The Higgs boson at the LHC: state of the art

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on behalf of the CMS & ATLAS collaborations

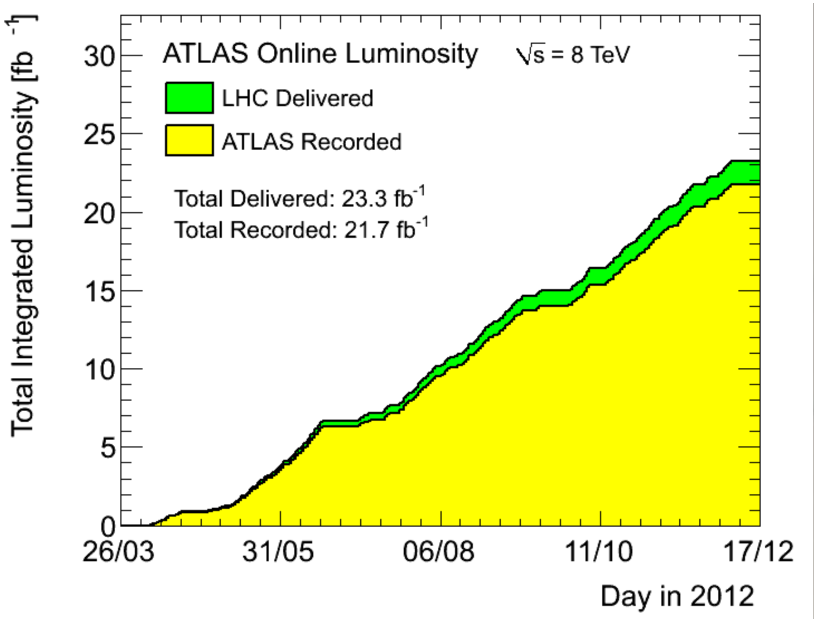
Breakthrough of the year in 2012

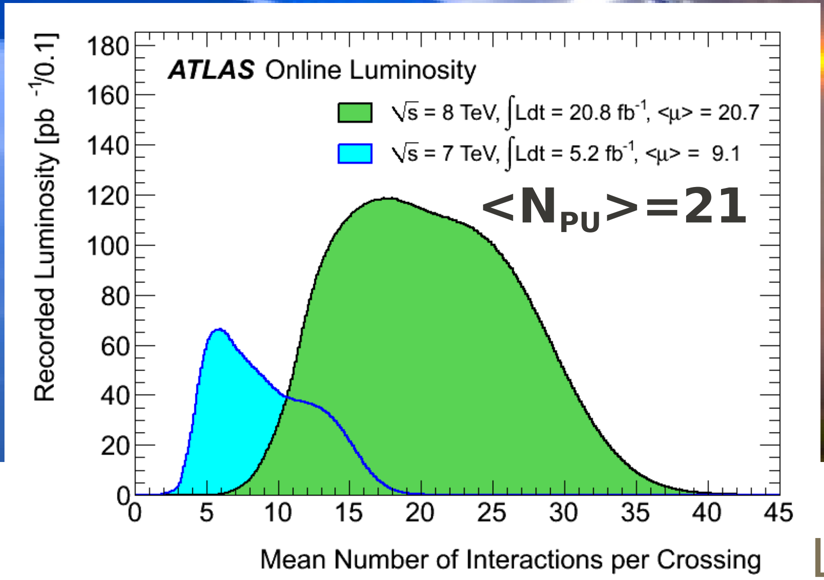
- The Higgs boson or Standard Model scalar:
    - Discovered on July, 4th 2012, in the news world-wide!
    - Predicted almost 50 years ago to explain electroweak symmetry breaking through the Brout-Englert-Higgs mechanism
    - One of the main physics goals of the LHC and the ATLAS and CMS collaborations
    - All measurements indicate that the discovered particle looks very much as the Standard Model Higgs boson
    - EPS Prize 2013 awarded to the ATLAS and CMS collaborations

The Higgs boson factory and hunters

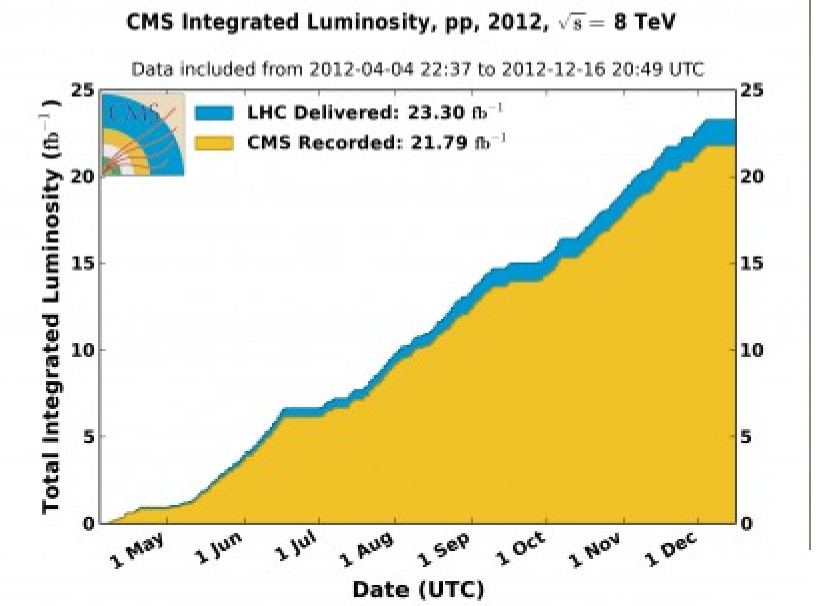
Outstanding performance of the Large Hadron Collider and of the detectors

~ 95% of data recorded!!!
~ 90% certified and used in publications





$<N_{PU}>=21$



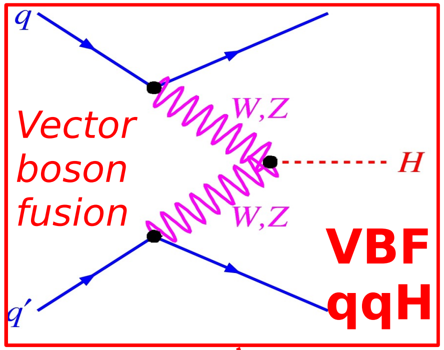
LHC reached the nominal pileup rate!

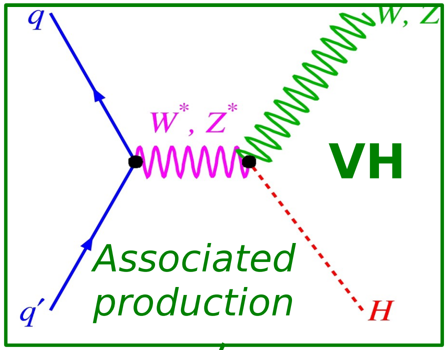
Higgs boson production

Total cross section (m_H = 125 GeV):

$\sigma(pp \rightarrow H) \approx 22$ pb

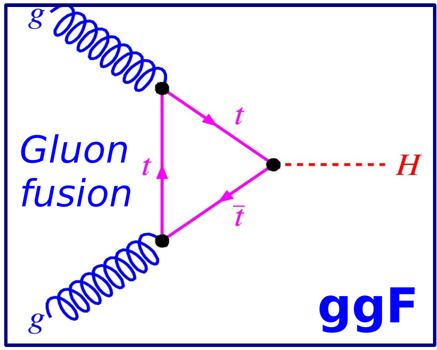
Vector boson mediated

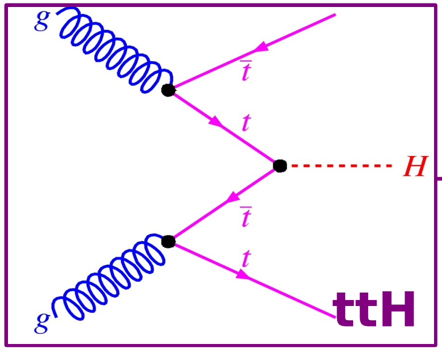


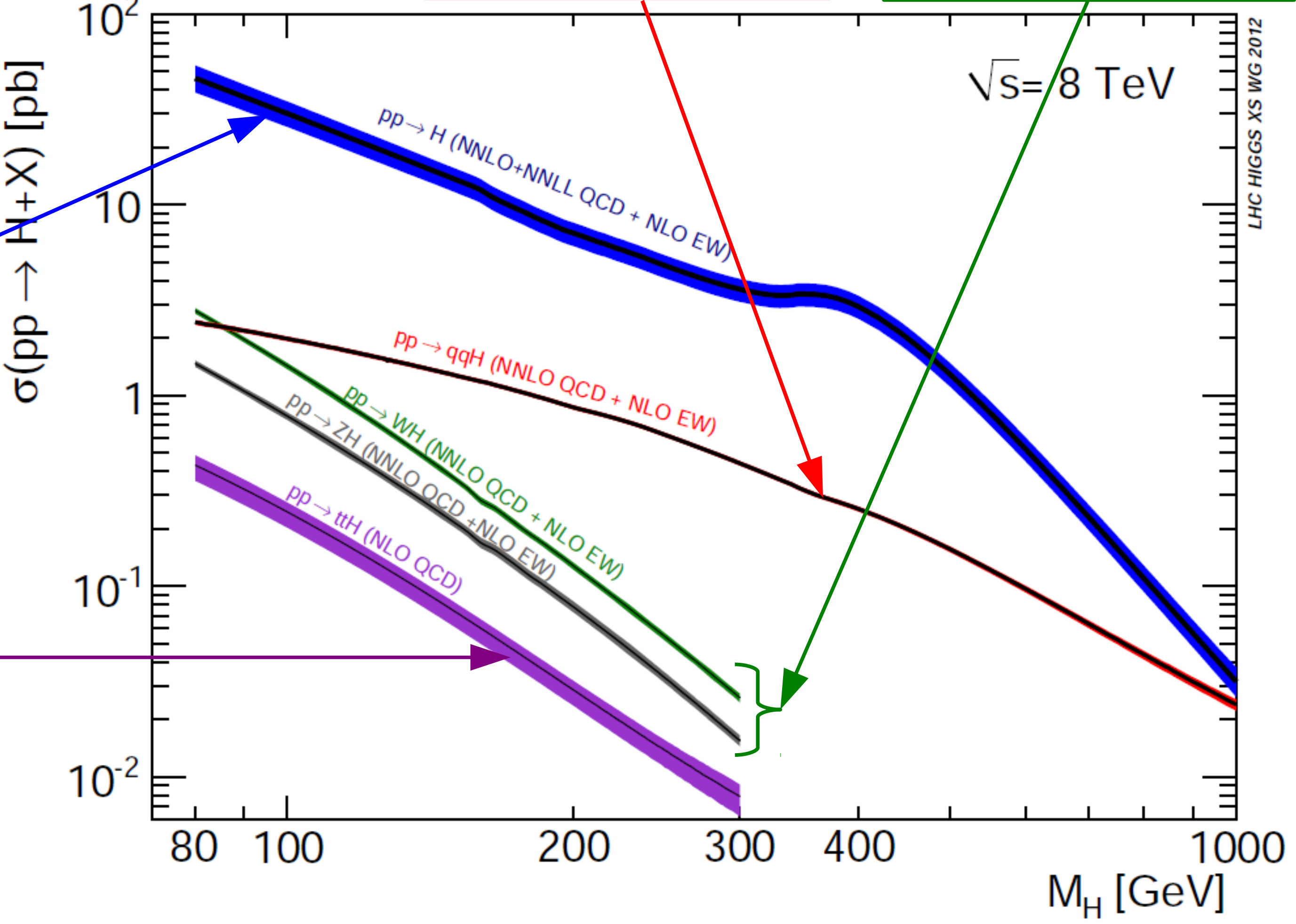


Fermion mediated

(top quark mediated)







Higgs boson decay modes

Favorites:

H → bb ~ 57%

H → WW ~ 22%

H → ττ ~ 6.2%

H → ZZ ~ 2.8%

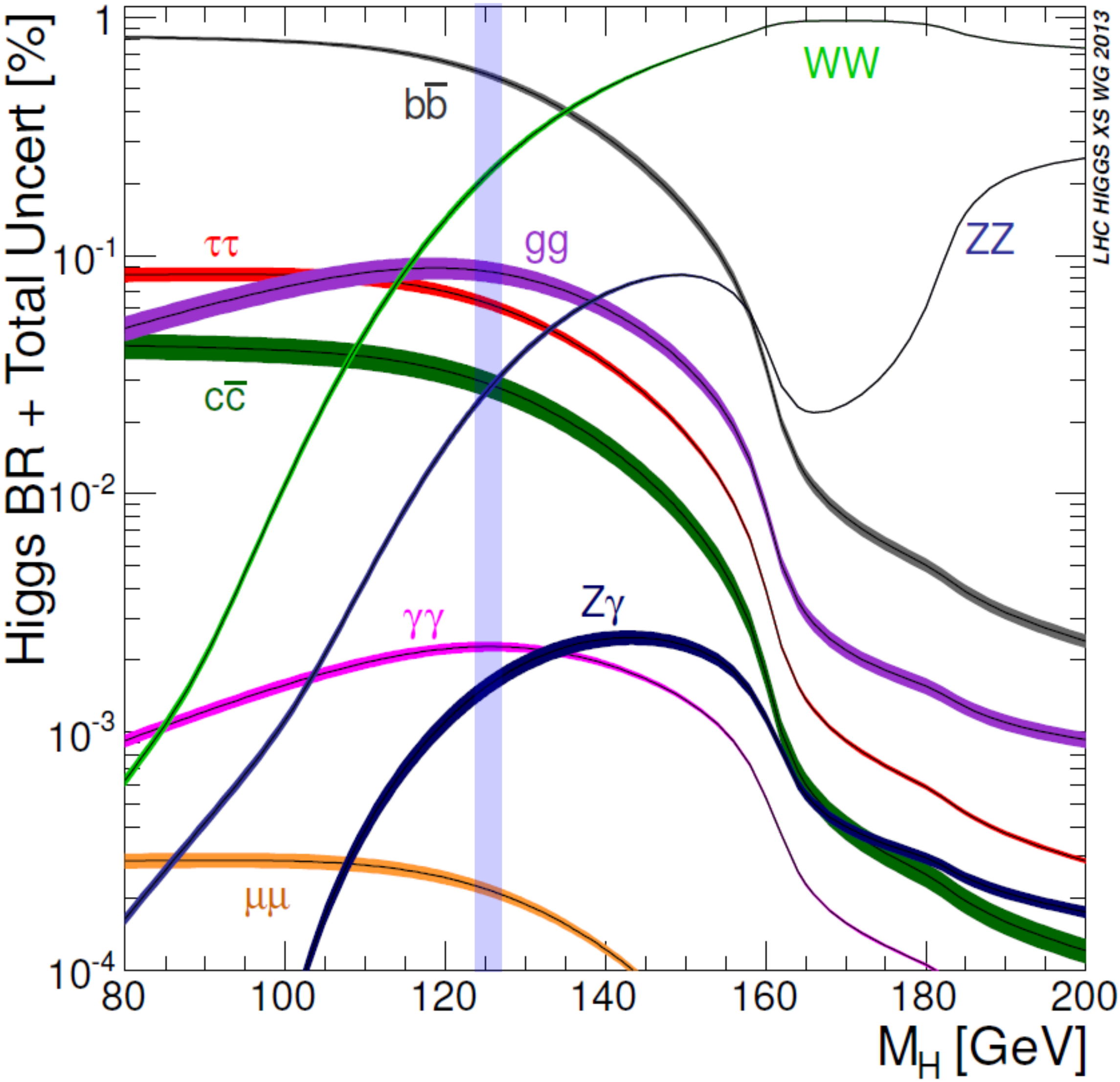
H → γγ ~ 0.2%

Very rare:

H → Zγ & H → μμ

'Challenging':

H → cc & H → gg



cleaner signal

&

better mass

resolution

(if no ν)

4 production channels, 5 main decay modes + W, Z, τ and t decay too
→ numerous results from ATLAS & CMS, only few highlighted

References

CMS Higgs public results

- $H \to \gamma\gamma$: CMS-PAS-HIG-13-016, CMS-PAS-HIG-13-001
- $H \to ZZ$: CMS-PAS-HIG-13-002
- $H \to WW$: CMS-PAS-HIG-13-003, CMS-PAS-HIG-13-022, CMS-PAS-HIG-13-009, CMS-PAS-HIG-13-017
- $H \to bb$: CMS-PAS-HIG-13-011, CMS-PAS-HIG-13-012
- $H \to \tau\tau$: CMS-PAS-HIG-13-004, CMS-PAS-HIG-12-053
- Combined, couplings, properties: CMS-PAS-HIG-13-005 + twiki
- ttH: CMS-PAS-HIG-13-015, CMS-PAS-HIG-13-019
- $H \to Z\gamma$: CMS-PAS-HIG-13-006
- H → invisible: CMS-PAS-HIG-13-013, CMS-PAS-HIG-13-018
- … and many more!

ATLAS Higgs public results

- $H \to \gamma\gamma$: ATLAS-CONF-2013-072, ATLAS-CONF-2013-012, ATLAS-CONF-2013-029
- $H \to ZZ$: ATLAS-CONF-2013-013
- $H \to WW$: ATLAS-CONF-2013-075, ATLAS-CONF-2013-030,ATLAS-CONF-2013-031
- $H \to bb$: ATLAS-CONF-2013-079
- $H \to \tau\tau$: ATLAS-CONF-2012-160
- Combined, couplings, properties: arXiv:1307.1427, arXiv:1307.1432, ATLAS-CONF-2013-034
- ttH: ATLAS-CONF-2013-135, ATLAS-CONF-2013-080
- $H \to Z\gamma$: ATLAS-CONF-2013-009
- $H \to \mu\mu$: ATLAS-CONF-2013-010
- H → invisible: ATLAS-CONF-2013-011
- … and many more!

Cross sections and branching fractions from:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

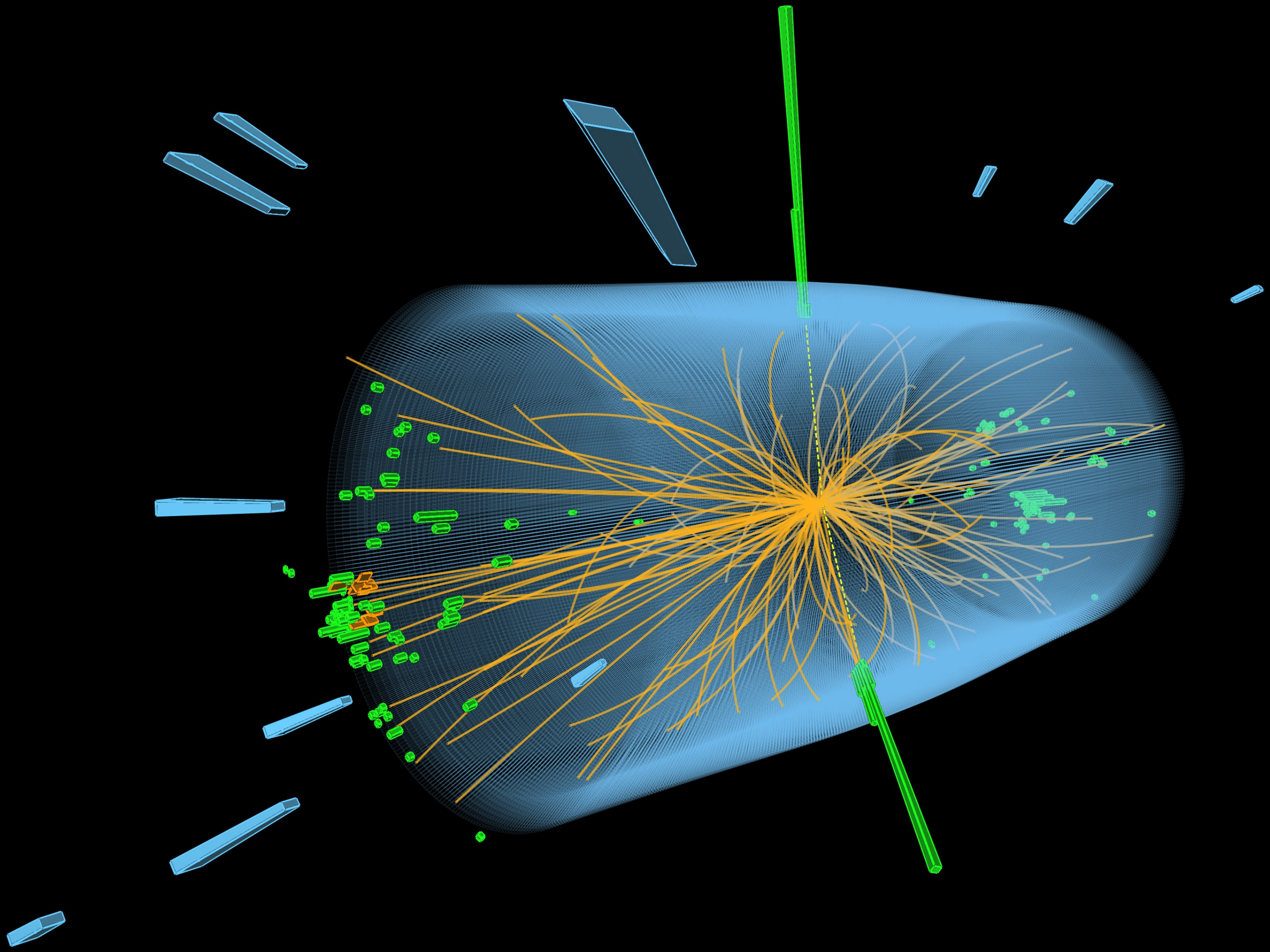
Preview

- Introduction

- Highlights from ATLAS and CMS:
  - H → bosons
  - H → fermions
  - Properties of the observed particle
  - Rare processes

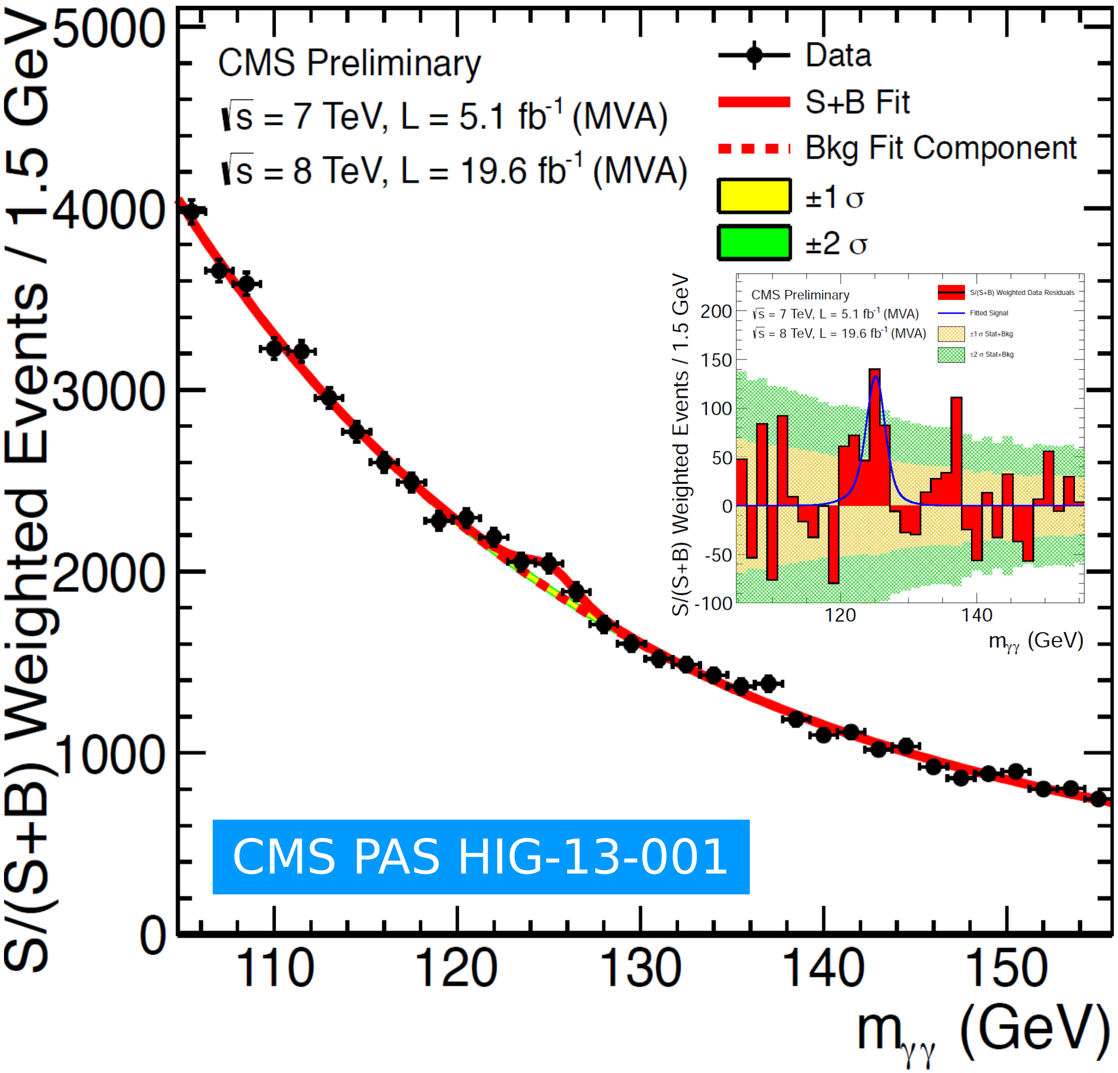
- Summary & conclusion

H → bosons



CMS H → γγ: fitting the $m_{\gamma\gamma}$ distribution

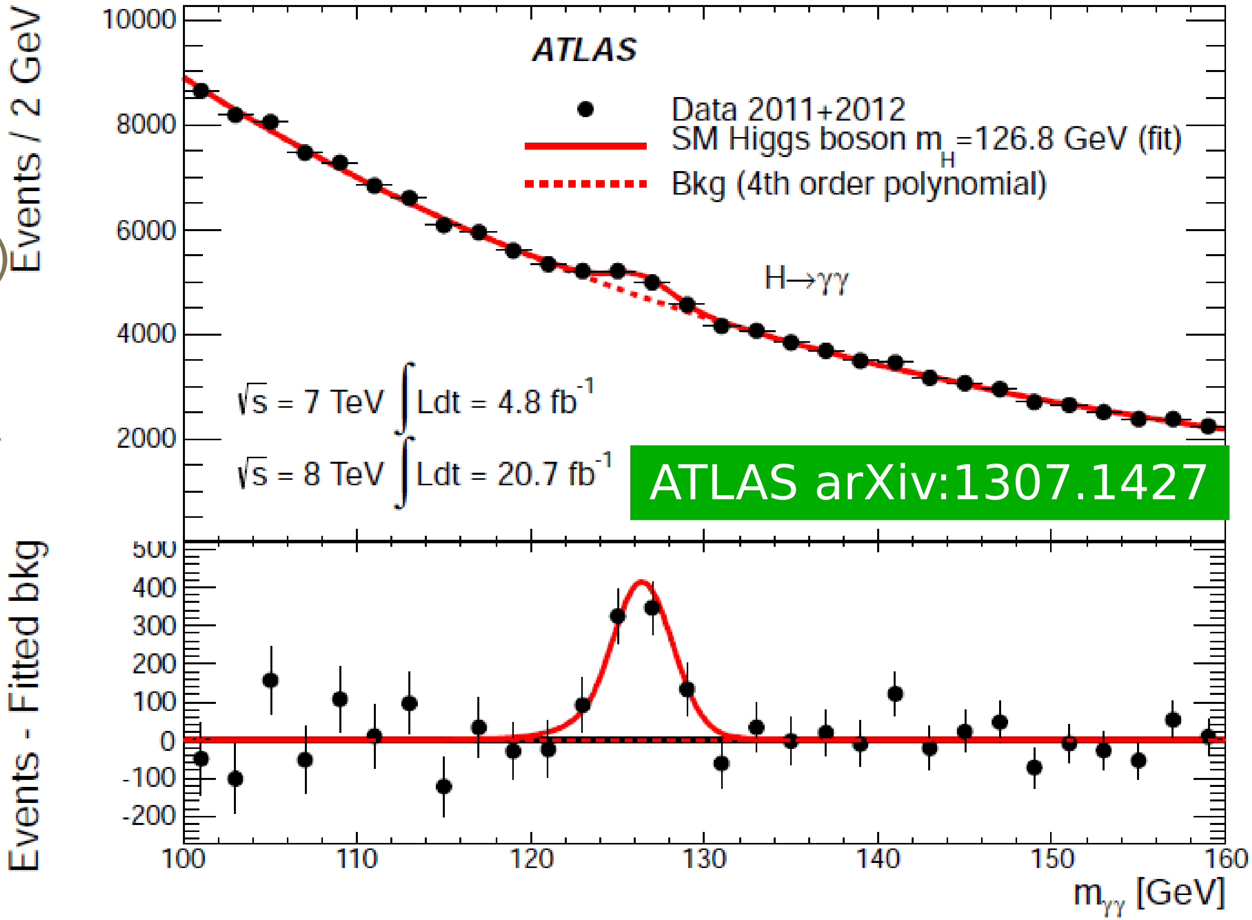
- Primary vertex selection: dedicated MVA technique
- Analysis in categories:
    - Lepton or ME_T tag (WH/ZH)
    - Dijet tag (VBF)
    - Untagged: 4 categories, based on MVA classifier
- Background fitted from data
    - Prompt γγ ~70%
    - Prompt γ + jet → fake γ
- Cross-check analysis: Cut-in-categories (CiC)



- **Significance:**
  MVA: 3.2σ (4.2σ expected)
  CiC: 3.9σ (3.5σ expected)
- **Signal strength:**
  $\mu = 0.78^{+0.28}_{-0.26}$ (m_H = 125 GeV)
- **Mass: m_H = 125.4 ± 0.8 GeV**

ATLAS H → γγ: clear observation

- Primary vertex selection: diphoton pointing
- Analysis in categories:
  - Lepton or dijet (low mass) or ME$_T$ tag (WH/ZH)
  - Dijet tag (VBF) using MVA
  - Untagged: 9 categories based on p_T,η,conversion
- Background estimated from data:
  - Prompt γγ: ~75%
  - γ+jet



ATLAS arXiv:1307.1427

- **Significance:** m_H= 126.5 GeV

  7.4σ (4.3σ expected)
- **Signal strength:**

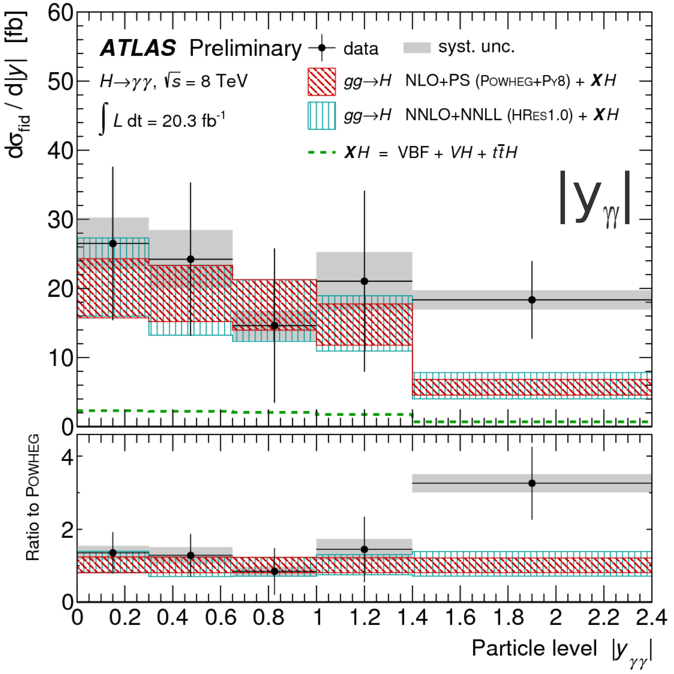
  $\mu = 1.65^{+0.34}_{-0.30}$
- **Mass: $m_H = 126.8 \pm 0.7 \pm 0.2$ GeV**

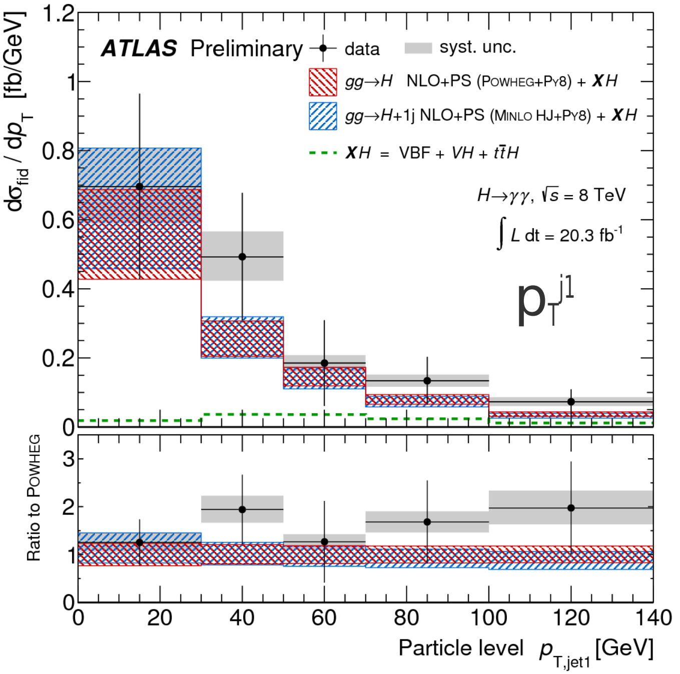
ATLAS H → γγ: differential distributions

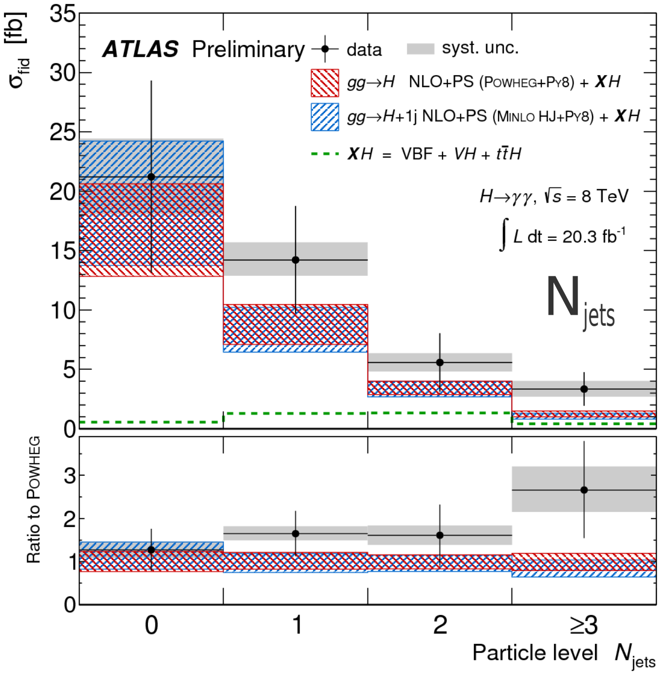
ATLAS-CONF-2013-072

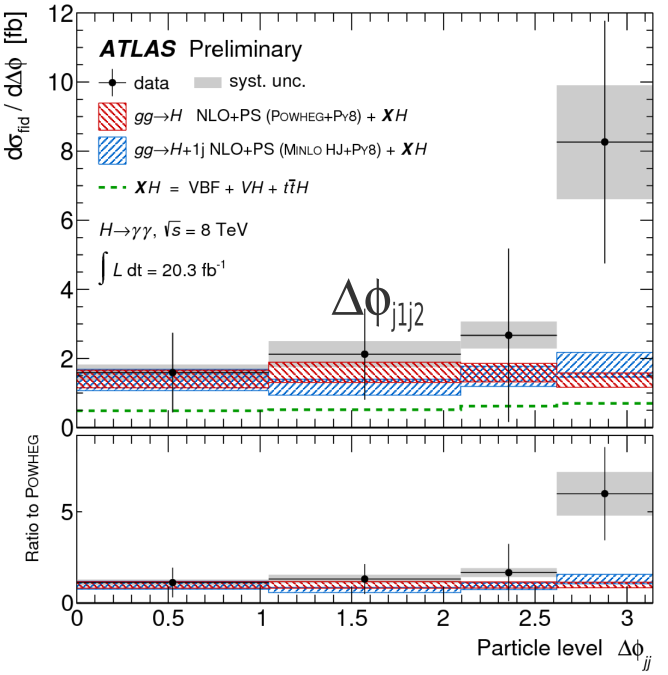
- Probe the spin and parity and test theoretical description of QCD
- Kinematic region:

  $|\eta|<2.37$, $E_T/m_{\gamma\gamma} > 0.35(0.25)$ for (sub)leading γ, 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
- 8 observables: $p_T^{\gamma\gamma}$, $|\cos\theta^*|$, $p_T^{\gamma\gamma jj}$, $\sigma_{N_{jets}=i}/\sigma_{N_{jets}\geq i}$
- No deviation from the standard model







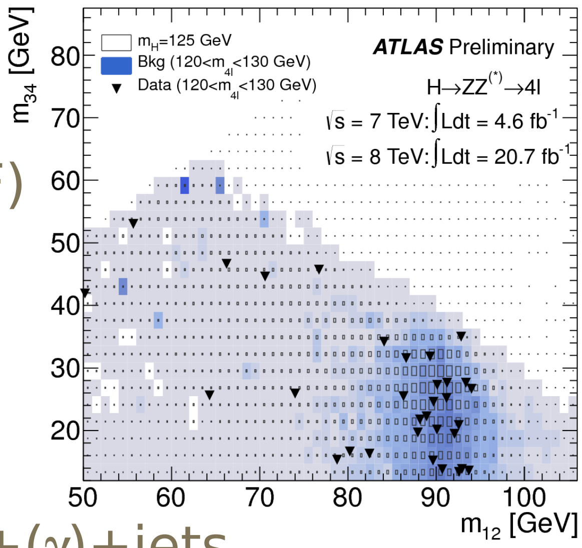


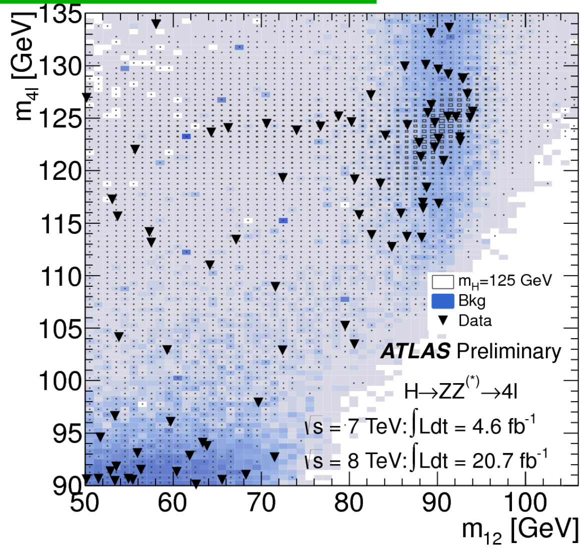
ATLAS $H \rightarrow ZZ^* \rightarrow 4l$: clear observation

ATLAS-CONF-2013-013

- $ZZ \rightarrow 4e$ or 4μ or $2e2\mu$
- Categories:
  - 2 well-separated jets (VBF)
  - additional lepton (VH)
  - untagged (ggH)
- Background contributions:

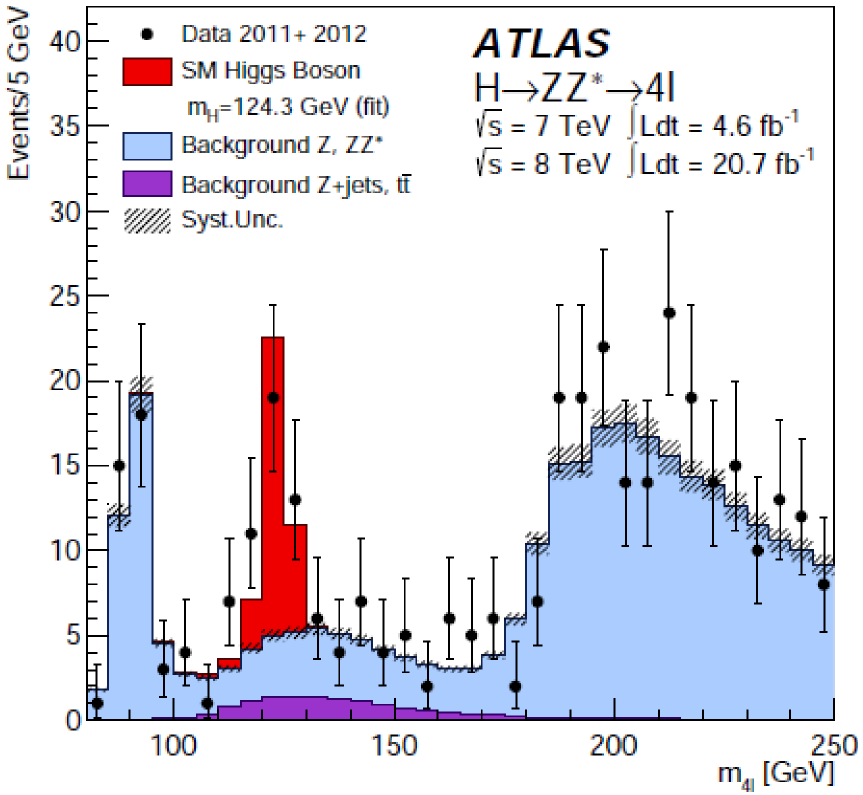
  direct ZZ ($Z\gamma^*$), Zbb, tt, (W)Z+(γ)+jets
- Recovery of final state radiation γ^*
- Shape analysis using the invariant mass of the 4 leptons: m_{4l}





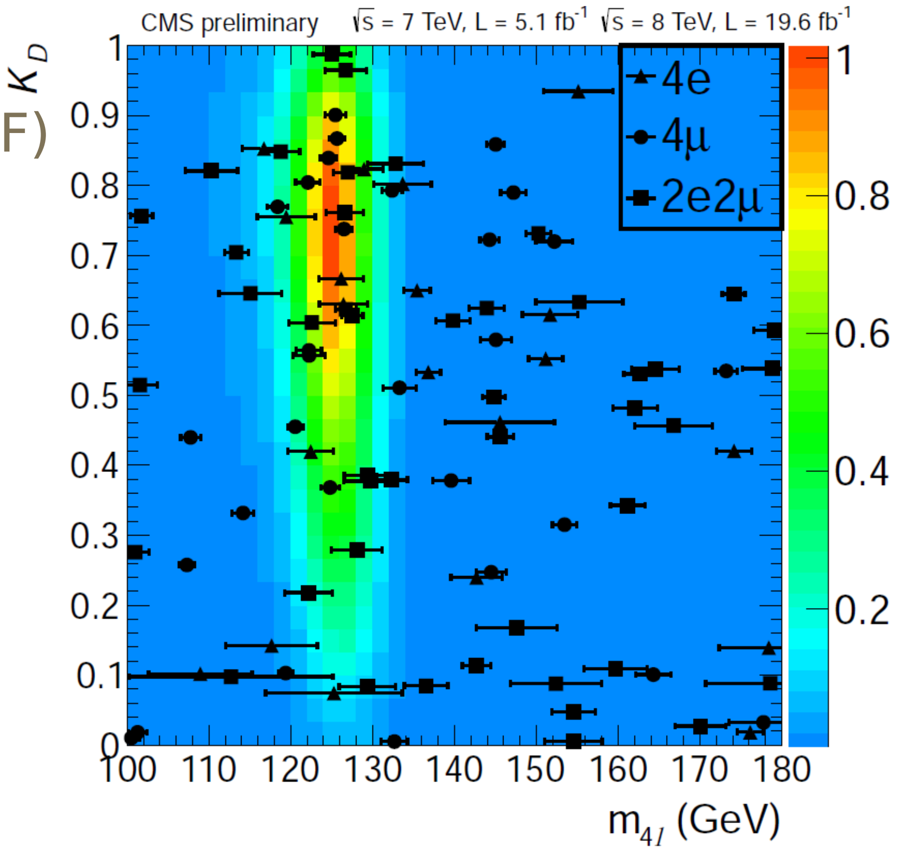
ATLAS arXiv:1307.1427

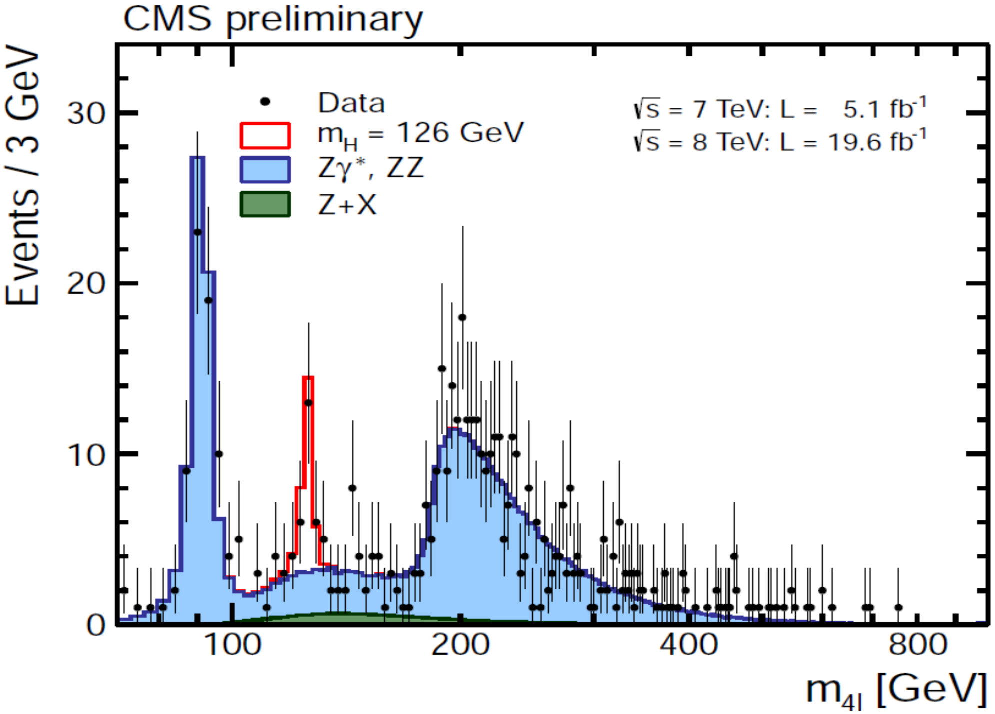
- **Significance: 6.6σ (4.4σ expected)**
- **Signal strength: $\mu = 1.7^{+0.5}_{-0.4}$**
- **Mass: $m_H = 124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV**



CMS $H \to ZZ^* \to 4l$: clear observation

- $ZZ \to 4e$ or 4μ or $2e2\mu$ or $2l2\tau$
- Categories: <2 jets (ggH) or ≥2 jets (VBF)
- 3 variables used in shape analysis:
  - Invariant mass: m_{4l}
  - V_D (VBF) or p_T^{4l}/m_{4l} (ggH)
  - $K_D = P_{sig}/(P_{sig}+P_{bkg})$ matrix element likelihood (MELA)





Significance: 6.7σ (7.1σ expected)

Signal strength: $\mu = 0.91^{+0.30}_{-0.24}$

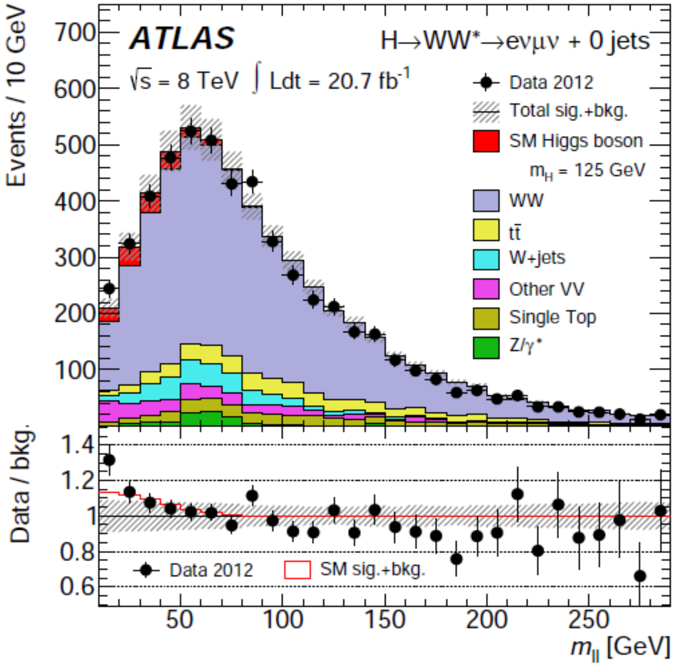
Mass: $m_H = 125.8 \pm 0.5 \pm 0.2$ GeV

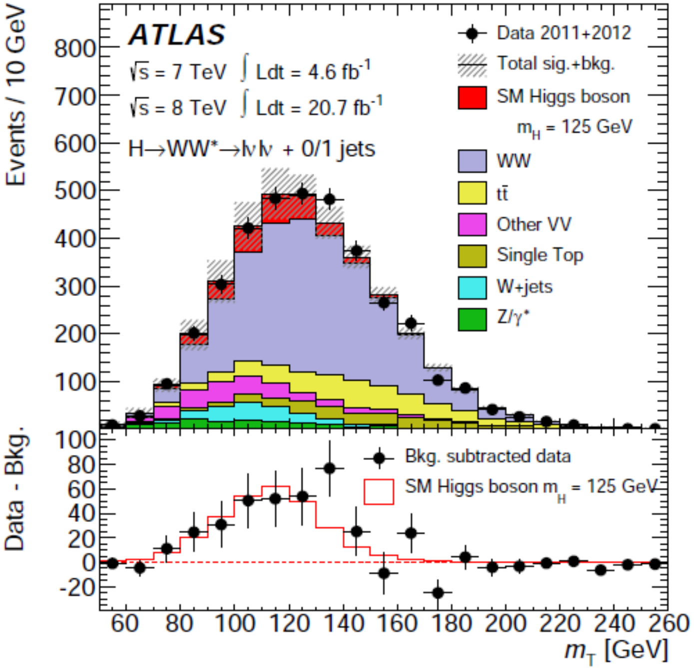
CMS PAS HIG-13-002

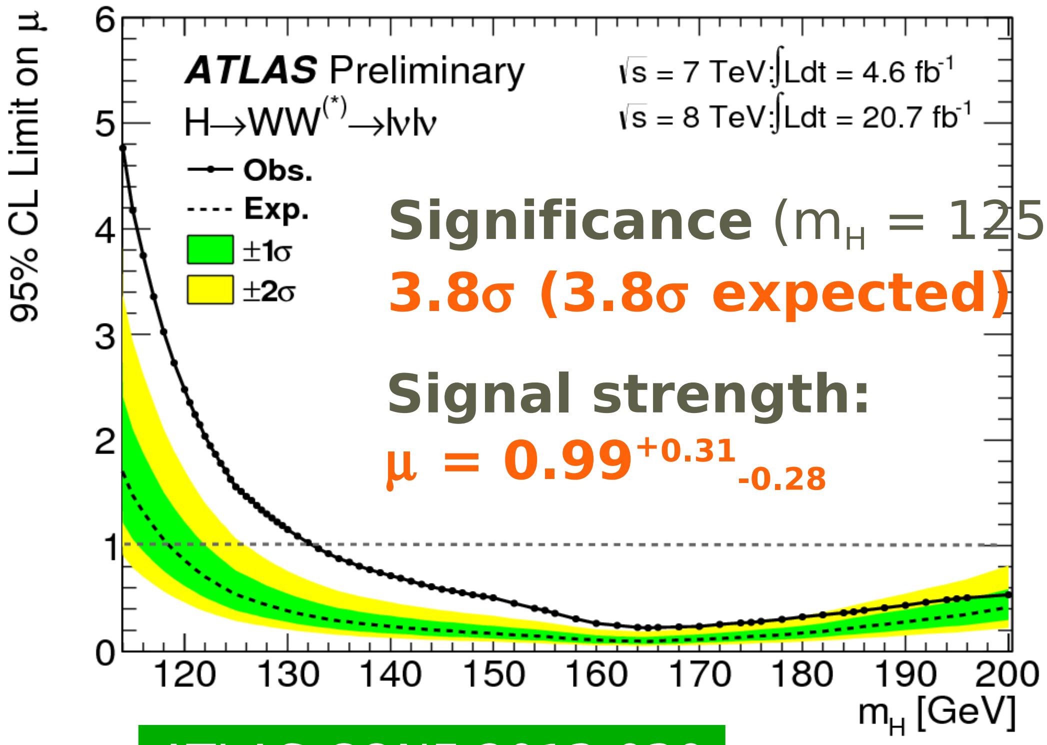
ATLAS H → WW* → 2l2ν: evidence

- Final states: ee, eμ, μμ + ME_T
- Low mass resolution because 2 neutrinos
- Events classified: 0, 1, ≥ 2 jets (ggH & VBF)
- Background: WW, tt, tW, Z/γ*, W+jets, diboson
- H spin 0 → W spin correlation propagated to leptons: used to reject WW → small m_{ll}, small $\Delta\phi_{ll}$
- m_T distribution is fitted in bins of m_{ll} /# jets

ATLAS arXiv:1307.1427







Significance (m_H = 125.5 GeV):

3.8σ (3.8σ expected)

Signal strength:

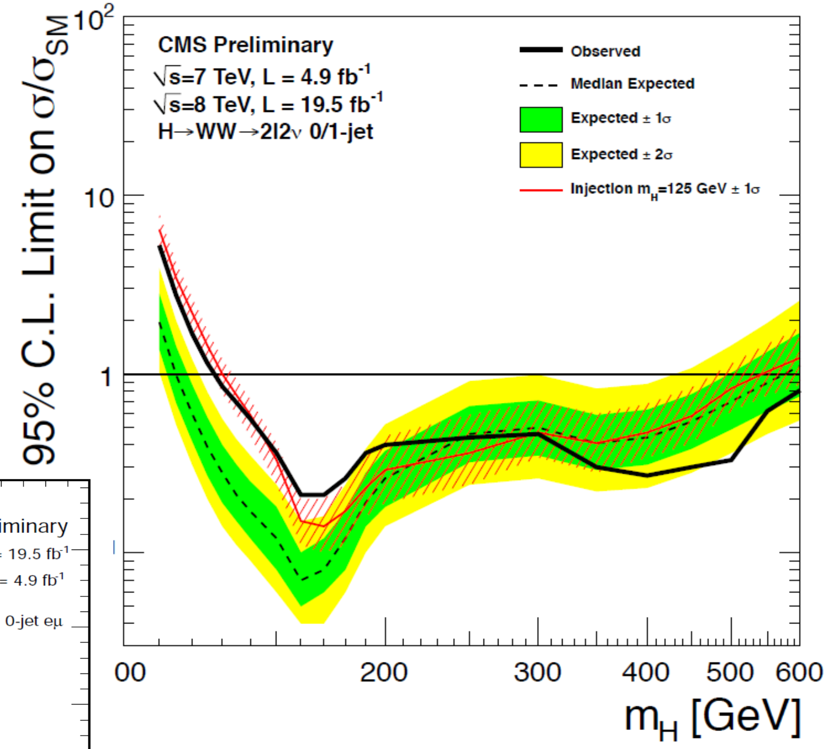
$\mu = 0.99^{+0.31}_{-0.28}$

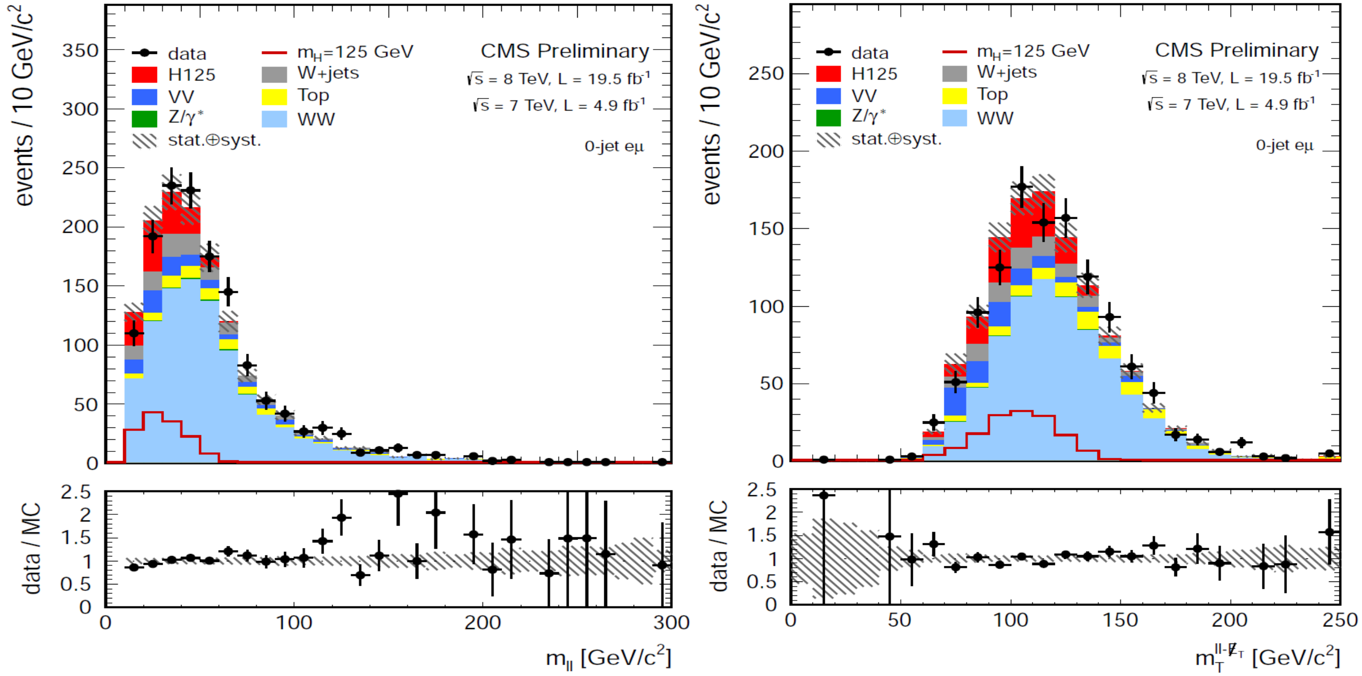
ATLAS-CONF-2013-030

CMS $H \to WW^* \to 2l2\nu$: close to observation

- Final states: ee, eμ, μμ + ME_T
- 0 and 1 jet categories (ggH)
- Cut-based approach for ee and μμ:

  m_{ll}, $\Delta\phi_{ll}$, m_T requirements optimized for each m_H value
- eμ : 2D (m_T, m_{ll}) shape analysis





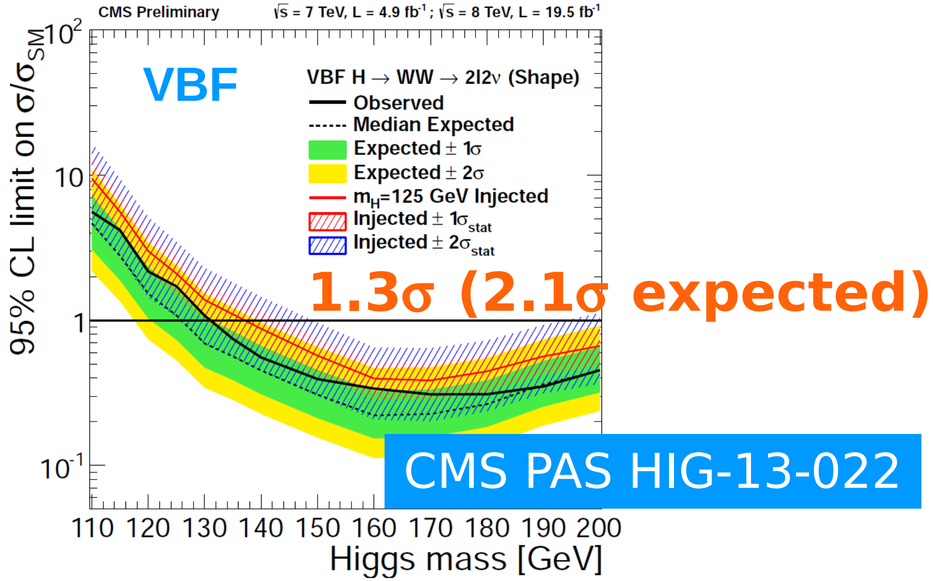
CMS PAS HIG-13-003

Significance (m_H=125 GeV): **4.0σ (5.1σ expected)**

Signal strength: μ = 0.76 ± 0.21

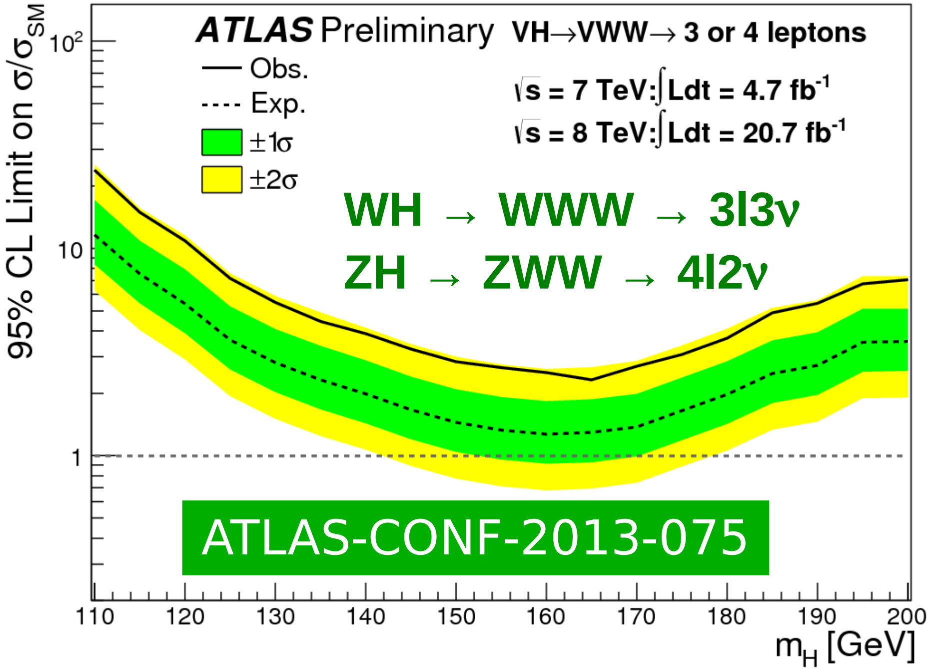
V-mediated H→WW*: increasing sensitivity

- Separate CMS H → WW VBF analysis (fit to m_{ll} distribution)
- Both ATLAS and CMS searched for VH → VWW:
  - ATLAS: V → leptons
  - CMS: V → leptons or V → hadrons



1.3σ (2.1σ expected)

CMS PAS HIG-13-022



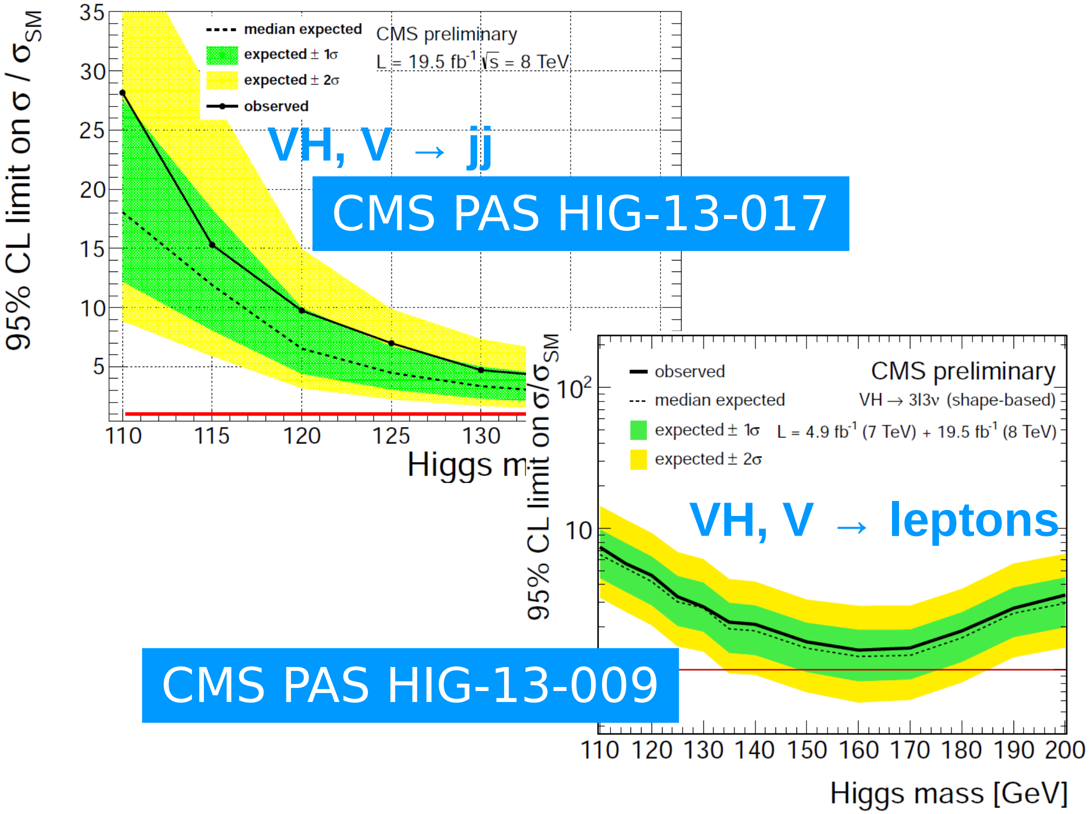
WH → WWW → 3l3ν
ZH → ZWW → 4l2ν

ATLAS-CONF-2013-075

ATLAS H→ WW combined result

Significance (m_H = 125 GeV):

3.8σ (4.0σ expected)



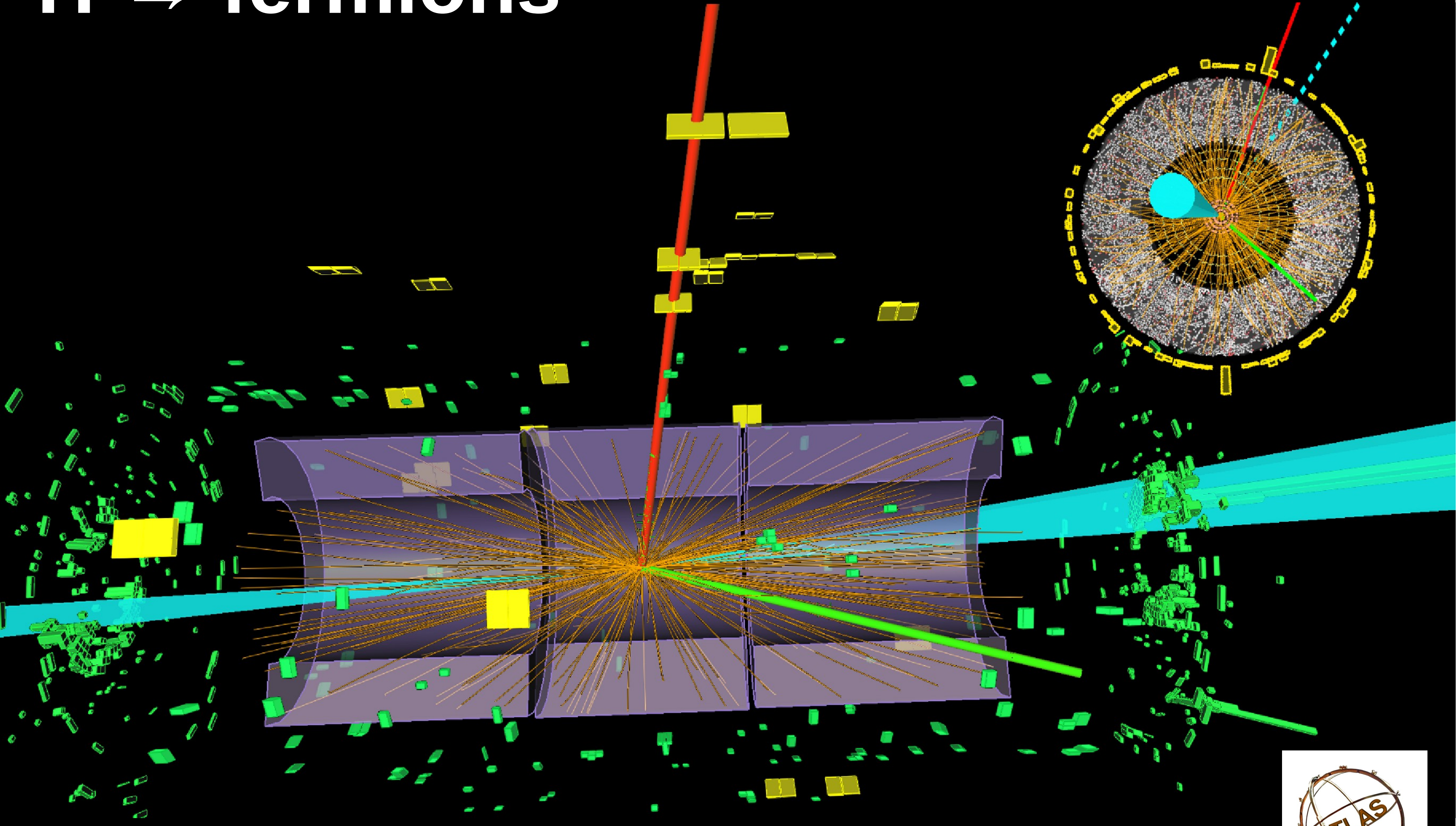
VH, V → jj

CMS PAS HIG-13-017

VH, V → leptons

CMS PAS HIG-13-009

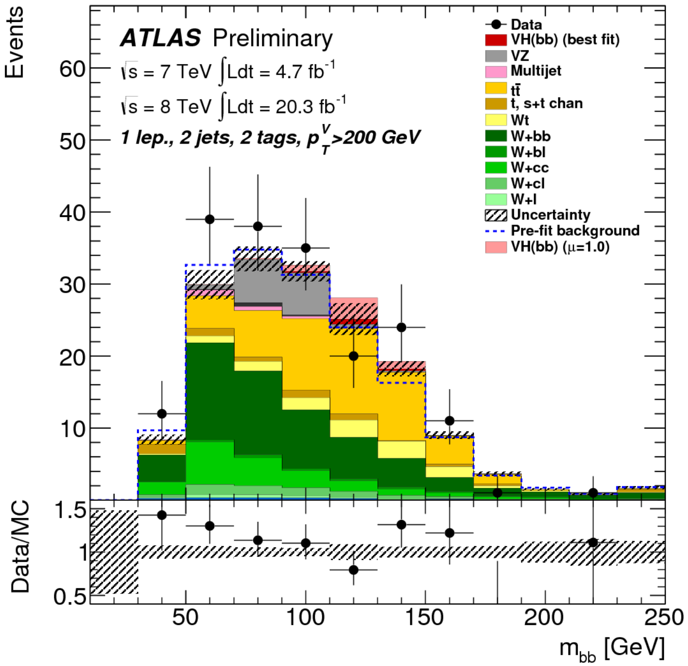
H → fermions

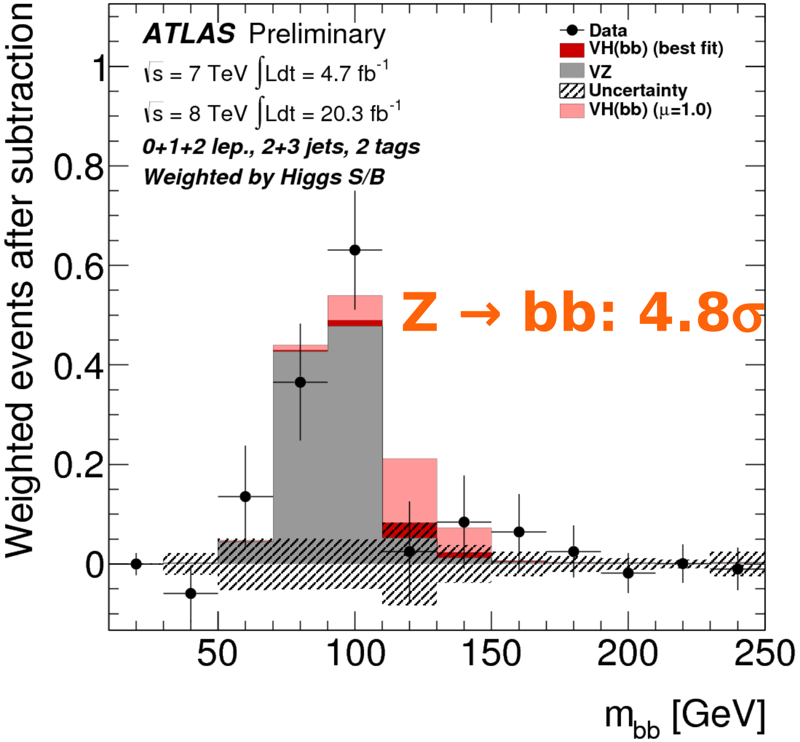


ATLAS H → bb produced with W or Z

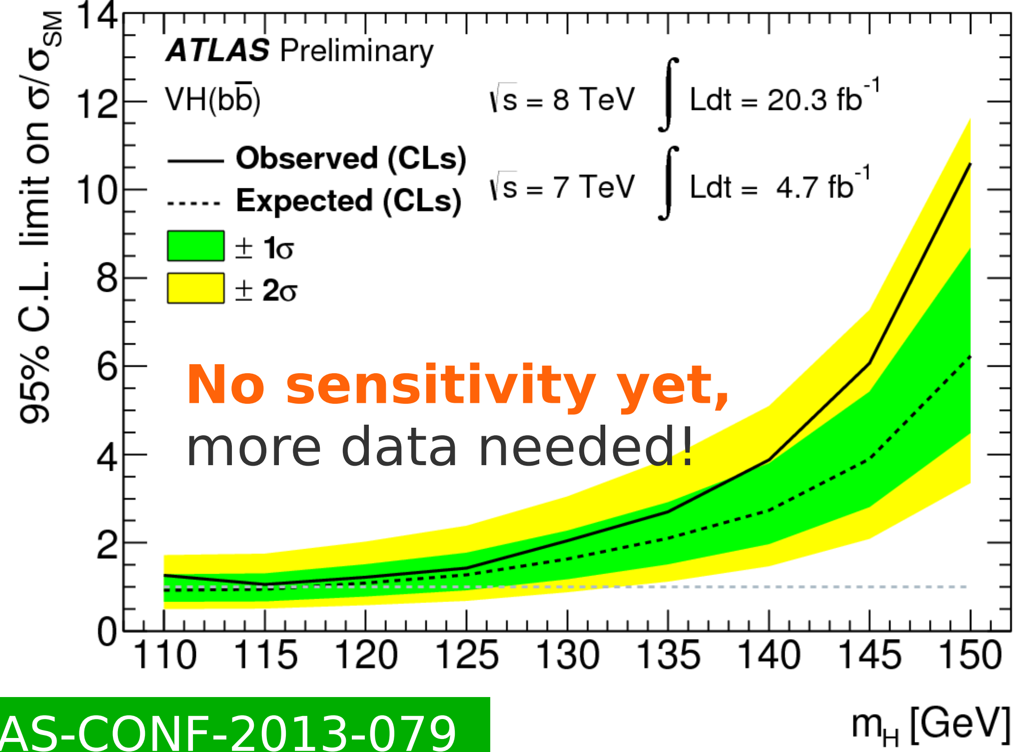
3σ evidence @ Tevatron arXiv:1303.6346

- W → eν,μν and Z → ee,μμ,νν + 2 b jets
- different regions according to $p_T^{W/Z}$ and the number of jets
- Background: tt, V+jets, VV
- Shape of m_{bb} fitted over all categories
- Benchmark: VZ → Vbb





Z → bb: 4.8σ

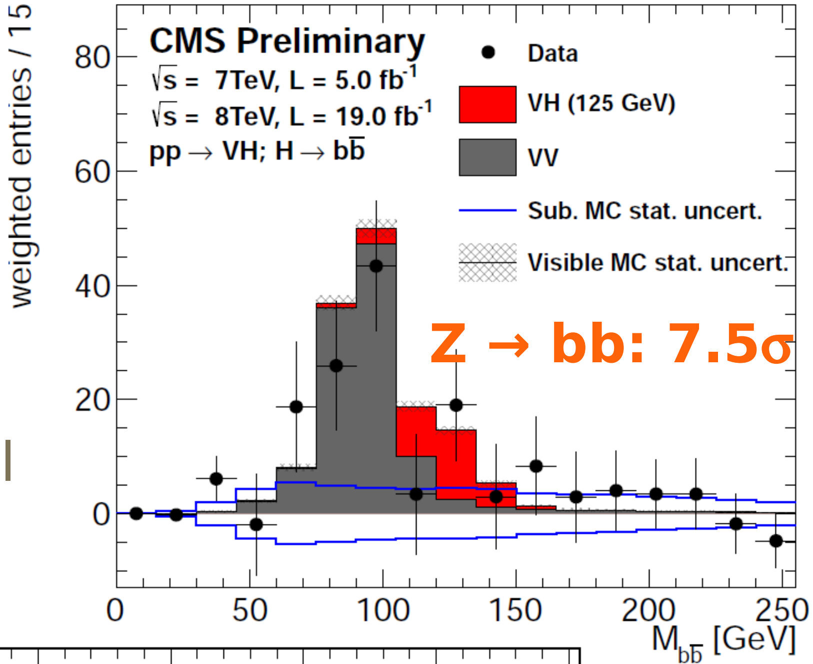


No sensitivity yet,
more data needed!

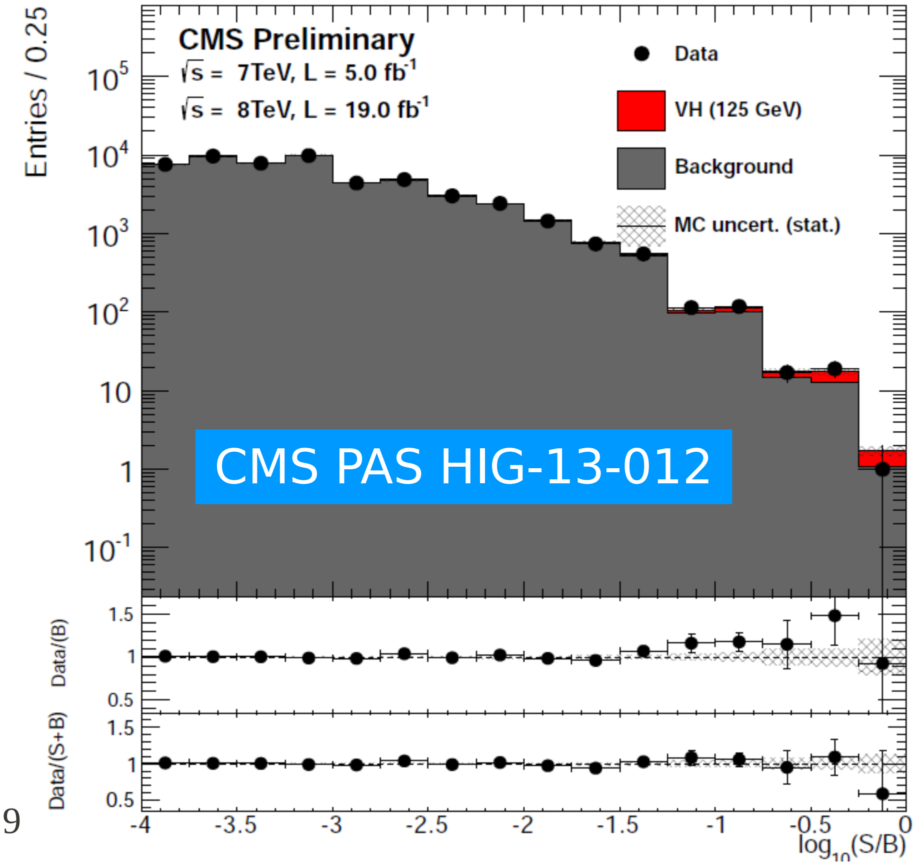
ATLAS-CONF-2013-079

CMS H → bb produced with W or Z

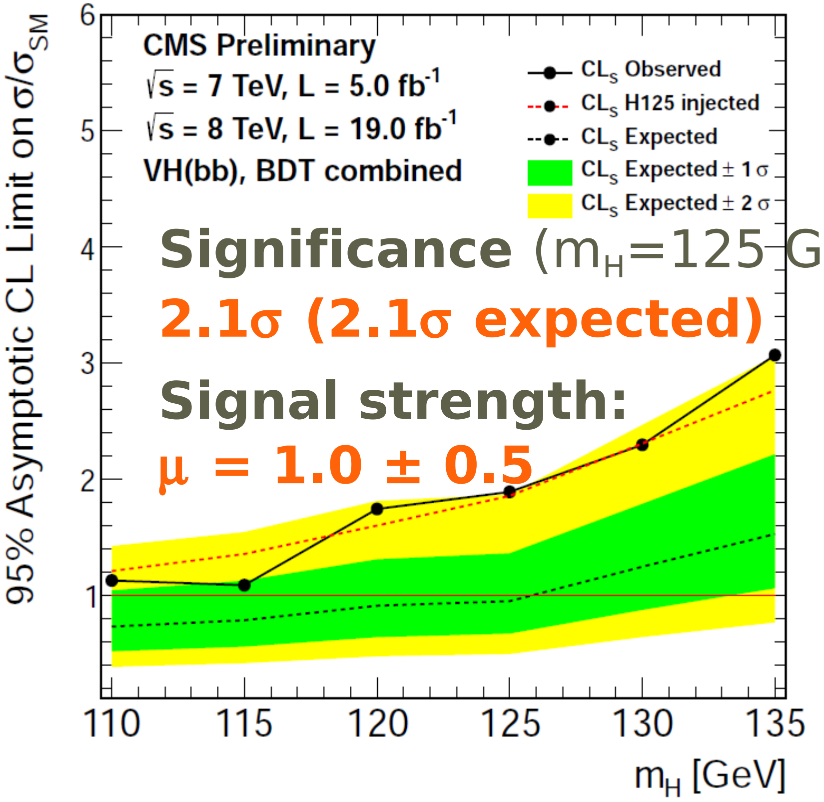
- W → eν,μν,τν and Z → ee,μμ,νν + 2 b jets
- 3 different regions according to $p_T^{W/Z}$
- m_{bb} resolution improved using MVA
- Events with ν classified using MVA into tt, V+jets, VV or signal categories (à la CDF)
- Another MVA is used to discriminate signal from background → shape is fitted



Z → bb: 7.5σ



CMS PAS HIG-13-012



Significance (m_H=125 GeV)**:**

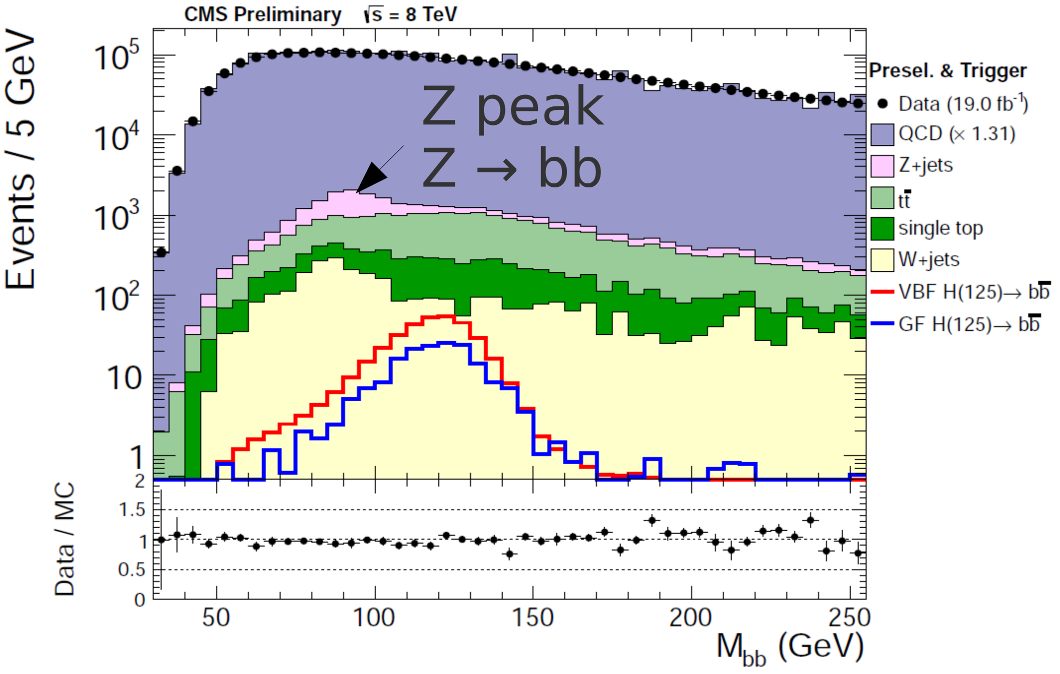
2.1σ (2.1σ expected)

Signal strength:

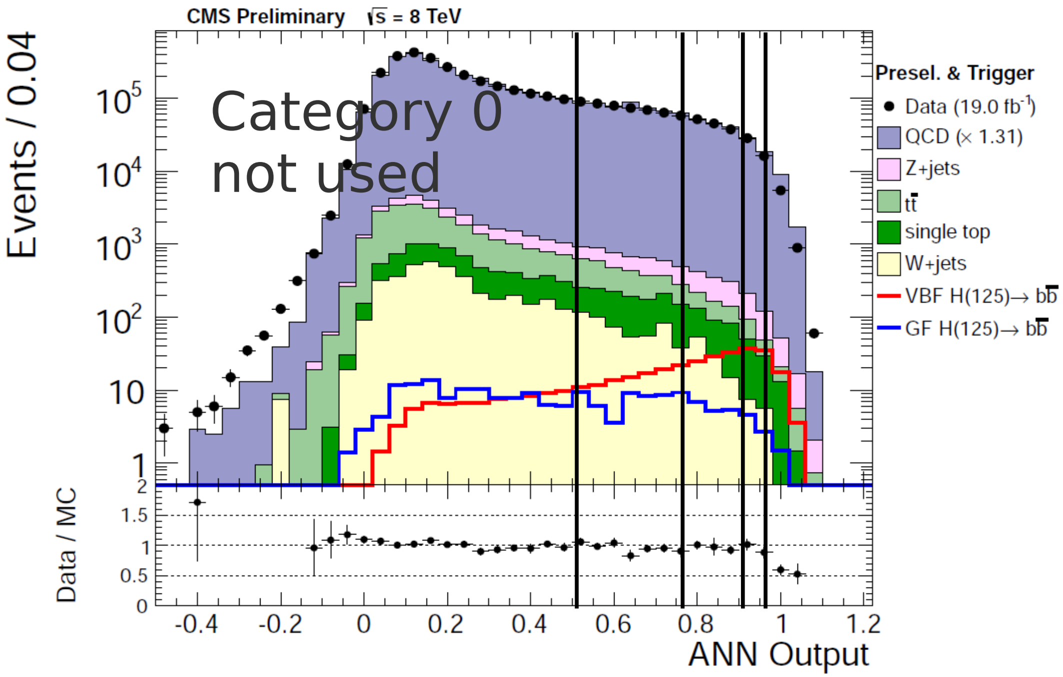
μ = 1.0 ± 0.5

CMS H → bb produced through VBF

- 1 or 2 b jets + 2 jets with large rapidity gap
- Background: QCD multijets, hadronic decays of W,Z, top
- MVA analysis with input variables sensitive to the VBF topology with 2 b jets
- Fit the m_{bb} distribution in each MVA category

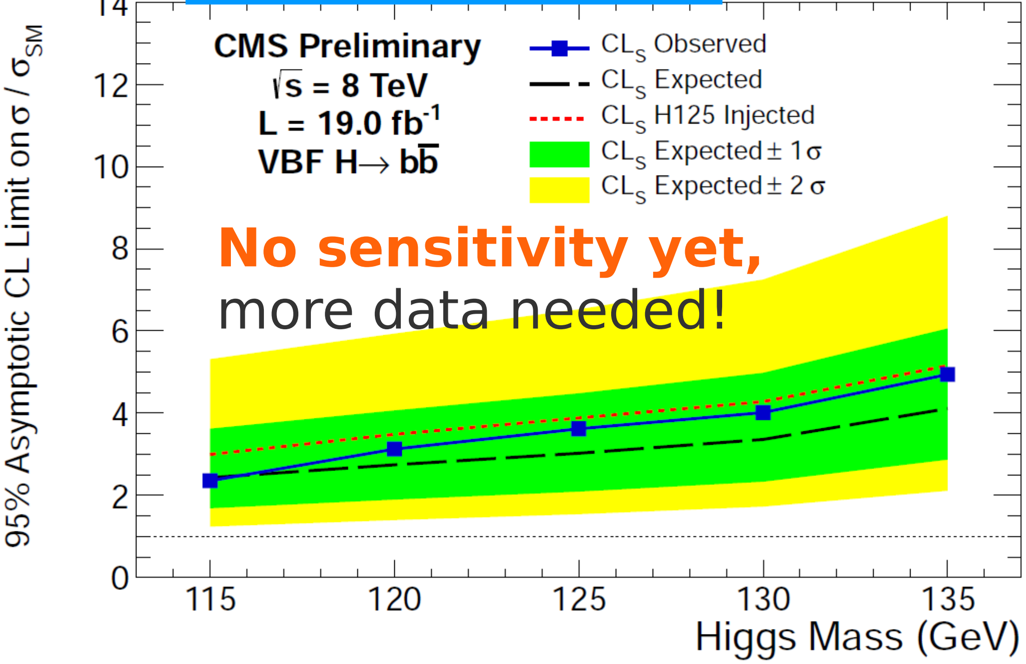


Z peak
Z → bb



Category 0
not used

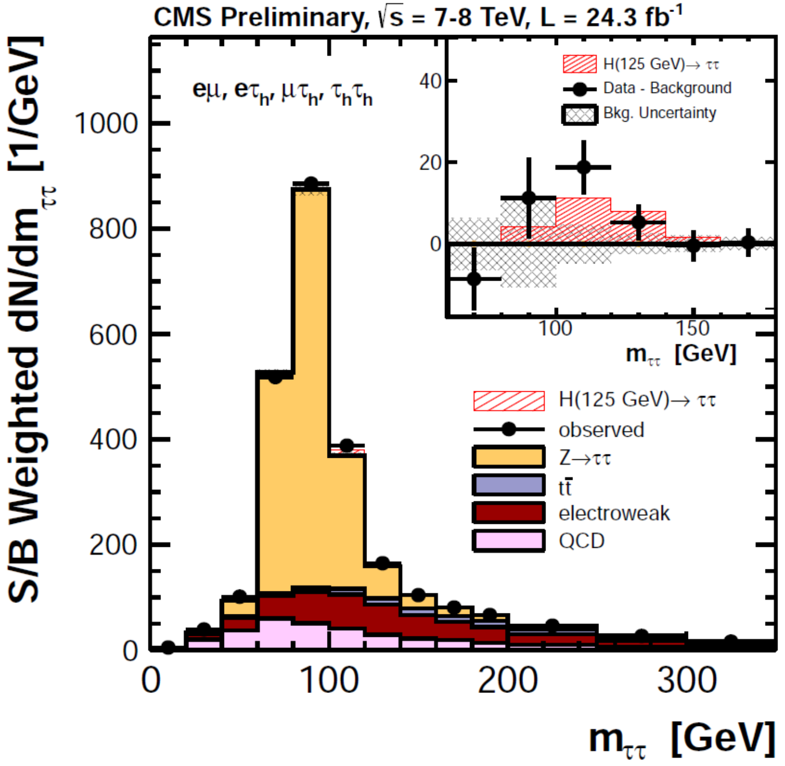
CMS PAS HIG-13-011

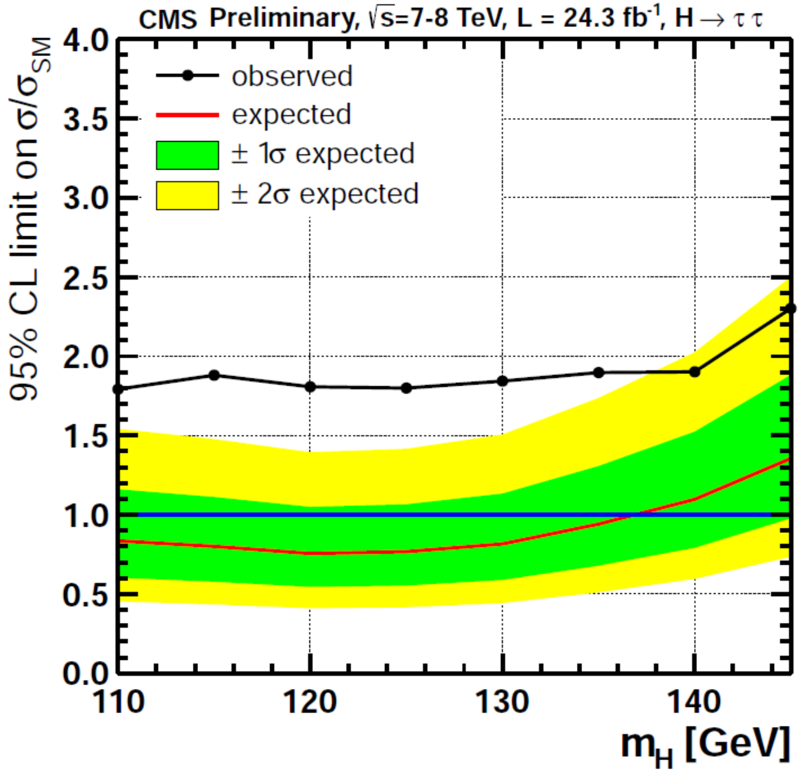


No sensitivity yet,
more data needed!

CMS H → ττ: close to evidence

- Final states: eμ, μμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ + jets
- 1 or 2 jets (0-jet is control region)
- Require ν from τ nearly collinear with visible decay products
- μμ channel: Z → μμ suppressed by MVA
- Reconstruct $m_{\tau\tau}$ distribution from visible and invisible decay products → with SVFit ~20% mass resolution





CMS PAS HIG-13-004 **ggH + VBF**

+

CMS PAS HIG-12-053 **VH (V → leptons)**

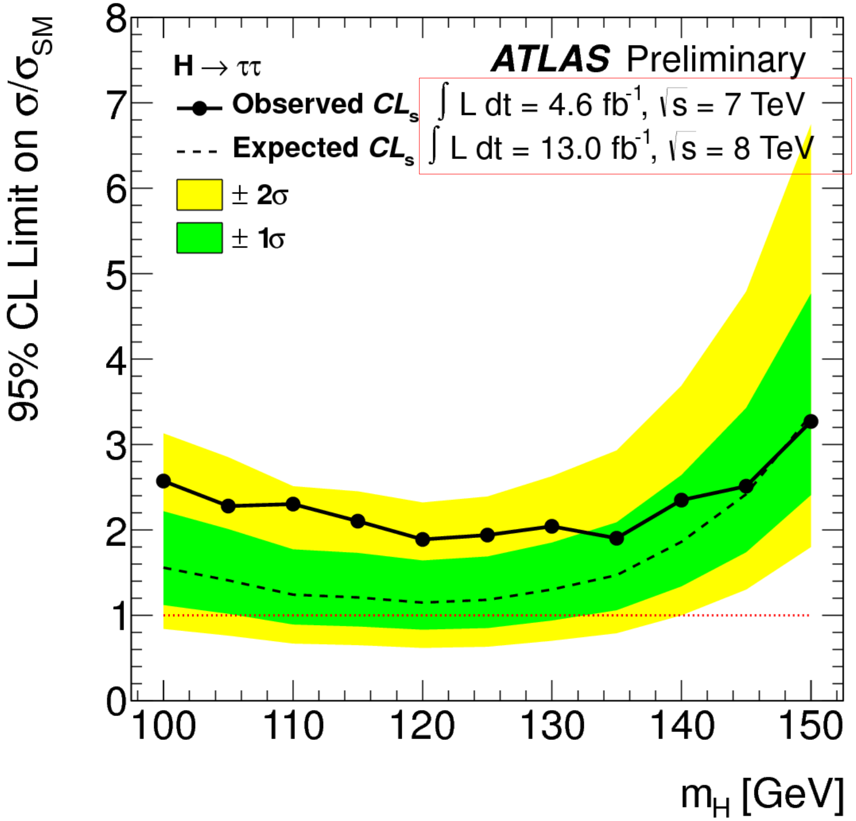
CMS comb. H→ττ result m_H=125 GeV)

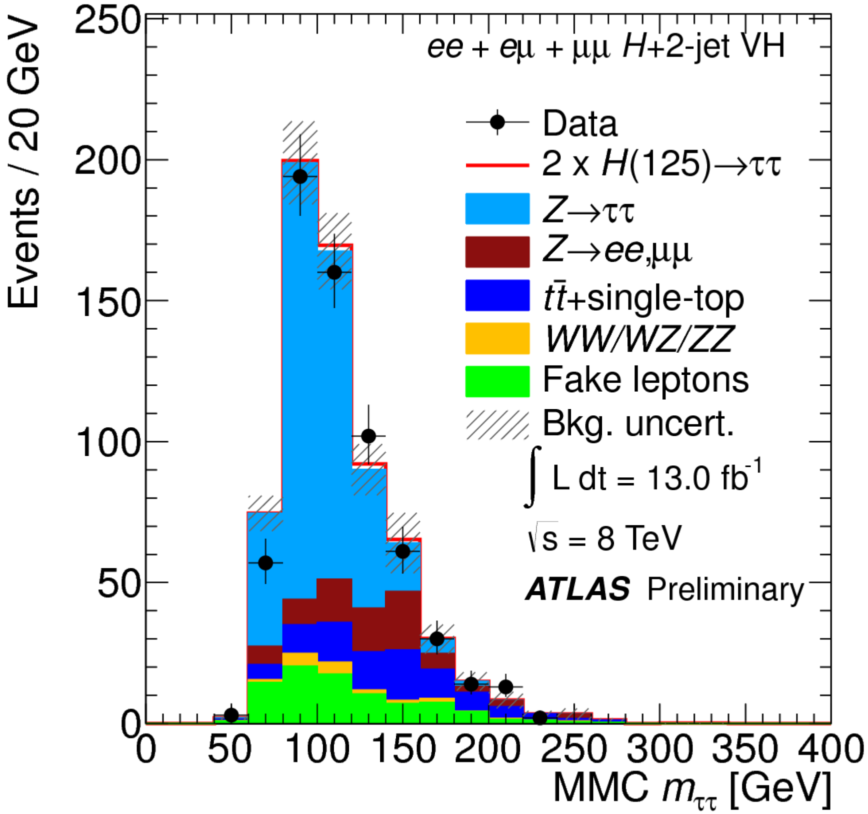
- **Significance: 2.9σ (2.6σ expected)**
- **Signal strength: 1.1 ± 0.4**

ATLAS H → ττ: not the final result

ATLAS-CONF-2012-160

- Final states: ee, eμ, μμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ + jets
- Similar techniques as CMS
- Reconstruct $m_{\tau\tau}$ distribution from visible and invisible decay products → with MMC ~13-20% mass resolution





For m_H=125 GeV:

- **Significance: 1.1σ (1.7σ expected)**
- **Signal strength: 0.7 ± 0.7**

Summary of the observed excesses

Decay mode	Expected (σ)	Observed (σ)	σ for m_H(GeV)
ZZ	4.4	6.6	124.3
γγ	4.3	7.4	126.5
WW	4.0	3.8	125.0
ττ	1.7	1.1	125.0

ATLAS arXiv:1307.1427

ATLAS-CONF-2013-075

ATLAS-CONF-2012-160

CMS PAS HIG-13-005

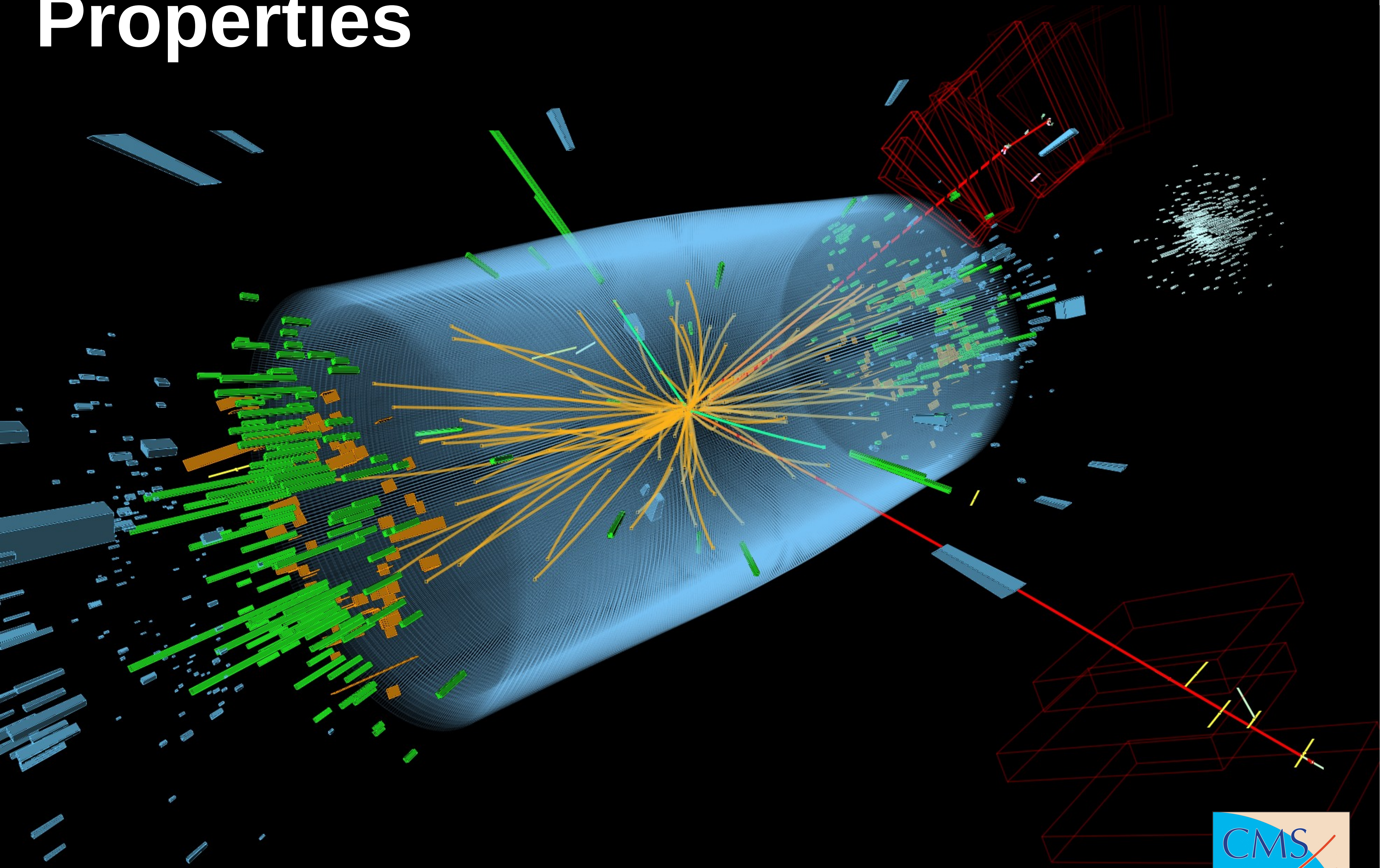
m_H=125.7 GeV

Decay mode	Expected (σ)	Observed (σ)
ZZ	7.1	6.7
γγ	3.9	3.2
WW	5.3	3.9
ττ	2.6	2.8
bb	2.2	2.0

Evidence for coupling to third generation down-type fermions! Significance: 3.4σ (3.4σ expected)

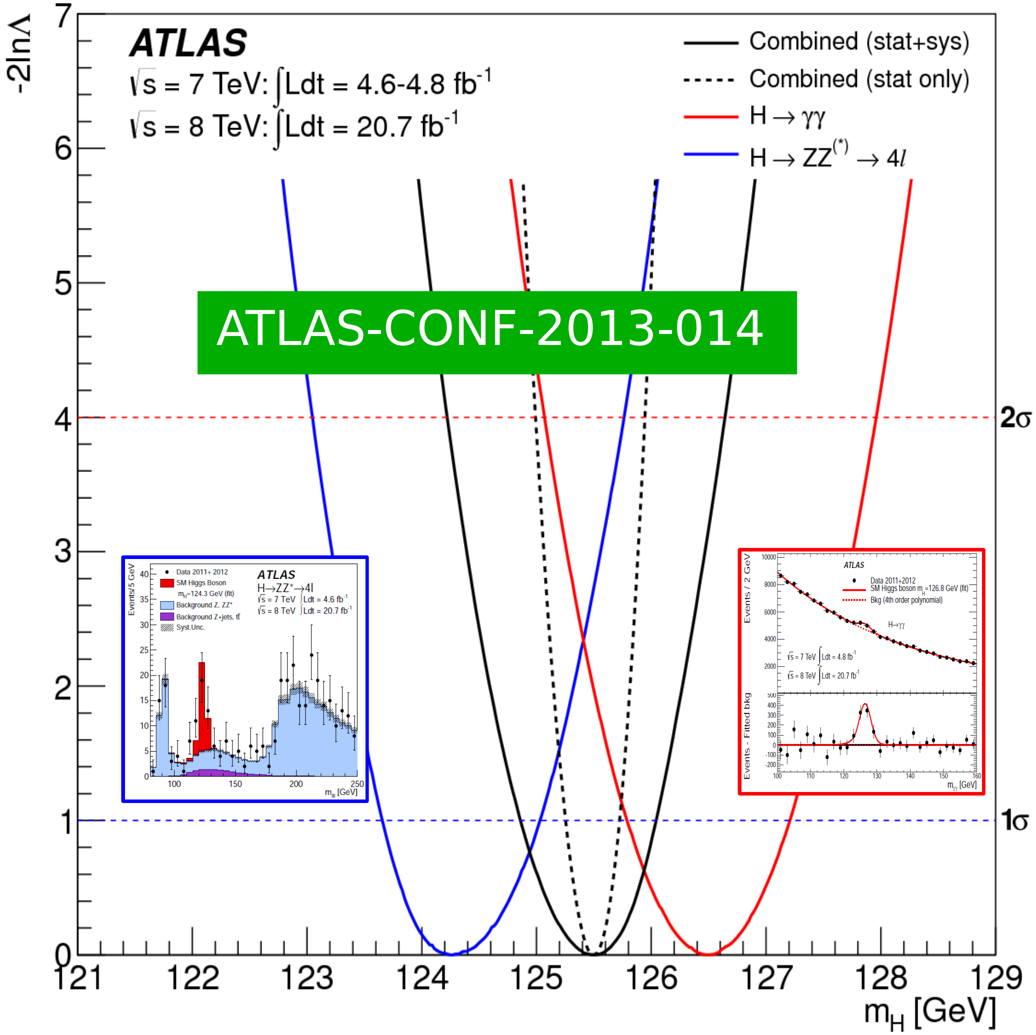
→ *see talks of Garoe Gonzalez Parra, Qiang Li, Stephen Cole*

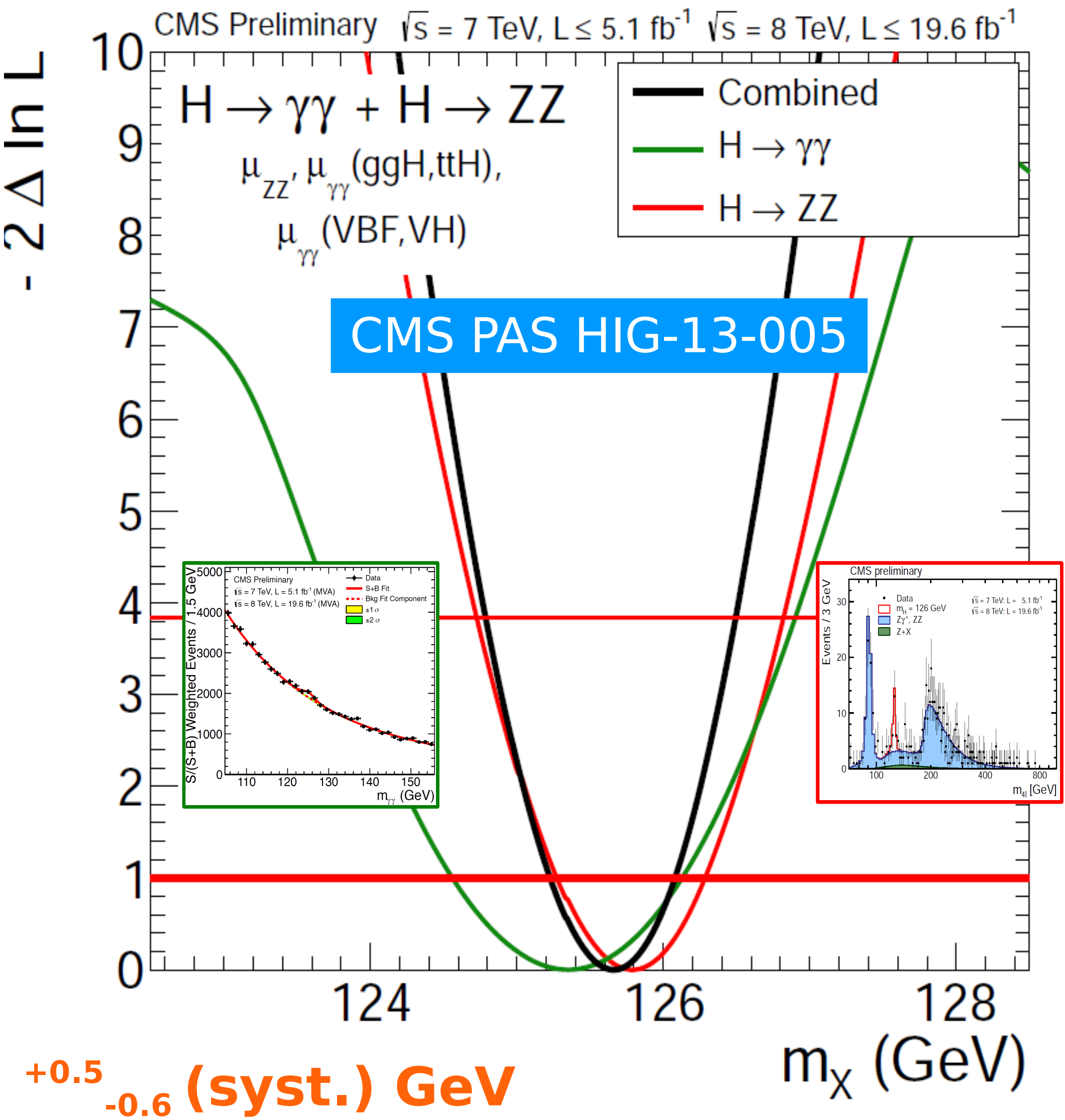
Properties



The Higgs boson mass measurement

- Mass measured from the H → γγ and H → ZZ* → 4l mass distributions



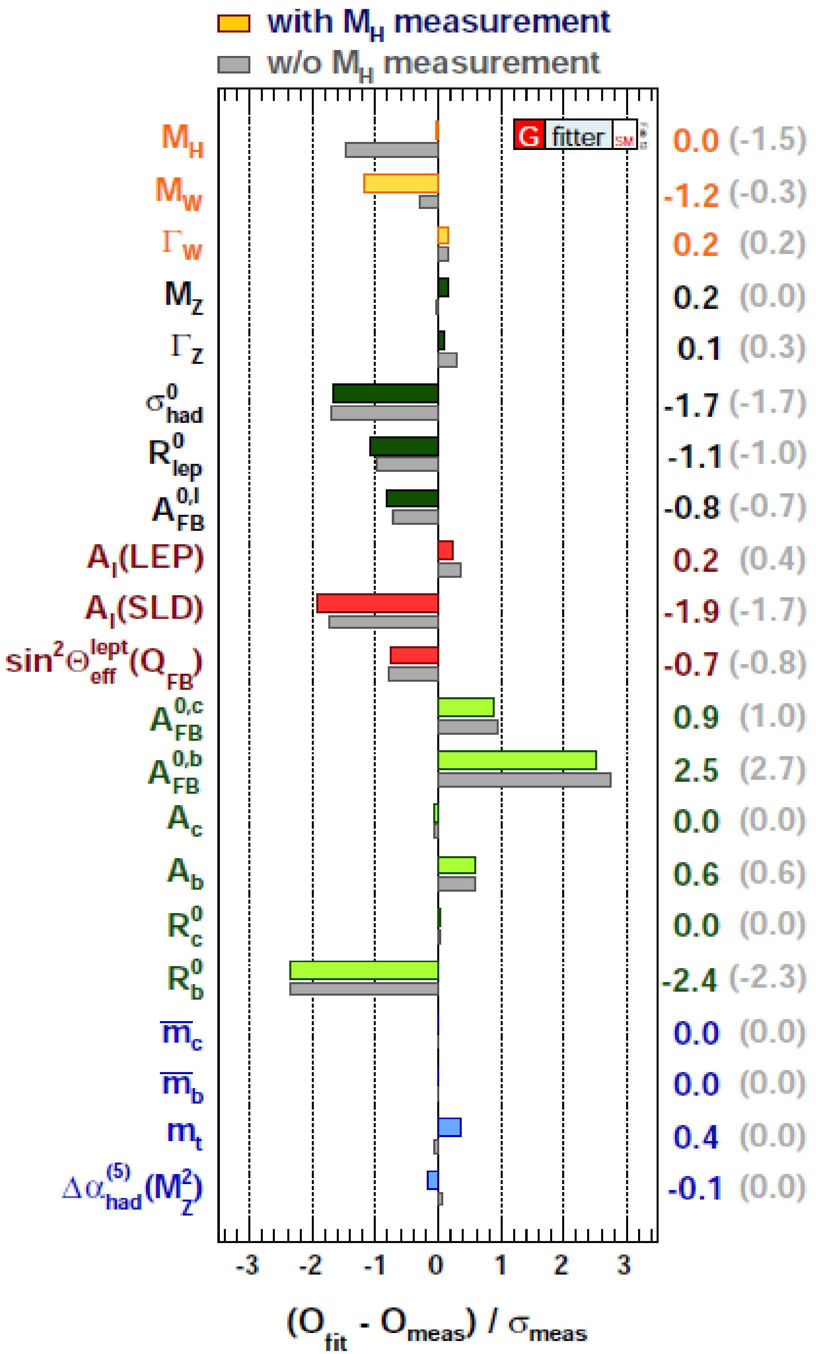


ATLAS: **m_H = 125.5 ± 0.2 (stat.) $^{+0.5}_{-0.6}$ (syst.) GeV**

CMS: **m_H = 125.7 ± 0.3 (stat.) ± 0.3 (syst.) GeV**

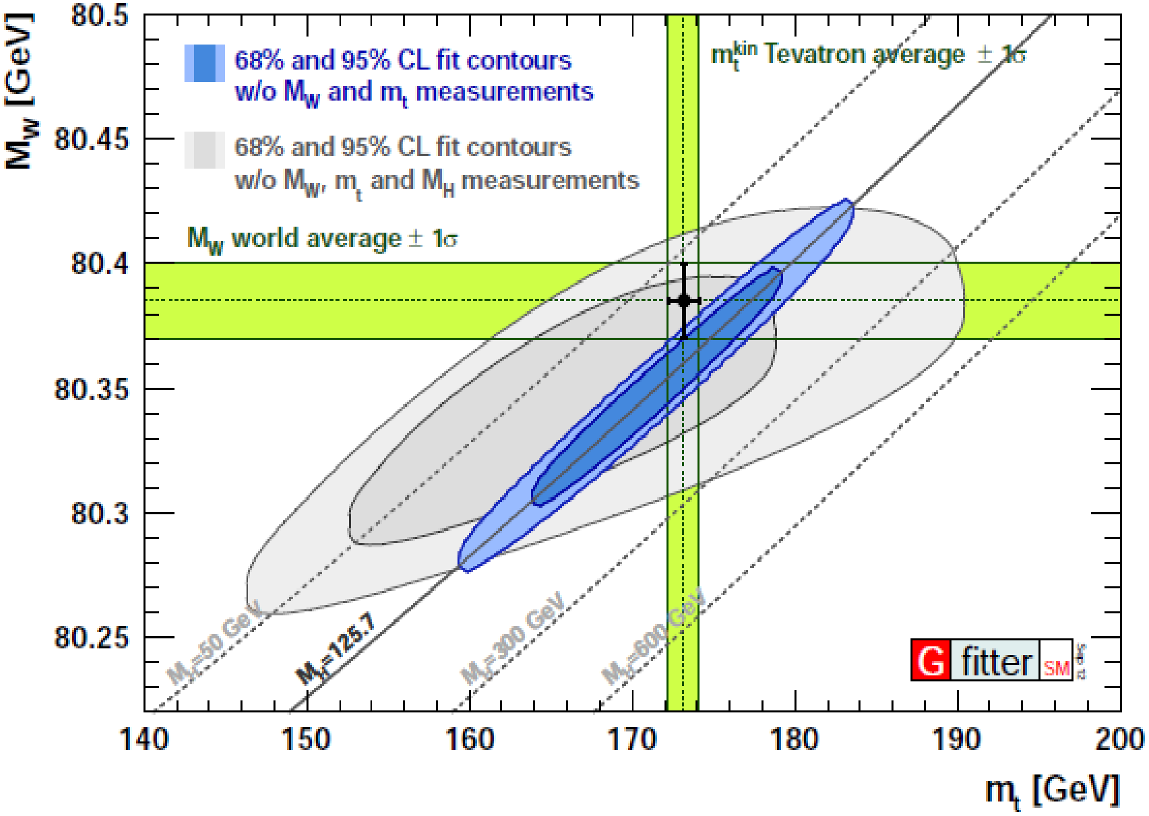
- Signal strengths not fixed to SM expectation, but profiled in the likelihood fit

Global electroweak fit: impressive consistency



Plot inspired by Eberhardt et al. [arXiv:1209.1101]

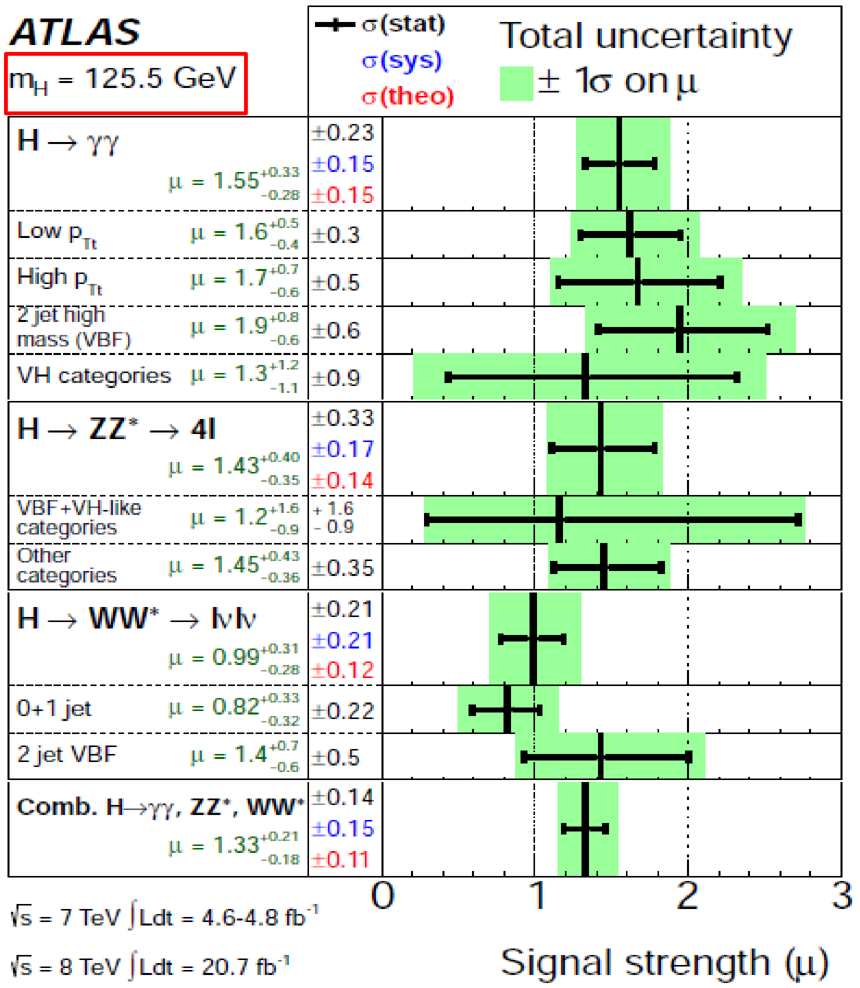
M. Baak et. al. arXiv:1306.0571



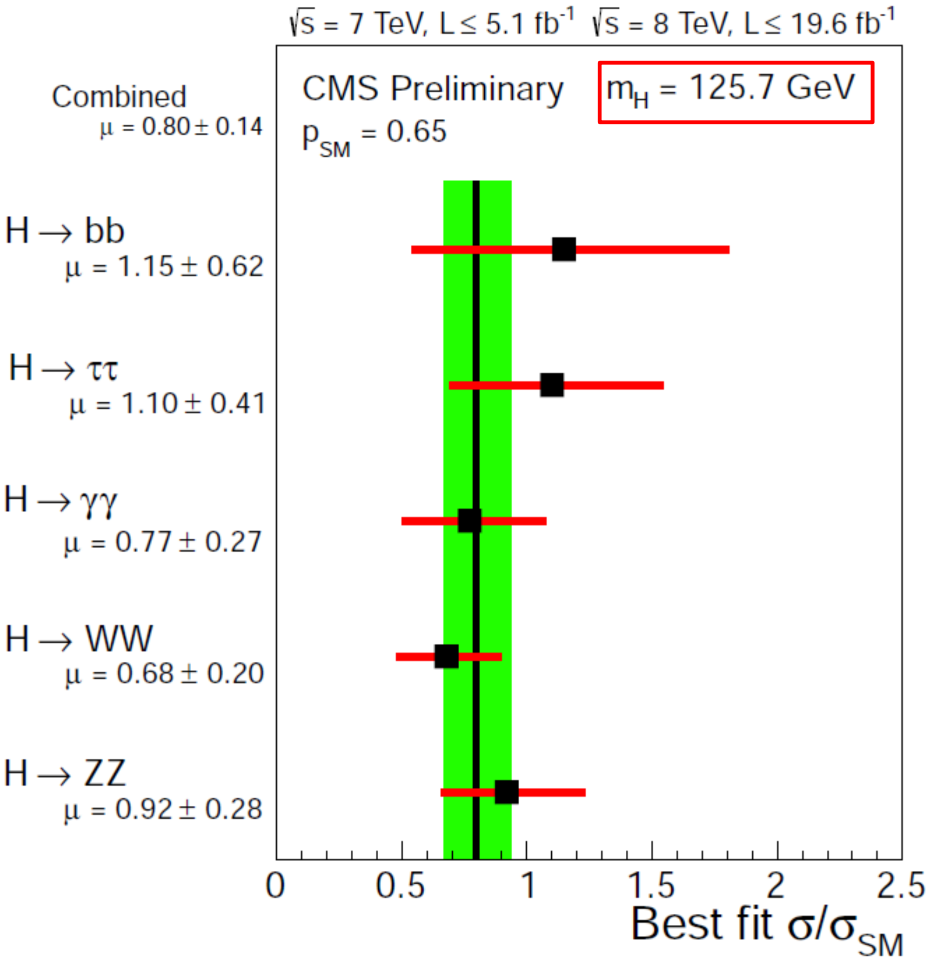
- The SM is cornered
- Effects of new physics can enter only through loop corrections
- Improve the precision of the electroweak observables further with future accelerators

The combined signal strength

ATLAS arXiv:1307.1427



CMS PAS HIG-13-005



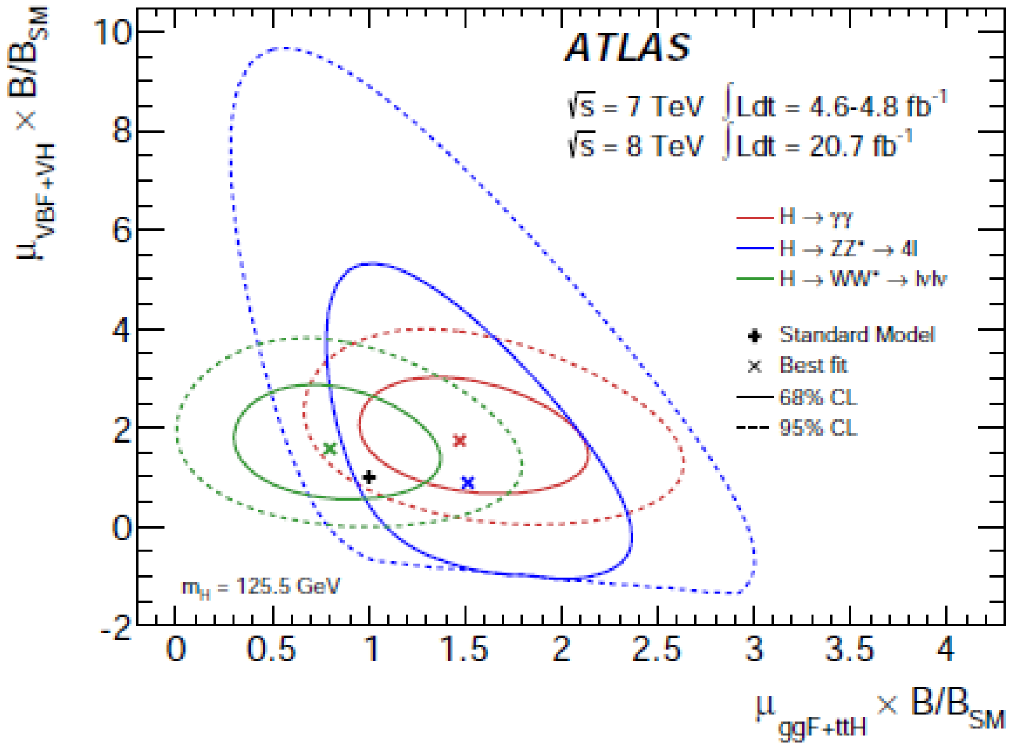
ATLAS (γγ,WW*,ZZ*): μ = 1.33±0.20(with bb and ττ: μ = 1.23±0.18)

CMS (γγ,WW*,ZZ*,bb,ττ): μ = 0.80±0.14

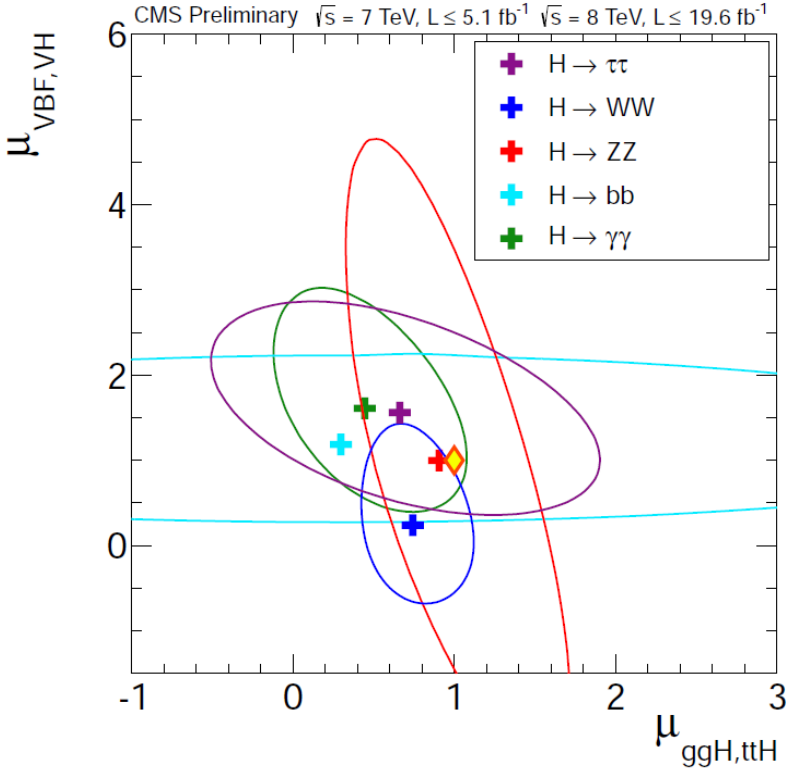
Evidence for production via vector boson fusion

- Separate VBF+VH channels from ttH+ggF channels
- Analyses not 100% pure → use simulation to correct for signal contamination from other production processes

ATLAS arXiv:1307.1427



CMS PAS HIG-13-005



ATLAS (γγ,WW*,ZZ*): **$\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.4}_{-0.3}(\text{stat})^{+0.6}_{-0.4}(\text{syst})$**

→ evidence (3.3σ) that a fraction of Higgs production occurs through VBF

Testing the Higgs boson couplings

- ATLAS & CMS follow the recommendations of the LHC Higgs Cross Section Working Group (arXiv:1307.1347)

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- Couplings tested by introducing scalefactors κ_j
- σ_j and Γ_j of particle j scale with κ_j^2 compared to SM prediction, e.g: the cross section of gg → H → $\gamma\gamma$ can be expressed as:

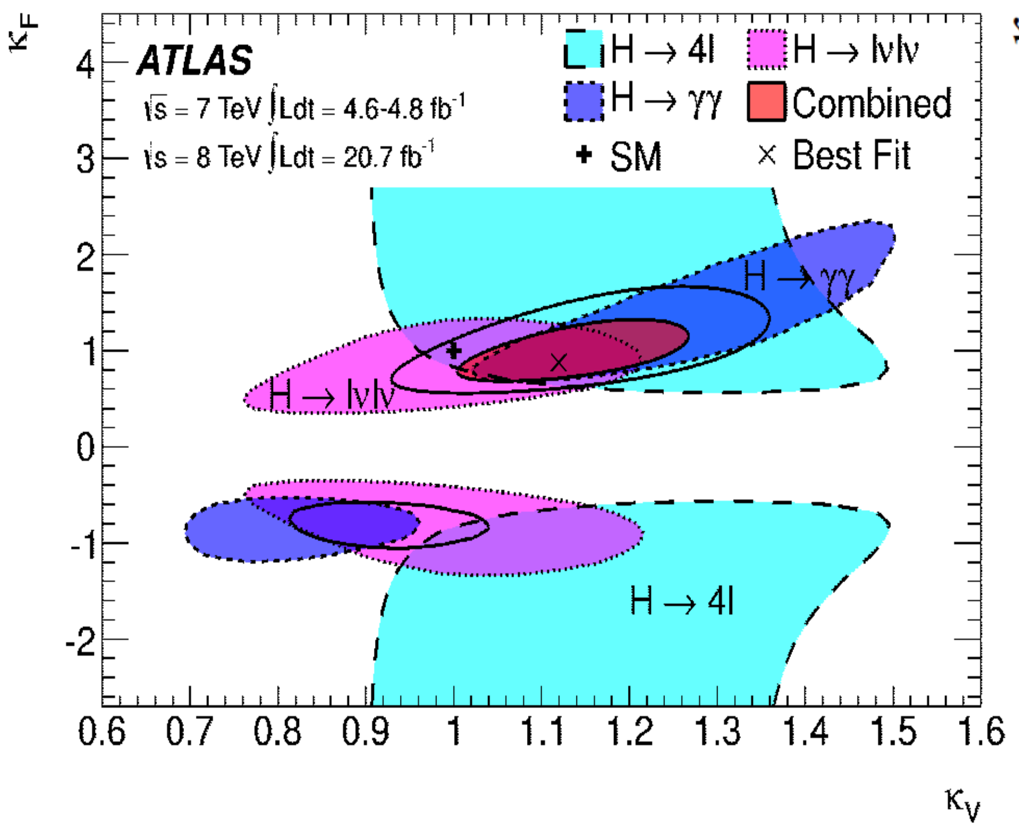
$$\frac{\sigma \cdot \mathrm{B}\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

- The following tests have been performed by ATLAS & CMS:
  - Couplings to the vector bosons and fermions
  - Ratio of couplings to the W and Z bosons (custodial symmetry)
  - Loop induced couplings & $\mathrm{BR}_{\mathrm{BSM}}$
  - Test for asymmetries in the couplings to fermions

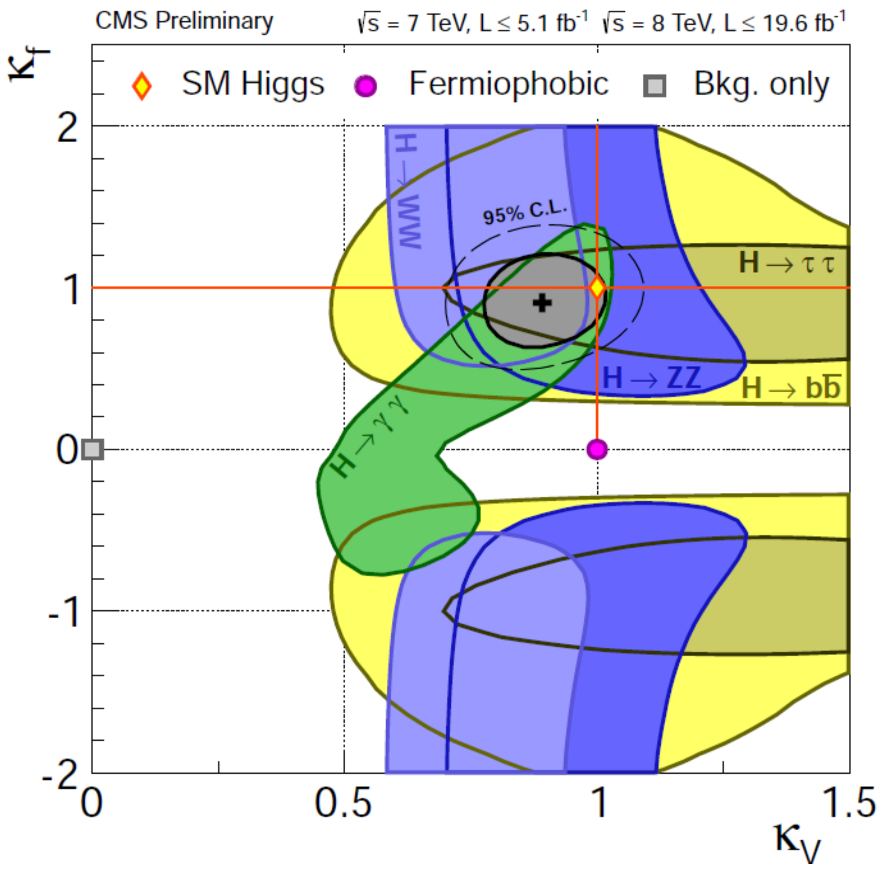
Couplings to fermions and bosons

- Assume a scalefactor κ_F for fermions and a scalefactor κ_V for bosons:
  → all Γ_j scale either as κ_F^2 or as κ_V^2, except $\Gamma_{\gamma\gamma}$ which scales as $|\alpha\kappa_F+\beta\kappa_V|^2$.
- No contributions from physics beyond the SM ($\Gamma_{BSM}=0$)

ATLAS arXiv:1307.1427



CMS PAS HIG-13-005



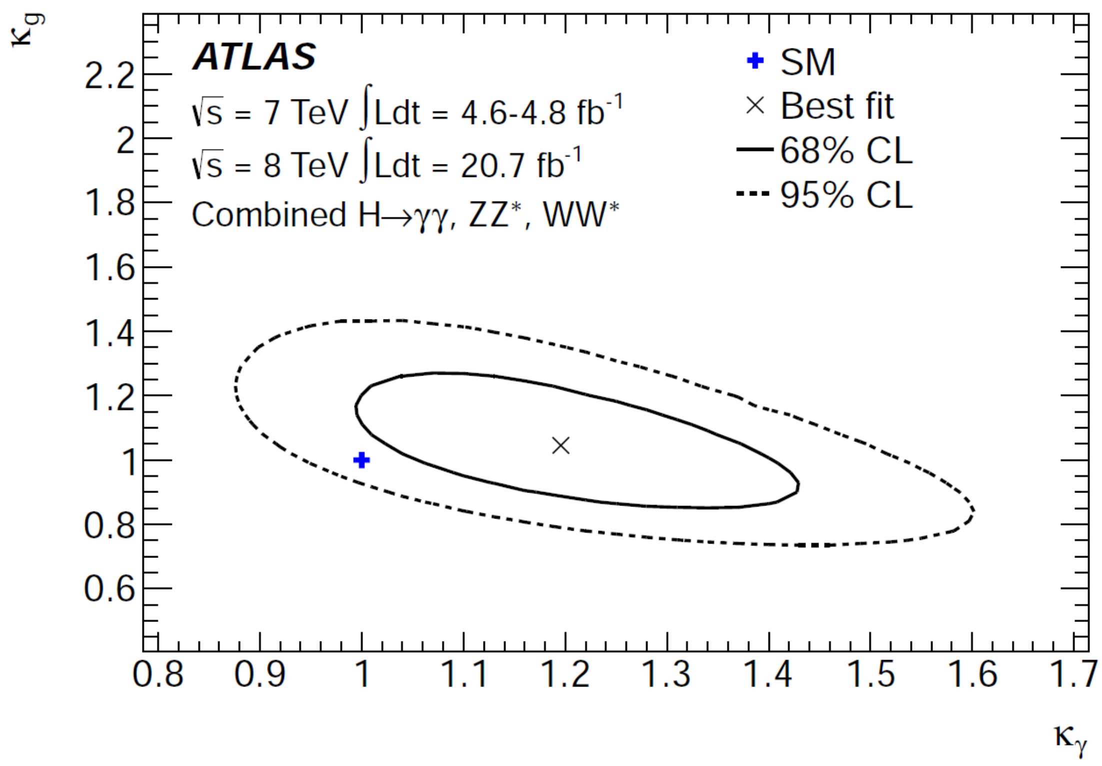
Consistent with SM prediction

Fermiophobic Higgs is excluded

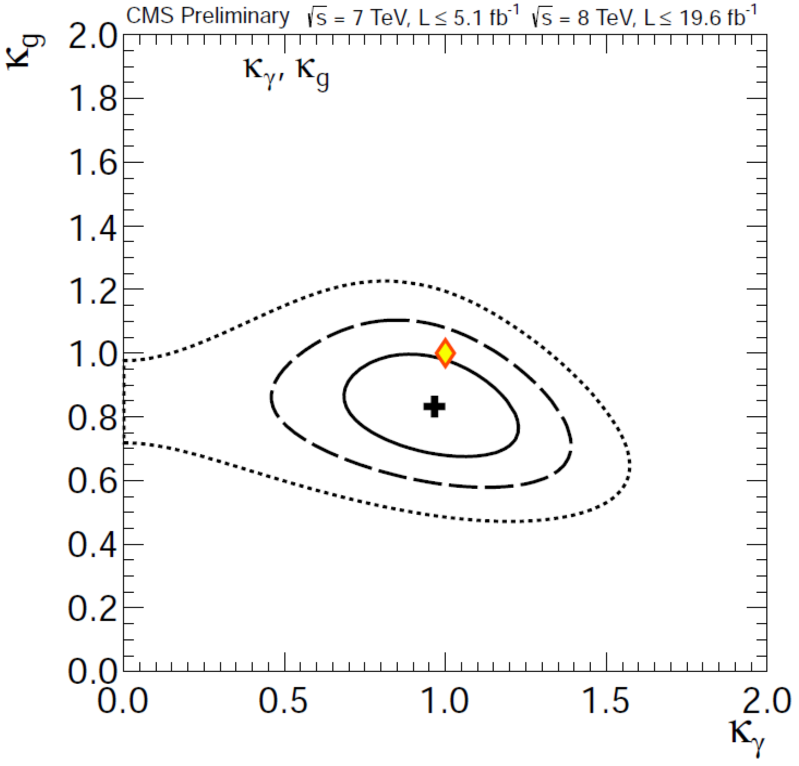
Constraints on production and decay loops

- New physics may appear in the loops gg → H and H → $\gamma\gamma$
- Allow new particles to contribute to the total Higgs boson width
- Assume all other couplings are equal to unity (SM strength)
- Keep κ_g and κ_γ as free parameters

ATLAS arXiv:1307.1427



CMS PAS HIG-13-005

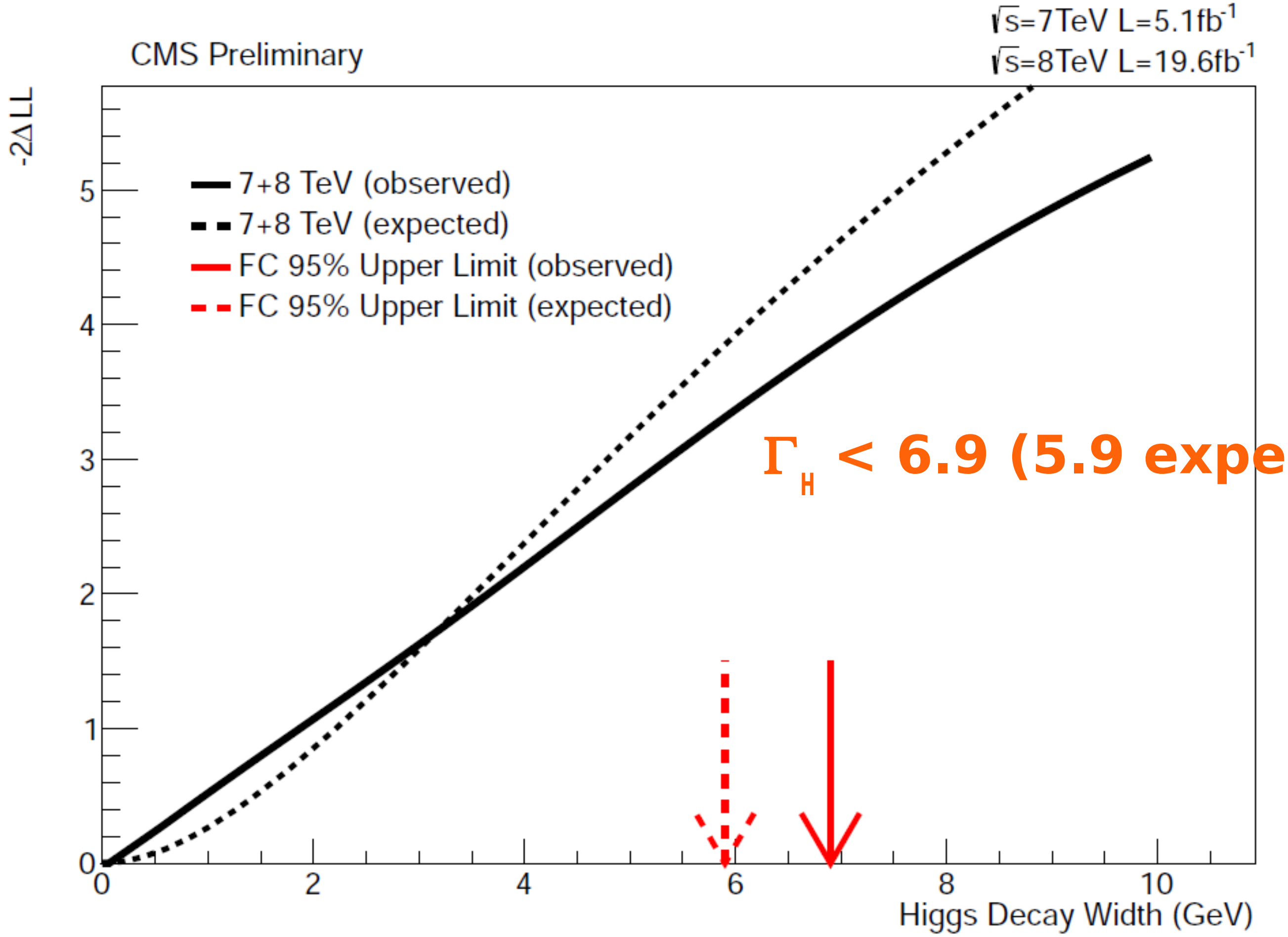


Consistent with SM prediction

Upper limit on the decay width from $H \rightarrow \gamma\gamma$

- Signal distribution is a convolution of a Breit-Wigner distribution with a Gaussian distribution

CMS PAS HIG-13-016



$\Gamma_H < 6.9$ (5.9 expected) GeV @ 95% CL

Tests of different spin-parity hypotheses

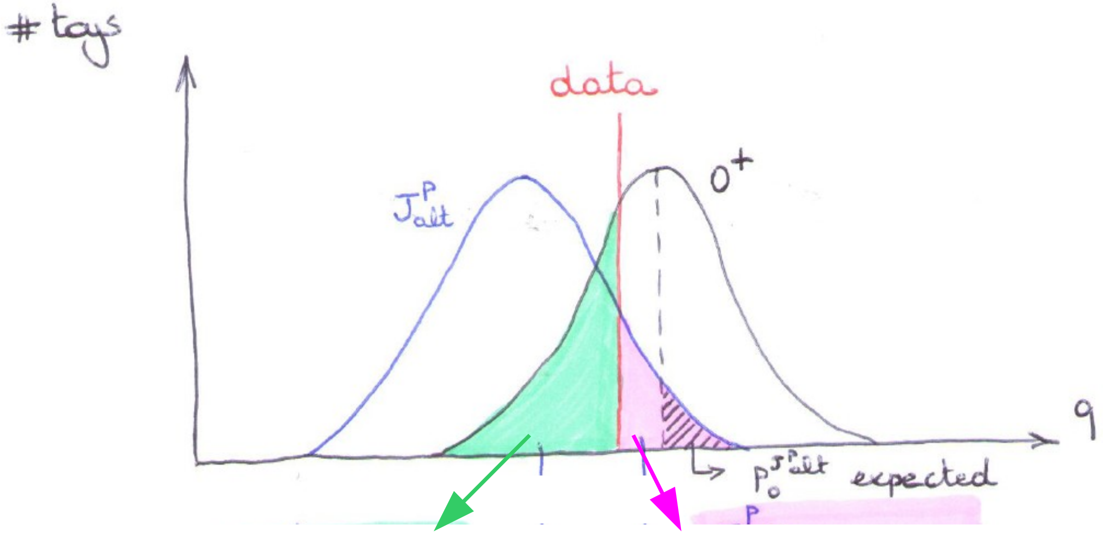
- The SM Higgs boson is spin-0 and CP-even ($J^P = 0^+$)
- Spin 1 hypothesis strongly disfavoured by the observation of H → γγ (Landau-Yang)
- Test the 0^+ hypothesis against 0^-, 1^+, 1^-, 2^+, using observables sensitive to the spin and parity of the new boson
- Test statistic:

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$

→ SM hypothesis

→ alternative hypothesis

- Distributions for q for 0^+ and for $J^P_{\rm alt}$ are obtained from toy experiments



1-$p_0(0^+)$ observed

$p_0(J^P_{\rm alt})$ observed

Exclude $J^P_{\rm alt}$ at X% CL if:

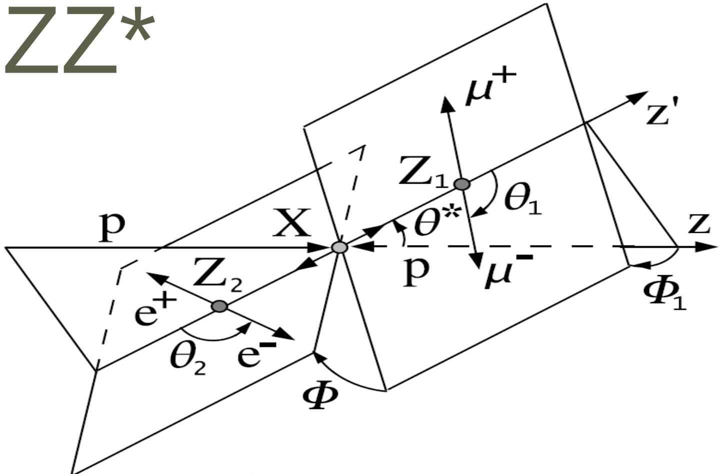
$$\mathrm{CL_s}(J^P_{\rm alt}) = \frac{p_0(J^P_{\rm alt})}{1 - p_0(0^+)} < 1\text{-}(X/100)$$

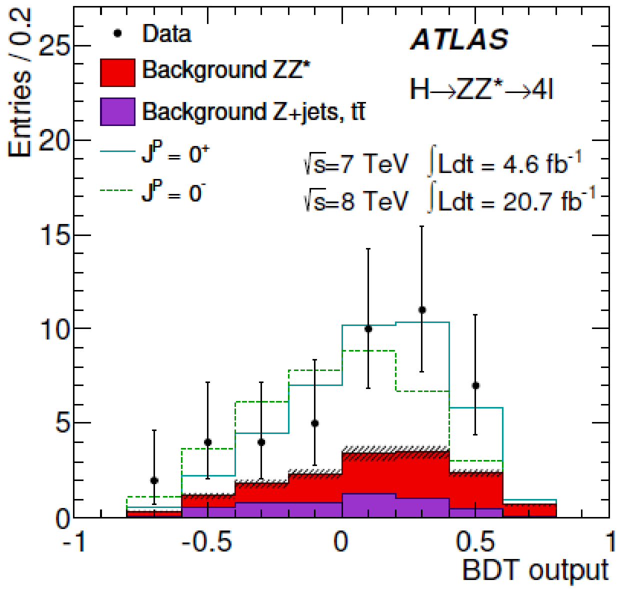
Very small $p_0(J^P_{\rm alt})$

→ data disagrees with $J^P_{\rm alt}$

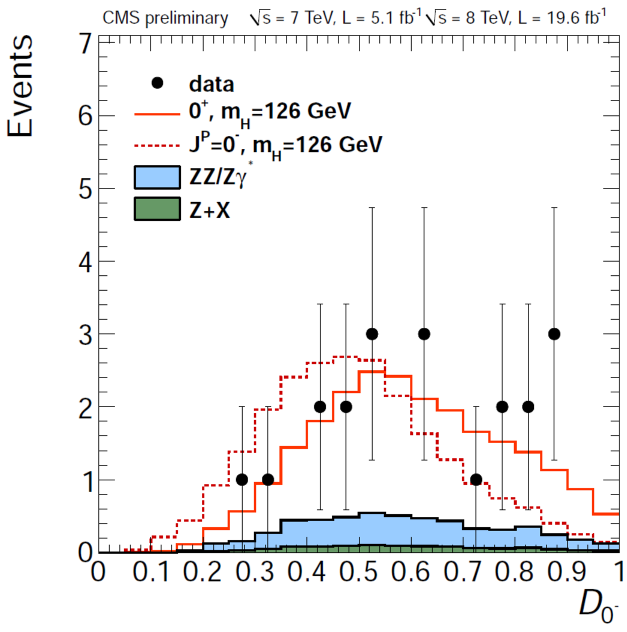
Test 0^- hypothesis with $H \to ZZ^*$

- $H \to ZZ^* \to 4$ charged leptons
- Full reconstruction of the final state
- Kinematic observables: m_{Z1}, m_{Z2} and the 5 production and decay angles
- ATLAS: observables combined with MVA
- CMS: observables used in matrix element likelihood approach

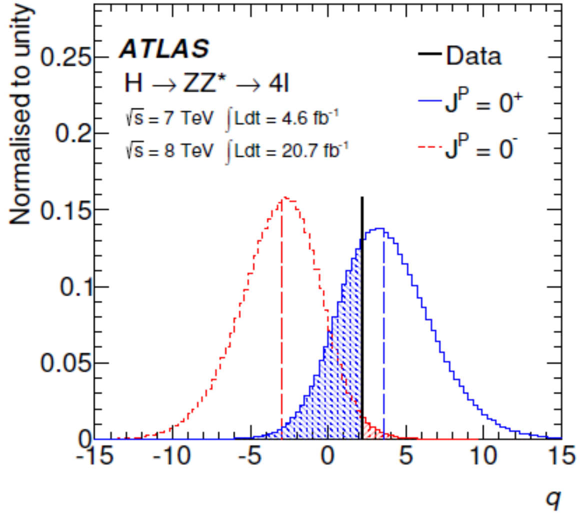


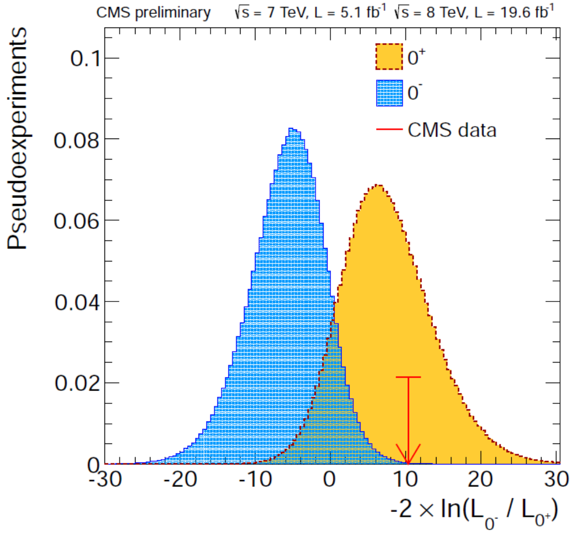


ATLAS arXiv:1307.1432



CMS PAS HIG-13-002





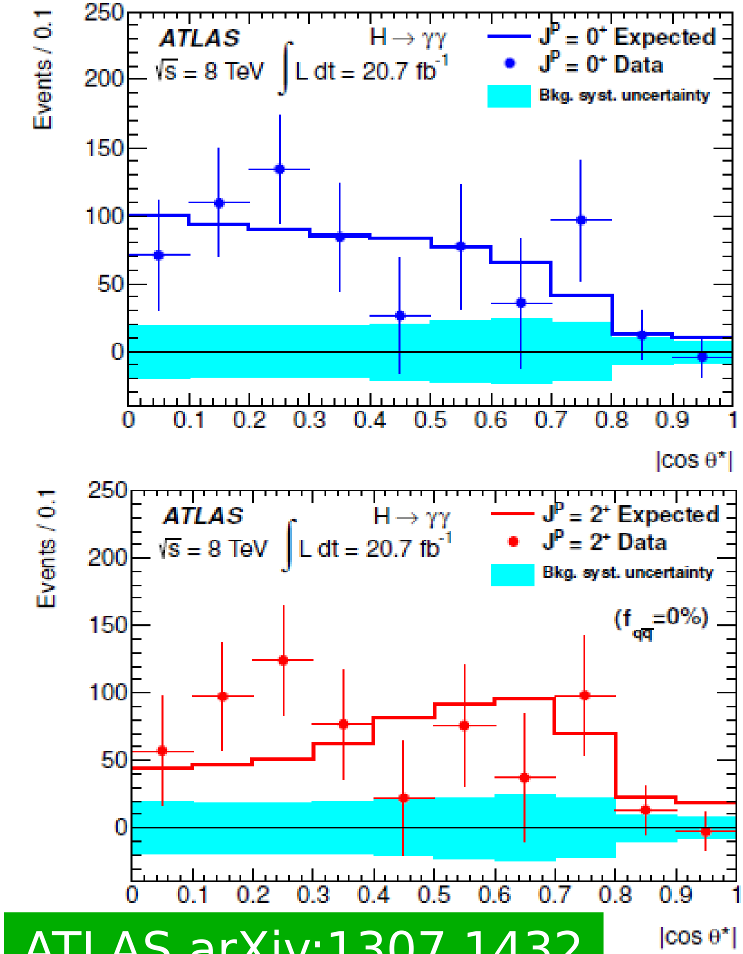
ATLAS: 0^- hypothesis is excluded @ 97.8% CL

CMS: 0^- hypothesis is excluded @ 99.84% CL

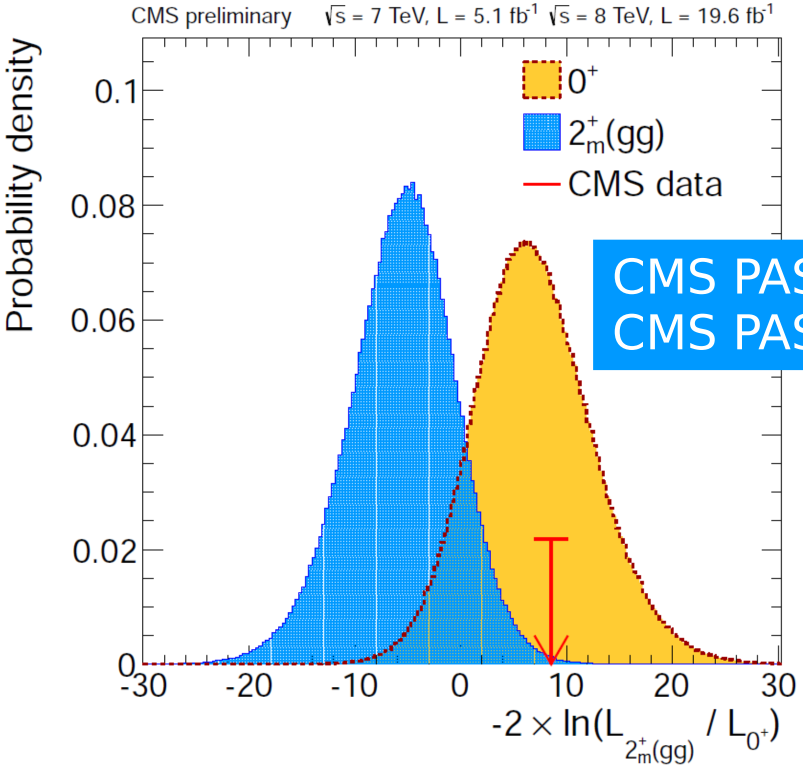
Test 2^+_m hypothesis with H → ZZ*/WW*/γγ

- Graviton resonance 2^+_m produced either through gg or qq → different f_{qq}
- H → WW: MVA combining m_{ll},$\Delta\phi^{ll}$, p_T^{ll}, m_T
- H → γγ: observable is scattering angle in Collins-Sopper frame:

$$\cos(\theta^*_{CS}) = 2 \times \frac{E_2 p_{z1} - E_1 p_{z2}}{m_{\gamma\gamma}\sqrt{m^2_{\gamma\gamma} + p^2_{T\gamma\gamma}}}$$



ATLAS arXiv:1307.1432



CMS PAS HIG-13-016
CMS PAS HIG-13-005

ATLAS combined: 2^+_m excluded @ more than 99.95% CL for all f_{qq}

CMS H → ZZ*/WW*: 2^+_m excluded @ 99.4% CL for f_{qq} = 0

Summary of the properties

- The mass of the new boson is measured with a precision of 0.50%!

  ATLAS: $m_H = 125.5 \pm 0.2\ (\mathrm{stat.})\ ^{+0.5}_{-0.6}\ (\mathrm{syst.})$ GeV

  CMS: $m_H = 125.7 \pm 0.3\ (\mathrm{stat.}) \pm 0.3\ (\mathrm{syst.})$ GeV

- The combined signal strength is compatible with unity:

  ATLAS ($\gamma\gamma$,WW*,ZZ*,bb,$\tau\tau$): $\mu = 1.23 \pm 0.18$

  CMS ($\gamma\gamma$,WW*,ZZ*,bb,$\tau\tau$): $\mu = 0.80 \pm 0.14$

- Evidence for production via vector boson fusion established

- Couplings to fermions and bosons are consistent with the SM prediction

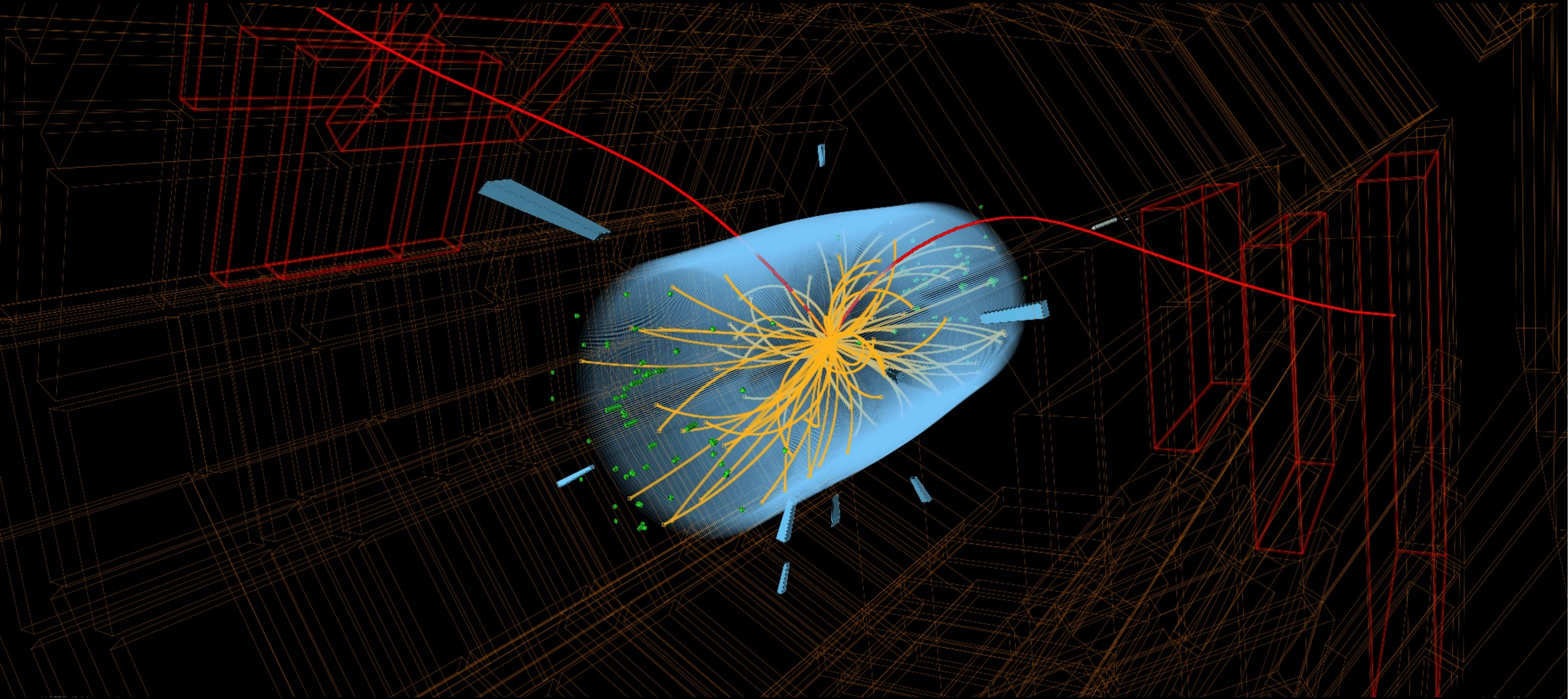
  → *see talks of Stefan Gadatsch and Stefano Casasso*

- An upper limit on the decay width is obtained for the first time

- The observed boson is consistent with the scalar hypothesis (0^+) and other hypotheses have been rejected at 97% CL or more

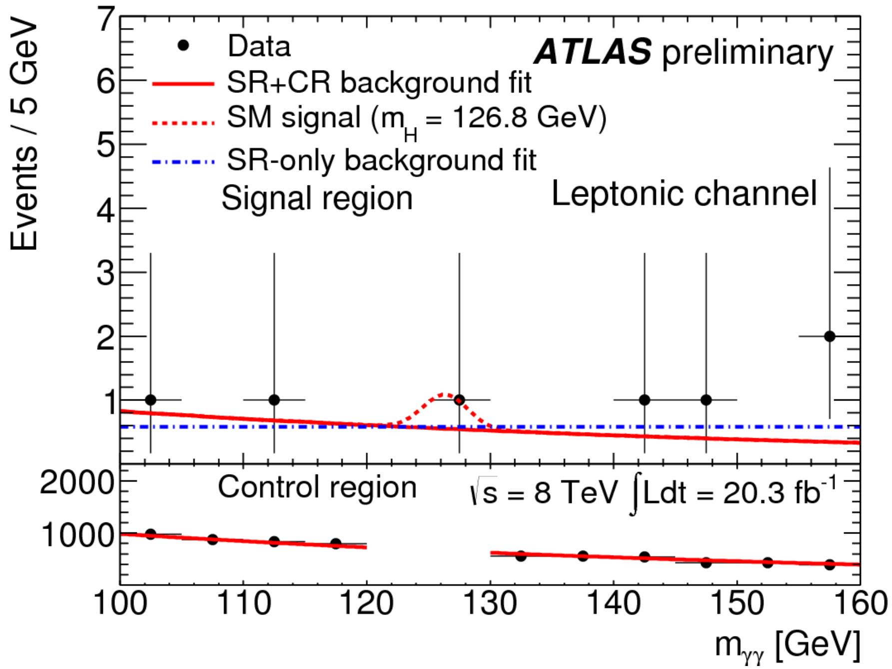
  → *see talks of Manuela Venturi and Kalanand Mishra*

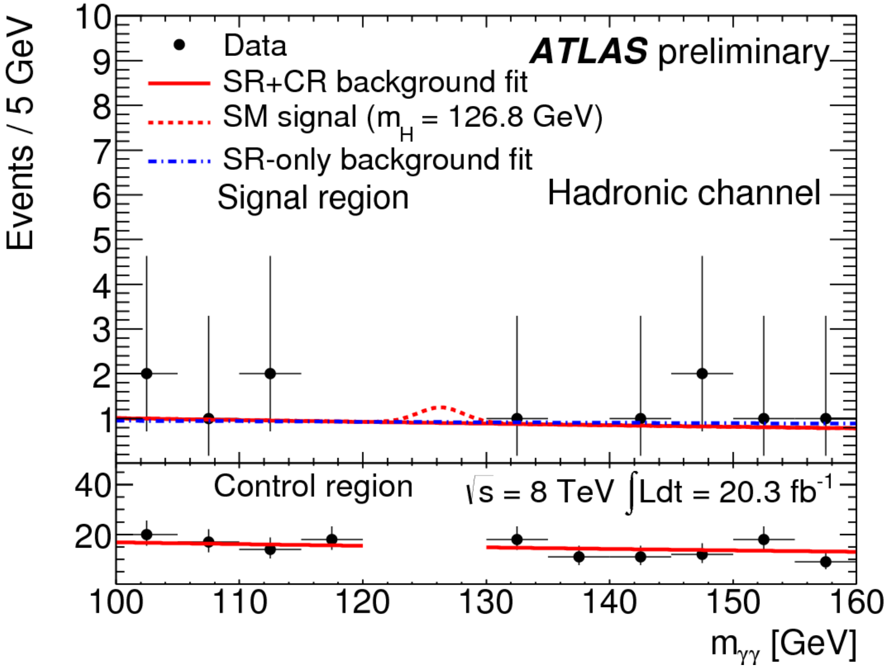
Rare processes

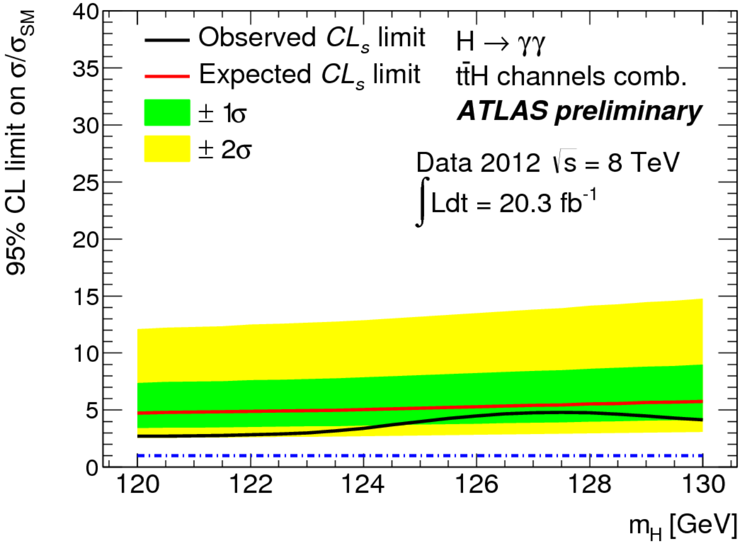


ATLAS H → γγ produced with tt

- Leptonic channel: γγ, ≥ 1 e/μ, ≥ 1 b jet, ME$_T$ > 20 GeV → 7 events
- Hadronic channel: γγ, 0 e/μ, ≥ 6 jets, ≥ 2 b jets → 11 events







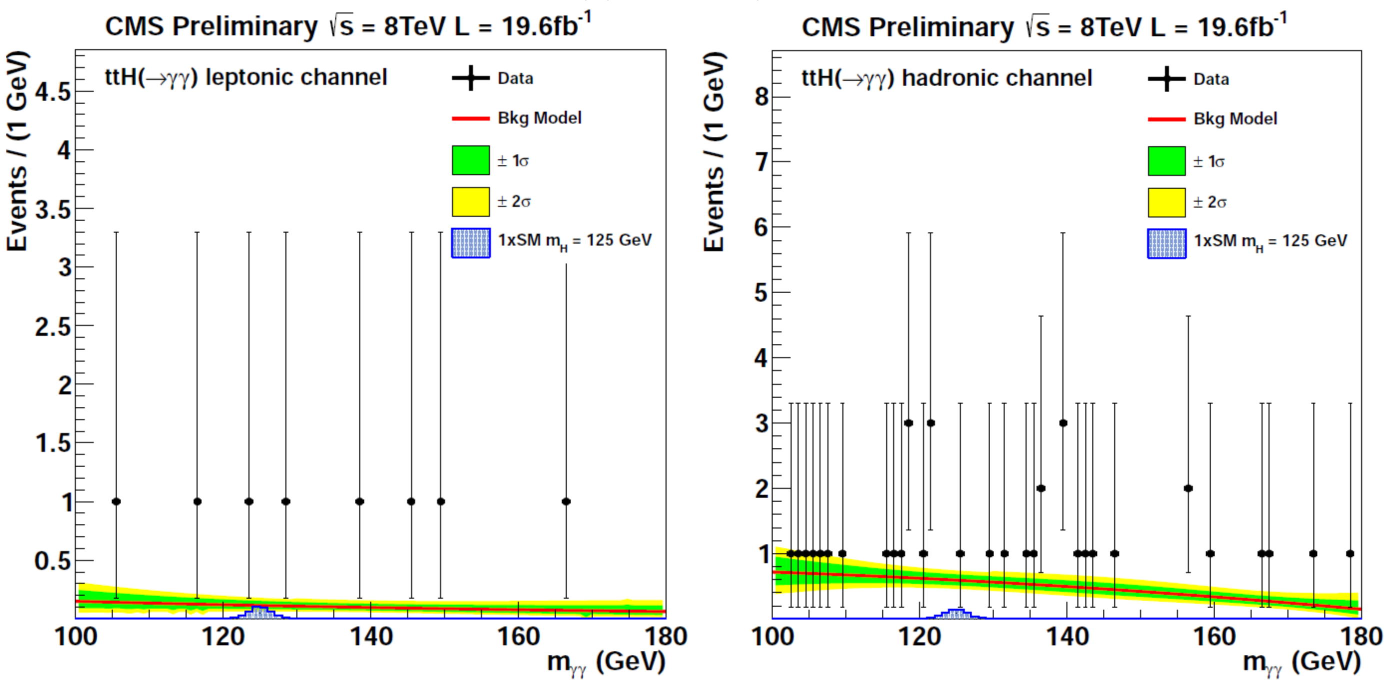
ATLAS-CONF-2013-080

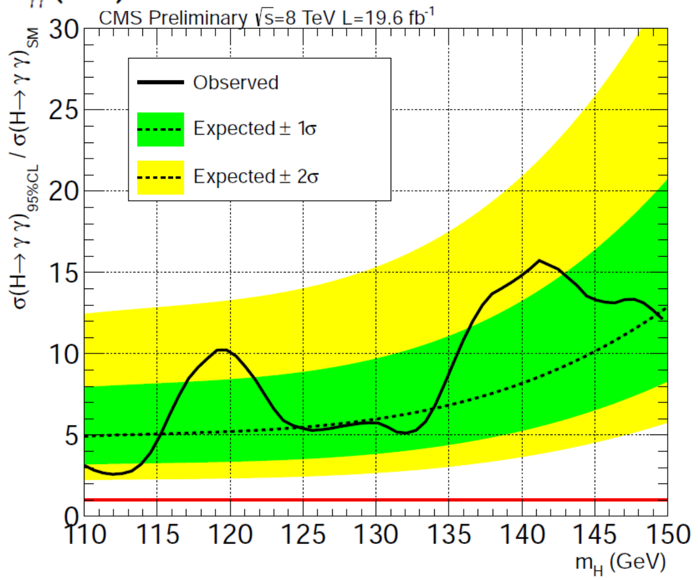
Signal strength: (m$_H$=126.8 GeV)

μ < 5.3 (6.4 expected) @ 95% CL

CMS H → γγ produced with tt

- Leptonic channel: γγ, ≥ 1 e/μ, ≥ 2 jets, ≥ 1 b jet → 8 events
- Hadronic channel: γγ, 0 e/μ, ≥ 5 jets, ≥ 1 b jet → 38 events





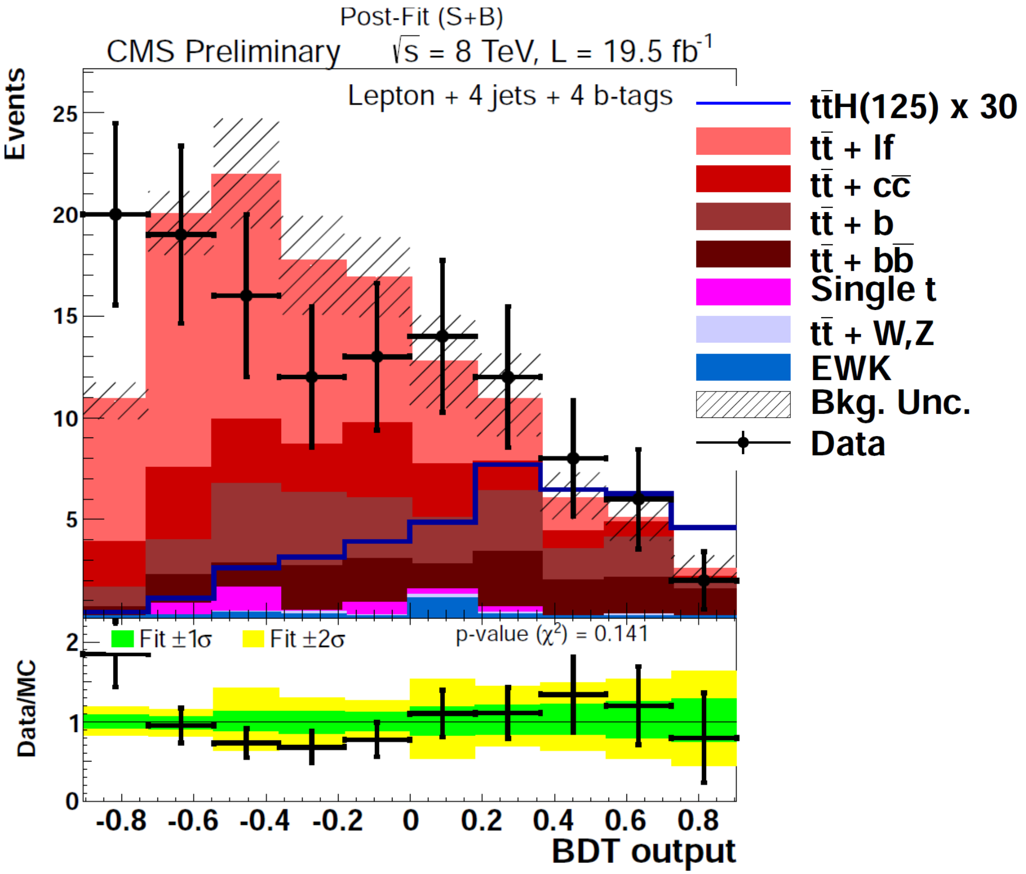
CMS PAS HIG-13-015

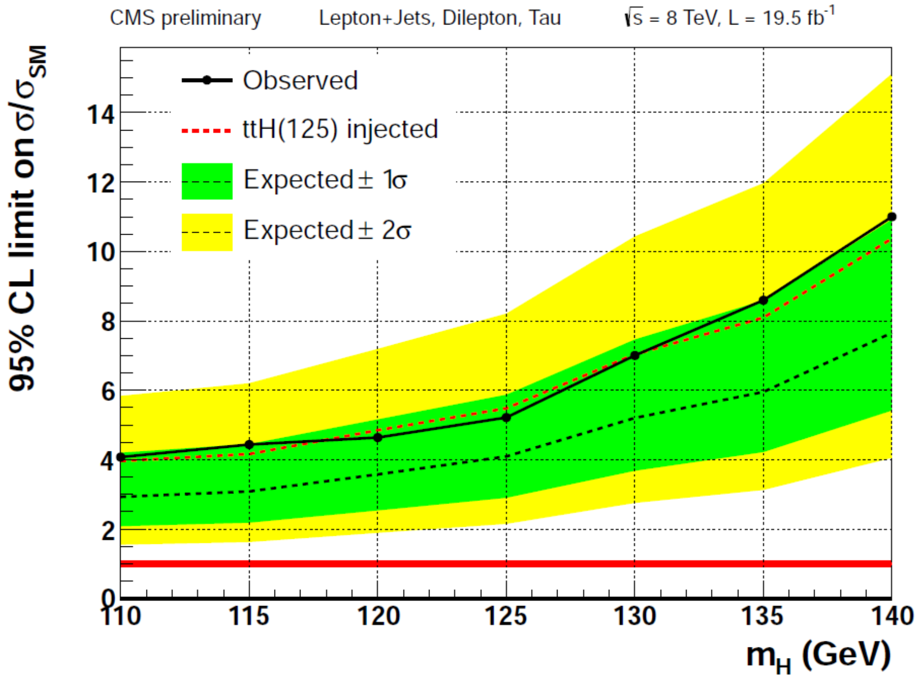
Signal strength: (m_H=125 GeV)

μ < 5.4 (5.3 expected) @ 95% CL

CMS H → bb and H → ττ produced with tt

- H → bb, fully leptonic tt: ≥ 3 jets, ≥ 2 b jets, 2 opposite charge e/μ
- H → bb, semi-leptonic tt: ≥ 4 jets, ≥ 2 b jets, 1 e/μ
- H → $\tau_h\tau_h$: semi-leptonic tt, ≥ 4 jets, ≥ 1 b jet, 2 τ_h jets, 1 e/μ
- Shape of MVA distributions (depending on # jets, # b jets) is fitted





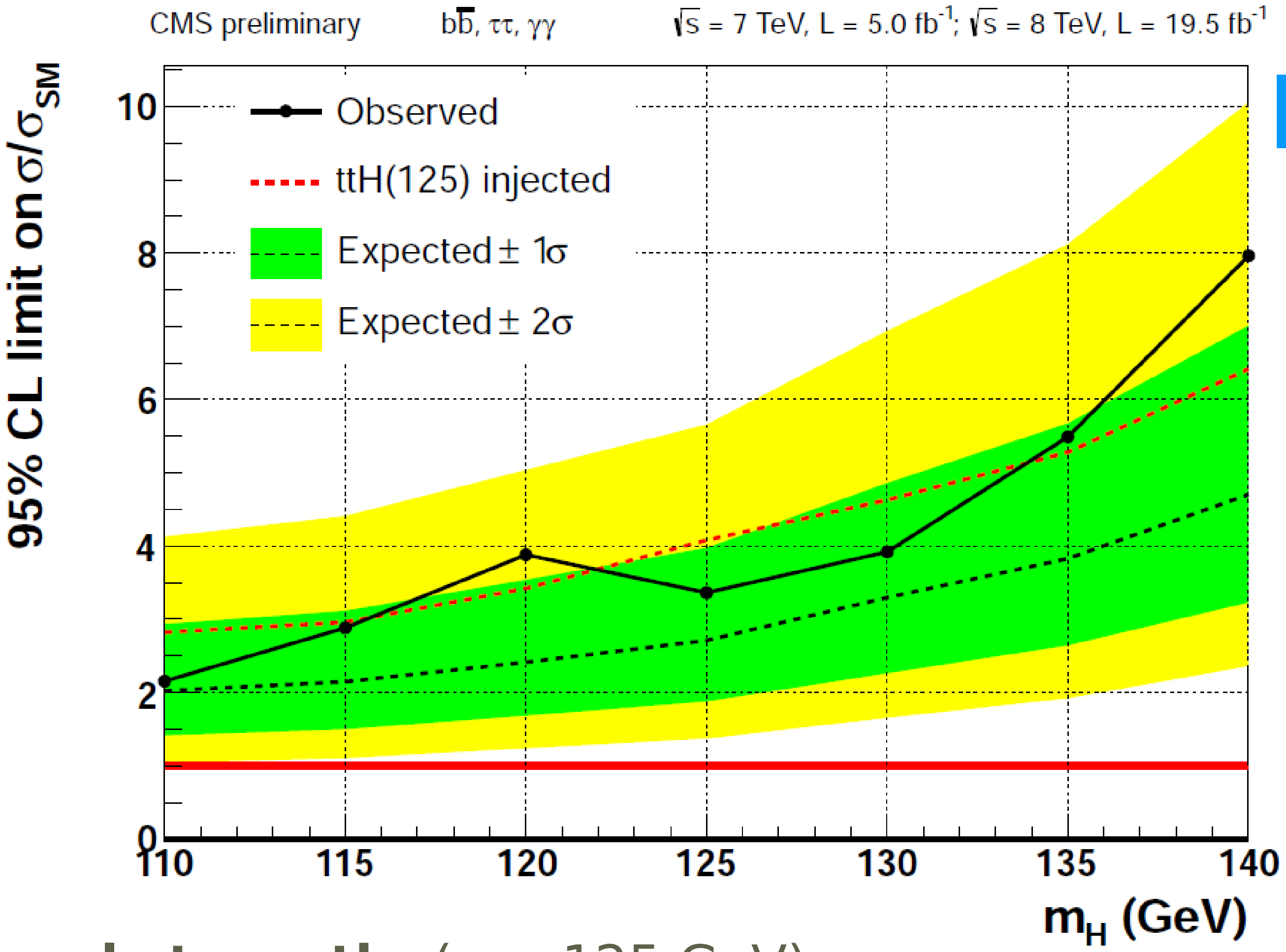
CMS PAS HIG-13-019

Signal strength: (m_H=125 GeV)

μ < 5.2 (4.1 expected) @ 95% CL

CMS combination ttH searches

- Combine the H → bb/ττ search with the H → γγ search



CMS PAS HIG-13-019

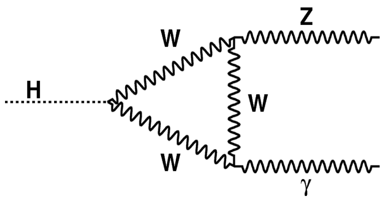
Signal strength: (m_H=125 GeV)

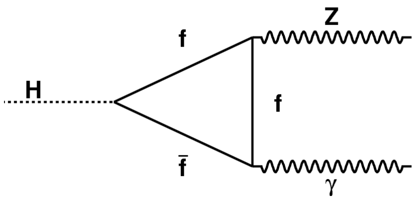
μ < 3.4 (2.7 expected) @ 95% CL

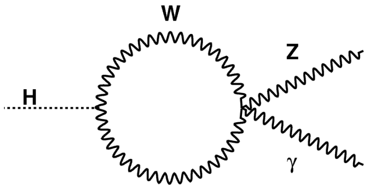
- Rapidly becoming sensitive to ttH production!

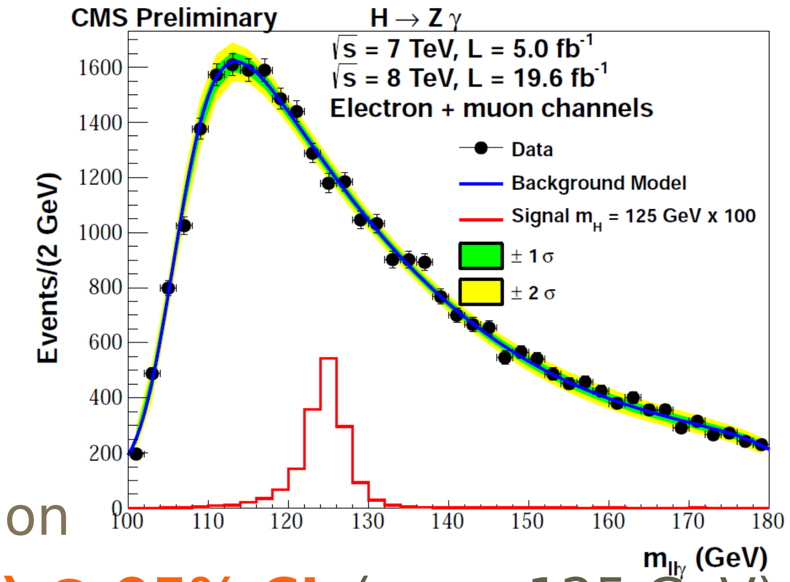
H → Zγ: test for new physics

- B(H → Zγ) comparable to (H → γγ), but multiply with B(Z → ll)
- Sensitive to new physics via loops:





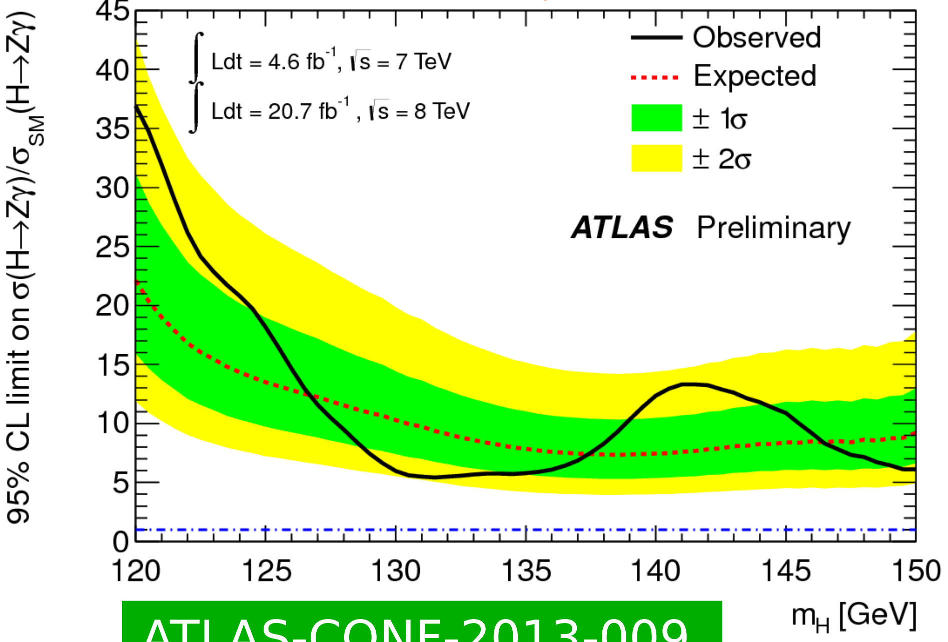




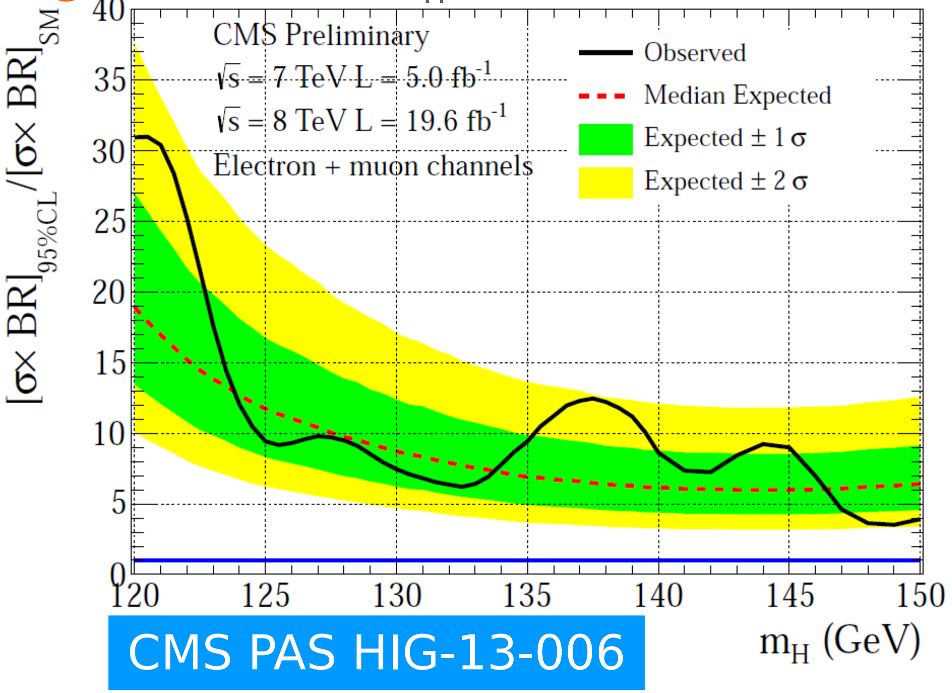
- Shape analysis: $m_{ll\gamma}$ or $\Delta m = m_{ll\gamma} - m_{ll}$ distribution

ATLAS signal strength **μ < 18.2 (13.5 exp.) @ 95% CL** (m_H = 125 GeV)

CMS signal strength **μ < 10 (12 exp.) @ 95% CL** (m_H = 125 GeV)



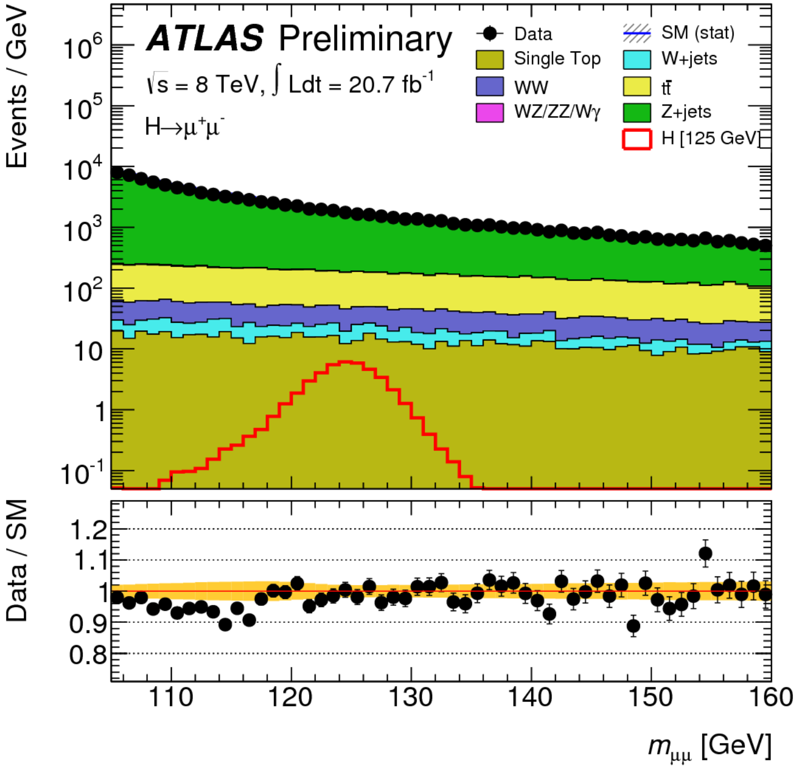
ATLAS-CONF-2013-009

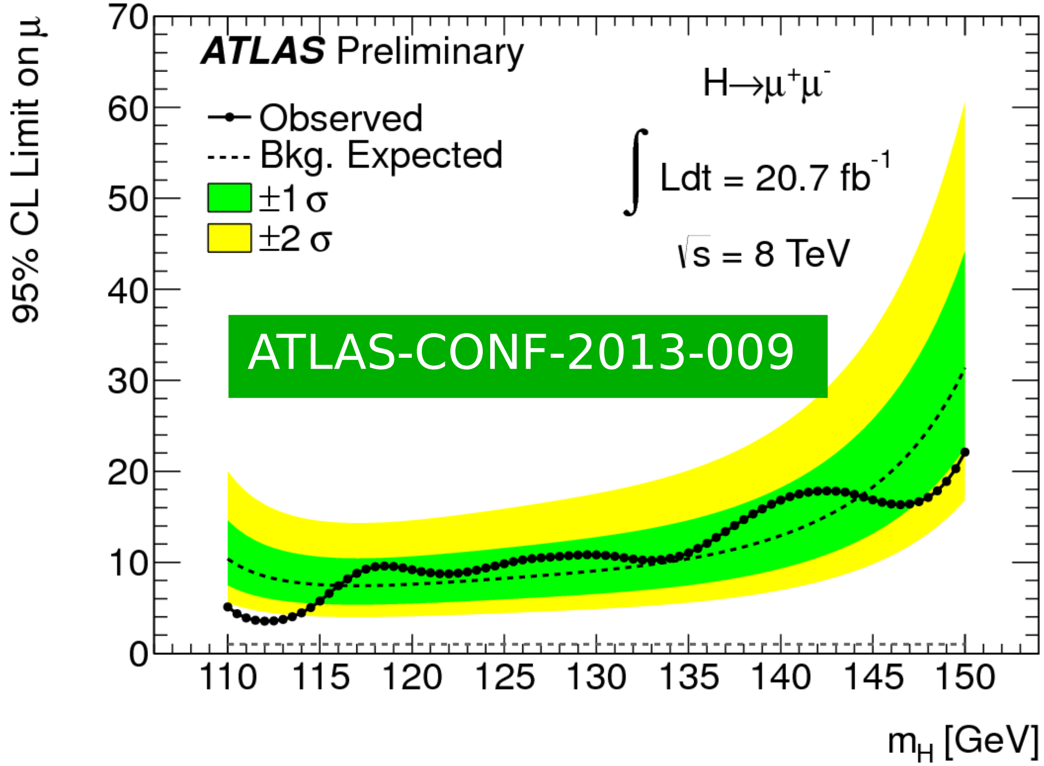


CMS PAS HIG-13-006

ATLAS H → μμ: very challenging!

- The only channel where the Higgs coupling to second generation fermions can be measured!
- In the Standard Model: $B(H \to \mu\mu) \sim 2\text{x}10^{-4}$ (much larger in MSSM!)
- Dominant irreducible background $Z/\gamma^* \to \mu\mu$
- 2 categories: central muons ($|\eta(\mu_{1,2})|<1$), non-central



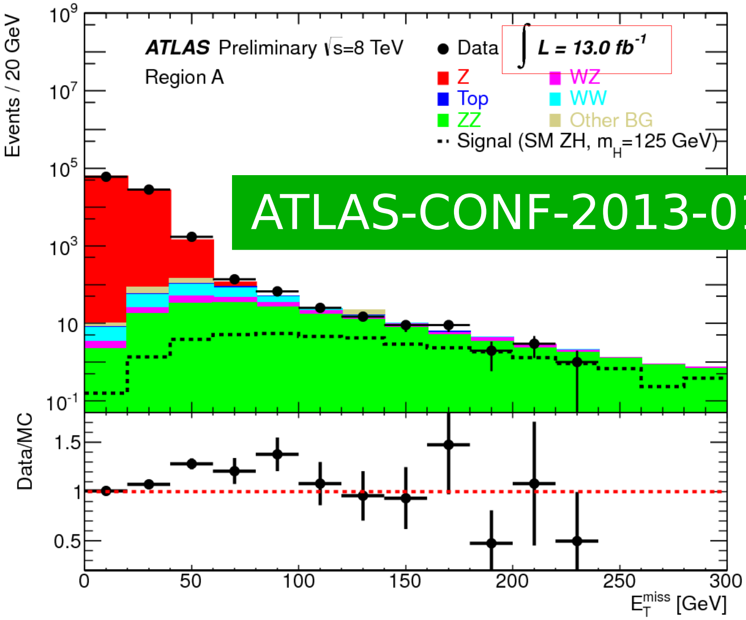


Signal strength: **μ < 9.8 (8.2 expected) @ 95% CL** (m_H = 125 GeV)

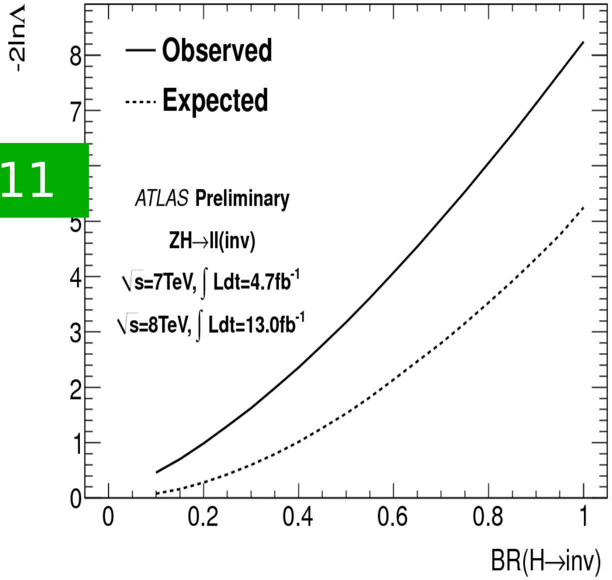
- Much more statistics needed!

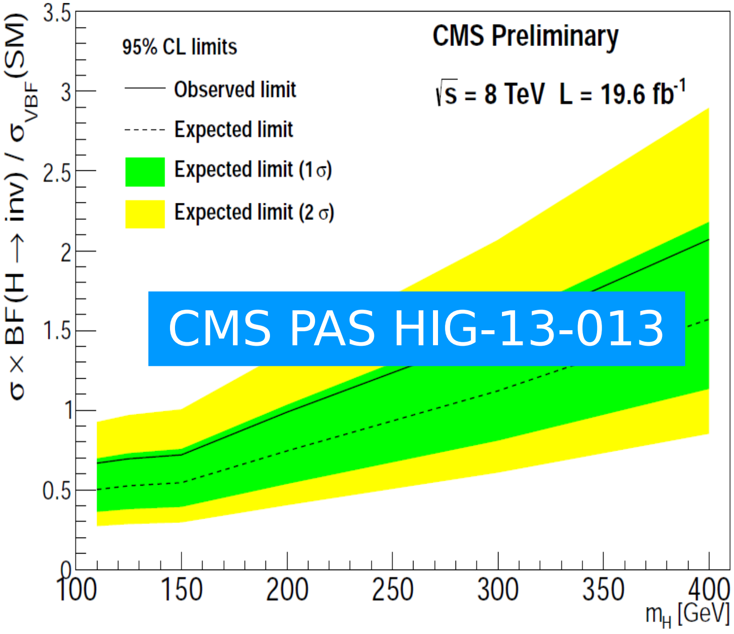
Direct search for H → invisible

- Many models beyond the SM accommodate invisible decay modes
  → place upper limit on the branching fraction
- CMS: ME$_T$ + 2 jets consistent with VBF topology
- ATLAS (CMS): ZH production, ME$_T$ + dilepton pair consistent with Z
- Contributions to the total background are estimated from control regions



ATLAS-CONF-2013-011





CMS PAS HIG-13-013

For m_H=125 GeV

ATLAS (ZH): BR(H → inv) < 0.65 (0.84 exp) @ 95% CL

CMS (ZH): BR(H → inv) < 0.75 (0.91 exp) @ 95% CL

CMS PAS HIG-13-018

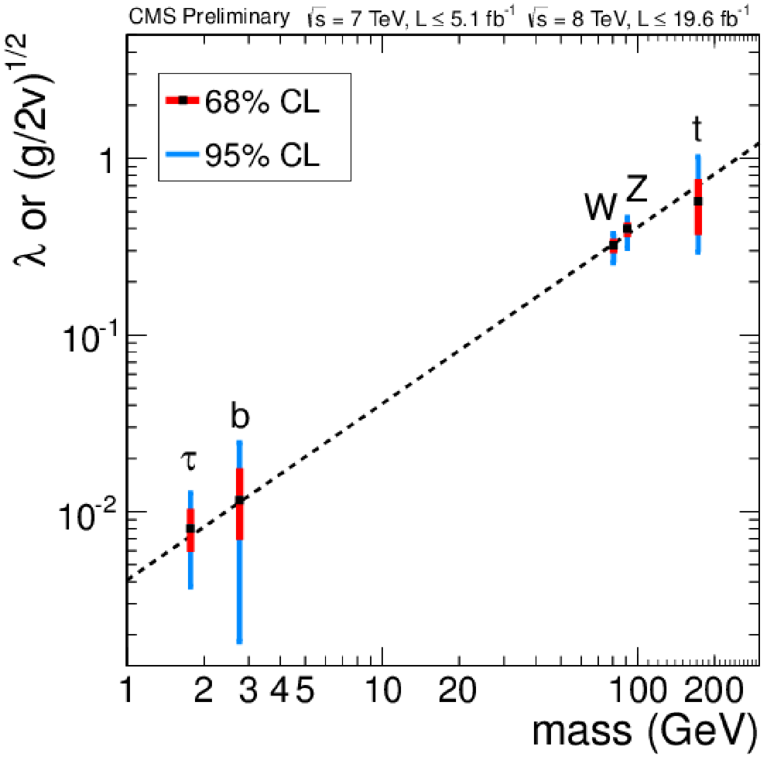
CMS (VBF): BR(H → inv) < 0.69 (0.53 exp) @ 95% CL

The observed particle looks like the Higgs boson

1 year after the discovery of a new boson, its properties have been measured with increasing precision:

- It couples to bosons (W, Z, γ)
- Direct evidence for couplings to fermions
- Signal strength is as expected
- All coupling tests are compatible with the SM prediction
- Evidence for V-mediated production
- The mass is measured with a great precision
- First direct limit on the width
- It favors the scalar spin-parity (0^+) hypothesis
- No sign yet (direct or indirect) for BSM contributions

→ see talks of Pamela Ferrari, Daniel Dominiguez Vazquez, Gianni Masetti, Valdir Salustino Guimaraes



We are not there yet...

- The final (ATLAS+CMS combined) results of Run I will come soon:
  - Observation of H → WW
  - Evidence for H → bb and H → $\tau\tau$
  - Mass combination, ...

- In 2015: higher center of mass energy and luminosity:
  - More precise measurements
  - Observe H → bb and H → $\tau\tau$
  - Observation of ttH production

- Ultimately (HL-LHC):
  - Observe Zγ
  - H → $\mu\mu$: confirm coupling to the 2nd generation
  - Higgs self-coupling

- **The Higgs boson allows us to test the Standard Model and opens an other window on new physics!**

We are not there yet...

- The final (ATLAS+CMS combined) results of Run I will come soon:
  - Observation of $H \to WW$
  - Evidence for $H \to bb$ and $H \to \tau\tau$
  - Mass combination, ...

- In 2015: higher center of mass energy and luminosity:
  - More precise measurements
  - Observe $H \to bb$ and $H \to \tau\tau$
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- Ultimately (HL-LHC):
  - Observe $Z\gamma$
  - $H \to \mu\mu$: confirm coupling to the 2nd generation
  - Higgs self-coupling

- **The Higgs boson allows us to test the Standard Model and opens an other window on new physics!**

Backup

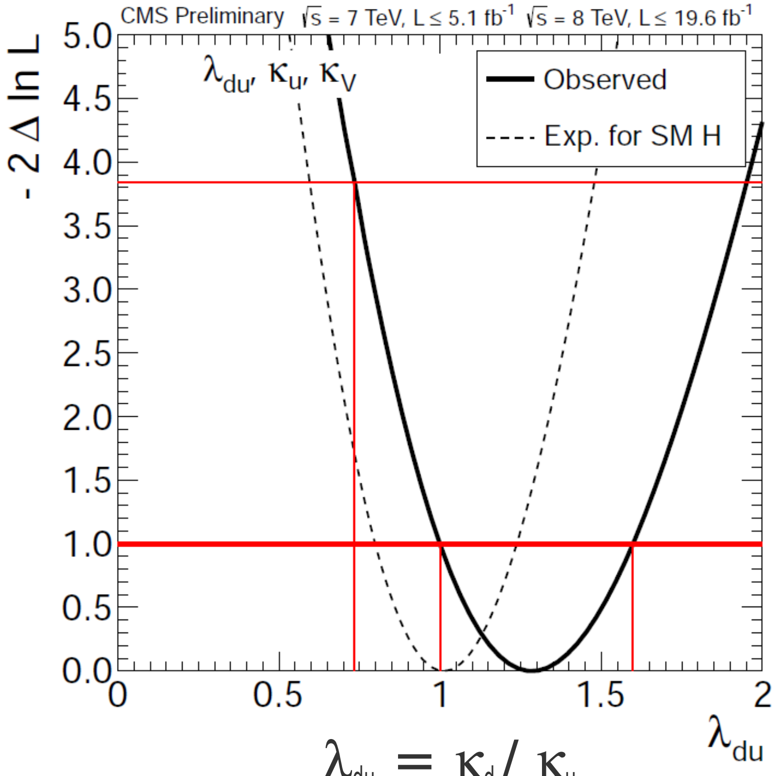
- Asymmetric fermion couplings
- Test of custodial symmetry
- Indirect constraints on BR(H → BSM)

Asymmetric fermion couplings

CMS PAS HIG-13-005

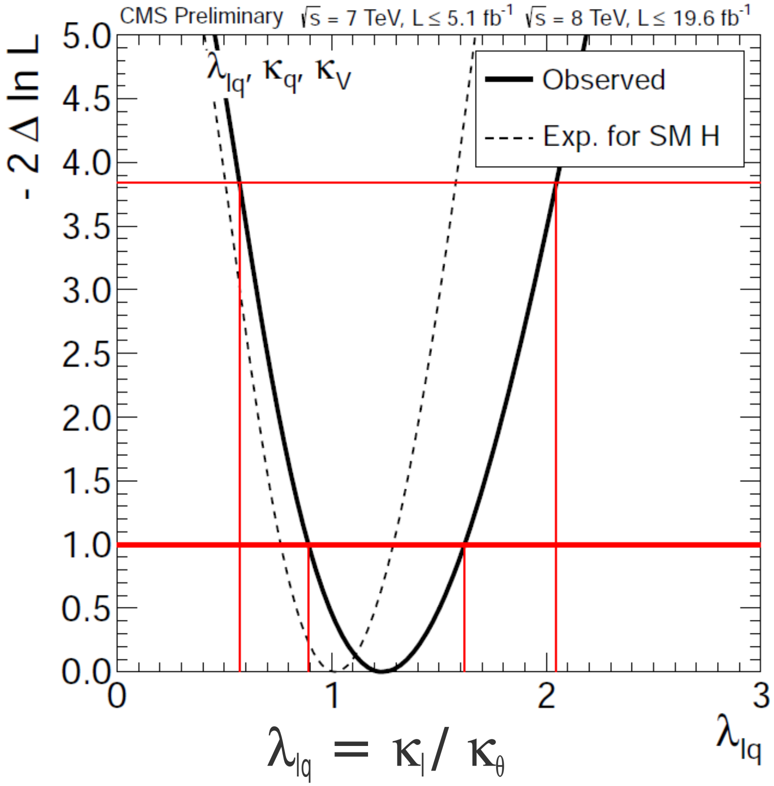
- Assume $\Gamma_{BSM} = 0$
- Fermion couplings might be modified in 2 Higgs boson doublet models

Free parameters: $\lambda_{du} > 0, \kappa_V, \kappa_u$



$\lambda_{du} = \kappa_d / \kappa_u$

Free parameters: $\lambda_{lq} > 0, \kappa_V, \kappa_q$



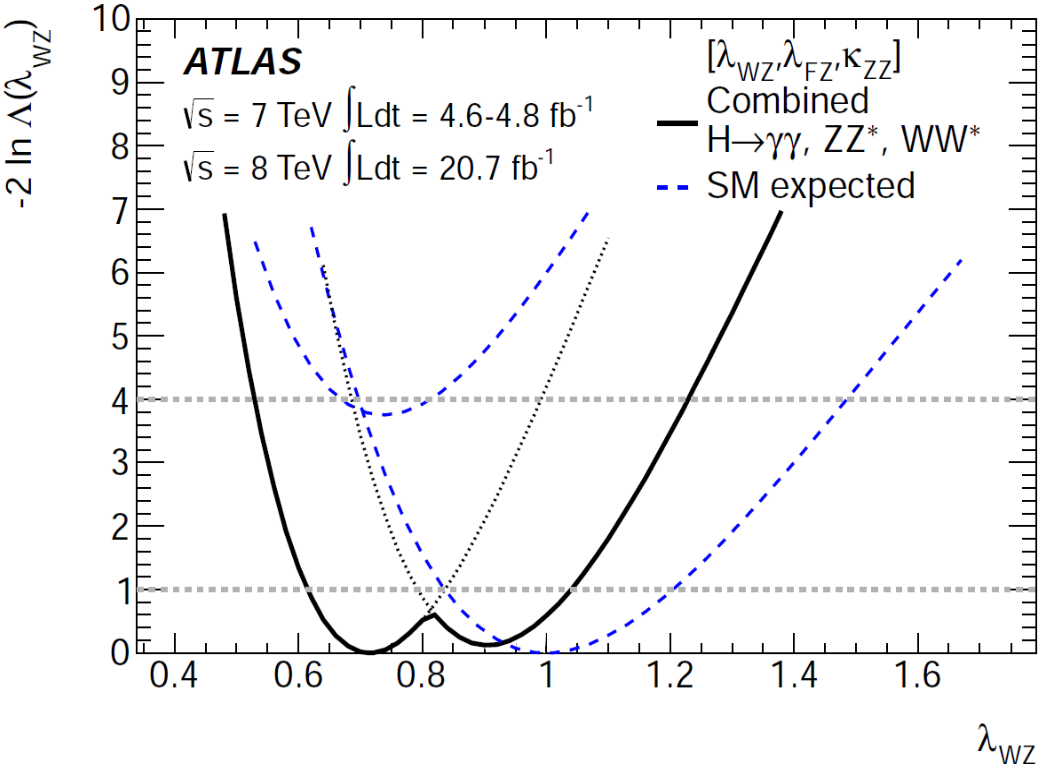
$\lambda_{lq} = \kappa_l / \kappa_\theta$

Consistent with SM predictions

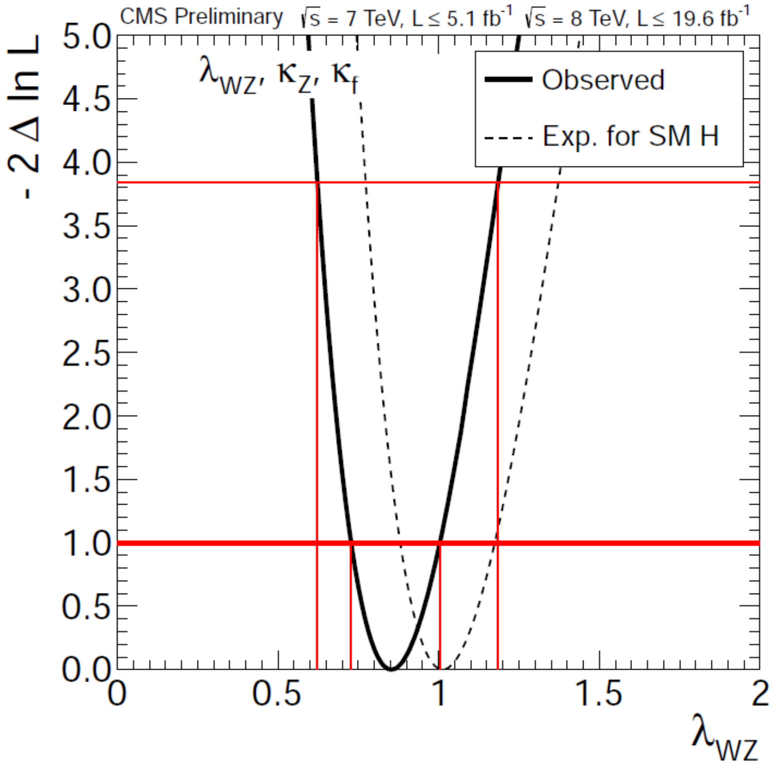
Test of custodial symmetry

- $\lambda_{WZ} = \kappa_W / \kappa_Z$
- No contributions from physics beyond the SM (Γ_{BSM}=0)

ATLAS arXiv:1307.1427



CMS PAS HIG-13-005



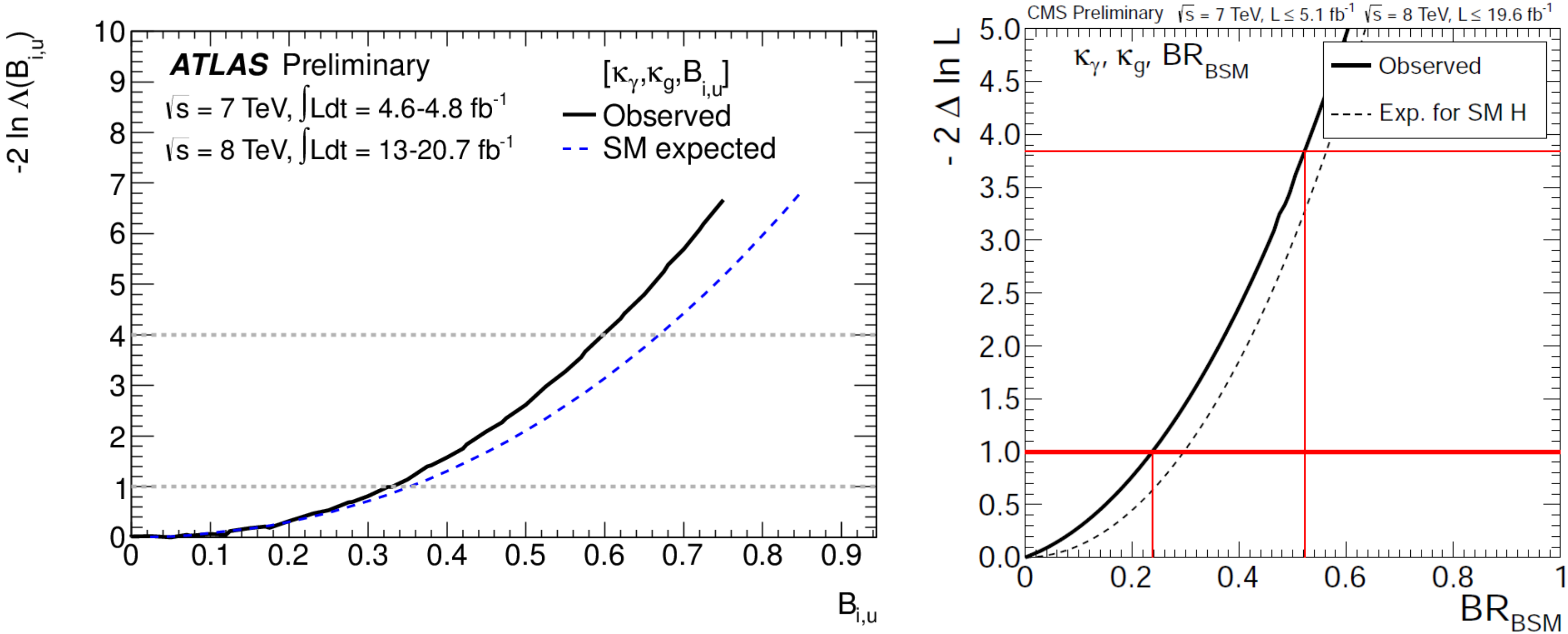
Consistent with SM prediction of λ_{WZ}=1

Constraints on BR(H → BSM)

- New physics may appear in the loops gg → H and H → $\gamma\gamma$
- BR(H → BSM) = $BR_{BSM} = \Gamma_{BSM}/\Gamma_H$ (with $\Gamma_H = \Gamma_{SM}+\Gamma_{BSM}$)
- Sensitive to invisible and undetectable decay modes
- Free parameters in the fit are: κ_g, κ_γ and BR_{BSM} (others = SM value)

ATLAS-CONF-2013-034

CMS PAS HIG-13-005



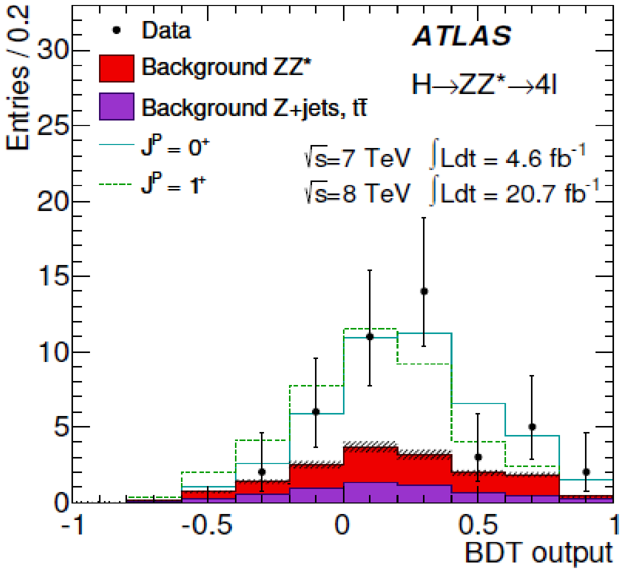
ATLAS: BR_{BSM} < 0.6 @ 95% CL

CMS: BR_{BSM} < 0.52 @ 95% CL

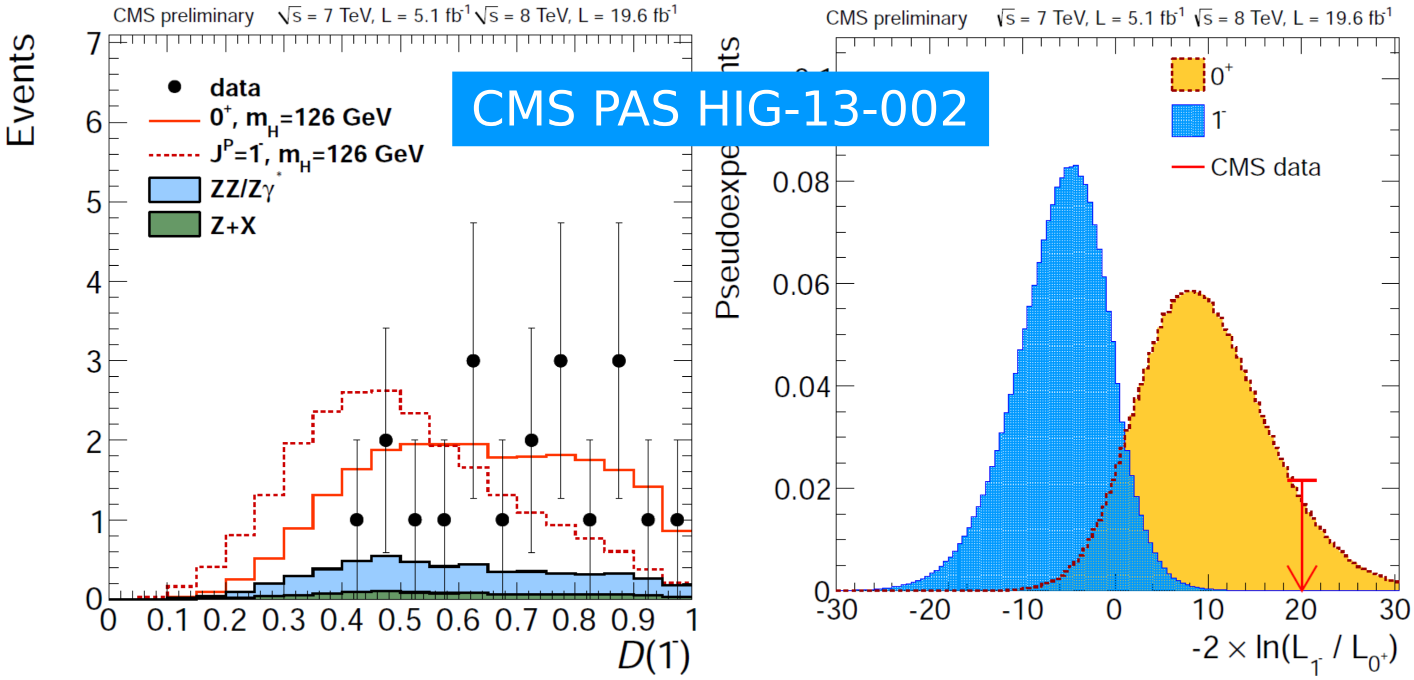
Test $1^+/1^-$ hypothesis with $H \rightarrow ZZ^*$ ($H \rightarrow WW^*$)

- Spin 1 hypothesis is not compatible with $H \rightarrow \gamma\gamma$ observation, still tested!
- $H \rightarrow ZZ \rightarrow 4$ leptons:

  → same technique as 0^-
- ATLAS $H \rightarrow WW \rightarrow l\nu l\nu$: full reconstruction of the final state is not possible, use m_{ll}, $\Delta\phi_{ll}$, p_T^{ll}, m_T and combine with MVA



ATLAS arXiv:1307.1432



CMS PAS HIG-13-002

ATLAS combined: 1^+ excluded @ 99.97% CL, 1^- excluded @ 99.7% CL

CMS $H \rightarrow ZZ^*$: $1^+/1^-$ excluded @ more than 99.99% CL