SM Higgs in Boson Decay Modes at CMS

Stoyan Stoynev (Northwestern University)

On behalf of the CMS Collaboration

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SUSY 2014

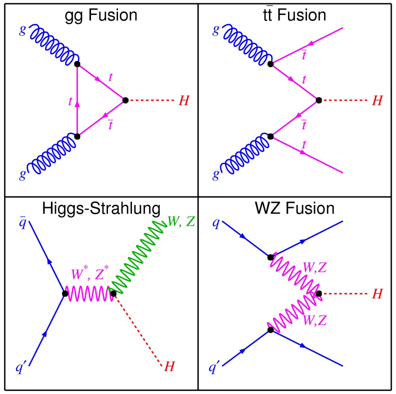
Production and decay modes of Higgs (@LHC)

In SM:

Four main Higgs production mechanisms

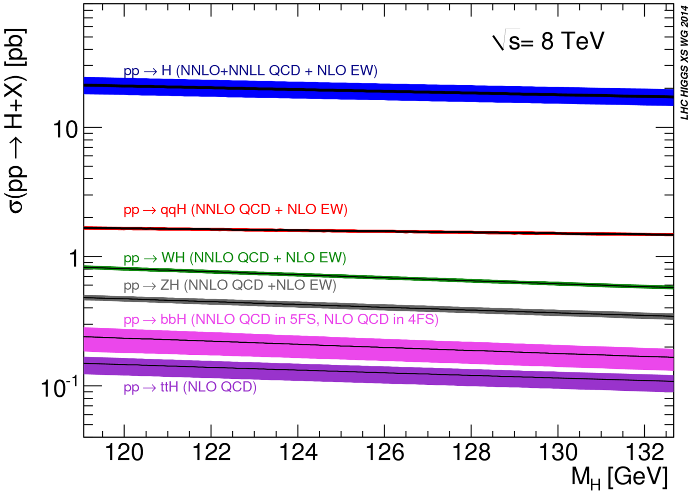
Each allowing to test the Higgs properties from different perspective

ggF | ttH
VH | VBF

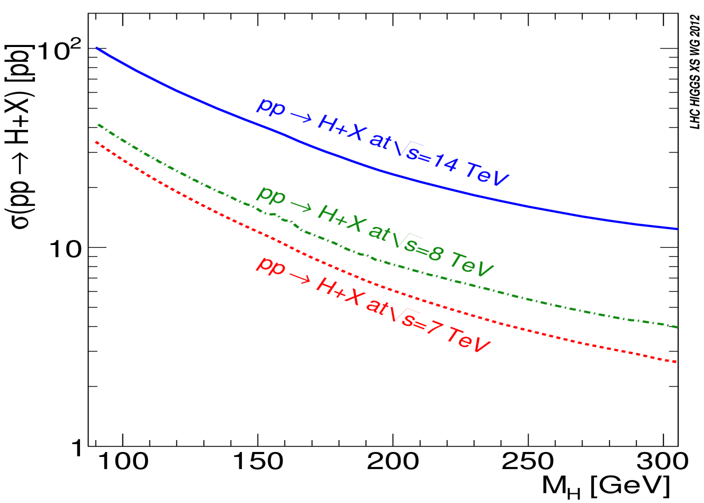


~ 0.5 M Higgs bosons expected to have been born at CMS to date

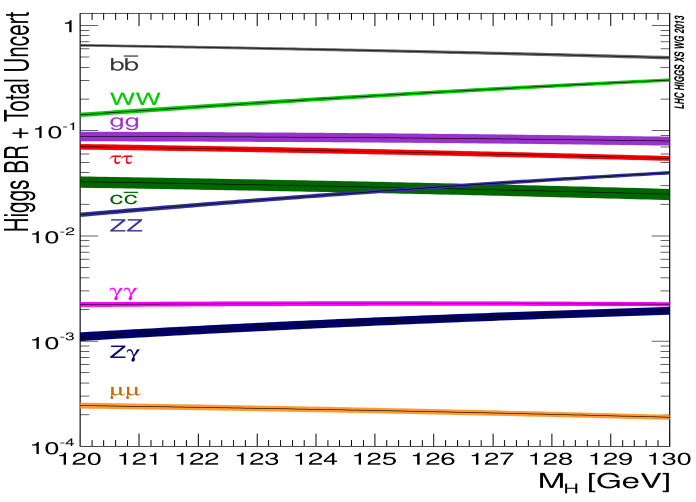
The dominant Higgs production mode is ggF



Higgs production cross-section increases with collision energy (25% between 7 and 8 TeV)



Bosonic decay modes cover the spectrum between low and high branching fractions



Bosonic decay modes are all well covered experimentally by featured search signatures

Thus **ZZ**, $\gamma\gamma$ and **WW** are main discovery modes and **Z**γ allows for further SM tests
The complimentary $\gamma^{*}\gamma$ mode plays a crucial role in rare Higgs decays (by interference)

H→$\gamma\gamma$

A di-photon provides relatively clean final-state topology

Events from specific production mechanisms are further identified and classified by the presence of additional objects in the final state

The analysis searches for a (narrow) peak over smooth background – a simultaneous fit to the di-photon invariant mass distributions in all event classes is performed

One of the two channels providing excellent precision for the Higgs mass reconstruction:

$$m_{\gamma\gamma} = \sqrt{(2 E_1 E_2 (1 - \cos\alpha))}$$

The new final result comes with many improvements over the preliminary one:

- Final set of calibrations
- MC includes time dependent description
- Analysis chain completely re-optimized
- Exclusive channels expanded to include all production modes
- New method for modeling the background
- Considerable effort in studying the energy scale uncertainties (reduced by a factor of three for the invariant mass)

Results made public less than a month ago

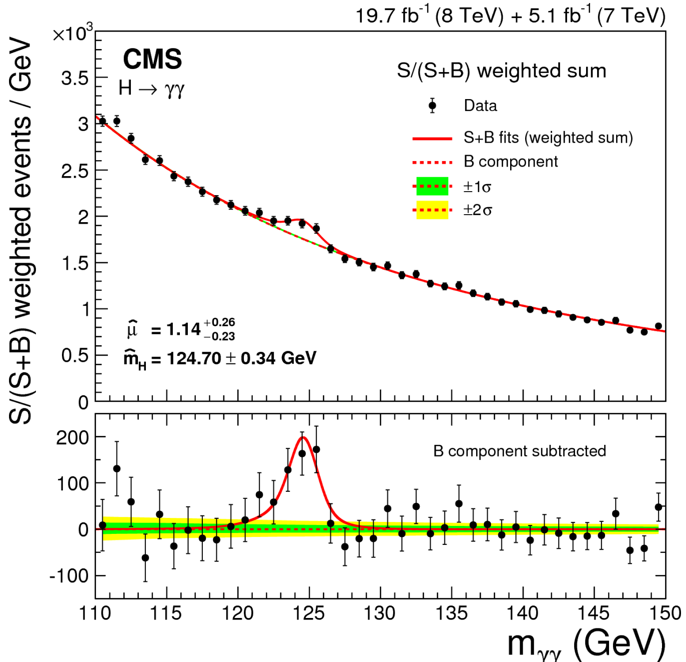
arXiv:1407.0558 [hep-ex]

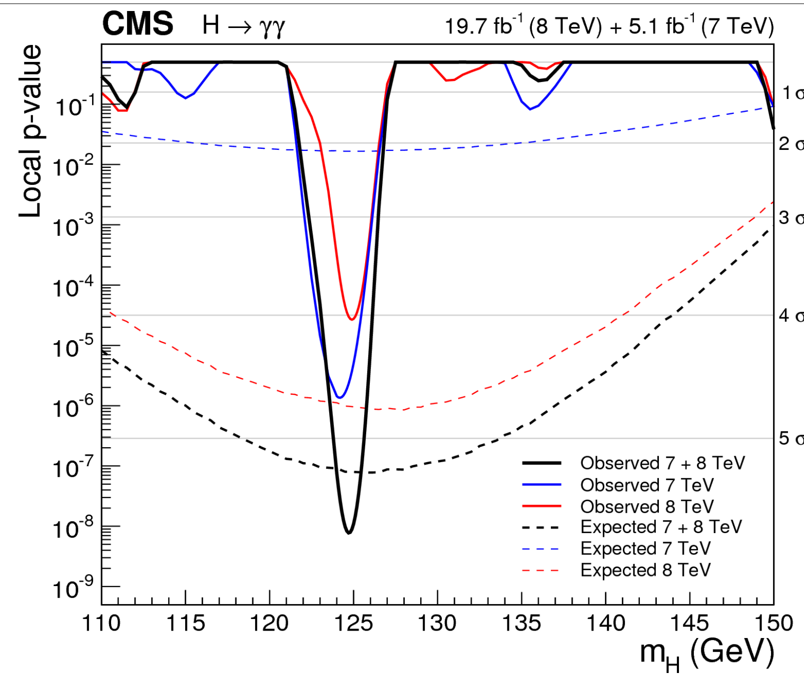
(CMS-HIG-13-001,

CERN-PH-EP-2014-117)

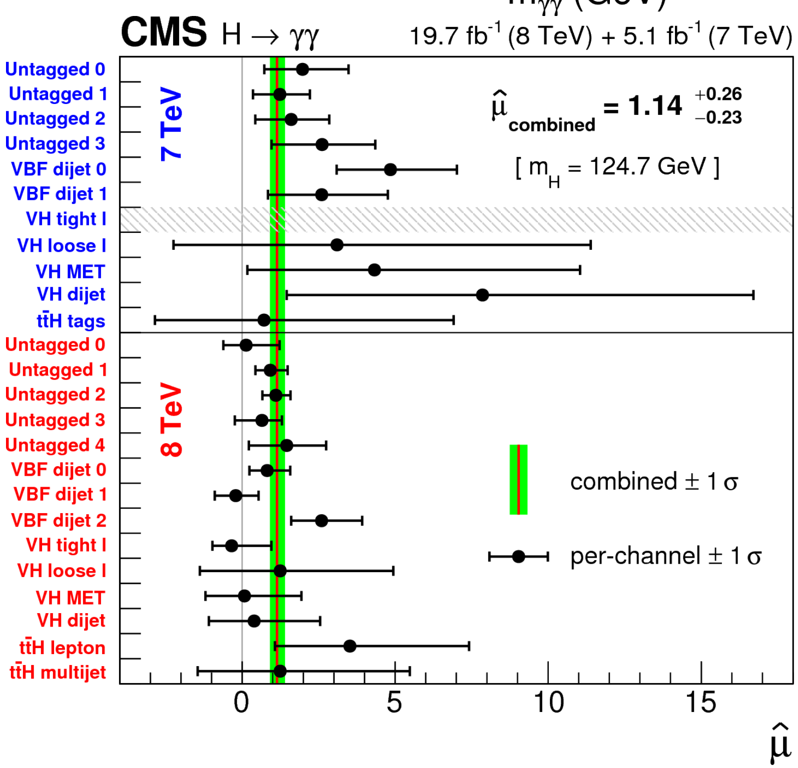
Change	Improved energy resolution (new calibration + new regression)	New event selection (re-training + re-categorization)	Background modeling
Improvement over preliminary result (PAS)	**~9%**	**~9%**	**~7%**

H→γγ (2)





arXiv:1407.0558 [hep-ex]



A signal with significance of 5.7σ is observed (5.2σ expected)

mass $$m_H = (124.70 \pm 0.31\, stat \pm 0.15\, syst)\, GeV$$

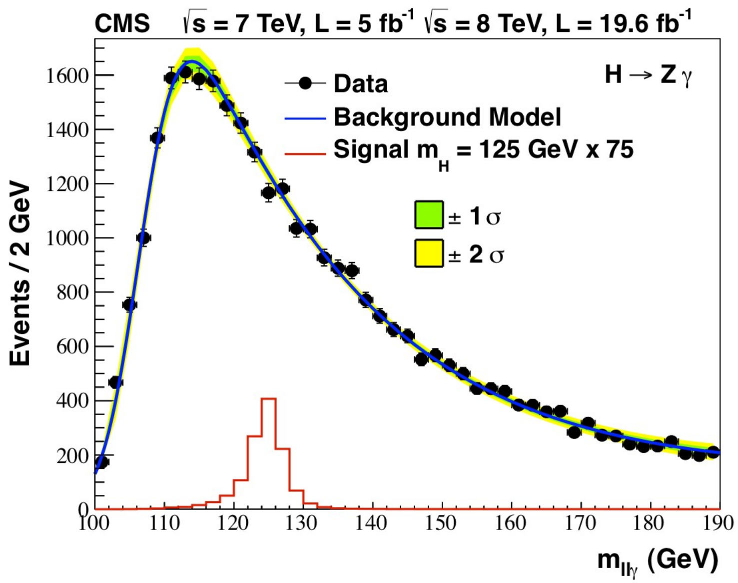
signal strength $$\mu = 1.14 \pm 0.21\, stat \; {}^{+0.09}_{-0.05}\, syst \; {}^{+0.13}_{-0.09}\, theo$$

Fermionic and bosonic couplings consistent between each other. Overall – properties consistent with SM Higgs boson.

The measurement is still statistically limited.

H→Zγ and H→γ*γ (Dalitz decay)

Search similar to the di-photon decay mode except the experimental signature is different. Multiple categories are also introduced for Zγ. Lepton Z/γ* decay modes are exploited.

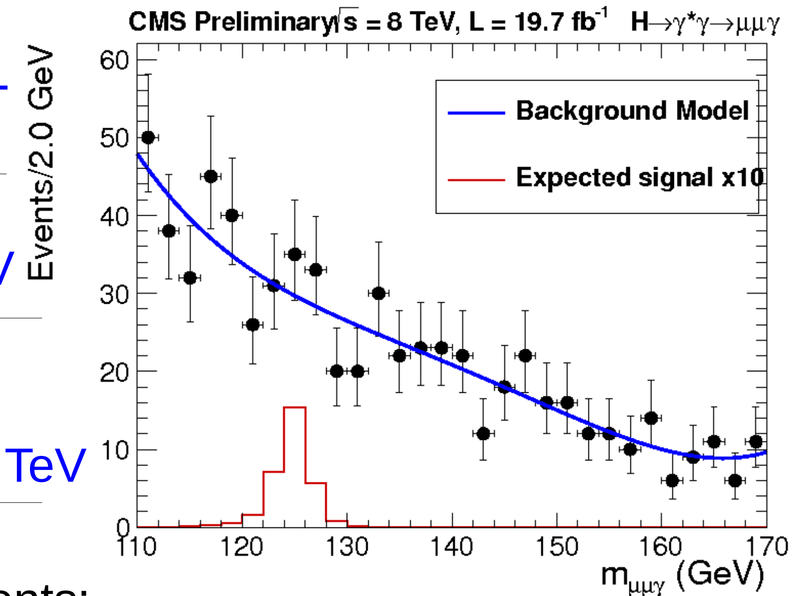


H→Zγ | **H Dalitz**

Close-by leptons back-to-back to the photon

$p_T(\gamma)$~ 30 GeV | $p_T(\gamma)$ ~ 60 GeV

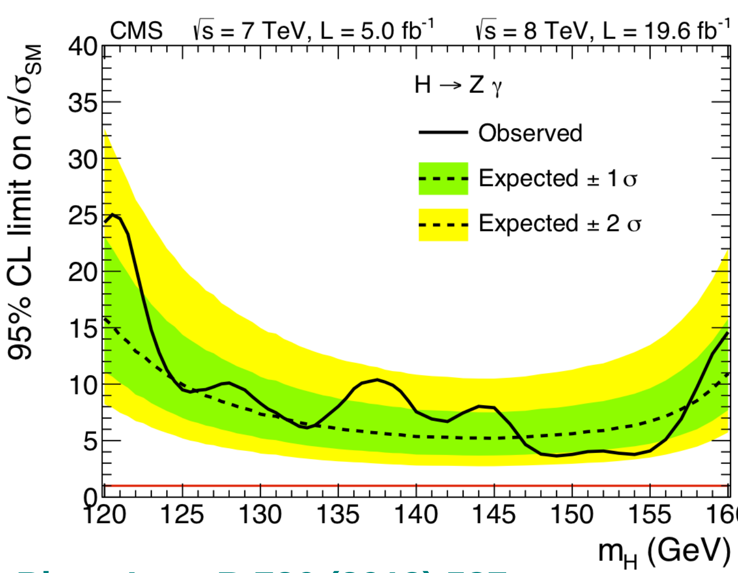
Electrons + muons, 7 TeV + 8 TeV | Only muons, only 8 TeV



Comparative requirements:

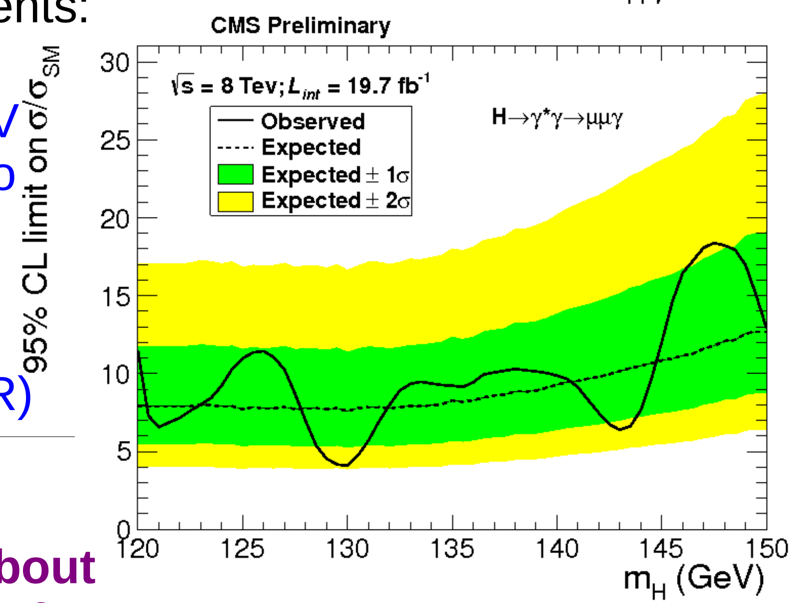
M(ll)> 50 GeV | M(ll)< 20 GeV, J/Ψ , Υ veto

di-lepton with mass closest to Z | di-lepton with lowest mass (ΔR)



Results /H(125)/:

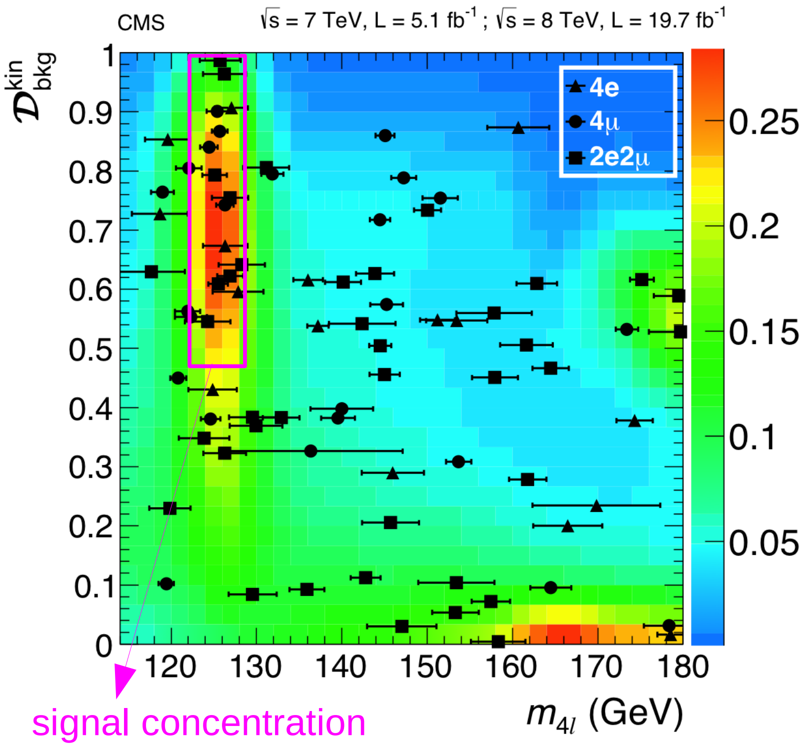
Both limits are set at about one order of magnitude from SM



Phys. Lett. B 726 (2013) 587

CMS-PAS-HIG-14-003

H→ZZ

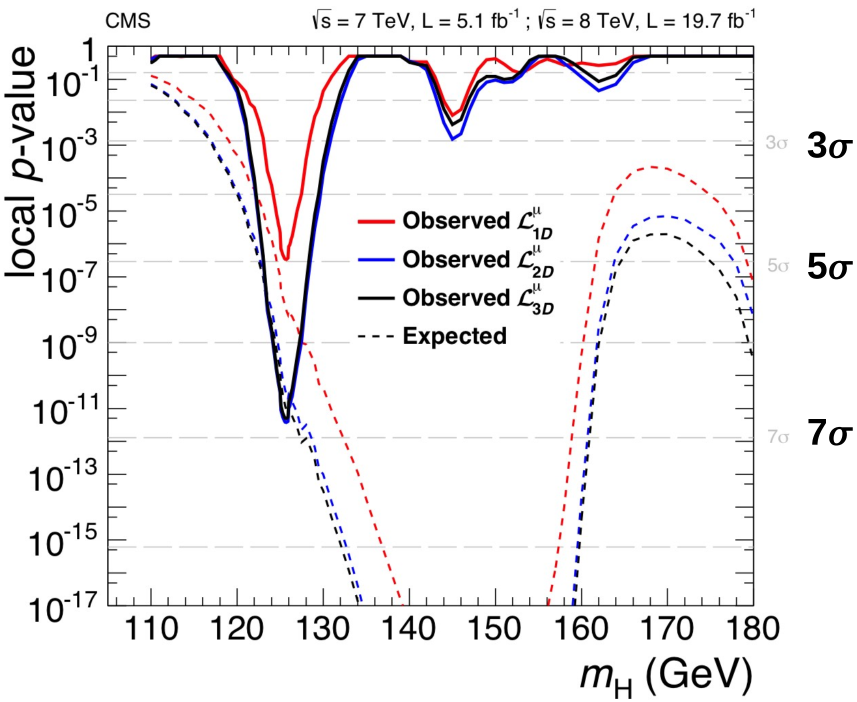


Lepton Z decay modes exploited to provide cleanest signature and build m_{4l}

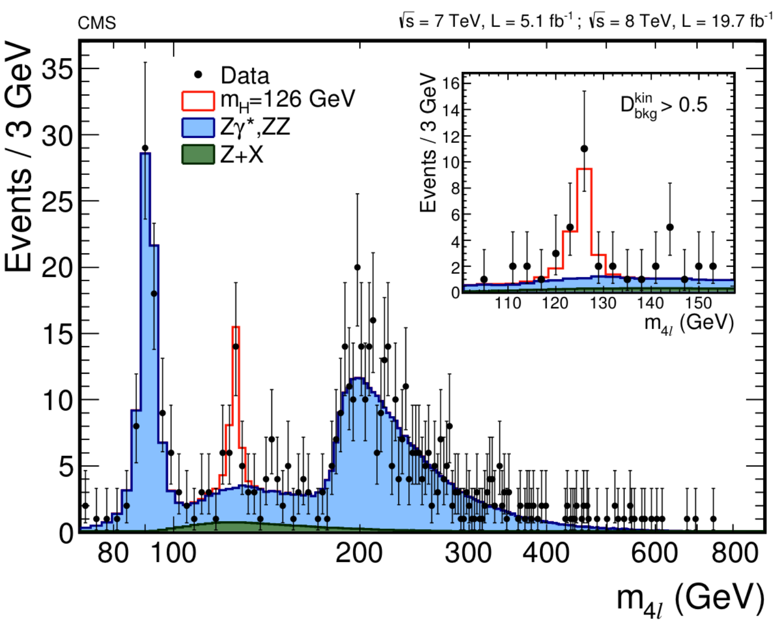
Additional kinematic information from the event (kinematic discriminant)

Categorize events as dijet-tagged and untagged (further discriminate VBF by the p_T of the four-lepton system)

3D fit of m_{4l}, kinematic and dijet discriminants or $p_T(4l)$



Phys. Rev. D 89, 092007 (2014)



A signal with significance of 6.8σ is observed (6.7σ expected)

$$m_H = (125.6 \pm 0.4\ stat \pm 0.2\ syst)\ GeV$$

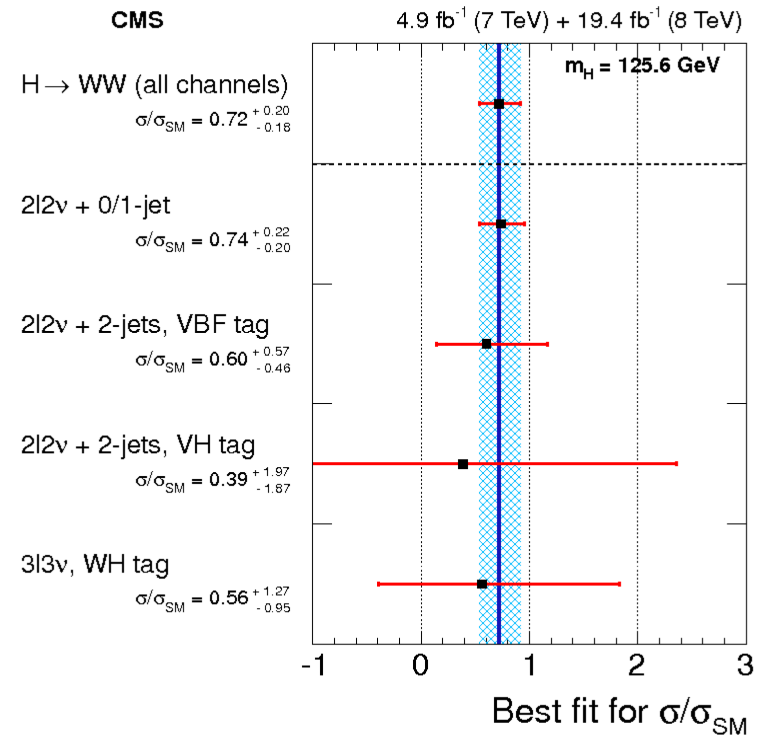
$$\mu = 0.93^{+0.26}_{-0.23}\ stat\ ^{+0.13}_{-0.09}\ syst$$

H→WW

Highest (bosonic) branching ratio but large background and harder to identify; lepton decay modes exploited

Events from specific production mechanisms are further identified and classified by the presence of additional objects in the final state

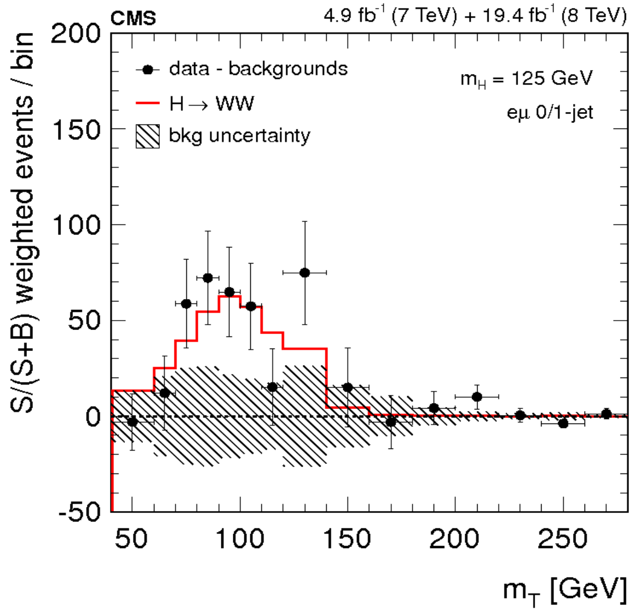
In 0/1-jet categories the signal is extracted by 2D shape analysis: reconstructed Higgs boson transverse mass m_T and charge di-lepton invariant mass m(ll).

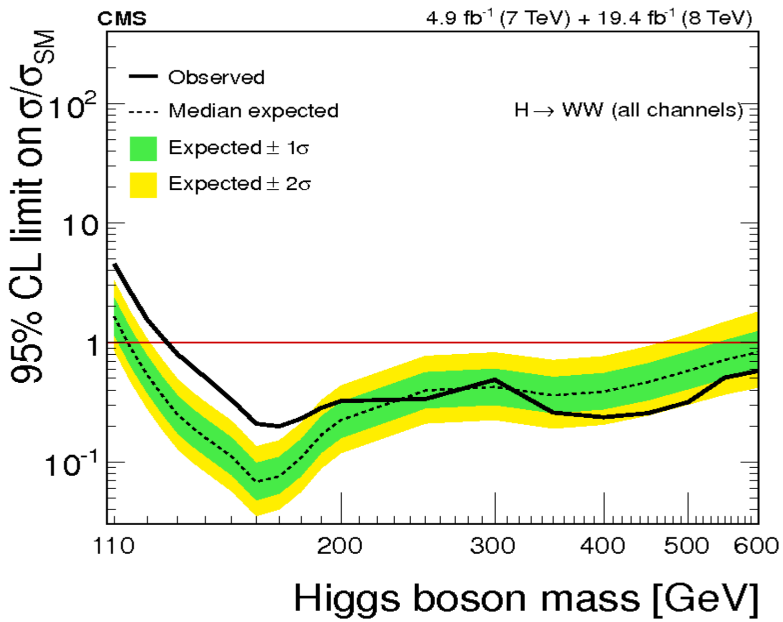


A signal with significance of 4.3σ is observed (5.8σ expected)

Consistent with m_H = 125.6 GeV and

$$\mu = 0.72 \pm 12\, stat \pm 0.10\, syst \,{}^{+0.12}_{-0.10}\, theo$$





JHEP 01 (2014) 096

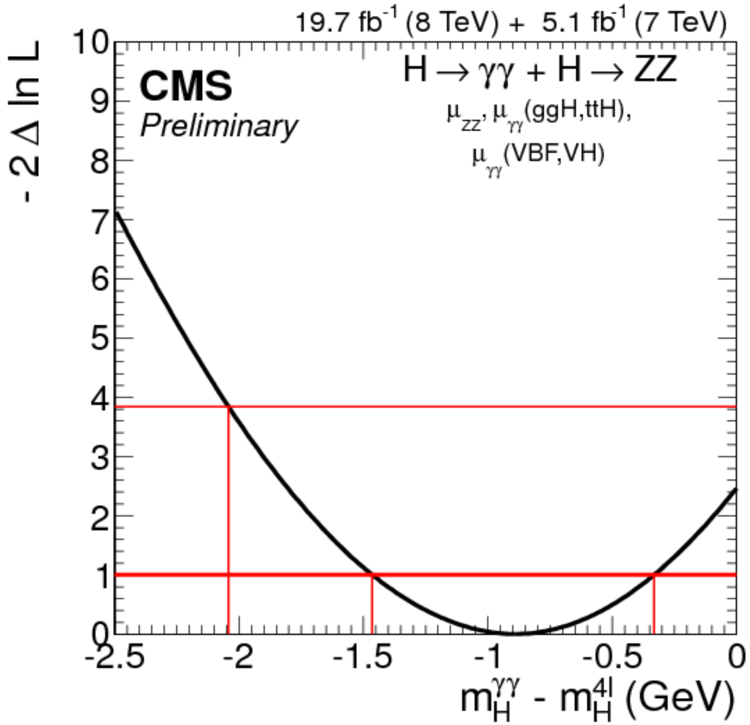
Higgs mass from ZZ and di-photon decay modes

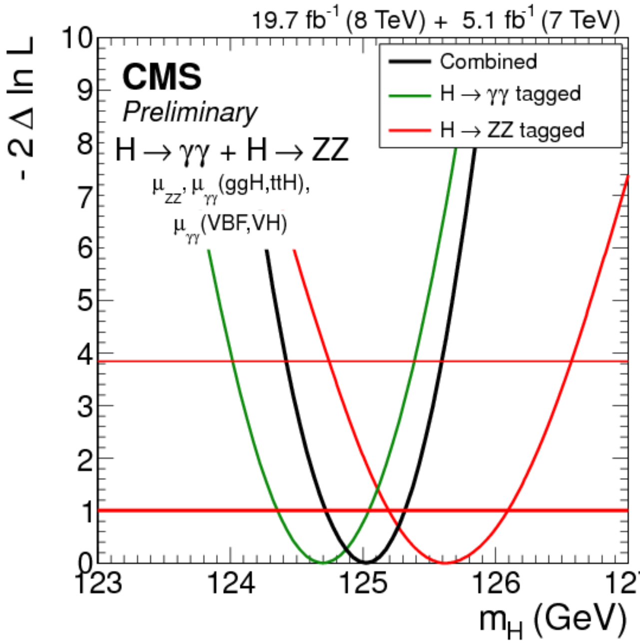
The high resolution decay channels $\gamma\gamma$ and **ZZ** are used to extract the Higgs mass – the best-fit value is extracted from a scan of the combined test statistics

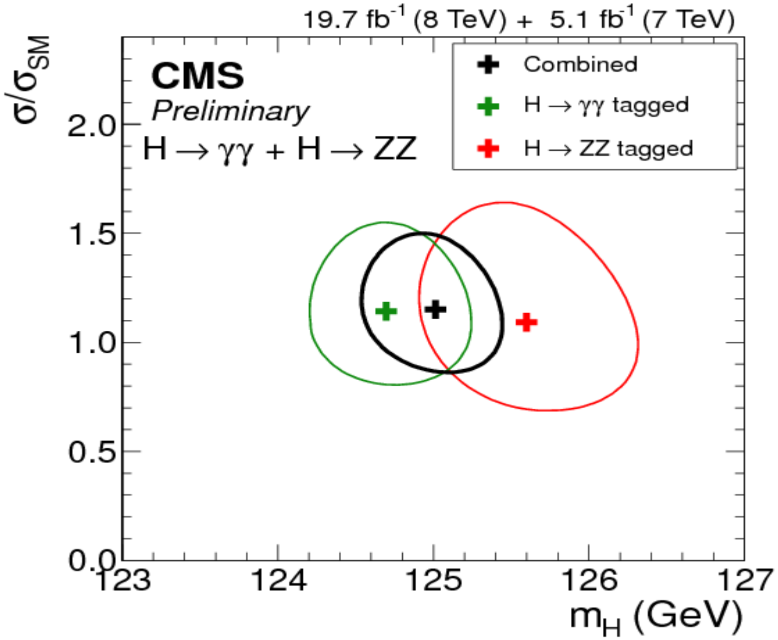
$$m_H = (125.03 \pm^{+0.26}_{-0.27}\, stat \pm^{+0.13}_{-0.15}\, syst)\, GeV$$

Signal strength modifiers for (ggF, ttH)→$\gamma\gamma$, (VBF, VH)→$\gamma\gamma$ and H→ZZ are NOT fixed to SM in order to get as much as model independent mass measurement as possible

The measurements from the single channels agree at 1.6 sigma level







These are recent results

CMS-PAS-HIG-14-009

Higgs width from ZZ decay mode

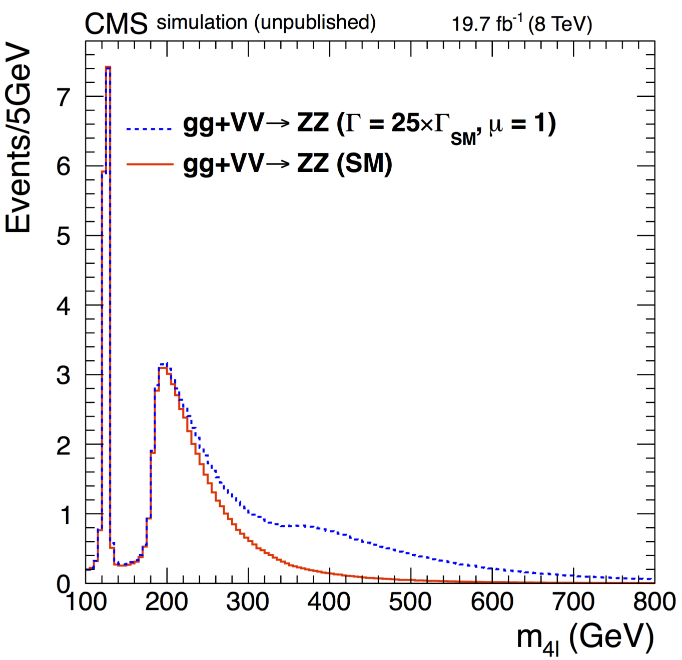
Direct measurement of the Higgs width is limited by the detector resolution (GeV scale) – not possible to measure the predicted SM value of 4.15 MeV (at m_H=125.6 GeV)

However it can be constrained by off-shell **H→ZZ** events with mild model dependence (same coupling on/off-shell is assumed) at few 10s of MeV

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

(it works because H*→VV is not negligible)

Combining charged four-lepton 4l and 2l2ν decay channels provides 20% stronger limits



arXiv:1405.3455 [hep-ex]

(CMS-HIG-14-002,

CERN-PH-EP-2014-078)

In 4l (off-shell):

- Build kinematic discriminant D_{gg} for gg→ZZ production using matrix element likelihood approach (MELA)

$$\mathcal{D}_{gg} = \frac{\mathcal{P}^{gg}_{tot}}{\mathcal{P}^{gg}_{tot} + \mathcal{P}^{q\bar{q}}_{bkg}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{bkg}}{a \times \mathcal{P}^{gg}_{sig} + \sqrt{a} \times \mathcal{P}^{gg}_{int} + \mathcal{P}^{gg}_{bkg}}\right]^{-1}$$

- Build 4l invariant mass (> 220 GeV)
- Perform likelihood fit with two-dimensional pdfs

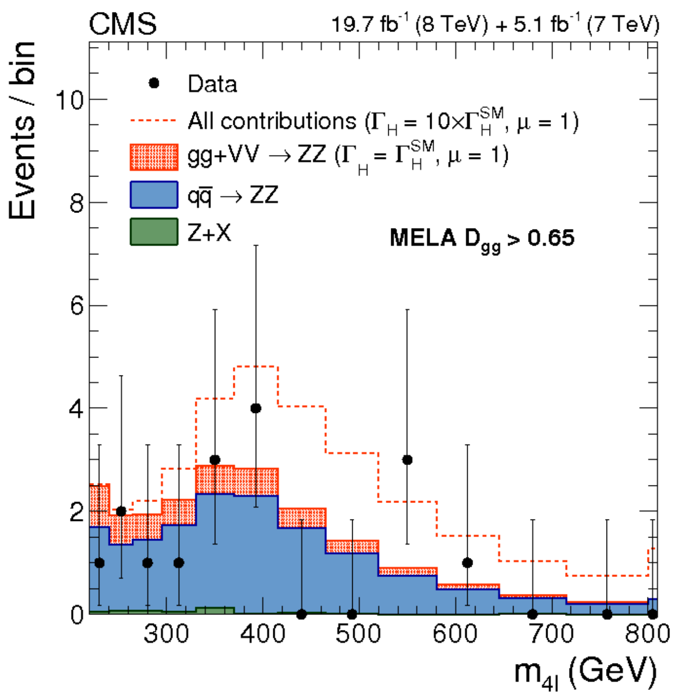
In 2l2ν (off-shell):

- After selecting an isolated lepton pair and MET in the event > 80 GeV
- Build the transverse mass (>180 GeV)

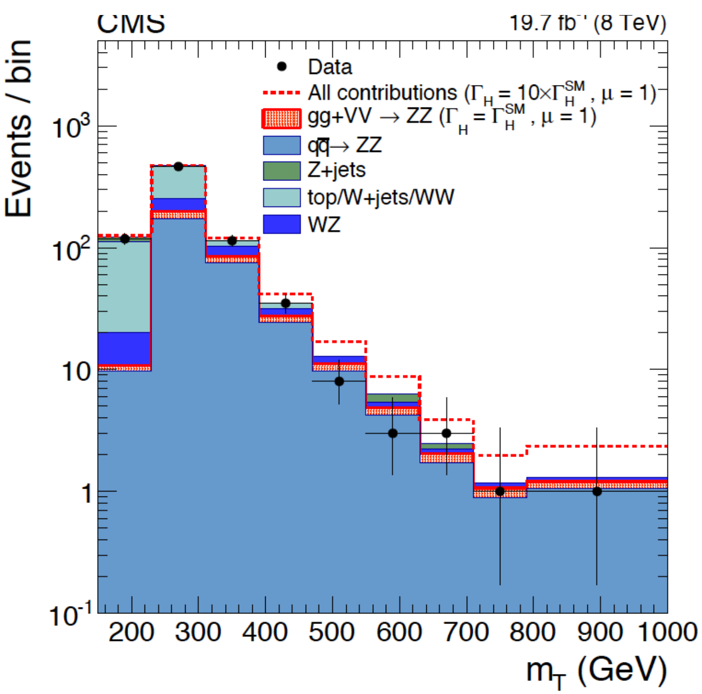
$$m_T^2 = \left[\sqrt{{p_{T,2\ell}}^2 + {m_{2\ell}}^2} + \sqrt{{E_T^{miss}}^2 + {m_{2\ell}}^2}\right]^2 - \left[\vec{p}_{T,2\ell} + \vec{E}_T^{miss}\right]^2$$

- It enters the likelihood fit

Higgs width from ZZ decay mode (2)



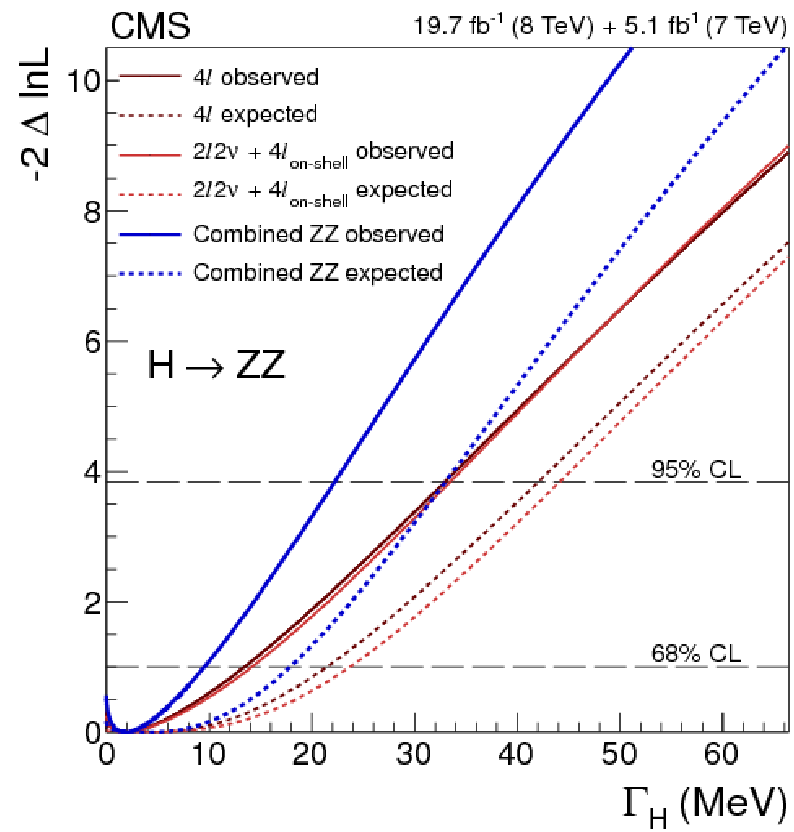
4l



2l2ν

arXiv:1405.3455 [hep-ex]

Likelihood profiling



$$\Gamma/\Gamma_{SM} < 5.4\,(8.0\ expected)\ @\ 95\ CL$$

$$\Gamma < 22\ MeV\ (33\ expected)\ @\ 95\ CL$$

$$observed: \Gamma_H = 1.8\ MeV\ {}^{+7.7}_{-1.8}\ MeV$$

$$expected: \Gamma_H = 4.2\ {}^{+13.5}_{-4.2}\ MeV$$

Higgs Spin and Parity (highlights)

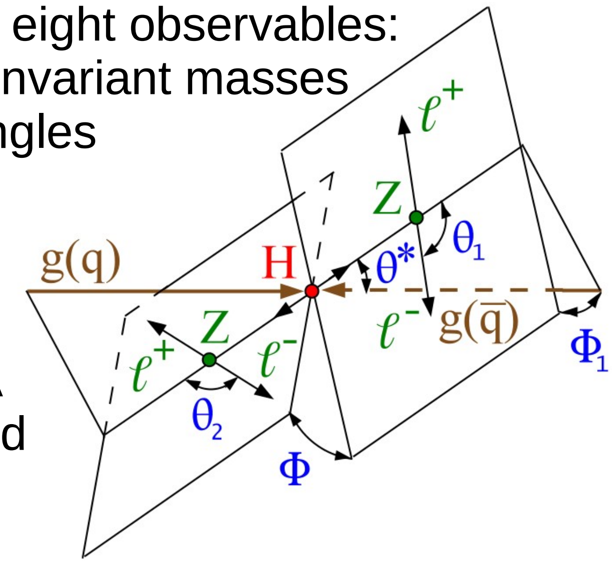
The Higgs bosonic decays are the ones used to tests the spin statistics and parity

ZZ is the richest and well defined state and is the main player; **WW** has larger statistics but Higgs is partially reconstructable; $\gamma\gamma$ can give additional information by precise differential cross-section measurements

All hypothesis tests (by likelihood fits) are consistent with the new state being a scalar particle (no anomalous couplings observed)

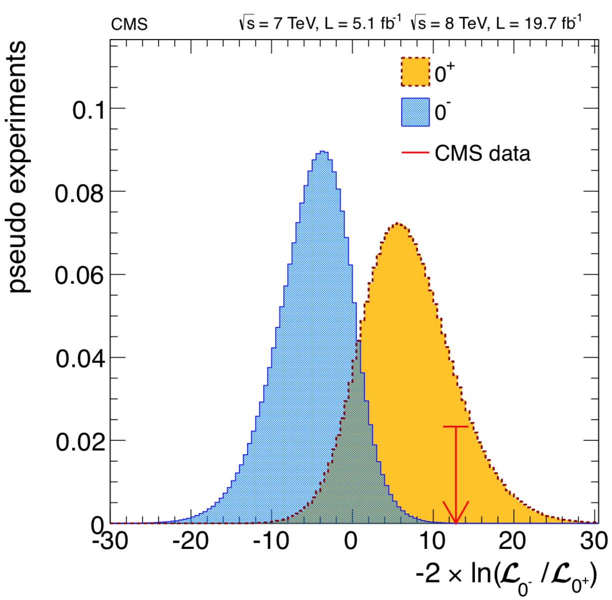
H→ZZ, eight observables:
- three invariant masses
- five angles

MELA applied

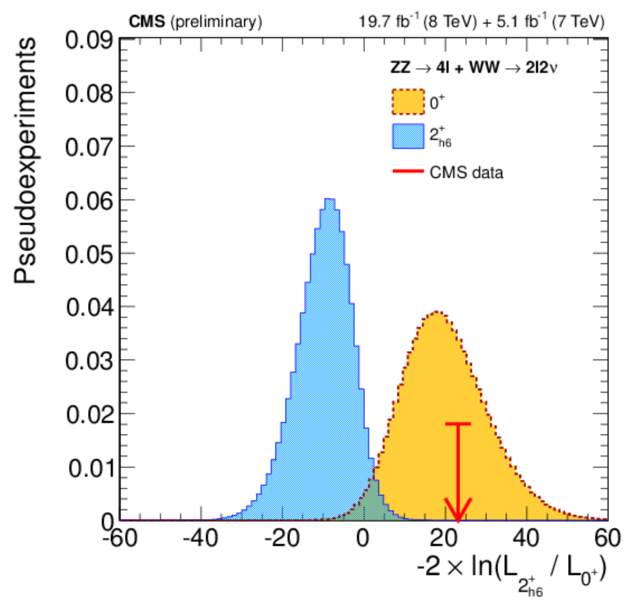


Phys. Rev. D 89, 092007 (2014)
arXiv:1407.0558 [hep-ex]
CMS-PAS-HIG-14-012
CMS-PAS-HIG-14-014

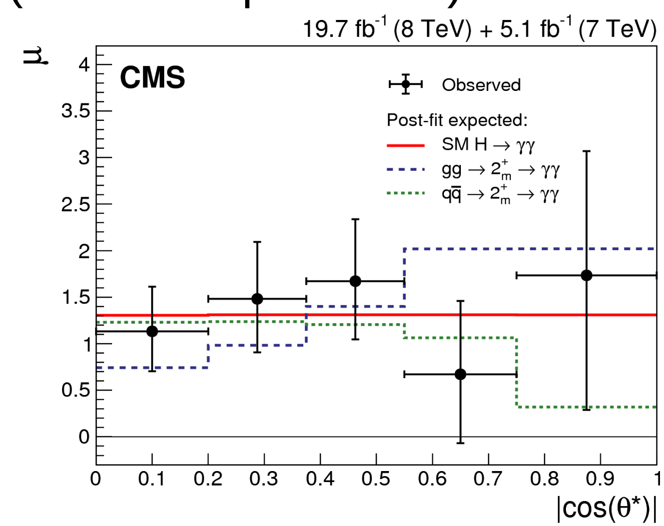
Parity tests with ZZ



Spin/parity tests with ZZ and WW



Diphoton differential measurements (Collins-Soper frame)



Summary

Chanel	Data (fb^{-1})	Specialty	Significance Obs. (exp.),	Mass (GeV)	Signal strength	$J^P = 0^+$	Higgs width Obs. (exp.)
$H\rightarrow\gamma\gamma$	4.9 + 19.7	Mass, discovery, couplings	**5.7** (5.2)	124.70 $\pm$0.31 $\pm$0.15	1.14 $^{+0.26}_{-0.23}$	≈	<2.4 (3.1) GeV @95% CL
$H\rightarrow ZZ$	5.1 + 19.7	Mass, width, discovery, couplings	**6.8** (6.7)	125.6 $\pm$0.4 $\pm$0.2	0.93 $^{+0.29}_{-0.25}$	yes	< 22 (33) MeV (off-shell/on-shell measurements)
$H\rightarrow WW$	4.9 + 19.4	Cross-section, couplings	4.3 (5.8)	125.5 $^{+3.6}_{-3.8}$	0.72 $^{+0.20}_{-0.18}$	yes	-

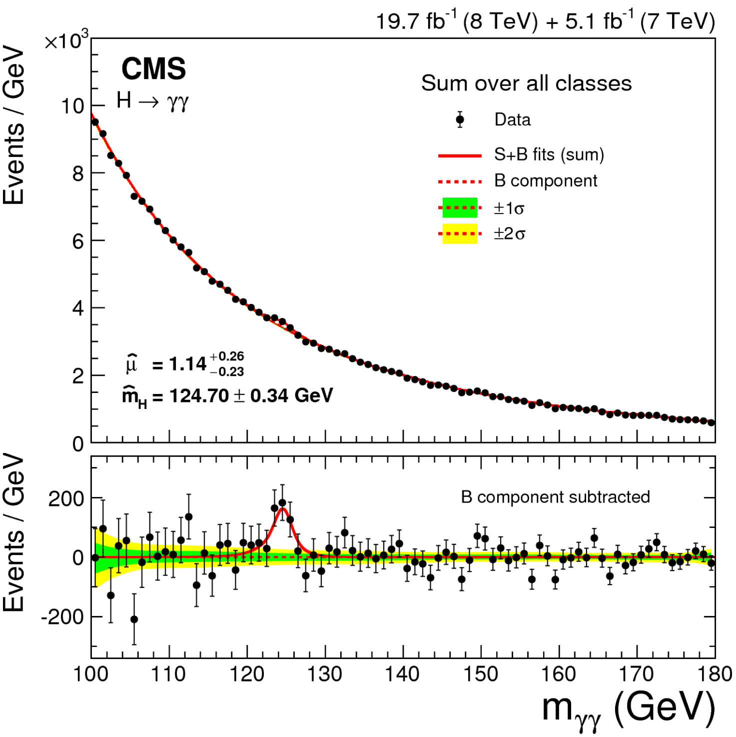
- The observed significance of the Higgs-boson like particle at ~ 125 GeV mass in the main bosonic channels establishes the new state

- The signal strengths are compatible with the SM cross-section
- Bosonic channels also provide very precise mass measurement of the new state
- The width of the new particle is tightly constraint and also consistent with SM Higgs
- Spin/parity tests of the new particle suggests it is a scalar

- All clues point strongly to SM Higgs boson

The rates of the rare decay modes $Z\gamma$ and $\gamma^*\gamma$ were constrained and analyses established

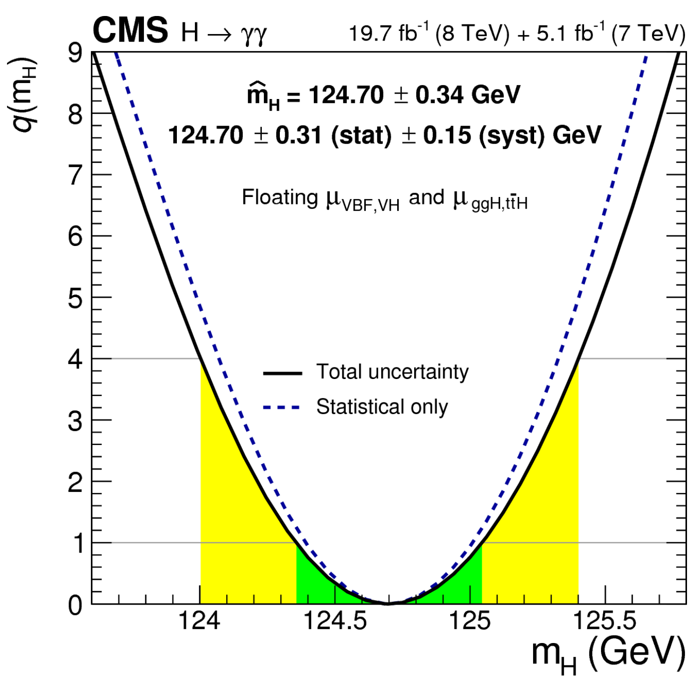
Back up

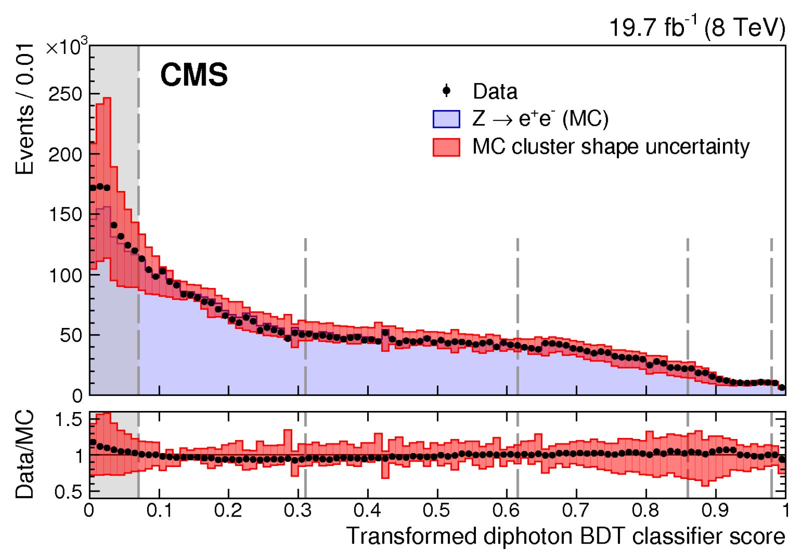


$H\rightarrow\gamma\gamma$

Source of uncertainty	Uncertainty in $\hat{\mu}$
Production cross sect. and branching frac.	0.11
Shower shape modelling (Section 9)	0.06
Energy scale and resolution	0.02
Other	0.04
All syst. uncert. in the signal model	0.13
Statistical	0.21
Total	0.25

Source of uncertainty	Uncertainty in $\hat{m}_H$ (GeV)
Imperfect simulation of electron-photon differences	0.10
Linearity of the energy scale	0.10
Energy scale calibration and resolution	0.05
Other	0.04
All systematic uncertainties in the signal model	0.15
Statistical	0.31
Total	0.35



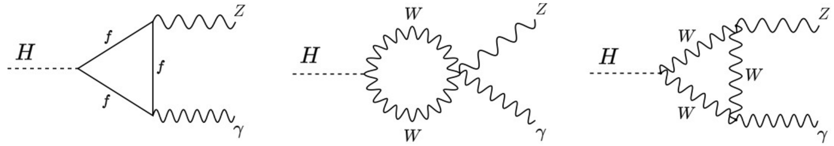


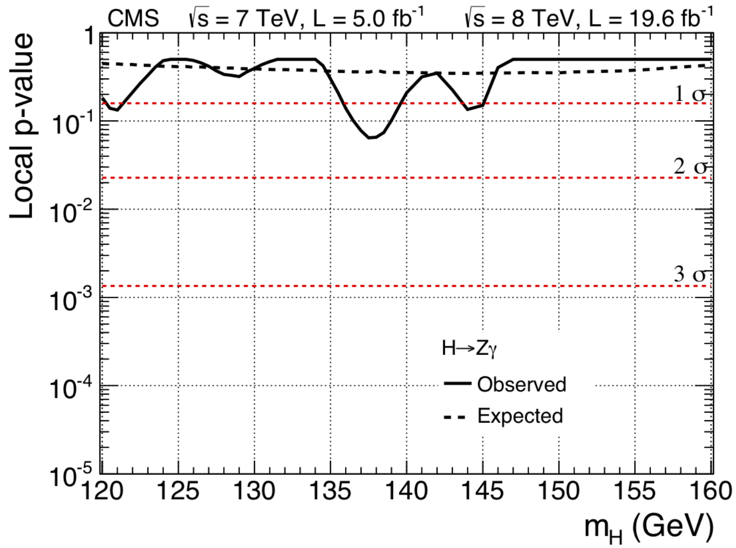
Back up

H→Zγ

Table 2: Definition of the four untagged event classes and the dijet-tagged event class, the fraction of selected events for a signal with $m_{\mathrm{H}} = 125\,\mathrm{GeV}$ produced by gluon-gluon fusion at $\sqrt{s} = 8\,\mathrm{TeV}$, and data in a narrow bin centered at 125 GeV. The bin width is equal to two times the effective standard deviation (σ_{eff}). The expected full width at half maximum (FWHM) for the signal is also listed.

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
	Event class 1	
	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons $0 < \lvert\eta\rvert < 1.44$ $R_9 > 0.94$	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 > 0.94$
Data	17%	20%
Signal	29%	33%
σ_{eff} (GeV)	1.9 GeV	1.6 GeV
FWHM (GeV)	4.5 GeV	3.7 GeV
	Event class 2	
	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons $0 < \lvert\eta\rvert < 1.44$ $R_9 < 0.94$	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 < 0.94$
Data	26%	31%
Signal	27%	30%
σ_{eff} (GeV)	2.1 GeV	1.9 GeV
FWHM (GeV)	5.0 GeV	4.6 GeV
	Event class 3	
	Photon $0 < \lvert\eta\rvert < 1.44$ At least one lepton $1.44 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $0 < \lvert\eta\rvert < 1.44$ Both leptons in $\lvert\eta\rvert > 0.9$ or one lepton in $2.1 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data	26%	20%
Signal	23%	18%
σ_{eff} (GeV)	3.1 GeV	2.1 GeV
FWHM (GeV)	7.3 GeV	5.0 GeV
	Event class 4	
	Photon $1.57 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $1.57 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data	31%	29%
Signal	19%	17%
σ_{eff} (GeV)	3.3 GeV	3.2 GeV
FWHM (GeV)	7.8 GeV	7.5 GeV
	VBF class	
	Photon $0 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $0 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data	0.1%	0.2%
Signal	1.8%	1.7%
σ_{eff} (GeV)	2.6 GeV	2.2 GeV
FWHM (GeV)	4.4 GeV	3.8 GeV





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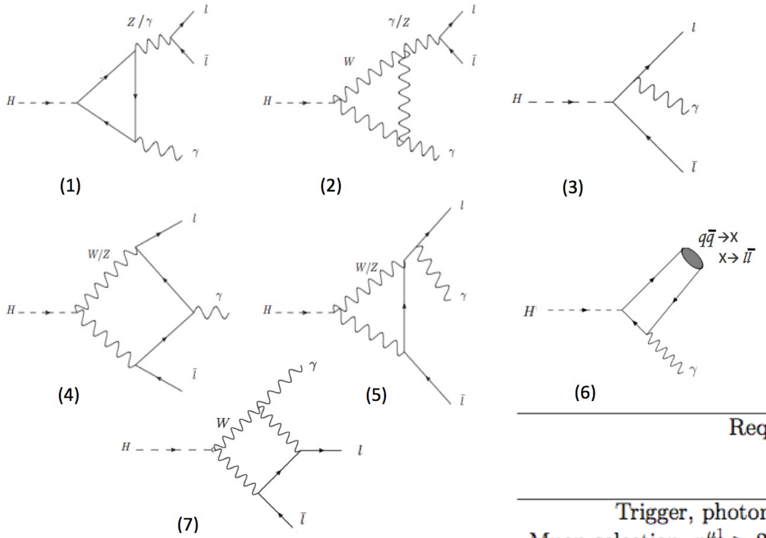
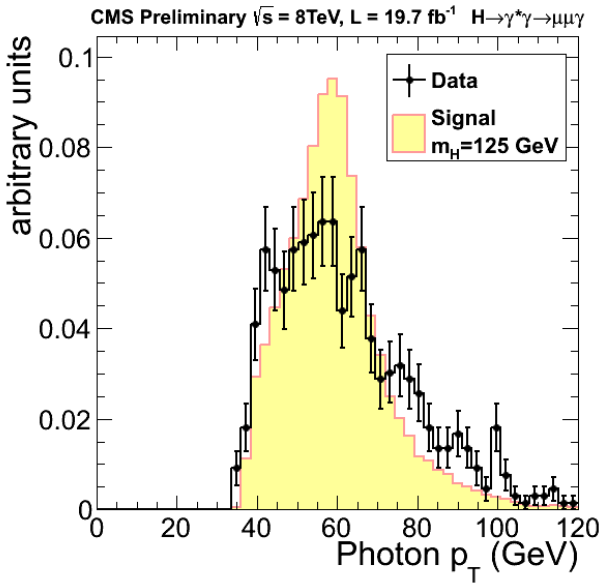
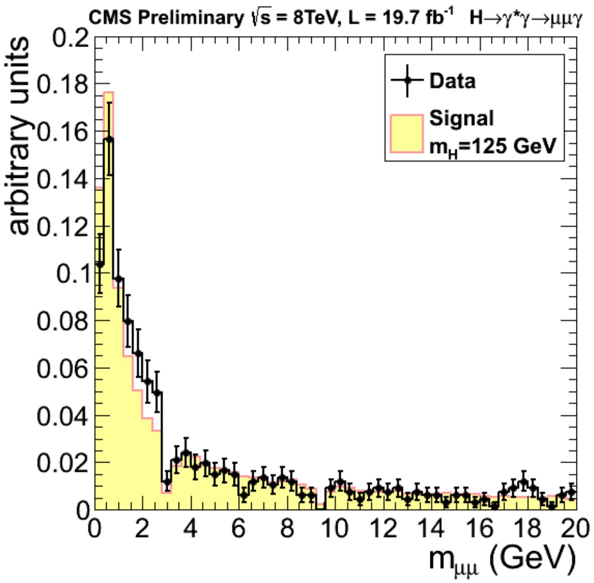
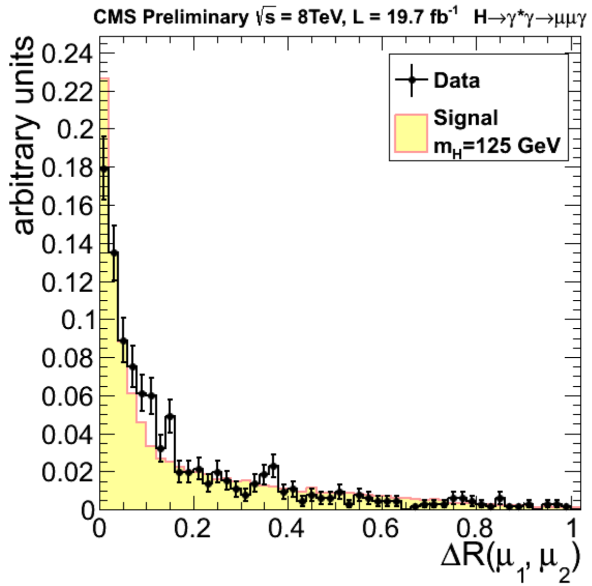
H→γ*γ

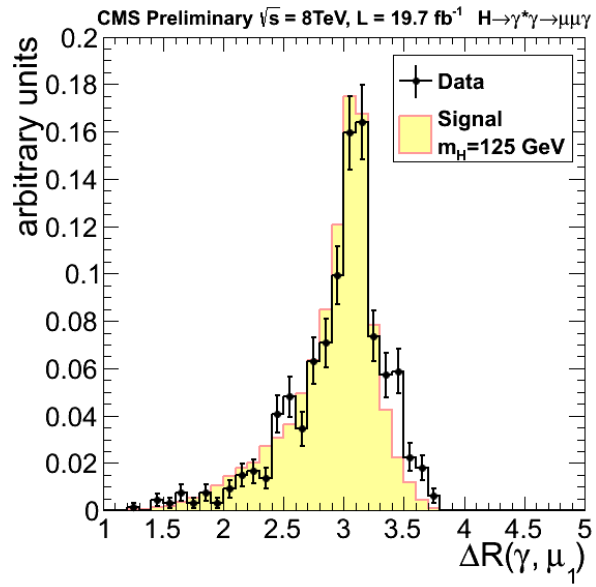




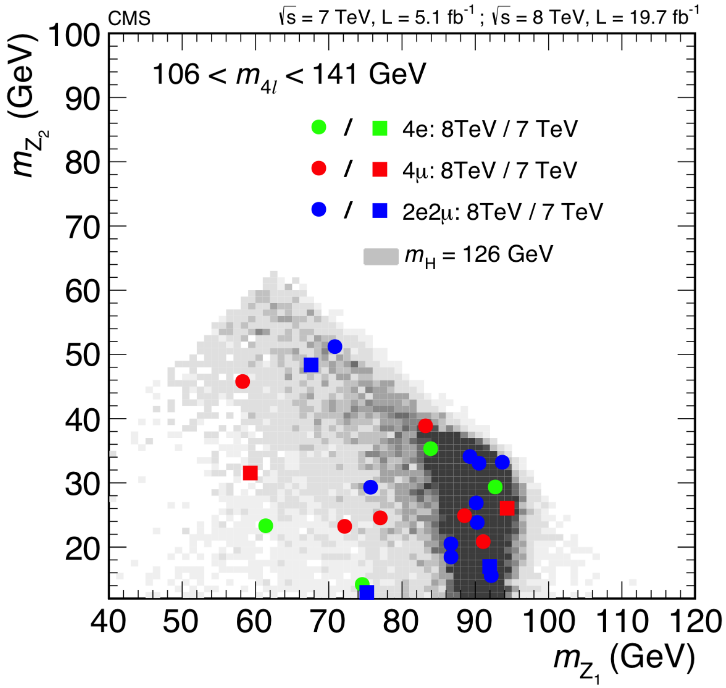
Requirement	Observed event yield	Expected number of signal events for $m_H = 125$ GeV
Trigger, photon selection, $p_T^{\gamma} > 25$ GeV	0.6M	6.2
Muon selection, $p_T^{\mu 1} > 23$ GeV and $p_T^{\mu 2} > 4$ GeV	55836	4.7
110 GeV $< m_{\mu\mu\gamma} <$170 GeV	7800	4.7
$m_{\mu\mu} < 20$ GeV	1142	3.9
$\Delta R(\gamma, \mu) > 1$	1138	3.9
Removal of resonances	1020	3.7
$p_T^{\gamma}/m_{\mu\mu\gamma} > 0.3$ and $p_T^{\mu\mu}/m_{\mu\mu\gamma} > 0.3$	665	3.3
122 GeV $< m_{\mu\mu\gamma} <$ 128 GeV	99	2.9



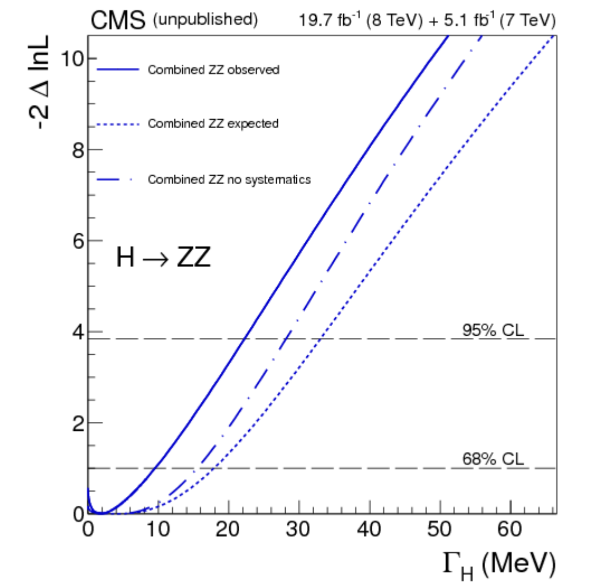


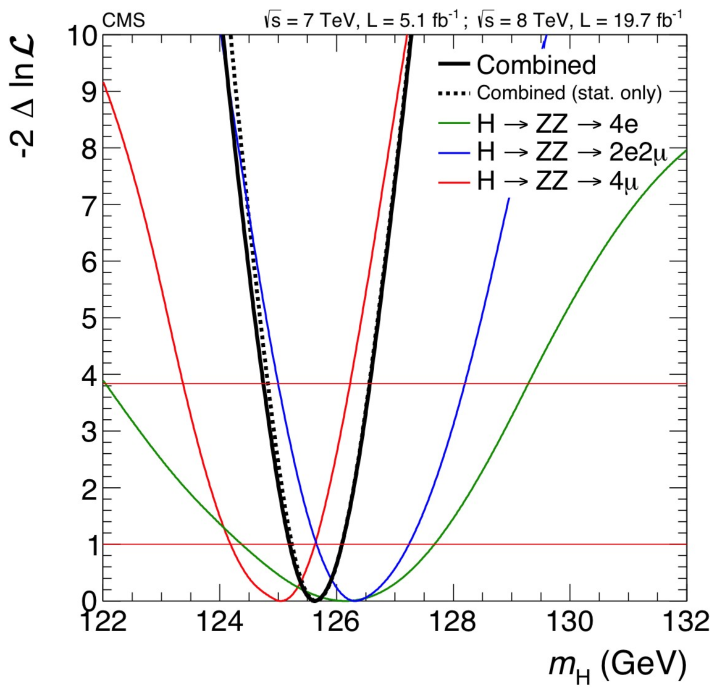


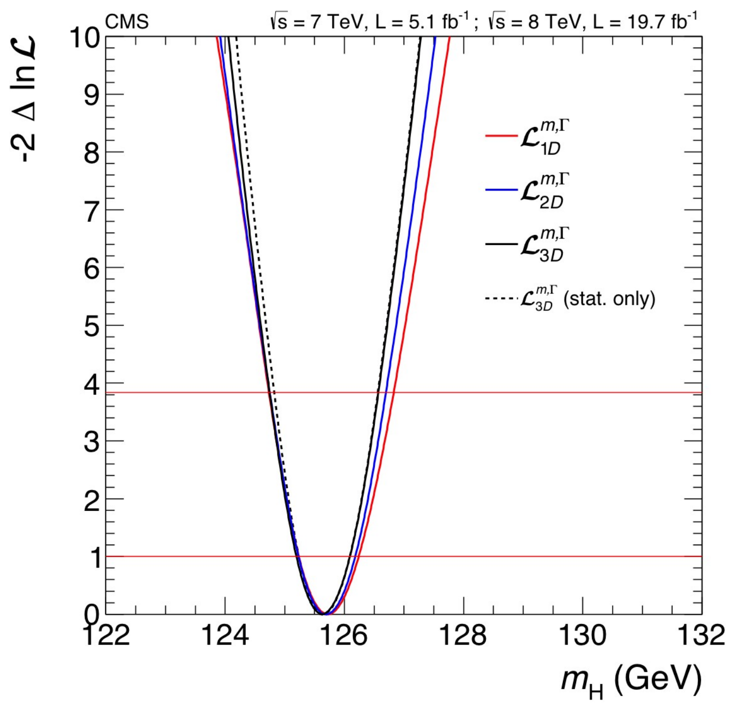
Back up

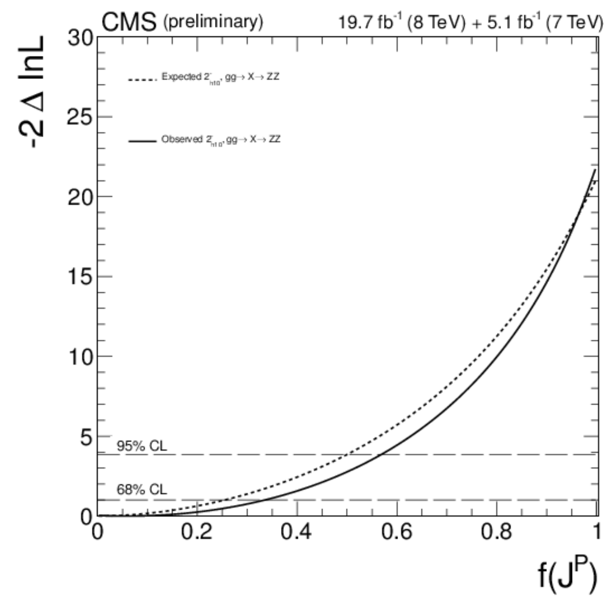

CMS
√s = 7 TeV, L = 5.1 fb⁻¹ ; √s = 8 TeV, L = 19.7 fb⁻¹
106 < m_{4l} < 141 GeV
4e: 8TeV / 7 TeV
4μ: 8TeV / 7 TeV
2e2μ: 8TeV / 7 TeV
m_H = 126 GeV
m_{Z_2} (GeV)
m_{Z_1} (GeV)

H→ZZ


CMS (unpublished)
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
Combined ZZ observed
Combined ZZ expected
Combined ZZ no systematics
H → ZZ
95% CL
68% CL
-2 Δ lnL
Γ_H (MeV)

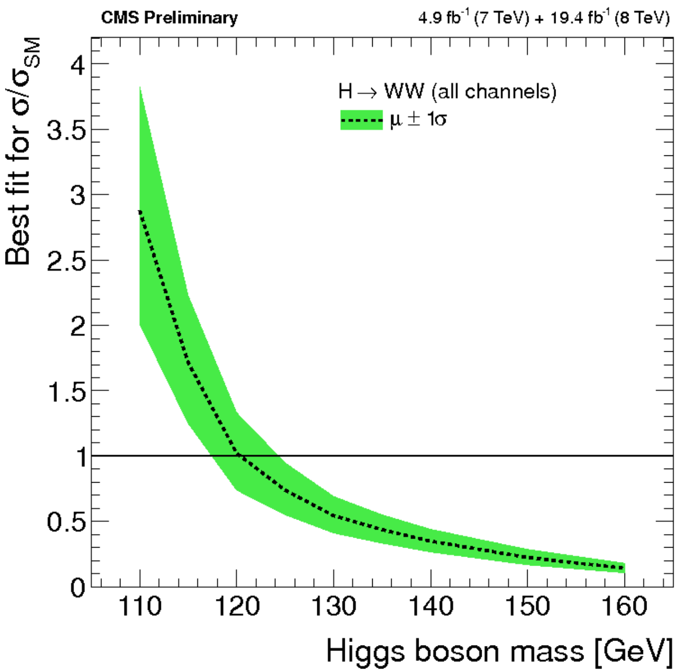

CMS
√s = 7 TeV, L = 5.1 fb⁻¹ ; √s = 8 TeV, L = 19.7 fb⁻¹
Combined
Combined (stat. only)
H → ZZ → 4e
H → ZZ → 2e2μ
H → ZZ → 4μ
-2 Δ ln $\mathcal{L}$
m_H (GeV)


CMS
√s = 7 TeV, L = 5.1 fb⁻¹ ; √s = 8 TeV, L = 19.7 fb⁻¹
$\mathcal{L}^{m,\Gamma}_{1D}$
$\mathcal{L}^{m,\Gamma}_{2D}$
$\mathcal{L}^{m,\Gamma}_{3D}$
$\mathcal{L}^{m,\Gamma}_{3D}$ (stat. only)
-2 Δ ln $\mathcal{L}$
m_H (GeV)

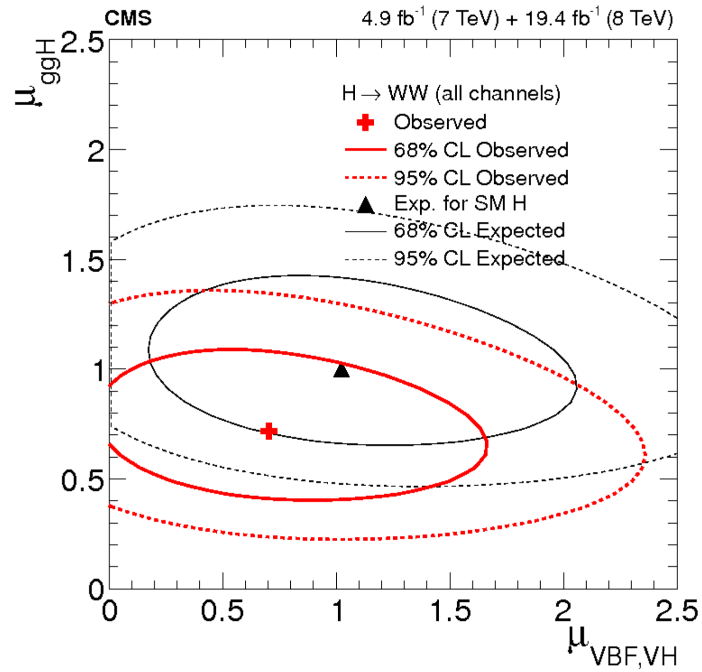

CMS (preliminary)
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
95% CL
68% CL
-2 Δ lnL
$f(J^P)$

Back up

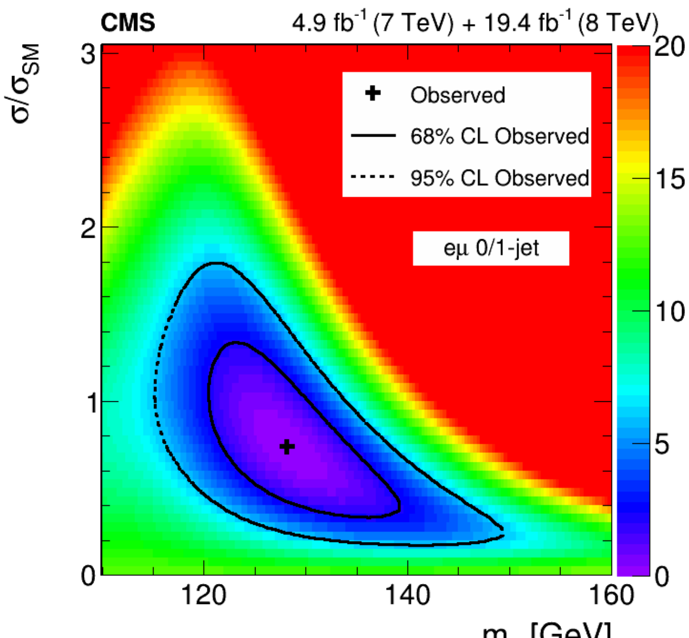
H→WW



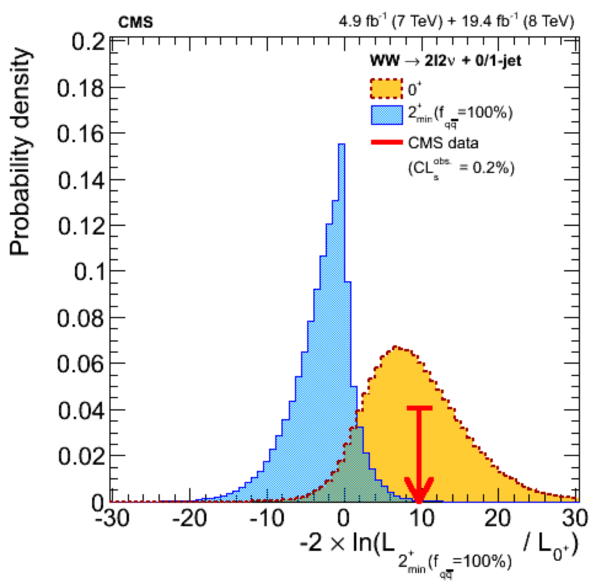
CMS Preliminary
4.9 fb-1 (7 TeV) + 19.4 fb-1 (8 TeV)
H → WW (all channels)
μ ± 1σ
Best fit for σ/σSM
Higgs boson mass [GeV]



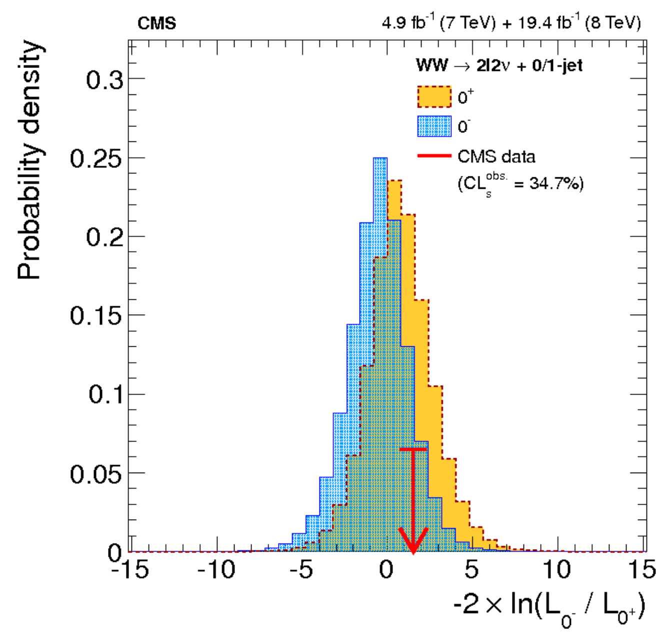
CMS
4.9 fb-1 (7 TeV) + 19.4 fb-1 (8 TeV)
H → WW (all channels)
Observed
68% CL Observed
95% CL Observed
Exp. for SM H
68% CL Expected
95% CL Expected
μggH
μVBF,VH



CMS
4.9 fb-1 (7 TeV) + 19.4 fb-1 (8 TeV)
Observed
68% CL Observed
95% CL Observed
eμ 0/1-jet
σ/σSM
mH [GeV]

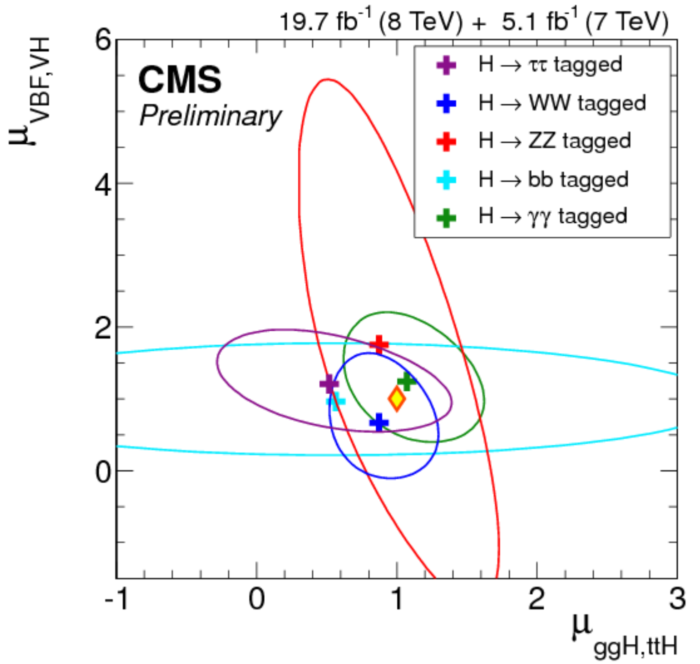


CMS
4.9 fb-1 (7 TeV) + 19.4 fb-1 (8 TeV)
WW → 2l2ν + 0/1-jet
0+
2+min(fqq̄=100%)
CMS data
(CLsobs. = 0.2%)
Probability density
-2 × ln(L2+min(fqq̄=100%) / L0+)

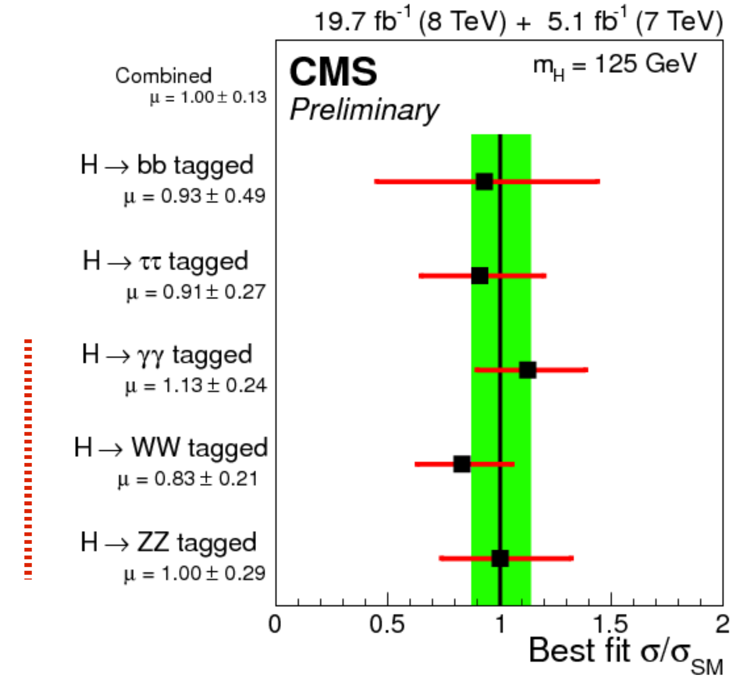


CMS
4.9 fb-1 (7 TeV) + 19.4 fb-1 (8 TeV)
WW → 2l2ν + 0/1-jet
0+
0-
CMS data
(CLsobs. = 34.7%)
Probability density
-2 × ln(L0- / L0+)

Back up

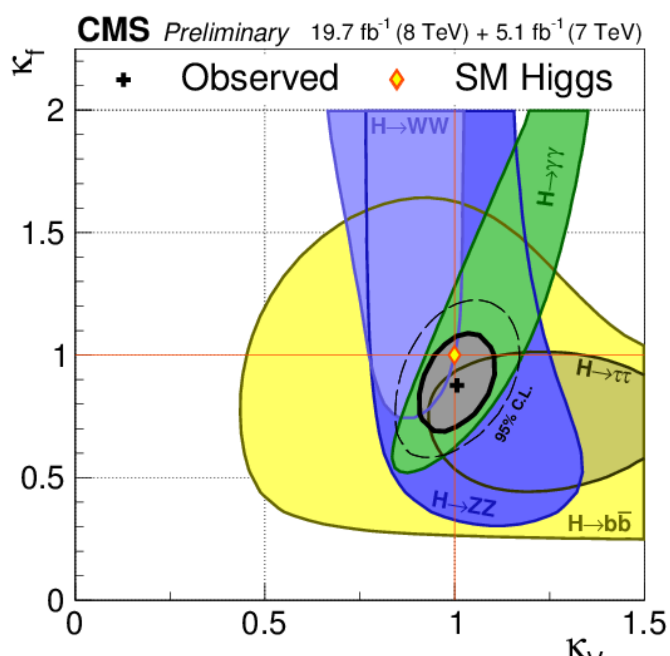


19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
Preliminary
H → ττ tagged
H → WW tagged
H → ZZ tagged
H → bb tagged
H → γγ tagged
μVBF,VH
μggH,ttH

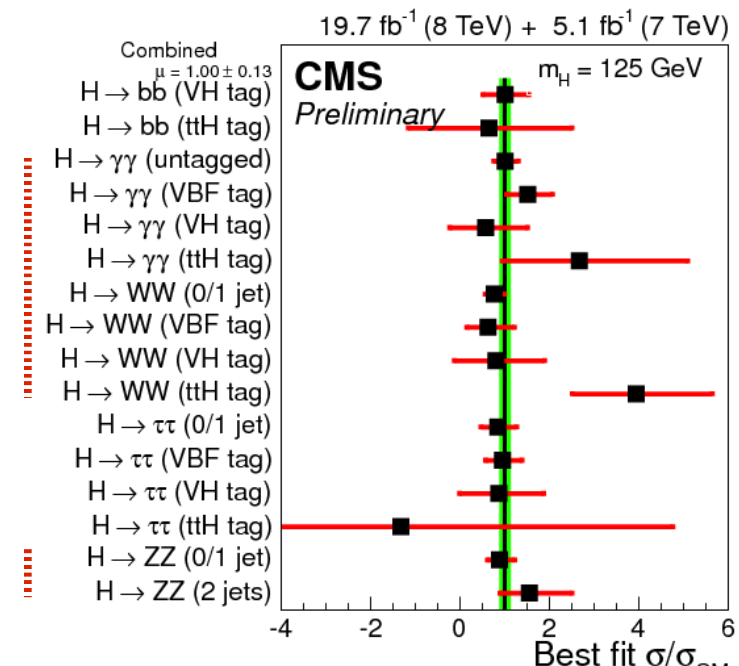


19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
Preliminary
mH = 125 GeV
Combined
μ = 1.00 ± 0.13
H → bb tagged
μ = 0.93 ± 0.49
H → ττ tagged
μ = 0.91 ± 0.27
H → γγ tagged
μ = 1.13 ± 0.24
H → WW tagged
μ = 0.83 ± 0.21
H → ZZ tagged
μ = 1.00 ± 0.29
Best fit σ/σSM

MORE



CMS Preliminary 19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
Observed
SM Higgs
H→WW
H→γγ
H→ττ
H→ZZ
H→bb̄
95% C.L.
κf
κV



19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
Preliminary
mH = 125 GeV
Combined
μ = 1.00 ± 0.13
H → bb (VH tag)
H → bb (ttH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → γγ (VH tag)
H → γγ (ttH tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → WW (ttH tag)
H → ττ (0/1 jet)
H → ττ (VBF tag)
H → ττ (VH tag)
H → ττ (ttH tag)
H → ZZ (0/1 jet)
H → ZZ (2 jets)
Best fit σ/σSM