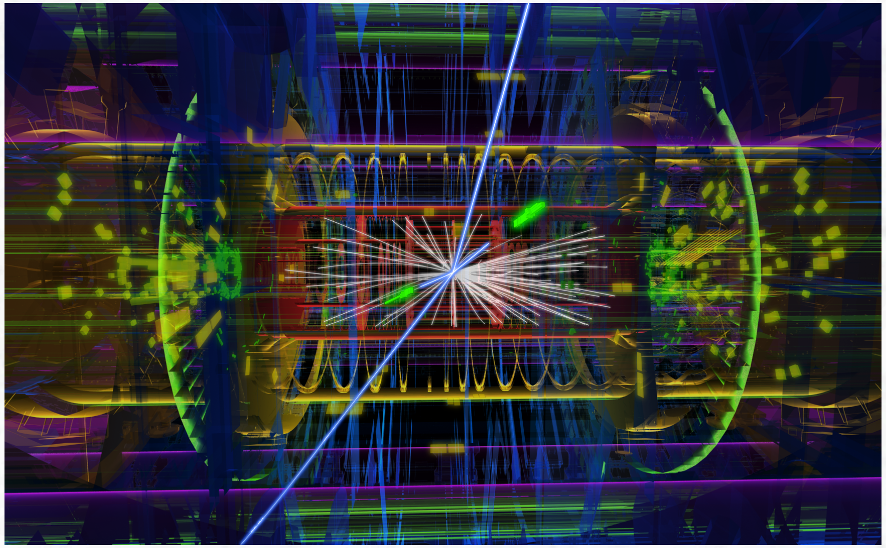
Higgs analyses at the LHC

Part IIb: VH, H → bb
Part III: Higgs boson parameters



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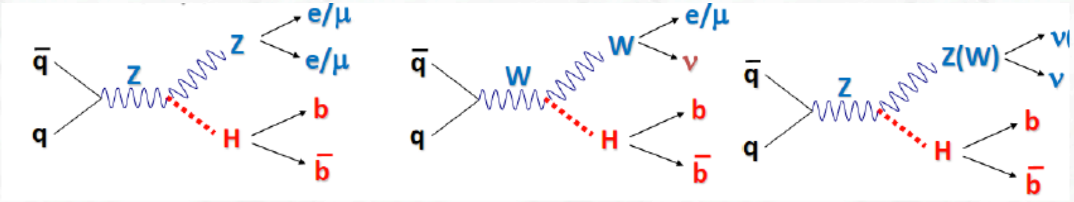
Search for VH production with H → bb decays



- Exploit three leptonic vector boson decay modes
  → split analysis in 0, 1, and 2-lepton categories

- Require 2 b-tagged jets
  (working point for 70% efficiency)

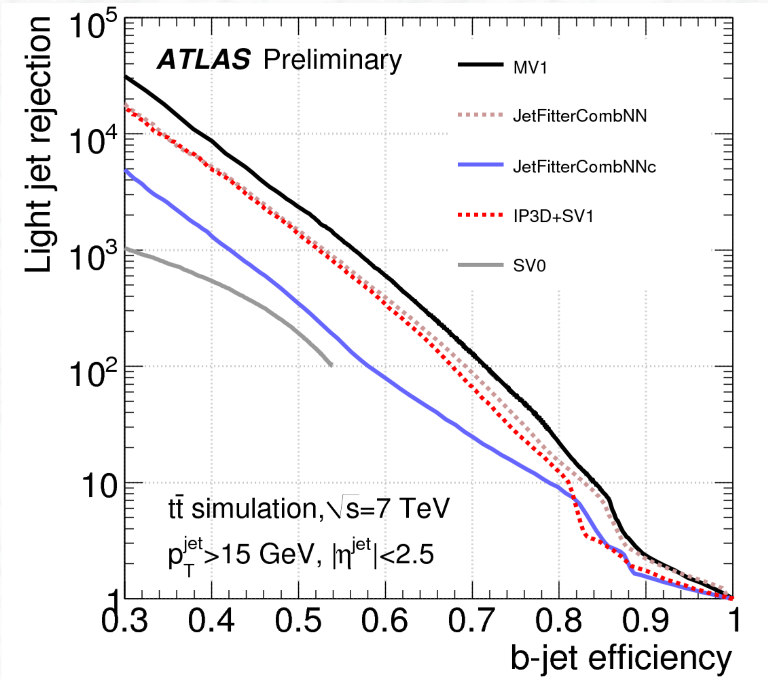
- Major background: W/Z bb, W+jets, tt

- Signal-to-background ratio improves for "boosted Higgs boson",
  split analysis in bins of $p_T(V)$

  ATLAS: in total 15 categories
  (0,1,2 jets × p_T bins)

  CMS: multivariate analysis

ATLAS-CONF-2012-161



Event selection for H → bb analyses

(i) Basic event selection for the three channels

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_T^{\text{jet}_1} > 45$ GeV $p_T^{\text{jet}_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_T^{\text{miss}} > 120$ GeV $p_T^{\text{miss}} > 30$ GeV $\Delta\phi(\boldsymbol{E}_T^{\text{miss}}, \boldsymbol{p}_T^{\text{miss}}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_T^{\text{miss}}, \text{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_T^{\text{miss}}, b\bar{b}) > 2.8$	$E_T^{\text{miss}} > 25$ Gev	$E_T^{\text{miss}} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

(ii) Further topological criteria in intervals of $p_T(V)$

	p_T^V [GeV]	0-90	90-120	120-160	160-200	>200
All Channels	$\Delta R(b, \bar{b})$	0.7-3.4	0.7-3.0	0.7-2.3	0.7-1.8	<1.4
1-lepton	E_T^{miss} [GeV]	>25				>50
	m_T^W [GeV]	40-120			<120	

Definition of signal and control regions

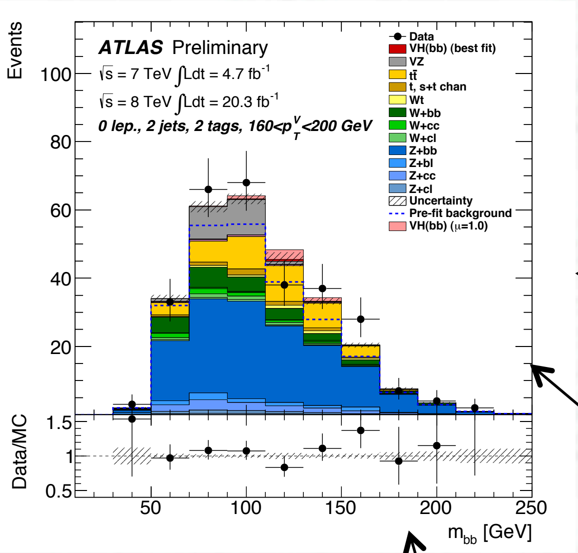
	2jets, 1tag	3jets, 1tag	2jets, 2tag	3jets, 2tag	top e-μ CR
3 p_T^V bins x **0-lepton**	CR	CR	SR	SR	-
5 p_T^V bins x **1-lepton**	CR	CR	SR	SR	-
5 p_T^V bins x **2-lepton**	CR	CR	SR	SR	CR

CR=Control Region (low S/B)
SR=Signal Region

top e-μ CR: 1 electron+1 muon, m_{ll}>40 GeV

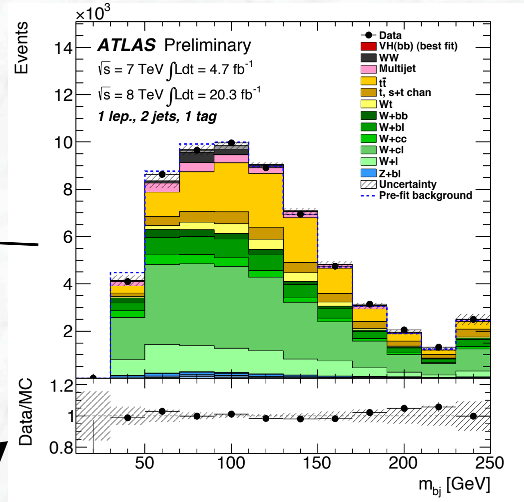
- Common nuisance parameters across regions
- Systematic uncertainties on extrapolation between control and signal regions

Background normalization, interplay of regions



Signal region: 0 leptons, 2 jets, 2 b-tags

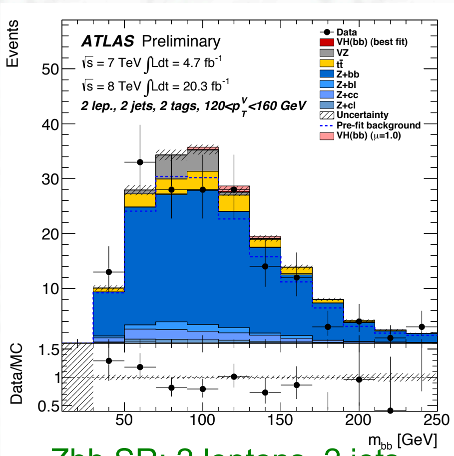
W+jets



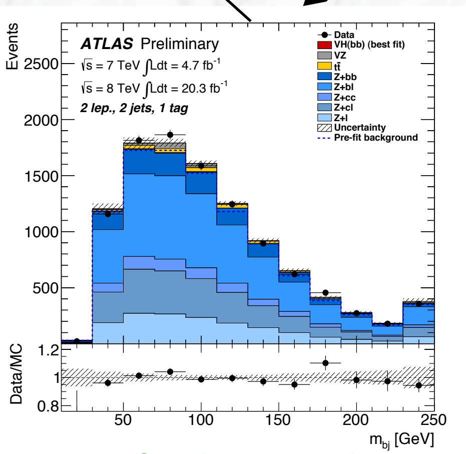
W+jets CR: 1 leptons, 2 jets, 1 b-tag

Z+jets, Zbb

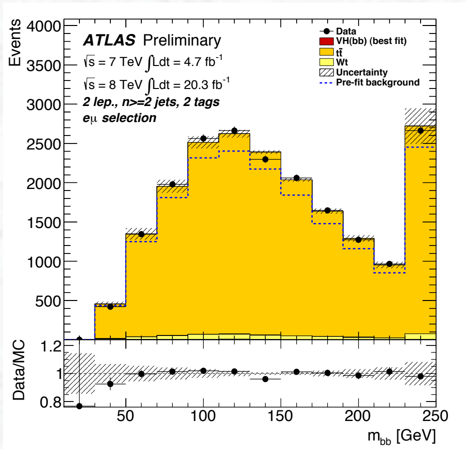
Top



Zbb SR: 2 leptons, 2 jets, 2 b-tags



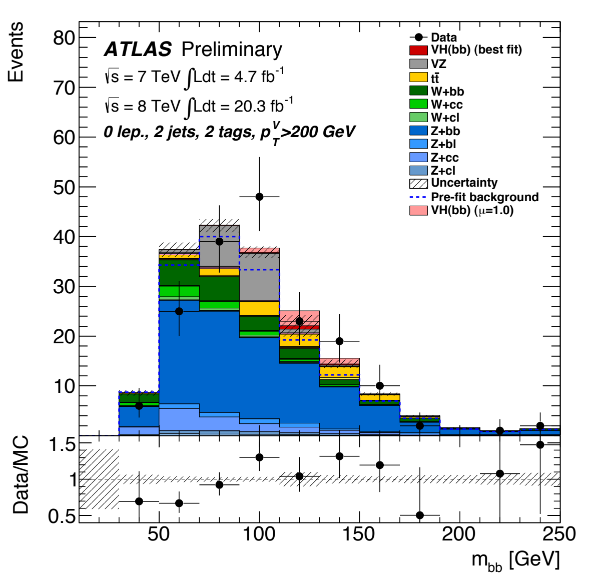
Z+jets CR: 2 leptons, 2 jets, 1 b-tags



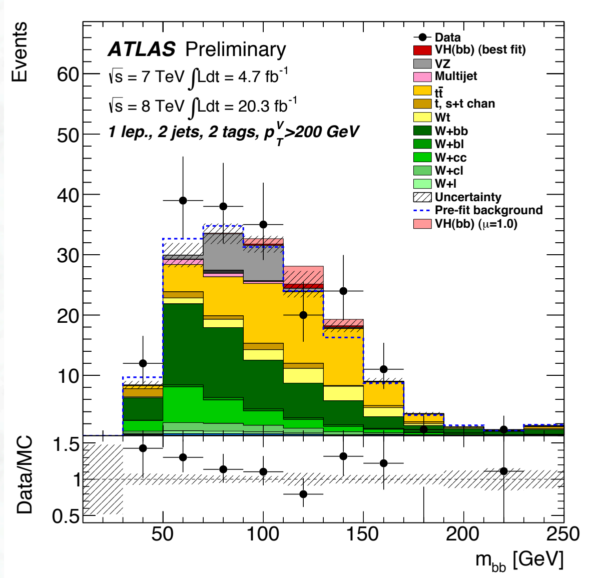
Top CR: 2 leptons, >=2 jets, 2 b-tags, eμ selection

Reconstructed mass distributions

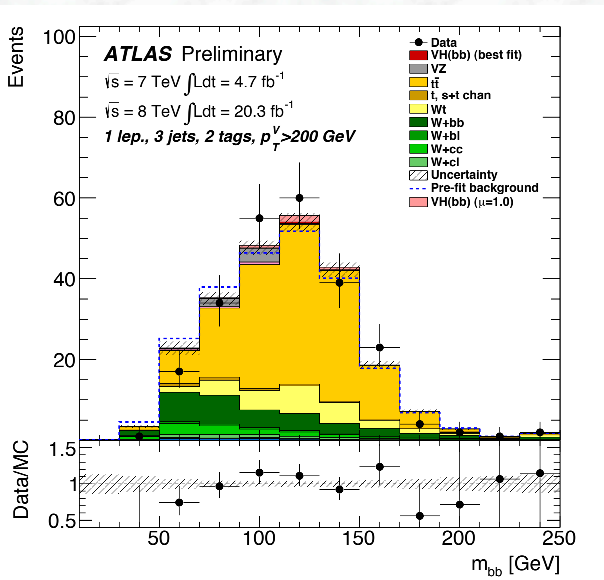
-full data set, 7 and 8 TeV (a selection, high p_T bins)-



0 lepton



1 lepton

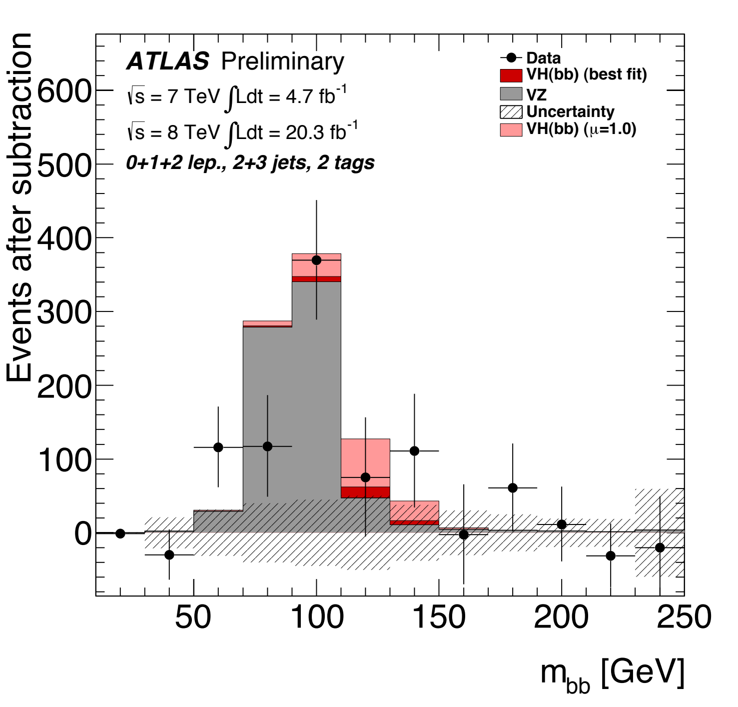


2 leptons

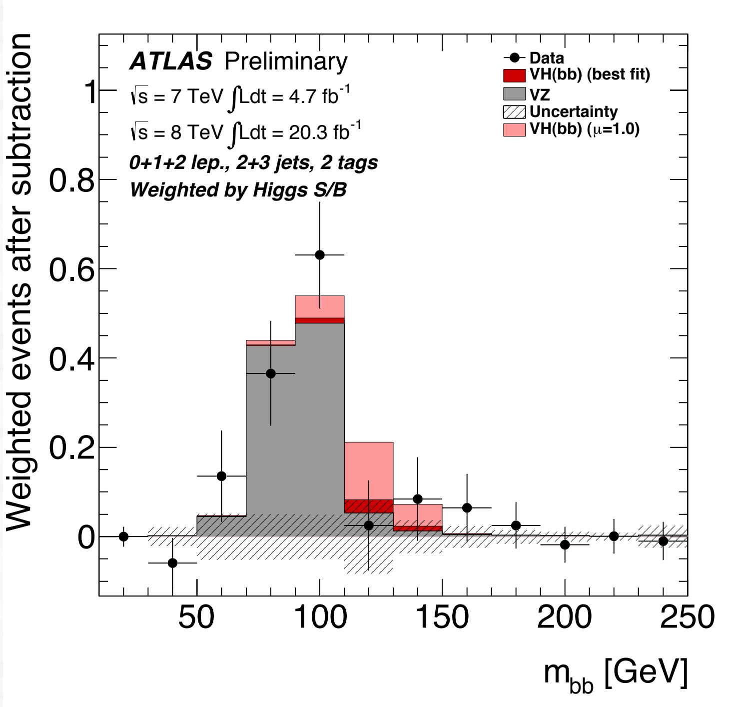
ATLAS-CONF-2013-079

Demonstration of di-boson production with Z → bb in ATLAS

combination (all bins, channels)
data - background



weighted distribution, by S/B ratio



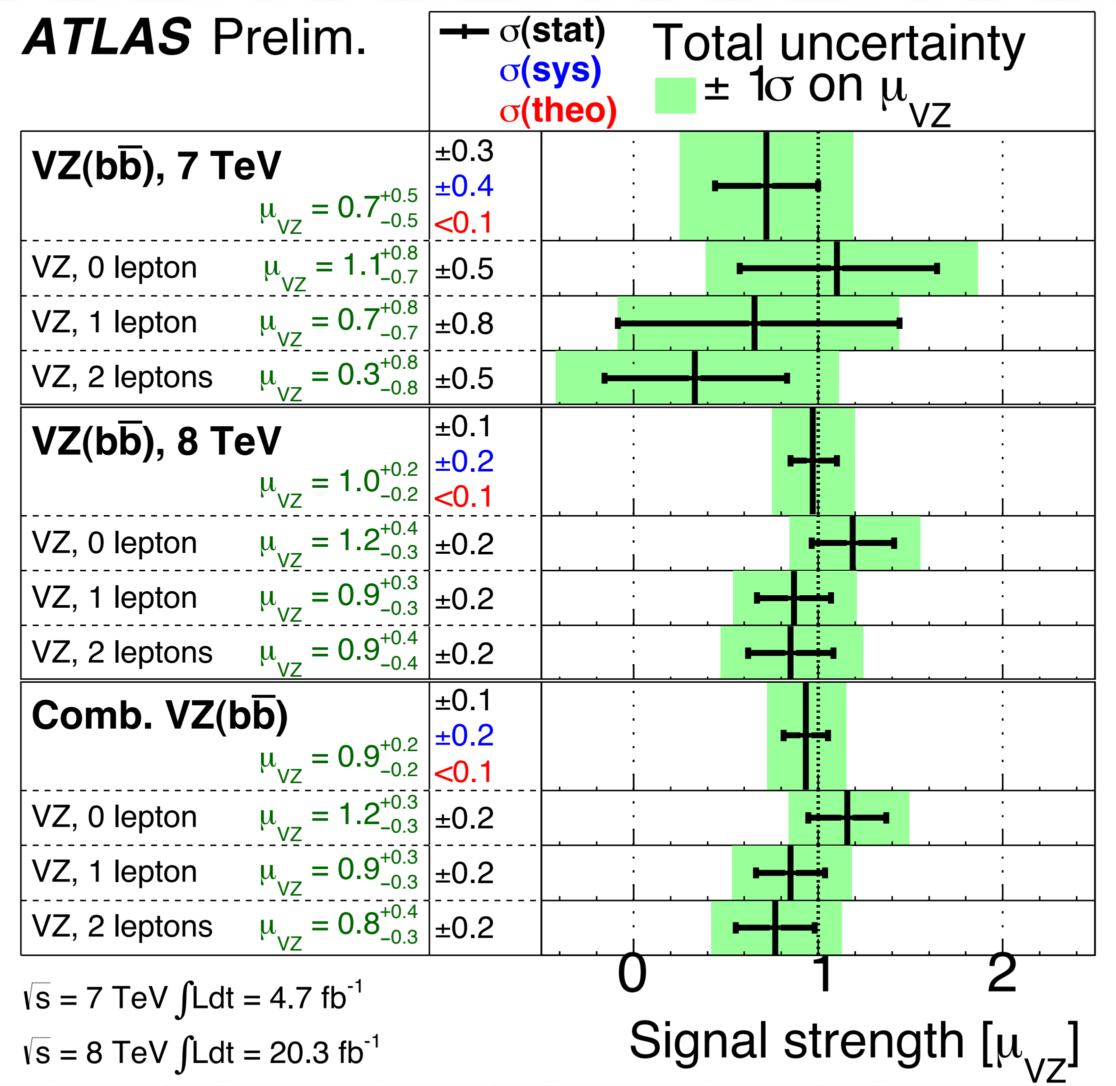
Di-boson signal established
(important "calibration" signal; a Standard Model Higgs boson signal is included as background)

Significance 5.1σ

$\mu_{WZ+WW} = 0.90 \pm 0.20$

ATLAS-CONF-2013-079

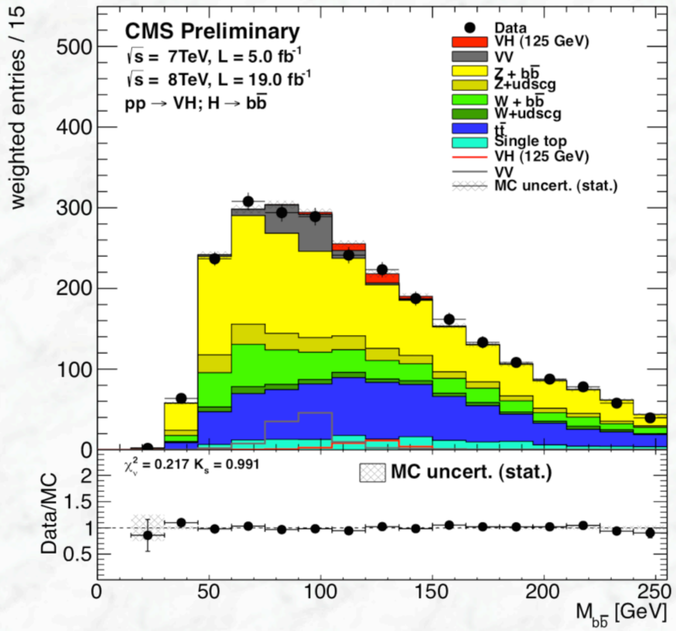
Di-boson signal strength



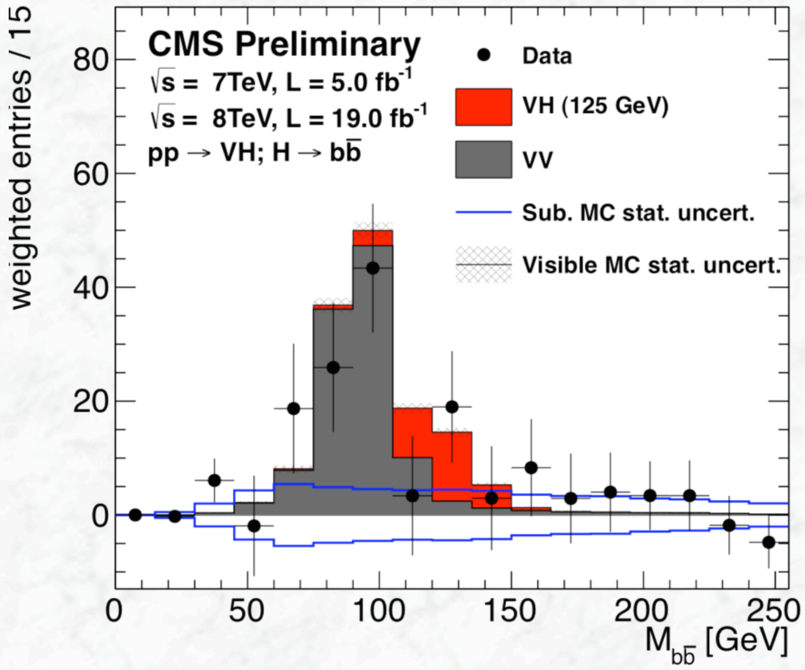
ATLAS-CONF-2013-079

Demonstration of di-boson production with Z → bb in CMS

Weighted (by S/B ratio) m_{bb} mass distribution



Weighted (by S/B ratio) background-subtracted m_{bb} mass distribution



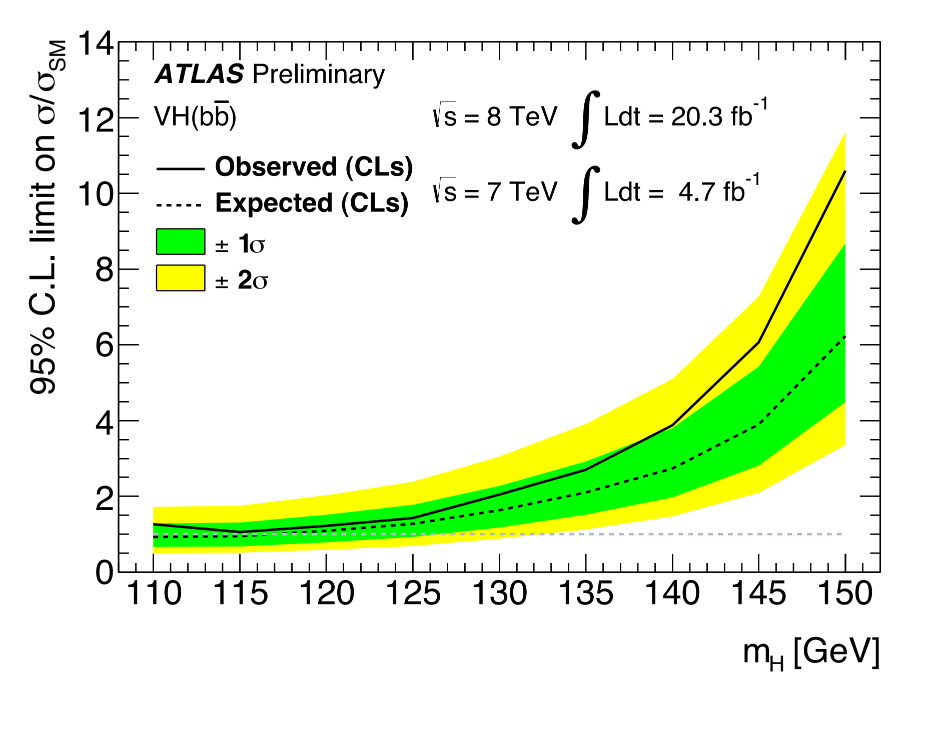
- Di-boson signal established

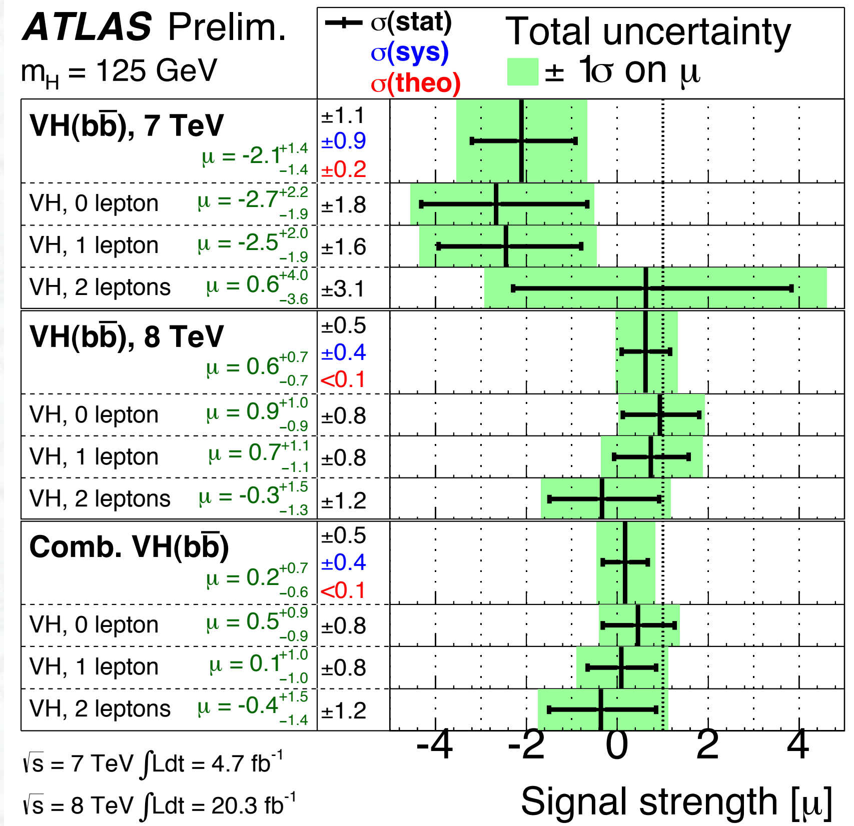
- Signal size consistent with expectations from Standard Model

CMS PAS HIG-13-012

ATLAS results on the search for VH, H → bb decays

ATLAS-CONF-2013-079





m_H = 125 GeV:

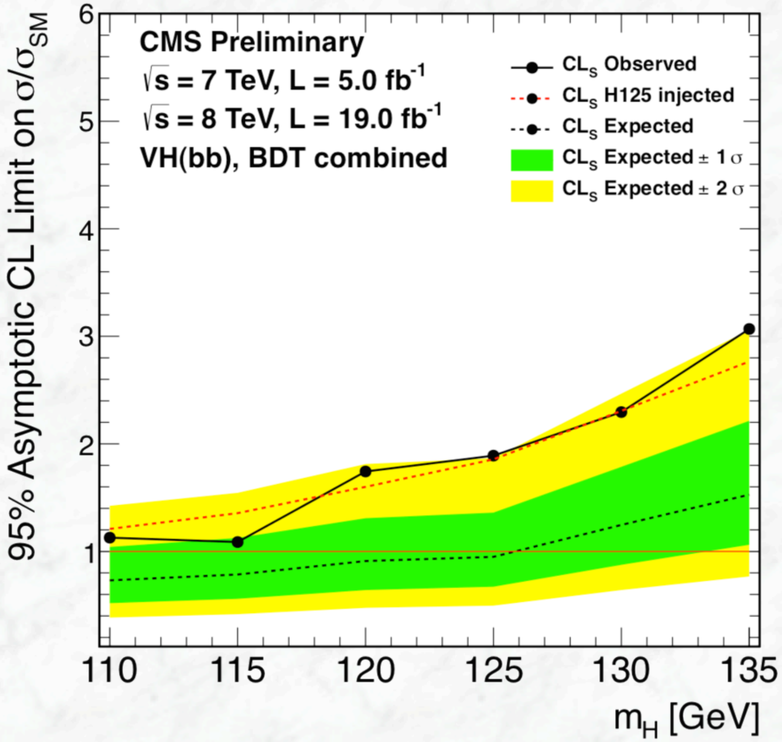
Observed 95% CL: 1.4 σ_{SM}
Expected (no Higgs): 1.3 σ_{SM}

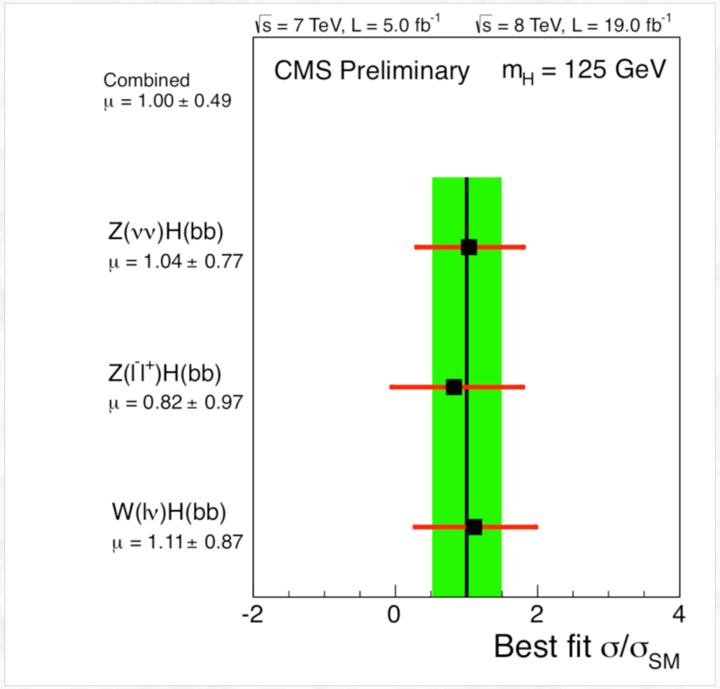
μ_H = 0.2 ± 0.5 (stat) ± 0.4 (syst)

Probability of obtaining a result more background-like than the observed in the presence of a SM signal (μ=1) is 0.11

CMS results on the search for VH, H → bb decays

CMS PAS HIG-13-012





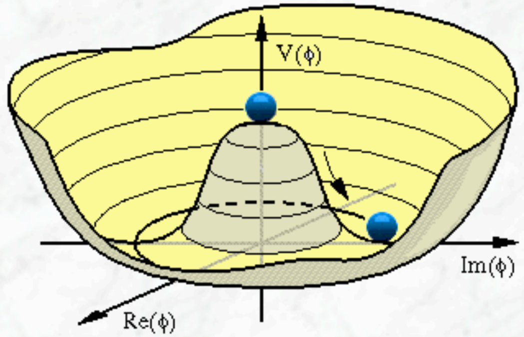
m_H = 125 GeV:

Observed 95% CL: 1.89 σ_{SM}

Expected (no Higgs): 0.95 σ_{SM}

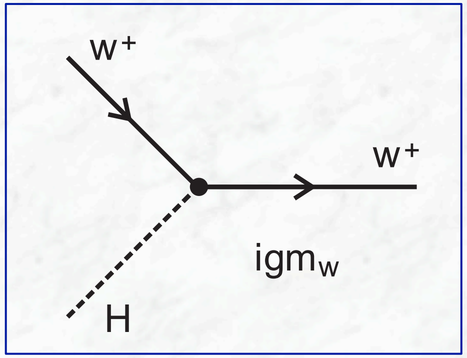
μ_H = 1.00 ± 0.49

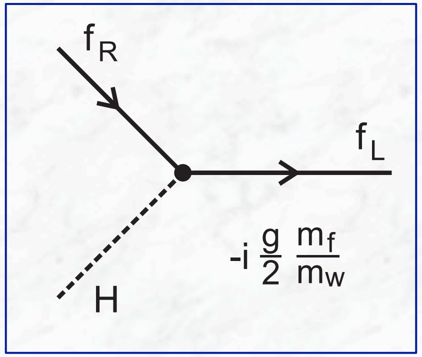
Is the new particle the Higgs Boson ?



- Production rates ?

  Couplings to bosons and fermions





- Spin, J^P quantum number

Higgs boson parameters

- After the discovery of the new boson, the most important question is:

  - What are its properties ?
    (mass, spin, couplings, …)

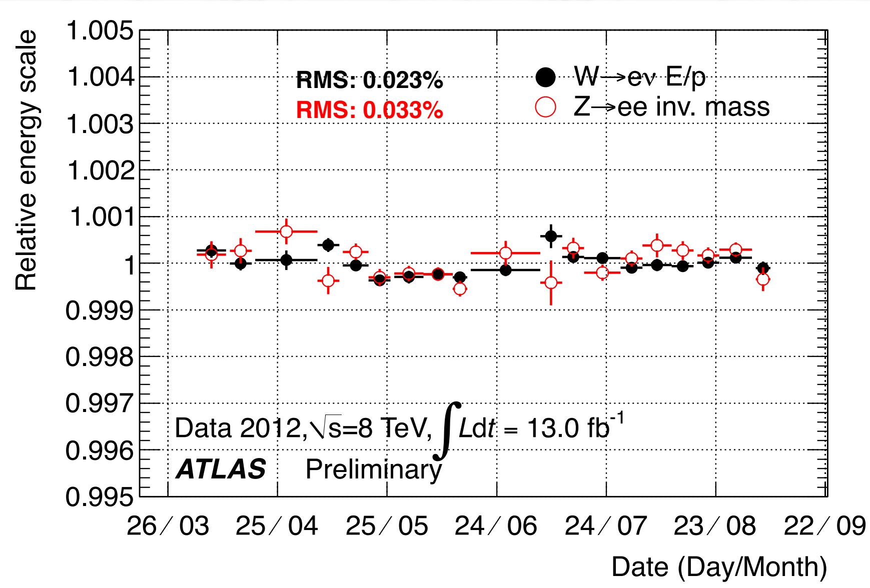
  - Is it the Higgs boson of the Standard Model?
    Or can we finds signs of Physics Beyond the Standard Model by studying its properties?

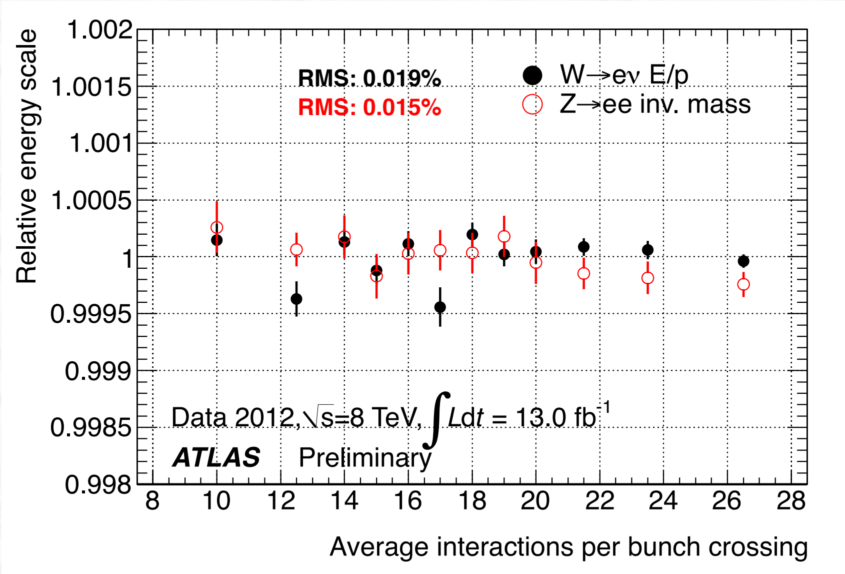
- Much attention of the LHC (and Tevatron) collaborations and from the theory community has been devoted to these questions during the past year.

The Higgs boson mass

- The mass of the Higgs boson can be precisely determined by using the measurements in the high resolution H → γγ and H → ZZ* → 4l channels

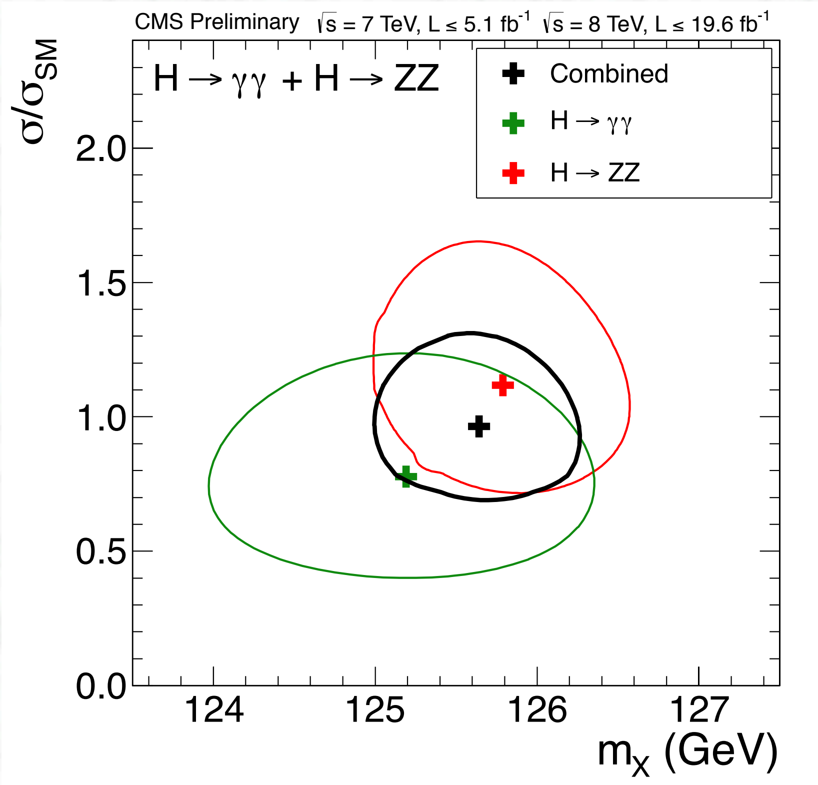
- Relevant here are the lepton/photon energy calibration, its stability and the good lepton / photon energy resolution

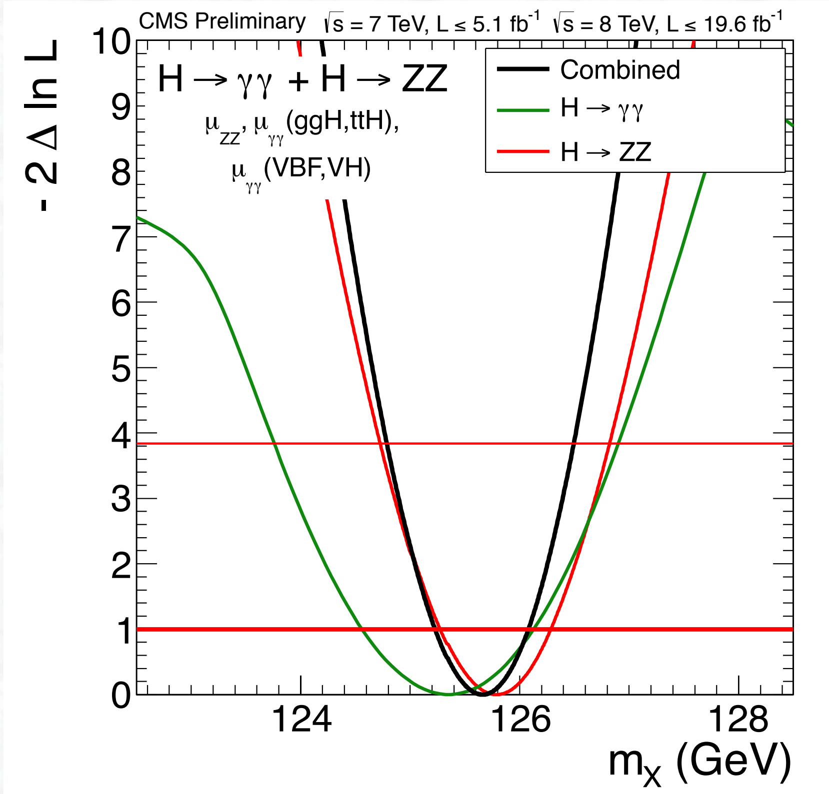




Higgs boson mass: results from CMS

CMS PAS HIG-13-005



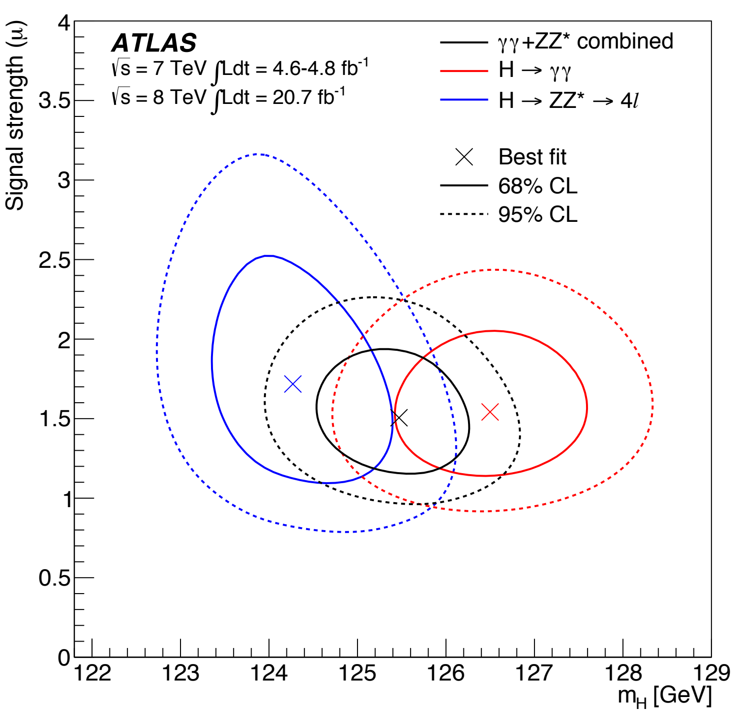


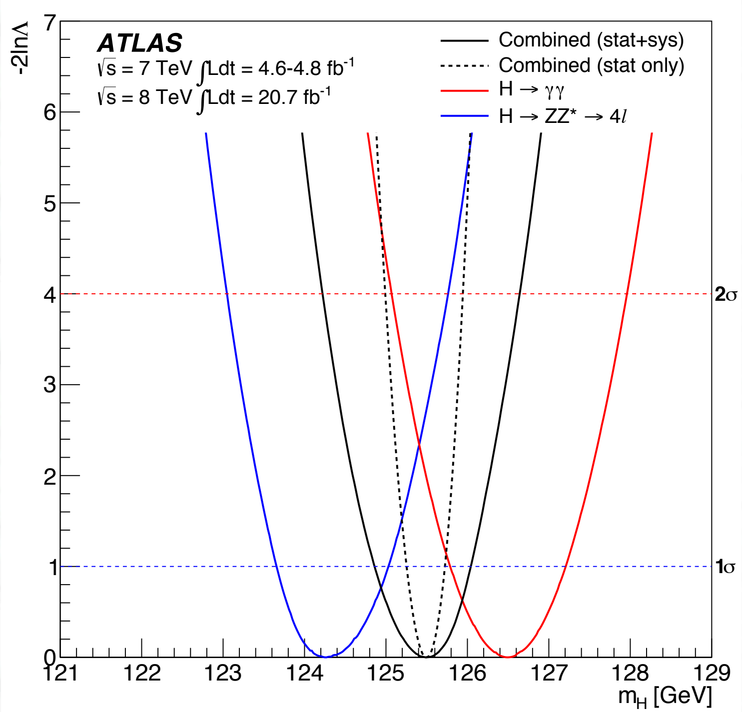
$$m_H = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst})\ \text{GeV}$$

In the combination the relative signal strength for the two decay modes is constrained by the SM values

Higgs boson mass: results from ATLAS

ATLAS arXiv:1307.1427

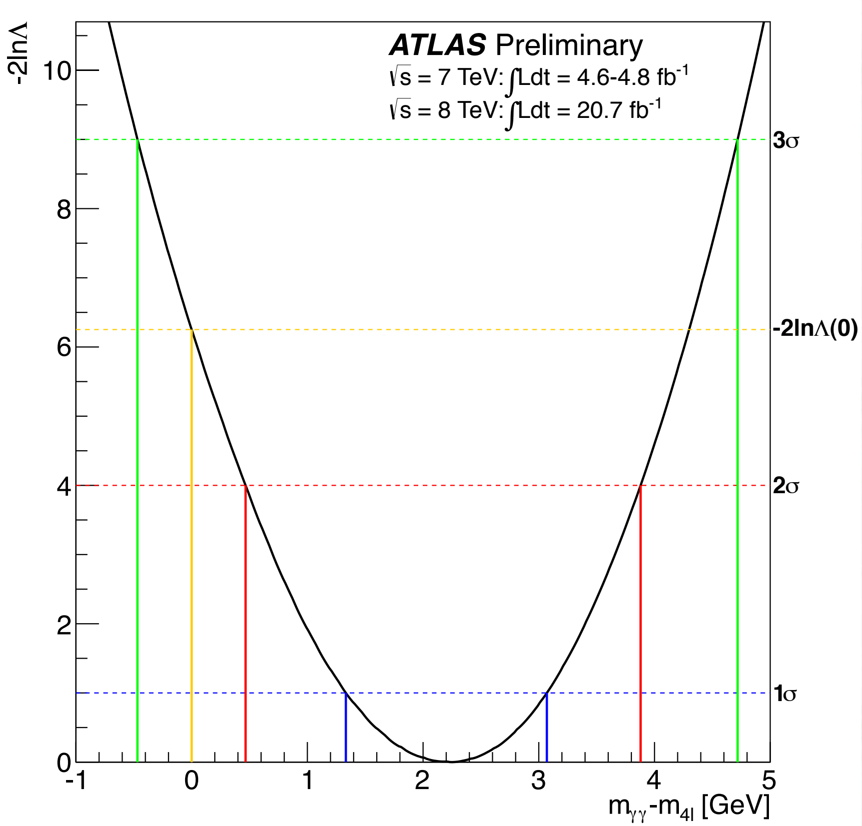




$$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})\ \text{GeV}$$

Consistency between the fitted mass values

ATLAS-CONF-2013-014



Likelihood as a function of the mass difference, Δm_H, profiling over the common mass m_H. The signal strength parameters $\mu_{\gamma\gamma}$ and μ_{4l} are allowed to vary independently.

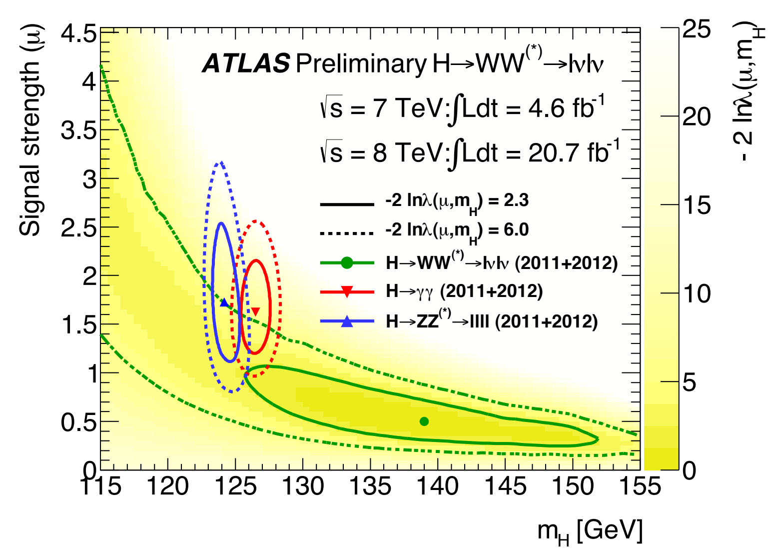
Consistency between the fitted mass values from likelihood value for $\Delta m = 0$ w.r.t. best fit value for Δm.

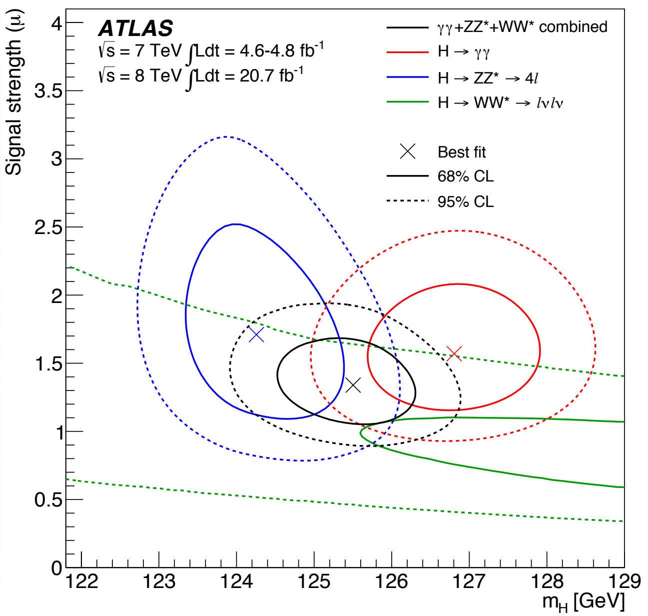
$$\Delta m = 2.3^{+0.6}_{-0.7}\text{(stat)} \pm 0.6\ \text{(syst) GeV}$$

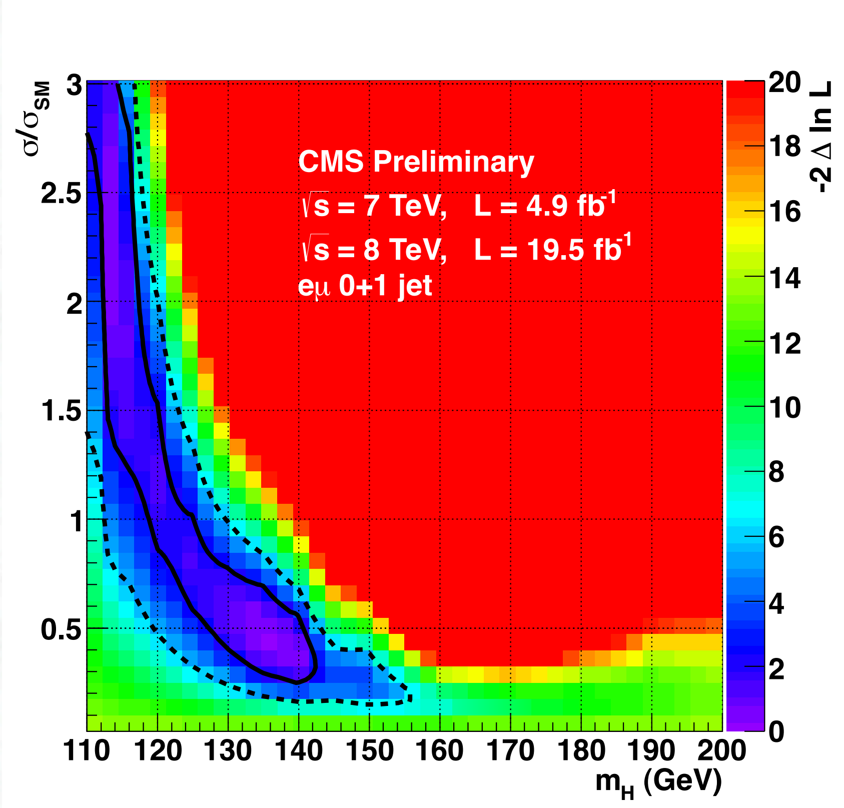
- Probability for disfavoring the $\Delta m = 0$ hypothesis by more than observed is 1.5% (2.4σ)
- Increases to 8%, by fixing the three principle sources contributing to the e/γ energy scale uncertainty (material, pre-sampler energy scale, calibration procedure) to their $\pm 1\sigma$ values

Consistency with the H → WW* channel (mass vs. signal strength)

ATLAS-CONF-2013-030

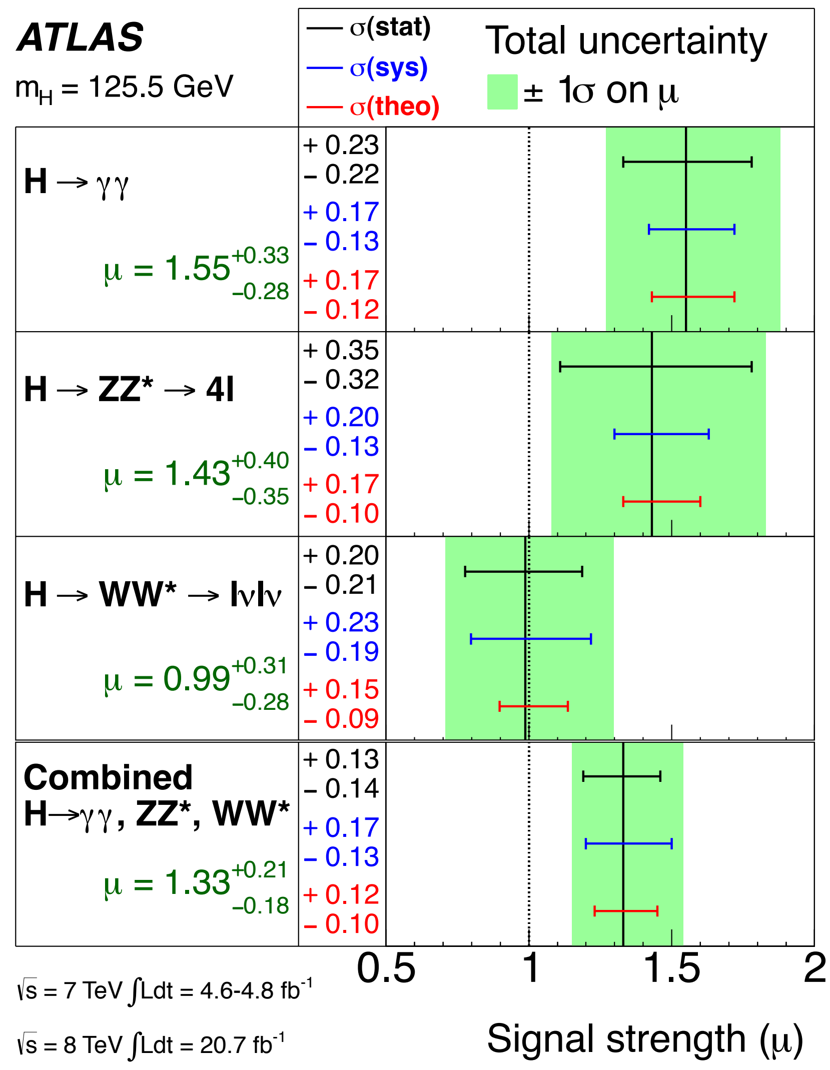






Signal strength in di-boson decay modes

-including full data set-



- Data are consistent with the hypothesis of a Standard Model Higgs boson:

$$\mu = 1.33^{+0.21}_{-0.18}$$

- Experimental uncertainties are still too large to get excited about "high" $\gamma\gamma$ signal strength

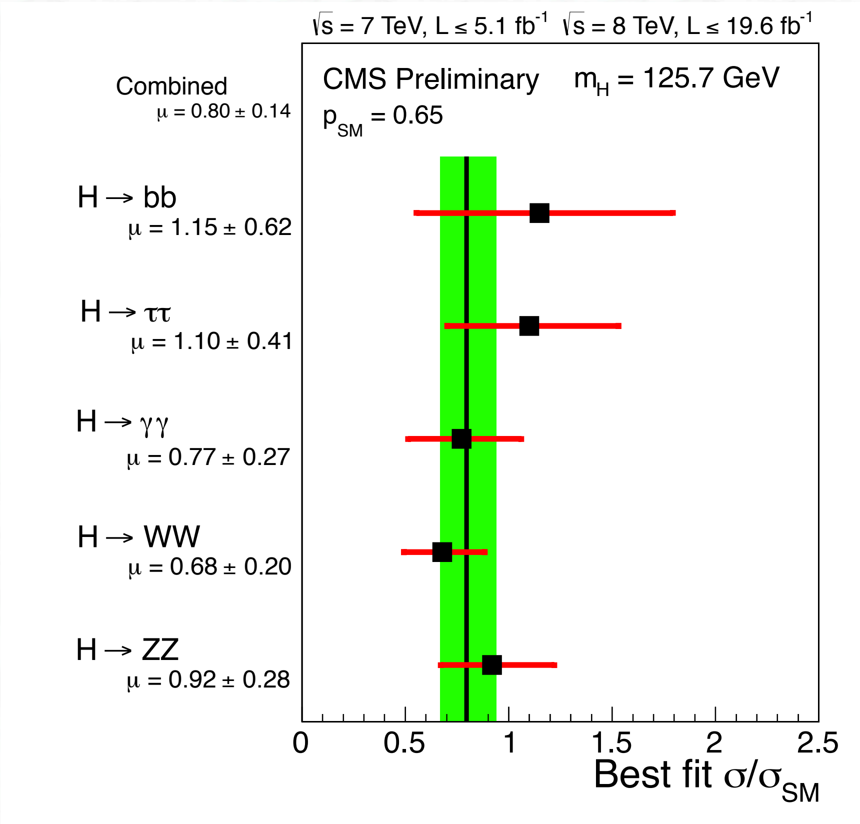
- Signal strengths in fermionic decay modes have large uncertainties, but are compatible with SM value of 1;

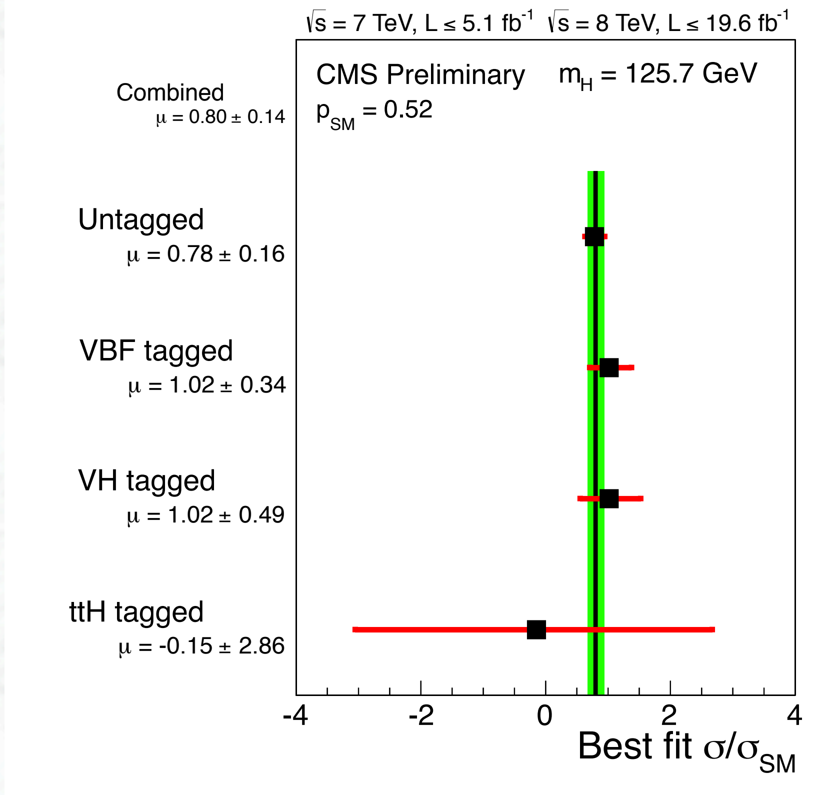
  If preliminary H → ττ and H → bb results are included:

$$\mu = 1.23 \pm 0.18$$

Ratios of production cross sections for the various processes (ggF, VBF,..) fixed to SM values

Signal strength in all decay and production modes
-including full data set-



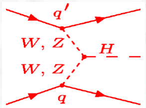


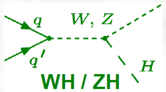
- Data are consistent with the hypothesis of a Standard Model Higgs boson:

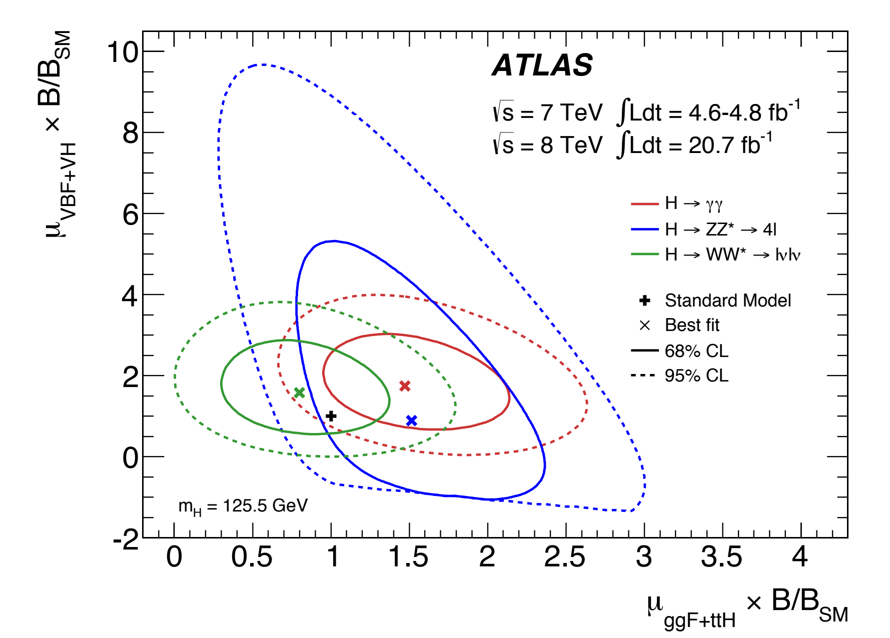
$$\mu = 0.80 \pm 0.14$$

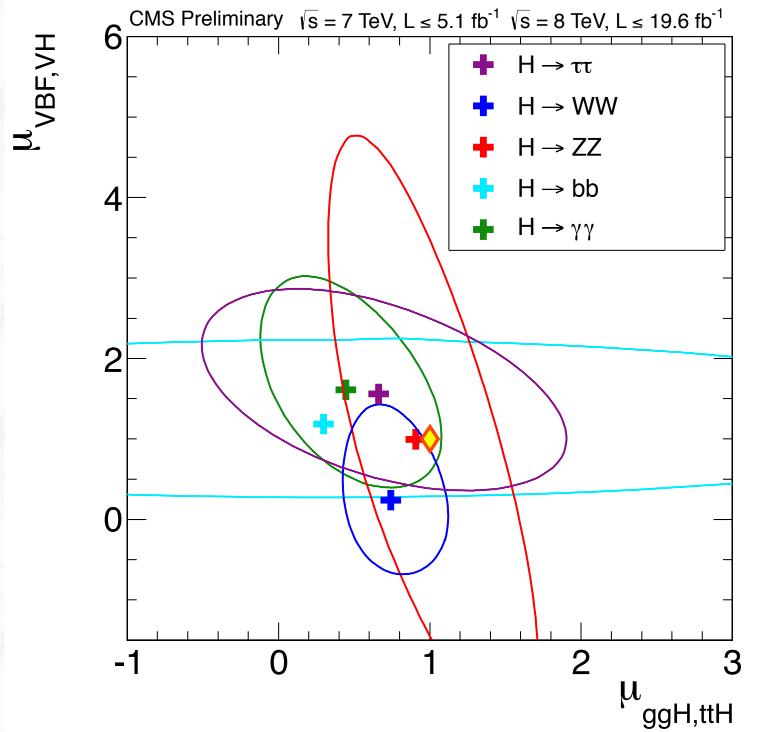
- Signal strengths in fermionic decay modes have large uncertainties, but are compatible with SM value of 1

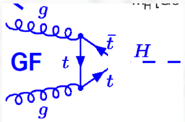
Gluon fusion versus vector-boson fusion

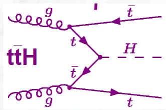








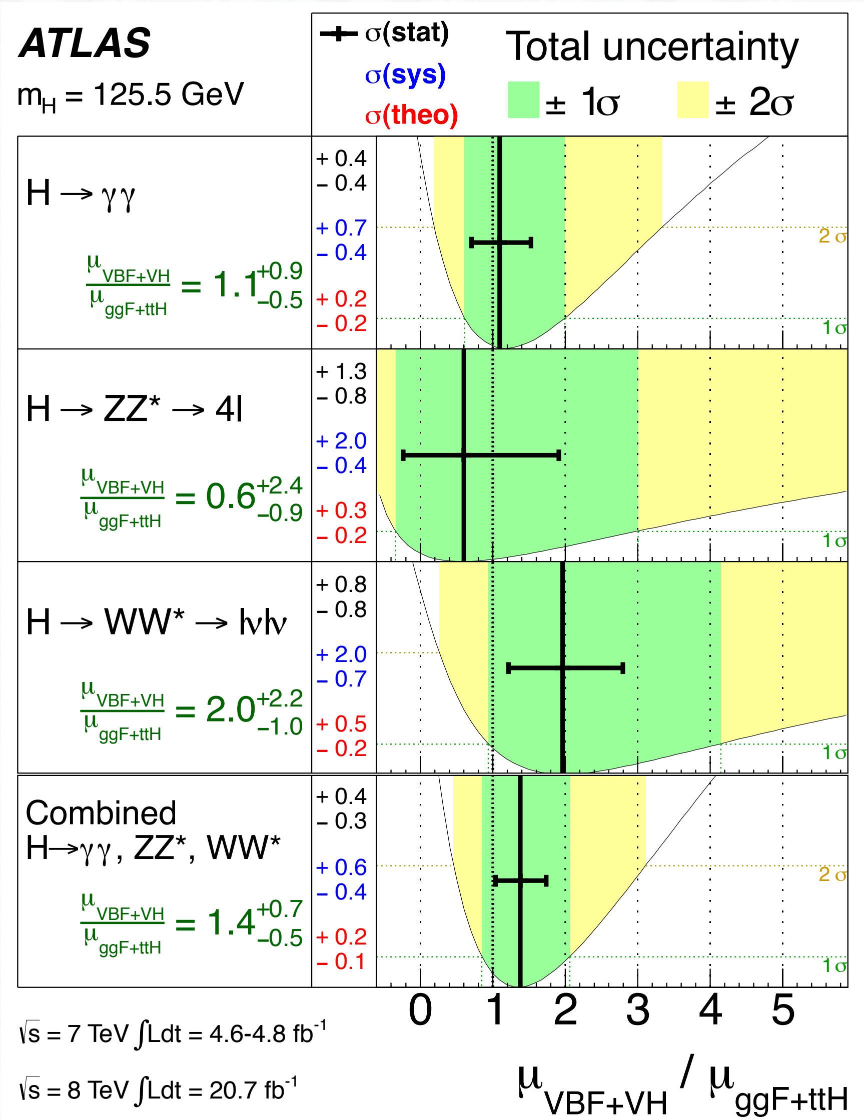




- Sensitivity to (ggF + ttH) and (VBF+VH) production fractions, modulo branching ratio factors B/B_{SM}
- Good agreement with the Standard Model, within the large uncertainties

- A combination of the different decay modes is not performed, since it would require introducing hypotheses on the relative branching ratios;

Evidence for production via vector boson fusion

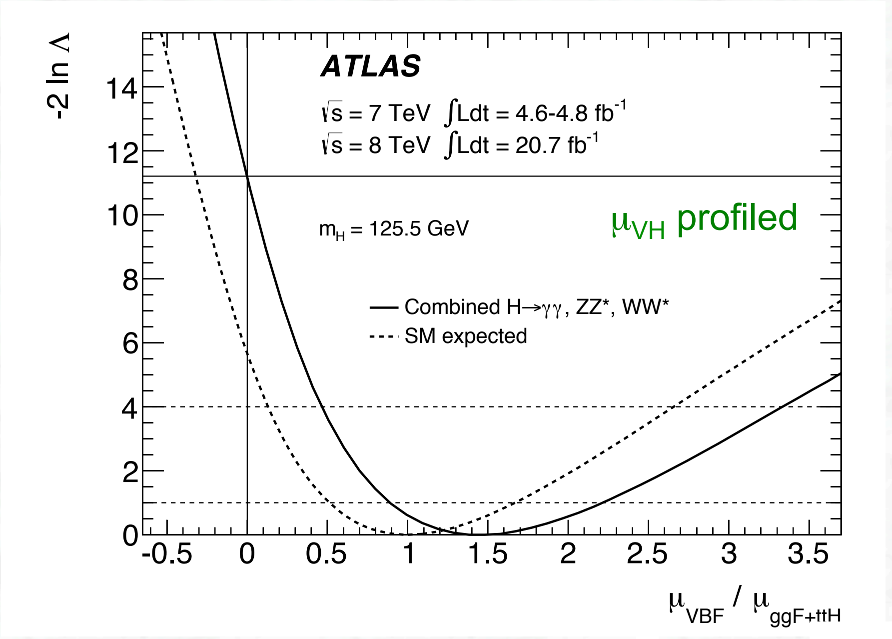


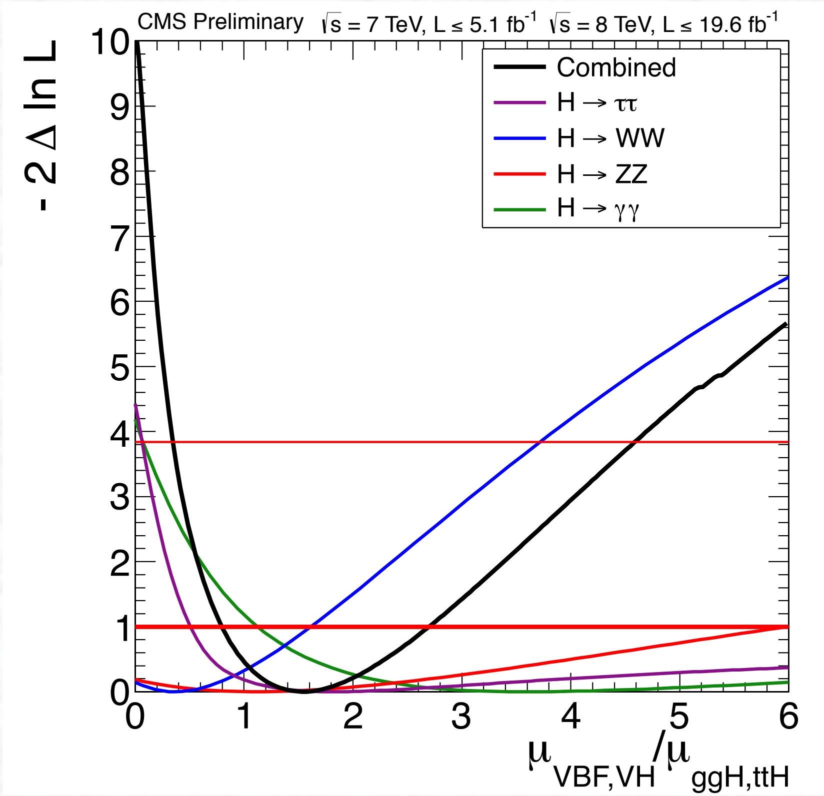
- Fit for the ratio of μ_{VBF+VH} / $\mu_{ggF+ttH}$ for the individual channels (model independent)

- Good agreement with SM expectation for individual channels and the combination)

Next step: combination of results

Evidence for production via vector boson fusion





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

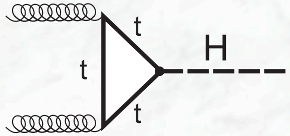
3.3σ evidence for VBF production

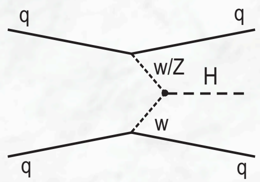
3.2σ evidence for V-boson mediated production

Higgs boson couplings

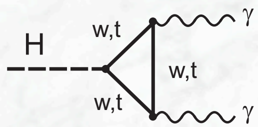
- Production and decay involve several couplings

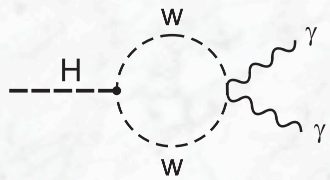
Production:





Decays: e.g. H → γγ (best example)
(Decay widths depends on W and top coupling,
destructive interference)





- Standard Model couplings are tested by introducing coupling scale factors κ

$$g_i = \kappa g_i^{SM}$$

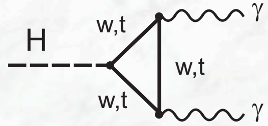
- Standard Model tree level amplitudes:

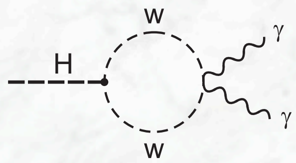
$$\Gamma_{ff} \propto \left(\kappa_f \frac{m_f}{v} \right)^2 = \kappa_f^2 \cdot \Gamma_{ff}^{SM}$$

$$\Gamma_{VV} \propto \left(\kappa_f \frac{m_V^2}{v} \right)^2 = \kappa_V^2 \cdot \Gamma_{VV}^{SM}$$

Higgs boson couplings

- Example: H → γγ $\Gamma_{\gamma\gamma} \propto \left|1.28\kappa_W - 0.28\kappa_t\right|^2 \cdot \Gamma_{\gamma\gamma}^{SM}$





  - Loop scaling factors can be expressed in terms of κ_f and κ_V

  - The analysis is also done in terms of effective loop couplings κ_g and κ_γ

Higgs boson couplings

- Benchmarks defined by LHC cross section working group (leading-order tree-level framework):

  - Signals observed originate from a single resonance; (mass assumed here is 125.5 GeV)

  - Narrow width approximation: → rates for given channels can be decomposed as:

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

i, f = initial, final state
Γ_f, Γ_H = partial, total width

  - Modifications to coupling strength are considered (coupling scale factors κ), tensor structure of Lagrangian assumed as in Standard Model

Scaling of cross sections with κ_F and κ_V factors

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

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

(i) Couplings to fermions and bosons

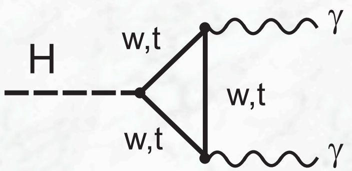
- Assume only one scale factor for fermion and vector couplings:

  $\kappa_V = \kappa_W = \kappa_Z$
  $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

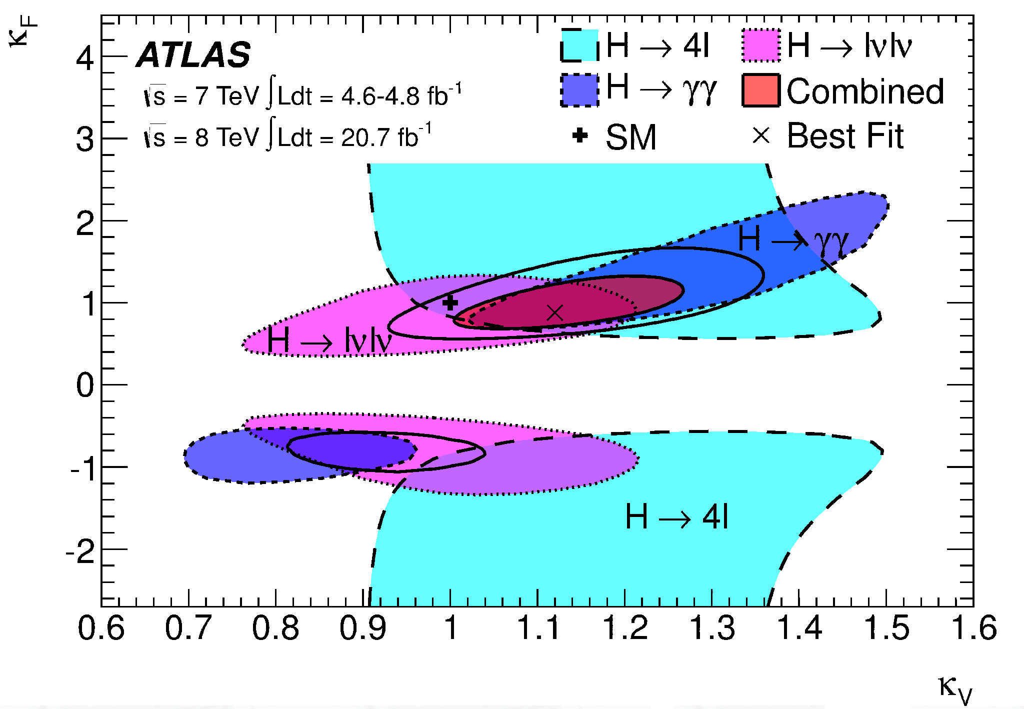
  The size of the current data set is insufficient to quantify all parameters

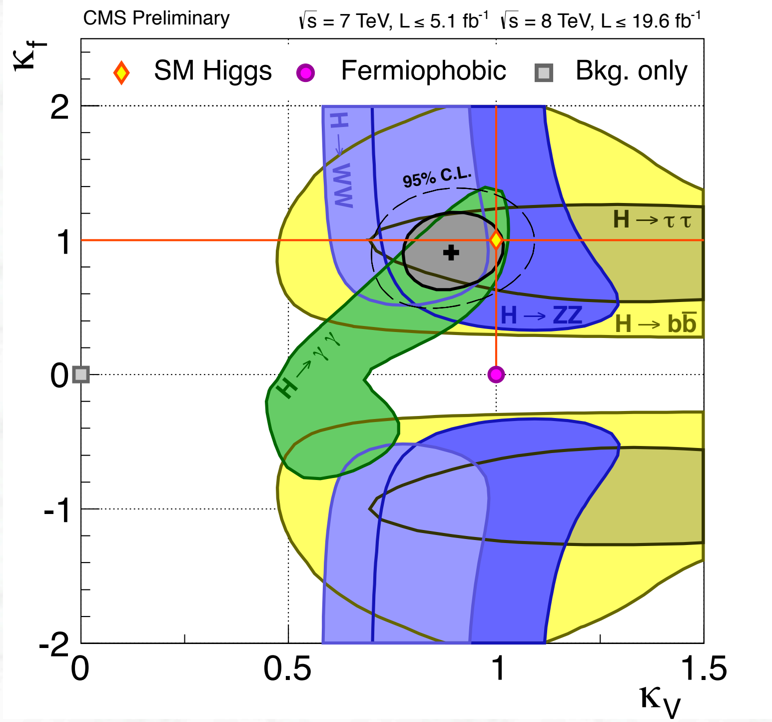
- Assume that $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ loops and the total Higgs boson width depend only on κ_V and κ_F
  (no contributions from physics beyond the Standard Model)

- Sensitivity to relative sign between κ_F and κ_V only from interference term in $H \rightarrow \gamma\gamma$ decays (assume $\kappa_V > 0$)



(i) Couplings to fermions and bosons (cont).





Results: Data are consistent with the SM expectation;

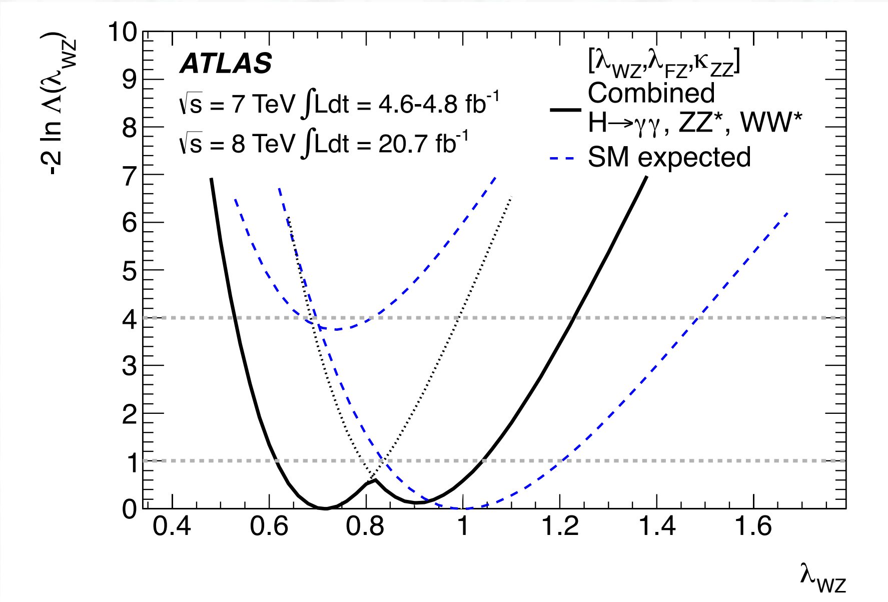
68% CL intervals: $\kappa_F \in [0.76, 1.18]$
(ATLAS) $\kappa_V \in [1.05, 1.22]$

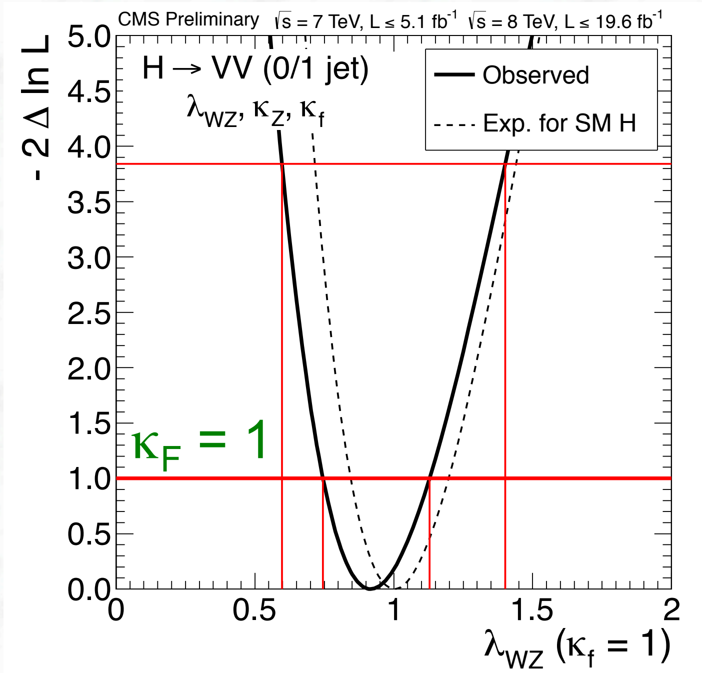
95% CL intervals: $\kappa_F \in [0.61, 1.31]$
(CMS) $\kappa_V \in [0.74, 1.06]$

(ii) Ratio of couplings to the W and Z bosons

- Relation between m_W and m_Z in the Standard Model requires $\lambda_{WZ} := \kappa_W/\kappa_Z = 1$ (ρ parameter required to be 1)

- Sensitivity via VBF and VH production and H → WW and H → ZZ rates

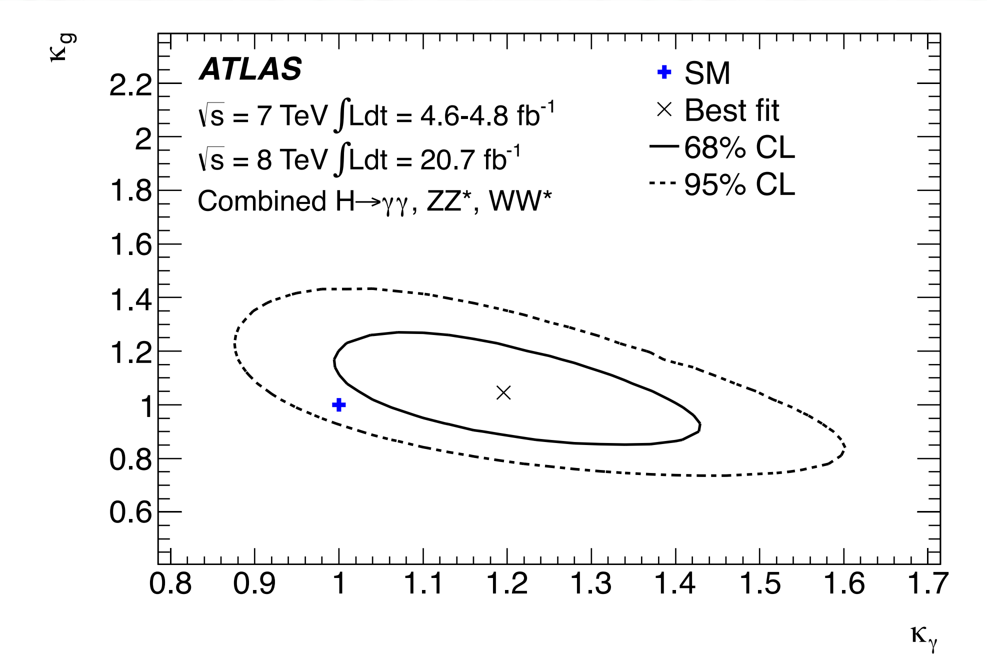


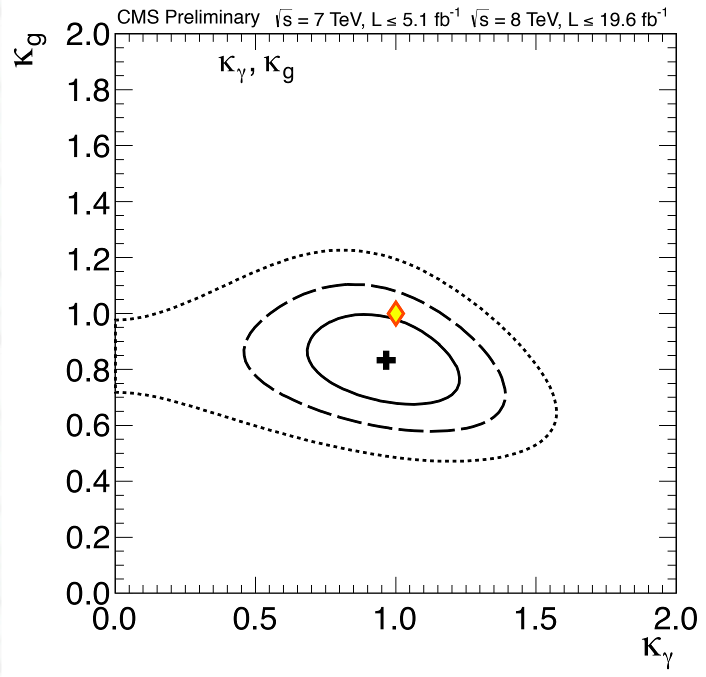


68% CL intervals: $\lambda_{WZ} \in [0.61, 1.04]$

(iii) Constraints on production and decay loops

- Test on contributions from other particles contributing to loop-induced processes
- Assume nominal couplings for all SM particles $\kappa_i = 1$
  and that the new particles do not contribute to the Higgs boson width
- Fit for effective scale factors κ_g and κ_γ





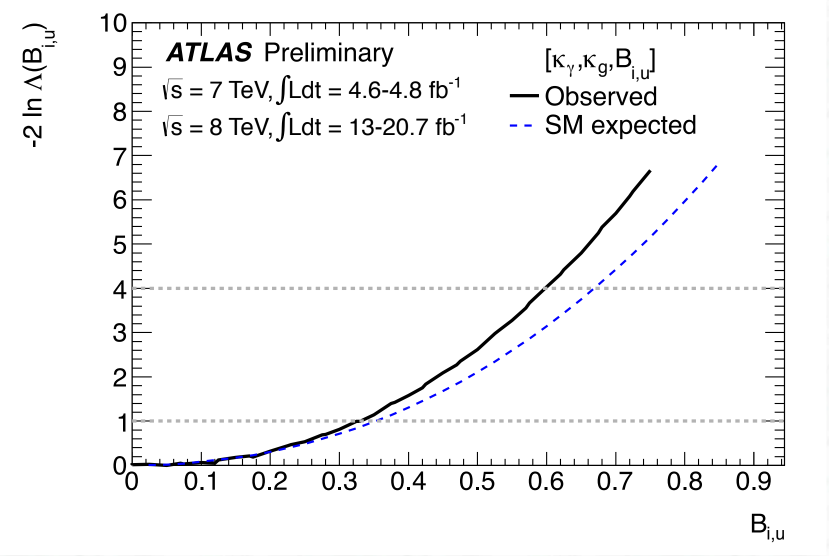
Best fit values: $\kappa_g = 1.04 \pm 0.14$
(ATLAS) $\kappa_\gamma = 1.20 \pm 0.15$

95% CL intervals: $\kappa_\gamma \in [0.59, 1.30]$
CMS $\kappa_g \in [0.63, 1.05]$

(iv) Constraints on invisible decays (BR_{BSM})

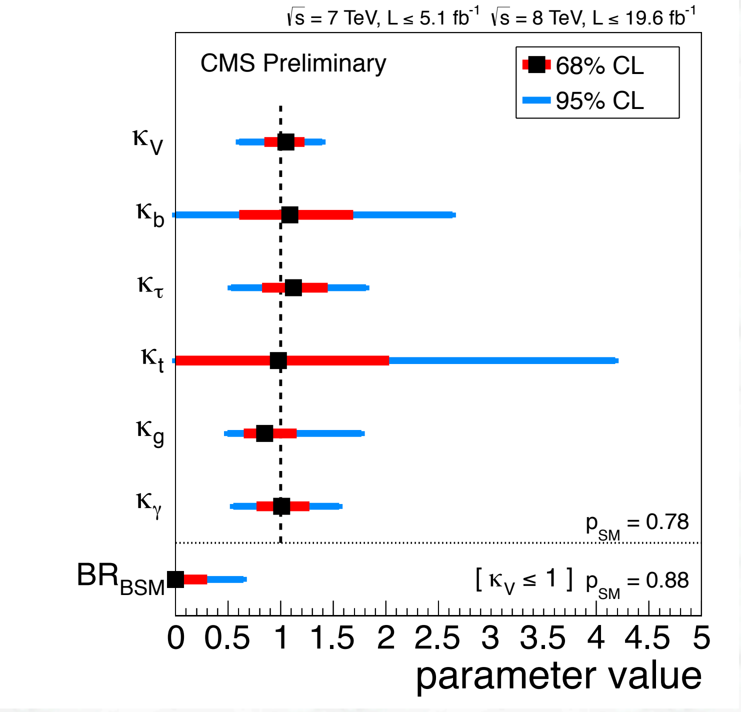
- There might be invisible decays that would increase the total decay width:
- $\Gamma_H = \Gamma_{SM} + \Gamma_{BSM}$ ($BR_{BSM} = \Gamma_{BSM} / \Gamma_H$)

Assume nominal couplings for all SM particle $\kappa_i = 1$
Three fitted parameters: k_g, k_γ and BR_{BSM}



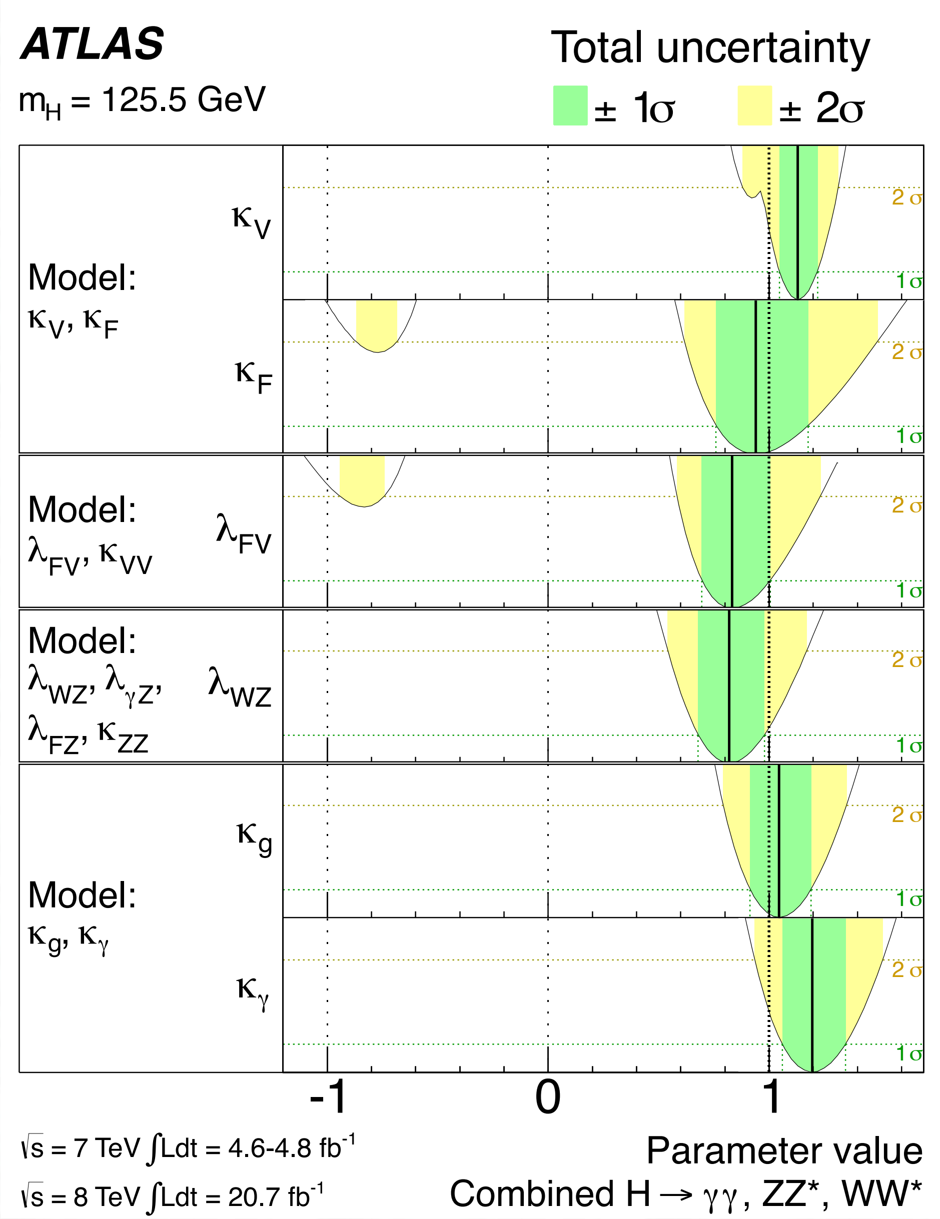
BR$_{BSM}$ < 0.60 (95% CL)
0.67 (expected)

Assume $k_V \leq 1$ (motivated by EWSB)
Fit for seven parameters



BR$_{BSM}$ < 0.64 (95% CL)
0.66 (expected)

Summary of coupling scale factor measurements



$$\lambda_{FV} = \kappa_F / \kappa_V$$

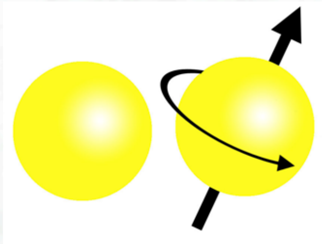
$$\kappa_{VV} = \kappa_V \kappa_V / \kappa_H$$

If assumption of no contributions from new particles to the Higgs boson width is relaxed, only the ratio of k_F/k_V can be measured

Extended fit, decouple $H \rightarrow \gamma\gamma$ event rate from the measurement of λ_{WZ}

- κ_V constrained at ±10% level
- Couplings to fermions indirectly observed (5σ)
- κ_W/κ_Z found to be consistent with one
- No evidence for significant anomalous contributions to the $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ loops
  (for fixed nominal couplings of SM particles and no BSM contributions to Higgs width)

Spin and Parity



Wolfgang Pauli and Niels Bohr studying the motion of a gyro (1952, at the opening of the institute for theoretical physics in Lund /Sweden)

Standard Model Higgs boson: $J^P = 0^+$

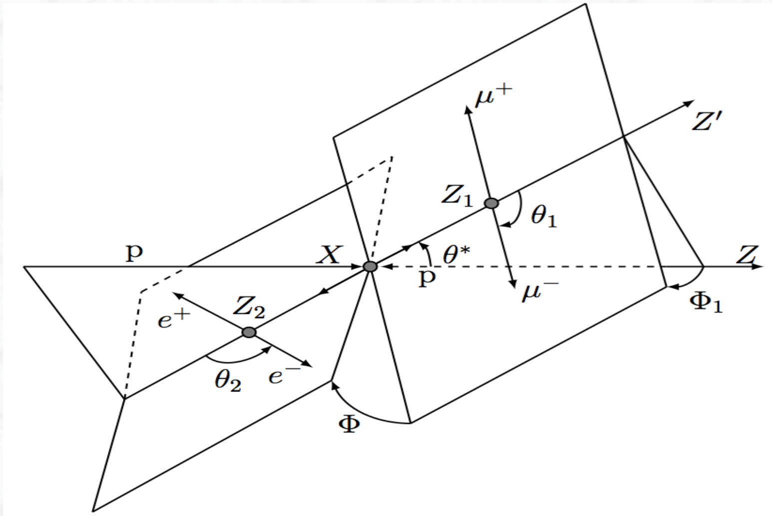
→ strategy is to falsify other hypotheses (0^-, 1^-, 1^+, 2^-, 2^+)

and demonstrate consistency with the 0^+ hypothesis

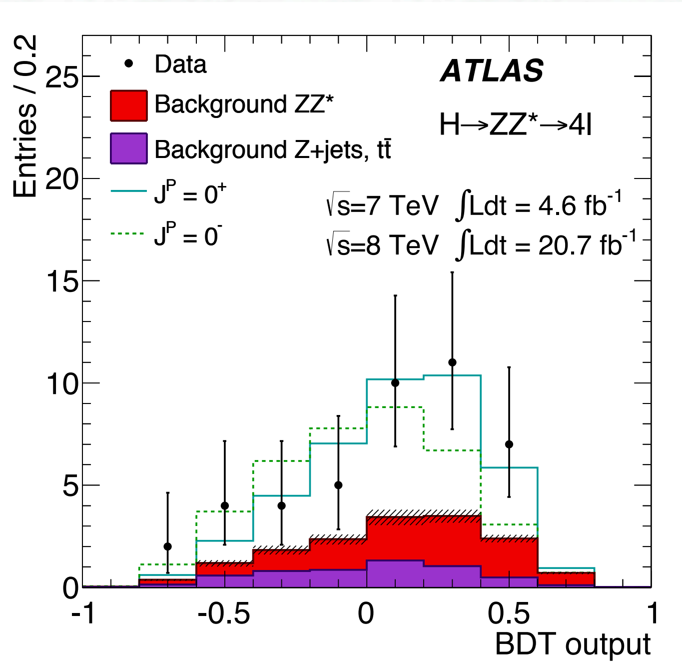
Spin 1: strongly dis-favoured by observed H → $\gamma\gamma$ decays, Landau-Yang theorem

$J^P = 0^-$ versus $J^P=0^+$ (H → $ZZ^{(*)}$ → 4ℓ events)

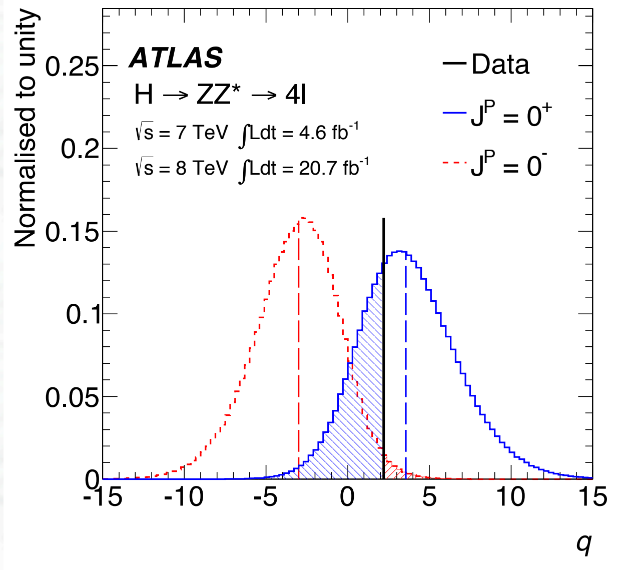
- Sensitive variables:
  - Masses of the two Z bosons
  - Production angle θ^*
  - Four decay angles Φ_1, Φ, θ_1 and θ_2



- Perform multivariate analysis
  (Boosted decision tree, similar sensitivity using matrix-element method)



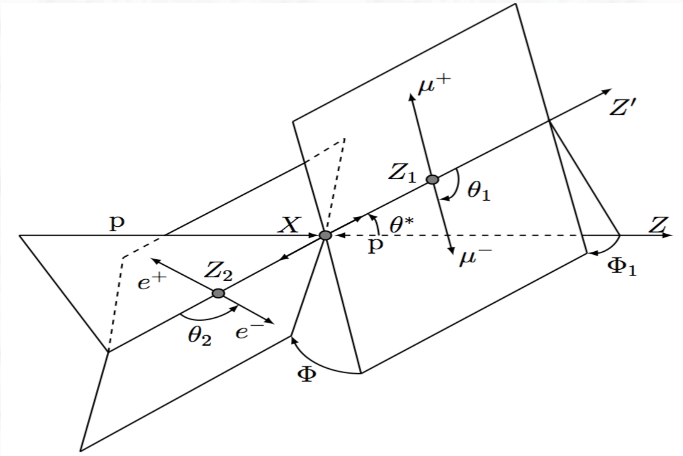
ATLAS arXiv:1307:1432

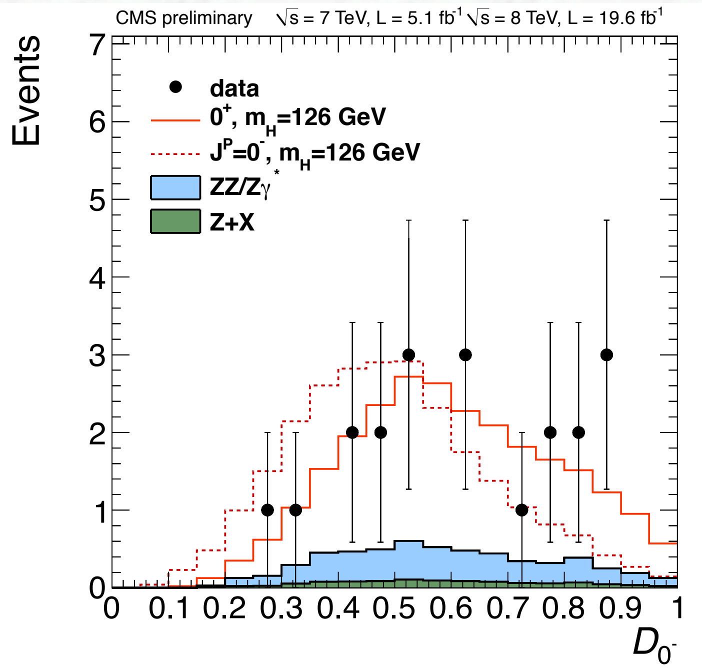


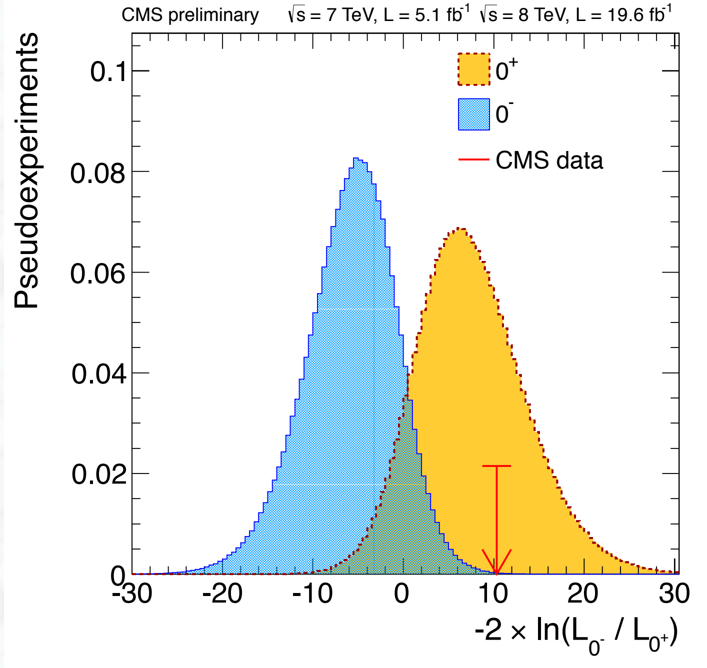
Exclude $J^P=0^-$ (vs. 0^+) with 97.8% CL

$J^P = 0^-$ versus $J^P=0^+$ ($H \to ZZ^{(*)} \to 4\ell$ events)

- Sensitive variables:
  - Masses of the two Z bosons
  - Production angle θ^*
  - Four decay angles Φ_1, Φ, θ_1 and θ_2
- Matrix-Element based discriminant D_{JP}







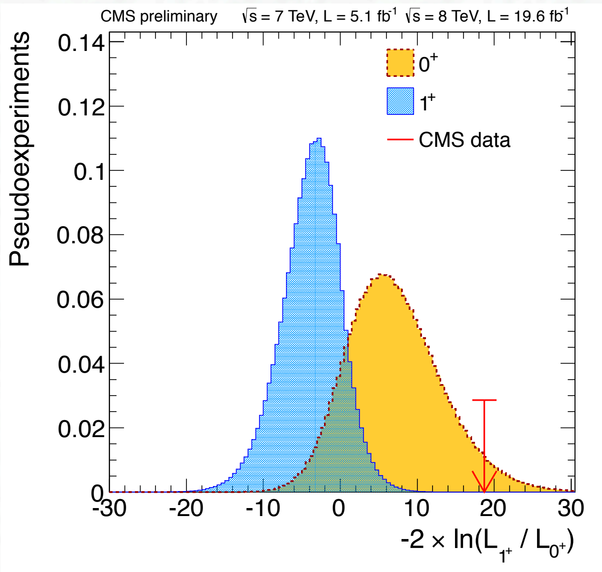
CMS PAS HIG-13-005

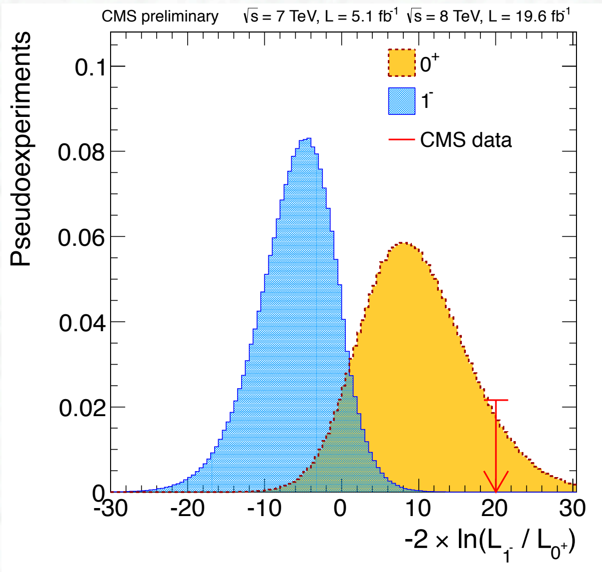
Exclude $J^P=0^-$ (vs. 0^+) with 99.8% CL

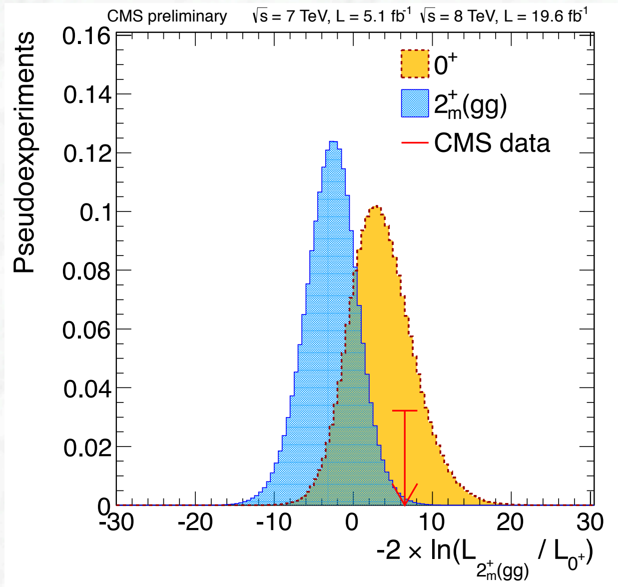
Further CMS results based on H → ZZ$^{(*)}$ → 4ℓ decays

CMS PAS HIG-13-005

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%







$J^P = 1^{+/-}$ versus $J^P=0^+$ (H → ZZ* and H → WW* events)

- H → ZZ*, as before: BDT separation based on masses and angles
- H → WW*: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $p_T(\ell\ell)$, m_T carry information on spin, combine these variables using a BDT analysis

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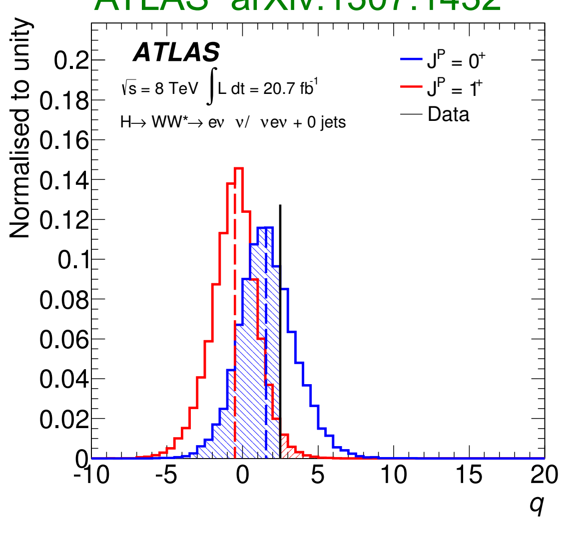
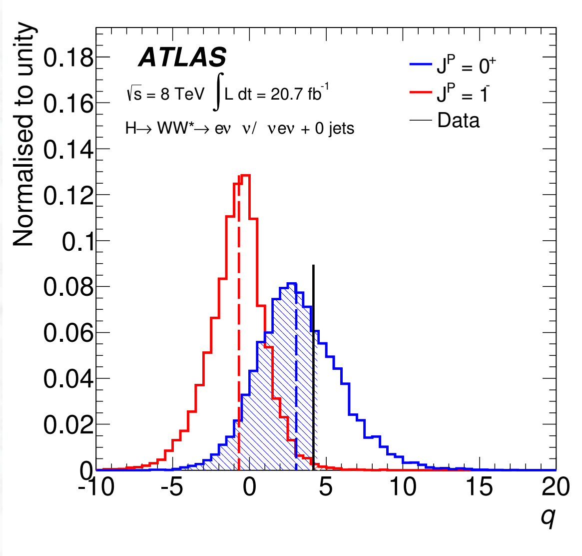




H → WW*

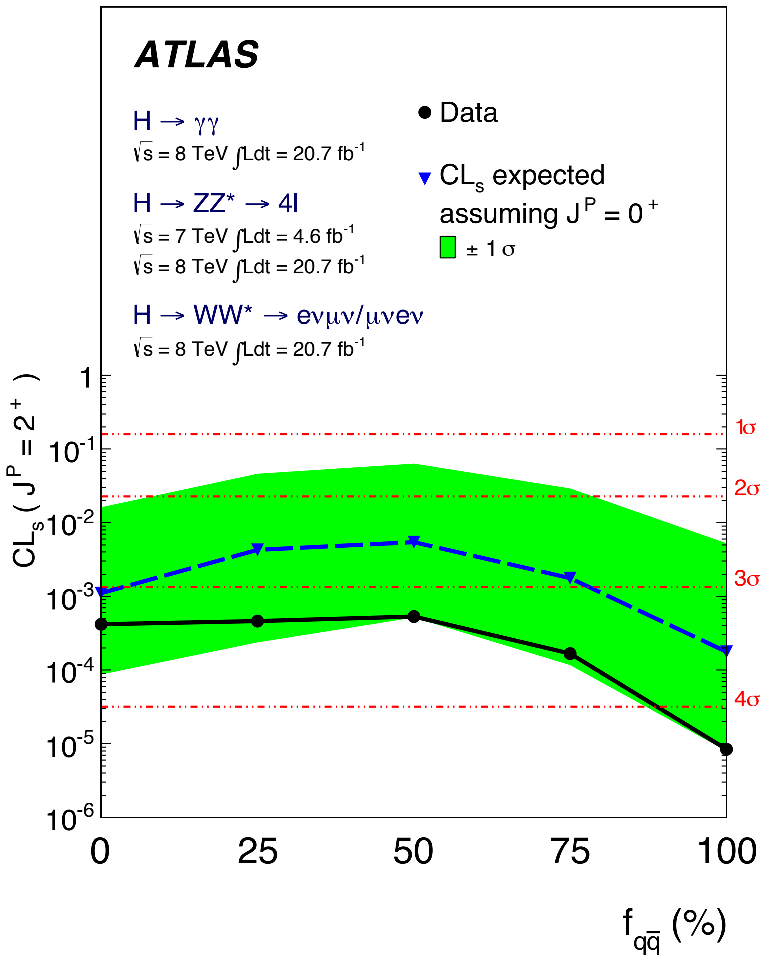
$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})}$$

q = test statistics to discriminate between two spin hypotheses

	p_0 (0^+)	CL (1^+) Exclusion	p_0 (0^+)	CL (1^-) Exclusion
H → ZZ*	0.55	99.8%	0.1	94%
H → WW*	0.70	92%	0.66	98%
Combination	0.62	99.97%	0.33	99.7%

$J^P = 2^+$ versus $J^P=0^+$ ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, and $H \rightarrow WW^*$ events)

ATLAS arXiv:1307:1432



- Spin 2: consider graviton-like tensor, equivalent to a Kaluza-Klein graviton

  (Y. Gao et al, Phys. Rev. D81 (2010) 075022)

- Production via gluon fusion and qq annihilation possible;
  Studies are performed as a function of the qq annihilation fraction (f_{qq})

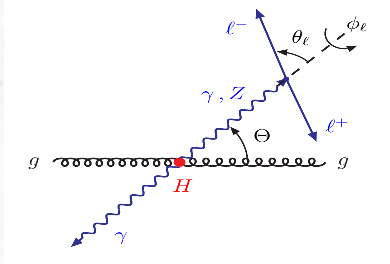
- Specific model 2^+_m:
  minimal couplings to SM particles

  (f_{qq} = 4% at LO, however, large uncertainties)

- Observed exclusion (combination of $\gamma\gamma$, ZZ^* and WW^*) of $J^P = 2^+$ (versus the SM $J^P = 0^+$) exceeds 99.9%, independent of f_{qq};
  Complementary behaviour of the different channels

Example: H → γγ contribution

Use decay angle w.r.t. collision axis



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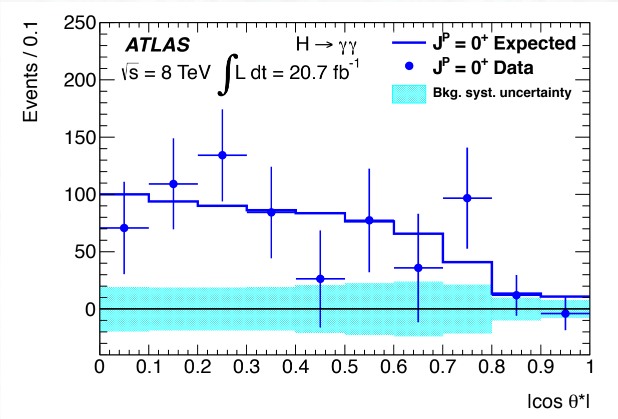
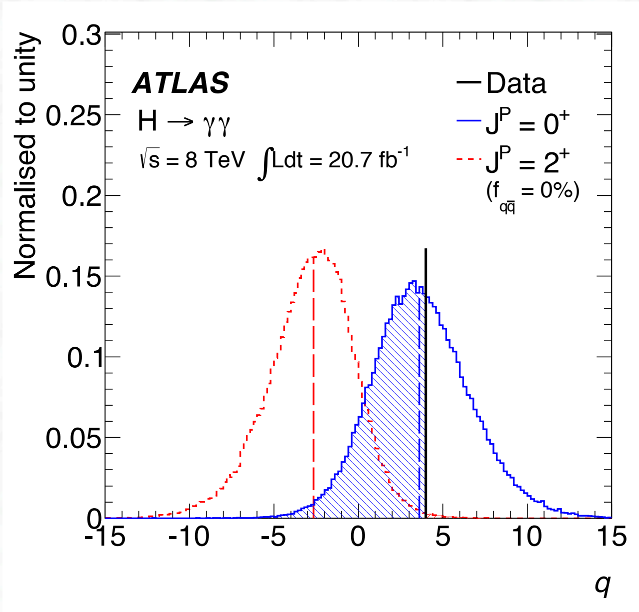
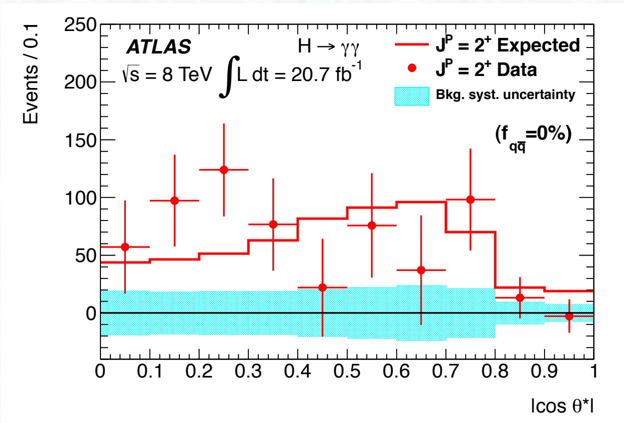




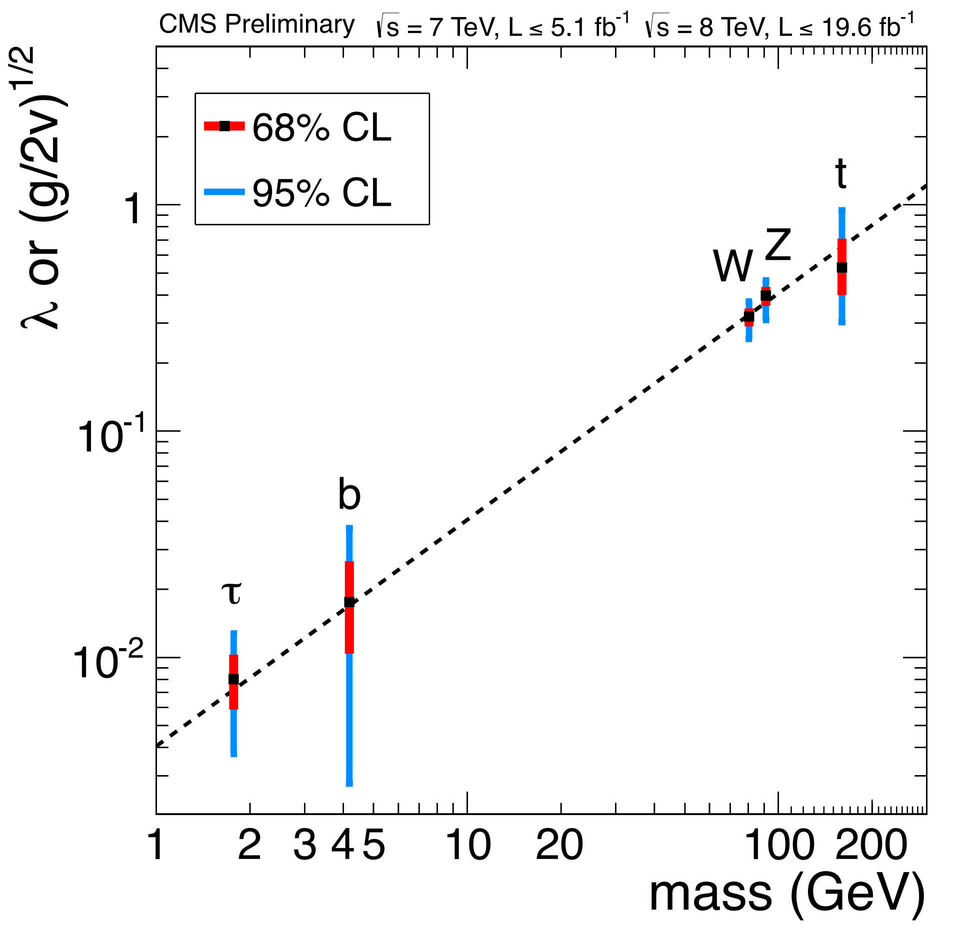


Exclude $J^P=2^+$ (produced via gluon fusion, $f_{qq}= 0$) (vs. 0^+) via H → γγ decays with 99.3% CL

cos θ* distribution in signal region, after background subtraction

CMS summary on coupling results

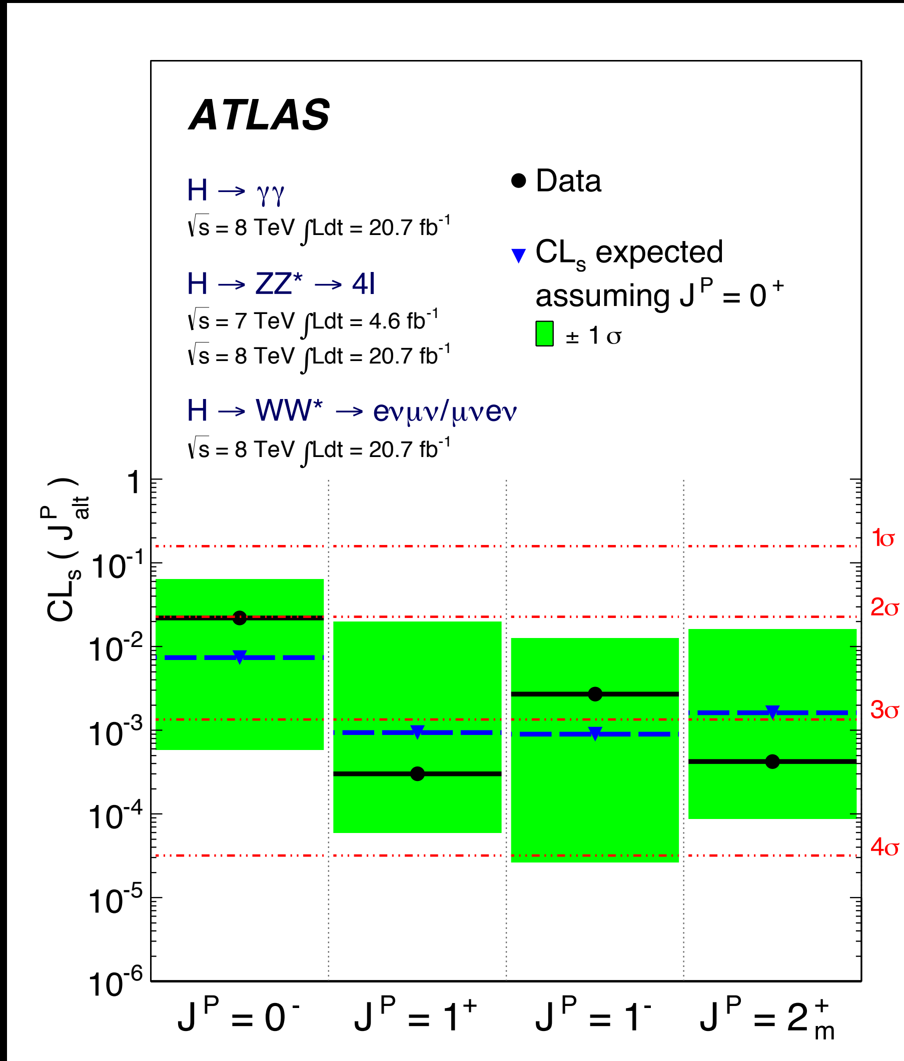
CMS PAS HIG-13-005



"The consistency of the couplings of the observed boson with those predicted for the Standard Model Higgs boson is tested in various ways, and no significant deviations are found."

ATLAS summary on spin results

ATLAS arXiv:1307:1432



"These studies provide evidence for the spin-0 nature of the Higgs boson, with positive parity being strongly preferred."

Summary

- A milestone discovery announced in July 2012
- Signals have been impressively confirmed with additional data;
  The discovery phase has turned into the measurement phase
- ATLAS and CMS data are consistent with the expectations for the Standard Model Higgs boson (within present uncertainties)

  - Production rates and coupling strengths
  - Evidence for VBF production
  - Evidence for spin-0 (0^- disfavoured)

- Exciting times ahead of us to study the Higgs boson with higher precision (> 2015) and to look for surprises (deviations? more Higgs bosons? …)

End of lectures