# The Higgs Boson Profile at CMS

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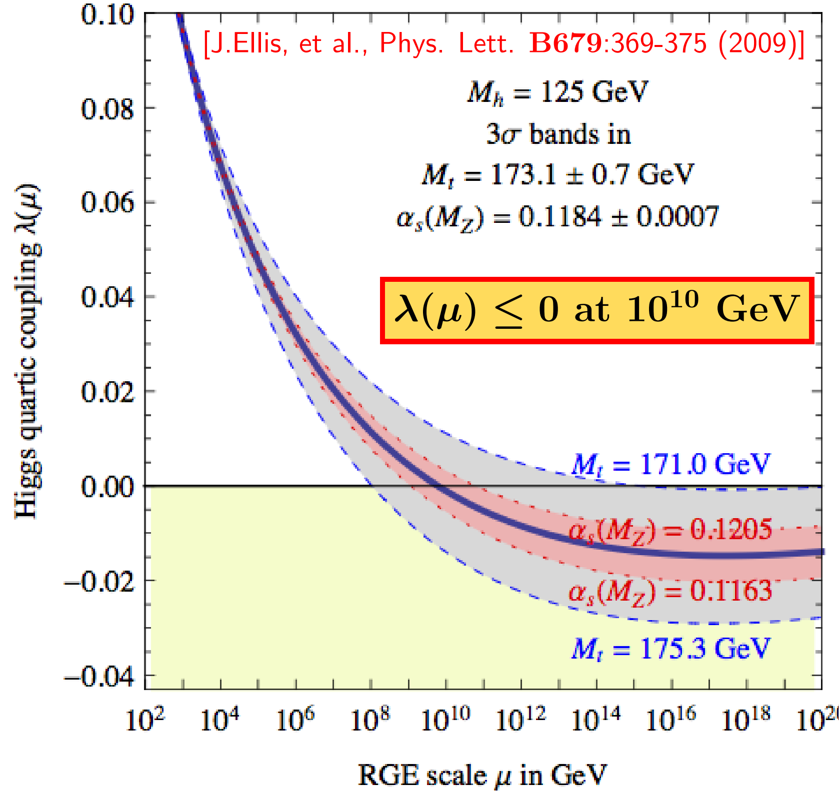
**With the discovery of a Higgs boson the SM is now complete!**

- Major questions of PP justified by experimental observations remain unresolved
  - **DM** points to new type particle
  - **BAU** requires $\not{B}, \not{L}$ processes
  - **Neutrino mass** suggests sterile or Majorana neutrino

*The SM begins to unravel when probed much beyond the range of current accelerators*
(unstable vacuum at the Plank scale!)



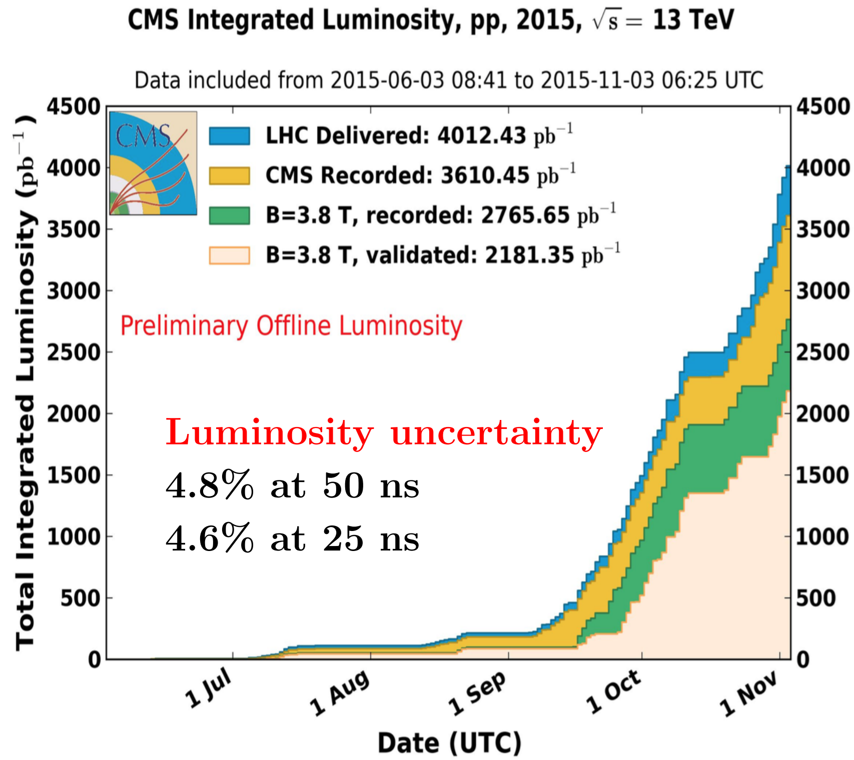

- **Indirect searches** through precision measurements (rare processes)
  - many BSM models predict

$$\Delta g_{HXX}/g_{HXX} \leq 1 - 10\%$$

  - Is Higgs potential $\lambda(\mu)$ as expected? (check consistency)

*Everything proves that NP must exist, but...* **At What Energy Scales?**

**LHC restarted in 2015 with a collision energy of ≃13 TeV and 25 ns bunch spacing**

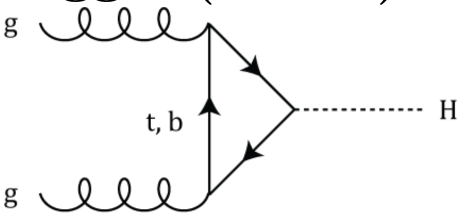



- **CMS detector for Run-2:** improvements during LS1
  - **DAQ and L1:** computers, trigger
  - **tracker/pixel:** cold operation
  - **HCAL:** new photosensors
  - **muon:** 4th station
  - new luminosity telescopes
  - new beam pipe
- **Available Run-1 dataset**
  - **7 TeV:** $\leq$5.1 $fb^{-1}$
  - **8 TeV:** $\leq$19.6 $fb^{-1}$

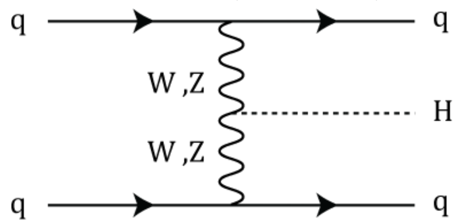
*LHC can ultimately deliver about* **100 $fb^{-1}$** *of data for next 3 years*

- **Run-2 13 TeV dataset**
  - **2.2 $fb^{-1}$– good for all**
  - **2.6 $fb^{-1}$– good for many** ($|\eta| \leq 3$ for jets and MET)
  - **2.7 $fb^{-1}$– good for muons**

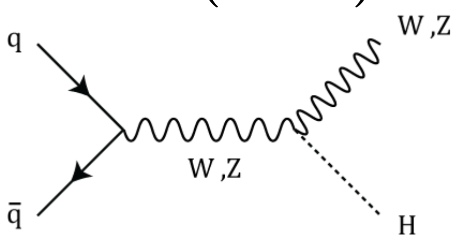
**ggH (87.4%)**



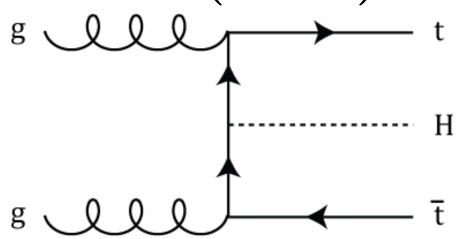

**VBF (7.1%)**




**VH (4.9%)**




**ttH (0.6%)**

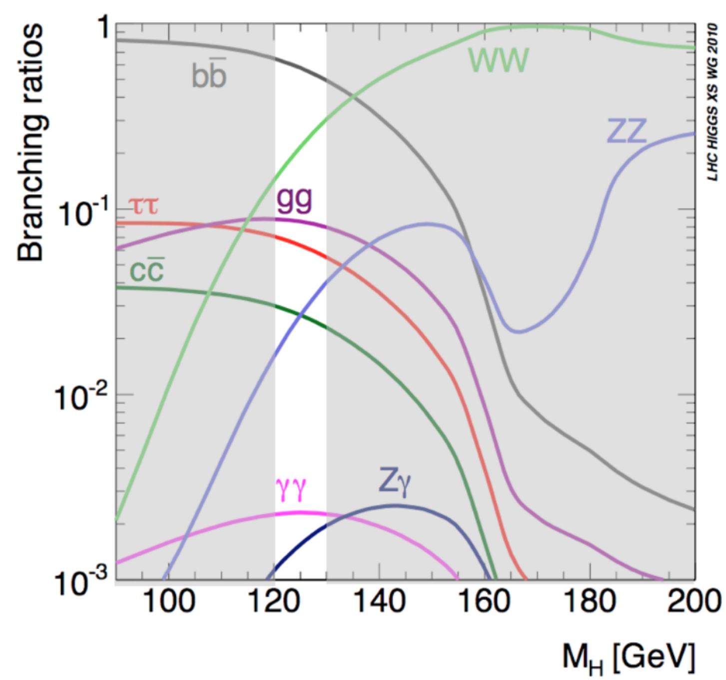


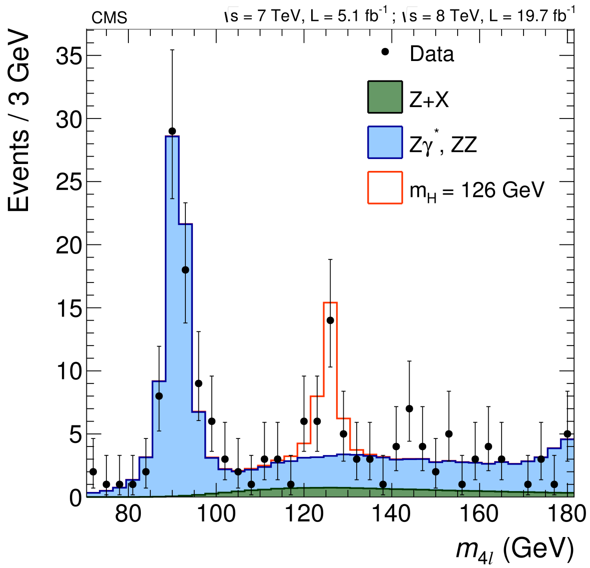

## Typical theory uncertainty

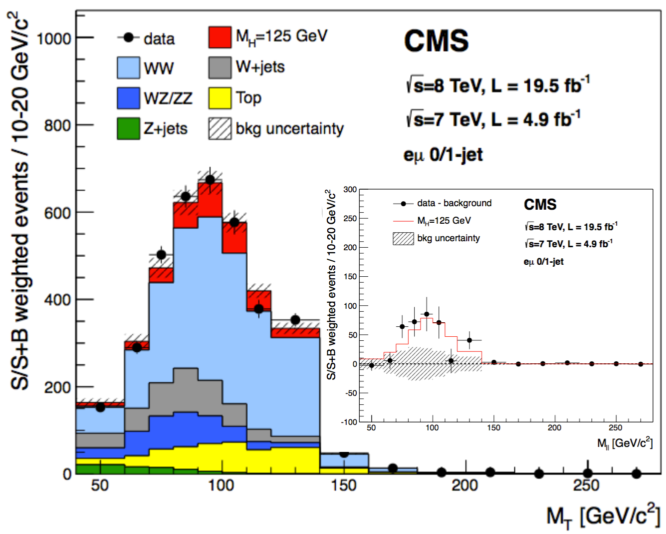
| Production | Theory unc. | Precision |
|---|---|---|
| ggH | 7% | $N^3LO+N^3LL$ |
| VBF | 5% | NLO |
| VH | 5% | NNLO |
| ttH | 15% | NLO |

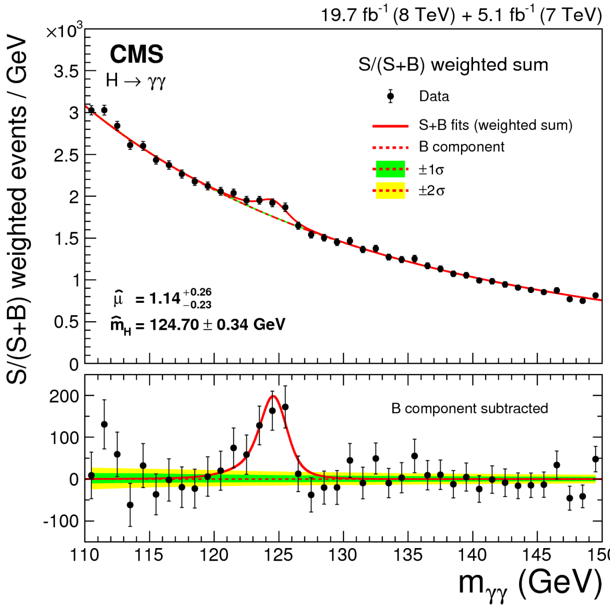
## Decay fractions at 125 GeV

| Decay | BR | $\sigma_M/M$ |
|---|---|---|
| $H\to\gamma\gamma$ | 0.2% | 1-2% |
| $H\to ZZ^*(4l)$ | $1.2\cdot10^{-4}$ | 1-2% |
| $H\to WW^*$ | 21% | 20% |
| $H\to bb$ | 60% | 10% |
| $H\to\tau\tau$ | 6.4 | 10% |

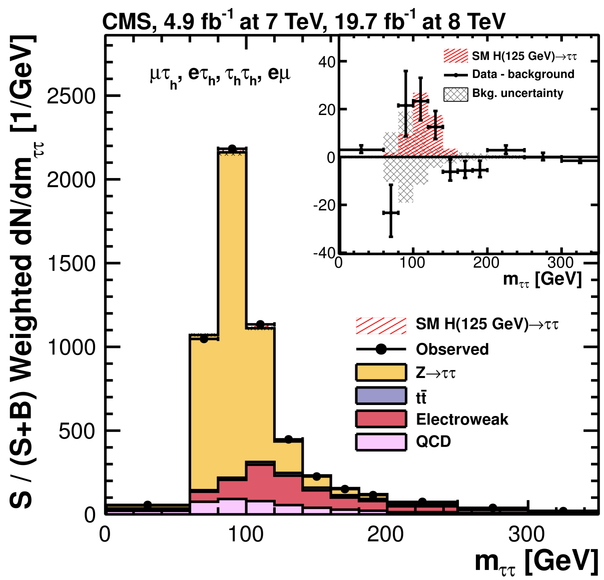


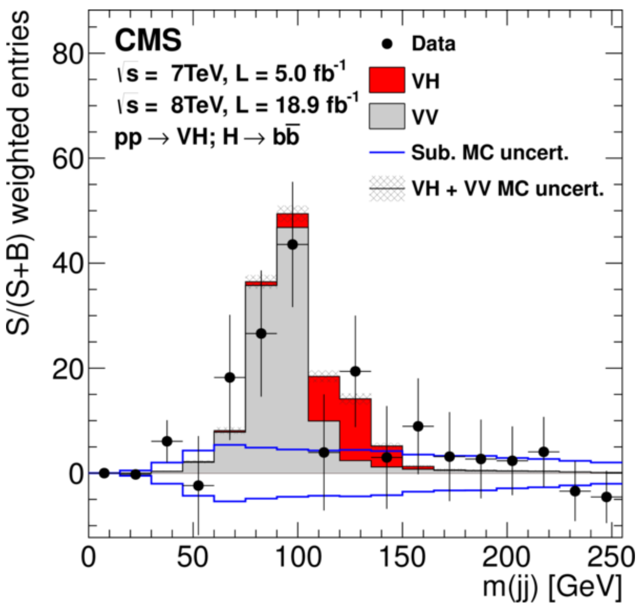


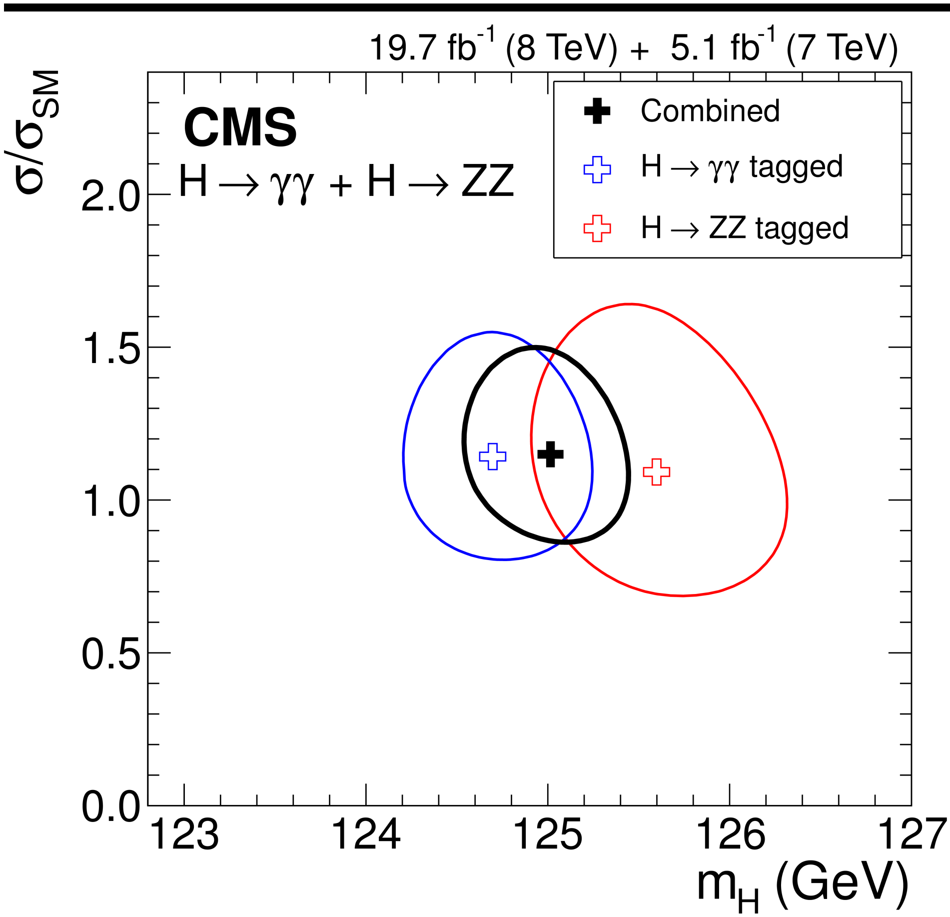



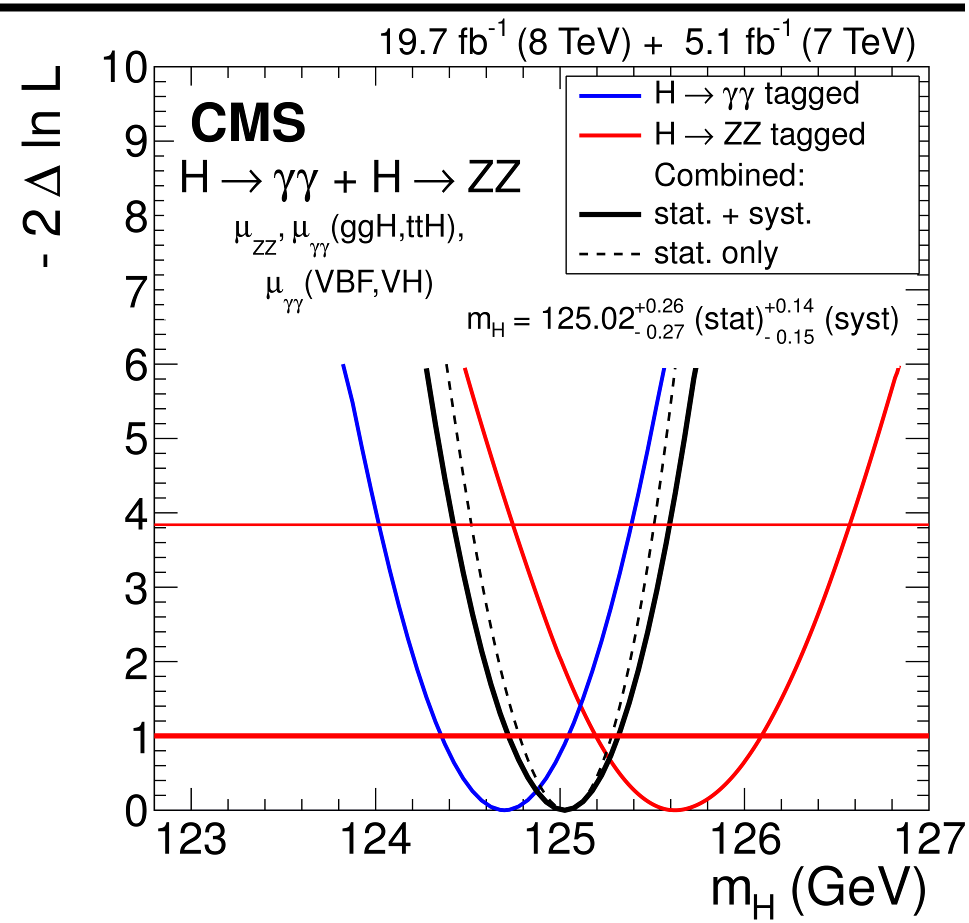

Solid signal in 3 bosonic decay channels and fermionic final states starting to build up excess





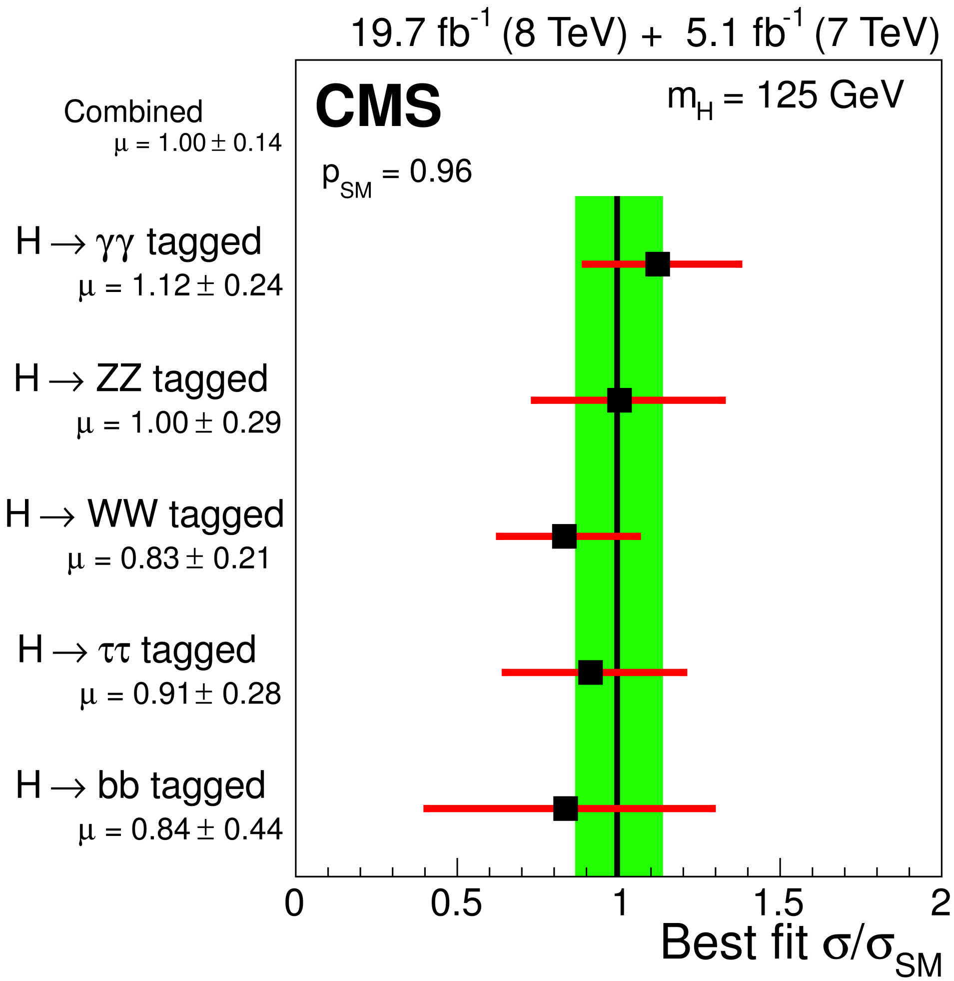

[HIG-14-009]

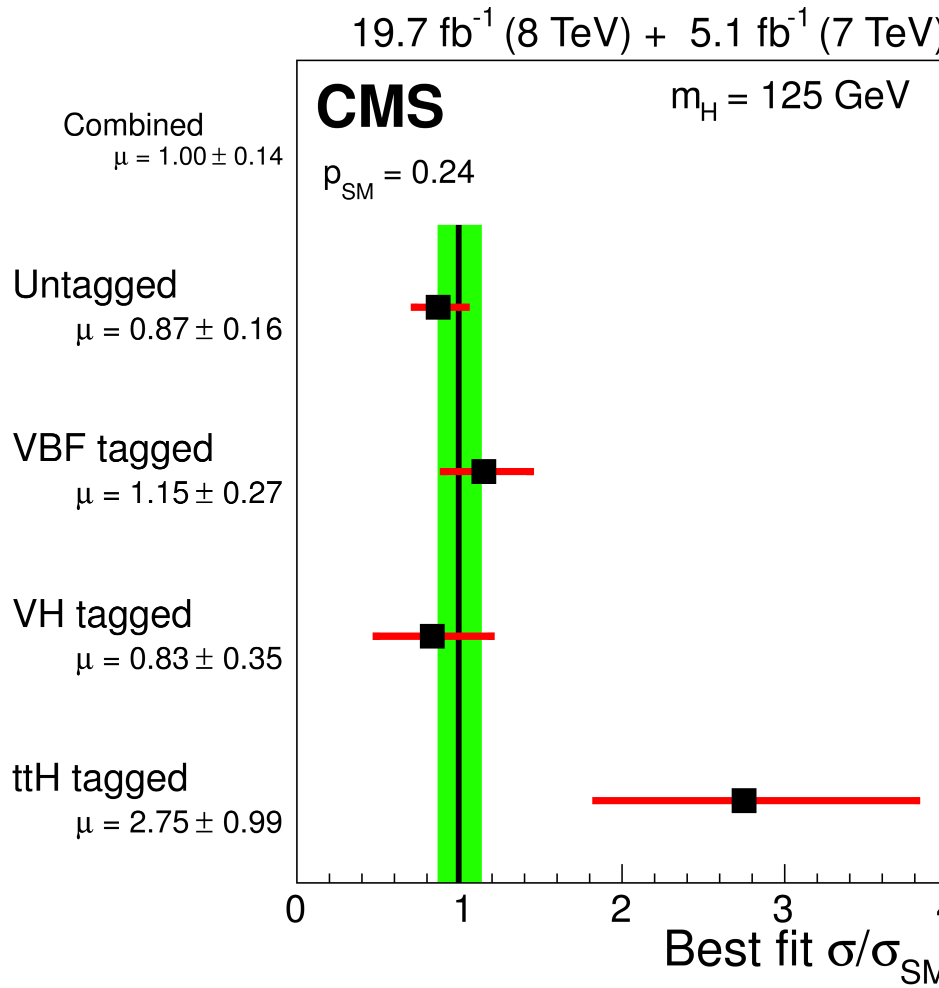



☞ Likelihood scan for m$_X$ and $\mu$: relative yields are defined by the SM

☞ To reduce model dependence: allow for free cross sections in five channels and fit for the common mass

$$\boldsymbol{m_X = 125.02 \pm 0.27(\mathrm{stat}) \pm 0.15(\mathrm{syst})\ \ \mathrm{GeV}}$$



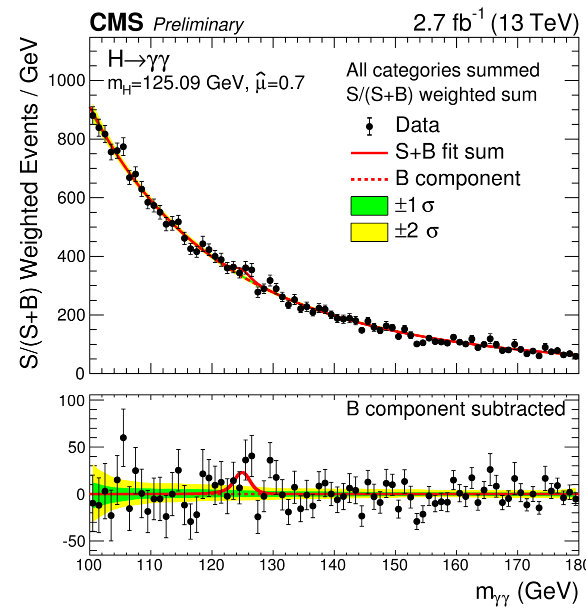




*Event yields in different production and decay tags are self-consistent*

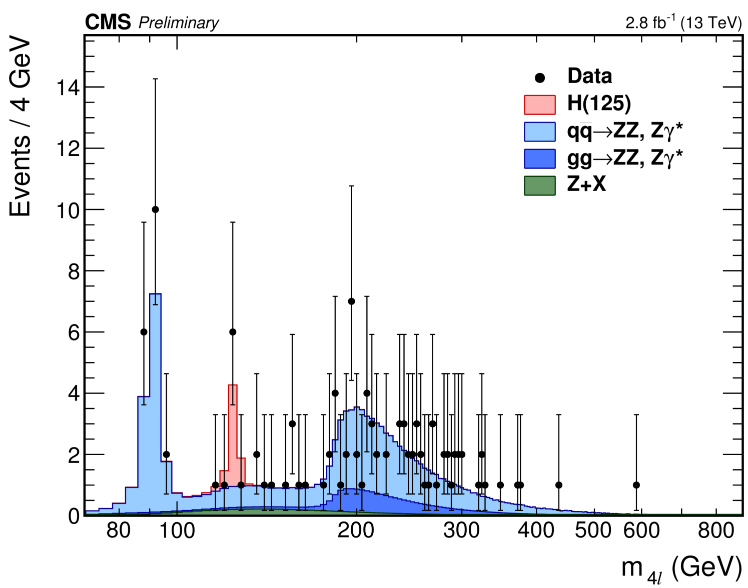
☞ Overall best-fit signal strength in the combination:

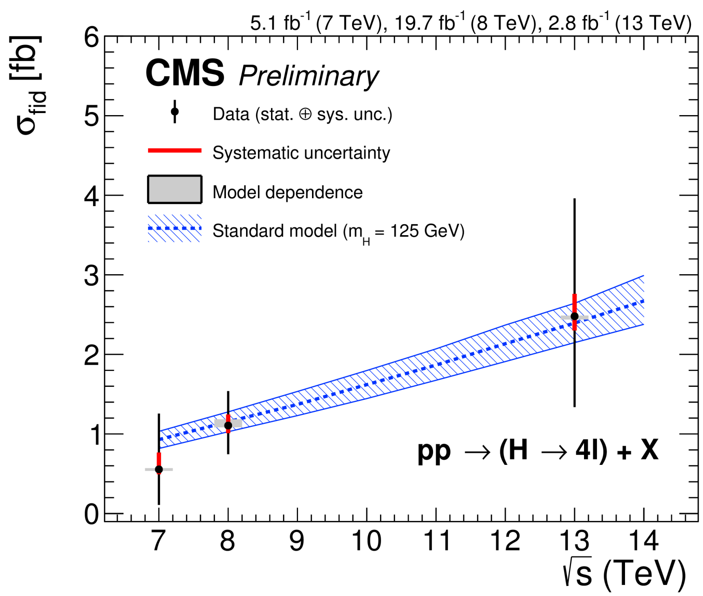
$$\boxed{\boldsymbol{\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.09(\mathrm{stat}) \pm 0.08(\mathrm{theo}) \pm 0.07(\mathrm{syst})}}$$

## The return of the Higgs boson




- ☞ $\mathbf{H \to \gamma\gamma}$:
  - signal strength $\mu = 0.69^{+0.42}_{-0.47}$
  - observed (expected) significance $\mathbf{1.7(2.7)\sigma}$
- ☞ $\mathbf{H \to ZZ \to 4l}$:
  - observed (expected) significance $\mathbf{2.5(3.4)\sigma}$
  - fiducial cross section $\sigma = 2.48^{+1.48}_{-1.14}$



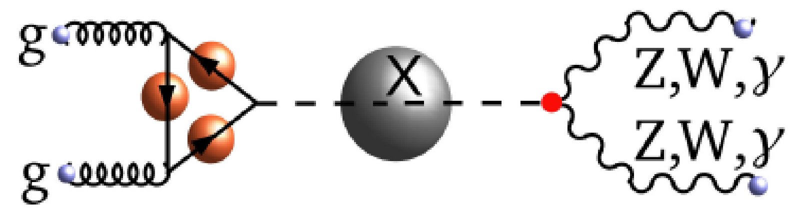

*Results for mixed $m_H = 125$ GeV are consistent with the Run-1 analyses*

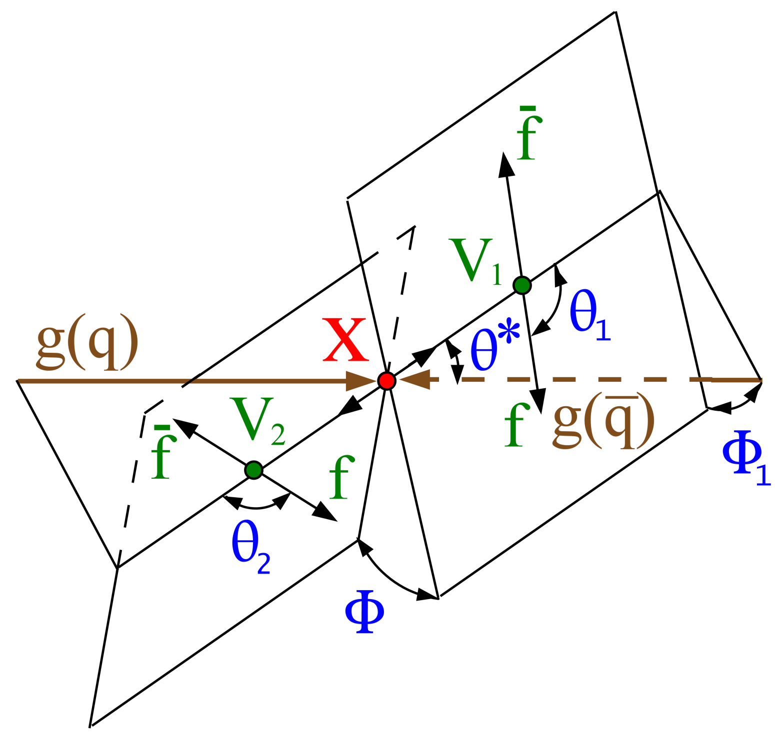
## Tensor structure of the Higgs sector ($J^{CP}$ numbers) can be best probed by angular analysis

- Allow assessing the individual terms in a generic parameterization of the Lagrangian
- Mixing between CP-even and CP-odd state can in particular being studied
- The decay amplitude for a **spin-0** boson

$$A = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}(a_1 g_{\mu\nu}M_X^2 + a_2 q_{1\mu}q_{2\nu} + a_3\epsilon_{\mu\nu\alpha\beta}q_1^\alpha q_2^\beta)$$

  - SM-Higgs $\rightarrow$ ZZ,WW:
    - ➔ $a_1 \neq 0$, $a_2 \sim O(10^{-2})$, $a_3 \sim O(10^{-11})$
  - SM-Higgs $\rightarrow \gamma\gamma$:
    - ➔ $a_1 = -a_2/2 \neq 0$
  - BSM pseudo-scalar Higgs
    - ➔ $a_3 \neq 0$

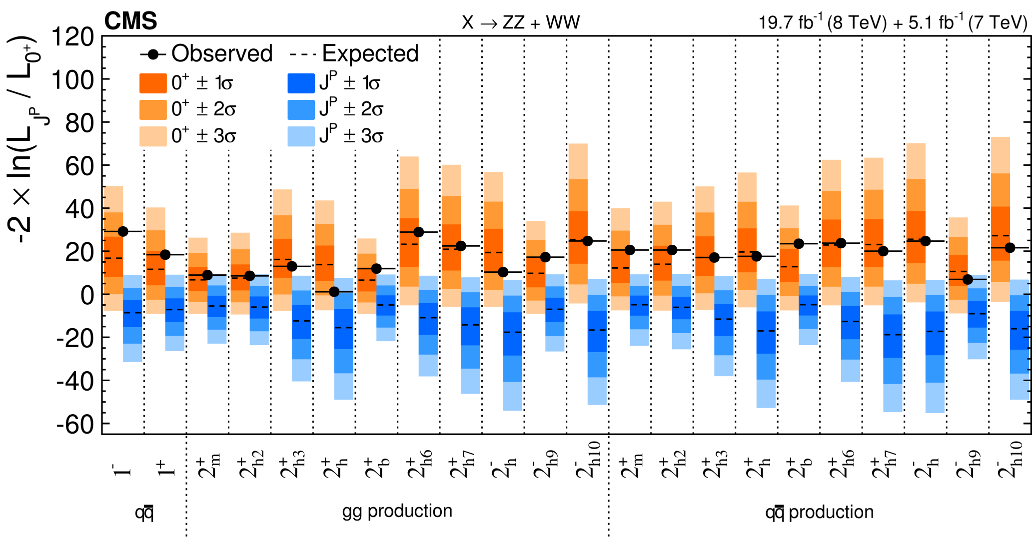


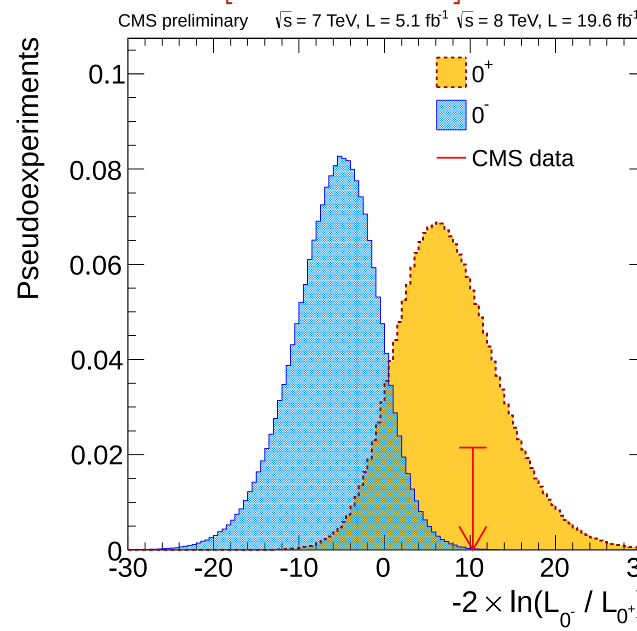
## Spin and CP-parity hypotheses are discriminated by angular analysis

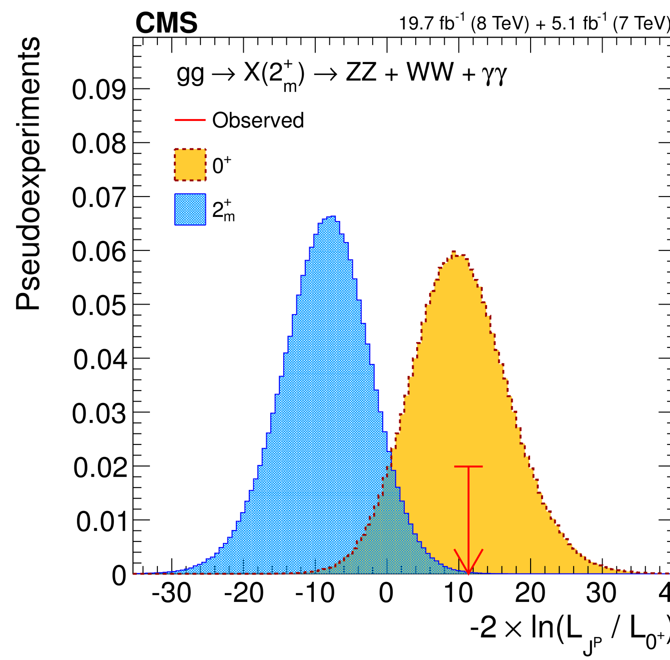
☞ **Spin-0 and 2** are only allowed by H$\rightarrow \gamma\gamma$ (Landau-Yang theorem)

**The data disfavours the $0^-$ ($2^+_m$) hypothesis with 99.98% (99%) CL**




[HIG-14-018]




*The observation is well compatible with SM Higgs expectations ($0^+$)*

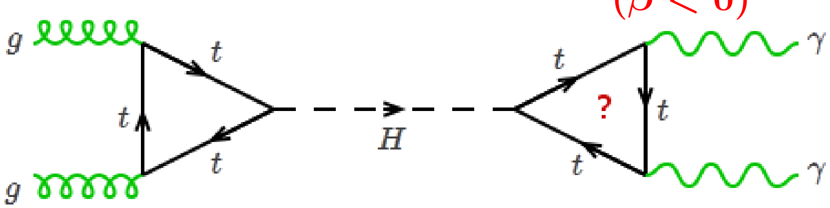
## Extracting Higgs couplings requires assumptions at LHC

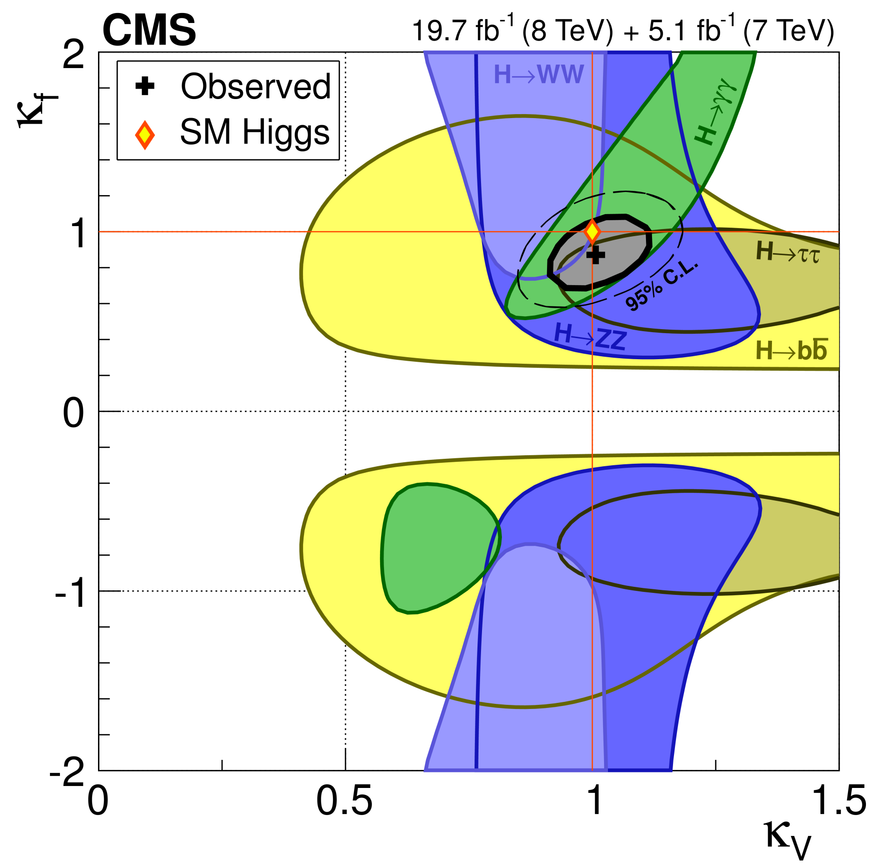
$$\sigma\mathcal{B}(ii \to H \to ff) \sim \frac{\Gamma_{ii}\Gamma_{ff}}{\Gamma_H} = \sigma_{SM} \cdot \mathcal{B}_{SM} \frac{k_i^2 \cdot k_f^2}{k_H^2}$$

- Total width $\Gamma_{\mathrm{H}} \propto k_H^2$ is not measurable **(zero width approximation!)**
  - assumed $k_H = \Sigma\, k_i BR_i$, for i in SM
- Estimate Higgs boson couplings into **"Vectorial"** and **"Fermionic"** sets:
  - H$\to$ $\gamma\gamma$ is the only channel that is sensitive to $k_V$ or $k_F$ relative sign
    - ➔ possible to sort out degeneracy

$\Gamma_{gg} \sim k_F^2$

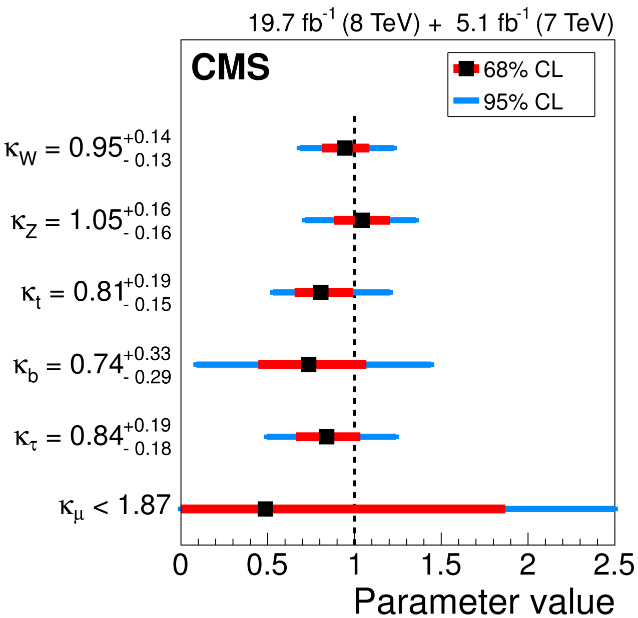
$\Gamma_{\gamma\gamma} \sim |\alpha k_V + \beta k_F|^2$
$(\beta < 0)$



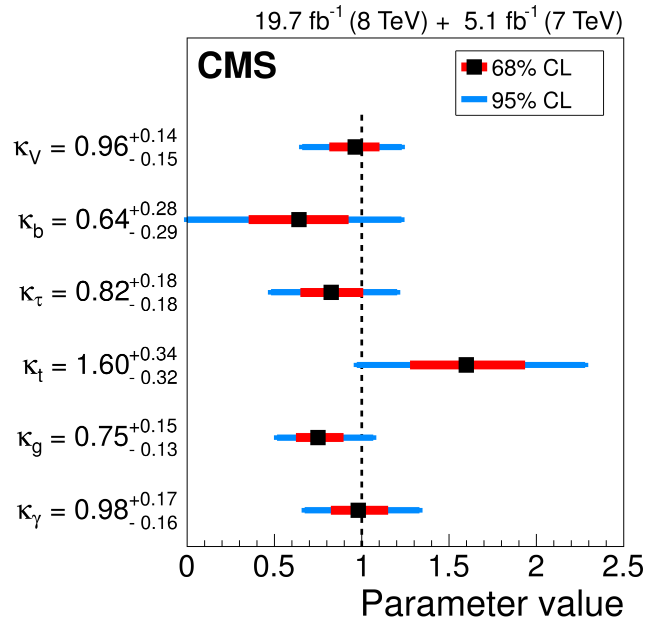




*In agreement with the SM within uncertainties*

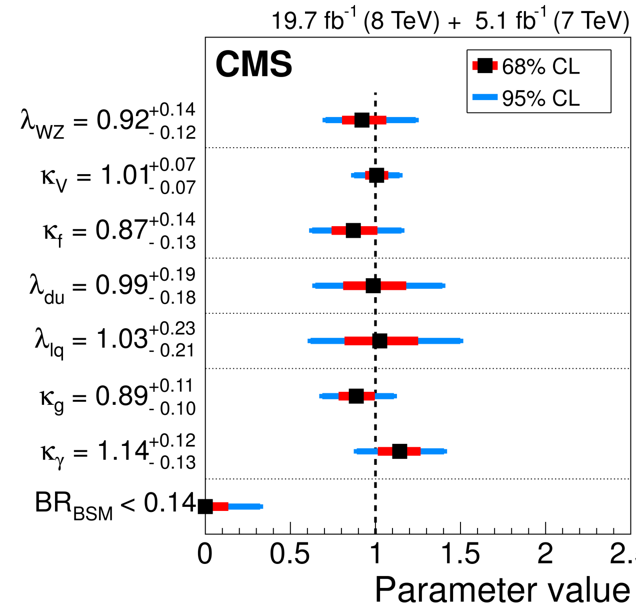
## *Compatibility with the SM Higgs Boson Couplings*




*The generic five-parameter model not effective loop couplings*
(the SM structure is assumed for loop-induced couplings)




*Effective loop couplings assuming* $\Gamma_{\mathrm{BSM}} = 0$




New particles can modify the loop-mediated couplings and contribute to the total width

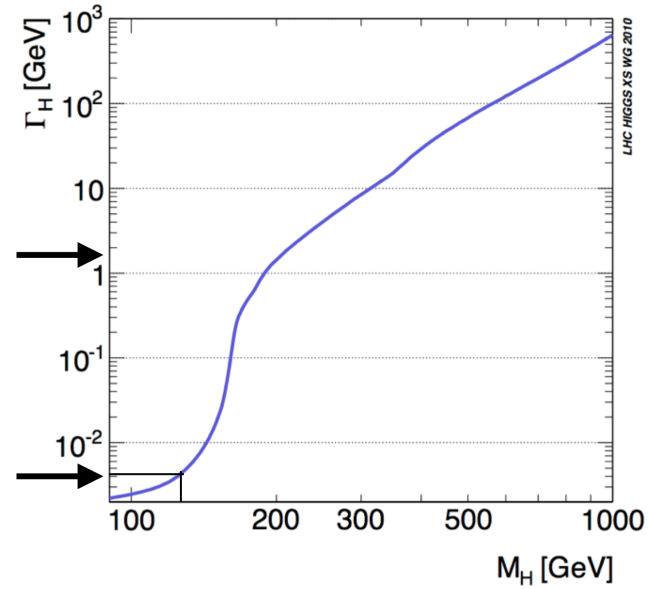
$$\Gamma_{tot} = \sum \Gamma_{i(SM)} + \Gamma_{BSM}$$

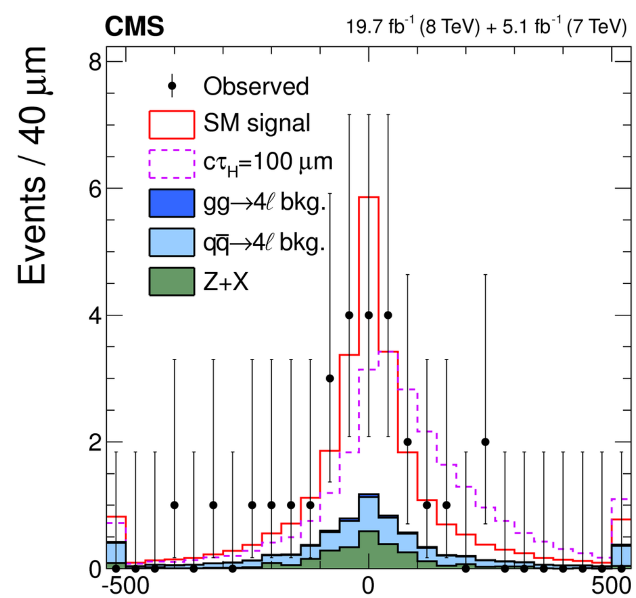
**No significant deviations from the SM Higgs boson are found so far**

**In the SM $\Gamma_{\rm H} \sim 4.1\text{MeV}$ for $m_{\rm H} = 125\text{GeV}$**

- **Direct measurement exploits $m_{4l}$ and $m_{\gamma\gamma}$ spectra**
  - limited by experimental resolution (1-2%)
  - $\mathbf{\Gamma_H \leq 1.7\ GeV}$ at 95% CL (exp. 2.3 GeV)
- A lower bound on the Higgs width can be derived from its lifetime
  - measure displacement vertex between H production and decay in $\rm H \to ZZ \to 4l$
  - $\mathbf{\Gamma_H \geq 3.5 \times 10^{-3}\ eV}$ at 95% CL

*Model independent measurement of $\Gamma_{\rm H}$ is systematically limited at LHC*



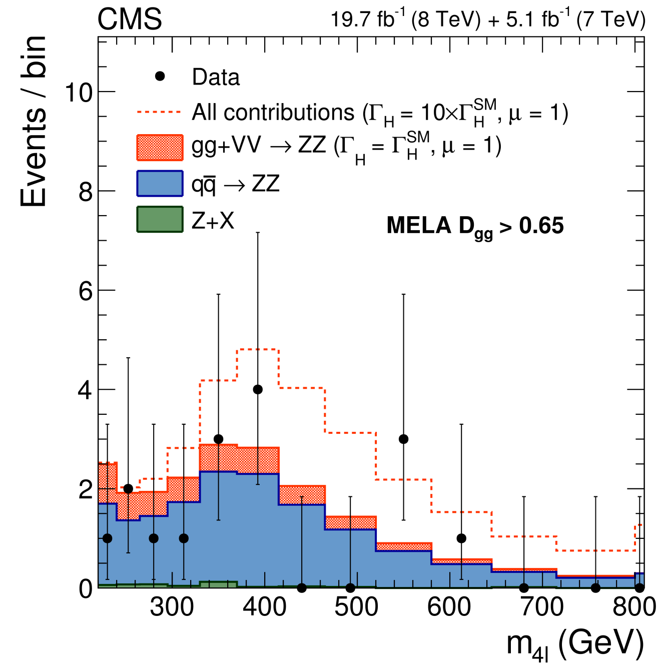



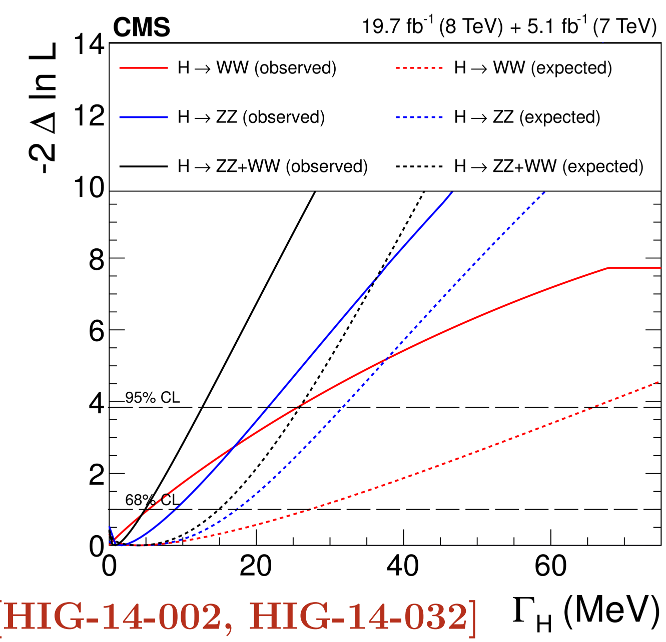

[HIG-14-036]

**Indirect limit on $\Gamma_H$ can be derived with number of assumptions through off-shell Higgs boson production**

- Deploy off-shell production in gluon fusion and VBF processes with the Higgs boson decaying into **ZZ and WW states**
  - $\sigma_{\mathrm{off-shell}} \sim g_{gg}^2 g_V^2$ does not depend on total width $\Gamma_H$ as $\sigma_{\mathrm{on-shell}}$ does
  - main continuum $gg(qq) \to ZZ/WW$ production at high mass
  - assume the on-shell and off-shell couplings are the same
  - $\mathbf{\Gamma_H \leq 13\ MeV}$ at 95% CL (exp. 26 MeV)

*Statistically limited measurement (systematic uncertainty can be pinned down to 2 MeV)*




[HIG-14-002, HIG-14-032]

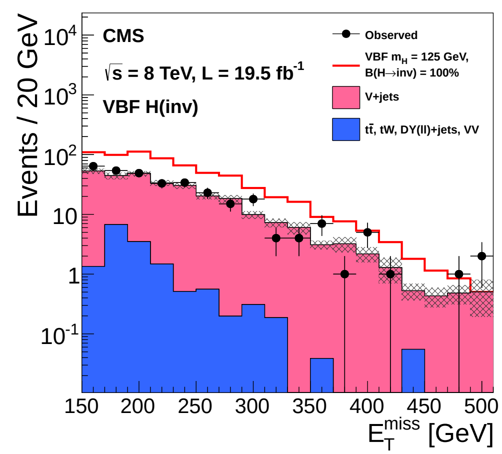
[HIG-16-009]

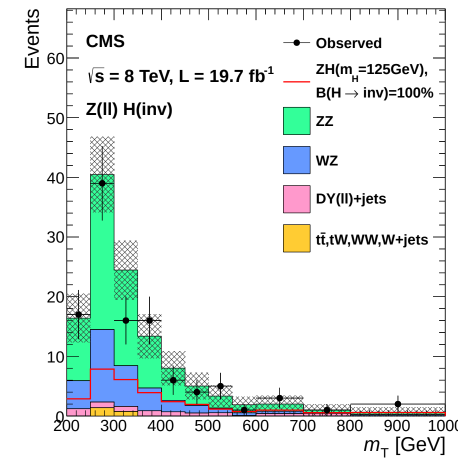
## A non-zero partial decay width to invisible particles could provide evidence for NP

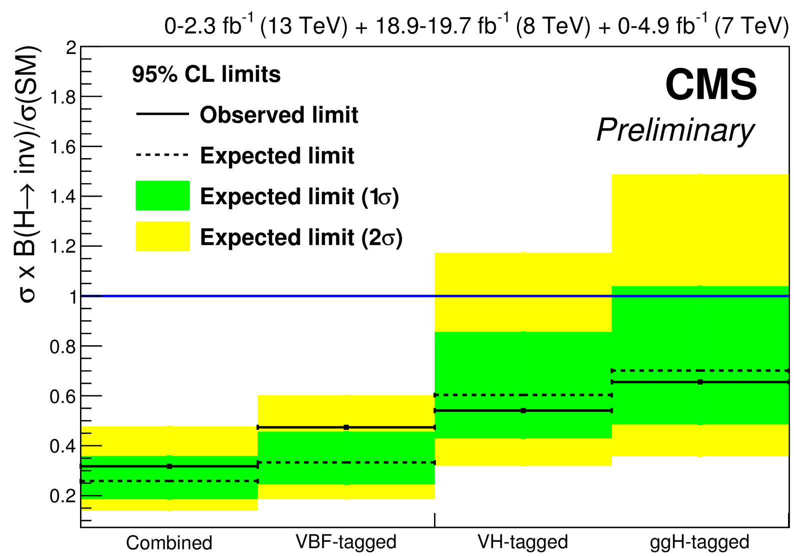
☞ Direct 95% CL on $\mathrm{BR_{inv}}$ using **VBF, VH and GF** tagged events

| Channel | obs. | exp. |
|---|---|---|
| **7+8 TeV** | | |
| VBF | 0.57 | 0.40 |
| VH | 0.60 | 0.69 |
| GF | 0.67 | 0.71 |
| **13 TeV** | | |
| VBF | 0.69 | 0.62 |
| VH | 1.3 | 1.3 |
| Comb. | **0.32** | **0.26** |

☞ Precision could be **pinned down to 5%** level to $\mathrm{BR_{inv}}$ at HL-LHC




*Consistent with global coupling fit:*
$\mathrm{BR_{inv}} < 0.52$ *at 95% CL*

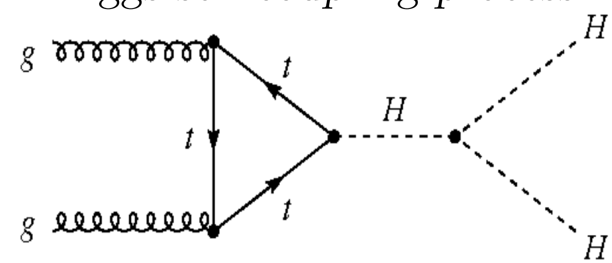
## Double Higgs production among the main objectives of LHC, but this process is very challenging

- **Low rate makes high demands on detectors and integrated luminosity**
  - tiny cross section
  - $\sigma(\mathrm{HH}) = 10.0 \pm 1.4$ fb at 8 TeV
  - very challenging at HL-LHC too
    - ➔ $\sigma(\mathrm{HH}) = 40 \pm 3$ fb at 14 TeV
- **Self coupling diagrams interferes destructively with double Higgs processes**
  - look for a deficiency in a small signal
- The most sensitive decay is $\mathbf{HH \to \gamma\gamma b\bar{b}}$

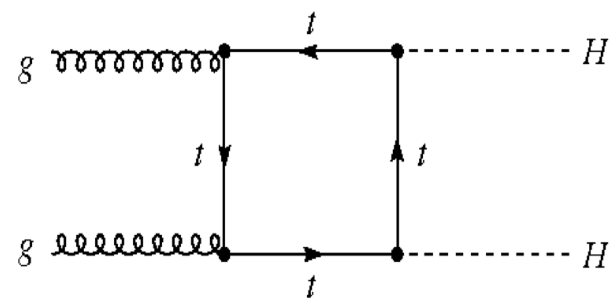
*Start exclusion of the Higgs boson anomalous trilinear coupling $\lambda$:*

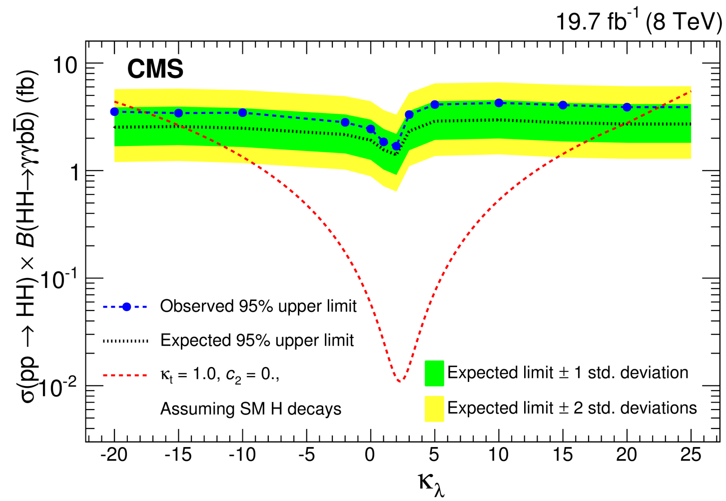
$$\mathbf{-17 \leq k_\lambda < 22.5}$$

*Higgs self coupling process*




*SM Double Higgs production*




[HIG-13-032]

# Higgs Boson Milestones

## ☞ Discovery of the Higgs boson at 125 GeV

- ➠ **consistency with SM predictions**

## ☞ Higgs boson as a test of SM

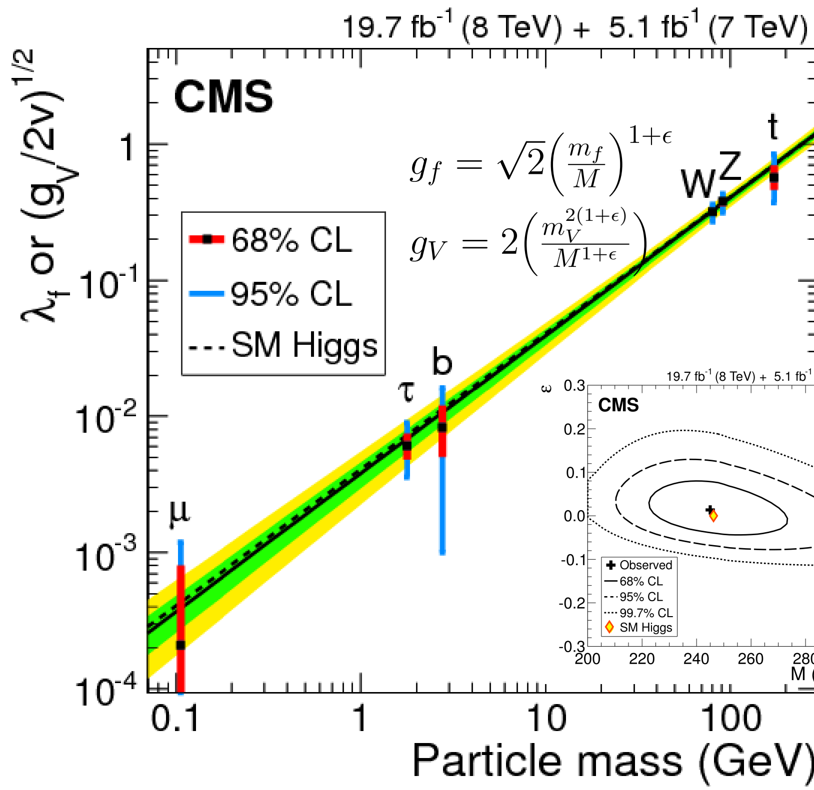
**Run-2**

- ➠ observe VBF and VH productions
- ➠ observe $\tau^+\tau^-$ and bb decay modes
- ➠ constrain invisible width (VBF/VH)
- ➠ constrain width form on/off-shell
- ➠ observe ttH production
- ➠ observe rare decays $\mu^+\mu^-$ and $Z\gamma$
- ➠ measure couplings better than 5%
- ➠ observe pair production

**HL-LHC**

## ☞ Higgs boson as a probe for NP

- ➠ flavour-violating decays
- ➠ Higgs boson as a DM portal
- ➠ CP mixing in the Higgs sector
- ➠ other partners in the scalar sector

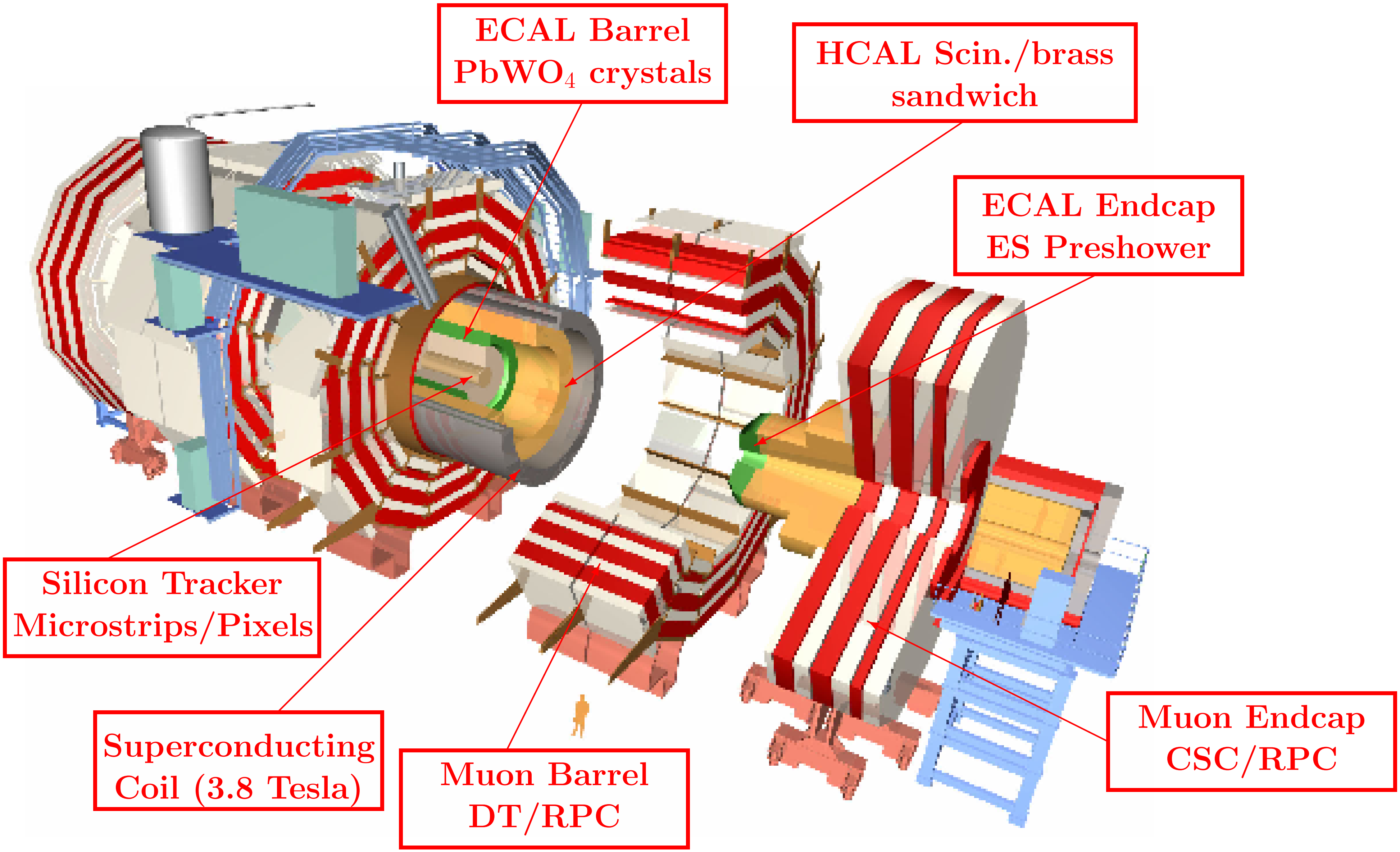



*Any deviation from a straight line points to New Physics*

**The discovery of a Higgs boson completed the SM,**
**but major questions remain**

- **Vigorous update of the main Higgs results with the full RUN1 statistics 20(8 TeV)+5(7 TeV) $fb^{-1}$ is available at CMS**
- **A new challenging program has just started at LHC 13 TeV RUN2**
- **The boson that we found looks rather "standard" scalar at first sight**
  - fermionic final states starting to build up excess
  - **data disfavor the pseudo-scalar $0^-$ and spin-2 hypotheses**
  - couplings are in agreement within uncertainties with the SM predictions
  - on and off-shell Higgs boson production bound **the Higgs "width"** under specific model-dependent assumptions
  - search for invisible Higgs decays, key indicator for NP, is straightforward
- **LHC is a main source of information and will continue to drive our initial observations in the coming years**
  - vast Higgs physics program ahead that will profit from a HL-LHC phase

**Backup**


ECAL Barrel
PbWO$_4$ crystals
HCAL Scin./brass
sandwich
ECAL Endcap
ES Preshower
Silicon Tracker
Microstrips/Pixels
Superconducting
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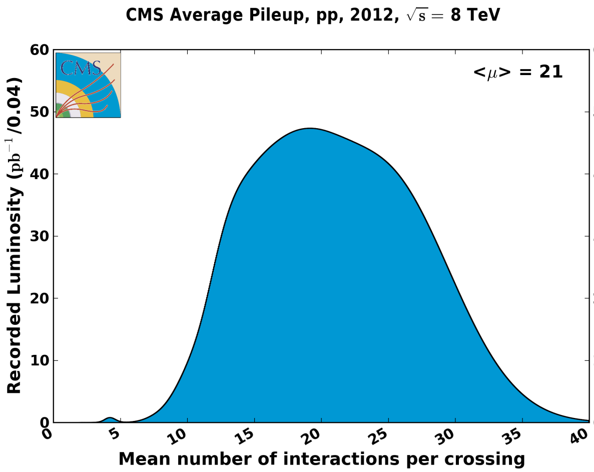
Muon Barrel
DT/RPC
Muon Endcap
CSC/RPC



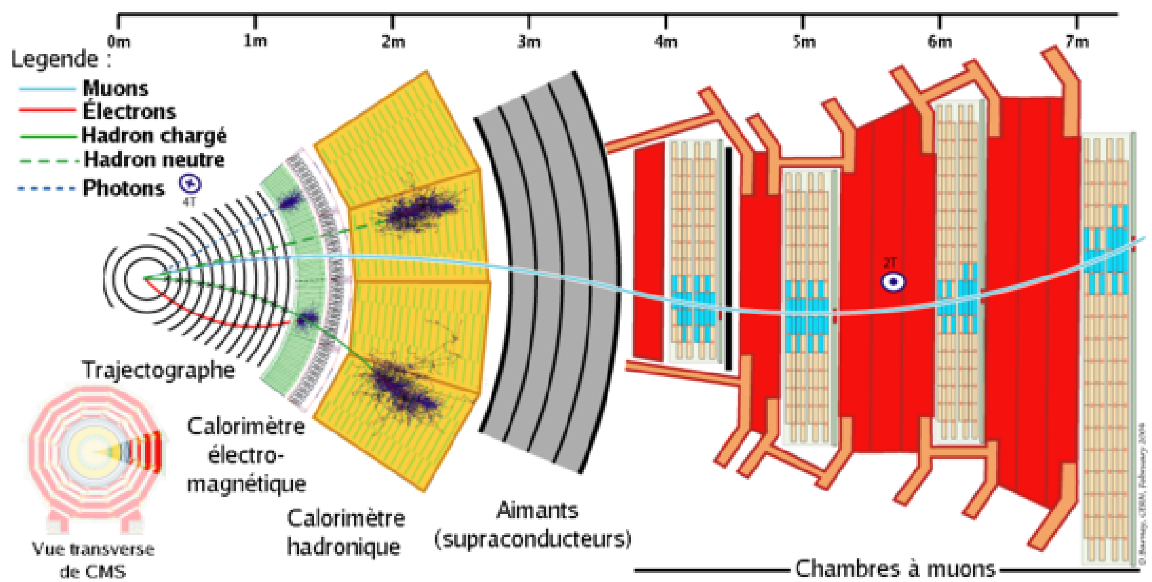

☞ Excellent performance of the CMS experiment in 2012

- 90% of recorded data for physics (all subdetectors on)
- peak luminosity $7 \times 10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ at 8 TeV CM energy
- **mean pile-up (PU) 21 events**

☞ **Particle Flow** algorithm:

- provides a global event description in form of list of particles
- improvements in jet, $\tau$ and $E_T^{\mathrm{miss}}$ measurement

*Remarkably improves reconstruction performance at high PU*



## Effect of New Physics on couplings:

$$\Delta g_{HXX}/g_{HXX} \leq 5\% \times \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

- SUSY model modifies tree level couplings and predicts largest effect for b and $\tau$

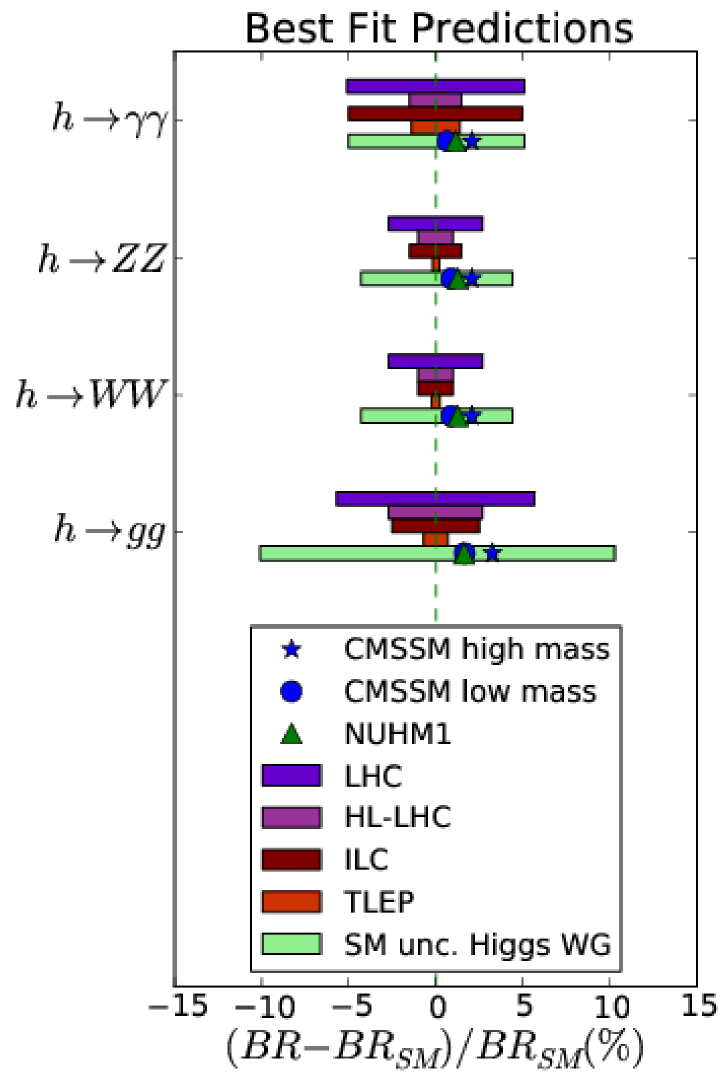
$$\frac{k_{b,\tau}}{k_{b,\tau}^{SM}} \simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2$$

- **Loop induced** couplings are modified due to a scalar top-partner contribution as

$$\frac{k_g}{k_g^{SM}} \simeq 1 + 1.4\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \quad \frac{k_\gamma}{k_\gamma^{SM}} \simeq 1 - 0.4\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

- **Compositness models** reduce couplings according to compositness scale ($\xi^{SM} = 0$)

$$\frac{k_V}{k_V^{SM}} = \sqrt{1-\xi}, \quad \frac{k_f}{k_f^{SM}} = \frac{1-(1+n)\xi}{\sqrt{1-\xi}}, \quad n = 0, 1, 2$$

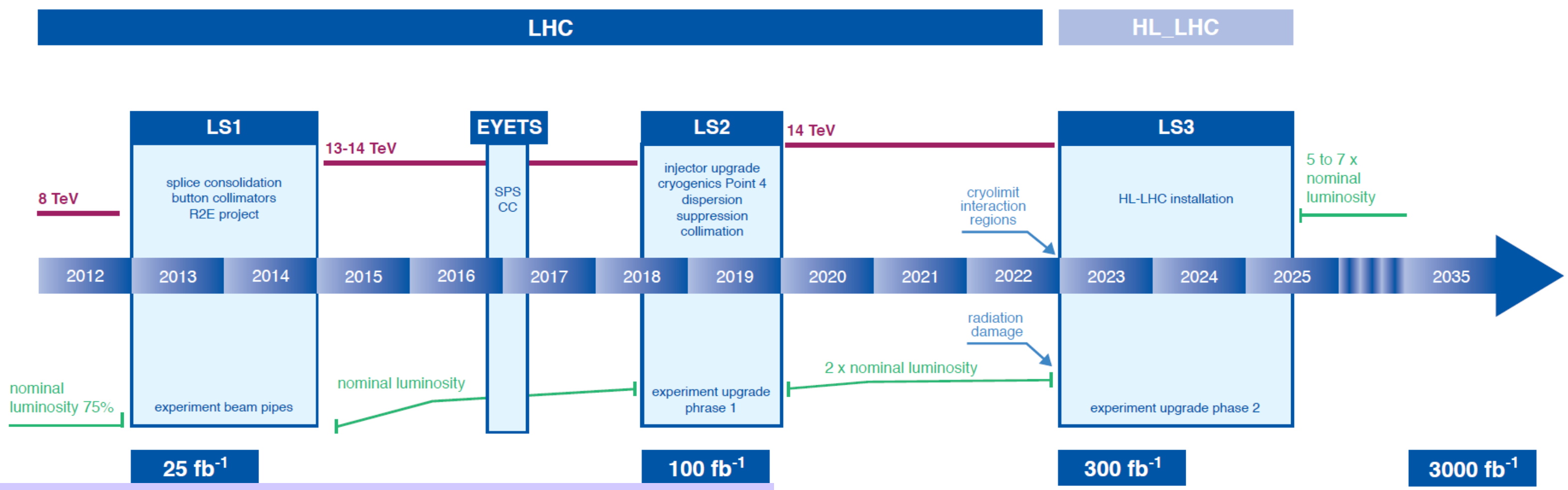



**$\Delta k/k \simeq$0.1-1% precision is needed for discovery!**

# LHC Up To 2021 and Beyond

**The exploitation of the full potential of the LHC is the highest priority of the Energy Frontier in both Europe and US**

## New LHC / HL-LHC Plan




- ☞ LHC approved running to deliver **300 $\mathrm{fb}^{-1}$ by 2022**
- ☞ Post LS3 operation (Phase II) at $\mathbf{L = 5 \times 10^{34}\ cm^{-2}\,s^{-1}}$ **3000 $\mathrm{fb}^{-1}$ over 10 years**
- ☞ Major upgrades required on the LHC **(replace more than 1.2 km):**

- ☞ Experiments will undergo a series of **detector and trigger upgrades**
  - ➠ to cope with radiation damage and high pileup **(140 PU events)**
  - ➠ to maintain or enhance the current physics performance