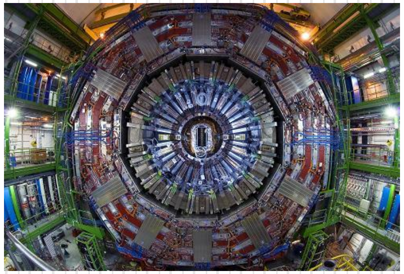
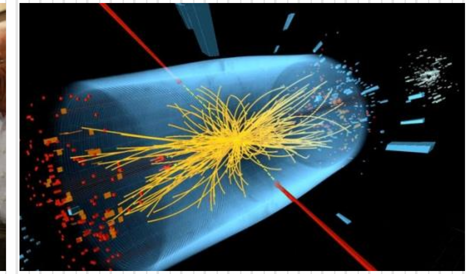
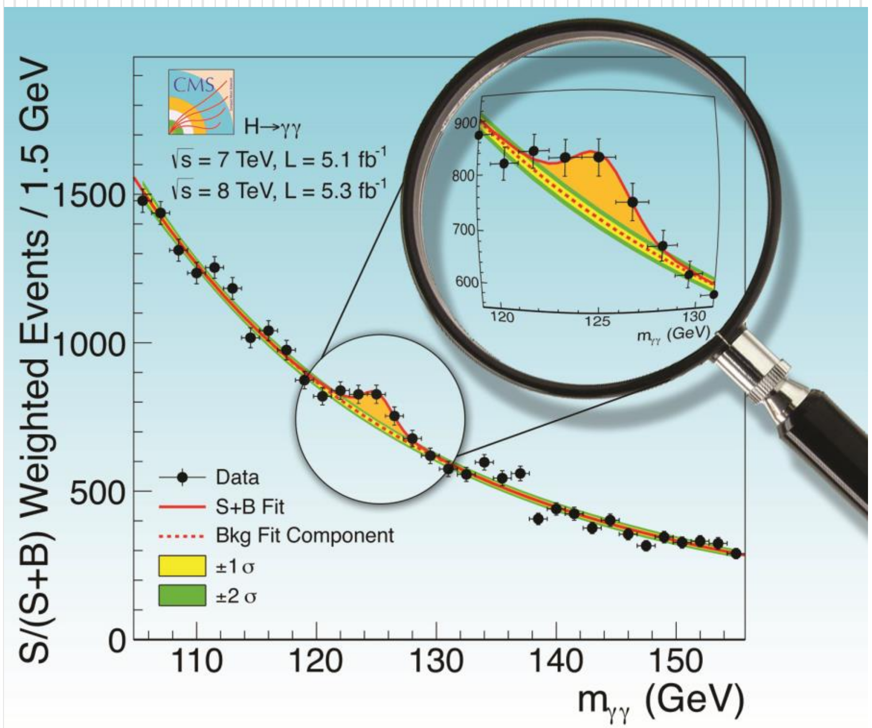




Does the Boson Couple to Fermions?



Jim Olsen

Princeton University

(On behalf of CMS, ATLAS, CDF, D0)

XXVIth Recontres de Blois

Blois, France

May 19, 2014

Outline

- Importance of Higgs fermionic couplings
- Search for the SM Higgs boson coupling to:
  - Muons
  - Top quarks
  - Bottom quarks
  - Taus
- Summary

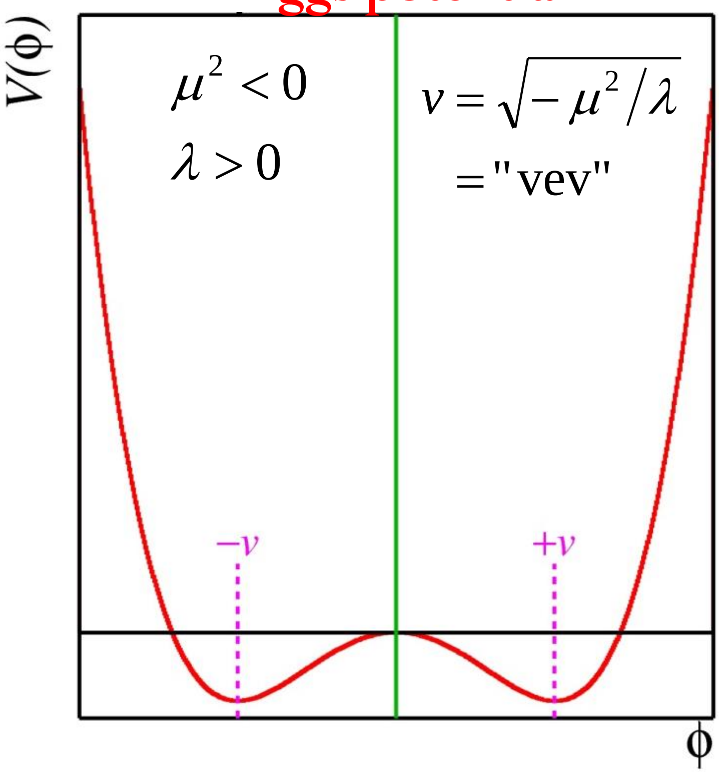
Note: analysis details will be further discussed in parallel session talks by Vivek Jain, Likija Zivkovic, and Christian Meineck

"The SM Higgs boson"

A single **elementary** scalar particle ($J^P = 0^+$), quantum of the Higgs field that gives mass to the gauge bosons **and the fermions**

$$\mathcal{L} = (D_\mu \phi)^* (D^\mu \phi) - \underbrace{(\mu^2 \phi^2 + \lambda \phi^4)} - \tfrac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

Higgs potential



$$v = \left(\sqrt{2} G_F\right)^{-\frac{1}{2}} \cong 246\ \text{GeV}$$

$$m_H = \sqrt{2\lambda} v$$

Because λ is not predicted, the Higgs boson mass is a free parameter in the SM

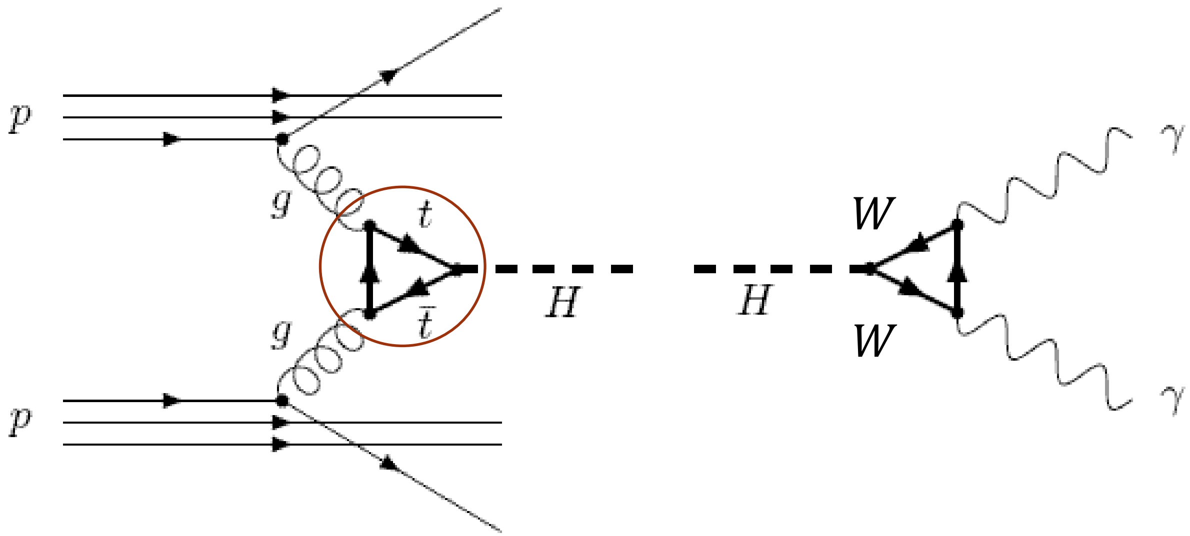
Gauge boson and fundamental fermion masses:

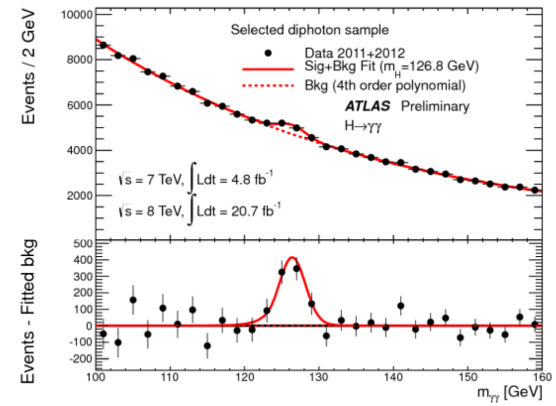
$$m_W = \frac{gv}{2}, \quad m_Z = \frac{m_W}{\cos\theta_W}, \quad m_f = \frac{g_f v}{\sqrt{2}}$$

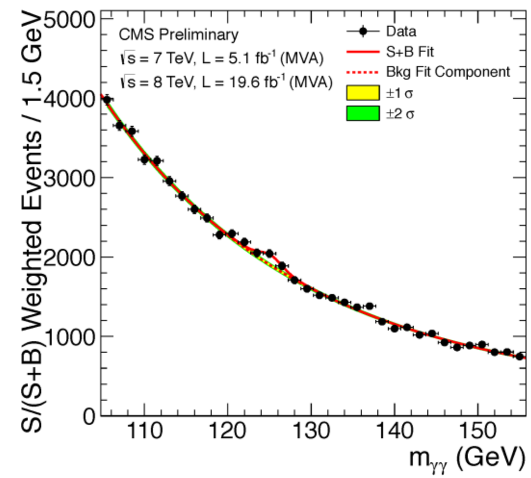
Importance of Fermionic Couplings

- **The new particle discovered at the LHC in 2012 is clearly a boson, and all evidence to date is that it is a $J^P = 0^+$ state that couples to the fundamental particles according to mass**
  - Signal strengths (σ x BF) in the $\gamma\gamma$, ZZ, and WW decay channels are all consistent with the SM expectation (see previous talk)
  - Extensive spin-parity studies exclude most alternative hypotheses, although still room here for surprises
- **The Higgs mechanism, with a single complex scalar doublet, also explains fermion masses via Yukawa couplings**
  - This is not necessary, we could have additional Higgs bosons that generate the fermion mass, or separate scalar doublets that generate the masses of the up- and down-type fermions
  - It is therefore essential to establish whether or not the new boson h(126) also couples to fermions with the strength predicted by the SM

Indirect evidence for fermion coupling

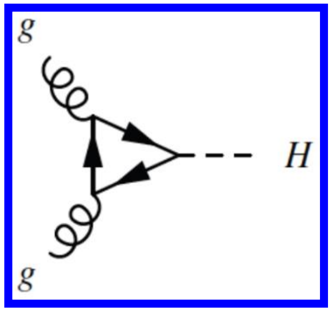




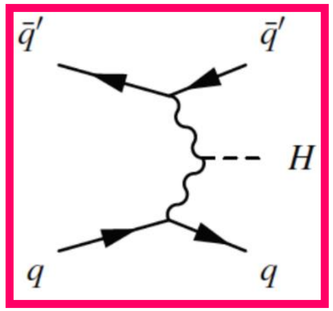


In the context of the SM Higgs boson phenomenology, we already have strong **indirect** evidence for a coupling to the top quark via the loop in the dominant production mechanism.

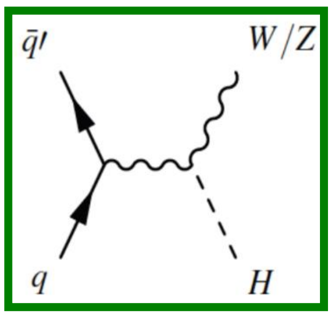
SM Higgs Production at the LHC



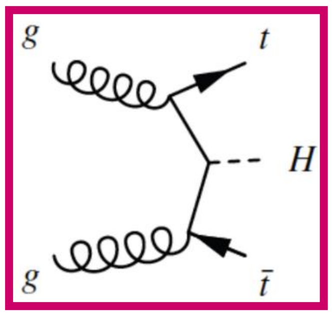
Gluon Fusion



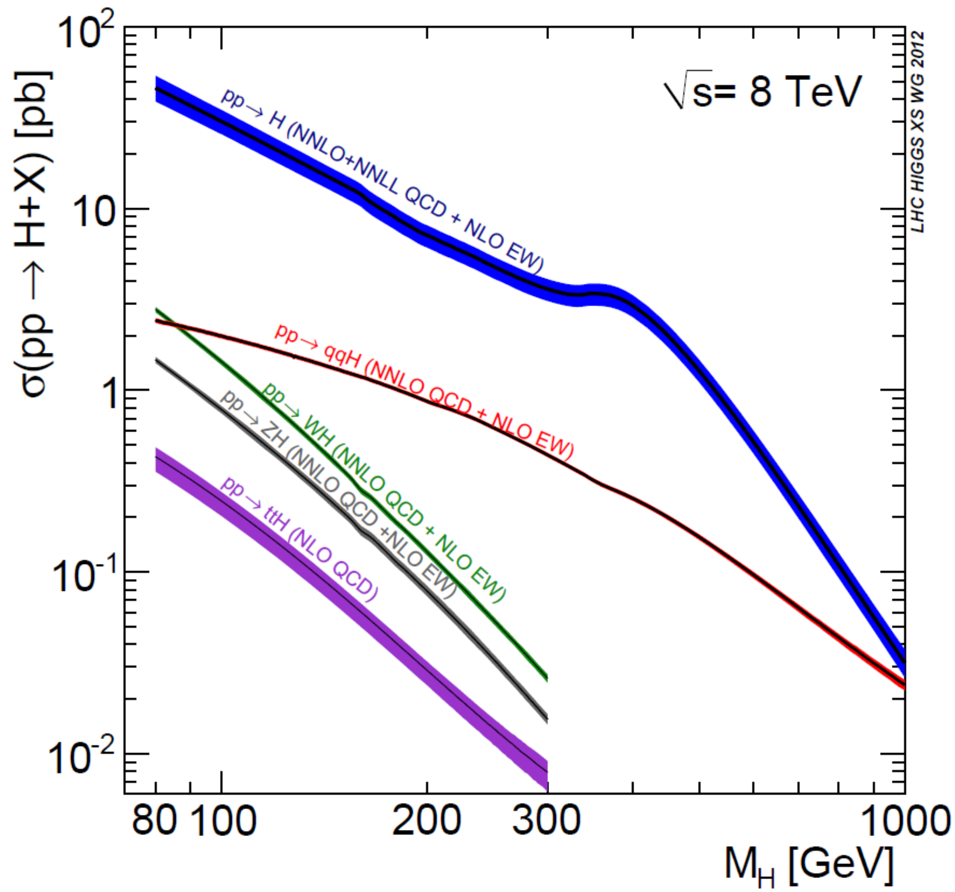
Vector-Boson Fusion



Higgs-strahlung

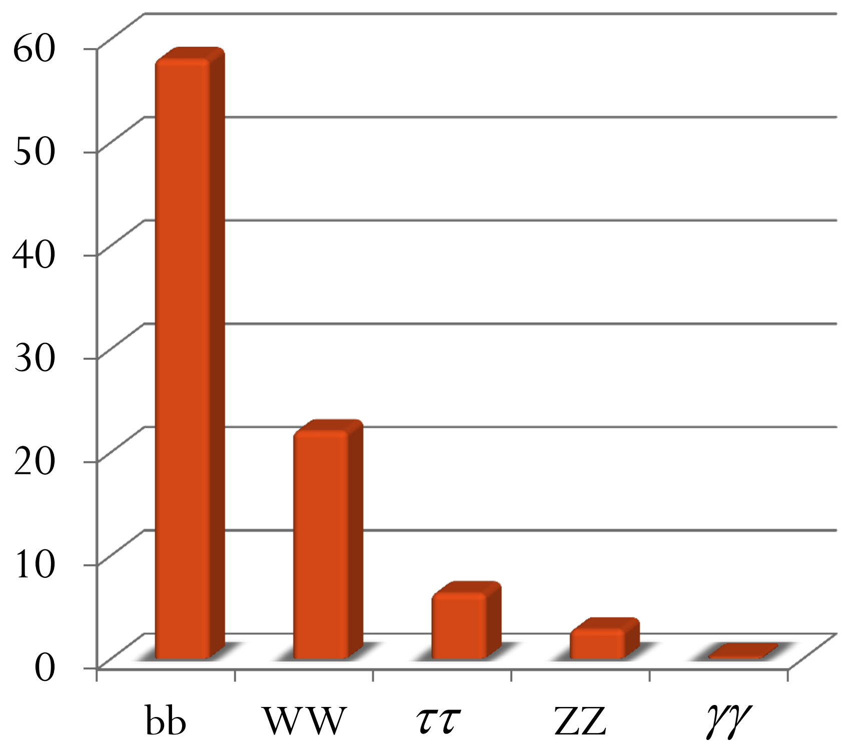


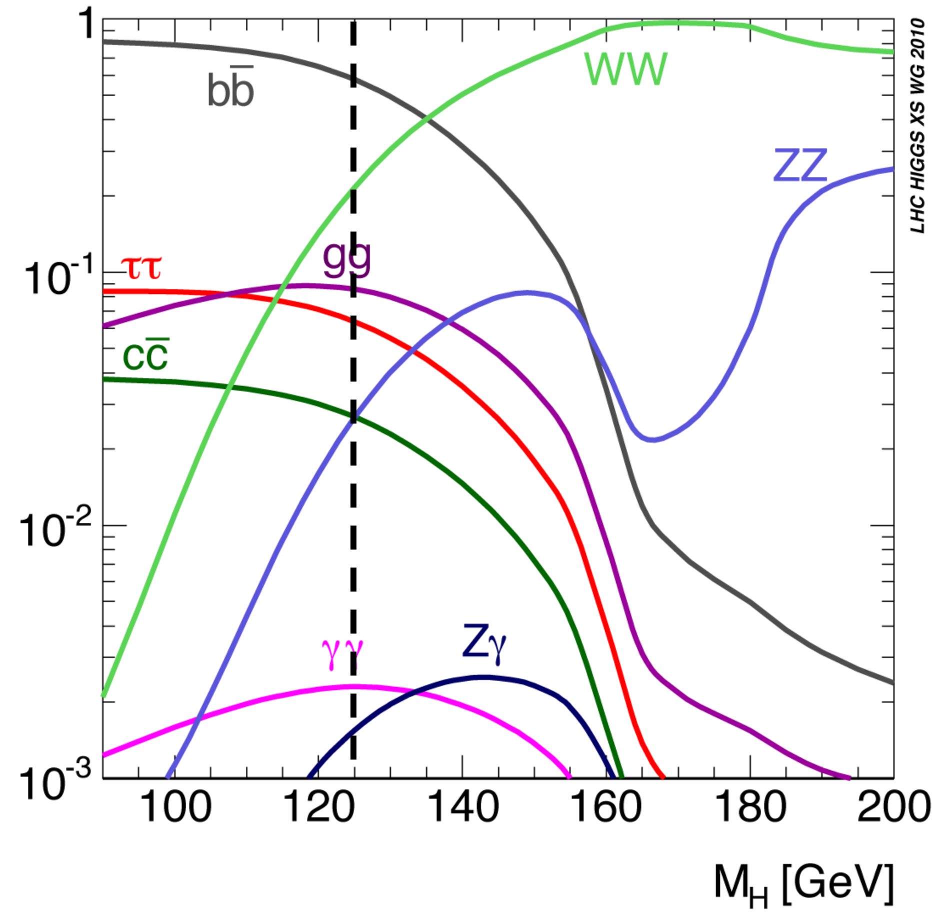
Top Fusion ($t\bar{t}H$)



LHC in 2012 at record luminosity (7 x 10^{33} $cm^{-2}s^{-1}$) and energy (8 TeV) was producing SM Higgs bosons (M_H = 125 GeV) at a rate **~750/hr**

Decay Channels





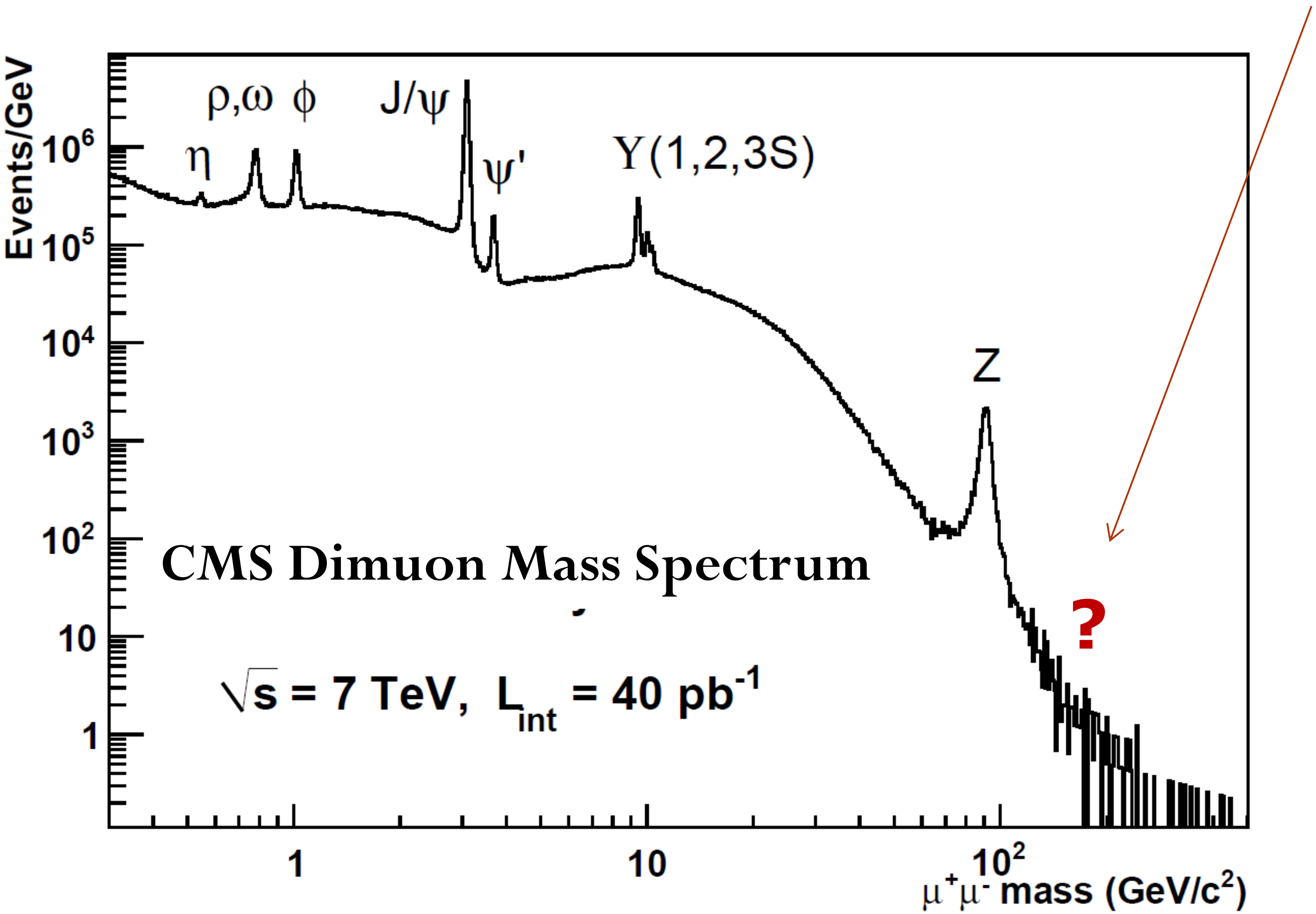
Fortuitous! Only region in m_h where

- Cross sections are large
- Fermion decays (bb+ττ) are accessible
- Natural width is negligible

Search for H $\rightarrow$ $\mu\mu$

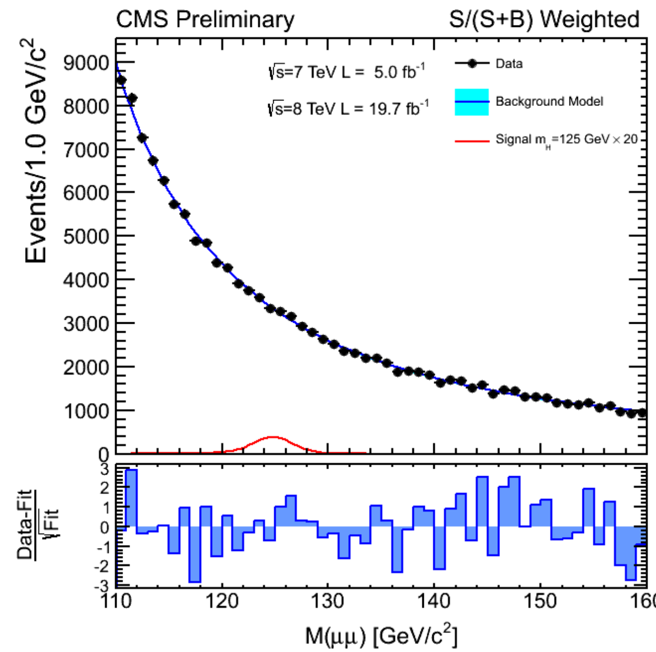
Fermionic Bump Hunting: H → μμ

Fully reconstructed final state, would appear just past Z peak

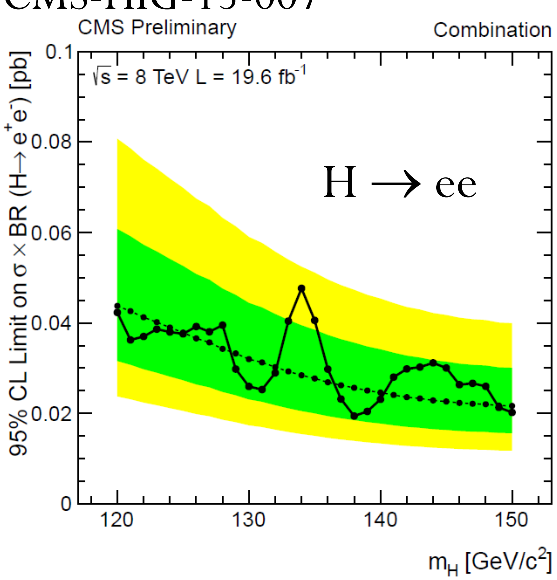


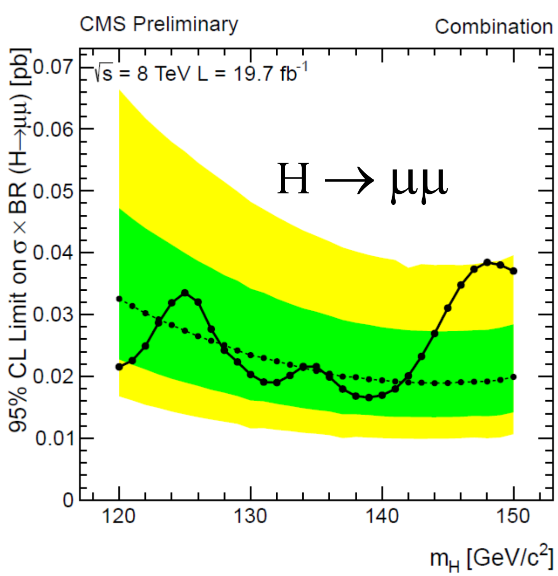
Higgs → μμ (and ee)

- If this is the SM Higgs boson, coupling to leptons should go like $g \propto m_l$
  - μμ/ee decays should be highly suppressed relative to ττ
- Have not seen μμ/ee yet → this particle does not obey lepton universality!

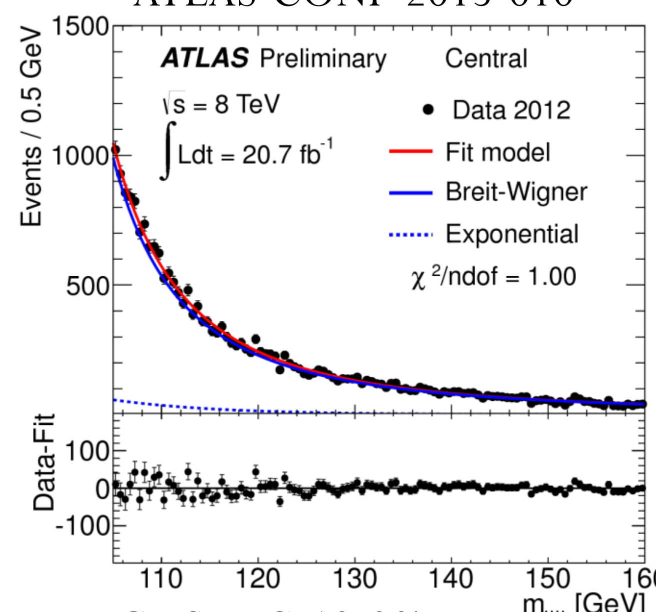


CMS-HIG-13-007





ATLAS-CONF-2013-010

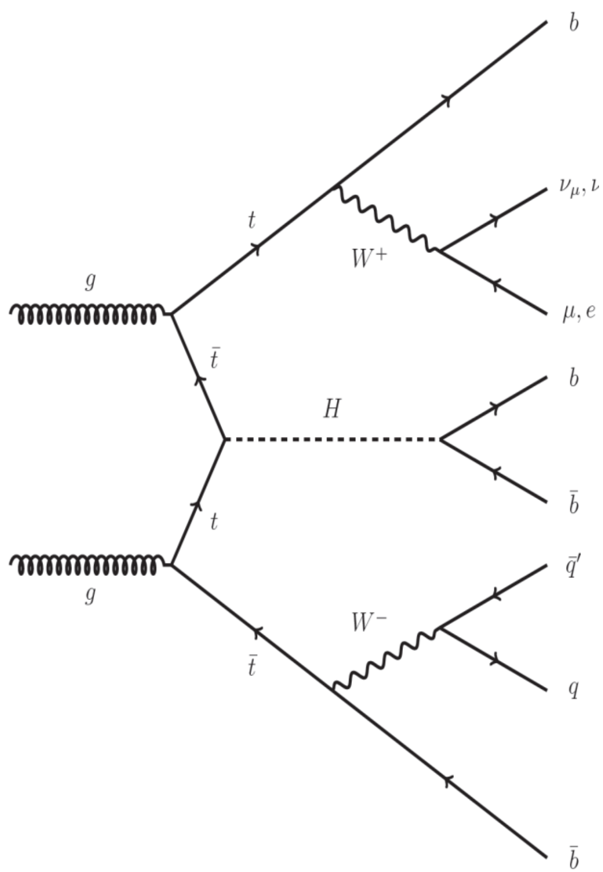


CMS-HIG-13-007

Search for Higgs-top couplings

Search for ttH production

- **Top is the heaviest fermion**
  - Strong coupling to Higgs
  - But $2m_t \gg m_H$, only directly sensitive to coupling in production (ttH, tHq, tH)
- **Critical channel**
  - Only direct access to tops coupling to Higgs
  - Will be even more critical in the next run at higher energy: $\sigma(13\,\text{TeV})/\sigma(8\,\text{TeV}) \sim 4$
- **Strategy**
  - Combine as many H decay modes as possible
  - Topology and extensive b-jet identification techniques are exploited by both experiments



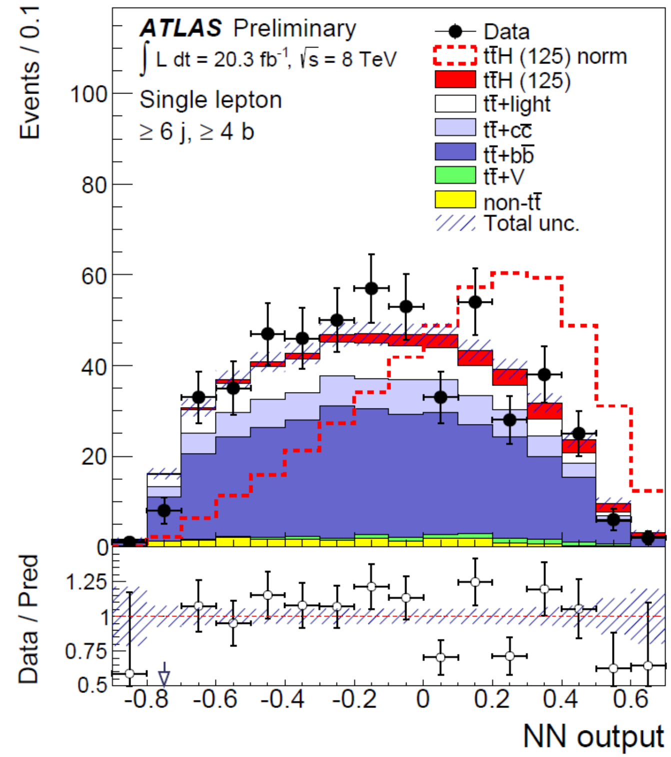
ATLAS-CONF-2014-011

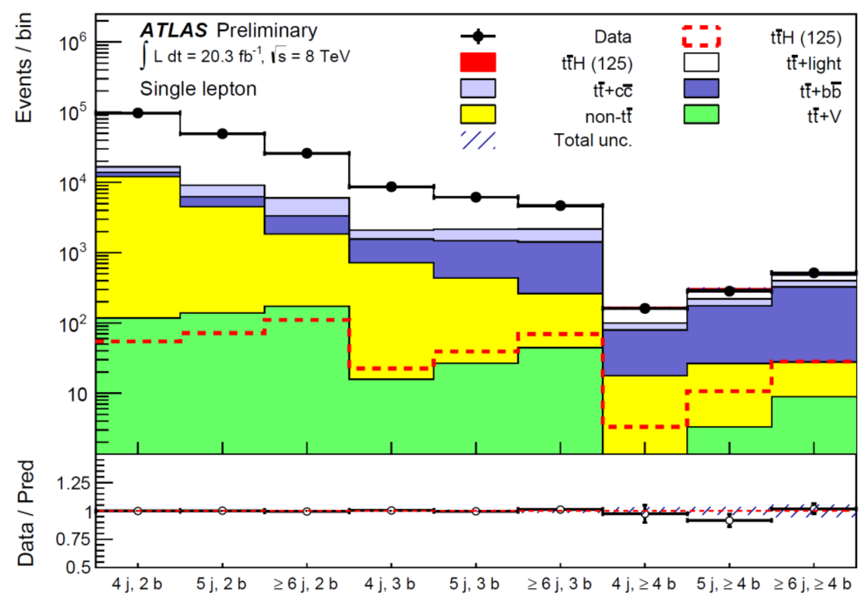
ttH Results: ATLAS

- **ATLAS analysis summary**
  - New result! Mostly sensitive to H → bb, but some sensitivity to other channels as well
  - Categorize events by number of jets and b jets, S/B = ~0 – 7%
  - Significance (125 GeV) = 1.3σ
  - **Exp (obs) μ < 2.6 (4.1) x SM**

Signal Strength	μ	error
Single Lepton	1.3	1.6
Dilepton	2.9	2.3
Combination	1.7	1.4

ATLAS also looks for ttH(γγ): $\mu < 5.3$
ATLAS-CONF-2013-080

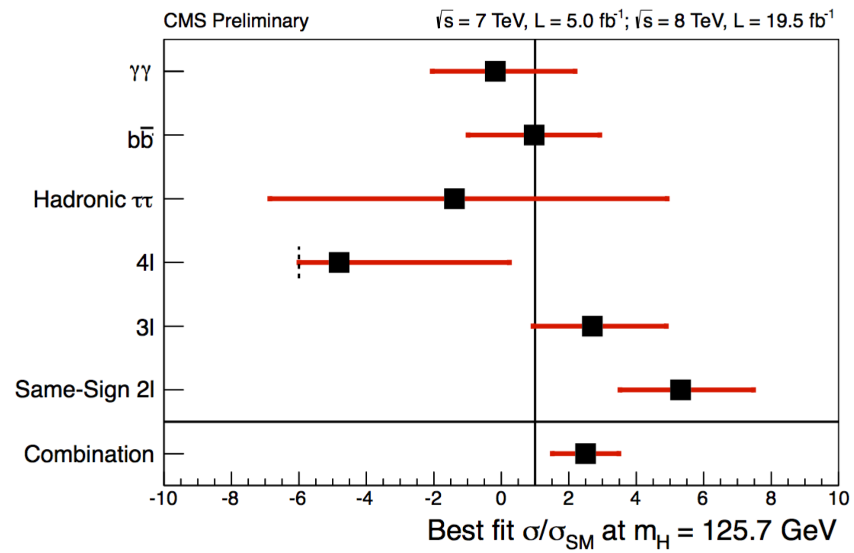




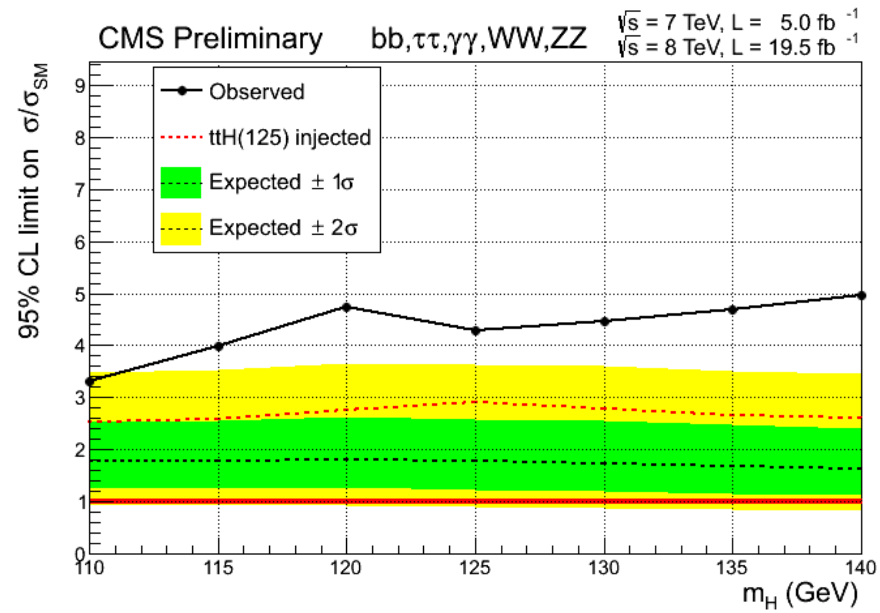
ttH Results: CMS

CMS-HIG-13-015
CMS-HIG-13-019
CMS-HIG-13-020

- **CMS analysis summary**
  - Uses H → bb, ττ, γγ, multilep
    - Multilep includes WW, ZZ, ττ
  - Significance (125.7 GeV) = 2.7σ
  - **Exp (obs) μ < 1.8 (4.3) x SM**



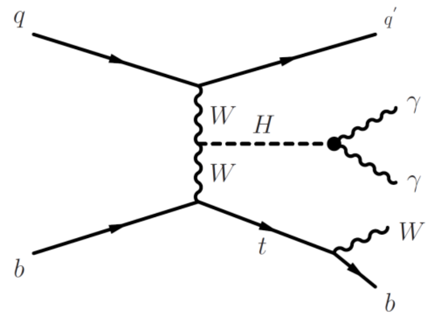
ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$

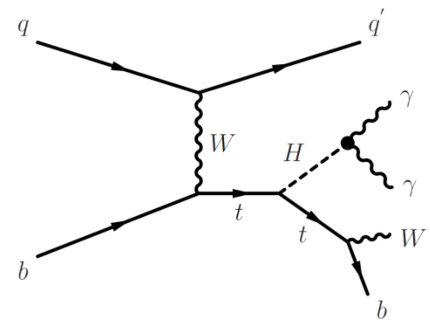


Search for Higgs + single top quarks

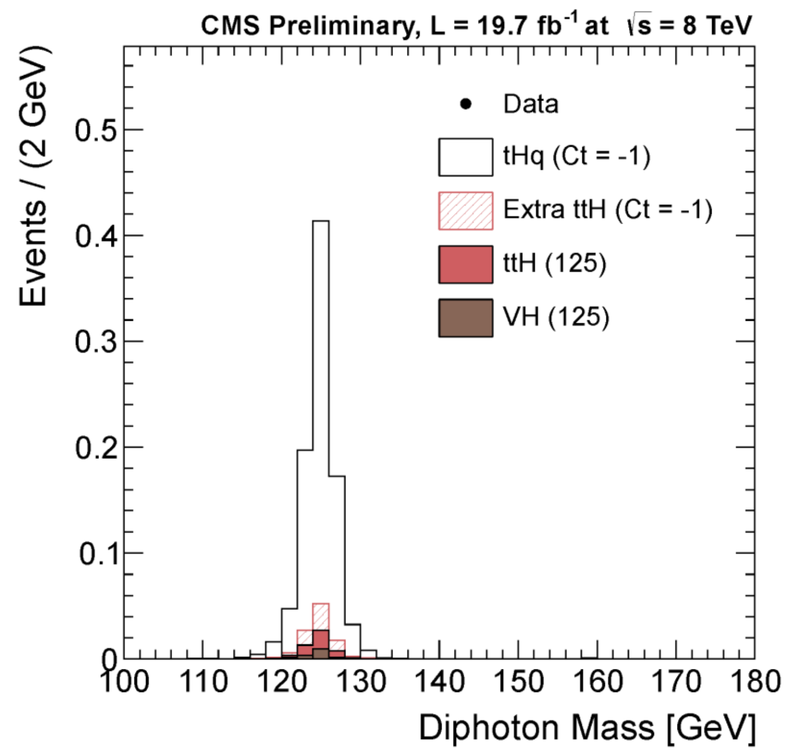
- SM Higgs couplings to W bosons and top quarks have opposite sign
  - σ(tHq) ~ 18 fb
- New physics with opposite-sign coupling to top quarks (C_t = -1) could lead to large enhancements
  - 15x for single top + Higgs
  - 2x for H → γγ
- First search at LHC, looking for tHq, H → γγ production
  - No events observed in data

$$\sigma_{obs}/\sigma_{C_t=-1} < 4.1 \text{ @ } 95\% \text{ C.L.}$$





CMS-HIG-14-001



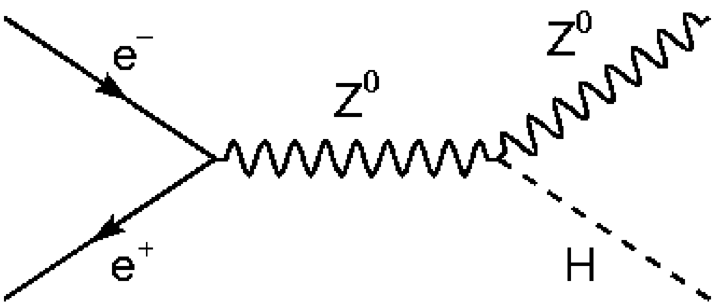
Search for $H \rightarrow b\bar{b}$

LEP Legacy

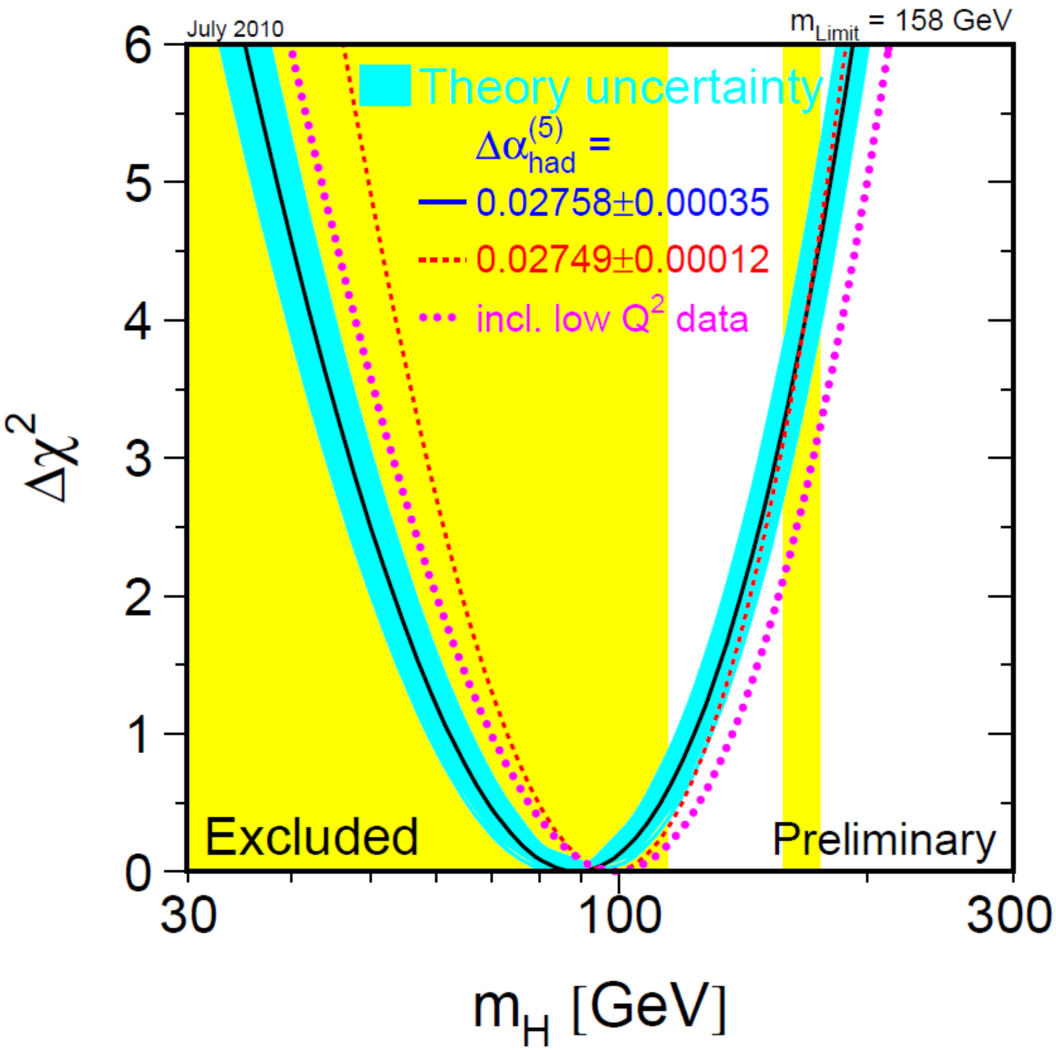
Search strategy:

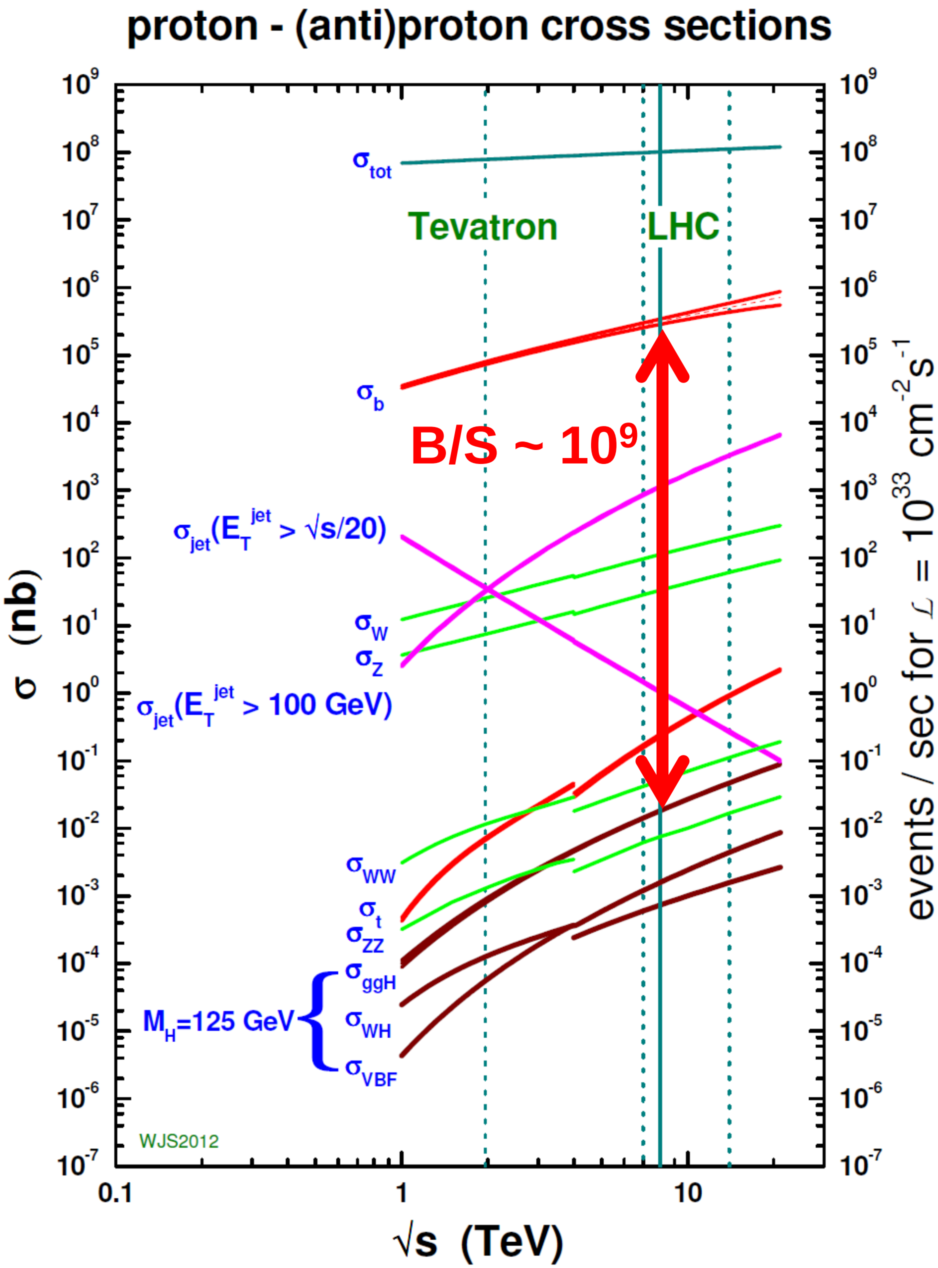
Produced via Higgs-strahlung

Decaying to $b\bar{b}$ or $\tau\bar{\tau}$



$m_H > 114.4$ GeV



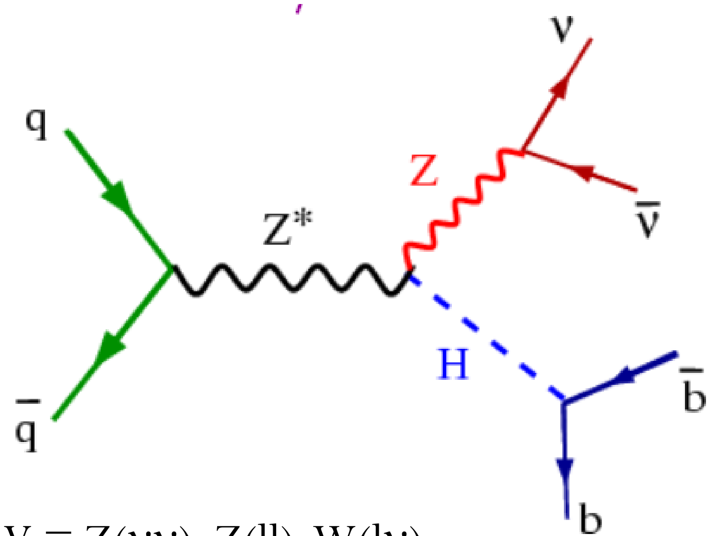


Inclusive H → bb at hadron colliders?

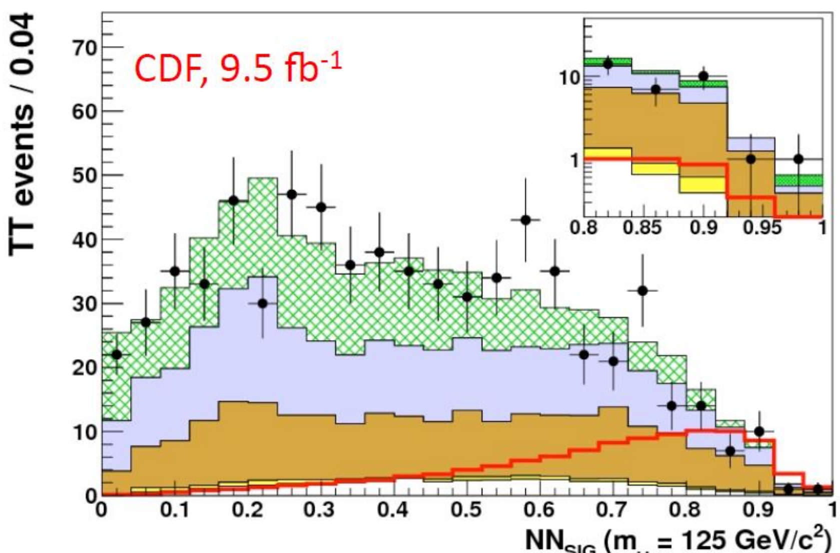
Overwhelmed by QCD production of bottom-quark jets (B/S ~ 10^8)

Need to find another haystack: VH, H → bb (boosted @ LHC)

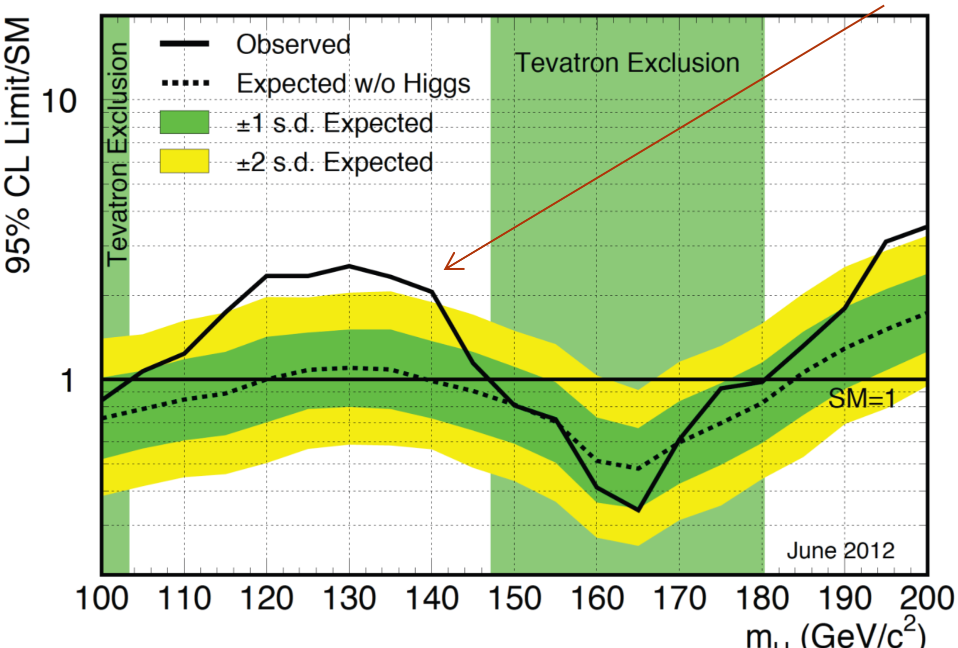
Tevatron Search for VH, H $\rightarrow$ $b\bar{b}$



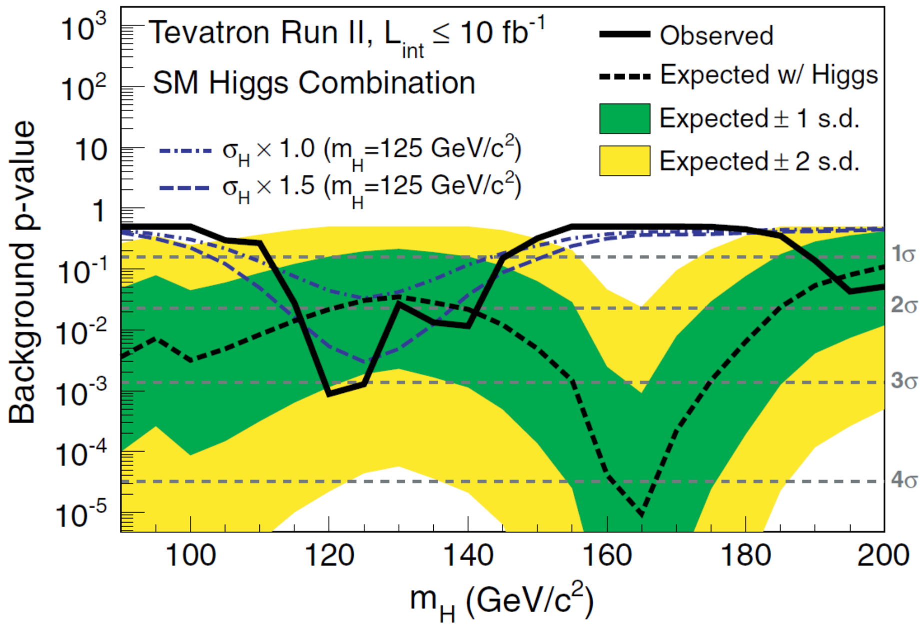
V = Z(νν), Z(ll), W(lν)



- Primary search channel for $m_H < 140$ GeV
- Highly optimized analyses using MVA techniques
- At time of LHC discovery, excess in wide mass region near 125 GeV



Tevatron Combined Results



Full Tevatron combination shows broad excess in the low-mass region 115 – 140 GeV.

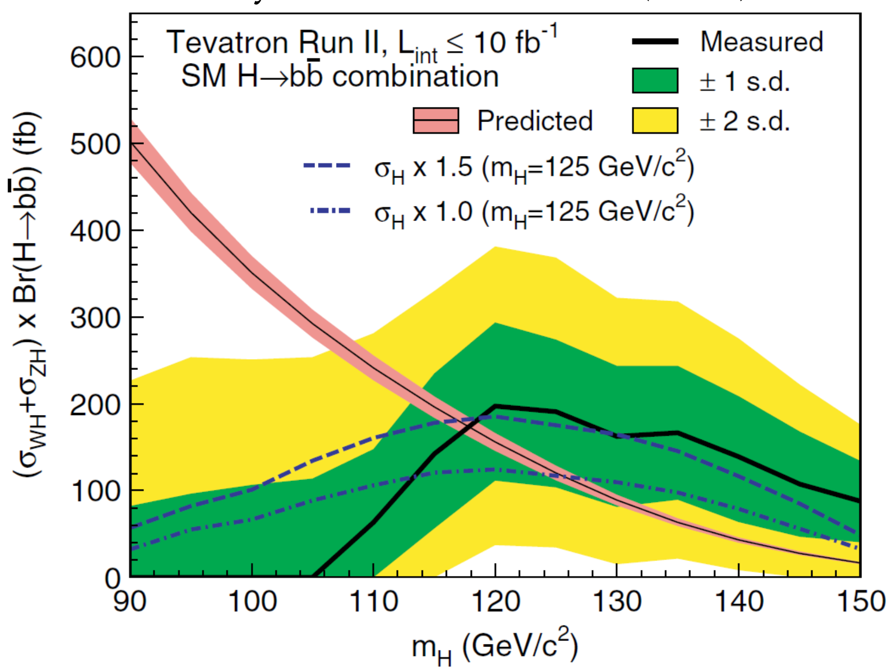
Peak significance of 3σ @ 120 GeV

VH(bb) sub-combination (m_h = 125 GeV) :

$$\sigma_{obs} = 0.19^{+0.08}_{-0.09}\ \text{pb}$$

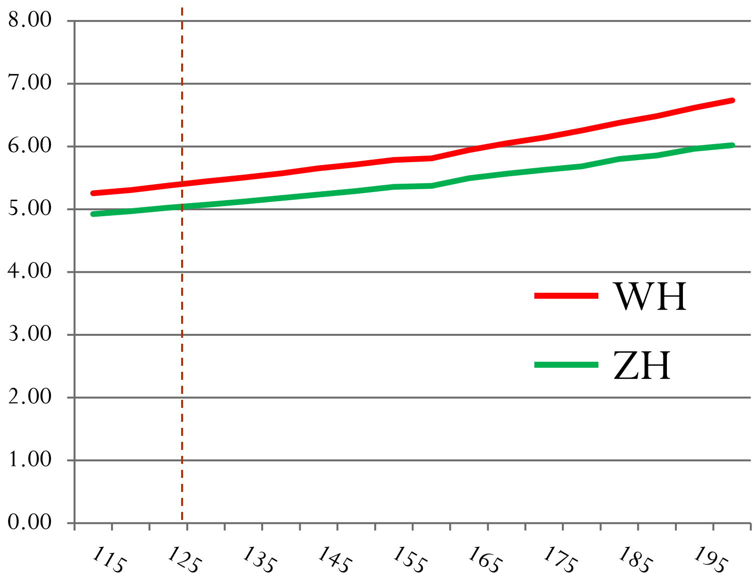
$$\sigma_{SM} = 0.12 \pm 0.01\ \text{pb}$$

Phys. Rev. D88, 052014 (2013)

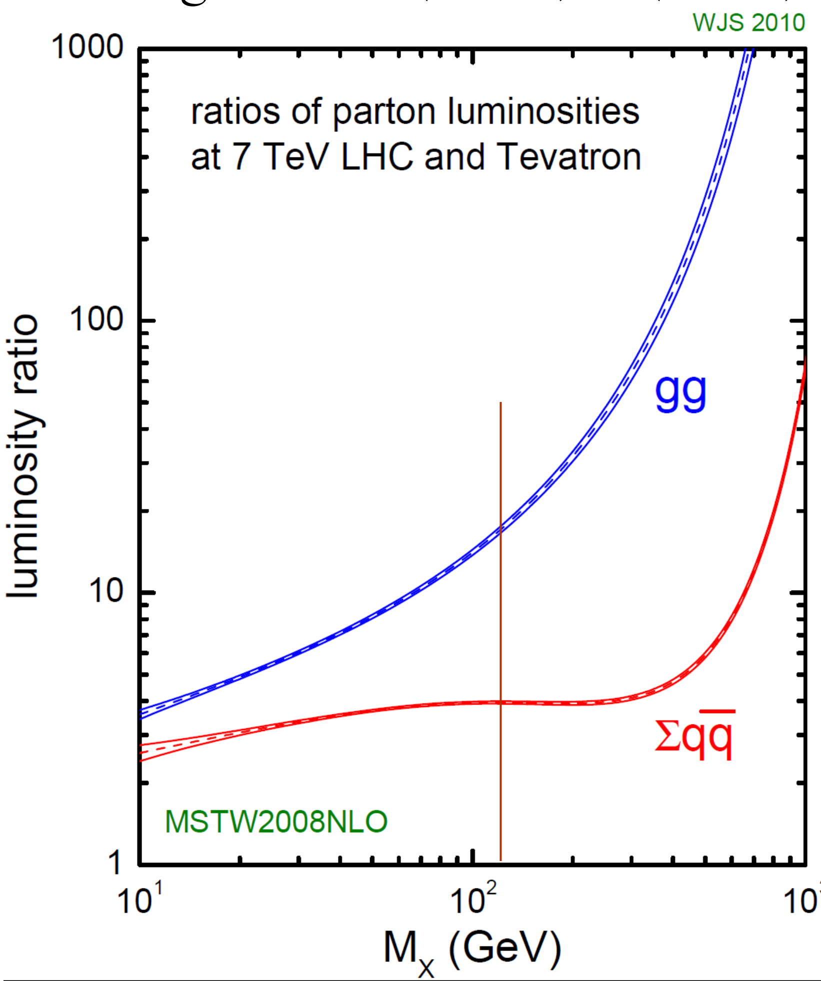


VH Production: LHC vs. Tevatron

Signal: VH(8 TeV)/VH(2TeV)



Background: L(7 TeV)/L(2TeV)



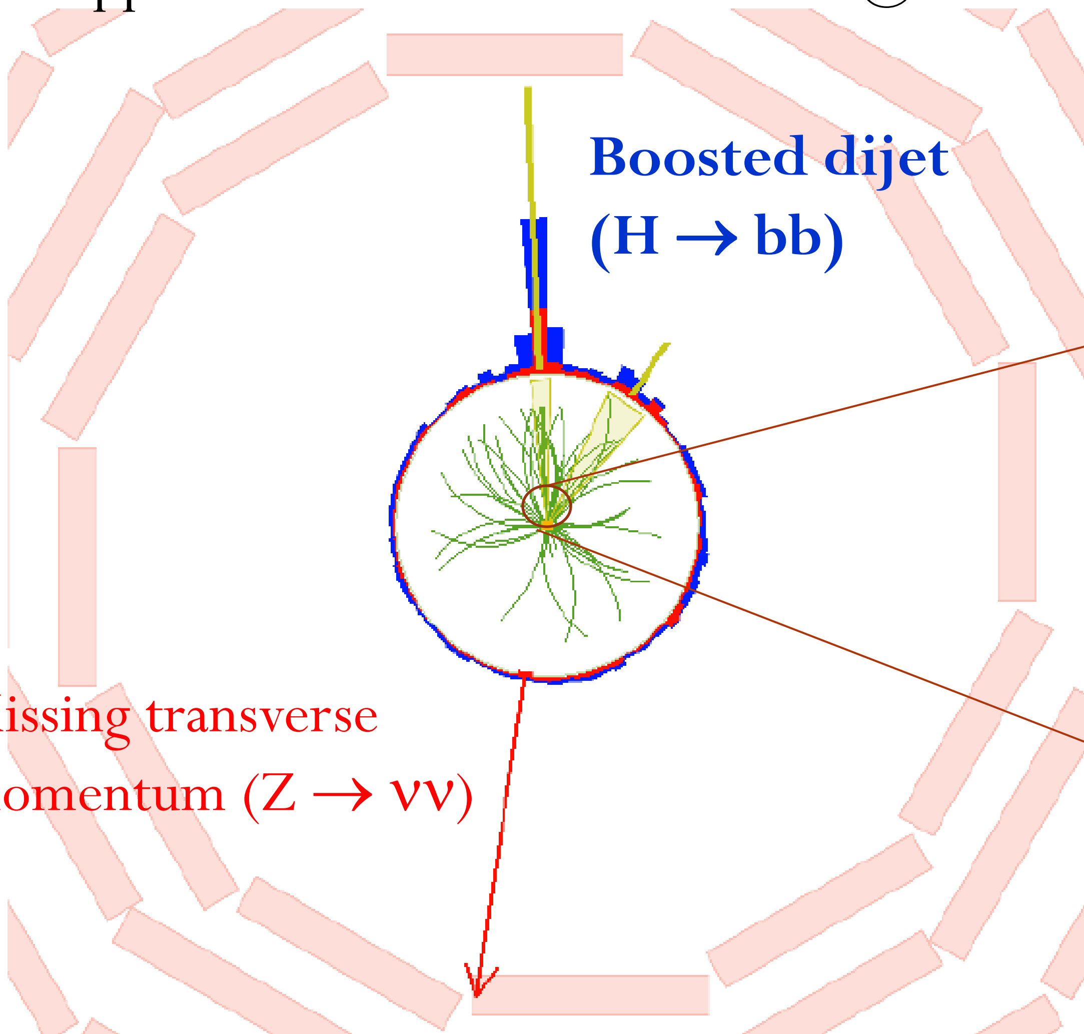
Signal increases ~5x

Gluon-initiated bkg increases ≥ 20x

Still challenging at LHC, but more cross section to burn → boost

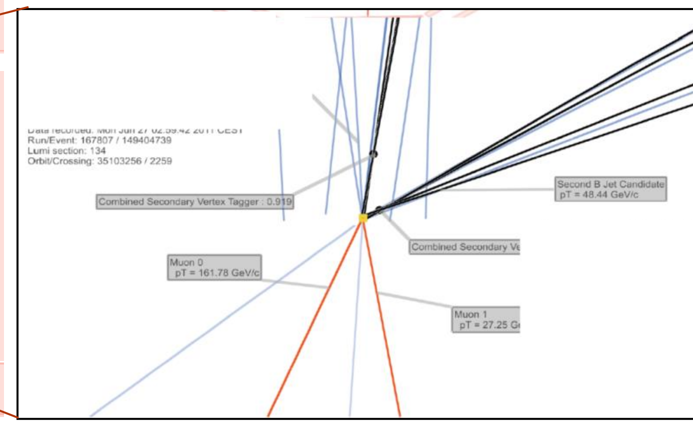
Anatomy of boosted VH(bb) @ LHC

$pp \to ZH \to \nu\nu + b\bar{b}$ candidate @ CMS



Boosted dijet
($H \to bb$)

Missing transverse momentum ($Z \to \nu\nu$)



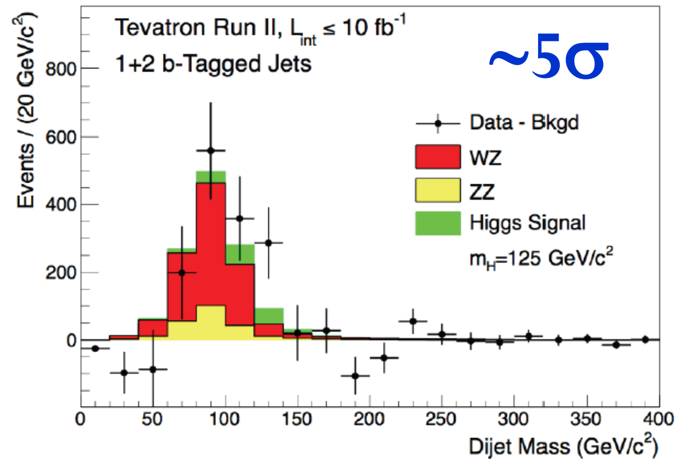
Dominant backgrounds:

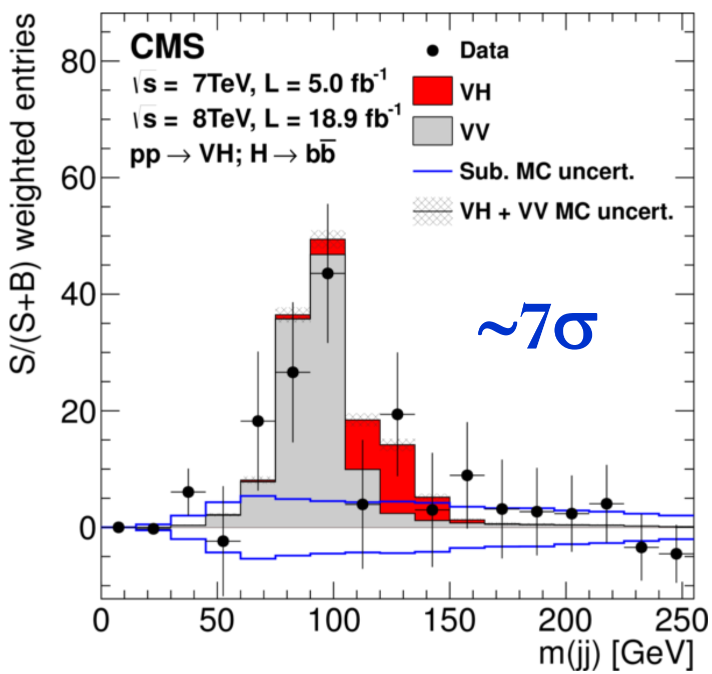
- V + b jets
- $t\bar{t}$
- VZ with $Z \to b\bar{b}$

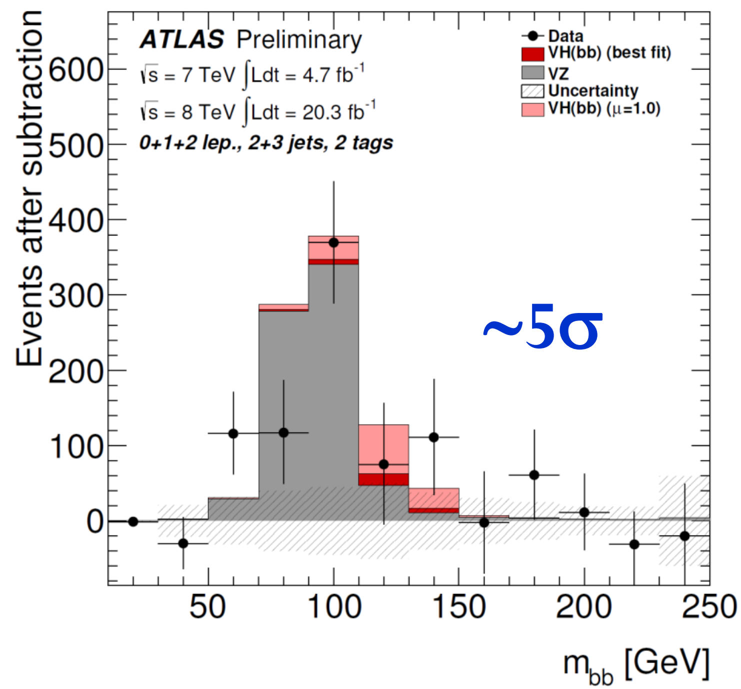
Jets displaced from primary pp interaction (b jets)

Proof-of-principle: VZ, Z → $b\bar{b}$

- Search for Z → bb by optimizing for m = 91 GeV (instead of 126)
- Same techniques as in Higgs search, fully validates analysis
- Pioneered at the Tevatron, now also established at the LHC

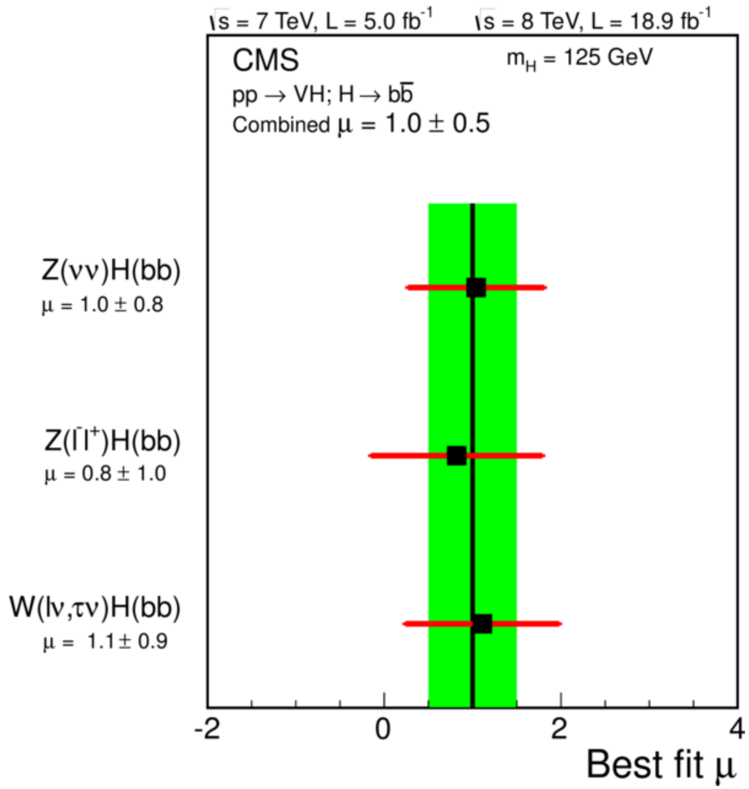




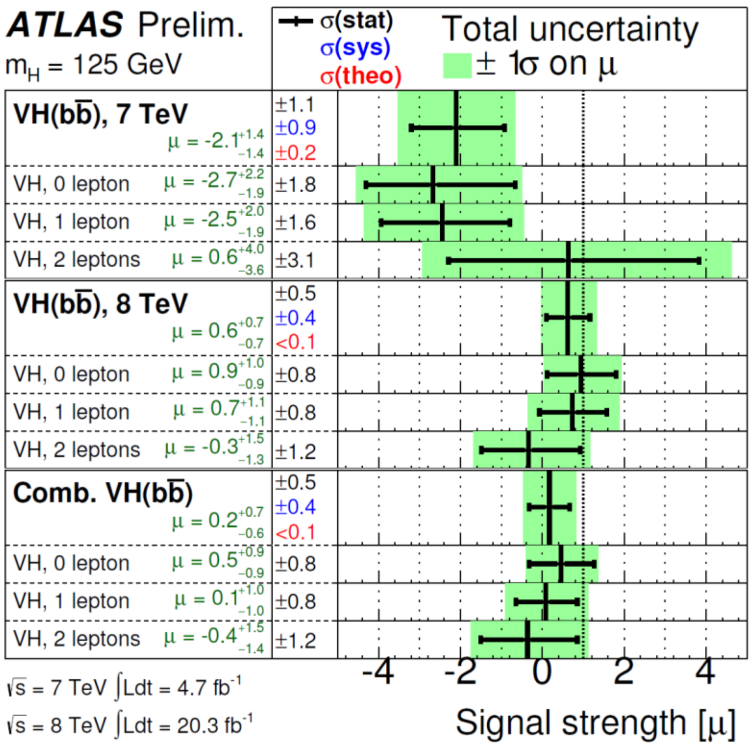


VH, H → $b\bar{b}$ results @ LHC

Phys. Rev. D 89, 012003 (2014)



ATLAS-CONF-2013-079



CMS (m_H = 125 GeV):

- **2.1 σ (2.1 σ) exp (obs)**
- $\boldsymbol{\mu = 1.0 \pm 0.5}$

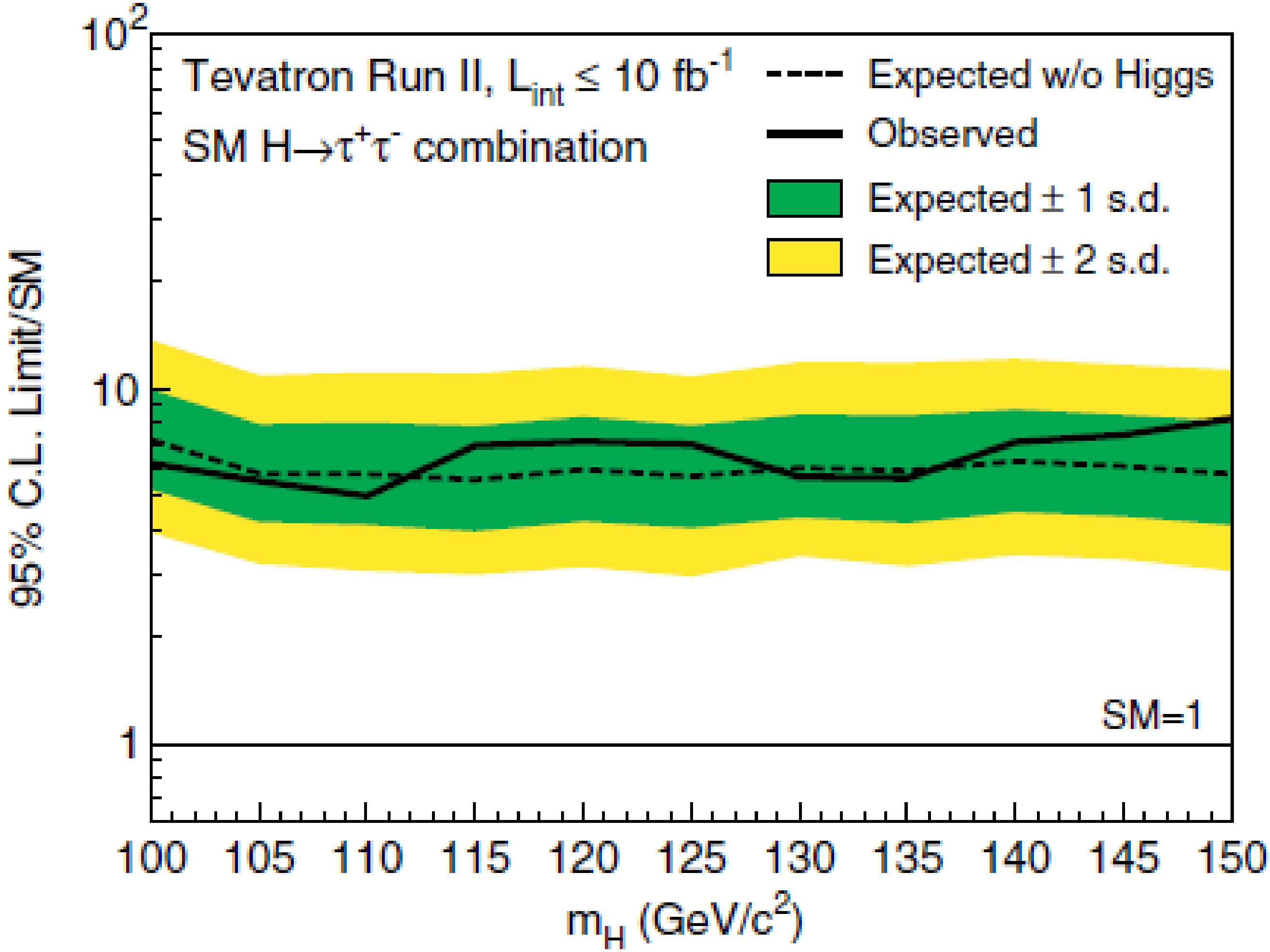
ATLAS (m_H = 125 GeV):

- **95% C.L. < 1.4 x SM**
- $\boldsymbol{\mu = 0.2^{+0.7}_{-0.6}}$

Hint is there, but a clear signal for H → bb will only come in Run 2

Search for H $\rightarrow$ $\tau\tau$

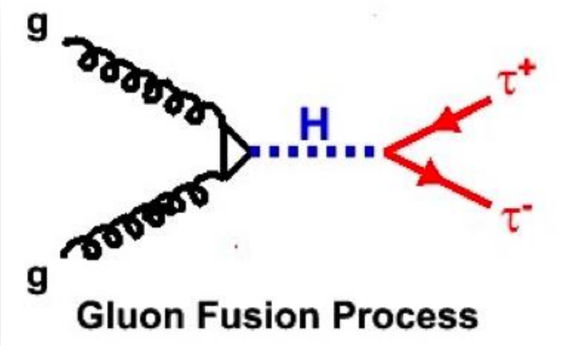
$H \rightarrow \tau\tau$ at the Tevatron

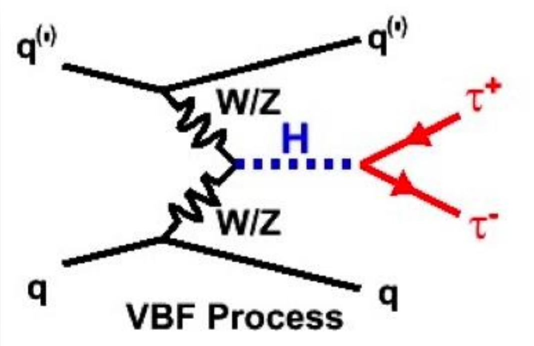


$\mu < 7$ @ 95% C.L.

H → ττ at the LHC: Overview

- **Importance of H → ττ:**
  - Only sensitive probe of SM lepton coupling
  - Complementarity with H → bb in down-type fermion couplings
  - Largest σ x Br for SM $m_H < 130$ GeV
  - Sensitivity to BSM models
  - One of the most watched questions to be answered in 2013: does h(126) decay to taus?
- **Broad-based search strategy**
  - Dominant background: Z → ττ
  - Mass reconstruction with MVA technique
  - Event categorization by production channel and kinematics





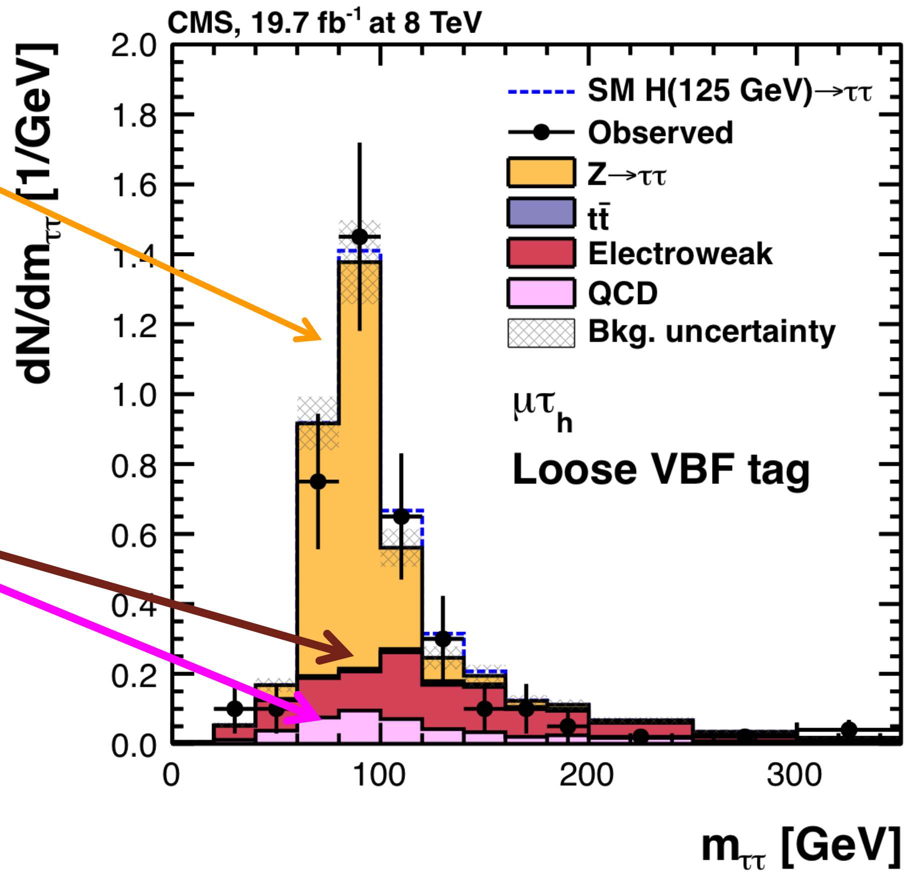
Anatomy of H → ττ

Z → ττ

- Dominant background
- Modeled in data using Z → μμ decays

Fake τ

- QCD multijet and W+jets
- Modeled from data using SS/OS or fake rates



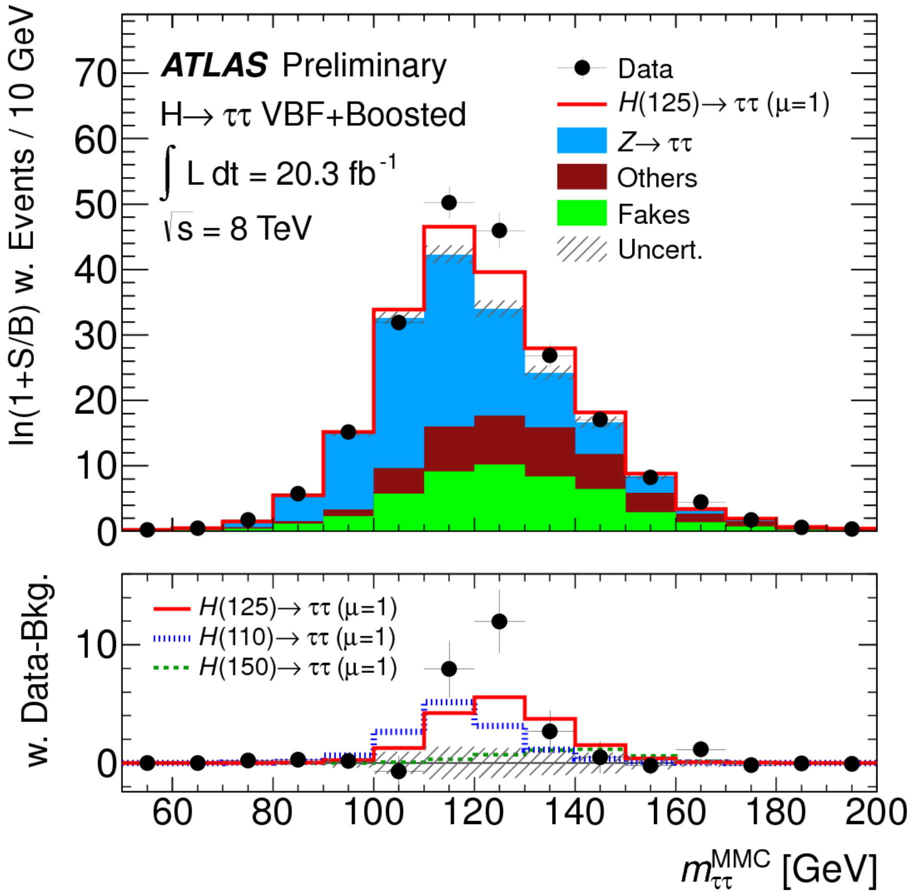
All possible signal decays are used: μτ, eτ, eμ, μμ, ee, ττ

Also all possible production channels: ggF, VBF, VH, ttH

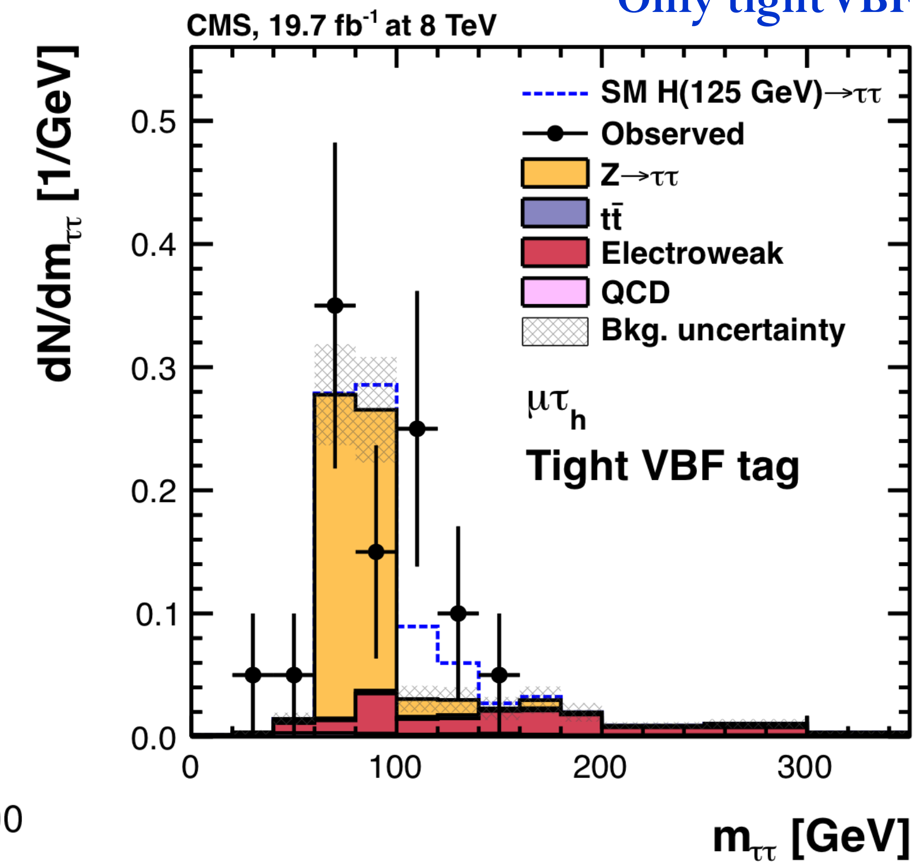
H → ττ: ATLAS and CMS

Signal starting to pop out above background in the tau-pair invariant mass distributions for both experiments

All categories

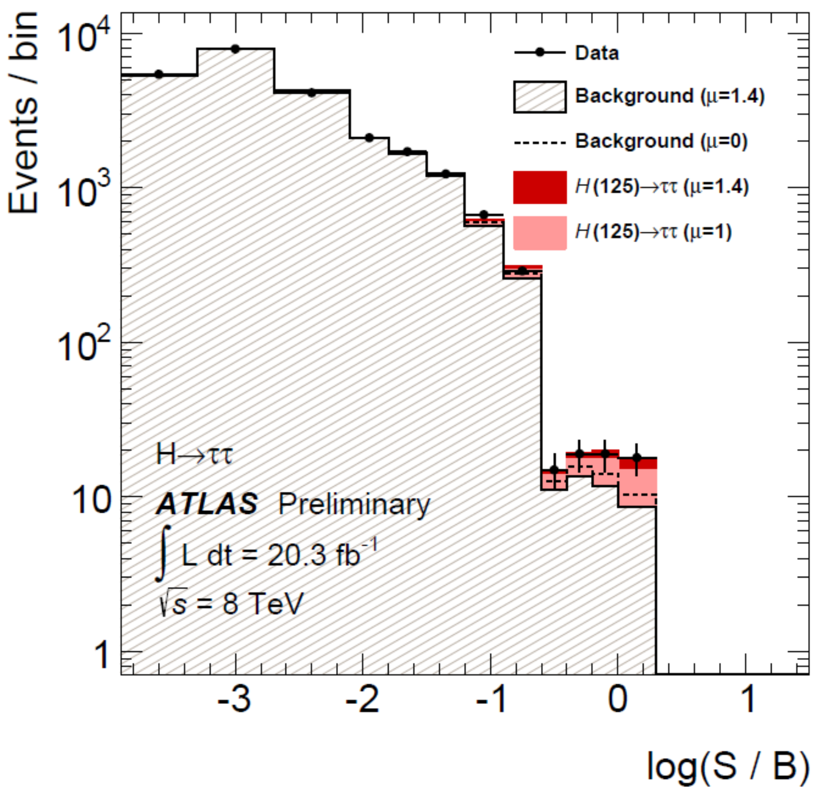


Only tight VBF

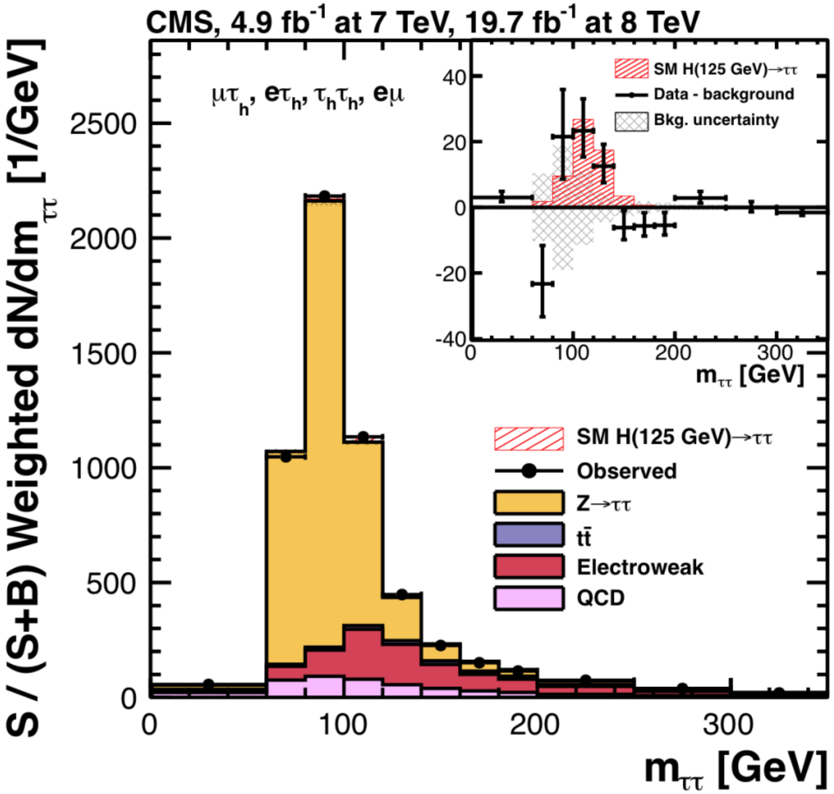


$H \rightarrow \tau\tau$: ATLAS and CMS

ATLAS-CONF-2013-108



CMS-HIG-13-004, accepted by JHEP



ATLAS (m_H = 125 GeV):

- 3.2 σ (4.1 σ) exp (obs)
- $\mu = 1.4^{+0.5}_{-0.4}$

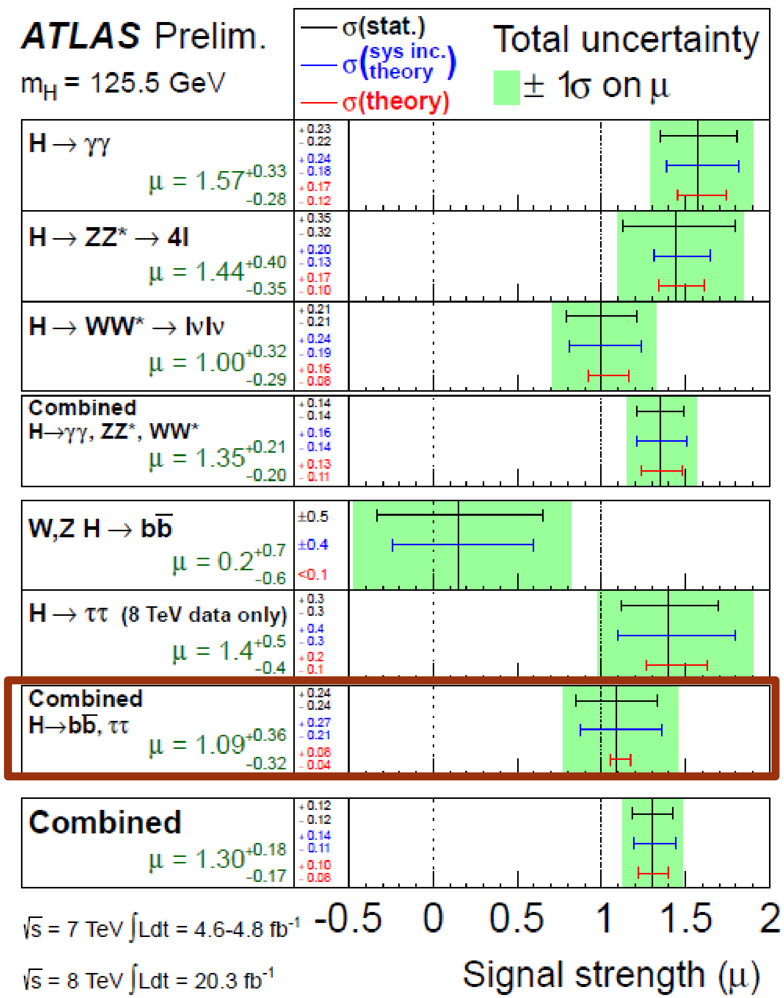
CMS (m_H = 125 GeV):

- 3.7 σ (3.2 σ) exp (obs)
- $\mu = 0.78 \pm 0.27$

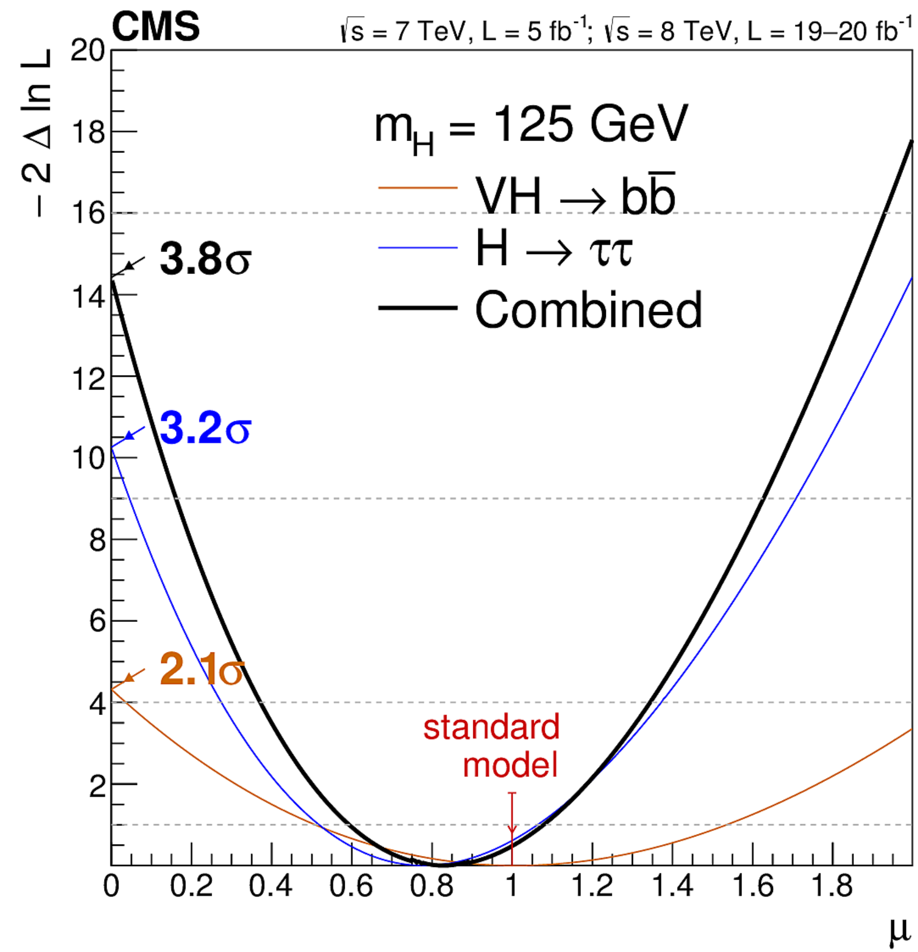
Strong evidence for Higgs decays to tau leptons!

Fermion Combination

ATLAS-CONF-2014-009



CMS-HIG-13-033, accepted by Nature



ATLAS: ττ + bb → 3.7 σ

CMS: ττ + bb → 3.8 σ

Summary

- Intense search for signs of a Higgs boson coupling to fermions at LEP, Tevatron, and LHC for past ~15 years
- Discovery of a Higgs boson at the LHC has focused the search to a specific question: does h(126) couple to fermions?
  - The Tevatron has shown 3σ evidence for $H \rightarrow b\bar{b}$
  - After analyzing the full Run 1 dataset, ATLAS and CMS have now produced clear evidence for $H \rightarrow \tau\tau$ decays
    - ATLAS: 4.1 σ
    - CMS: 3.2 σ
  - LHC experiments each have evidence for $\tau\tau$ + bb @ > 3 σ
- There is no sign of $\mu\mu$ or ee decays, confirming that h(126) couples to mass and does not respect lepton universality
- Nearing the start of LHC Run 2, we now know quite a bit about the fermionic couplings of the Higgs boson!