Higgs boson measurements at CMS

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Introduction & overview

- BEH mechanism(*) one of key features of the Standard Model:

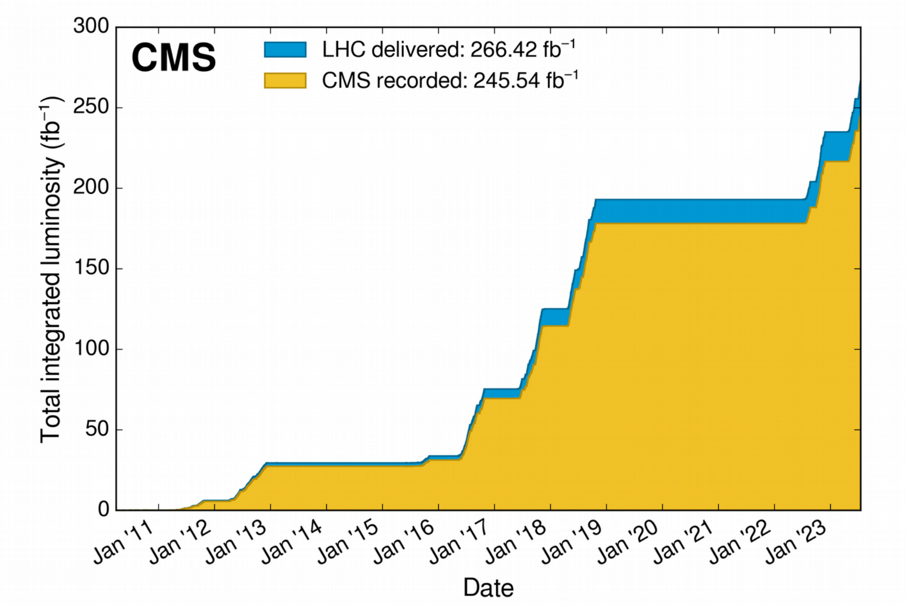
  a scalar field, with a non-zero vacuum expectation, responsible for the masses of particles
  - necessary for both gauge boson and fermion masses
  - predicts relation between gauge boson masses and couplings
    - preserves unitary of VV→VV scattering (through cancellation of diagrams with exchange of V_L and H)
    - essential for renormalisability of the SM
  - predicts existence of (at least one) Higgs boson
- Discovery of the boson confirmed the mechanism and gives insights to its details
- Higgs boson is special
  - The only (fundamental) scalar particle in SM

    (a dynamic explanation of BEH mechanism à la BCS theory will be a breakthrough)
  - Neither matter nor force carrier
  - Couples proportionally to mass

(*) Brout-Englert-Higgs(-Hagen-Guralnik-Kibble) – BEH(HGK) – mechanism

Higgs measurements

- Many measurements enabled with large data-sets already collected
  - **Precision measurements:**
    mass & width,
    cross-section & couplings (incl. 3rd generation fermions),
  - **Rare processes:**
    coupling to 2nd generation:
    $H \rightarrow \mu\mu$, $H \rightarrow cc$,
    self coupling (HH),
    H->Zγ/γγ* (BSM in loops),
    "Invisible" decays
  - **BSM searches:**
    additional Higgs bosons,
    exotic decays,
    anomalous couplings



Collected pp data:

- Run-1 at 7&8TeV (2010–12) : ~5+20/fb
- Run-2 at 13 TeV (2015–18): ~140/fb
- Run-3 at 13.6 TeV (2022,23...): ~40+30/fb (no results yet)

=> No. of Higgs bosons at CMS $O(10^7)$

Higgs measurements

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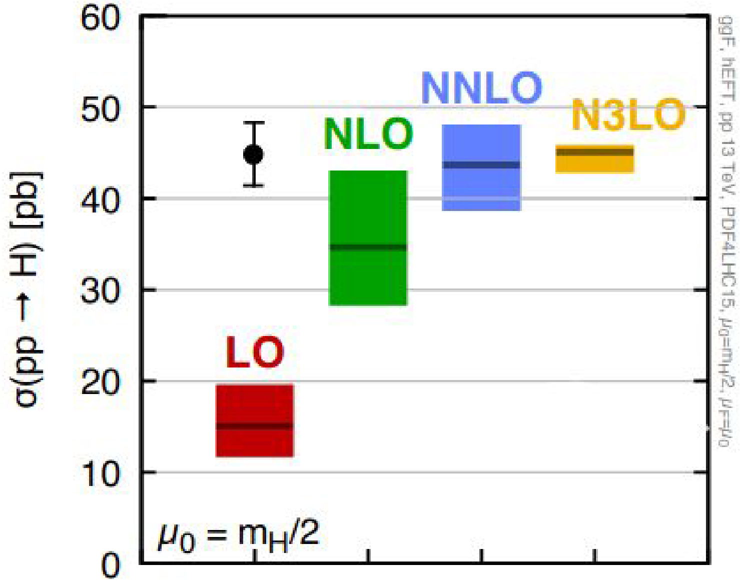
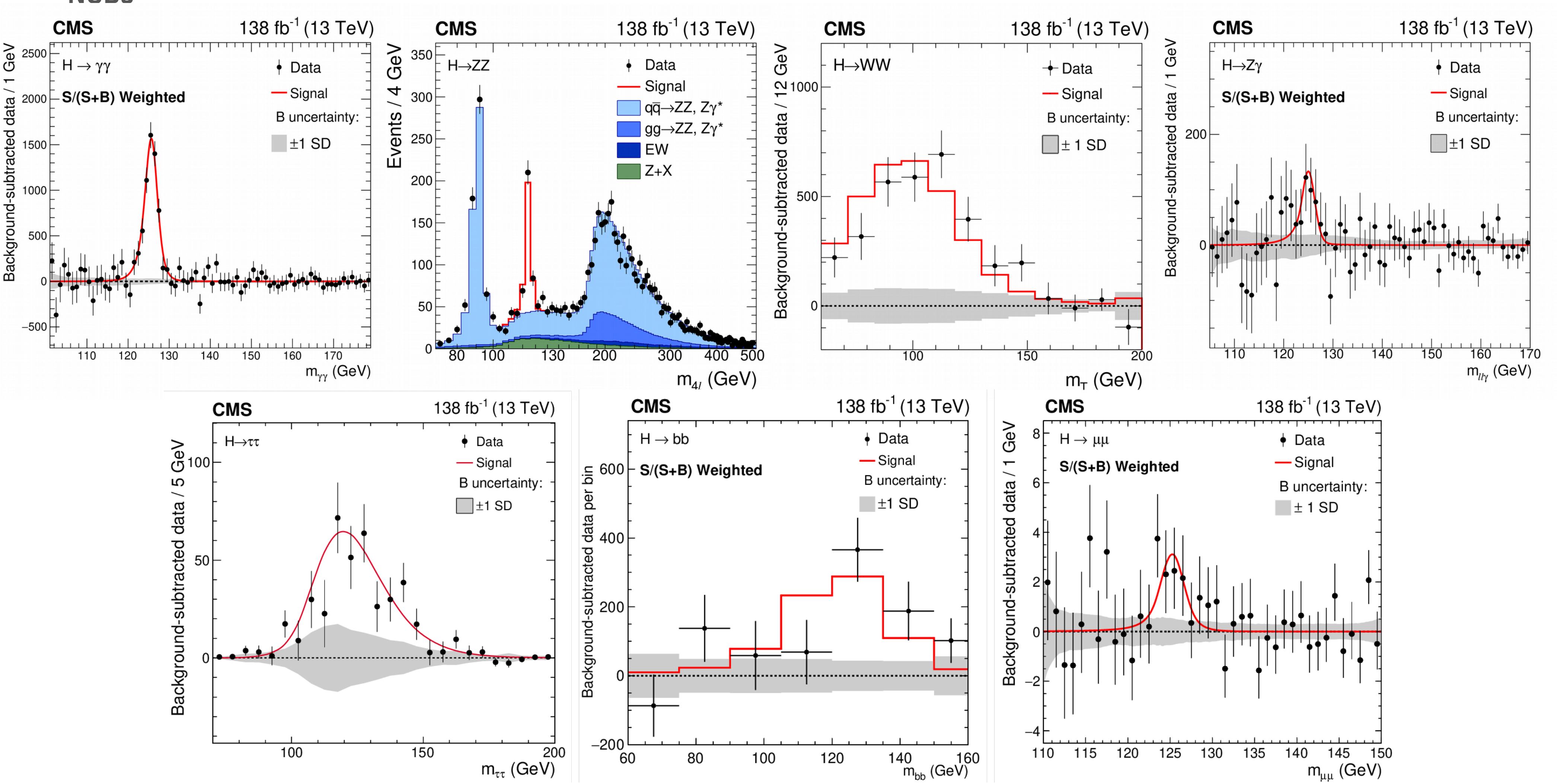


Great results thanks to collective efforts!

- excellent performance of the LHC machine
- extensive understanding of the performance of the CMS experiment
- precision theoretical description of the Higgs boson as well as the backgrounds.
- application of sophisticated analysis techniques incl. machine learning

This talk: *selection from a plethora of very interesting analyses preformed since Higgs boson discovery.*

Appetiser: H mass peaks



Only the H→ZZ*→4ℓ (ℓ=e,μ) peak visible for „naked eye” without background subtraction

Typically S/B << 1 => precise background estimation crucial for Higgs measuremts

Mass measurement

m_H is a free parameter of the Standard Model

m_H measured with fully reconstructedm high-resolution final states:

$H\to\gamma\gamma$, $H\to ZZ^*\to 4\ell$ (ℓ=e,μ)

Mass measurement requires excellent calibration of photon energies ($H\to\gamma\gamma$)...

Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

Calibrate reconstructed energy of photons with MC, MC/data with $Z\to ee$ events with account for differences between e and γ

and lepton momenta ($H\to ZZ^*\to 4l$)

- recover final state radiation photons
- fit lepton momenta with Z_1 mass constraint (usually on-shell Z boson) for each event
- compute m_{4l} with uncertainty at event basis (with refitted lepton momenta)

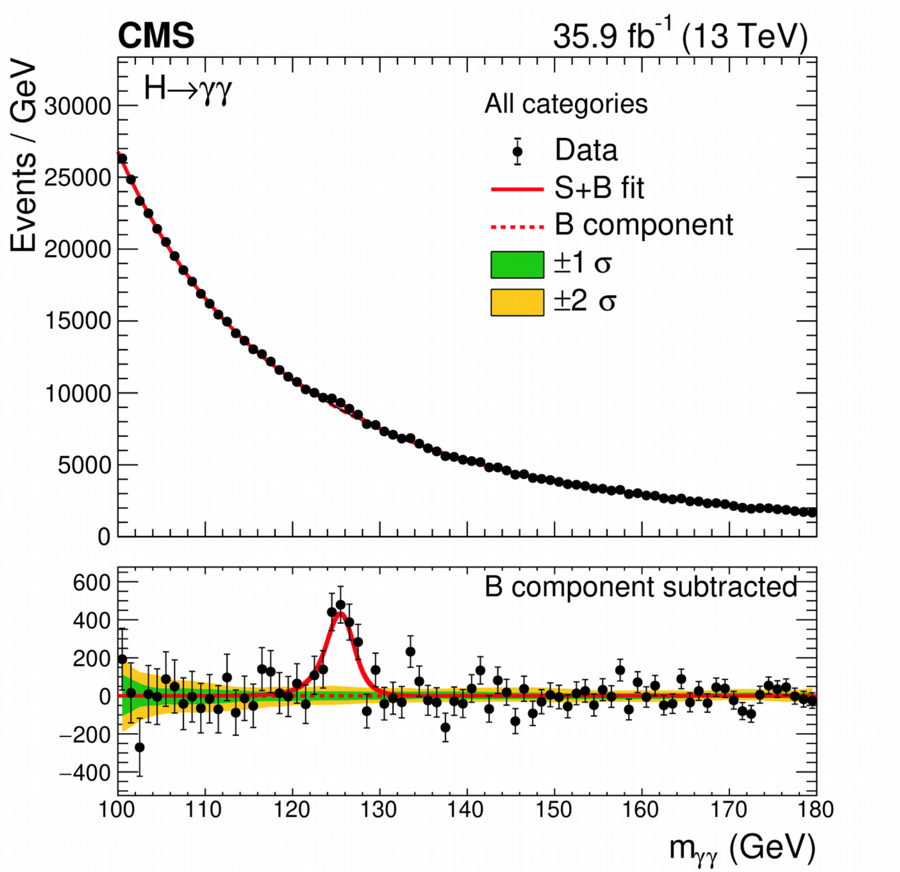
Measured with likelihood fit dependent on signal-strength parameter and m_H floating in the fit (+nuisance parameters for systematic uncertenties)

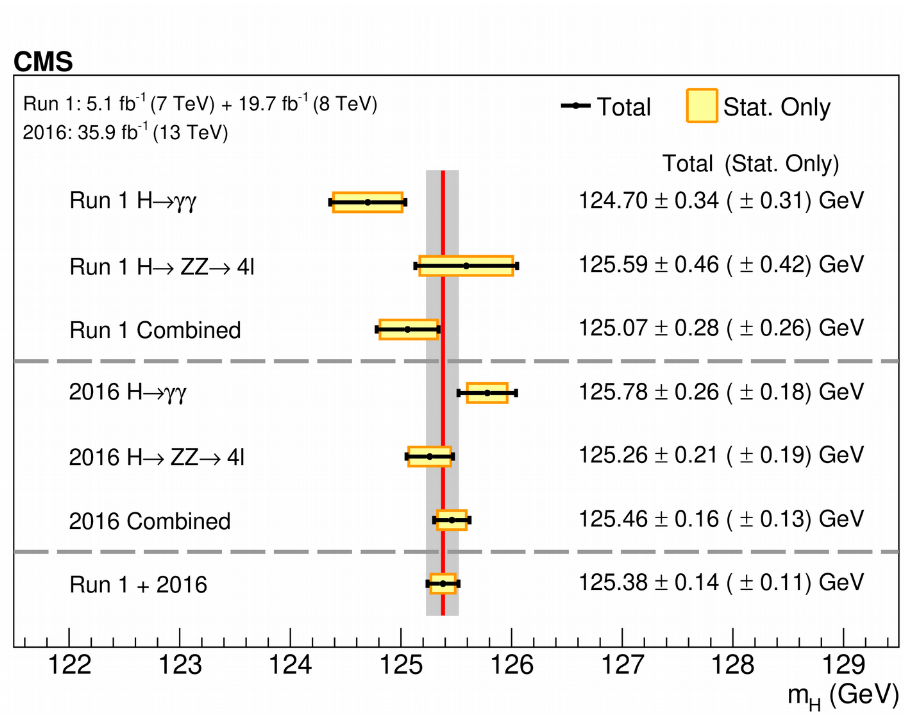
- di-photon mass in $H\to\gamma\gamma$ channel
- 3D fit in $H\to ZZ\to 4l$ with m_{4l}, its resolution and kinematic bkg/sig discriminant

m_H: recent combined results

Combining $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ with Run 1 (5.1+19.7/fb) + 2016 data (36/fb)

Phys. Lett. B 805 (2020) 135425
JHEP 11 (2017) 047





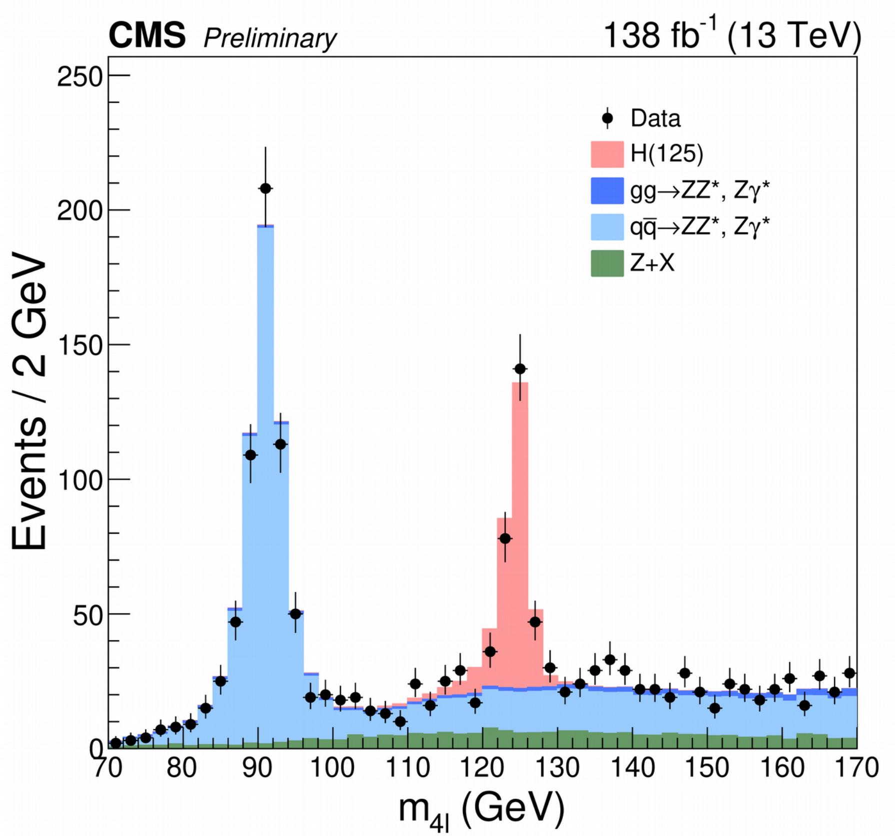
Result: m_H = 125.38 ± 0.11 (stat.) ± 0.09 (sys.) GeV

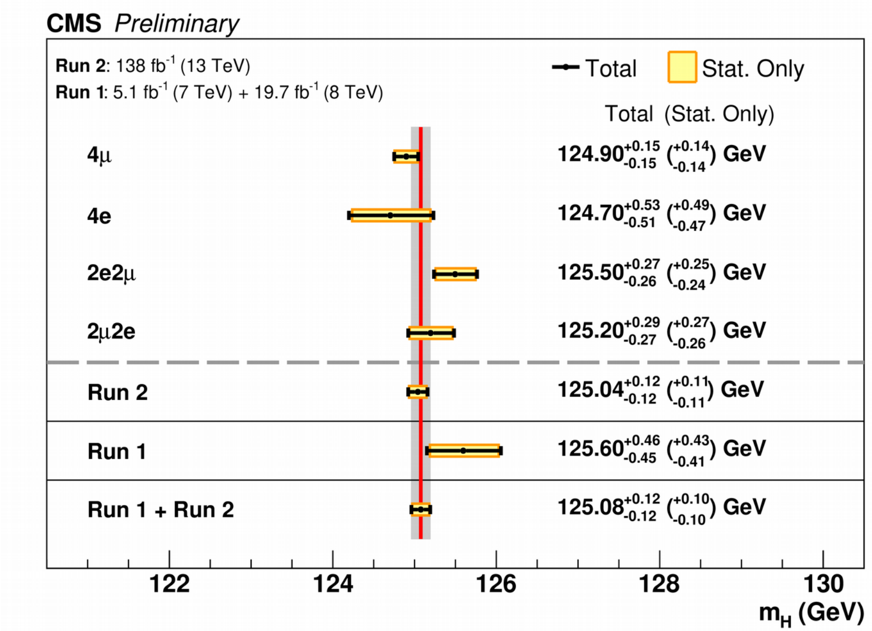
Statistical uncertainty dominates

m_H: H → 4ℓ w/ full Run-2 data

H → ZZ* → 4ℓ with Run 1 (5.1+19.7/fb) + Run-2 data (138/fb) (preliminary)

CMS-PAS-HIG-21-019





Result: m_H = 125.08 ± 0.10 (stat.) ± 0.05 (sys.) GeV

Statistical uncertainty bigger than systematic

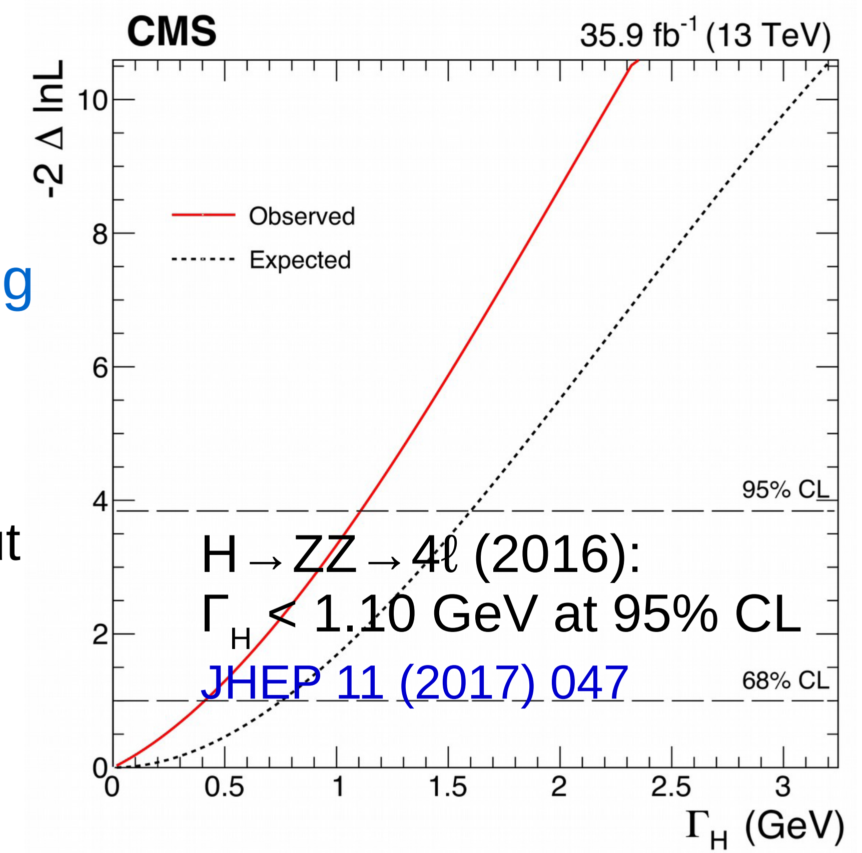
Perspectives on m_H measurement

- m_H known with high precision of ~0.1%
- Big effort to calibrate leptons and photons in Run-2 lead to reduction of systematic uncertainty on m_H
  - Statistical component remains dominant (as in Run-1 measurement)
- More precise m_H value can be expected
  - Using full Run 2 dataset in both channels
  - and combining channels (and experiments)

  however, more accurate m_H is not required by any prediction
  - Precise calibration will be motivated by other physics

Total width mesurement

- When m_H is known Γ_H is predicted within Standard Model
  - Γ_H = 4.1 MeV for m_H = 125 GeV
- Deviations from this prediction would mean BSM physics
  - $\Gamma_{H\ inv./undet.}$ < ~10% at 95 CL
- The extraction of H couplings requires making assumption on Γ_H
  - e.g. no BSM decays, and Γ_H computed as a function of all coupling modifiers (κ)
  - or, invisible or undetected decays allowed, but $\kappa_{W,Z} \leq 1$
- Expected Γ_H is much smaller than detector resolution of O(1 GeV) (O(1%))



- Is width measurement possible at LHC?
  - Scanning of σ(μμ→H) in function √s with muon collider considered as best method
  - Similarly one can consider σ(ee→H) with e+e- collider, but eeH coupling very small

Γ_H measurement: principles

- Off-shell $H^* \to VV$ (V=W,Z)
  - Competing effects from BW (resonant shape) and $\Gamma_{H \to VV}$
  - ~10% of $gg \to H \to ZZ$ cross section for $m_{zz} > 2m_z$
- This feature can be used to measure of the total Higgs width

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

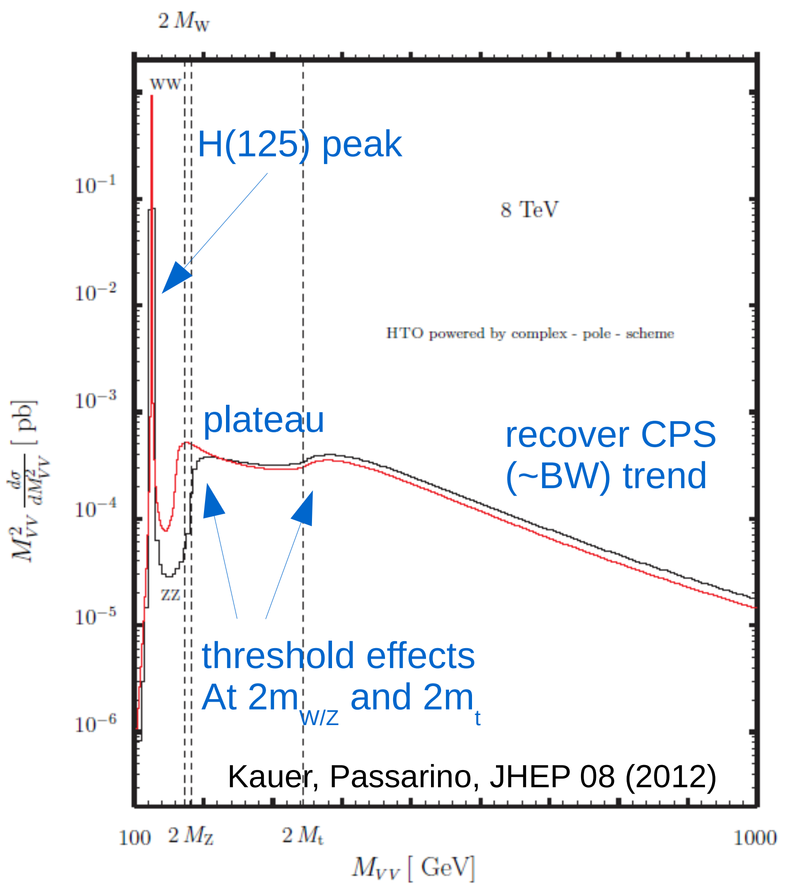
Integrated around m_H

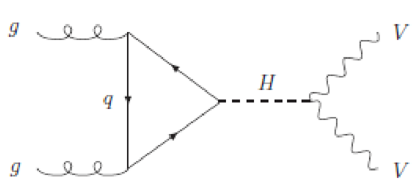
Integrated for $m_{ZZ} > 2m_z$ where $(m_{ZZ} - m_H) >> \Gamma_H$

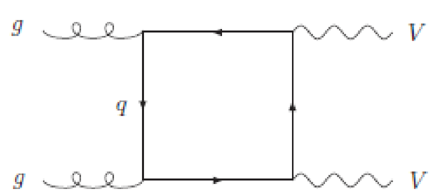
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

=> combined on-shell and off-shell measurements allow to constrain width

- Significant (destructive) interference with $gg \to VV$ continuum should be accounted for

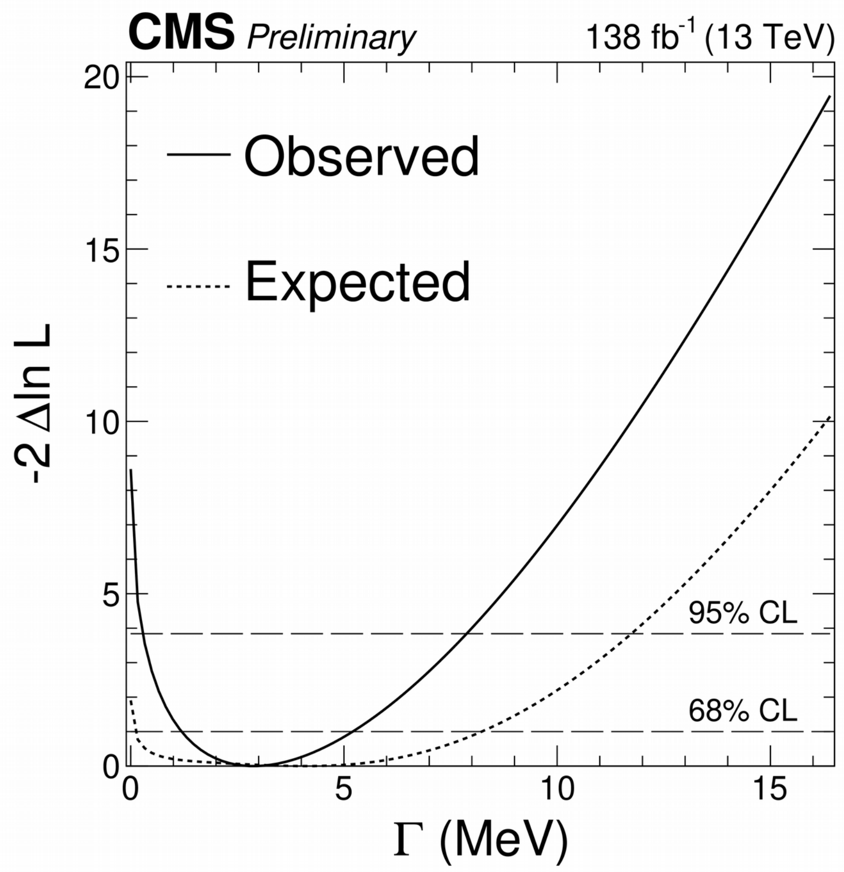






Higgs total width: results

CMS-PAS-HIG-21-019



$\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV (in agreement with the SM expectation of 4.1 MeV)

Lack of off-shell production excluded with >3 standard deviations

Perspectives on Γ_H measurement

- Off-shell production with ZZ decays provide a way to measure Γ_H at LHC!
  - involves a few (weak) assumptions
- Precision is still smal (~100%)
  - still plenty room for new physics
- Systematic uncertainties can still improve e.g. on ZZ background
- Statistical uncertainties on off-shell yields are still large
  - these will improve for sure

Combined measurements

- Individual analyses study specific Higgs boson production & decay mode, i.e. its specific characteristic

  => need to combine them to get a maximally wide view of the Higgs boson
- Combine = perform common fit (with common parameters) across several individual analyses

	ggH	VBF	VH	ttH/tH
$H\to\gamma\gamma$	√	√	√	√
$H\to ZZ$	√	√	√	√
$H\to WW$	√	√	√	√
$H\to\tau\tau$	√	√	√	√
$H\to bb$	√		√	√
$H\to\mu\mu$	√	√	√	√
$H\to Z\gamma$	√	√	√	√
$H\to$ inv.	√	√	√	

- Results from recent combination: Nature 607 (2022), 60
- Most of the main production x decay channels included

Signal strength

- Signal strength μ scales production cross section and branching fractions relative to SM predictions:

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \qquad \mu^f = \frac{\mathcal{B}^f}{\mathcal{B}^f_{\mathrm{SM}}} \qquad \mu_i^f = \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

or a global factor scaling all channels:

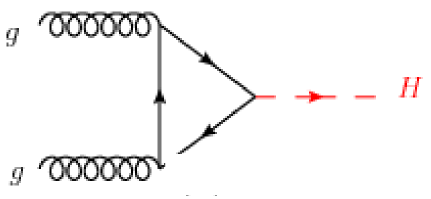
$\mu = 1.002 \pm 0.057 =$

$= 1.002 \pm 0.036$ (theo) ± 0.033 (syst) ± 0.029 (stat)

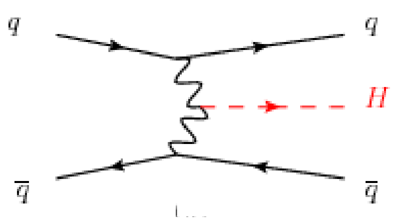
=> precision of ~6% still with significant contribution from statistics

Higgs boson production at LHC

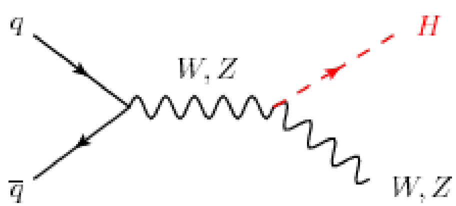
Cross-section at 13 TeV (m_H=125.38 GeV)



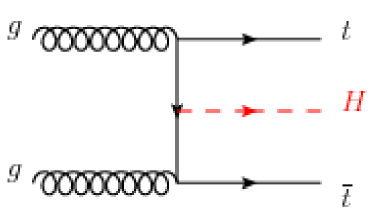
gluon-gluon fusion (ggH)
48.31±2.44 pb



vector boson fusion
(VBF / qqH)
“tagging forward jets”
3.771±0.807 pb

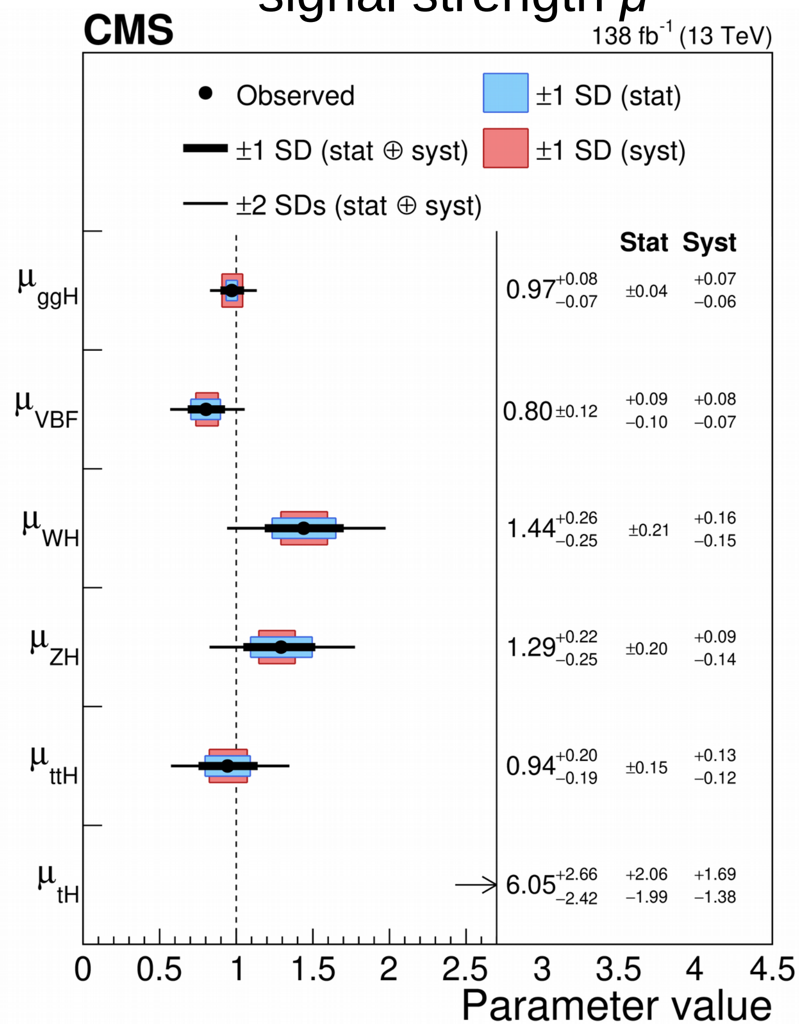


associated W/Z
production (VH)
WH: 1.359±0.028 pb
ZH: 0.877±0.036 pb



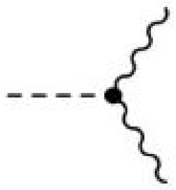
associated ttH (bbH)
& tH production
ttH: 0.503±0.035 pb
bbH: 0.482±0.097 pb
tH: 0.092±0.008 pb

signal strength μ^i

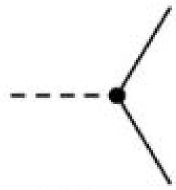


Agreement with SM
gluon-gluon fusion precision <10%!
10-20% precision on other main production processes

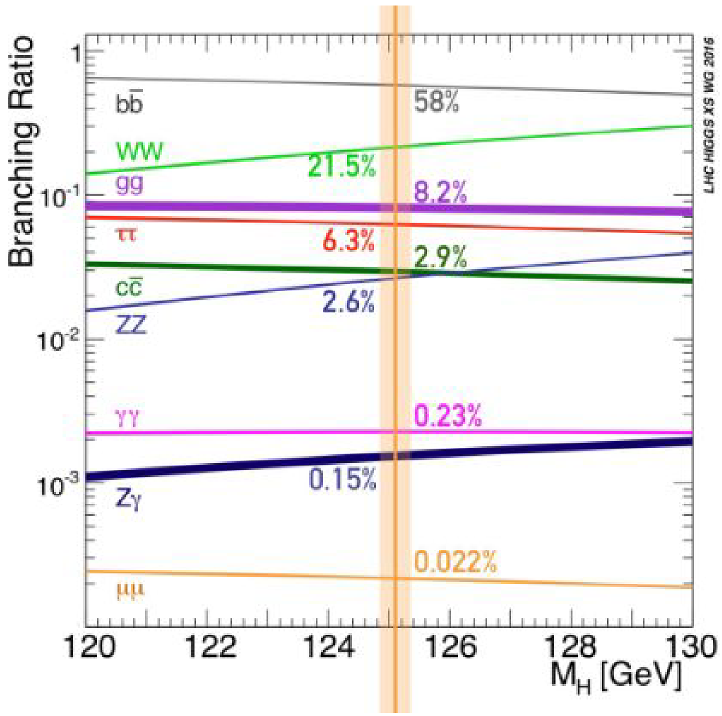
Higgs boson decays



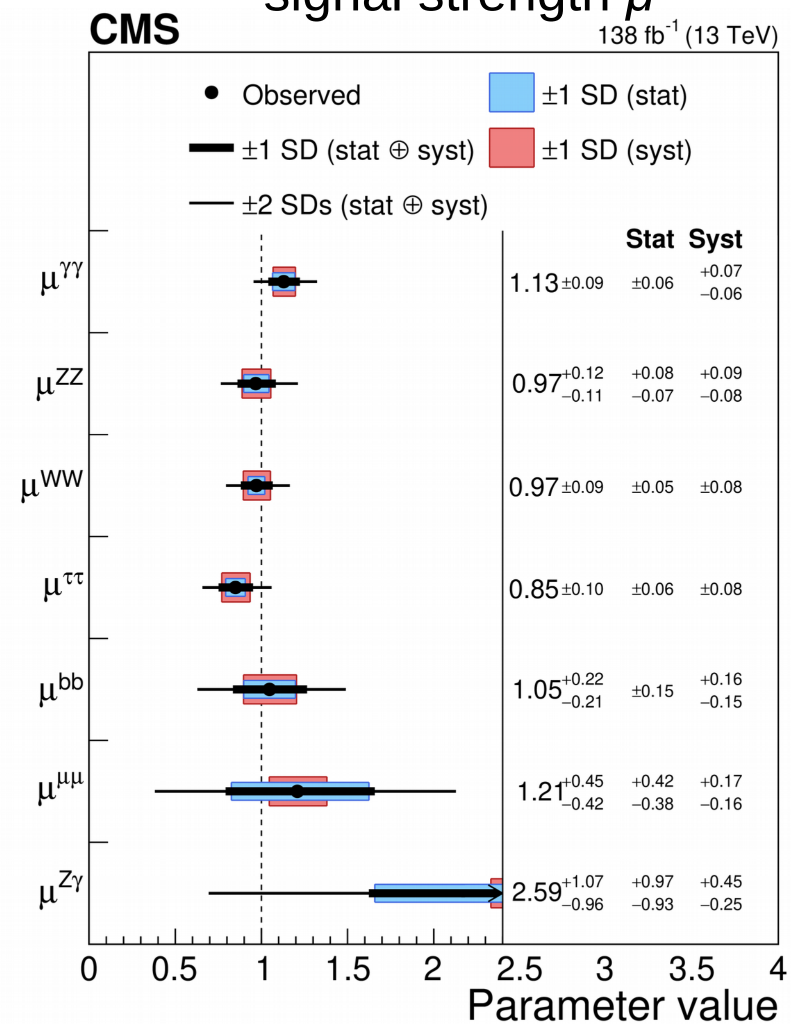
$$g_V = 2\frac{m_V^2}{v}$$



$$g_F = \sqrt{2}\frac{m_f}{v}$$



signal strength μ^f



Agreement with SM

Precision on main bosonic decays & decays to τ ~10%

Precision on H→bb ~20%

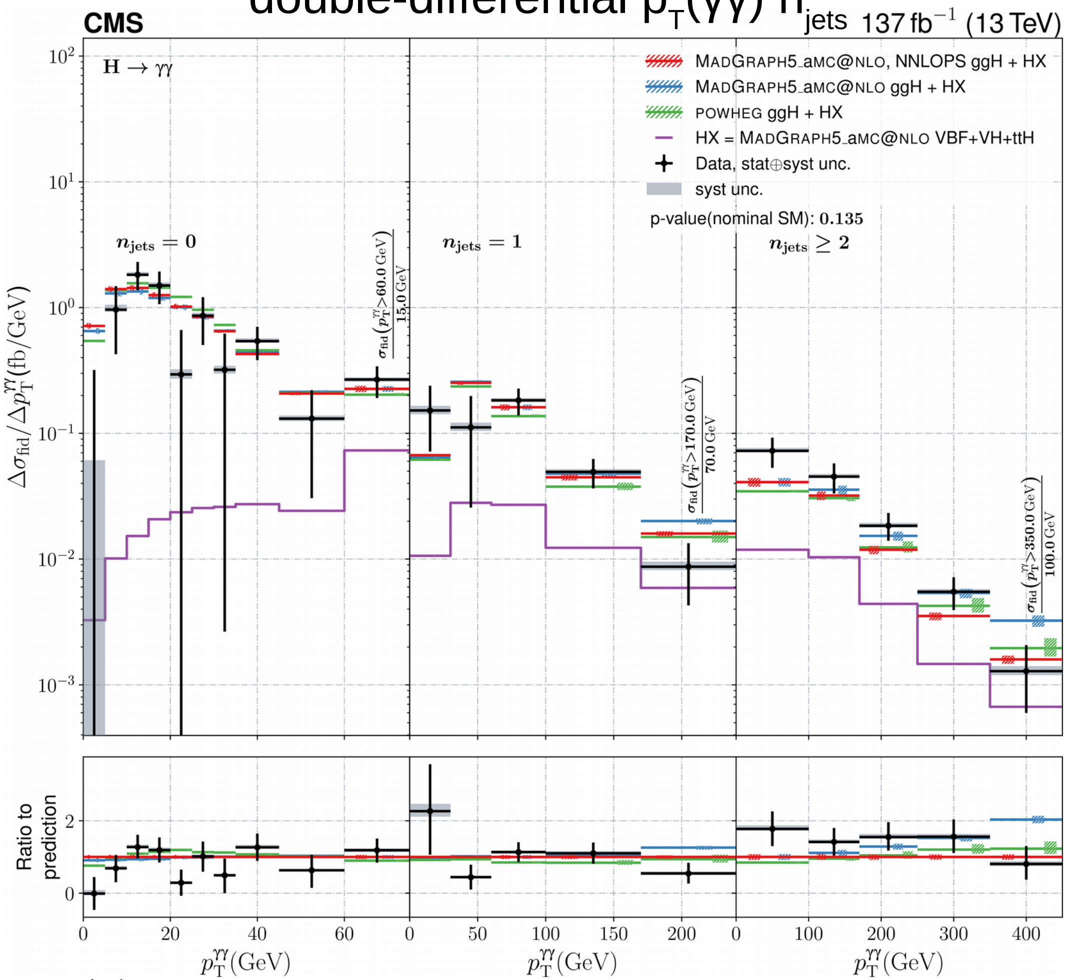
Uncertainties on rare decays (μμ, Zγ) still sizeable

Differential cross sections

Differential cross section measurements in several channels:
H → γγ, H → ZZ → 4ℓ, H → ττ, H → WW → 2ℓ2ν
in their respective fiducial phase space

Example: set of measurements in H → γγ (JHEP07(2034) 091)

double-differential $p_T(\gamma\gamma)$ n_{jets}



$\sigma_{fid} = 73.4^{+5.4}_{-5.3}(\text{stat})^{+2.4}_{-2.2}(\text{syst})$ fb

SM: 75.4±4.1 fb

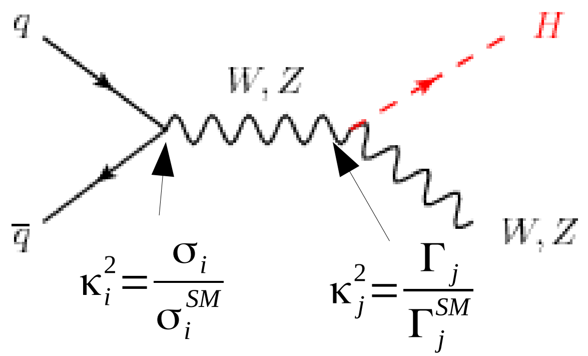
Opportunity to study:

- dynamics of H production,
- constrains of couplings,
- additional jet structure...

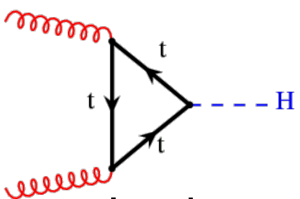
Good agreement with the SM

Coupling measurements

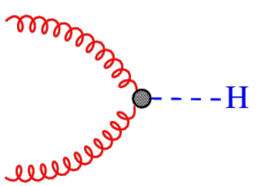
Coupling modifier, $\kappa = g/g_{SM}$, framework
=> parametrisation of inclusive production and decay rates
(assumes factorisation, i.e. zero-width approx.)



Loop scaling factors (κ_g, κ_{γ}.) can be expressed in terms SM coupling scaling factors (resolved) or treated as free parameters => effective couplings sensitive on BSM



resolved: κ_t, κ_b

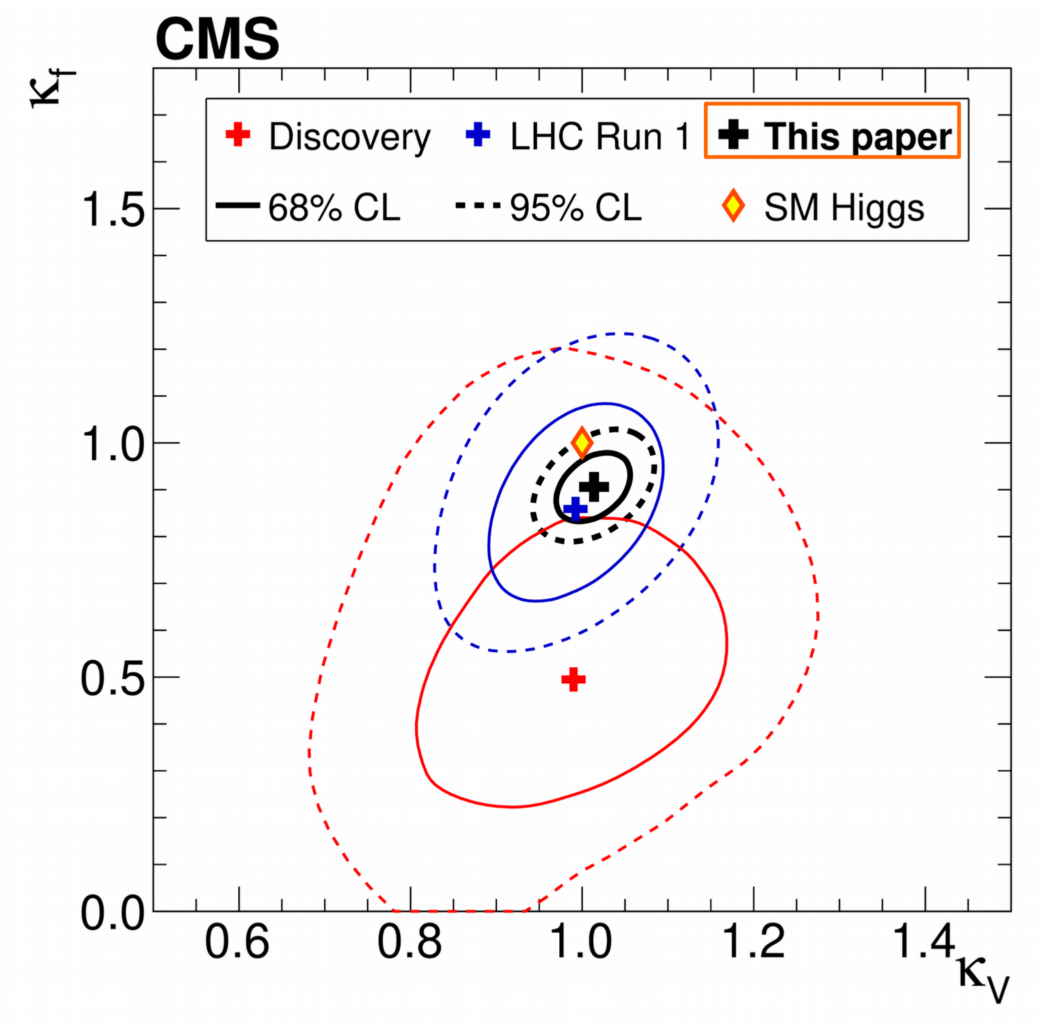


effective: κ_g

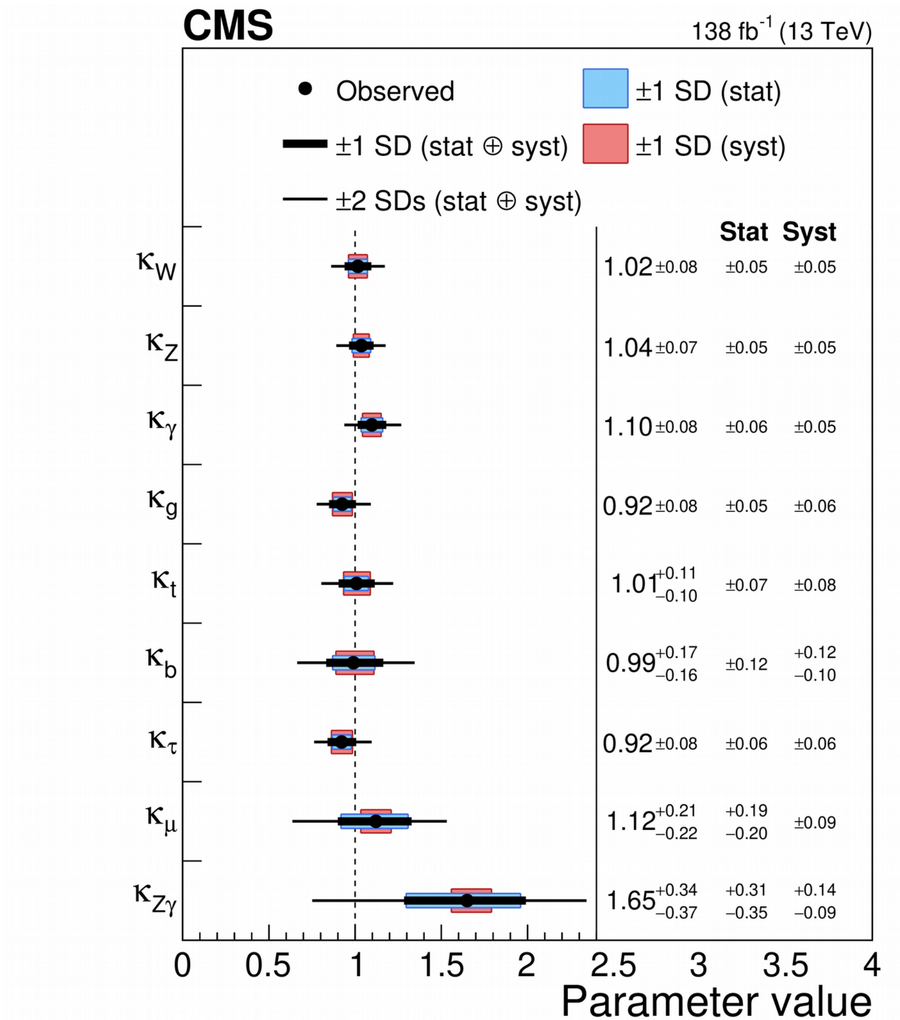
Γ_H requires assumptions, $\kappa_H = \kappa_H(\kappa_W, \kappa_Z, \ldots)$,
because of inaccessible decays
(SM-like, i.e. resolved and no BSM couplings, or with inv./undet. allowed with $\kappa_{W,Z} \leq 1$ and effective loops)

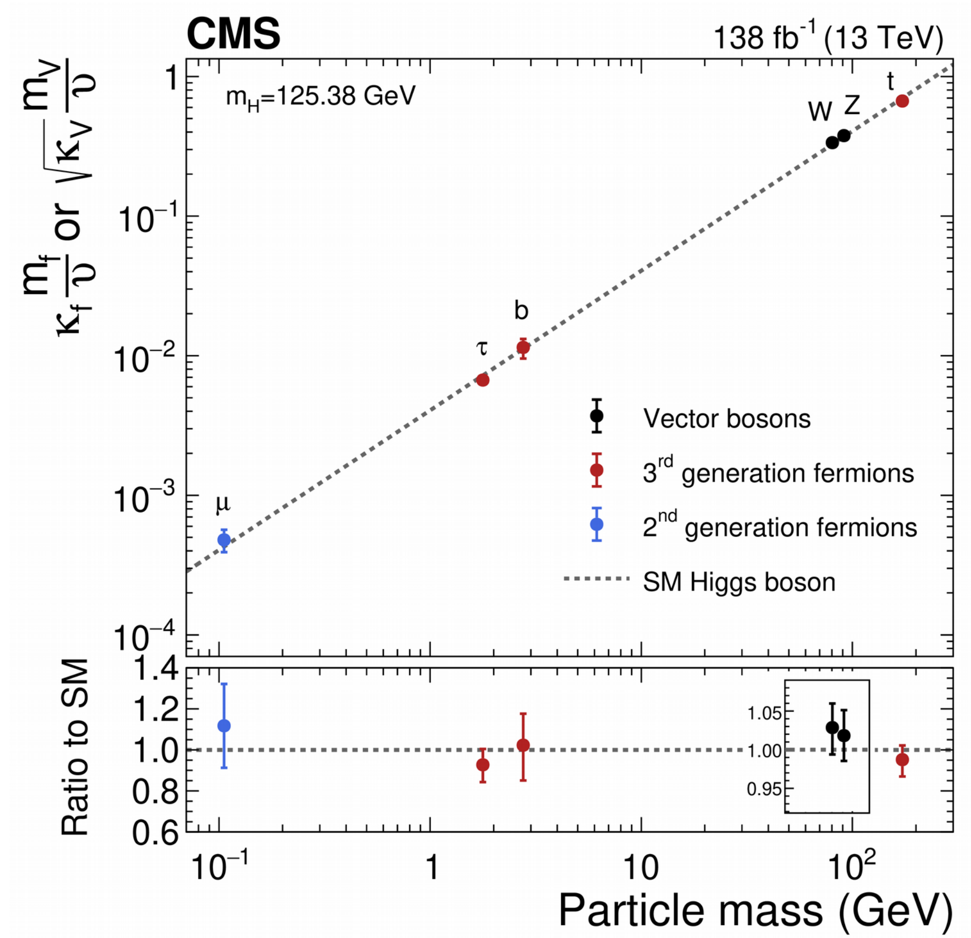
Couplings: vector bosons vs fermions

Scale all vector boson couplings with κ_V, all fermion couplings with κ_F



Individual couplings



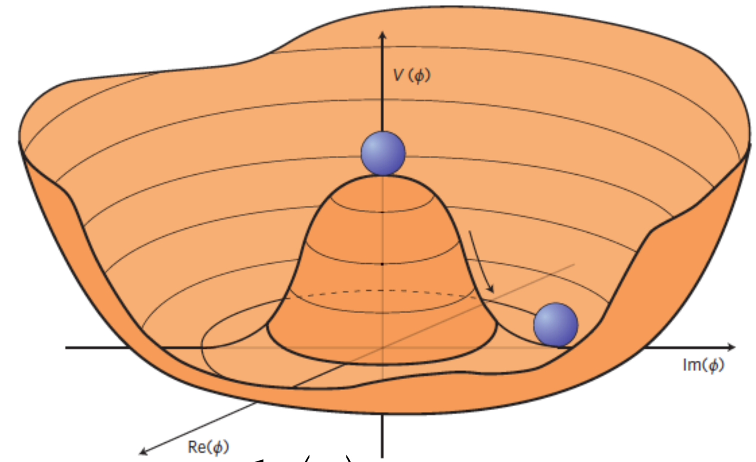


Couplings follow expectation of the SM

Higgs self-coupling

Determining the Higgs potential, are H self-couplings as predicted by SM?

- Higgs boson self-couplings defined by m_H in SM



$$\langle \Phi_0 \rangle = \frac{1}{2}\begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = \sqrt{\mu^2/\lambda}$$

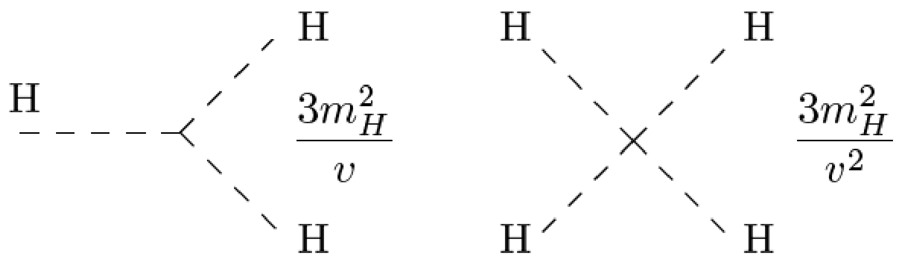
$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$\Phi \to v + H$

$$V = V_0 + \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$$

Mass term

Self- and quadratic couplings
Proportional to m_H in SM



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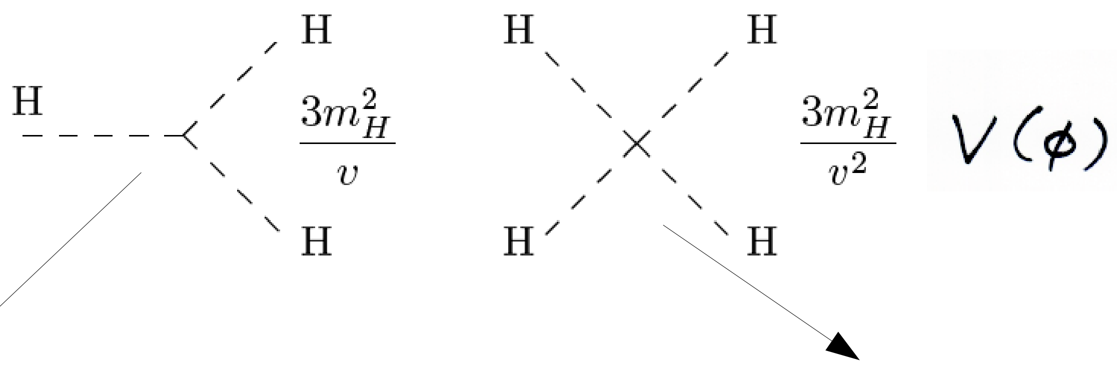
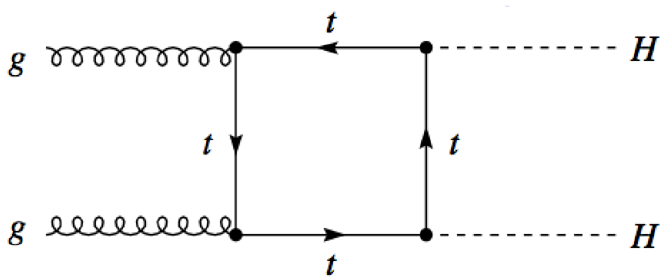
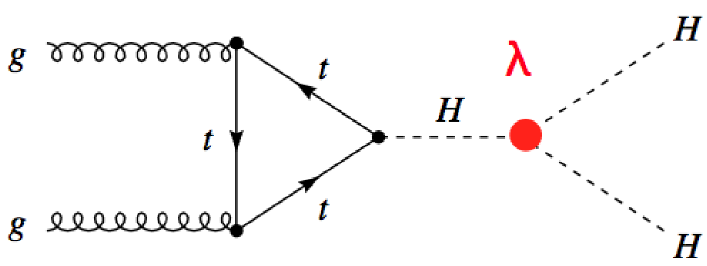


Very difficult due to the “direct” double H production, which interferes with the signal

Probably hopeless in any planned experiment

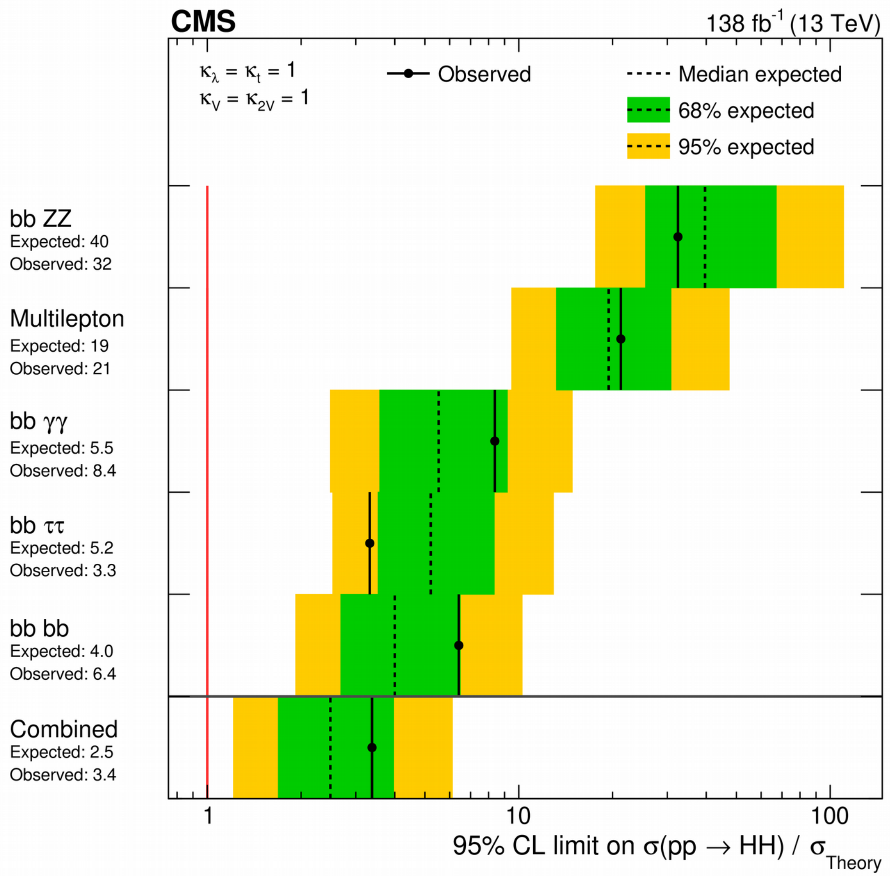


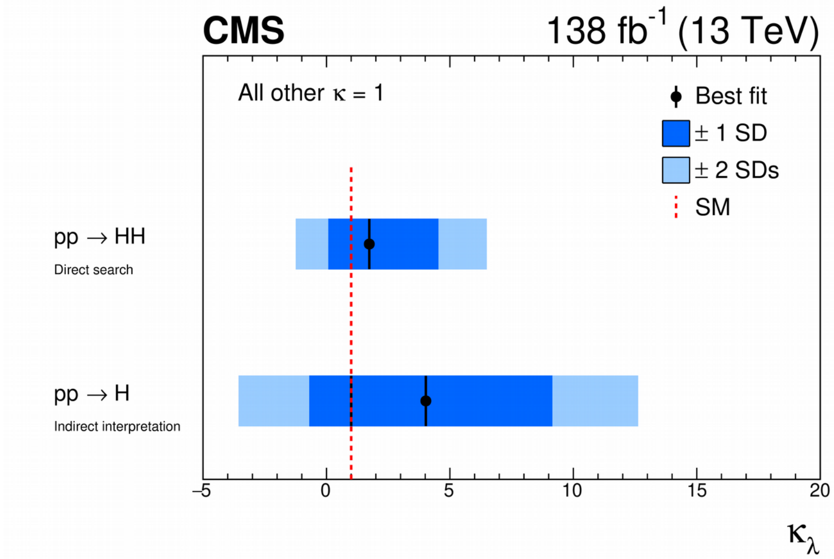


HH events from the self-interaction diagrams are soft

Multitude of HH channels, no golden one => Complex analyses (ML usage)

Search for HH process





Current (Run-2) sensitivity to observe HH with ~3×SM cross-section => need 3/ab of HL-LHC data

Constraints for $\kappa_\lambda = \lambda_{HHH}/\lambda_{SMHHH}$ at 95% CL:

- $-1.3 < \kappa_\lambda < 6.4$ (only HH) and
- $-3.6 < \kappa_\lambda < 12.6$ (loop corrections to single-H cross-section)

Summary

- Only a small sample Higgs measuremnts at CMS presented today
- We have learned much about the Higgs boson since its discovery
  - Its mass is known with ~0.1% precision
  - First measurements of its total withdth (with off-shell decays) performed
  - Cross-section known with up to ~10% precision
  - Couplings to other particles probed
- Still need to establish couplings to 2nd generation fermions
  - Coupling to muons on the reach of LHC, c-quark probably not

  and Higgs self coupling
  - HH pair production should be observed in HL-LHC

=> Results in agreement with the Standard Model

- Data-taking continues:
  - Waiting for good amount of Run-3 data
  - HL-LHC, with upgraded CMS detector, improved theory calculations and analysis techniques will enable even more precise measurements