Measurements of the properties of the Higgs boson

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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

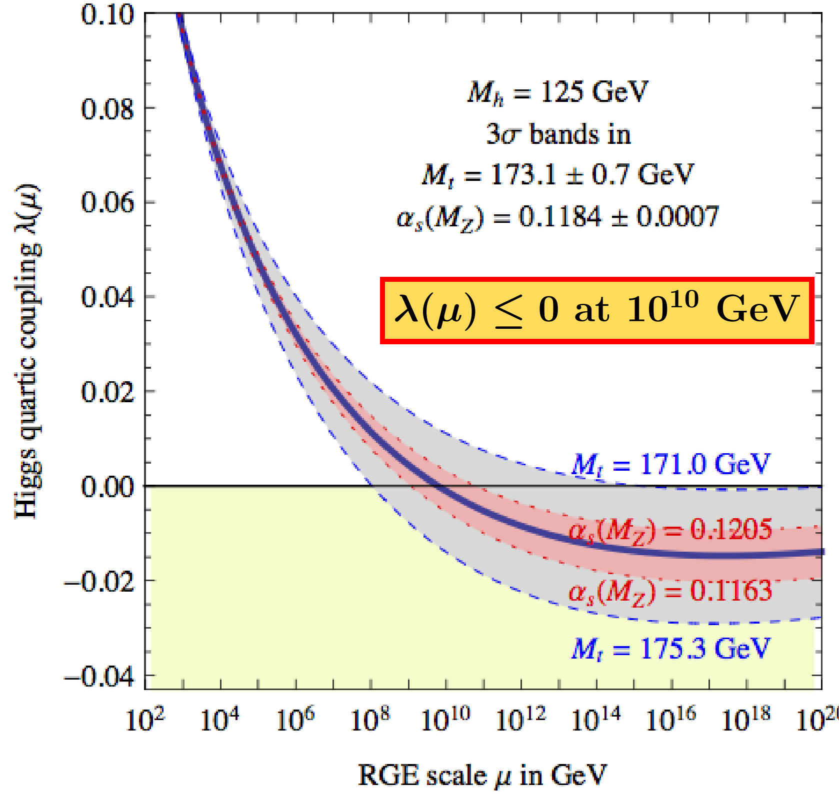
☞ **Indirect searches** through precision measurements (rare processes)

- ➠ many BSM models predict

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

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

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



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

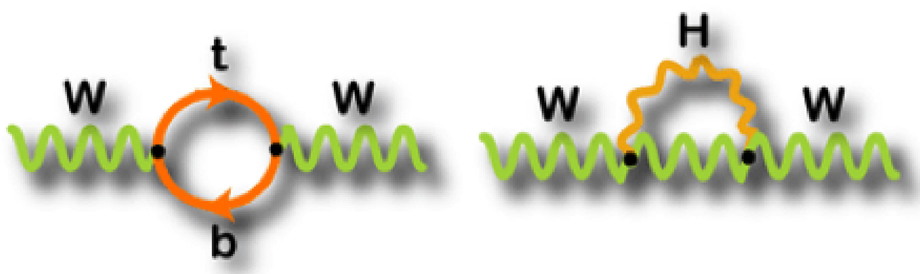
☞ SM is self-consistent model accounting all PP phenomena at energy of current accelerators

➠ with $\mathbf{m_H}$ all parameters of SM are known

☞ $\mathbf{m_W}$ is a fundamental parameter of the SM

$$\mathbf{m}_{W} = \sqrt{\frac{\pi\alpha}{G_F\sqrt{2}}}\frac{1}{\sin\theta_W\sqrt{1-\Delta R}}$$

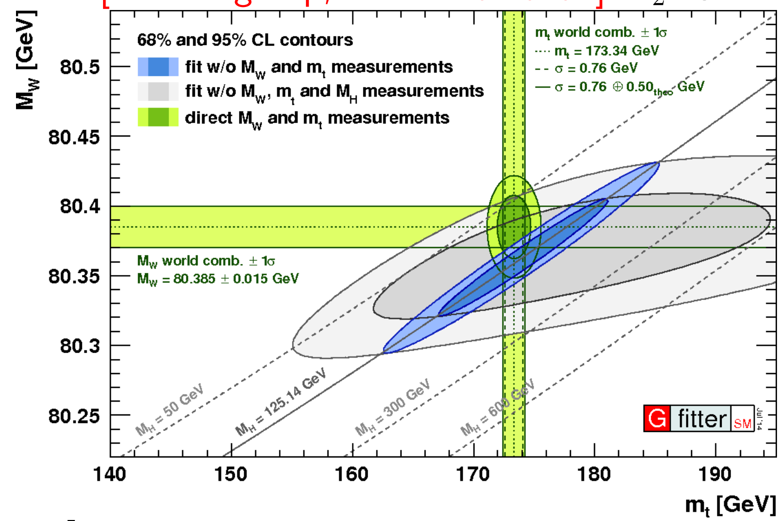
Radiative corrections $\Delta R \sim 4\%$:

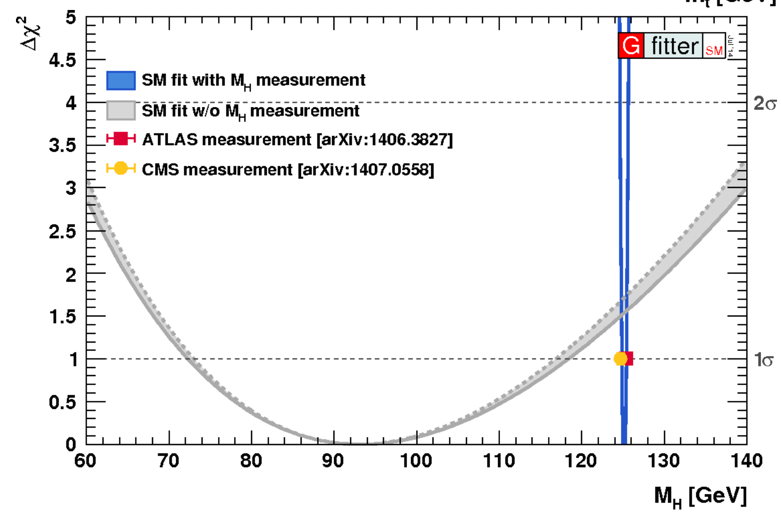


$\Delta R \sim m_t^2$ $\Delta R \sim \log m_H$

m_W = 80385±15 MeV, $\mathrm{m_t}$=173.2±0.9 GeV
current p-value for (data|SM)=0.2

[GFitter group, arXiv:1407.3792] N$_2$LO-test



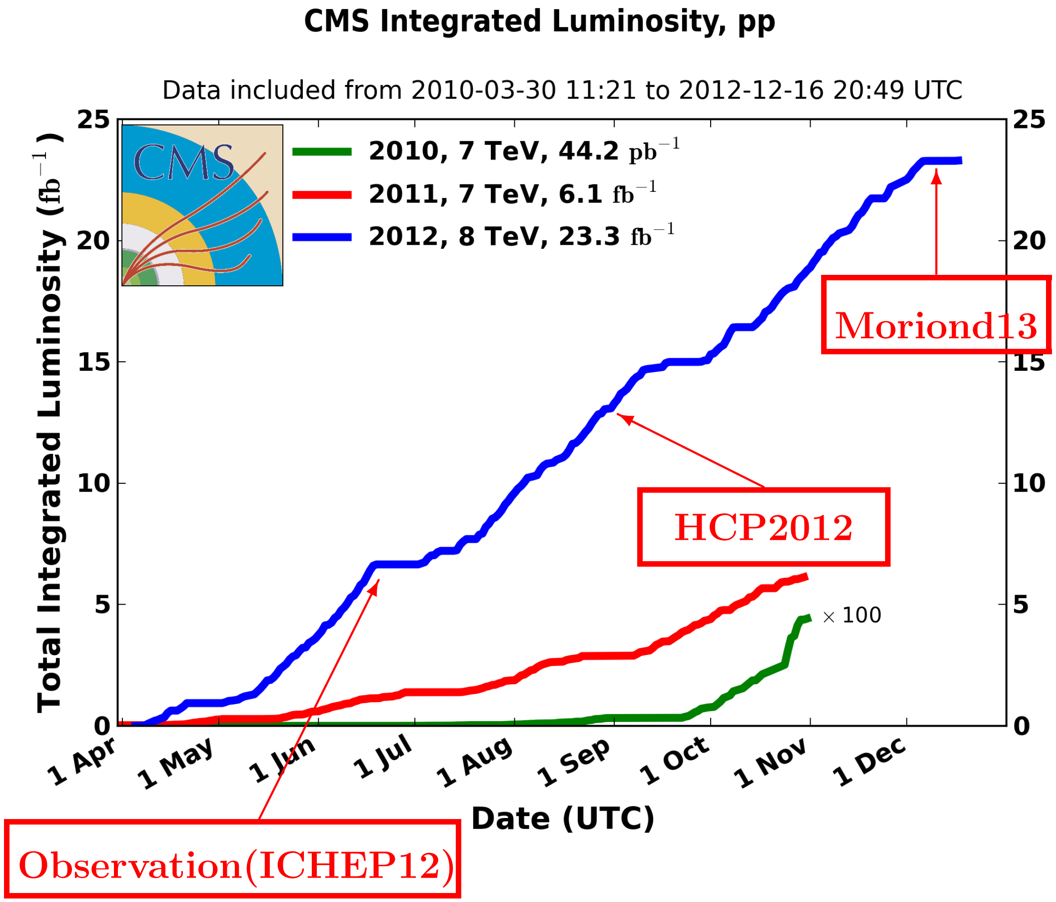


Precision tests of further consistency of the SM are mandatory!

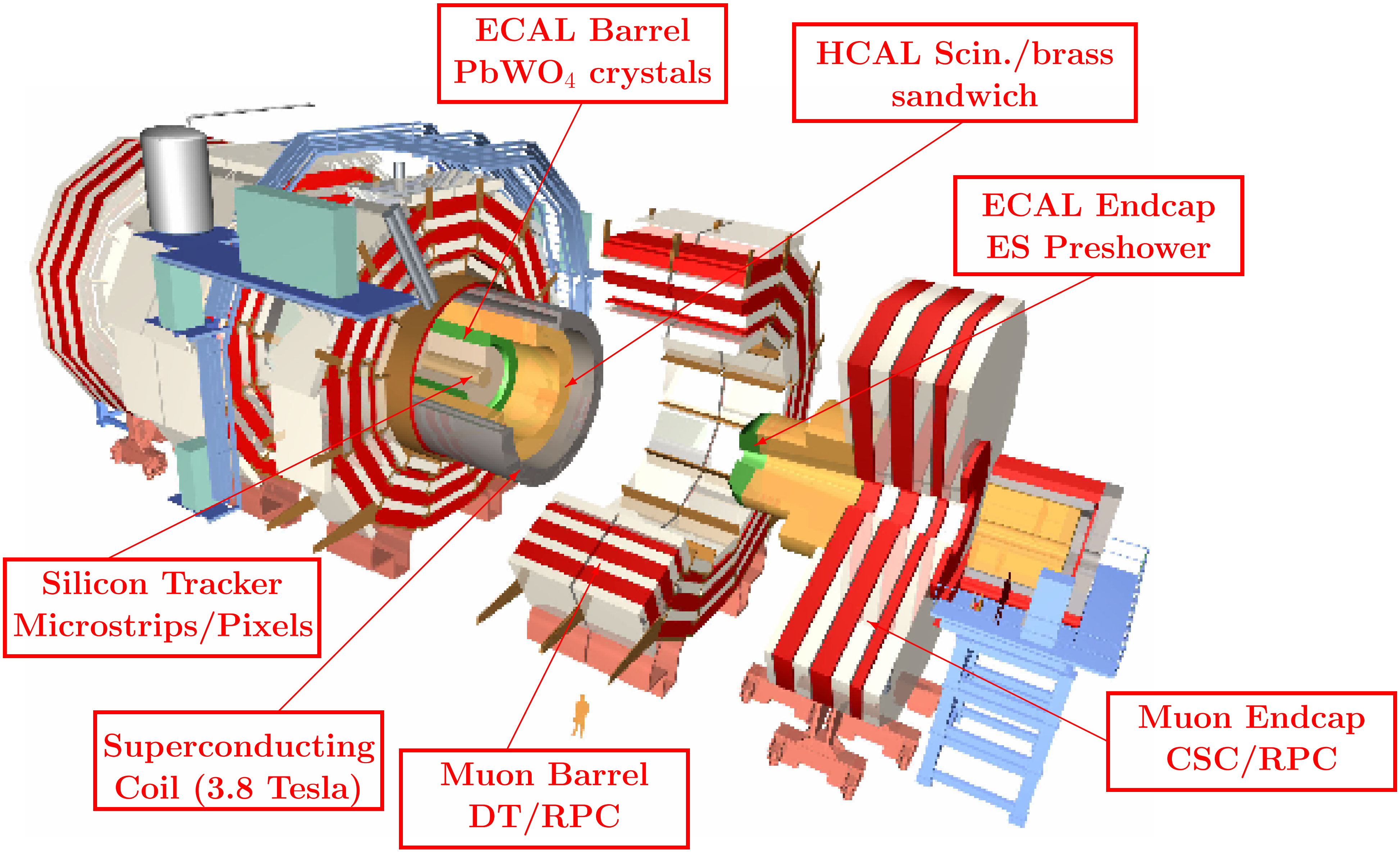
Extremely successful operation of the LHC for these 3 years

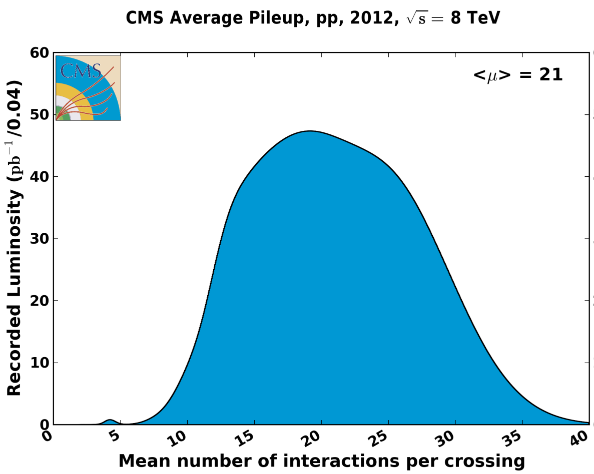
- Started with 7 TeV collisions
- Upgraded center-of-mass energy to 8 TeV in 2012
- Available dataset for the analyses with all subdetectors on
  - **7 TeV:** $\leq$5.1 fb^{-1}
  - **8 TeV:** $\leq$19.6 fb^{-1}
  - high detector efficiency

LHC restarted in 2015 with a collision energy of $\simeq$13 TeV



$\sqrt{s}$=**8 TeV:** *25-30% higher cross section than 7 TeV at 125 GeV Higgs boson mass*


ECAL Barrel
$PbWO_4$ crystals
HCAL Scin./brass
sandwich
ECAL Endcap
ES Preshower
Silicon Tracker
Microstrips/Pixels
Superconducting
Coil (3.8 Tesla)
Muon Barrel
DT/RPC
Muon Endcap
CSC/RPC



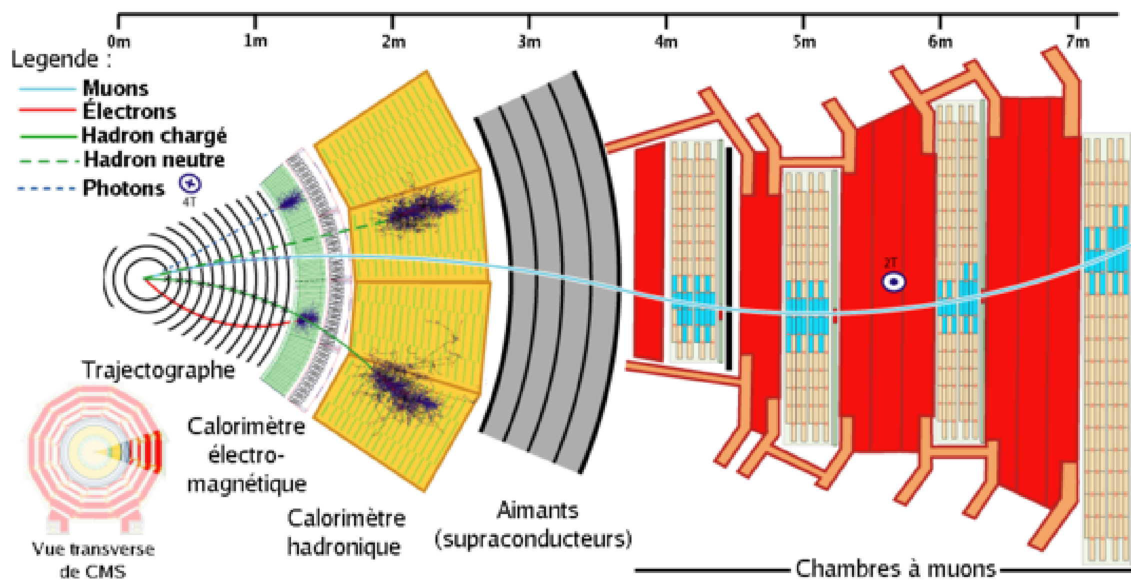
☞ Excellent performance of the CMS experiment in 2012

- 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:

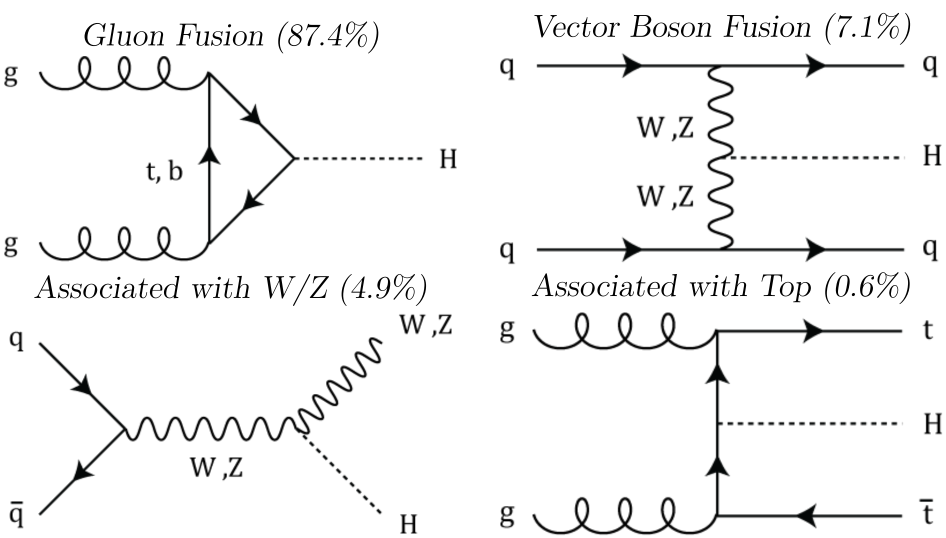
- provides a global event description in form of list of particles
- improvements in jet, τ and E_T^{miss} measurement

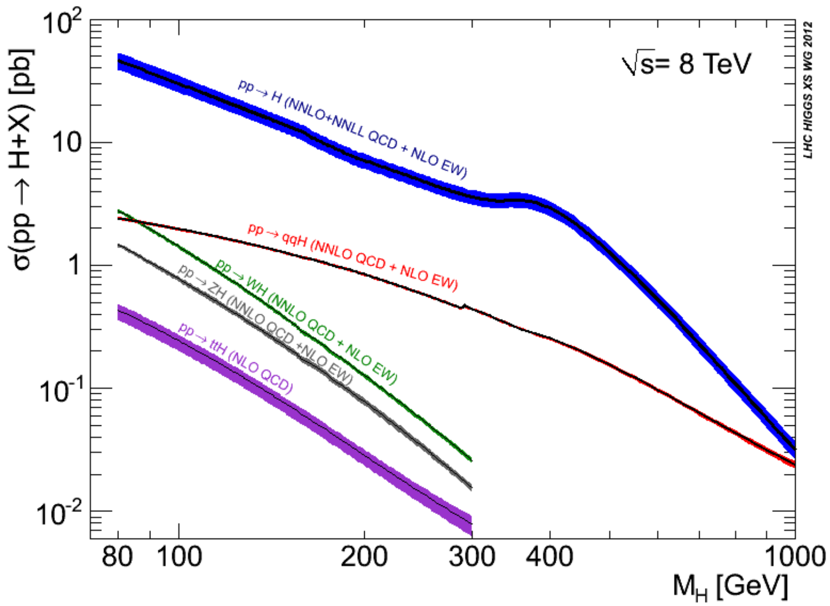
Remarkably improves reconstruction performance at high PU



Higgs Boson Production

Gluon fusion (GF) and Vector Boson Fusion (VBF) are the two most copious Higgs production processes at LHC



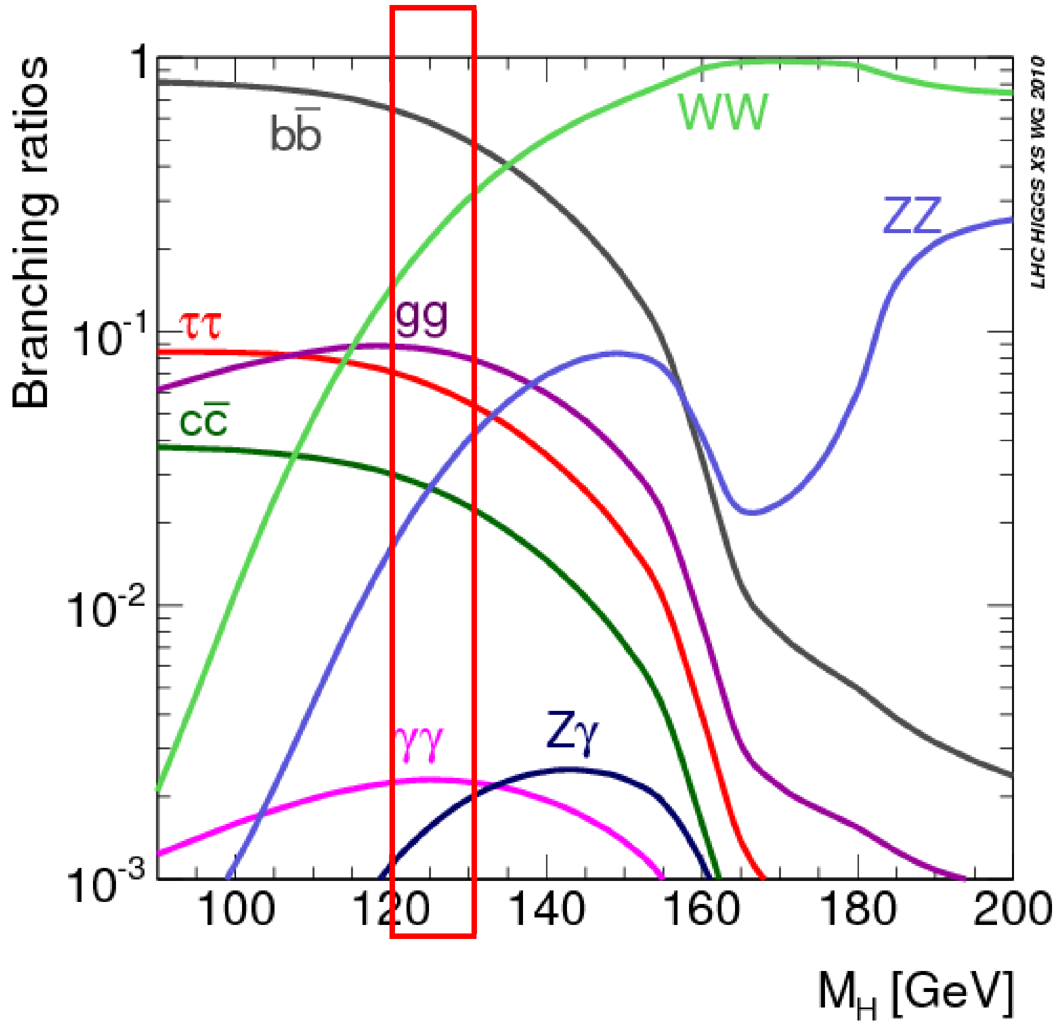


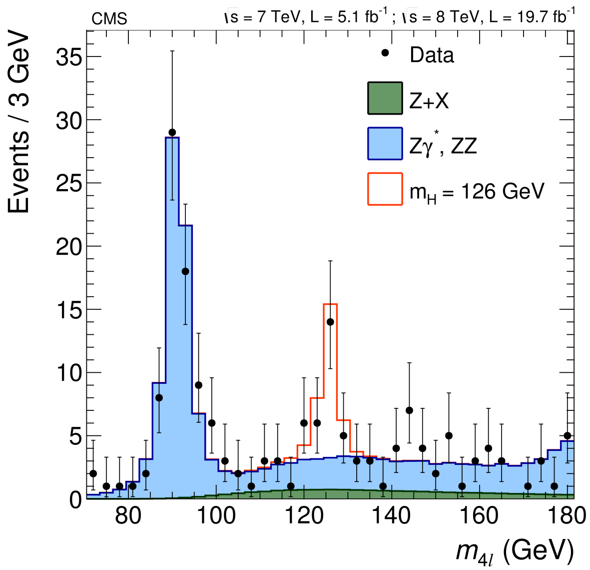
GF and VBF provide wealth of information on its couplings to bosons and fermions today

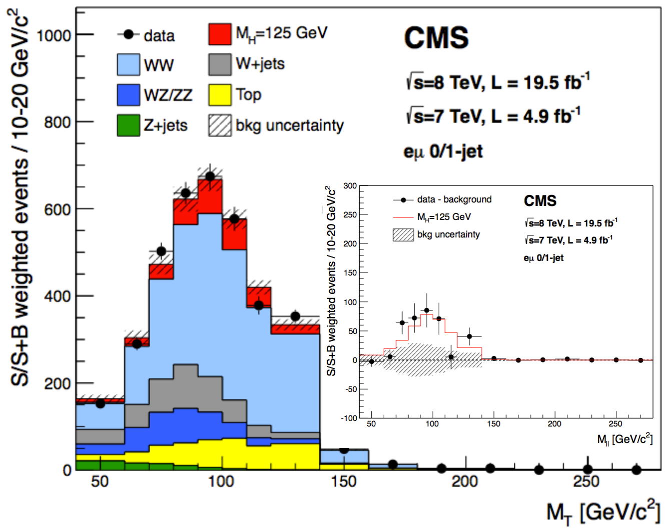
Very rich mass region but also very challenging...

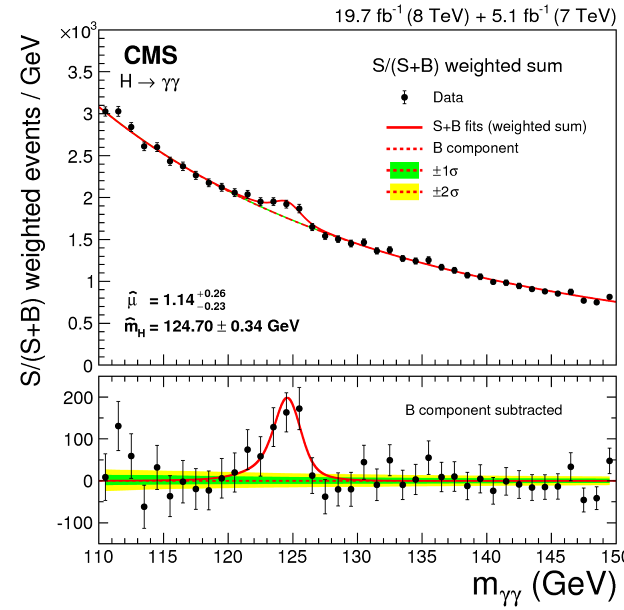
- 5 decay modes exploited: $\gamma\gamma, ZZ, WW, \tau\tau, bb$
- 2 best mass resolution decay modes (~1%): $\gamma\gamma, ZZ$
- Also includes searches in $\mathrm{H} \to \mathrm{Z}\gamma$ and $\mathrm{H} \to \mu^+\mu^-$

Decay	Exp. Sign. at 125.7 GeV	σ_M/M
H→ $\gamma\gamma$	3.9	1-2%
H→ZZ→4l	7.1	1-2%
H→WW→2l2ν	5.3	20%
H→bb	2.2	10%
H→$\tau\tau$	2.6	10%

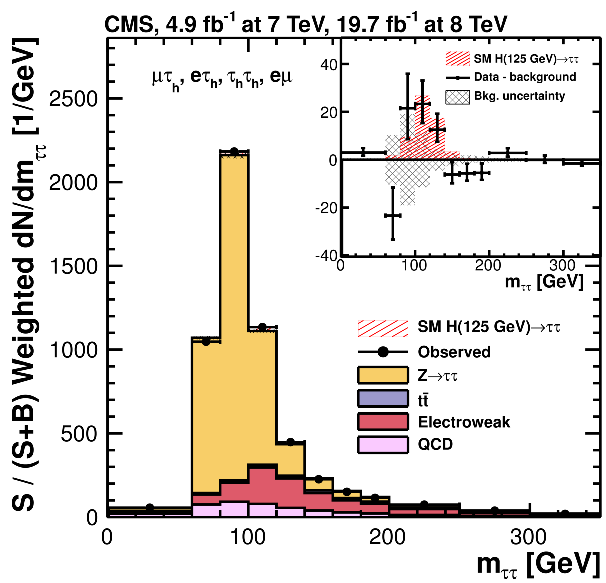


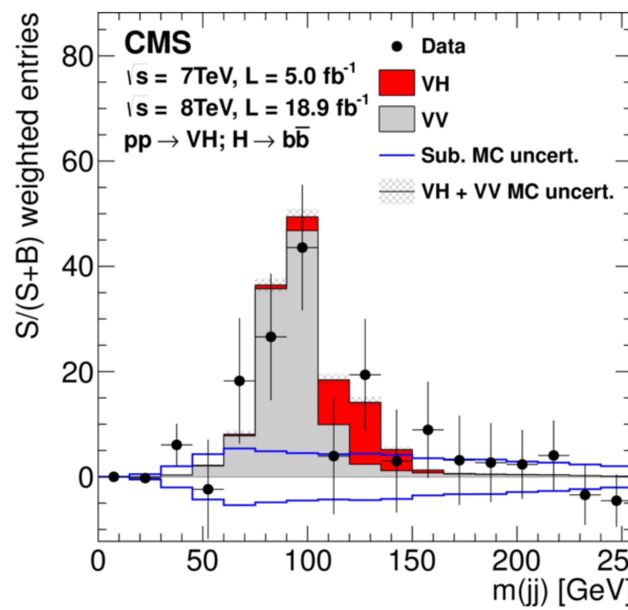


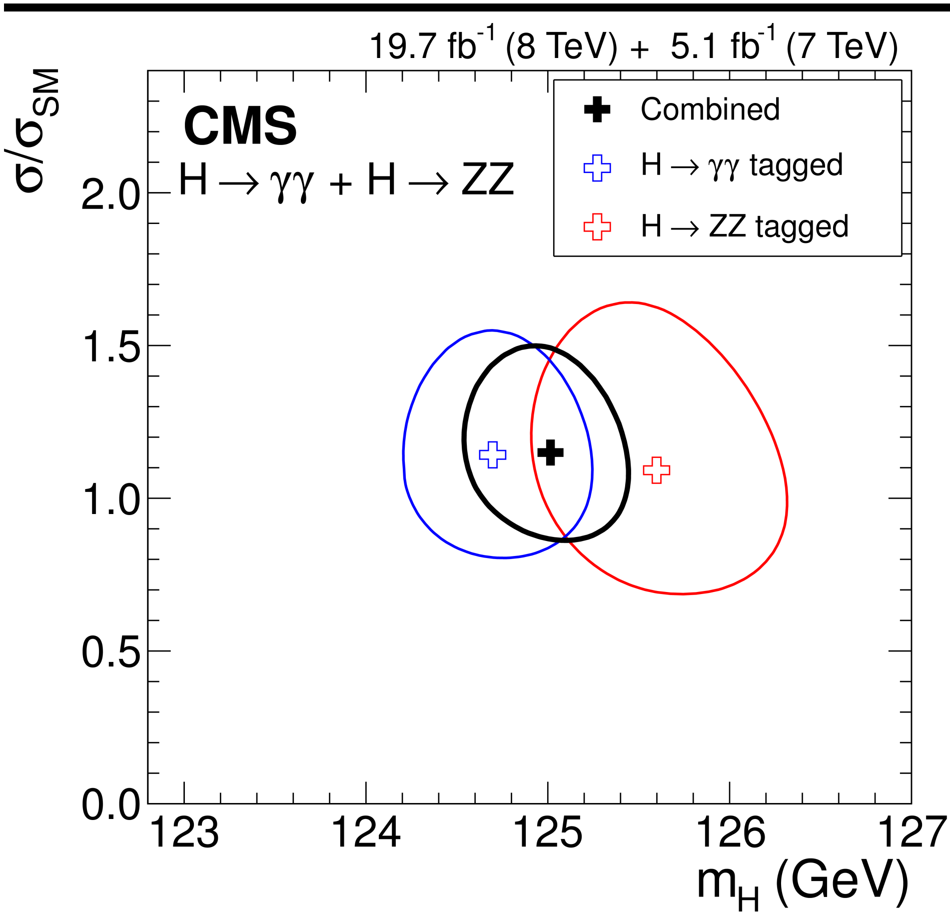


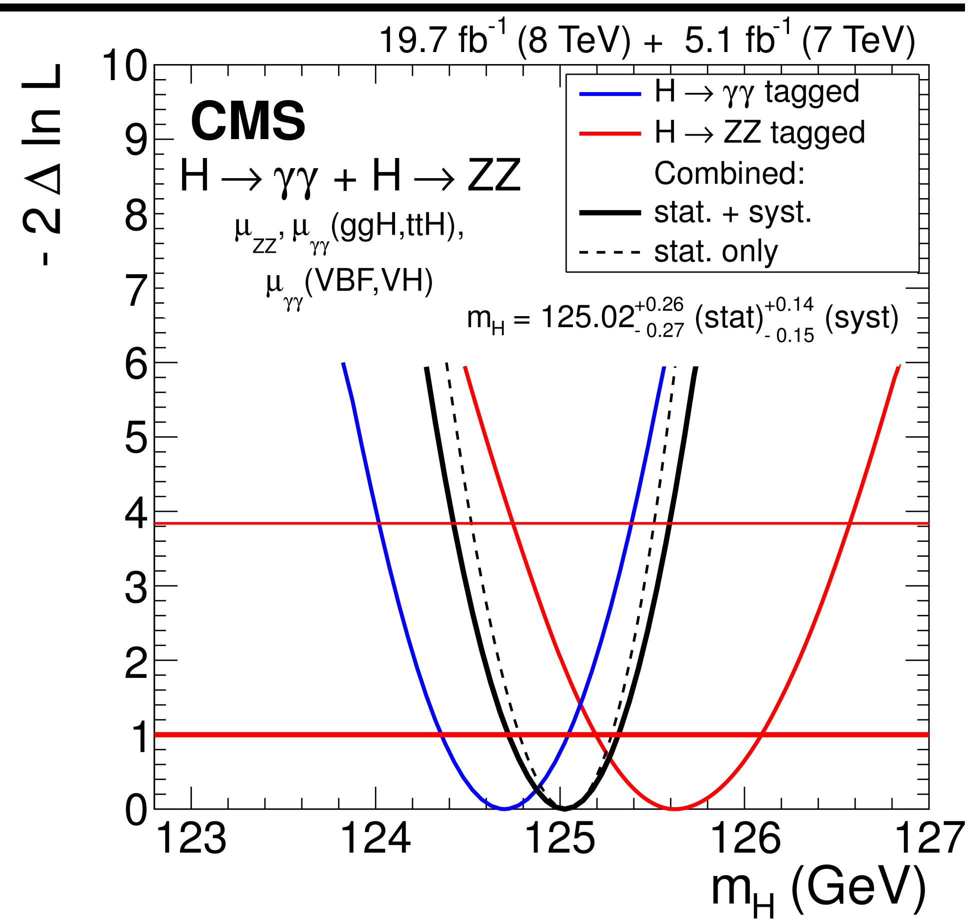


Solid signal in 3 bosonic decay channels and fermionic final states starting to build up excess







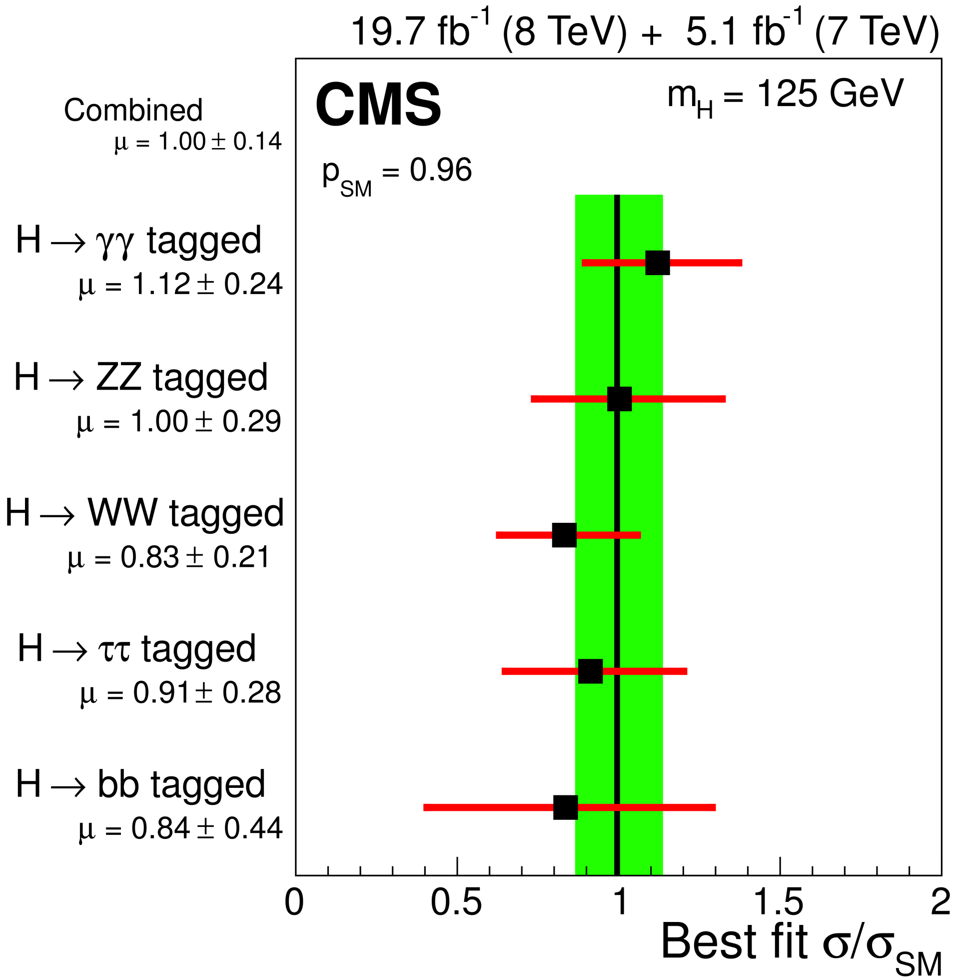


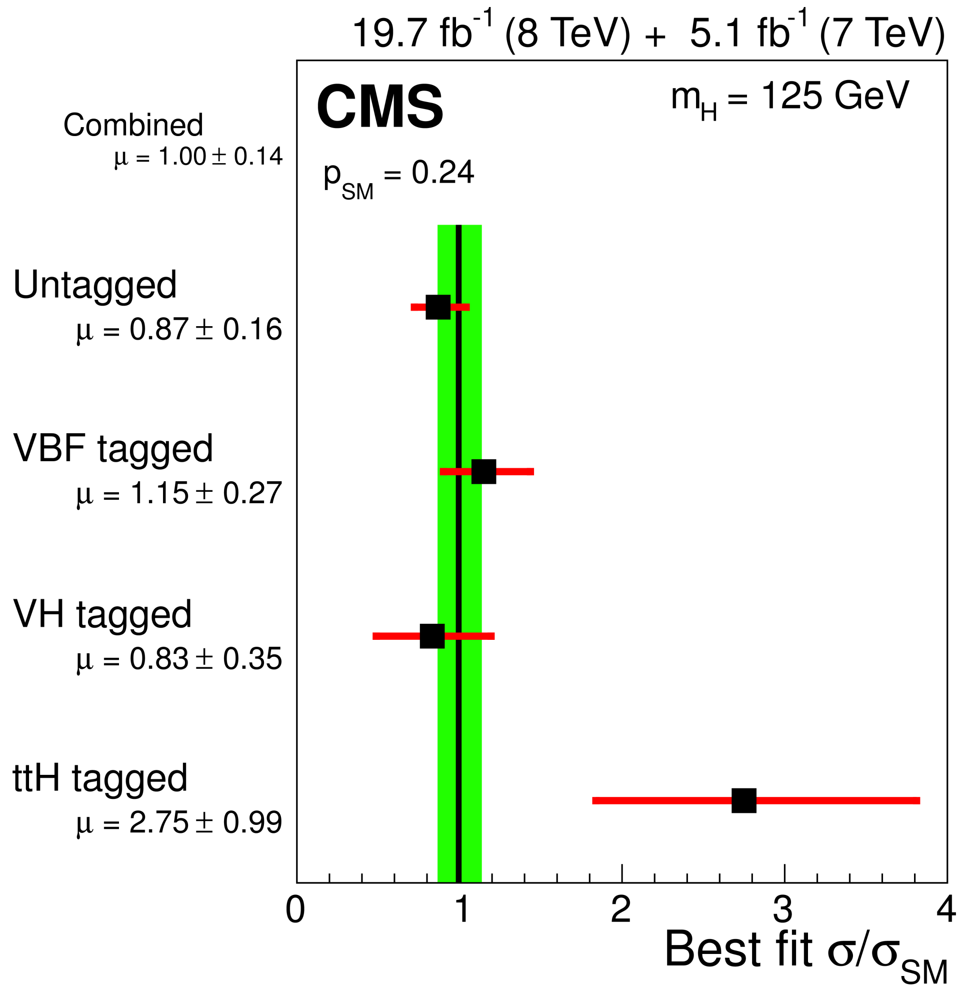
[HIG-14-009]

- Likelihood scan for m_X and μ: 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

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





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

☞ Overall best-fit signal strength in the combination:

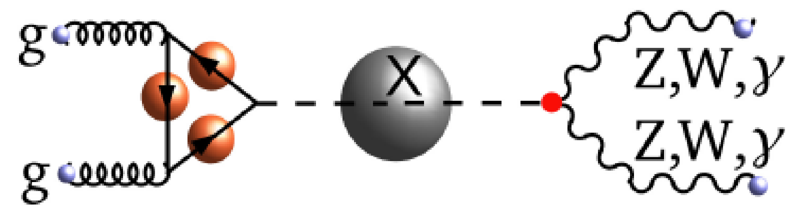
$$\boldsymbol{\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.09(\mathrm{stat}) \pm 0.08(\mathrm{theo}) \pm 0.07(\mathrm{syst})}$$

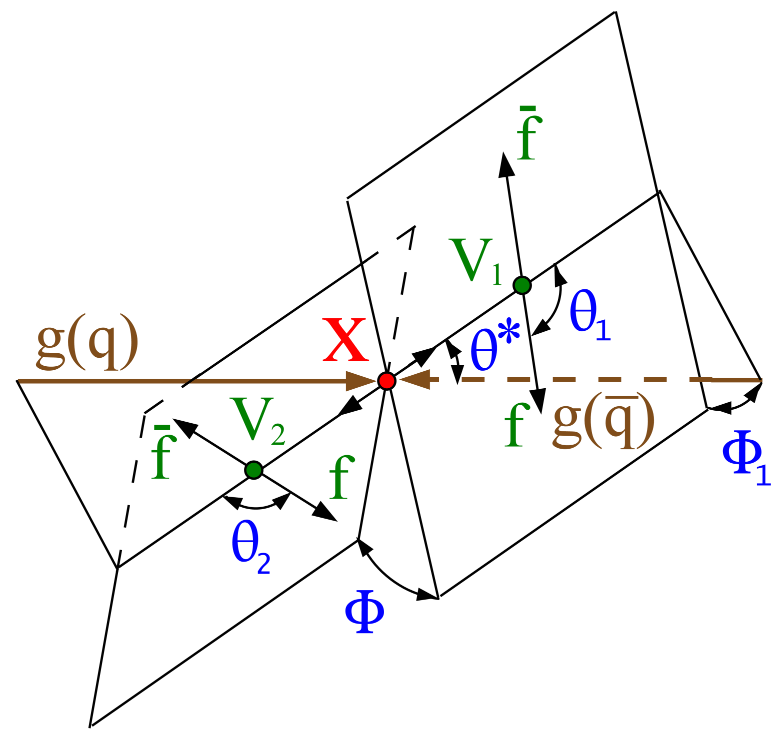
Tensor structure of the Higgs sector (J^{CP} numbers) can be best probed by angular analysis

- 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
    - ➔ $a_3 \neq 0$



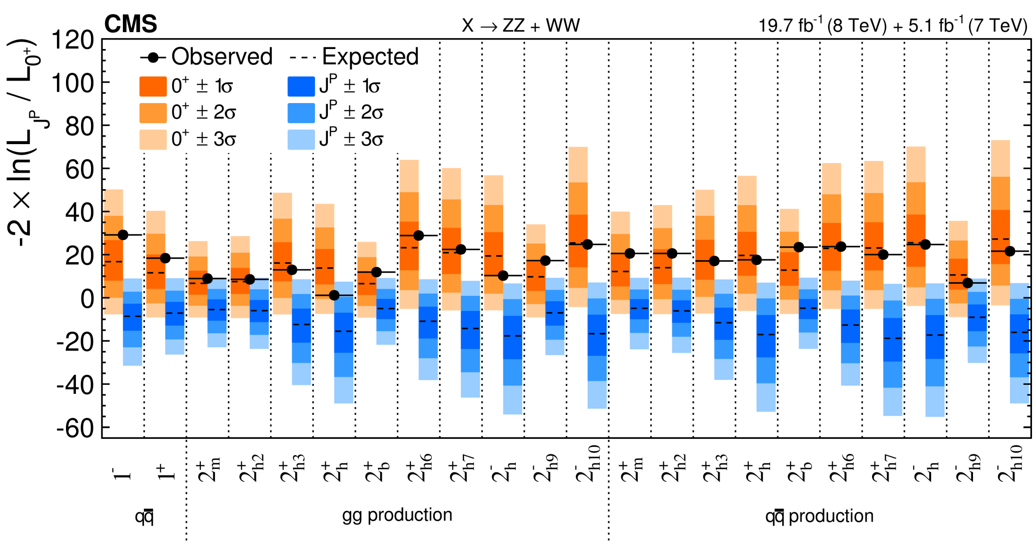


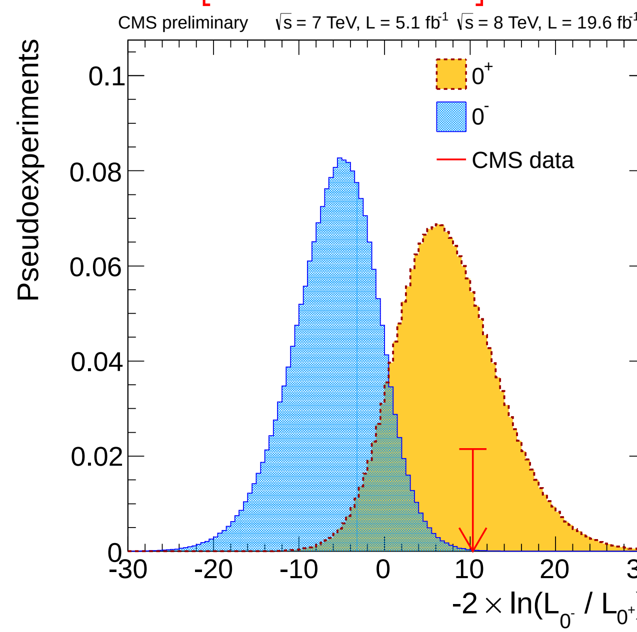
[HIG-13-002]

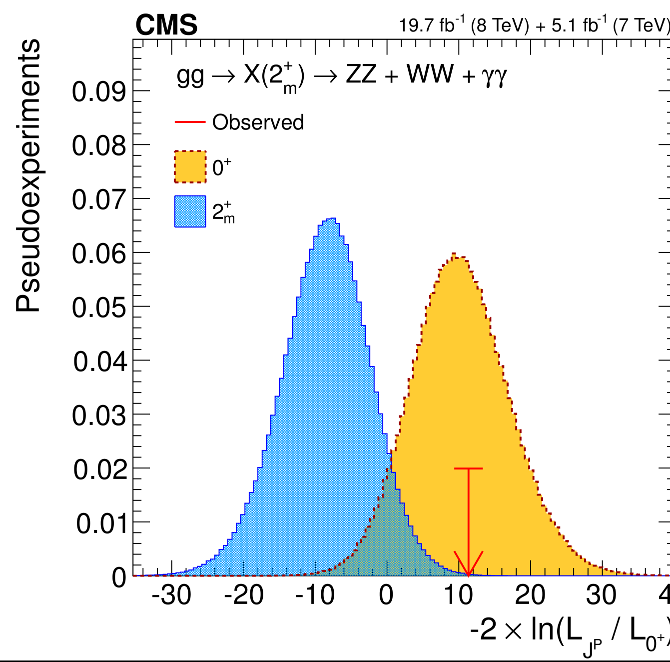
Spin and CP-parity hypotheses are discriminated by angular analysis

☞ **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







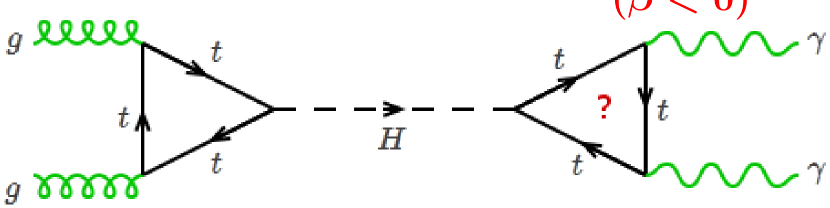
The observation is well compatible with SM Higgs expectations (0^+)

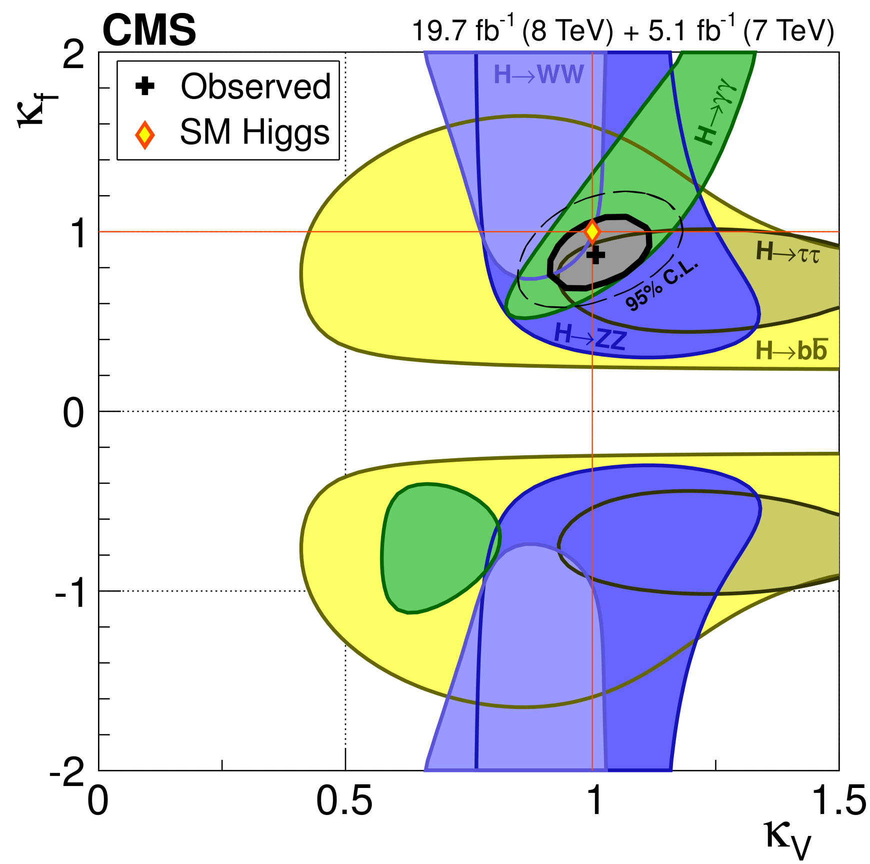
Extracting Higgs couplings requires assumptions at LHC

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

- 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

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

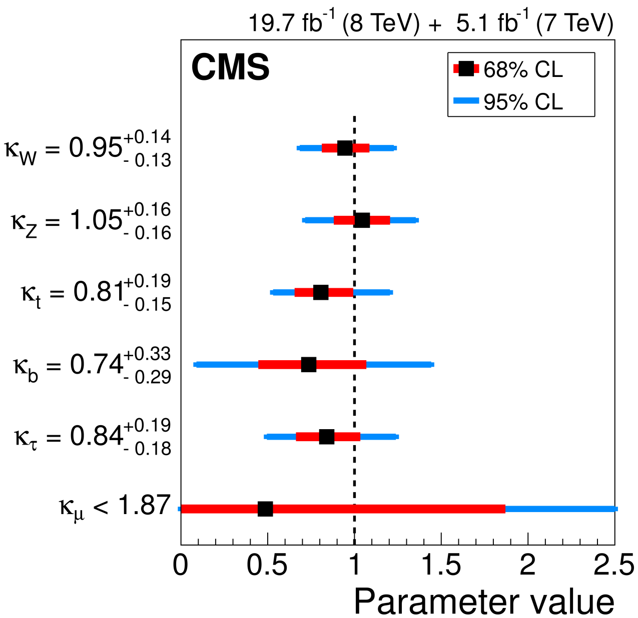




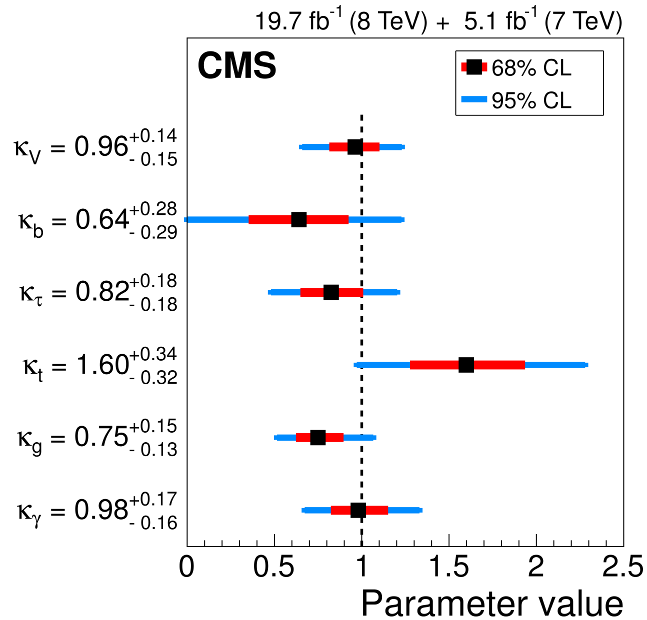
In agreement with the SM within uncertainties

Summary of Coupling Measurements

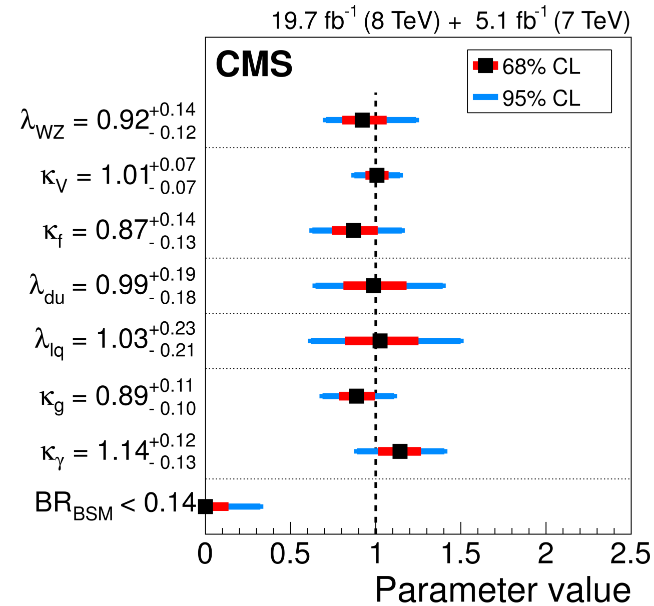
Compatibility with the SM Higgs Boson Couplings



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



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



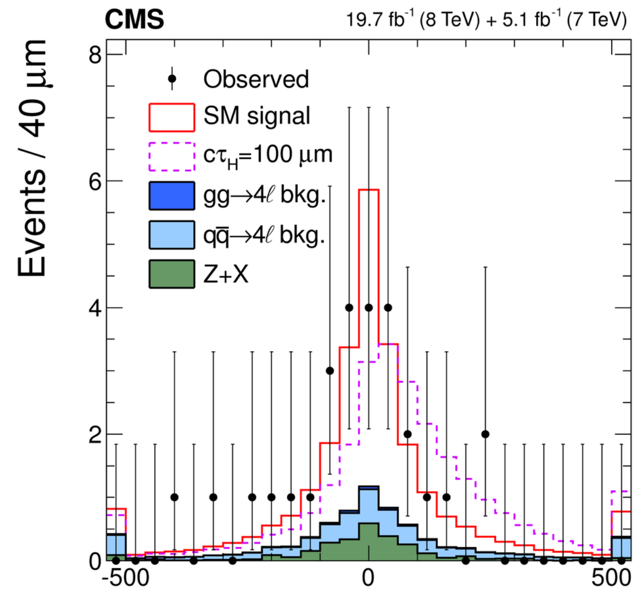
New particles can modify the loop-mediated couplings and contribute to the total width

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

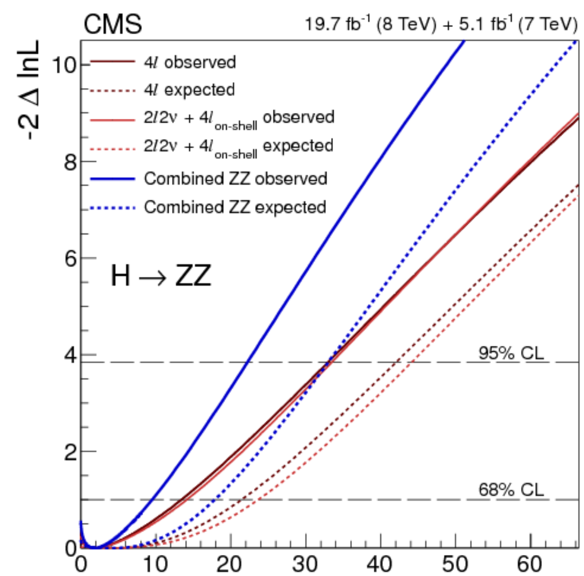
No significant deviations from the SM Higgs boson are found so far

In the SM $\Gamma_H \sim 4.1$MeV for $m_H = 125$GeV

- Direct measurement exploits m_{4l} and $m_{\gamma\gamma}$ spectra
  - limited by experimental resolution (1-2%)
  - **$\Gamma_H \leq 1.7$ GeV** at 95% CL (exp. 2.3 GeV)
- A lower bound on the Higgs width from its lifetime
  - measure displacement vertex between H production and decay in $H \to ZZ \to 4l$
  - **$\Gamma_H \geq 3.5 \times 10^{-3}$ eV** at 95% CL
- Indirect limit through off-shell production
  - $\sigma_{off-shell} \sim g_g^2 g_V^2$ does not depend on total width Γ_H as $\sigma_{on-shell}$ does
  - assume the on-shell and off-shell couplings are the same
  - **$\Gamma_H \leq 22$ MeV** at 95% CL (exp. 33 MeV)



[HIG-14-036]



[HIG-14-002]

Invisible Higgs Decays $\mathrm{BR_{inv}}$

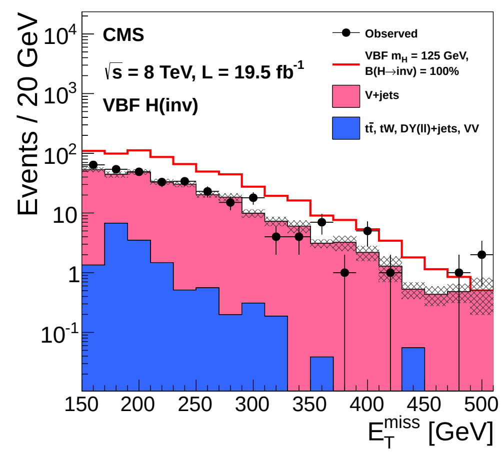
[HIG-15-012 (new)]

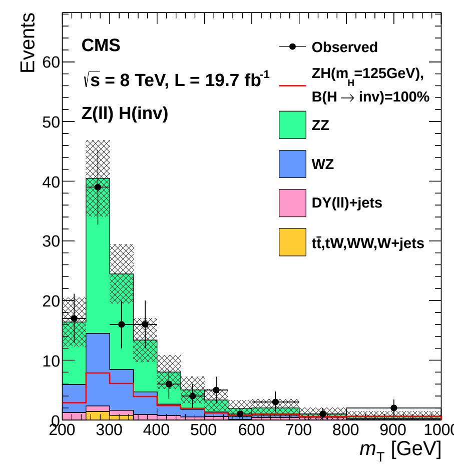
A non-zero partial decay width to invisible particles could provide evidence for NP

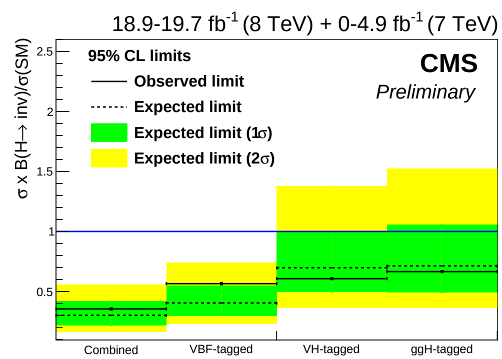
☞ Direct 95% CL on $\mathrm{BR_{inv}}$ using **VBF,VH and GF** tagged events

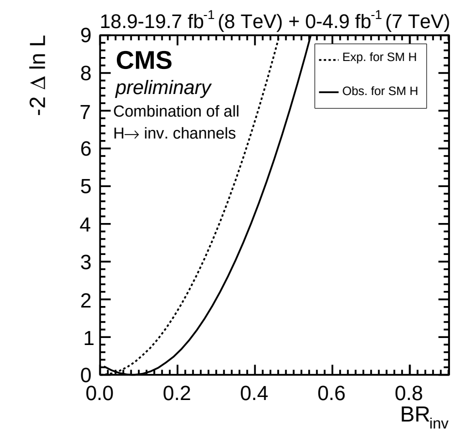
Channel	obs.	exp.
VBF	0.57	0.40
VH	0.60	0.69
GF	0.67	0.71
Comb.	0.36	0.30

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





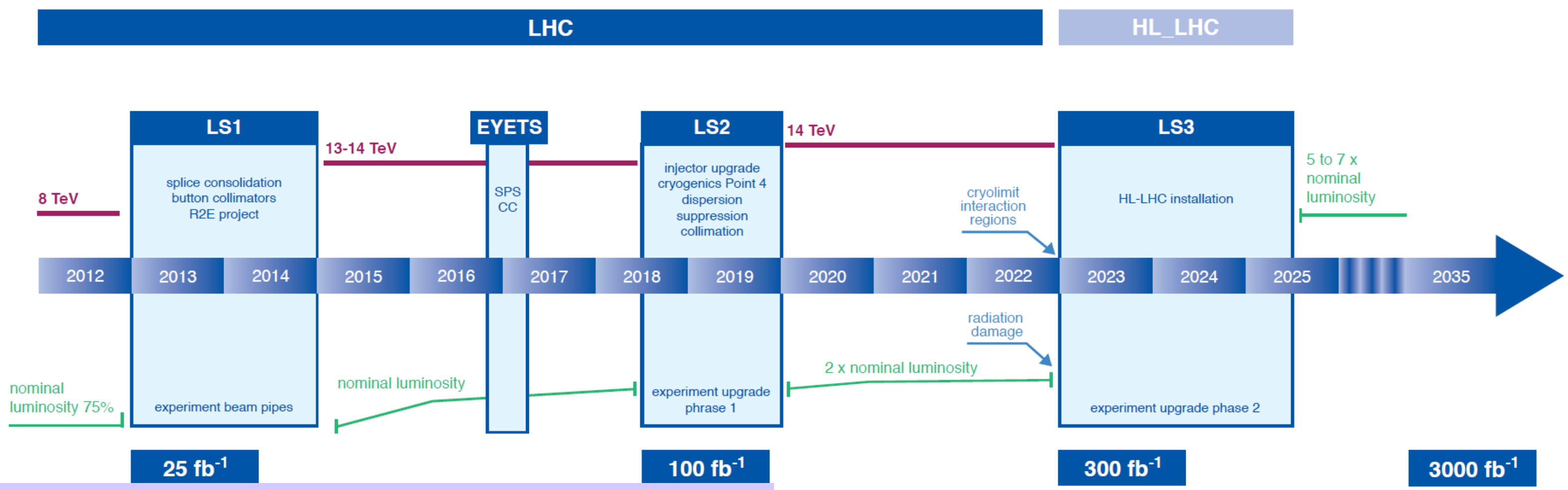




Consistent with global coupling fit:
$\mathrm{BR_{inv}} < 0.52$ *at 95% CL*

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 fb^{-1} by 2022**
- Post LS3 operation (Phase II) at $\mathbf{L = 5 \times 10^{34}\ cm^{-2}\,s^{-1}}$ **3000 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

HL-LHC is the benchmark Higgs factory

(a couple of Higgs per sec)

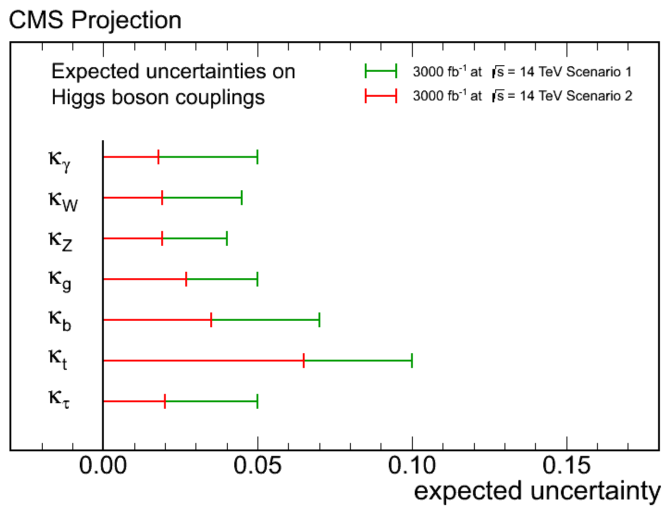
☞ Most of the exclusive final states are accessible

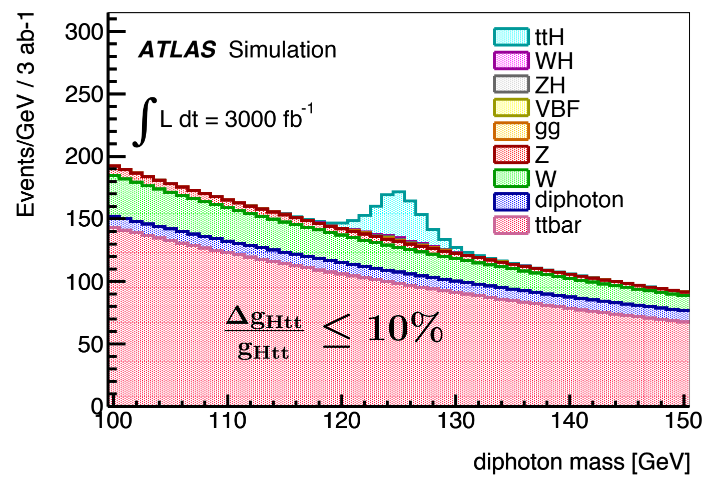
- **20K** $\mathrm{H} \to \mathrm{ZZ} \to 4\mathrm{l}$
- **30K** $\mathrm{H} \to \mu\mu$
- **50** $\mathrm{H} \to \mathrm{J}/\psi\gamma$

Channel	σ, pb (14 TeV)	Rate, Hz L=50 $\mathrm{pb}^{-1}\ \mathrm{s}^{-1}$ (14TeV)	Events, L=3ab^{-1} (14TeV)	Events, L=30 fb^{-1} (8TeV)
GF	50.4	2.52	150M	600K
VBF	4.2	0.21	13M	48K
WH	1.5	0.08	4.5M	21K
ZH	0.9	0.04	2.6M	12K
ttH	0.6	0.03	1.8M	4K

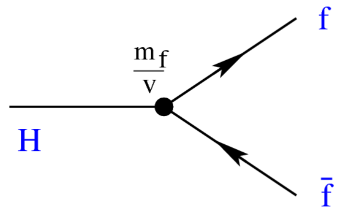
HL-LHC enable to probe most of the couplings including direct ttH observation

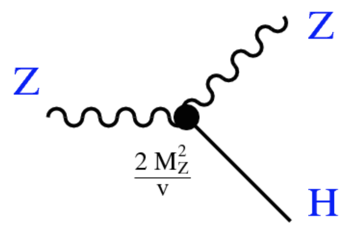
Systematics:
Scenario 1 unchanged
Scenario 2 scaled $1/\sqrt{\mathrm{L}}$

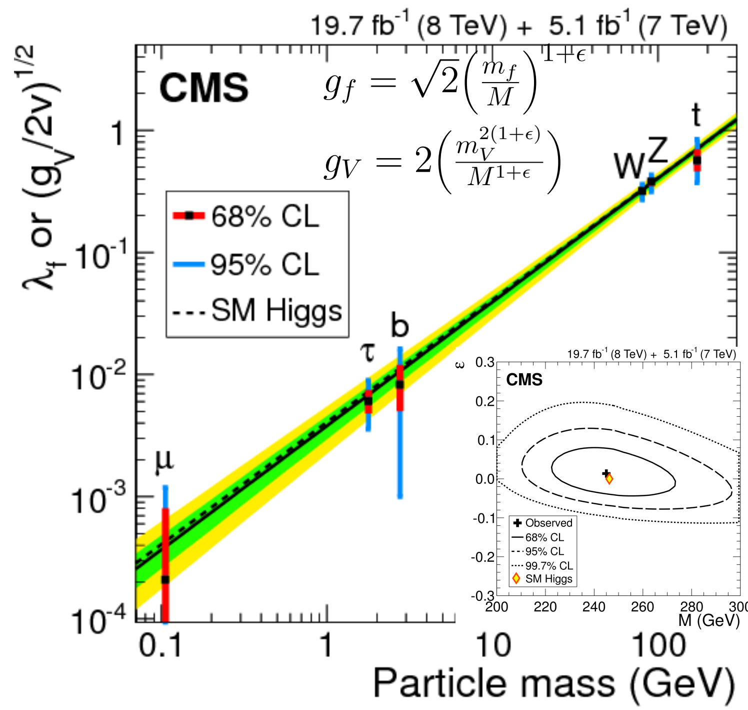




Theoretical uncertainties affects the ultimate precision achievable by LHC experiments (2-5%). Reducing them it is for sure worth the effort!



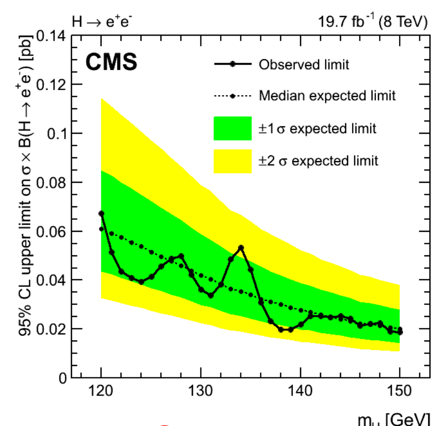


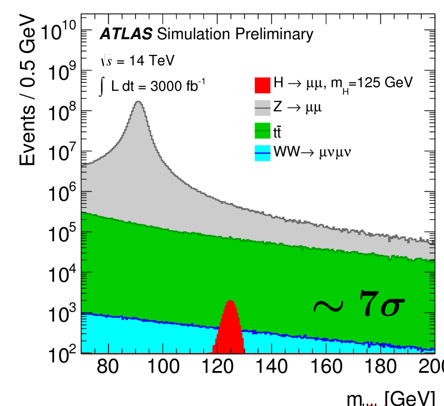


☞ LHC potential to probe **3 generations**

- a few % precision for **3rd generation**
  - ➔ Higgs decays to fermions $(\tau\tau, \mathrm{bb})$
- access to **2nd generation** fermions
  - ➔ possibly test lepton universality:
    $$\boldsymbol{\sigma_{H\to\tau\tau}/\sigma_{H\to\mu\mu} = (m_\tau/m_\mu)^2}$$
- **1st generation** is out of LHC reach
  - ➔ $g_{H\mu\mu}/g_{Hee} \simeq 200$
  - ➔ 1 $H \to ee$ event is expected

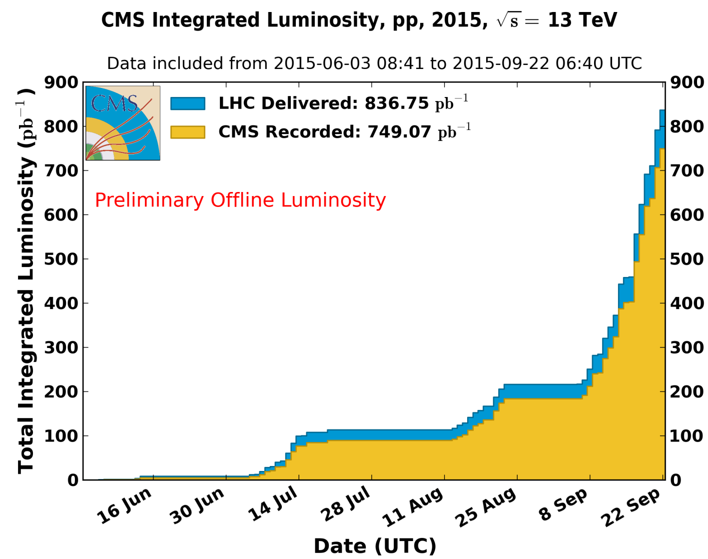
Many alternative models can be probed via the 1nd and 2nd generations

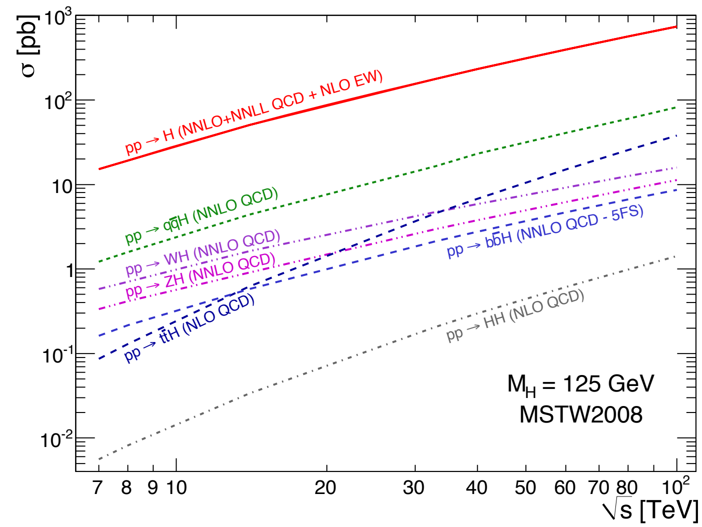




Observation of $H \to \mu\mu$ at LHC is tough, but possible!

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





- ☞ **CMS can ultimately record about 100 fb^{-1} of data for next 3 years**
- ☞ **CMS detector for RUN2:** improvements during long shutdown LS1
  - ➠ **DAQ and HLT:** computers, trigger
  - ➠ **tracker/pixel:** cold operation
  - ➠ **HCAL:** new photosensors
  - ➠ **muon:** 4th station
  - ➠ new luminosity telescopes
  - ➠ new beam pipe

$\sqrt{s}$=14 TeV: *2.6 (4.7) higher cross section than 8 TeV for GF and VBF (ttH) (grow background too)*

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**

☞ **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
- precision on Higgs properties are expected to be pinned down to a few percent

A new challenging program has just started at LHC 13 TeV RUN2

Backup

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 τ

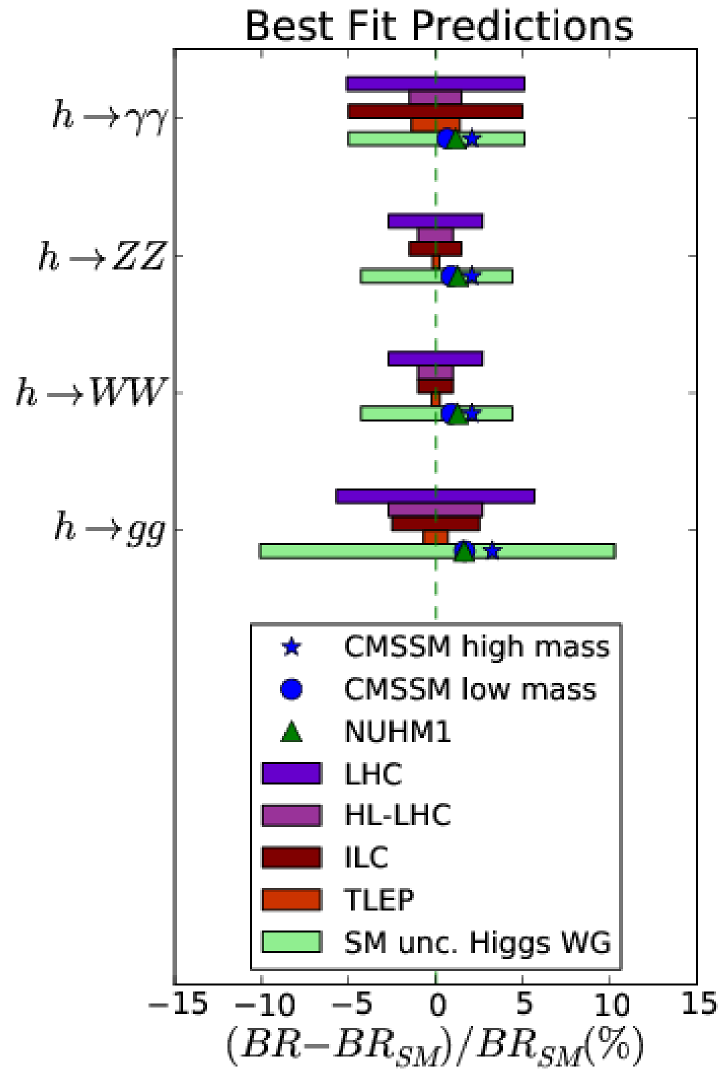
$$\frac{k_{b,\tau}}{k^{SM}_{b,\tau}} \simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2$$

- **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!