Overview of Higgs Physics at the LHC

Jim Olsen
Princeton University
(On behalf of CMS and ATLAS)

42nd SLAC Summer Institute

August 6, 2014

Outline

- Discovery of a Higgs boson at the LHC
- From discovery to measurement: h(125) properties
- h(125) as a scout for New Physics
- Summary and future prospects

N.B. – the treatment here is broad and therefore lacking in details, see links below and throughout the talk for more info.

ATLAS public Higgs results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
CMS public Higgs results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

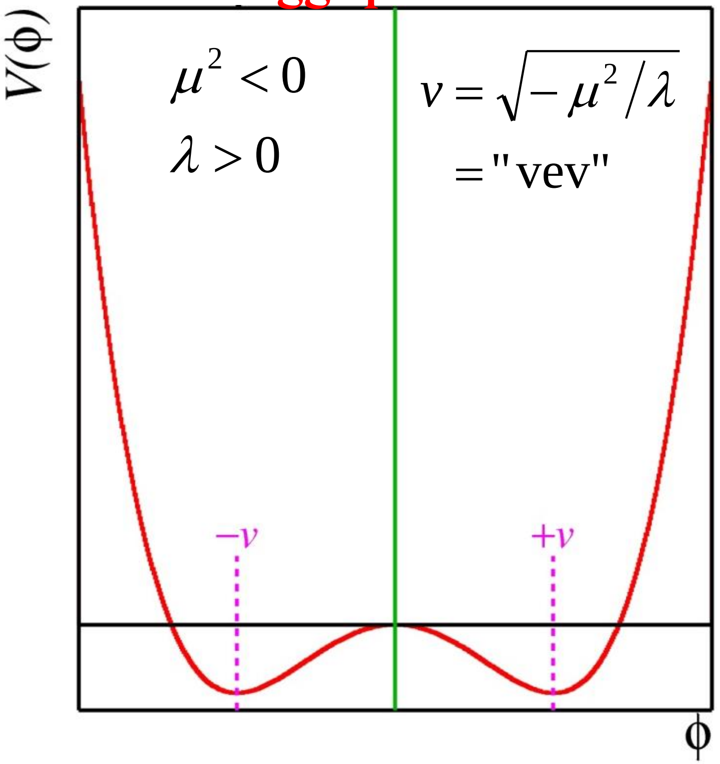
Discovery of a Higgs Boson at the LHC

“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 fermions

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

Higgs potential



$$\boxed{\begin{gathered} v = \left(\sqrt{2} G_\mathrm{F}\right)^{-\frac{1}{2}} \cong 246\,\mathrm{GeV} \\ m_H = \sqrt{2\lambda} v \end{gathered}}$$

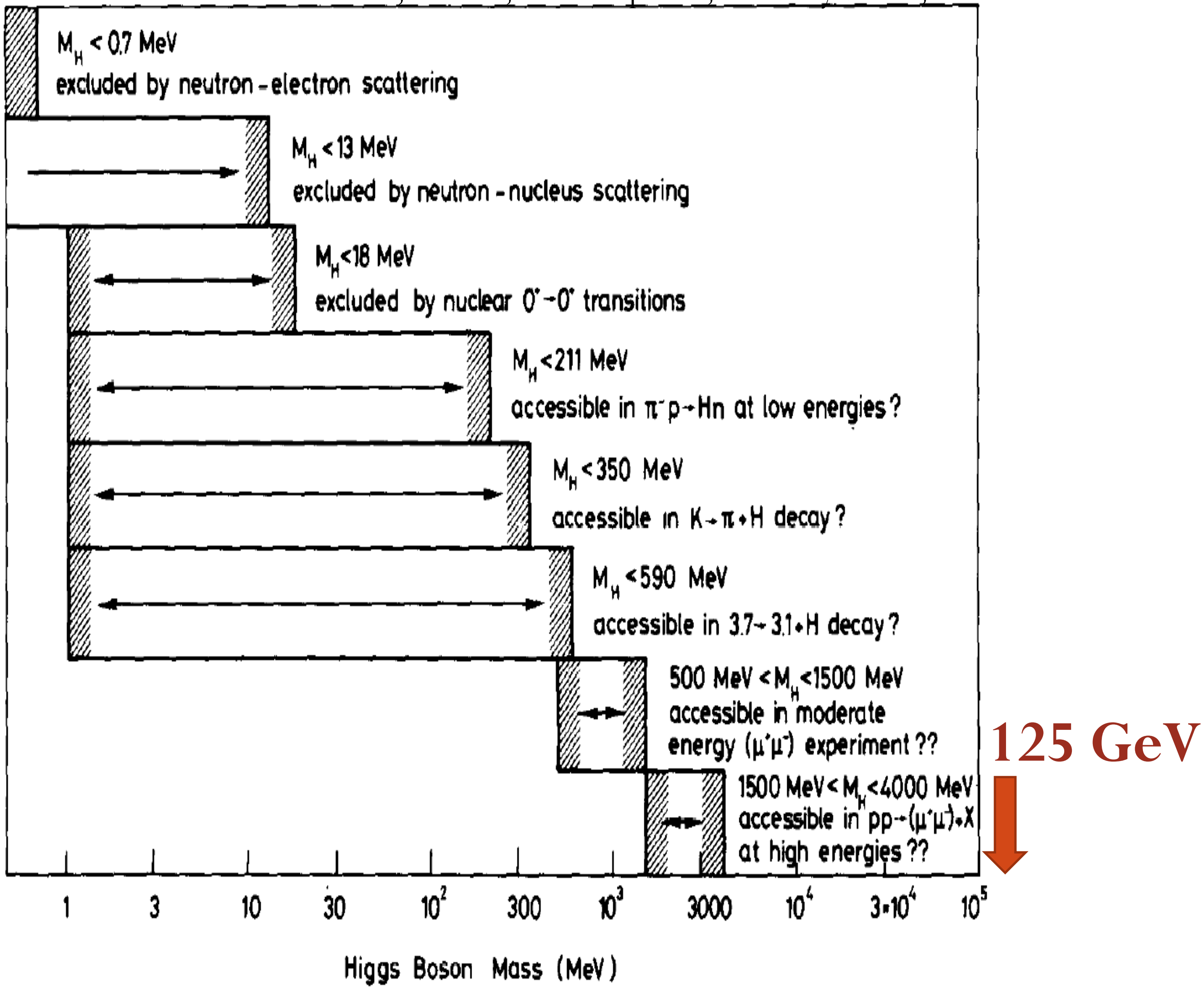
μ and λ not predicted, so the Higgs boson mass is a free parameter in the SM

Gauge boson and fundamental fermion masses:

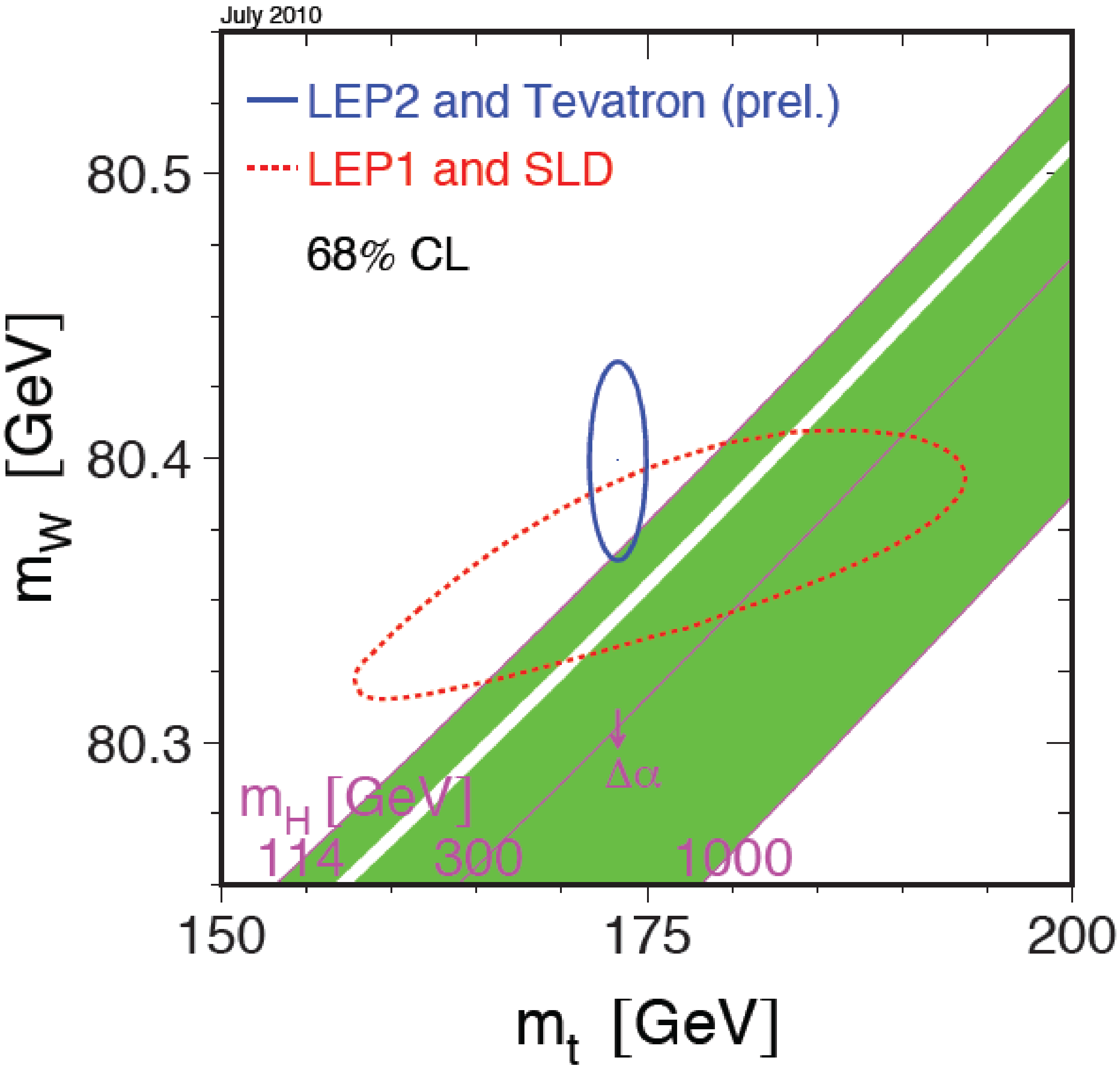
$$m_W = \frac{gv}{2}, m_Z = \frac{m_W}{\cos\theta_W}, m_f = \frac{g_f v}{\sqrt{2}}$$

Higgs Hunting: 1975

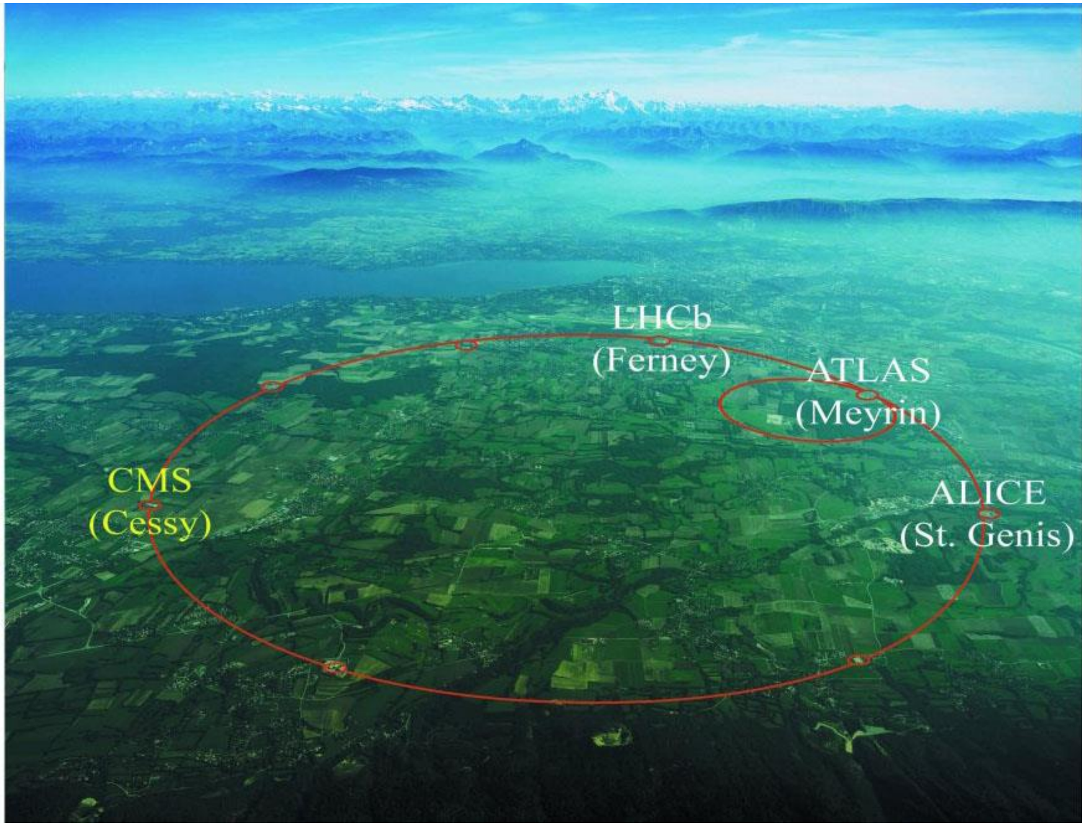
Ellis, Gaillard, and Nanopoulos, Nucl. Phys. B106, 292



At the dawn of the LHC era



Large Hadron Collider



pp collider inside the 27km LEP tunnel (built: 1998-2008)

Highest energy collider ever built (8 trillion electron volts)

1232 superconducting dipole magnets with B > 8 Tesla

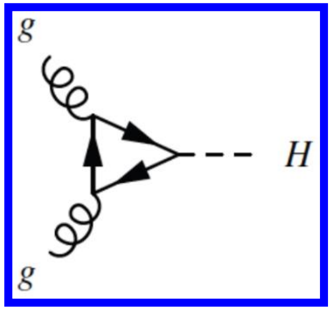
Magnets are colder than space

World's largest cryogenic plant

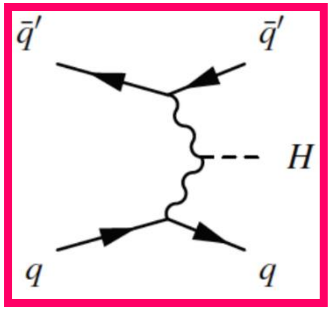
Dot dot dot

> 1 million Higgs bosons have been produced by the LHC

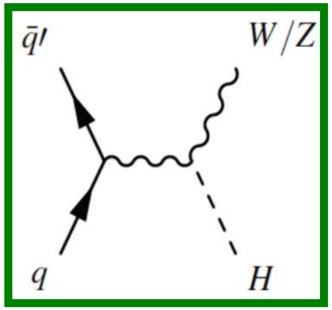
Primary Production Channels at the LHC



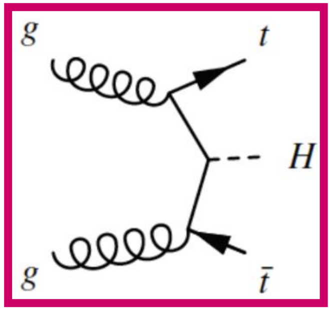
Gluon Fusion



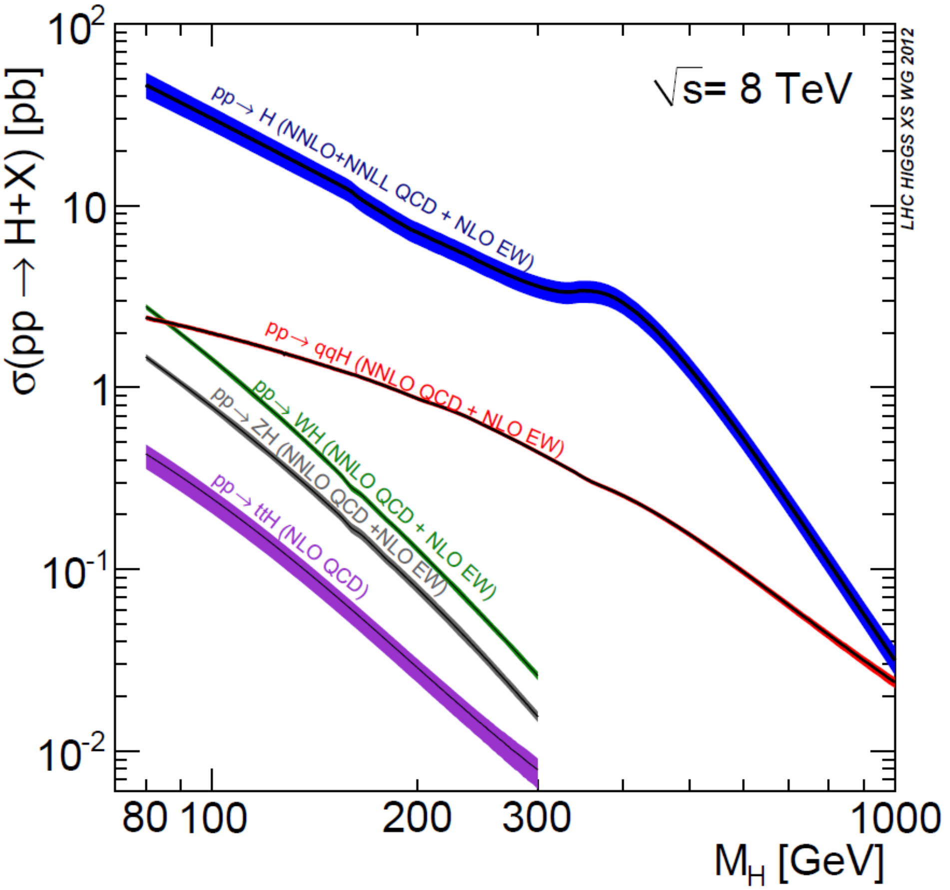
Vector-Boson Fusion



Higgs-strahlung



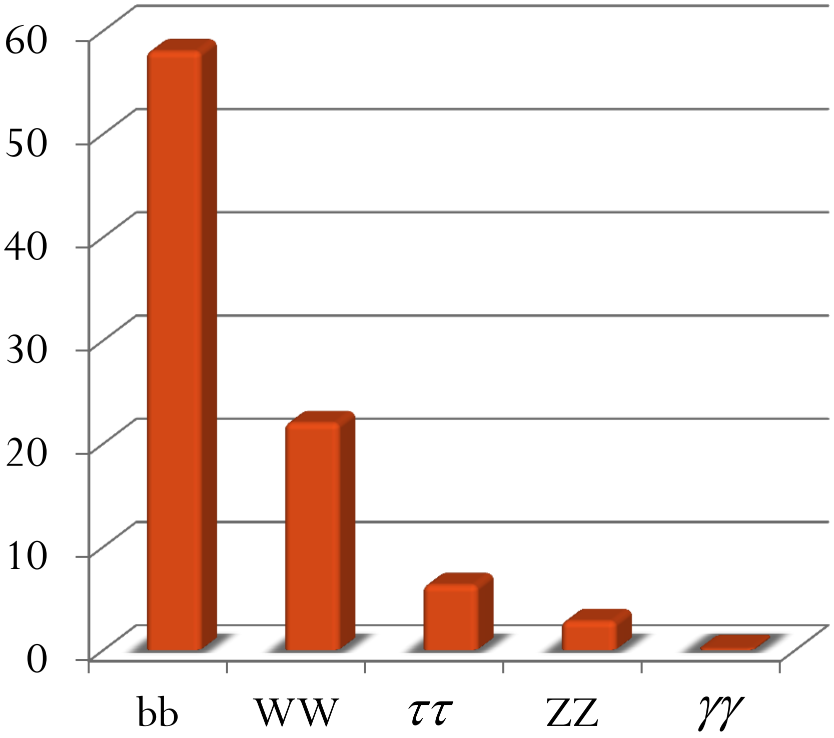
Top Fusion ($t\bar{t}H$)

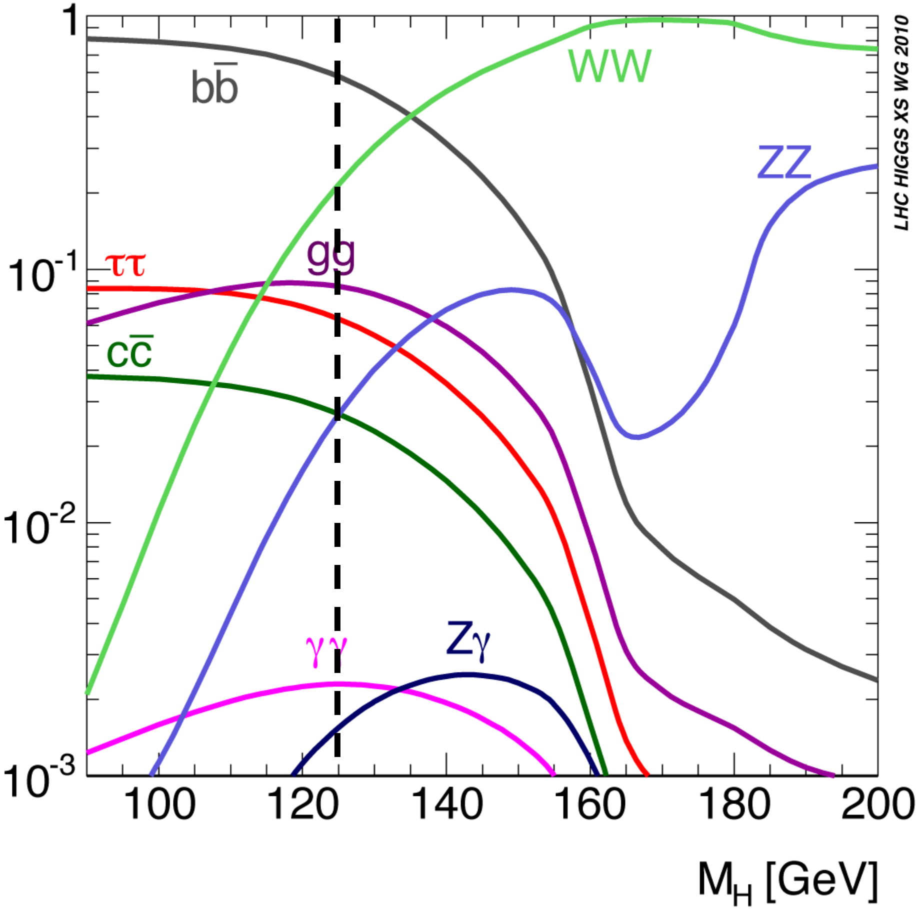


LHC in 2012 at record luminosity (7 x 10^{33} $cm^{-2}s^{-1}$) was producing SM Higgs bosons (M_H = 125 GeV) at a rate **~550/hr per experiment**

How does it decay?

Br (%) for $m_H = 125$ GeV

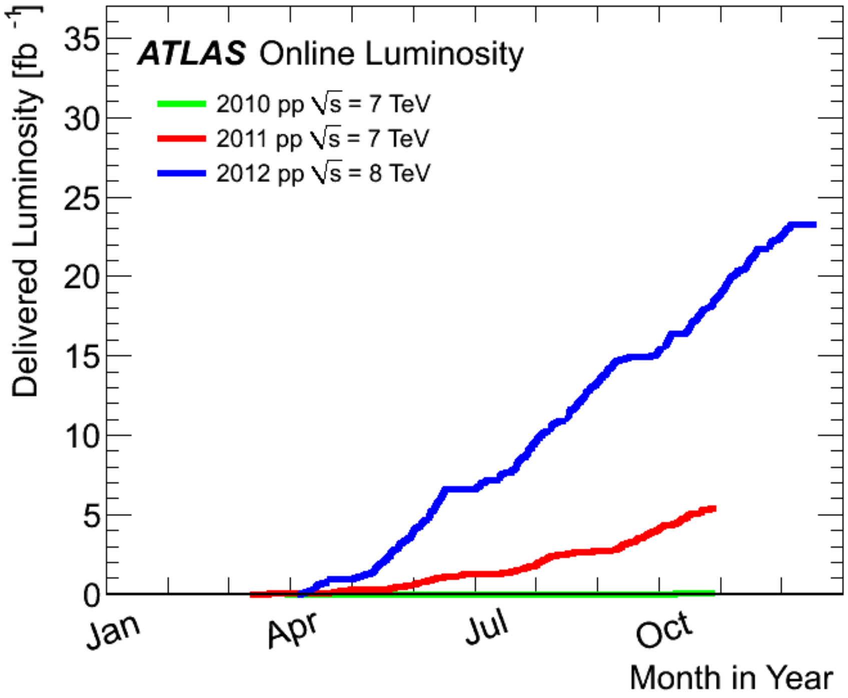


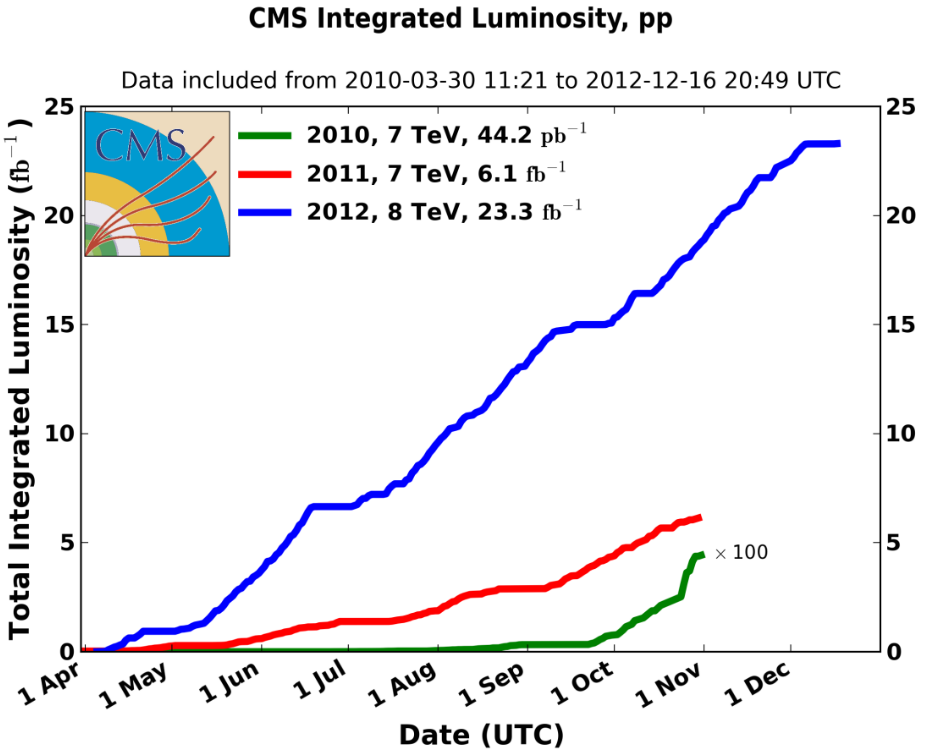


125 GeV is fortuitous! Only region in m_h where

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

Run 1 LHC + ATLAS/CMS Performance

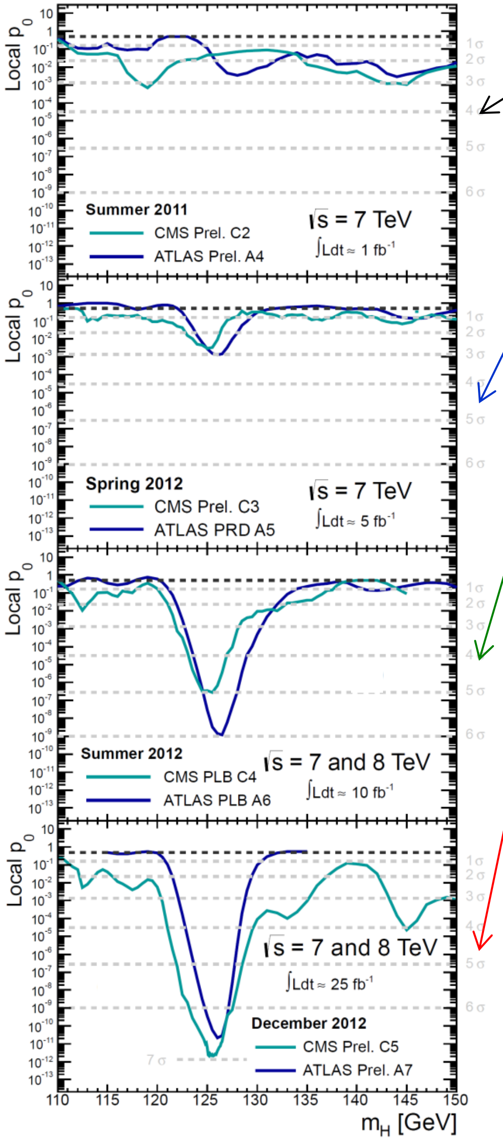




- Phenomenal performance:
  - Record luminosity (> 5 x 10^{33}) obtained soon after startup in 2012
  - Sustained data collection rate of > 1.0 fb^{-1} /wk
  - Delivered/recorded @ 8 TeV = [23.3 / 21.3 (ATLAS) , 21.8 (CMS)] fb^{-1}

Higgs Discovery (and Exclusion)

From the PDG:
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-higgs-boson.pdf



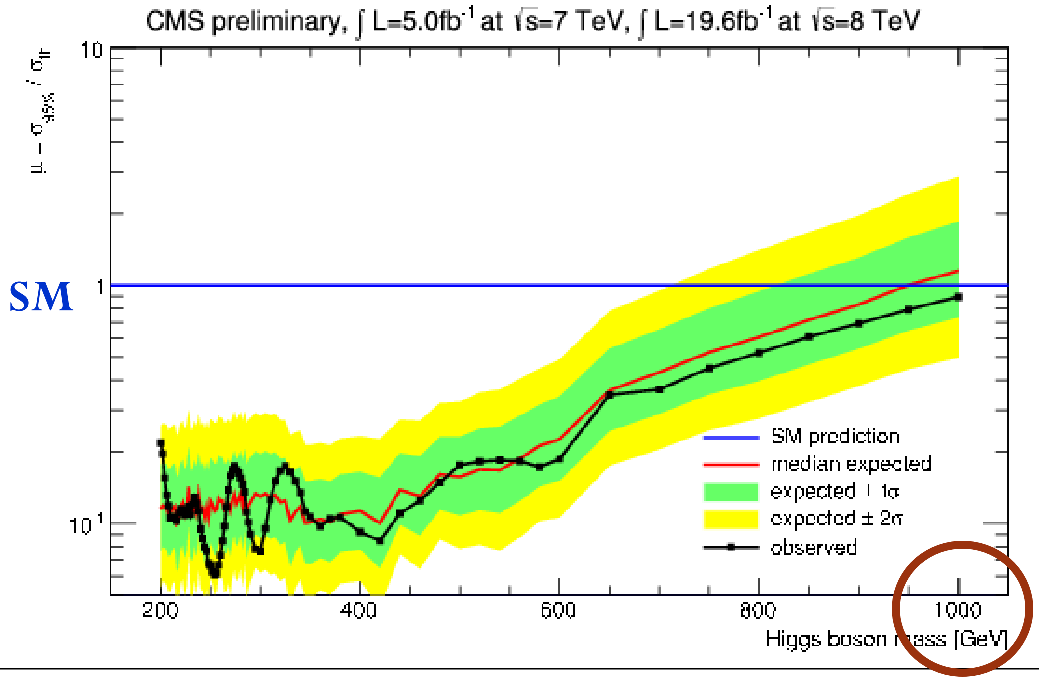
Summer 2011: drops in the bucket

End of 2011: tantalizing hint, the trail begins

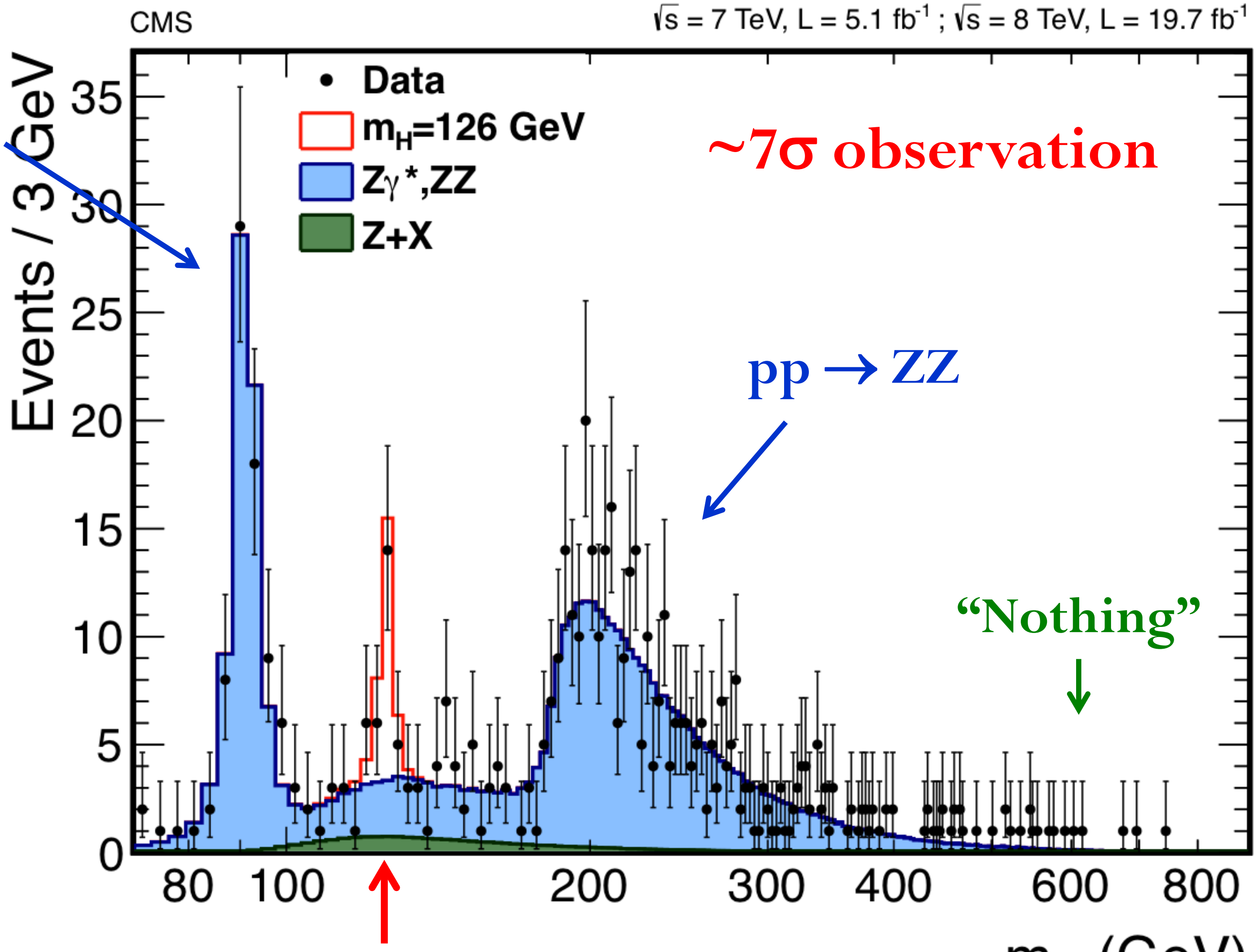
Summer 2012: discovery! 5σ from both experiments

End of 2012: confirmation! Measurement era begins

…and we did not find a SM-like Higgs anywhere else:



Golden Channel: $H \to ZZ^* \to 4\ell$



$Z \to 4\ell$

~7σ observation

$pp \to ZZ$

"Nothing"

Higgs Boson

Significance (in σ) by decay channel

Channel	ATLAS (expected)	ATLAS (observed)	CMS (expected)	CMS (observed)
$h \rightarrow \gamma\gamma$	4.1	**7.4**	5.2	**5.7**
$h \rightarrow ZZ$	4.4	**6.6**	6.7	**6.8**
$h \rightarrow WW$	3.7	**3.8**	5.8	**4.3**
$h \rightarrow \tau\tau$	3.2	**4.1**	3.6	**3.4**
$h \rightarrow bb$	1.6	**~0**	2.1	**2.1**

Recent News:

Solid evidence for fermionic decays from ATLAS and CMS (Nov, 2013)

First 5σ observation of $h \rightarrow \gamma\gamma$ in CMS (July, 2014)

From Discovery to Measurement: Properties of h(125)

Is it the SM Higgs Boson?

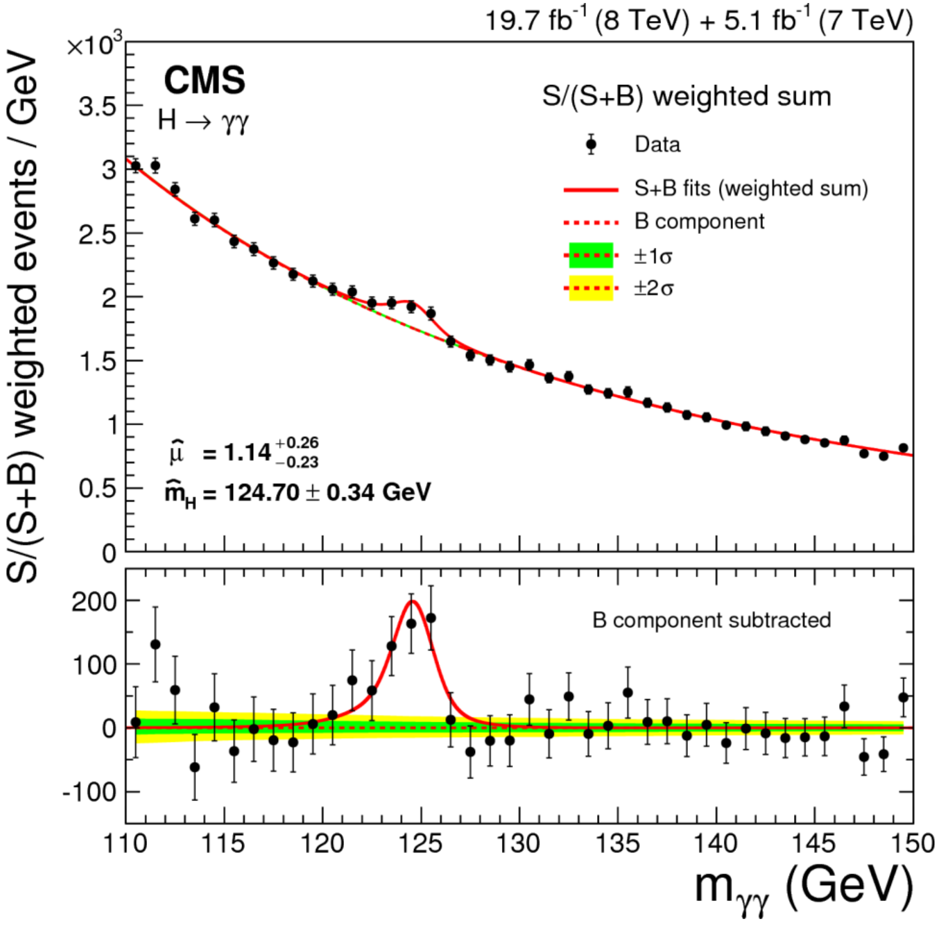
- When a new particle is discovered, the first step is to measure its properties with the highest possible precision
  - Mass
  - Quantum numbers: spin, parity
  - Signal strength (μ); does it couple to known particles as expected?
  - Total width (lifetime)
  - CP properties

$\mu \equiv [\sigma \times \mathrm{BF}]/[\sigma \times \mathrm{BF}]_{\mathrm{SM}}$

- If h(125) is the SM Higgs boson it is a $J^{PC} = 0^{++}$ fundamental particle that couples to the gauge bosons and fermions according to their mass via a single vacuum expectation value
  - **Any deviation from this expectation is a sign of New Physics**

Combined Mass from γγ and ZZ

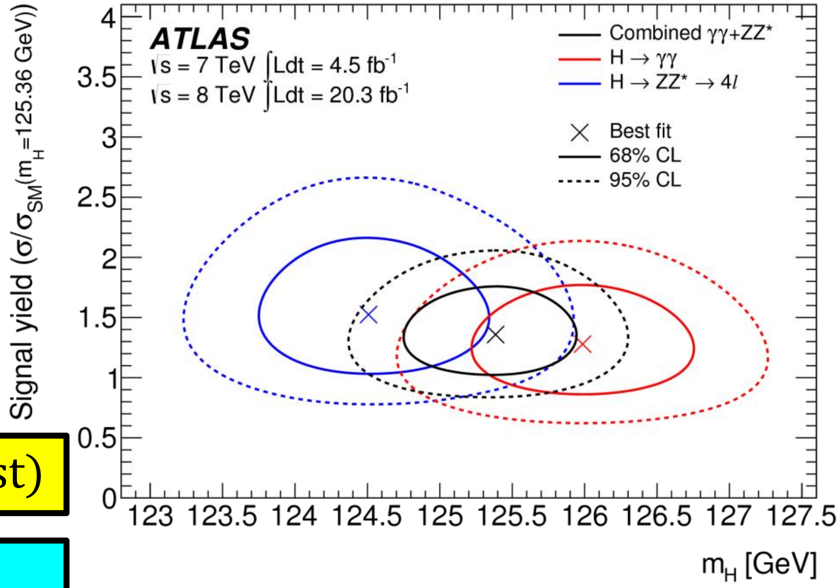
arXiv:1407.0558 (submitted to EPJC)



Final h → γγ result and preliminary combined mass from CMS

Final combined mass from ATLAS

Now working on ATLAS/CMS combined mass measurement



$$m_H(\text{ATLAS}) = 125.36\ \pm 0.37\ (\text{stat})\ \pm 0.18\ (\text{syst})$$

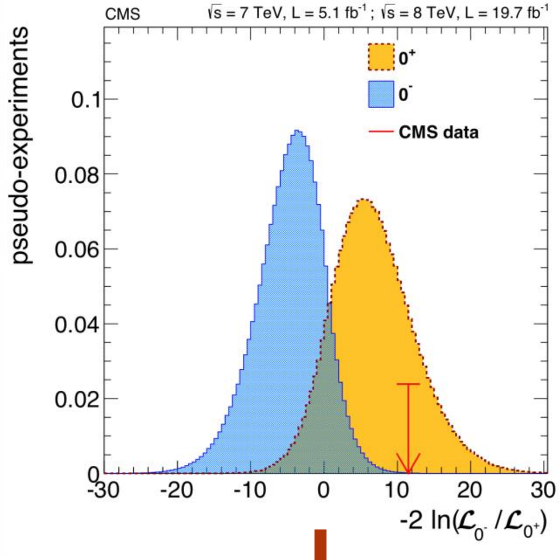
$$m_H(\text{CMS}) = 125.03\ {}^{+0.26}_{-0.27}\ (\text{stat})\ {}^{+0.13}_{-0.15}(\text{syst})$$

arXiv:1406.3827 (accepted by PRD)

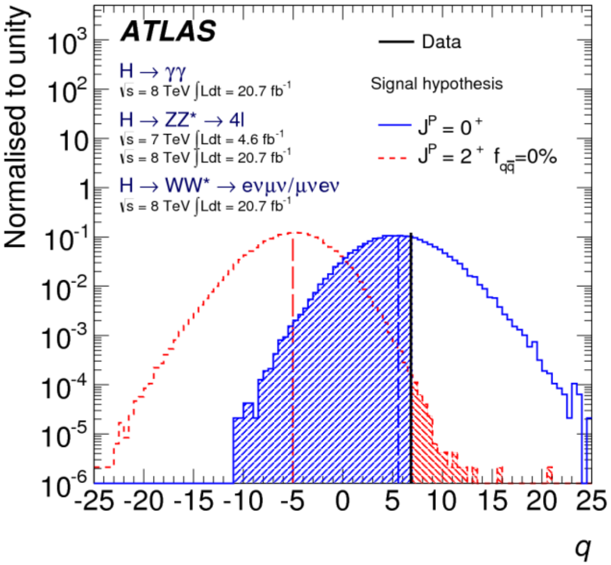
Spin and parity

Phys. Lett. B 726 (2013)

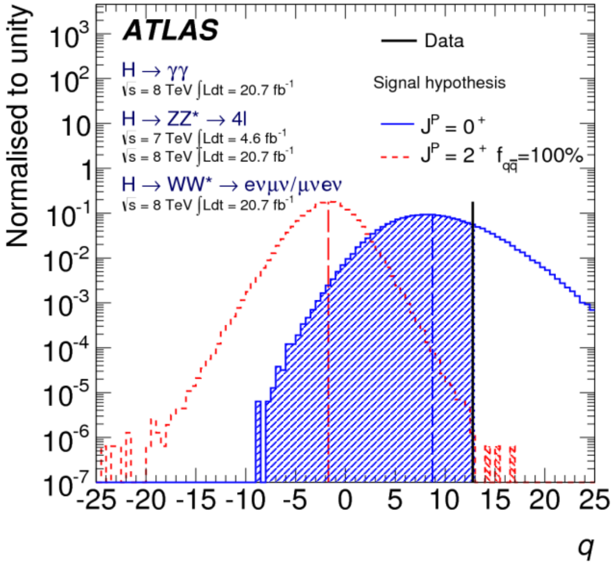
Scalar vs. Pseudoscalar



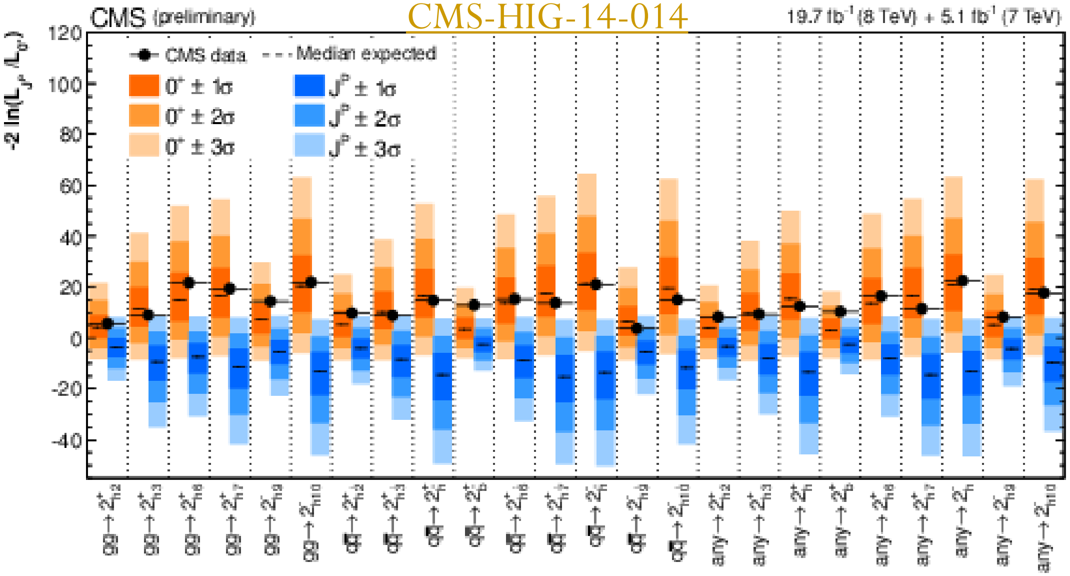
Scalar vs. Tensor (gg)



Scalar vs. Tensor (qq)



CMS-HIG-14-014

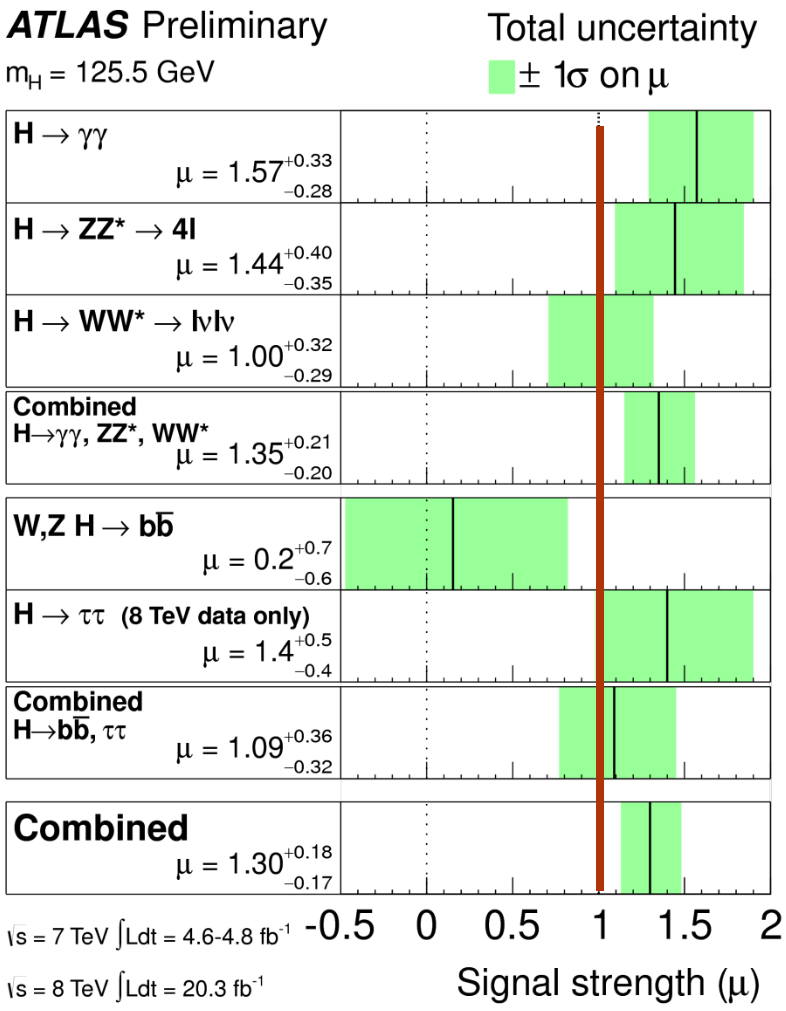


Alternative J^P assignments are disfavored by both CMS and ATLAS.

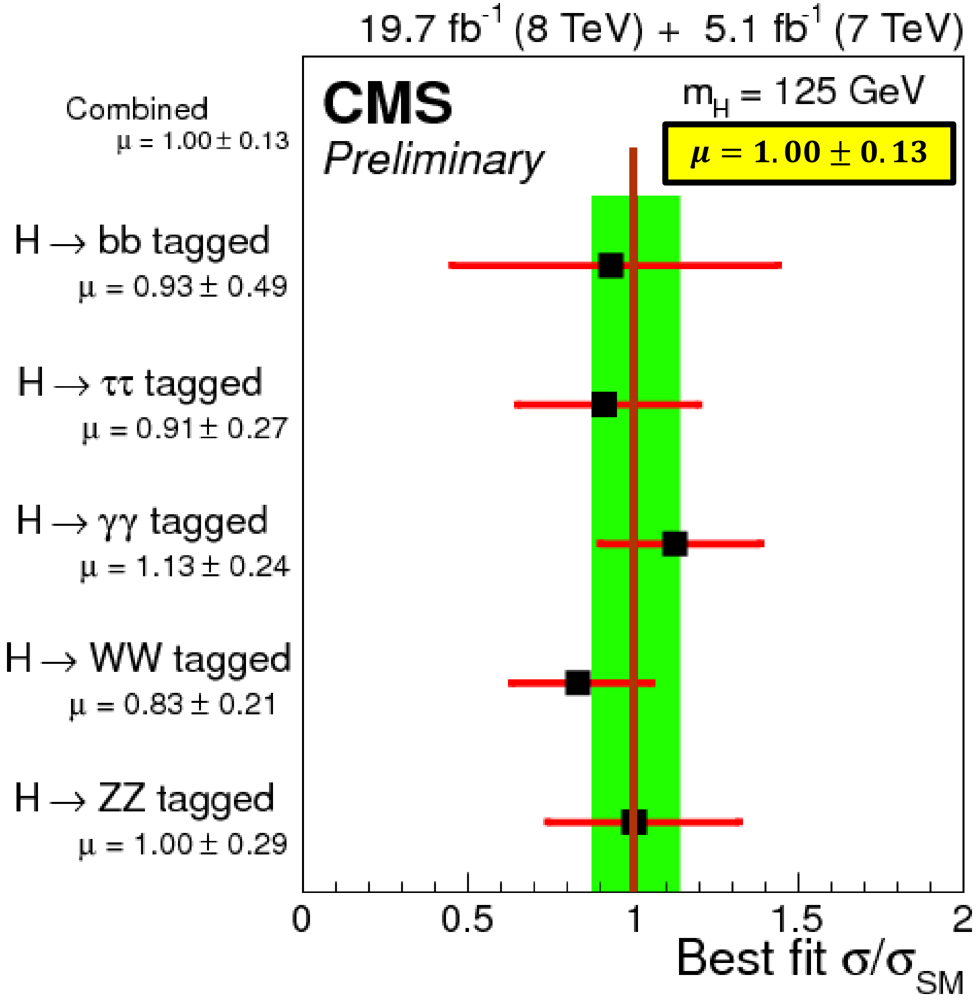
Signal strength by decay channel

$\boldsymbol{\mu = 1.30 \pm 0.18}$

ATLAS-CONF-2014-009



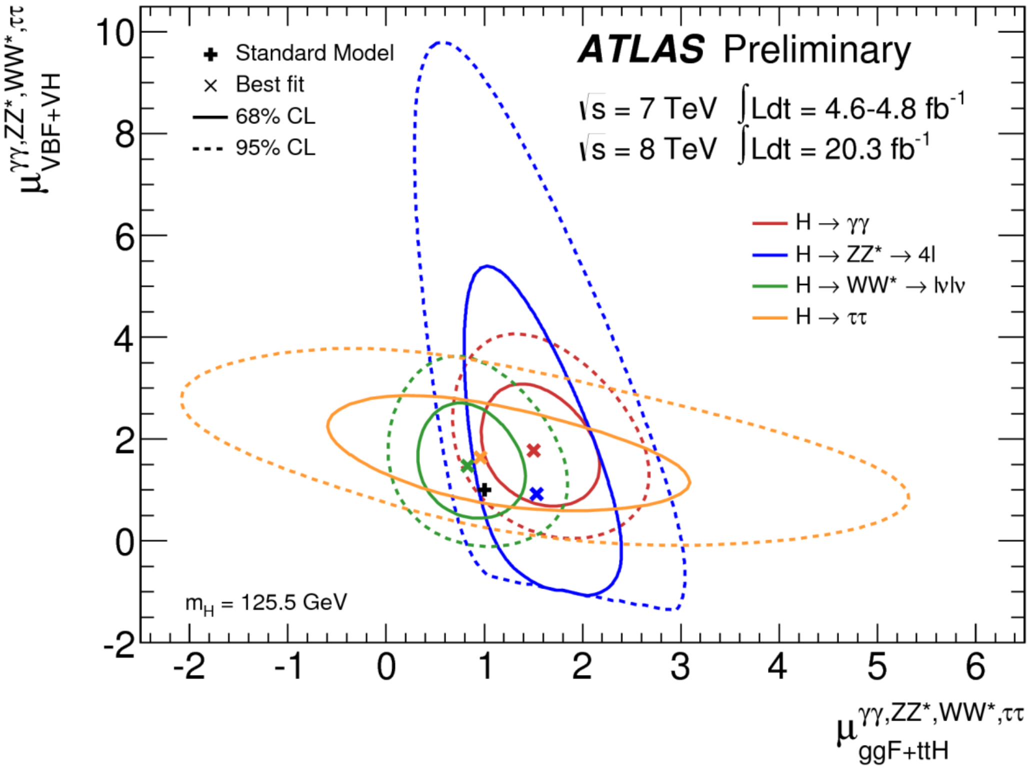
CMS-HIG-14-009



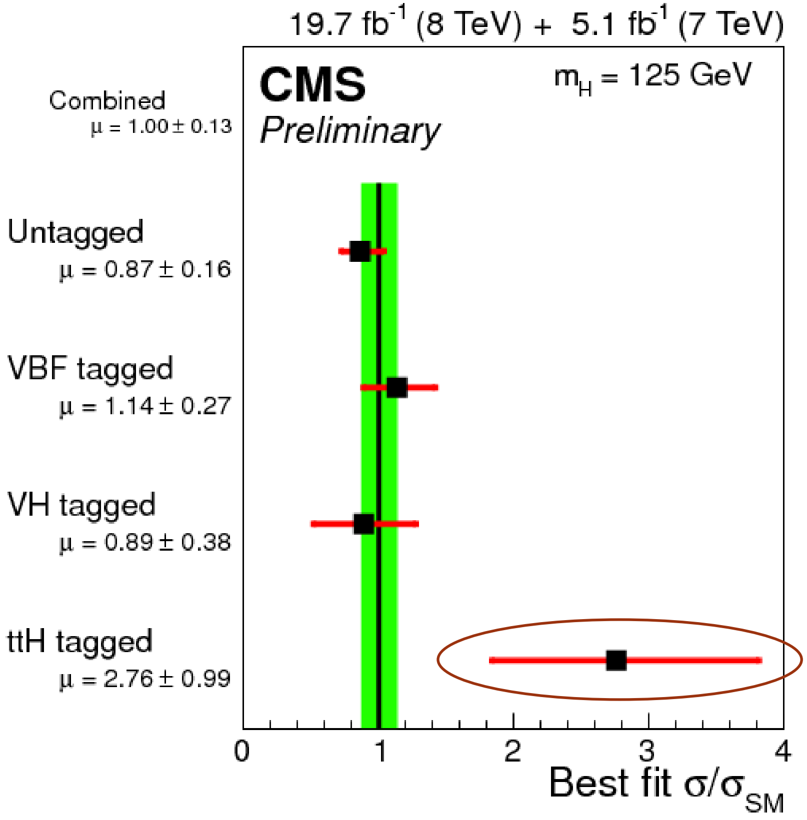
Both experiments are consistent with the SM expectation

Signal strength by production

ATLAS-CONF-2014-009



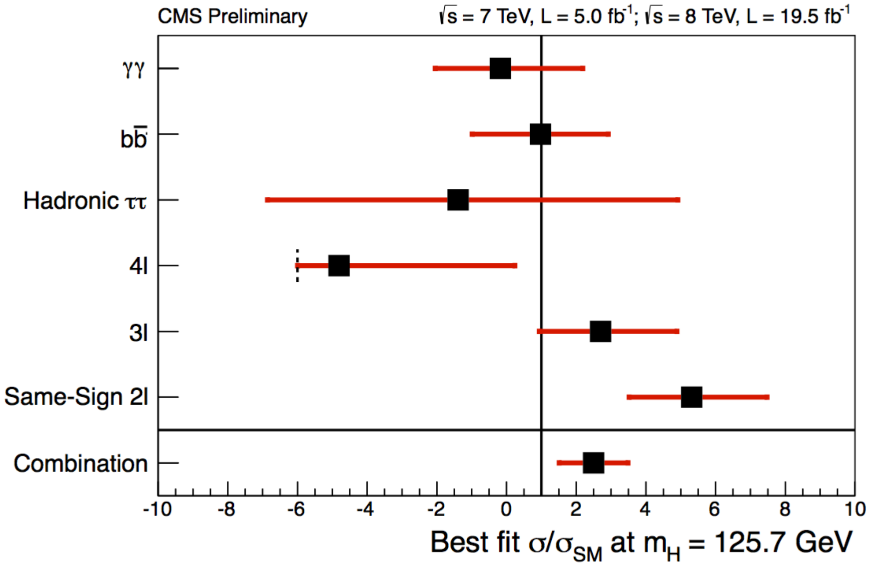
CMS-HIG-14-009



Both experiments have > 3σ evidence for VBF production, and all results are consistent with SM (slight excess of ttH)

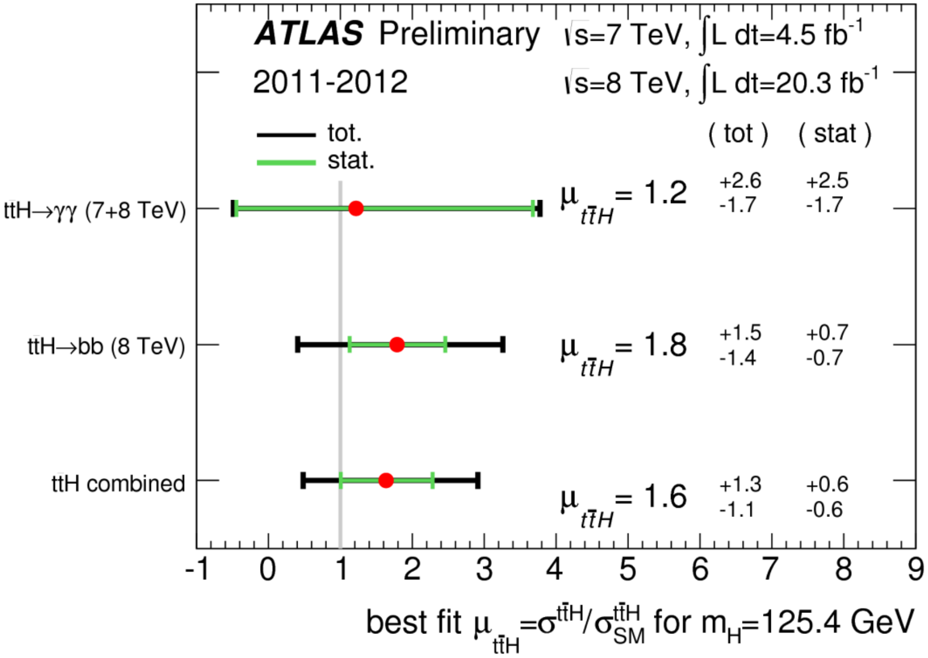
Results on ttH Production

CMS-HIG-13-029 (to be submitted soon)



- **CMS summary**
  - Uses H → bb, ττ, γγ, multilep
    - CMS-HIG-13-029
    - CMS-HIG-14-009
  - Combined signal strength @ 125: **μ = 2.8 ± 1.0 (2σ from SM)**

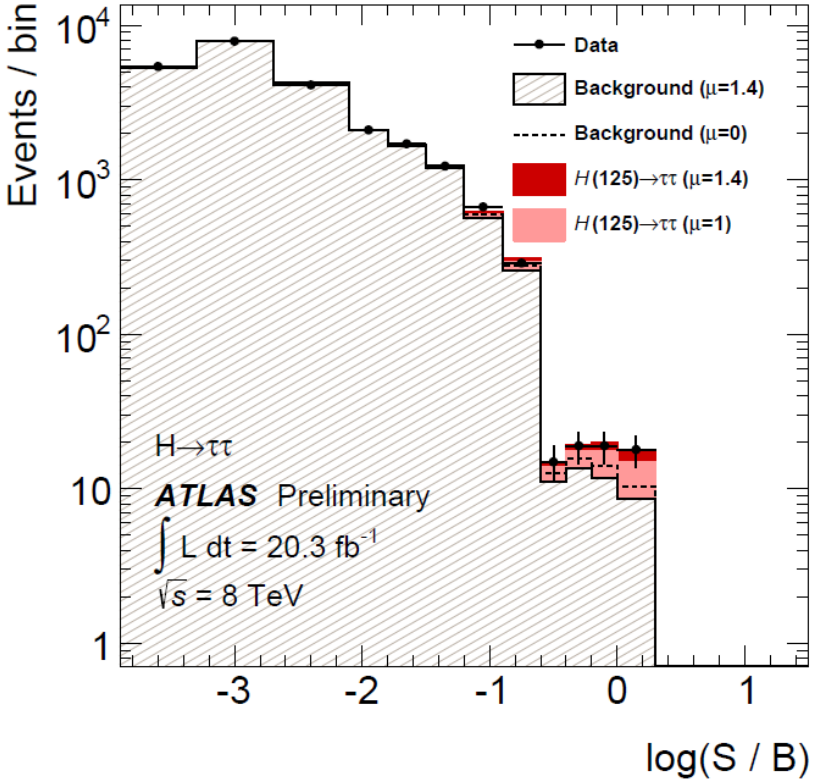
- **ATLAS summary**
  - Dominantly uses H → bb and γγ
    - ATLAS-CONF-2014-011
    - ATLAS-CONF-2014-043
  - Combined signal strength @ 125.4: **μ = 1.6 ± 1.4**



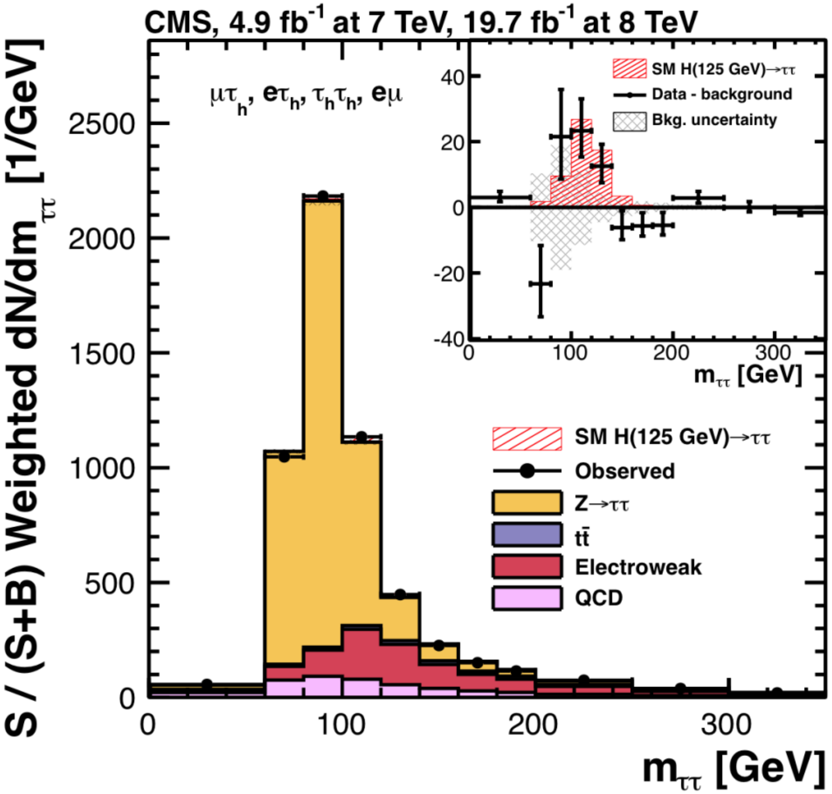
ATLAS-CONF-2014-011, ATLAS-CONF-2014-043

Evidence for Fermionic Decays: h → ττ

ATLAS-CONF-2013-108



JHEP 05 (2014) 104



ATLAS (m_H = 125 GeV):

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

CMS (m_H = 125 GeV):

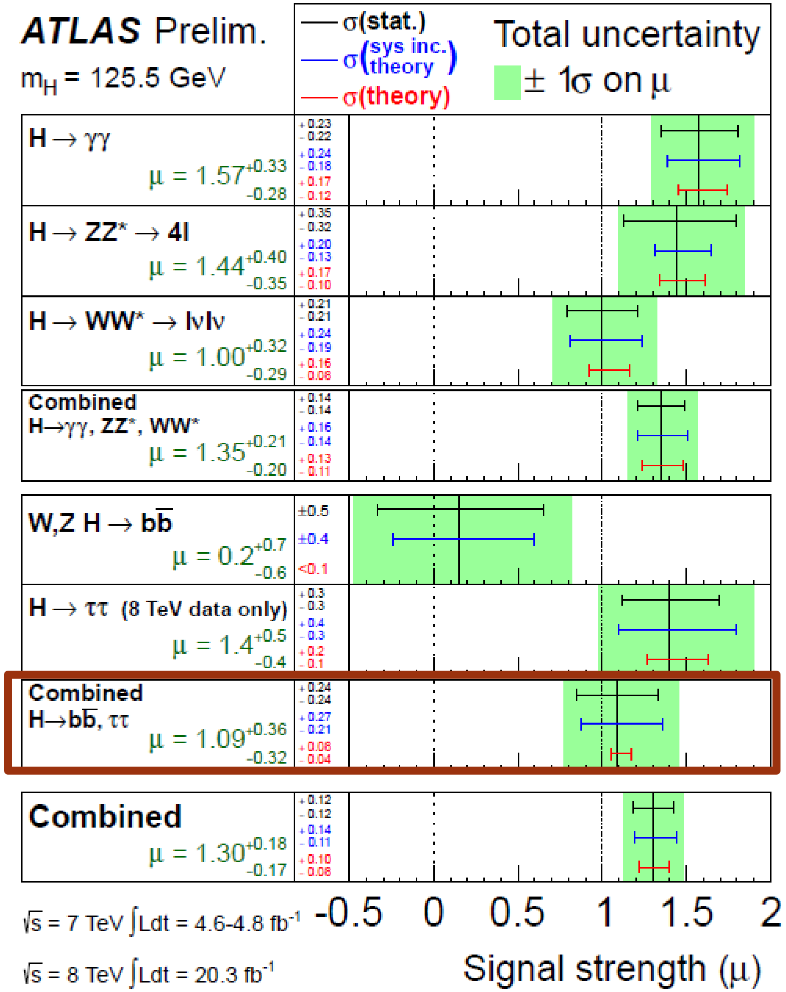
- **3.7 σ (3.2 σ) exp (obs)**
- $\boldsymbol{\mu = 0.78 \pm 0.27}$

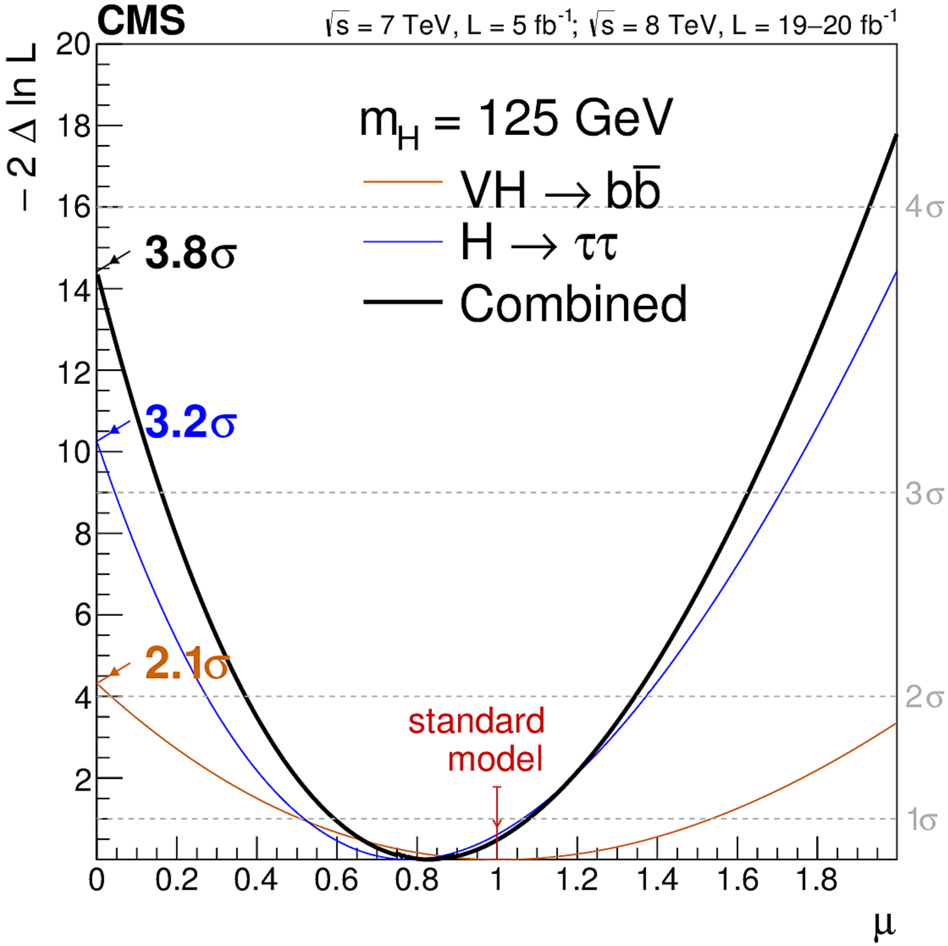
Solid evidence for Higgs decays to tau leptons!

Fermion Combinations

ATLAS-CONF-2014-009

Nature Physics 10 (2014) 557



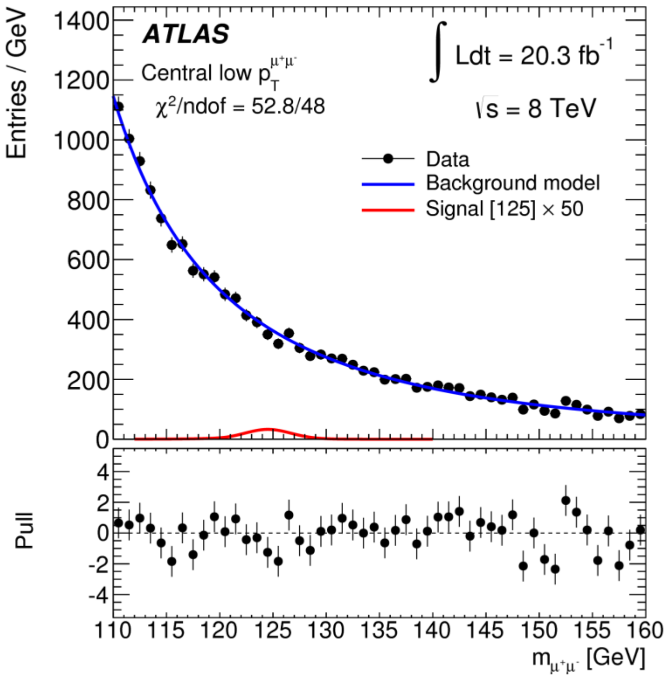


ATLAS: ττ + bb → 3.7 σ

CMS: ττ + bb → 3.8 σ

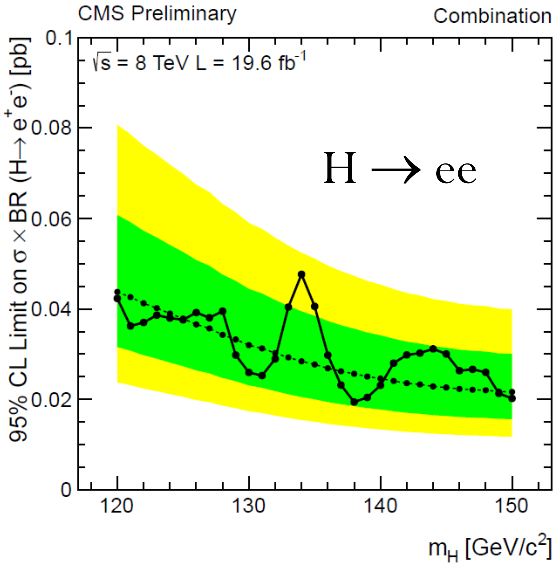
Higgs → μμ (and ee)?

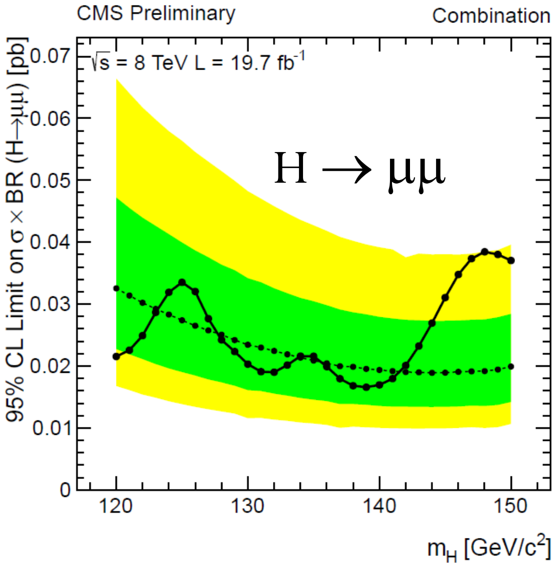
- If this is the SM Higgs boson, coupling to leptons should go like $g \propto m_l$
  - μμ/ee decays should be highly suppressed relative to ττ
- Have not seen μμ/ee yet → this particle appears to couple according to mass!

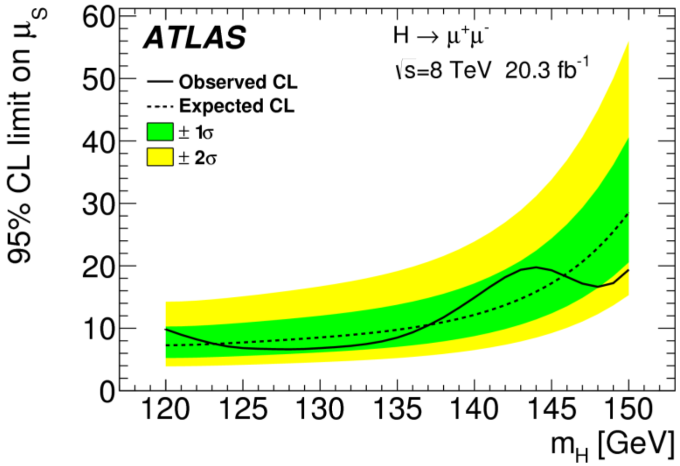


arXiv:1406.7663 (submitted to PLB)

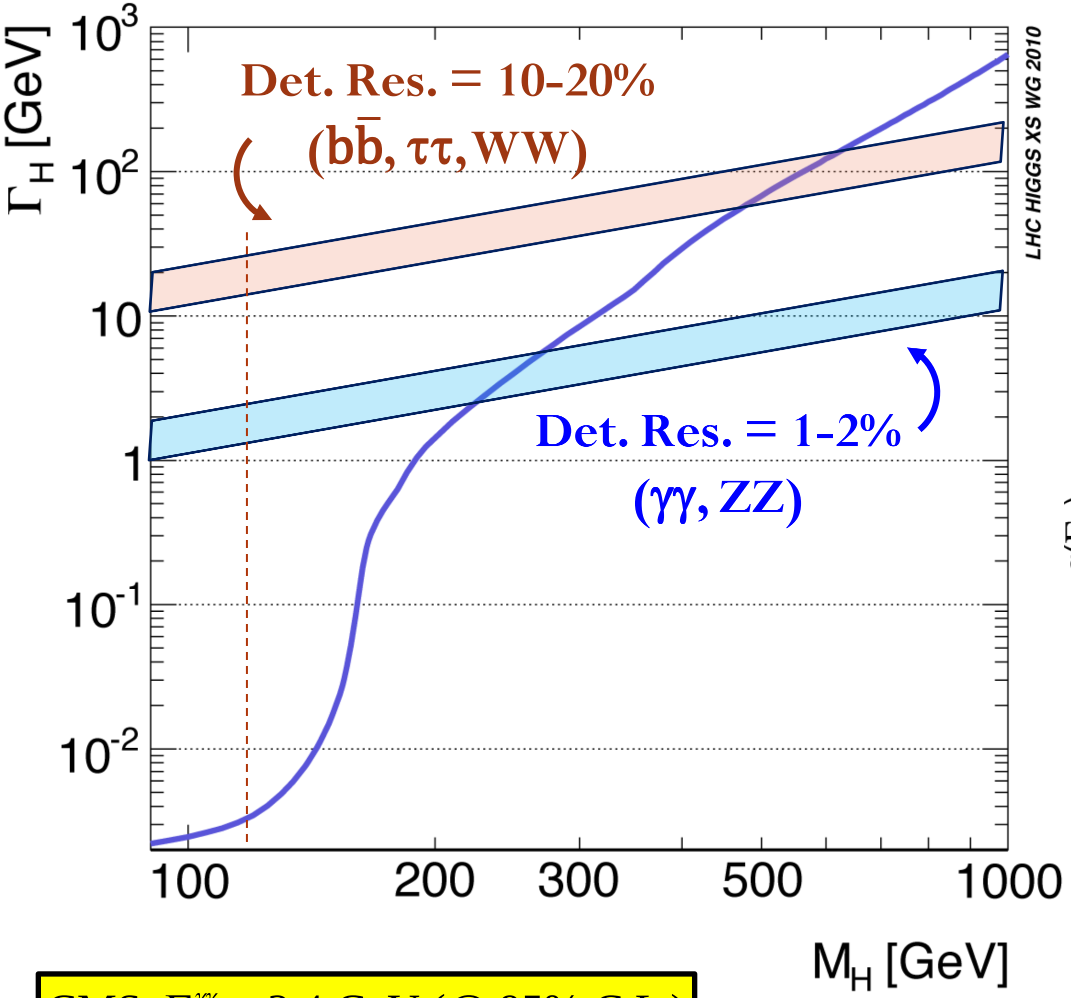
CMS-HIG-13-007

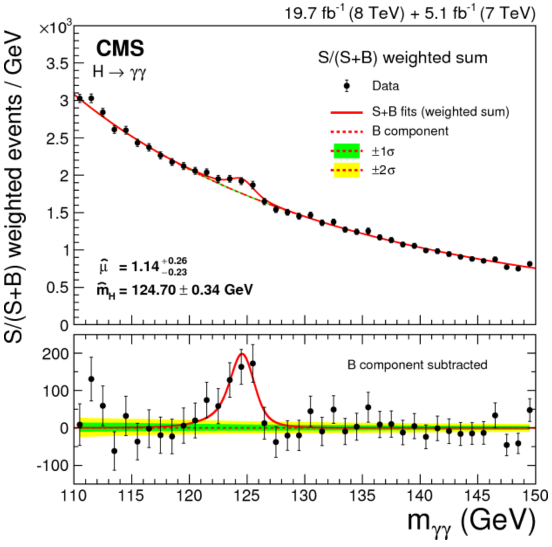


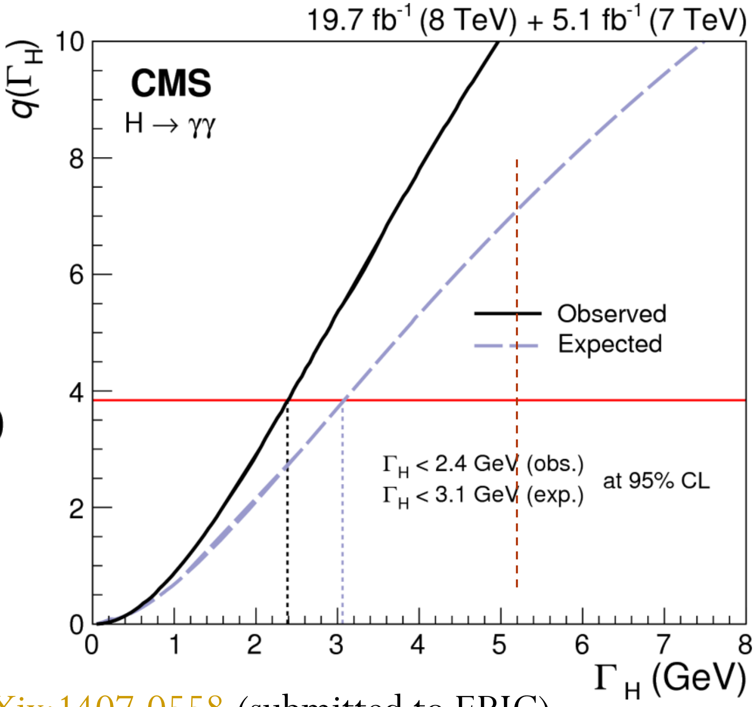




Measuring Higgs Width Directly?





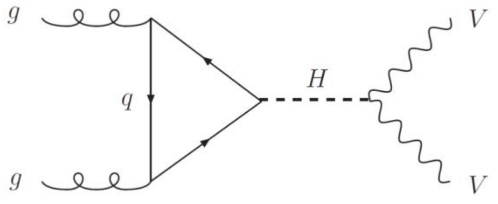


CMS: $\Gamma_H^{\gamma\gamma} < 2.4$ GeV (@ 95% C.L.)

ATLAS: $\Gamma_H^{4l} < 2.6$ GeV (@ 95% C.L.)

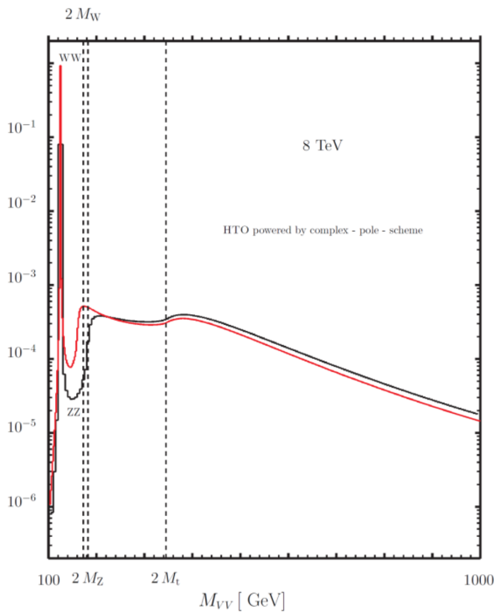
arXiv:1407.0558 (submitted to EPJC)

Higgs width from off-shell production

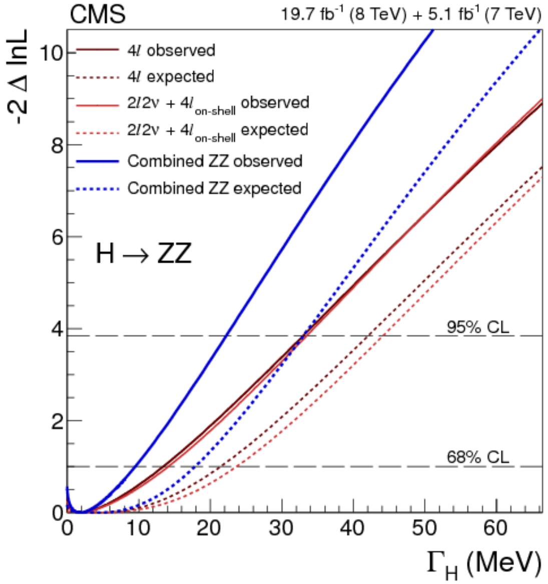


Higgs boson as a propagator:

$$\sigma \propto \frac{g_{\mathrm{ggH}}^{2} \cdot g_{\mathrm{ZZH}}^{2}}{\left(q^{2} - m_{\mathrm{H}}^{2}\right)^{2} + m_{\mathrm{H}}^{2}\Gamma_{\mathrm{H}}^{2}}$$



[Phys. Lett. B 736 (2014) 64]



On peak depends on Γ_{h}, but off-peak does not. Assuming equal couplings on/off-shell, ratio of signal strengths gives direct access to Γ_{h}.

CMS: $\Gamma/\Gamma_{SM} < 4.2$ @ 95% C.L.

$\rightarrow \Gamma_{SM} < 17.4$ MeV

ATLAS: $\Gamma/\Gamma_{SM} < 5.7$ @ 95% C.L.

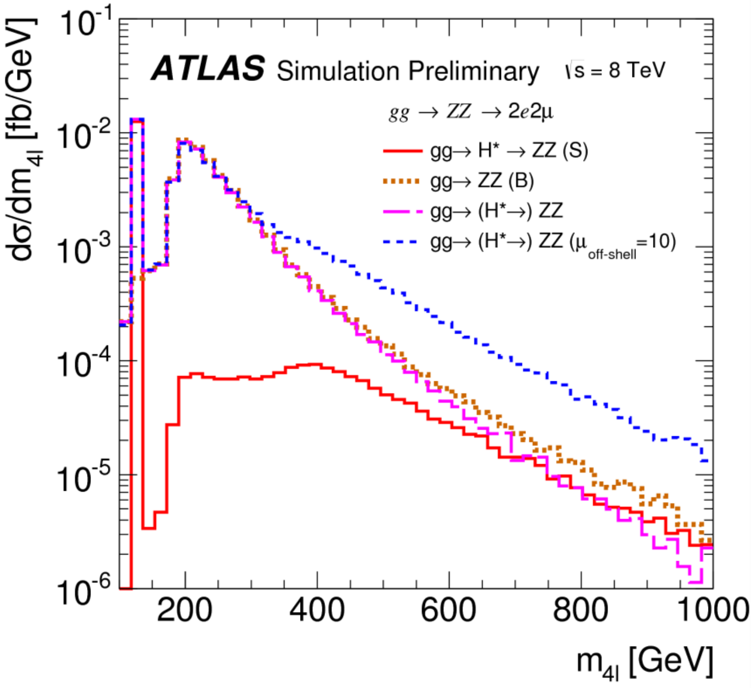
Now talking about MeV instead of GeV!

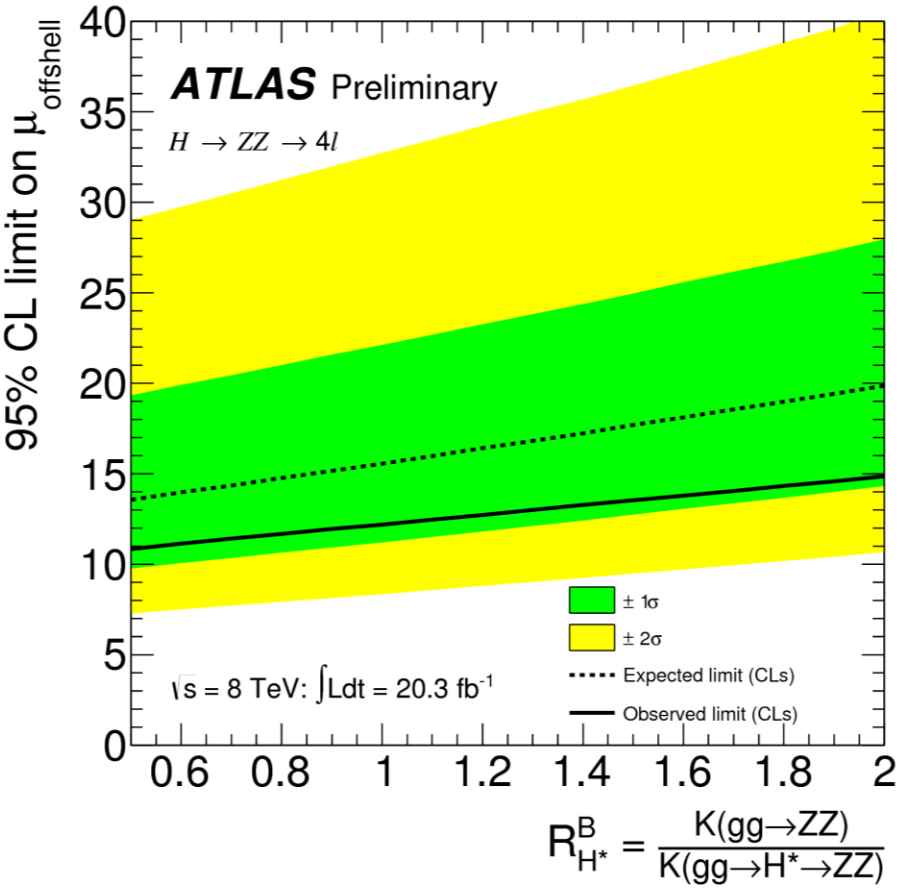
Limits on Off-shell Higgs Production

Effective Higgs couplings could vary with mass (e.g., due to New Physics)

$$\mu_{OffShell} \equiv \frac{\sigma_{OffShell}^{gg\to H^*\to ZZ}}{(\sigma_{OffShell}^{gg\to H^*\to ZZ})_{SM}} = (\kappa_g^2 \kappa_V^2)_{OffShell}$$

ATLAS-CONF-2014-042





Observed (expected) 95% C.L. limits: $\mu < 6.7\ (7.9)$

Production: differential distributions

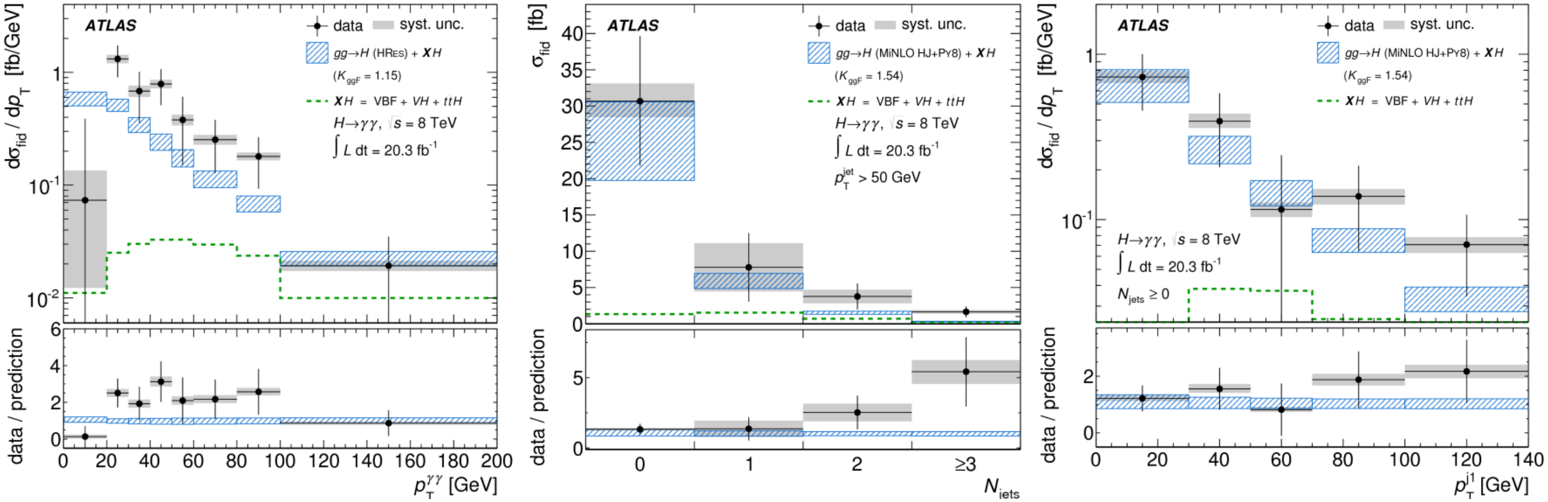
Starting to get enough events to measure differential cross sections

→ important check of theory calculations

h → γγ

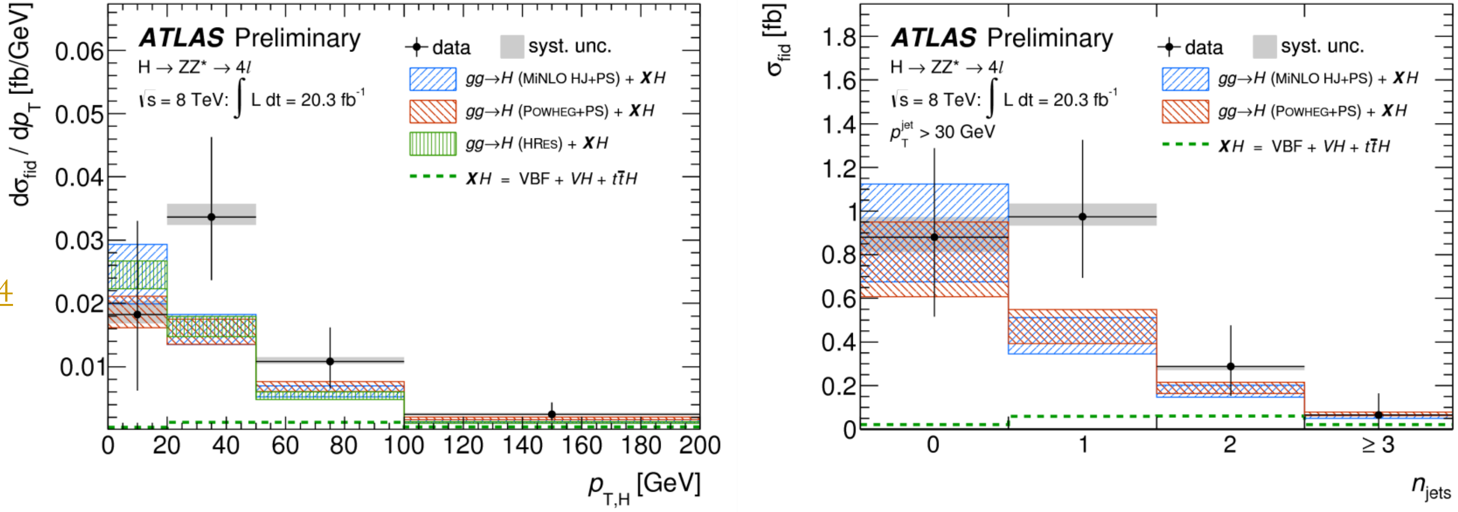
arXiv:1407.4222

(submitted to JHEP)



h → 4l

ATLAS-CONF-2014-044



h(125) as a Scout for New Physics

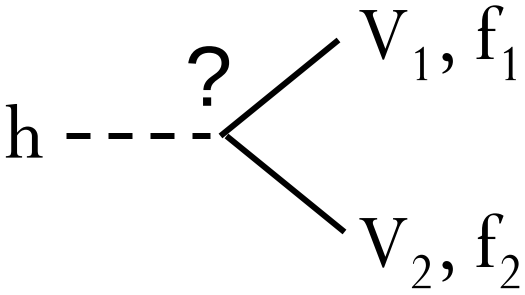
Theoretical Perspective

- The SM is not complete, there are specific questions to answer. Some examples:
  - Higgs mass: is our universe ‘fine-tuned’?
  - Why is the EWK scale so far from the GUT scale?
  - What is the nature of dark matter?
- An extended Higgs sector could help in answering some of these questions
  - Models with additional Higgs bosons:
    - MSSM: H, h, A, H^+, H^-
    - NMSSM: add a singlet
- Can the Higgs help us find dark matter?

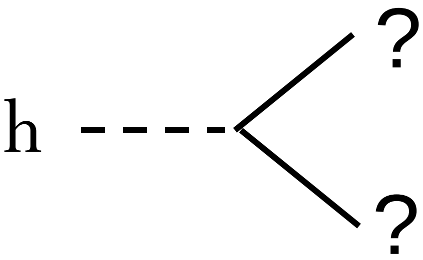
ATLAS and CMS are searching for all of these

Experimental Perspective

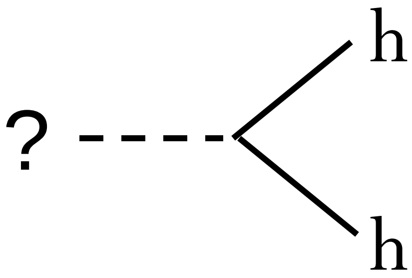
We have a new particle, h(125), use it as a ‘scout’ to search for other particles and/or new interactions



Anomalous couplings (J^P, production, LFV)



Exotic (invisible) decays, e.g. dark matter



Heavy resonances (Higgs, SUSY, Exotica) decaying to the observed Higgs boson

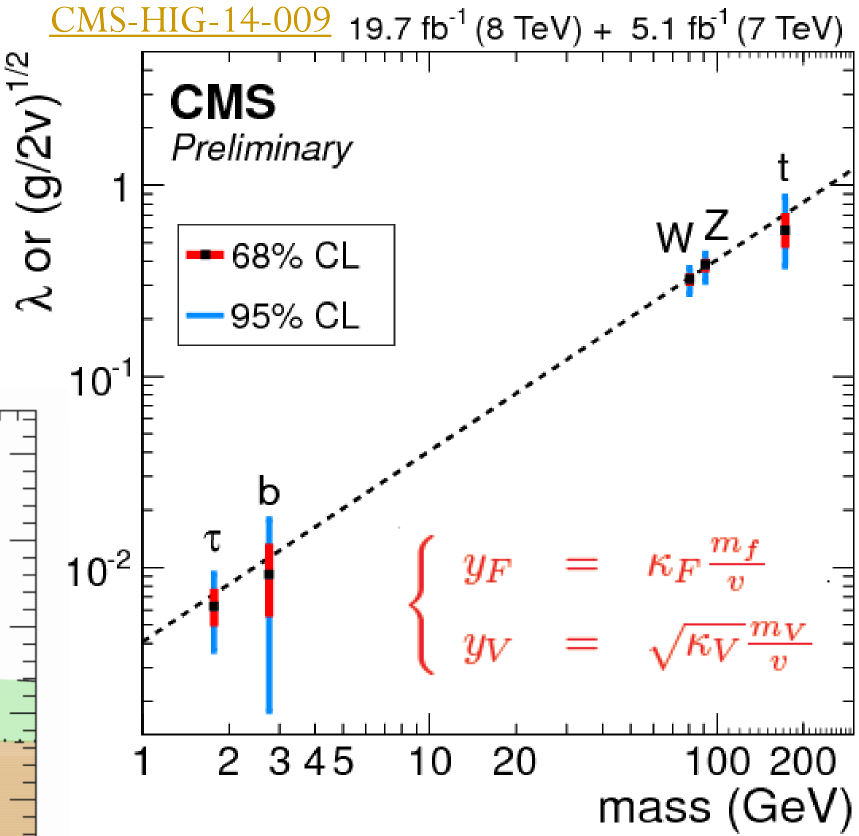
Any other Higgs bosons (e.g., MSSM)?

Looking for Deviations in Couplings (I)

$$\sigma(XX \to H) \times BR(H \to YY) \approx \frac{g_x^2 g_y^2}{\Gamma_{tot}}$$

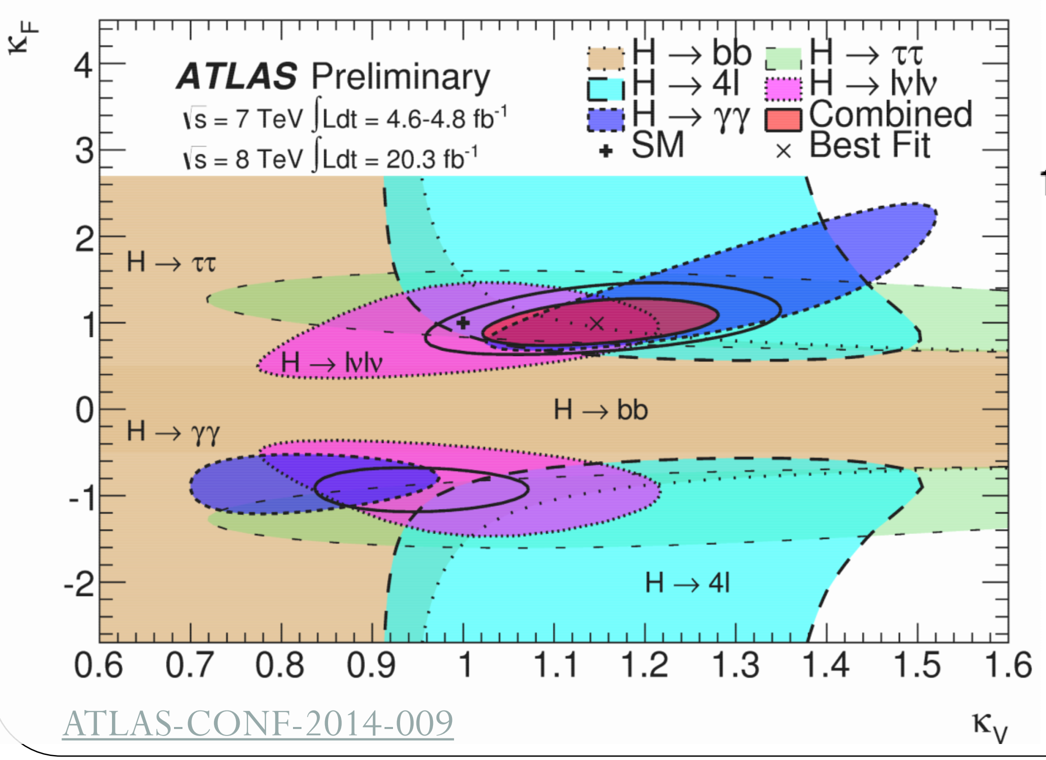
Look for deviations from SM ("the kappas"):

$$\kappa_x = \frac{g_X}{g_X^{\mathrm{SM}}}$$



$$\begin{cases} y_F = \kappa_F \frac{m_f}{v} \\ y_V = \sqrt{\kappa_V} \frac{m_V}{v} \end{cases}$$

CMS-HIG-14-009



ATLAS-CONF-2014-009

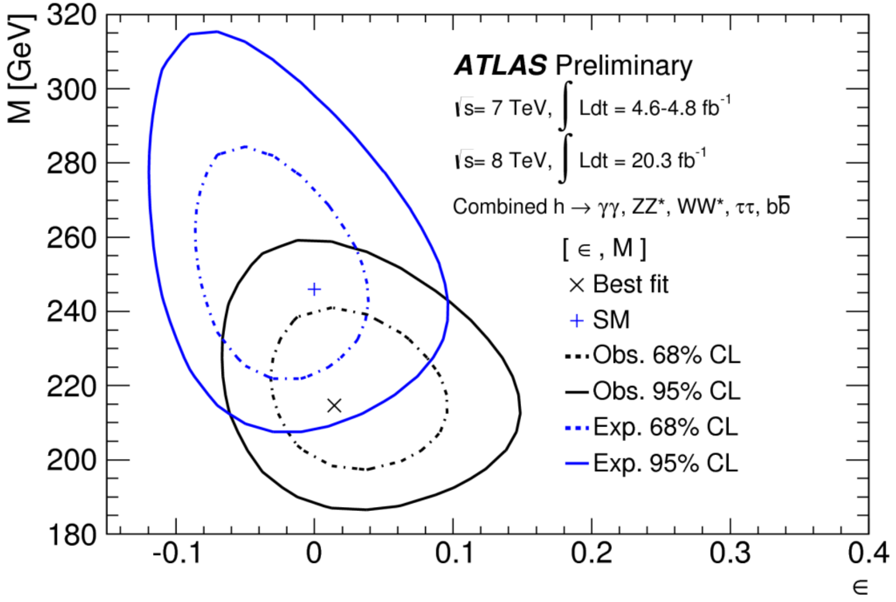
So far, all measured couplings are consistent with SM (κ = 1)

Looking for Deviations in Couplings (II)

Further testing mass scaling of couplings to fermions and bosons:

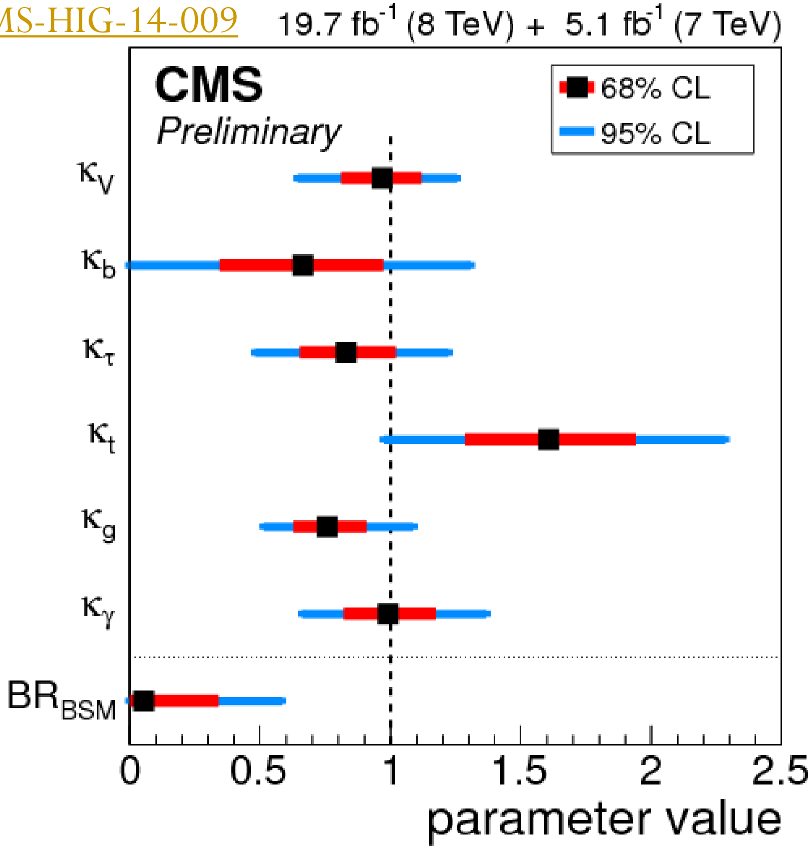
$$\kappa_{f,i} = v\frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}}$$

$$\kappa_{V,j} = v\frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$



ATLAS-CONF-2014-010

CMS-HIG-14-009



Testing generic model with effective loop couplings (κ_g , κ_γ), ttH from direct searches

Probing the Scalar Nature of h → VV

- Methodology used to determine pseudoscalar nature of π^0
- a_i terms can be complex
- Parameterize as cross section fractions f_{a1}, f_{a2}, f_{a3}, $f_{\Lambda 1}$

$$
\begin{aligned}
A(X_{J=0}\to V_1V_2) \sim\ & v^{-1}\Bigg(\Bigg[\overset{\text{tree-level SM h}\to\text{ZZ}}{a_1} - e^{i\phi_{\Lambda_1}}\frac{q^2_{Z_1}+q^2_{Z_2}}{(\Lambda_1)^2}\Bigg] m_Z^2\epsilon^*_{Z_1}\epsilon^*_{Z_2}\\
\text{ZZ,WW}\longrightarrow\ & + a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu}\tilde{f}^{*(Z_2),\mu\nu}\\
\text{Z}\gamma \longrightarrow\ & + a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu}\tilde{f}^{*(\gamma),\mu\nu}\\
\gamma\gamma \longrightarrow\ & + \underbrace{a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu}}_{\text{CP even}} + \underbrace{a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu}\tilde{f}^{*(\gamma_2),\mu\nu}}_{\text{CP odd}}\Bigg)
\end{aligned}
$$

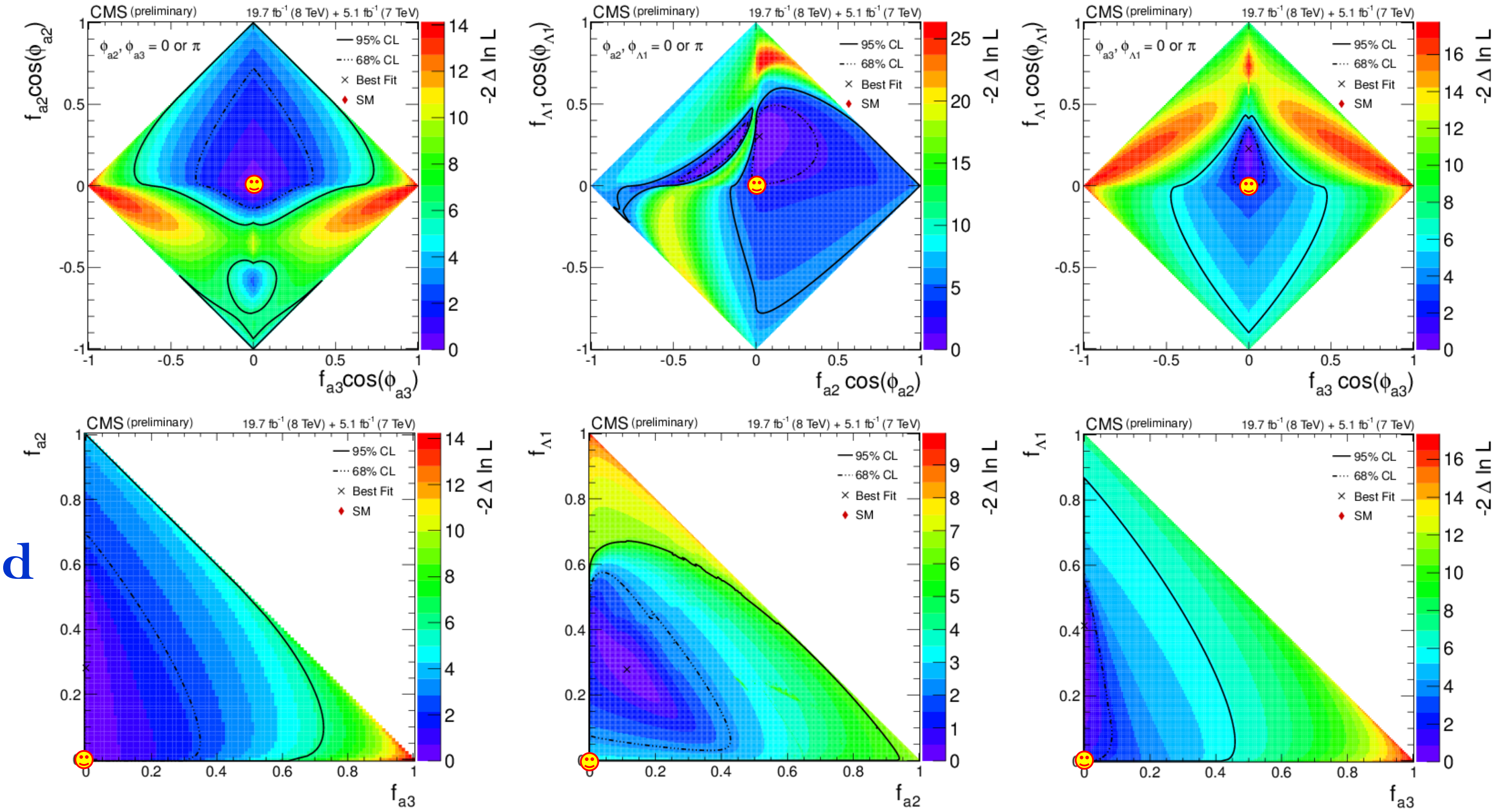
Results on Anomalous h → VV couplings

CMS-HIG-14-014

f_{a2} vs. f_{a3} **$f_{\Lambda1}$ vs. f_{a2}** **$f_{\Lambda1}$ vs. f_{a3}**

a_i's real

Phases profiled



Several analyses considered, including full 8 D fit, and simpler 2/3D fits

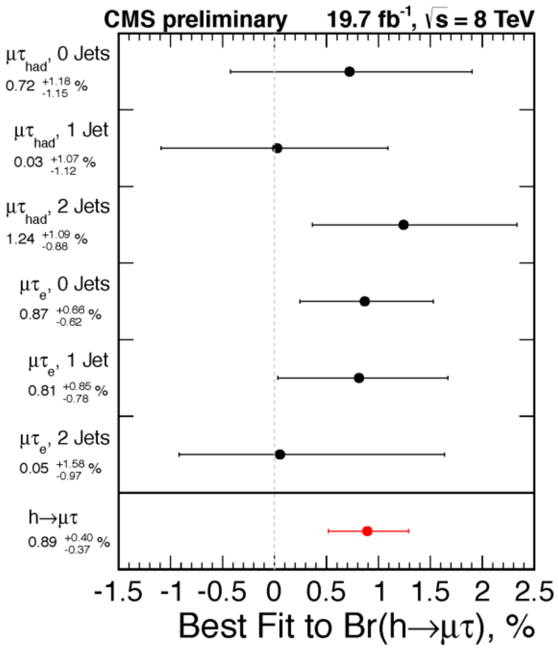
All results are consistent with SM expectations (denoted by 🙂)

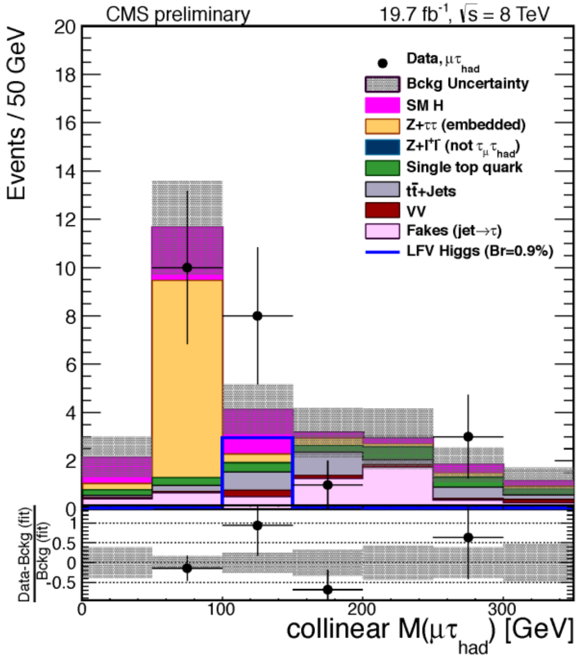
LFV Couplings: search for h → τμ

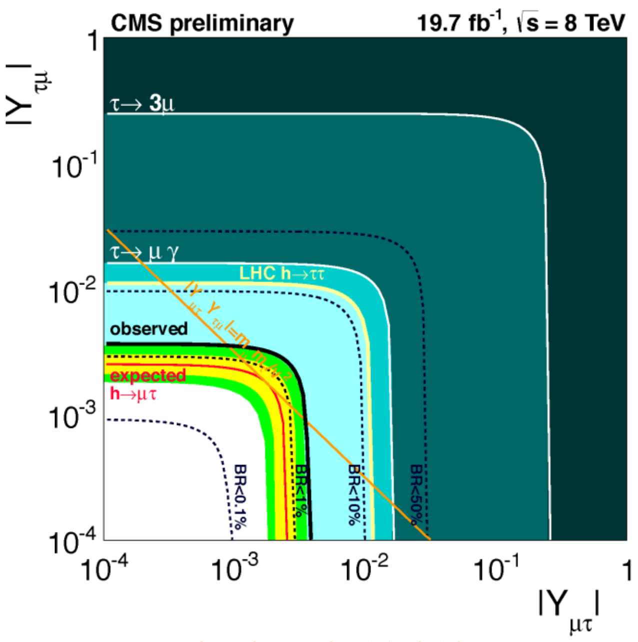
Lepton flavor violation in the t sector not as strongly constrained as μ/e

Use h(125) to search for LFV couplings in h → τμ

CMS results: $B(h \rightarrow \tau\mu) = (0.89^{+0.40}_{-0.37})\%, < 1.57\%$ @ 95% C.L.







CMS-HIG-14-0105

Directly Constraining BR(h → invisible)

Looking for h → missing energy:

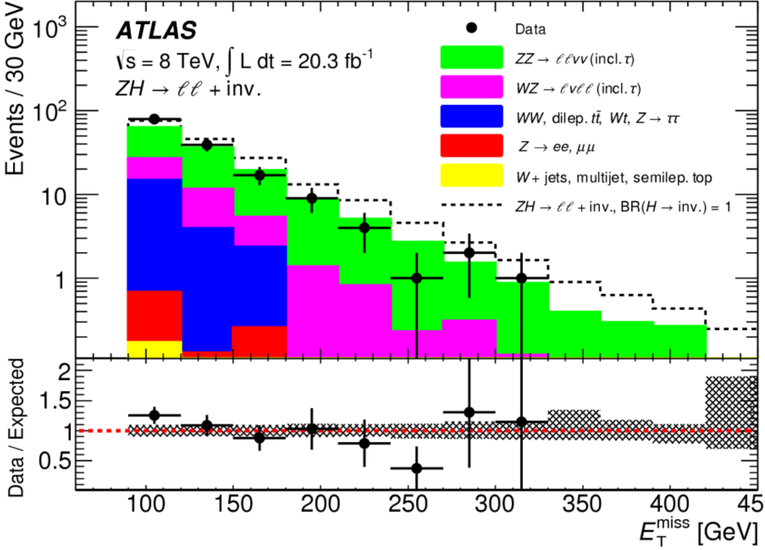
ATLAS search in Z(ll)h, h → inv

CMS search in Z(ll)h, Z(bb)h, VBF h → inv

ATLAS: BR(inv) < 0.75 (0.62) @ 95% C.L.

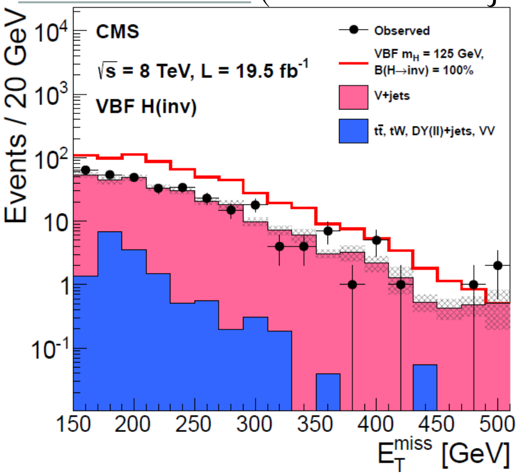
CMS: BR(inv) < 0.58 (0.44) @ 95% C.L.

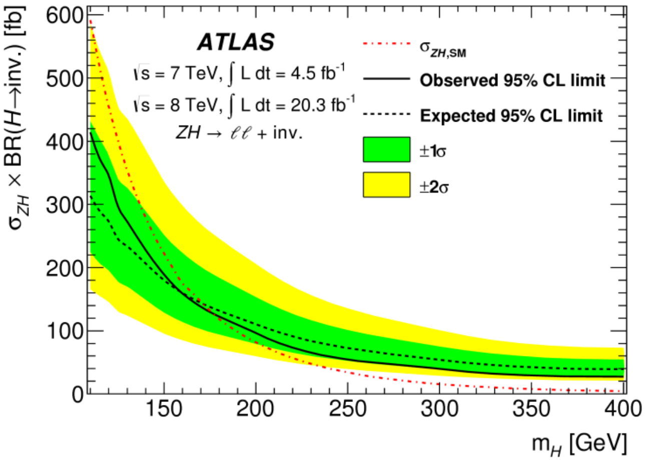
Phys. Rev. Lett. 112, 201802 (2014)

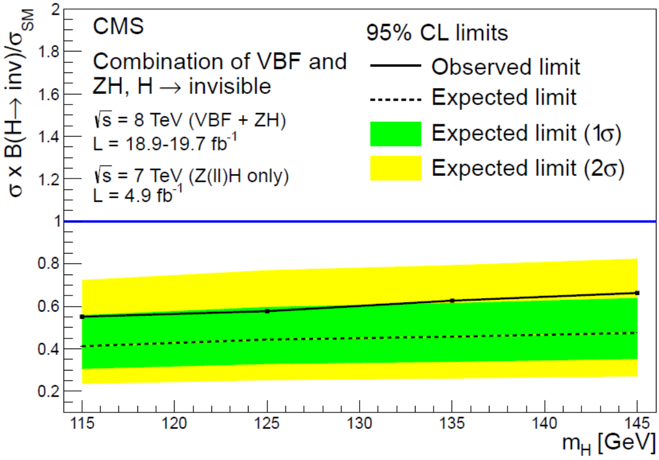


See also arXiv:1408.0011

arXiv:1404.1344 (submitted to EPJC)



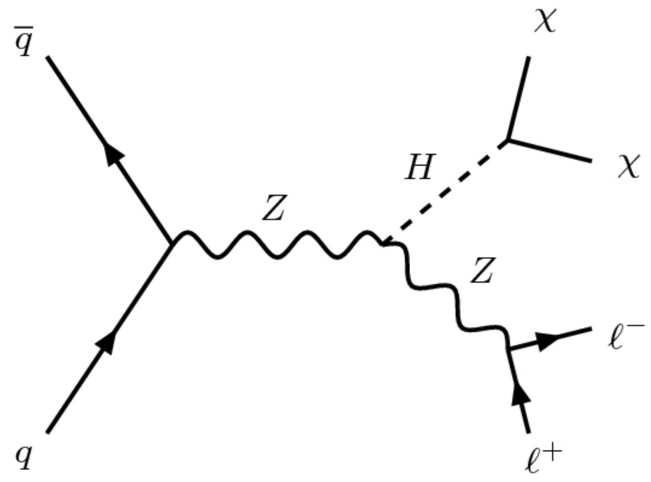




Constraints on Dark Matter

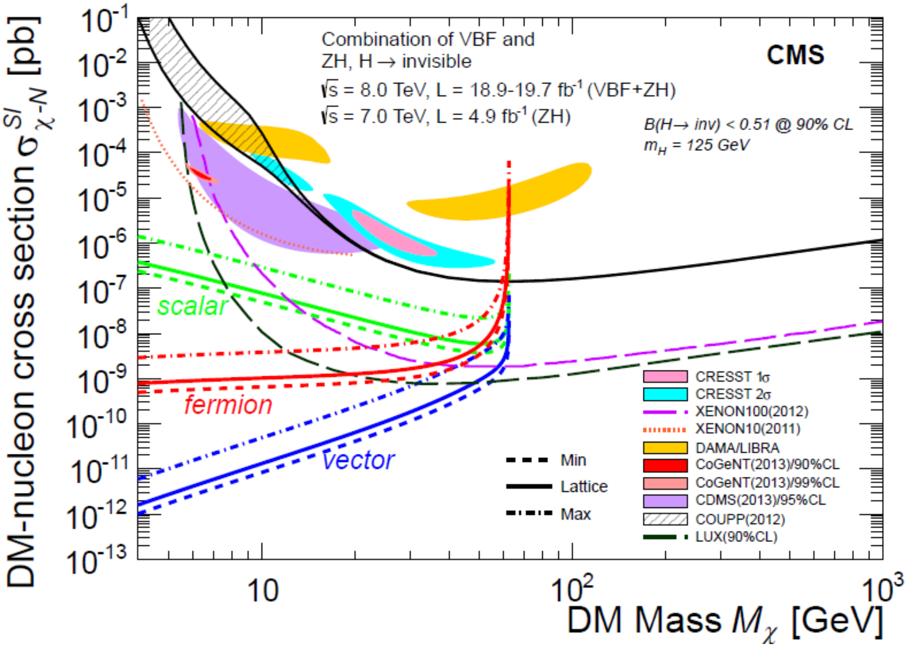
"Higgs portal" models, WIMPS couple weakly to SM particles except for the Higgs boson

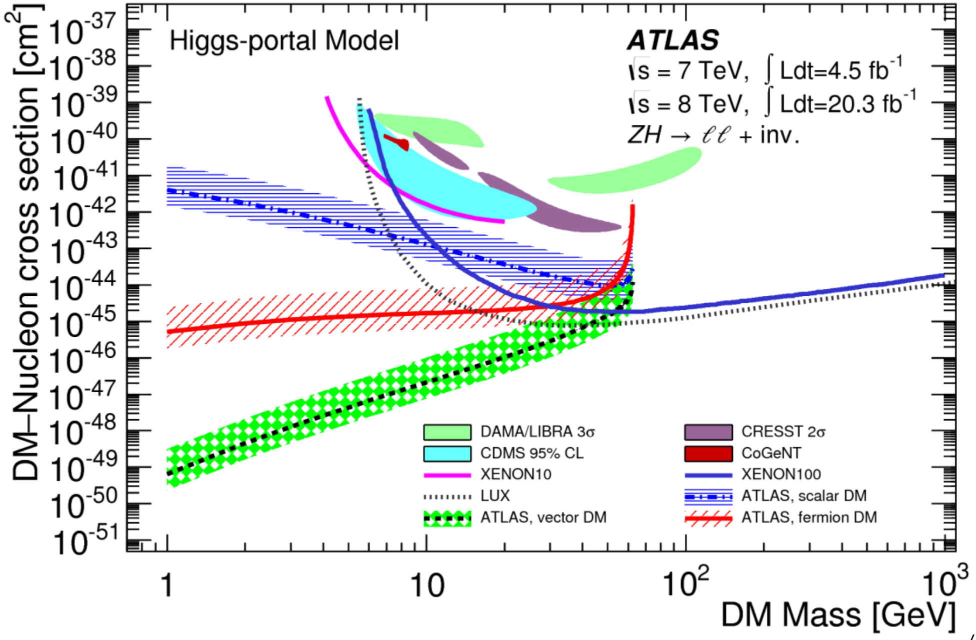
Constraints on DM-nucleon cross sections for different DM spin and mass hypotheses



arXiv:1404.1344 (submitted to EPJC)

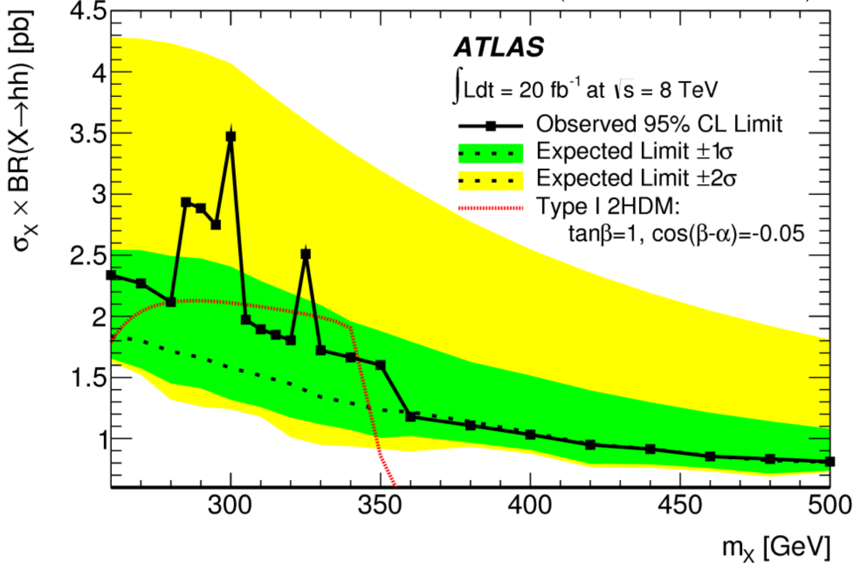
Phys. Rev. Lett. 112, 201802 (2014)



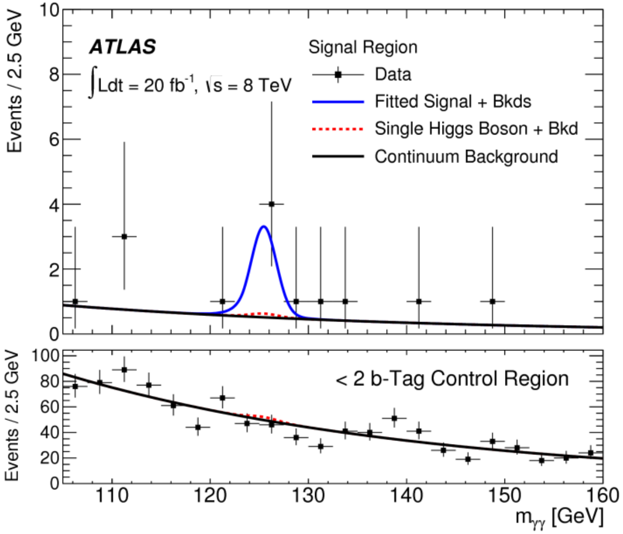


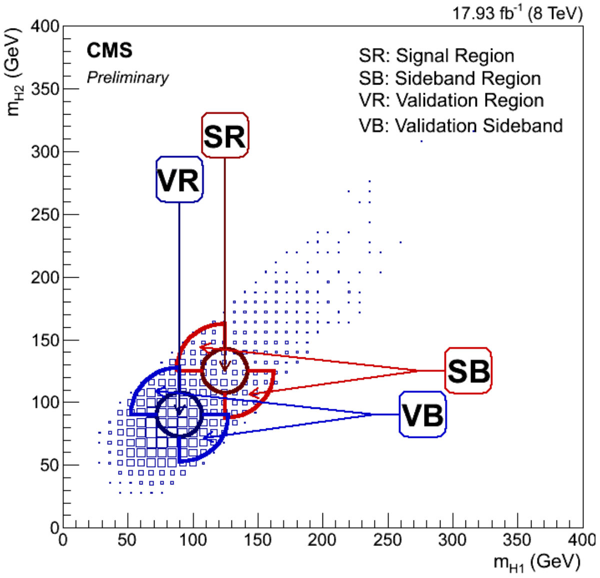
Di-Higgs Resonances: X → hh → γγbb, 4b

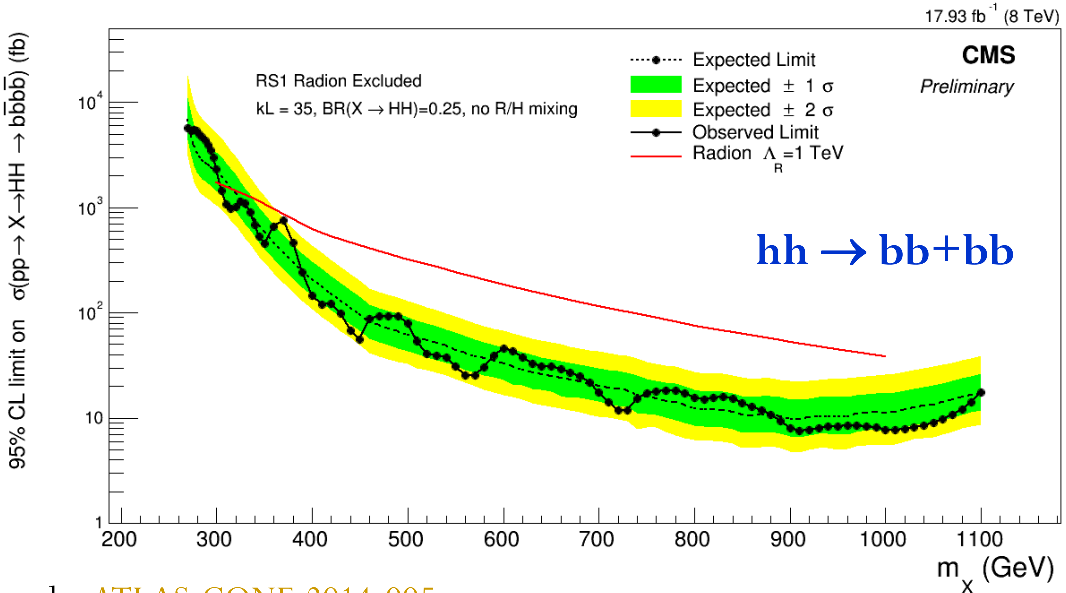
hh → γγ+bb arXiv:1406.5053 (submitted to PRL)



See also CMS-HIG-13-032







hh → bb+bb

See also ATLAS-CONF-2014-005

Any other Higgs bosons? MSSM Search

Two Higgs doublets:

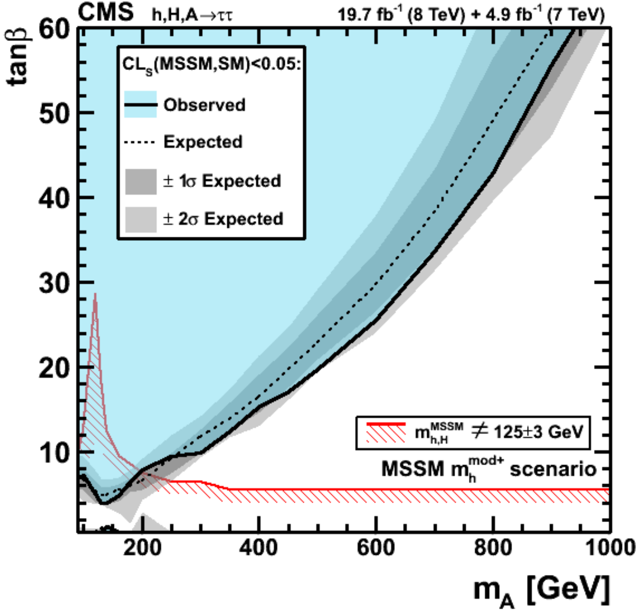
$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

2 scalars:	h, H
1 pseudo-scalar:	A
2 charged Higgs bosons:	H^+, H^-

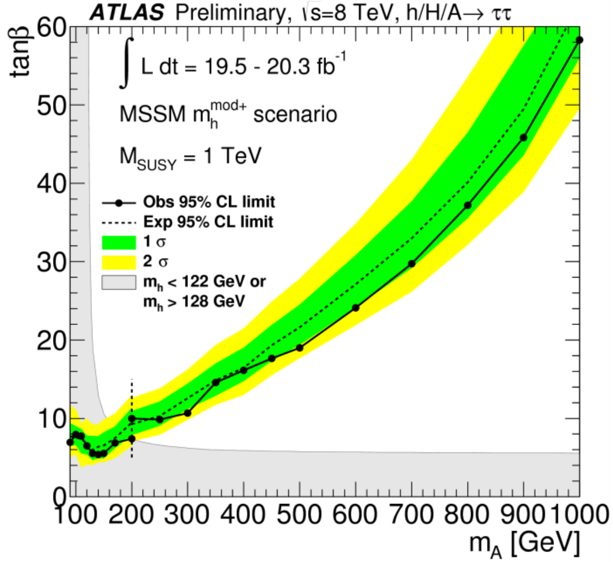
Two different vev's for up- and down-type fermions, tanβ is the ratio of vev's

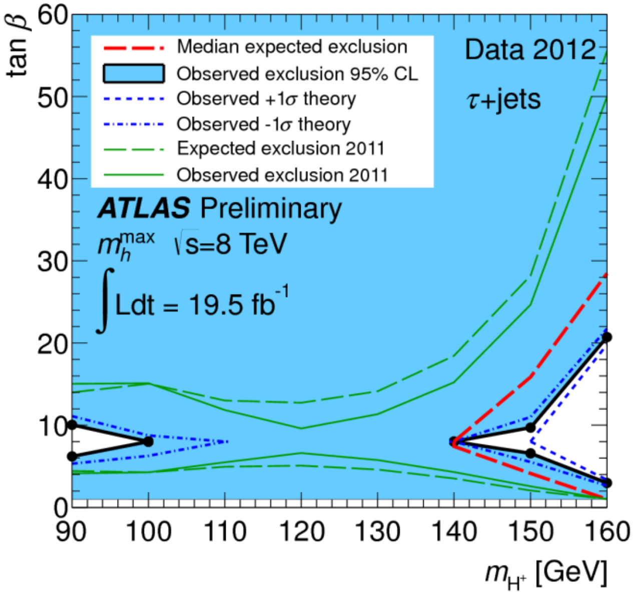
Exclusion limits in plane of tanβ vs. mass

CMS-HIG-13-021 (to be submitted)

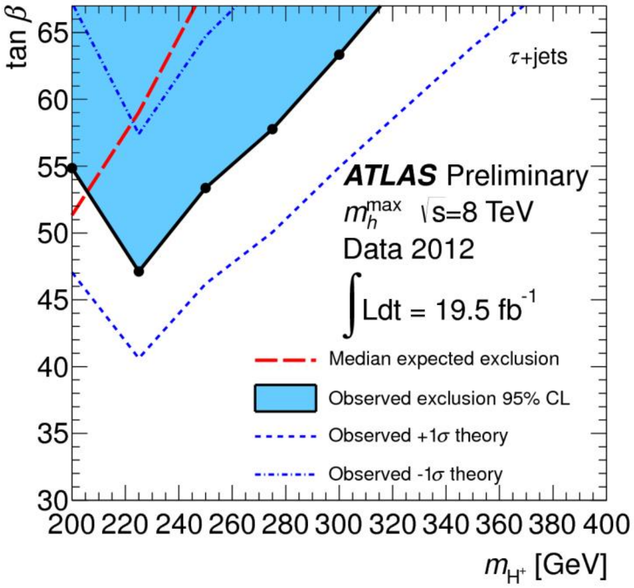


ATLAS-CONF-2014-049





ATLAS-CONF-2013-090



Summary

- The new particle @ 125 GeV looks like the SM Higgs boson
  - Consistent mass between CMS and ATLAS (only one particle)
  - Solid 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
  - Γ_H consistent with narrow SM prediction
- No signs of any other particle:
  - No other SM-like Higgs bosons found
  - No other BSM Higgs bosons found
  - No sign of anomalous couplings of h(125)

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

Further study of h(125) and search for BSM Higgses in Run 2

LHC Schedule: 2015 – 2035

Run 2: 13 TeV and 10x more data

→ Extend searches, Higgs physics becomes precision physics