Standard Model Higgs boson at CMS

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on behalf of the CMS Collaboration

Kruger 2014: Third Biennial Workshop
on Discovery Physics at the LHC

What is the Standard Model Higgs boson?

- EWSB mechanism introduce a complex scalar field
  - W and Z getting mass
  - One scalar physical particle: the Higgs boson H
- Last piece of the Standard Model
- Yukawa interactions with the fermions: generate mass
- Mass as free parameter ($\sim [114.4 - 1000]$ GeV)

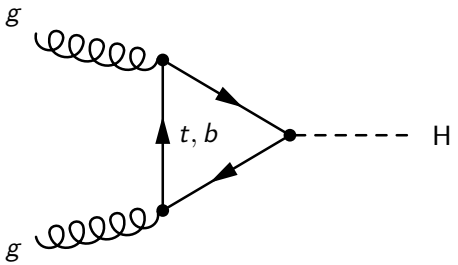
What about the one we discovered? **Is it the one?**
(One of the) only place where we did actually see something in Run I data

Menu

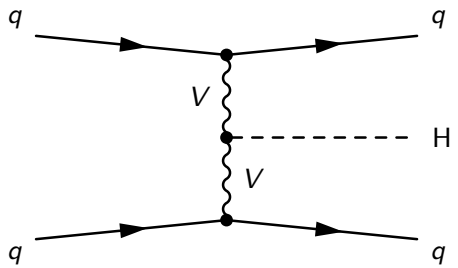
1. How did we find it?
2. What did we find exactly?

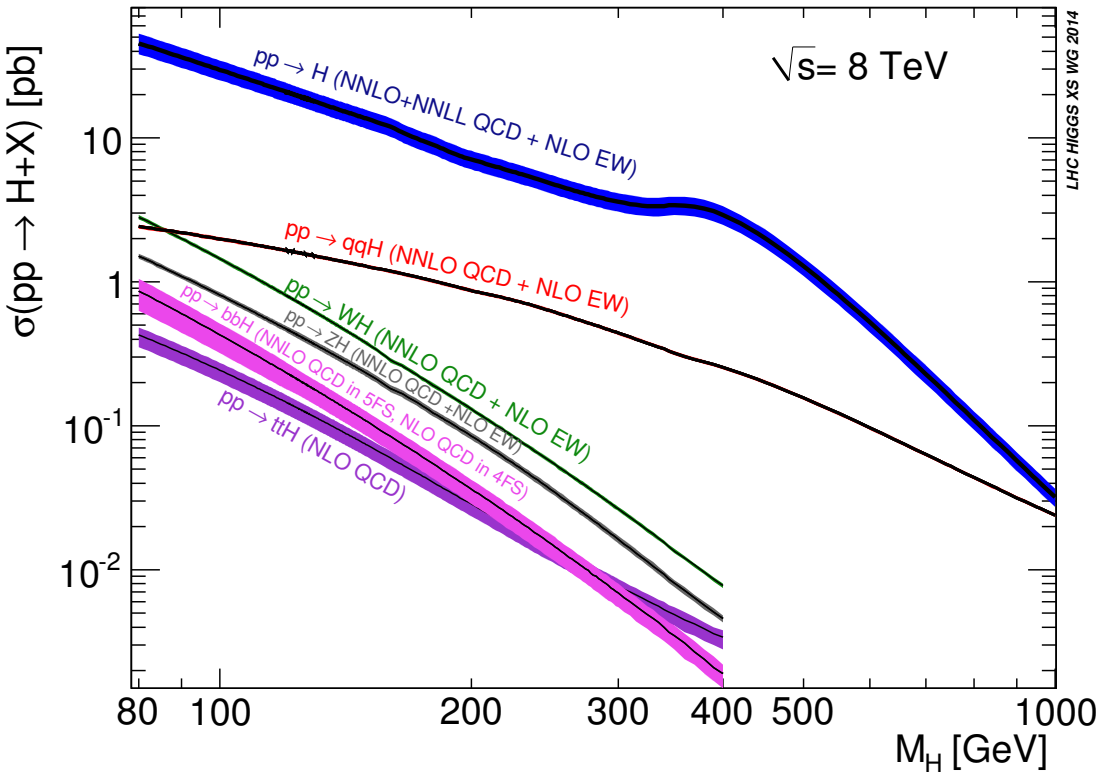
Production of the SM Higgs boson

Gluon Fusion (ggH)

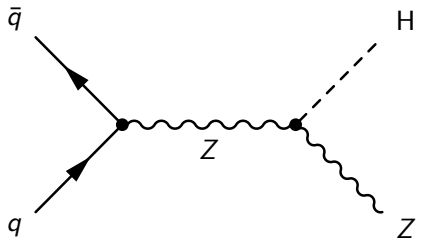


Vector Boson Fusion (VBF)

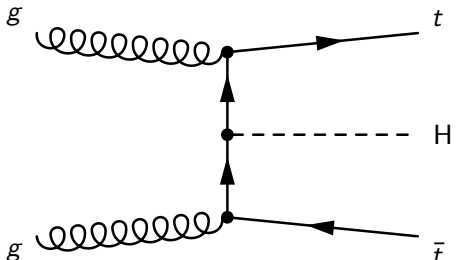




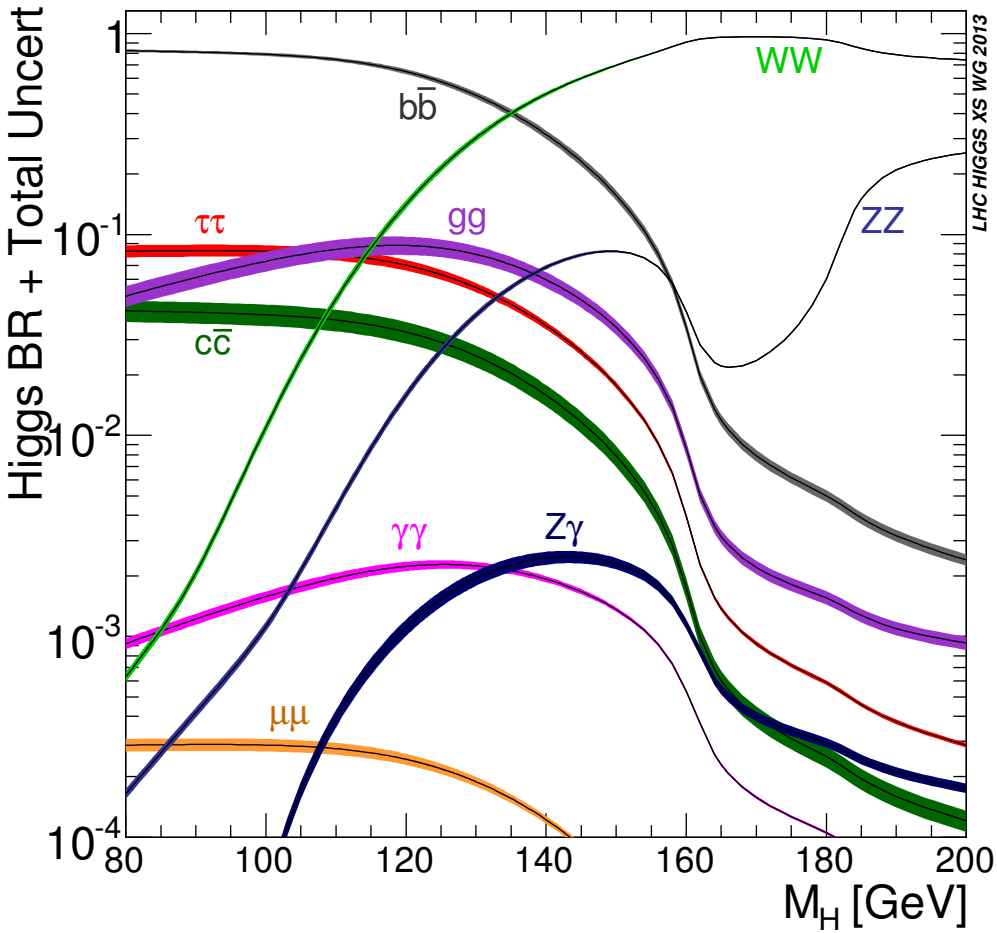
W/Z associated (WH/ ZH)



$t\bar{t}$/ $b\bar{b}$ associated (ttH/ bbH)



Decay of the SM Higgs boson

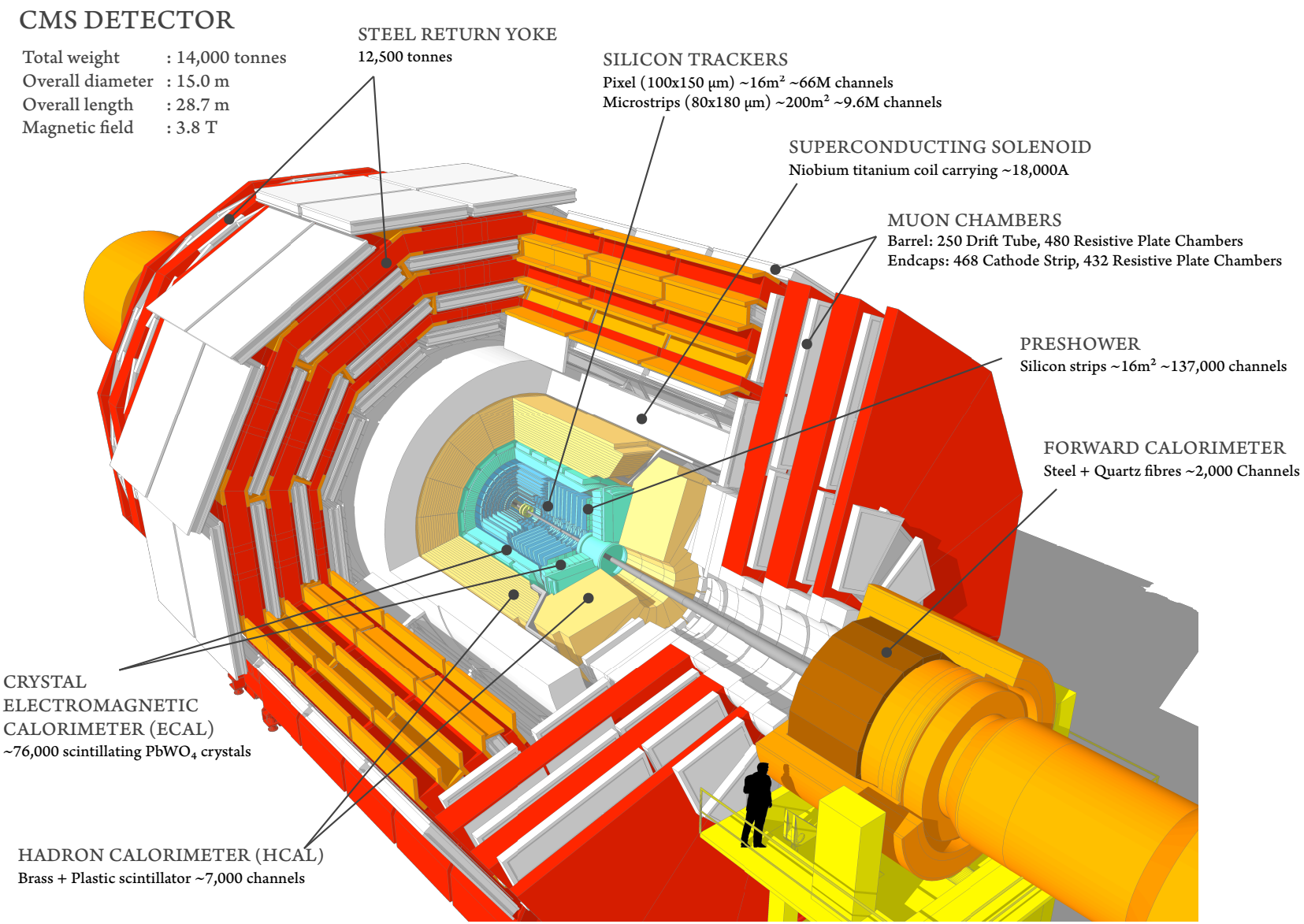


Search channels:

- Decay directly: HWW, HZZ, $Hb\bar{b}$, $H\tau\tau$, $H\mu\mu$
- Decay through loops $H\gamma\gamma$, $HZ\gamma$
- Overwhelmed by QCD: Hgg, $Hc\bar{c}$

How did we find it?

The Compact Muon Solenoid experiment



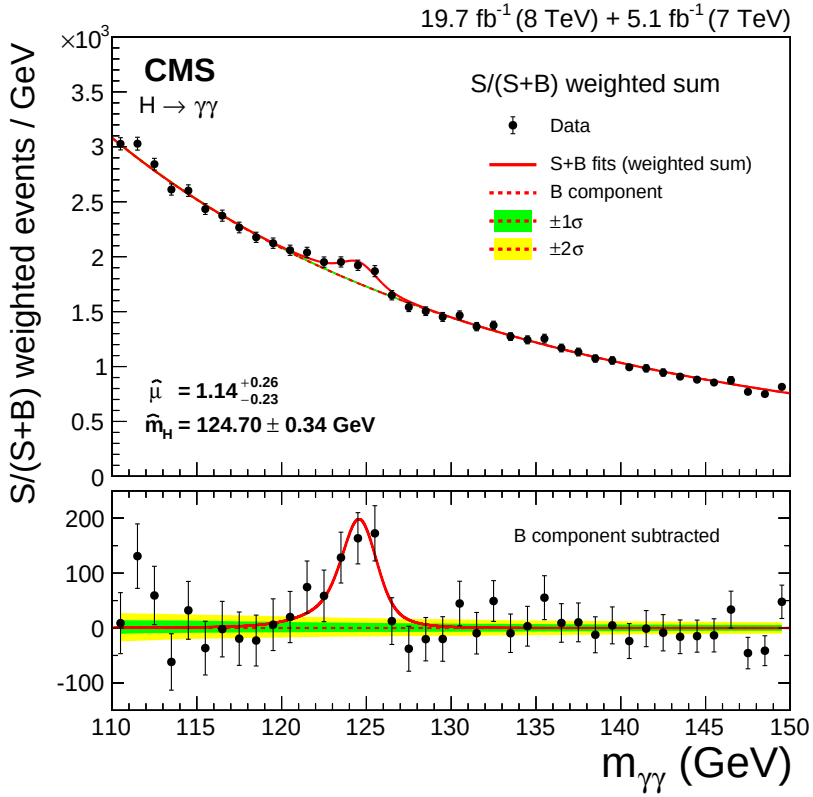
Preamble

- Focus on analysis of Run I data:
  - $\sqrt{s} = 7 - 8\,\text{TeV}$, $\int L \sim 25\,\text{fb}^{-1}$, <pu>$\sim 20$
- Analysis criteria tighten with $\sqrt{s}$, L, <pu>
  - Trigger, p_T, isolation, identification, kinematics, ...
- Global Event Description (aka Particle Flow)
  - Charged/neutral hadrons, muons, electrons, photons
  - Substract PU from isolations, jet clustering, PU jet identification
- Correct simulation for data-MC differences
- Interference between signal and background accounted for
- **Focus on the boson at $m_H \sim 125\,\text{GeV}$**
- Similar dijet tag (VBF production)
  - Two forward jets, rapidity gap, high m_{jj}, recoil in transverse plane

$H\gamma\gamma$ final state (I)

JHEP 06 (2013) 081 Eur. Phys. J. C 74 (2014) 3076

- BR($H\gamma\gamma$) $= 0.228\%$
- ggH, VBF, W-ZH, ttH
- QCD background ($\gamma\gamma$, γj)
- Search in $[110 - 150]$ GeV
- $\epsilon_{\text{trigger}} = 99.4\%$
- $\epsilon \cdot \mathcal{A} \sim 49\%$
- Fit to $m_{\gamma\gamma}$
  - **Excellent γ resolution**



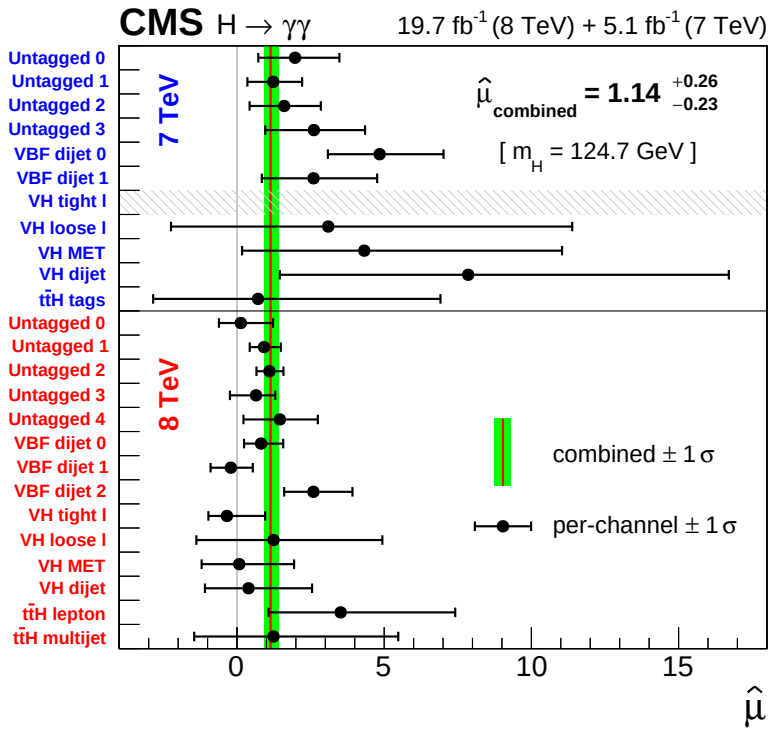
Analysis: two isolated photons

- Vertex BDT, photon E and $\sigma(E)$ BDTs, photon ID BDT
- Categories on BDT, production process

$H\gamma\gamma$ final state (II)

JHEP 06 (2013) 081 | Eur. Phys. J. C 74 (2014) 3076

- Final calibration, improved simulation, improved energy scale uncertainties
- 25 event categories
- Background modeling: discrete profiling (enveloppe)
  - Good uncertainty coverage



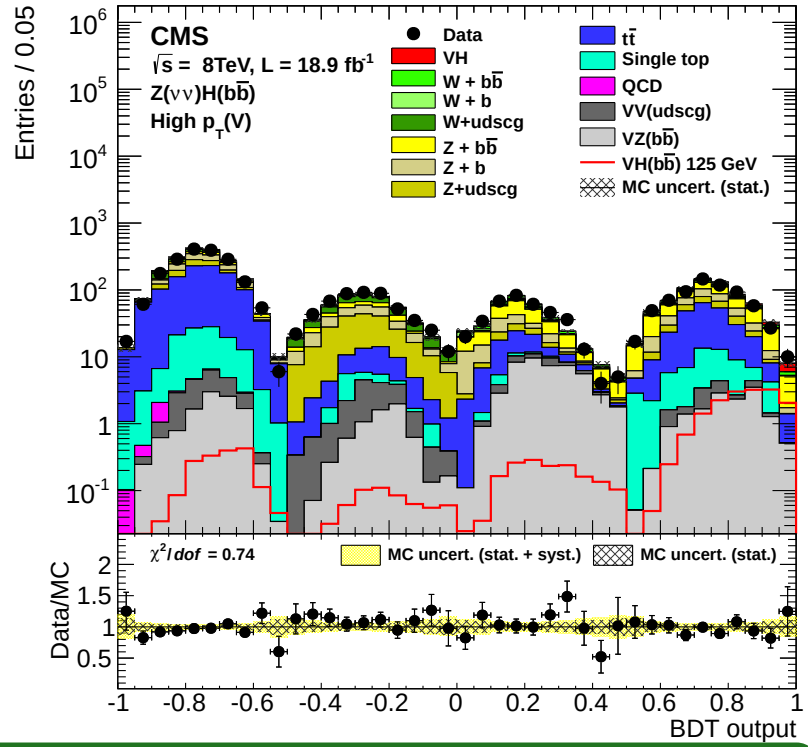
Results

- Observed a 5.7σ (5.2) **excess**
- $\mu = 1.14^{+0.26}_{-0.23}$
- Mass: $m_H = 124.70 \pm 0.31(\text{stat}) \pm 0.15(\text{syst})$ GeV
- Width: $\Gamma_H = 2.4(3.1)$ GeV
- Spin: favors 0^+

$H b\bar{b}$ final state (I)

JHEP 06 (2013) 081 Phys. Rev. D 89, 012003 (2014)

- BR($H b\bar{b}$)= 57.7%
- WH and ZH production:
  - W($l\nu$)H, W($\tau_h\nu$)H
  - Z(ll)H, Z($\nu\nu$)
- Backgrounds: Vjets, t, $t\bar{t}$, VV, QCD multijets **($\gg$ VH)**
- Search in [110 – 135]
- $\epsilon_{\text{trigger}} \gtrsim 90\%$

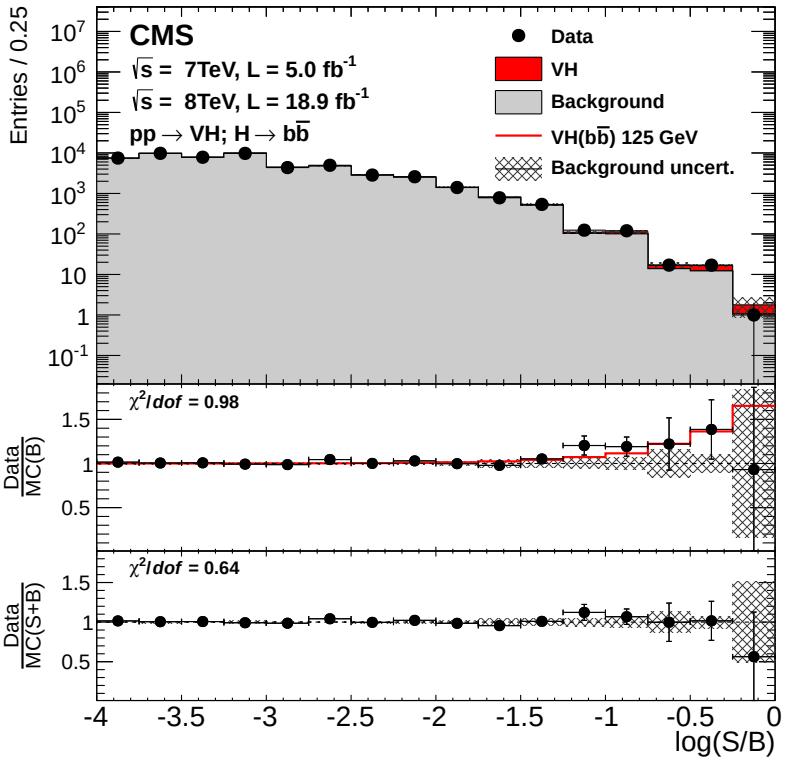


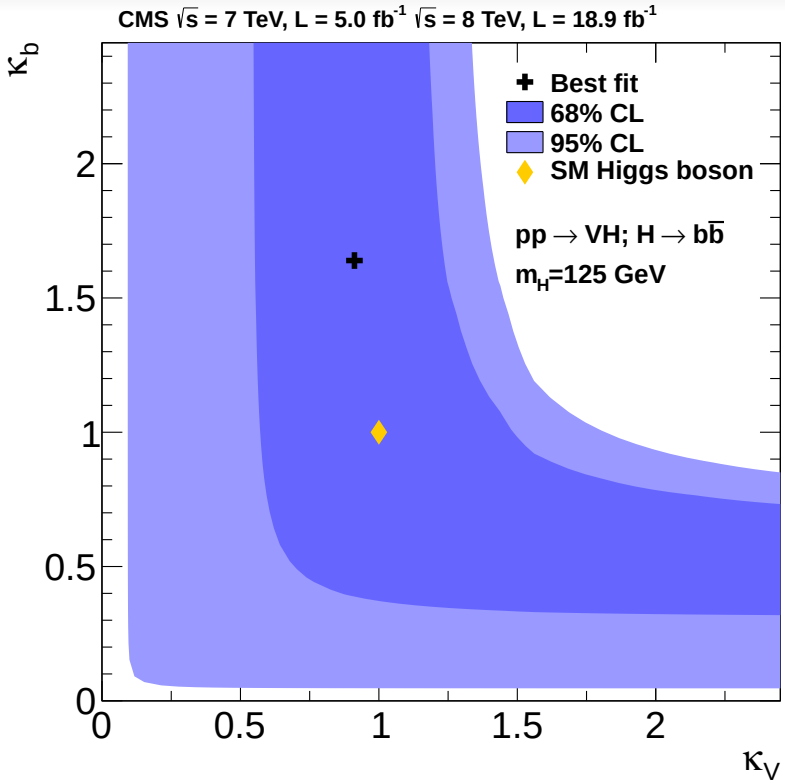
Analysis

- Isolated leptons, PF jets, PF $\not\!\!E_T$, CSV b-jets, HPS τ_h
- Boost categories in $p_T(V)$; $p_T(H)$
- Fit to a BDT discriminant
  - m_{jj}, N_{aj}, CSVmin, $\Delta R(jj)$, ...
  - 3 BDT to separate $t\bar{t}$, VJets, VV, VH

$H\bar{b}b$ final state (II)

JHEP 06 (2013) 081 Phys. Rev. D 89, 012003 (2014)





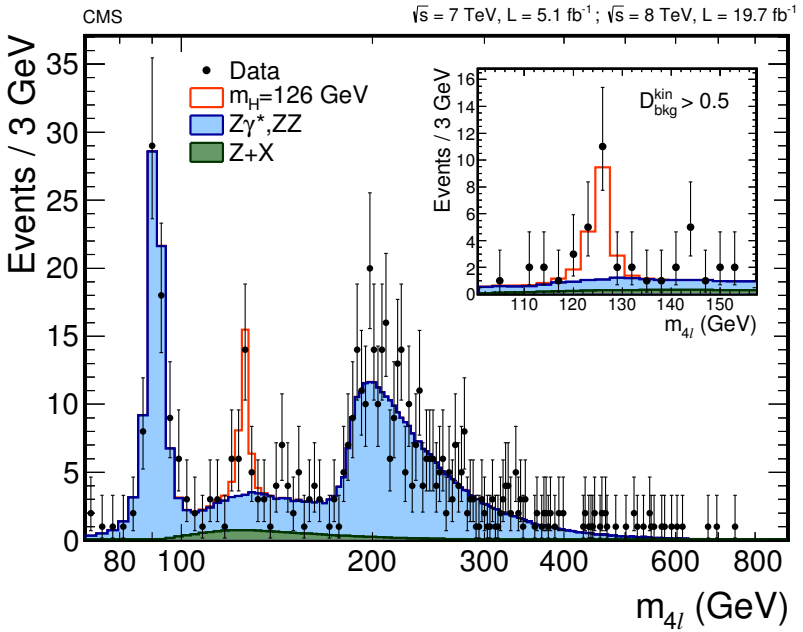
Results: excess compatible with an excess at 125 GeV

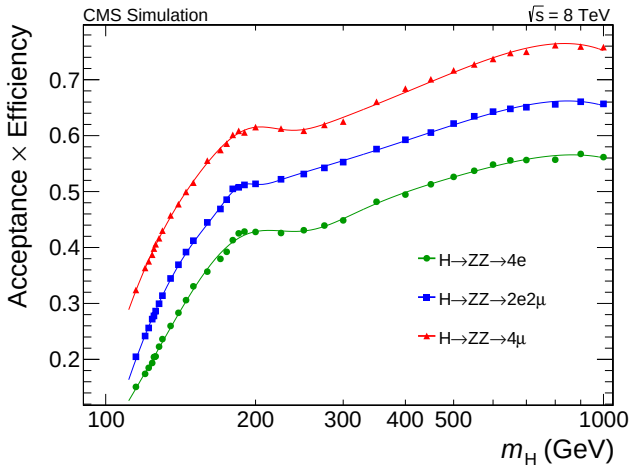
- Simultaneous fit to 14 BDT distributions
- Limit at 95% CL of $1.89\sigma_{\mathrm{SM}}$ ($0.95\sigma_{\mathrm{SM}}$) observed (expected)
- **Excess** of 2.1σ (2.1σ) observed (expected)
- $\mu = 1.00 \pm 0.05$

HZZ final state (I)

JHEP 06 (2013) 081 | Phys. Rev. D 89 (2014) 092007

- BR (HZZ) (4*l*) $= 2.64\%(0.0125)\%$
- Search in $[110 - 1000]$ GeV
- Bkgs: ZZ, Zγ, Zjets, t$\bar{\text{t}}$
- $\epsilon_{\text{trigger}} \gtrsim 98\%$
- Low yield, narrow resonance: **accurate calibration, selection efficiency**





Analysis

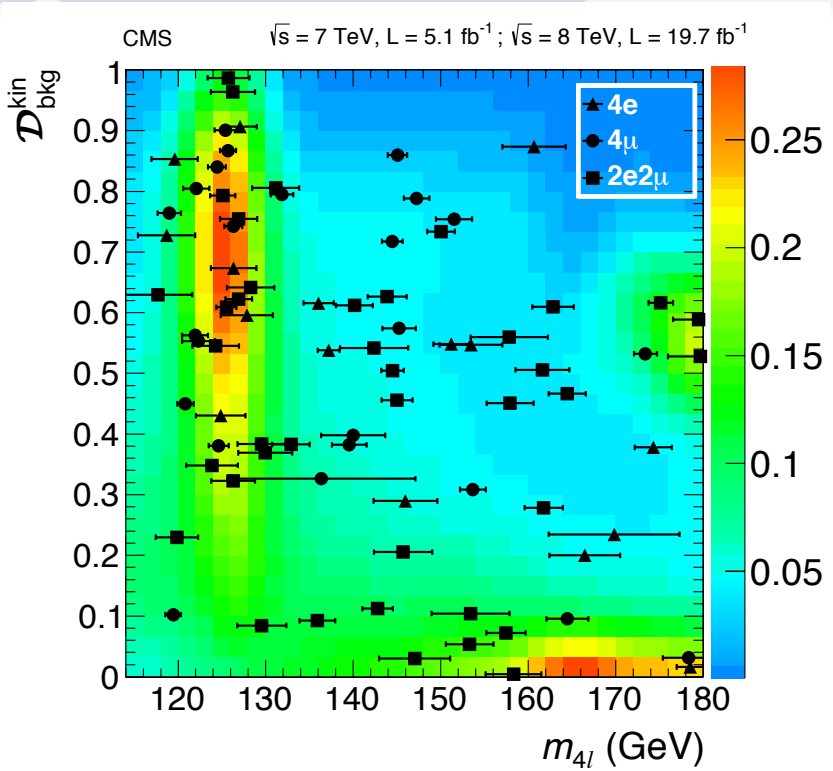
- Isolated leptons, FSR recovery (2 GeV), *e*-ID/p_T BDT
- $p_T^e > 7$ GeV, $p_T^\mu > 5$ GeV

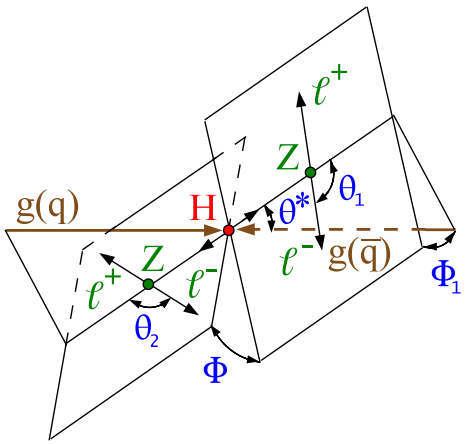
HZZ final state (II)

JHEP 06 (2013) 081 Phys. Rev. D 89 (2014) 092007

Categories

- ggH, VBF, W-ZH, ttH
- ZZ from simulation, $Z + X$ from control sample
- Matrix Element Likelihood Analysis (MELA)
  - Kinematic discriminants
  - 3D/3D/2D likelihood for μ, σ_{excl} / m_H, Γ_H / J^P





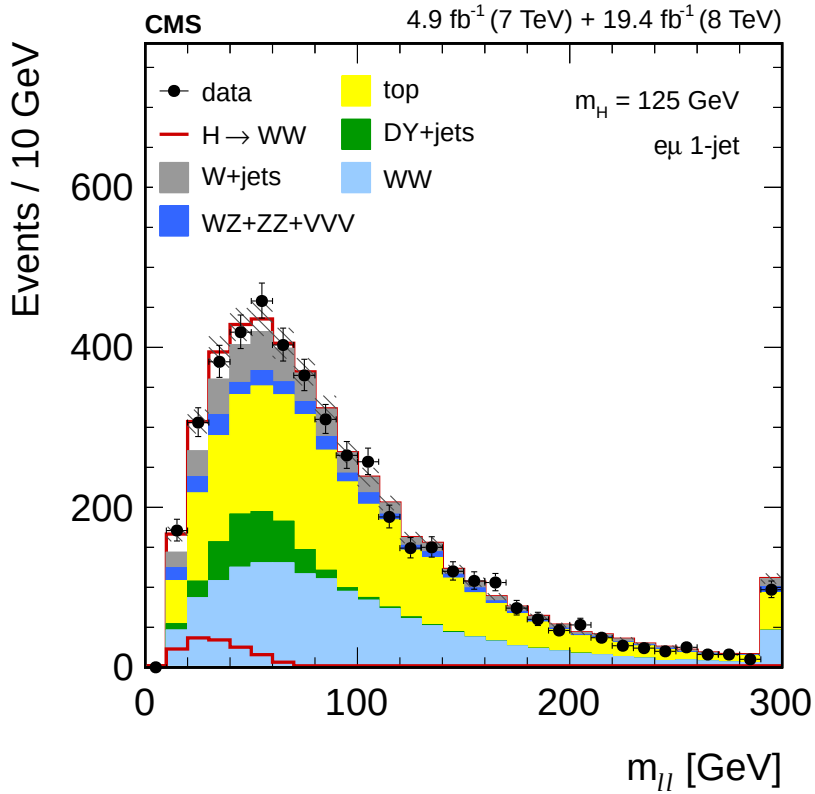
Results

- **Excess** of 6.8 σ (6.7) at 125.7 GeV
- $m_H = 125.6 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$ GeV
- $\mu = 0.93^{+0.26}_{-0.23}(\text{stat})^{+0.13}_{-0.09}(\text{syst})$

HWW final state (I)

JHEP 06 (2013) 081 JHEP 01 (2014) 096

- BR(HWW) = 21.5%
- Leptonic final states
- m_{ll}, m_T/counting for signal extraction
- Search range 110-600 (-200 for VH)
- **Backgrounds evaluated from data**: WW,$t\bar{t}$, VJets, VV
- $\epsilon_{\text{trigger}} \gtrsim 97\%$



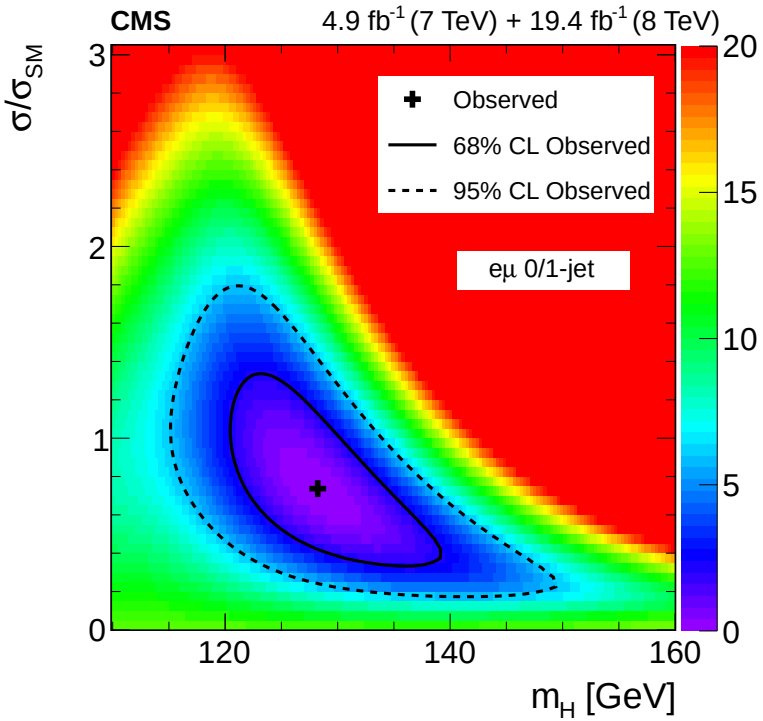
Analysis

- Leptons identified and isolated
- $m_T^2 = 2p_T^{ll} \not{E}_T(1 - \cos\Delta\phi(ll, \not{E}_T))$

HWW final state (II)

JHEP 06 (2013) 081 JHEP 01 (2014) 096

- Five exclusive categories:
  - $2l2\nu + 0, 1$ jet (ggH, HWW, $W(l\nu)$)
  - $2l2\nu + 2$ jets (VBF, HWW, $W(l\nu)$)
  - $2l2\nu + 2$ jets (W-ZH, HWW, $V(qq)$, $W(l\nu)$)
  - $3l3\nu + 2$ jets (WH, HWW, $W(l\nu)$)
  - $3l\nu + 2$ jets (ZH, HWW, $Z(ll)$, $W(l\nu)$, $W(qq)$)
- Pseudo-experiments: robust background estimations



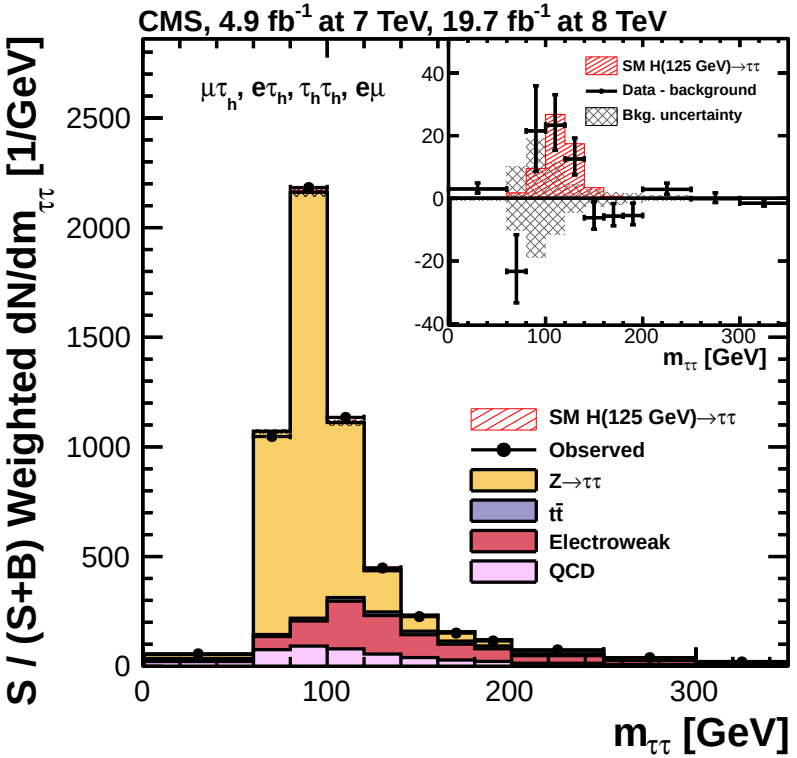
Results

- Observe **excess** at 4.3σ (5.8) for $m_H = 125.6\,\text{GeV}$
- $\mu = 0.72^{+0.20}_{-0.18}$
- $m_H = 128.2^{+6.6}_{-5.3}\,\text{GeV}$

$H\tau\tau$ final state (I)

JHEP 06 (2013) 081 JHEP 05 (2014) 104

- BR($H\tau\tau$) = 6.32%
- $\mu\tau_h, e\tau_h, \tau_h\tau_h, ee, \mu\mu, e\mu$
- Signal from $m_{\tau\tau}$; m_{vis}
- $\epsilon^{\tau_h}_{\text{reconstruction}} \sim 60 - 70\%$
- **Backgrounds**: DY,$t\bar{t}$, QCD, Wjets, VV, HWW
- $\epsilon_{\text{trigger}} > 90\%$
- Search range [90-145] GeV

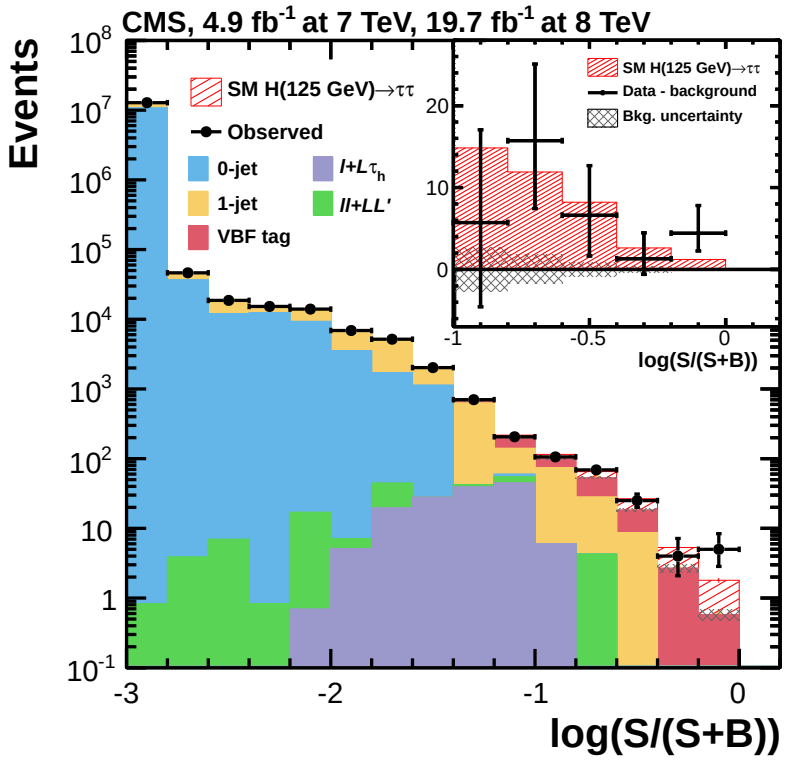


- Isolated leptons, HPS τ_h, b-tag veto
- SVFIT (iff τ only source of true $\not{E}_T$): maximum likelihood fit to reconstruct $m_{\tau\tau}$

$H\tau\tau$ final state (II)

JHEP 06 (2013) 081 JHEP 05 (2014) 104

- Background estimation
  - DY: DY($\mu\mu$) with embedded taus
  - DY(ll): misID from tag and probe
  - Wjet, $t\bar{t}$: control region
  - QCD: control region
  - VV, t, HWW from simulation
- Boost $p_T^{\tau\tau}$, p_T^L categories



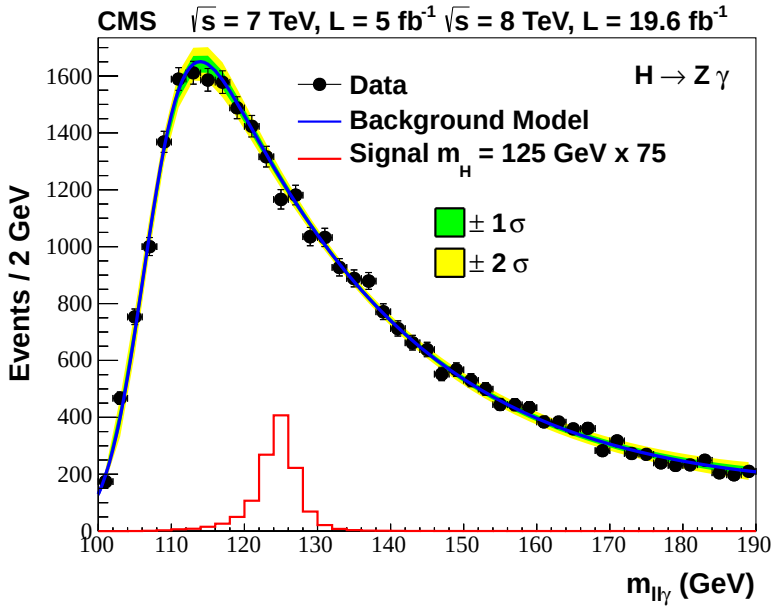
Results

- Observe **excess** of 3.2σ (3.7) for $m_H = 125\,\text{GeV}$
- $\mu = 0.78 \pm 0.27$
- $m_H = 122 \pm 7\,\text{GeV}$

$HZ\gamma$ final state

Phys. Lett. B 726 (2013) 587 | CMS-PAS-HIG-14-003

- BR($HZ\gamma$) = 0.154%
- $\epsilon_{\text{trigger}}^{ee\gamma;\mu\mu\gamma} \sim 60 - 98; 91\%$
- OSSF lepton pair
- Backgrounds: $Z\gamma$ ISR, $Z\gamma$ FSR, Zjets
- Categories barrel/endcap, γ conversion, dijet
- Fit to $m_{ll\gamma}$ spectrum



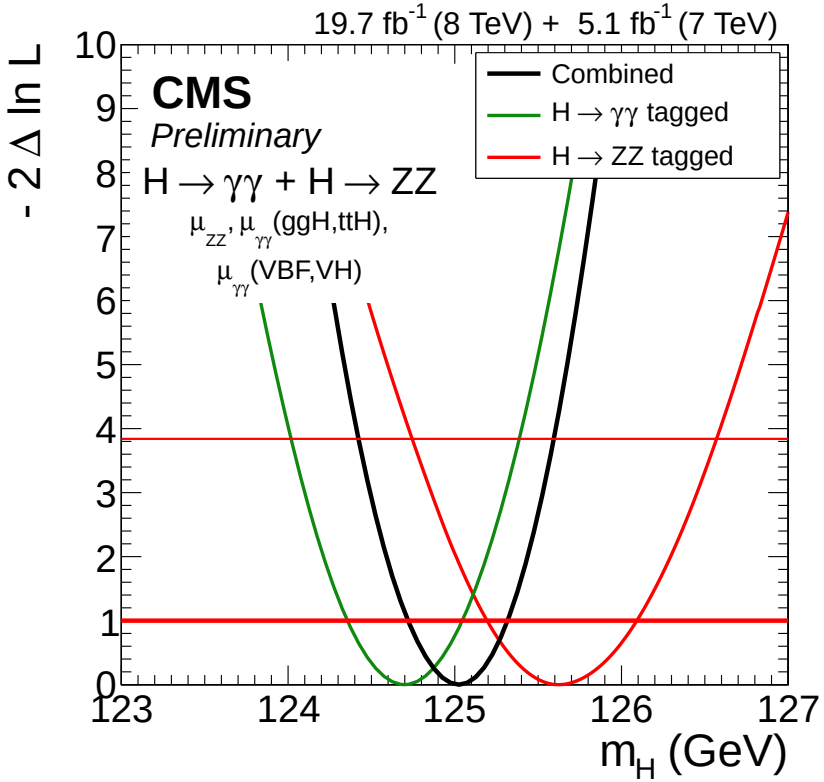
Results

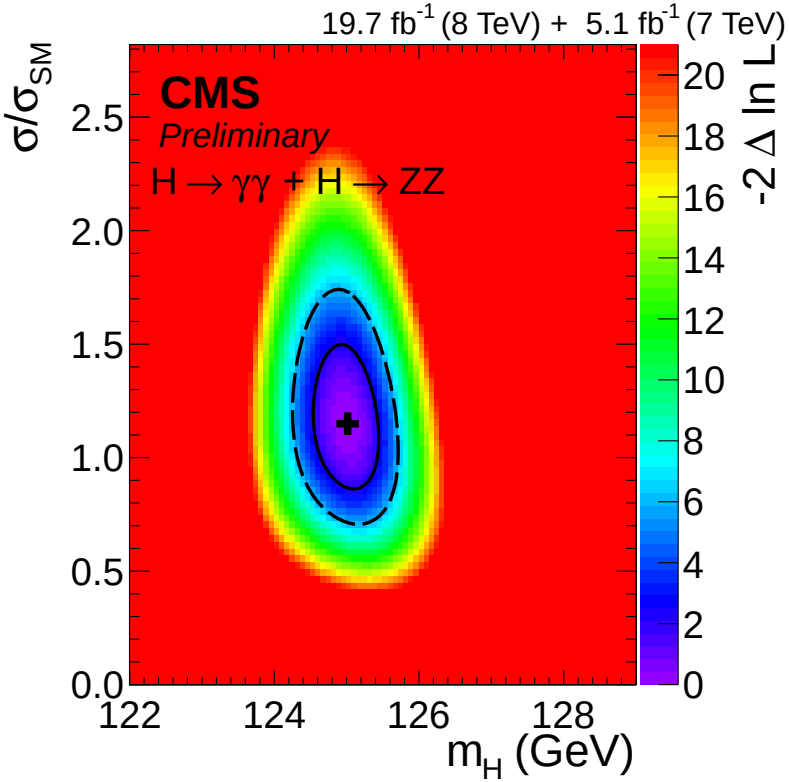
- **No excess** seen
- Dalitz decay $\gamma\gamma^* \to \mu\mu\gamma$ no excess either

What did we find?

Mass and signal strength

CMS-PAS-HIG-14-009





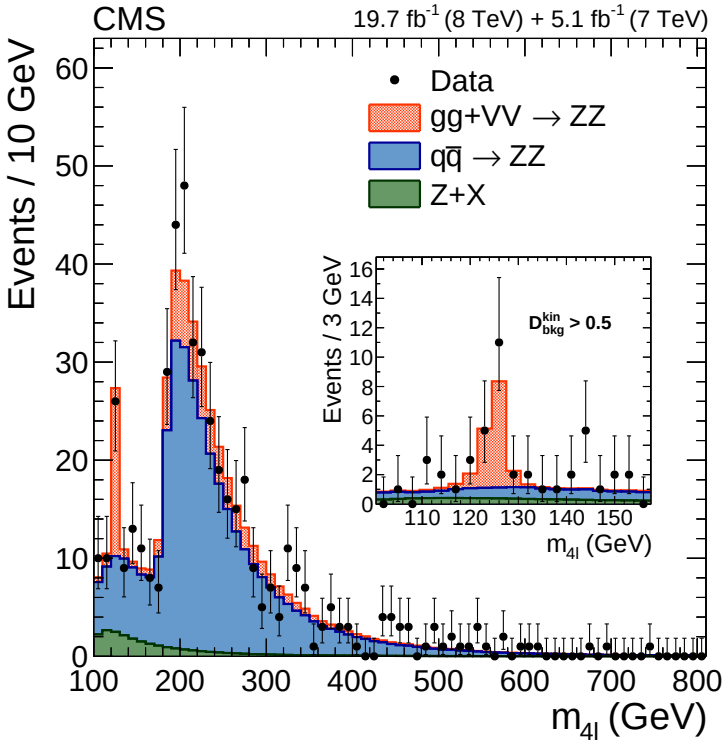
- $m_H = 125.03^{+0.26}_{-0.27}(\text{stat})^{+0.13}_{-0.15}(\text{syst})$ **GeV**
- $\mu = 1.00 \pm 0.09(\text{stat})^{+0.08}_{-0.07}(\text{theo}) \pm 0.07(\text{syst})$

Width

Phys. Rev. D 89 (2014) 092007 | Eur. Phys. J. C 74 (2014) 3076 | Phys. Lett. B 736 (2014) 64

$\Gamma_h^{SM} = 4.07\,\text{MeV}$

- Direct measurement:
  - HZZ $\Gamma_H < 3.4\,\text{GeV}$ (2.8)
  - H$\gamma\gamma$ $\Gamma_H < 2.4\,\text{GeV}$ (3.1)
- Indirect measurement HZZ
  - Assumes ggH dominated by top loop
  - Assumes no NP
  - $\Gamma_H < 22\,\textbf{MeV}$ (33)
    ($\Gamma_H = 1.8^{+7.7}_{-1.8}\,\text{MeV}$)



$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

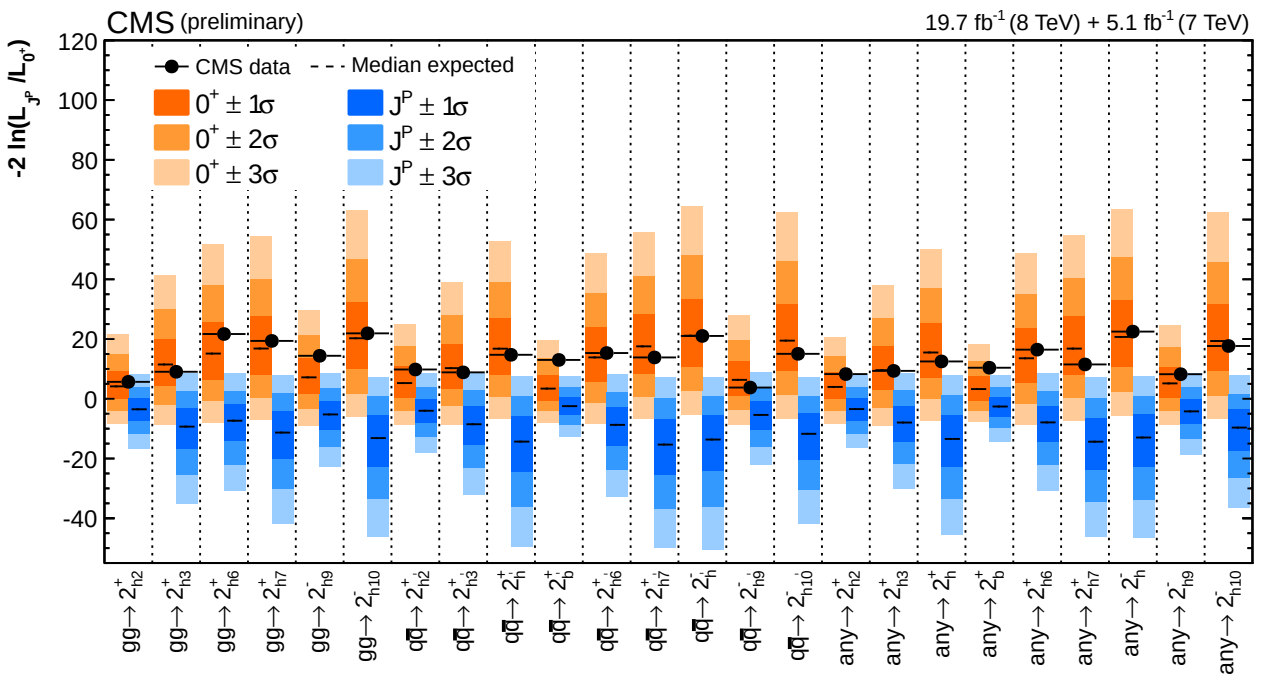
$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

- Applicable to VBF
- On-shell range: $[105.6 - 140.6]\,\text{GeV}$
- Off-shell $> 220\,\text{GeV}$

Spin-parity

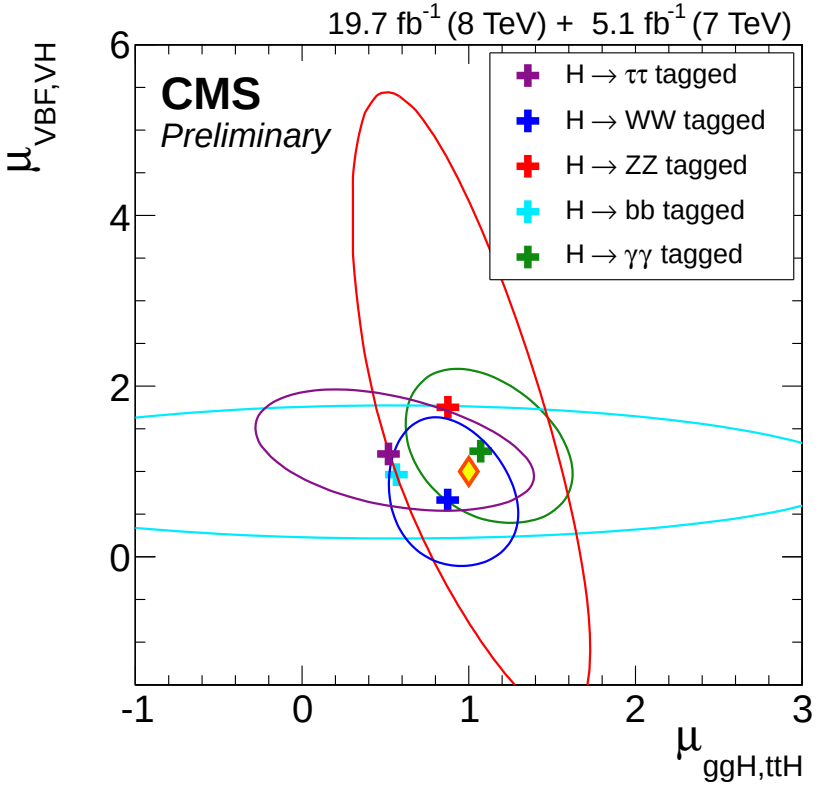
Eur. Phys. J. C 74 (2014) 3076 | CMS-HIG-14-018 (PRD)

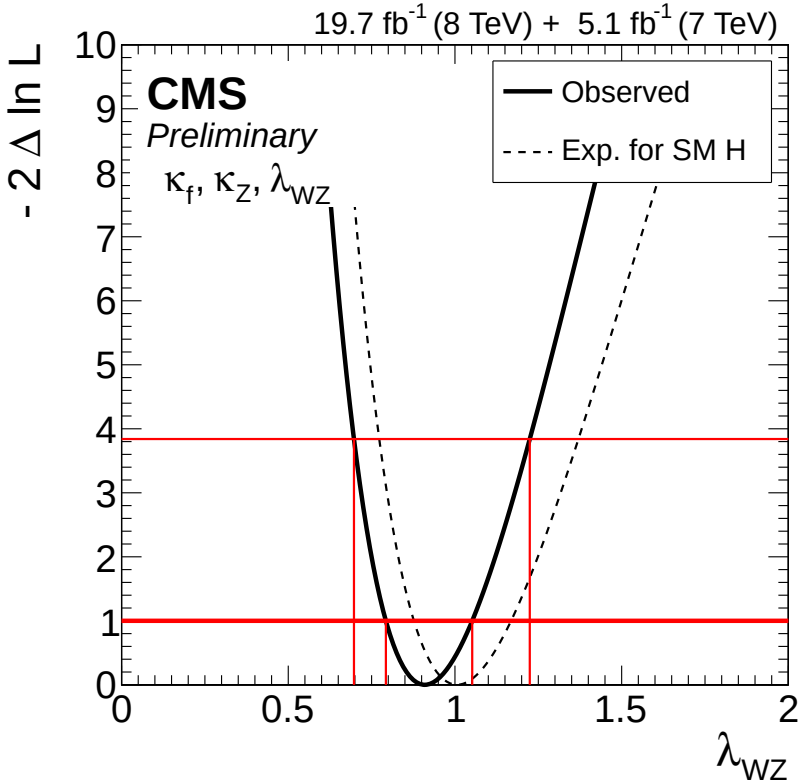
- Spin 1 excluded by observation of $H\gamma\gamma$ (Laundau-Yang th.)
- $H\gamma\gamma$: fit on $\cos\theta^*_{CS}$
- HZZ : kinematic discriminant
- HWW : binned ML
- Tested also mixtures (and not only pure states)
- **All tests favors $J^{PC} = 0^{++}$**



Custodial symmetry

CMS-PAS-HIG-14-009



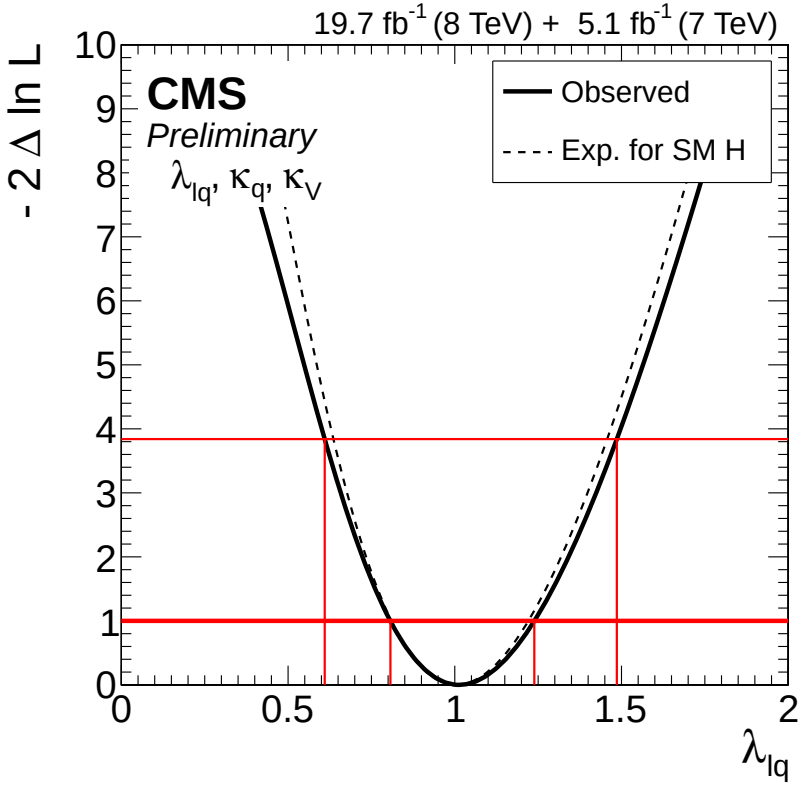


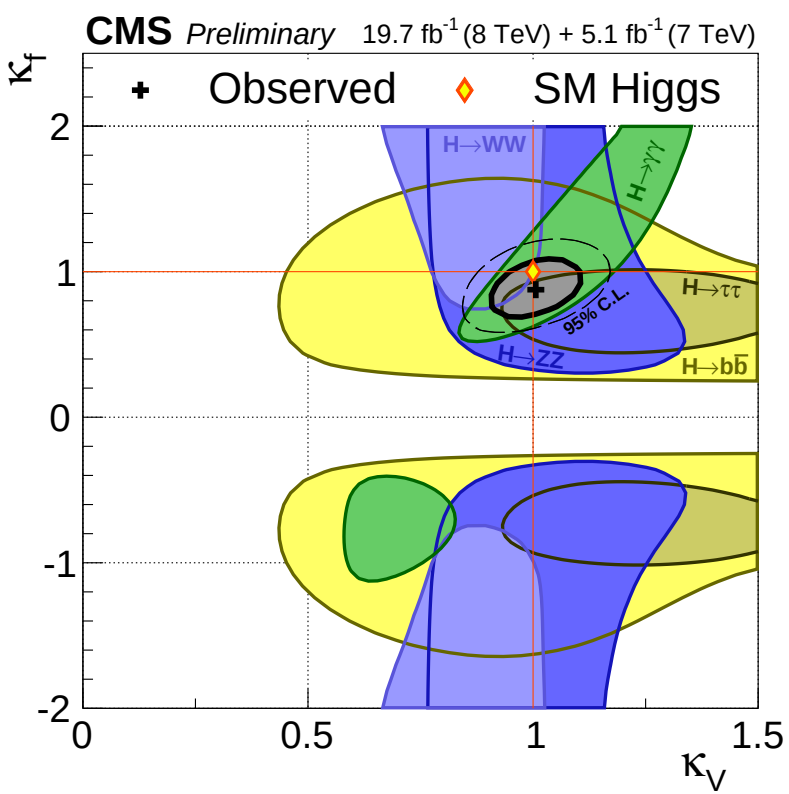
- Couples '**as a Higgs boson**' to W and Z bosons
- Symmetry between W and Z couplings

Couplings to fermions

Nature Physics 10 (2014) 557 | CMS-PAS-HIG-14-009

- **Observation** of coupling to fermions at 4.4σ (3.8)
- $\mu = 0.83 \pm 0.24$
- Similar coupling to quark and leptons



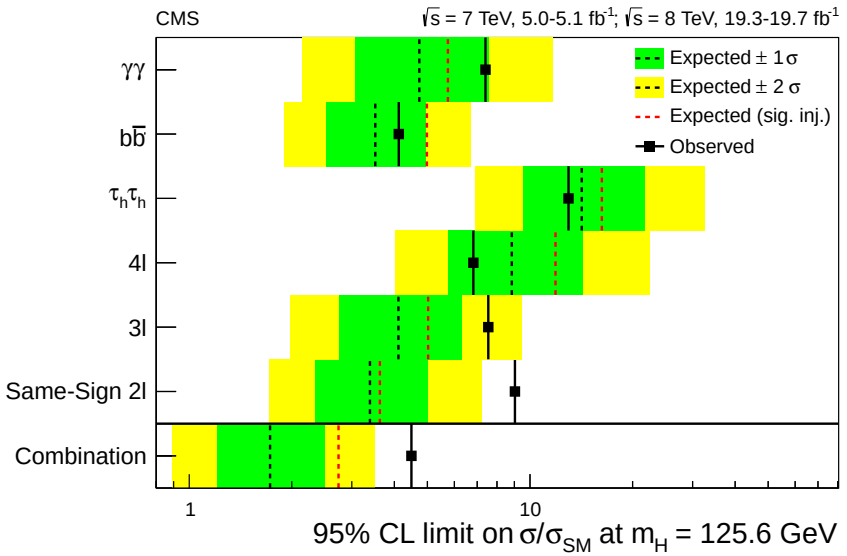


Coupling to top quark

JHEP 09 (2014) 087

$m_H < 2 \cdot m_t$

- HWW, $H b\bar{b}$, $H\gamma\gamma$, $H\tau\tau$, HZZ
- Hadrons (b, τ_h)
  - MVA to separate from $t\bar{t}$
- Photons ($H\gamma\gamma$)
  - Fit to $m_{\gamma\gamma}$ QCD bkg
- Leptons (OS pair or $N_l \geq 3$)
  - MVA for misID
  - MVA for search
- ttH($\sigma = 130$ fb) all decays



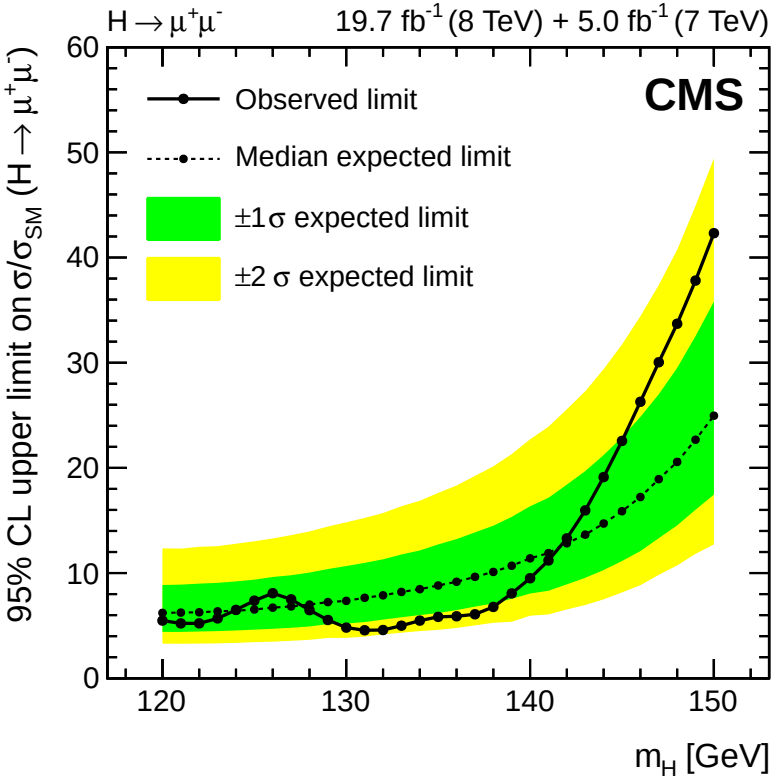
Results

- Observes an **excess** of 3.4σ (1.2) for $m_H = 125.6$ GeV
- $\mu = 2.8^{+1.0}_{-0.9}$
- What about bbH ? Softer spectra...

Lepton universality: $H\mu\mu$ final state

CMS-HIG-13-007 (PLB)

- BR($H\mu\mu$) = 0.0219%
- BR(Hee) = 5×10^{-9}
- Search in $[120 - 150]$ GeV
- Bkg from m_{ll} fit (DY, $t\bar{t}$,VV)
- Categories in (ggH/ VBF), tight/loose, η range, p_T^{ll}

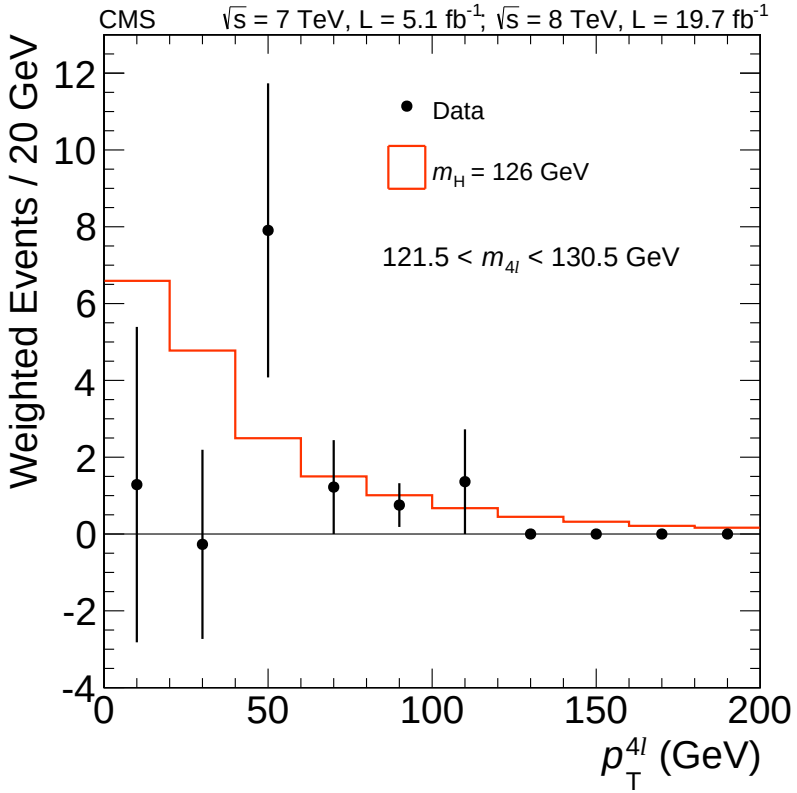


Results

- $H\mu\mu$ search: excludes $7.4\sigma_{SM}$ $(6.5^{+2.8}_{-1.9})$; $\mu = 0.8^{+3.5}_{-3.4}$
- Hee search: excludes 0.041 pb $(0.052^{+0.022}_{-0.015})$, aka $3.7 \times 10^5 \sigma_{SM}$
  - Expect 10^{-3} (SM)Hee events VS 0.23 (SM)$H\gamma\gamma$...
- **Exclusion of universal coupling to leptons**

Differential cross-section

Phys. Rev. D 89 (2014) 092007

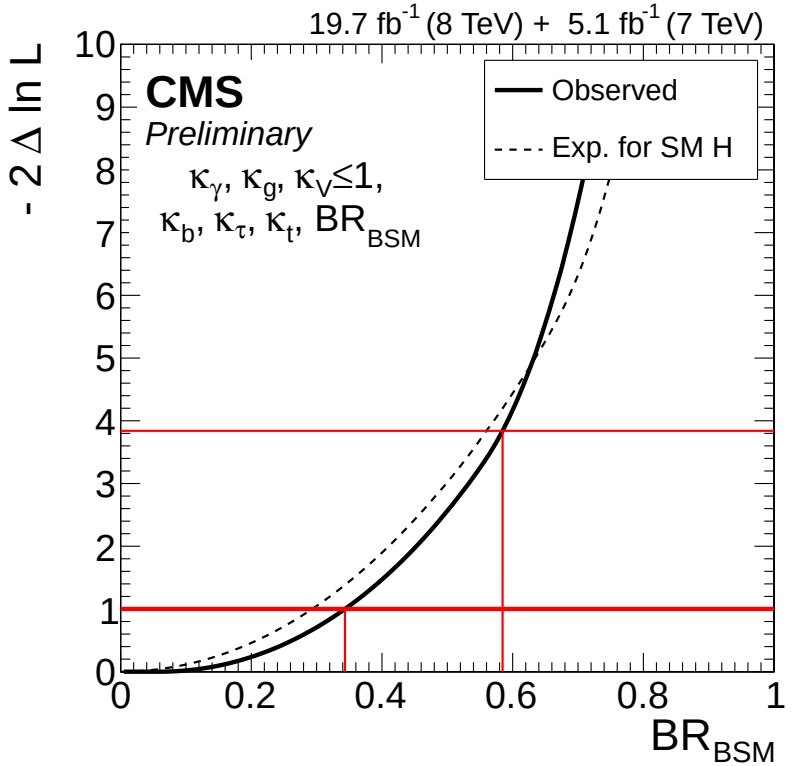


- Kinematics **compatible with expectations**
- Differential cross section from $H\gamma\gamma$ decays in progress

Invisible decays

Eur. Phys. J. C 74 (2014) 2980 | CMS-PAS-HIG-14-009

- BR($HZZ(4\nu)$) = 0.113%
  - Higgs portal for BSM
- Direct search by asking some recoil
  - VBF: single bin counting
  - ZH(ll): fit to $(m_T, \Delta\phi(ll))$
  - ZH($b\bar{b}$): fit to BDT

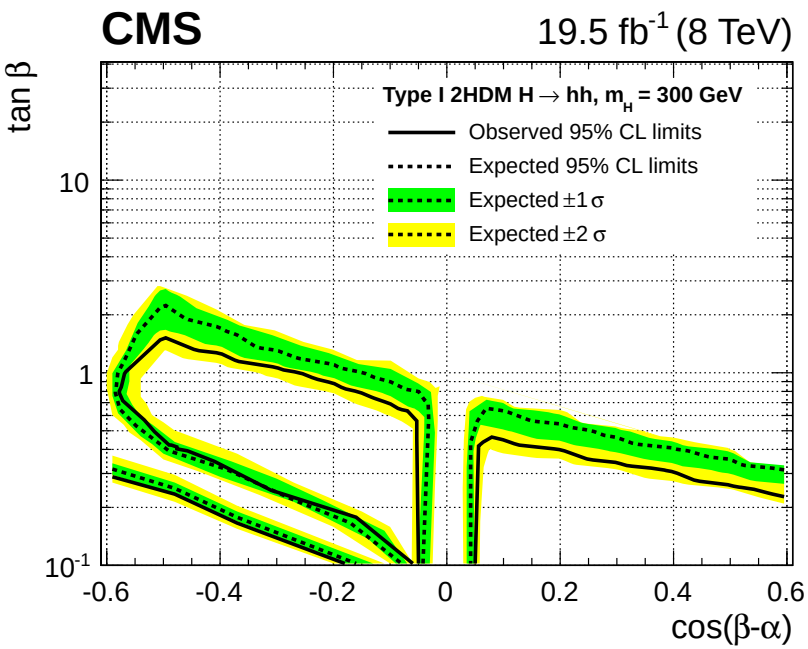


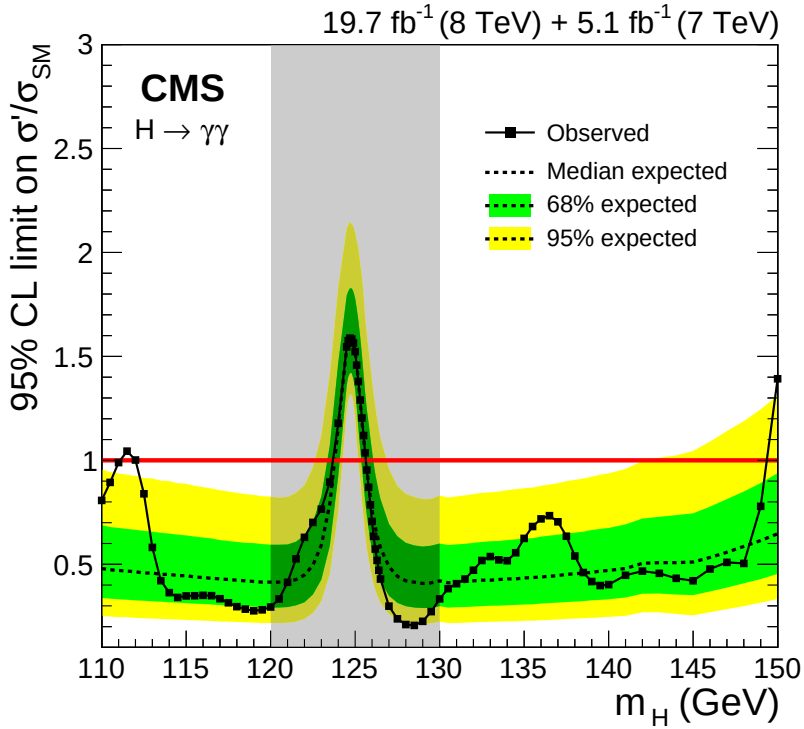
Results

- **No excess** in any of the searches limit: BR < 0.58 (0.44)

Minimal Higgs Sector

Eur. Phys. J. C 74 (2014) 3076 | CMS-HIG-13-025 (PRD)

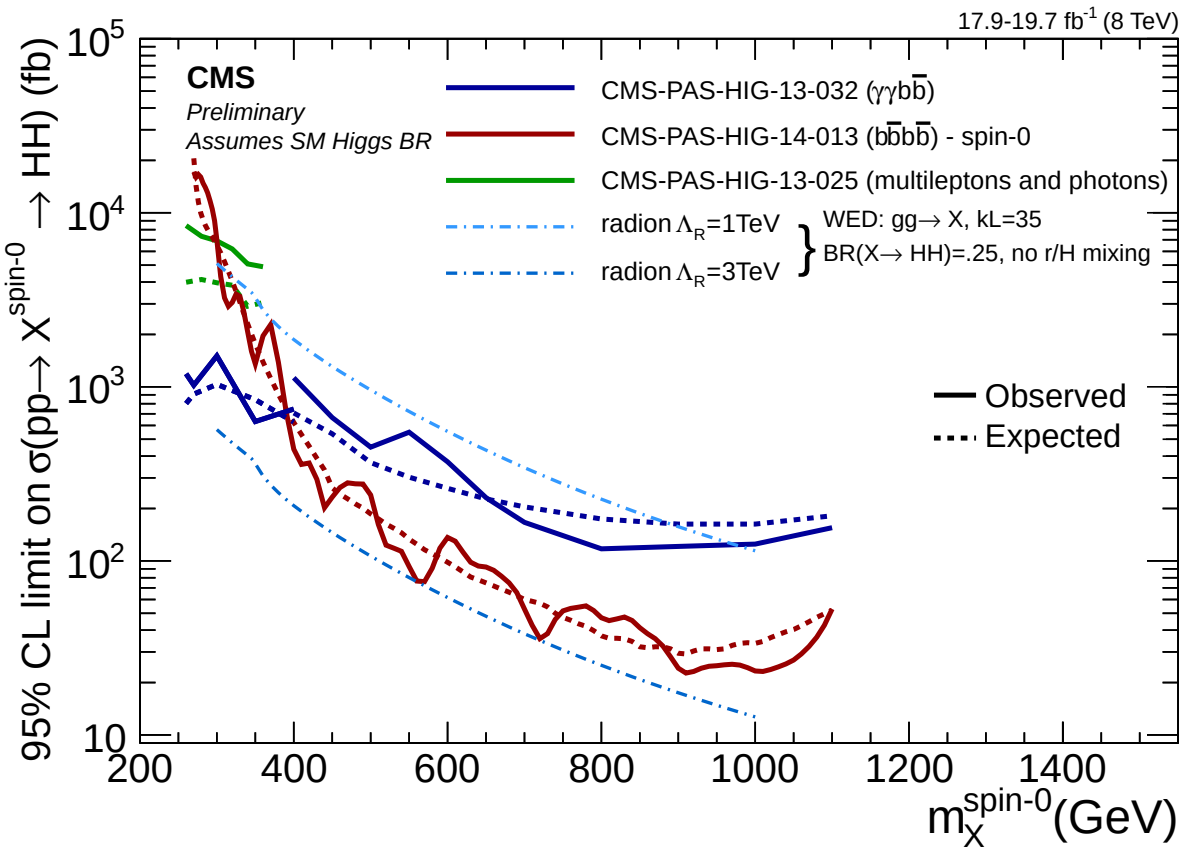




- 2HDM: 5 physical Higgs bosons H, $h(125)$, A, $H^{\pm}$
  - Generic search for $H \to hh$ and $A \to Zh$ in multilepton and photon final states
- Search for additional Higgs-boson like states in $H\gamma\gamma$
- **No excess** observed

Self coupling HHH

CMS-PAS-HIG-13-032 CMS-PAS-HIG-14-013



- Search for heavy resonance decaying into two $H(125)$
  - Dedicated searches in $H(b\bar{b})H(\gamma\gamma)$ and $H(b\bar{b})H(b\bar{b})$
- **No excess** observed
- Preparation to constrain **HHH and WWHH** couplings

Conclusions

Conclusions

What about the one we discovered? **Is it the one?**

- Mass in the expected range
- Spin-parity favors 0^+
- Signal strength and couplings match SM prediction

It is a one!

"Higgs boson and nothing else" was the worst-case outcome
but the story has not ended yet...:

- Rare and exotic decays ($t' \to tH$?, flavor changing, ...)
- Deviation from SM to be looked for
- Other Higgs bosons (higher/lower mass, charged, res. prod.)
- There remains unturned stones (HHH, WWHH)
- Other corners than the Higgs one

Run I legacy analyses are (mostly) all out

Eagerly preparing for Run II!