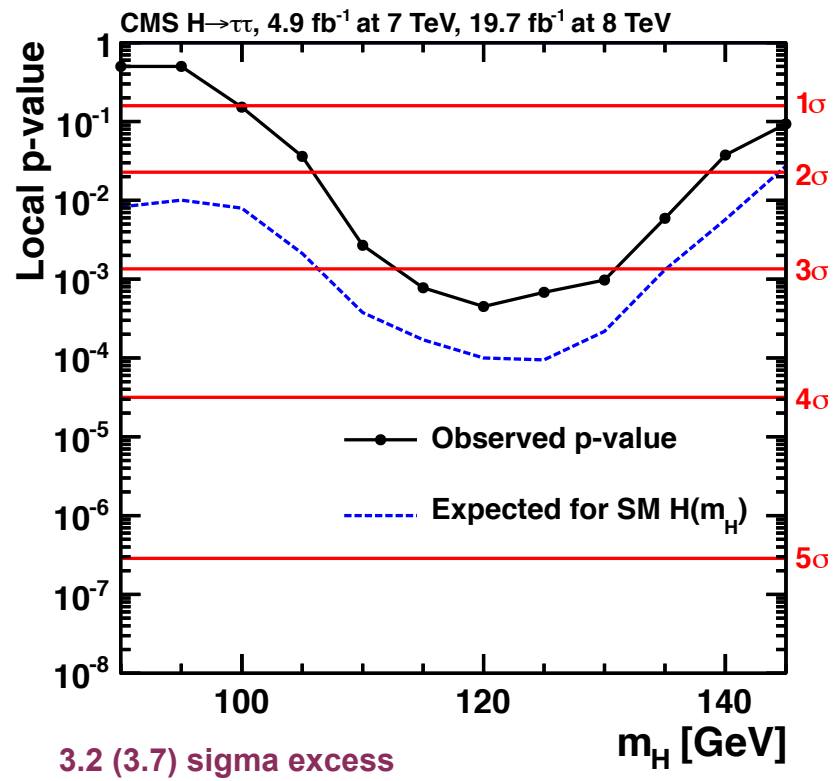


Run I ATLAS+CMS combined H→ττ:

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

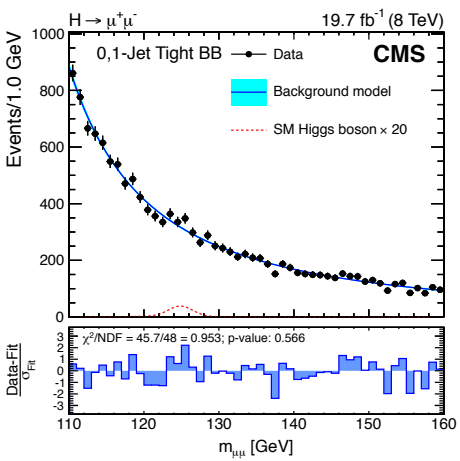
Best fit μ = 0.78 ± 0.27

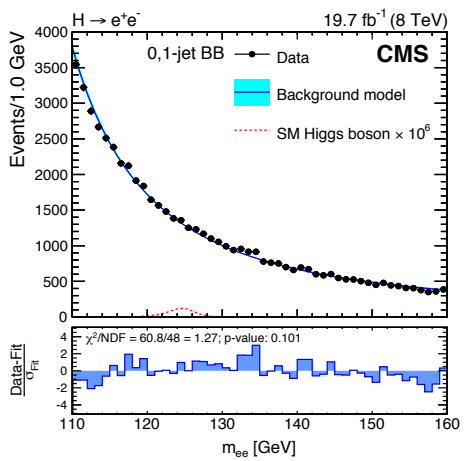
H→μμ/ee

PLB 744 (2015) 184

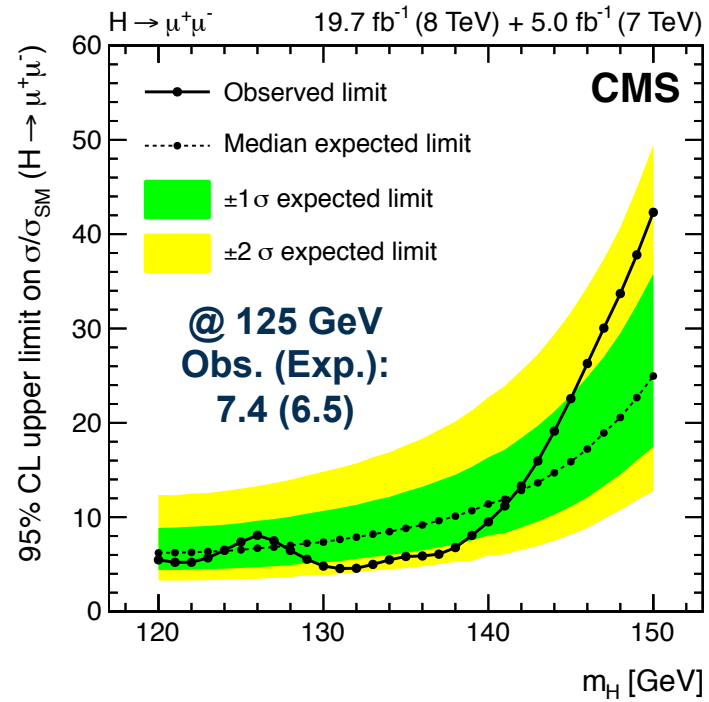
Analysis overview

- 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:

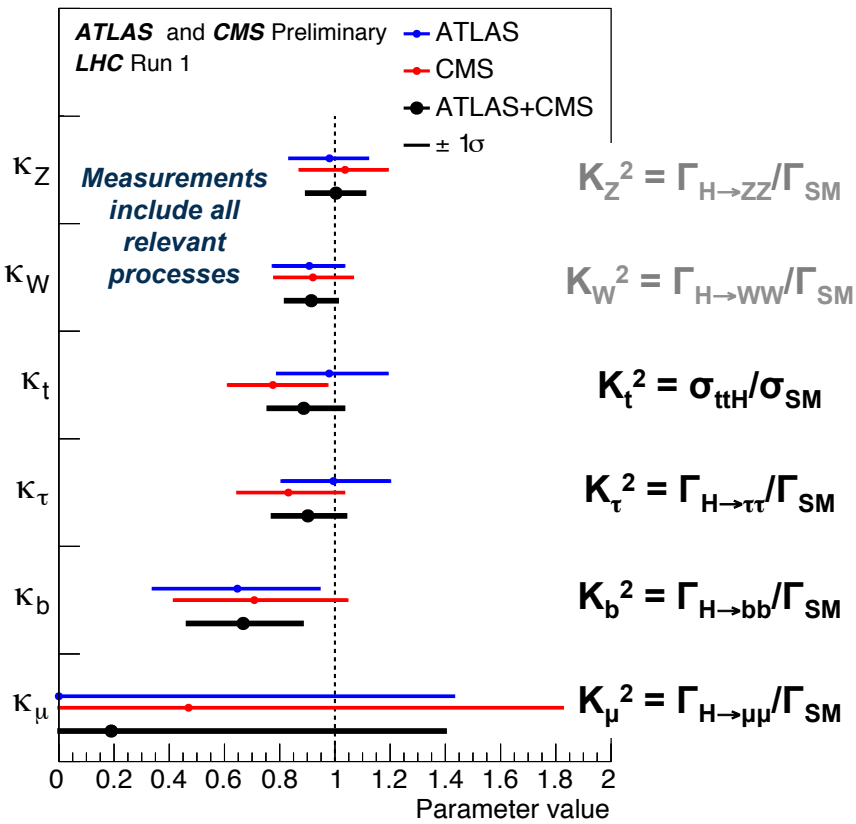
95% CL limit on $\mu = \sigma/\sigma_{SM} \sim 4 \times 10^5$

ATLAS+CMS combination

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

Run I: ~ 5 fb^{-1} @ 7 TeV, ~ 20 fb^{-1} @ 8 TeV

Coupling modifiers



$K_Z^2 = \Gamma_{H\to ZZ}/\Gamma_{SM}$

$K_W^2 = \Gamma_{H\to WW}/\Gamma_{SM}$

$K_t^2 = \sigma_{ttH}/\sigma_{SM}$

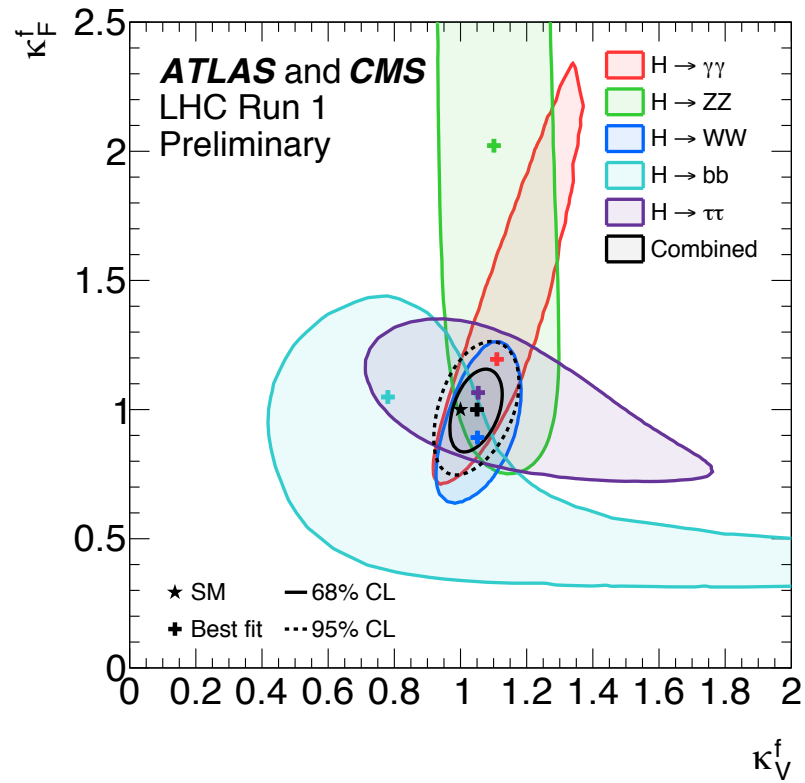
$K_\tau^2 = \Gamma_{H\to\tau\tau}/\Gamma_{SM}$

$K_b^2 = \Gamma_{H\to bb}/\Gamma_{SM}$

$K_\mu^2 = \Gamma_{H\to\mu\mu}/\Gamma_{SM}$

Vector – fermion CM contours

$K_Z = K_W = K_V$ $\quad$ $K_t = K_\tau = K_b = K_F$



Data consistent with Standard Model predictions for all parameterisations

Di-Higgs production

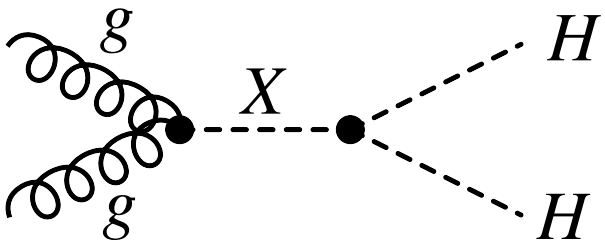
X→HH overview

Motivation

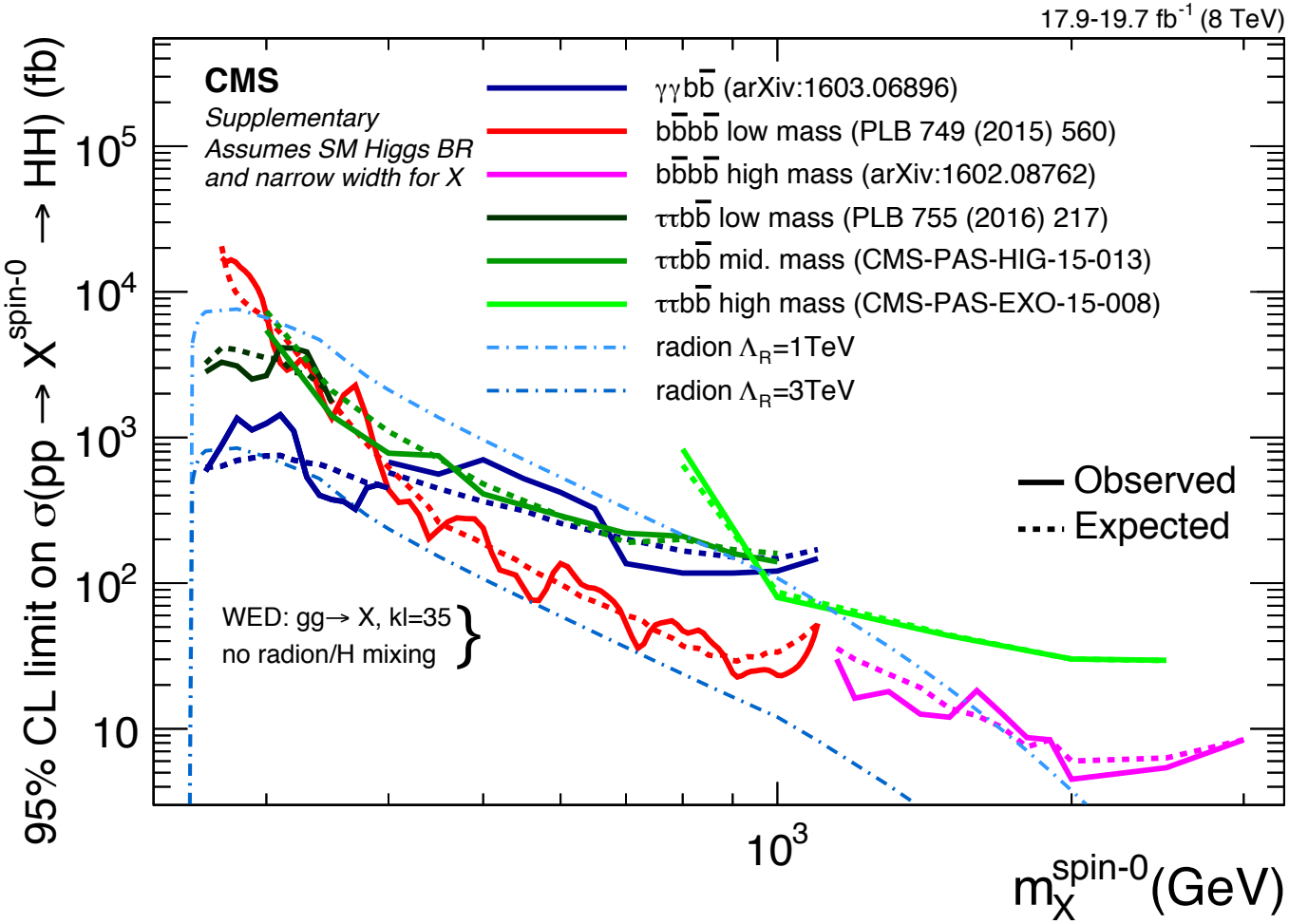
- Several BSM models predict narrow-width HH resonances
  - Heavy Higgs
  - Spin-0 radion
  - KK-graviton in extra dimensions
- Production cross section unknown
- Higher LHC energy opens up a new range of search possibilities

Search strategy

- The aim is to reconstruct the resonant particle mass
  - First reconstruct 2 SM Higgs
  - Analyses employ different techniques for m_H reconstruction
- SM t-tbar production is a major background
  - Analyses use different techniques for background rejection



Run I X→HH comparison



95% CL upper limit on:

$\sigma(pp \to X \to HH)$

with spin-0 X

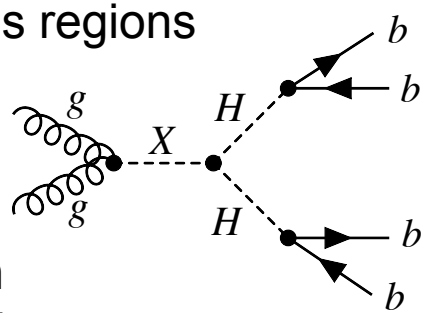
13 TeV

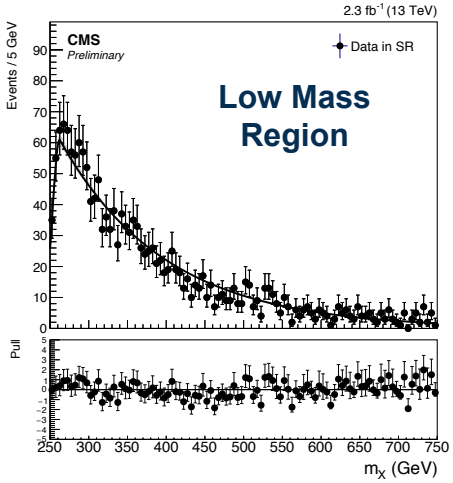
X→H(bb)H(bb)

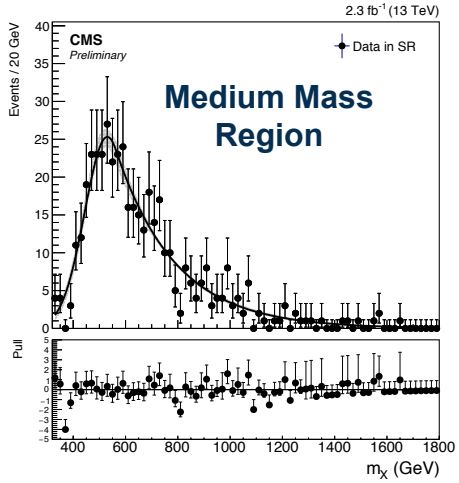
CMS-HIG-16-002

Analysis overview

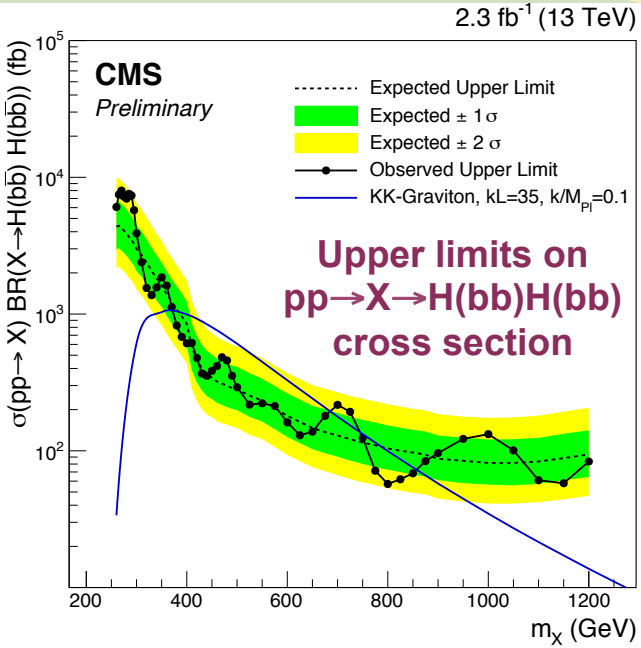
- Search in 2 mass regions
- Requires at least 4 b-tagged jets
- 2 b-jet pairs with mass close to Higgs mass







Results – Run II



RS1 KK-Graviton with kL = 35, k/M_{Pl} = 0.1, observed (expected) exclusion range at 95% CL: 775-850 (390-790) GeV

Same RS1 KK-Graviton exclusion at 8 TeV: Observed (expected) range 380-800 (360-900) GeV

PLB 749 (2015) 560

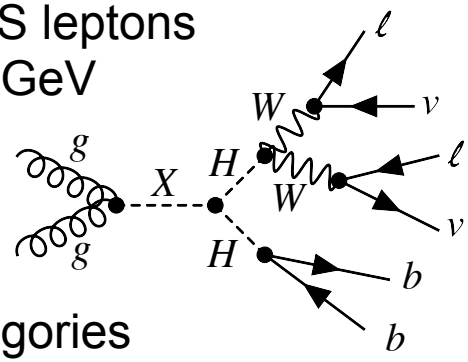
13 TeV
First time @ LHC

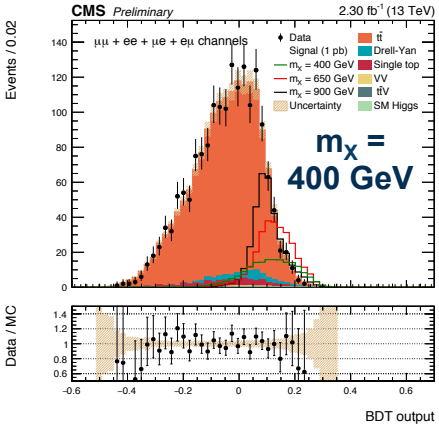
X→H(bb)H(WW)

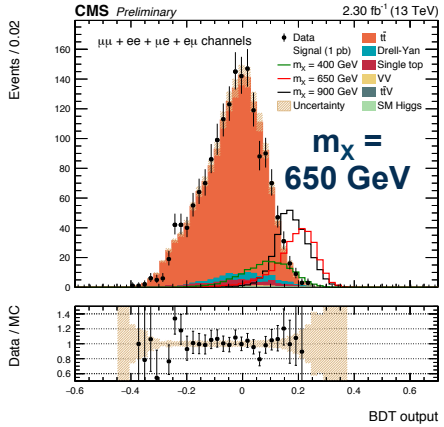
CMS-HIG-16-011

Analysis overview

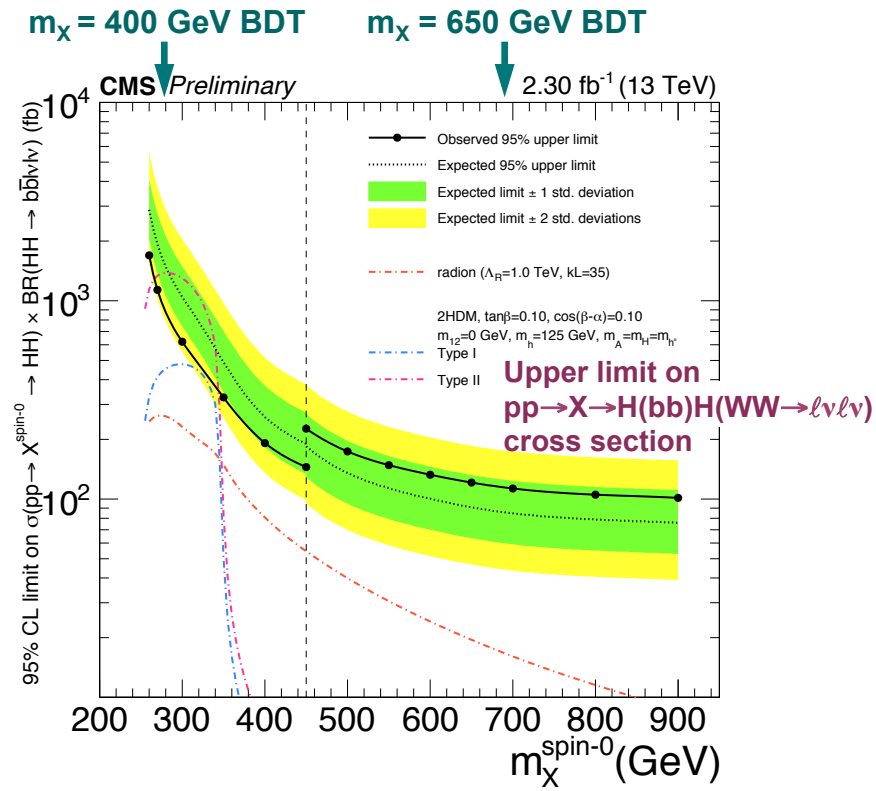
- Requires 2 OS leptons with $m_{\ell\ell}$ > 12 GeV
- At least 2 b-jets
- BDT used to define categories
  - 2 signal masses used for training







Results – Run II



For 500 < m_X < 900 GeV
Obs. (Exp.) exclusion @ 95% CL: 174–101 (135–76) fb

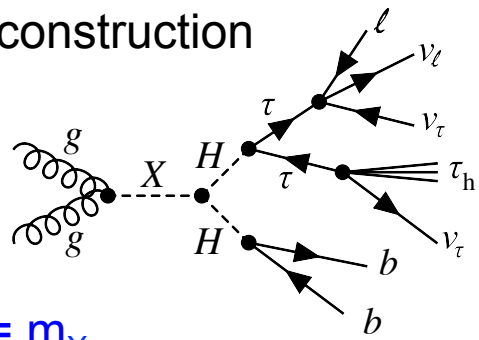
13 TeV

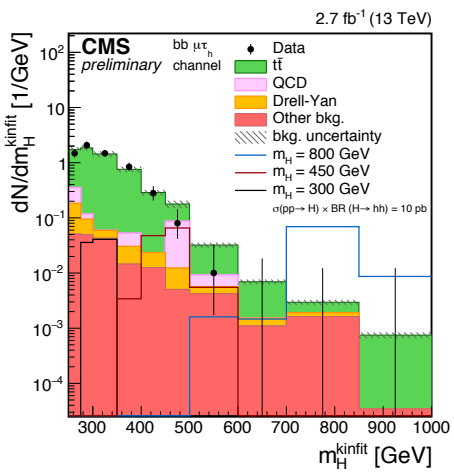
X→H(bb)H(ττ)

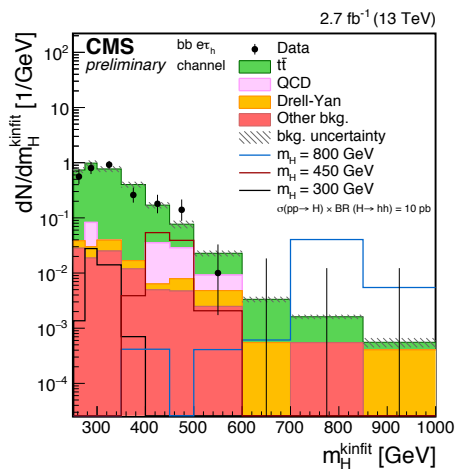
CMS-HIG-16-013

Analysis overview

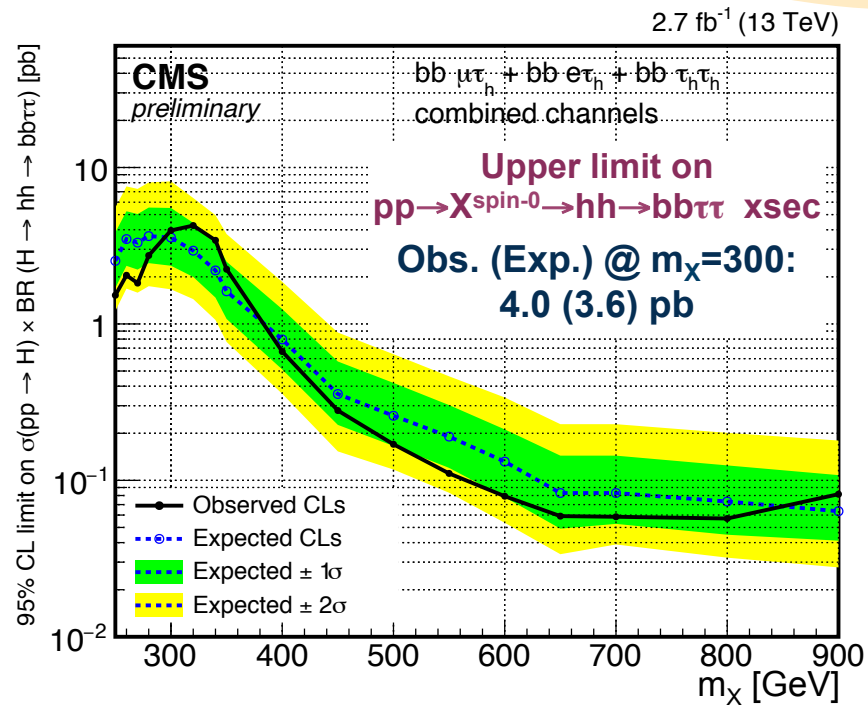
- Likelihood reconstruction of $m_{\tau\tau}$
- $m_{\tau\tau}$, m_{bb} = 80-160 GeV
- $m_{bbL\tau} = m_{HH} = m_X$ reconstructed using kinematic fit







Results – Run II



Spin-0 limit at 8 TeV:

Obs. (exp.) @ m_X=300 GeV:
~ 5.4 (7.8) pb

CMS-HIG-15-013

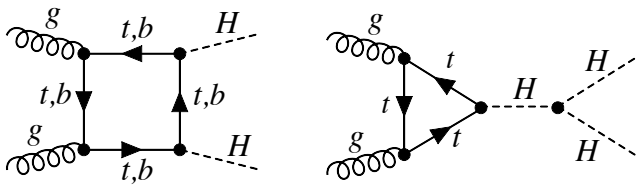
13 TeV Non resonant H(bb)H(ττ)

CMS-HIG-16-012

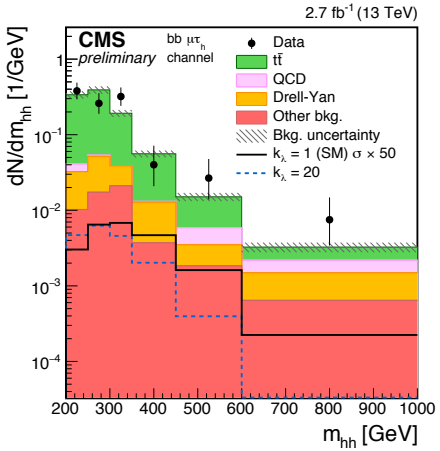
Analysis overview

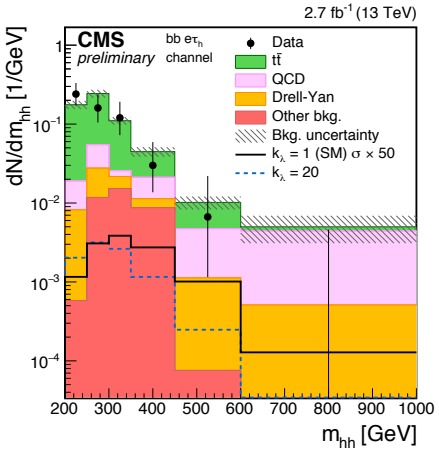
- Very sensitive to BSM physics

SM production

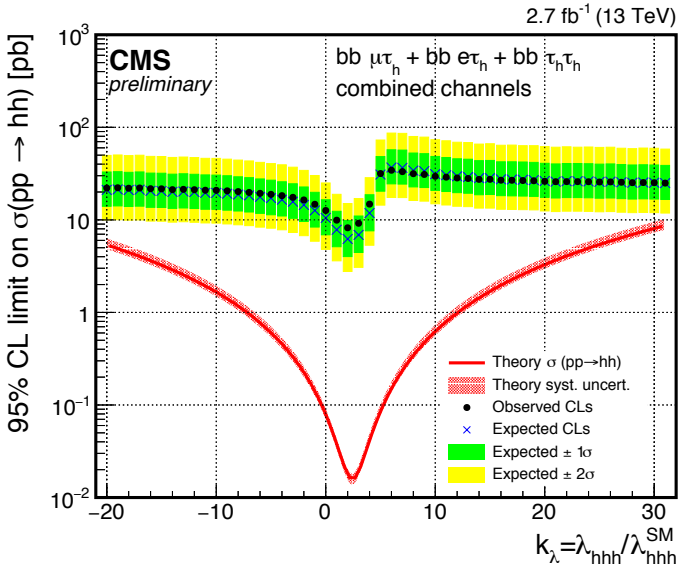


- Likelihood reconstruction of $m_{\tau\tau}$
  - $m_{\tau\tau}$, m_{bb} = 80-160 GeV
- $m_{bbL\tau}$ = m_{HH} final discriminant





Results – Run II



Ratio of anomalous trilinear coupling to SM coupling ($k_\lambda = \lambda_{hhh}/\lambda^{SM}_{hhh}$)

Upper limit on pp→hh cross section

Obs. (Exp.) @ k_λ = 1: 8.8 (7.2) pb

~ 230 (190) x SM prediction

At 8 TeV:

Observed (expected) limit = 53 (84) x SM prediction

CMS-HIG-15-013

Summary

Summary

- Strong Run I results for CMS and ATLAS:
  -

Significance (σ)	CMS Obs. (Exp.)	ATLAS+CMS Obs. (Exp.)
ttH production	3.6 (1.3)	4.4 (2.0)
H→bb	2.0 (2.5)	2.6 (3.7)
H→ττ	3.2 (3.7)	5.5 (5.0)

  - H→μμ/ee low sensitivity – still needs more data
- Di-Higgs: BSM exclusions, on the way to SM HH sensitivity

What's next?

- More data in 2016
  - Expect ~ 30 fb^{-1} by year end
  - All analyses will reach higher sensitivities than Run I
- First results for VH/VBF, H→bb, H→ττ, & H→μμ/ee in Run II
- Updated ttH, H→bb results – including fully hadronic channel
- Observations of new physics?

Backup

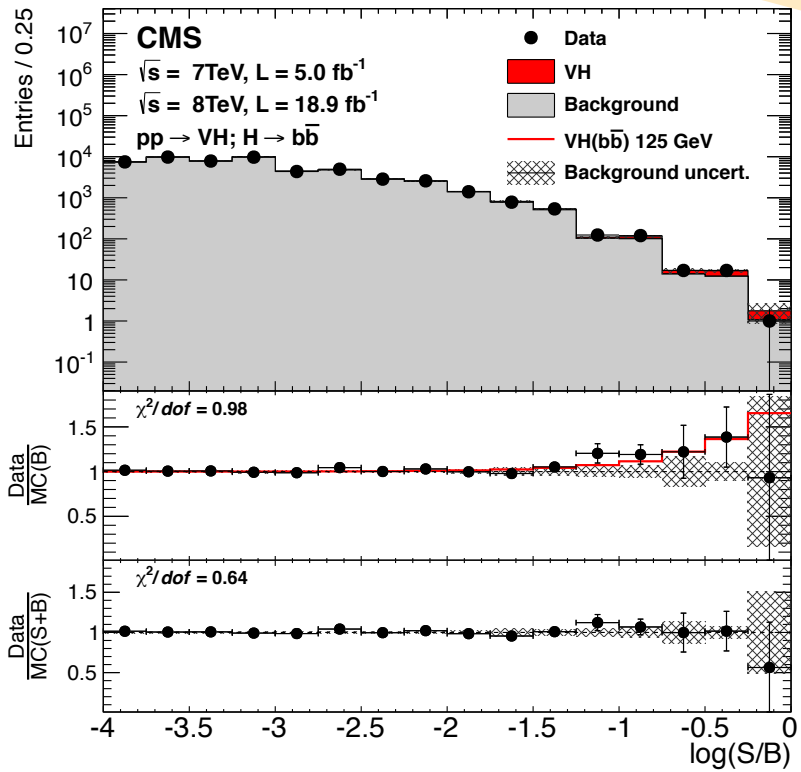
VH, H→bb

Analysis overview

- Channels include: W(μν)H, W(eν)H, W(τν)H, Z(μμ)H, Z(ee)H, Z(νν)H
- Major backgrounds: V+jets, tt, single-top, VV
- Associated vector boson tagged using leptonic decay
- H→bb 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
- BDT discriminant

Results – Run I

PRD 89 (2014) 012003



Fully Hadronic

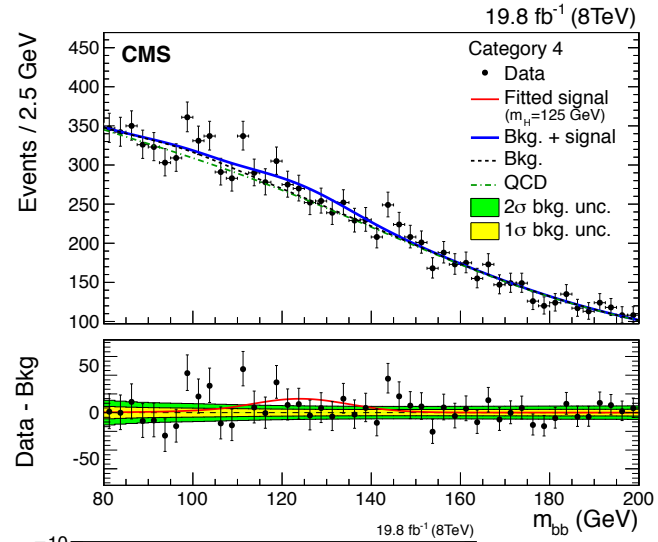
VBF H→bb

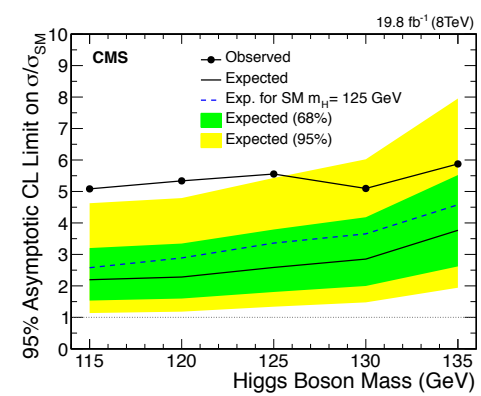
Analysis overview

- pp→qqH has large cross section
- Major backgrounds: QCD multijet, V+jets, tt, single-top
- 2 forward light quarks
  - $|\Delta\eta_{qq}|>2.5$, 3.5 (trigger dependant)
  - m_{qq} > 250, 750 GeV
- H→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
- 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

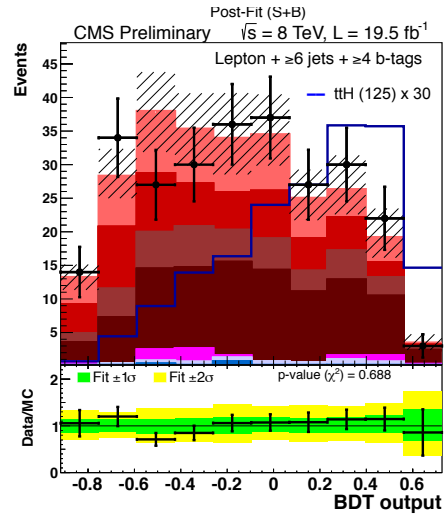
- Small cross section, but provides a direct probe of the Higgs/top Yukawa coupling y_t
  - Important since y_t ~ 1 in SM
- Lepton+jets & dilepton channels
- Major backgrounds: tt+jets (including tt+bb), single-top, V+jets, VV, tt+V
- 1 or 2 opposite sign leptons
- At least 4 (l+jets) or 3 (DL) jets
  - Including at least 2 b-tags
  - Boosted top and Higgs in Run II
- Several event categories
  - Based on N_{jets} and $N_{b\text{-}jets}$
- BDT and Matrix Element discriminants used

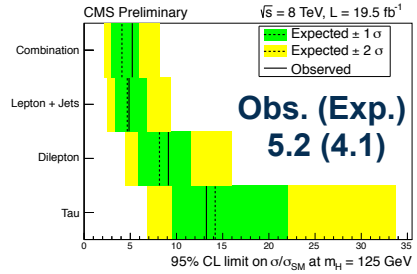
Results – Run I

CMS-PAS-HIG-13-019

EPJC 75 (2015) 251

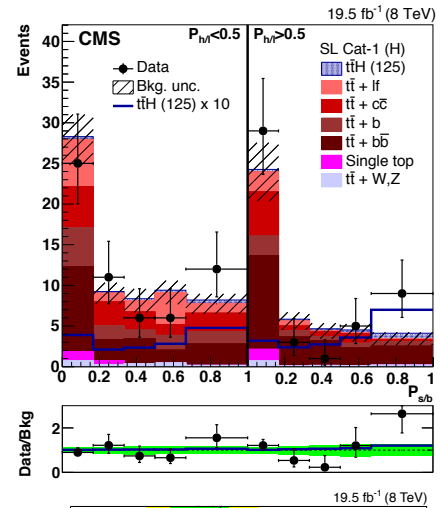
BDT

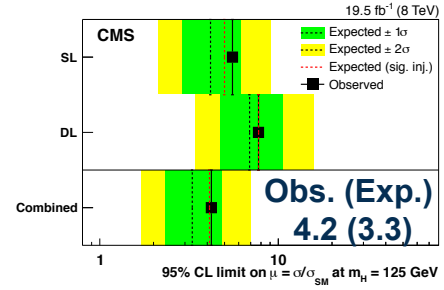




Best fit μ = 0.9 +2.5/-2.4

Matrix Element





Best fit μ = 1.2 +1.6/-1.5

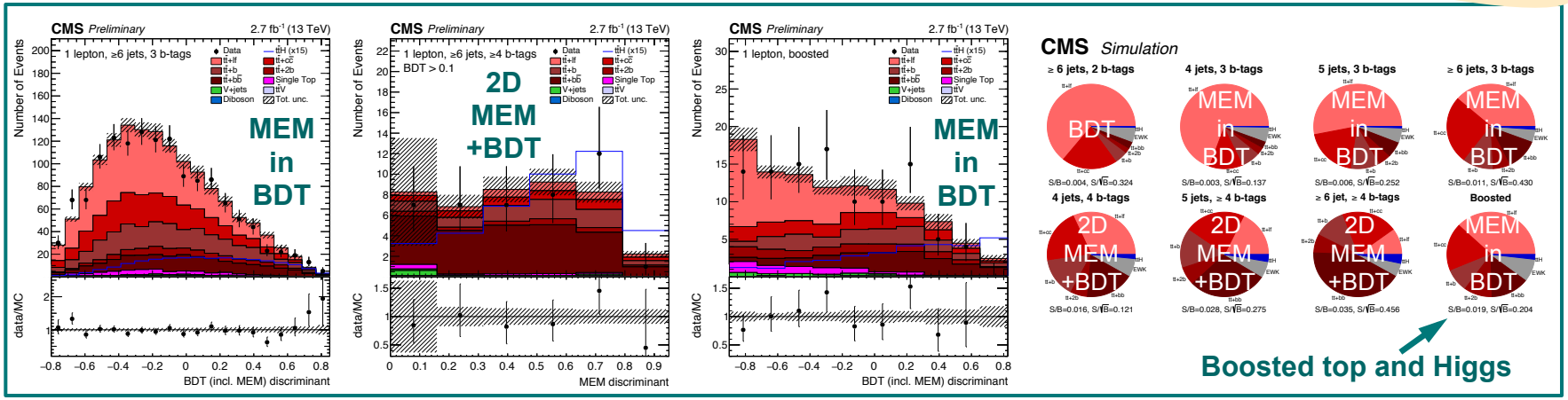
13 TeV

ttH, H→bb

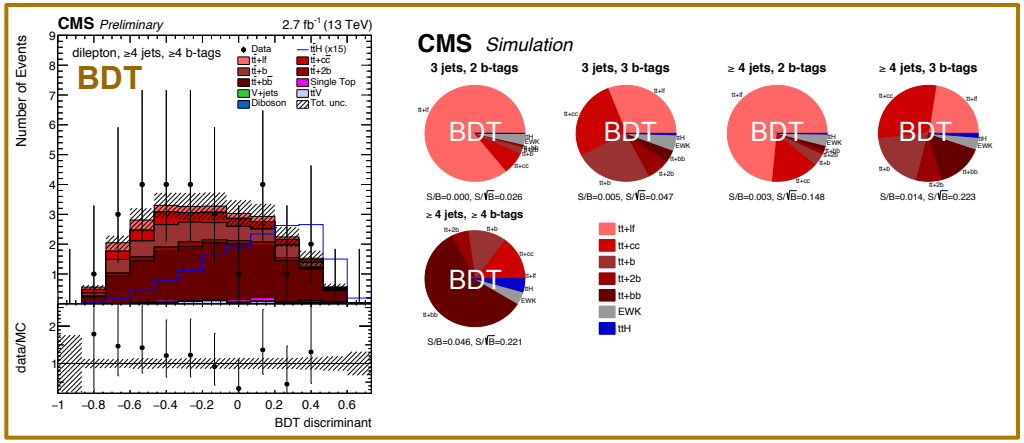
CMS-HIG-16-004

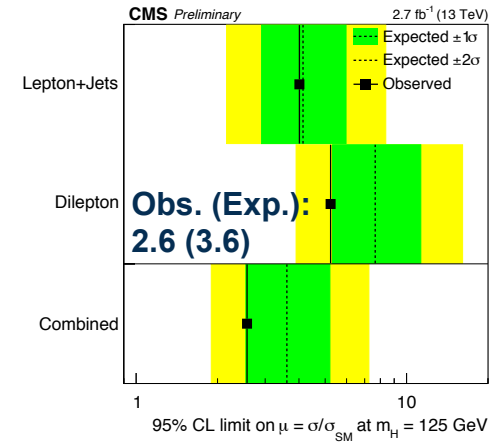
Results – Run II

lepton + jets



dilepton





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

1.7 sigma below SM expectation

13 TeV

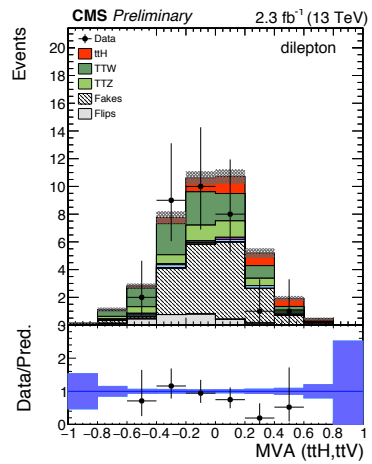
ttH, multileptons

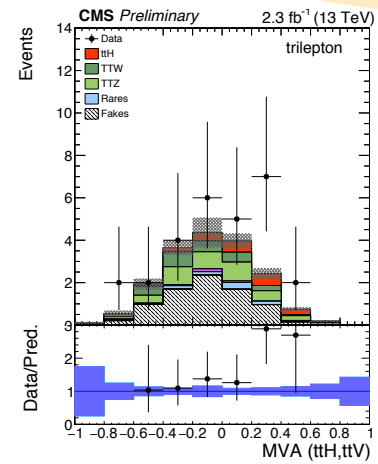
CMS-HIG-15-008

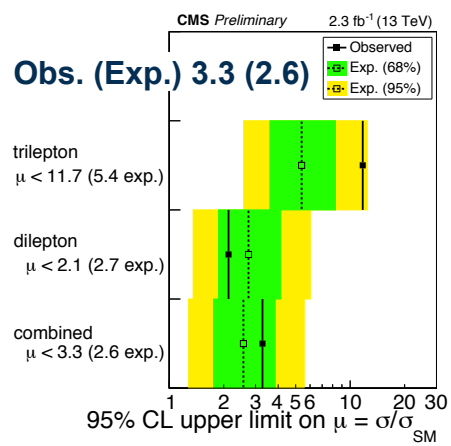
Analysis overview

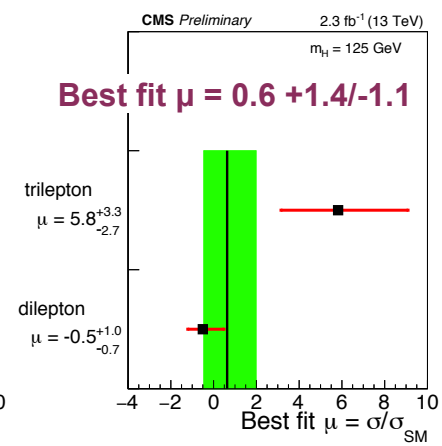
- Channels include: ttH(ZZ*), ttH(WW*), ttH(ττ)
  - Leptonic top and Z,W,τ decays
  - 1 hadronic top and Z,W,τ allowed
- Major backgrounds: ttV, VV, QCD (fake leptons)
- At least 2 (same sign) or 3 leptons
  - Z mass veto
- At least 4 or 2 jets
  - Including at least 1 b-tag
- Several events categories
  - Based on lepton flavour and b-tag
- BDT discriminant

Results – Run II









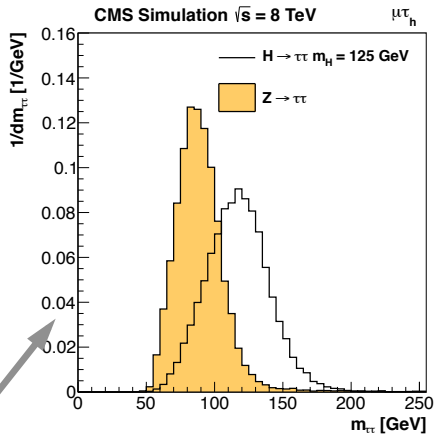
$H \to \tau\tau$

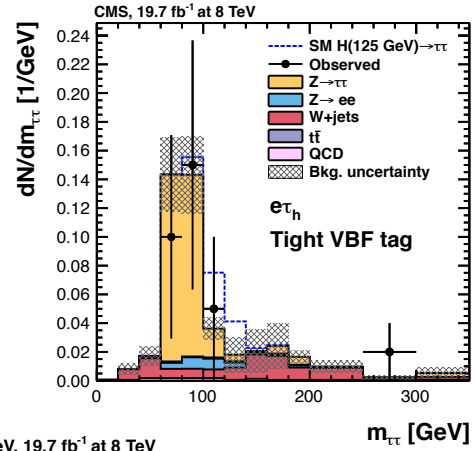
JHEP 05 (2014) 104

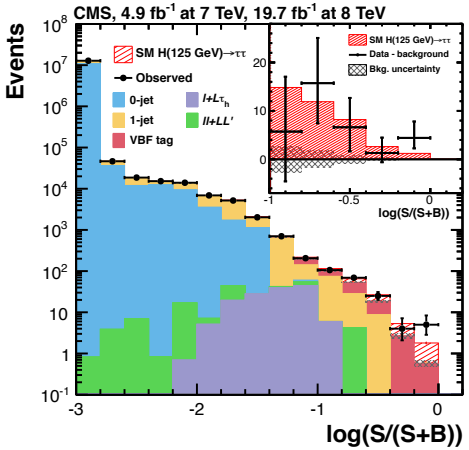
Analysis overview

- Production: gF, VBF, VH
- 3 channels: LL', ℓ+Lτ_h, $\ell\ell$+LL'
  - ee, μμ, eμ, eτ_h, μτ_h, $\tau_h\tau_h$,
  - μ+μτ_h, e+μτ_h/μ+eτ_h e+$\tau_h\tau_h$, μ+$\tau_h\tau_h$
  - $\ell\ell$ + μτ_h, eτ_h, eμ, $\tau_h\tau_h$
- Major backgrounds: DY $Z \to \tau\tau$, VV, W+jets, tt, QCD multijet
- Likelihood reconstruction of $m_{\tau\tau}$
- Several event categories
  - Based on N_{jets}, N_{leps} and ℓ, τ, H p_T
- BDT or $m_{\tau\tau}$ or m_{vis} discriminant

Results – Run I





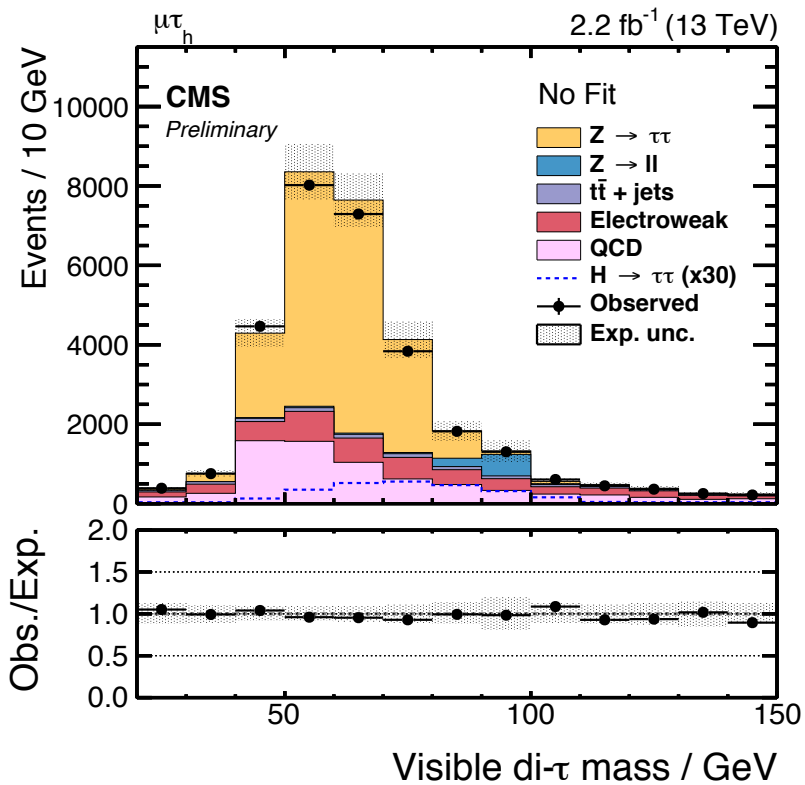


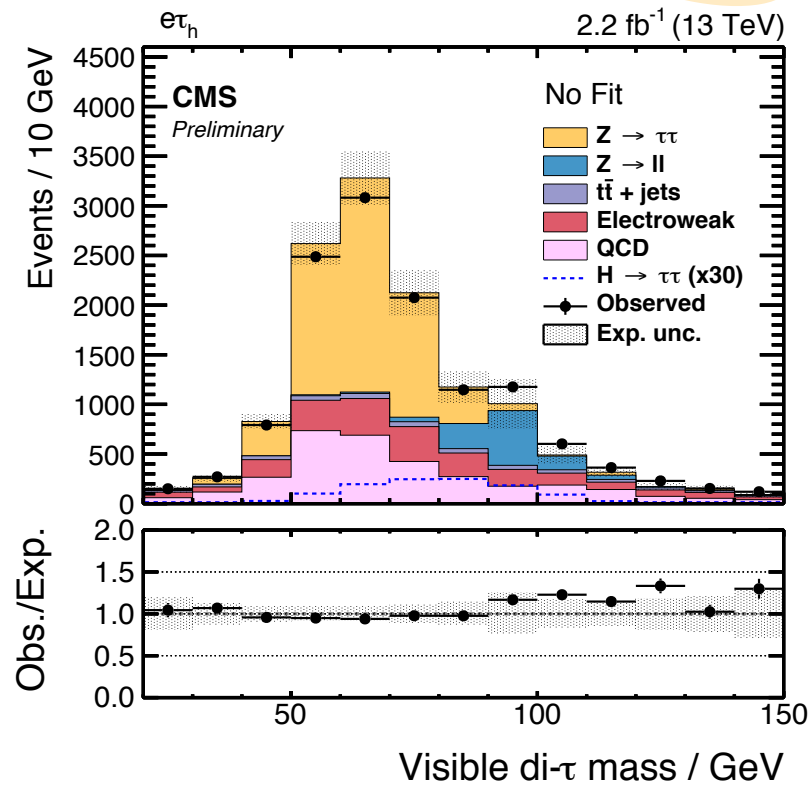
13 TeV

H→ττ

Results – Run II

Dec 15





Visible di-τ mass distribution in LL' events ($\mu\tau_h$ and $e\tau_h$ channels).

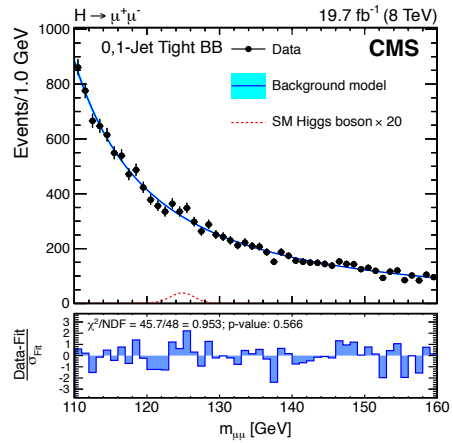
H→μμ/ee

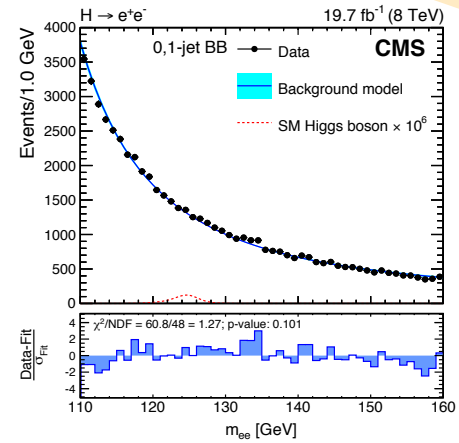
PLB 744 (2015) 184

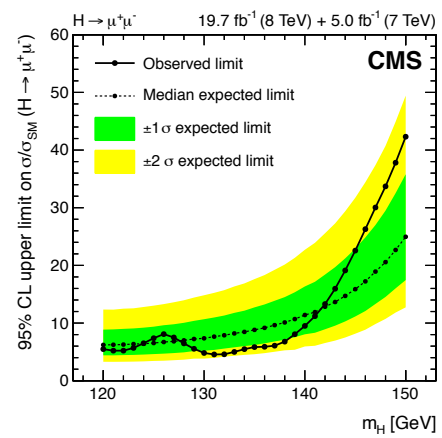
Analysis overview

- Small branching ratio
  - Cleanest of fermionic decays
  - Test of Yukawa coupling to second/third generation fermions
- Major backgrounds: DY $Z/\gamma \to \ell\ell$, tt, VV
- Search for peak in $m_{\ell\ell}$ spectrum
  - Over smoothly falling background
- Several event categories
- Based on N_{jets} and $p_T(\mu\mu)$ / m_{ee}
- 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 $\mu = \sigma/\sigma_{SM}$ = 0.8 +3.5/-3.4

For H→ee:

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

13 TeV

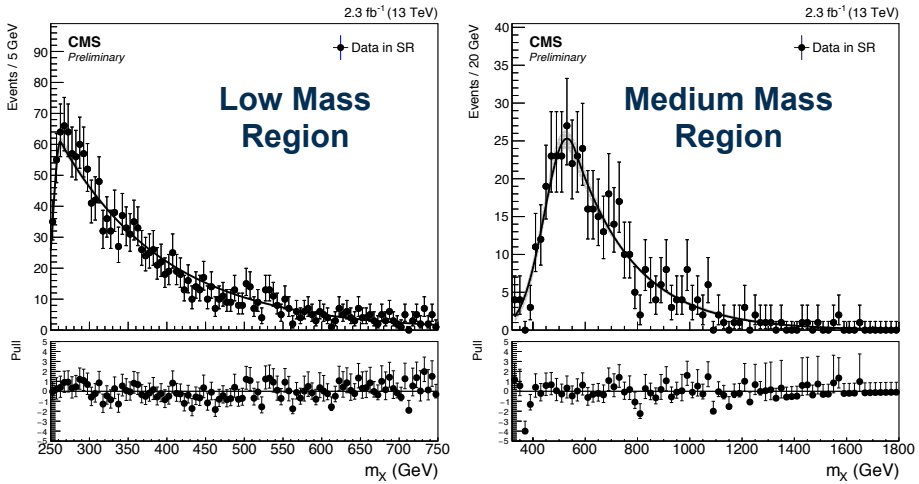
X→H(bb)H(bb)

CMS-HIG-16-002

Analysis overview

- Several BSM models posit narrow-width HH resonances
  - e.g. gravitons in extra dimensions
  - Production cross section unknown
- Search in 2 mass regions:
  - 260-400, 400-1200 GeV
- Backgrounds: QCD multijet, tt
  - Data driven from side-bands
  - GaussExp fit in SB and inverted SR
- At least 4 b-tagged jets
- Reconstruct H-H pair requiring:
  - $| m_{H_{1,2}} - 115 | < 34$ GeV
  - $\sqrt{\Delta m_{H_1}^2 + \Delta m_{H_2}^2} < \sigma_H$ (17, 23 GeV)

Results – Run II



13 TeV
First time @ LHC

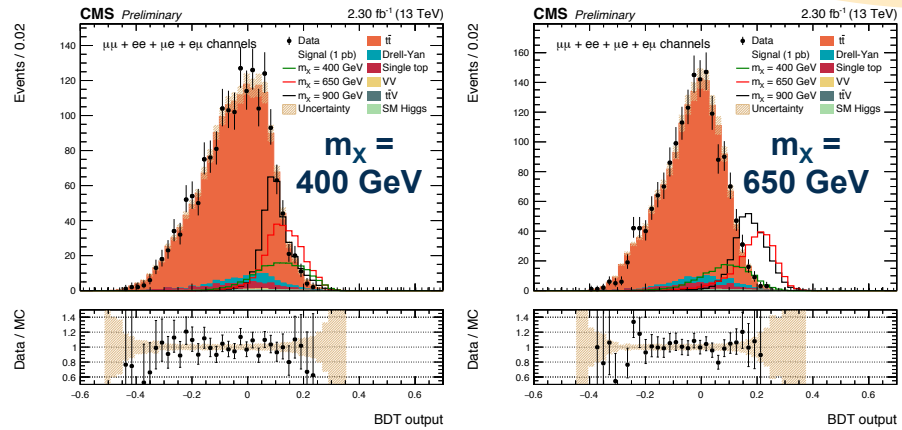
X→H(bb)H(WW)

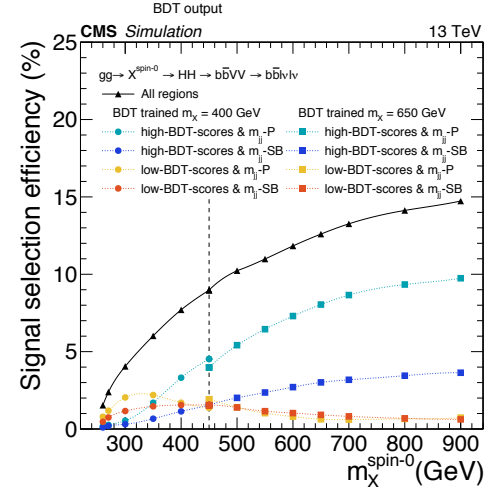
CMS-HIG-16-011

Analysis overview

- Extra dimensions models predict HH resonances
  - e.g. spin-0 radion, KK-graviton
- bb$\ell\nu\ell\nu$ channel: μμ, μe, eμ, ee
- Major backgrounds: tt, DY, single-top
- 2 OS leptons with $m_{\ell\ell}$ > 12 GeV
- At least 2 b-jets
  - 2 with highest CSV selected
- Cuts on $m_{\ell\ell}$, $\Delta R_{\ell\ell}$, ΔR_{jj}, $\Delta\phi_{\ell\ell,jj}$
  - BDT used to defined categories
- Maximum likelihood fit to all distributions

Results – Run II





13 TeV

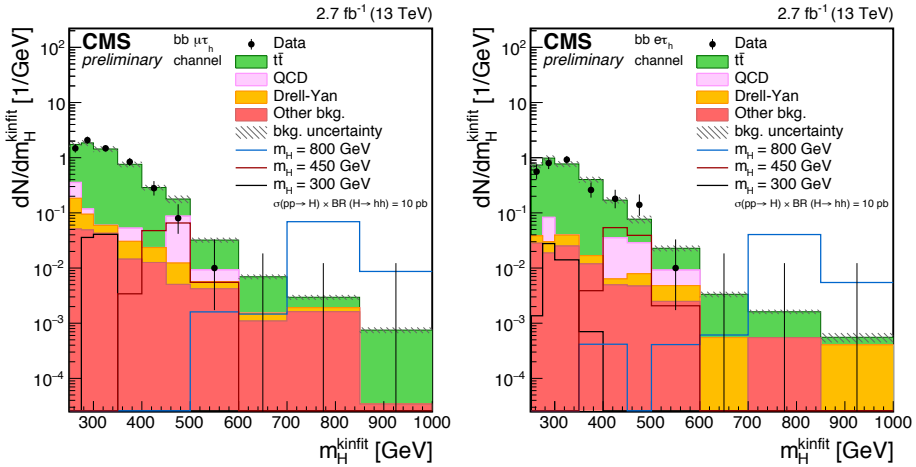
$X \rightarrow H(bb)H(\tau\tau)$

CMS-HIG-16-013

Analysis overview

- Search for heavy Higgs boson decaying into two SM Higgs
  - e.g. singlet model, MSSM
  - Unknown heavy Higgs mass
- 3 channels: $bbe\tau_h$, $bb\mu\tau_h$, $bb\tau_h\tau_h$
- Major backgrounds: tt, Z+jets, QCD multijet
- 2 OS leptons and 2 b-jets
  - No extra leptons
- Likelihood reconstruction of $m_{\tau\tau}$
- 80 GeV < $m_{\tau\tau}$, m_{bb} < 160 GeV
- $m_{bbL\tau} = m_{hh} = m_H$ reconstructed using kinematic fit

Results – Run II



13 TeV

Non resonant H(bb)H(ττ)

CMS-HIG-16-012

Analysis overview

- Higgs pair production very sensitive to BSM physics
  - Modelled by additional couplings
- 3 channels: bbeτ_h, bbμτ_h, bb$\tau_h\tau_h$
- Major backgrounds: tt, Z+jets, QCD multijet
- 2 OS leptons and 2 b-jets
  - No extra μ/e
- Likelihood reconstruction of $m_{\tau\tau}$
- 80 GeV < $m_{\tau\tau}$, m_{bb} < 160 GeV
- BDT vs. tt used in bb$\ell\tau_h$ channel
- $m_{bbL\tau}$ = m_{hh} final discriminant

Results – Run II