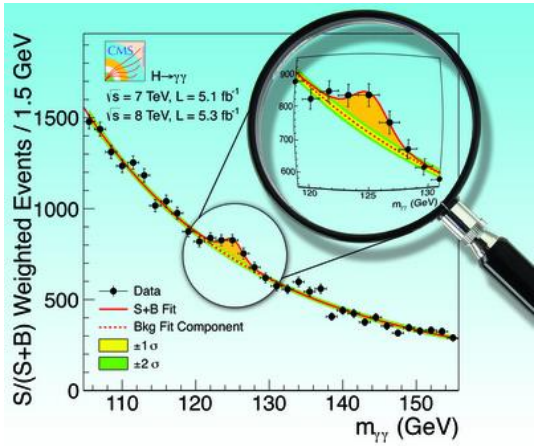


Measurements of the Higgs Boson properties by the CMS Experiment

Carlos Avila,

Universidad de los Andes, Colombia

On behalf of

The CMS collaboration

Is the boson discovered the SM Higgs boson?

SM HIGGS BOSON PROFILE

- Spinless,
- Neutral charge,
- even parity,
- Higgs mass is not predicted, it is a free parameter in the SM.
- Production cross sections, couplings to fermions and bosons, total width are well determined once the mass is fixed.

Charaterization of this new boson is of crucial importance…

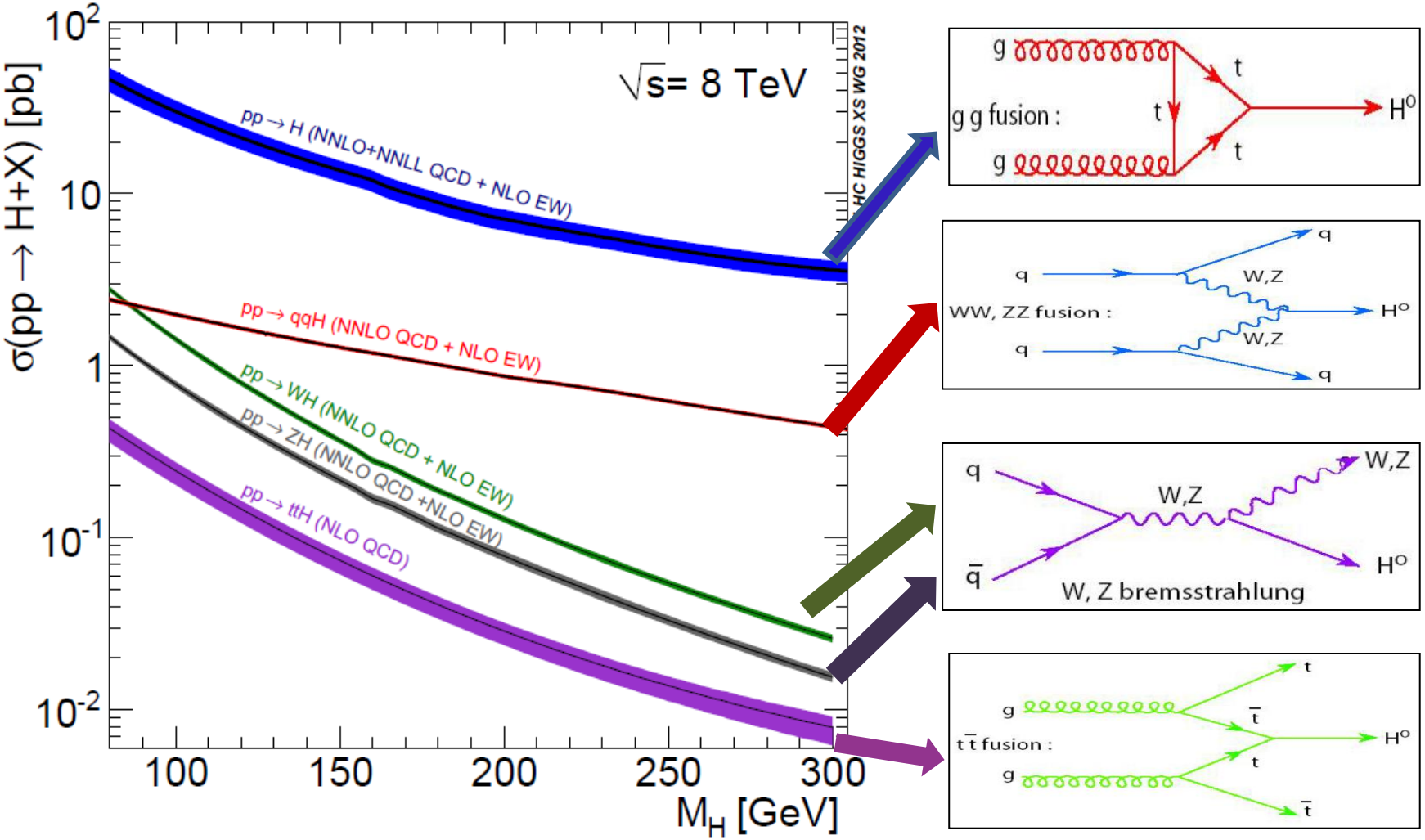
HIGGS PROFILE AT CMS

FROM RUN 1 DATA:

- 5.1 fb^{-1} at 7 TeV
- 19.7 fb^{-1} at 8 TeV

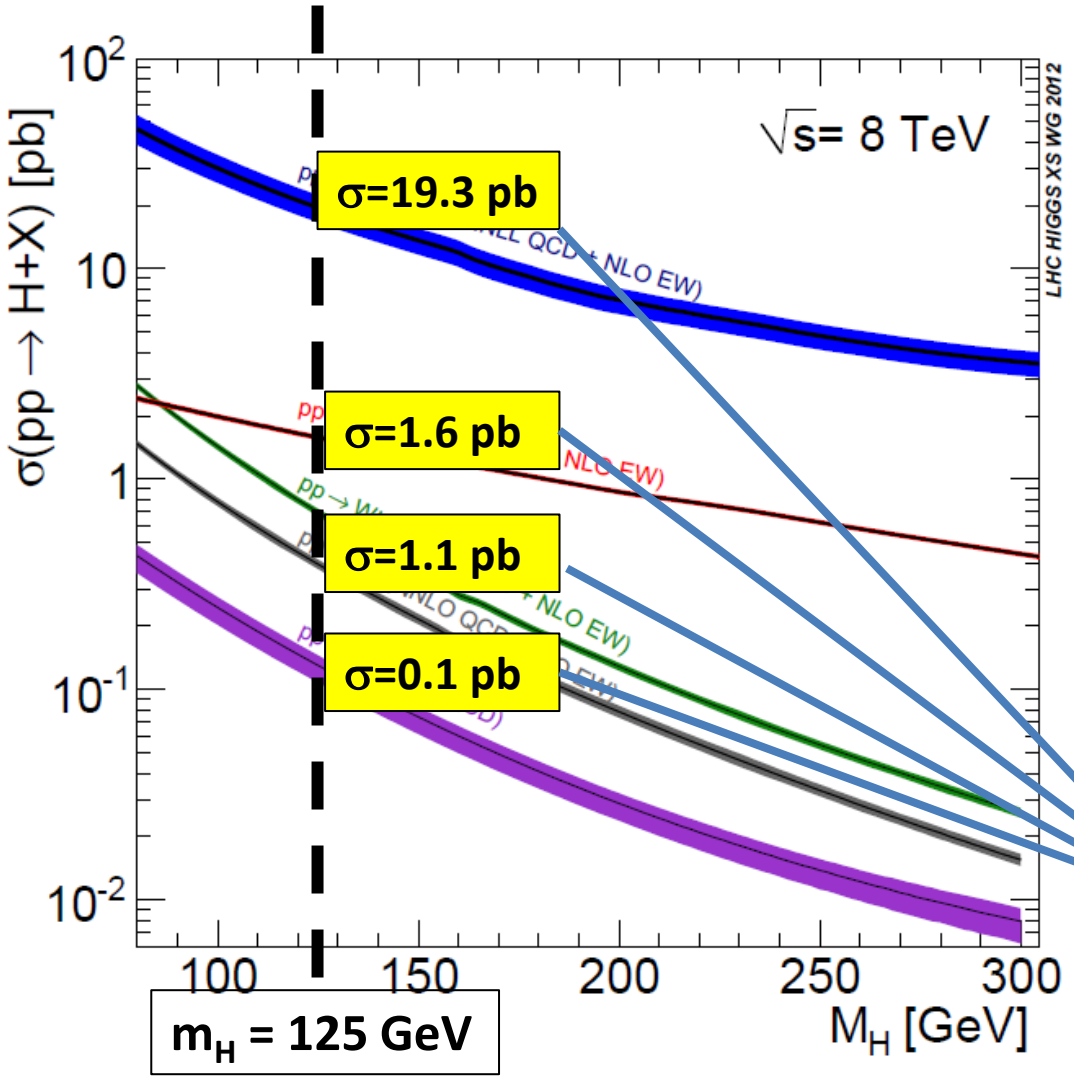
SM HIGGS CROSS SECTIONS

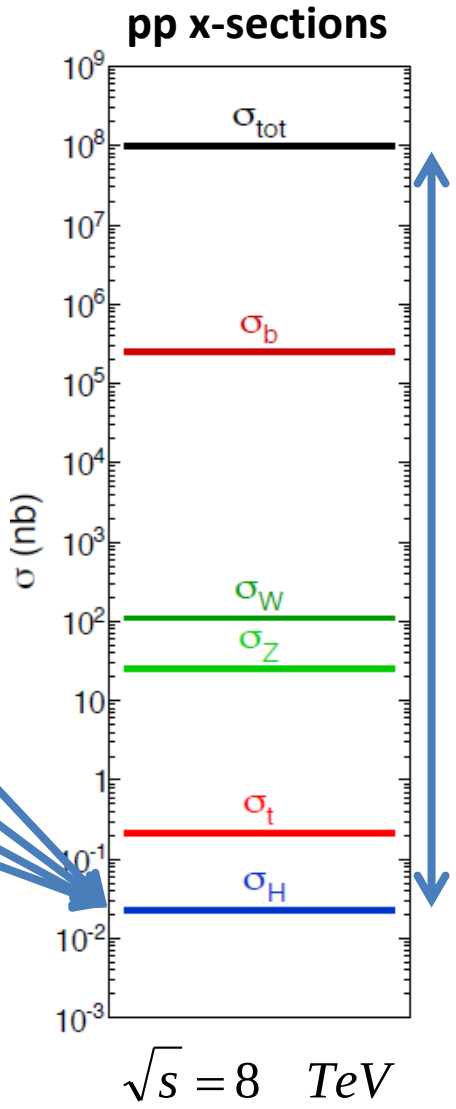
arXiv:1307.1347v2



SM HIGGS CROSS SECTIONS

arXiv:1307.1347v2





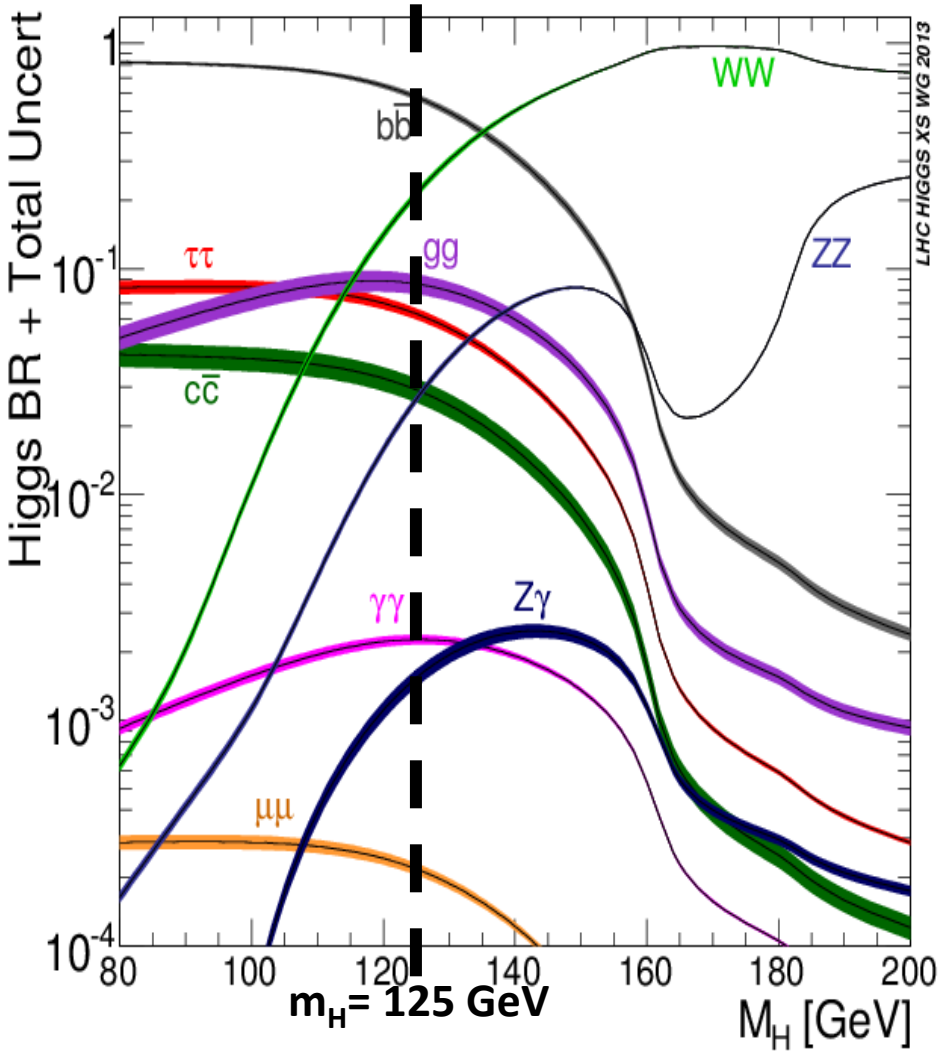
2 Higgs produced every 10^{10} pp collisions

$L_{run\ I}$ = 25 fb^{-1}

~ 550k Higgs produced in RUN I

SM HIGGS DECAYS

arXiv:1307.1347v2



m_H= 125 GeV

Decay	BR(%)
H→bb	57.7
H→WW	21.5
H→ττ	6.3
H→ZZ	2.6
H→ γγ	0.23
H→ Zγ	0.15
H→μμ	0.02
H→gg	8.6
H→cc	2.9
H→ss	0.02

Main Decay Channels

- H→ γγ
- H→ZZ
- H→WW
- H→ττ
- H →bb
- H→ Zγ
- H→μμ

HIGGS SIGNAL SIGNIFICANCE

EPJ C 75 (2015) 212 arXiv: 1506.01010

	ggH	qqH	VH	ttH	Significance Observed (expected)	σ_m/m
H→ZZ (4ℓ)	✓	✓	✓		6.5 (6.3) σ	1-2 %
H→ γγ	✓	✓	✓	✓	5.6 (5.3) σ	1-2 %
H→WW(2ℓ2ν)	✓	✓	✓	✓	4.7 (5.4) σ	15 %
H→ ττ	✓	✓	✓	✓	3.8 (3.9) σ	10-20%
H→ bb		✓	✓	✓	2.6 (2.7) σ	10%
H→μμ		✓	✓		0.4 (<0.1) σ	1-2%

MASS MEASUREMENT
Individual Channels

Two channels with very good mass resolution: **H→ γγ** and **H→ZZ→4ℓ** (ℓ=e,μ)
Narrow resonances over smooth backgrounds in the invariant mass distributions.

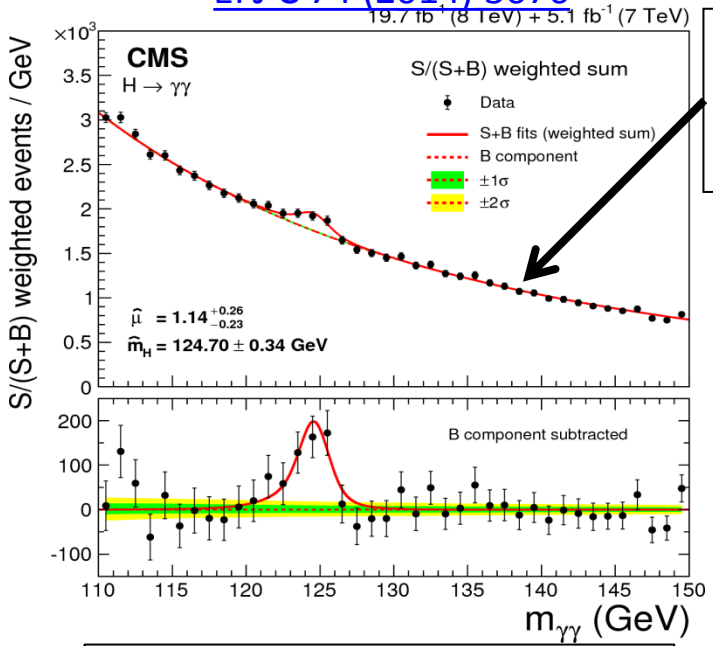
H→ γγ

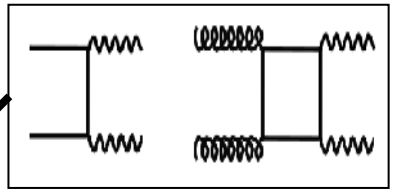
- Events classified into 11-14 exclusive categories
- Simultaneous fit to all $m_{\gamma\gamma}$ distributions
- Signal shape modeled from MC
- Background modeled by a function fit to data

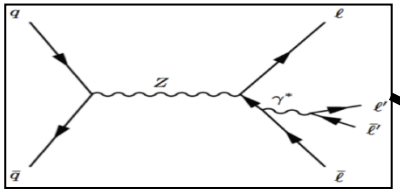
H→ZZ→4ℓ (4μ, 2e2μ,4e)

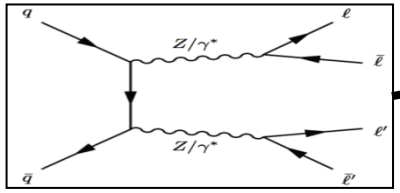
- Full kinematics info used to reduce background
- Isolated leptons, $p_T^e > 7$ GeV , $p_T^\mu > 5$GeV
- 3D Likelihood used for mass measurement.
- Signal and background modeled by MC

EPJ C 74 (2014) 3076

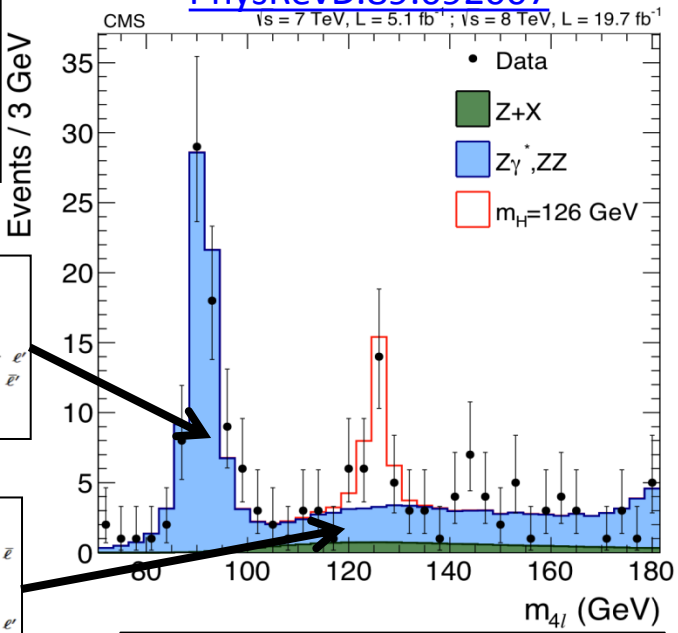








PhysRevD.89.092007



m_H=124.70±0.31±0.15 GeV

0.28% uncertainty

m_H=125.6±0.4±0.2 GeV

0.36% uncertainty

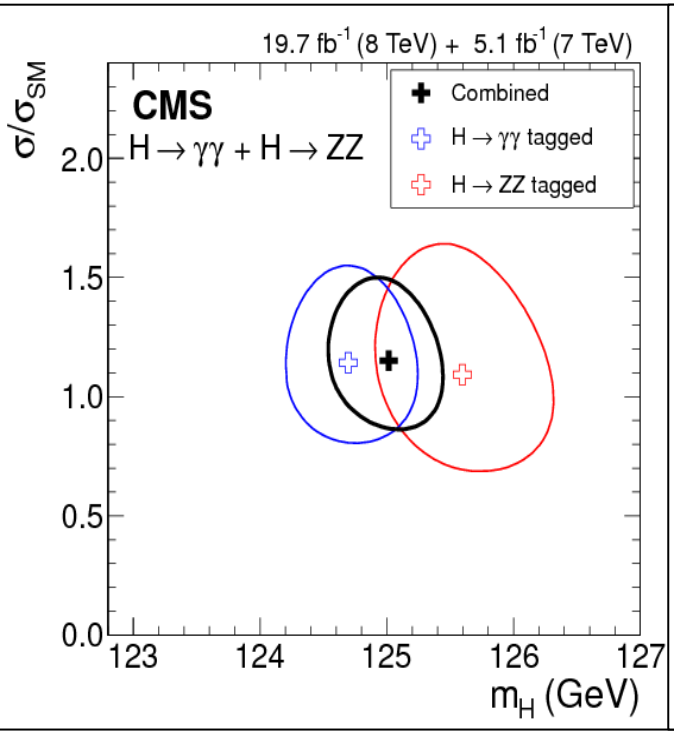
MASS MEASUREMENT

Combination of H→ γγ , H→ZZ channels

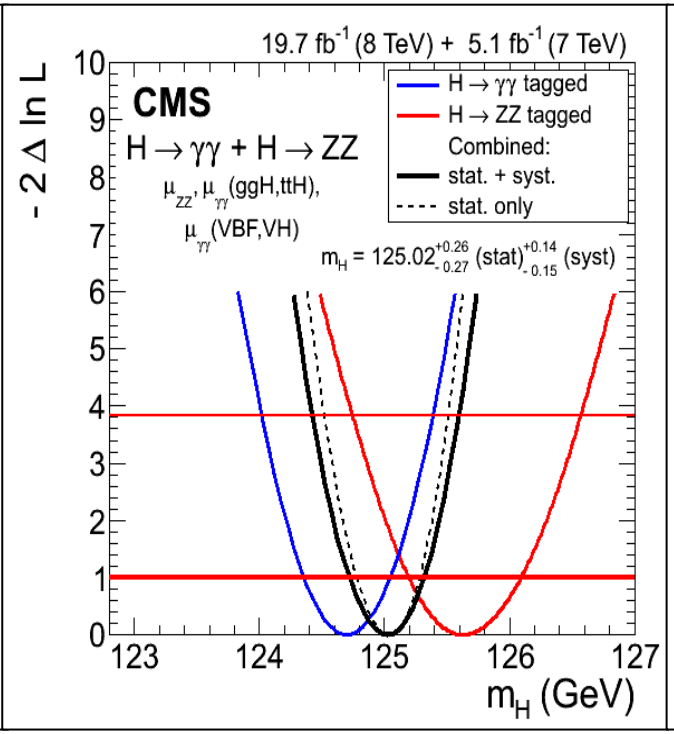
EPJ C 75 (2015) 212

- Assume single state with mass m_H for both channels
- m_H is extracted from the combined test statistic scan
- Production and decay ratios float freely in the scan

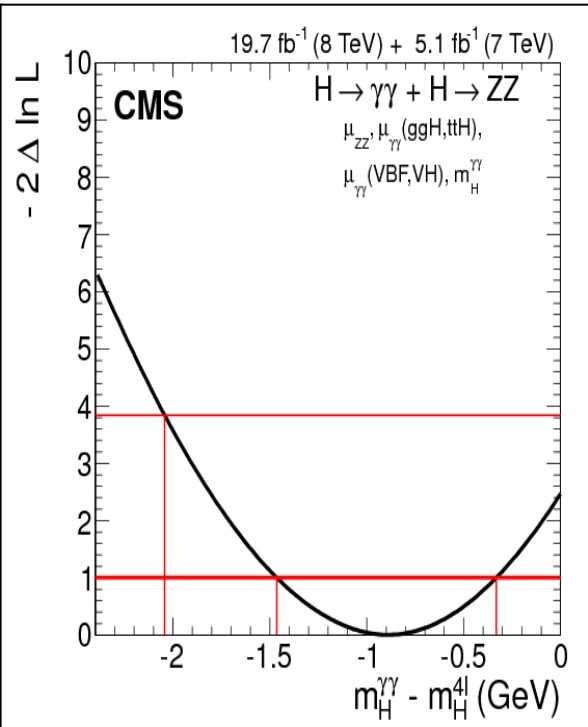
68% CL regions



Test statistic scan



Compatibility within 1.6 σ



$$m_H = 125.02^{+0.26}_{-0.27}(\text{stat})^{+0.14}_{-0.15}(\text{syst.})$$

0.25% uncertainty

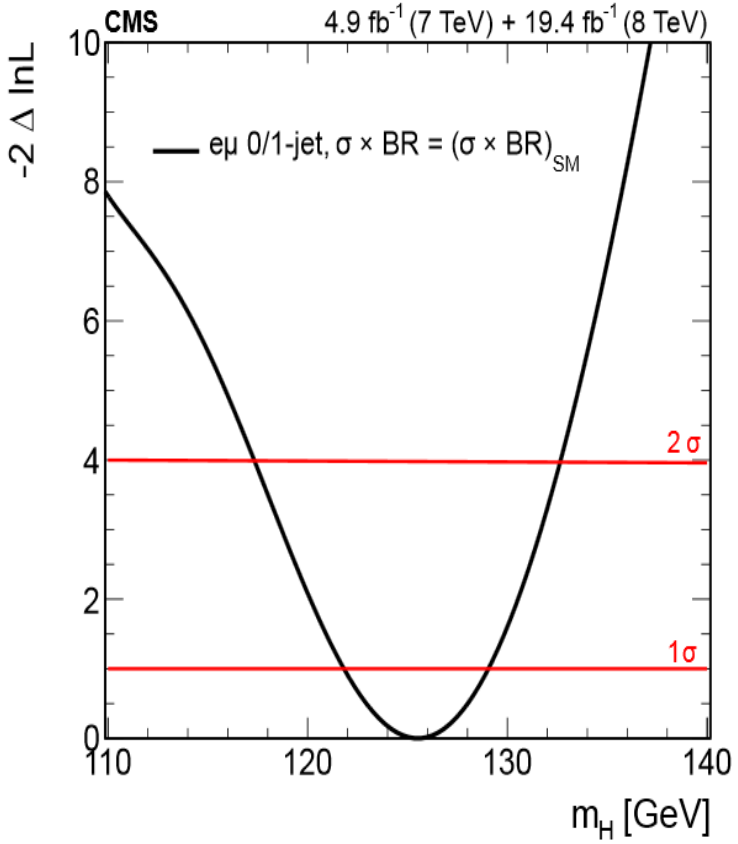
MASS MEASUREMENT

H→WW, H→ττ lower precision, but still within 5% uncertainty

Compatibility to other channels

JHEP 01 (2014) 096

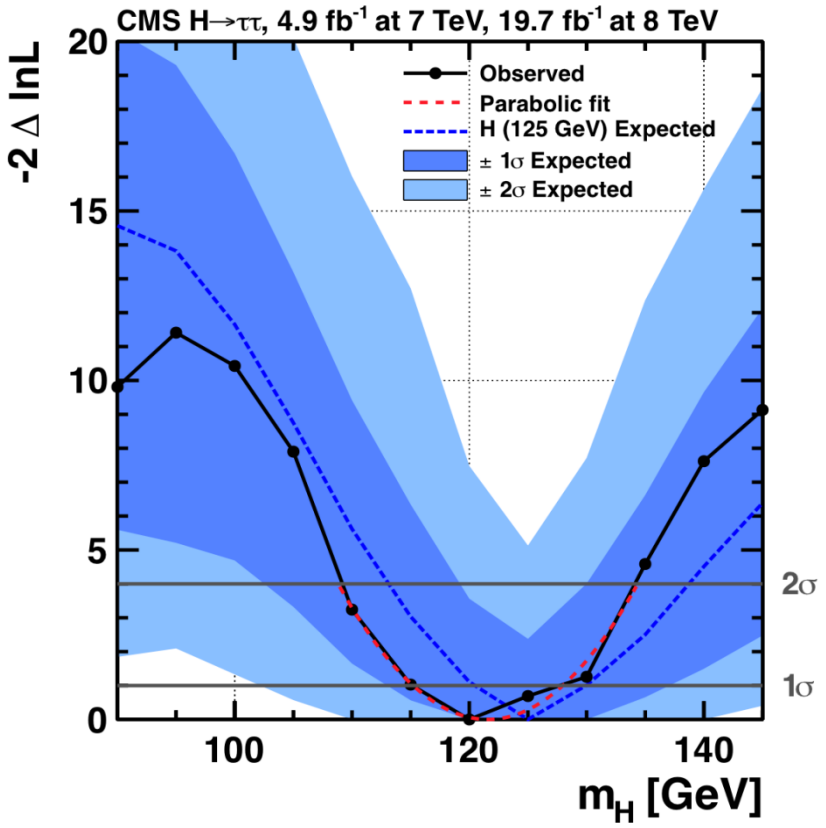
H→WW



$m_H = 125.5 \,^{+3.6}_{-3.8}$ GeV

JHEP 05 (2014) 104

H→ττ



$m_H = 122 \pm 7$ GeV

MASS MEASUREMENT

Combined measurement of ATLAS + CMS (H→ γγ , H→ZZ)

- H→γγ: Events are divided into different $m_{\gamma\gamma}$ categories to improve sensitivity.
- H→ZZ→$e^-e^+\mu^-\mu^+$, $e^-e^+e^-e^+$, $\mu^-\mu^+\,\mu^-\mu^+$ analyzed separately
  ATLAS: 2D fit to $m_{4\ell}$ and BDT background discriminant
  CMS : 3D fit to $m_{4\ell}$, BDT background discriminant and per-event uncertainty in $m_{4\ell}$

$$\Lambda(\alpha)=\frac{L\left(\alpha,\hat{\theta}(\alpha)\right)}{L\left(\hat{\alpha},\hat{\theta}\right)}=\frac{\text{Maximum likelihood for a given }\alpha}{\text{Global maximum likelihood}}$$

α = parameters of interest (eg. m_H)
θ = nuisance parameters (eg. systematics)

$\hat{\alpha},\hat{\theta}=$ Best fit values

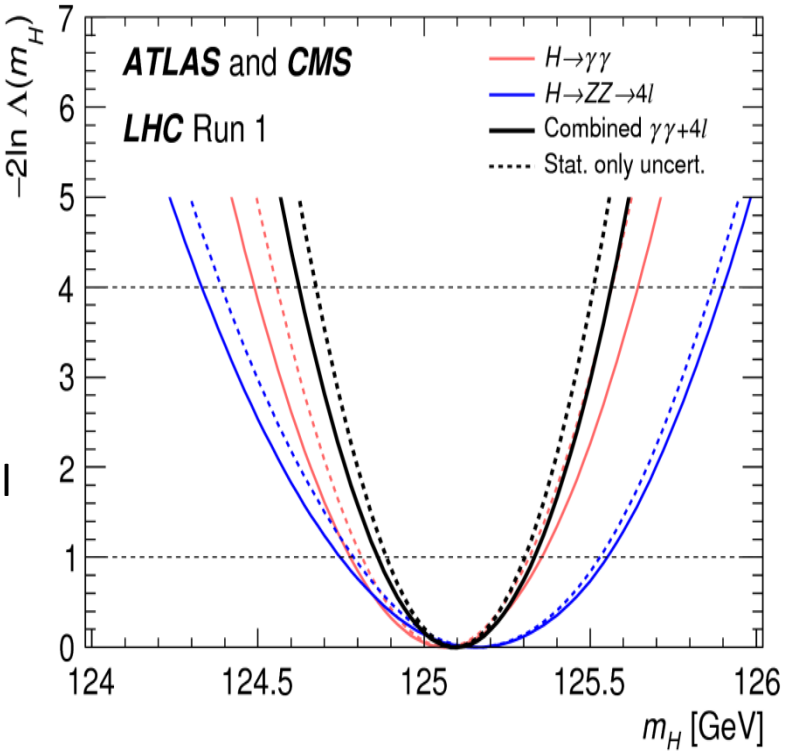
L(α,θ) = product of signal and background PDFs.

To combine: multiply likelihood terms for each channel

$$\Lambda(m_H)=\frac{L\left(m_H,\hat{\mu}^{\gamma\gamma}_{ggF+ttH}(m_H),\hat{\mu}^{\gamma\gamma}_{VBF+VH}(m_H),\hat{\mu}^{4\ell}(m_H),\hat{\theta}(m_H)\right)}{L\left(\hat{m}_H,\hat{\mu}^{\gamma\gamma}_{ggF+ttH},\hat{\mu}^{\gamma\gamma}_{VBF+VH},\hat{\mu}^{4\ell},\hat{\theta}\right)}$$

μ = signal strenght modifiers

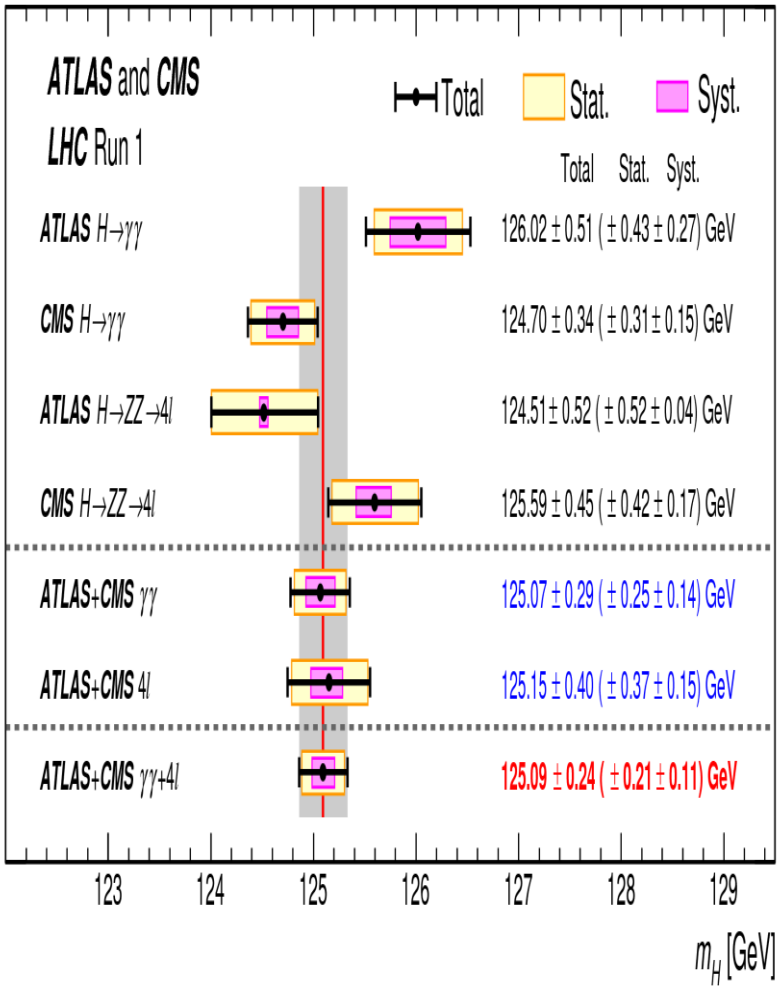
Phys. Rev. Lett. 114 (2015) 191803

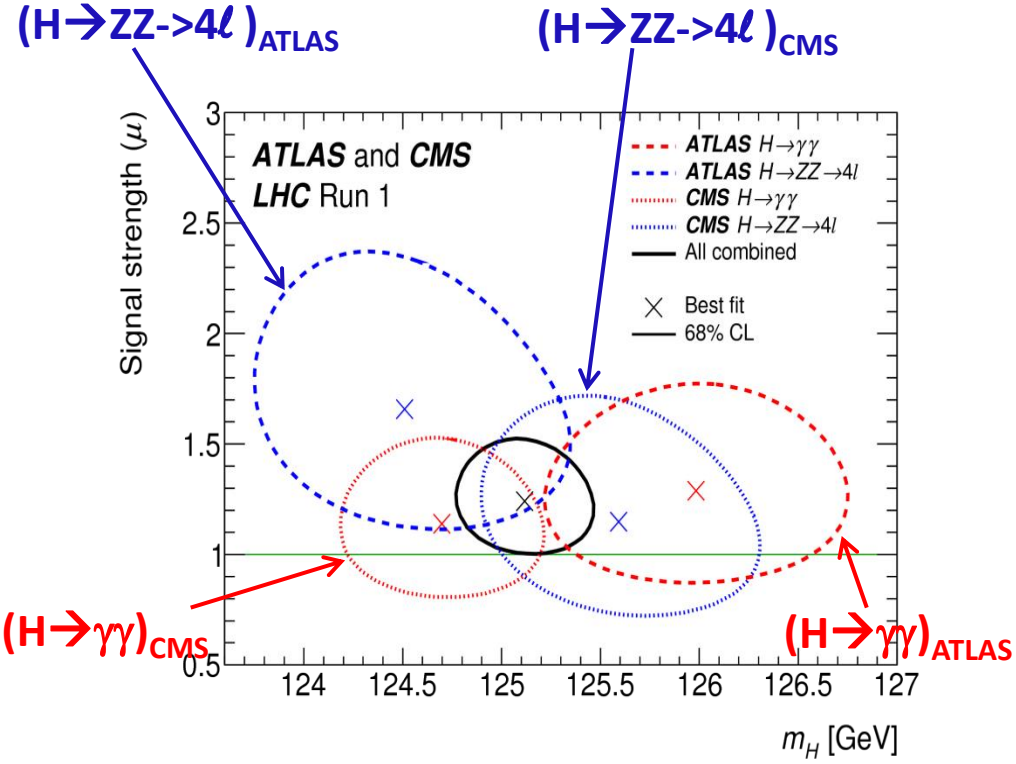


MASS MEASUREMENT

Combined measurement of ATLAS + CMS (H→ γγ , H→ZZ)

Phys. Rev. Lett. 114 (2015) 191803





m_H=125.09±0.21±0.11 GeV

0.19 % Uncertainty

HIGGS WIDTH LIMIT

From direct measurements

EPJ C 75 (2015) 212

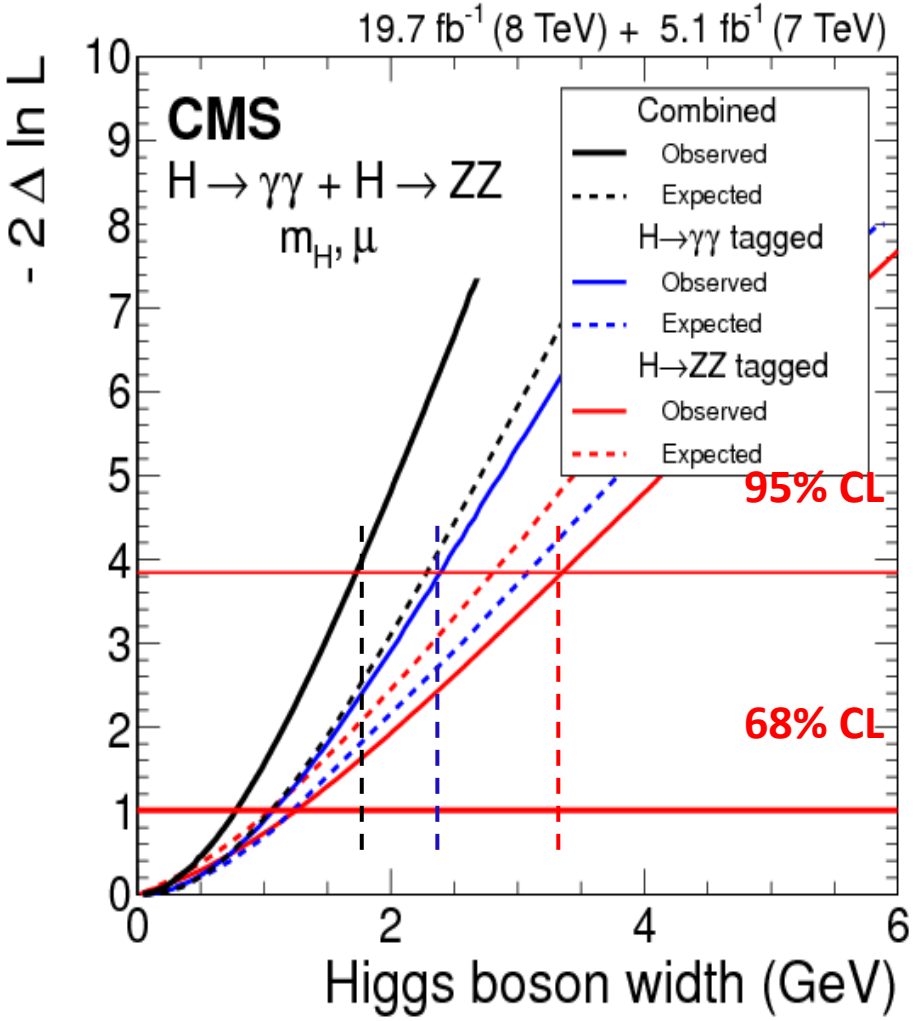
- $\Gamma_H^{SM} \sim 4$ MeV
- A scan of a profile likelihood estimator allows to caculate an upper limit on Γ_H (95% CL).
  Relativistic Breit-Wigner distribution is assumed for the signal.

$\Gamma_H^{ZZ \to 4\ell} \leq 3.4$ GeV

$\Gamma_H^{\gamma\gamma} \leq 2.4$ GeV

$\Gamma_H^{COMBINED} \leq 1.7$ GeV

- Upper limits far away from SM prediction.

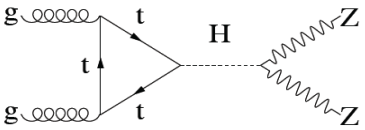


HIGGS WIDTH LIMIT
From off-shell ZZ production

H→ZZ→4ℓ , H→2ℓ2ν, (ℓ=e,μ),

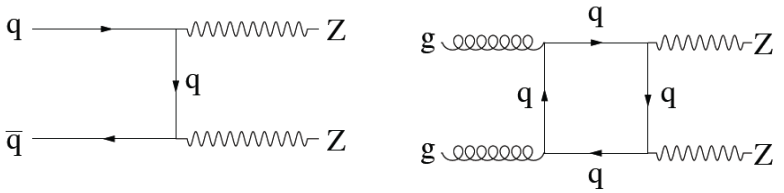
Phys. Lett. B 736 (2014) 64

Breit-Wigner production gg→H→ZZ:



$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{\left(m^2_{ZZ} - m^2_H\right)^2 + m^2_H \Gamma^2_H}$$

Dominant backgrounds:

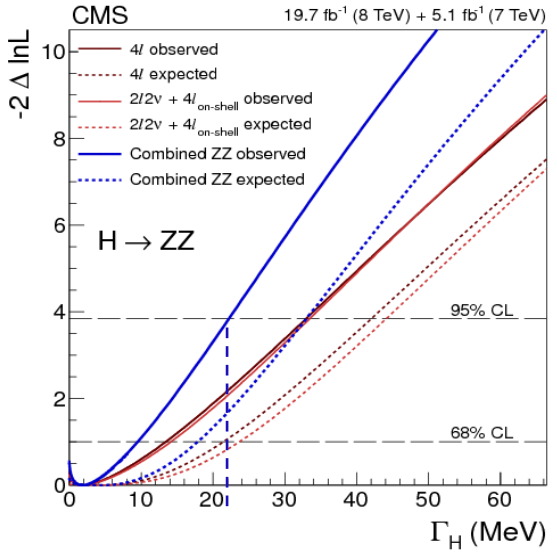


On-peak ($105.6<m_{4\ell}<140.6$ GeV) and off-peak cross sections ($m_{4\ell}>220$ GeV):

$$\sigma^{\text{on-shell}} = \int_{|m-m_H|\le n\Gamma_H} \frac{d\sigma}{dm}\cdot dm \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}} = \int_{m-m_H >> \Gamma_H} \frac{d\sigma}{dm}\cdot dm \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

$$\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H$$



- Must include interference between gg→H→ZZ and gg→Box→ZZ
- K-factor of gg→ZZ not well known, assume the same as signal and add a sytematic uncertainty.

$\Gamma_H < 22$ MeV at 95% CL

HIGGS LIFETIME & WIDTH LIMITS

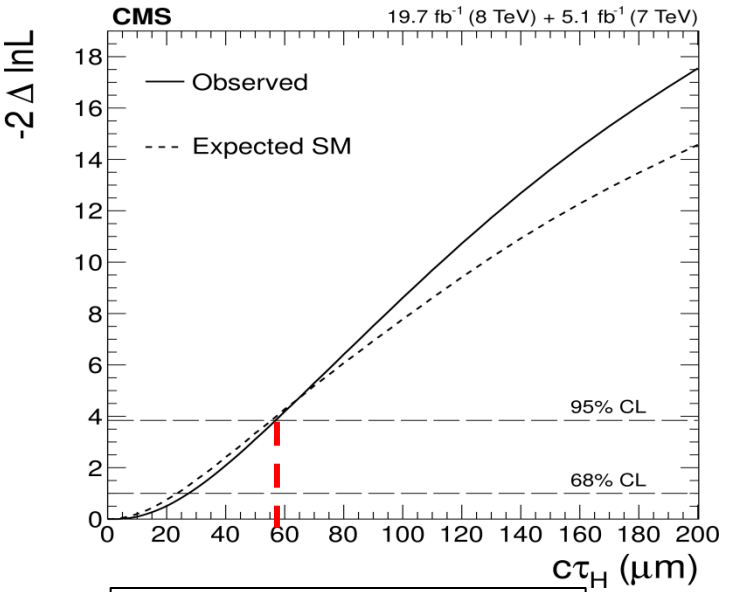
Universidad de los Andes

H→ZZ→4ℓ , (ℓ=e,μ), arXiv:1507.06656

$\tau_{H,SM}$ = 16 x 10^{-8} fs, beyond instrumental precision, we can stablish an upper limit.

- Lifetime derived from flight distance in the CMS detector: $\Delta t = \frac{m_{4\ell}}{p_T}\left(\Delta\vec{r}_T . \hat{p}_T\right)$

$\Delta\vec{r}_T$ = displacement vector between H production vertex and decay



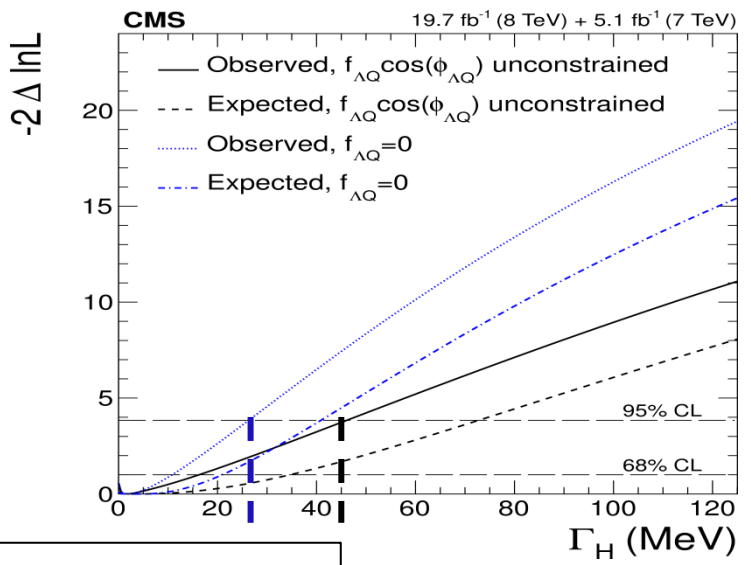
τ_H<1.9x10^{-13} s 95% CL

- Γ_H obtained from off-shell production technique + Anomalous H→VV couplings.

Effective cross section fraction:

$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}$$

$$A(\mathrm{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}}\frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}}\frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2}\right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$
$$+ a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$



Γ_H < 26 MeV for $f_{\Lambda Q}$=0

Γ_H < 46 MeV with $f_{\Lambda Q}$ unconstrained

At 95% CL.

SIGNAL STRENGTH, $\mu=\sigma/\sigma_{SM}$

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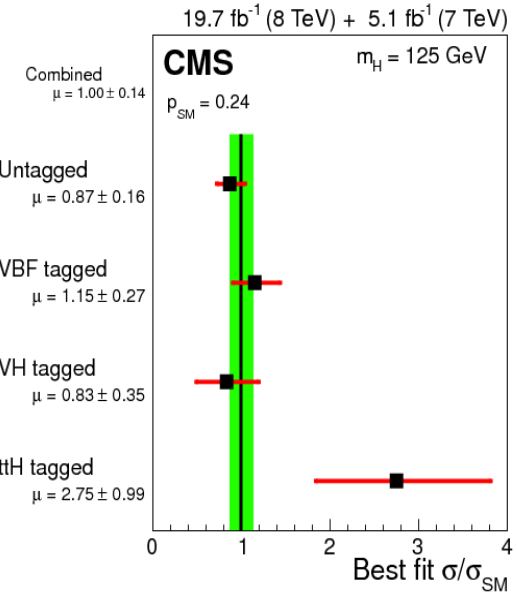

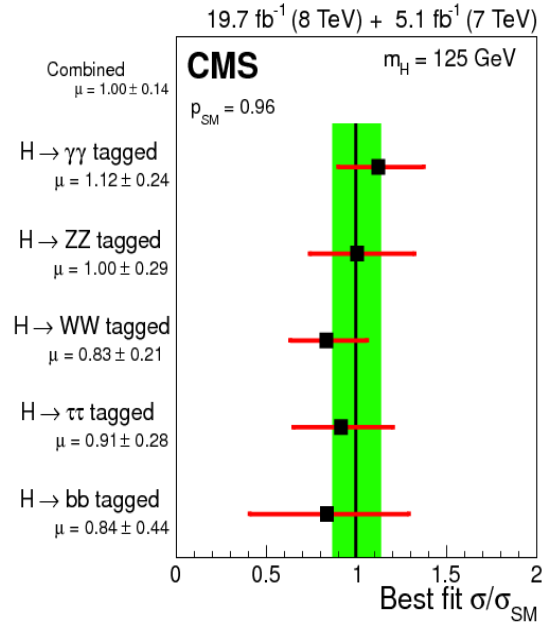

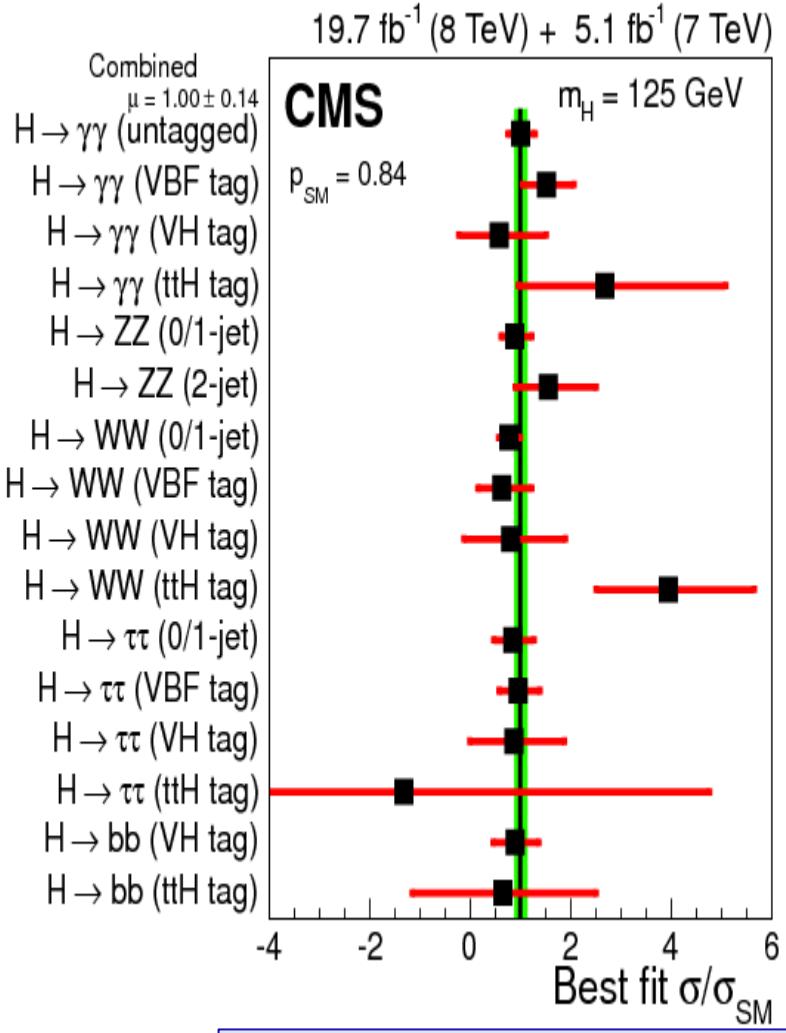

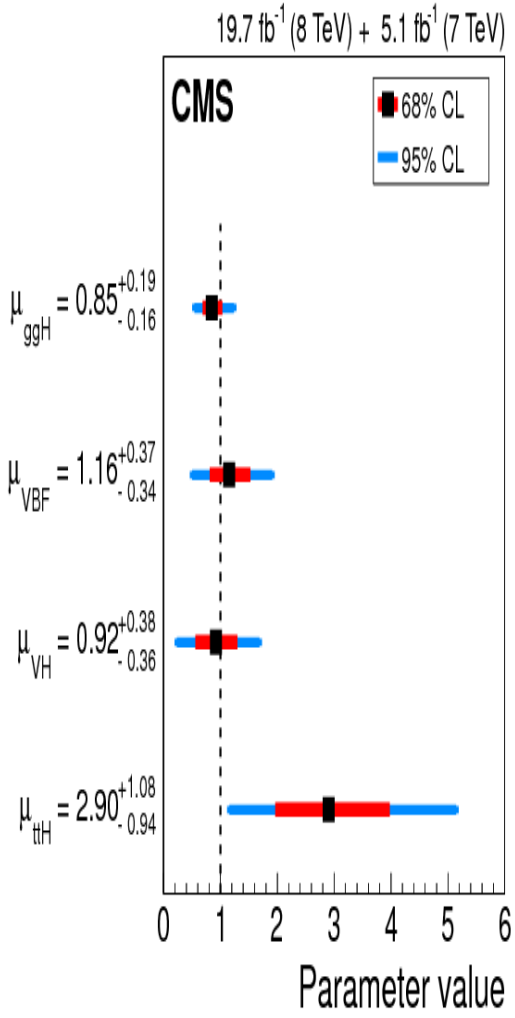

$\mu = 1.00 \pm 0.09$ (stat.) ± 0.08 (theory) ± 0.07 (syst.)

14 % Uncertainty

FERMION, BOSON MEDIATED PRODUCTION PROCESSES

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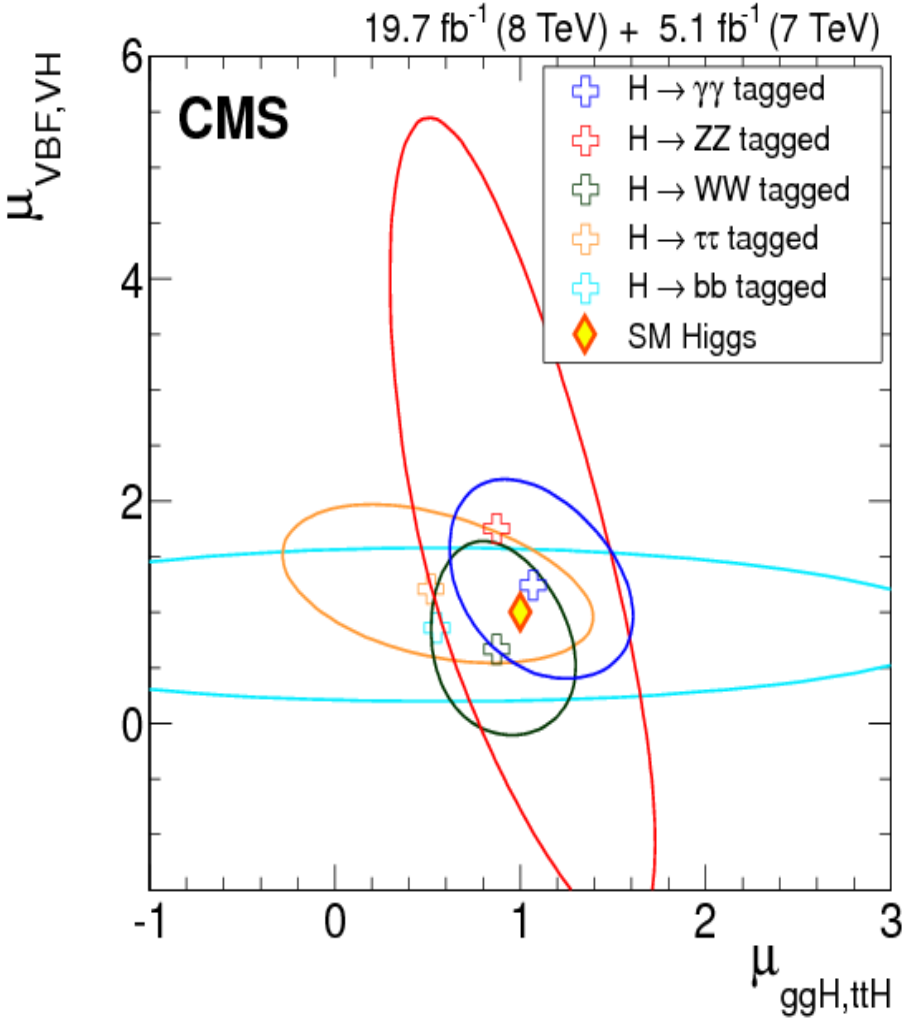

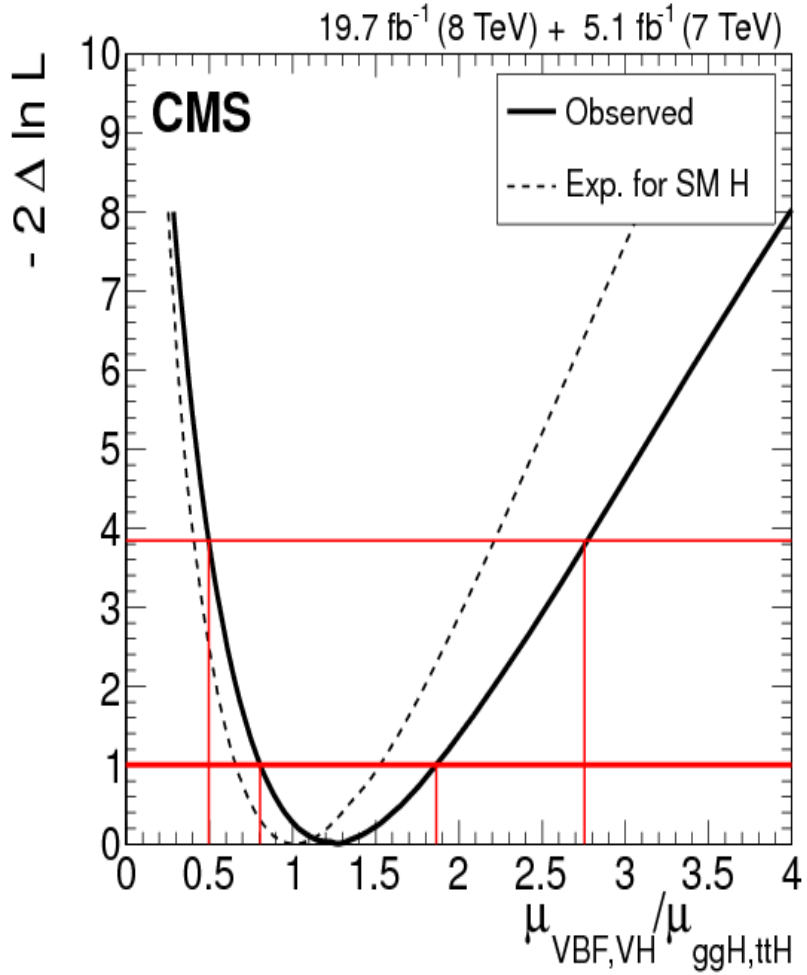

$$\frac{\mu_{\mathrm{VBF,VH}}}{\mu_{\mathrm{ggH,ttH}}} = 1.25^{+0.62}_{-0.44}$$

HIGGS COUPLINGS

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- All signals observed are assumed to come from a single state ($J^{PC}=0^{++}$) with mass of ~125 GeV.
- Zero width approximation is used: $\sigma \times BR(x \to H \to yy) = \frac{\sigma_x \Gamma_{yy}}{\Gamma_{tot}}$
- Scaling factors κ_i are defined to test deviations from SM: $\kappa_i^2 = \frac{\sigma_i}{\sigma_{SM}}$; $\kappa_i^2 = \frac{\Gamma_{ii}}{\Gamma_{ii}^{SM}}$;

$$\sigma \cdot BR(PC \to H \to DC) = \sigma_{SM}(PC \to H).BR(H \to DC) \cdot \frac{\kappa_{PC}^2 \kappa_{DC}^2}{\kappa_H^2}$$

PC=Production Channel ; DC=Decay Channel ; $\kappa_H^2 = \frac{\Gamma_{tot}}{\Gamma_{tot}^{SM}}$

DIFFERENT STUDIES:

- **Test of Custodial Symmetry:** $\lambda_{WZ}=\kappa_W/\kappa_Z$
- **Scaling of vector boson and fermion couplings:** $\kappa_V = \kappa_W = \kappa_Z$; $\kappa_f = \kappa_t = \kappa_b = \kappa_\tau$
- **Assimetries in Fermion couplings:** $\lambda_{du}=\kappa_d/\kappa_u$; $\kappa_u = \kappa_t = \kappa_c$; $\kappa_d = \kappa_b = \kappa_s = \kappa_\tau = \kappa_\mu$; $\lambda_{lq}=\kappa_l/\kappa_q$
- **Scaling of couplings with SM masses:** σ_{ggH}, Γ_{gg}, $\Gamma_{\gamma\gamma}$ are functions of κ_W , κ_Z , κ_t , κ_b , κ_τ , κ_μ
- **M, ε Model**: $\kappa_f = v\frac{m_f^\varepsilon}{M^{1+\varepsilon}}$; $\kappa_v = v\frac{m_v^{2\varepsilon}}{M^{1+2\varepsilon}}$

Custodial Symmetry

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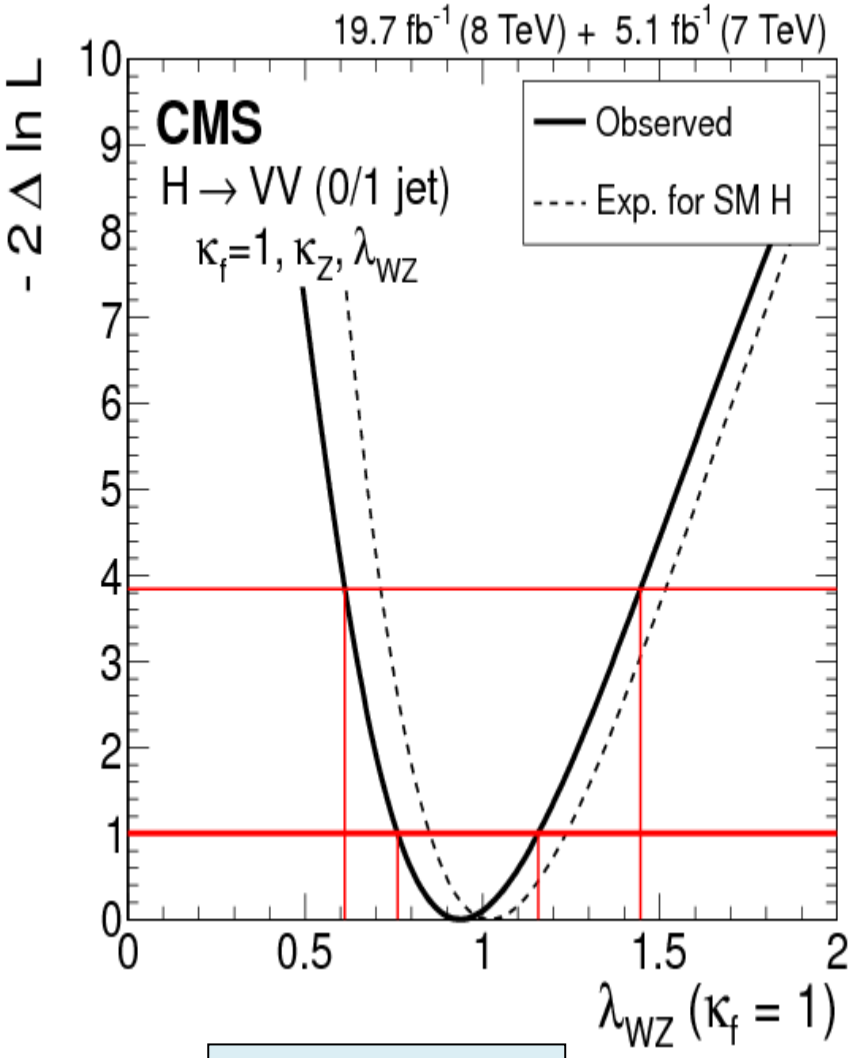
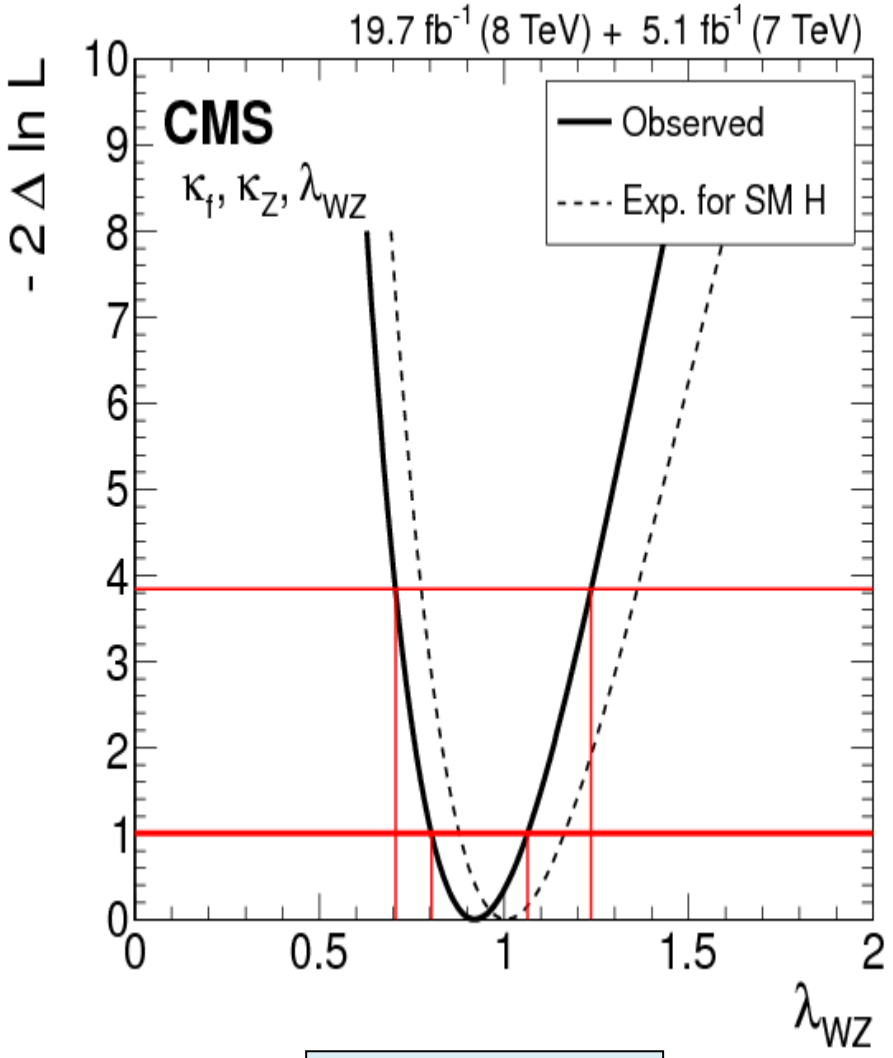
$\lambda_{WZ}=\kappa_W/\kappa_Z$



$$\lambda_{WZ} = 0.94^{+0.22}_{-0.18}$$



$$\lambda_{WZ} = 0.92^{+0.14}_{-0.12}$$

COUPLING TESTS

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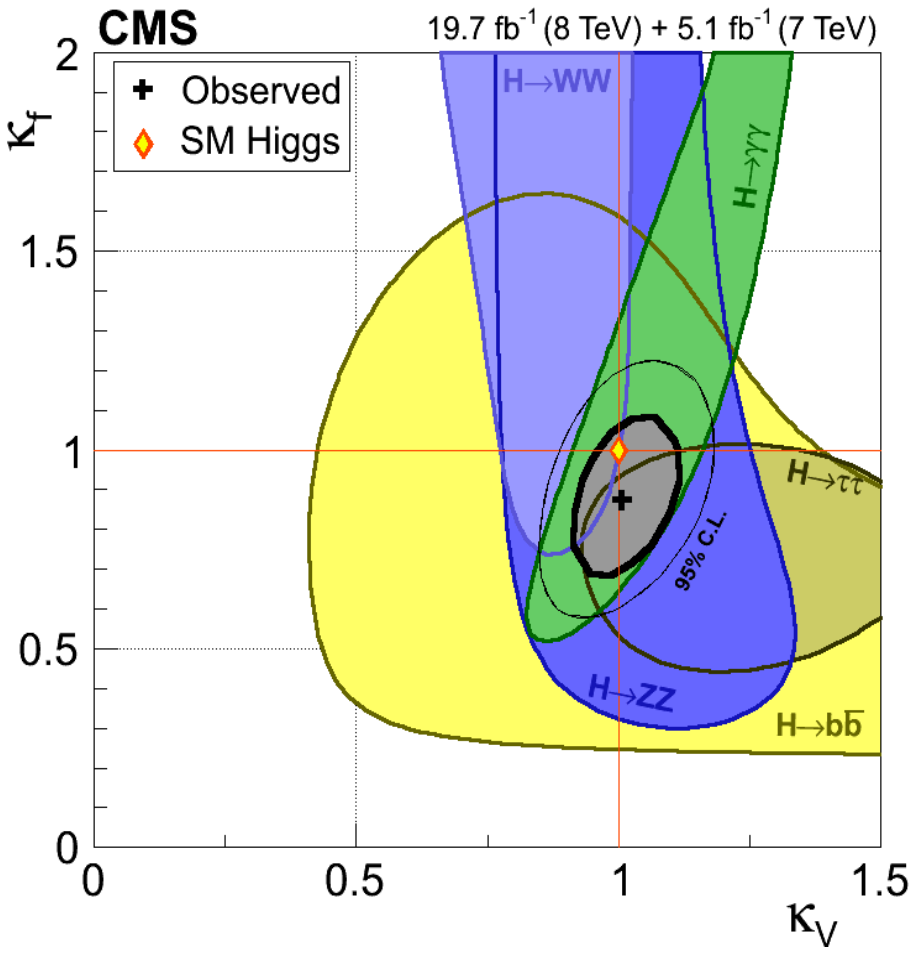
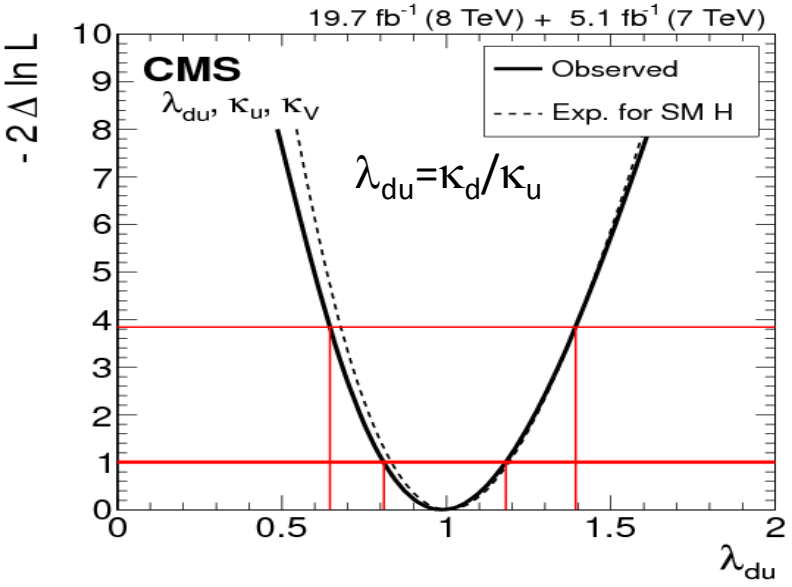
Vector boson / fermion couplings

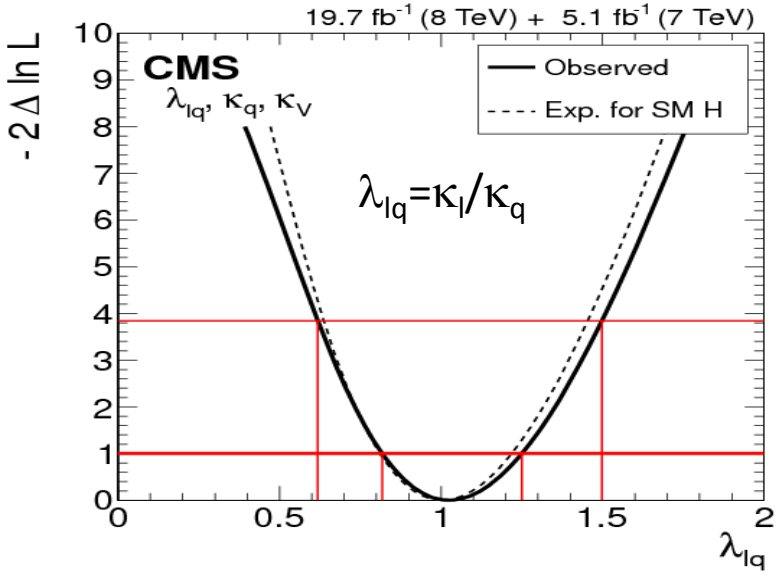


$\kappa_V = \kappa_W = \kappa_Z$

$\kappa_f = \kappa_t = \kappa_b = \kappa_\tau$

Assimetries of fermion couplings





COUPLING TESTS

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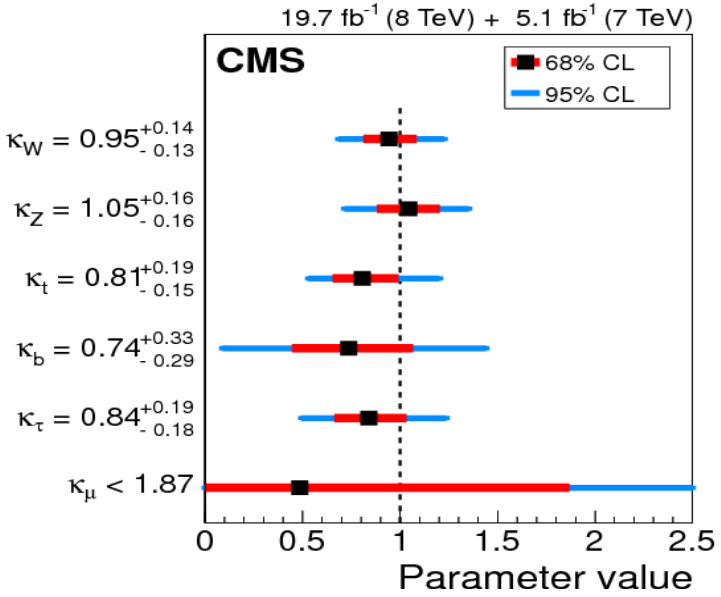
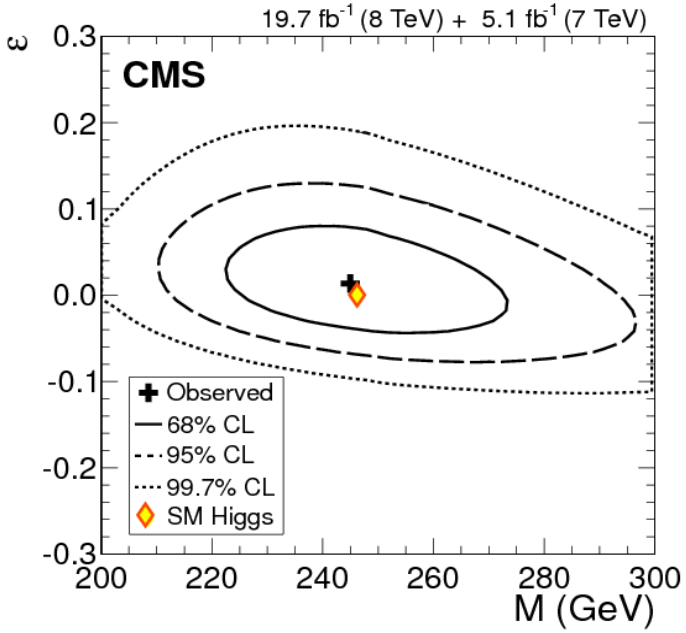
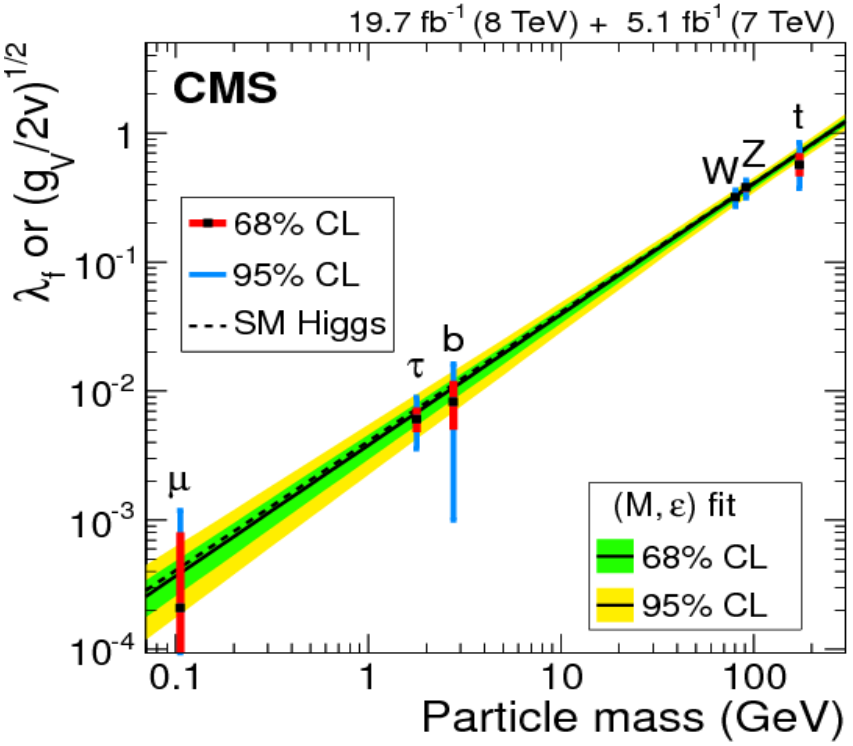






$$\kappa_f = \mathrm{v}\frac{m_f^{\varepsilon}}{M^{1+\varepsilon}} \qquad \kappa_\mathrm{v} = \mathrm{v}\frac{m_\mathrm{v}^{2\varepsilon}}{M^{1+2\varepsilon}}$$

$$g_\mathrm{v} = \kappa_\mathrm{v}\frac{2m_\mathrm{v}^2}{\mathrm{v}} \qquad \lambda_\mathrm{f} = \kappa_\mathrm{f}\frac{m_\mathrm{f}}{\mathrm{v}}$$

v = 246.2 GeV

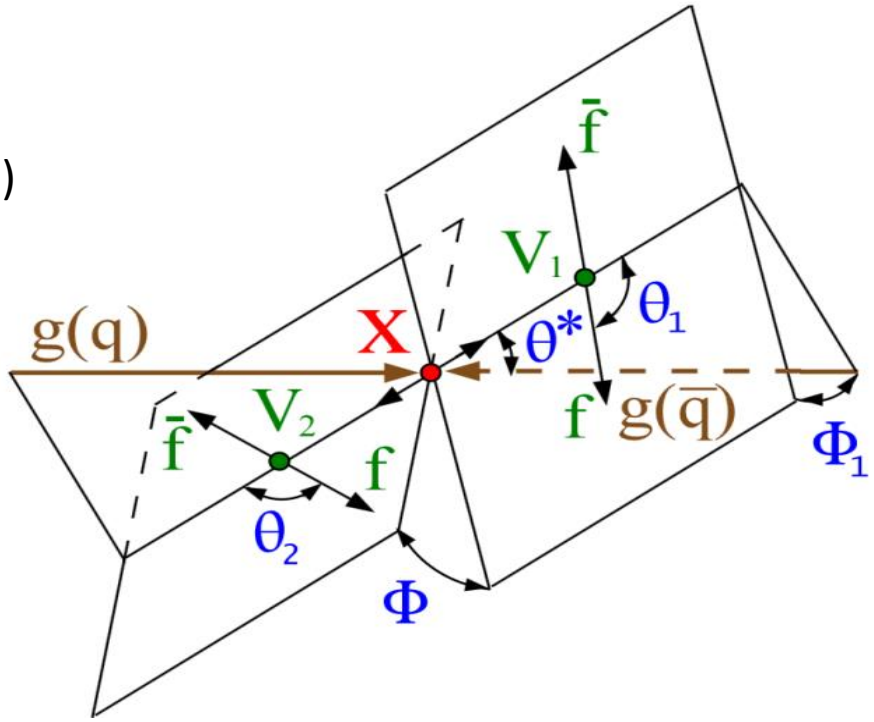
SPIN-PARITY

PRD 89 (2014) 092007 arXiv:1411.3441

- Non-zero Spin → correlation of kinematic distributions of production and decay.
- H→WW, ZZ, $\gamma\gamma$ useful to study spin-parity of the Higgs.

H→ZZ→4ℓ :

- 4ℓ system is fully reconstructed (8 observables)
- Use MELA approach.



H→WW→ℓν ℓν:

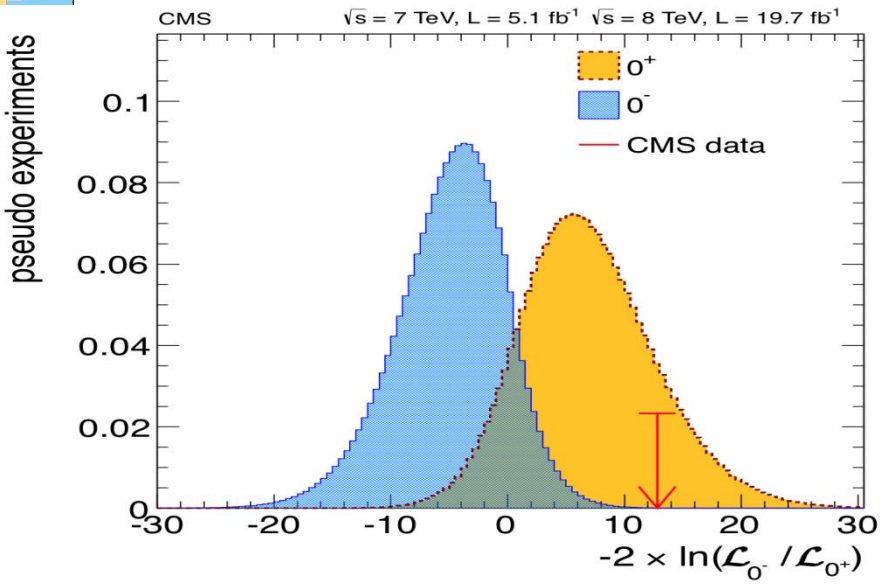
- 2 observables sensitive to X(J^P): $m_{\ell\ell}$, M_T

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

H→γγ :

- J=1 forbidden (Landau-Yang Theorem)
- cosθ* is the only sensitive variable of J^P at leading order

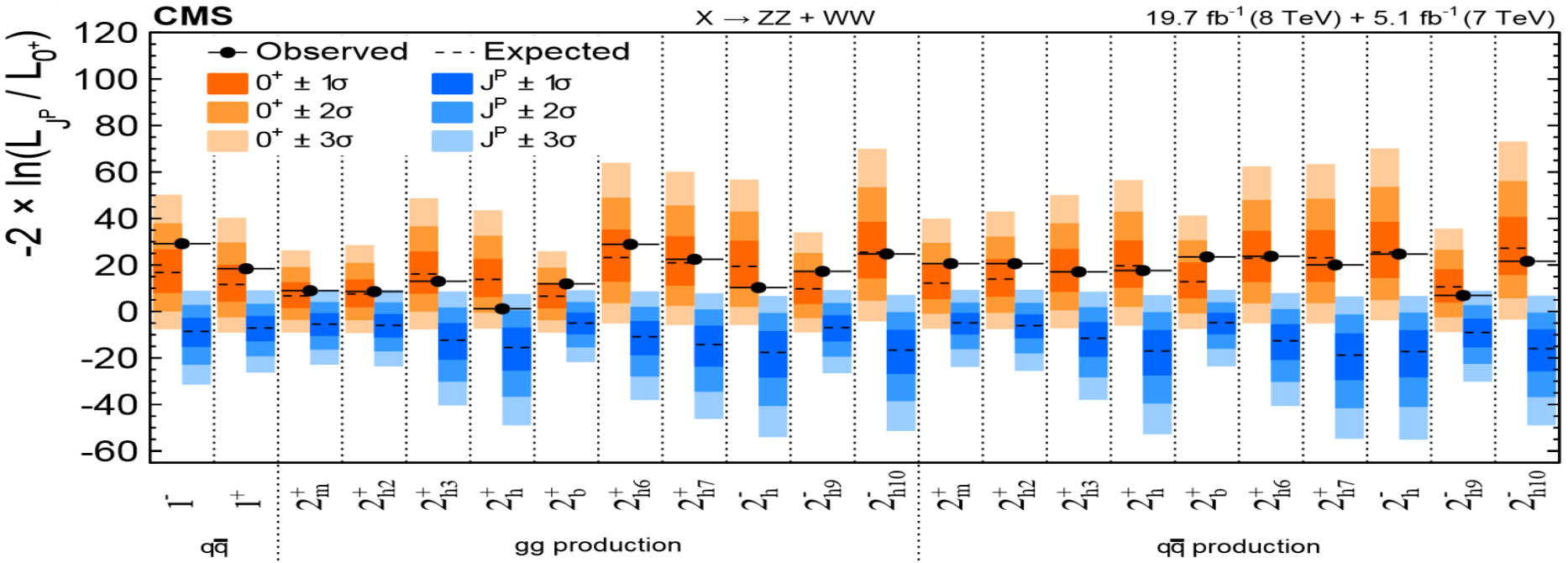
SPIN-PARITY



PRD 89 (2014) 092007 arXiv:1411.3441

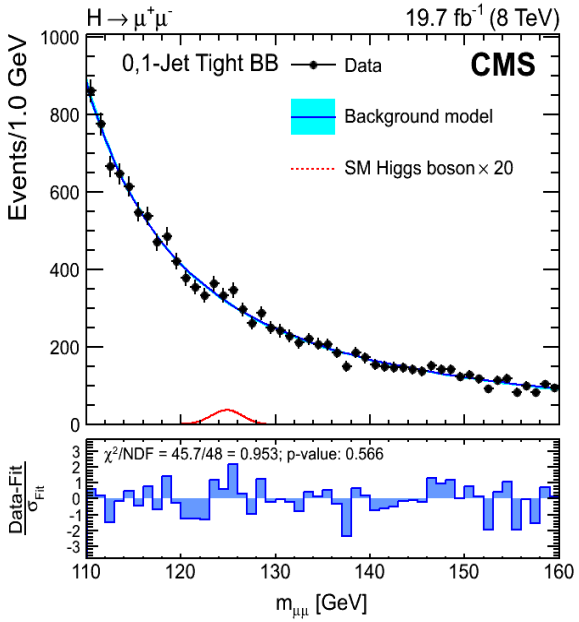
$$q = -2\ln\frac{L\left(data\middle|J^P + bkg\right)}{L\left(data\middle|H + bkg\right)}$$

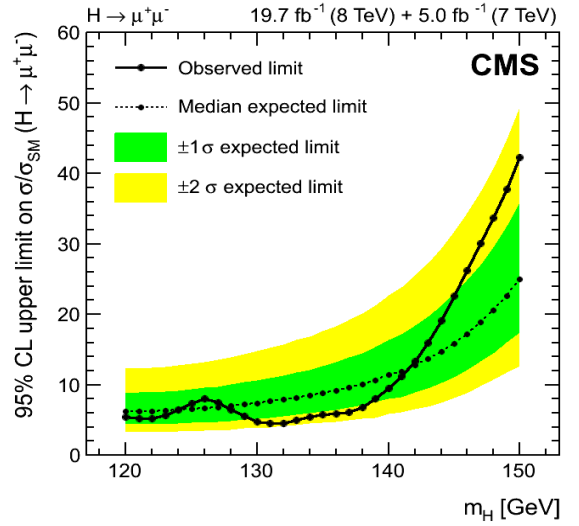
- $J^P=0^-$, 1^+, 1^- excluded at 99.9% CL
- Ten $J^P=2$ models excluded at 99% CL
- Data are compatible with 0^+ within ~ 1σ



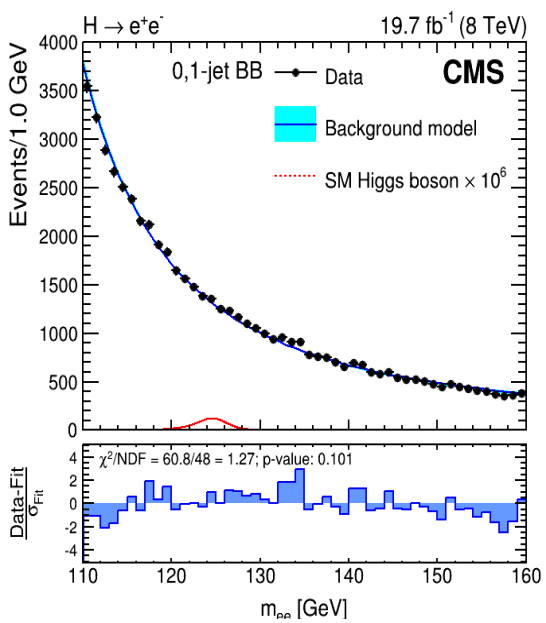
RARE DECAYS

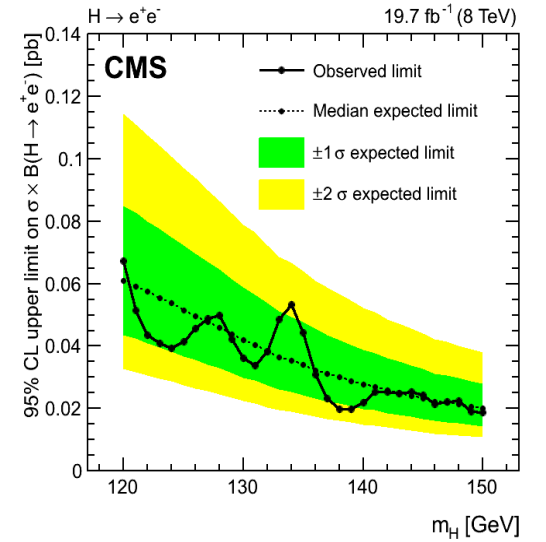
H→μμ





H→ee





PLB 744 (2015) 184

- H→μμ, H→ee cleanest of fermionic decays.
- $B_{SM}(H\to\mu\mu) = 2.2\times10^{-4}$
- $B_{SM}(H\to ee) = 5\times10^{-9}$
- search performed in [120,150] GeV
- $\sigma B(H\to\mu\mu)<0.033$ pb, 95% CL

  $B(H\to\mu\mu)<0.0016$, 95% CL

  $\mu = 0.8^{+3.5}_{-3.4}$
- $\sigma B(H\to ee)<0.041$ pb, 95% CL

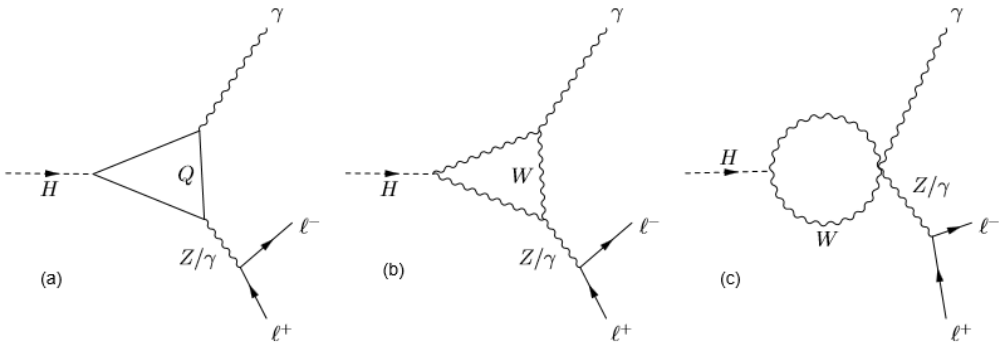
  $B(H\to ee)<0.0019$ (3.7×10^5 B_{SM})
- Leptonic couplings of the Higgs boson are not flavored-universal.

RARE DECAYS

$H \to \gamma^*\gamma \to \ell\ell\gamma$

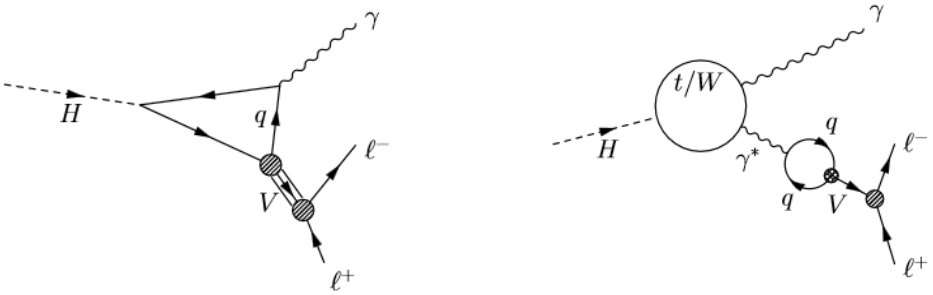
arXiv:1507.03031

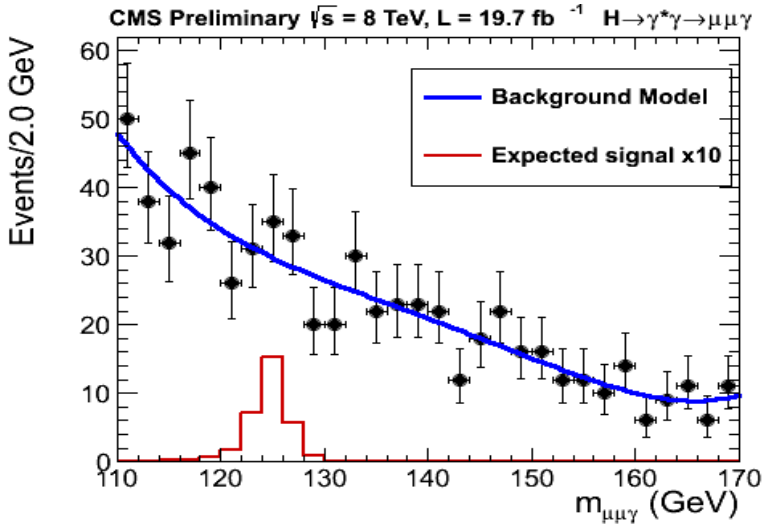
Dominant SM processes:

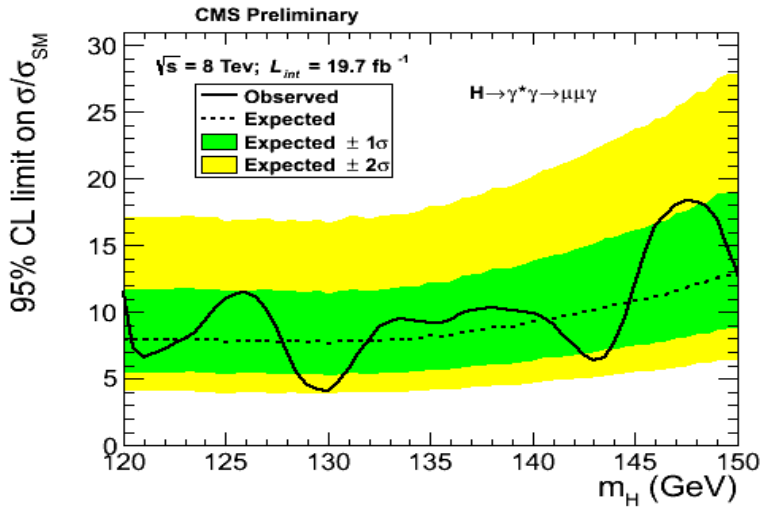


$$\frac{\Gamma(H \to \gamma^*\gamma \to ee\gamma)}{\Gamma(H \to \gamma\gamma)} \approx 2.9\%; \quad \frac{\Gamma(H \to \gamma^*\gamma \to \mu\mu\gamma)}{\Gamma(H \to \gamma\gamma)} \approx 1.1\%;$$

$$\frac{\Gamma(H \to Z\gamma \to \ell\ell\gamma)}{\Gamma(H \to \gamma\gamma)} \approx 2.2\%$$







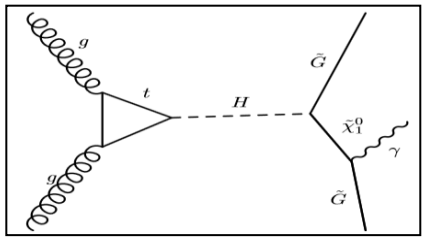
B(H→ (J/ψ)γ → $\ell\ell\gamma$)< 1.5x10^{-3}

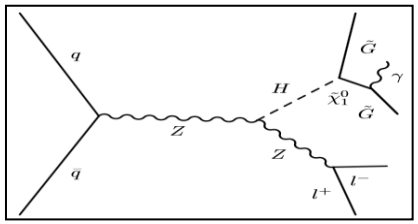
B(H→$\gamma^*\gamma \to \ell\ell\gamma$)< 7.7 ($6.4^{+3.4}_{-2.0}$)B_{SM}

INVISIBLE DECAYS

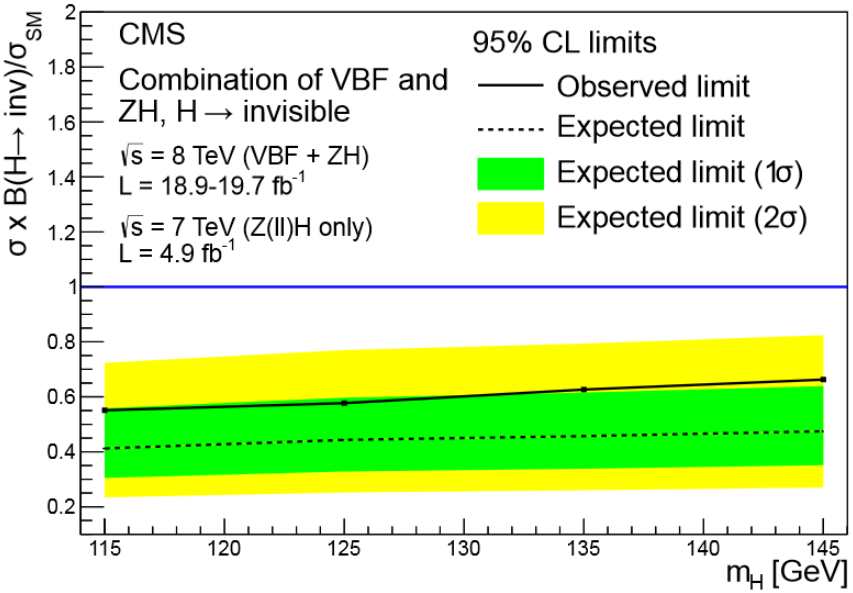
arXiv:1404.1344

arXiv:1507.00359

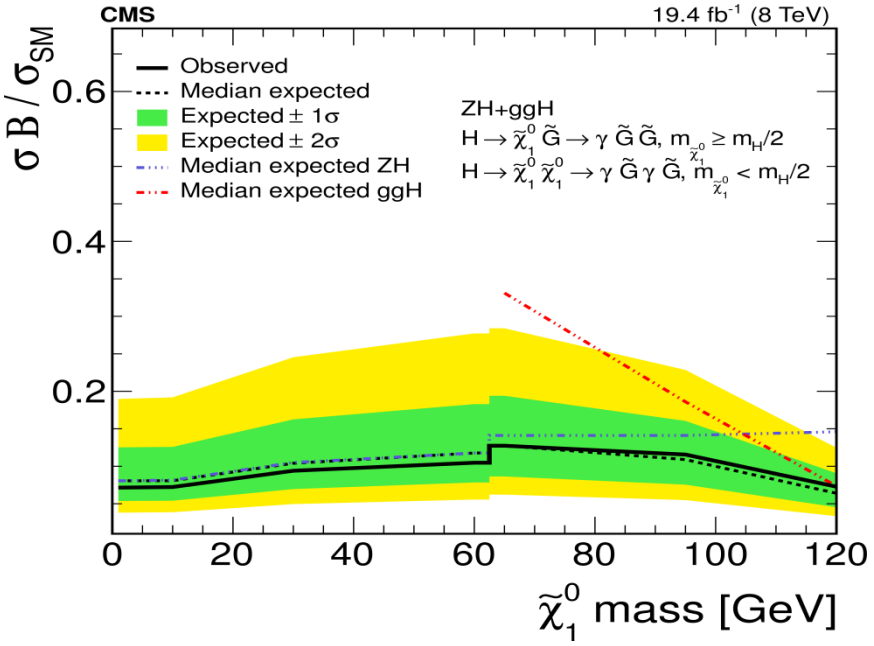




- **SM:** $B(H \to ZZ \to 4\nu) = 1.13 \times 10^{-3}$; $B(H \to Z\gamma \to \nu\nu\gamma) = 3 \times 10^{-4}$
- Observation of a large BR would be a sign of BSM:
  - LSPs in SUSY (neutralinos, gravitinos)
  - Graviscalars (Large extra dimensions)
  - Dark Matter.
- Direct search performed requiring some recoil:
  qqH, Z(ll)H,Z/W(qq´)H, H+ photons



$B(H \to \text{Invisible}) < 0.58(0.44)$ at 95% CL



Measurements consistent with bkg only hypothesis.

PROSPECTS FOR LHC RUN II

Universidad de los Andes

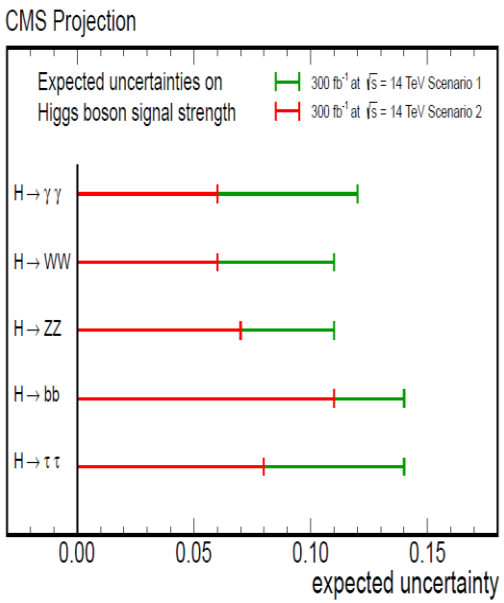
arXiv:1307.7135

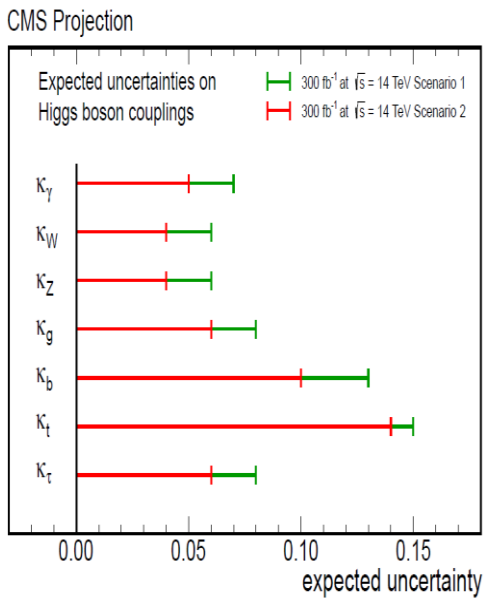
process	σ[pb] 8 TeV	σ[pb] 13 TeV	ratio
ggF	19.3	43.9	2.3
VBF	1.58	3.75	2.4
WH	0.705	1.38	2.0
ZH	0.415	0.870	2.1
ttH	0.129	0.509	**3.9**
bbH	0.204	0.512	2.5

Expected precision with L=300 fb^{-1}:

- 6% -14% in signal strength for individual channels.
- 5% in couplings to gauge bosons, 10% in couplings to fermions.
- 10%-20% sensitivity to CP-odd admixtures to scalar Higgs.

- With L=300 fb^{-1} and 13 TeV colision energy about 15 million Higgs will be produced (LHC Run II → Higgs Factory).
- High precision measurements of Higgs properties are very important to look for deviations from SM implying new physics.





SUMMARY

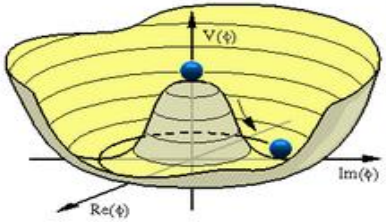
- The H(125) boson well-established as the SM Higgs in all measurements performed.
- Higgs mass, first LHC Higgs combined measurement:
  - $m_H = 125.09 \pm 0.21$ (stat.) ± 0.11 (syst.) GeV
  - 0.19% precision achieved, still dominated by statistics.
- Signal-strengths consistent with the SM prediction within the 20%-30% relative uncertainties.
- Data consistent with SM spin-parity 0^+ state.
  - Alternative J^P hypotheses excluded at the 99.9% CL
- Upper limit on Higgs width and τ_H from Off-shell production of $H \rightarrow ZZ \rightarrow 4\ell$:
  - $\Gamma < 5.5\ \Gamma_{SM}$ at 95% CL
  - $\tau_H < 1.9 \times 10^{-13}$ s
- No sign of invisible decays, $\mathcal{B}(H \rightarrow \text{inv}) < 0.58$ at 95% CL
  - Exotic decays, e.g. $H \rightarrow \mu\tau$ (LFV), $H \rightarrow \chi_1^0 G$ not observed
  - Upper limits at 95% CL on rare decays like $H \rightarrow \mu\mu/ee$, $H \rightarrow Z\gamma$, $H \rightarrow \ell\ell\gamma$
- Precision measurements at LHC Run II will allow to look for deviations from SM .

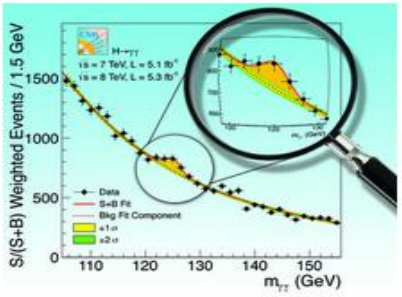
CMS HIGGS PUBLIC RESULTS

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

TWiki > CMSPublic Web > PhysicsResults > PhysicsResultsHIG (2015-07-27,

CMS Higgs Physics Results

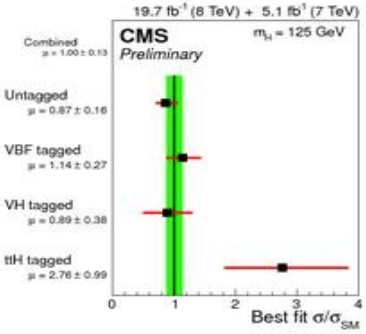




Preliminary Results

Publications

Highlights



Values of the best-fit σ/σSM for the combination (solid vertical line) and for subcombinations by analysis tags targeting individual production mechanisms:

png

Compact Muon Solenoid
LHC, CERN

Higgs Physics Publications

- Higgs Physics Publications
  - Legacy Papers
  - The 125-GeV Higgs Boson
    - Combinations
    - Mass
    - Couplings
    - Spin/Parity
    - Width
  - Decay Modes
    - Vector Bosons
    - WW
    - ZZ
    - $\gamma\gamma$
    - $Z\gamma$
    - Fermions
    - $\tau\tau$
    - $\mu\mu$ and ee
    - bb
    - Invisible
    - Lepton Flavour Violating
  - Rare Production Modes
    - VBF
    - VH
    - ttH
  - Searches
    - Supersymmetry
    - Exotica
    - Charged Higgs Bosons
  - Results with Partial Data
    - 7 TeV Data
    - 7 and 8 TeV Data
    - 8 TeV Data
  - Recent Preliminary Results in the Higgs Physics Group

THANKS !