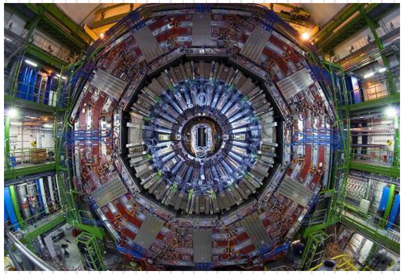
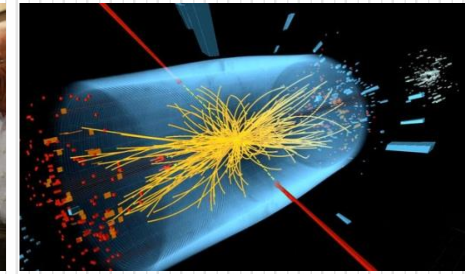
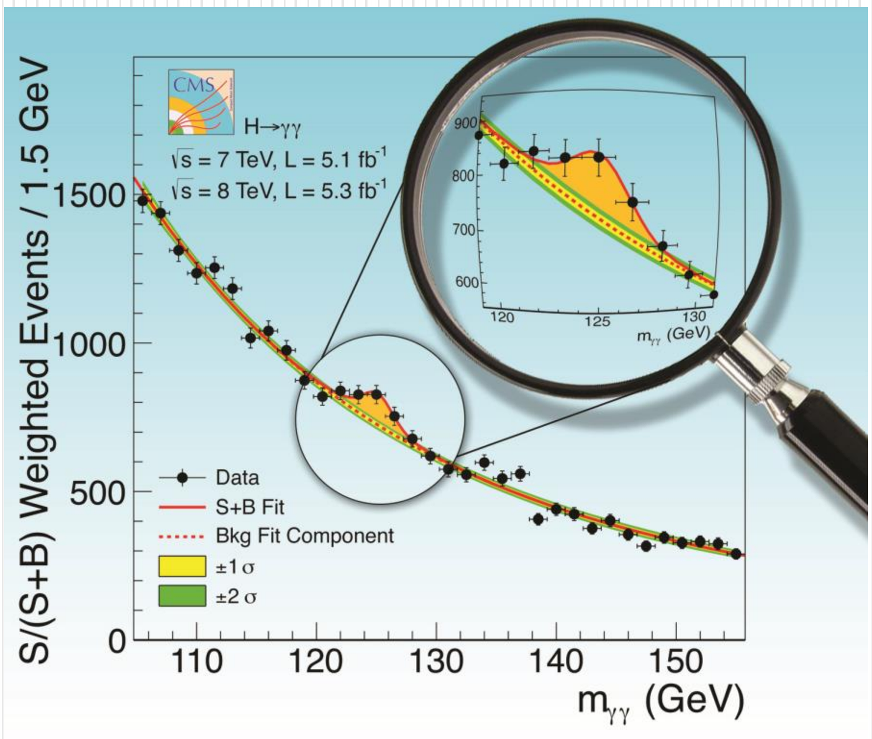


Higgs Measurements at the LHC



Jim Olsen

Princeton University

What Next at the LHC?

TIFR, Mumbai, India

January 6, 2014

Outline

- Introduction
- Higgs decays to bosons
- Higgs decays to fermions
- Higgs properties
- Beyond standard model Higgs

Some disclaimers:

- Not all results are shown (there are too many!)
- Analysis details, when given, are typically for CMS
- Results for both CMS and ATLAS are shown
- Emphasis is on SM Higgs

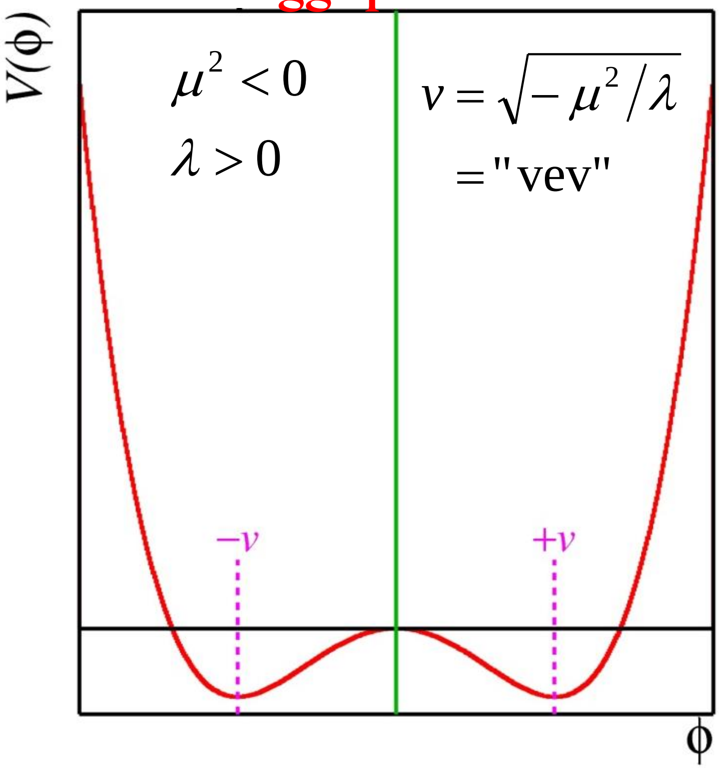
Introduction:
SM Higgs physics and pre-LHC search

"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

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

Higgs potential



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

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

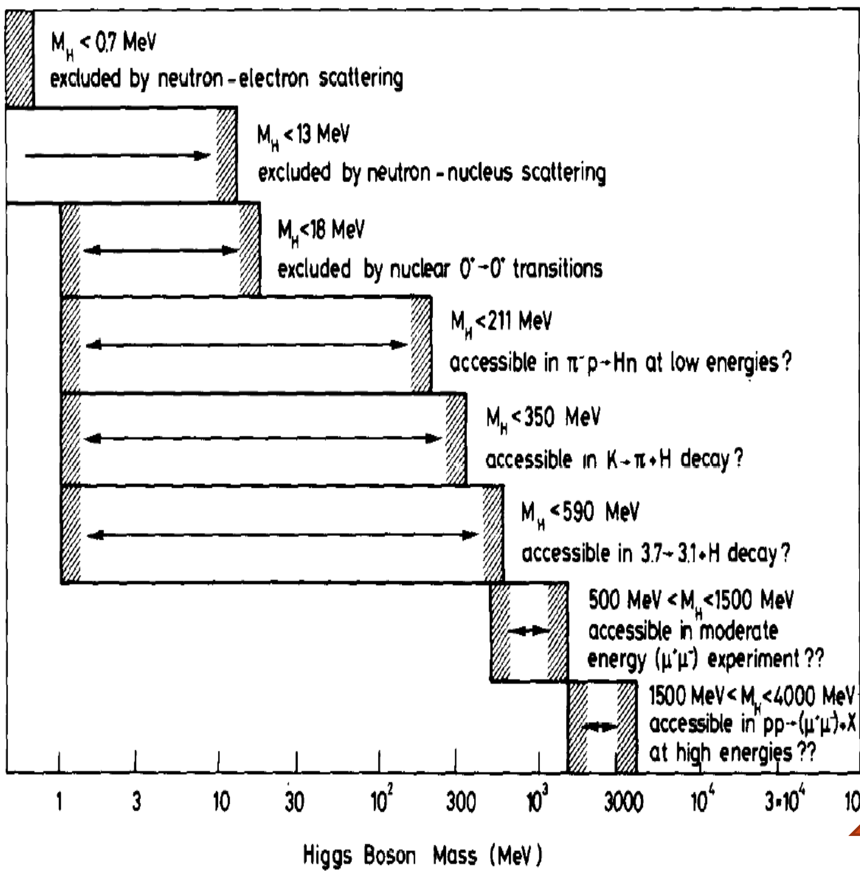
Because λ is not predicted, the Higgs boson mass is a free parameter in the SM

Gauge boson and fundamental fermion masses:

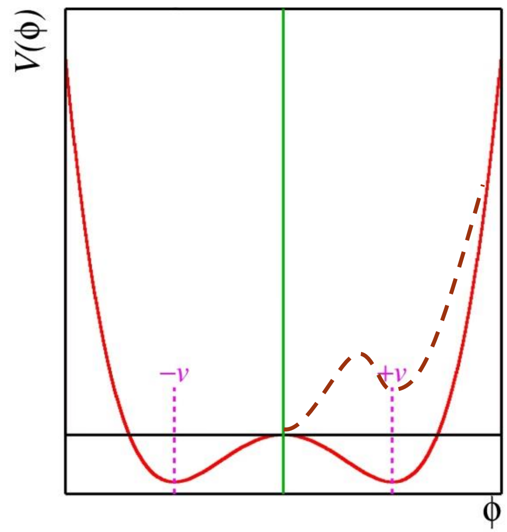
$$m_W = \frac{gv}{2}, m_Z = \frac{m_W}{\cos\theta_W}, m_f = \frac{g_f v}{\sqrt{2}}$$

Higgs search, 70's style:

Ellis, Gaillard, and Nanopoulos, Nucl. Phys. B106, 292 (1976)

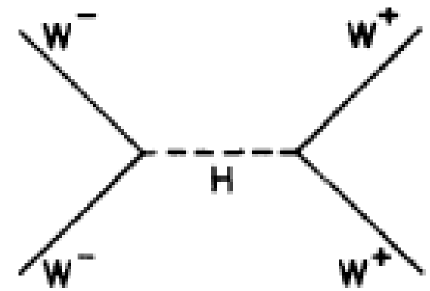


125 GeV



Requiring V(v) < V(0) gives: $m_H > 7$ GeV

Weinberg and Linde (1976)

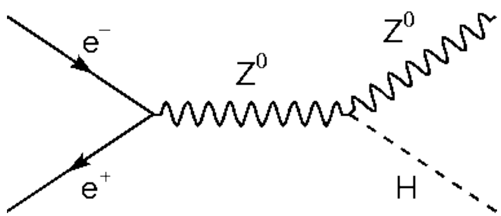


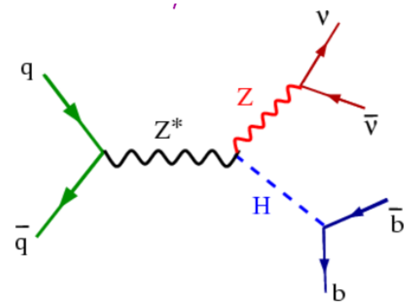
Requiring unitarity in WW scattering gives: mH < ~ 1 TeV

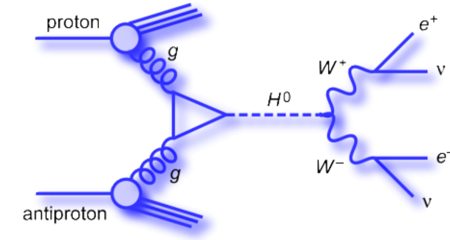
Lee, Quigg, Thakcer (1977)

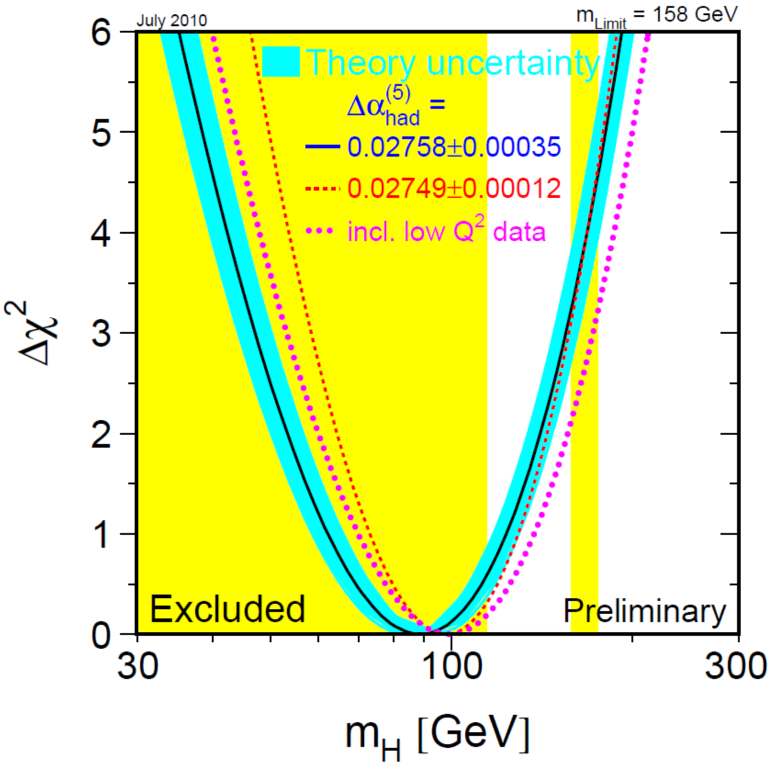
By 1980 we knew the mass of the Higgs boson was in the range 7 - 1000 GeV

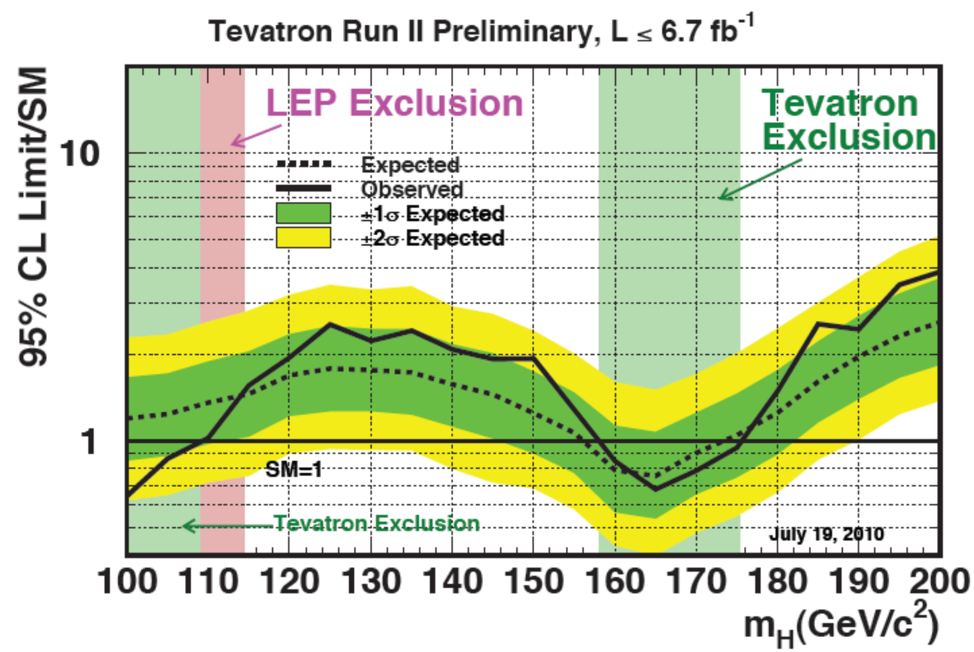
Pre-LHC: LEP and Tevatron







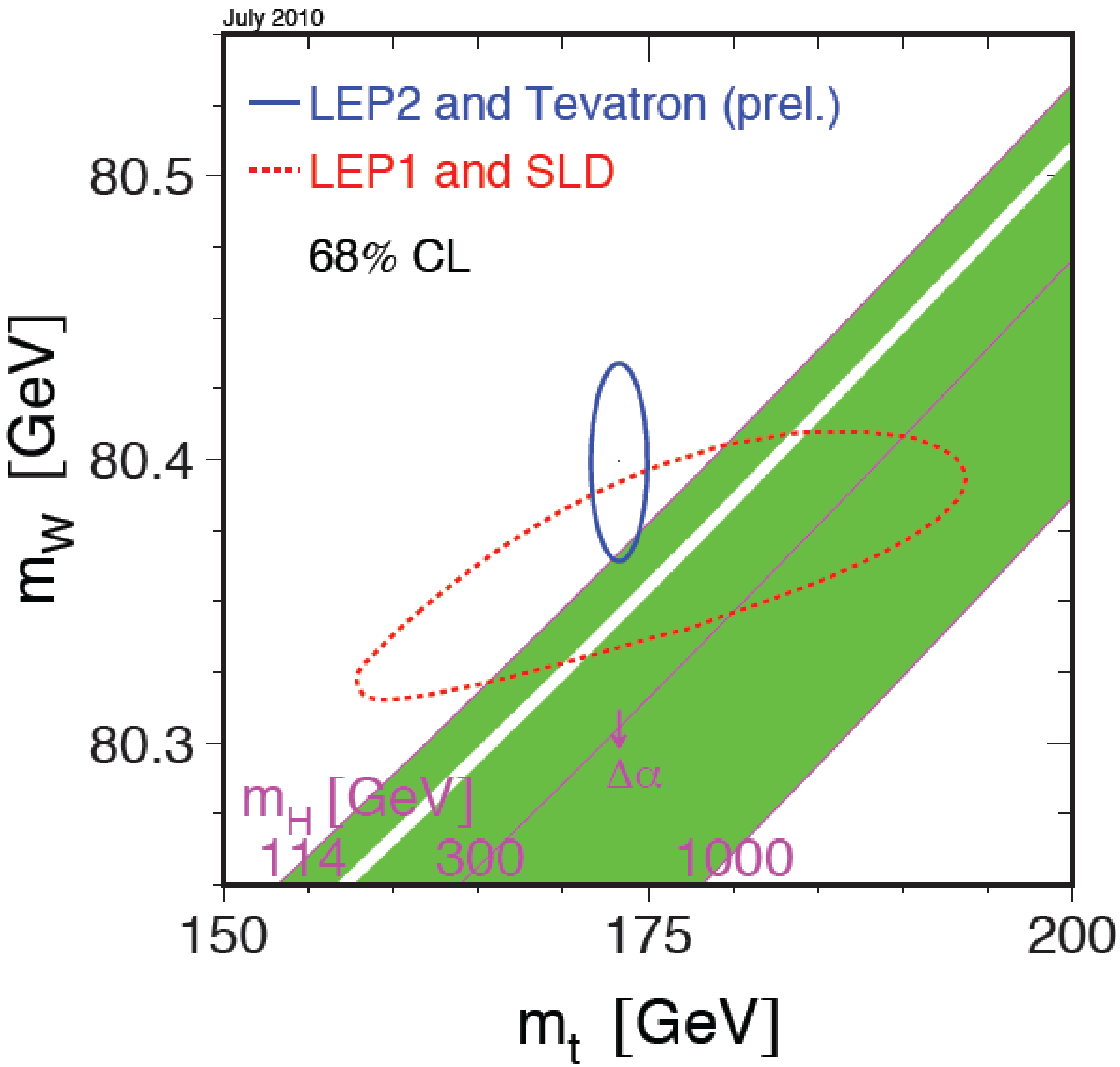




$m_H > 114.4$ GeV

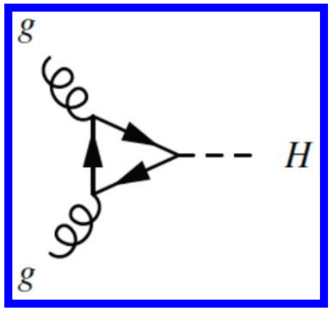
$m_H < 158$ or > 175 GeV

At the dawn of the LHC era

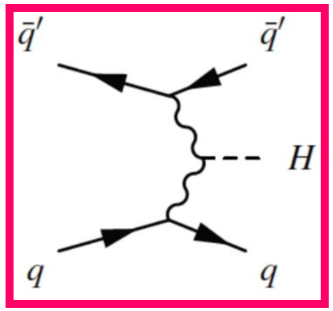


SM Higgs boson and the LHC

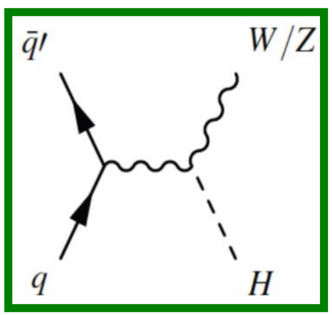
SM Higgs Production at the LHC



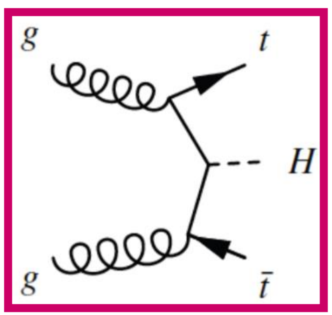
Gluon Fusion



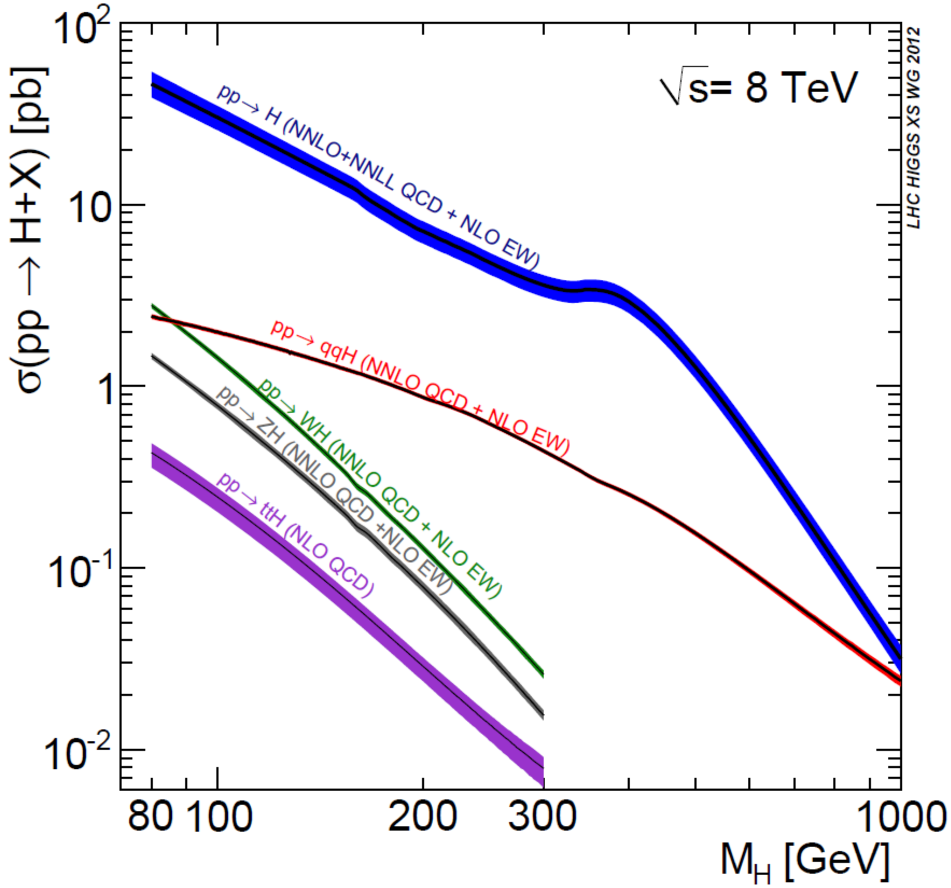
Vector-Boson Fusion



Higgs-strahlung

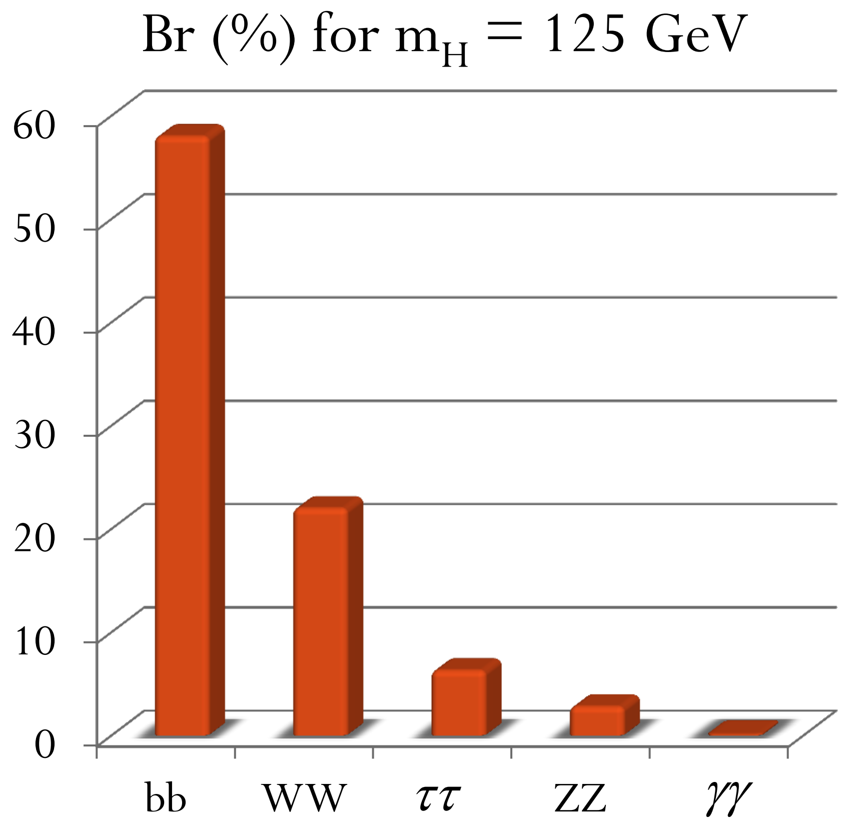


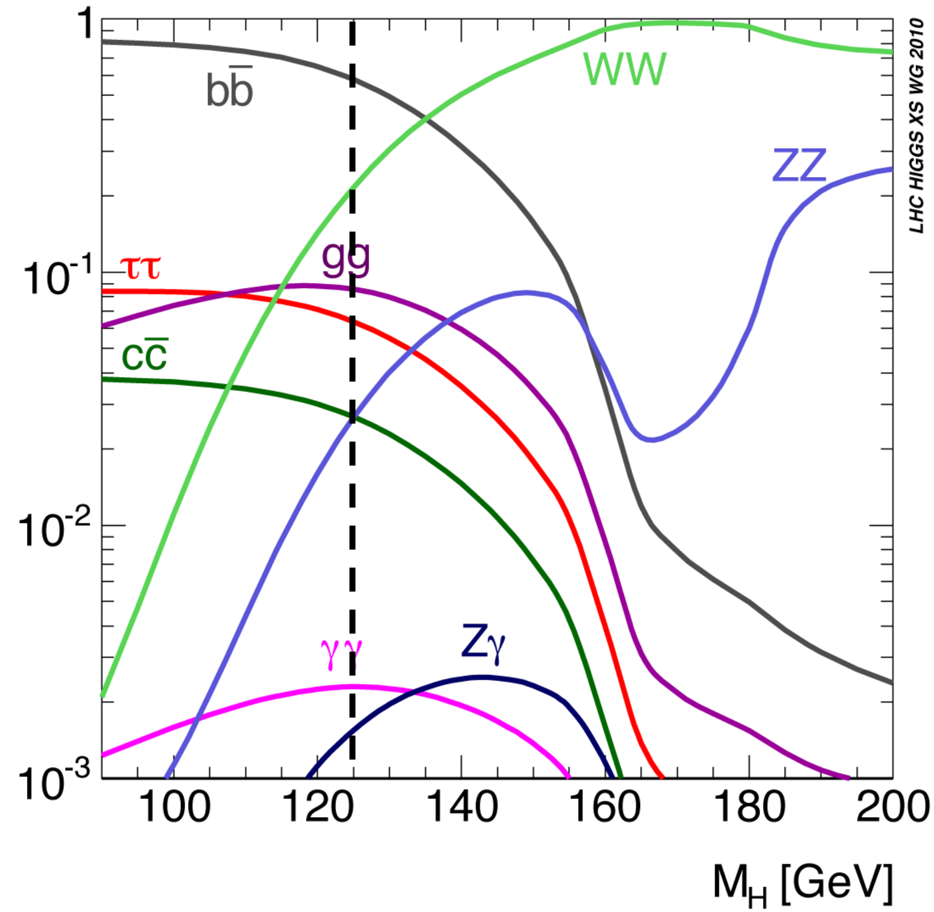
Top Fusion ($t\bar{t}H$)



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**

How does it decay?





Fortuitous! Only region in m_H where

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

What does it look like?

@Low mass

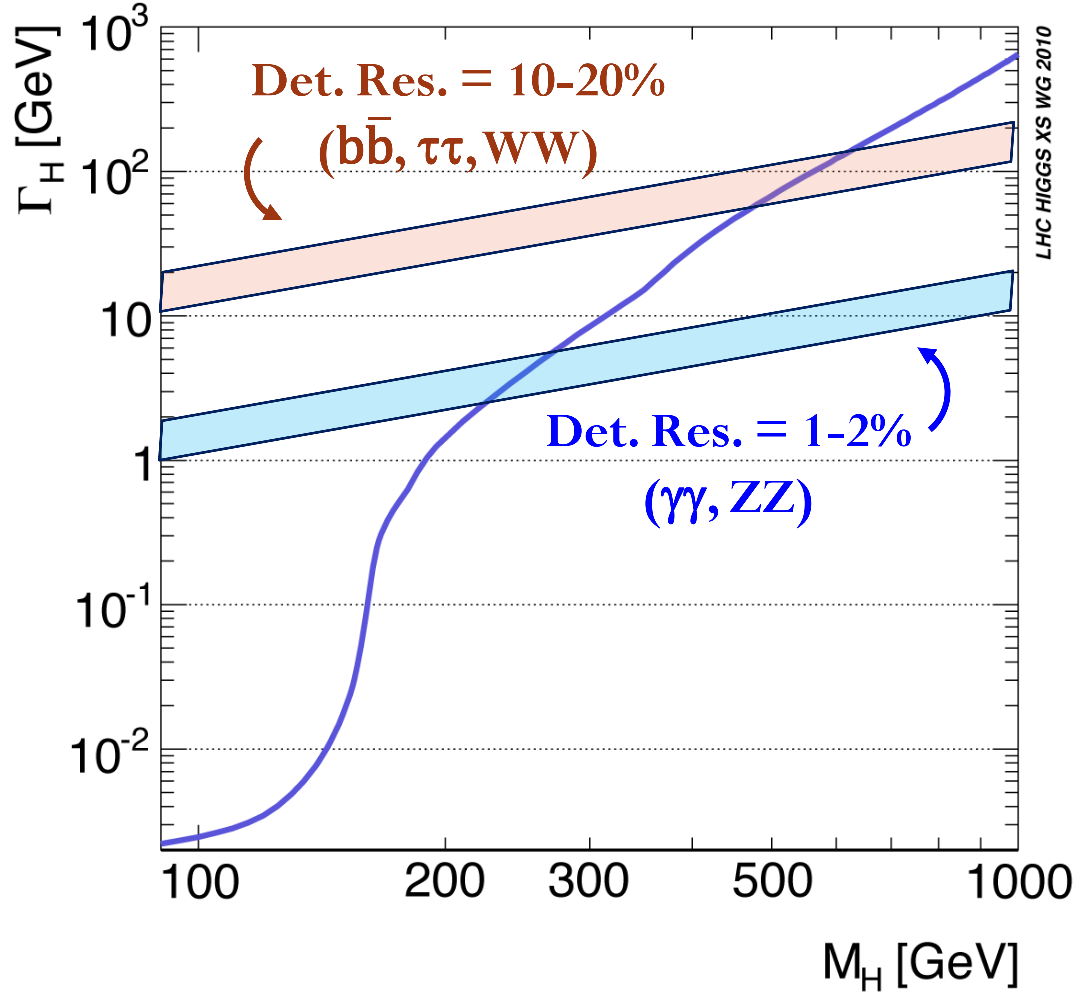
Narrow! $\Gamma_H / m_H \sim 10^{-5}$

Observed width dominated by ***detector resolution***

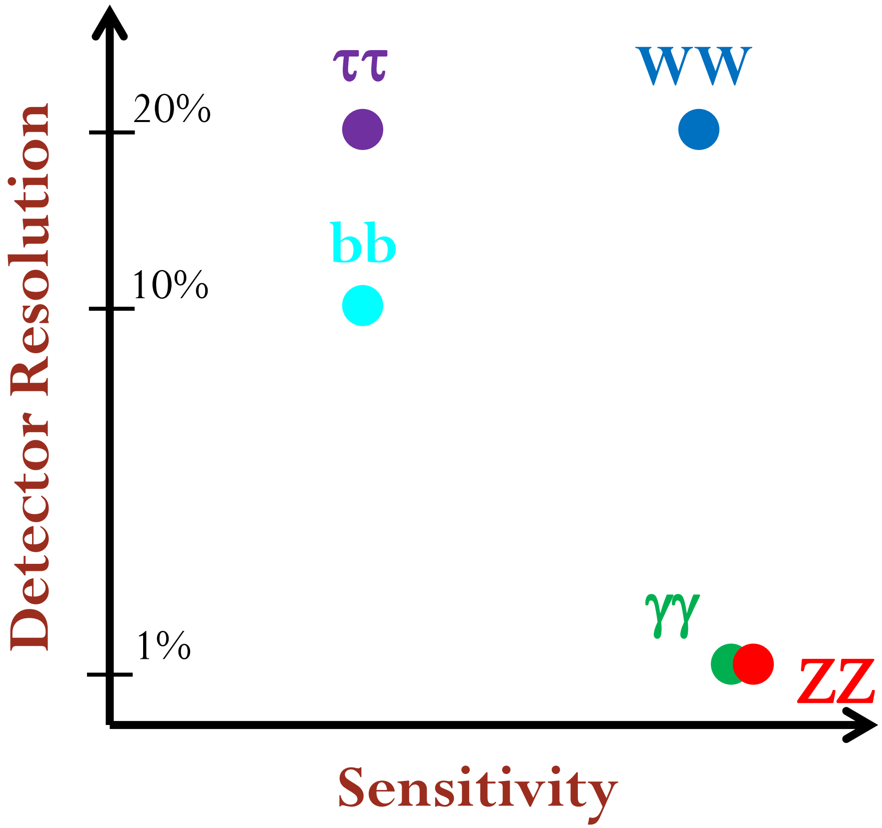
@High mass

Higgs becomes a broad resonance dominated by ***natural width***

Theory input is critical



SM Higgs Analyses @ LHC



Three classes of SM analysis:

1) High sensitivity, high resolution

   γγ, ZZ

2) High sensitivity, low resolution

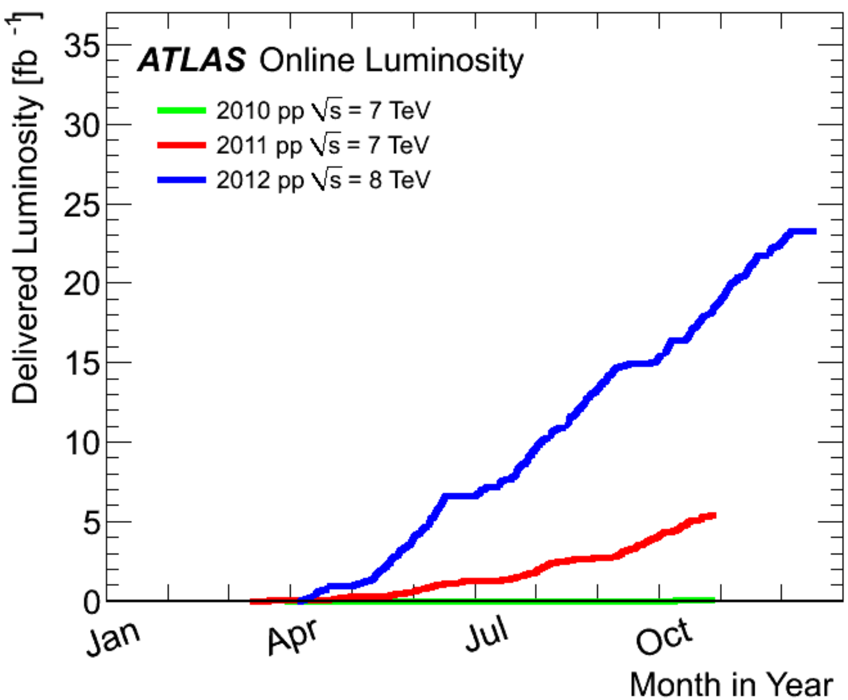
   WW

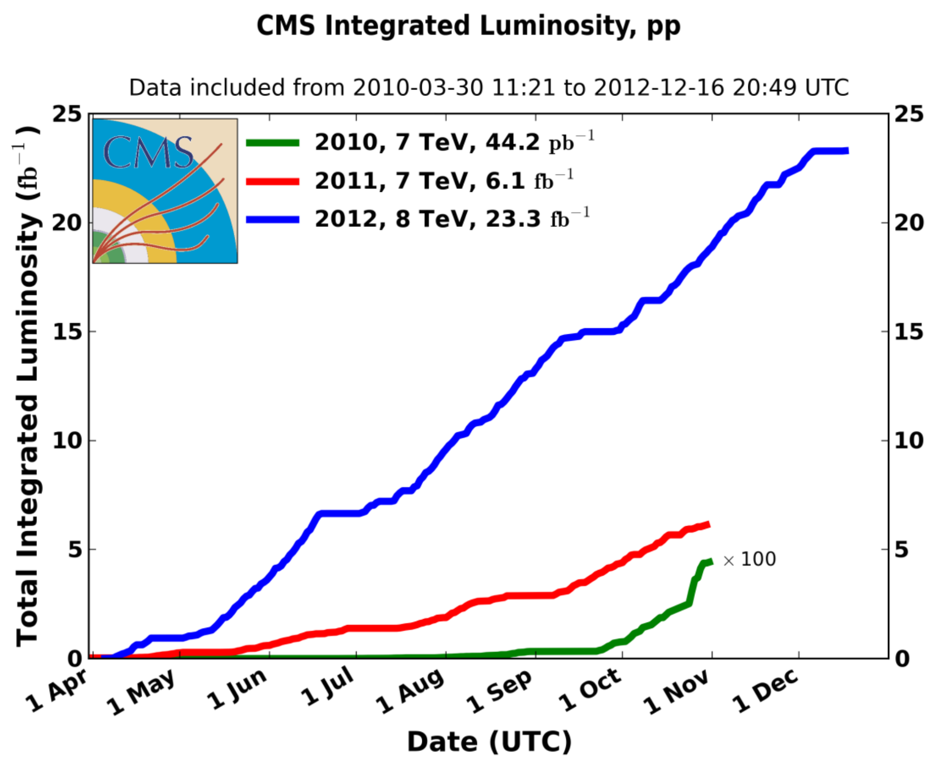
3) Low sensitivity, low resolution

   ττ, bb

All particles / physics objects are important: charged particles, photons, electrons, muons, taus, jets, missing energy, b tagging. Need **multi-purpose detectors** like ATLAS and CMS to find the Higgs boson at the LHC!

2012 LHC + ATLAS/CMS Performance



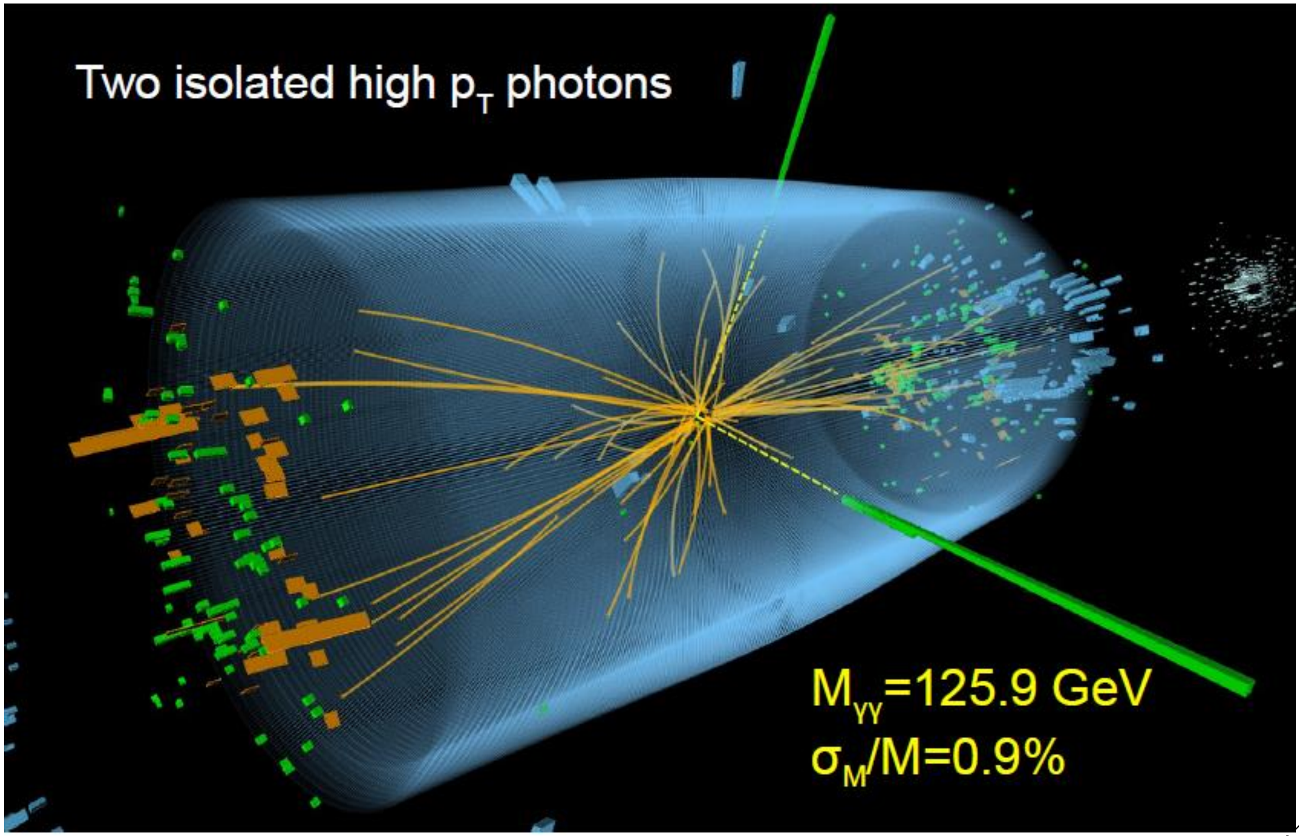


- Phenomenal performance:
  - Record luminosity (> 5 x 10^{33}) obtained soon after startup in 2012
  - Sustained data collection rate of > 1.0 fb^{-1} /wk
  - Total delivered / recorded @ 8 TeV = [23.3 / 21.3 (ATLAS) , 21.8 (CMS)] fb^{-1}

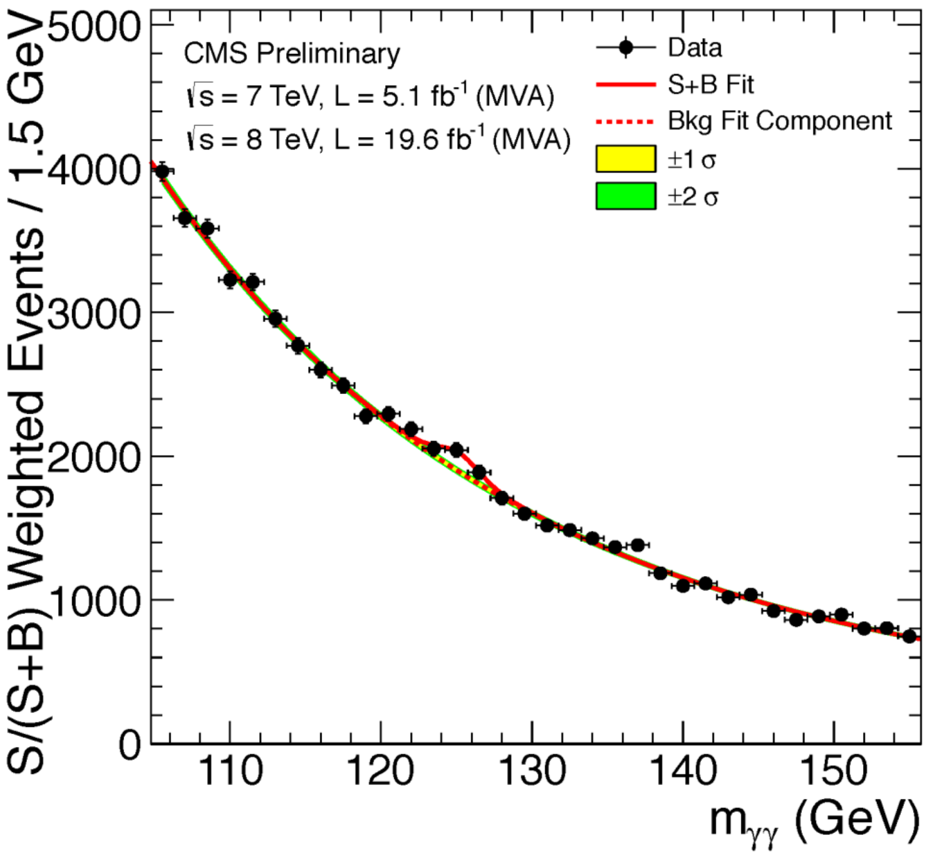
The new boson decaying to bosons

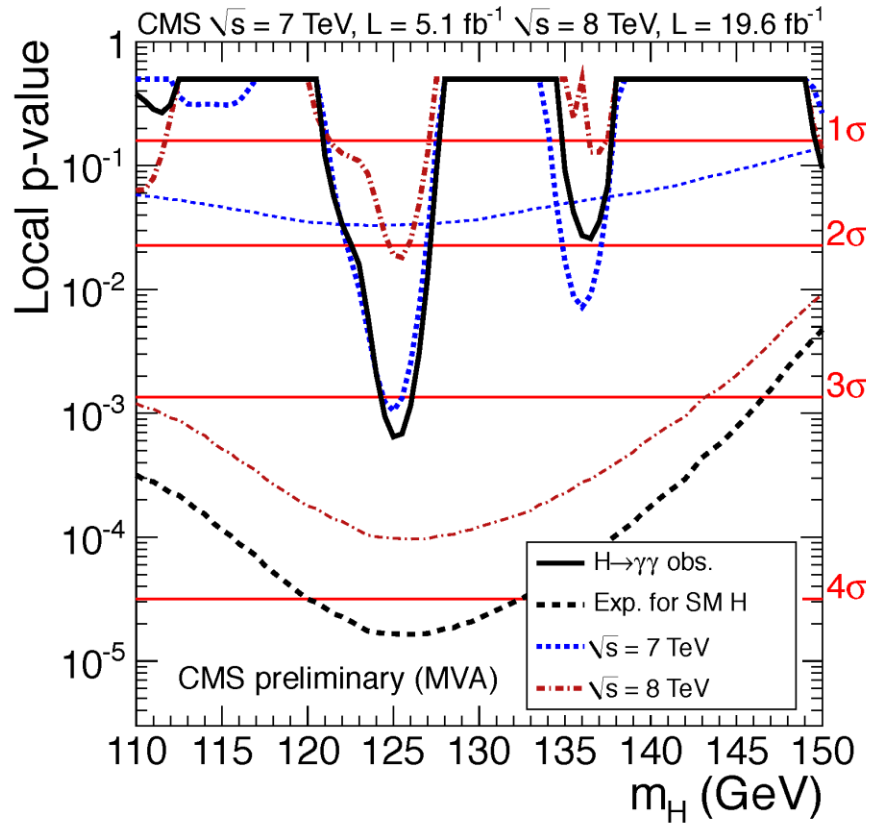
Overview of Search for $H \to \gamma\gamma$

- Experimental signature
  - Narrow (1-2%) diphoton resonance
  - Hard diphoton p_T spectrum
  - Isolated photons
  - VBF: spectacular diphoton+dijet



$H \to \gamma\gamma$: CMS results

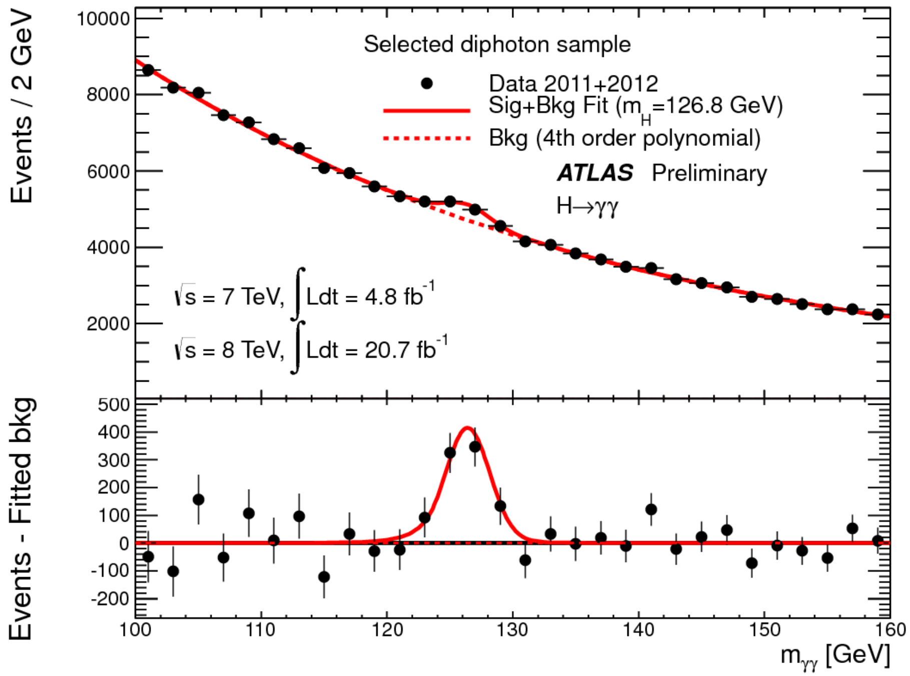




Best fit $\mu \equiv \sigma/\sigma_{SM} =$ 0.8 ± 0.3 @ 125.2 GeV

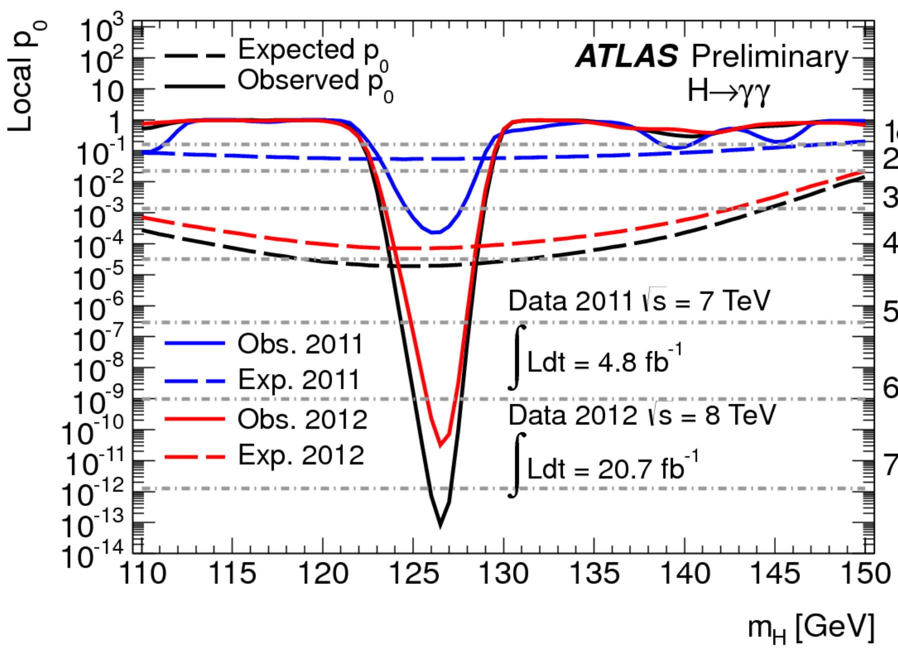
Exp (obs) significance = 4.2 σ (3.2 σ) at 125 GeV

$H \to \gamma\gamma$: ATLAS



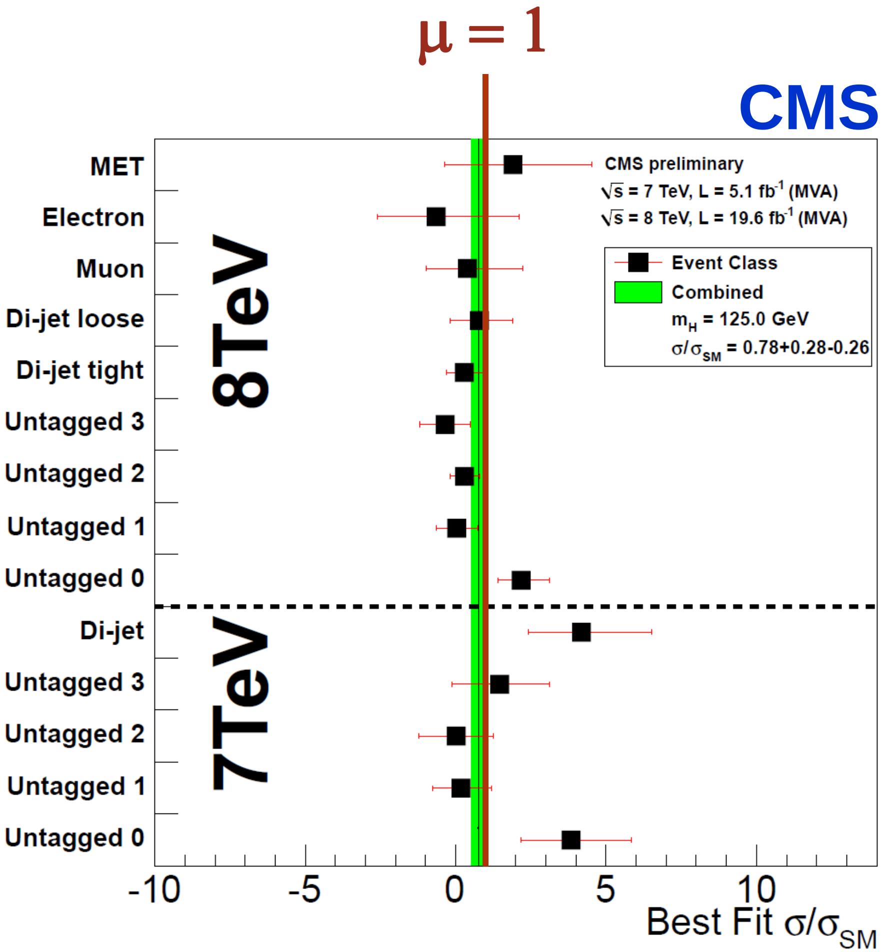
Exp (obs) significance = 4.1 σ (7.4 σ) @ 126.5 GeV

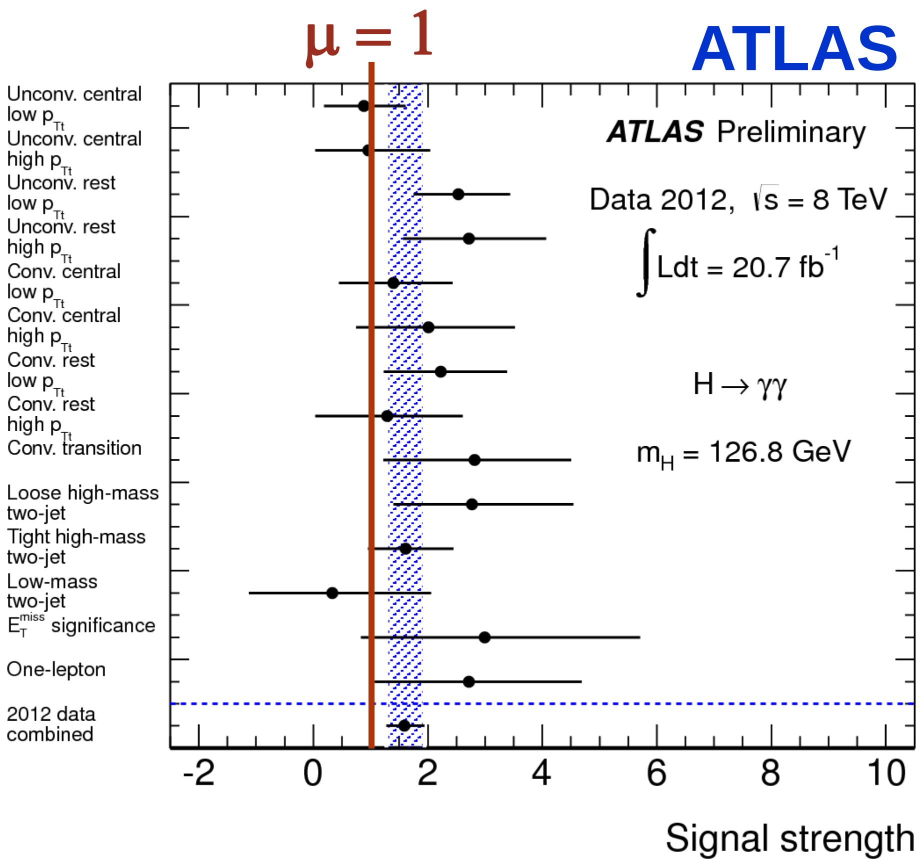
$$\mu = 1.7 \pm 0.3$$



ATLAS sees more signal events than expected in both 7 and 8 TeV data

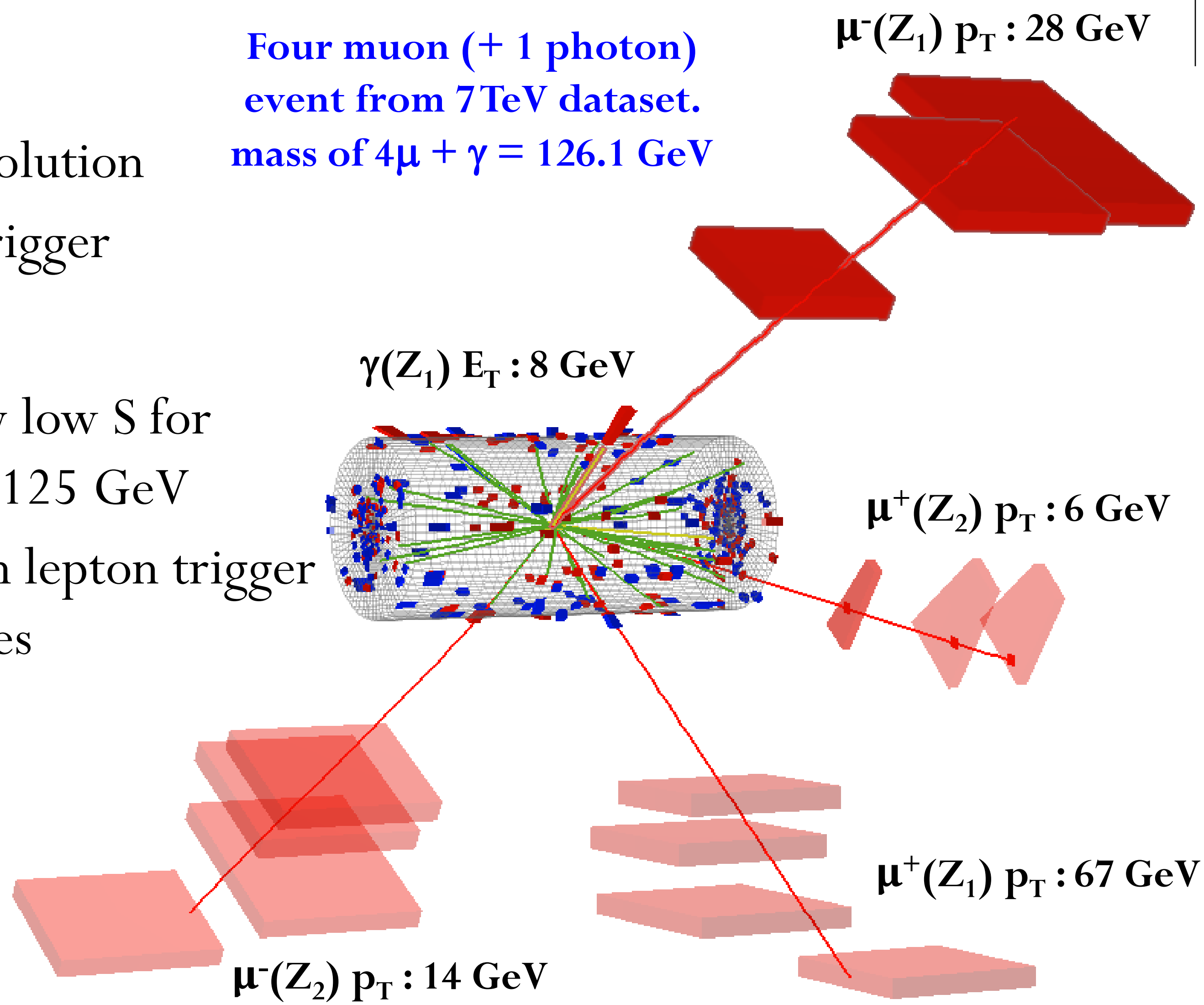
H → γγ: Signal strength by category



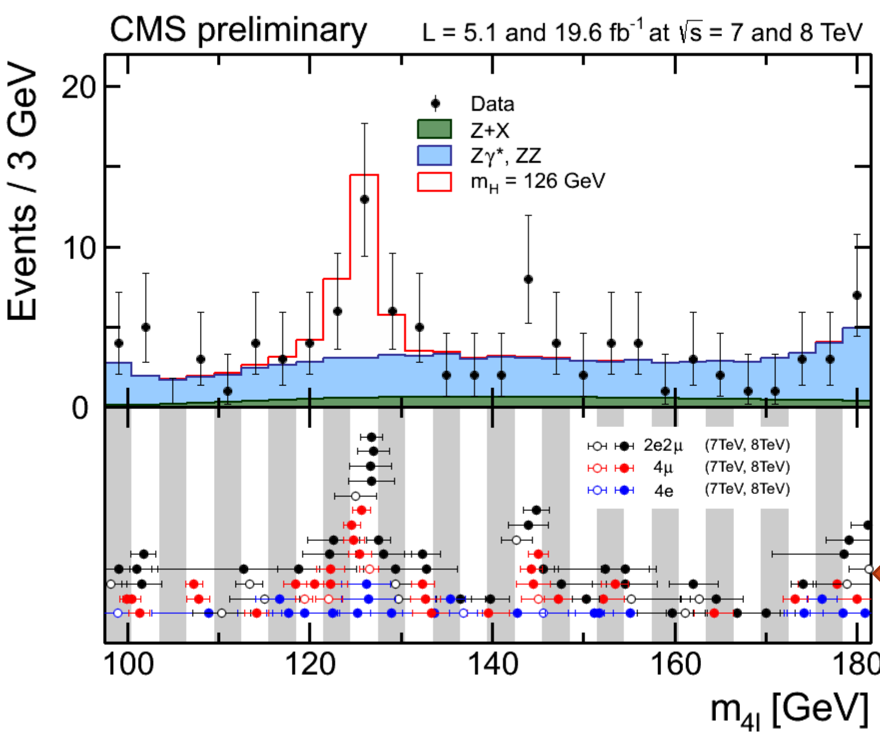


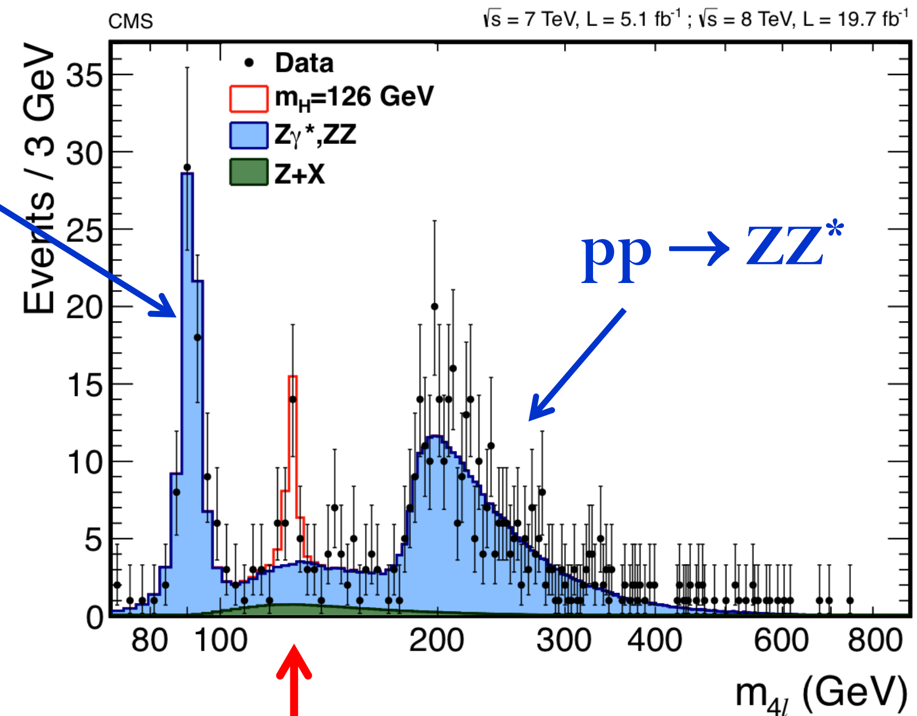
Overview of H → ZZ* → 4ℓ (ℓ=e,μ)

- **Advantages**
  - Very clean channel
  - Excellent mass resolution
  - Readily available trigger
- **Challenges**
  - High S/B, but very low S for Higgs masses near 125 GeV
  - Must maintain high lepton trigger and reco efficiencies



$H \rightarrow ZZ^* \rightarrow 4\ell$: CMS





$Z \rightarrow 4\ell$

$pp \rightarrow ZZ^*$

Higgs Boson

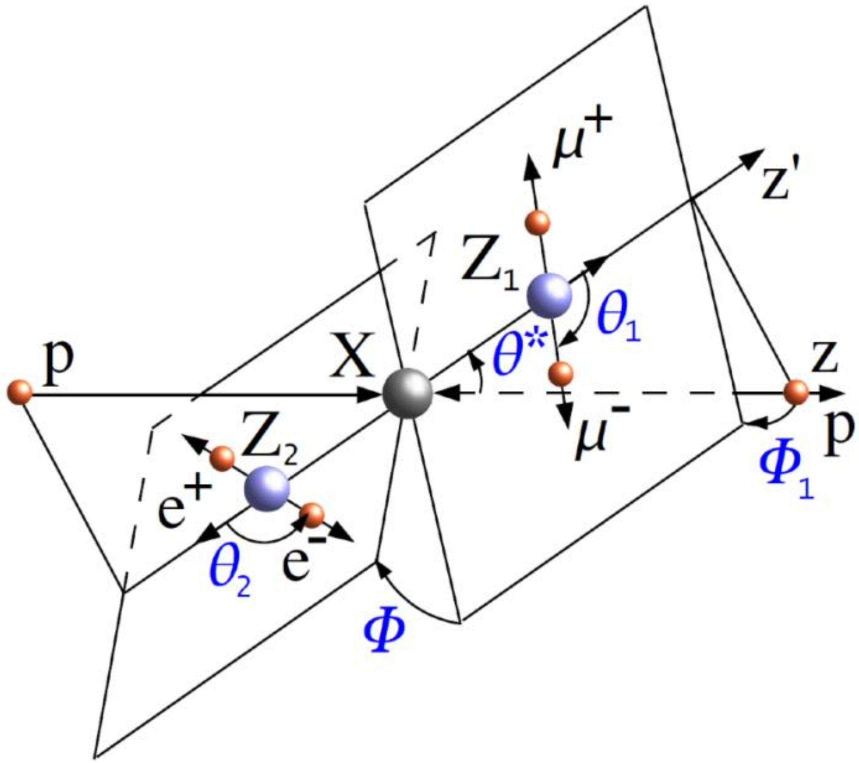
4-lepton mass for each event, including the uncertainty

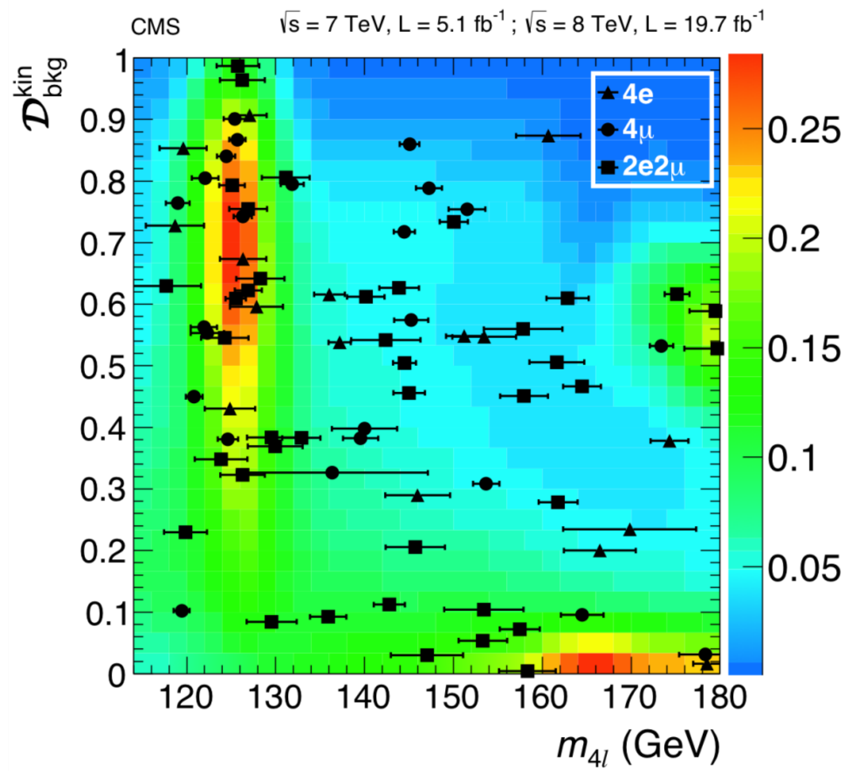
$H \to ZZ^* \to 4\ell$: CMS (MELA)

- Matrix Element Likelihood Analysis:

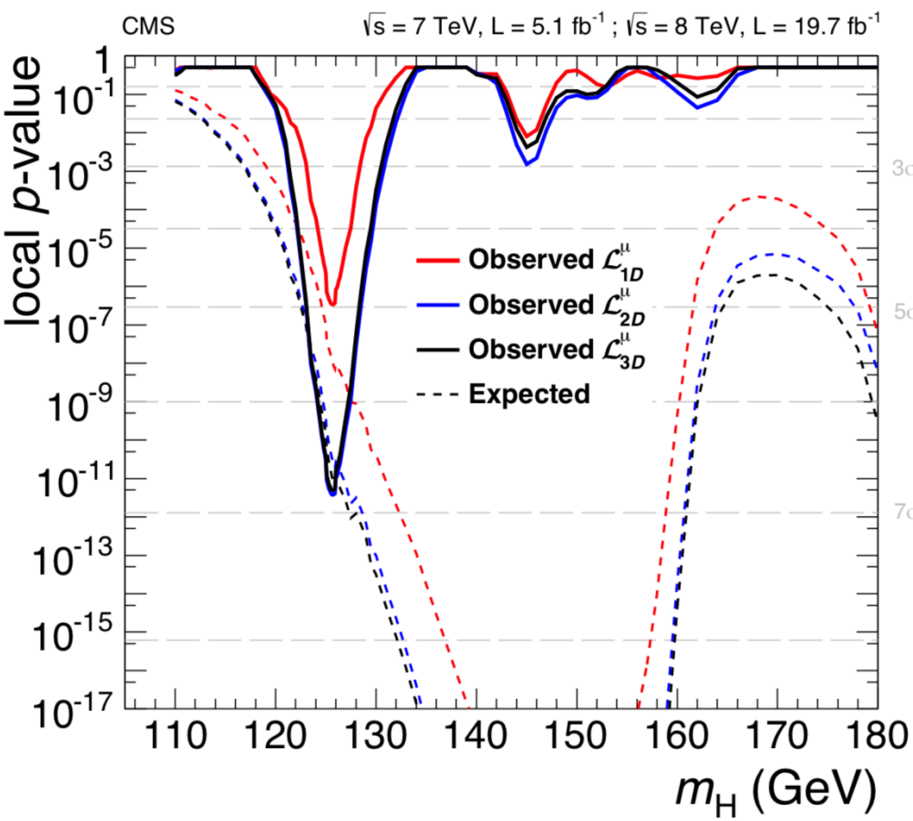
$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

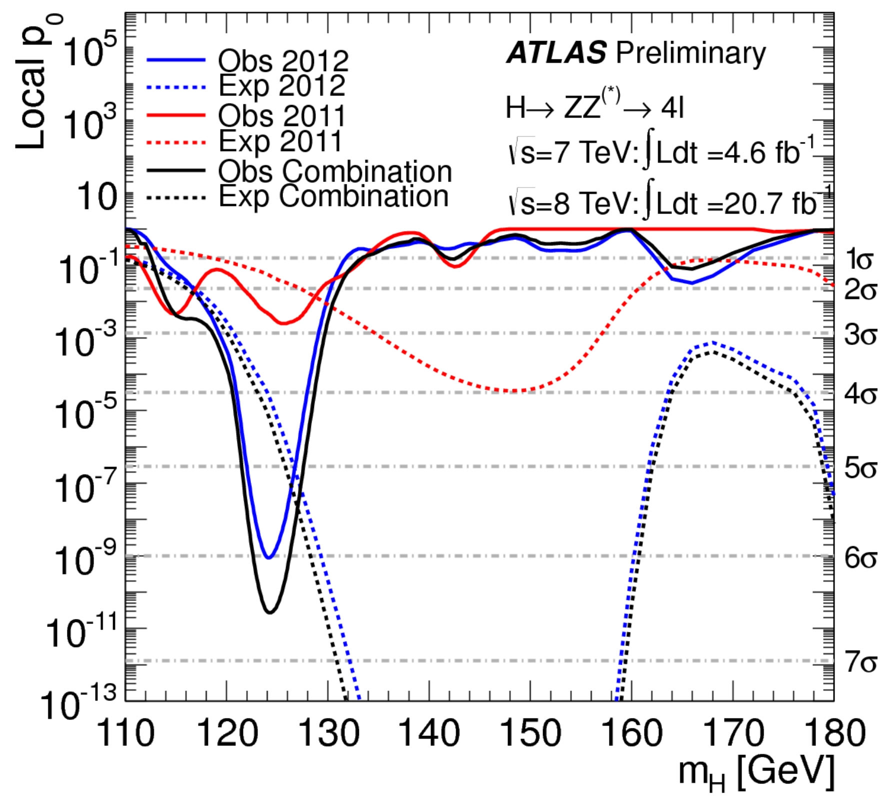
  - Exploit known kinematics and topology of a scalar X decaying to two heavy vector bosons then leptons





$H \to ZZ^* \to 4\ell$: CMS and ATLAS





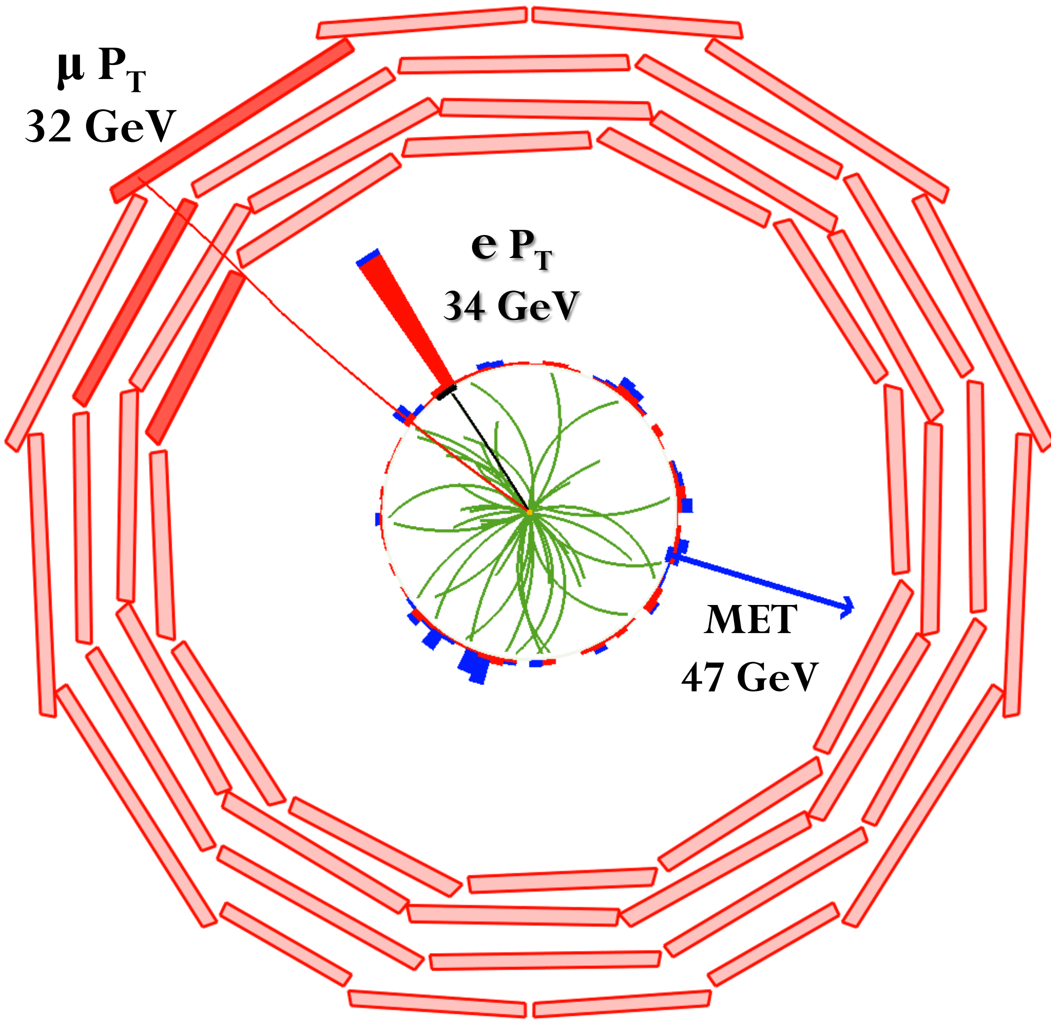
Exp (obs) significance = 6.7σ (6.8σ) @ 125.7 GeV

Exp (obs) significance = 4.4σ (6.6σ) @ 124.3 GeV

$\mu = 0.93^{+0.29}_{-0.25}$ (125.6 GeV)

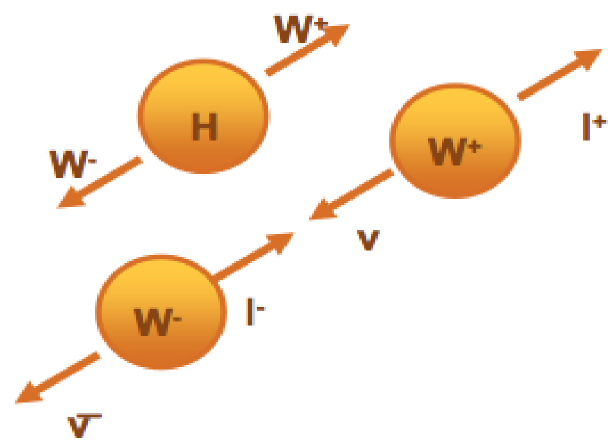
$\mu = 1.7^{+0.5}_{-0.4}$ (124.3 GeV)

$H \rightarrow WW^* \rightarrow 2\ell 2\nu$



- High sensitivity, low resolution
  - 2nd largest σ x BF
  - Charged leptons for trigger
  - Controllable backgrounds
  - Kinematic handles

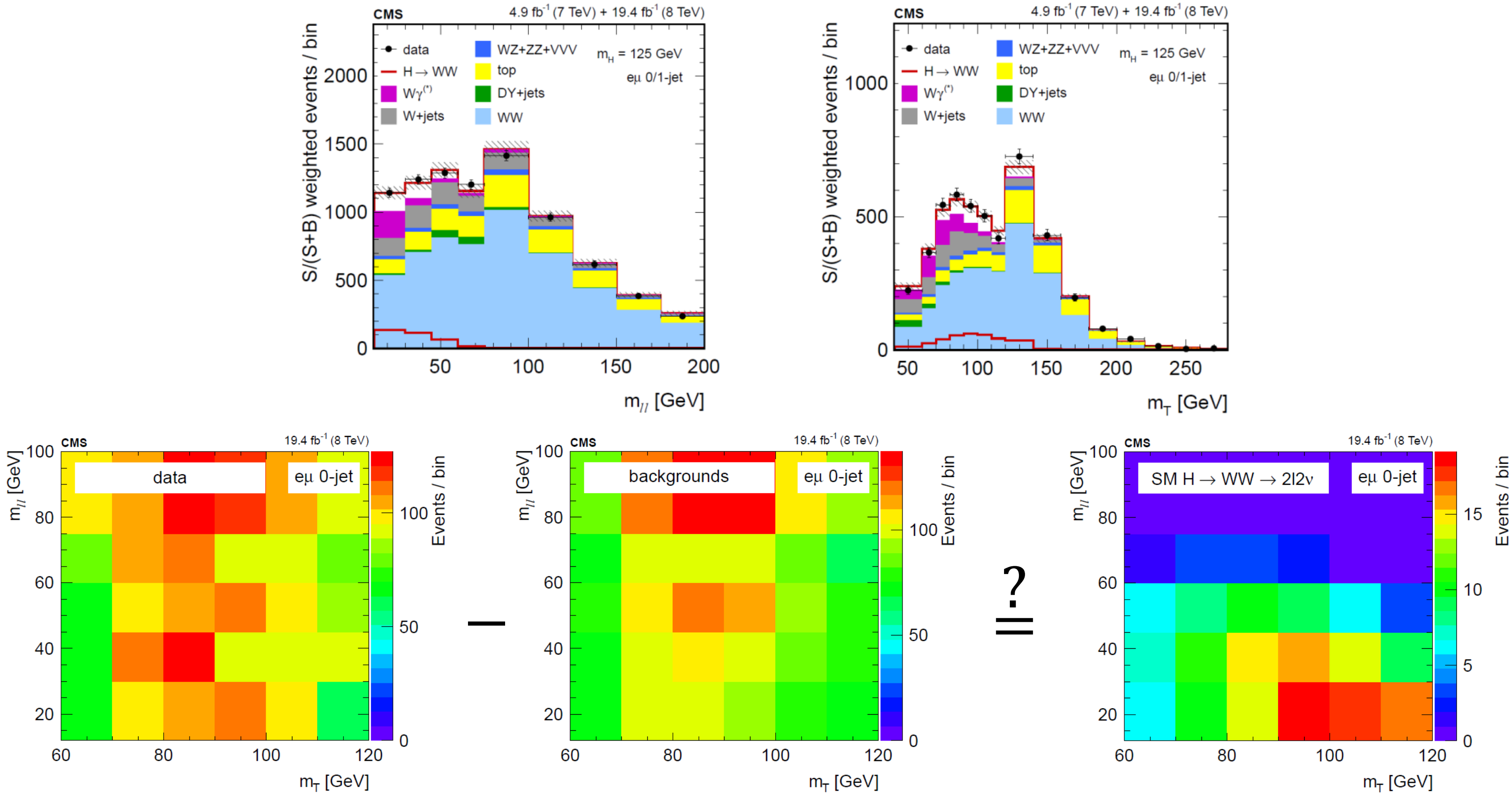
Spin-0 Higgs + V-A weak int. = small angle between ℓ's, and ν's



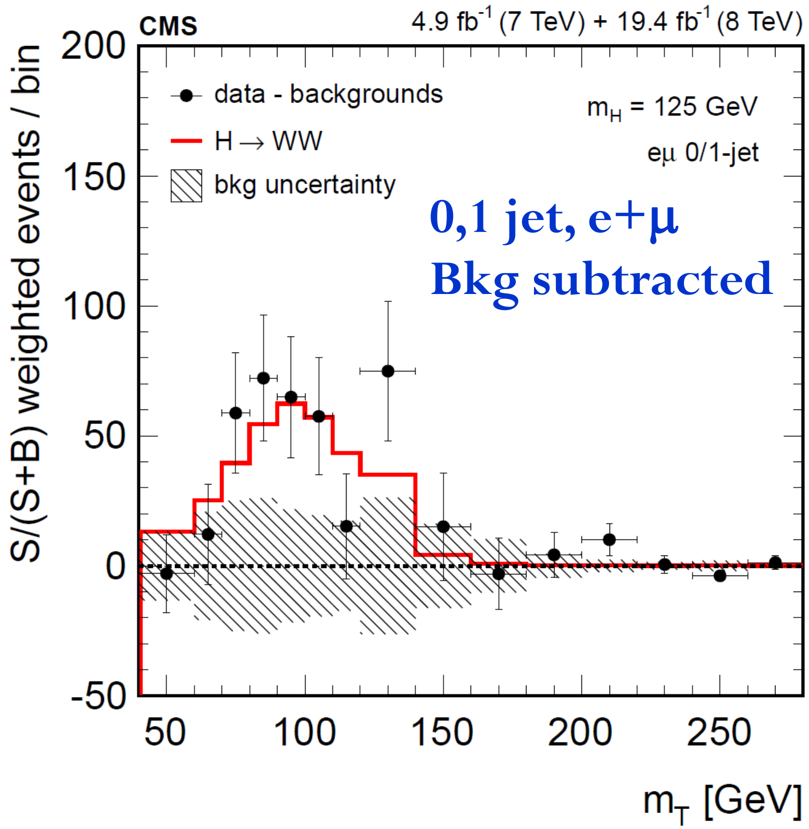
Only real drawback is no sharp mass peak (20% resolution in M_T)

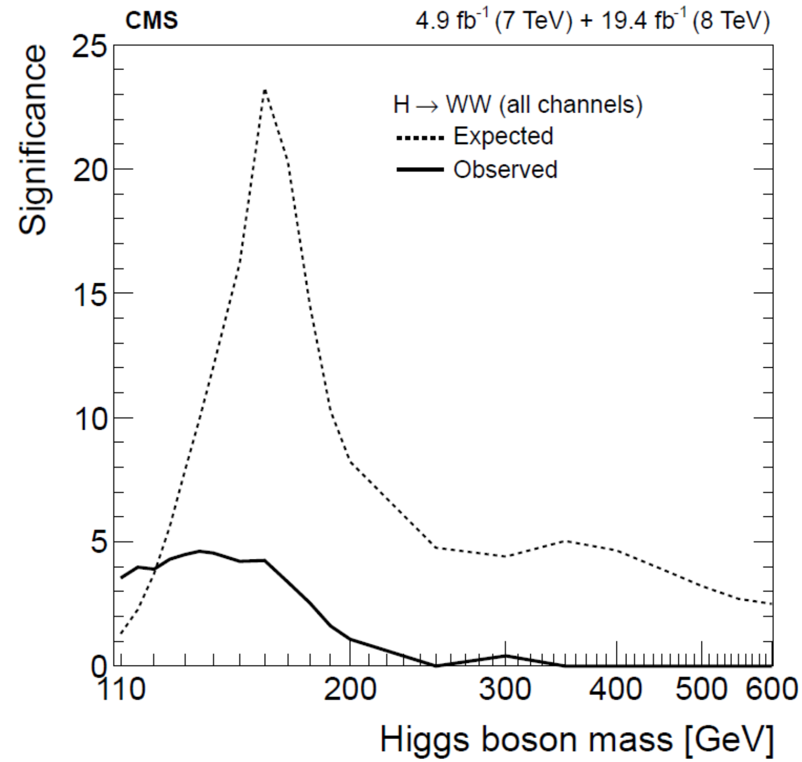
$H \to WW^* \to 2\ell 2\nu$: CMS Strategy

- Separate events into categories: 0, 1 jet, same/opp flavor
- Perform 2d fit over dilepton and transverse masses



$H \to WW^* \to 2\ell 2\nu$: CMS Results

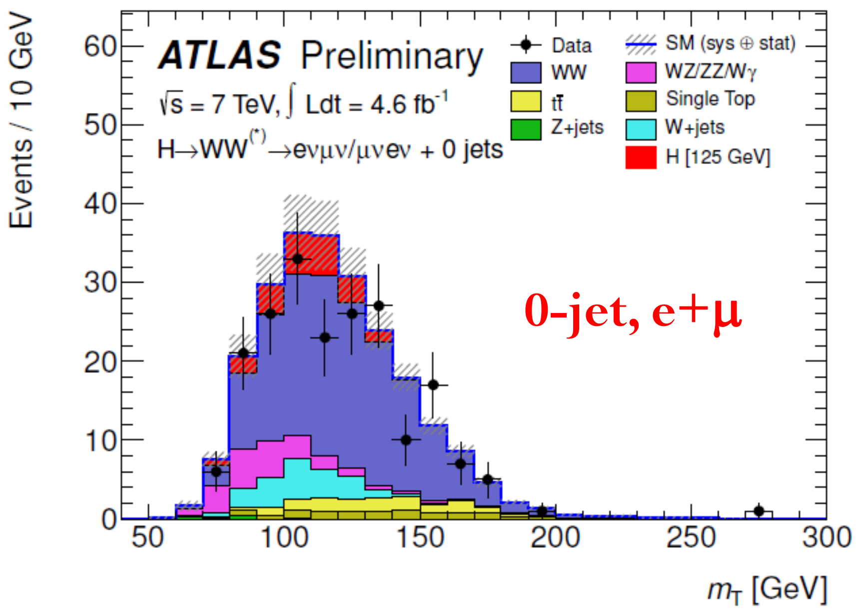


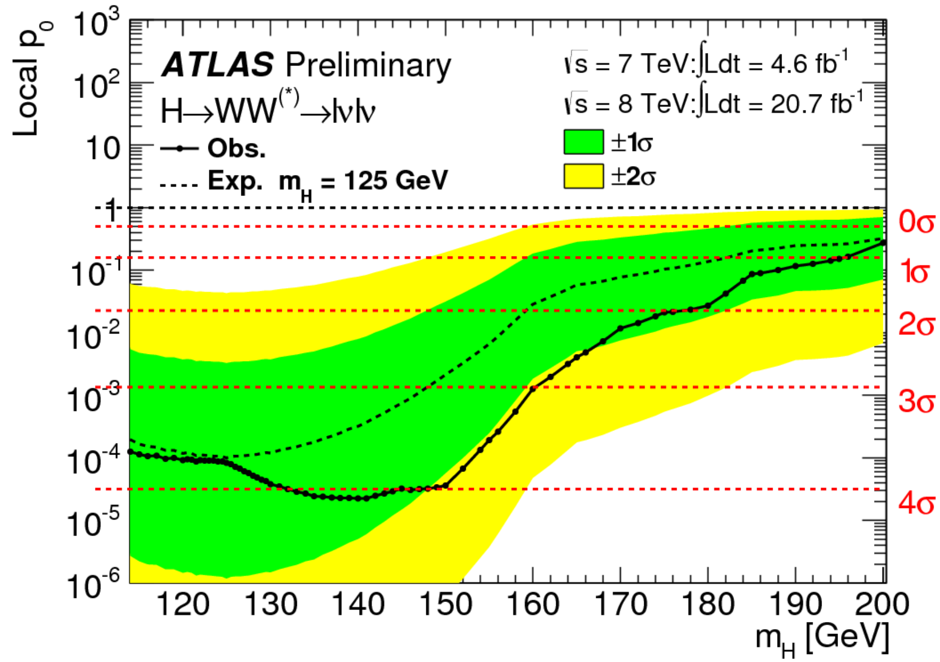


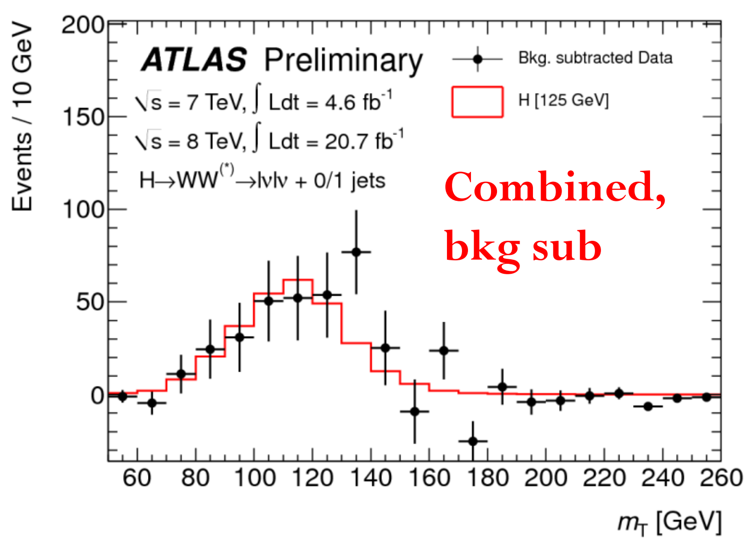
Exp (obs) significance =
5.8σ (4.3σ) @ 125.6 GeV

$$\mu = 0.72^{+0.20}_{-0.18}$$

$H \to WW^* \to 2\ell 2\nu$: ATLAS





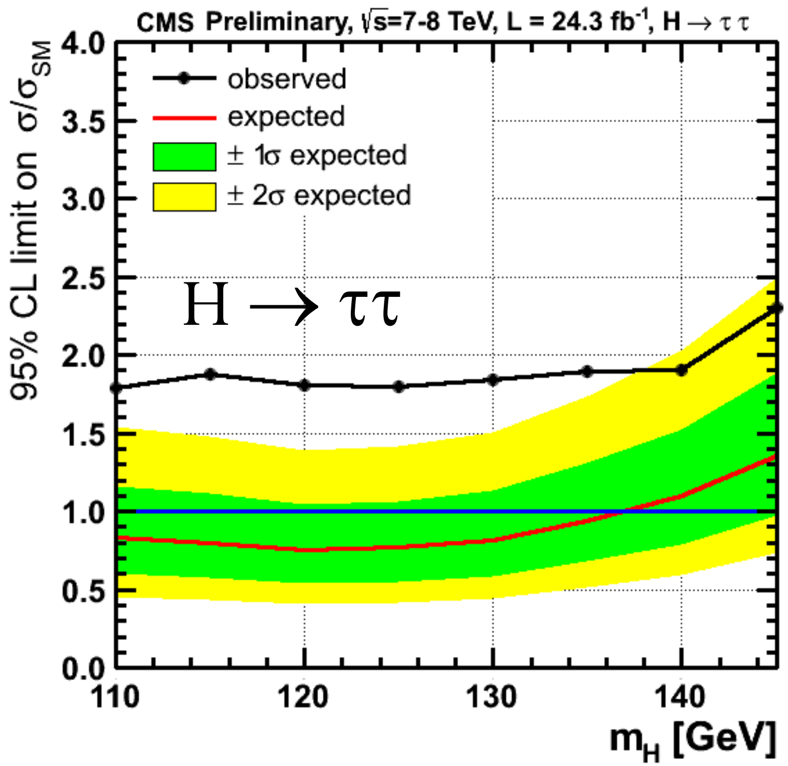


Exp (obs) significance = 3.7σ (3.8σ) @ 125 GeV

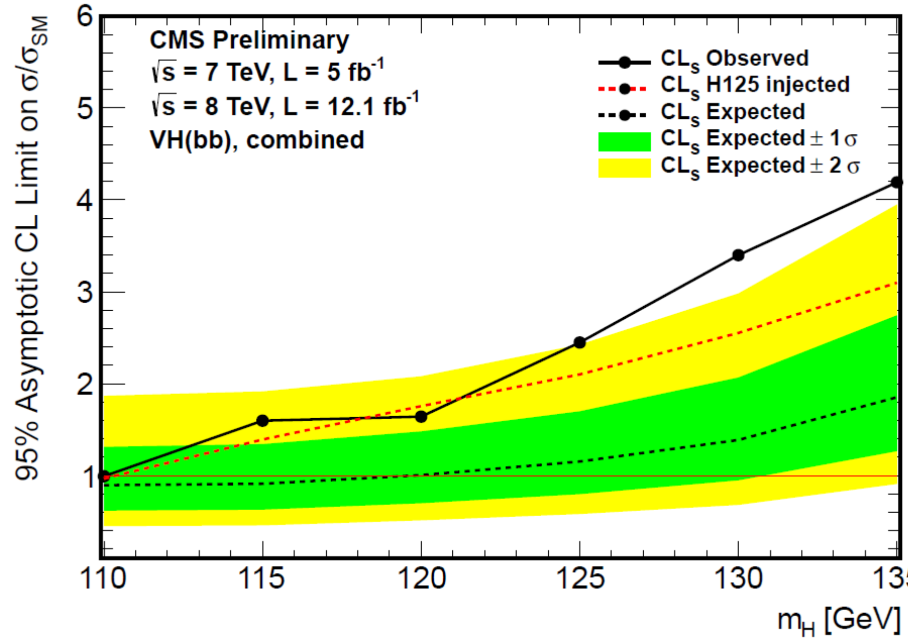
$\mu = 1.01 \pm 0.31$

The Boson Decaying to Fermions (does it?)

SM Higgs theory also explains the quark and lepton masses via Yukawa couplings: is this the SM Higgs?



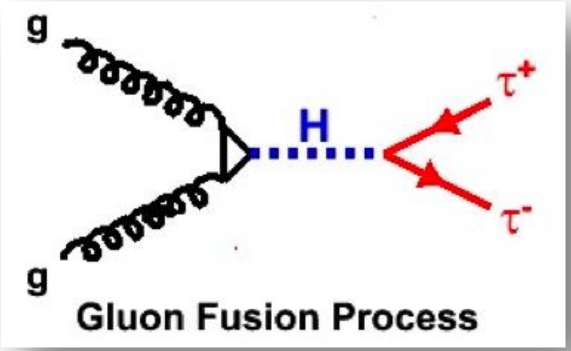
H → bb



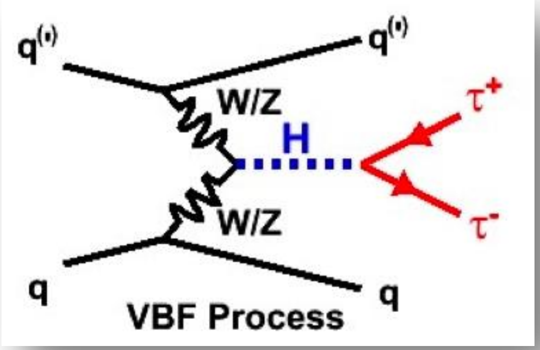
At CMS, **March, 2013**: excesses in ττ (2.9 σ) and bb (2.1 σ), combined observed significance of **3.4 σ** for m_H = 125 GeV. Higgs?

$H \to \tau\tau$: Overview

- **Importance of $H \to \tau\tau$:**
  - Only sensitive probe of SM lepton coupling
  - Complementarity with $H \to bb$ 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?



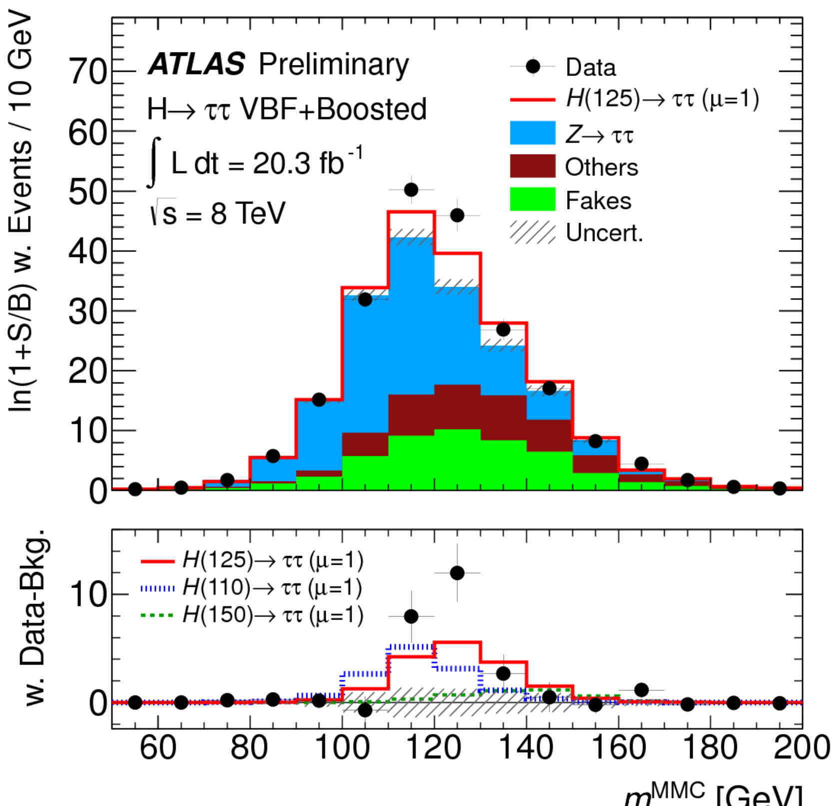
- **Broad-based search strategy**
  - Dominant background: $Z \to \tau\tau$
  - Mass reconstruction with MVA technique
  - Event categorization by production channel and kinematics

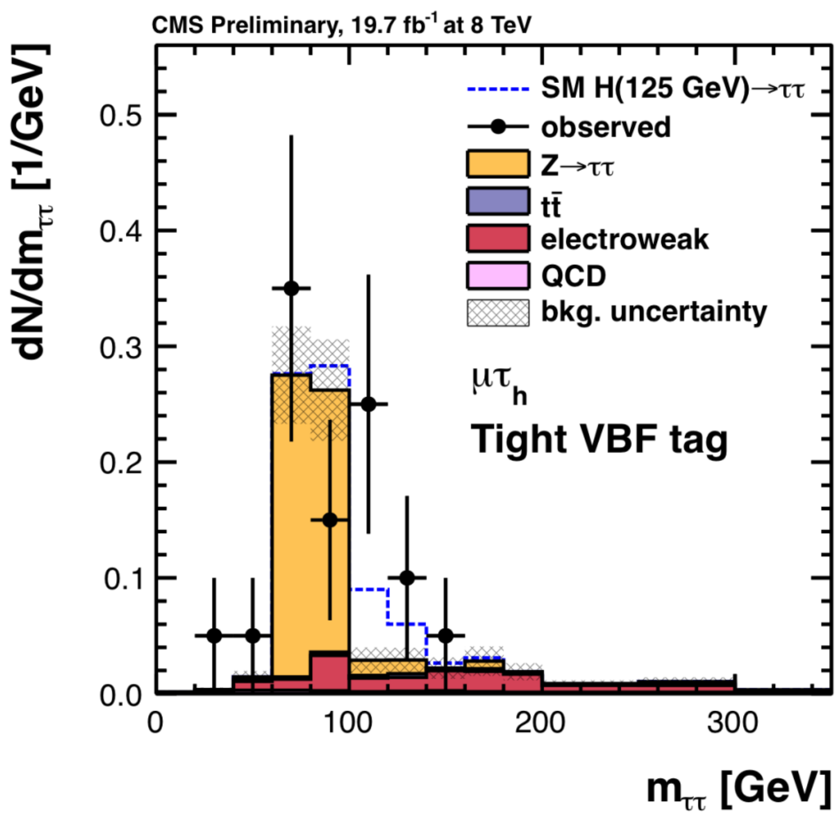


$H \to \tau\tau$: ATLAS and CMS

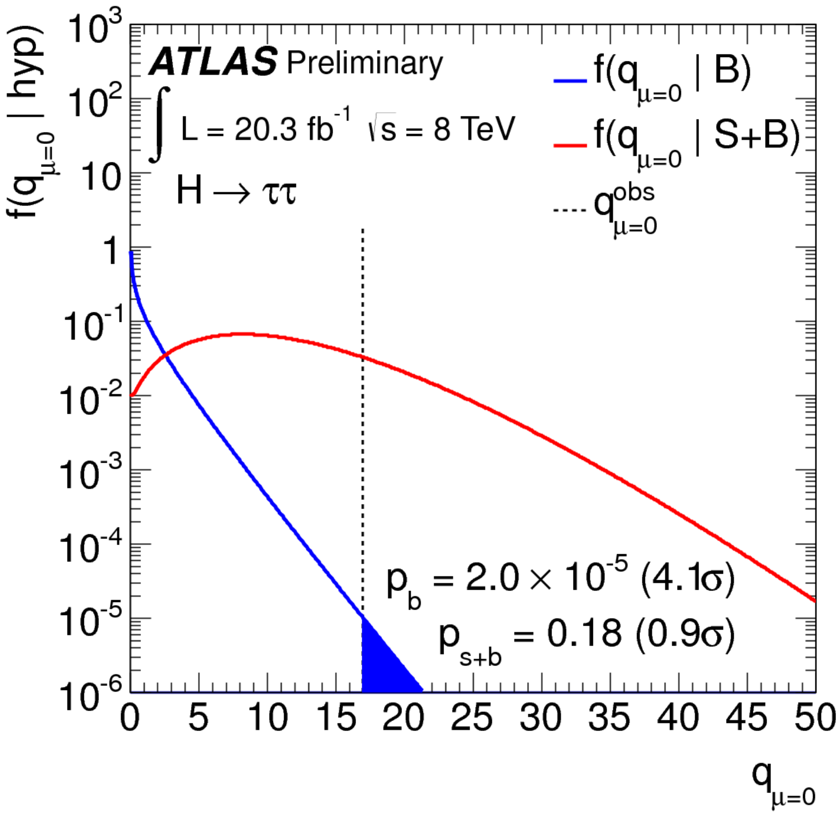
End of 2013: ATLAS and CMS show updated results on the full LHC dataset

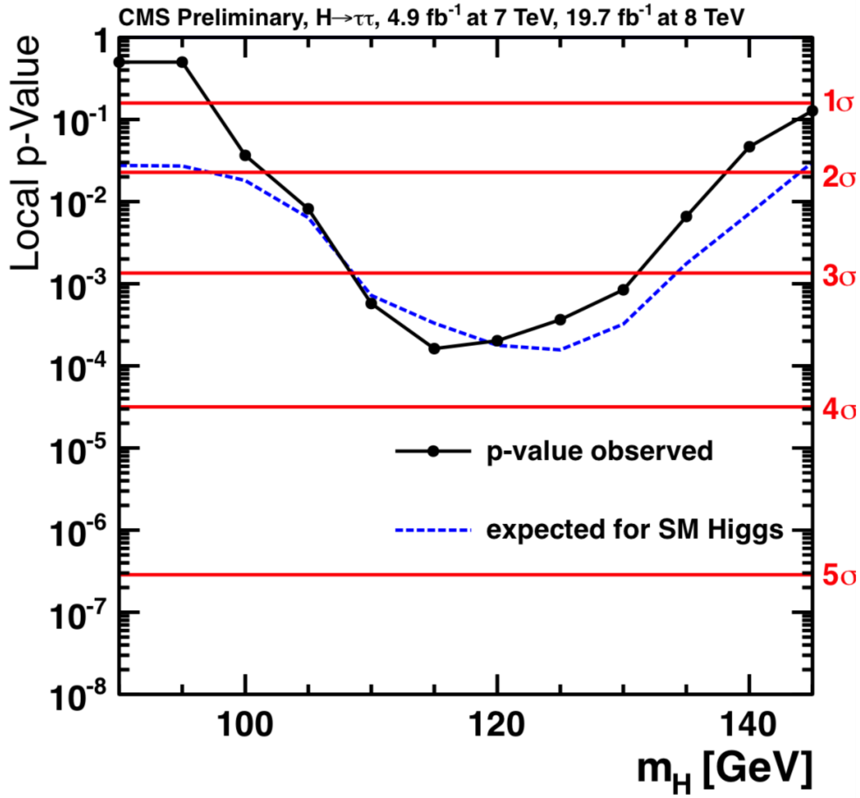
Weighted events in the clean VBF categories, signal already popping out above background in the tau-pair invariant mass distributions





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





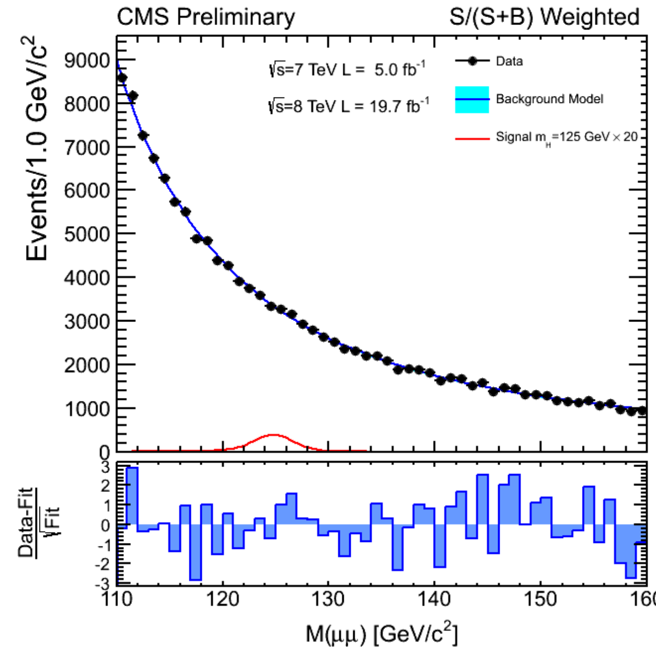
ATLAS ($m_H = 125$ GeV):
- 3.2 σ (4.1 σ) exp (obs)
- $\mu = 1.4^{+0.5}_{-0.4}$

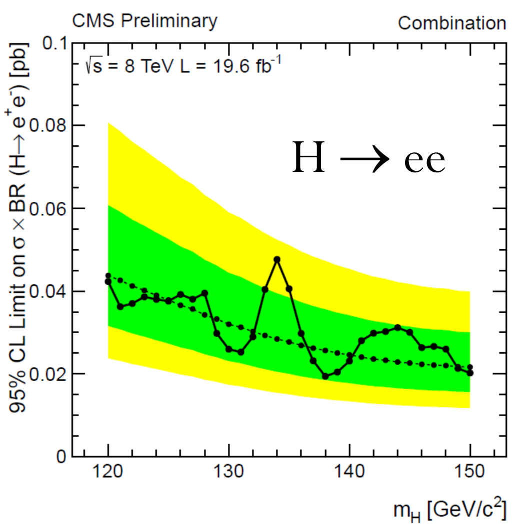
CMS ($m_H = 125$ GeV):
- 3.6 σ (3.4 σ) exp (obs)
- $\mu = 0.87 \pm 0.29$

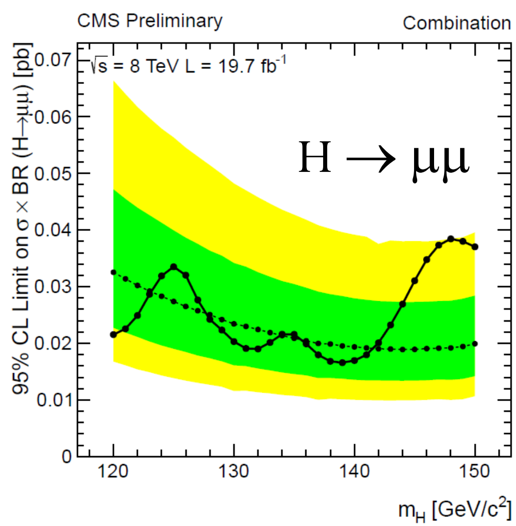
Strong evidence for Higgs decays to tau leptons!

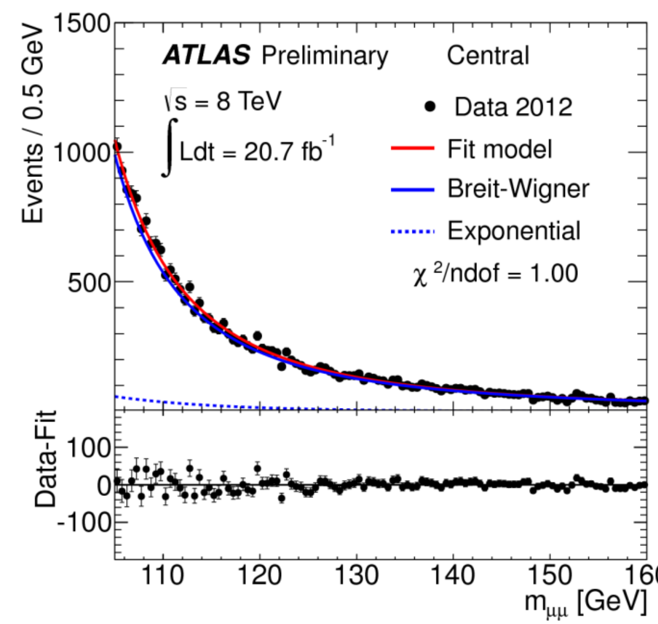
Higgs → μμ or ee?

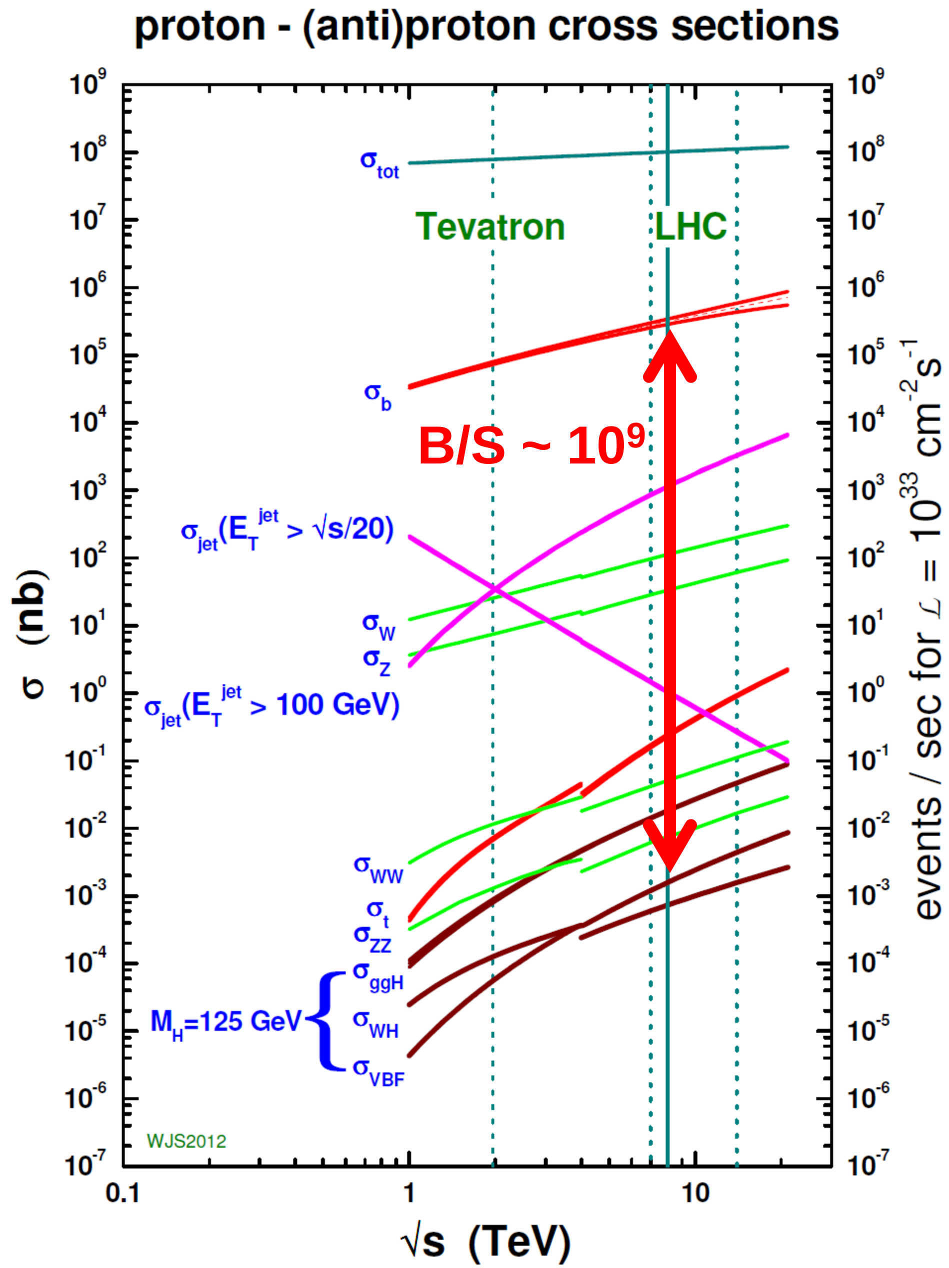
- If this is the SM Higgs boson, coupling to leptons should go like $g \propto m_l$
  - μμ/ee decays should be highly suppressed relative to ττ
  - This is what is observed at CMS and ATLAS
- Would have seen μμ/ee by now → this particle does not obey lepton universality!











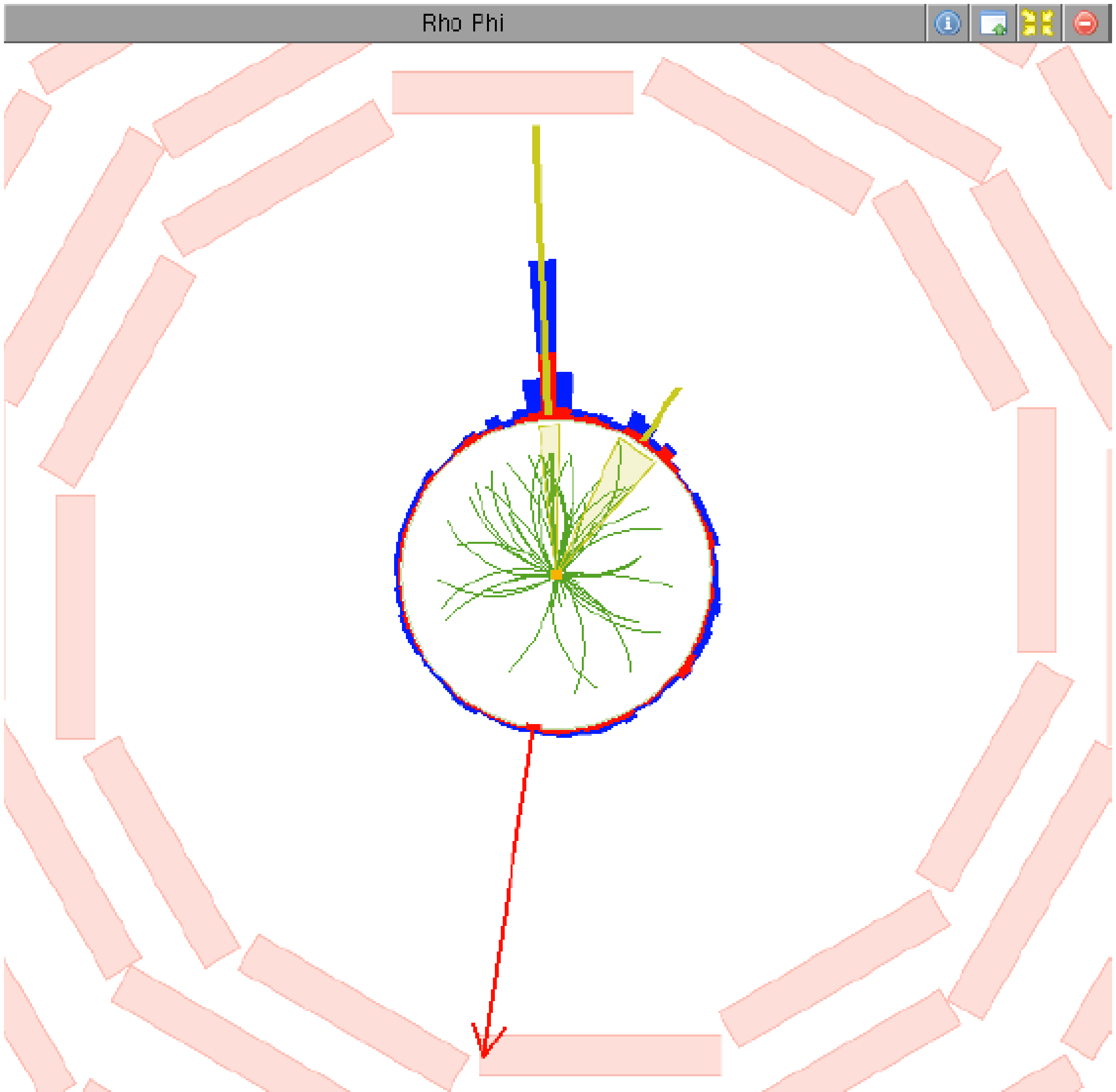
Inclusive H → bb?

Overwhelmed by QCD production of bottom-quark jets (B/S ~ 10^9)

Need to find another haystack!

Boosted VH, H → bb

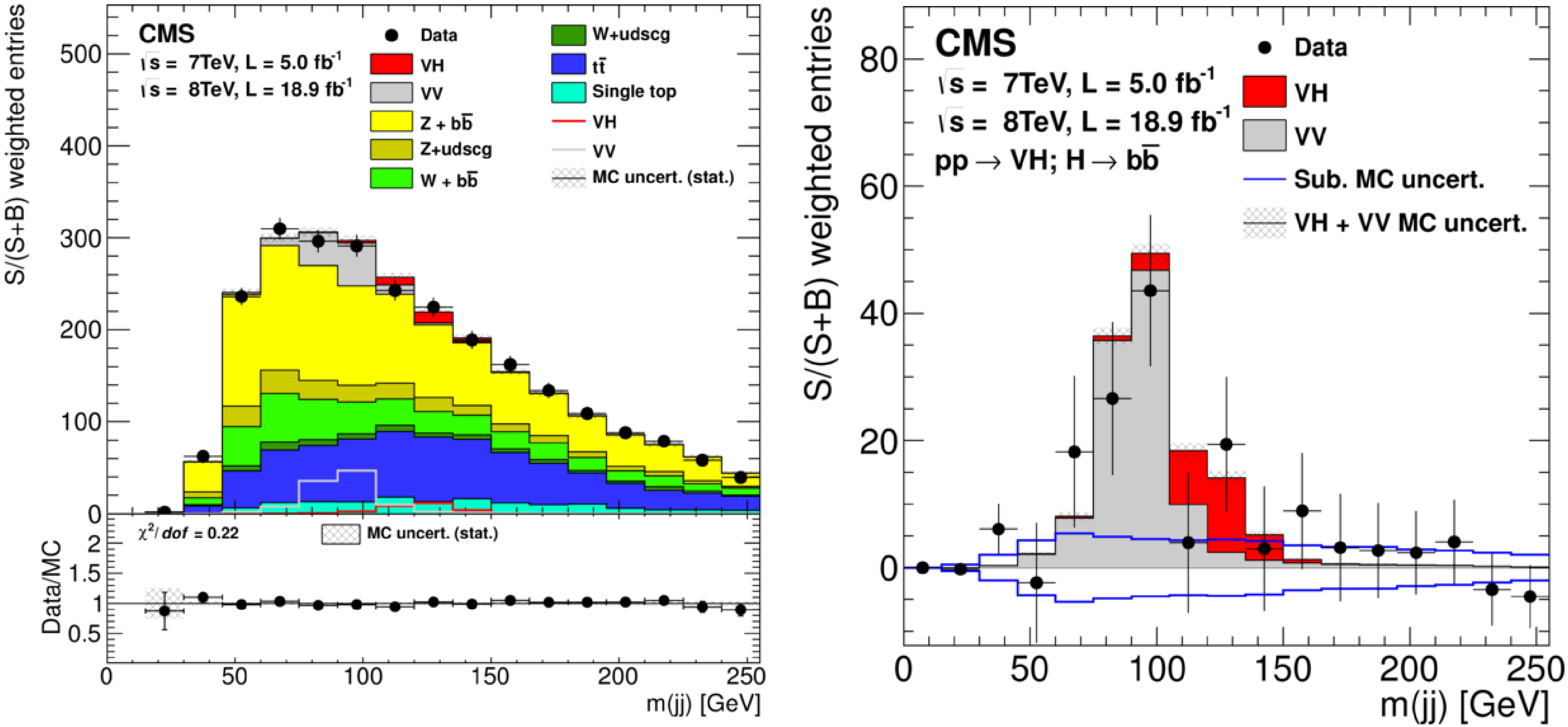
$Z(\nu\bar{\nu})H(b\bar{b})$ candidate



PD: /MET/Run2011B
Run: 177183
Lumi: 183
Event: 305295270

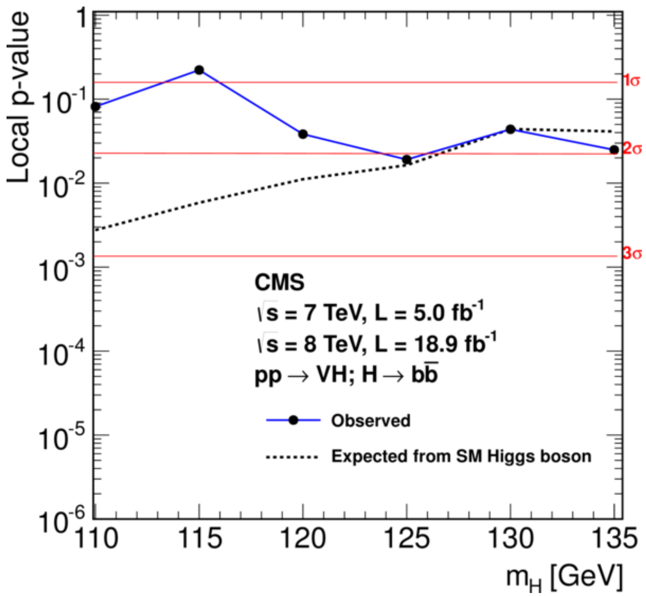
- M(jj) = 120.0 GeV
- p_T(jj) = 248.4 GeV
- Jets:
  - p_T = 209.5 GeV, CSV = 0.889
  - p_T = 46.2 GeV, CSV = 0.957
- MET:
  - 243.2 GeV

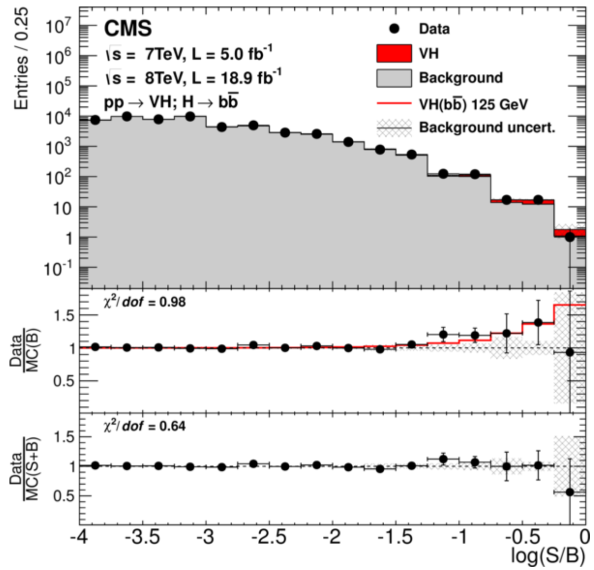
H → bb: CMS m_{jj} distribution

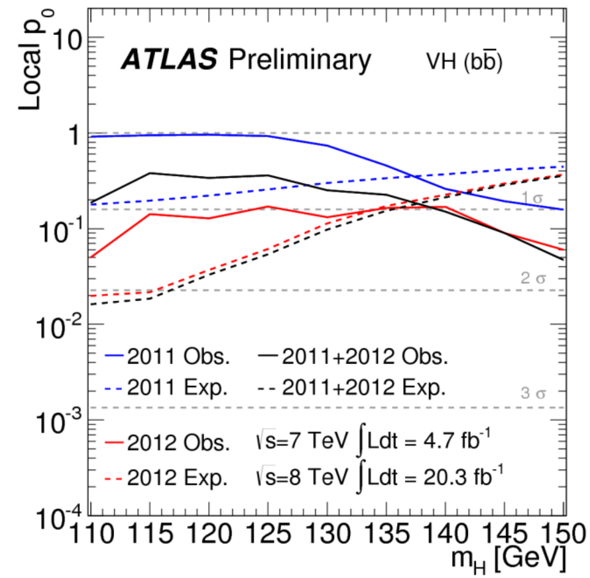


Already from Mjj plot: a clear VZ(+VH) peak above SM backgrounds with significance of VZ signal > 6 σ

H → bb: CMS and ATLAS







CMS ($m_H = 125$ GeV):

- 2.1 σ (2.1 σ) exp (obs)
- $\mu = 1.0 \pm 0.5$
- ττ + bb → 4.0 σ

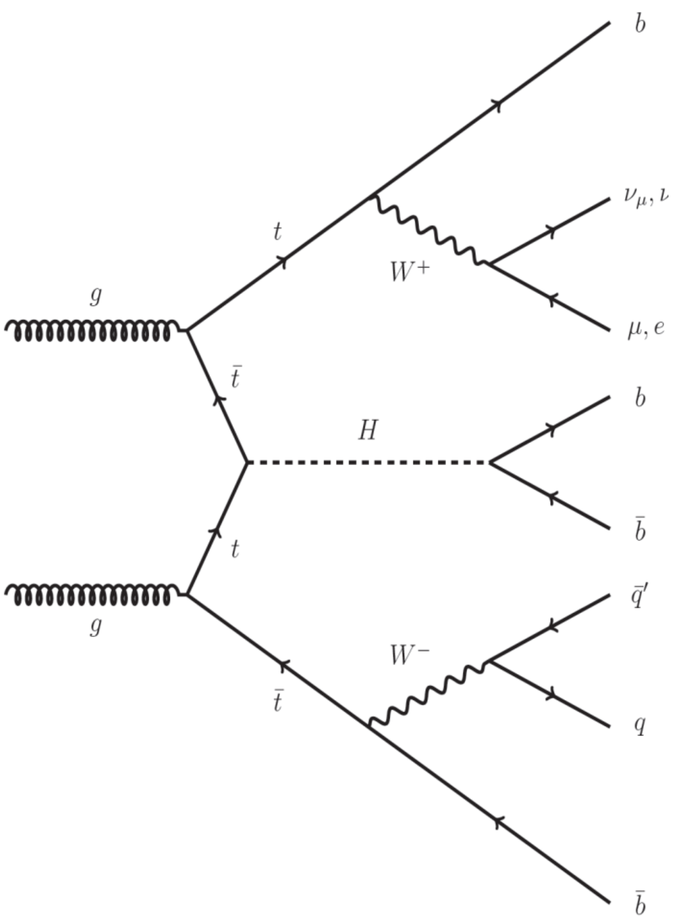
ATLAS ($m_H = 125$ GeV):

- 95% C.L. < 1.4 x SM
- ~1.6 σ exp sensitivity
- $\mu = 0.2 \pm 0.6$

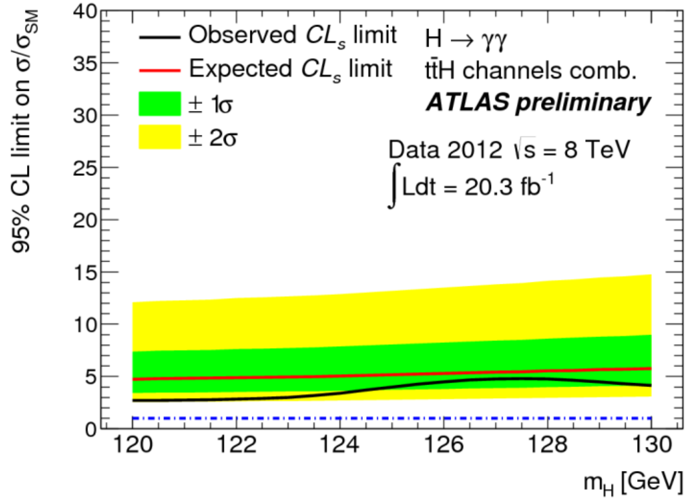
Hint is there, but a clear signal for H → bb will only come in Run 2

Search for Higgs-top coupling

- **Important channel**
  - Only access to real tops coupling to Higgs
  - Busy events!
- **Strategy**
  - Drops in the bucket!
    - Combine as many H decay modes as possible
    - Currently CMS has public: bb and γγ (new!)
    - Also include ττ and WW/ZZ (CMS)
  - Similar top reconstruction across channels
    - Bin in Njets and Nbjets
  - Higgs mass only useful (so far) in ttH(γγ)

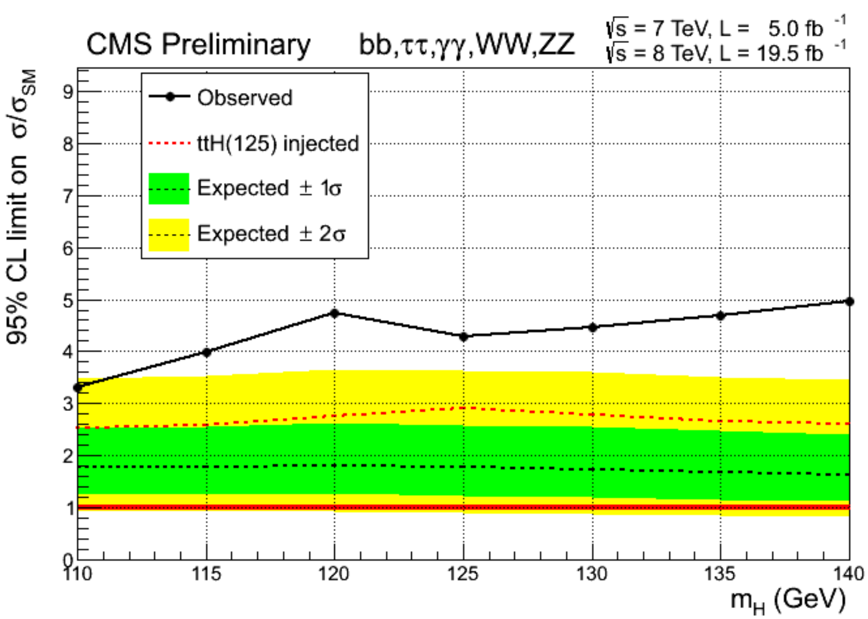


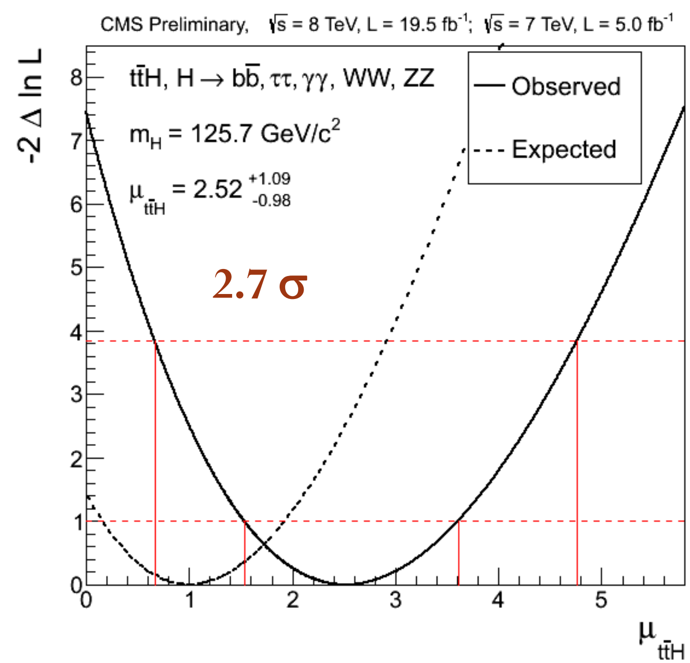
ttH Results: CMS and ATLAS



CMS ttH Results

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	$+2.5^{+1.1}_{-1.0}$

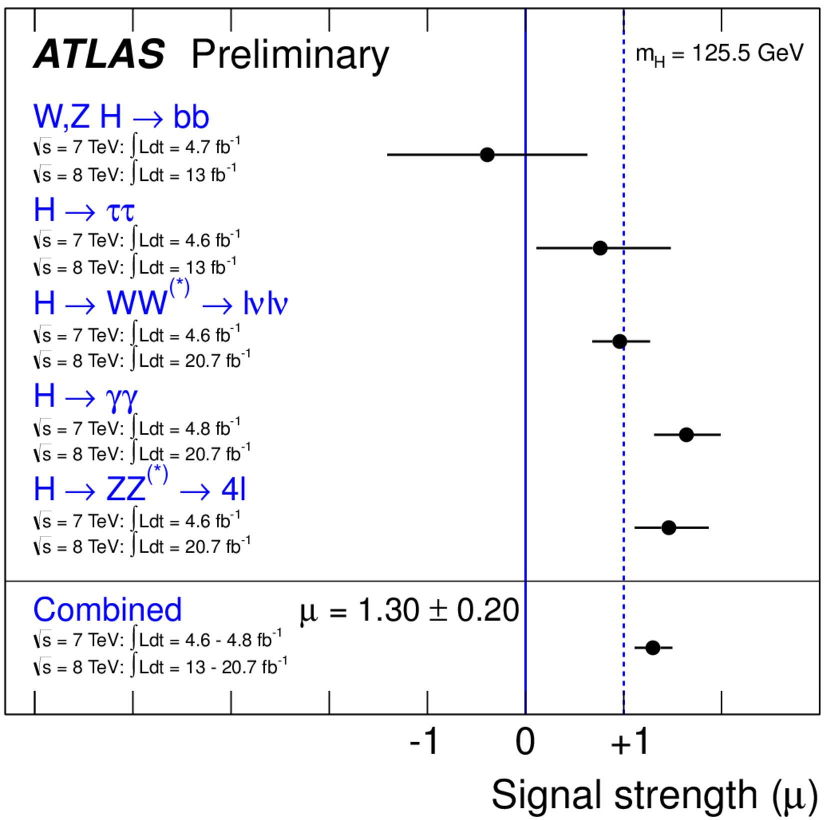


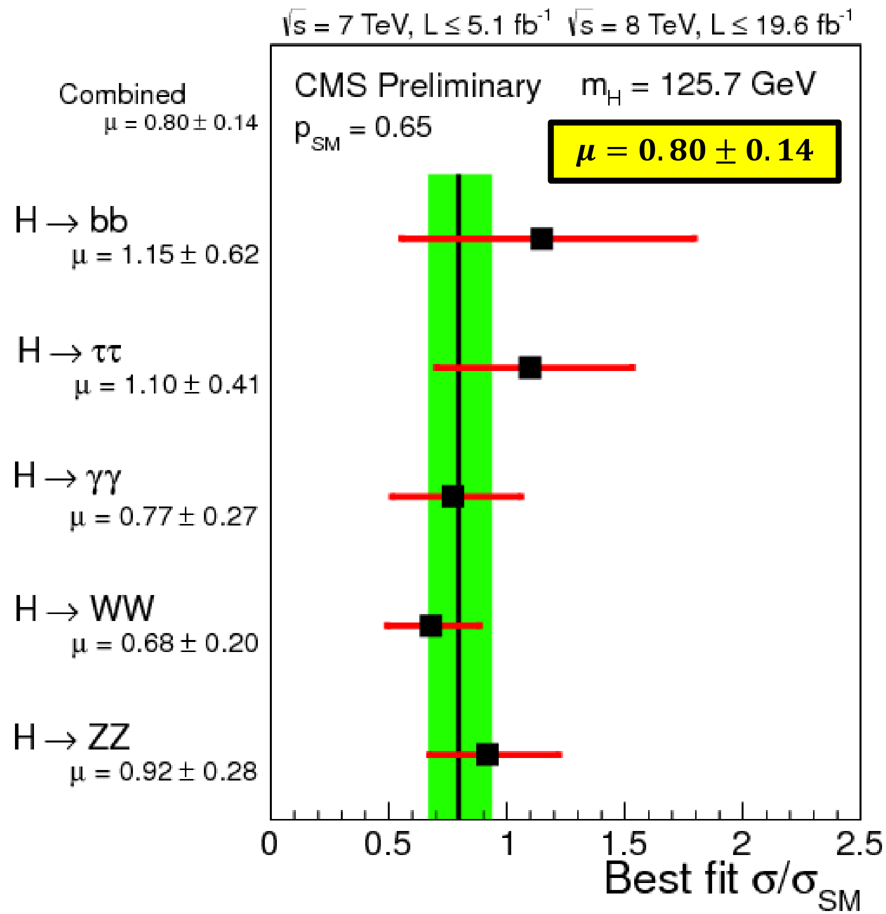


Properties of the New Boson (mostly from Moriond 2013)

Signal strength by decay channel

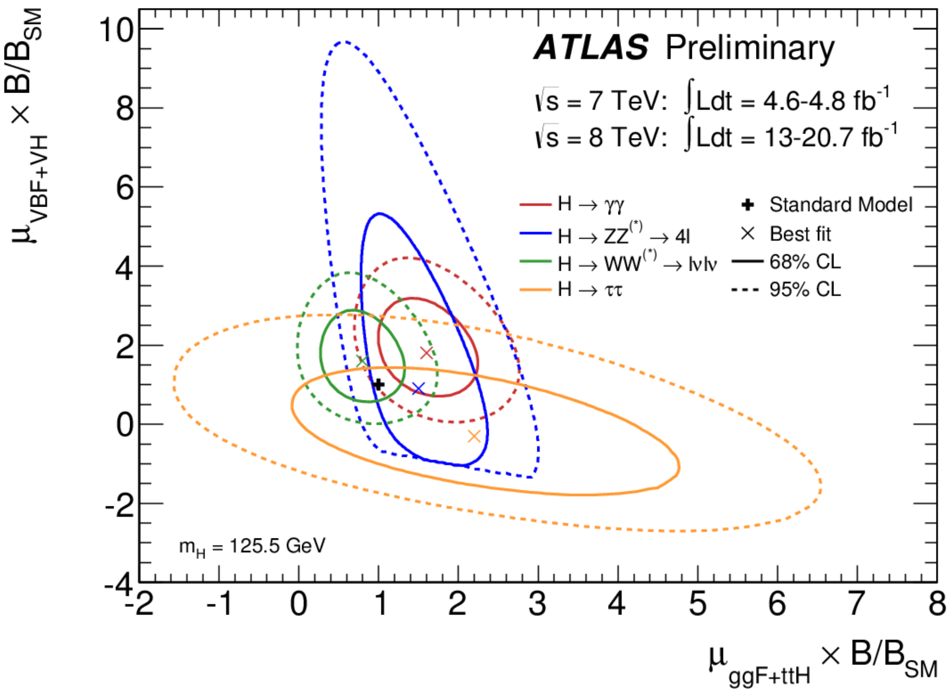
NB: Fermions updated for both CMS + ATLAS

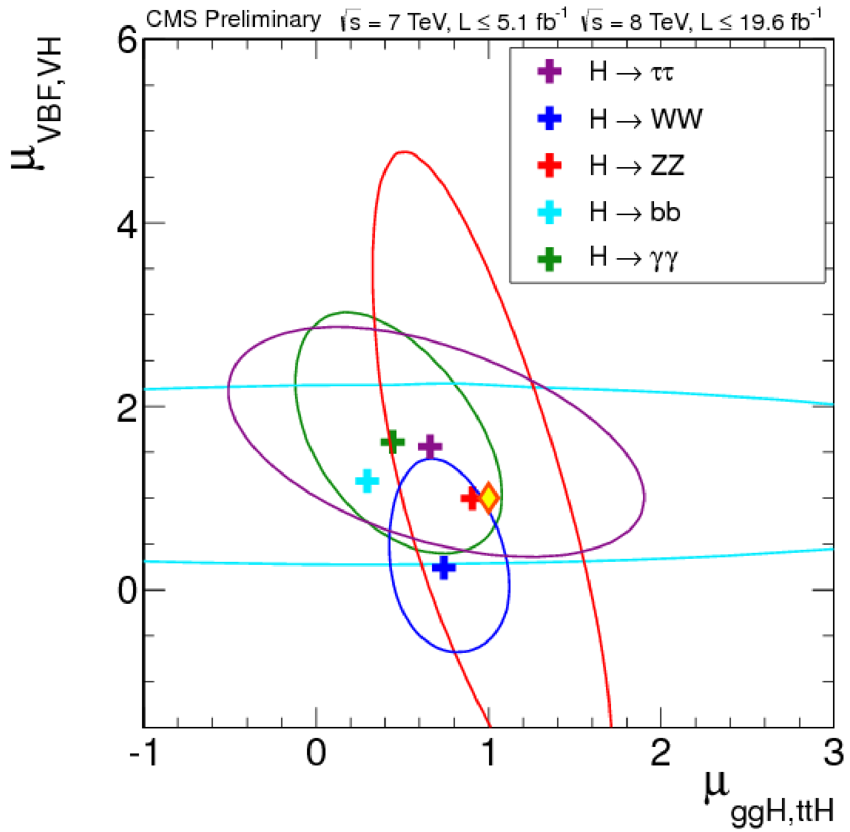




Both experiments are consistent with the SM expectation

Signal strength by production channel

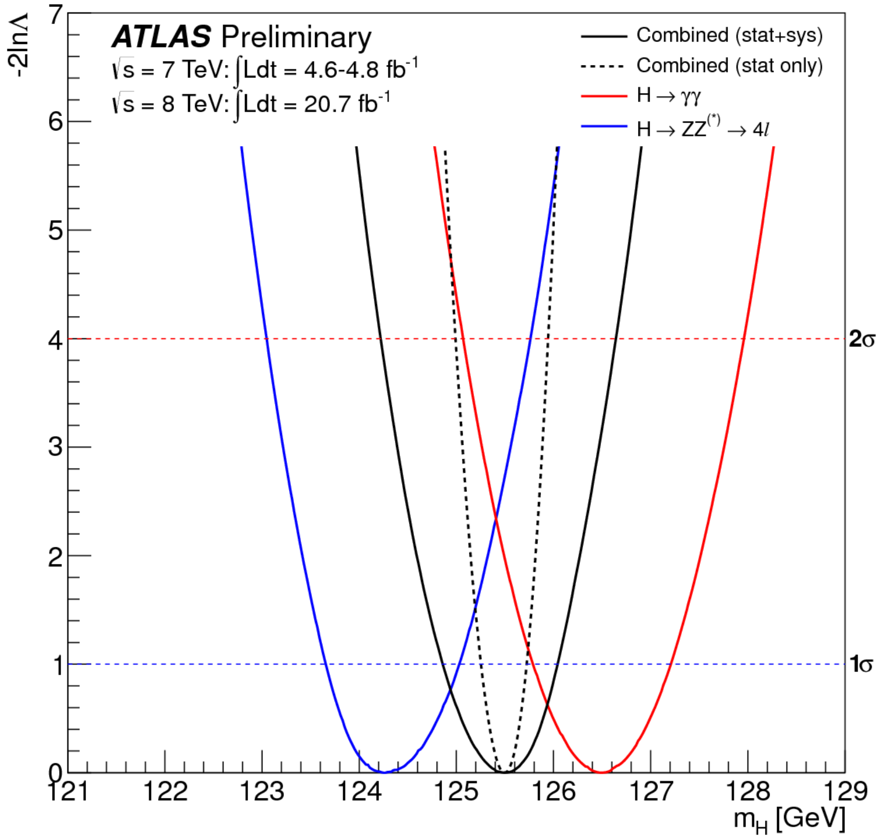


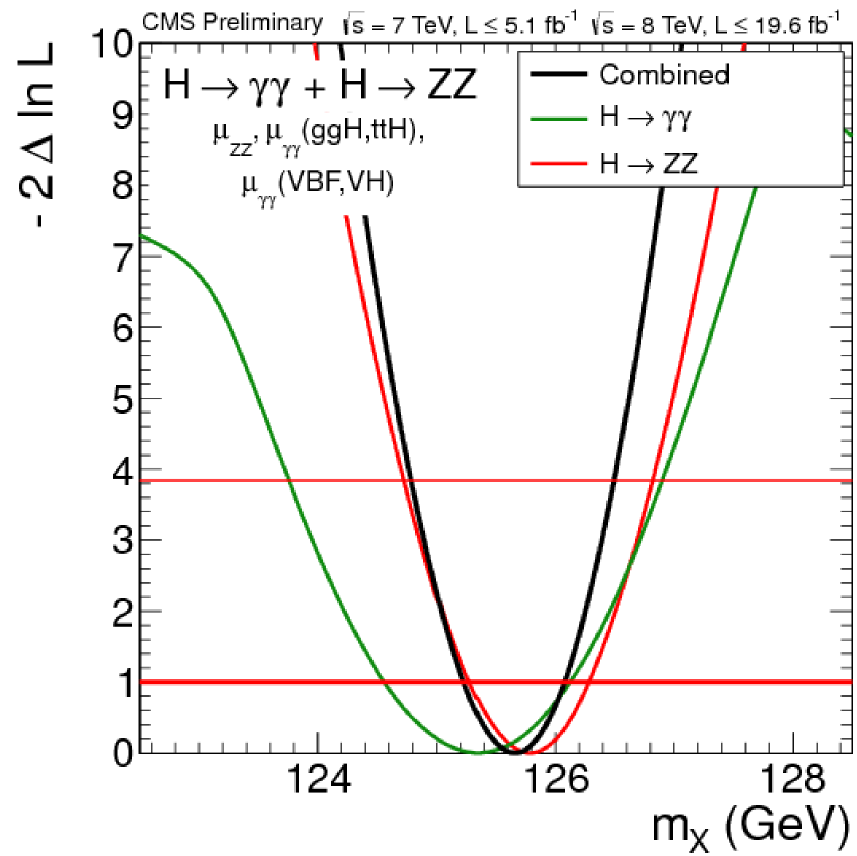


Production rate split boson vs. fermion also consistent with SM.

Both experiments have > 3 σ evidence for VBF production.

Mass from γγ and ZZ



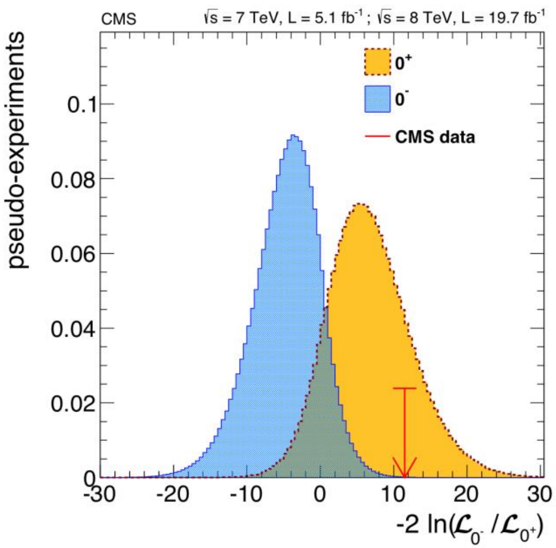


$m_H = 125.5 \pm 0.2\ (\text{stat}) \pm 0.5\ (\text{syst})$

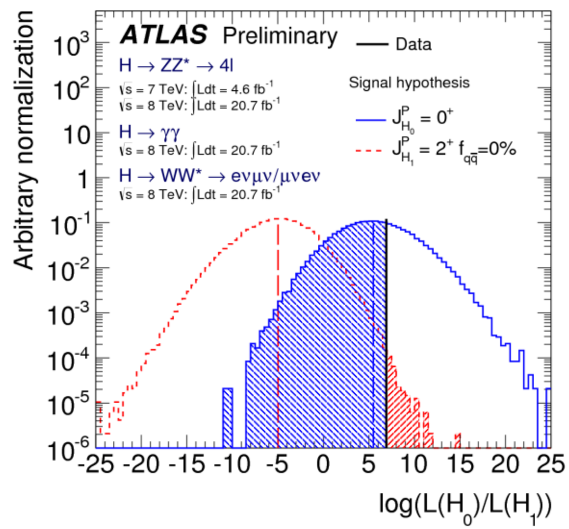
$m_H = 125.7 \pm 0.3\ (\text{stat}) \pm 0.3\ (\text{syst})$

Spin and parity

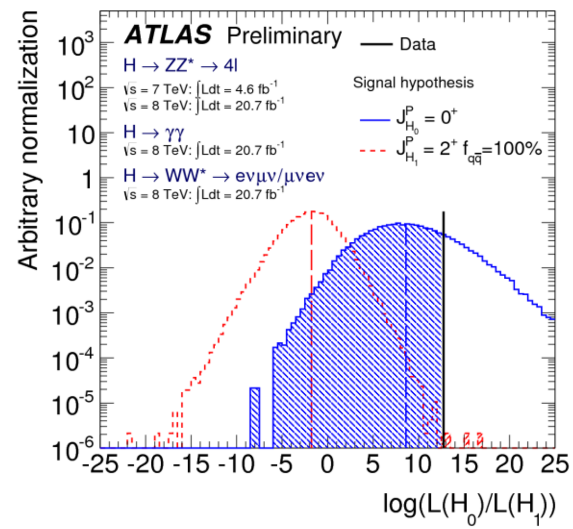
Scalar vs. Pseudoscalar

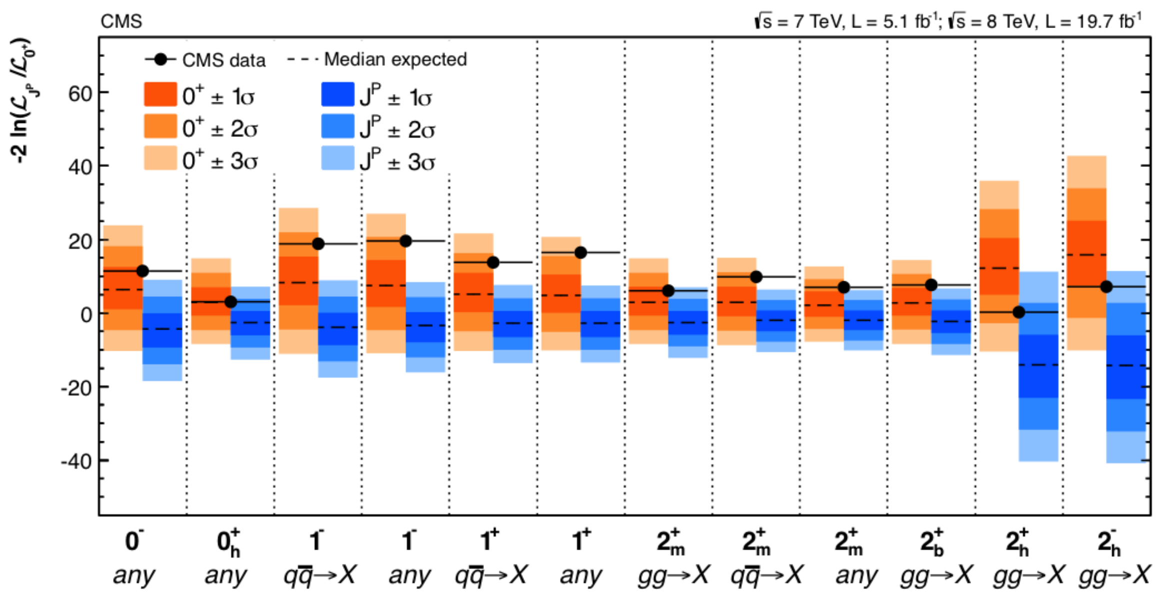


Scalar vs. Tensor (gg)



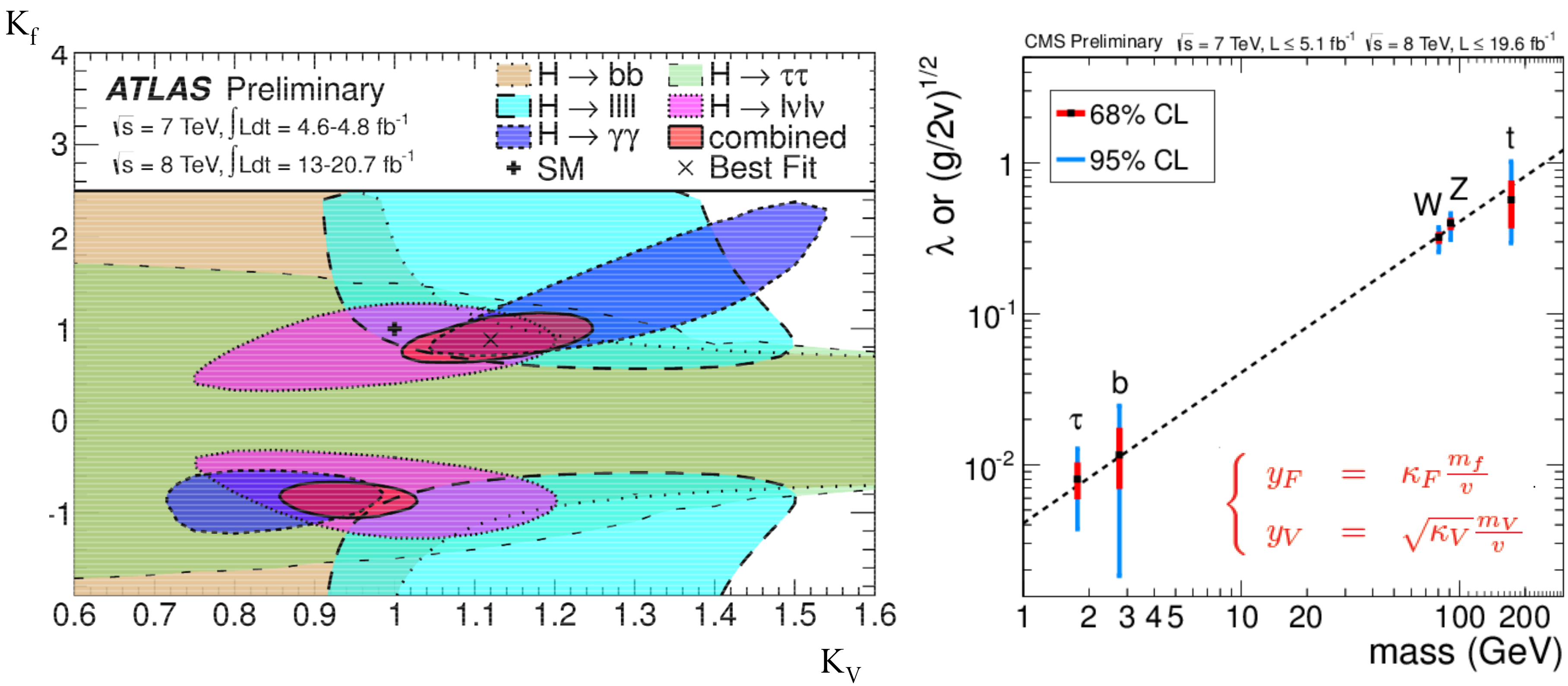
Scalar vs. Tensor (qq)





Alternative spin/parity assignments are disfavored by both CMS and ATLAS. Admixtures of different spin states are not yet ruled out.

Couplings



Fully consistent with the SM Higgs that gives mass to both bosons and fermions!

New results indicate that particle discovered at CERN is a Higgs boson

- CERN

ISSUES AND EXPERTS

Higgs boson and new pope confirmed

March 14, 2013

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'God particle' is for real

Scientists are confirming that a new subatomic particle discovered at the world's most powerful particle accelerator is indeed an elusive Higgs boson, also referred to as 'the God particle.' It was discovered during experiments at the Large Hadron Collider (LHC) at CERN, Switzerland last July. Scientists, who say they have a "long way to go" to know what kind of Higgs boson it is, are reporting the confirmation at the Moriond physics conference in Italy this week. The Higgs boson is the only particle in the Standard Model of Physics that has never been observed. SFU physicists **Dugan O'Neil, Bernd Stelzer** and **Michel Vetterli** are involved with ATLAS – one of two international physics experiments involving the LHC– and can comment on the news. Vetterli is currently at CERN where he'll spend the next year and can also do Skype interviews.

Michel Vetterli, +41 22 767 4368; vetz@triumf.ca; mikevetterli (Skype)
Dugan O'Neil, 778.782.5623; dugan_oneil@sfu.ca
Bernd Stelzer, 778.782.7731; stelzer@sfu.ca
Background: http://at.sfu.ca/eUnDFV

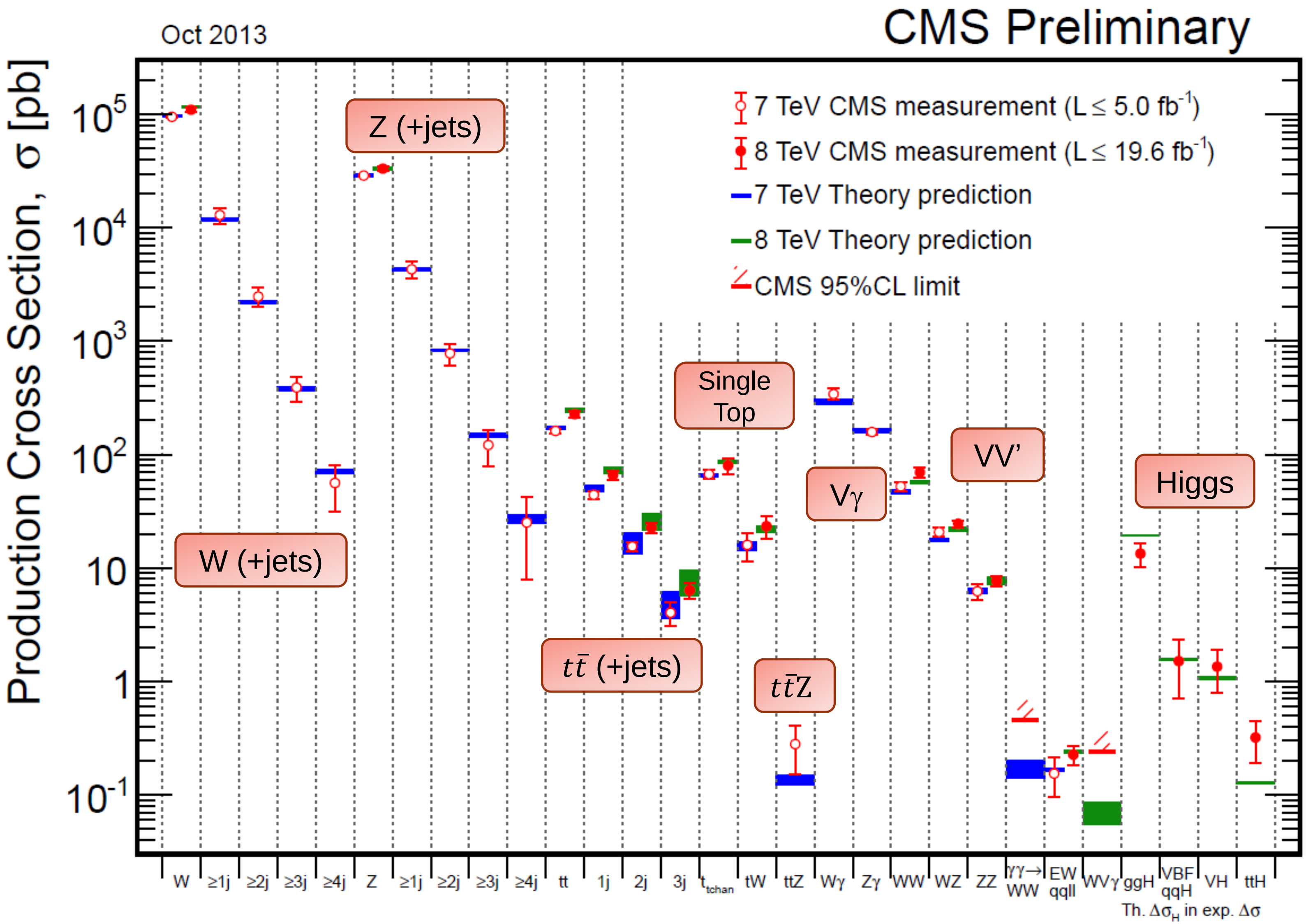
First non-European pope chosen

Jorge Mario Bergoglio of Argentina was elected yesterday as the new pope to lead the Roman Catholic Church. **Donald Grayston**, a retired religious studies professor at SFU, says that it is interesting the new pope comes from the new world.

"I don't think the Curia is ready to let go of its stranglehold on change," says Grayston. "But I'm betting that the non-Curia cardinals wanted to elect someone who could tackle the Curia. I see it as very appropriate, given that 40-percent of the world's Catholics live in Latin America."

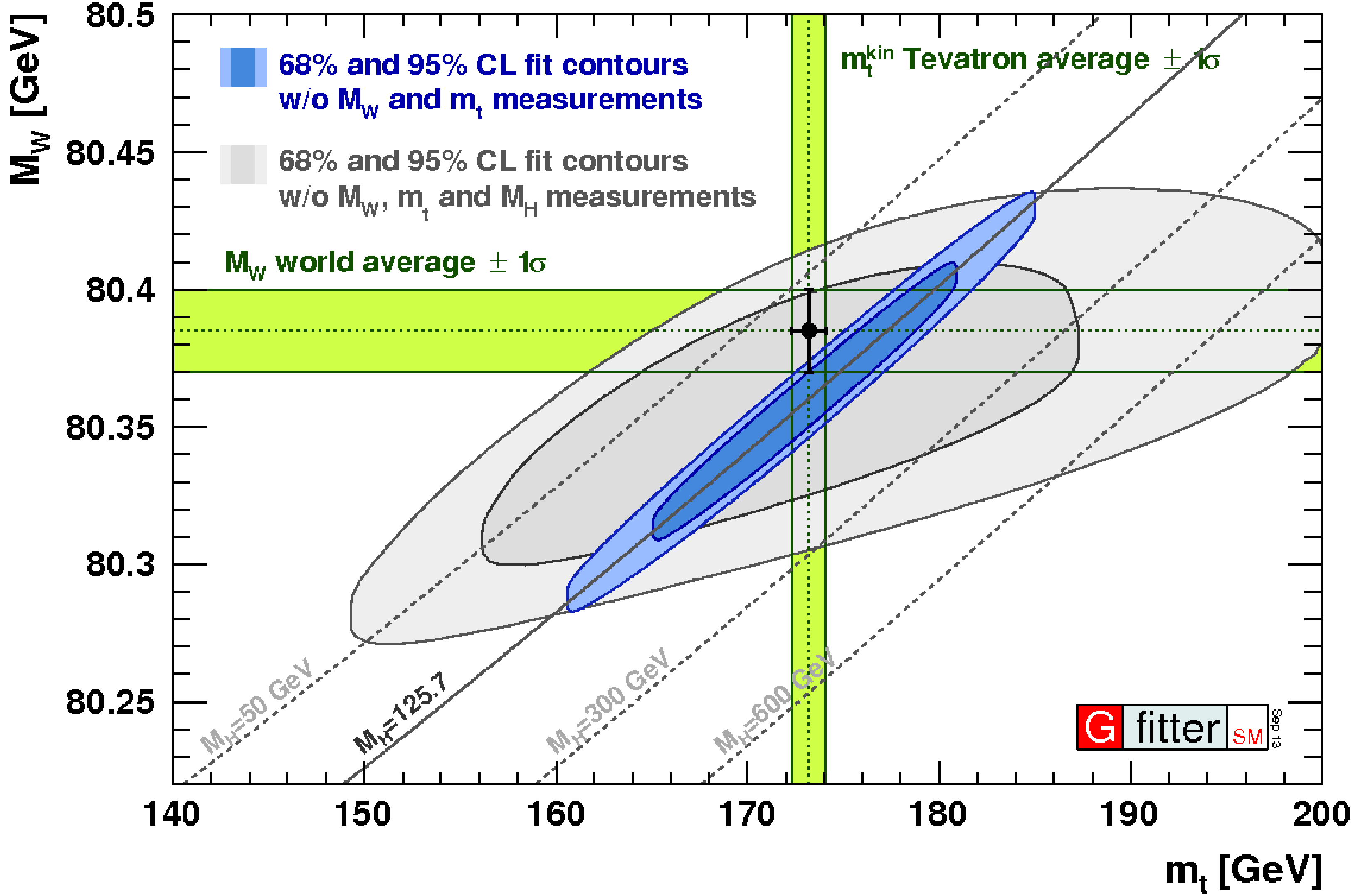
Are there any other Higgs bosons?
(or anything else?)

Standard Model: Mission Accomplished?

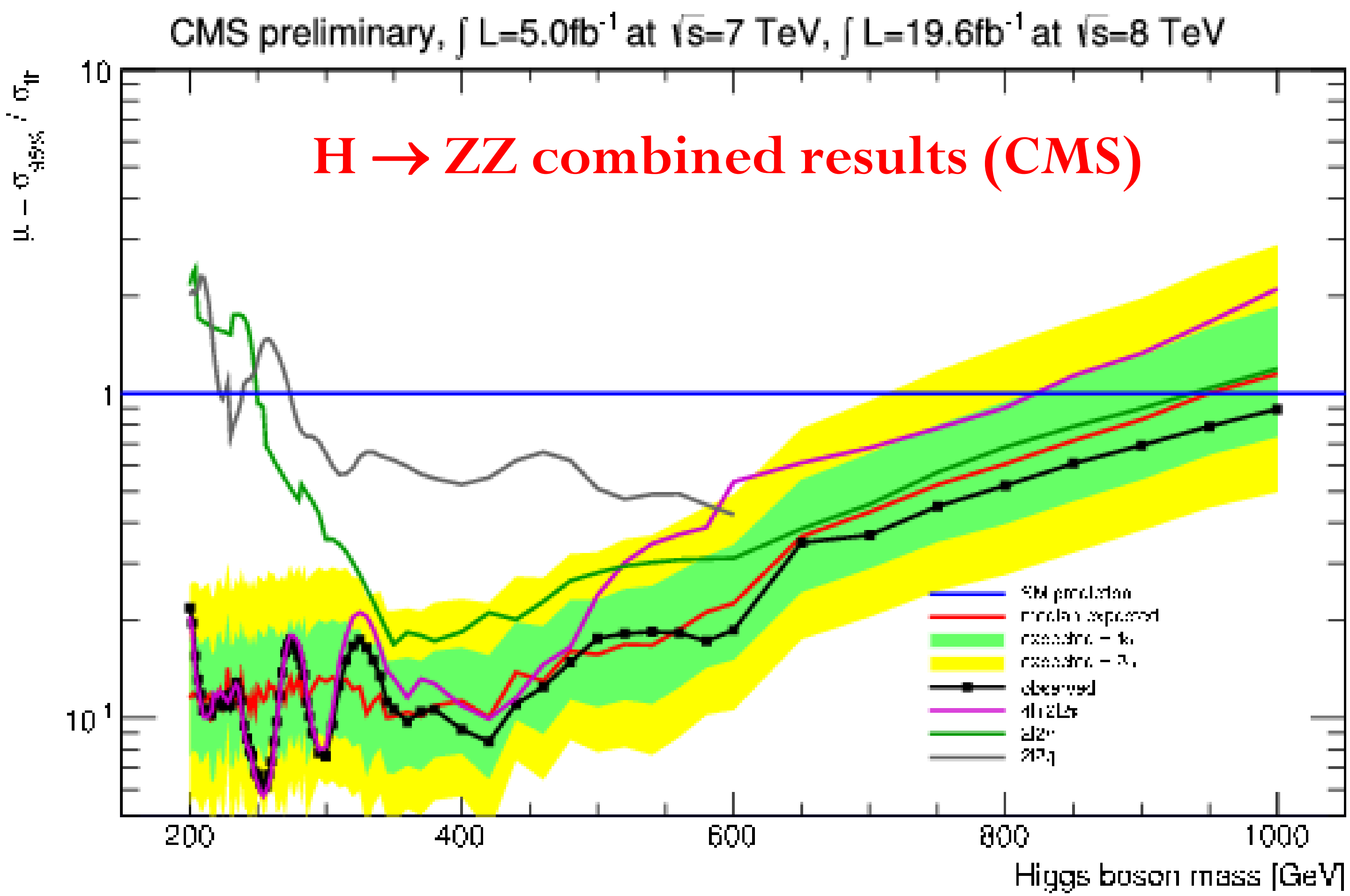


Exquisite agreement over 6 orders of magnitude!

Standard Model: Mission Accomplished?



Search for a high-mass Higgs Boson



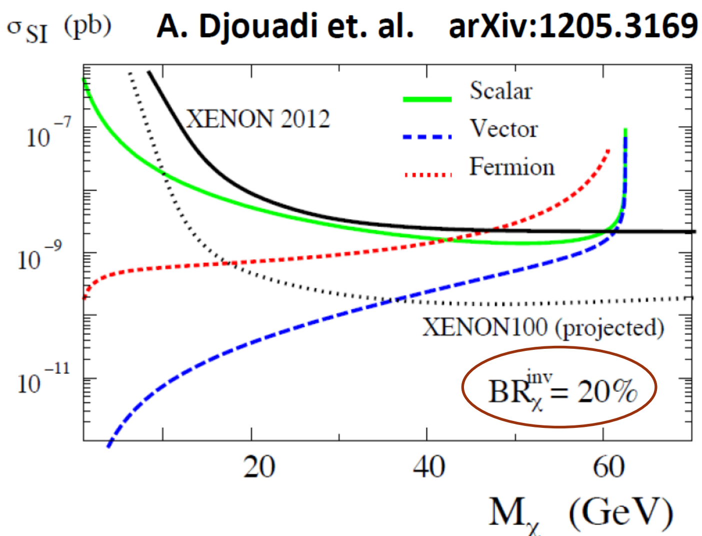
No sign of a SM Higgs boson up to ~1000 GeV

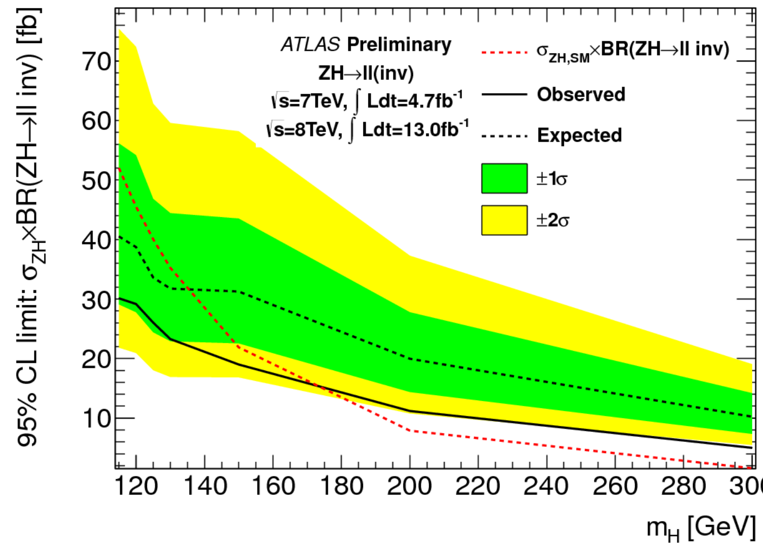
Searching for New Higgs-like Particles

- Experimentalist's perspective: we have a new particle, h(126), use it as a 'scout' to search for other particles
  - "Invisible" or exotic decays: $h \to ??$ (e.g. dark matter)
  - Decays of heavier particles: $X \to hh$
  - Unexpected production: $pp \to hX$
- Theorist's perspective: the SM is not complete, there are specific questions to answer, some examples
  - Fine-tuning? Hierarchy problem? Dark matter?
  - MSSM: H, h, A, H^+, H^-
  - NMSSM: add a singlet
  - General two-Higgs-doublet models (2HDM)
- CMS and ATLAS are pursuing with both perspectives in mind!

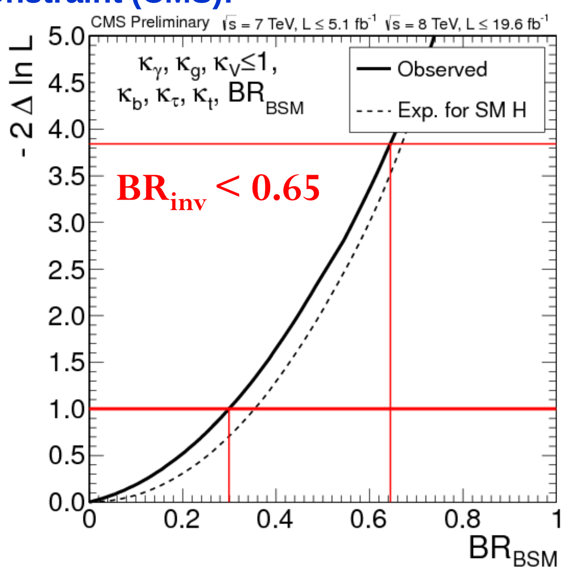
Search for h(126) → invisible

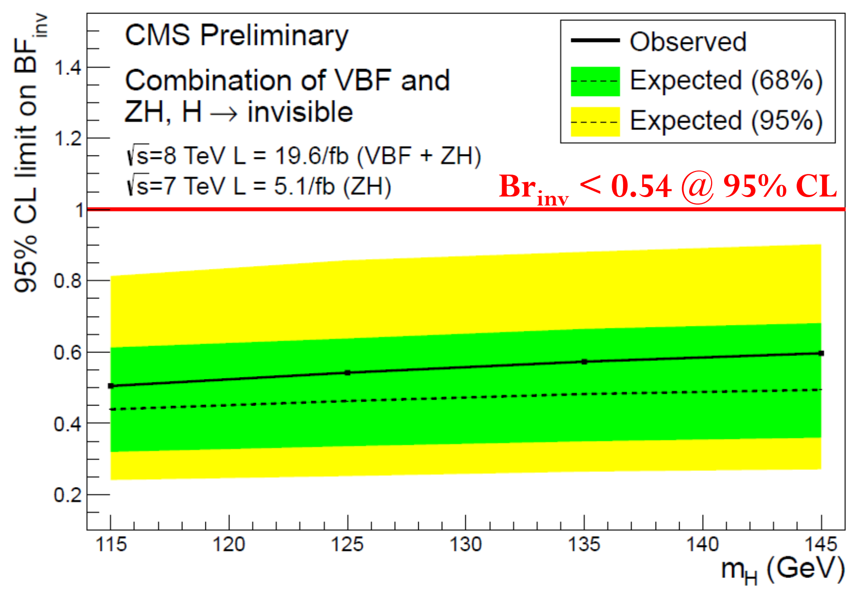
In the context of "Higgs-portal models":



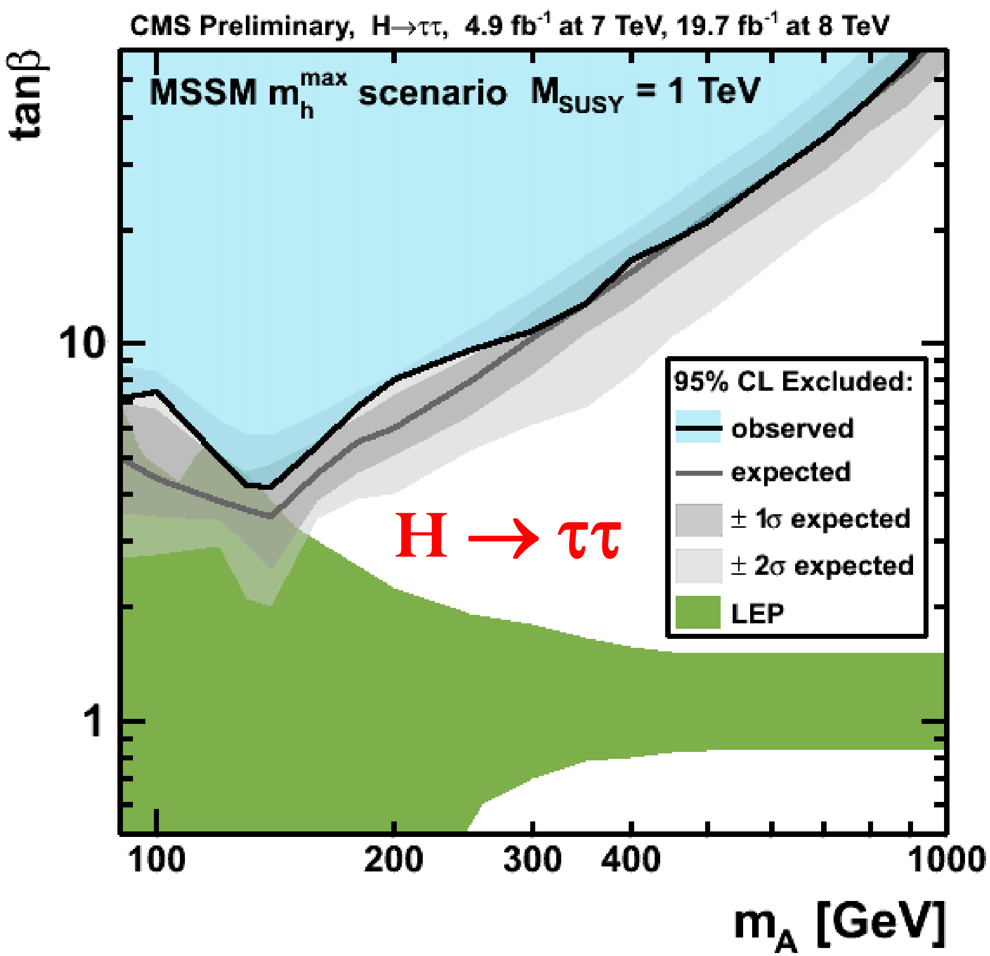


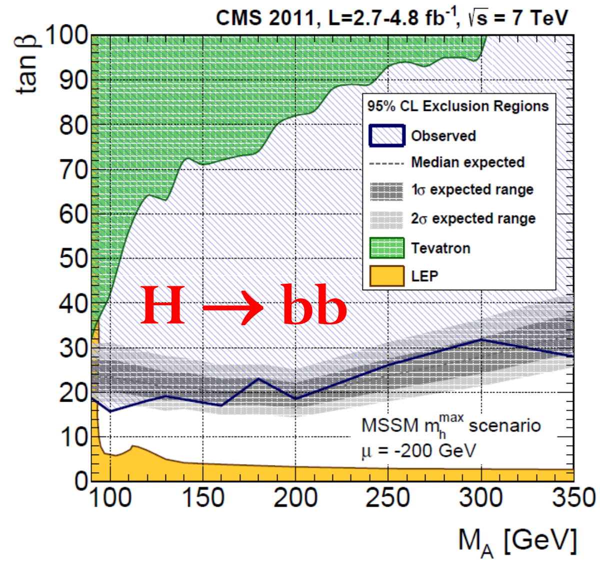
Indirect constraint (CMS):



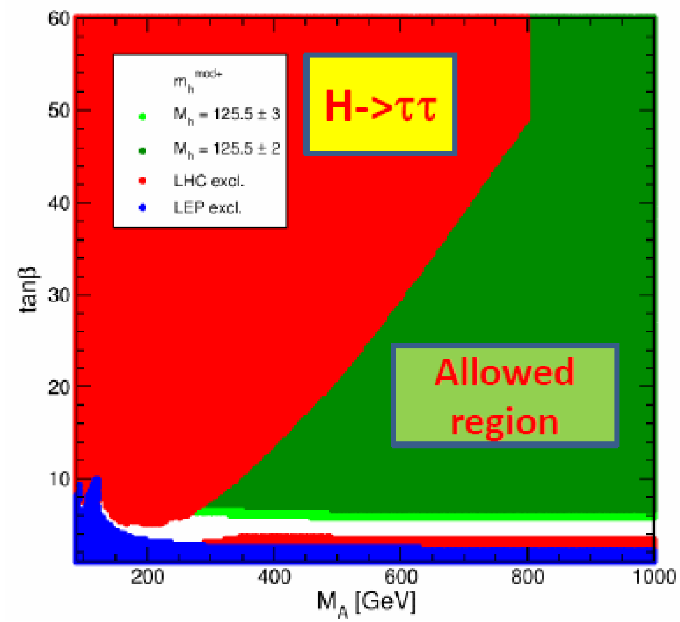


MSSM: neutral Higgs boson

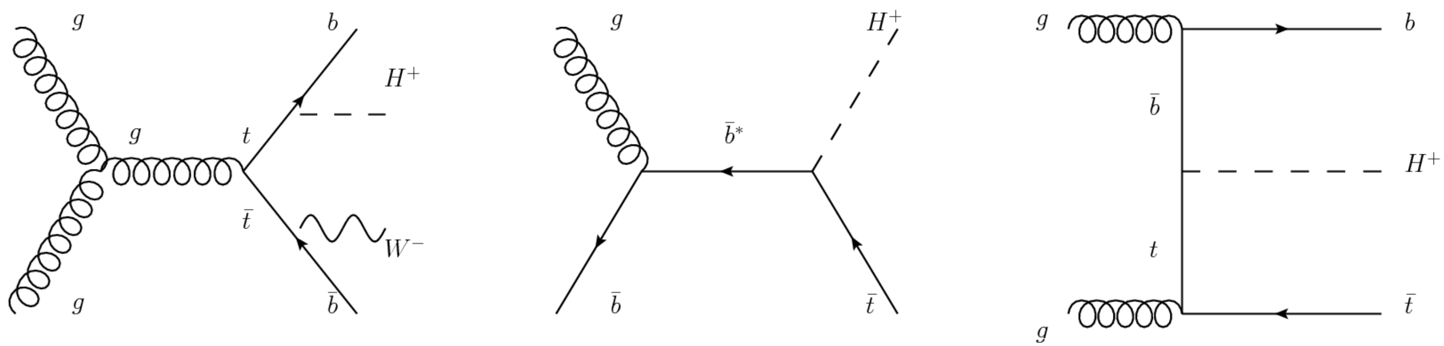


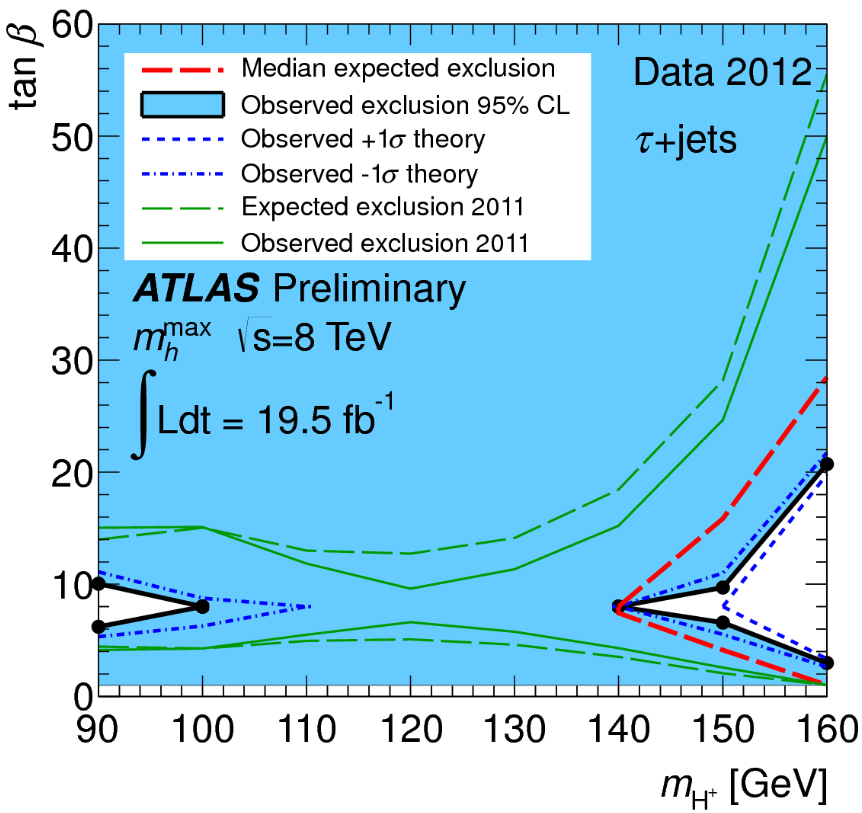


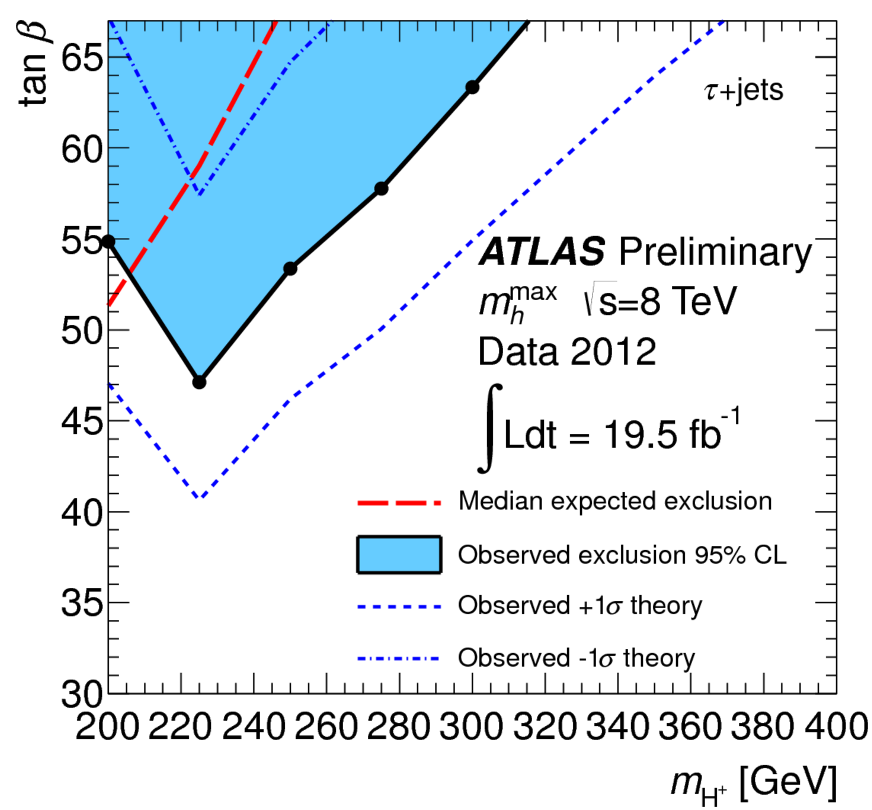
Still room for new physics in the mH-mod scenario



MSSM: charged Higgs boson (ATLAS)

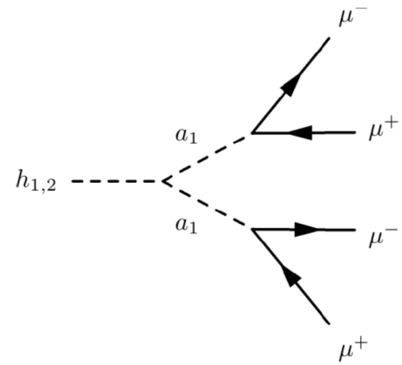


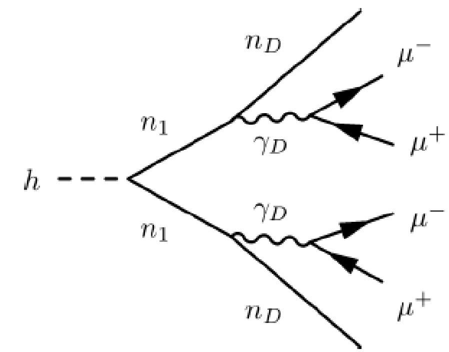


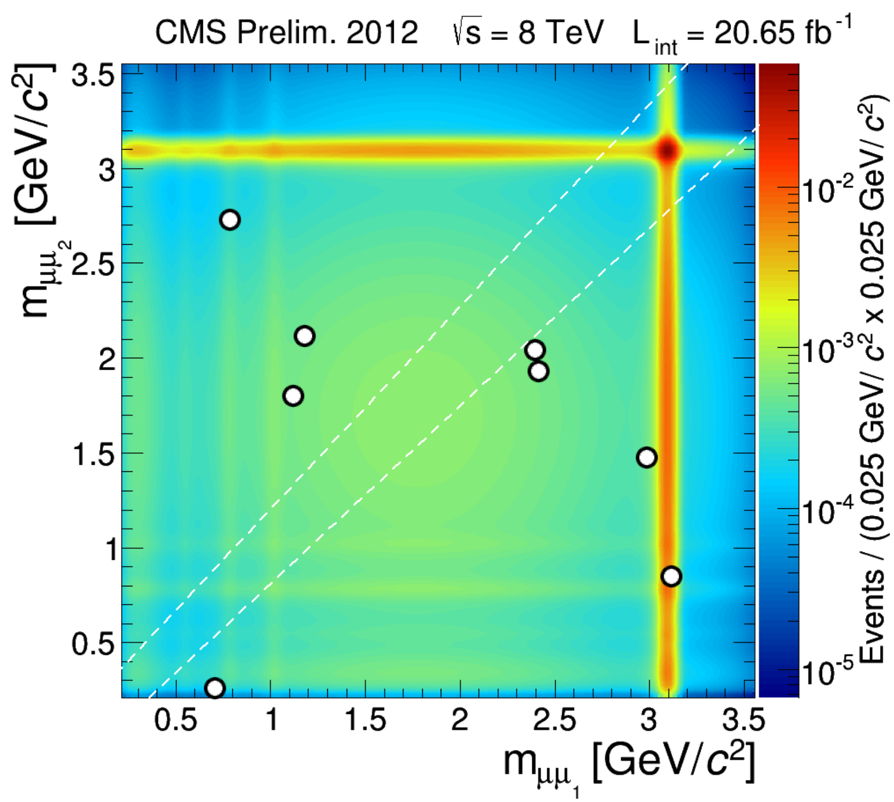


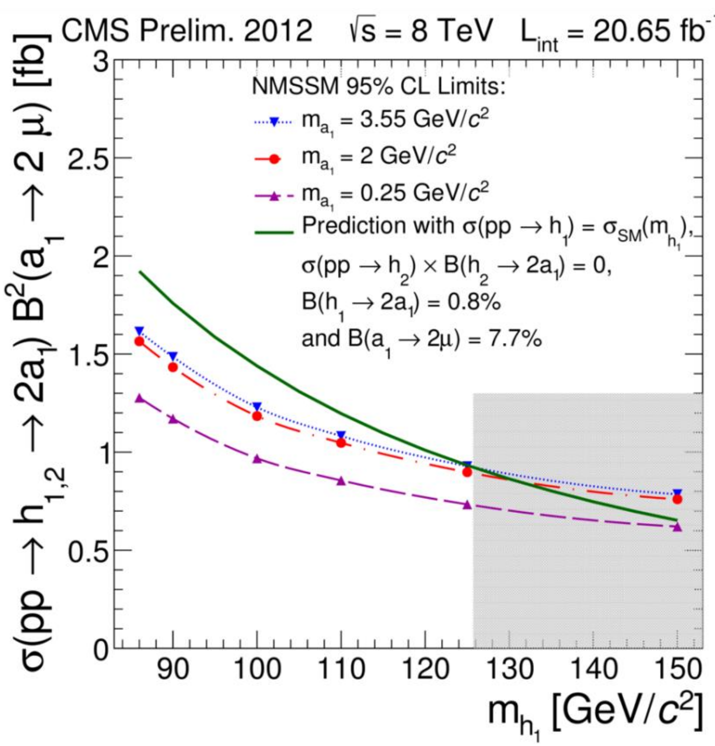
NMSSM Higgs: $h \to 2a \to 4\mu$ (CMS)

Low-mass ($2m_\mu < m_a < 2m_\tau$) Higgs particles decaying to highly collimated muons, dark sector particles, etc…



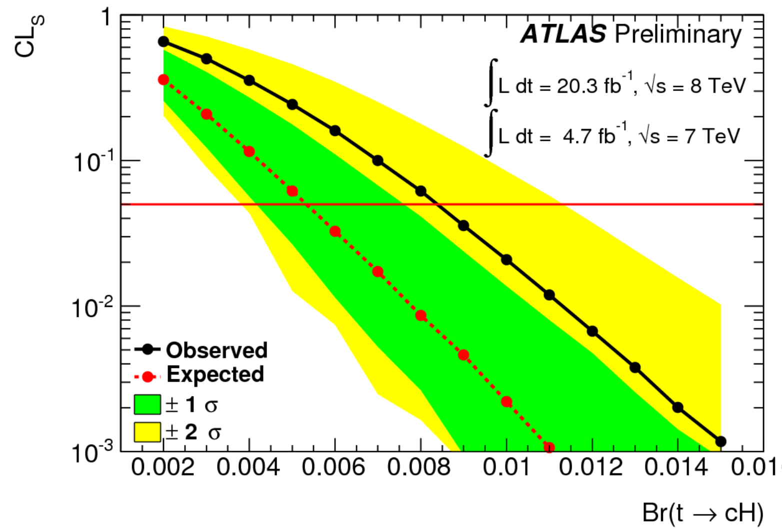






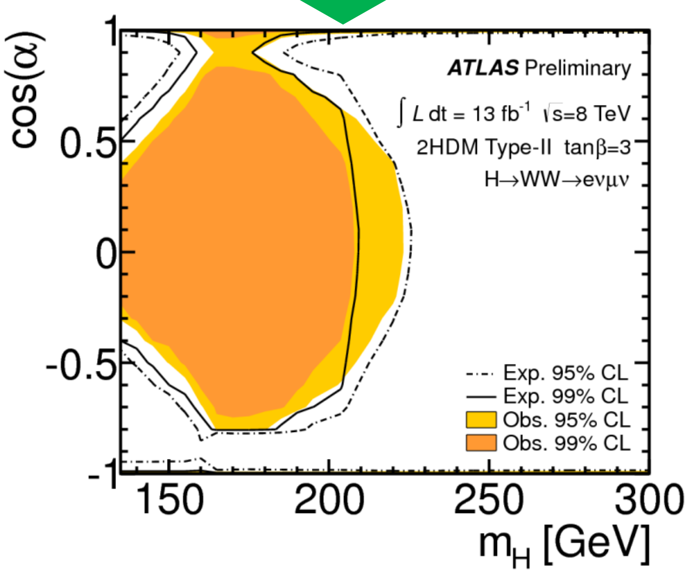
Extended Higgs Sector

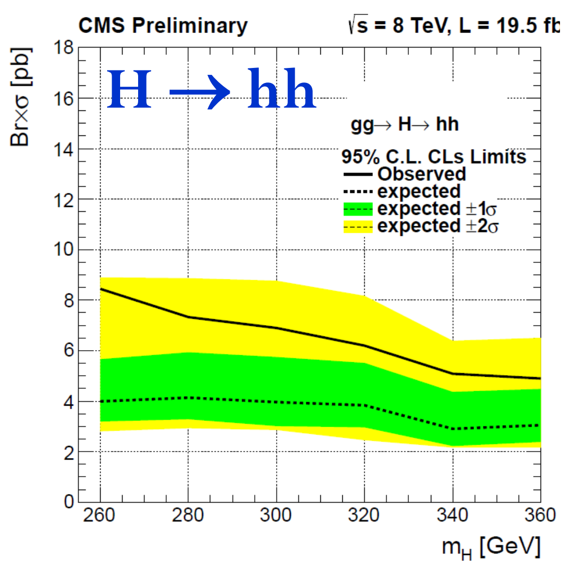
FCNC decays: t → cH (Type III 2HDM)

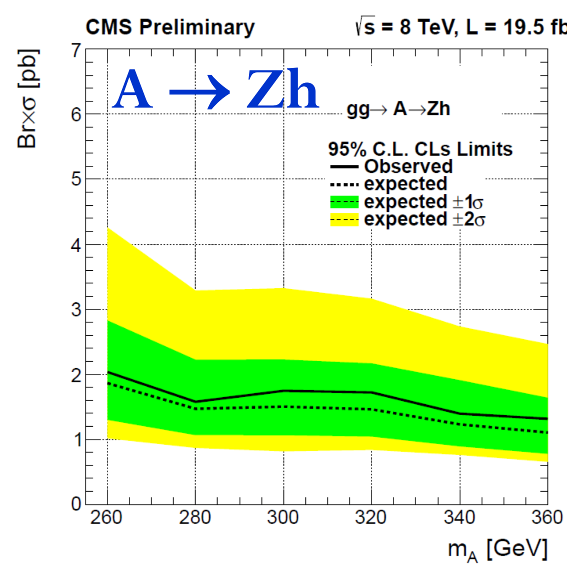


Search for H → hh and A → Zh
in lepton and photon final states

Direct search for H → WW







Summary

- The new particle @ "126 GeV" is observed to decay to all gauge bosons, and in the right proportion
- Consistent mass between CMS and ATLAS
- Now strong evidence also for $H \rightarrow \tau\tau$ (and not $\mu\mu$/ee)
- Spin-parity measurements disfavor alternative hypotheses
- Signal strength and couplings consistent with the SM
- No sign for any other SM-like Higgs boson
- No sign of (any of) the BSM Higgs bosons

If it is not the SM Higgs boson it certainly is a good actor!

Continuing studies of h(126), looking for new Higgs particles