Higgs boson decays to WW at CMS

Rebeca Gonzalez Suarez

University of Nebraska, Lincoln

Introduction

- The Electroweak symmetry breaking did not get an experimentally proved answer until 2012
- The description of Electromagnetic and weak couplings at low energy is very similar → Electromagnetic: ~α, Weak: ~$\alpha/(M_{W,Z})^2$
  - The same constant is involved, but the W and Z bosons have mass (and not small, m_W ~80GeV, m_Z ~ 91 GeV, compared to m_{proton}~0.9GeV)
- The Higgs mechanism (1964) provides an explanation of the EWK symmetry breaking in the Standard Model
  - With massive vector bosons and mass terms for the fermions
  - It has a side effect: an additional boson that has to be found
    - The mass of the boson is unknown (free parameter in the theory)
- **To find the Higgs boson → prove the Higgs mechanism**

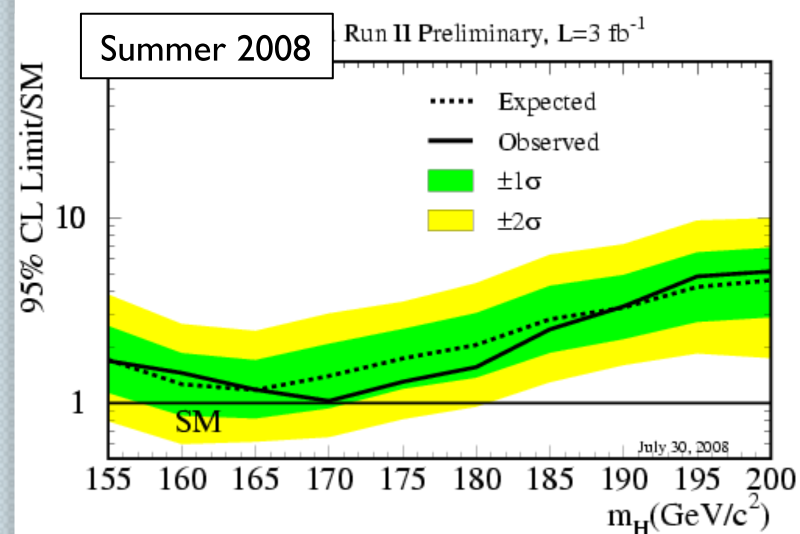
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

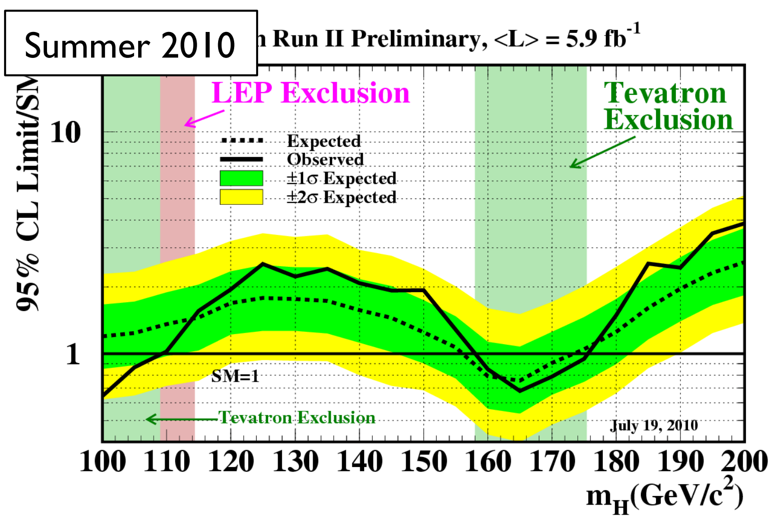
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

Higgs searches before the LHC

- The search for the Higgs boson started way before the LHC
- 95% CL mass limit from LEP = 114.4 GeV
- During the summer of 2008, just weeks before the first start up of the LHC, the Tevatron experiments presented their first exclusion limits:



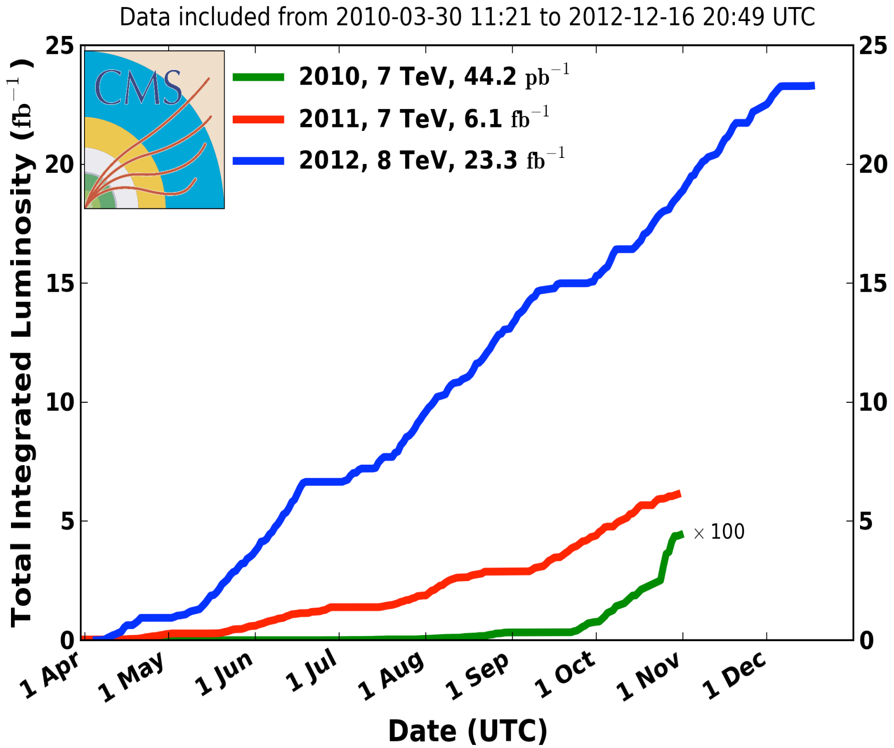


- And by the time the Run-1 started, the Tevatron had excluded a good part of the spectra around 160GeV

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
- It lasted three years
- CMS recorded **~5fb^{-1} of pp collisions at 7TeV and ~20fb^{-1} at 8TeV**
- Main result from Run-I:
    - **Higgs discovery**



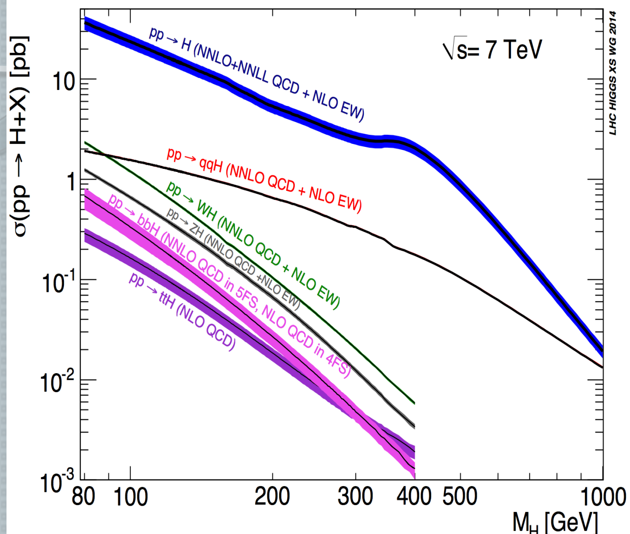
Higgs searches at the LHC

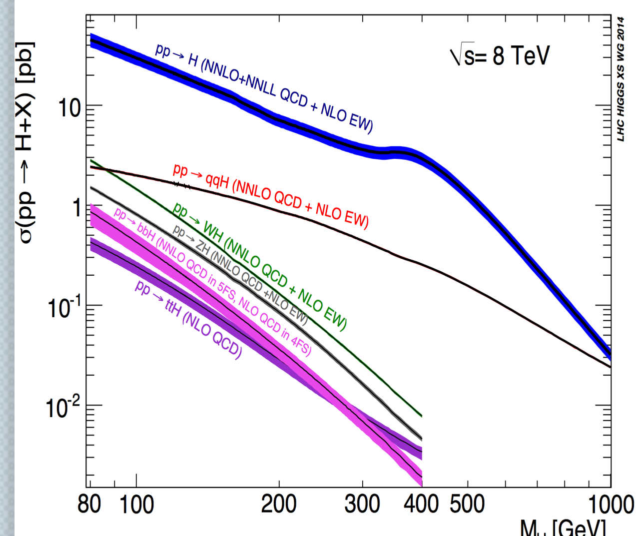
[arXiv:1207.7235](https://arxiv.org/abs/1207.7235)
Phys. Lett. B 716 (2012) 30
(Submitted 31 July 2012)

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

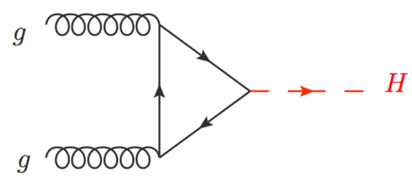
CMS discovery papers

Higgs production at the LHC

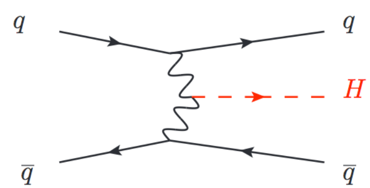




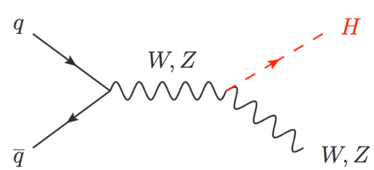
The first thing to consider when searching for the Higgs boson is the production mode



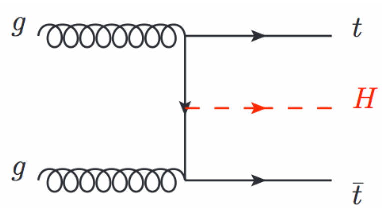
Gluon-gluon fusion
(ggH)
No hadronic activity



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)

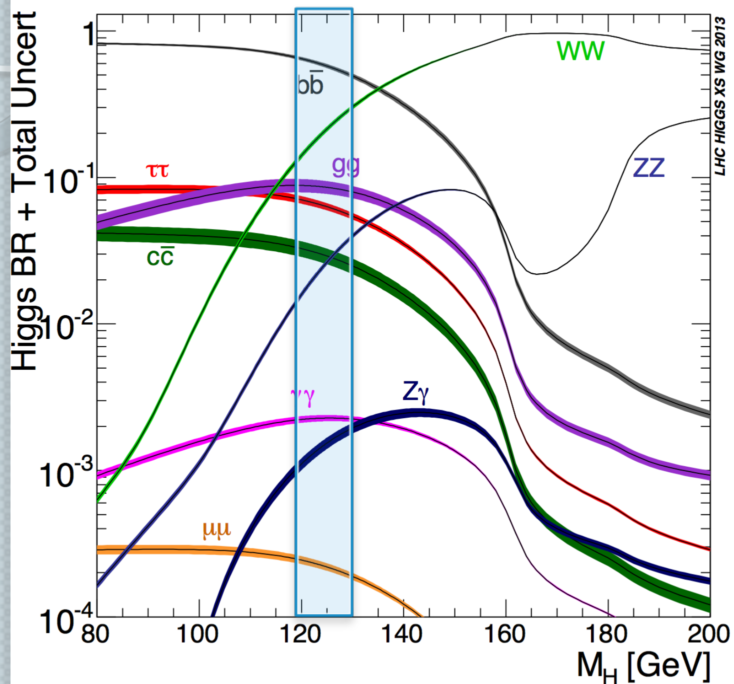
How many where produced?

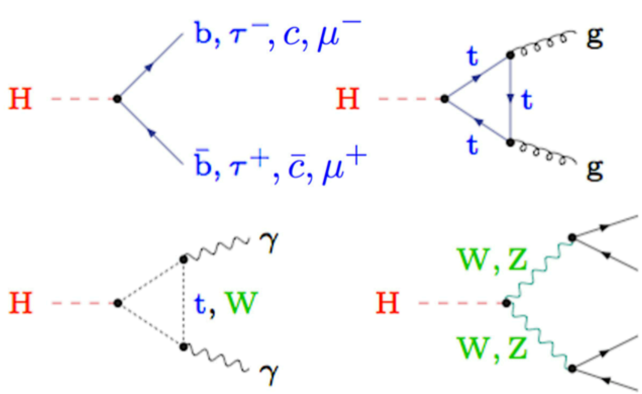
- For a mass of m_H = 125GeV

	7TeV		8TeV		
	σ [pb]	# events	σ [pb]	# events	Total events
ggH	15.13	74137	19.27	373838	447975
VBF	1.22	5978	1.578	30613.2	36591.2
WH	0.5785	2834.65	0.7046	13669.24	16503.89
ZH	0.3351	1641.99	0.4153	8056.82	9698.81
ttH	0.08632	422.968	0.1293	2508.42	2931.388
				Total:	513700.288

During the Run-I, **the LHC delivered ~0.5M of Higgs bosons**, most of them (87%) via gluon gluon fusion
Do we see them all?

Higgs decay channels





The observation of the Higgs also depends on its decay mode

Discovery mode → balance between Branching Ratio, clear experimental signature, and background contributions

H→ZZ→4l

Very clean experimental signature

H→ γ γ

Mass peak reconstruction

H→WW→2l

Clear experimental signature, no mass peak

H→ τ τ

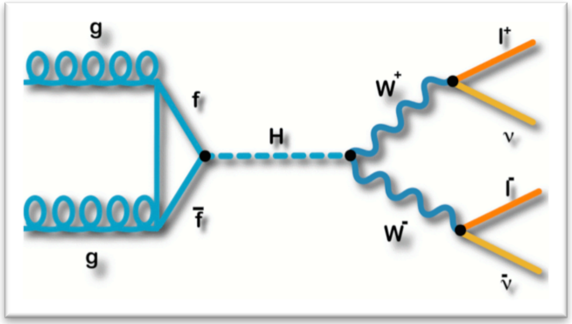
Accessible via VBF

H→ bb

Highest BR for low masses. Challenging experimentally

Why H→WW?

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



- **Two isolated leptons** (e,μ) with opposite charge
- **Substantial missing energy** (two neutrinos)
- **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→eν μν in events with 0/1-jets (gg), and it is the one that we will discuss in this presentation**

JHEP
Published for SISSA by Springer
Received: December 4, 2013
Accepted: December 18, 2013
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**

  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

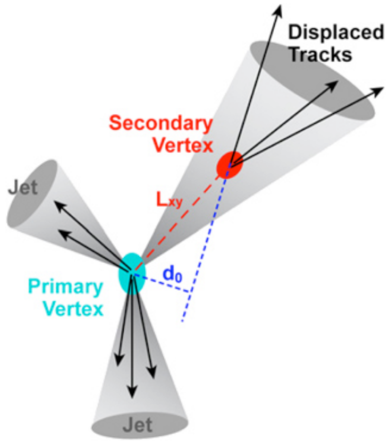
- **b - jet identification**

  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



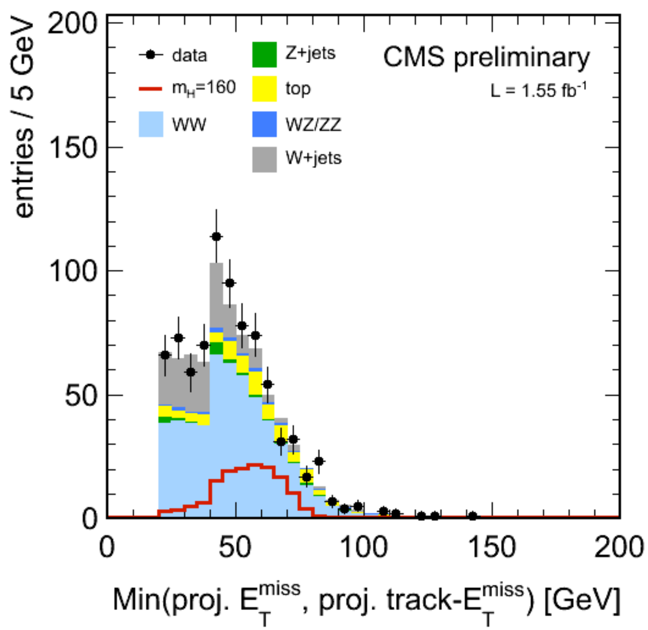
rejects 70% b-quark jets, keeps 95% of light quarks

Physics Objects

- **Missing transverse energy (MET)**

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

  - different estimators

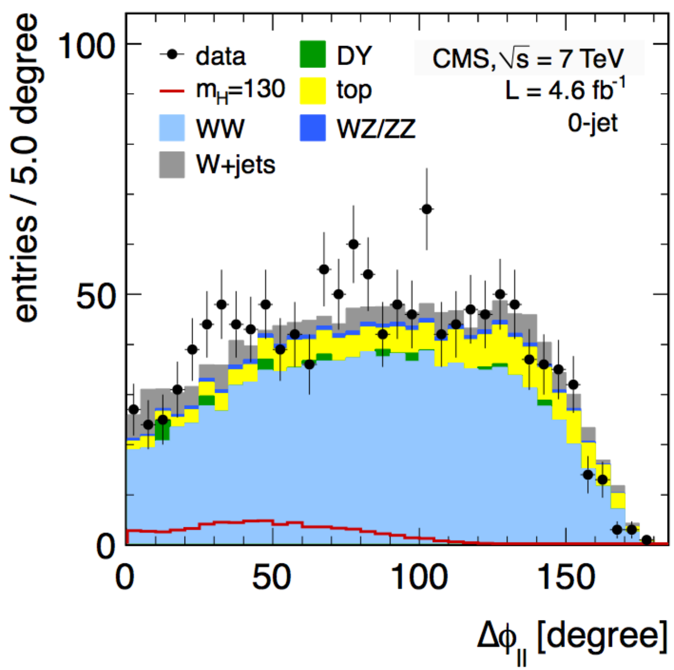


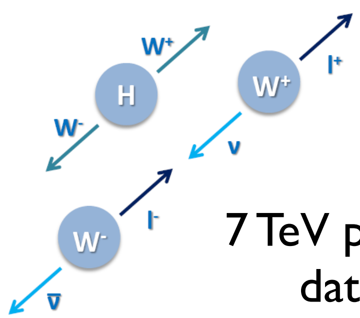
PAS HIG-11-014

- 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(π/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

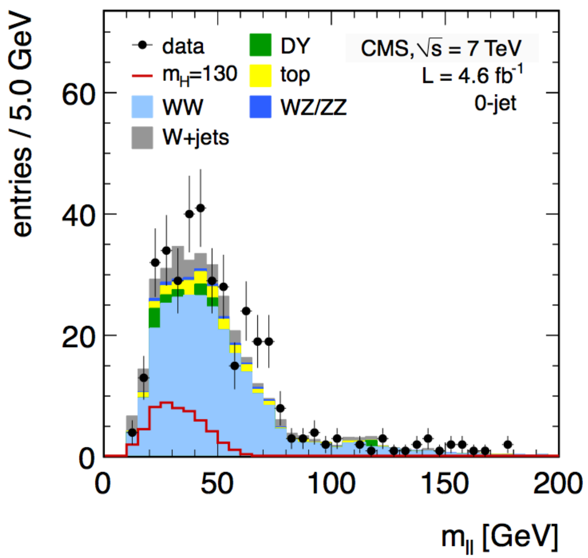




7 TeV paper data

Kinematics of the signal

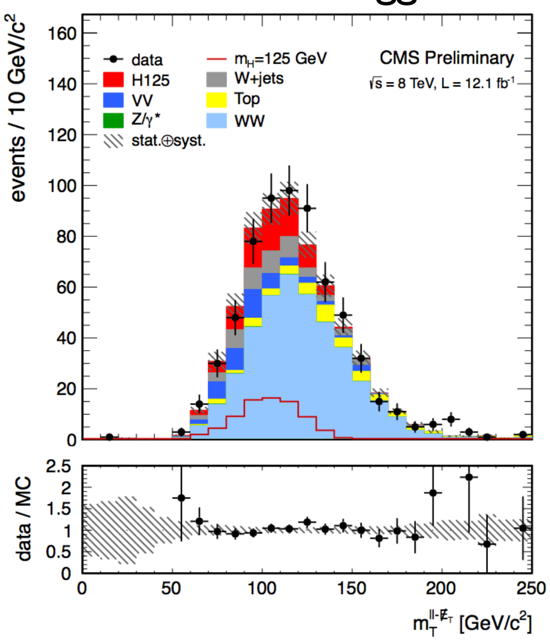
- Some backgrounds have the exact same final state, $WW \rightarrow 2l2\nu$ is the clearest case and the almost irreducible one
- There are three main observables to separate the signal from backgrounds:
  - $\Delta\Phi_{ll}$: opening angle between the two leptons in the transverse plane to the beam, correlated to the spin of the Higgs boson
  - m_{ll}: dilepton mass, one of the most discriminating kinematic variables for a Higgs boson with low mass, in particular against $Z/\gamma^* \rightarrow ll$



7 TeV paper eμ

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



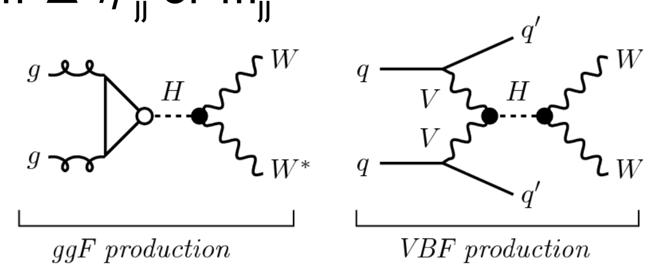
- **m_T:** the transverse mass of the final state objects which scales with the Higgs mass defined here as

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

PAS HIG-12-042
H→WW PAS for HCP 2012

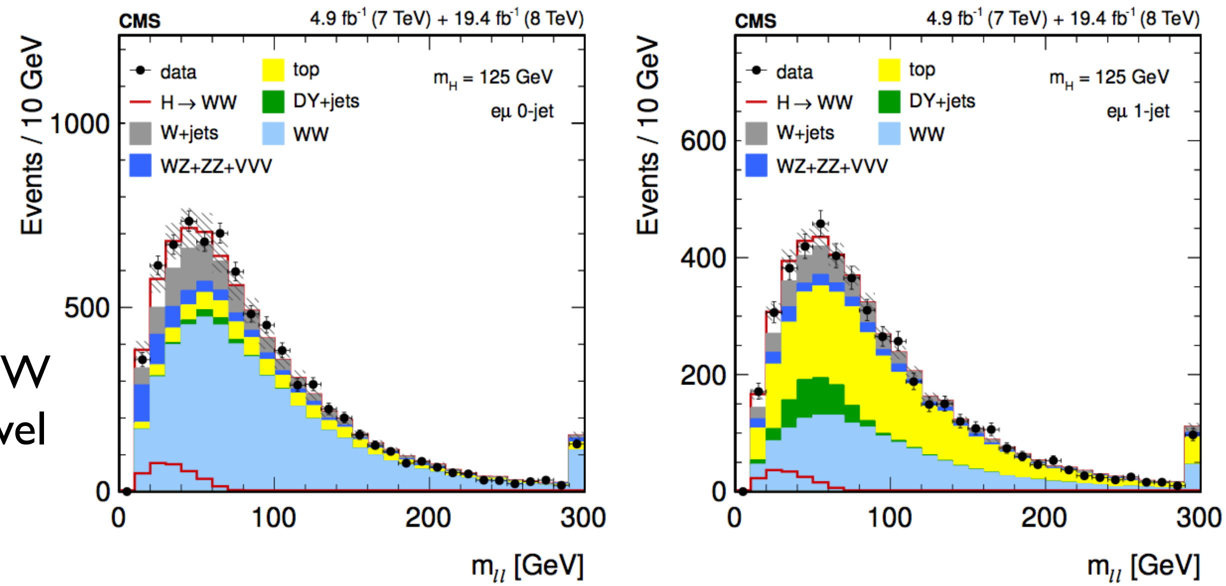
Definition of the WW selection

- **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 $\Delta\eta_{jj}$ or m_{jj}



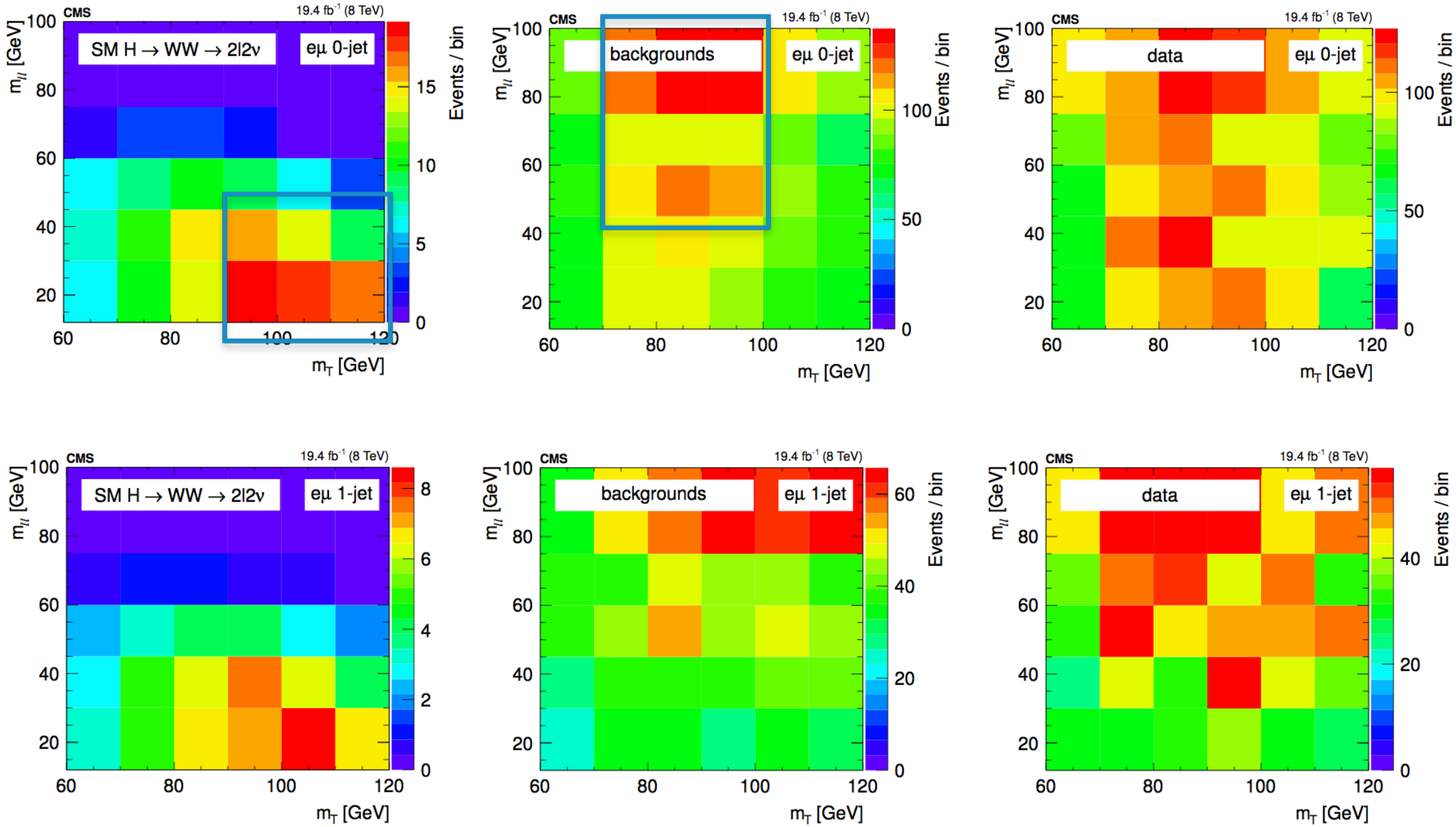
Analysis strategy

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

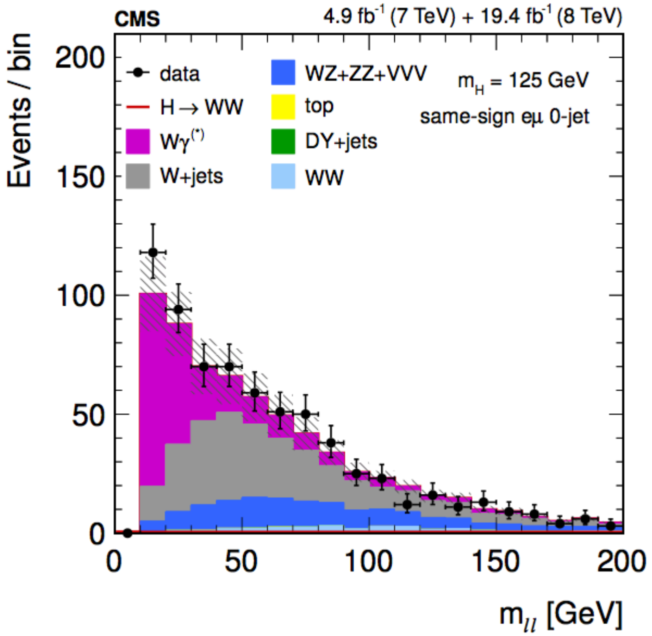


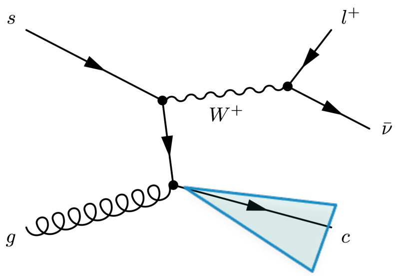
A binned template fit is performed to extract upper limits and significance

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 W γ (*))

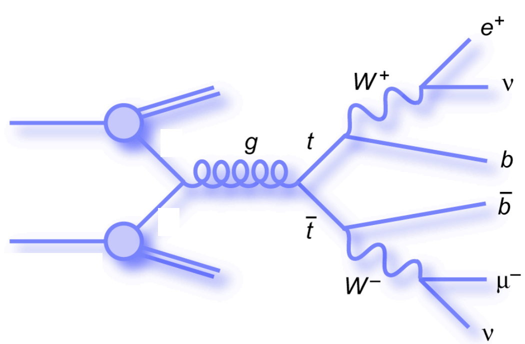


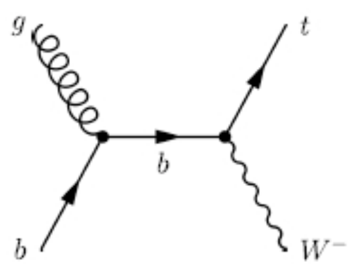


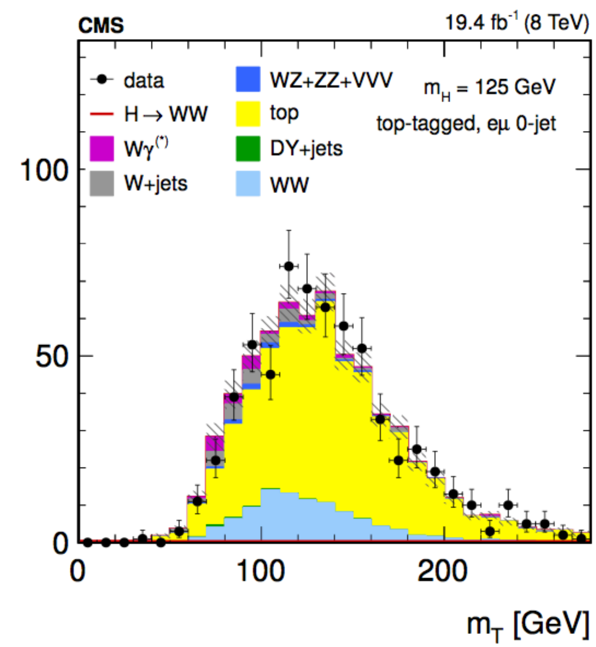
Potential "fake" lepton

Background estimates

- **Top**: Events from ttbar and single top tW
  - Shapes from simulation, **normalization from data**
  - Using top tagged events (rejected in the analysis) reweighted by efficiency measured in CR, defined using additional jets (1j in 0j, 2j in 1j)
  - Fit validated using top tagged events





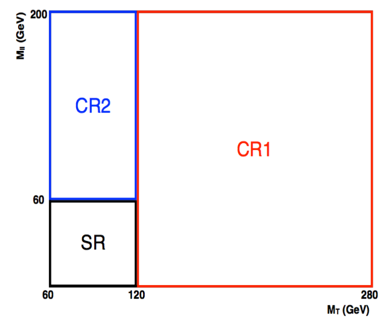


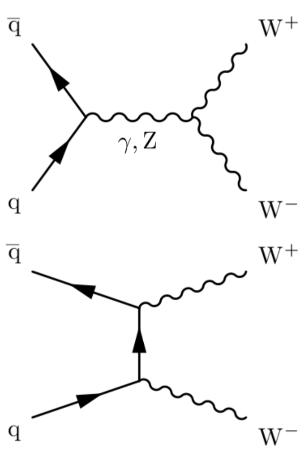
Background estimates

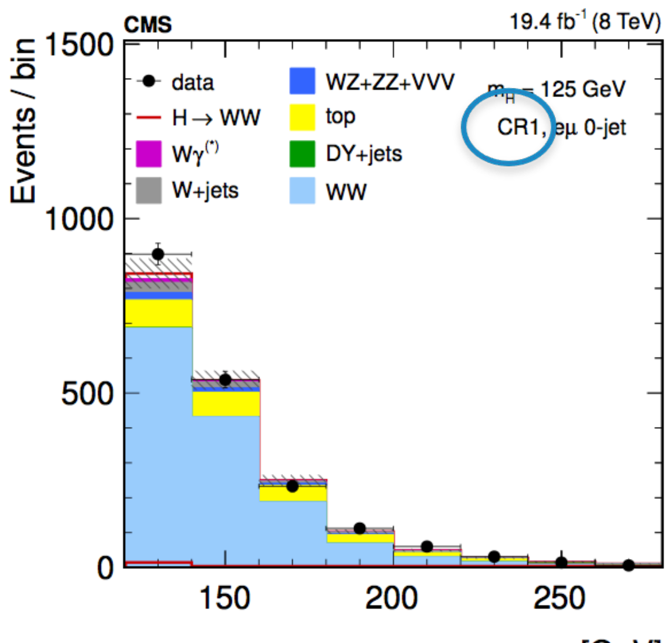
- **Drell-Yan:** in same flavor final states
  - shapes from simulation, **normalization from data** around the Z mass peak
- **W γ*:** shape from simulation, **normalization from data**
  - part of WZ not properly modeled in MC → low m_{ll} events where 1 lepton is lost (too soft)
  - simulated sampled compared with data in CR defined by different cuts (k-factor obtained)
- **W γ : shape from data**, normalization from simulation
  - data γ +lepton events reweighed with ratio γ ->lepton
- **WZ,ZZ,VVV:** simulation

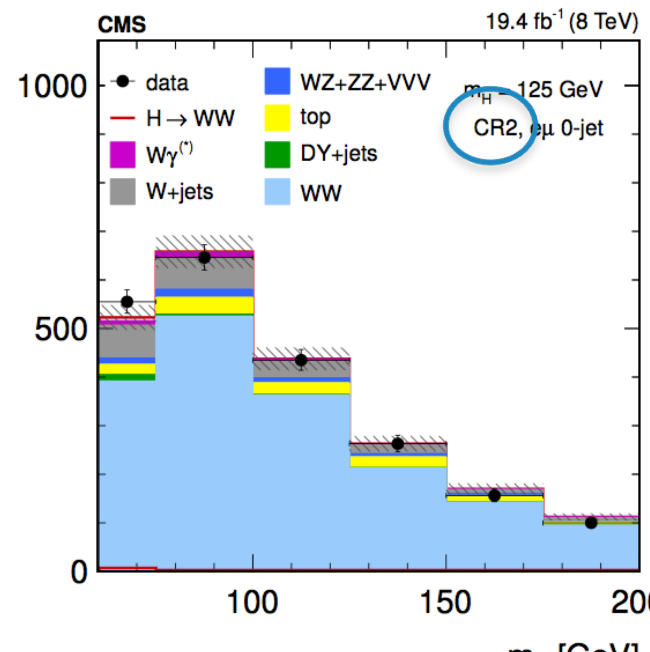
WW Background

- **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 $60 < m_{ll} < 200$

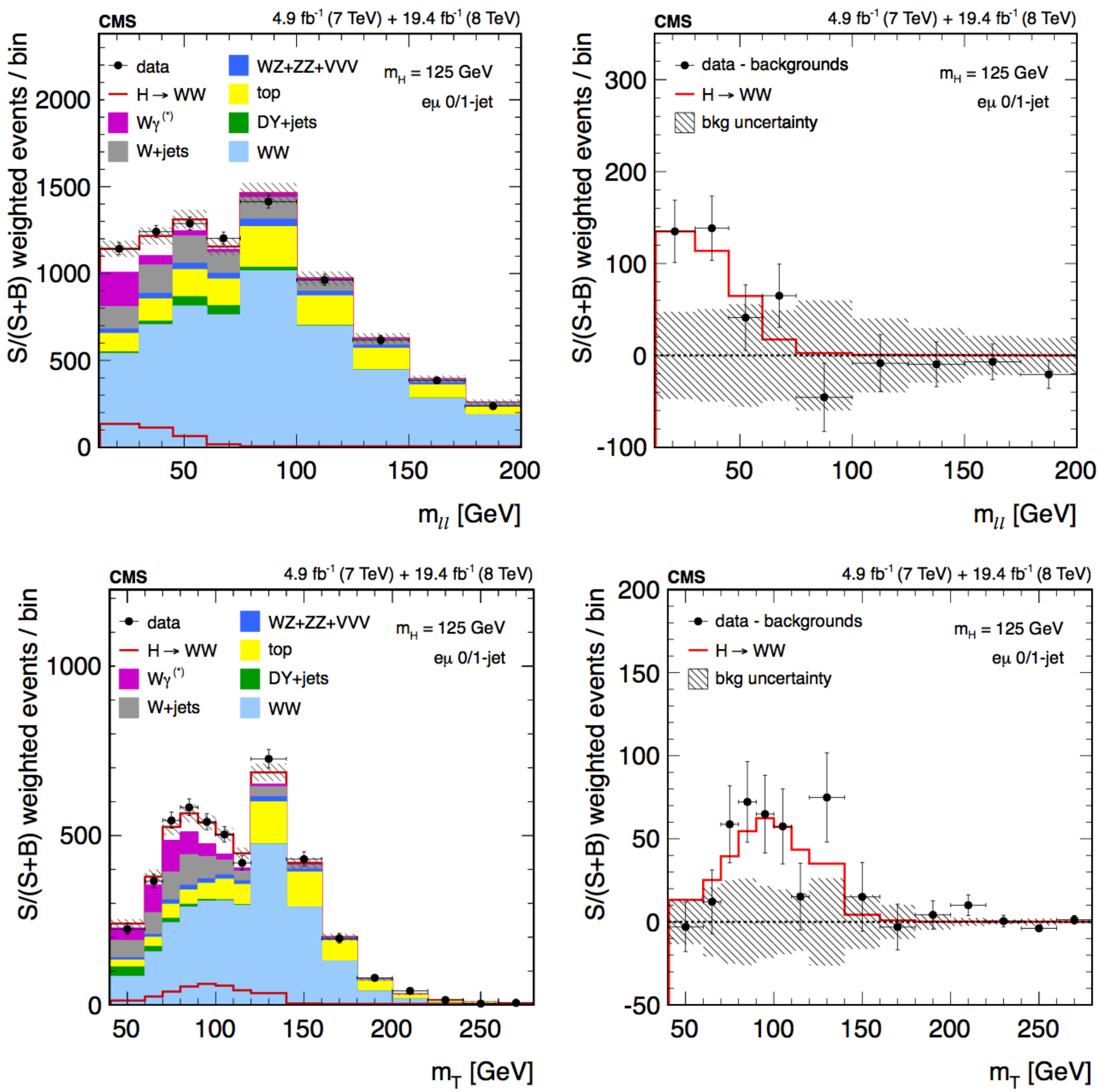






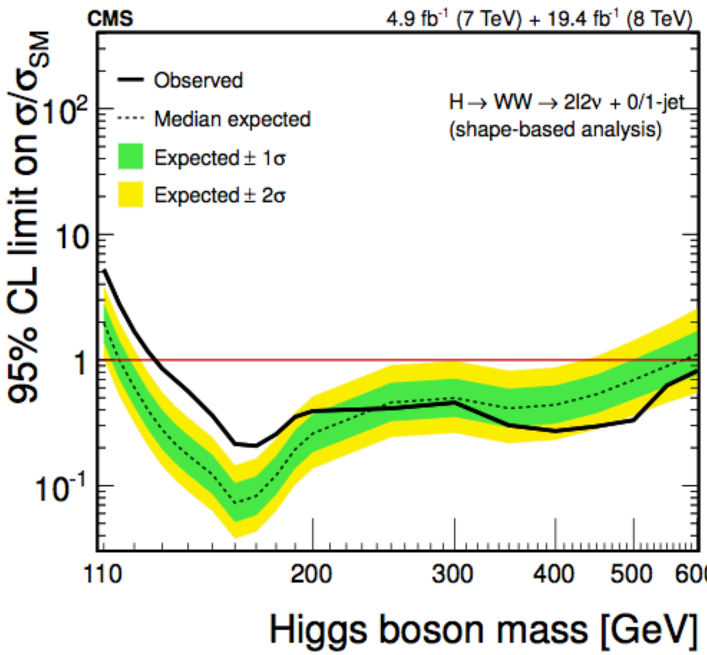


Final distributions



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

Results

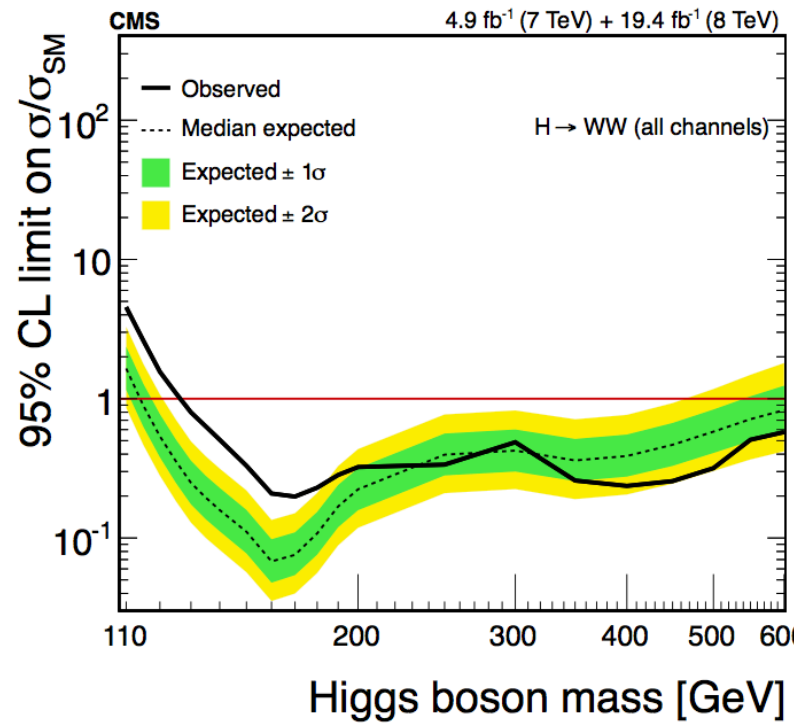


The eμ channel alone:

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

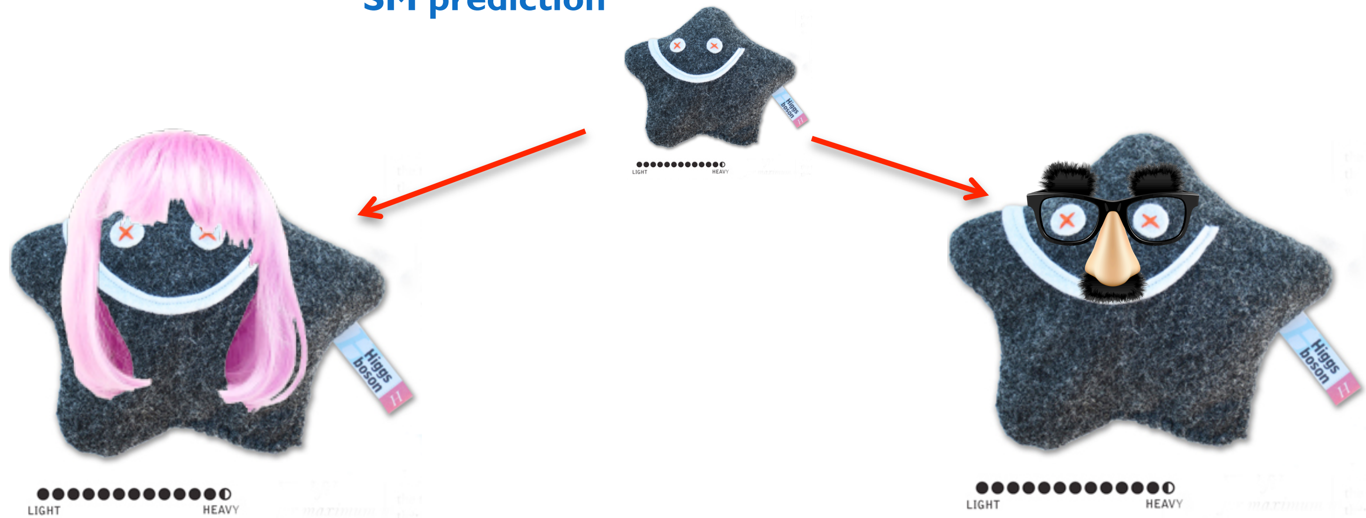


There is something

- 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…**

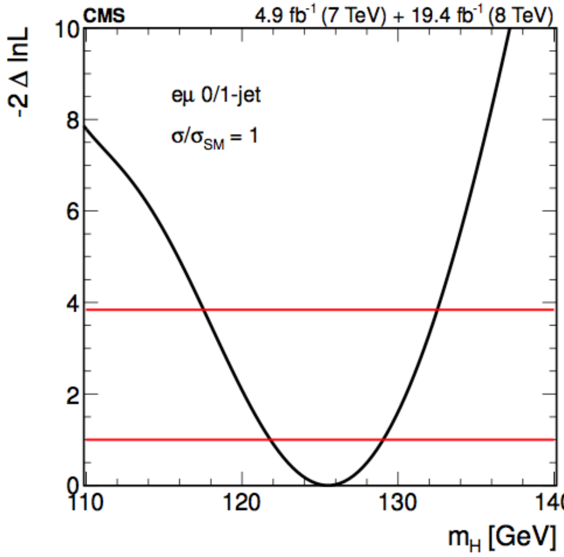
→ **How much can we explore using H→WW?**

Charge

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

Mass

- The H→WW excludes a Higgs mass range from **127 to 600** GeV
  - Expected range extends from 115 to 600 GeV→ Additional Higgs bosons excluded in 114–600 GeV
- Best-fit mass:
  - σ/σ_{SM}=1, **m_H = 125.5+3.6−3.8 GeV**
  - Without constraints, m_H = 128.2±6.6 GeV



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

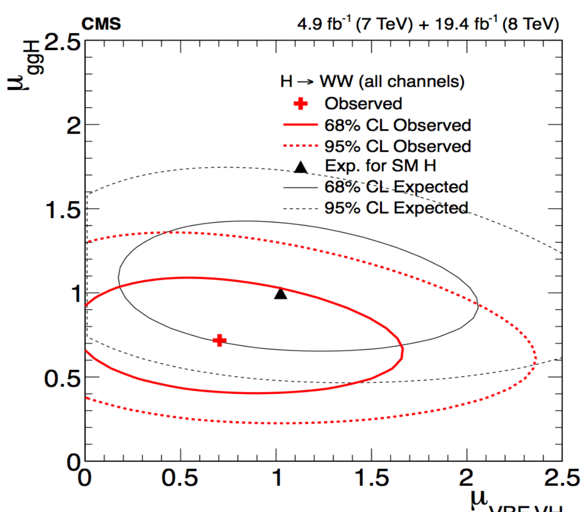
arXiv:1412.8662
Eur. Phys. J. C (2015) 75:212
Dec 2014

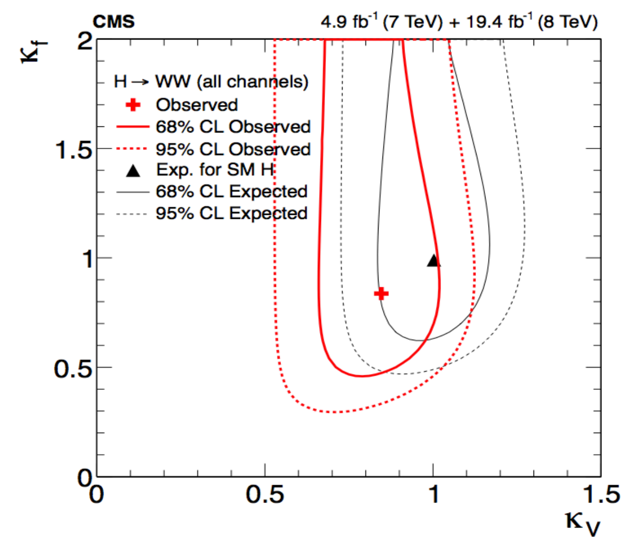
Couplings

- The values of μ_{ggH} and μ_{VBF} can be used to test the fermionic and bosonic couplings assigning coupling modifiers κ_V and κ_f to vector and fermion vertices → used to scale the expected product of σ xBR to match the signal yields in data

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

- 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**





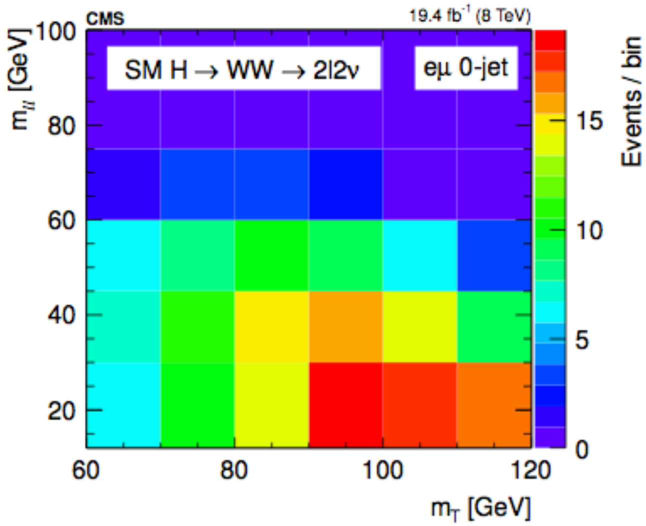
Spin and parity

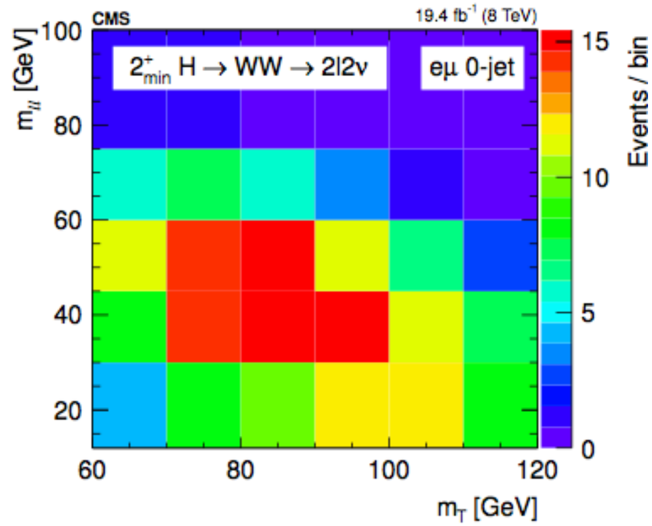
arXiv:1411.3441
Phys. Rev. D 92, 012004
November 2014

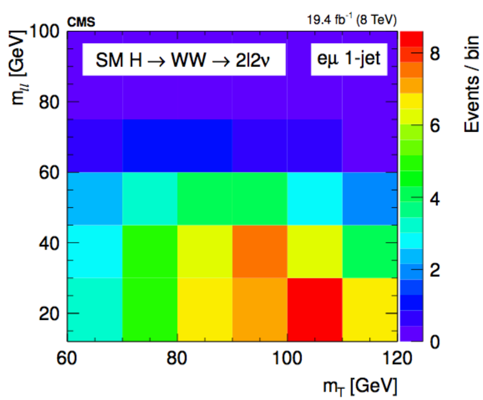
- Information from angular distributions of the decay products:
  - For example, in H→ZZ→4l, the final state is reconstructed fully and accurately
- In H→WW **the final state is not fully reconstructed, and there is more background contamination in the signal region, however**
  - There is potential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

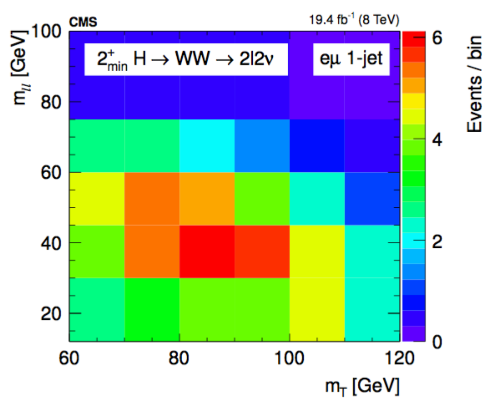
Spin studies in H→WW

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



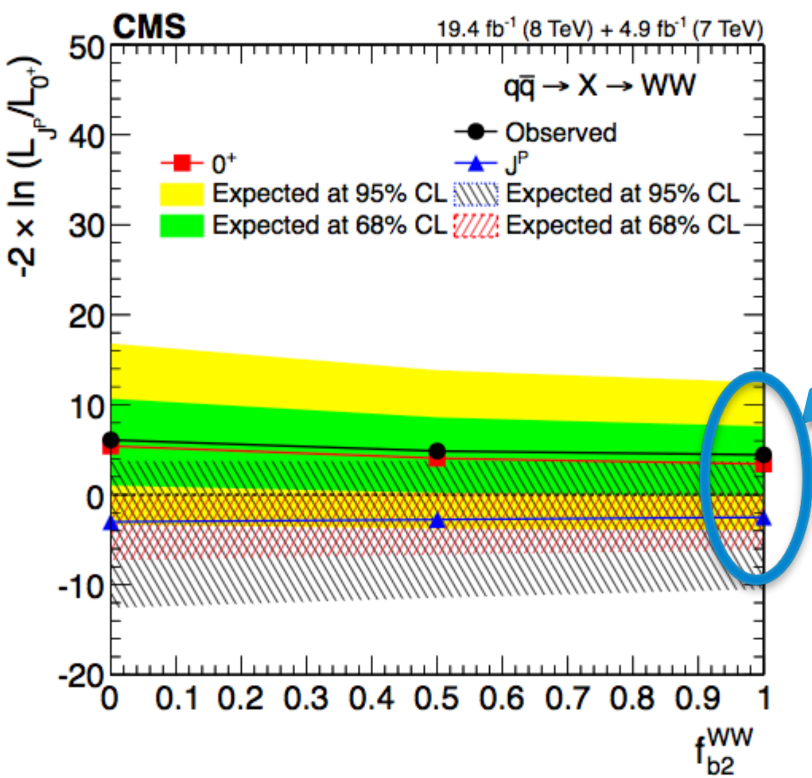


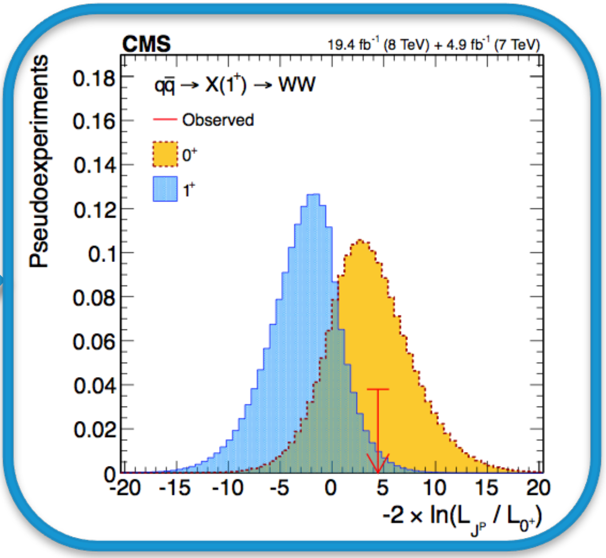




Spin-1

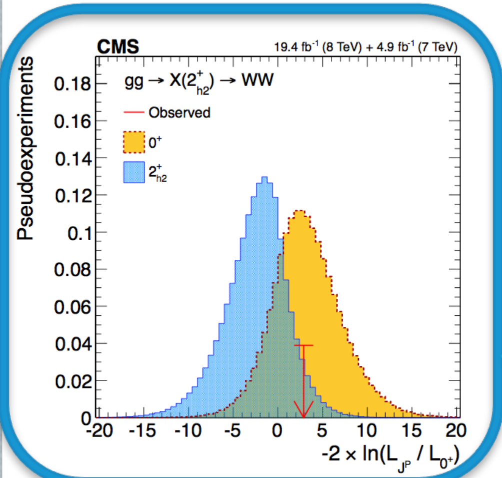
- J=1 not allowed for X→$\gamma\gamma$ by the Landau-Yang theorem
- Still we tested experimentally potential spin-1 models (in the hypothesis the excess is not the same resonance as $\gamma\gamma$) in H→WW: J^P=1$^-$, 1$^+$ and a mixed case



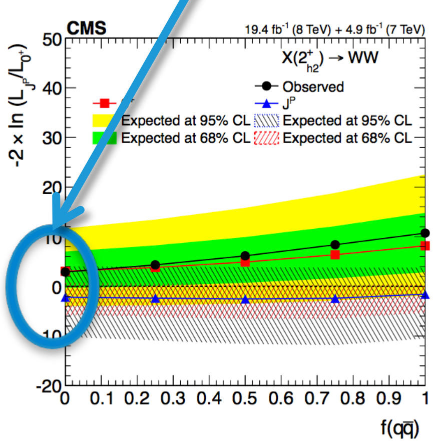


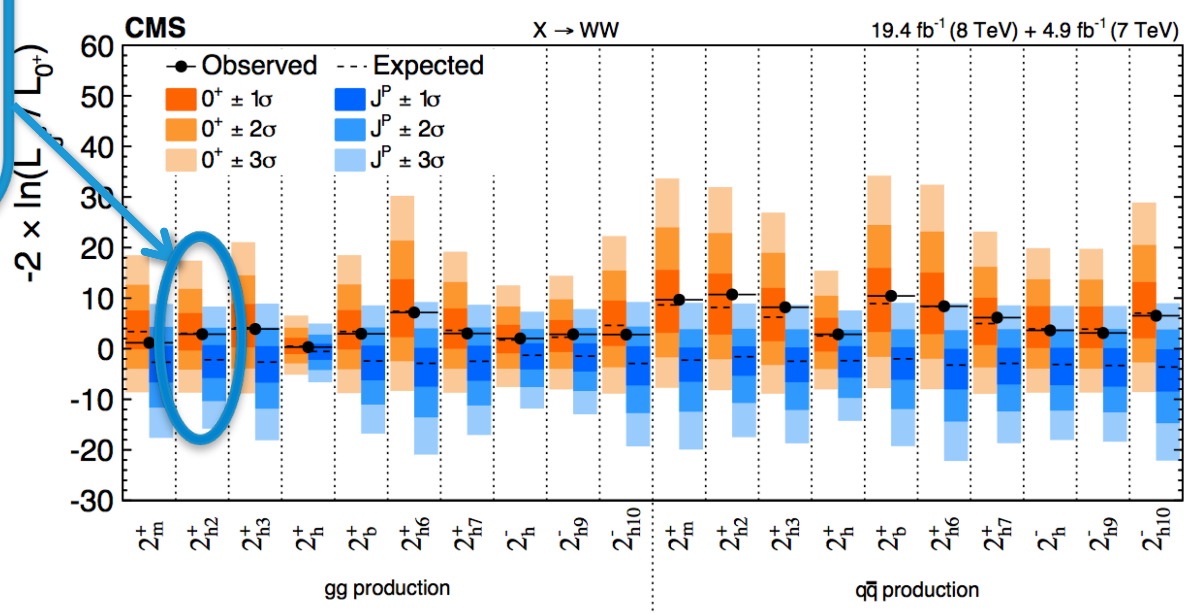
Spin-2

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



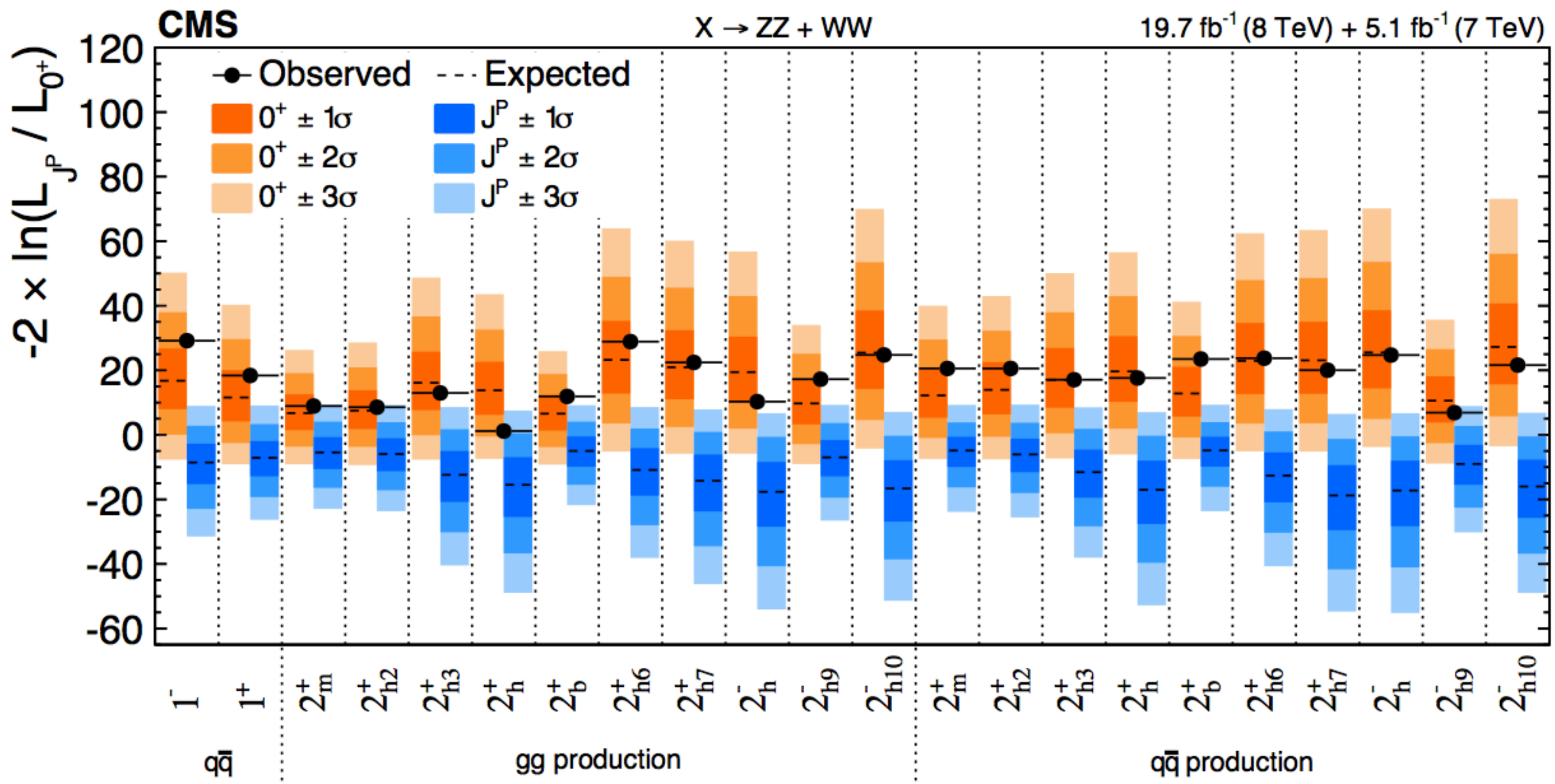
In all cases the data favor the SM hypothesis over the alternative spin-one or spin-two hypotheses





Better together

- 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}, $f_{\Lambda 1}$**

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

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

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

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

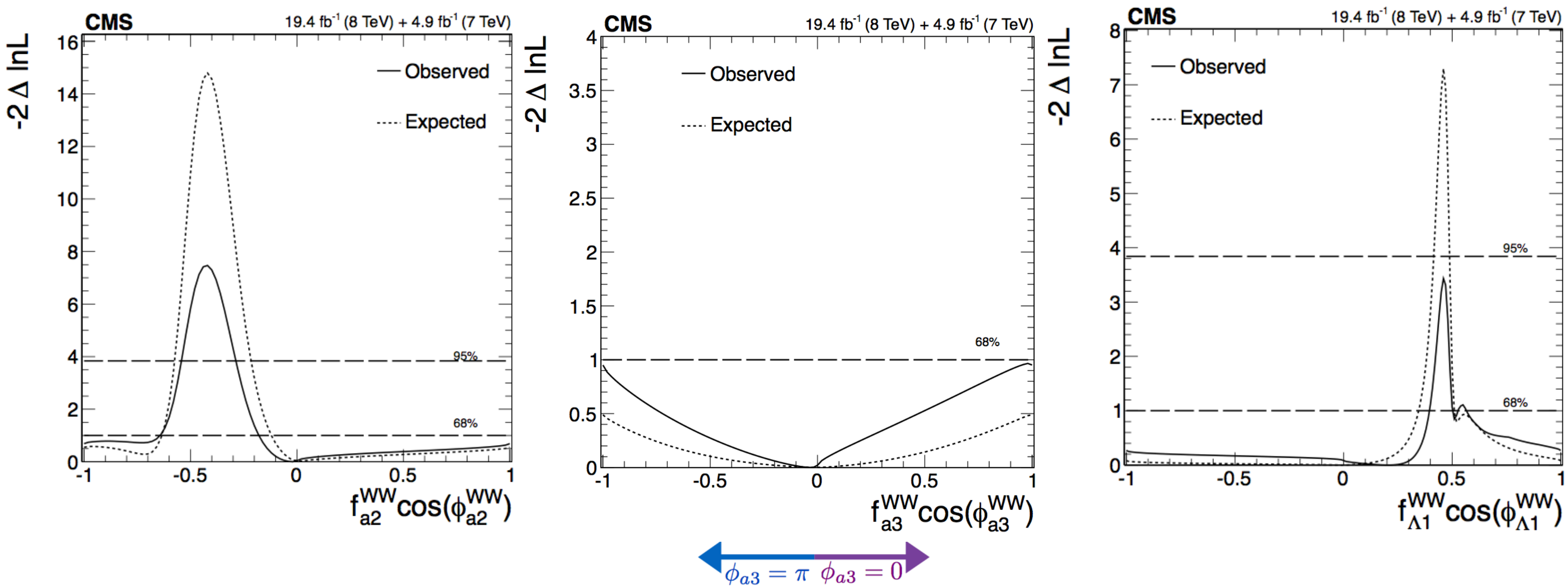
- Given the **measured value of f_x**, it is possible to extract the coupling constant:

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

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

H→WW Spin-0 studies

- We perform likelihood scans for the effective fractions using pure SM templates together with $f_i = 1$, mixed scenarios, and data



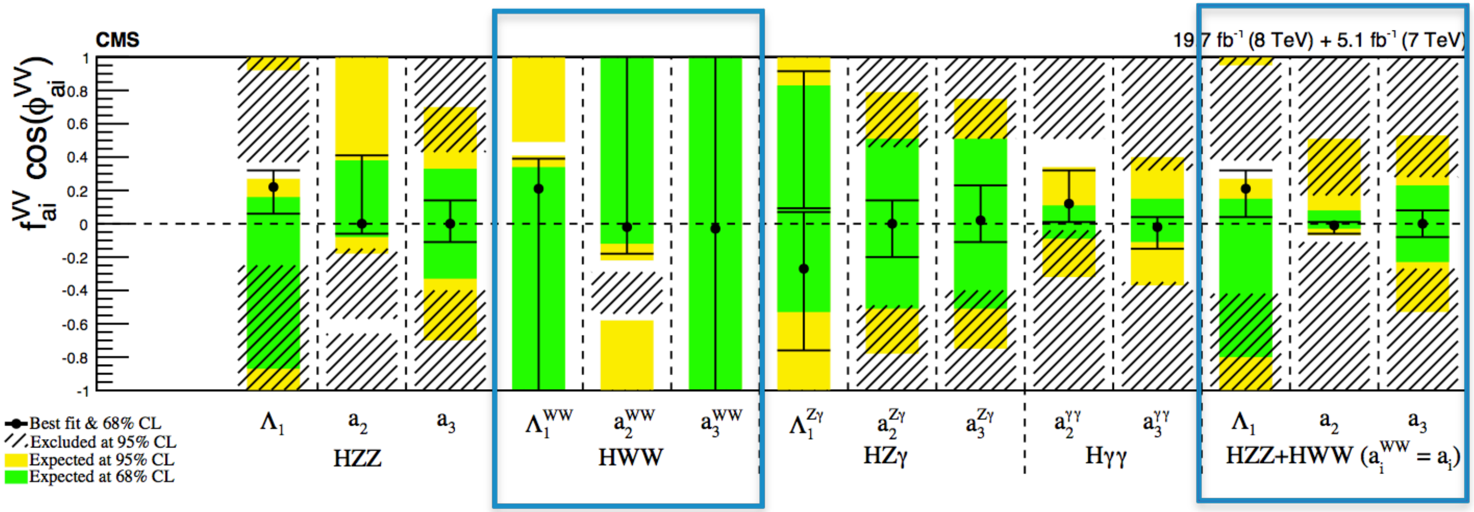
Couplings constrained to be real and all other anomalous couplings are fixed to the SM predictions in each case, cos ϕ term allows signed quantity: cos ϕ = −1 (π), +1 (0)

  - <u>Everything is **consistent with the SM**</u>

- H→WW has limited sensitivity for the measurement of f_{a2}, f_{a3} and $f_{\Lambda 1}$

H→WW and H→ZZ combination

Again H→ZZ drives the sensitivity in this kind of measurements, but in general, and in particular under certain assumptions (namely custodial symmetry between HZZ and HWW, that correlates the yields), the combination of H→ZZ and H→WW results provides improved sensitivity

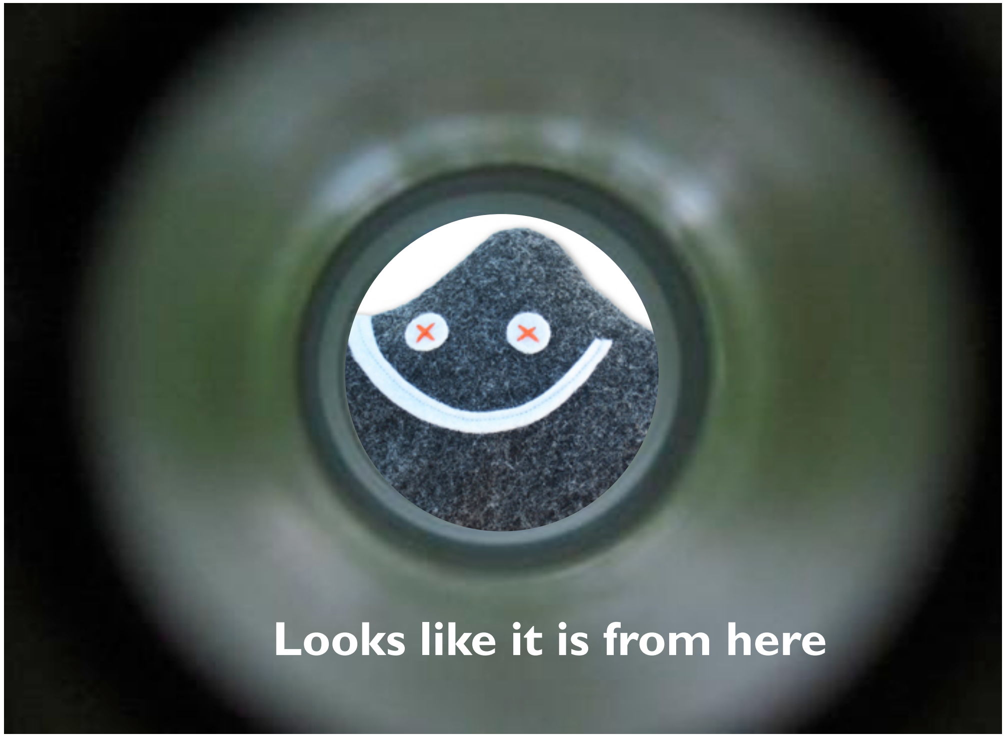


Summary of allowed confidence level intervals on anomalous coupling parameters in HVV interactions under the assumption that all the coupling ratios are real
→ compatible with a SM Higgs

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
  - **$J^{CP}=0^{++}$**

Is this guy exactly as we expect it?



But only more data will tell