Higgs Properties with the CMS detector

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UNIVERSITÀ DEGLI STUDI DI PADOVA

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~~Birth~~, life and death of the Higgs boson

And some extra details about the way this boson behaves.

In this talk Run1 and Run2 results:

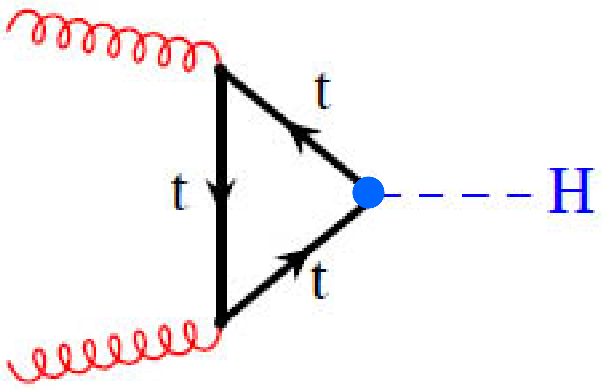
- NOT covering its birth: the production modes
  - See F. Fabozzi's talk
- Covering its diet: mass and width
- Covering how it looks like in a mirror (P) and how it spins (J)
- Covering its death: the branching ratios (couplings)

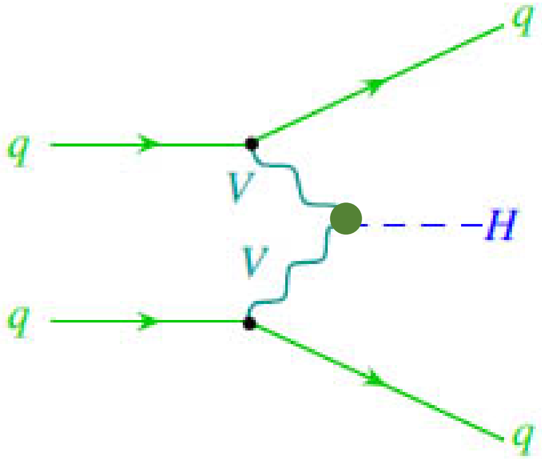
Birth(s)

Can not skip it entirely.

@13 TeV

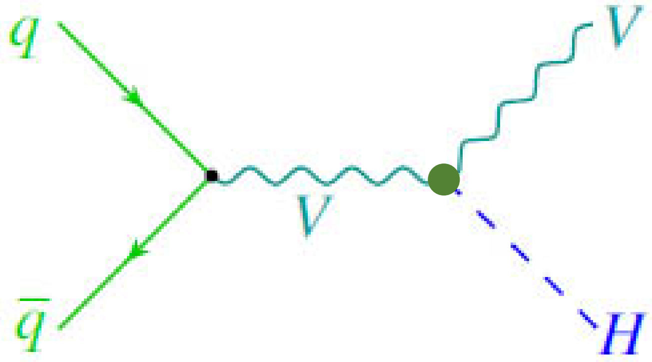
- **Gluon Fusion**
  48 pb

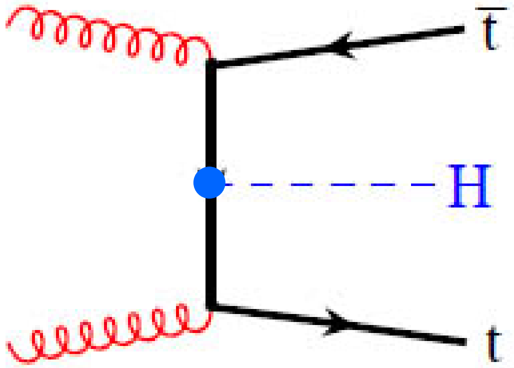




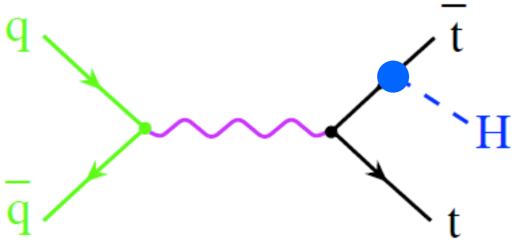
- **VBF**
  3.8 pb

- **WH, ZH**
  1.4+0.9 pb





- **ttH**
  0.5 pb



Charge, Charge conjugation, Spin, Parity

- Charge q_H: $H \to \gamma\gamma, ZZ, W^+W^-, b\bar{b}$, etc. $q_H = 0$ hypothesis seems to be slightly(!) favoured. Easy.
- Charge conjugation C_H: The C is multiplicative. We observed $H \to \gamma\gamma$, assuming C conservation, $C_H = even$. That was easy too.
- Spin and Parity: that's complicated. The short answer is that:

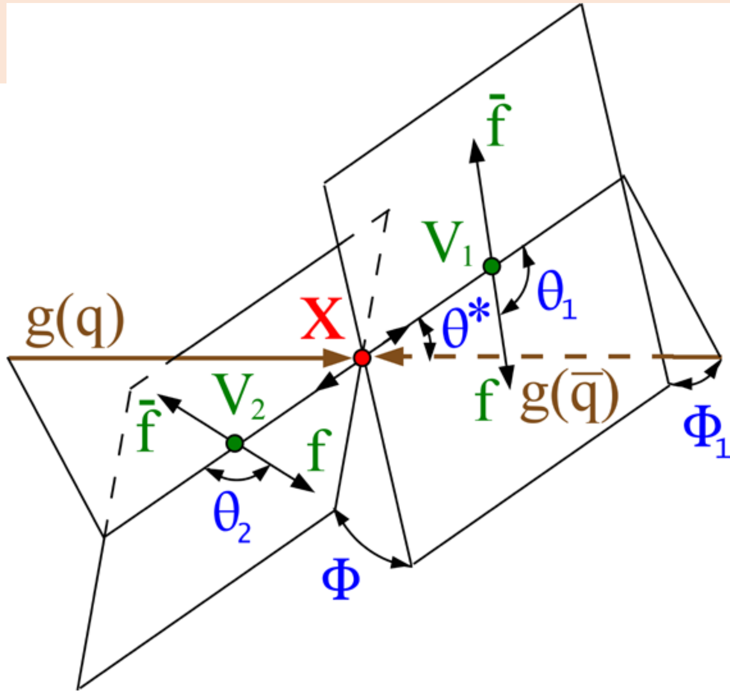
$$J^P = 0^+$$

Phys. Rev. D92, 012004 (2015).
(5+20 fb^{-1}) @ $\sqrt{s}$=7+8 TeV

Spin, Parity. The long(ish) answer

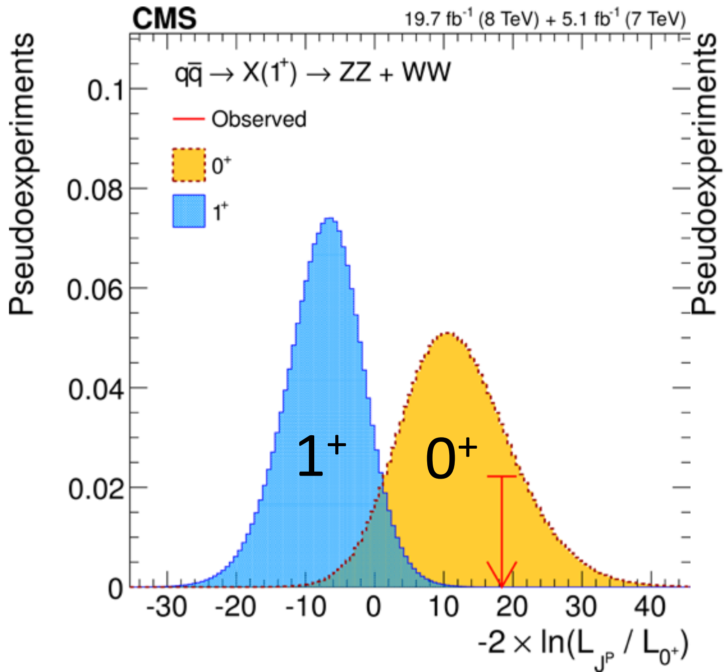
Use $H \to ZZ, Z\gamma^*, \gamma^*\gamma^* \to 4\ell$, $H \to WW \to \ell\nu\ell\nu$ and $H \to \gamma\gamma$ final states to test the HVV interactions.

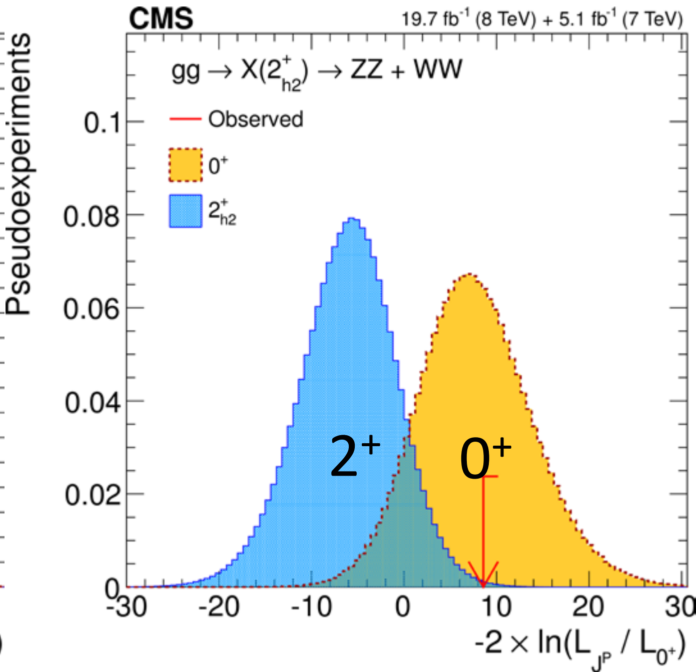
- For $H \to \cdots \to 4\ell$. The final state is described by 5 angles $\vec{\Omega} \equiv (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)$ and 3 invariant masses $m_1^{\ell\ell}, m_2^{\ell\ell}, m^{4\ell}$. Discriminant implemented in a ME approach.
- For $H \to WW \to \ell\nu\ell\nu$ two observables: $m_{\ell\ell}$ and m_T
- $H \to \gamma\gamma$ the only variable is $\cos\theta^*$ (in the Collins-Soper frame)



Extended likelihood maximized to:

- Measure the values of anomalous couplings under for $J = 0, 1, 2$ hypotheses
- Distinguish an alternative $J = 1$ *or* 2 hypothesis w.r.t. the $J = 0$ SM Higgs
  - With the test statistic $q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{0^+})$





Phys. Rev. D92, 012004 (2015).
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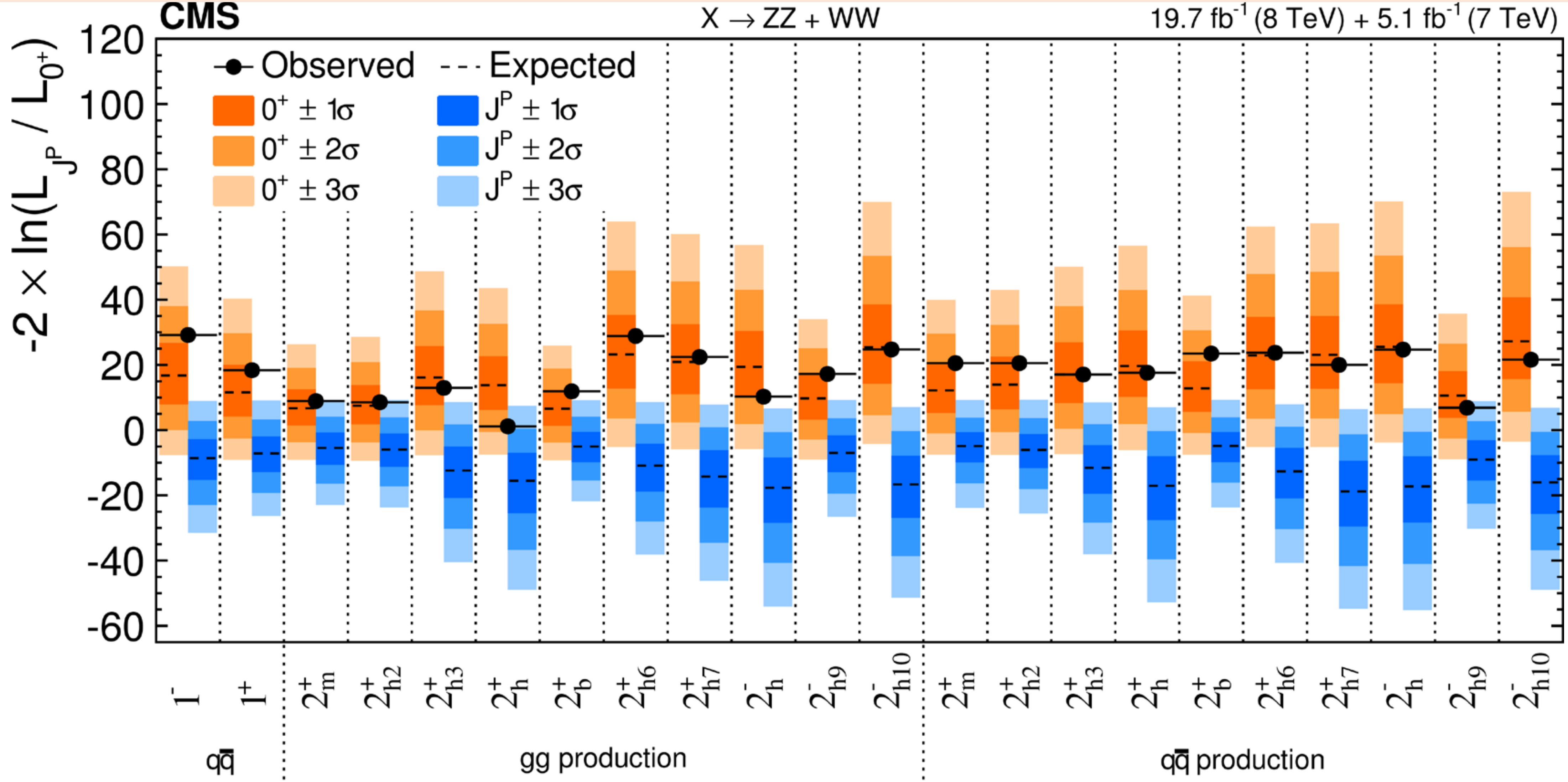
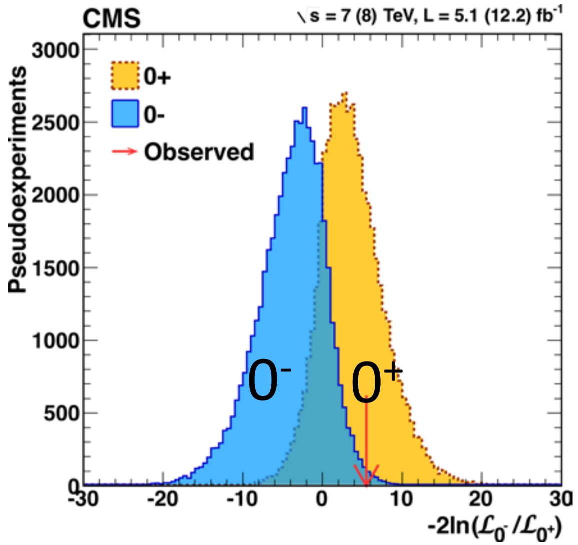
Spin, Parity. The long(ish) answer



0^- hypothesis already excluded at >95%CL w/ 12 pb^{-1} Run 1



- $J = 1$ and $J = 2$ disfavored at 98-99%CL

Diet - Γ_H

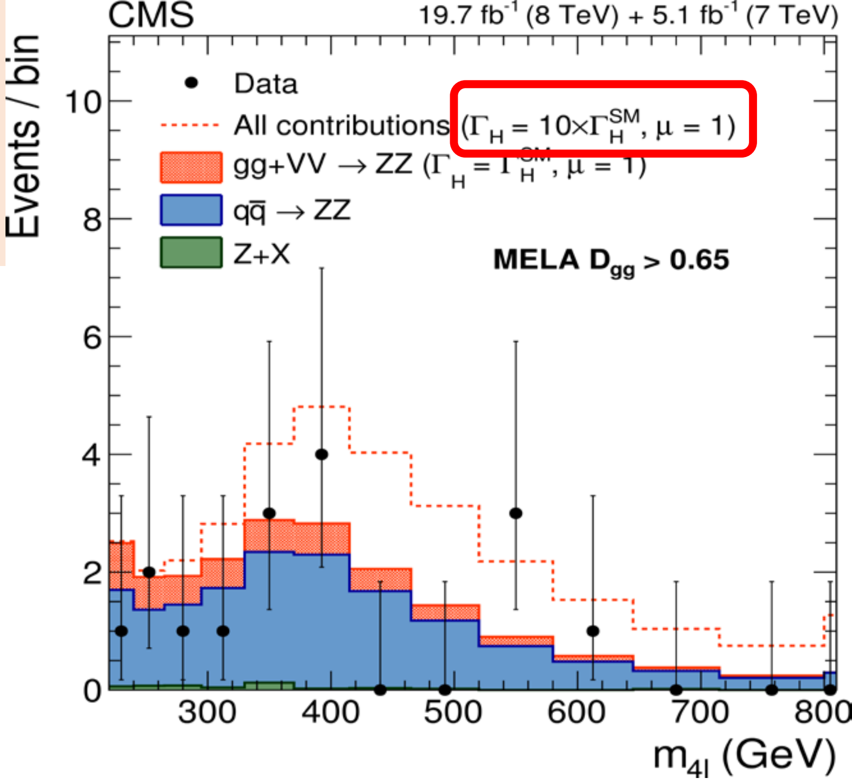
- In the SM, the Higgs boson width is very precisely predicted once the Higgs boson mass is known. For $m_H = 125.1\ GeV$, the Higgs boson has a very narrow width of $\Gamma_H = 4.2\ MeV$.
  - Dominated by the fermionic decays partial width (~75%), the vector boson modes are suppressed (~25%).
- Direct constraints on the Γ_H are much larger, O(1 GeV), than the expected natural width.
- Indirect constraints can be derived from:
  - The mass shift in the diphoton channel, where the effect of the interference between the main signal $gg \to H \to \gamma\gamma$ and the continuum irreducible background $gg \to \gamma\gamma$ is responsible for a non negligible mass shift ($\Delta m_H \sim 35 MeV$ → HL-LHC business).
  - Simultaneous on-shell and off-shell measurements in the VV channels.
    - $\sigma_{gg\to H\to VV}^{on-peak} \propto \frac{g_{ggH}^2 g_{HVV}^2}{\Gamma_H}$, while $\sigma_{gg\to H\to VV}^{off-peak} \propto g_{ggH}^2 g_{HVV}^2$

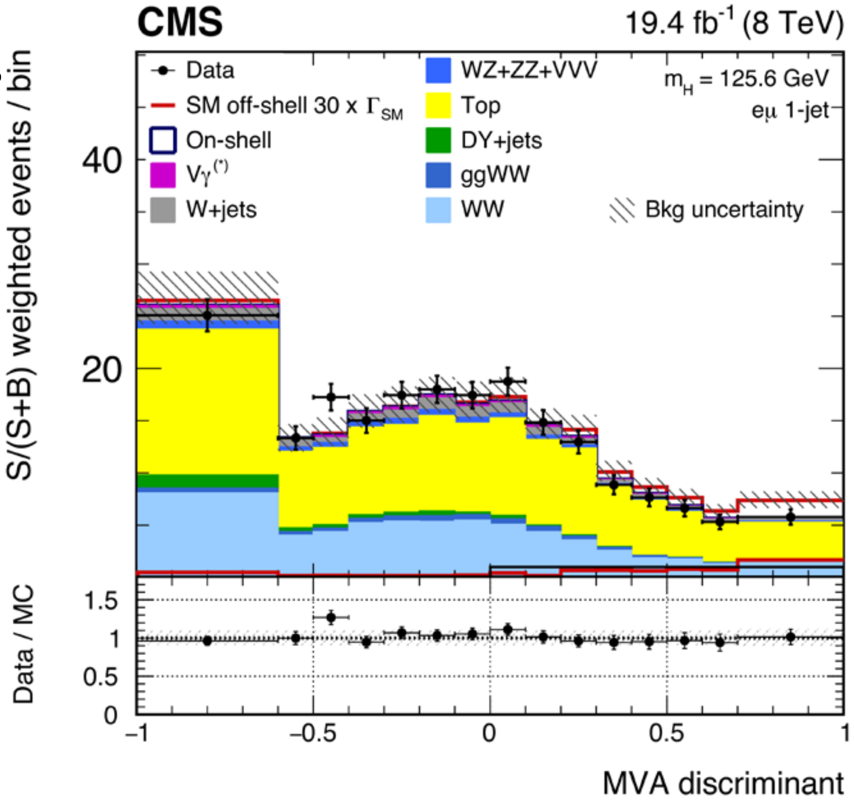
Γ_H with $H \rightarrow W^+W^-, ZZ$

CMS PAS HIG-14-032
CMS PAS HIG-14-002
(5+20 fb^{-1}) @ $\sqrt{s}$=7+8 GeV

Indirect constraint

- Assumptions:
  - The Higgs boson off- and on-shell production mechanisms are the same as in the SM and the ratio of couplings for off- and on-shell production are the SM ones.
  - There are no beyond-SM particles contributing.
  - Contributions from anomalous couplings are not considered.
- In the gluon fusion production mode: $\sigma^{off-peak}/\sigma^{on-peak} \sim 0.1$
- Final states:
  - $H \rightarrow ZZ \rightarrow 4\ell, H \rightarrow ZZ \rightarrow 2\ell 2\nu, H \rightarrow WW \rightarrow e\mu 2\nu$
    - $H \rightarrow WW$ uses also VBF production
  - Discriminators built with a ME approach (ZZ) or BDT (WW)



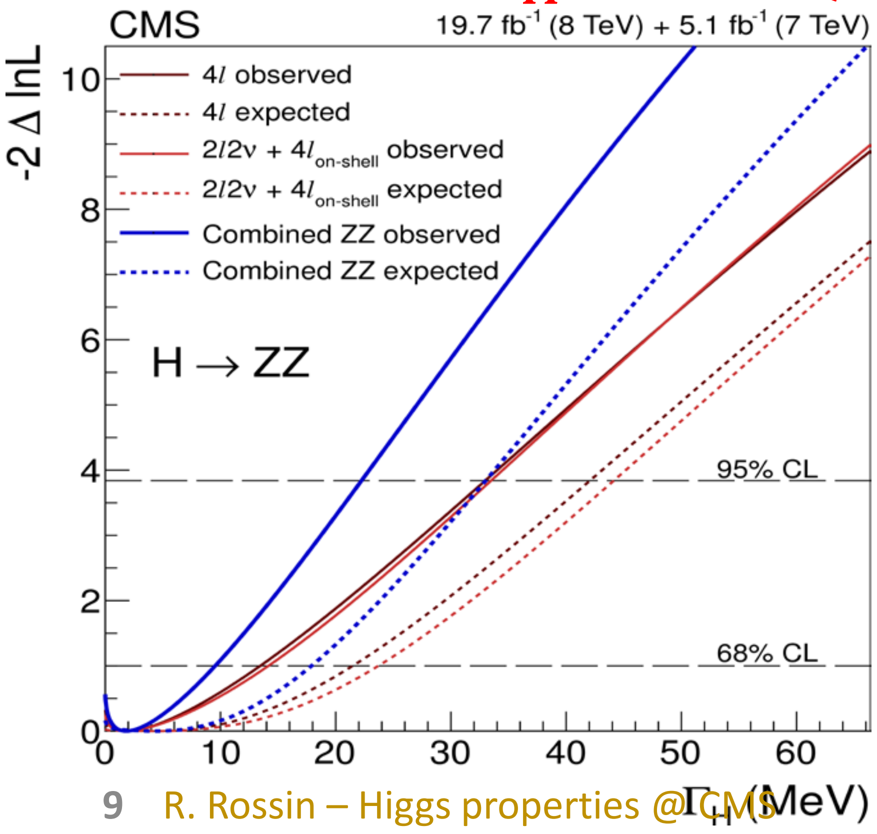


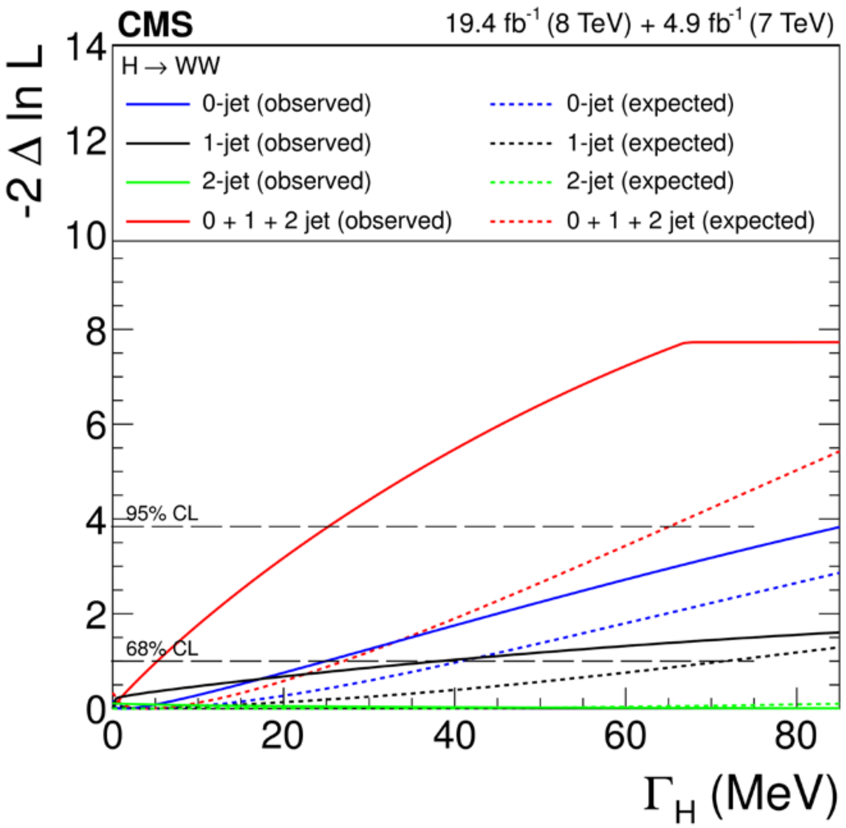
CMS PAS HIG-14-032
CMS PAS HIG-14-002
($5+20\ fb^{-1}$) @ $\sqrt{s}=7+8$ GeV

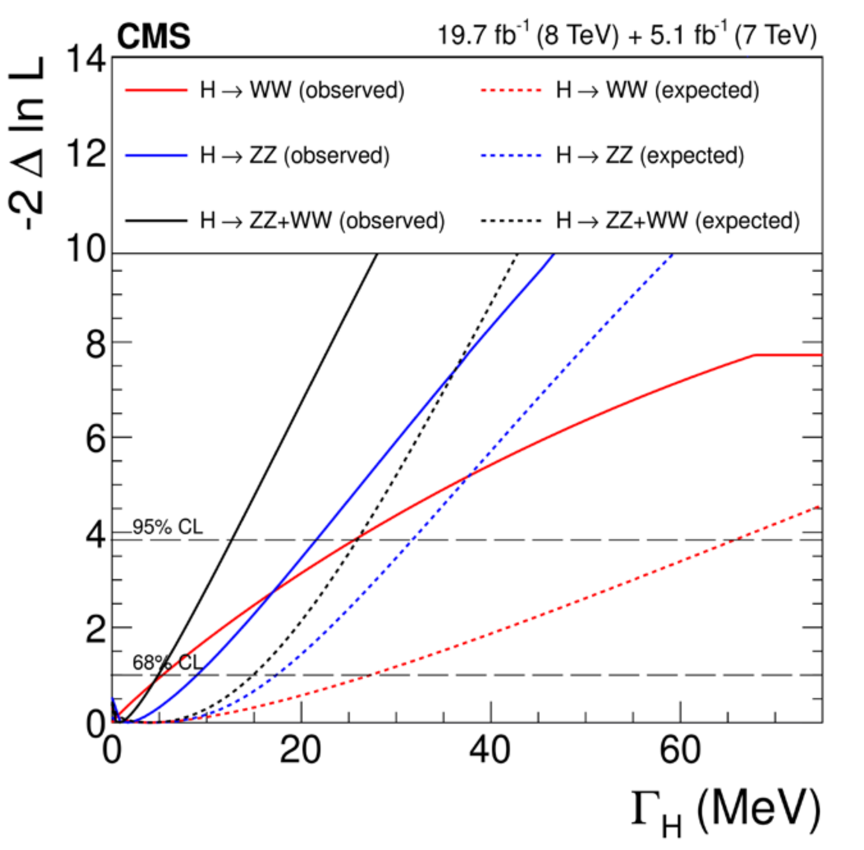
Γ_H with $H \to W^+W^-, ZZ$

- Observed (expected) limits from $H \to ZZ$: $\Gamma_H \leq 4.2\ (8.5) \times \Gamma_H^{SM}$ @ $95\% CL$
- Observed (expected) limits from $H \to WW$: $\Gamma_H \leq 6.2\ (16) \times \Gamma_H^{SM}$ @ $95\% CL$
- The combination of the two analyses provide:

$$\Gamma_H \leq 3.1\ (6.2) \times \Gamma_H^{SM} \text{ @ } 95\% CL \leftrightarrow \Gamma_H \leq 13\ (26)\ MeV$$



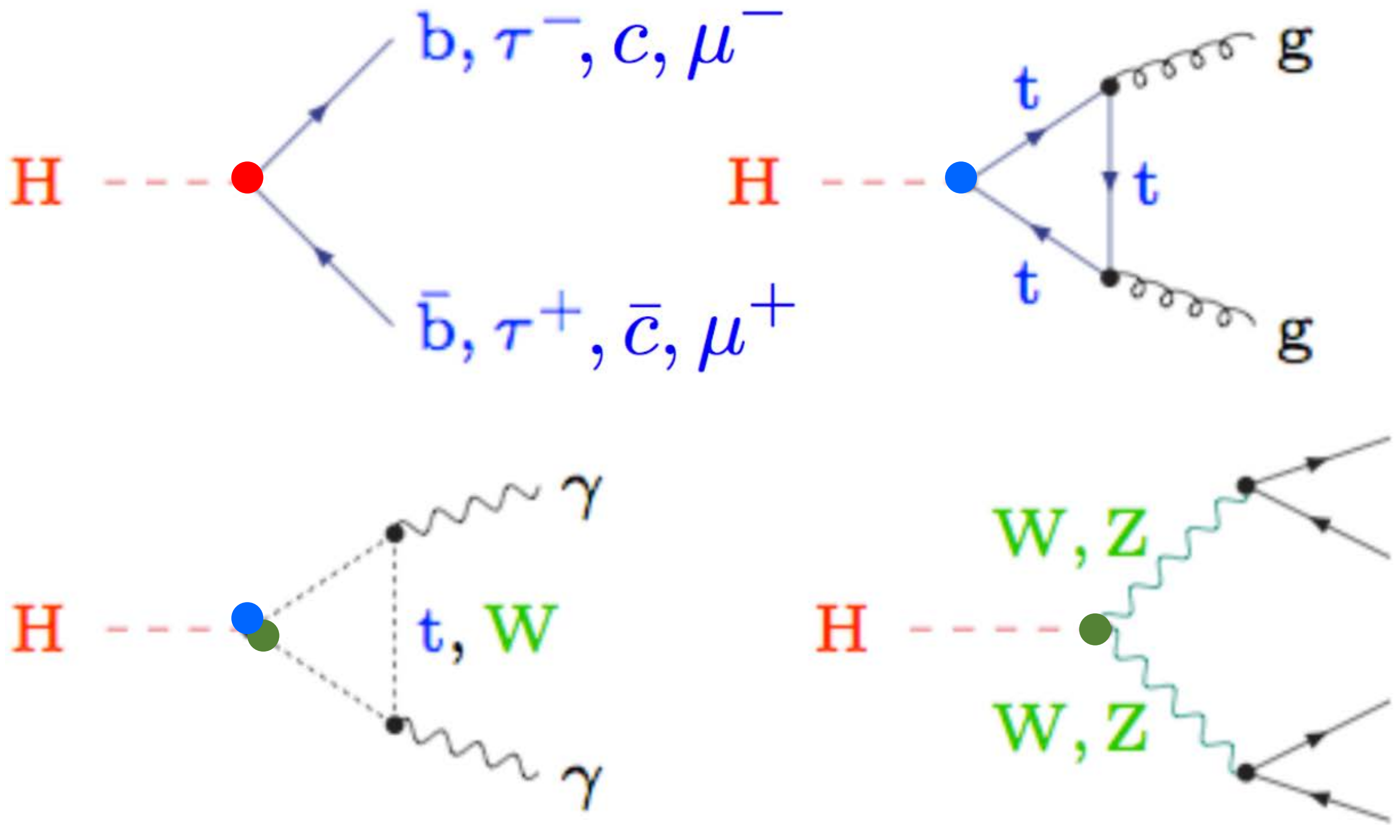




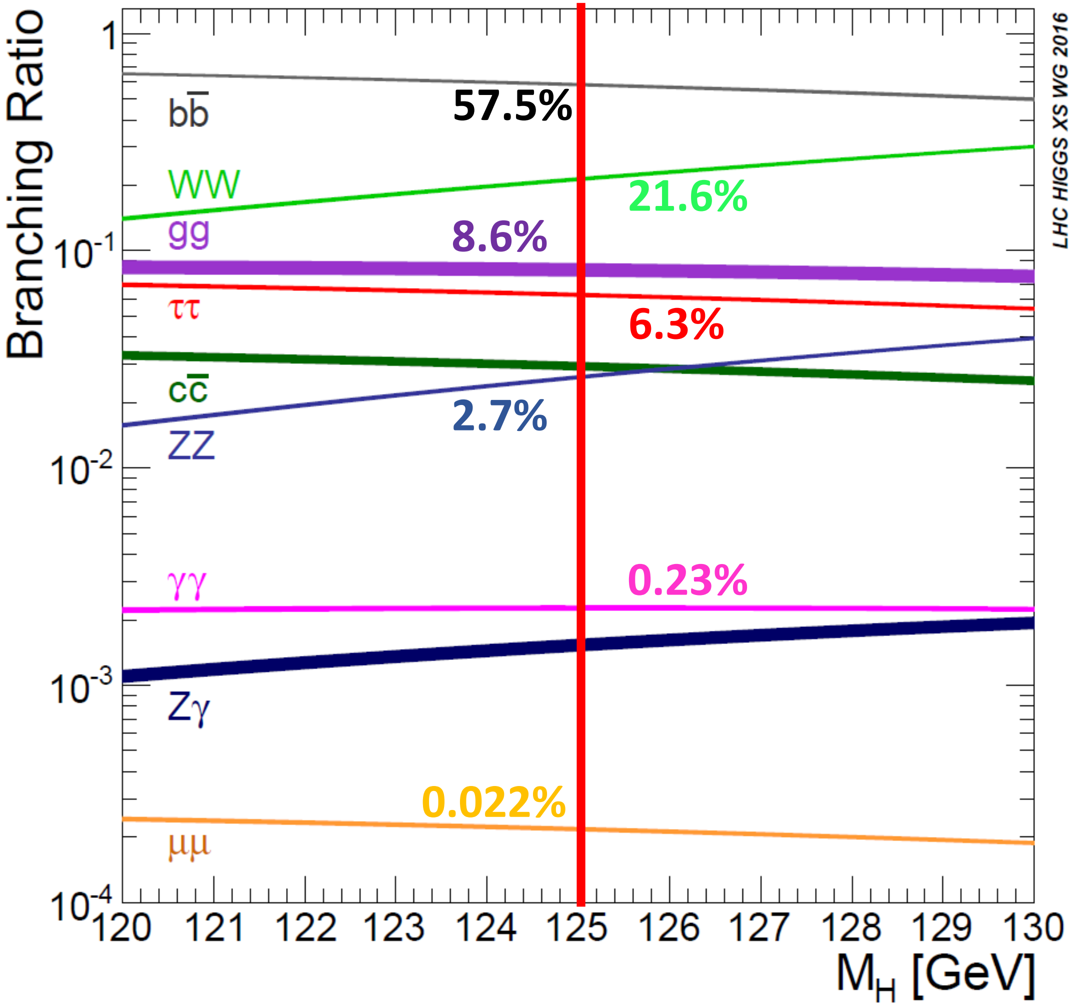
Death(s)

The decay modes are not truly independent from the production modes

- Branching ratios driven by the couplings and by kinematics



LHC Higgs Cross Section Working Group



ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002
(5+20 fb^{-1}) @ $\sqrt{s}$=7+8 TeV

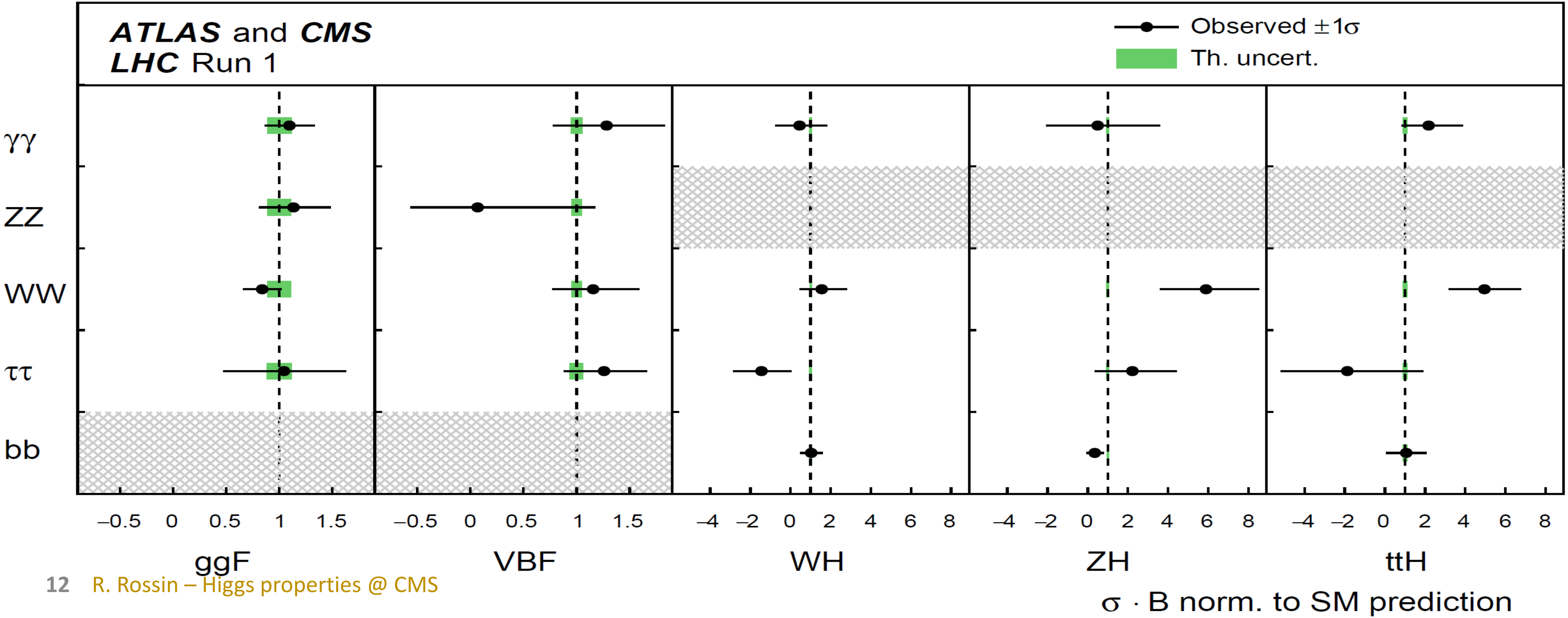
Couplings. The grand view

- In the LHC Run 1 dataset the predicted numbers of SM Higgs bosons produced per experiment are approximately 500000, 40000, 20000 and 3000 in the:
  - gluon fusion, vector boson fusion, the associated VH (WH+ZH) and ttH production modes.
- The Higgs are expected to decay through five main decay channels:
  - $\gamma\gamma, ZZ, WW, \tau^+\tau^-$ and $b\bar{b}$.
- To probe the production and decay modes individually it is necessary to **combine the analysis channels together.**
  - The total cross section is hard to measure for the production modes separately. As a consequence, neither the absolute branching fractions nor the total natural width of the Higgs boson can be directly measured.

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002
(5+20 fb^{-1}) @ $\sqrt{s}$=7+8 TeV

Couplings. The grand view

Of the 25 possible combinations of production and decay modes in the main channels, the fit to ATLAS and CMS data allows the measurement of 20.

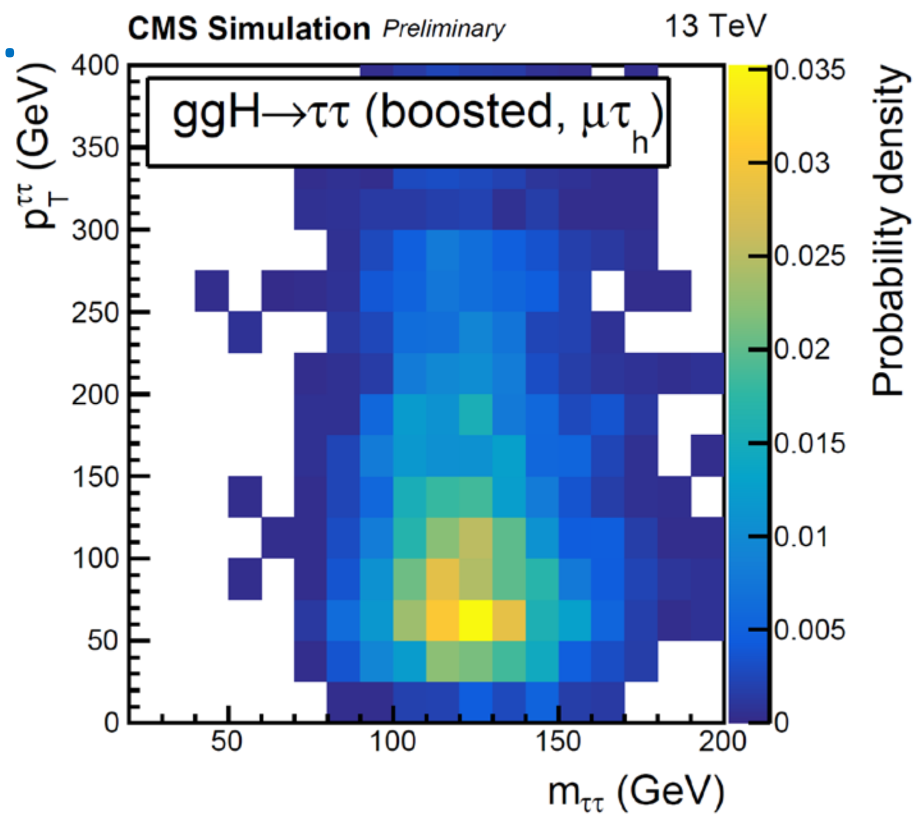


CMS PAS HIG-16-043 (36 fb^{-1})
NEW

Couplings with $H \rightarrow \tau\tau$

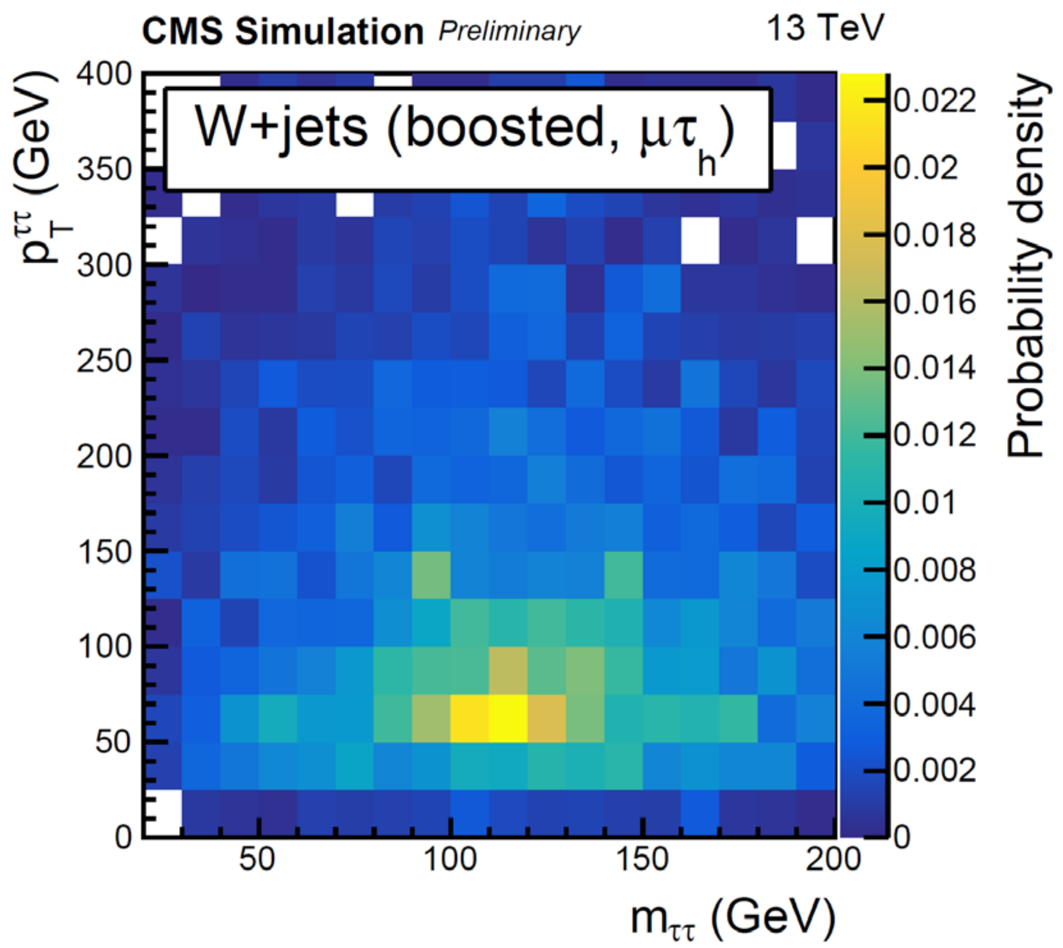
The Higgs boson is responsible for the mass generation mechanism for fermions, so it should be coupled to them.

- The decay channel $\tau\tau$ is the most promising because of its large BR (6.3%) and smaller background (w.r.t. $b\bar{b}$)
- Four exclusive τ-pair final states with the largest BRs.
  - $\mu\tau_h, e\tau_h, \tau_h\tau_h, e\mu$
- Three mutually exclusive categories per final state
  - 0-jet to constrain backgrounds (for ggH)
  - 2-jets for VBF
  - boosted (1 or more jets) for $ggH + jets$, captures VBF w/ escaping jet, VH with $V \rightarrow jj$



Couplings with $H \to \tau\tau$

- Largest irreducible background: Drell–Yan production of $Z/\gamma^* \to \tau\tau, \ell\ell$
  - MC predicted, calibrated on data
- Background from $W + jets$ production contributes to the $e\tau_h$ and $\mu\tau_h$ channels when $W \to \ell\nu$ and a jet is misidentified as a τ_h.
- The $t\bar{t}$ production is one of the main backgrounds in the $e\mu$ channel.
  - $W + jets$ and $t\bar{t}$ are modelled by simulation, yield is taken from data
- QCD multijet important in the $\ell\tau_h$ and $\tau_h\tau_h$
  - Predicted from SS and low-Iso regions

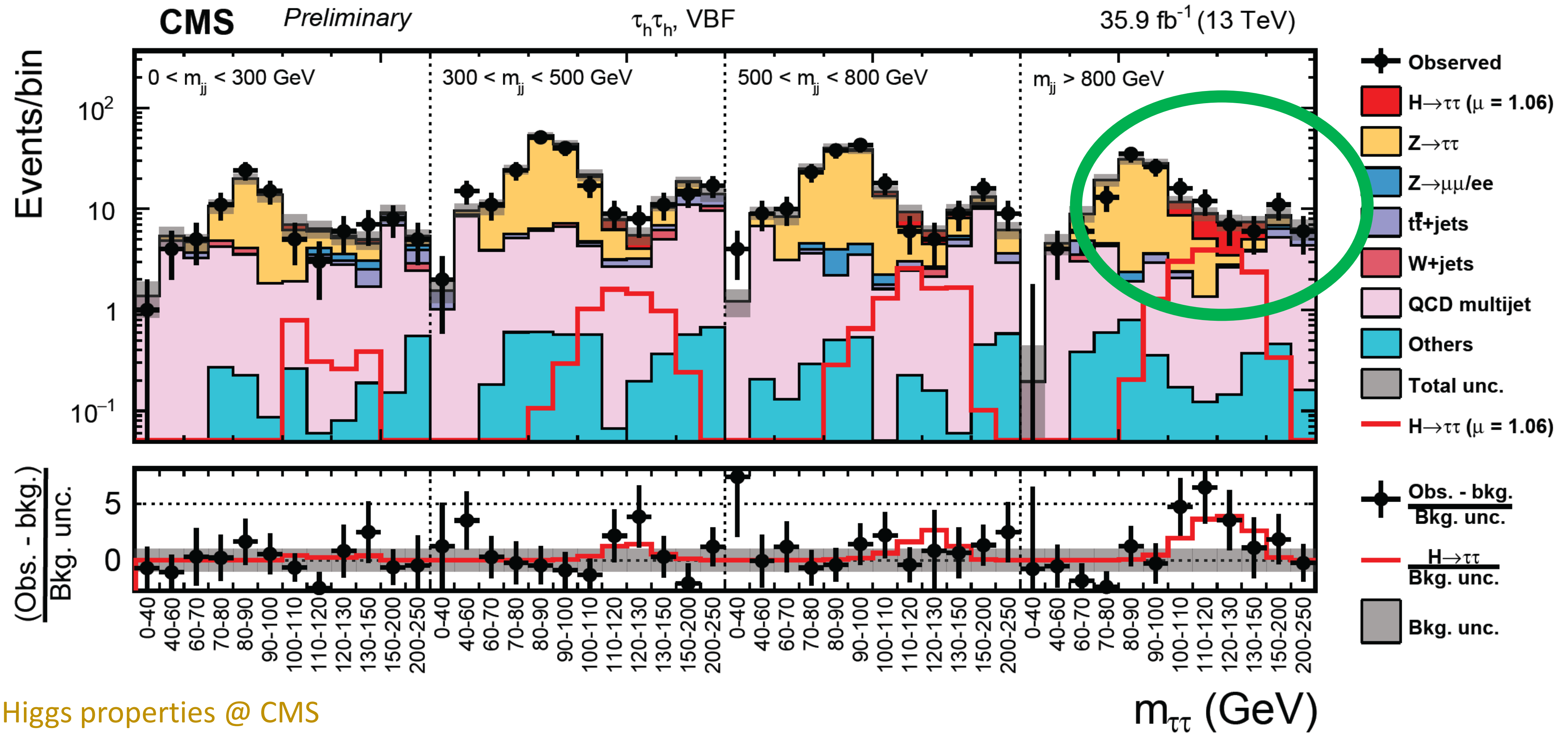


CMS PAS HIG-16-043 (36 fb^{-1})

NEW

Couplings with $H \rightarrow \tau\tau$

- The $H \rightarrow \tau\tau$ **signal** is estimated using a global maximum likelihood fit on two-dimensional distributions in all channels, together with control regions for the $t\bar{t}$, QCD multijet, and $W + jets$ backgrounds.



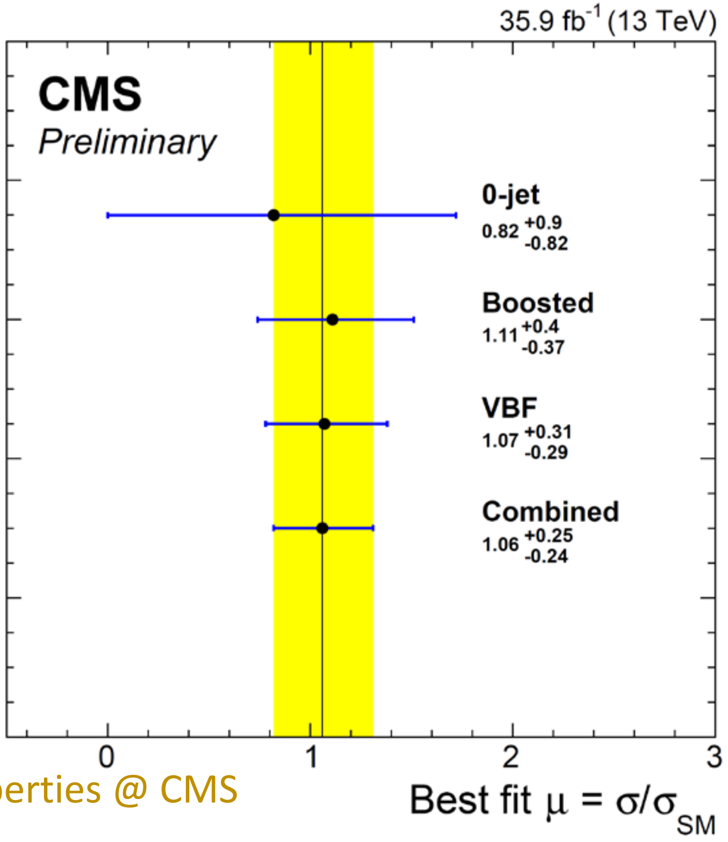
Couplings with $H \rightarrow \tau\tau$

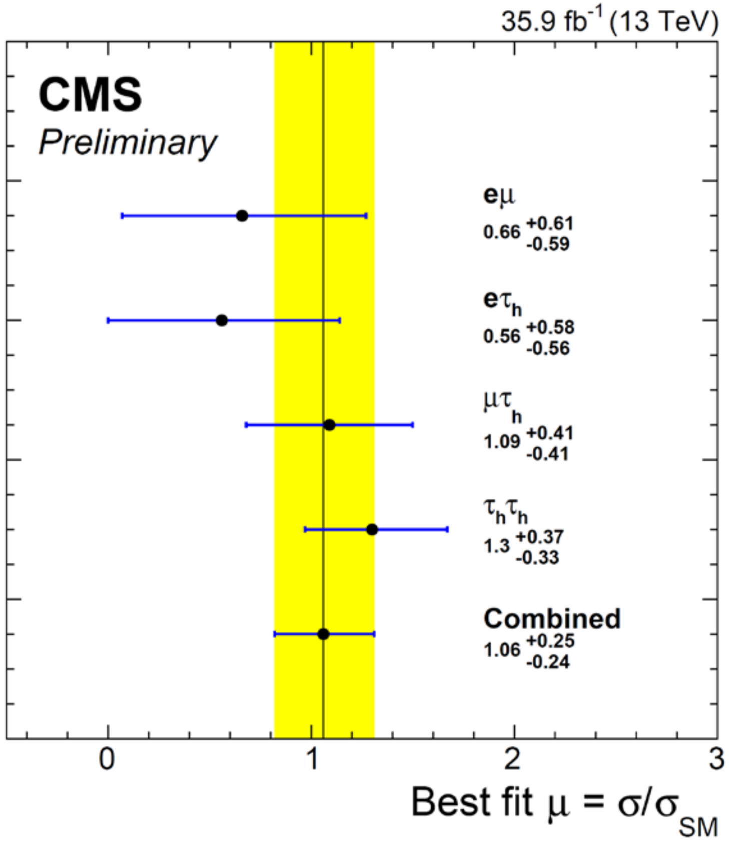
The signal yield is parameterized by the signal strength modifier $\boldsymbol{\mu}$ (a free parameter in the fit) to the SM production $\sigma^{prod} * BR(H \rightarrow \tau\tau)$.

- The corresponding best-fit value for the signal strength μ is

$$\hat{\mu} = 1.06^{+0.11}_{-0.09}(th.)^{+0.12}_{-0.12}(bbb.)^{+0.13}_{-0.12}(syst.)^{+0.15}_{-0.15}(stat.) = 1.06 \pm 0.25$$

Best-fit signal strength per category, for $m_H = 125\ GeV$



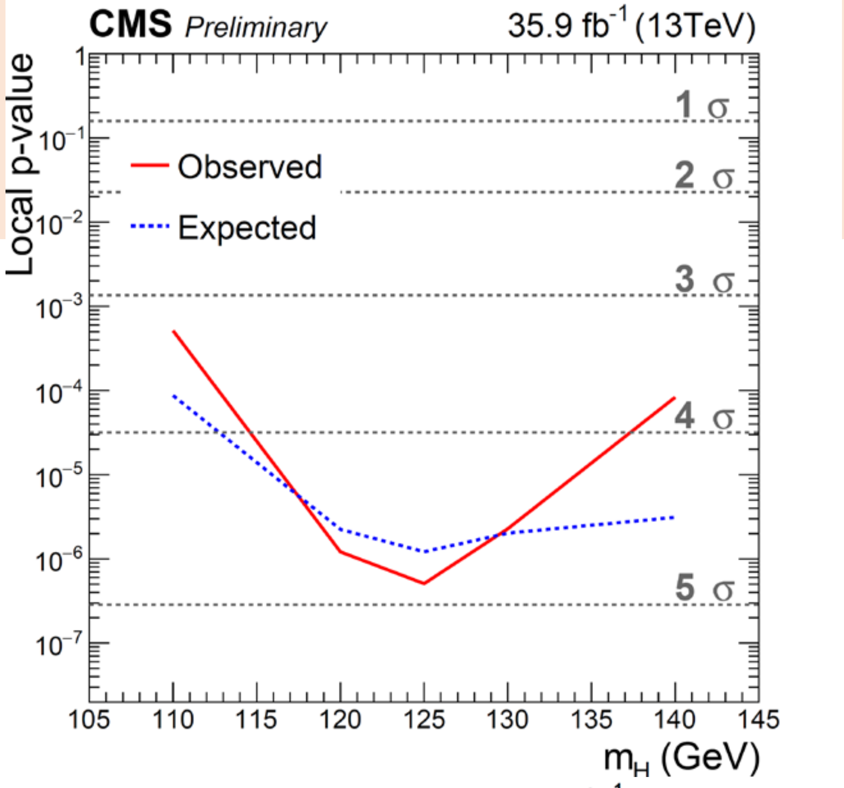


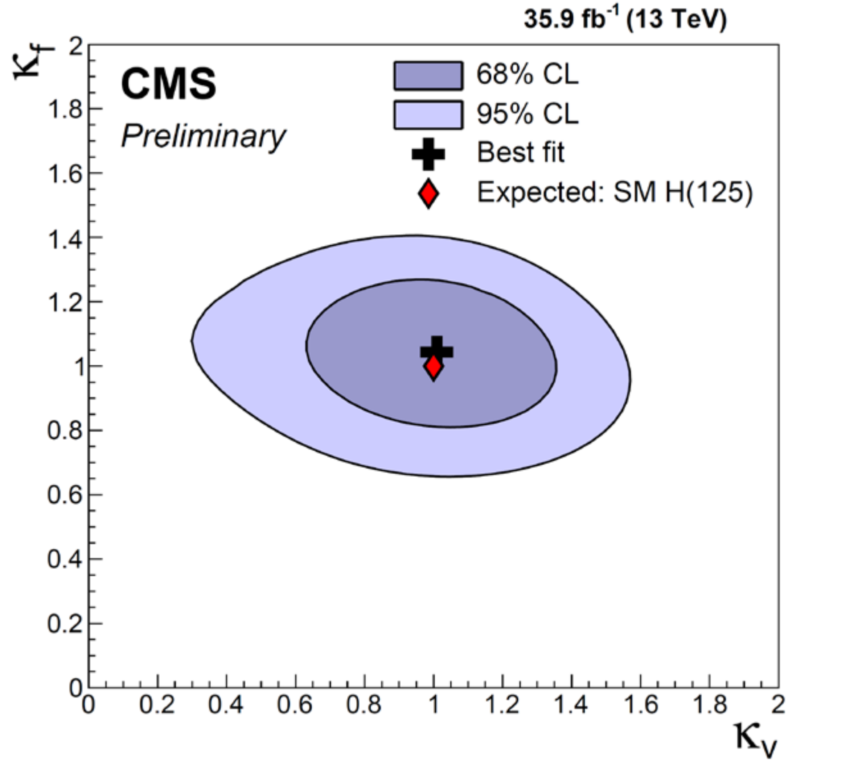
Best-fit signal strength per channel, for $m_H = 125\ GeV$

CMS PAS HIG-16-043 (36 fb-1)
NEW

Couplings with $H \rightarrow \tau\tau$

- The signal excess in data is evaluated using a profile-likelihood ratio test statistics and corresponds to an observed significance of 4.9σ (4.7σ expected).
- A likelihood scan is also performed (for $m_H = 125\ GeV$) in the (k_V, k_f) parameter space,
  - k_V and k_f quantify, respectively, the ratio between the measured and the SM value for the couplings of the scalar boson to vector bosons and fermions.
  - For this scan, scalar boson decays to pairs of W bosons are considered as part of the signal.
- Consistent with the SM expectation





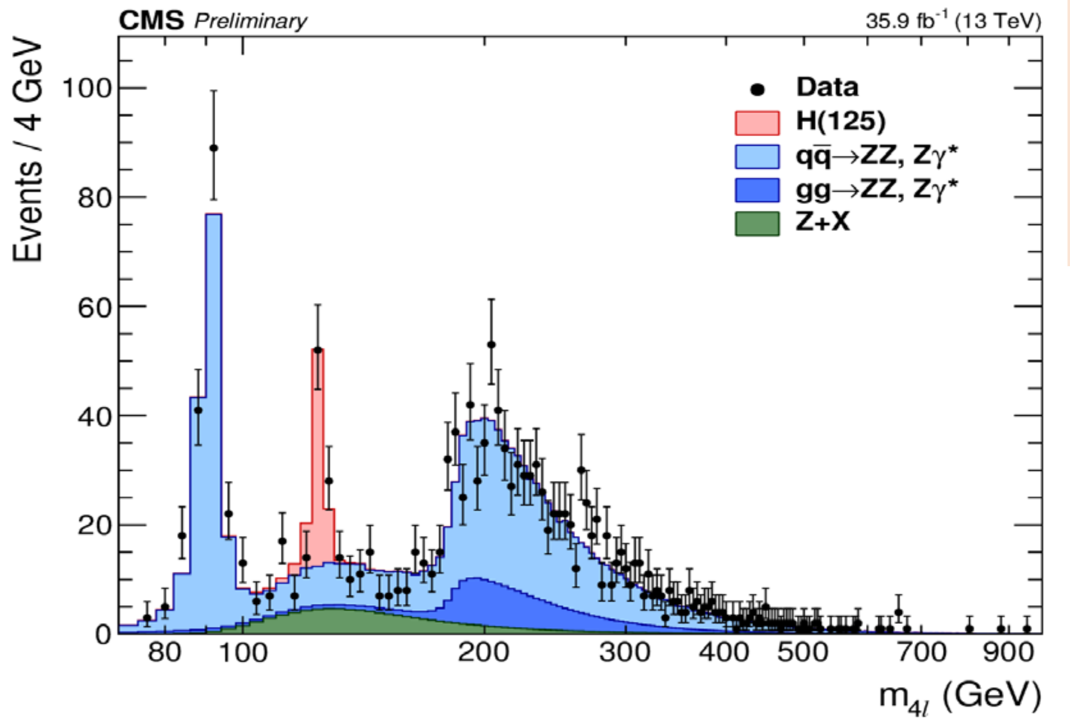
Couplings with $\boldsymbol{H \to ZZ \to \ell\ell\ell\ell}$

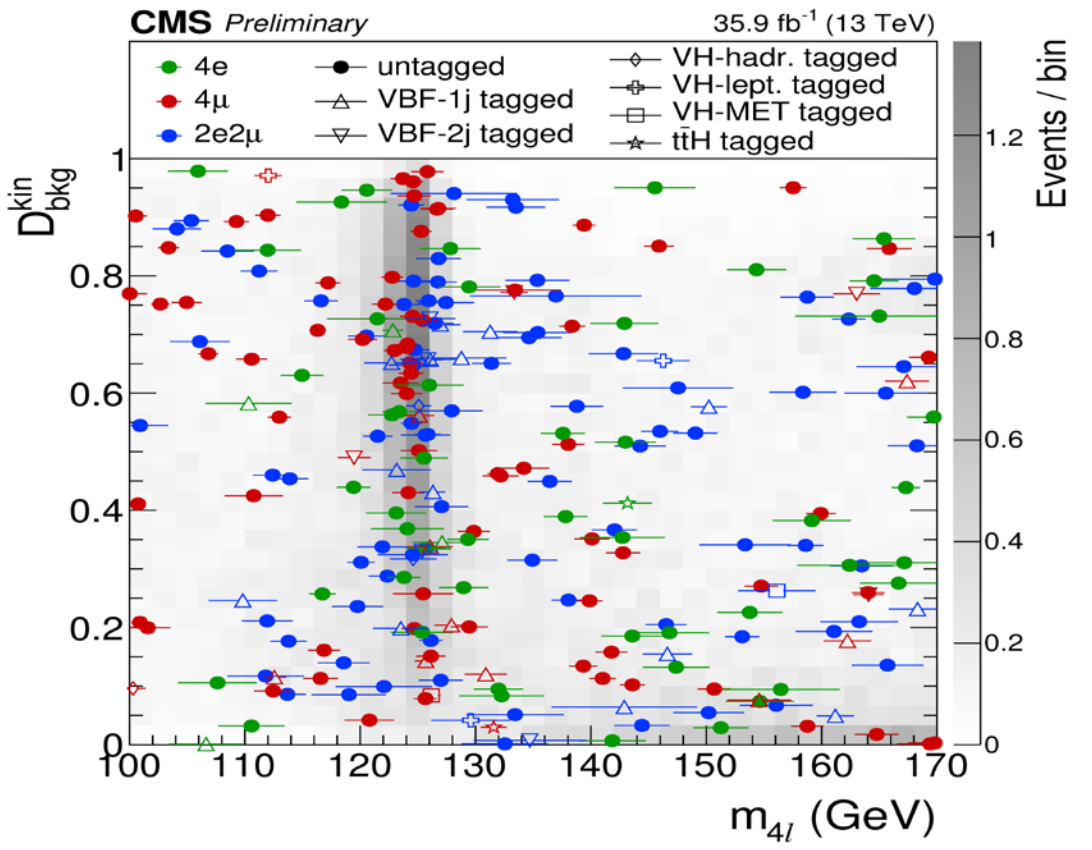
- The $H \to ZZ \to 4\ell$ decay channel ($\ell = e, \mu$) has a large signal-to-background ratio due to the complete reconstruction of the final state decay products and excellent lepton momentum resolution.
- This makes it one of the most important channels for studies of the Higgs boson's properties.
- Five production modes considered:
  - $ggH, VBF, WH, ZH, t\bar{t}H$
  - Events classified in 7 exclusive categories:
    - $VBF-2jet, VBF-1jet, VH_{leptonic}, VH_{hadronic}, VH_{MET}, t\bar{t}H, ggH$
- Final states with at least 4 leptons. 3 categories: $4e$, 4μ and $2e2\mu$
  - And possibly FSR photons

Couplings with $H \to ZZ \to \ell\ell\ell\ell$

- The irreducible backgrounds: via $gg \to ZZ$ or $q\bar{q} \to ZZ$
  - Estimated using simulation.
- The reducible backgrounds: arise mainly from $Z + jets$, $t\bar{t} + jets$, $Z\gamma + jets$, $WW + jets$ and $WZ + jets$ (collectively called $Z + X$)
  - Estimated from (OS and SS) control regions.
- Signal(s) and backgrounds fit with 2D templates in the 21 categories
  - The 2 variables are $m_{4\ell}$ and a background discriminator $\mathcal{D}_{bkg}^{kin}$ built from the $gg/q\bar{q} \to ZZ$ matrix elements
- The resulting signal strength modifier is:

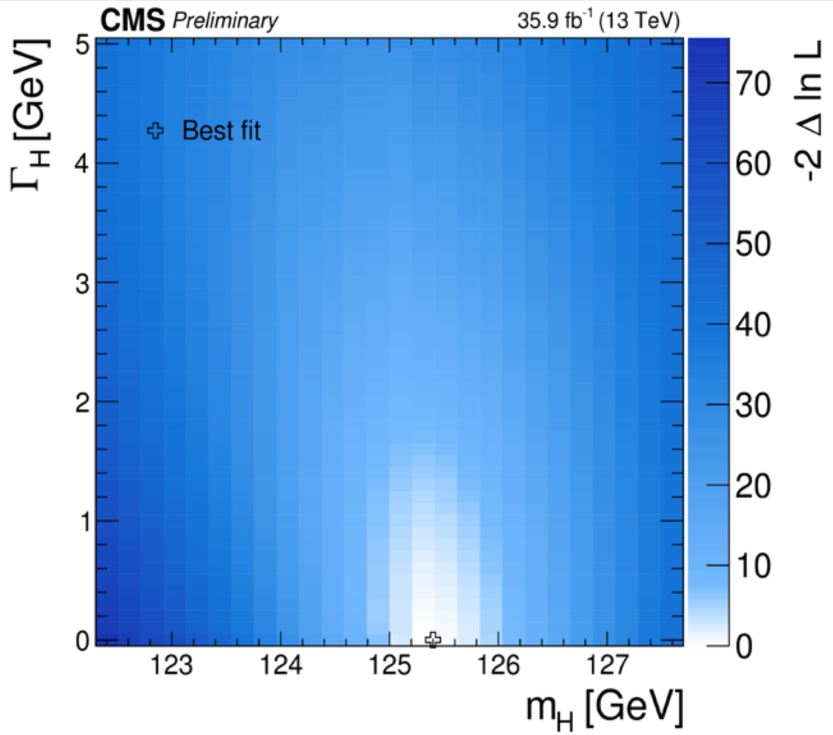
$$\mu = 1.05^{+0.15}_{-0.14}(stat.)^{+0.11}_{-0.09}(syst.) = 1.05^{+0.19}_{-0.17}$$





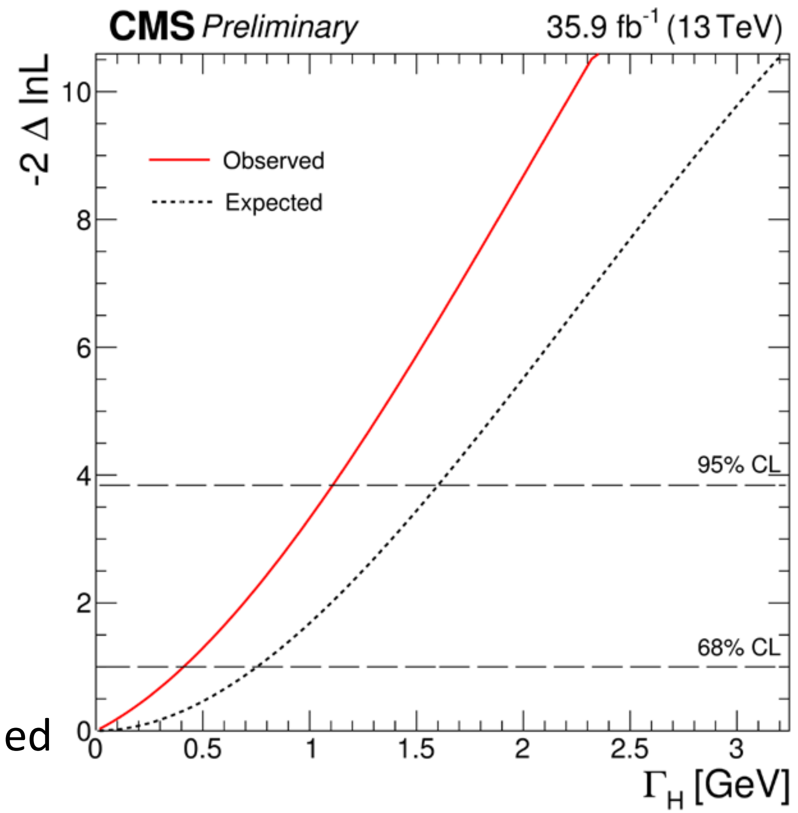
CMS PAS HIG-16-041 (36 fb-1)

Γ_{H} with $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$



- The direct measurement of the width Γ_{H} is performed using on-shell Higgs boson production, in the range $105 < m_{4\ell} < 140\ GeV$.
- The 4ℓ experimental invariant mass resolution is of the order of 1 GeV
  - Versus an expected SM width $\Gamma_H = 4.2 \times 10^{-3}\ GeV$ (for $m_H = 125\ GeV$)
- An unbinned maximum likelihood fit to the $m_{4\ell}$ distribution is performed with the strengths $\mu_{VBF,VH}$ and $\mu_{ggH,t\bar{t}H}$ unconstrained in the fit.
  - Main Γ_H uncertainty: $m_{4\ell}$ resolution.

$$\Gamma_H = 0.00^{+0.41}_{-0.00}\ GeV\ , \Gamma_H < 1.10\ GeV\ @95\%CL$$



m_H unconstrained

CMS PAS HIG-16-041 (36 fb[-1])

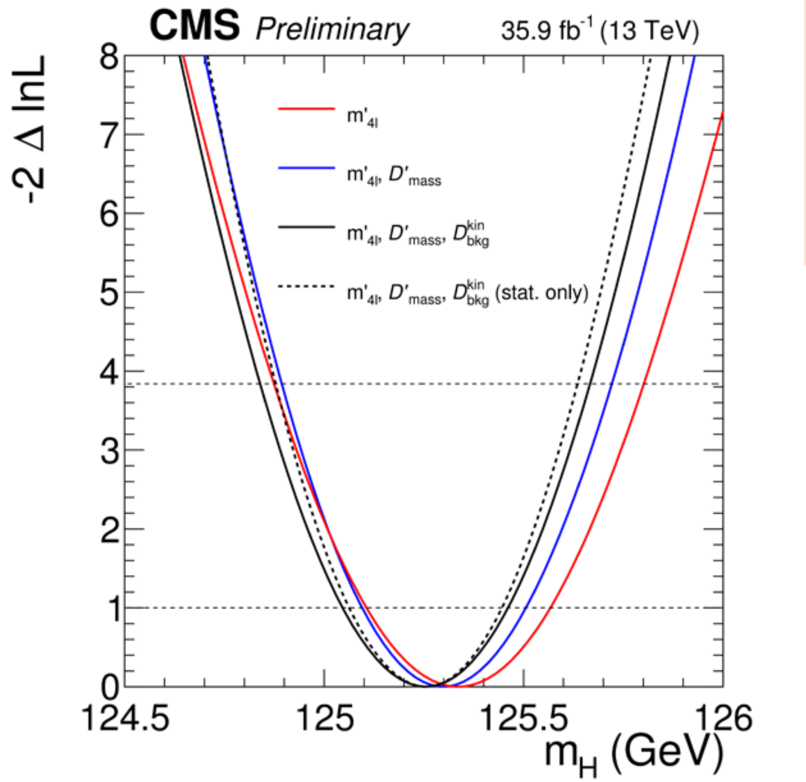
m_H with $H \to ZZ \to \ell\ell\ell\ell$

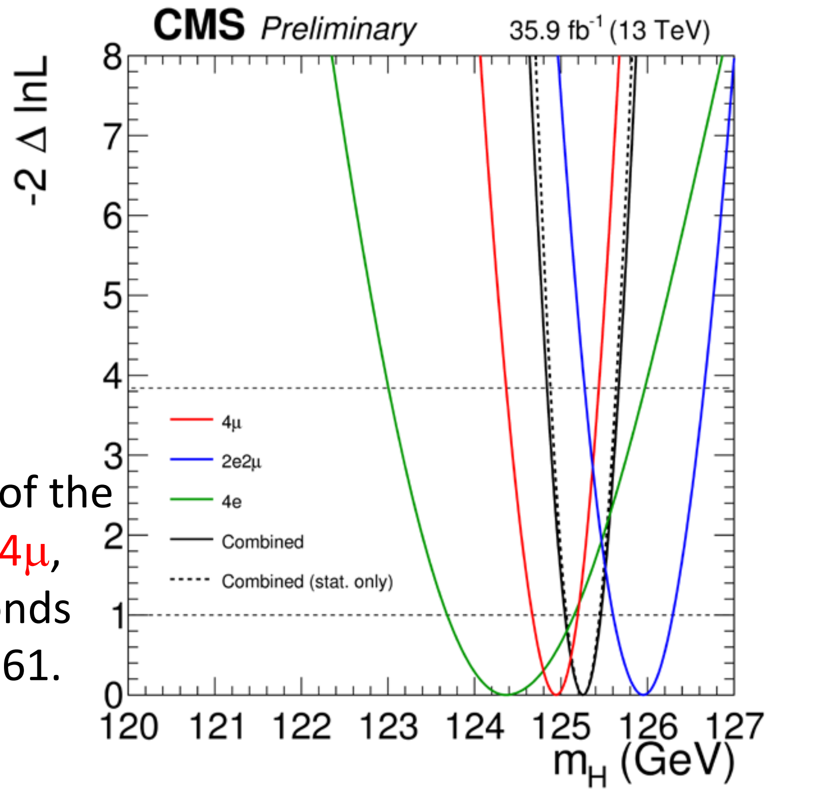
- The mass measurement is performed via 1D scans vs. m_H on the 1D $\mathcal{L}(m_{4\ell})$, 2D $\mathcal{L}(m_{4\ell}, \mathcal{D}_{mass})$ and 3D $\mathcal{L}(m_{4\ell}, \mathcal{D}_{mass}, \mathcal{D}_{bkg}^{kin})$ likelihoods.
  - While profiling the signal strength μ along with all other nuisance parameters
- The mass value with the lower total uncertainty is obtained from the 3D likelihood

$$m_H = 125.26 \pm 0.20(stat.) \pm 0.08(sys.)\ GeV$$

  - The observed unc. is $\sim 0.05\ GeV$ better than the predicted one
  - The systematic uncertainty is dominated by the uncertainty in the lepton momentum scale.
  - The Run1 ATLAS+CMS combination was:

$$m_H = 125.09 \pm 0.24(\pm 0.21\ \pm 0.11)\ GeV$$





The compatibility of the measurements in 4μ, 2e2μ, 4e corresponds to a p-value of 0.061.

m_H with $H \rightarrow \gamma\gamma$

- The $H \rightarrow \gamma\gamma$ decay channel provides a clean final state with a precisely reconstructed mass peak.
- Ideal for the precise characterization of the Higgs boson properties, e.g. m_H.
- The dominant backgrounds to $H \rightarrow \gamma\gamma$ consist:
  - The irreducible prompt diphoton production
  - The reducible backgrounds from $\gamma + jet$ and $jet + jet$ events.
    - A BDT is trained using simulated $\gamma + jet$ events to discriminate signal from non-prompt photons.
- The determination of the primary vertex from which the two photons originate impacts the diphoton invariant mass resolution.
  - If $z_0(\gamma\gamma)$ is known to better than about 1 cm, the invariant mass resolution is dominated by the photon energy resolution.

CMS PAS HIG-16-040 (36 fb[-1])

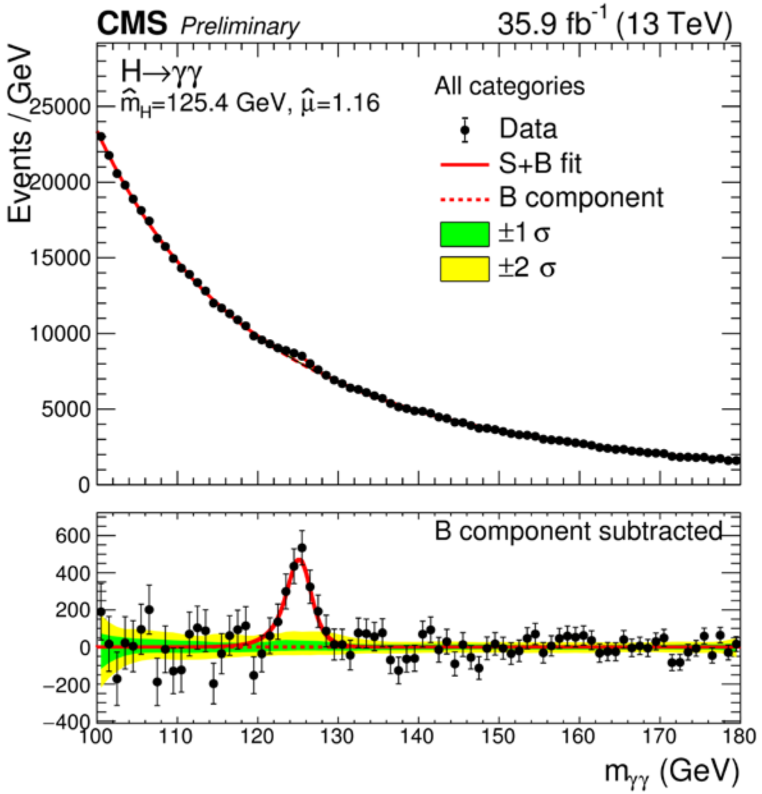
NEW

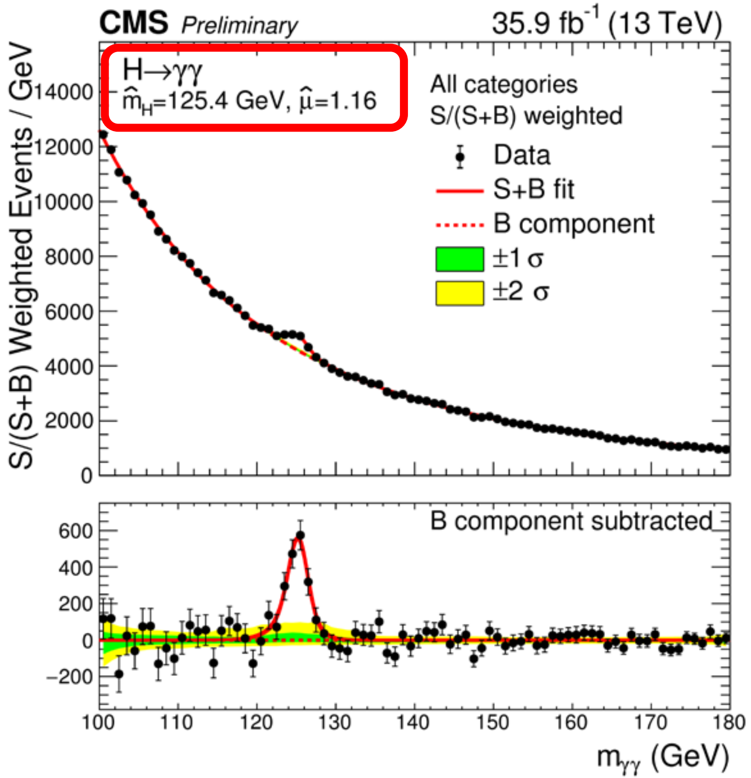
m_H with $H \to \gamma\gamma$

- Events are classified targeting different production mechanisms and according to their mass resolution and predicted signal-to-background ratio.
  - Several event categories for: $t\bar{t}H, VH, VBF, ggH$ production modes
- One simultaneous fit is performed to the $m_{\gamma\gamma}$ distributions of all categories, with a single overall signal strength μ and a single overall m_H free to vary. The best fit values are:

$$\hat{\mu} = 1.16^{+0.11}_{-0.10}(stat.)^{+0.09}_{-0.08}(syst.)^{+0.06}_{-0.05}(theo.)$$

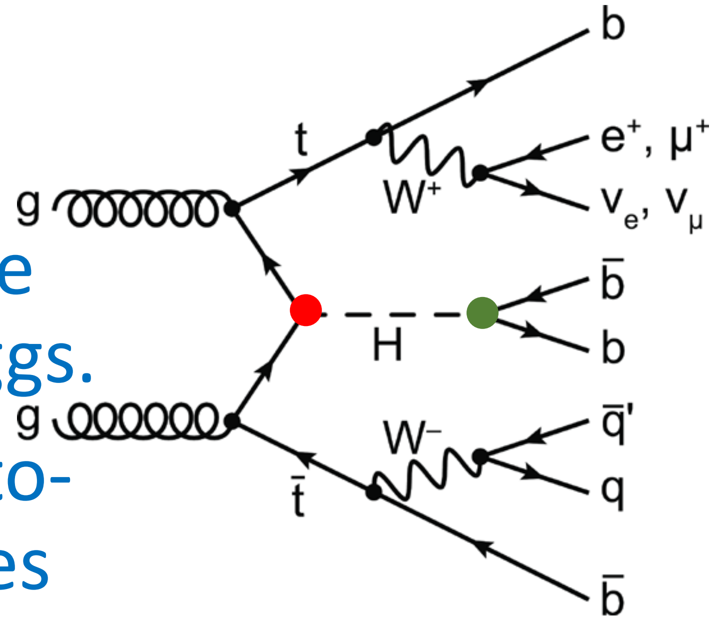
$$m_H = 125.4 \pm 0.15(stat.) \pm 0.2 \div 0.3(\sim syst.)$$

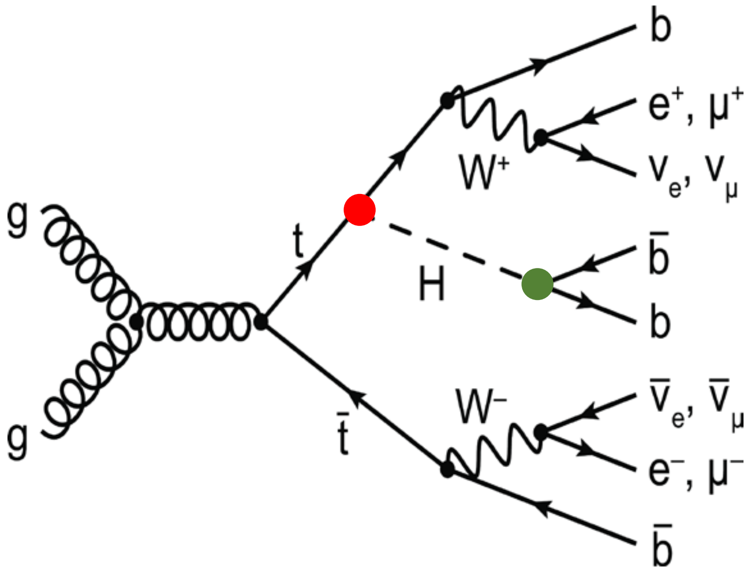




Couplings to fermions with $t\bar{t}H$ (and $H \rightarrow b\bar{b}$)

- The measurement of the associated production $t\bar{t}H$ is a direct probe of the top–Higgs coupling.
- The $H \rightarrow b\bar{b}$ probes the bottom-Higgs coupling and has the largest branching fraction (0.58 ± 0.02) for a $125\ GeV$ Higgs.
- BDT and MEM techniques are used to improve the signal-to-background separation. The information of both techniques are used to derive a single discriminant.
  - The BDTs utilize information related to object kinematics, event shape, and the jet-btag discriminant.
  - The MEM discriminant is constructed as ratio of the probability density values of the signal and background hypothesis





CMS PAS HIG-16-038 (12.9 fb^{-1})

Couplings to fermions with $t\bar{t}H$

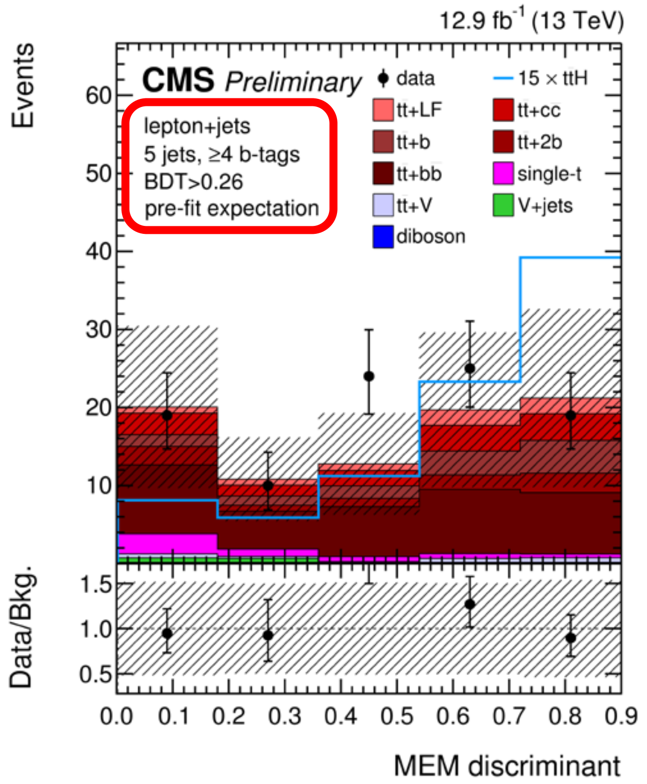
- The signal strength modifier $\mu = \sigma/\sigma_{SM}$ of the $t\bar{t}H$ production is determined in a simultaneous binned maximum-likelihood fit to the data across all analysis categories. The best-fit value:

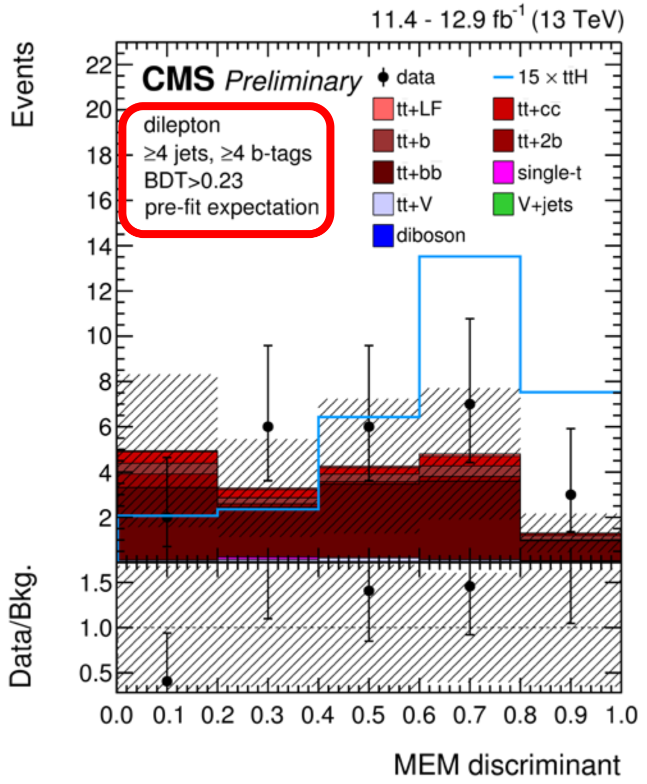
$$\mu = -0.19^{+0.45}_{-0.44}(stat.)^{+0.66}_{-0.68}(syst.) = -0.19^{+0.80}_{-0.81}$$

  - This is 1.5σ from the SM expectation.

- The value obtained for μ is both compatible with the SM expectation and no signal: an upper limit at 95% CL is calculated. The observed (expected) UL:

$$\mu < 1.5\ (1.7)\ @95\%CL$$

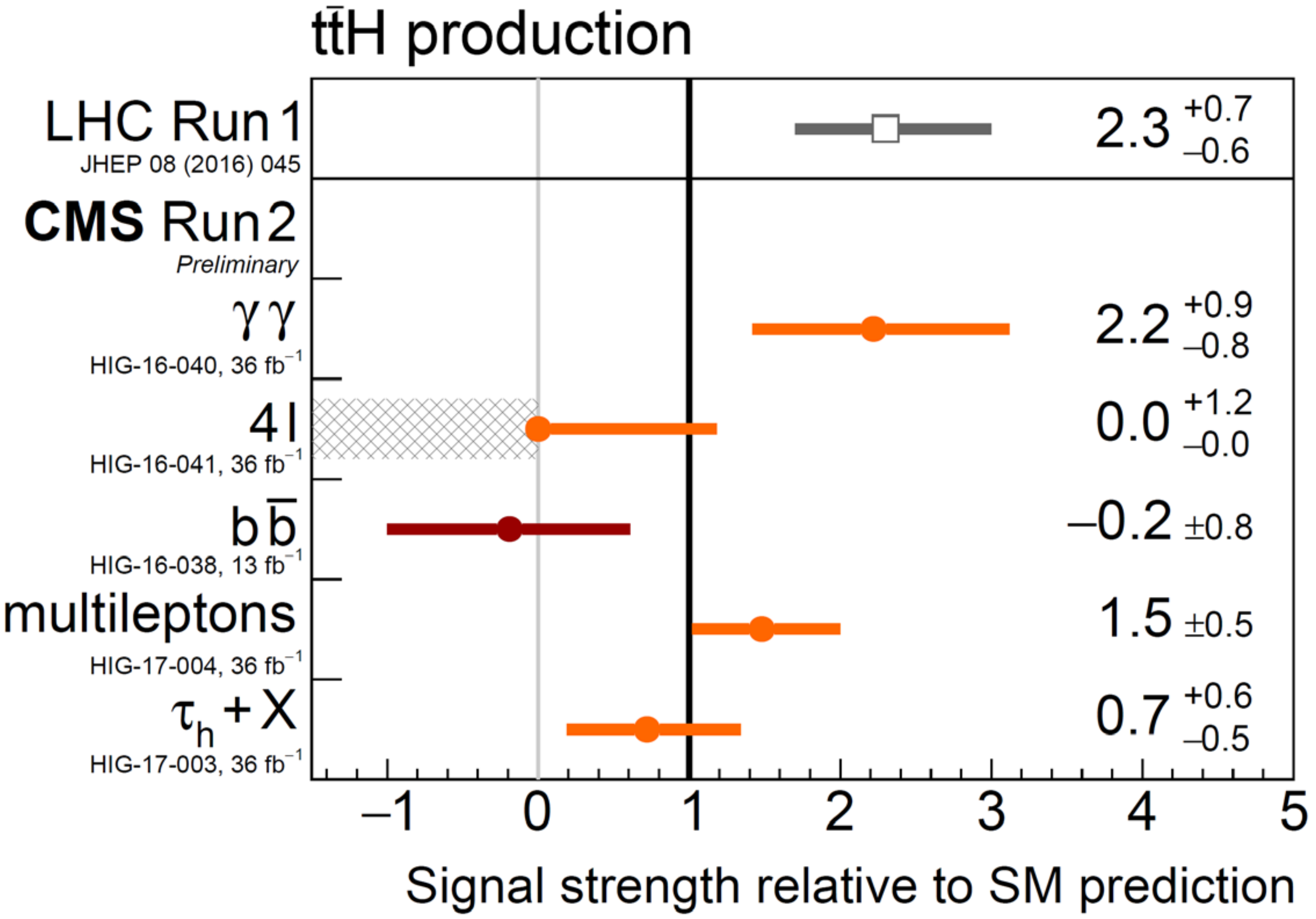




CMS PAS HIG-16-038 (12.9 fb^{-1})
CMS PAS HIG-16-040 (36 fb^{-1})
CMS PAS HIG-16-041 (36 fb^{-1})
CMS PAS HIG-17-003 (36 fb^{-1})
CMS PAS HIG-17-004 (36 fb^{-1})

$t\bar{t}H$ couplings. The Run 2 summary

- The $t\bar{t}H$ production mode has a small cross section $(0.5\,pb \cong \sigma_{gg\to H}/100)$ but provides pure(er) final states.
- Run 1 showed a 2σ excess w.r.t. SM expectations
- We have now 4 analysis with the full Run 2 dataset available.
- Still no conclusive results, but the good news is that we are already testing k_t in all the main H decay modes.



Conclusions

- CMS has analysed 36 fb^{-1} of pp collisions @ $\sqrt{s} = 13\ TeV$, measuring Higgs properties like signal strengths, mass, width.
- For now, the BSM landscape looks very much like this

Conclusions

I would have been much happier with this