COMBINATION OF RESULTS ON THE HIGGS BOSON & MEASUREMENT OF ITS PROPERTIES AT CMS

LHC Physics 2014, New York

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on behalf of the CMS collaboration

Higgs signatures explored at CMS

- CMS explored a large set of accessible signatures
  - Strong evidence in bosonic & fermionic channels!
  - Details on individual bosonic and fermionic decays in talks by X. Janssen & J. Konigsberg (Higgs 1)
    Higgs overview talk by M. Klute (SM Higgs plenary)

Signal significance

Decay	ZZ	WW	γγ	ττ	bb
Expected [σ]	6.7	5.8	4.2	3.7	2.3
Observed [σ]	6.8	4.3	3.2	3.2	2.1

- Significant set of explored signatures used for combined measurements
  - Results in this talk: **CMS-HIG-13-005, CMS-HIG-13-002, CMS-HIG-13-023, HIG-13-030**

Channels explored by CMS, subset used for combined results

	bb	ττ	WW	ZZ	γγ	Zγ	μμ	inv.
inclusive (ggH)		✔ (green)	✔ (red)	✔ (red)	✔ (red)	✔ (green)	✔ (grey)	
VBF tag	✔ (grey)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (grey)	✔ (grey)	✔ (grey)
VH tag	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)			✔ (grey)
ttH tag	✔ (green)	✔ (grey)	✔ (grey)	✔ (grey)	✔ (grey)			

✔ (red) : **combined properties measurement: mass, spin-parity**

✔✔ (red, green) : used for **combination results: deviations of couplings (CMS-HIG-13-005)**

Mass of the new boson

- Mass measurement using high resolution channels:

H→ZZ→4l

- Very good control of the leptons scale and resolution, exploits per-event mass uncertainties

H→γγ

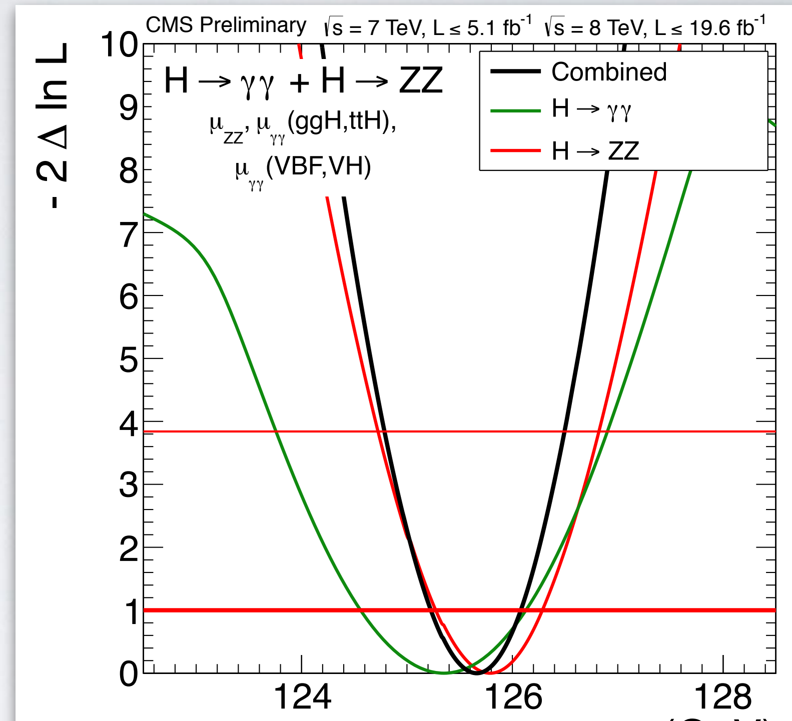
- Good resolution, systematics on the extrapolation from the Z→ee to H→γγ

- Combined mass measurement (2013)
  - **individual signal strengths independently profiled**

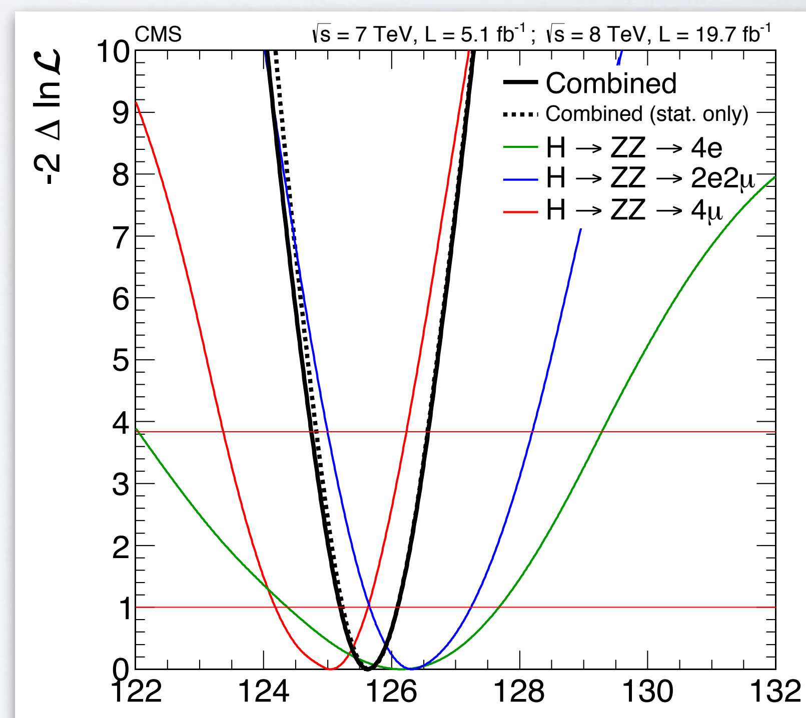
➡ **m_H = 125.7 ± 0.3$_{STAT}$ ± 0.3$_{SYST}$ GeV**

- **Latest** measurement in **H→ZZ→4l** (2014)
  - **public results: CMS-HIG-13-002**

➡ **m_H = 125.6 ± 0.4$_{STAT}$ ± 0.2$_{SYST}$ GeV**



CMS-HIG-13-005

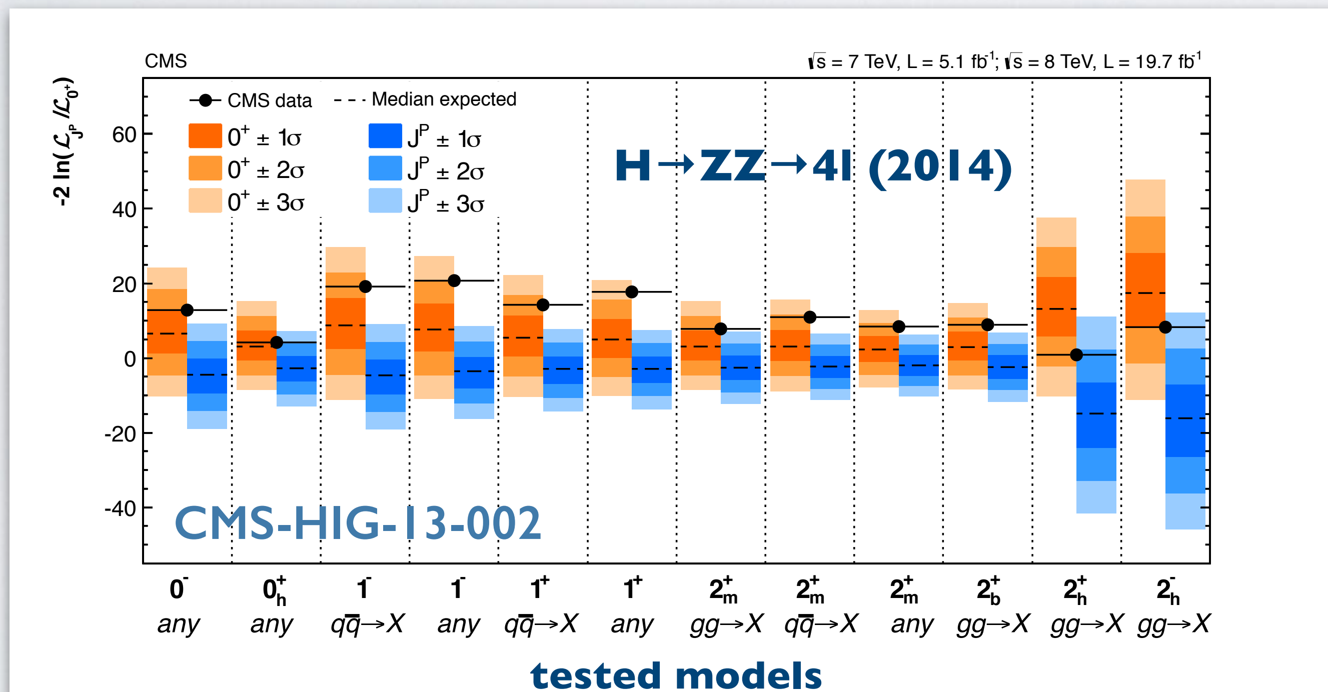


CMS-HIG-13-002

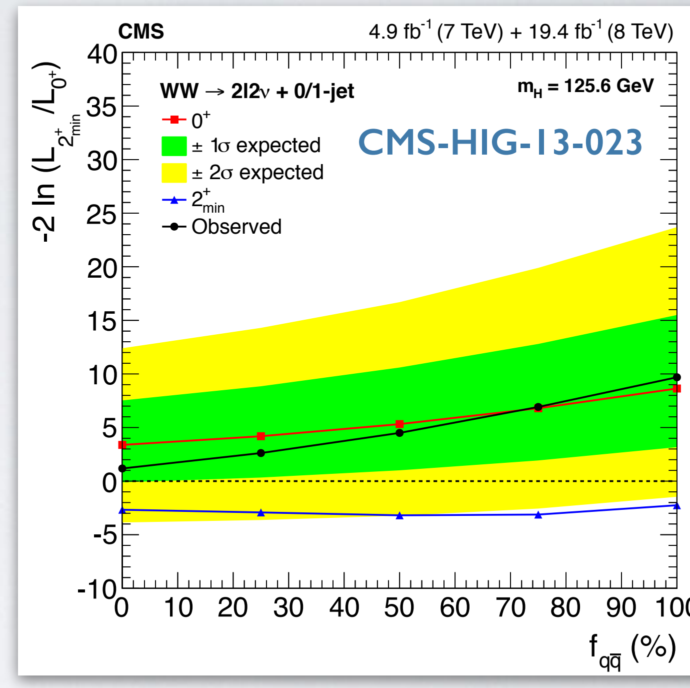
See talk by X. Janssen for details on individual channels

Alternative J^P hypotheses

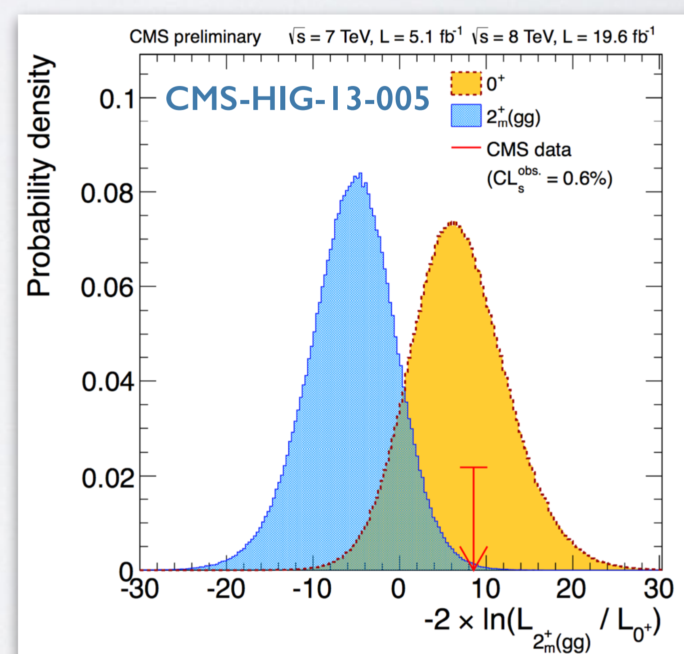
- Tested the compatibility of the new boson with alternative J^P hypotheses
  - **exploit shapes of kinematic observables** (angles, inv. masses)
    $H \to ZZ \to 4l$, $H \to WW \to 2l2\nu$, $H \to \gamma\gamma$
  - *HWW* tested spin-2 hypotheses (2_m^+) for diff. prod. mechanisms
  - Many hypotheses excluded using the *HZZ* channel @99%C.L.



HWW exclusion of 2_m^+



Combined test-statistics: $gg \to 2_m^+$



- Combined test for hypothesis **$gg \to 2_m^+$** (*HWW & HZZ*, 2013)
  - Hypothesis $gg \to 2_m^+$ is excluded at 99% CL

$J^P = 0^+$ strongly favoured by measurements

CP-odd contribution in H → ZZ → 4l decays

- Probe for fractional presence of the CP-odd contribution (0^-) in the scalar decays:

$$A(X \to VV) = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$$

A_2 contribution assumed to be 0

  - $\mathbf{0_m^+}$ / $\mathbf{0^-}$ decays governed by the $\mathbf{A_1}$ / $\mathbf{A_3}$ amplitudes (total x-sections $\boldsymbol{\sigma_{0m+}}$ / $\boldsymbol{\sigma_{0-}}$),
  - Explore it using **H → ZZ → 4l** decay channel
  - Total cross-section insensitive to interference between the CP-odd and CP-even components

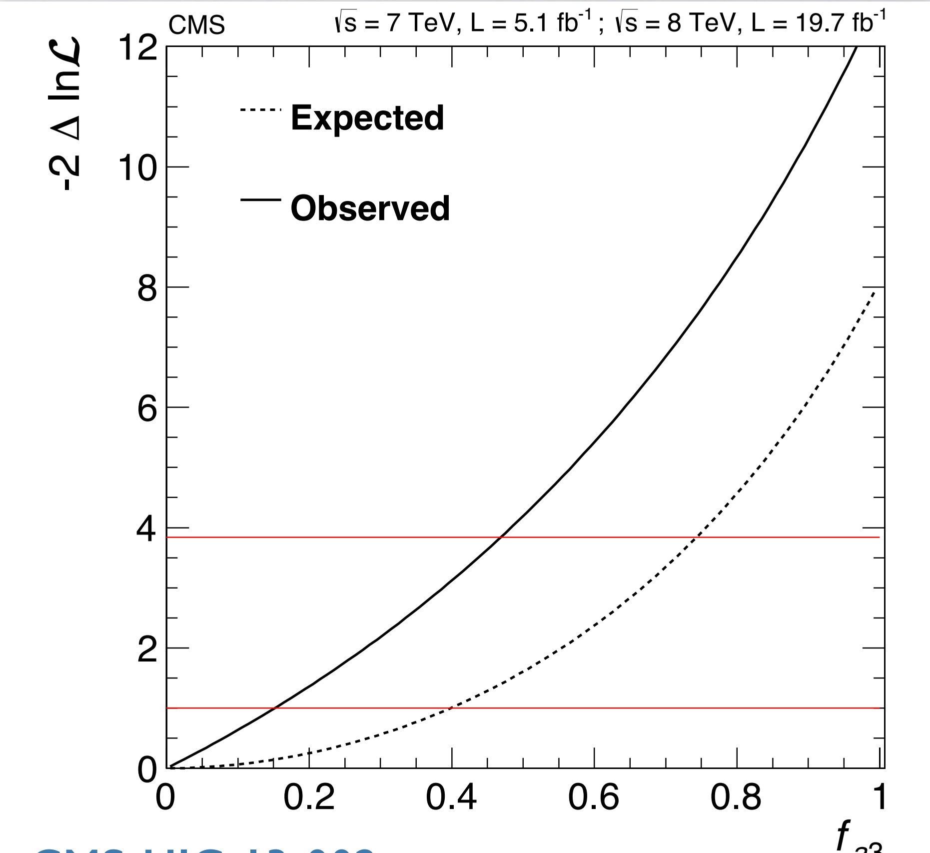
- Use shapes of kinematic observables for SM Higgs ($\mathbf{0_m^+}$) and $\mathbf{0^-}$ states and fit the data for their relative presence (the total event yield is taken from data)

$$f_{a3} = \frac{\sigma_{0-}}{\sigma_{0_m^+} + \sigma_{0-}}$$

defined for 2e2μ final state

Upper limit on the fractional x-section f_{a3} in data:

→ f_{a3} **< 0.51** (@95%CL)

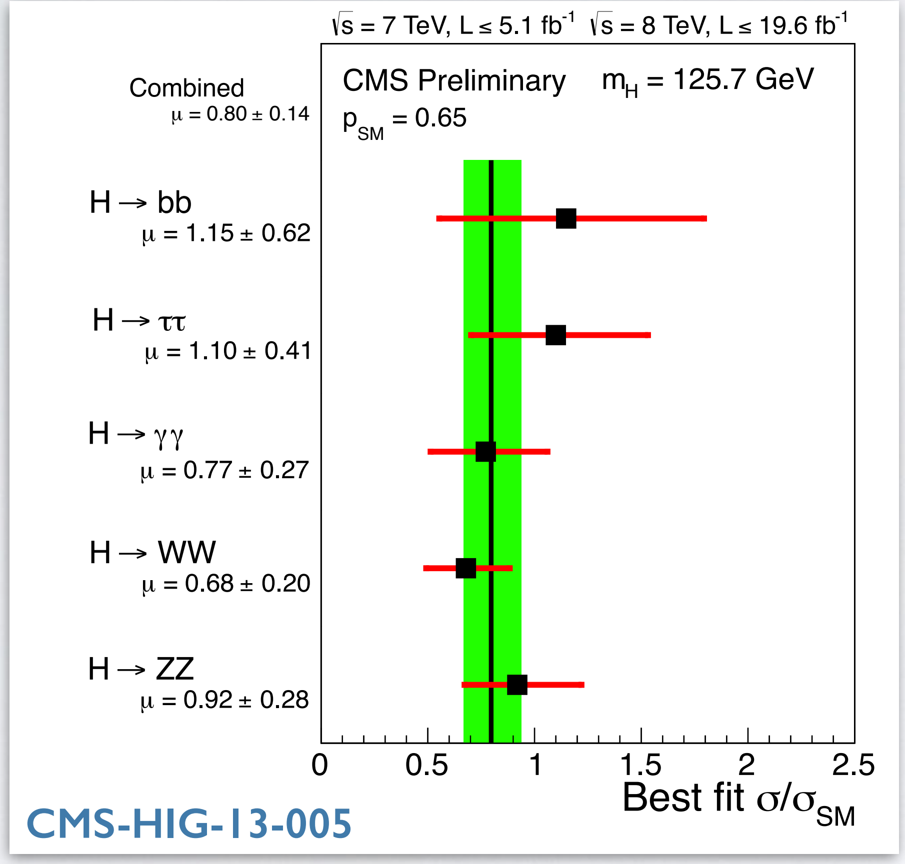


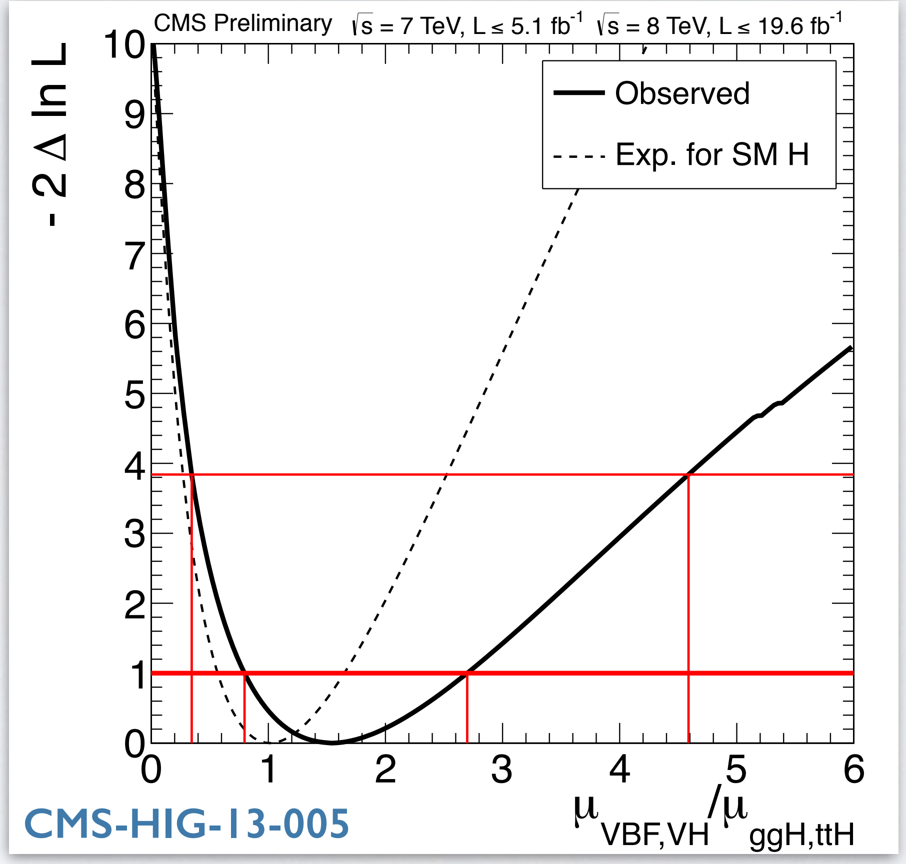
CMS-HIG-13-002

Search for deviations - Production modes

- Signal strength (μ) results explored for various decay and production modes
  - Results from individual modes compatible to SM Higgs predictions!

  ➡ probe the couplings by expanding around that reference point!





- Ratio of **μ**s in production modes with fermionic and bosonic couplings: $\mu_{VBF,VH}/\mu_{ggH,ttH}$
  - Best-fit $\mu_{VBF,VH}/\mu_{ggH,ttH} = 1.538^{+1.161}_{-0.743}$ **(3.2σ against a zero ratio)**

  ➡ **evidence for vector-boson induced production!**

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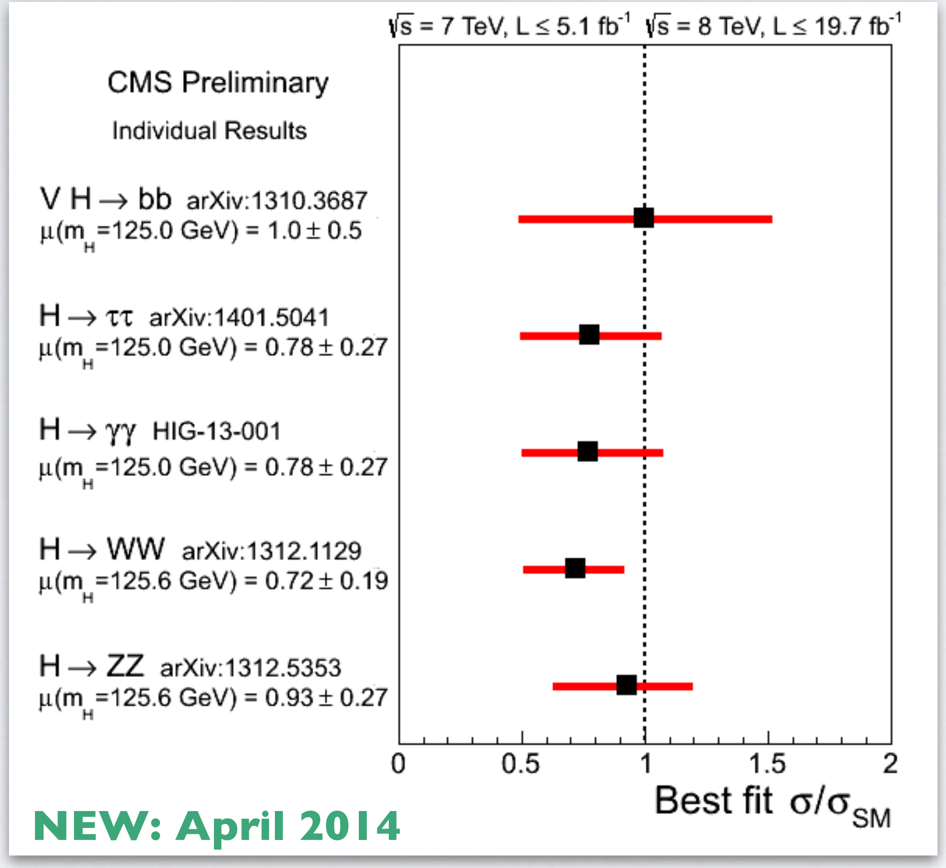

Most of the updated results ready:
New CMS Higgs combination coming soon…

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Search for deviations - Couplings

- Search for deviations from SM in the scalar couplings (LHC XS WG benchmarks)
- **Assumptions:**
  - Observed signals originate from a single narrow resonance
  - Parametrise deviations only with couplings strengths modifiers {**κ**$_x$}

$$(\sigma \cdot BR)(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- **Procedure:**
  - Scale SM x-sections & SM partial widths as function of parameters {**κ**$_x$}.

$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

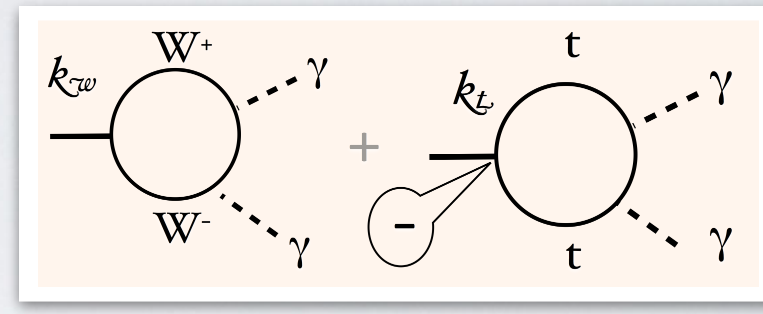
In cases of loop processes, **κ**$_x$ can be expressed as a function of more fundamental **κ**$_y$

  - If BSM decays are allowed - scale down all SM decays uniformly

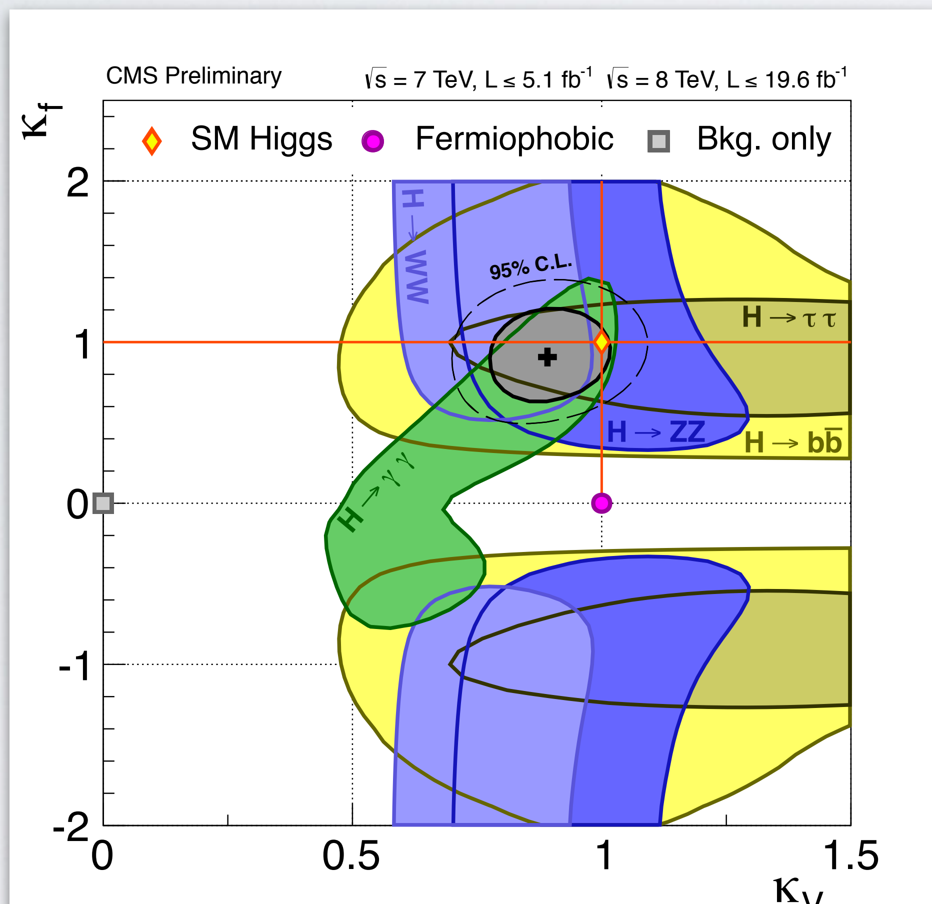
- **Scenarios:**
  - **Fermion vs. vector boson** couplings and **asymmetries** in couplings
  - Searches for **new physics in loops and decays**
  - **Simultaneous fit** of coupling modifiers

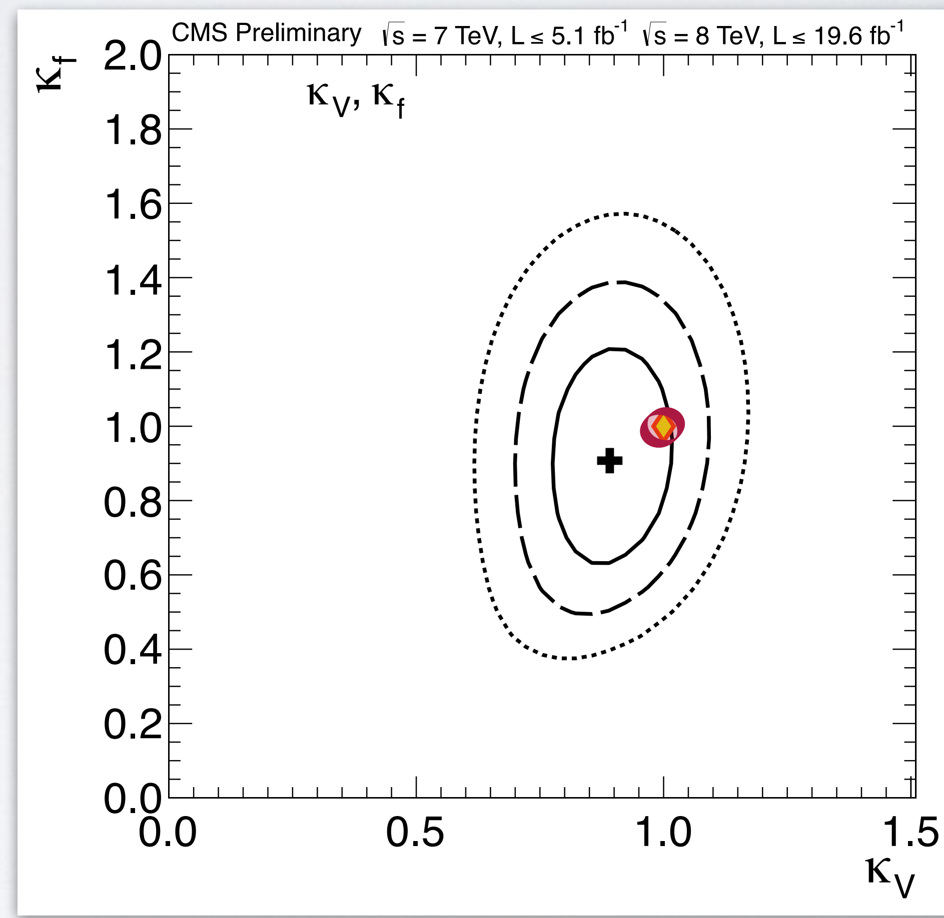
Asymmetries in couplings

- Test universality between couplings/modifiers to vector bosons and fermions ($\kappa_Z = \kappa_W = \boldsymbol{\kappa_V}$ and $\kappa_t = \kappa_b = \kappa_\tau = \boldsymbol{\kappa_f}$)



- In $H \rightarrow \gamma\gamma$ loop we are sensitive to sign of $\boldsymbol{\kappa_f \kappa_V}$ through interference (choose $\boldsymbol{\kappa_V} > 0$)



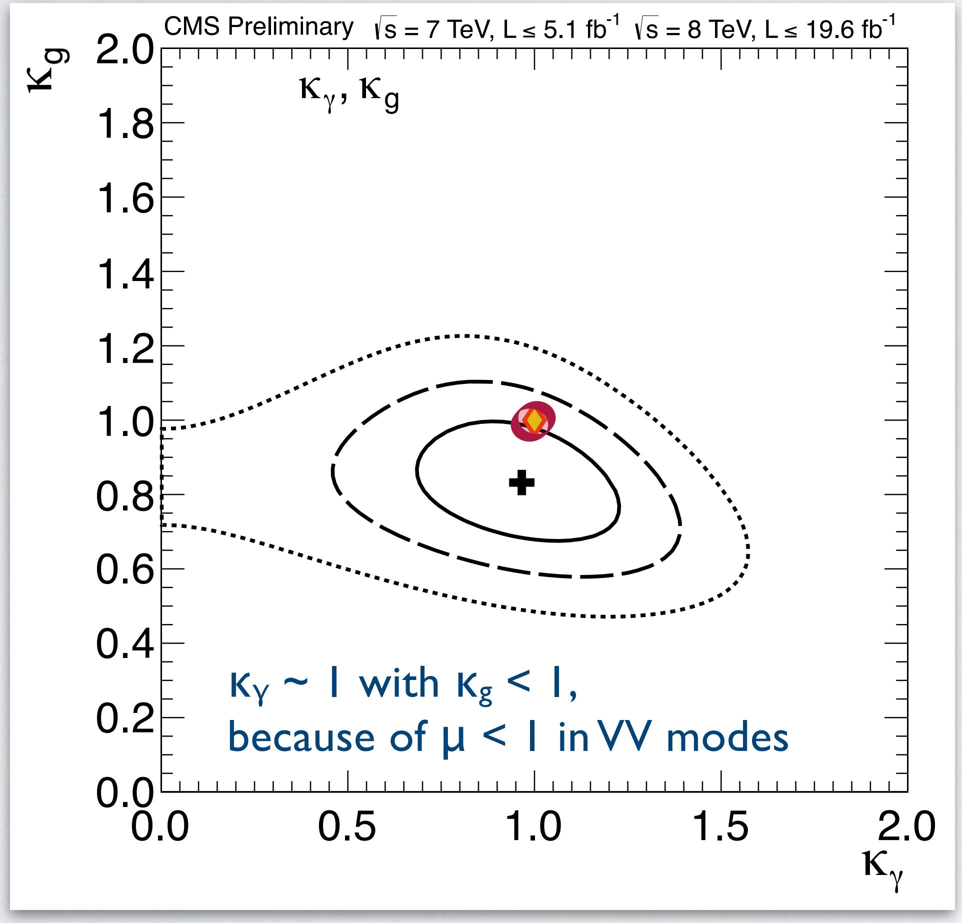


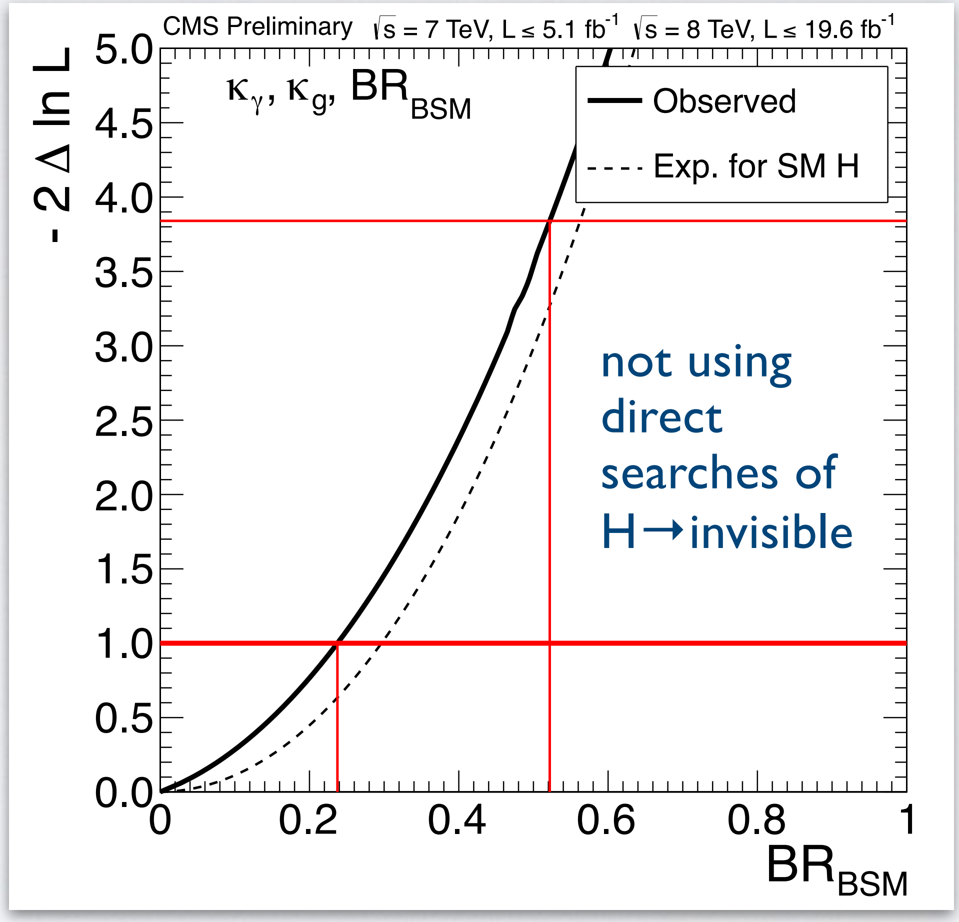
compatible with SM ($\kappa_f = \kappa_V$), clear preference for $\kappa_f > 0$

- Also tested (**HIG-13-005**): Custodial symmetry, lepton-quark and up-down universality

New physics in loops and decays

- Probe for new physics in **loops** - allow general κ_g & κ_γ modifiers of ggH and Hγγ
  - Assume no additional new physics in Higgs width, all other SM tree-level couplings
- Probe new physics in **loops & decays** - allow κ_g & κ_γ modifiers with $BR_{BSM} > 0$
  - Constrain total width from observed σ · BR's assuming SM tree-level couplings



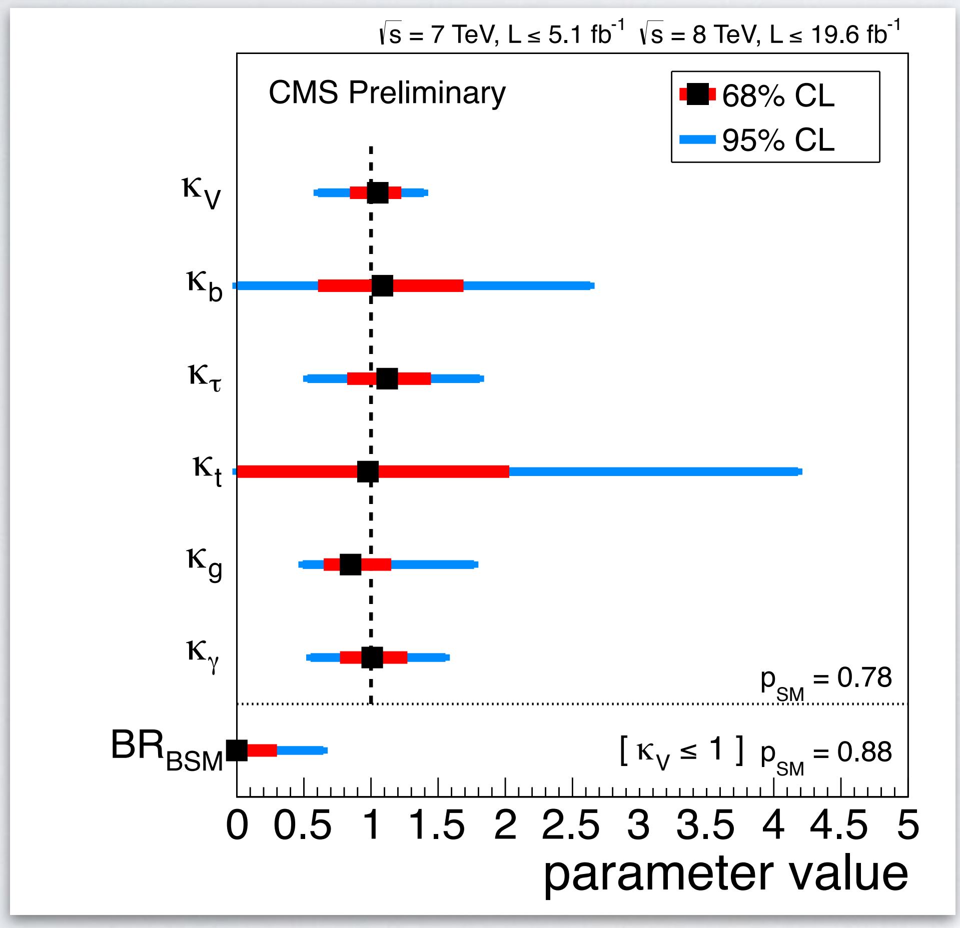


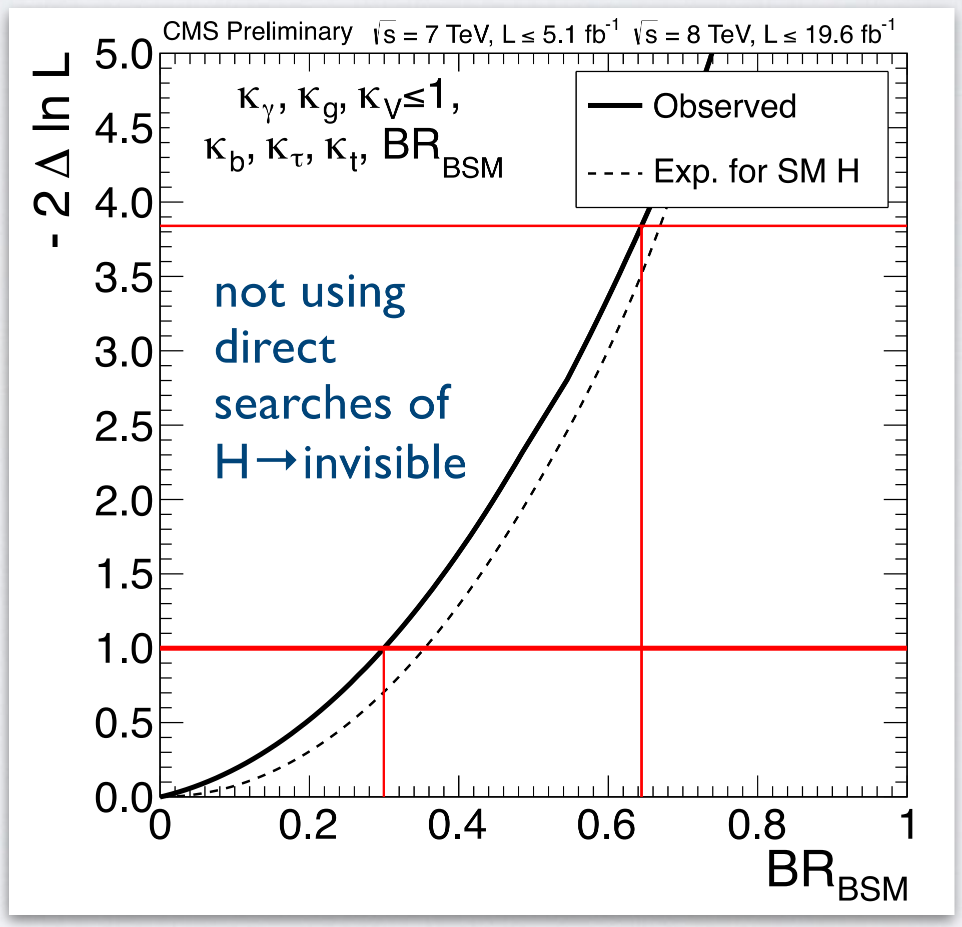
$BR_{BSM} < 0.52$ @ 95%C.L.

Effective couplings to gluons and photons in agreement with SM

Simultaneous fit of coupling modifiers

- Probe for 6 couplings simultaneously: κ_V ; κ_t , κ_b , κ_τ ; κ_g , κ_γ
  - assume custodial and up-down fermion symmetry:
    $\kappa_W = \kappa_Z = \kappa_V$ & $\kappa_u = \kappa_c = \kappa_t$ & $\kappa_d = \kappa_s = \kappa_b$ & $\kappa_e = \kappa_\mu = \kappa_\tau$
  - No BSM decays: $BR_{BSM} = 0$
- In addition allow $BR_{BSM} > 0$, by adding requirement $\kappa_V \leq 1$ (common in EWSB)



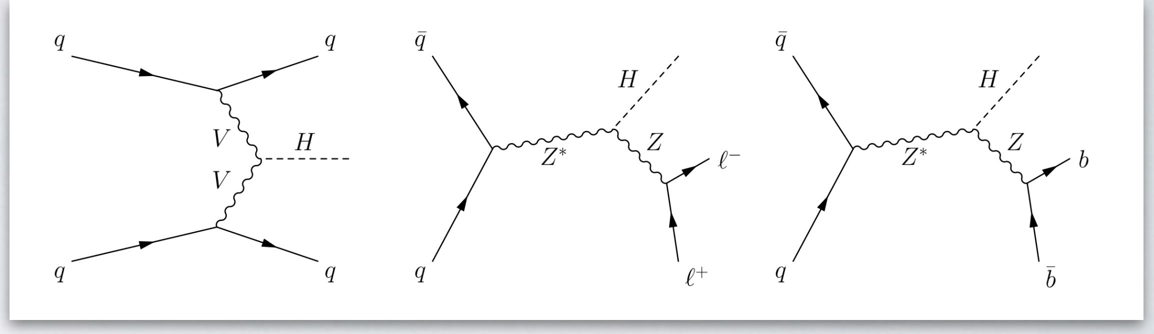


BR_{BSM} < 0.64 @ 95%C.L.

All effective couplings in good agreement with SM

Searches for H→invisible

- Performed search using the **VBF and associated ZH production** modes



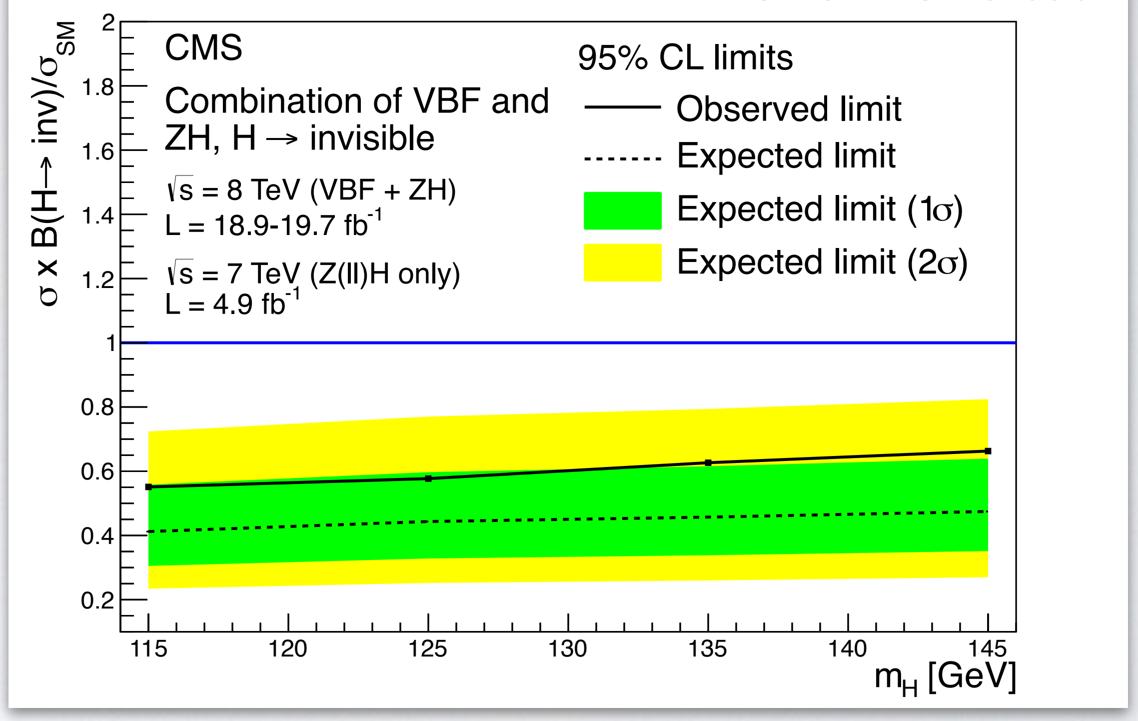
- **Sensitive to non-SM invisible decays** of the observed Higgs boson,
  - also sensitive to additional bosons with similar production and large invisible BR

- Combined all search VBF/ZH channels

  Upper limit on the invisible BR, m_H=125GeV

  $BR_{invisible}$ < 0.58 @ 95% C.L.

CMS-HIG-13-030



- Results also interpreted in terms of a Higgs-portal model of DM interactions.
  - DM interaction with nucleons through Higgs exchange diagram
  - reported limits for DM candidate as scalar, vector, or Majorana fermion (**CMS-HIG-13-030**)

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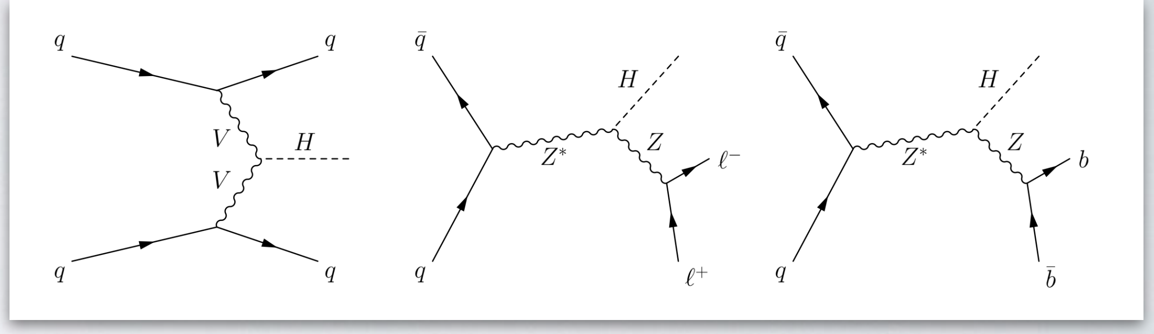

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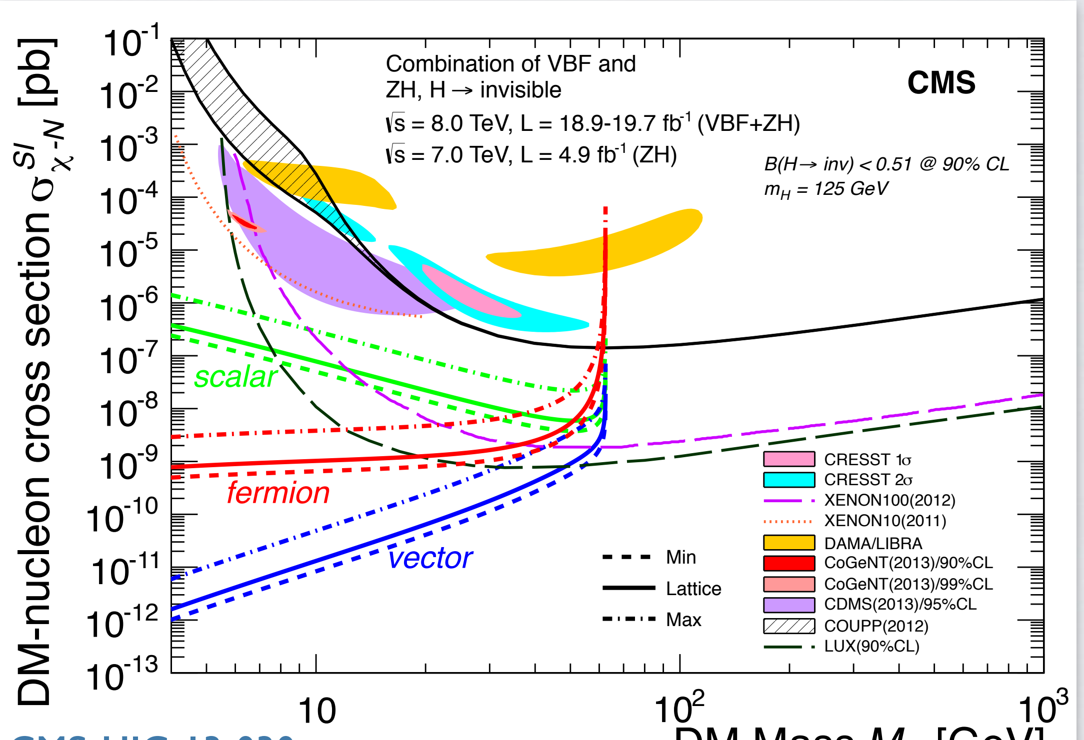


CMS-HIG-13-030

- Results also interpreted in terms of a Higgs-portal model of DM interactions.
  - DM interaction with nucleons through Higgs exchange diagram
  - reported limits for DM candidate as scalar, vector, or Majorana fermion (**CMS-HIG-13-030**)

Summary

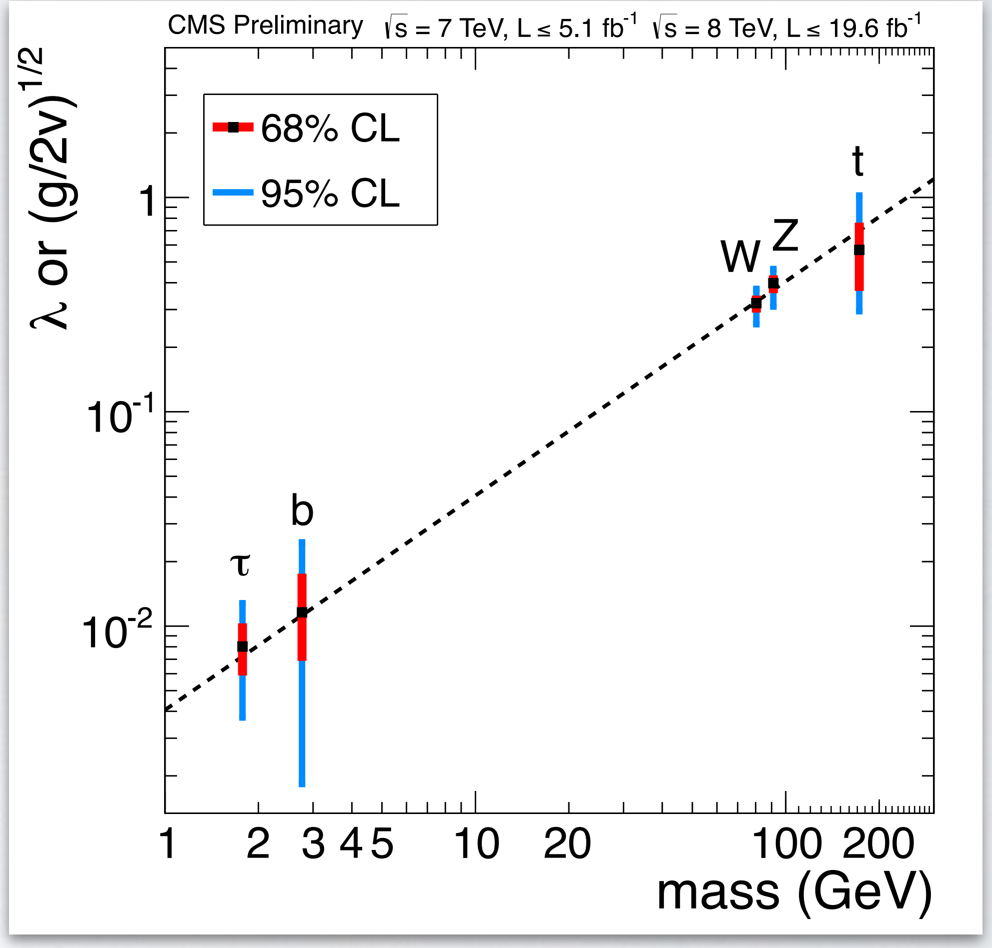
- CMS has analysed a comprehensive set of production and decay channels
  - Measured properties combining information from different channels:

    mass: $m_H = 125.7 \pm 0.3_{STAT} \pm 0.3_{SYST}$ GeV

    spin-parity: compatible with $J^P = 0^+$

    total width: $\Gamma < 22$ MeV @ 95%C.L.

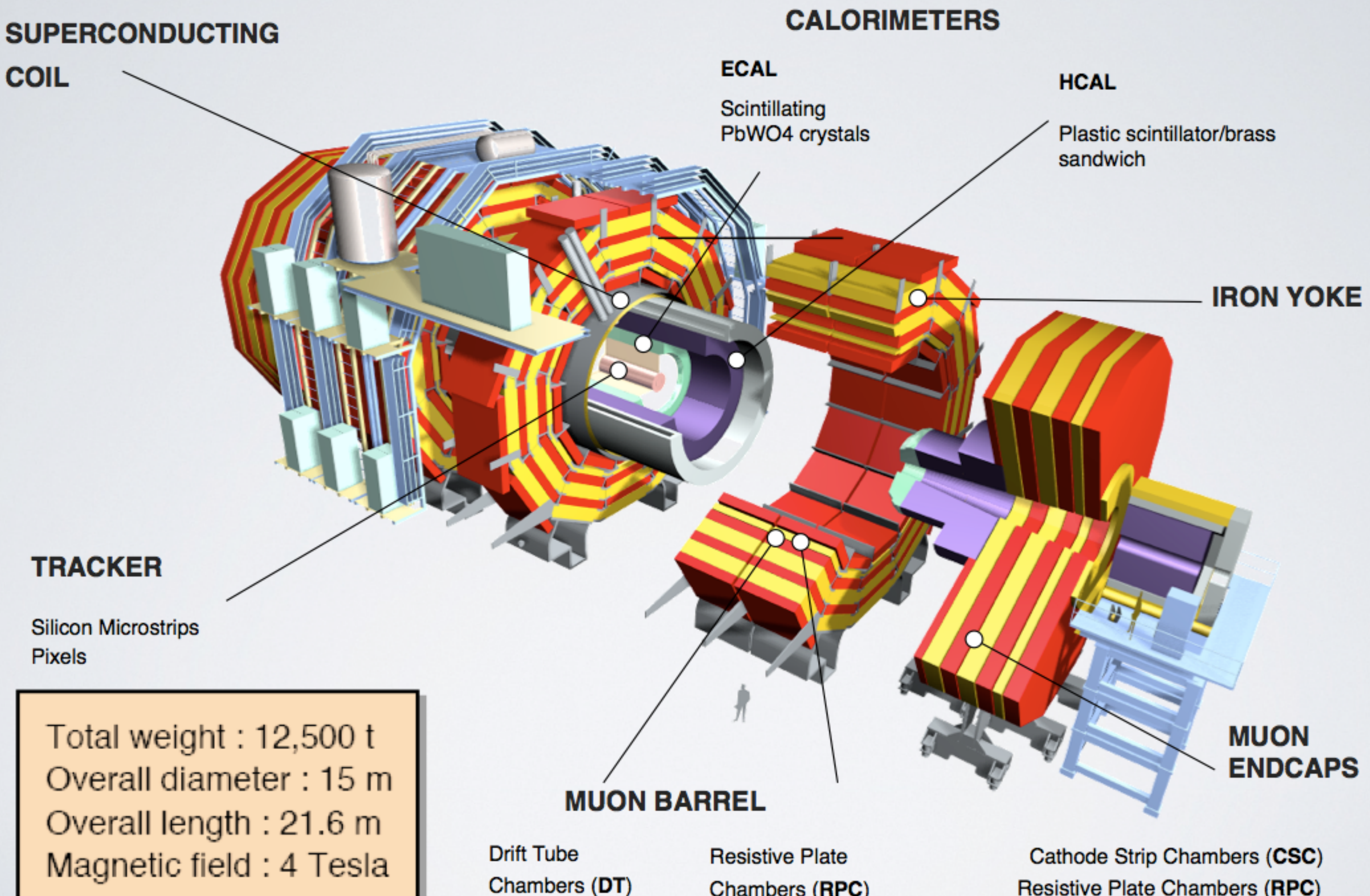
Effective couplings expressed as a function of the particle mass



- A wide range of Higgs coupling tests is performed
  - No significant deviation from SM predictions observed within the uncertainties
- Combined results for H→invisible
- Next combination of CMS results expected soon
- All measurements show:
  the new boson is compatible with the SM Higgs boson!

Backup slides

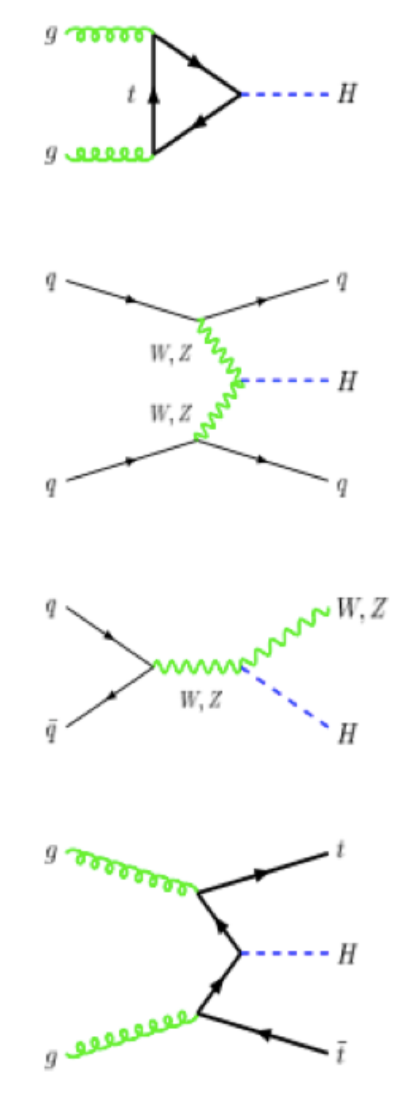
Compact Muon Solenoid



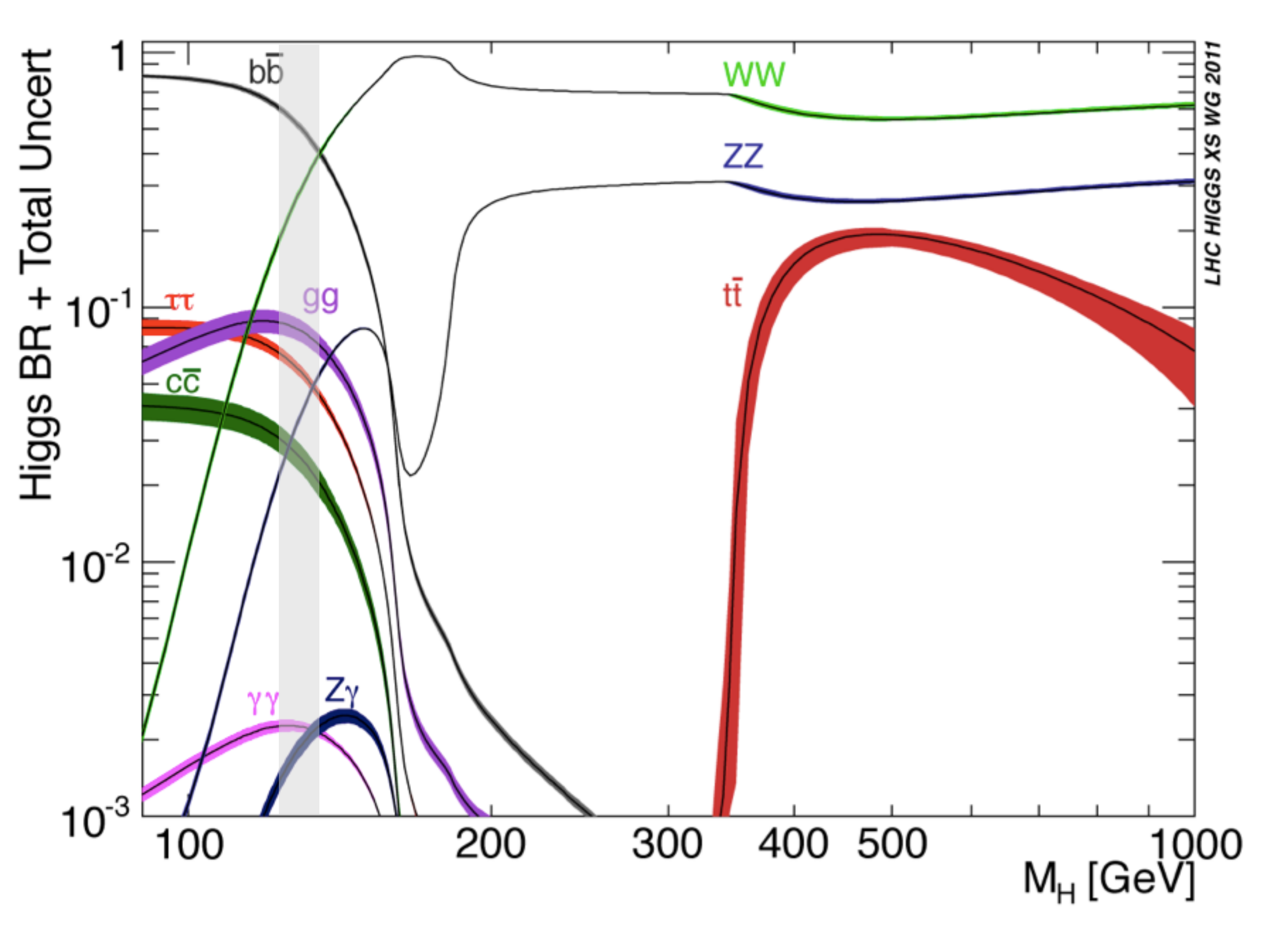
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Higgs production and decay modes

Production



Decay modes and branching ratios



LHC Higgs XS WG:
arXiv:1101.0593,
arXiv:1201.3084,
arXiv:1209.0040

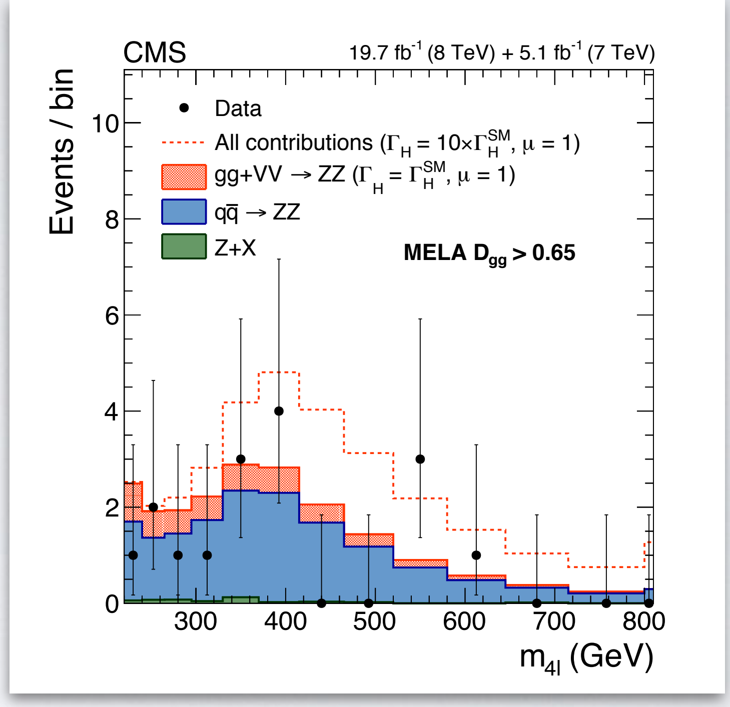
➡ common inputs to experiments

➡ Main contributions:

- Low mass: **H→γγ, H→ZZ (also H→WW)**
- Intermediate/high mass: **H→WW, H→ZZ**

Constraint on Higgs boson width

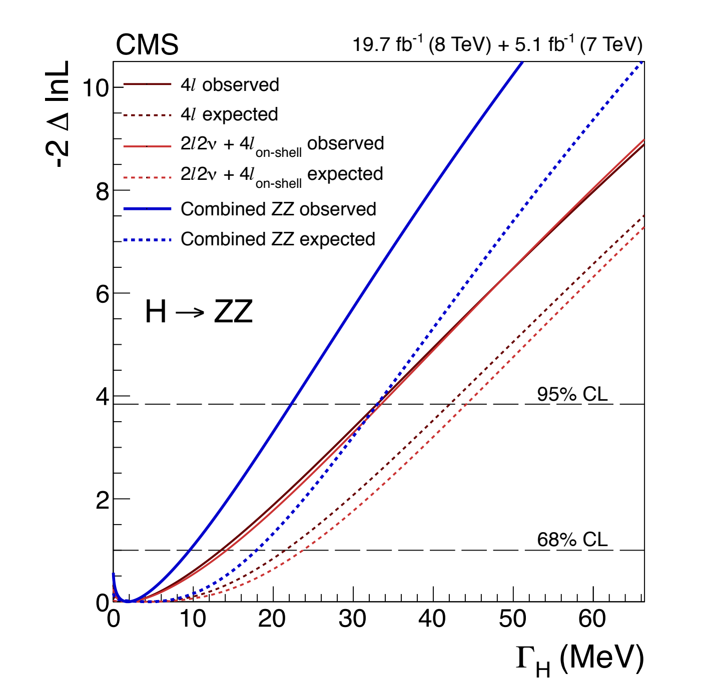
- Experimental resolution strongly limits direct width (Γ_H) measurement to ~1GeV
  - SM Higgs decay width is **4.15 MeV** at m_H = 125.6 GeV



- Important theoretical advances [*] :
  made possible to constrain the Higgs boson width using its off-shell production & decay away from the peak.

$$\sigma^{\text{on-peak}}_{gg\to ZZ} \propto \frac{g^2_{ggH}g^2_{HZZ}}{\Gamma} \qquad \sigma^{\text{off-peak}}_{gg\to ZZ} \propto g^2_{ggH}g^2_{HZZ}$$

➡ **experimental constraints on the width Γ_H with mild model-dependence**



- Channels H → ZZ → 4l and H → ZZ → 2l2ν
  m_{ZZ} distribution can be used alone,
  but kinematic observables improve sensitivity
  (sig-bkg interference significant, accounted properly)

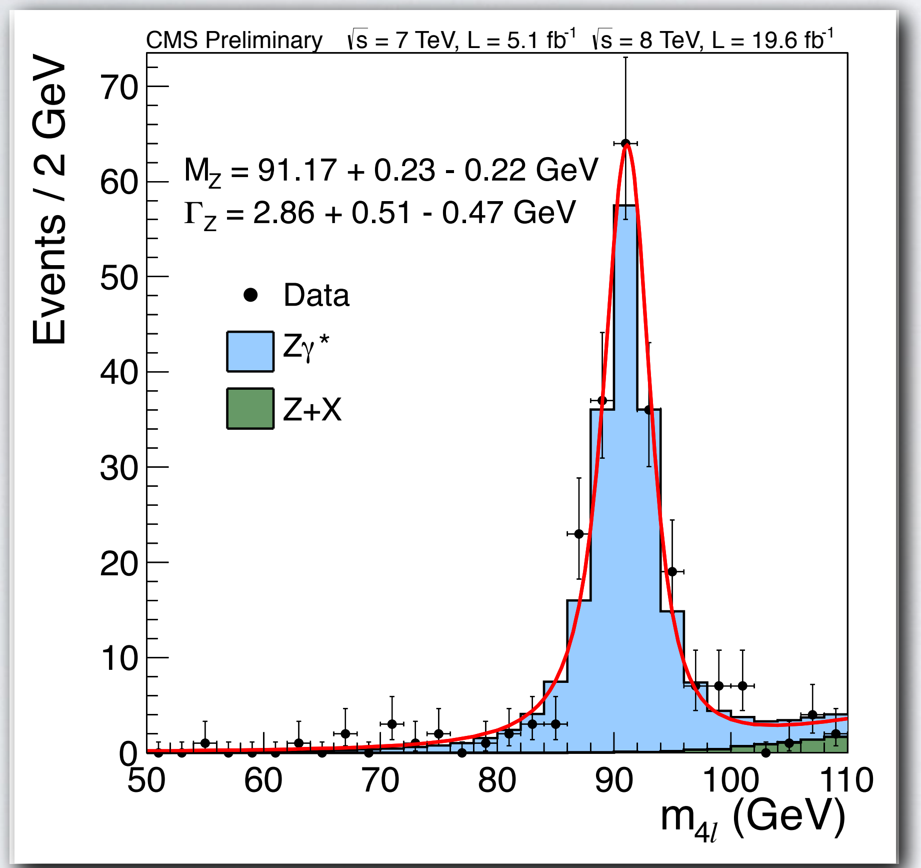
➡ **Γ_H < 22 MeV at 95% C.L.,**
Γ_H < 5.4 x $\Gamma_{H,\ SM}$

[*] JHEP 08 (2012), Phys Rev D 88 (2013) 054024, **see also talk by X. Janssen for details**

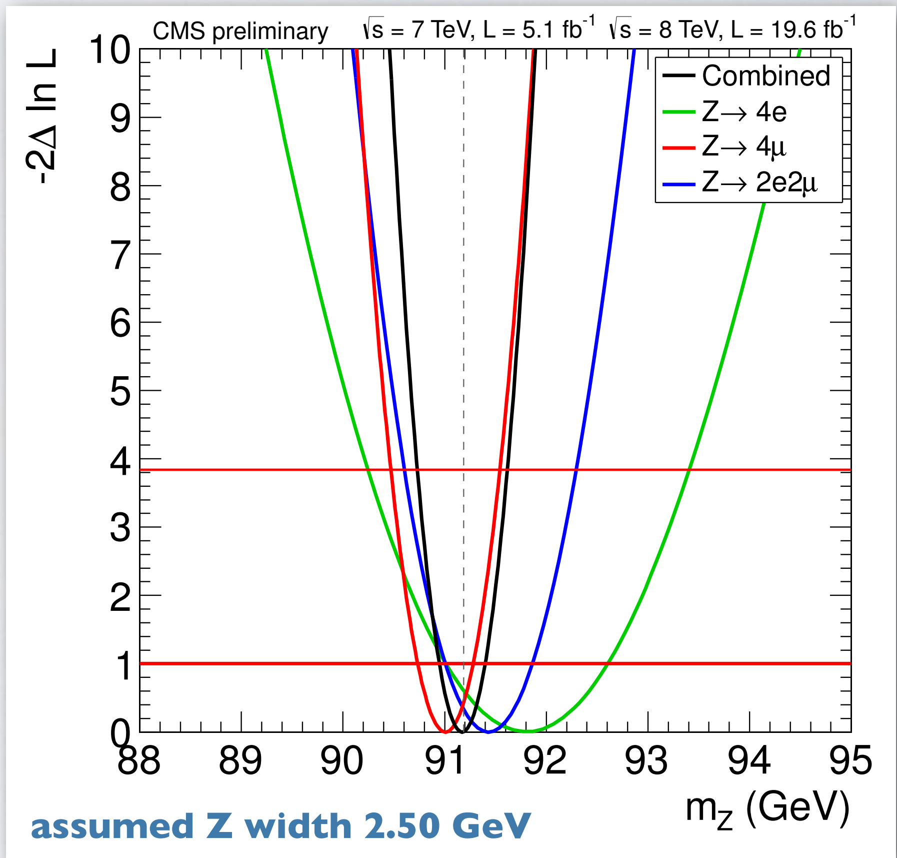
Mass measurement validation with Z → 4l

- Perform the mass measurement of the near-by Z → 4l resonance
  - **identical procedure** as for the new boson mass measurement (without δm_{4l} and KD),
  - **relaxed phase space** due to the limited statistics (m_{Z2} > 4 GeV)

fit for Z mass/width in Z → 4l events



likelihood scans for 4e, 4μ, 2e2μ



Compatible with the PDG values within uncertainties.