Is it the Higgs?
Characterization of the H(125) resonance (spin, parity, tensor structure) with leptonic WW decays

Rebeca Gonzalez Suarez
University of Nebraska, Lincoln

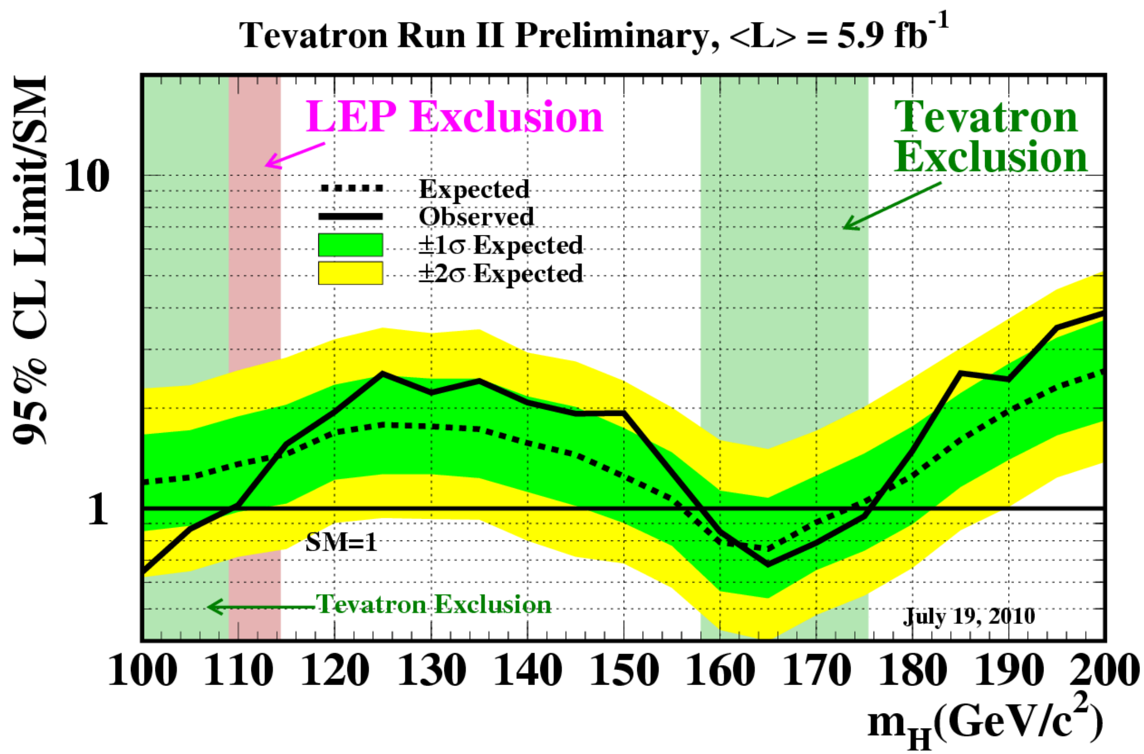
5 years ago Tomorrow

- The LHC entered the 7TeV regime with **3.5TeV beams** circulating (collisions to come in March 30th)

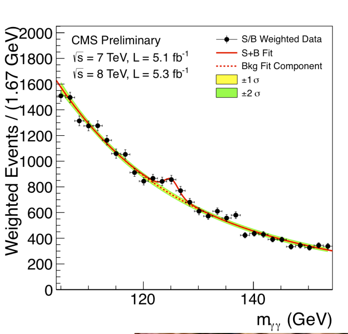
- The Run-1 of the LHC was just starting

Higgs searches panorama in 2010

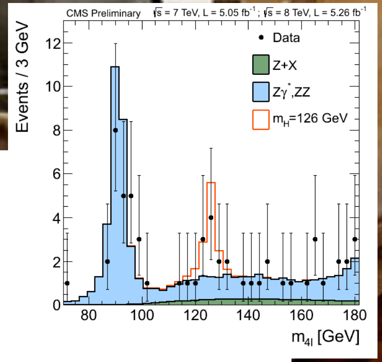
- Simulation-based studies since the physics TDR in 2006
- We were hoping to find the Higgs boson (or to exclude its presence in the intermediate mass range) in a **reasonable timescale**, this was our roadmap



Higgs searches panorama in 2012



[arXiv:1207.7235](https://arxiv.org/abs/1207.7235)
Phys. Lett. B 716 (2012) 30
(Submitted 31 July 2012)



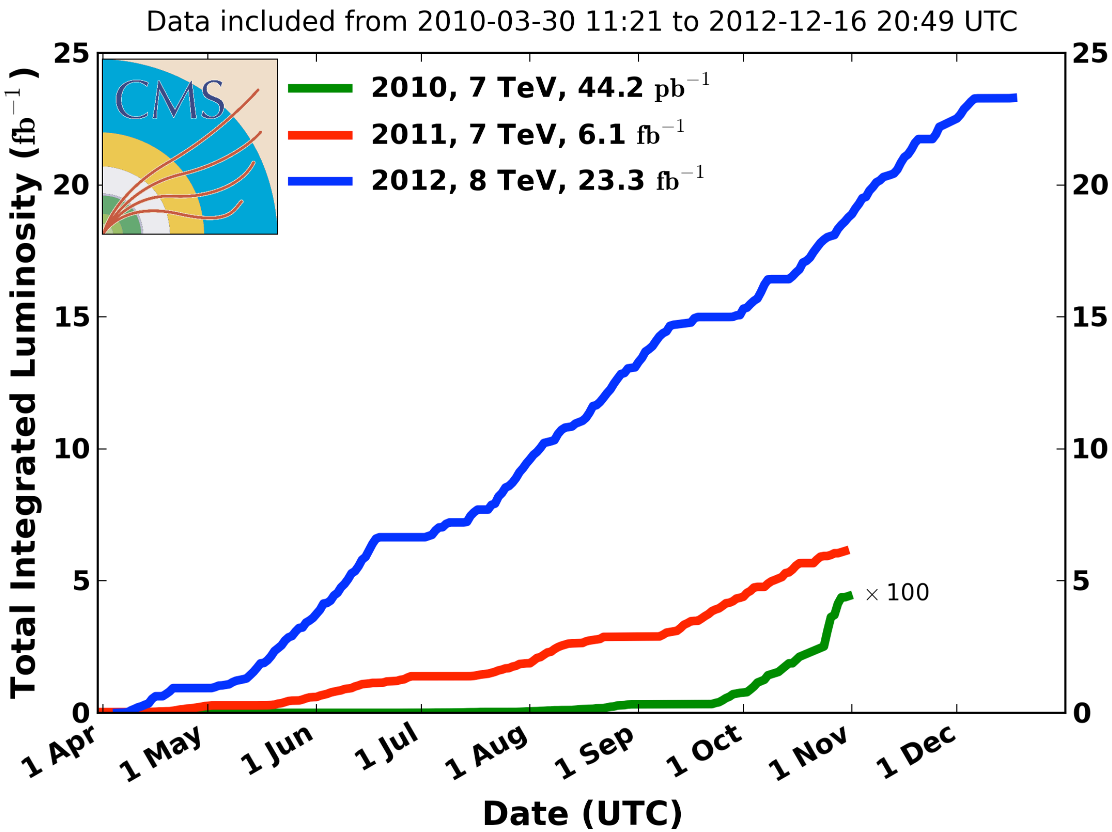
[arXiv:1303.4571](https://arxiv.org/abs/1303.4571)
JHEP 06 (2013) 081
(Submitted **19 March 2013**)

CMS discovery papers

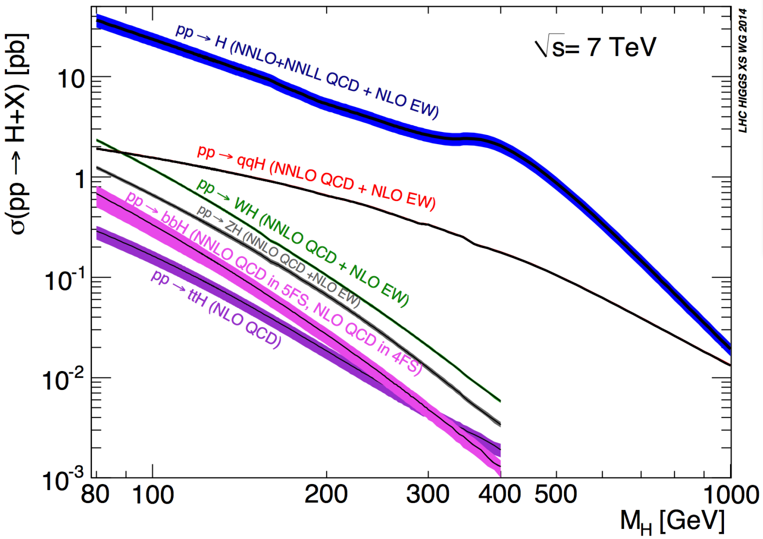
The Run-1 of the LHC

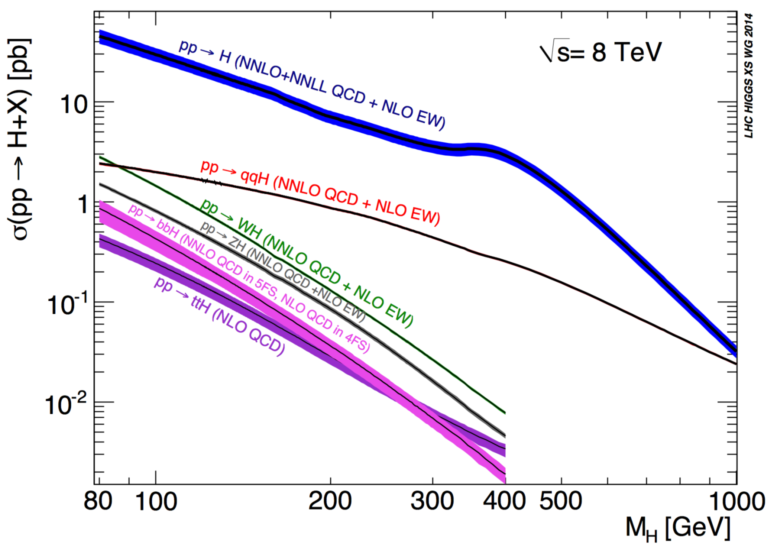
Year	Overview	COM energy	Integrated luminosity [fb^{-1}]
2010	Commissioning	7 TeV	0.04
2011	Exploring limits	7 TeV	6.1
2012	Production	8 TeV	23.1

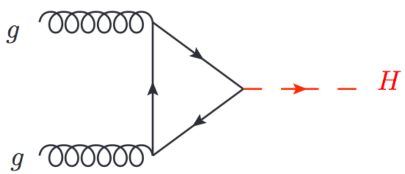
- The Run-1 of the LHC ended in February 2013
- During three years, CMS recorded **~5fb^{-1} of pp collisions at 7TeV and ~20fb^{-1} at 8TeV**



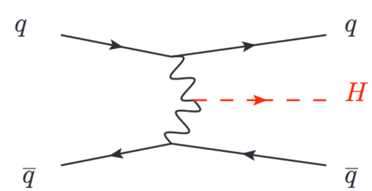
Higgs production at the LHC



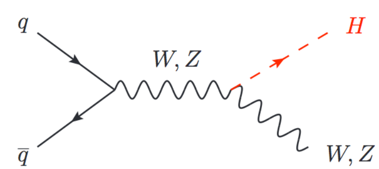




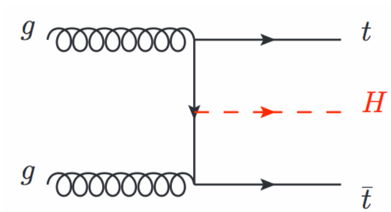
Gluon-gluon fusion (ggH)
Dominant mode
No hadronic activity



Vector Boson Fusion
(VBF) 2 forward jets

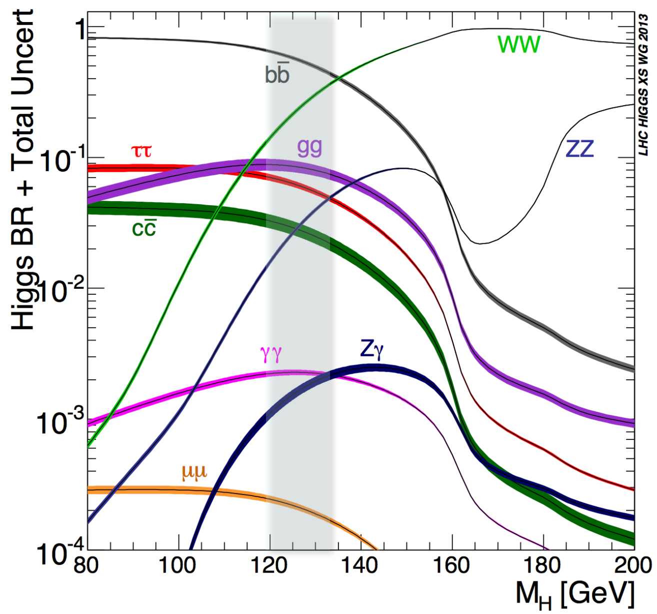


Associated production with a W or a Z boson
(WH,ZH)



Associated production with a **top/anti-top pair**
(ttH)

Higgs decay channels



Discovery decay mode → balance between Branching Ratio and clear experimental signature

H→ZZ→4l

Very clean experimental signature

H→γγ

Mass peak reconstruction

H→WW→2l

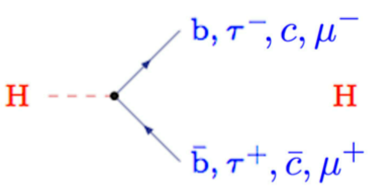
Clear experimental signature, no mass peak

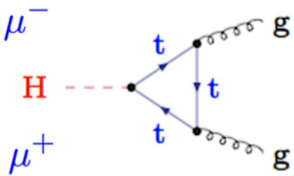
H→ ττ

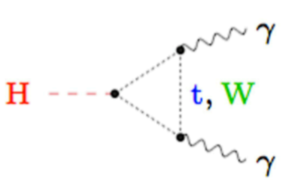
Accessible via VBF

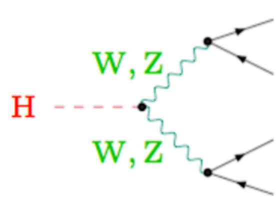
H→ bb

Highest BR for low masses. Challenging experimentally



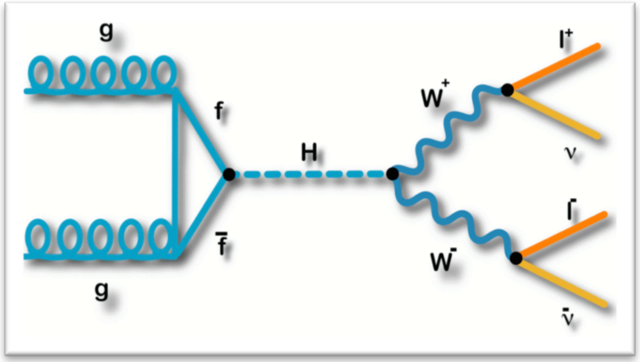






Why H⟶WW?

- **Sensitive in the intermediate mass range** [120-200]
  - 2d largest BR around 125 GeV ⟶ **BR $_{H\rightarrow WW}$ ~ 22%**
- **Clear signature in leptonic decays** (**BR$_{W\rightarrow l\nu}$ ~ 10%**)



- **Two isolated leptons** (e,μ) with opposite charge
- **Substantial missing energy** (two neutrinos in the final state)
- **Depending on the production mode**
  - ggH ⟶ **little to no jet activity**
  - VBF has **2 forward jets**
  - **+** other production modes (VH, ttH) provide even more specific signatures (not covered today)

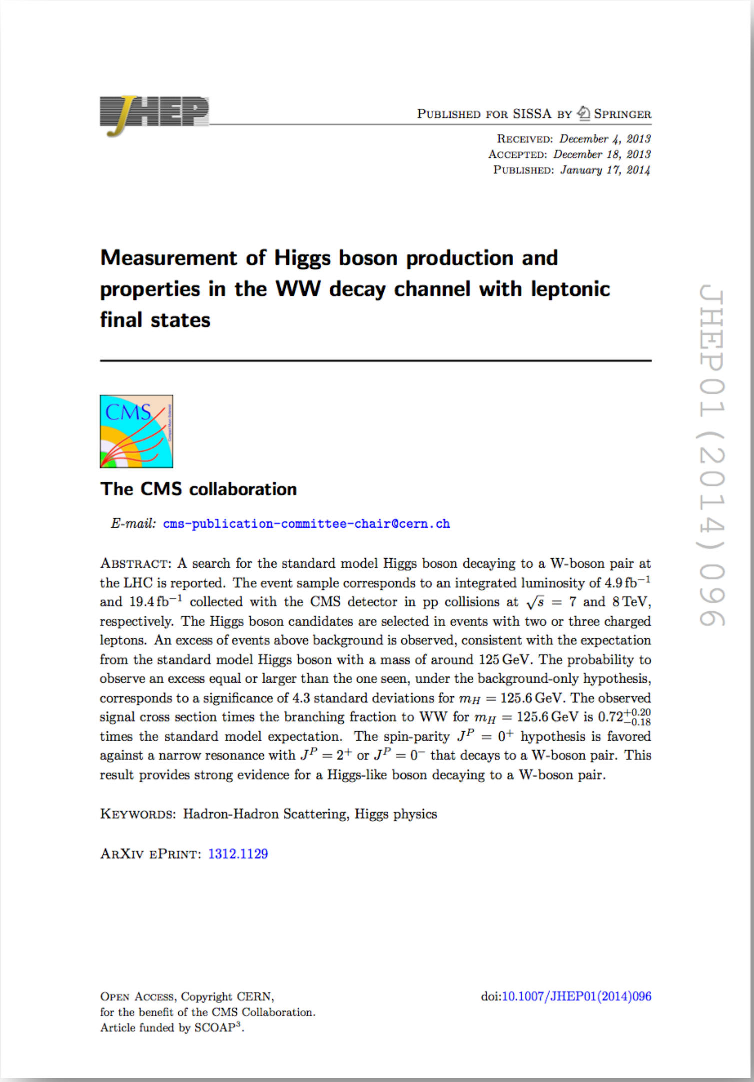
- Not possible to reconstruct full final state due to the neutrinos, no mass peak
- **Large background** contribution (genuine and instrumental)
  - WW (irreducible), top, Drell-Yan, W+jets, QCD…

Legacy publication

- The final Run-1 word from CMS in this decay channel uses the full dataset at **7 and 8 TeV** and was published in JHEP in January last year:

H→WW legacy paper
arXiv:1312.1129
JHEP 01 (2014) 096

- Several processes were studied in detail, ggH, VBF, WH, ZH in 2 and 3 leptons signatures
- **The main analysis, that drives the sensitivity for this decay, is the, H→WW→eνμν in events with 0/1-jets (ggH), and it is the one that we will discuss in this presentation**


JHEP
Published for SISSA by Springer
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Published: January 17, 2014

Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

Abstract: A search for the standard model Higgs boson decaying to a W-boson pair at the LHC is reported. The event sample corresponds to an integrated luminosity of 4.9 fb^{-1} and 19.4 fb^{-1} collected with the CMS detector in pp collisions at $\sqrt{s}$ = 7 and 8 TeV, respectively. The Higgs boson candidates are selected in events with two or three charged leptons. An excess of events above background is observed, consistent with the expectation from the standard model Higgs boson with a mass of around 125 GeV. The probability to observe an excess equal or larger than the one seen, under the background-only hypothesis, corresponds to a significance of 4.3 standard deviations for $m_H = 125.6$ GeV. The observed signal cross section times the branching fraction to WW for $m_H = 125.6$ GeV is $0.72^{+0.20}_{-0.18}$ times the standard model expectation. The spin-parity $J^P = 0^+$ hypothesis is favored against a narrow resonance with $J^P = 2^+$ or $J^P = 0^-$ that decays to a W-boson pair. This result provides strong evidence for a Higgs-like boson decaying to a W-boson pair.

Keywords: Hadron-Hadron Scattering, Higgs physics

ArXiv ePrint: 1312.1129

doi:10.1007/JHEP01(2014)096

JHEP01(2014)096

Physics Objects

- Events are selected using single and double lepton triggers
  - Single: e 17-27 GeV μ 17-24 GeV
  - Double (ee,eμ,μμ): 17, 8 GeV

- The analysis uses leptons, missing transverse energy, jets and b-jet identification

- **Leptons**

  Against backgrounds without two prompt leptons (W+jets, QCD…)

  Selected following specific quality criteria, isolated
  - **Electrons** $|\eta| < 2.5$
  - **Muons** $|\eta| < 2.4$

- **Jets**

  Backgrounds with high jet multiplicity or with central jets (ttbar)
  - Anti-k_t 0.5, $p_T > 30$ $|\eta| < 4.7$

Physics Objects

- **b - jet identification**

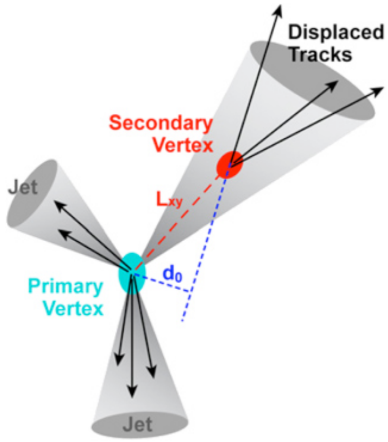
  For jets coming from b-decays (ttbar, tW)

  top quarks decays ~100% of times as t→Wb

  Two tagging techniques, taking advantage of the properties of b-jets: B hadrons fly a few mm before decaying; and in ~40% of cases, B hadron decays include a soft lepton (e/μ) from b→l or b→c→l

  - b-tag algorithm based on lifetime
  - soft muon identification: p_T> 3 no isolation

rejects 70% b-quark jets, keeps 95% of light quarks

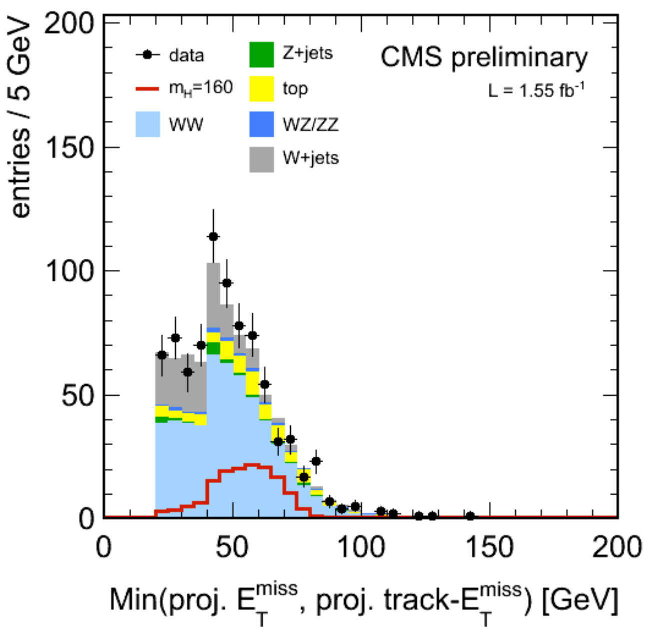


Physics Objects

- **Missing transverse energy (MET)**

  Against backgrounds with no genuine MET (Drell-Yan→l^+l^-)

  - different estimators

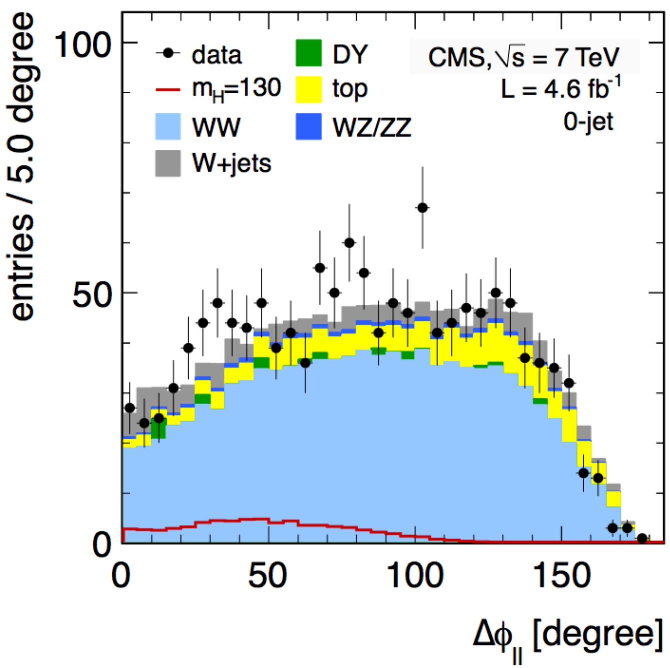


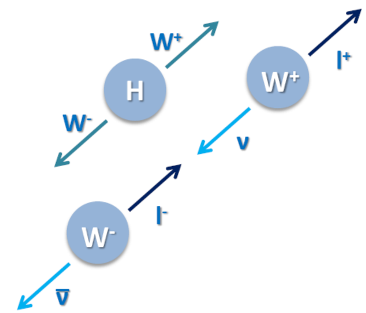
PAS HIG-11-014

- Particle Flow MET (PF MET), which uses all CMS detector subsystems and reconstructs a full list of stable particles
- Tracker MET, that uses charged particles only, and it is less dependent on pileup effects
- Projected MET = MET*sin[min($\pi/2, \Delta\Phi_{\text{MET-closest lepton}}$)]
- MET estimator: **min** 2 projected MET quantities, **PF and Tracker MET**

Kinematics of the signal

- Some backgrounds have the exact same final state
  - WW→2l2ν is the clearest case and the almost irreducible one
- There are three main observables to separate the signal from backgrounds:
  - **$\Delta\Phi_{ll}$:** opening angle between the two leptons in the transverse plane to the beam, correlated to the spin of the Higgs boson





7 TeV paper data

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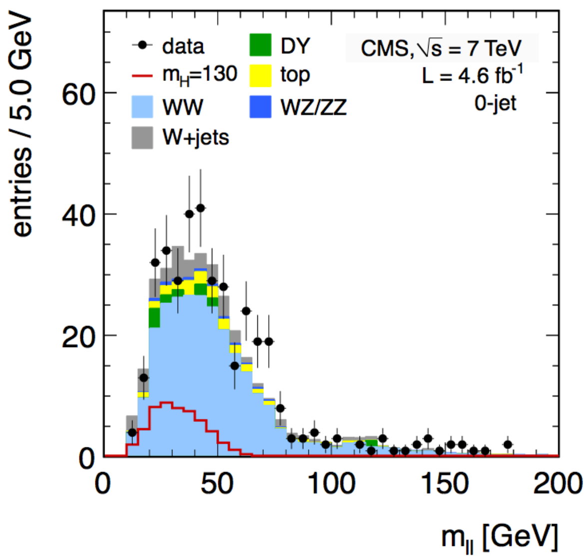
  - **m_{ll}:** the dilepton mass, one of the most discriminating kinematic variables for a Higgs boson with low mass, in particular against Z/γ*→ ll



7 TeV paper eμ

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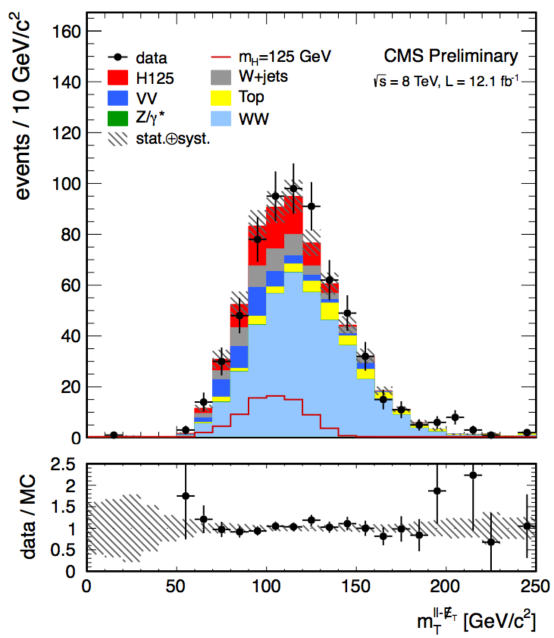


- m_T: the transverse mass of the final state objects which scales with the Higgs mass defined here as

$$m_T^2 \;=\; 2p_T^{\ell\ell}E_T^{miss}(1-\cos\Delta\phi(\ell\ell,\vec{E}_T^{miss}))$$

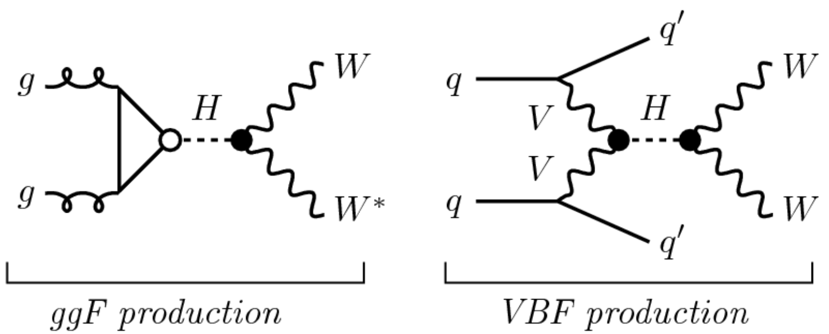
PAS HIG-12-042
H→WW PAS for HCP 2012

Definition of the WW selection

- **Exactly two leptons, eμ, with opposite charge, p_T > 20, 10 GeV**
- **MET** estimator **> 20 GeV**
- **Exactly 0 or exactly 1 jet**

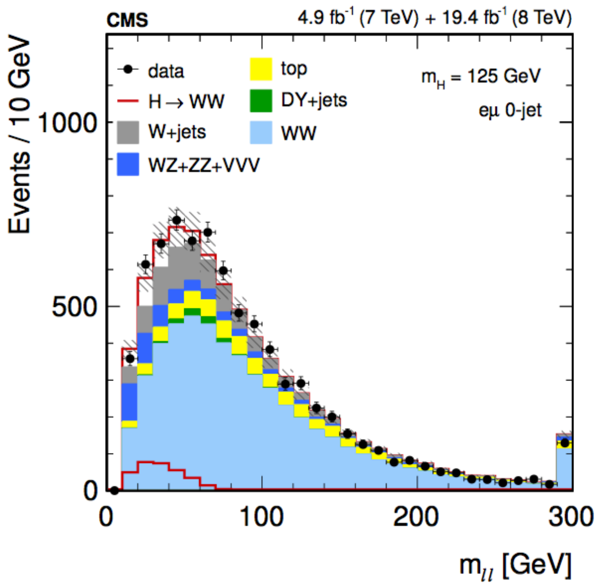
- A region with: **reasonable S/B and a good description of background**
  - m_{ll} > 12 GeV
  - p_T^{ll} > 30 GeV
  - m_T > 30 GeV
  - Veto events with b-jets (b-tagging and soft μ)

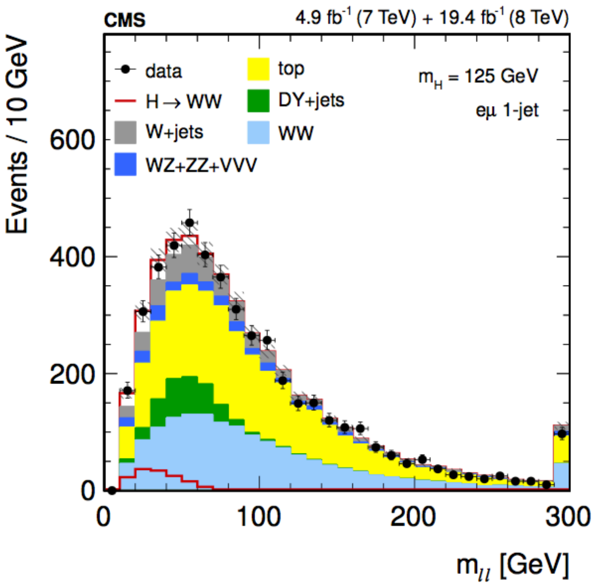
- For the same flavor (ee/μμ) case, additional cuts around the Z mass peak, and for other production modes different cuts are applied, like VBF (the second most important) that has cuts on $\Delta\Phi_{ll\text{-}jj}$, $\Delta\eta_{jj}$ or m_{jj}



Analysis

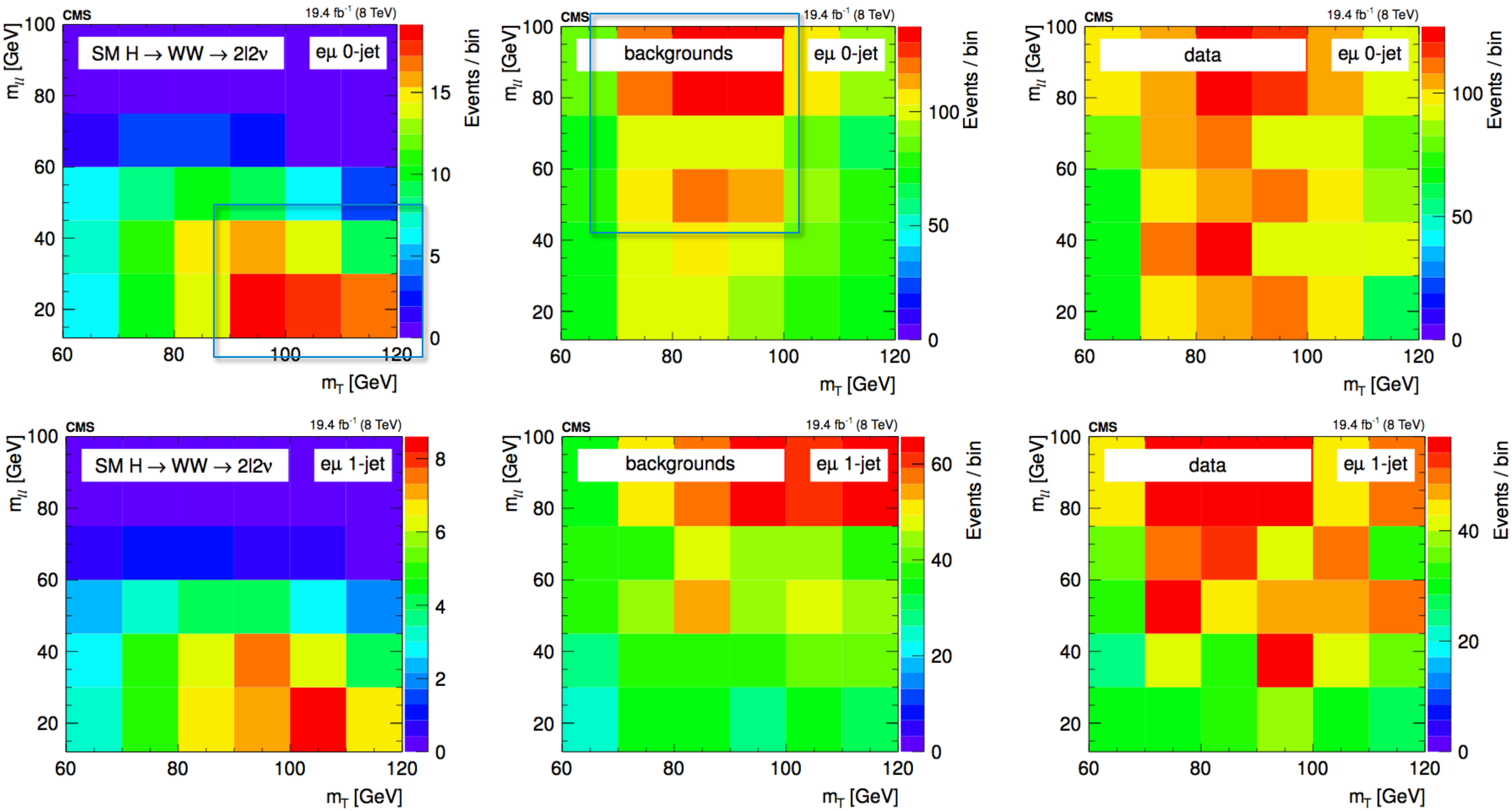
m_{ll} at the WW selection level





- After the WW selection, the analysis is **split in categories** and has different approaches depending on the final state (e.g. cut-based for ee and μμ)
- The (**ggH, eμ**) analysis is based on a **2D shape analysis** of m_T - m_{ll}, with 9 bins for m_{ll}, and 14 for m_T
  - m_{ll} [12,200], m_T [60,280] for m_H <= 250 GeV
  - m_{ll} [12,600], m_T [80, 600] for m_H > 250 GeV

2D templates

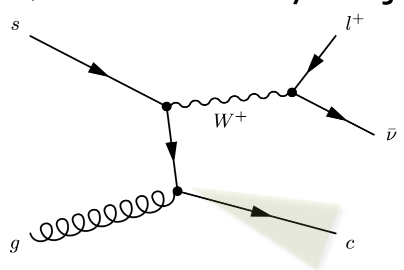


A binned template fit is performed in this case to extract upper limits and significance

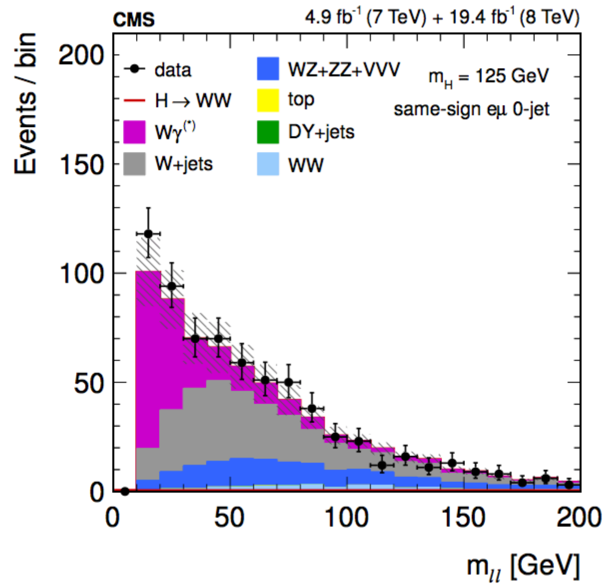
Background estimates

- Central part of the analysis, data-driven as much as possible
- **Non-prompt leptons (W+jets, QCD):** Leptonic decays of heavy quarks, hadrons misidentified as leptons, electrons from photon conversions.

  Fully data-driven: normalization and shapes
  Pass-fail sample reweighed by pass efficiency estimated in data (multijet)
  Closure test in simulation, validated in same-sign region (dominated by W+jets and Wγ(*))



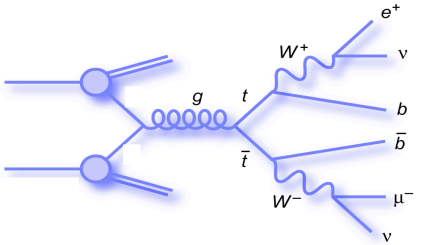
Potential "fake" lepton

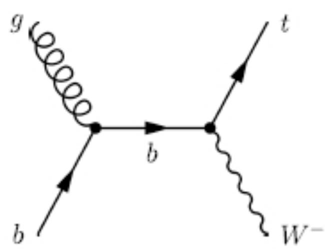


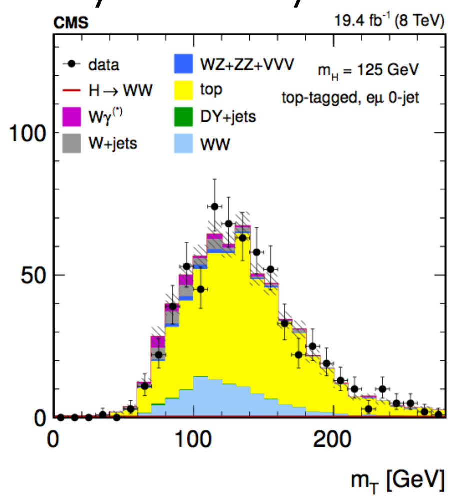
- **Drell-Yan:** in same flavor final states
  - shapes from simulation, **normalization from data** around the Z mass peak
- **WZ,ZZ,VVV:** simulation

Background estimates

- **Top**: Events from ttbar and single top tW
  - Shapes from simulation, **normalization from data**
  - Using top tagged events rejected in the analysis, weighted by efficiency measured in control regions with additional jets
  - Fit validated using top tagged events.



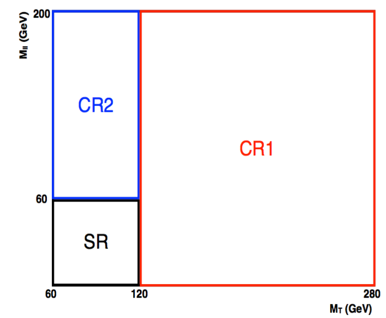


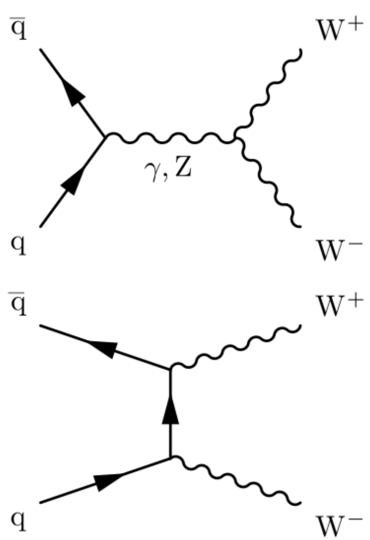


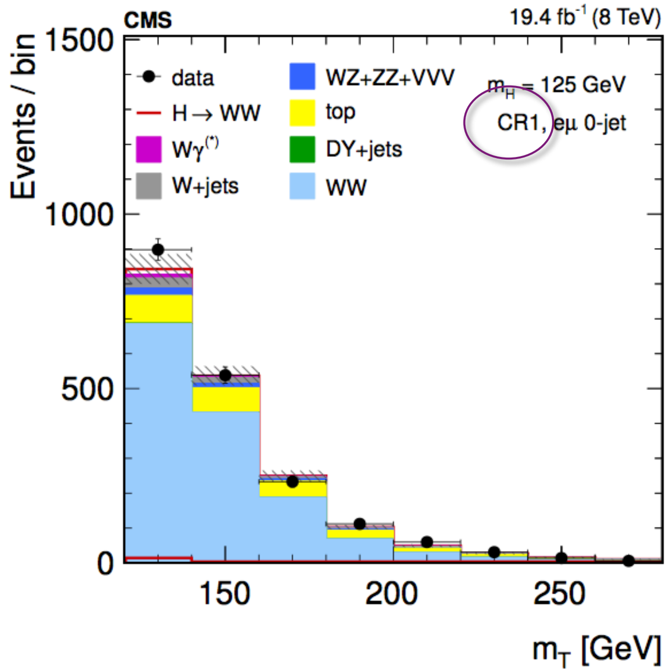
- **Wγ*:** shape from simulation, **normalization from data**
  - part of WZ not properly modeled → low m_{ll} events where 1 lepton is lost simulated sampled compared with data in CR defined by different cuts (k-factor obtained)
- **Wγ: shape from data**, normalization from simulation
  - data γ+lepton events reweighed with ratio γ->lepton

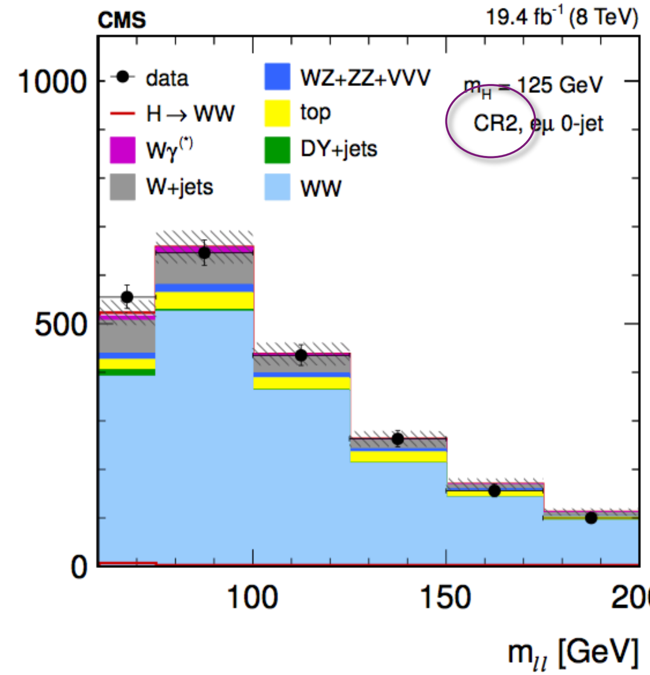
WW Background

- **Fit validated** in two control regions, similar statistics, purity 70-75%
  - output of fit in one extrapolated to the other:
    - **high m_T CR1:** $120 < m_T < 280$ and $12 < m_{ll} < 200$
    - **high m_{ll} CR2:** $60 < m_T < 120$ and $60 < m_{ll} < 200$

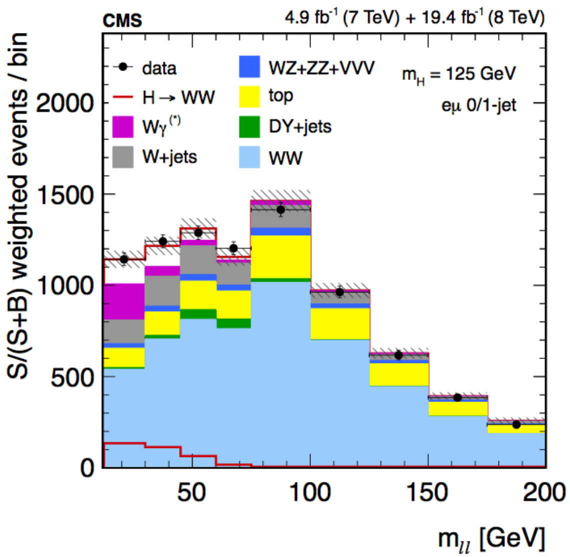


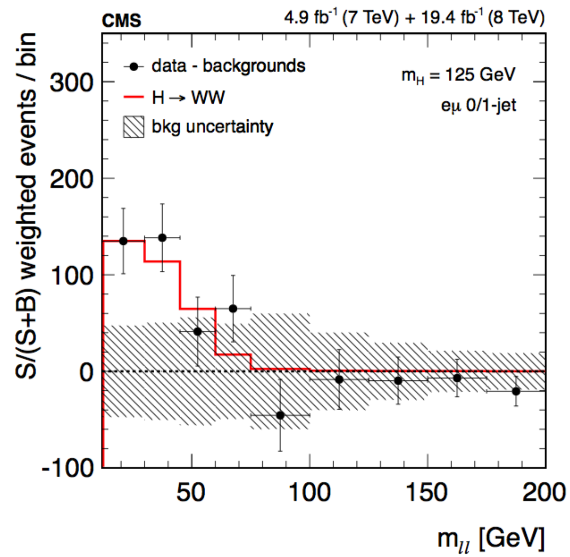


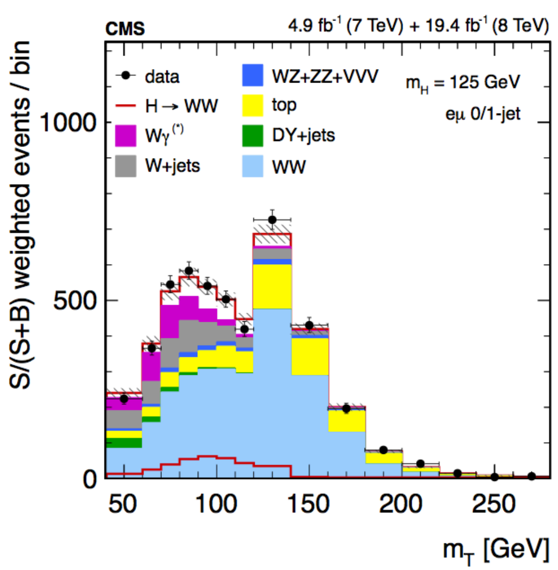


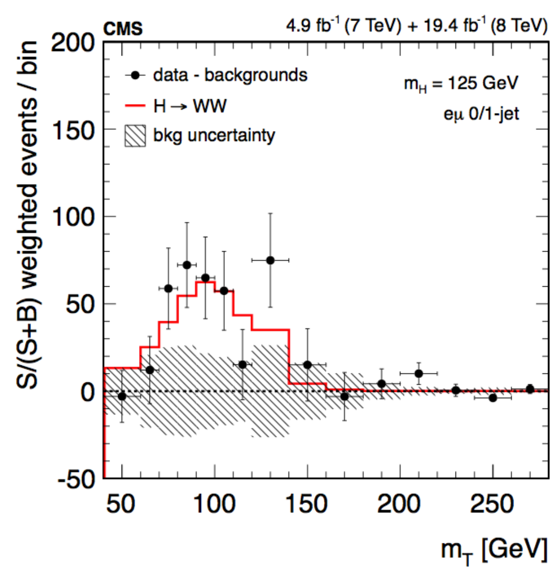


Final distributions



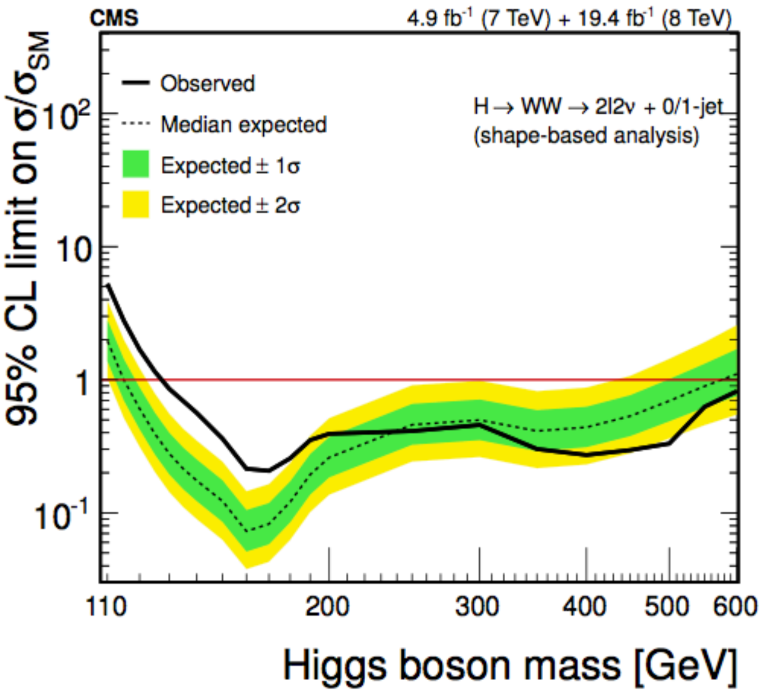






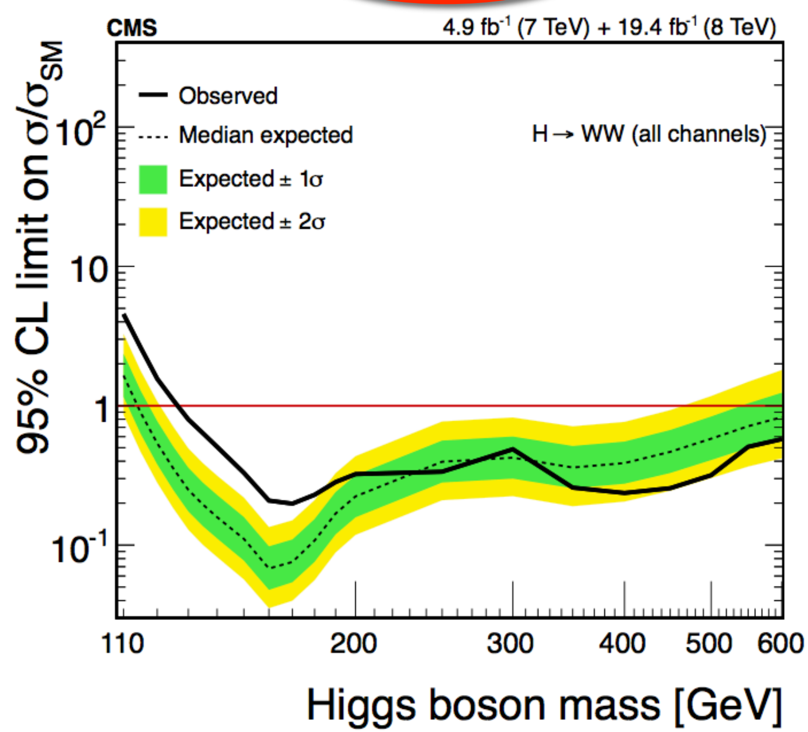
- **Data compared with signal and background events**
- **Background-subtracted data compared with best-fit signal component**

Results



The eμ channel alone:

95% CL		Significance		σ/σ_{SM}
Exp.	Obs.	Exp.	Obs.	
0.4	1.2	5.2	4.0	0.76±0.21



Full H→WW result

Significance		σ/σ_{SM}
Exp.	Obs.	
5.8	4.3	0.72+0.20-0.18

There is definitely something

- Something that decays via X→WW→2l2ν
- There is confirmation from other decays (in some decays stronger than in WW, in other decays less so)
- **But is it the Higgs?**

SM prediction

Reality?

Reality?

- Handles to find deviations with respect to the SM expectations:
  - **Mass, Charge, Spin, Parity…**

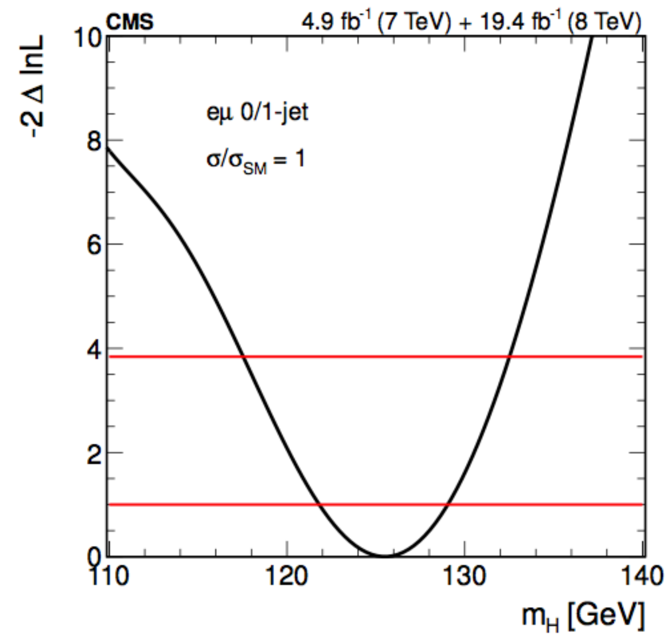
  → **How much can we explore using H→WW?**

Charge

- The charge is 0, it is a neutral particle.

Mass

- The $H \to WW$ excludes a Higgs mass range from **127 to 600** GeV
  - Expected range extends from 115 to 600 GeV
  - Additional Higgs bosons with SM-like properties excluded in the mass range 114–600 GeV assuming a 125 boson
- Best-fit mass:
  - $\sigma/\sigma_{SM}=1 \to$ **$m_H = 125.5+3.6-3.8$ GeV**
  - without the constraint $\to$ $m_H = 128.2 \pm 6.6$ GeV



CMS Higgs mass value (driven by γγ and ZZ):
$m_H = 125.02$ +0.26-0.27 (stat) +0.14-0.15 (syst)

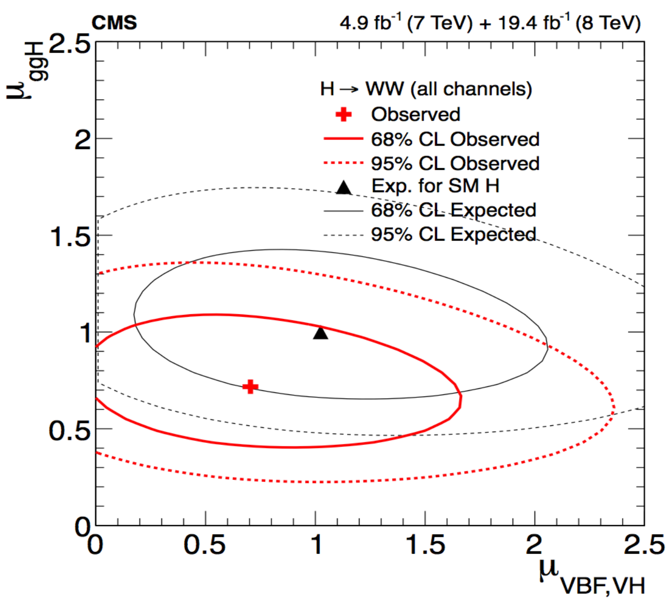
Legacy mass paper
arXiv:1412.8662
Accepted by JHEP
Submitted Dec 2014

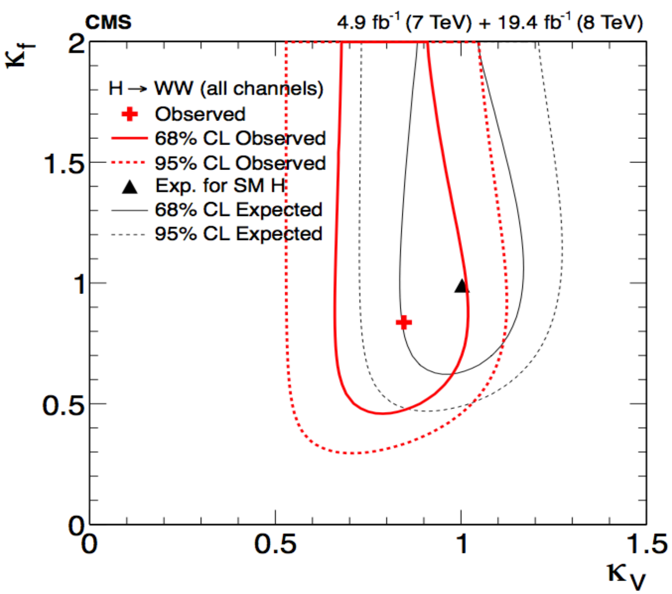
Couplings

- The values of μ_{ggH} and μ_{VBF} can be used to test the fermionic and bosonic couplings
- Coupling modifiers κ_V and κ_f are assigned to vector and fermion vertices → used to scale the expected product of σxBR to match the signal yields observed in data

$$\sigma \times \mathrm{BR}(\mathrm{X} \to \mathrm{H} \to \mathrm{WW}) = \kappa_i^2 \frac{\kappa_\mathrm{V}^2}{\kappa_\mathrm{H}^2} \sigma_\mathrm{SM} \times \mathrm{BR}_\mathrm{SM}(\mathrm{X} \to \mathrm{H} \to \mathrm{WW})$$

- κ_i is κ_f for ggH, κ_V for VBF; and κ_H is the total decay width ~ κ_f^2
  - **μ_{ggH} is sensitive to κ_V and μ_{VBF}, which scales with κ_V^4/κ_f^2 is more sensitive to κ_f**





Spin and parity

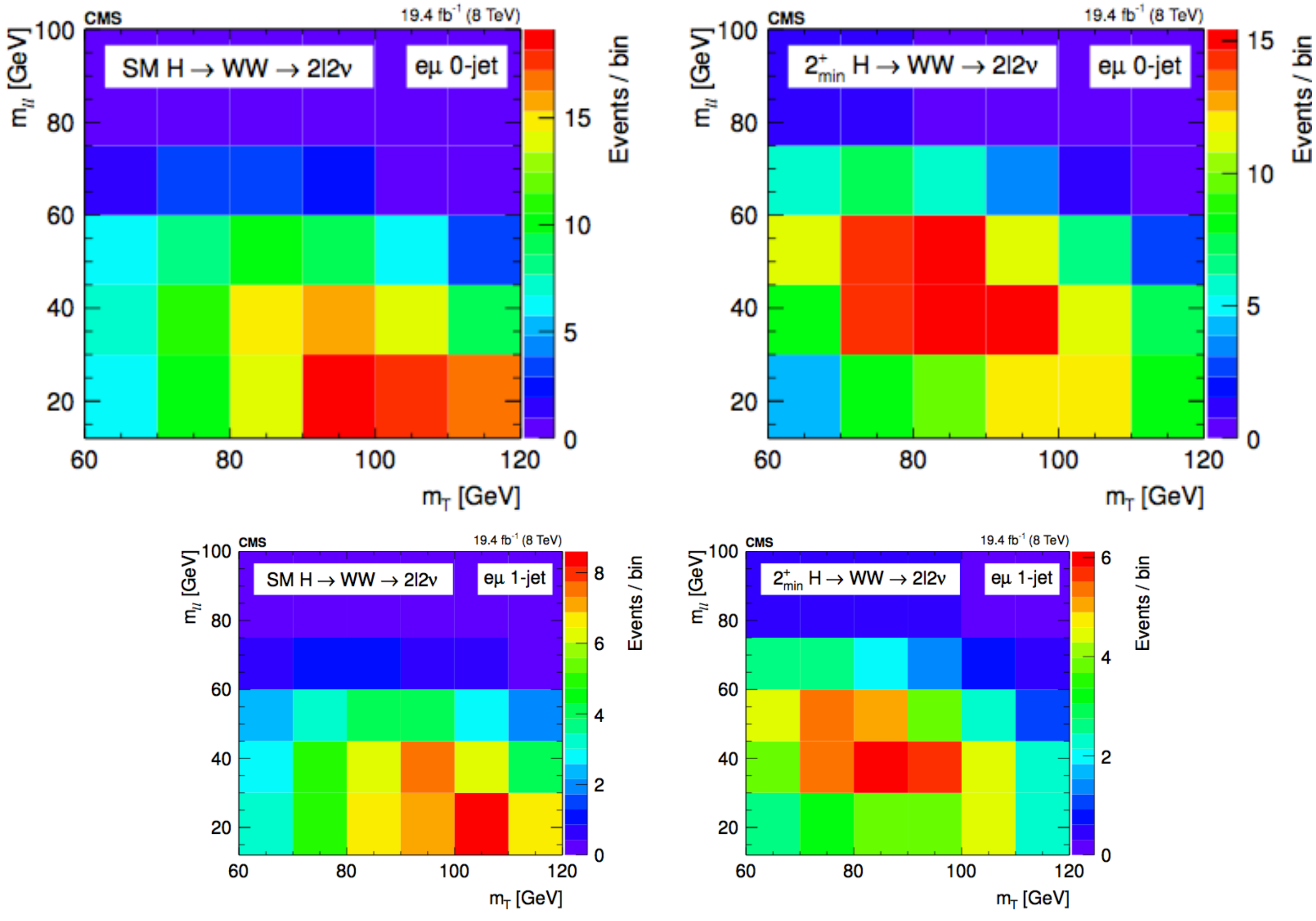
arXiv:1411.3441
Submitted to PRD
November 2014

- Information from angular distributions of the decay products:
  - For example, in H→ZZ→4l, the final state is reconstructed fully and accurately
- In H→WW **the final state is not fully reconstructed, and there is more background contamination in the signal region, however**
  - There is potential gain in the combination of HWW with other final states

- We extract all the possible information using the same templates used for the SM Higgs search
- Interpretation of the signal events in terms of
  - **Hypothesis test of SM against exotic spin-1 and spin-2 Higgs boson**, using the same model as in the SM Higgs search and the test statistic $\mathbf{q = -2\ln(L_{JP}/L_{0+})}$ to quantify the consistency of the two models with data
  - **Anomalous couplings with respect to SM of a spin-0 Higgs boson** using fractions of cross sections

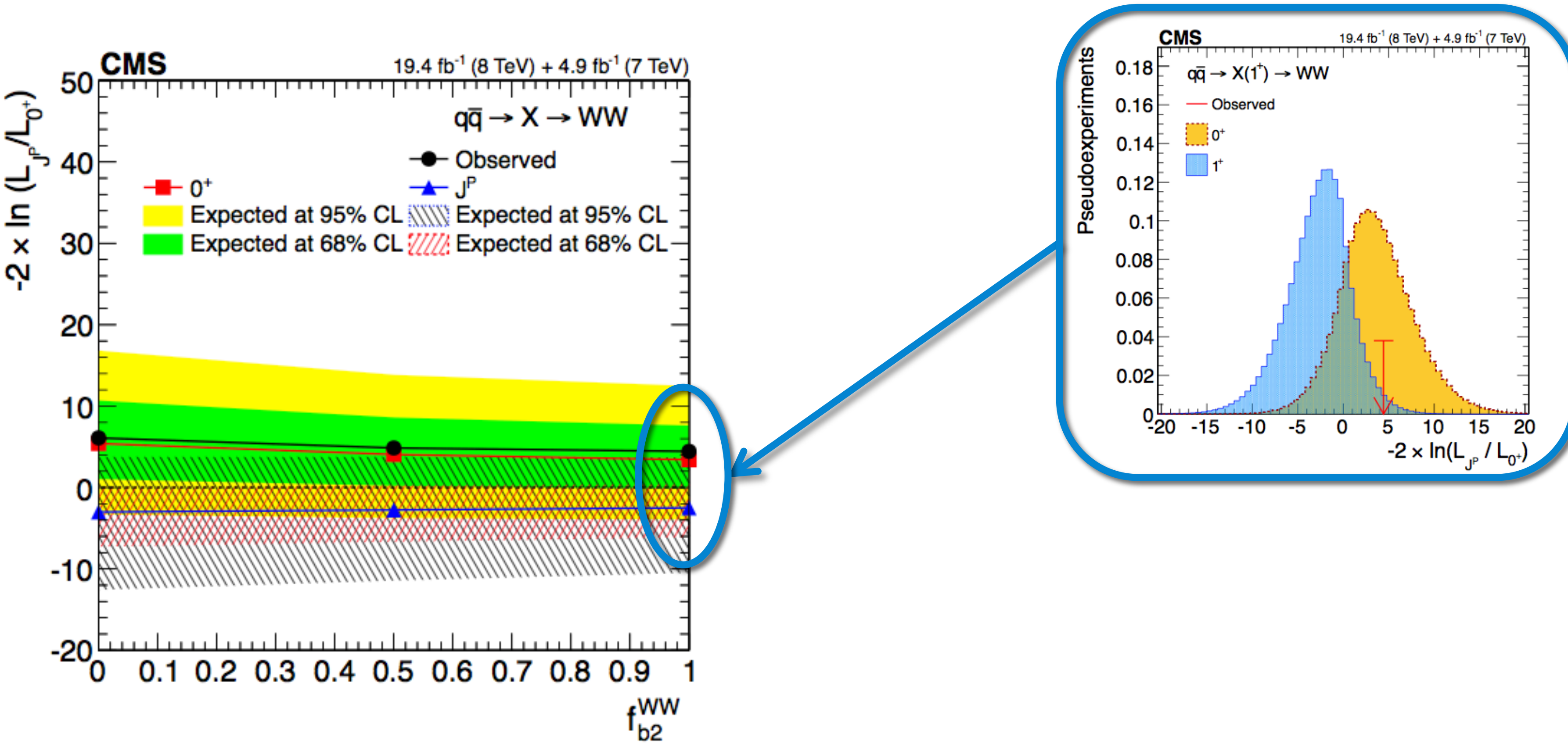
Spin studies in H→WW

- The same 2D templates used in the eμ analysis are also optimal to discriminate between different spin hypotheses



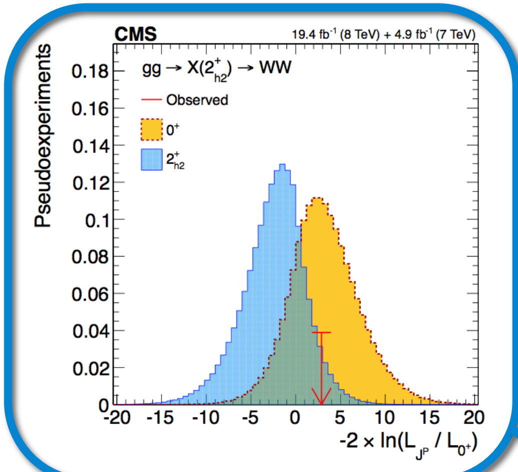
Spin-1

- J=1 not allowed for X→$\gamma\gamma$ by the Landau-Yang theorem
- Still we tested experimentally potential spin-1 models (in the hypothesis the excess is not the same resonance as $\gamma\gamma$) in H→WW: J^P=1$^-$, 1$^+$ and a mixed case

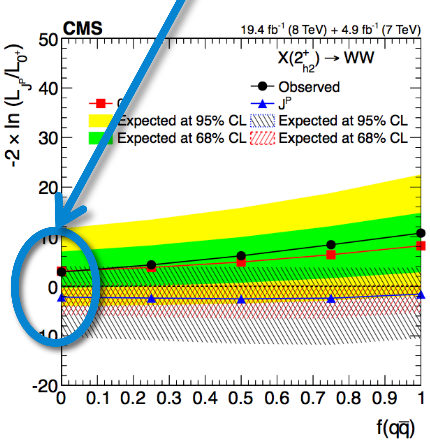


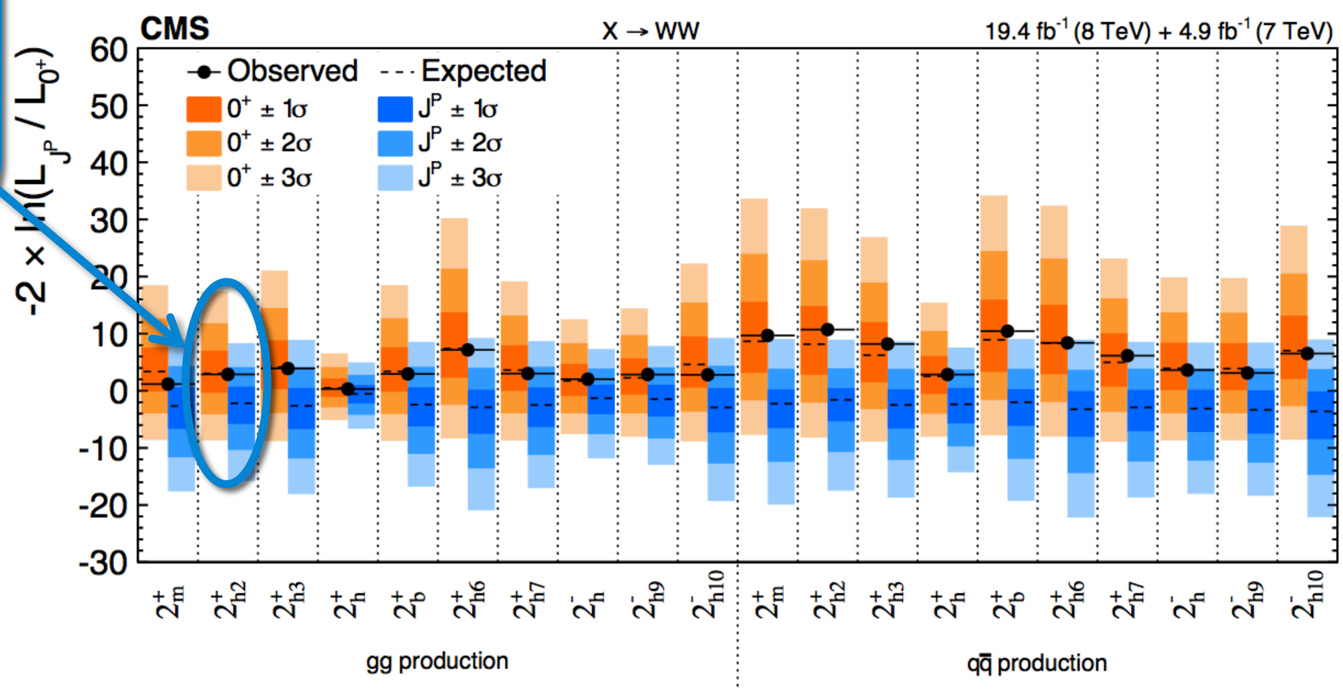
Spin-2

- J=2 tested for different production modes (gg, qq), ten different models tested, separation studied as a function of the qqH component, f_{qq}



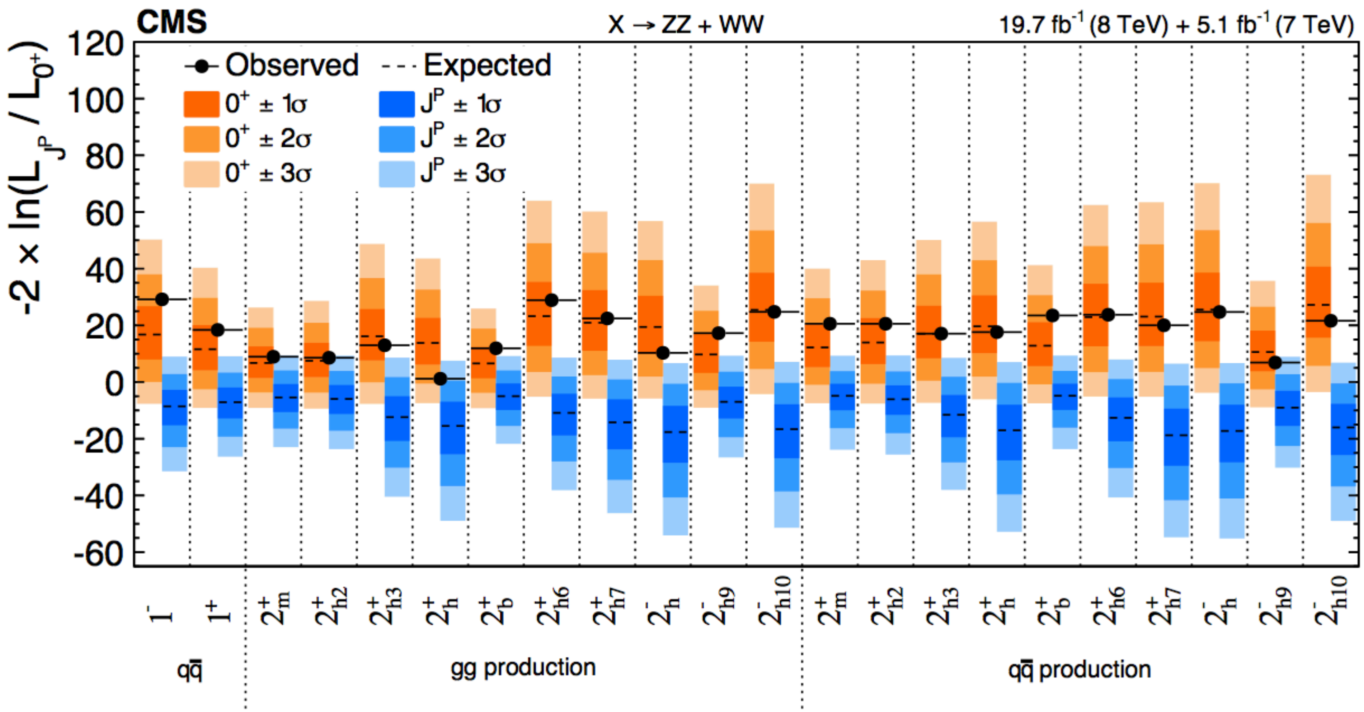
In all cases the data favor the SM hypothesis over the alternative spin-one or spin-two hypotheses





H⟶WW and H⟶ZZ combination

- The main player in separating exotic spin hypotheses is the H⟶ZZ decay, but H⟶WW contributes to the combination



All the exotic models are excluded at **more than 99.9% CL**

(It is a spin 0 boson)

Spin 0 amplitude in H→VV

- The observed Higgs boson appears to be predominantly a **J^{CP}=0^{++}** state
  - It still could be a mixture of CP states and the couplings to gauge bosons could have small **anomalous components**

- The decay amplitude for a spin-0 boson to a pair of V bosons (V = Z, W, g, γ) is defined, up to dimension 5, as:

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \underbrace{\frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2}}_{\substack{\Lambda_1 \text{ term} \\ \text{leading momentum expansion}}} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \underbrace{a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu}}_{\substack{a_2 \text{ term} \\ \text{CP even state}}} + \underbrace{a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}}_{\substack{a_3 \text{ term} \\ \text{CP odd state}}}$$

  - a1 is the SM amplitude
  - Λ1 is a higher-term of an expansion in momentum
  - a2 and a3 control the CP-even and CP-odd amplitudes

Spin 0 amplitude in H⟶VV

- We choose a parameterization that relates fractions of the cross sections to the couplings: f_{a2}, f_{a3}, $f_{\Lambda 1}$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4 + \dots}, \qquad \phi_{\Lambda 1},$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4 + \dots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4 + \dots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

σ_i is the effective cross-section when $a_i = 1$ and $a_{j\neq I} = 0$

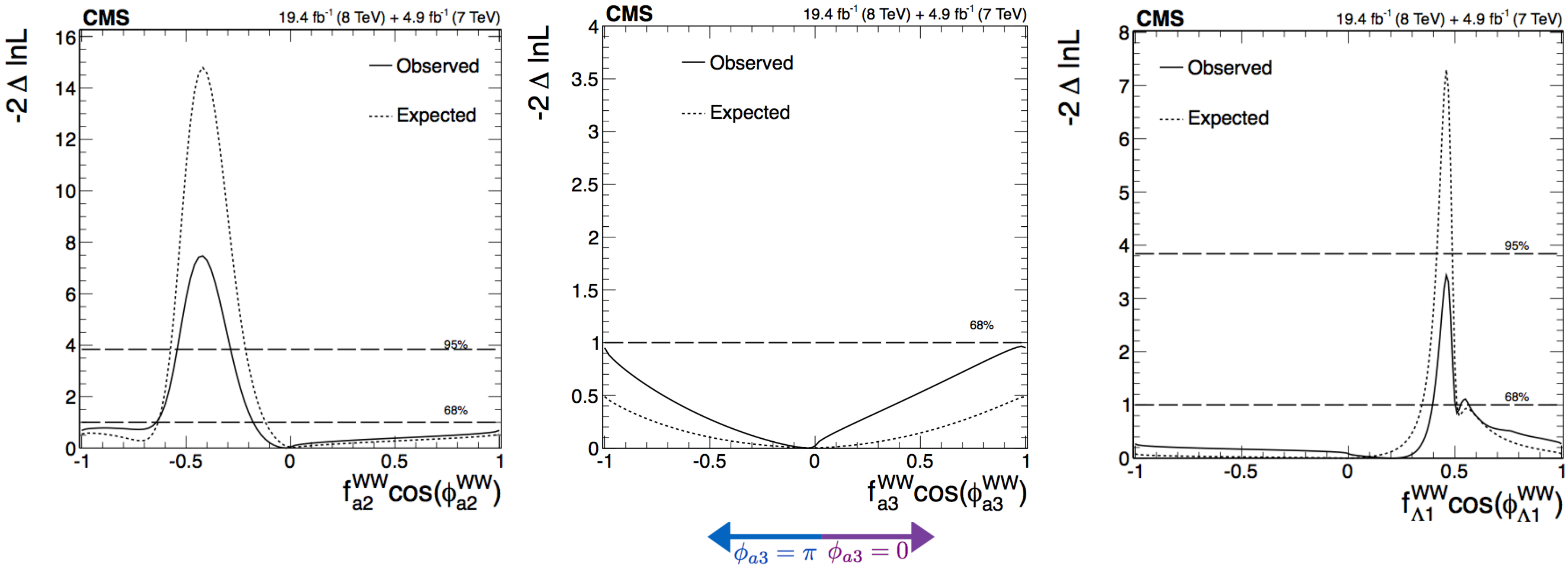
- Given the **measured value of f_x**, it is possible to extract the coupling constant:

$$\frac{|a_i|}{|a_1|} = \sqrt{f_{ai}/f_{a1}} \times \sqrt{\sigma_1/\sigma_i}, \qquad \Lambda_1\sqrt{|a_1|} = \sqrt[4]{f_{a1}/f_{\Lambda 1}} \times \sqrt[4]{\tilde{\sigma}_{\Lambda 1}/\sigma_1},$$

- Where $f_{a1} = 1 - f_{a2} - f_{a3} - f_{\Lambda 1} - \dots$, is the SM contribution, which is expected to dominate

H⟶WW Spin-0 studies

- The likelihood scans for the effective fractions are **consistent with the SM**
- H⟶WW has limited sensitivity for the measurement of f_{a2}, f_{a3} and $f_{\Lambda 1}$



Couplings constrained to be real and all other anomalous couplings are fixed to the SM predictions in each case, cos ϕ term allows a signed quantity where cos ϕ = −1 (π) or +1 (0)

- When combined with H → *ZZ* there is a sizeable improvement on the sensitivity

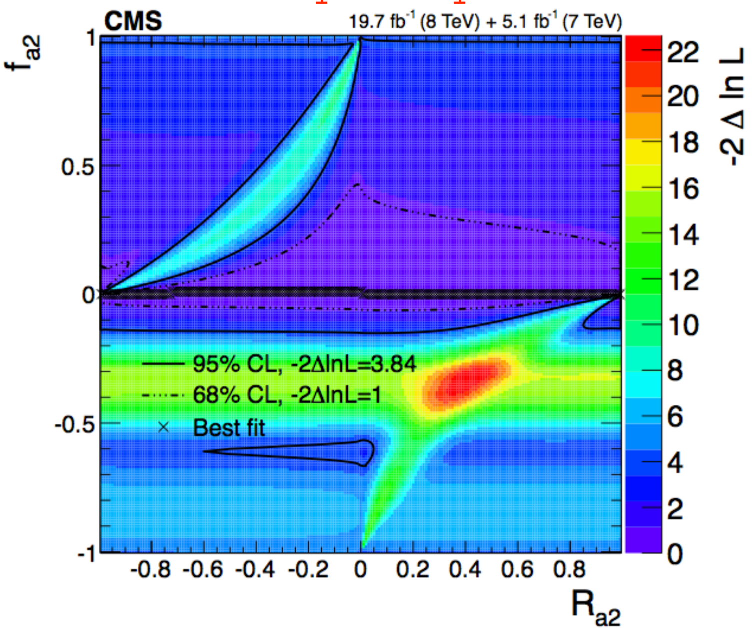
H→WW and H→ZZ combination

- General relationship between HWW and HZZ couplings: $a_i^{WW}/a_1^{WW} = r_{ai}\,(a_i^{ZZ}/a_1^{ZZ})$

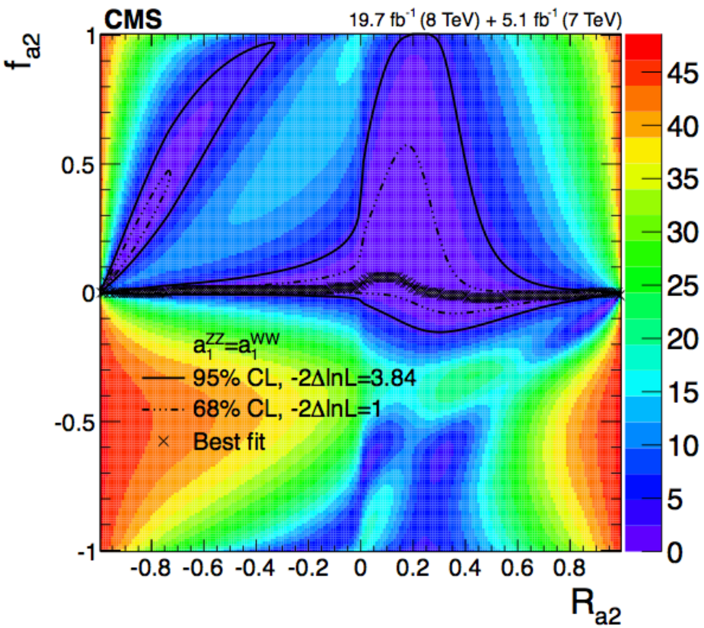
$$r_{ai} = \frac{a_i^{\mathrm{WW}}/a_1^{\mathrm{WW}}}{a_i/a_1} \qquad r_{ai}\,[-\infty, +\infty] \longrightarrow R_{ai} = \frac{r_{ai}|r_{ai}|}{1+r_{ai}^2} \qquad R_{ai}\,[-1,+1]$$

- We have two scenarios for combination: arbitrary relationship between W and Z couplings or custodial symmetry

$a_1^{WW} \neq a_1^{ZZ}$

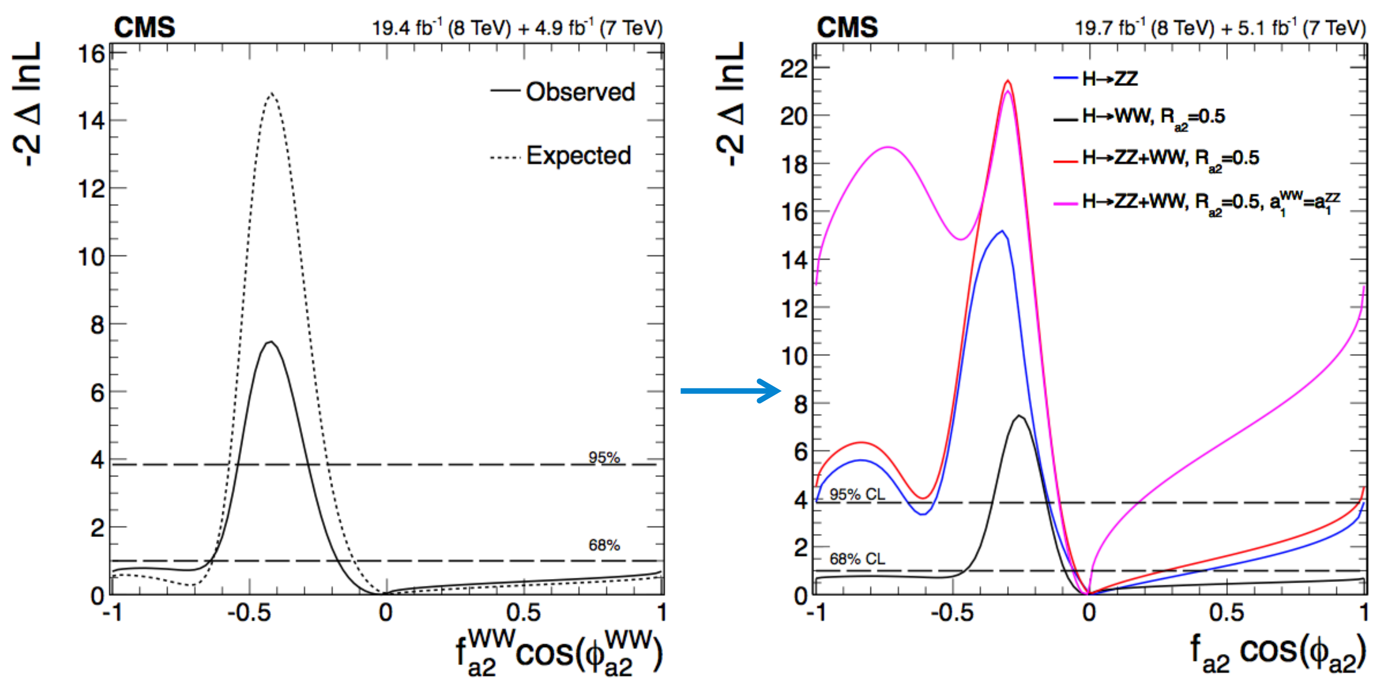


$a_1^{WW} = a_1^{ZZ}$



H⟶WW and H⟶ZZ combination

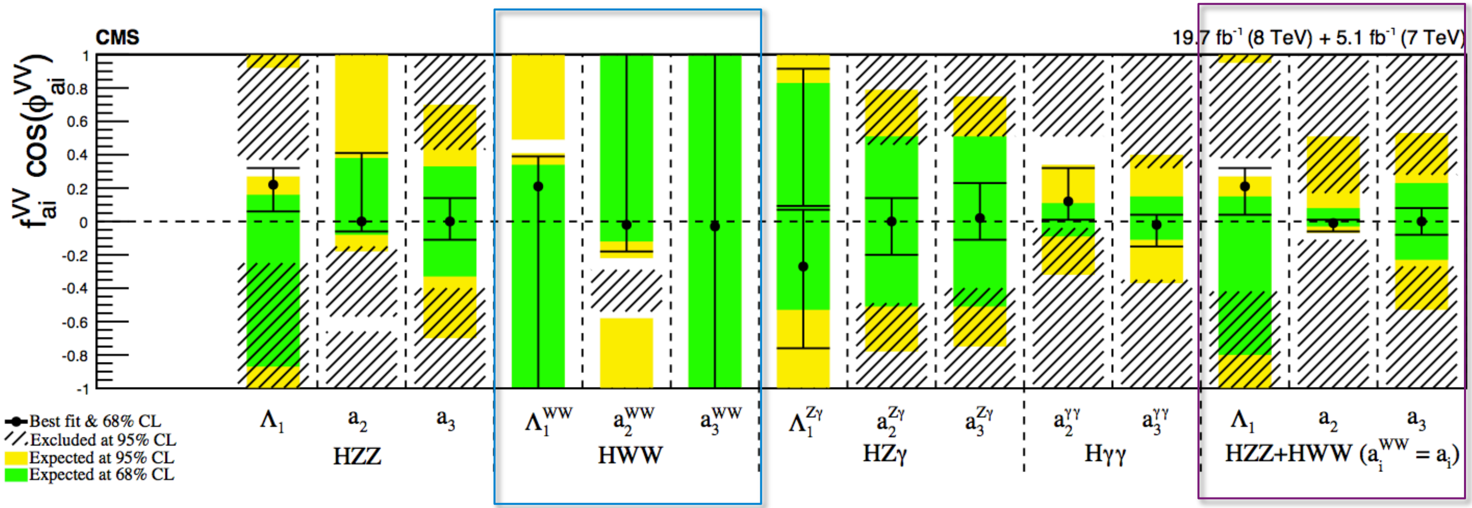
- Choosing R_{a2}=0.5 (r_{a2}=1) for illustration purposes.
- Not assuming custodial symmetry the result is close to the sum of the two individual curves, as expected. In the custodial symmetry scenario greater exclusion is achieved because the yields are related in WW and ZZ:



Summary of anomalous couplings

Consistent with SM. When assuming custodial symmetry: pure 0_h^+ excluded at 99.93% CL and pure 0^- excluded at 99.99% CL

Parameter	Observed	Expected	$f_{ai}^{VV}=1$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.21^{+0.11}_{-0.17}$ $[-0.42, 0.38]$	$0.00^{+0.15}_{-0.80}$ $[-1, 0.27] \cup [0.95, 1]$	0.56% (13%)
$f_{a2}\cos(\phi_{a2})$	$-0.01^{+0.02}_{-0.05}$ $[-0.11, 0.17]$	$0.00^{+0.08}_{-0.03}$ $[-0.07, 0.51]$	0.03% (0.25%)
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.08}_{-0.08}$ $[-0.27, 0.28]$	$0.00^{+0.23}_{-0.23}$ $[-0.53, 0.53]$	<0.01% (0.08%)

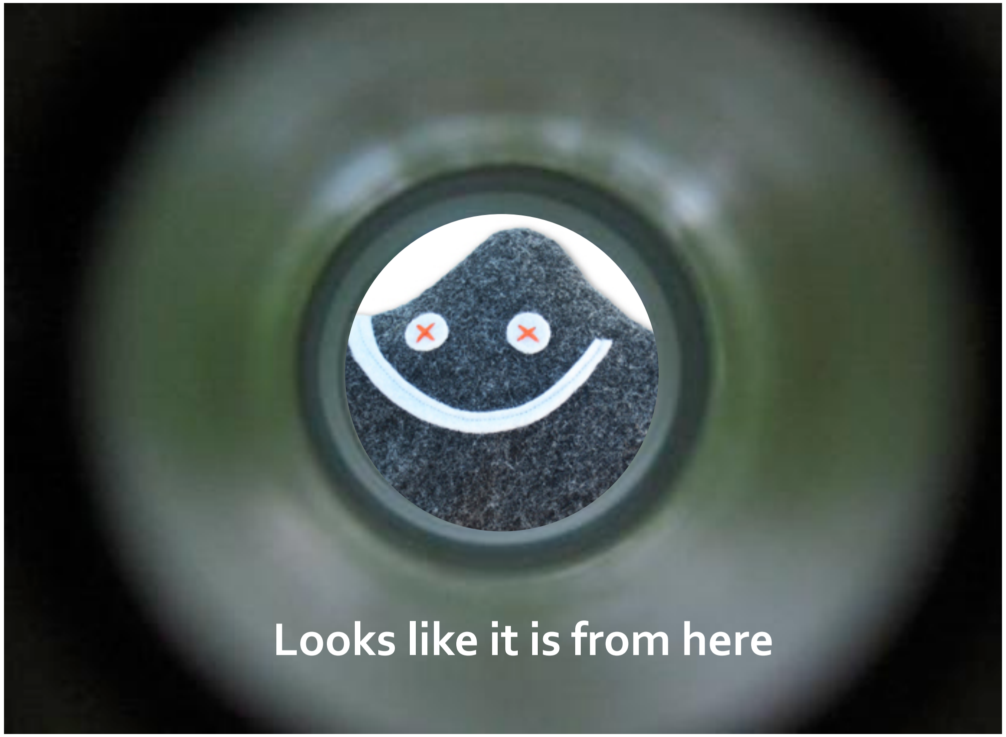


Summary of allowed confidence level intervals on anomalous coupling parameters in HVV interactions under the assumption that all the coupling ratios are real

So, it is the Higgs?

- We have a new particle that decays like the SM Higgs would
- With a **mass** ~ 125GeV
- **Neutral**
- Scalar **couplings** to fermions and vector bosons compatible with a SM Higgs
- $\mathbf{J^{CP}=0^{++}}$

Is this guy exactly as we expect it?

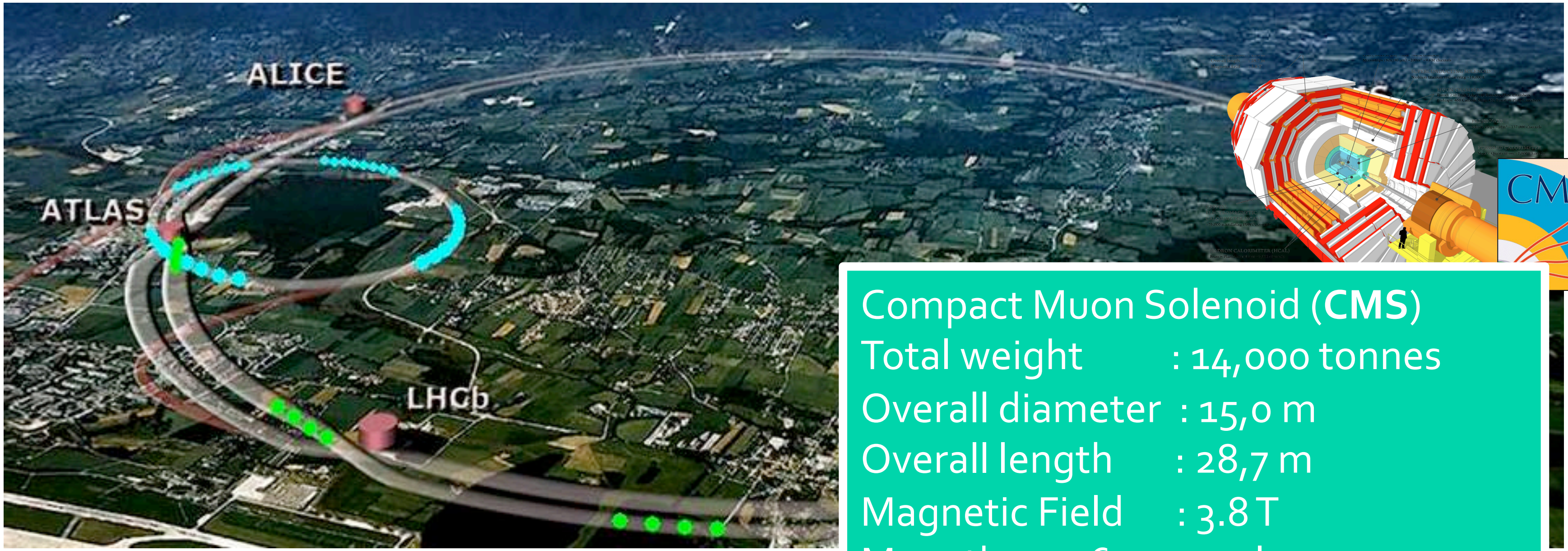


But only more data will tell

Backup

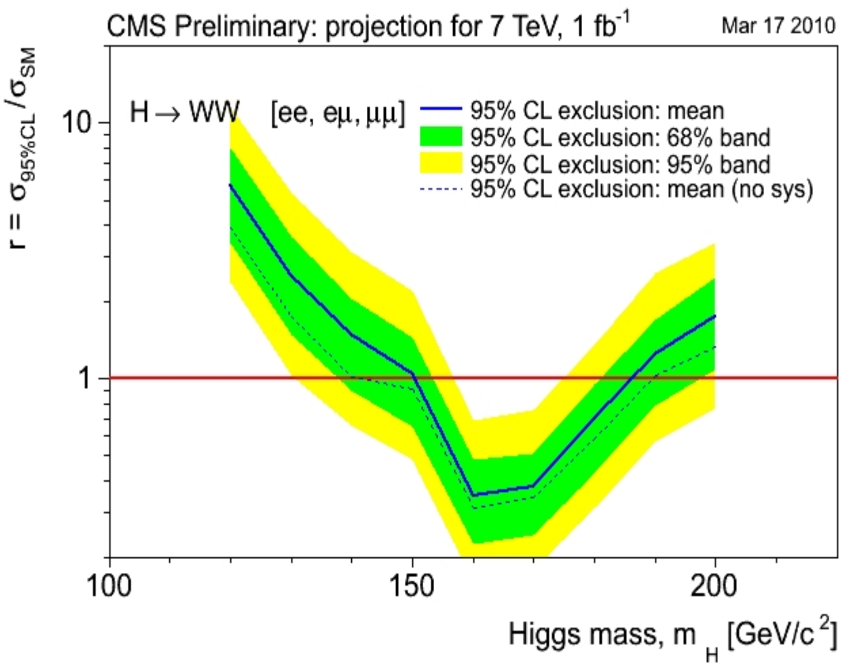
The CMS experiment at the LHC

The Large Hadron Collider (LHC) at CERN is the largest particle accelerator of the world. It has 4 big experiments (ALICE, ATLAS, CMS, LHCb), two of them (CMS and ATLAS) are intended for general purposes and complementary

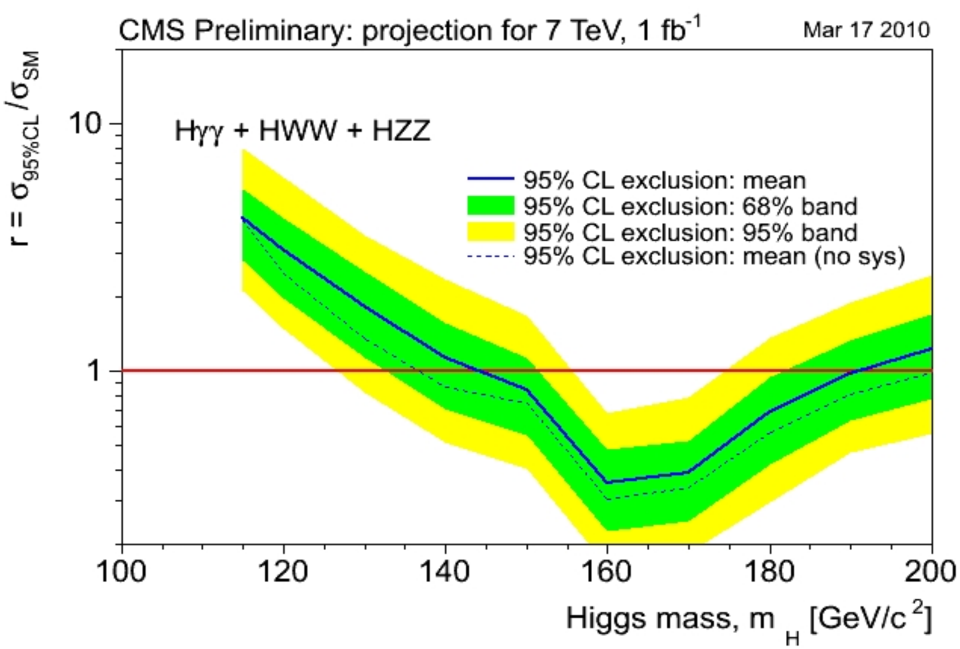


Compact Muon Solenoid (**CMS**)
Total weight : 14,000 tonnes
Overall diameter : 15,0 m
Overall length : 28,7 m
Magnetic Field : 3.8 T
More than 2,600 people
41 countries

H→WW projections for 7 TeV



H→WW alone
Discovery level sensitivity (~5σ) :
$160<m_H<170$ GeV
Exclusion 95%CL: $150<m_H<185$ GeV



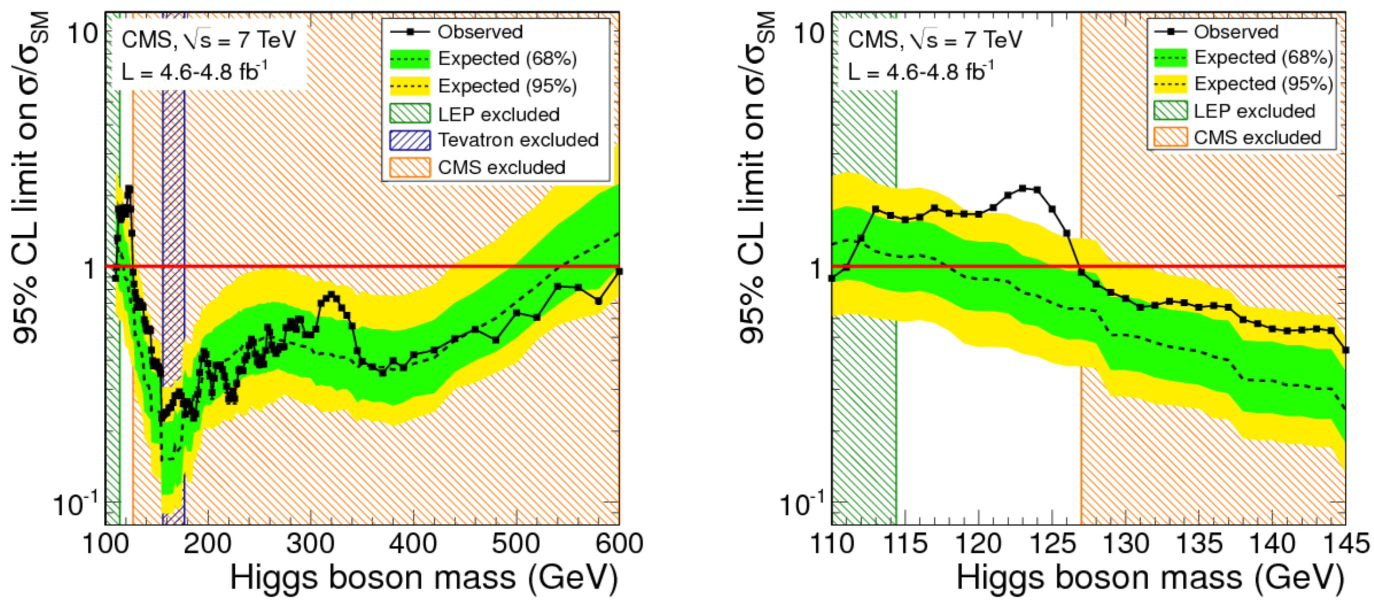
Combination of the main modes
Expected exclusion 95%CL
145< mH <190 GeV

7 TeV results

arXiv:1202.1489
Phys. Lett. B 710 (2012) 91
(Submitted 7 Feb 2012)

arXiv:1202.1488
Phys. Lett. B 710 (2012) 26
(Submitted 7 Feb 2012)

- At 7TeV H→WW excluded the mass range [129 - 270] GeV/c² at 95% C.L.
- The combination excluded from 127–600 GeV/c² at 95% CL, the expected exclusion was 118–543 GeV/c²
  - **An excess above the background was observed**, the largest, with a local significance of **3.1 σ** corresponding to a mass hypothesis of 124 GeV/c²



Systematic uncertainties

Source	$H \to WW$	$q\bar{q} \to WW$	$gg \to WW$	Non-Z resonant WZ/ZZ	$t\bar{t} + tW$	$Z/\gamma^* \to \ell\ell$	W + jets	$V\gamma^{(*)}$
Luminosity	2.2–2.6	—	—	2.2–2.6	—	—	—	2.2–2.6
Lepton efficiency	3.5	3.5	3.5	3.5	—	—	—	3.5
Lepton momentum scale	2.0	2.0	2.0	2.0	—	—	—	2.0
$\vec{E}_T^{miss}$ resolution	2.0	2.0	2.0	2.0	—	—	—	1.0
Jet counting categorization	7–20	—	5.5	5.5	—	—	—	5.5
Signal cross section	5–15	—	—	—	—	—	—	—
$q\bar{q} \to WW$ normalization	—	10	—	—	—	—	—	—
$gg \to WW$ normalization	—	—	30	—	—	—	—	—
WZ/ZZ cross section	—	—	—	4.0	—	—	—	—
$t\bar{t} + tW$ normalization	—	—	—	—	20	—	—	—
$Z/\gamma^* \to \ell\ell$ normalization	—	—	—	—	—	40	—	—
W + jets normalization	—	—	—	—	—	—	36	—
MC statistics	1.0	1.0	1.0	4.0	5.0	20	20	20

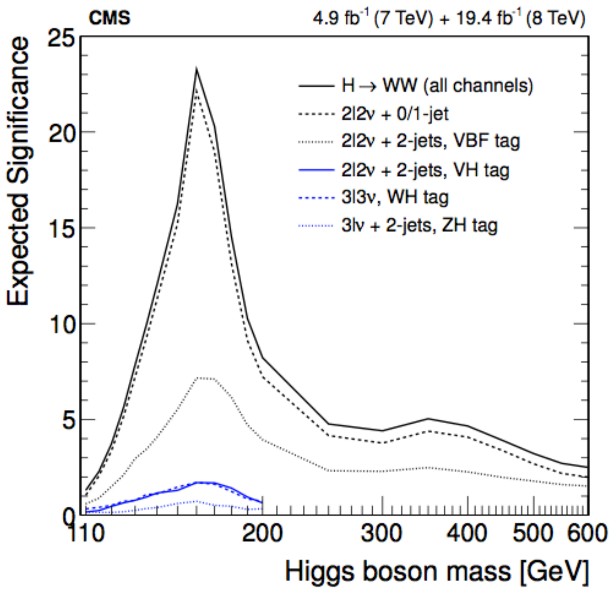
Event Yields

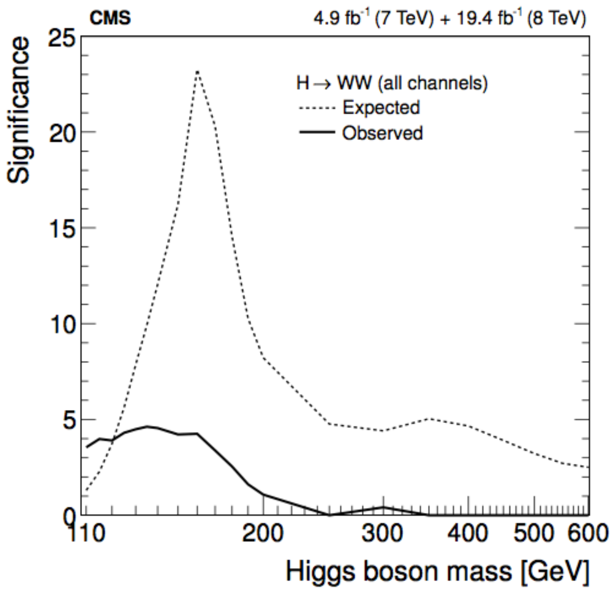
Channel	0-jet		1-jet	
Energy	7 TeV	8 TeV	7 TeV	8 TeV
WW	861 ± 12	4185 ± 63	249.9 ± 4.0	1268 ± 21
$WZ + ZZ + Z/\gamma^*$	22.7 ± 1.2	178.3 ± 9.5	26.4 ± 1.4	193 ± 11
$t\bar{t} + tW$	91 ± 20	500 ± 96	226 ± 14	1443 ± 46
W+jets	150 ± 39	620 ± 160	60 ± 16	283 ± 72
$W\gamma^{(*)}$	68 ± 20	282 ± 76	10.1 ± 2.8	55 ± 14
Background	1193 ± 50	5760 ± 210	573 ± 22	3242 ± 90
Signal $gg \to H$	50 ± 10	227 ± 46	17.1 ± 5.5	88 ± 28
Signal VBF+VH	0.44 ± 0.03	10.27 ± 0.41	2.09 ± 0.12	19.83 ± 0.81
Observed	1207	5747	589	3281

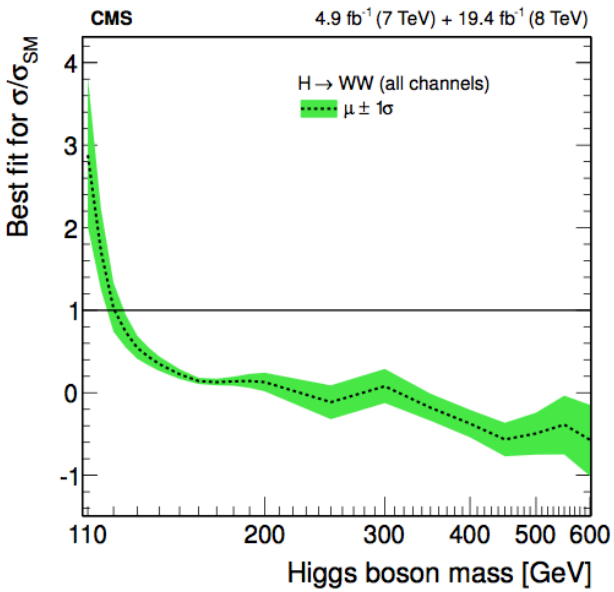
A bit more on the fit

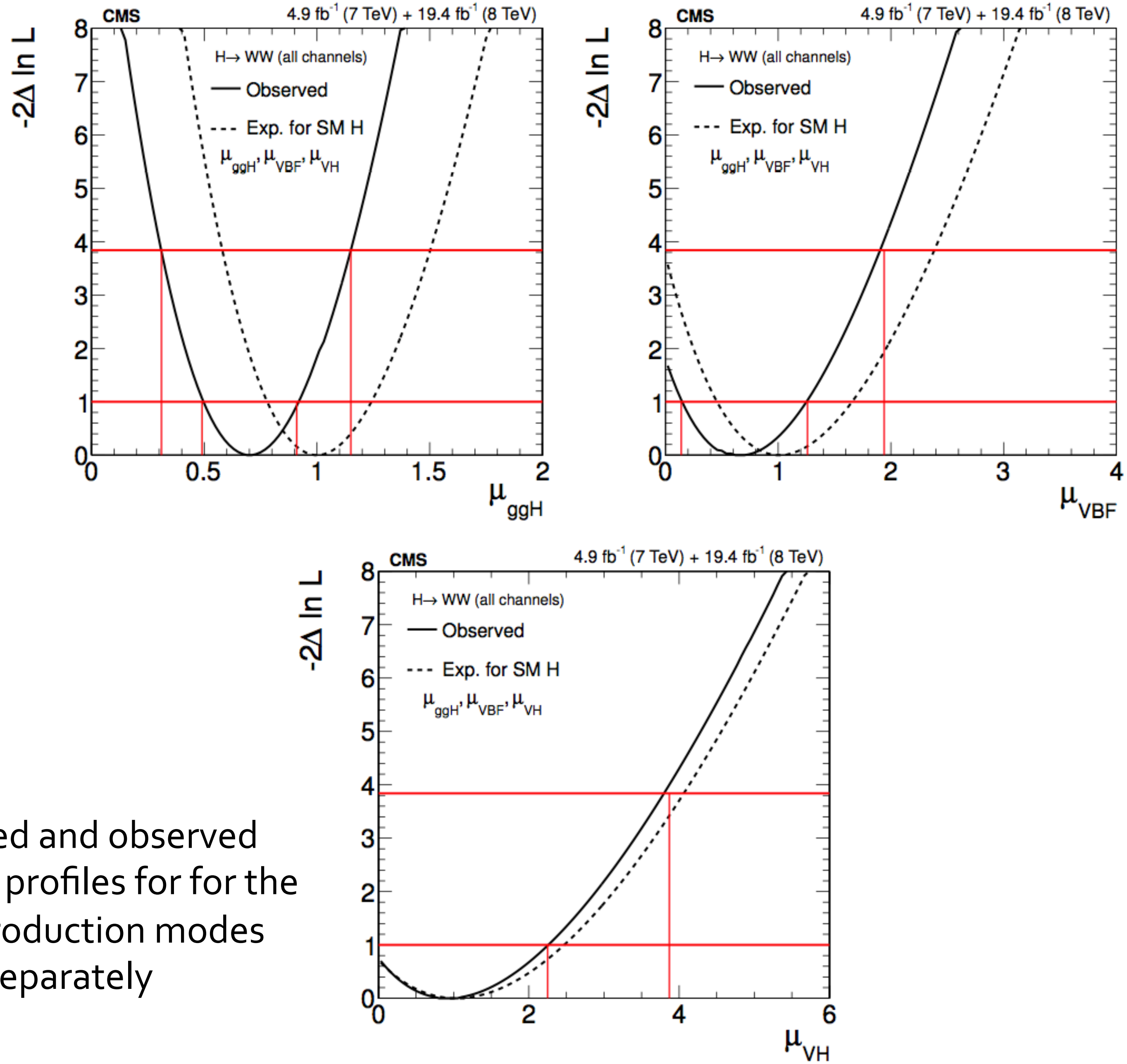
- Just a handful of nuisances where the uncertainty is reduced by more than 50% by the fit:
  - Related to WW, Top and a couple of experimental syst.

- Fit was investigated in three ways:
  - with toys
    - cut-based does not constrain nuisances, the variations are accounted for by the signal
    - shape based does, pulls width ~1
    - Correlations → fit looses power, width < 1
    - interpretation of results in full HWW data card is non trivial
  - control regions
  - alternative pdfs for nuisances


CMS
4.9 fb-1 (7 TeV) + 19.4 fb-1 (8 TeV)
Expected Significance
H → WW (all channels)
2l2ν + 0/1-jet
2l2ν + 2-jets, VBF tag
2l2ν + 2-jets, VH tag
3l3ν, WH tag
3lν + 2-jets, ZH tag
Higgs boson mass [GeV]

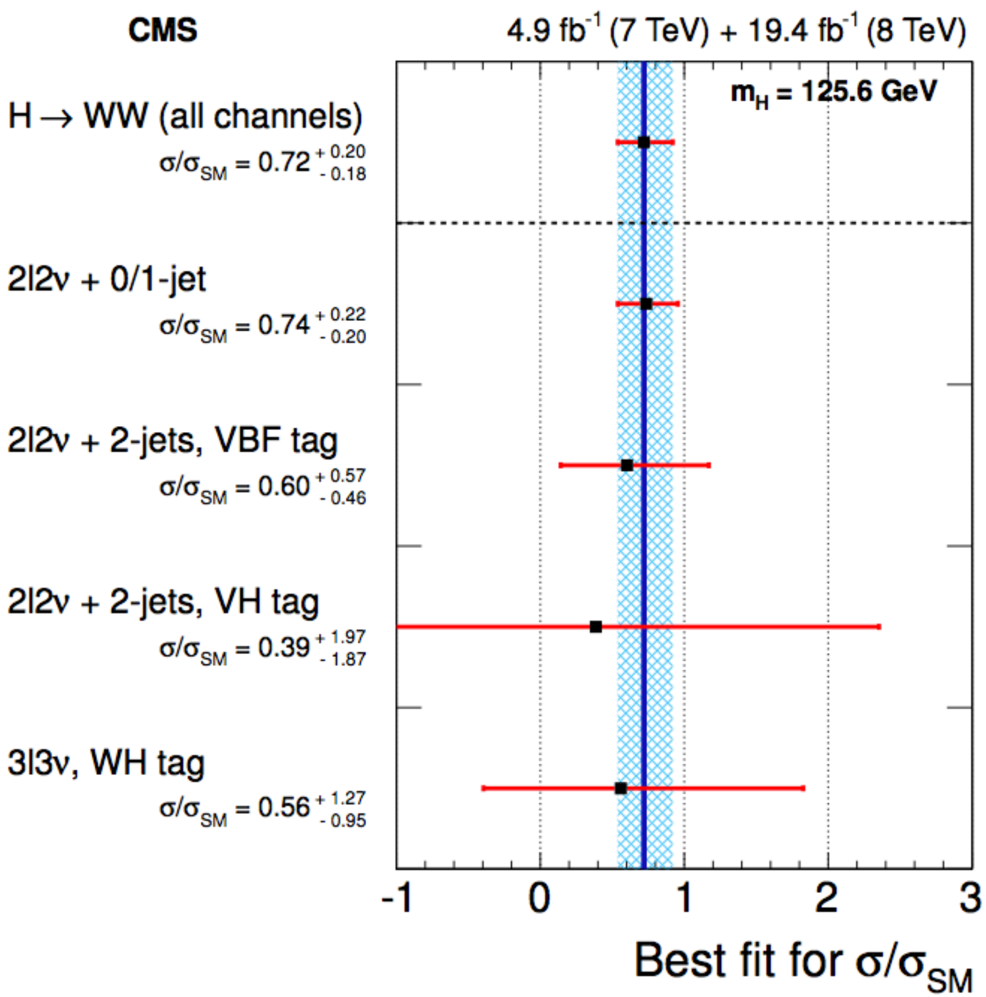

CMS
4.9 fb-1 (7 TeV) + 19.4 fb-1 (8 TeV)
Significance
H → WW (all channels)
Expected
Observed
Higgs boson mass [GeV]


CMS
4.9 fb-1 (7 TeV) + 19.4 fb-1 (8 TeV)
Best fit for σ/σSM
H → WW (all channels)
μ ± 1σ
Higgs boson mass [GeV]



Expected and observed likelihood profiles for for the three production modes separately

Signal strength



- The signal strength quantifies the compatibility of the size of the excess observed with the expectation for a SM Higgs signal
- σ/σ_{SM} value for $m_H = 125.6$GeV is **0.72**$+0.20\ -0.18 = 0.72$ ±0.12(stat.) $+0.12\ -0.10$(th. syst.) ±0.10 (exp. syst.)
- The results from all categories are consistent within the uncertainties

Spin-2 scenarios

Table 2: List of spin-two models with the production and decay couplings of an exotic X particle. The subscripts m (minimal couplings), h (couplings with higher-dimension operators), and b (bulk) distinguish different scenarios.

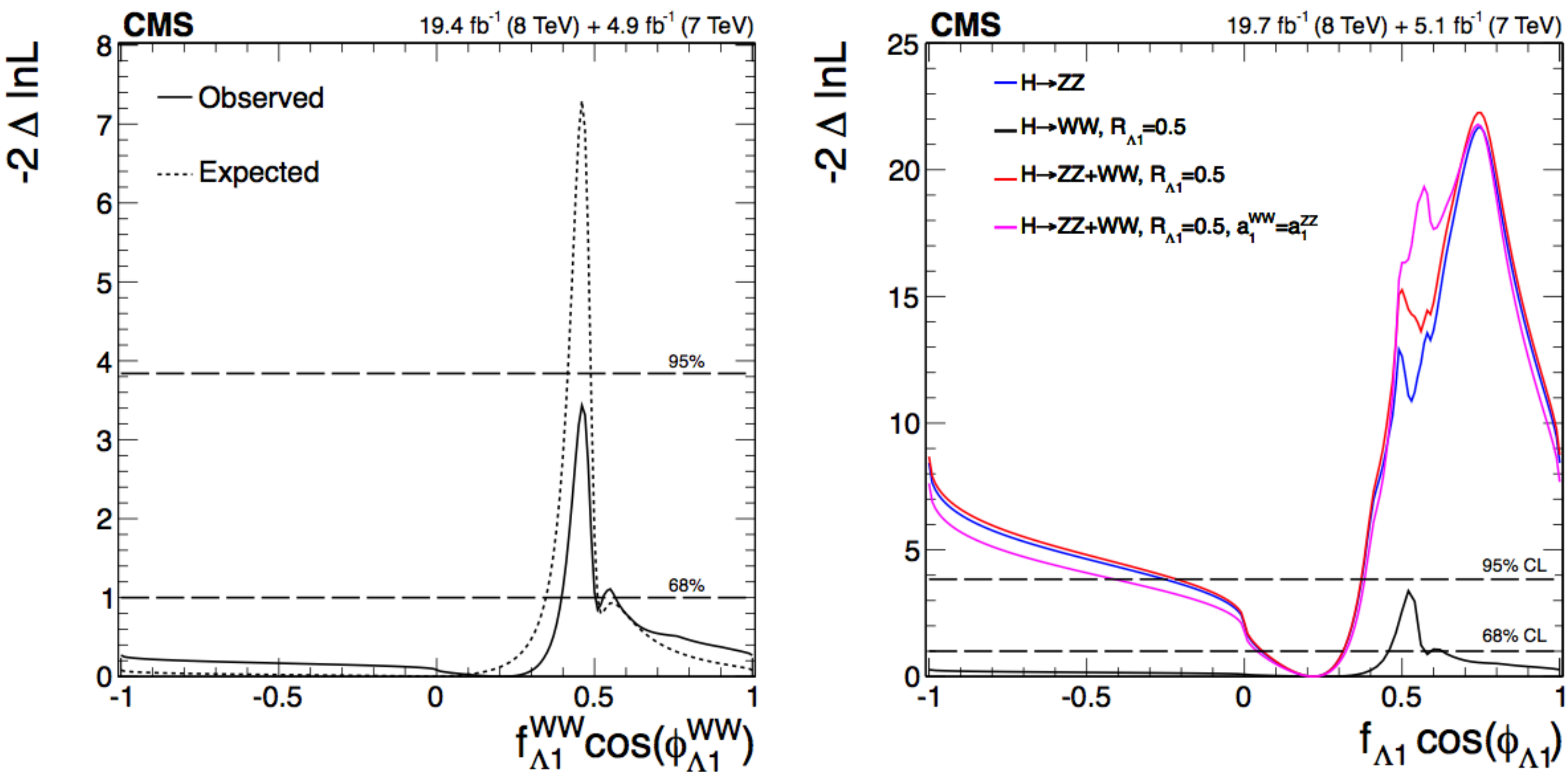
J^P Model	$gg \to X$ Couplings	$q\bar{q} \to X$ Couplings	$X \to VV$ Couplings
2_m^+	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} = c_5^{VV} \neq 0$
2_{h2}^+	$c_2^{gg} \neq 0$	$\rho_1 \neq 0$	$c_2^{VV} \neq 0$
2_{h3}^+	$c_3^{gg} \neq 0$	$\rho_1 \neq 0$	$c_3^{VV} \neq 0$
2_h^+	$c_4^{gg} \neq 0$	$\rho_1 \neq 0$	$c_4^{VV} \neq 0$
2_b^+	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_1^{VV} \ll c_5^{VV} \neq 0$
2_{h6}^+	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_6^{VV} \neq 0$
2_{h7}^+	$c_1^{gg} \neq 0$	$\rho_1 \neq 0$	$c_7^{VV} \neq 0$
2_h^-	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_8^{VV} \neq 0$
2_{h9}^-	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_9^{VV} \neq 0$
2_{h10}^-	$c_8^{gg} \neq 0$	$\rho_2 \neq 0$	$c_{10}^{VV} \neq 0$

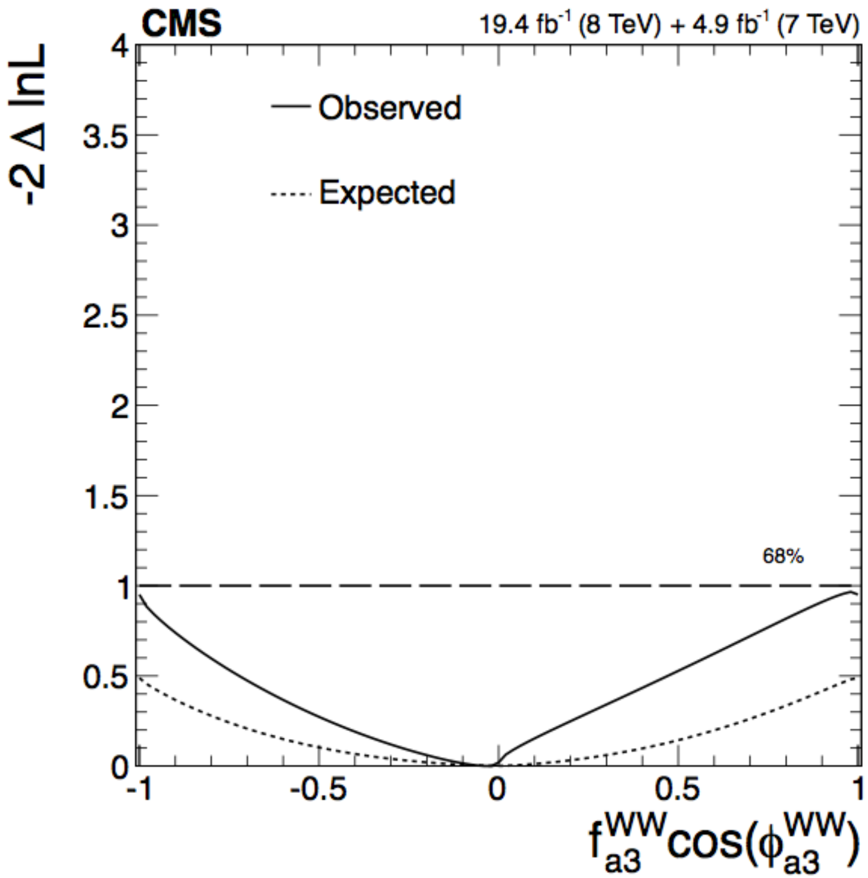
Table 10: List of spin-two models tested in the X → WW analysis. The expected separation is quoted for two scenarios, for the signal production cross section obtained from the fit to data for each hypothesis, and using the SM expectation ($\mu = 1$). The observed separation shows the consistency of the observation with the SM Higgs boson or an alternative J^P model, from which the CL_s value is derived. The constraints on the non-interfering J^P fraction are quoted in the last two columns. Results from Ref. [14] are explicitly noted.

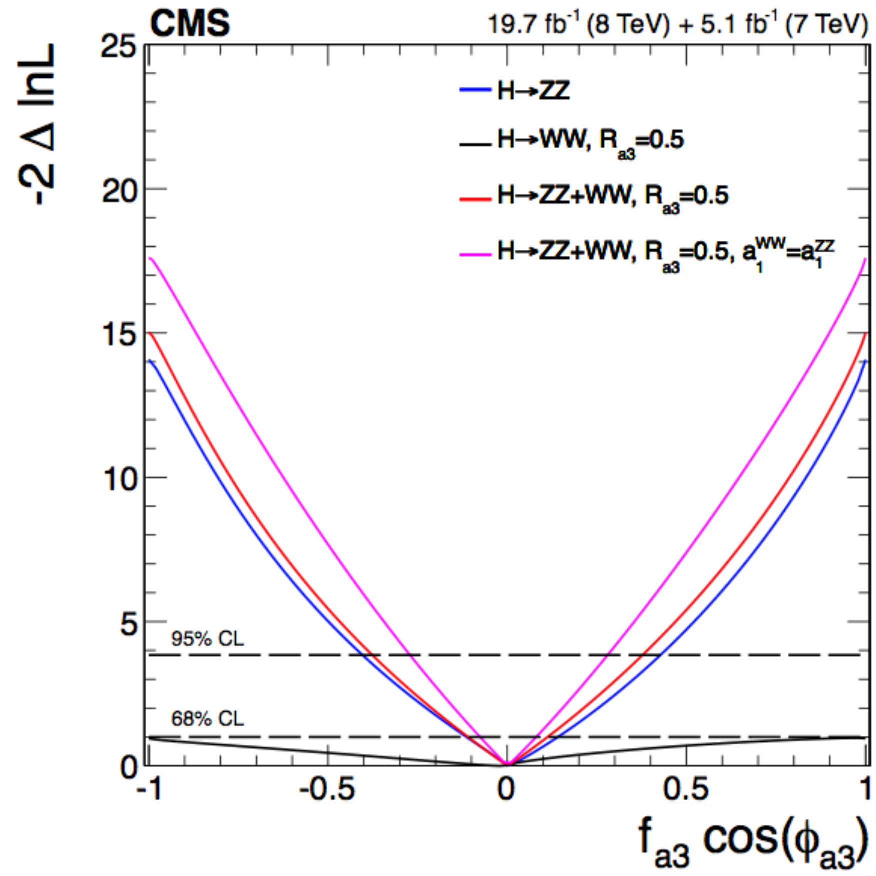
J^P Model	J^P Mrod.	Expected (μ=1)	Obs. 0^+	Obs. J^P	CL_s	$f(J^P)$ 95% CL Obs. (Exp.)	$f(J^P)$ Best Fit
2^+_m [14]	gg	1.8σ (2.9σ)	$+0.6\sigma$	$+1.2\sigma$	16%	<1.00 (0.87)	$0.50^{+0.42}_{-0.50}$
2^+_{h2}	gg	1.7σ (2.6σ)	0.0σ	$+1.6\sigma$	10%	<1.00 (0.91)	$0.00^{+0.71}_{-0.00}$
2^+_{h3}	gg	1.9σ (2.8σ)	$+0.1\sigma$	$+1.9\sigma$	5.2%	<0.99 (0.82)	$0.00^{+0.62}_{-0.00}$
2^+_h	gg	0.7σ (1.3σ)	$+0.1\sigma$	$+0.6\sigma$	52%	<1.00 (1.00)	$0.13^{+0.87}_{-0.13}$
2^+_b	gg	1.8σ (2.7σ)	$+0.1\sigma$	$+1.7\sigma$	8.6%	<1.00 (0.89)	$0.03^{+0.68}_{-0.03}$
2^+_{h6}	gg	2.5σ (3.4σ)	$+0.0\sigma$	$+2.6\sigma$	0.88%	<0.81 (0.69)	$0.00^{+0.50}_{-0.00}$
2^+_{h7}	gg	1.8σ (2.5σ)	$+0.2\sigma$	$+1.7\sigma$	8.1%	<1.00 (0.85)	$0.01^{+0.64}_{-0.01}$
2^-_h	gg	1.2σ (2.3σ)	-0.1σ	$+1.4\sigma$	19%	<1.00 (1.00)	$0.00^{+0.78}_{-0.00}$
2^-_{h9}	gg	1.4σ (2.5σ)	-0.2σ	$+1.6\sigma$	12%	<1.00 (1.00)	$0.00^{+0.66}_{-0.00}$
2^-_{h10}	gg	2.0σ (3.3σ)	$+0.4\sigma$	$+1.6\sigma$	7.8%	<1.00 (0.85)	$0.36^{+0.46}_{-0.36}$
2^+_m [14]	$q\bar{q}$	2.7σ (3.9σ)	-0.2σ	$+3.1\sigma$	0.25%	<0.76 (0.68)	$0.00^{+0.45}_{-0.00}$
2^+_{h2}	$q\bar{q}$	2.6σ (3.7σ)	-0.4σ	$+3.3\sigma$	0.16%	<0.66 (0.70)	$0.00^{+0.32}_{-0.00}$
2^+_{h3}	$q\bar{q}$	2.3σ (3.3σ)	-0.4σ	$+2.9\sigma$	0.56%	<0.76 (0.75)	$0.00^{+0.40}_{-0.00}$
2^+_h	$q\bar{q}$	1.6σ (2.3σ)	-0.1σ	$+1.7\sigma$	8.8%	<1.00 (0.95)	$0.00^{+0.67}_{-0.00}$
2^+_b	$q\bar{q}$	2.8σ (3.8σ)	-0.2σ	$+3.2\sigma$	0.18%	<0.71 (0.68)	$0.00^{+0.38}_{-0.00}$
2^+_{h6}	$q\bar{q}$	2.8σ (3.7σ)	0.0σ	$+2.9\sigma$	0.41%	<0.80 (0.70)	$0.00^{+0.52}_{-0.00}$
2^+_{h7}	$q\bar{q}$	2.2σ (3.1σ)	-0.2σ	$+2.5\sigma$	1.6%	<0.85 (0.80)	$0.00^{+0.48}_{-0.00}$
2^-_h	$q\bar{q}$	2.0σ (2.9σ)	$+0.1\sigma$	$+1.9\sigma$	5.1%	<1.00 (0.87)	$0.01^{+0.67}_{-0.01}$
2^-_{h9}	$q\bar{q}$	2.0σ (2.9σ)	$+0.2\sigma$	$+1.8\sigma$	6.2%	<1.00 (0.86)	$0.10^{+0.64}_{-0.10}$
2^-_{h10}	$q\bar{q}$	2.6σ (3.6σ)	$+0.1\sigma$	$+2.5\sigma$	1.1%	<0.90 (0.78)	$0.07^{+0.58}_{-0.07}$

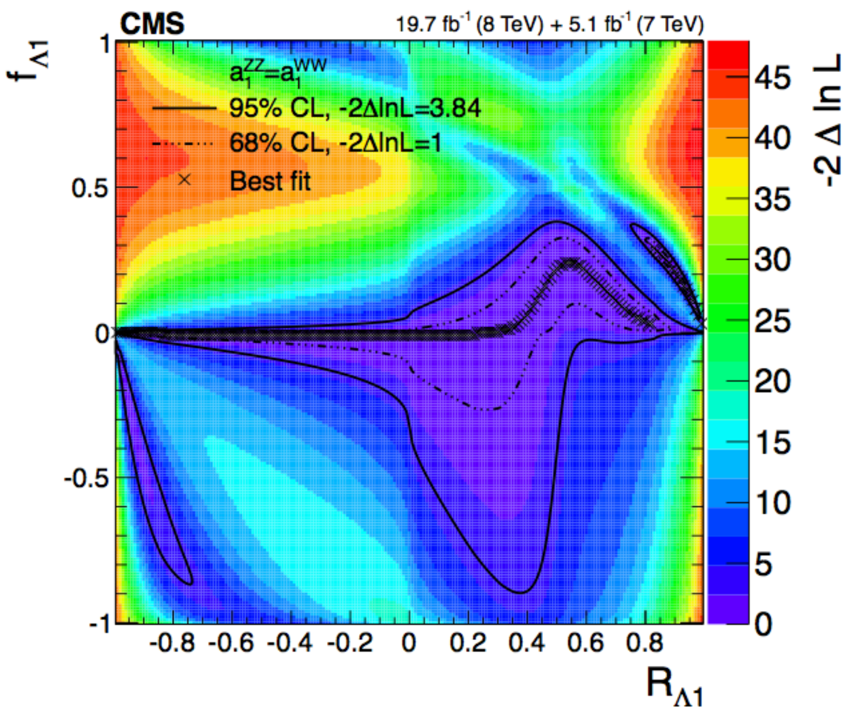
Table 11: List of spin-one and spin-two models tested in the combination of the X $\rightarrow$ ZZ and X $\rightarrow$ WW channels. The combined expected separation is quoted for two scenarios, for the signal production cross section obtained from the fit to data for each hypothesis and using the SM expectation ($\mu = 1$). For comparison, the former expectations are also quoted for the individual channels as in Tables 7-10. The observed separation shows the consistency of the observation with the SM Higgs boson model or an alternative J^P model, from which the CL_s value is derived.

J^P Model	J^P Prod.	Expected X $\rightarrow$ ZZ	Expected X $\rightarrow$ WW	Expected (μ=1)	Obs. 0^+	Obs. J^P	CL_s
1^-	$q\bar{q}$	2.9σ	2.2σ	3.6σ (4.6σ)	-1.2σ	$+4.9\sigma$	<0.001%
1^+	$q\bar{q}$	2.4σ	1.8σ	3.0σ (3.8σ)	-0.8σ	$+4.3\sigma$	0.004%
2^+_m	gg	1.9σ	1.8σ	2.4σ (3.4σ)	-0.4σ	$+2.9\sigma$	0.53%
2^+_{h2}	gg	2.0σ	1.7σ	2.5σ (3.3σ)	-0.2σ	$+2.8\sigma$	0.52%
2^+_{h3}	gg	3.2σ	1.6σ	3.7σ (4.3σ)	$+0.4\sigma$	$+3.5\sigma$	0.031%
2^+_h	gg	3.8σ	0.7σ	3.8σ (4.2σ)	$+1.7\sigma$	$+2.1\sigma$	1.9%
2^+_b	gg	1.6σ	1.8σ	2.4σ (3.2σ)	-0.9σ	$+3.4\sigma$	0.16%
2^+_{h6}	gg	3.4σ	2.5σ	4.2σ (4.9σ)	-0.5σ	$>5\sigma$	<0.001%
2^+_{h7}	gg	3.8σ	1.8σ	4.2σ (5.0σ)	-0.1σ	$+4.7\sigma$	<0.001%
2^-_h	gg	4.2σ	1.2σ	4.3σ (5.0σ)	$+1.0\sigma$	$+3.4\sigma$	0.039%
2^-_{h9}	gg	2.5σ	1.4σ	2.8σ (3.5σ)	-1.0σ	$+4.2\sigma$	0.009%
2^-_{h10}	gg	4.2σ	2.0σ	4.6σ (5.3σ)	$+0.1\sigma$	$+4.9\sigma$	<0.001%
2^+_m	$q\bar{q}$	1.7σ	2.7σ	3.1σ (4.3σ)	-1.0σ	$+4.5\sigma$	0.002%
2^+_{h2}	$q\bar{q}$	2.2σ	2.6σ	3.3σ (4.3σ)	-0.8σ	$+4.4\sigma$	0.002%
2^+_{h3}	$q\bar{q}$	3.1σ	2.6σ	3.8σ (4.5σ)	0.0σ	$+4.1\sigma$	0.005%
2^+_h	$q\bar{q}$	4.0σ	1.6σ	4.3σ (4.5σ)	$+0.2\sigma$	$+4.3\sigma$	0.002%
2^+_b	$q\bar{q}$	1.7σ	2.8σ	3.1σ (4.2σ)	-1.3σ	$+4.8\sigma$	<0.001%
2^+_{h6}	$q\bar{q}$	3.4σ	2.8σ	4.3σ (5.0σ)	-0.1σ	$+4.8\sigma$	<0.001%
2^+_{h7}	$q\bar{q}$	4.1σ	2.2σ	4.6σ (5.0σ)	$+0.3\sigma$	$+4.5\sigma$	<0.001%
2^-_h	$q\bar{q}$	4.3σ	2.0σ	4.7σ (5.2σ)	$+0.1\sigma$	$+5.0\sigma$	<0.001%
2^-_{h9}	$q\bar{q}$	2.4σ	2.0σ	3.1σ (3.8σ)	$+0.5\sigma$	$+2.7\sigma$	0.55%
2^-_{h10}	$q\bar{q}$	4.0σ	2.6σ	4.7σ (5.3σ)	$+0.5\sigma$	$+4.6\sigma$	<0.001%

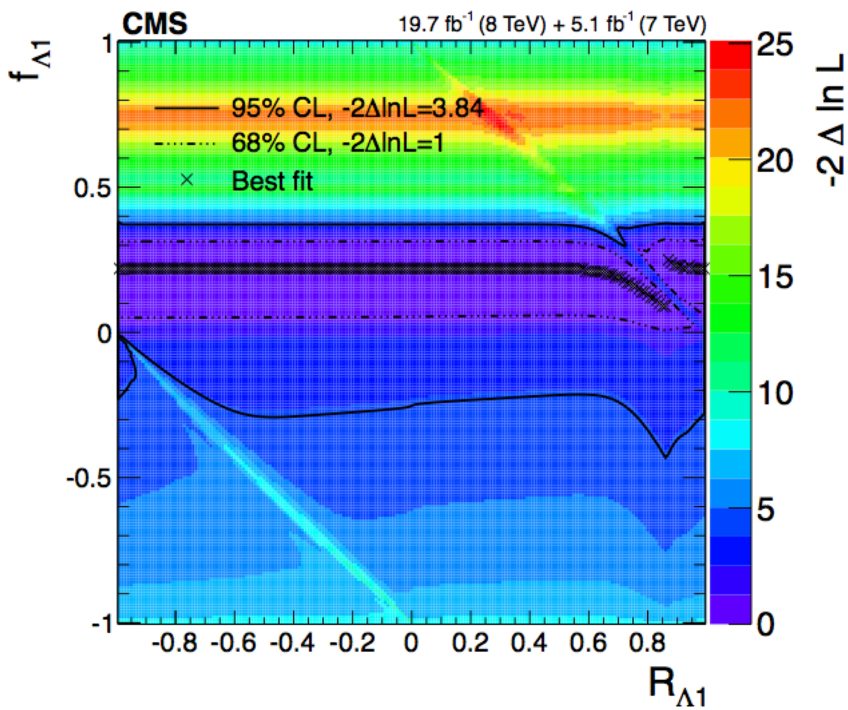

CMS
19.4 fb^{-1} (8 TeV) + 4.9 fb^{-1} (7 TeV)
Observed
Expected
95%
68%
-2 Δ lnL
$f_{\Lambda 1}^{WW} \cos(\phi_{\Lambda 1}^{WW})$
CMS
19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
H→ZZ
H→WW, $R_{\Lambda 1}$=0.5
H→ZZ+WW, $R_{\Lambda 1}$=0.5
H→ZZ+WW, $R_{\Lambda 1}$=0.5, $a_1^{WW}=a_1^{ZZ}$
95% CL
68% CL
-2 Δ lnL
$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$


CMS
19.4 fb-1 (8 TeV) + 4.9 fb-1 (7 TeV)
Observed
Expected
68%
-2 Δ lnL
$f_{a3}^{WW}\cos(\phi_{a3}^{WW})$

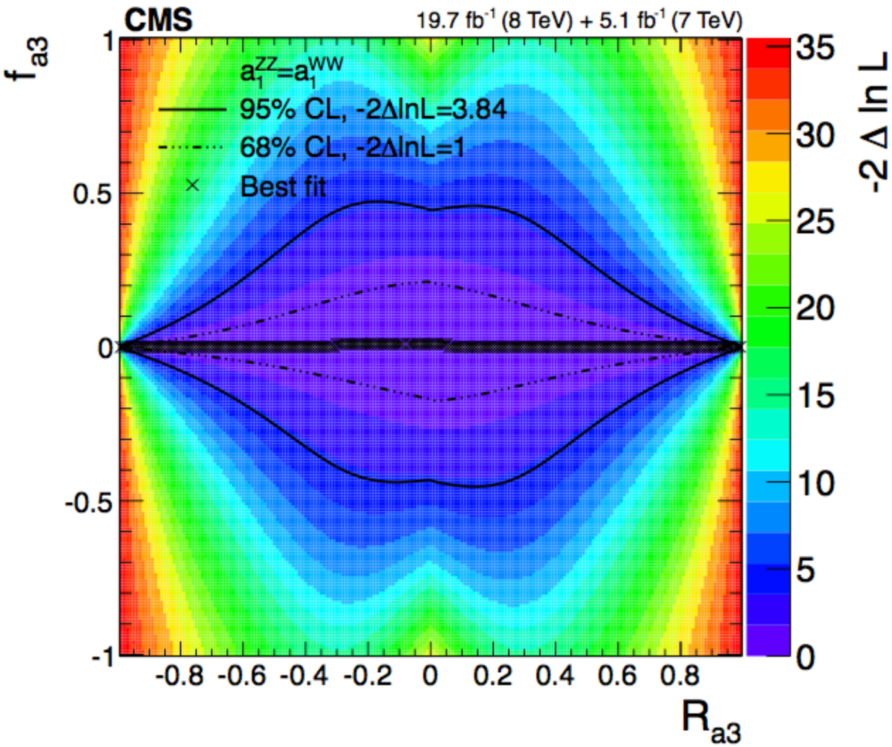

CMS
19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
H→ZZ
H→WW, R_{a3}=0.5
H→ZZ+WW, R_{a3}=0.5
H→ZZ+WW, R_{a3}=0.5, $a_1^{WW}=a_1^{ZZ}$
95% CL
68% CL
-2 Δ lnL
$f_{a3}\cos(\phi_{a3})$

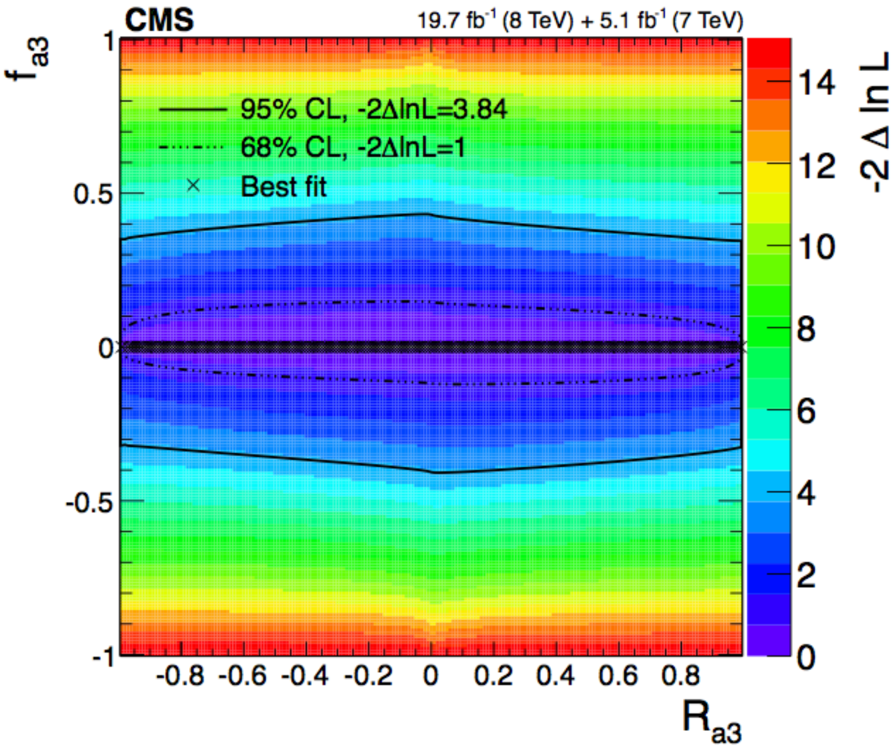


CMS
19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
a1ZZ=a1WW
95% CL, -2ΔlnL=3.84
68% CL, -2ΔlnL=1
Best fit
fΛ1
RΛ1
-2 Δ ln L



CMS
19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
95% CL, -2ΔlnL=3.84
68% CL, -2ΔlnL=1
Best fit
fΛ1
RΛ1
-2 Δ ln L


CMS
19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
a1ZZ=a1WW
95% CL, -2ΔlnL=3.84
68% CL, -2ΔlnL=1
Best fit
fa3
Ra3
-2 Δ ln L


CMS
19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
95% CL, -2ΔlnL=3.84
68% CL, -2ΔlnL=1
Best fit
fa3
Ra3
-2 Δ ln L