Higgs measurements at CMS

Giuseppe Bagliesi
INFN - Pisa

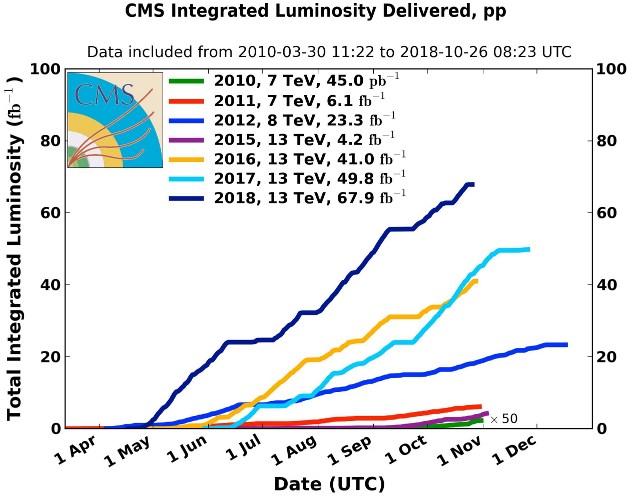
On behalf of the CMS collaboration

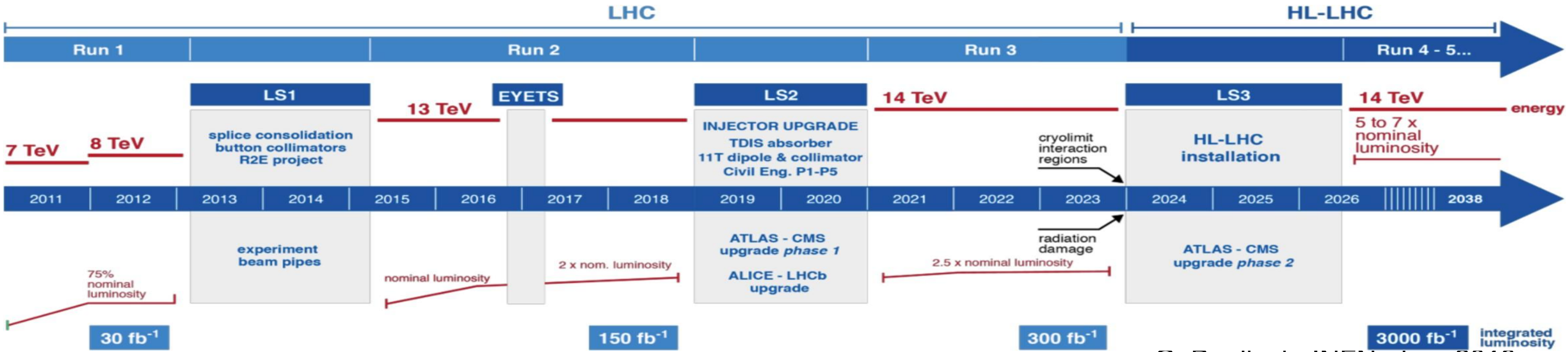
The Higgs boson

- Higgs boson, discovered by Atlas and CMS in 2012, was a big success of LHC
  - Final constituent of the Standard Model
  - Spontaneous symmetry breaking mechanism is responsible for generating particle masses
  - First fundamental scalar particle found so far
- We know that this is not the end of the story
  - Dark matter, neutrino masses, baryon asymmetry are not explained by SM
- Studying the Higgs boson properties we can contribute in improving our understanding of nature
  - Deviations from the SM prediction may indicate new physics

Current status of LHC and CMS experiment

- A peak lumi of $2x10^{34}cm^{-2}s^{-1}$ was achieved
- Run1 =~30/fb, Run2 =~163/fb
- Run2: ~35 pileup interaction per beam crossing
- Many analyses based on the full Run2 dataset are still ongoing





Higgs production and decays at LHC

~88%

σ=49 pb / 6.9M Higgs in 140fb^{-1}

~7%

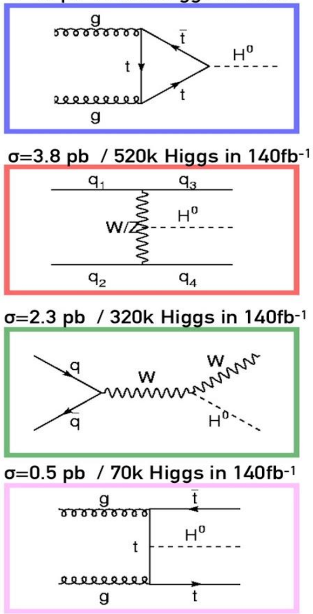
σ=3.8 pb / 520k Higgs in 140fb^{-1}

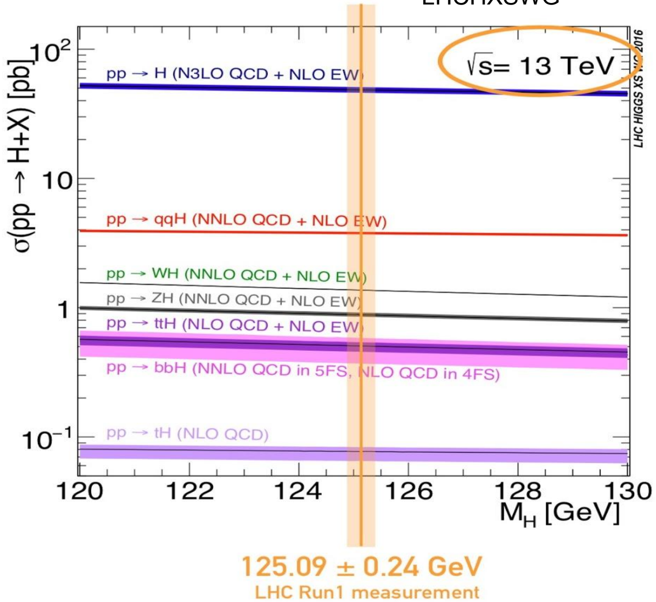
~4%

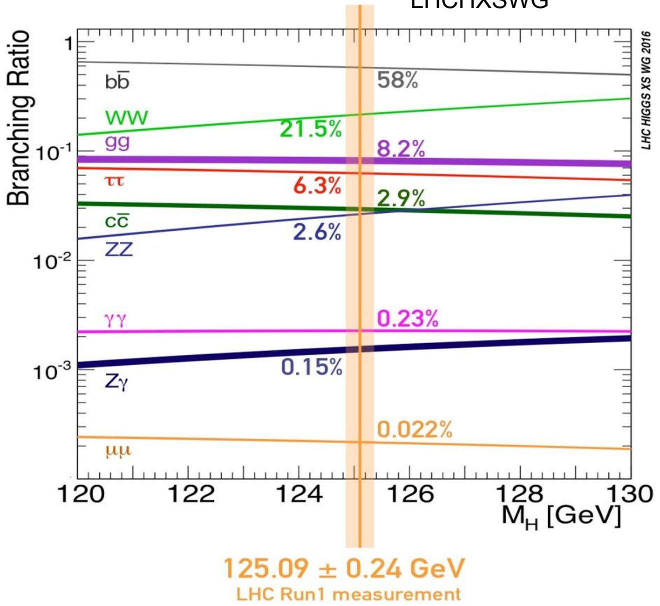
σ=2.3 pb / 320k Higgs in 140fb^{-1}

~1%

σ=0.5 pb / 70k Higgs in 140fb^{-1}







Outline

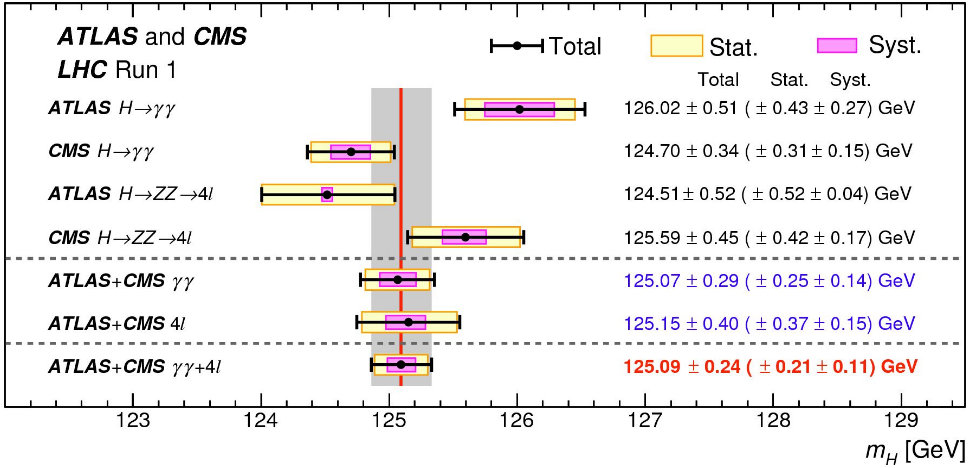
- Higgs mass and width measurements
- Higgs to gauge bosons decays (ZZ, WW, $\gamma\gamma$)
- Higgs decays to third generation fermions (bb, ττ)
- Higgs decays to light fermions (cc, $\mu\mu$)
- ttH and tH production measurements
- Higgs cross section measurements and combinations
  - Extrapolations for HL-LHC

Higgs boson mass and width

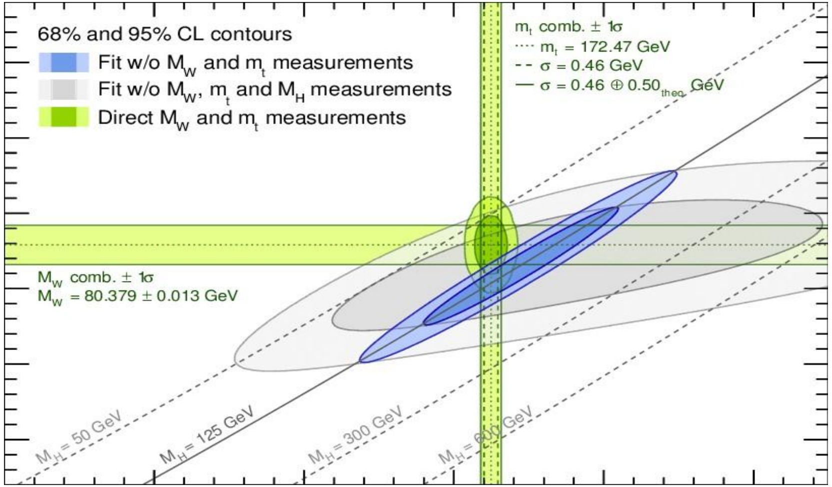
Higgs Boson Mass

- The mass is the only free parameter of the Higgs sector in SM
  - Fixing the mass value determines all the SM Higgs properties
- Golden channels for mass measurement: H→ ZZ → 4l and H→ $\gamma\gamma$

PRL 114, 191803 (2015)



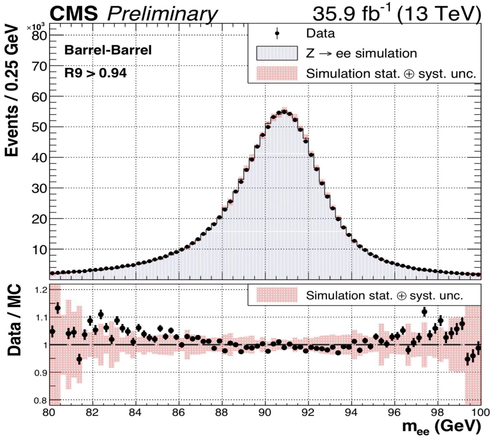
Eur. Phys. J. C (2014) 74:3046



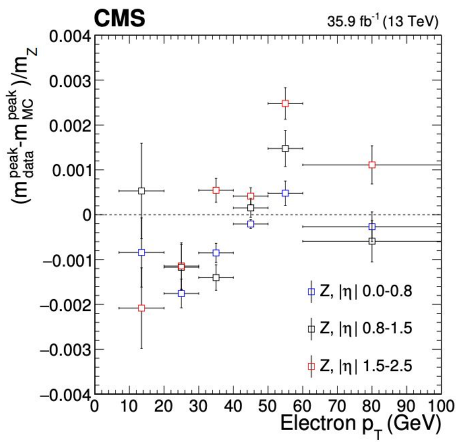
Run1 data: ~0.2% precision with Atlas + CMS combination

m_H measurement

- Fit data with a m_H dependent model, obtained with MC
- Simulation must be based on a very good and precise understanding of the detector response
- The Higgs mass resolution depends on the resolution of the decay products
- $Z \rightarrow \mu\mu$, ee
  - mass resolution: ~1% (barrel), 1.5% (endcap)
- $H \rightarrow$ ZZ mass scale uncertainty (MC vs data)
  - 4μ ~0.04 %, $2e2\mu$ 0.1%, 4e 0.3%



Z→ ee reconstruction



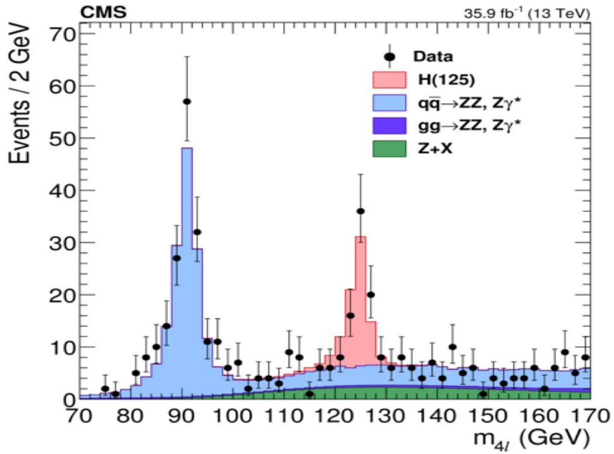
Mass scale uncertainty

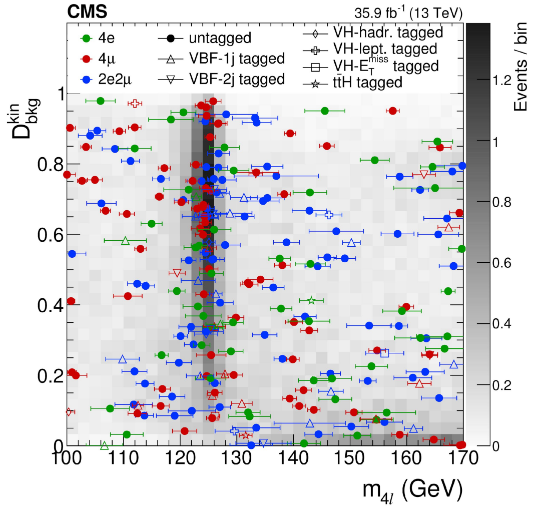
CMS DP 2019/022, JHEP 11 (2017) 047, CMS-PAS-HIG-19-004

m_H with $H \rightarrow ZZ \rightarrow 4l$

JHEP 11 (2017) 047

- Three event categories: 4μ, $2e2\mu$, $4e$
- Particle flow algorithm used for particle reconstruction
- Momenta of two leptons forming Z_1 are refit (improving m_H measurement of 10%)
- To extract m_H, a global fit is performed on the three events categories and various production processes (ME based discriminant)
- Result with Run2 (2016 data):
    - m_H = **125. 26 ± 0.20** (*stat*) **± 0.08** (syst) GeV
        - **So far best Higgs boson mass measurement in a single channel**





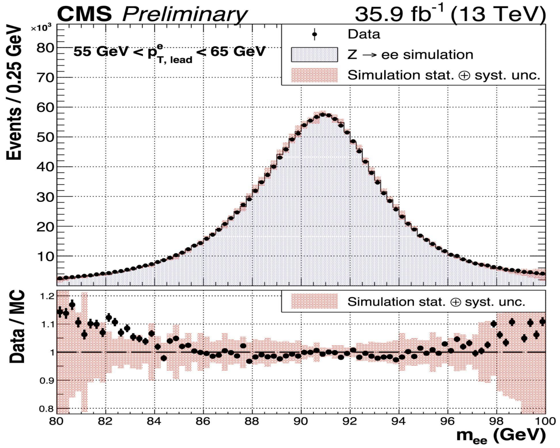
m_H with $H\rightarrow \gamma\gamma$ (new results on Run1 data)

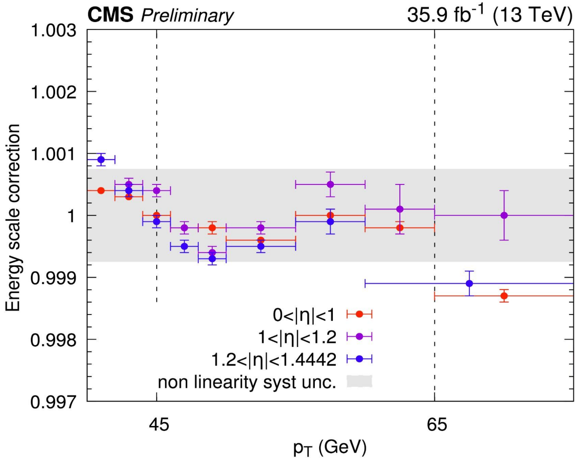
CMS-PAS-HIG-19-004

- Diphoton vertex selected with a dedicated BDT
- Dedicated BDT for photon identification and di-photon pair selection
- Events categories: 3 VBF and 4 Untagged
  - based on BDT score of being signal-like

Improvements with respect to the previous analysis HIG-16-040

- Improved detector calibration
- More granular run and spatial dependent (η, p_T, R_9) scale correction
- Photon energy scale systematic
  - Electron energy scale uncertainties propagated to photon energy scale

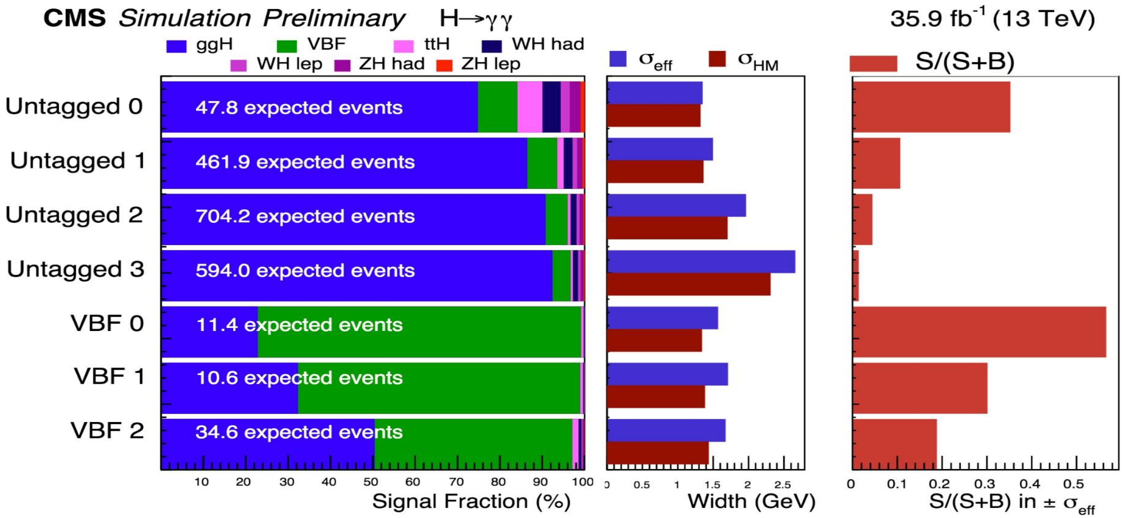


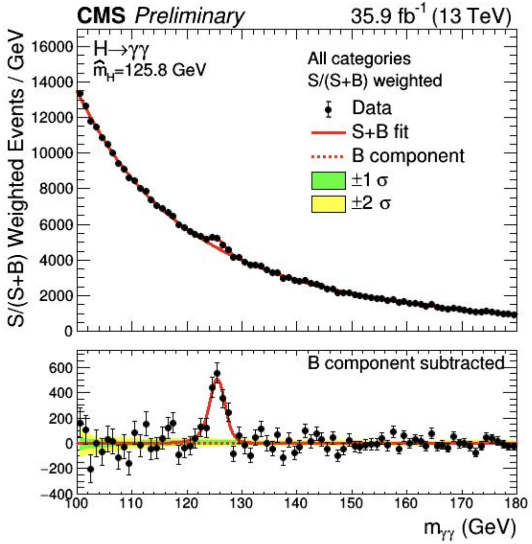


R_9: the ratio of the sum of energy deposited in a 3×3 crystal array, centred on the crystal with the highest energy, to the sum of the energy in the whole cluster

m_H with H→ $\gamma\gamma$ (new results on Run1 data)

CMS-PAS-HIG-19-004





Events categories based on BDT score of being signal-like

σ_{eff}=HW of the interval containing 68.3% of mass distribution
σ_{HM}=FWHM/2.34

Backgrounds extracted from fit to data

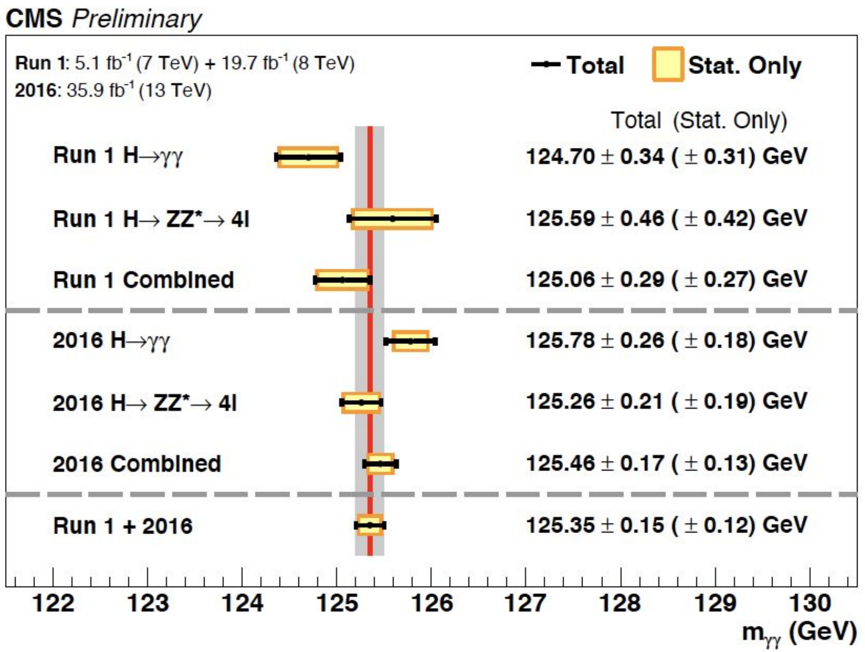
m_H = 125.78 ± 0.26 (0.18 (stat) ± 0.18 (syst)) GeV

Combination of H→ $\gamma\gamma$ and H→ 4l channels

CMS-PAS-HIG-19-004

Systematics in the combination

- Luminosity uncertainty correlated
- e/γ energy scale uncertainties between the two channels are treated as uncorrelated
    - Several checks have been done



Run1 + 2016 data **m_H = 125.35±0.12(stat)±0.09(syst) GeV**

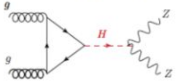
Actually this is the most precise m_H measurement, uncertainty ~ 0.12%

Higgs boson width measurement

JHEP 11 (2017) 047

- **SM prediction Γ_H = 4.1 MeV**
- Direct measurements of the width are limited by detector resolution (~1 GeV)
- A much more precise determination is obtained with the "off-shell technique" (next slide)

Breit-Wigner production pp → *H* → *ZZ*

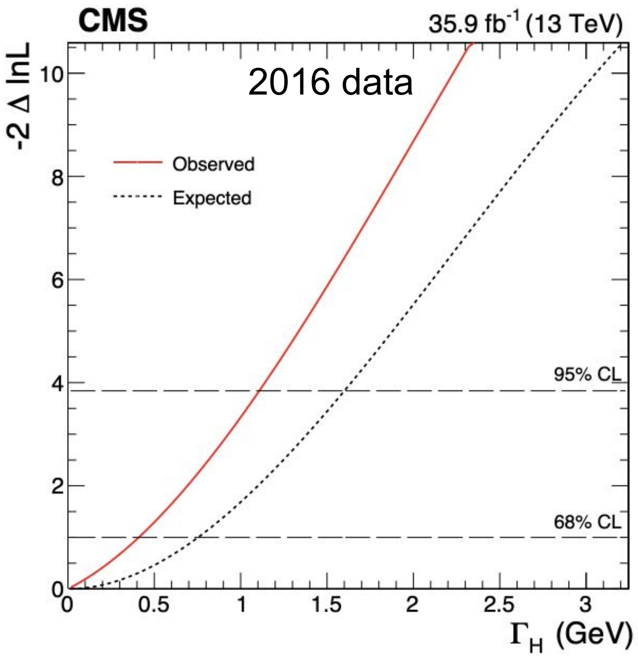


$$\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

On-peak cross sections: $\sigma^{on-shell} = \int_{|m-m_H| \leq n\Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim \frac{g_g^2 g_Z^2}{m_H \Gamma_H}$

Off-peak cross sections: $\sigma^{off-shell} = \int_{m-m_H \gg \Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim g_g^2 g_Z^2$

Off-peak to on-peak ratio $\frac{\sigma^{off-shell}}{\sigma^{on-shell}} \sim \Gamma_H$



Γ_H < 1.10 GeV at 95% CL

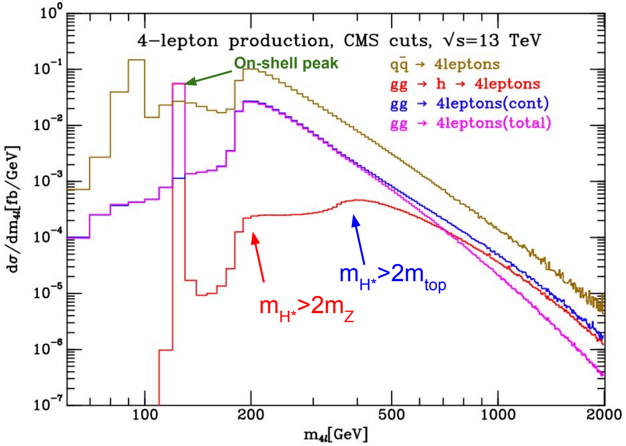
Γ_H measurement with off shell technique

PRD 99 (2019) 112003

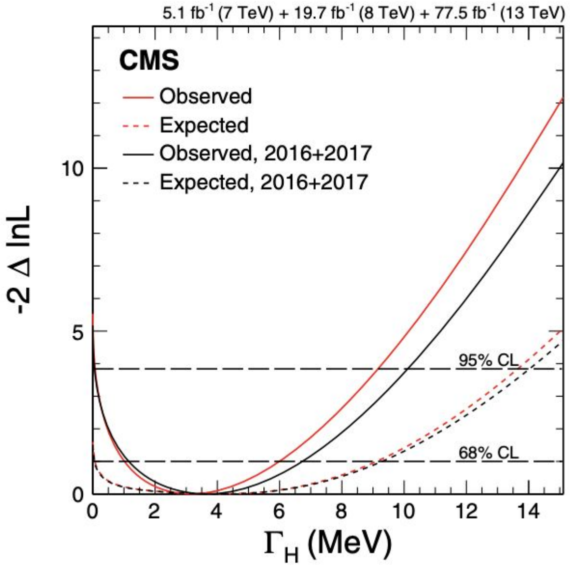
Main Assumptions:

- Higgs Couplings do not depend on on-shell off-shell production mechanism
- Signal region does not depend on on-shell off-shell production (excluding the expected increase in efficiency in the off-shell region)

arXiv:1311.3589v1



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



Run1 + 77.5/fb Run2:

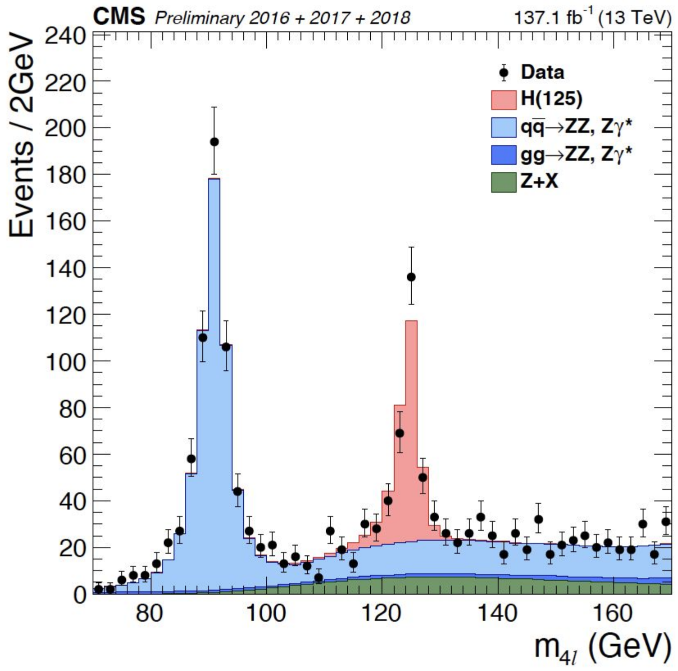
$0.08 < \Gamma_H < 9.16$ MeV

Higgs decays to gauge bosons (ZZ, WW, $\gamma\gamma$)

H→ 4l decays

CMS-PAS-HIG-19-001

- Full Run2 results are available (137/fb at 13 TeV)
- 4 leptons invariant mass and other angular variables exploiting the scalar nature of Higgs boson are used to discriminate against background
- Backgrounds
  - irreducible : ZZ, $Z\gamma^*$
  - Reducible: Z+jets estimated in control regions
- Measure is still statistically dominated
  - Systematic from lepton efficiencies and irreducible background estimate



Fiducial cross section is defined in a phase space as close as possible to the measured phase space (m_H = 125.09 GeV)

$$\sigma_{\text{fid.}} = 2.73^{+0.23}_{-0.22}(\text{stat.})^{+0.24}_{-0.19}(\text{syst.})\ \text{fb}$$

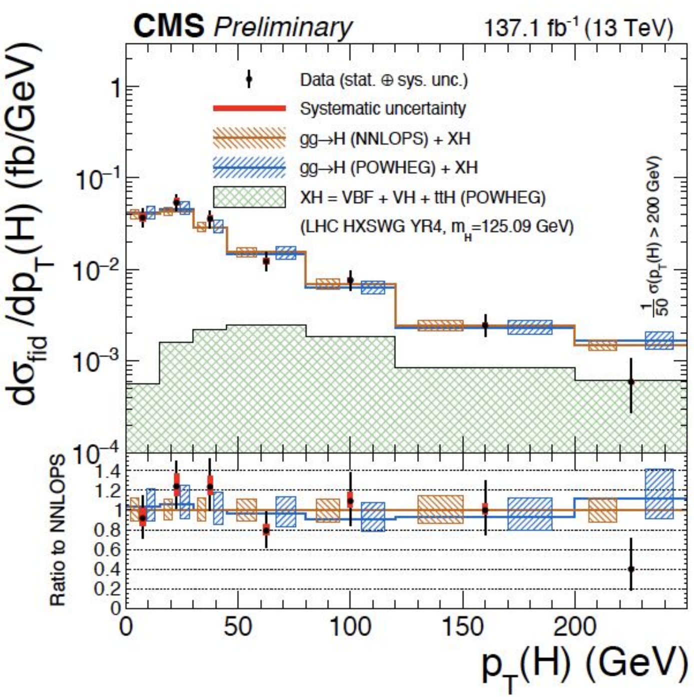
Signal strength modifier (meas. / SM prediction)

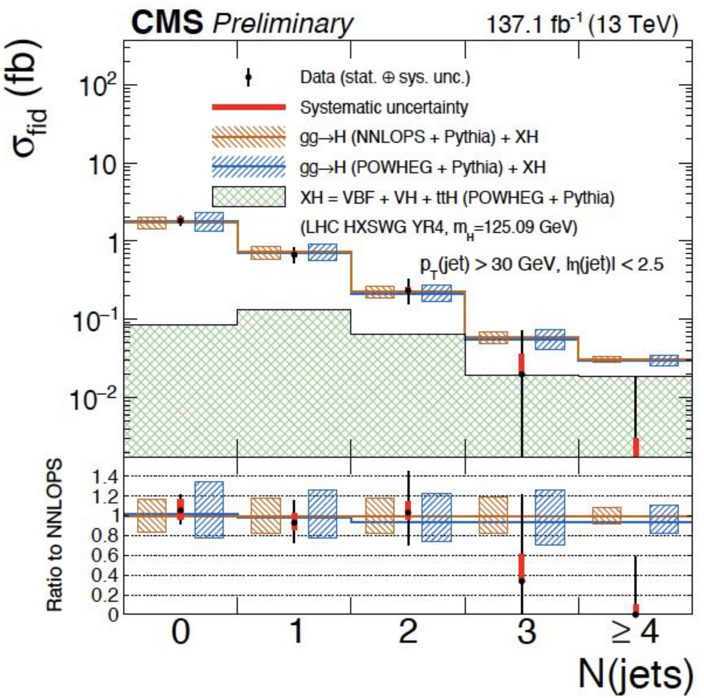
$$\mu = 0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$$

H→ 4l differential cross section

CMS-PAS-HIG-19-001

- Measure the production rate in different regions of Higgs boson phase space: P_T, rapidity, N_{jets}, P_T^{jet1}, m_{jj}, … and compare with various predictions





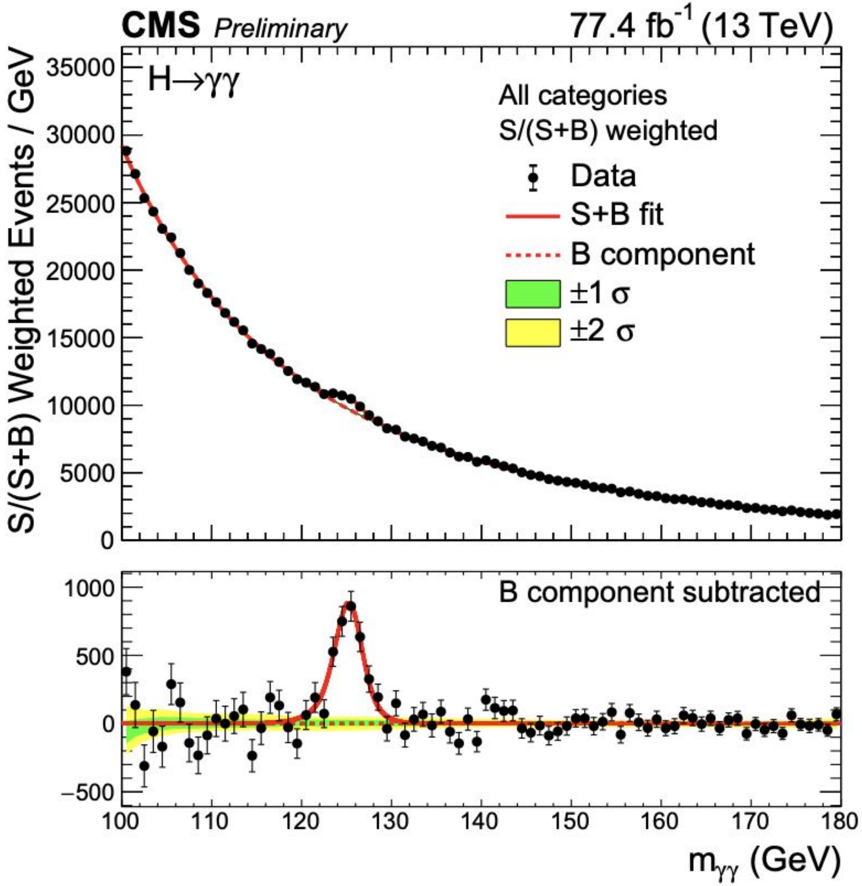
$H \rightarrow \gamma\gamma$

CMS-PAS-HIG-18-029

- Based on 2016 and 2017 datasets (77.4/fb at 13 TeV)
- Strategy:
  - Fit a signal on top of a smoothly falling background
- Challenges:
  - Photon to vertex association
  - Huge background

Signal strength modifier μ

Gluon fusion prod.	$1.15^{+0.15}_{-0.15}$
VBF production	$0.8^{+0.4}_{-0.3}$

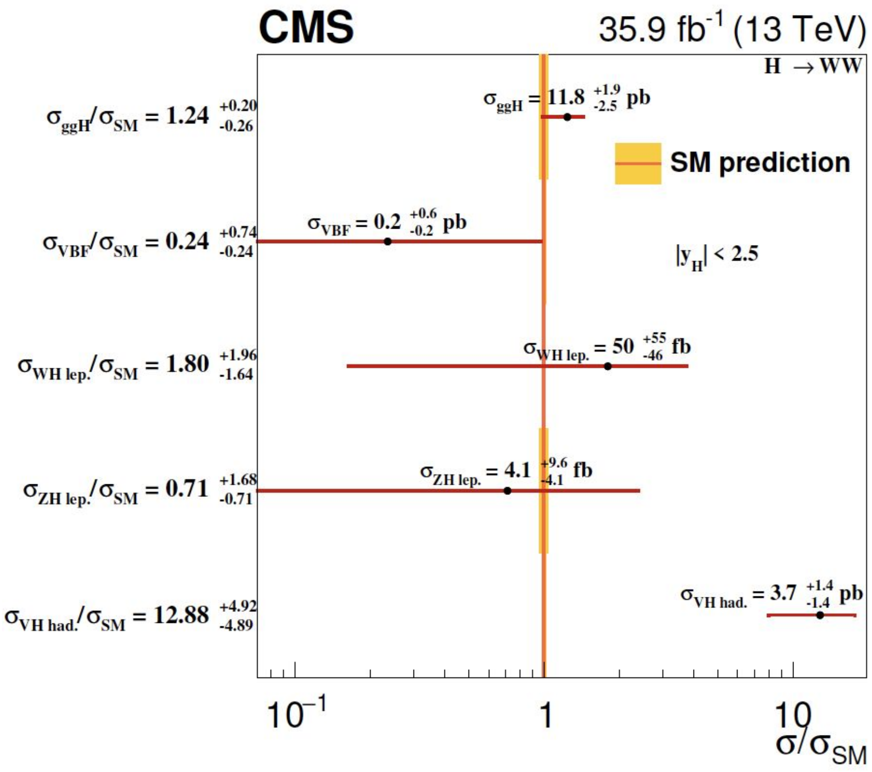


H→ WW→ lνlν

CMS-PAS-HIG-16-042,
PLB 791 (2019) 96

- 2016 data results (35.9/fb at 13 TeV)
- Complicated final state, all physics objects are involved
- Large signal, moderate/large background
- e/μ final state (shape based) and same flavor (cut and count)
- Discriminating variable m_{ll} vs m_T

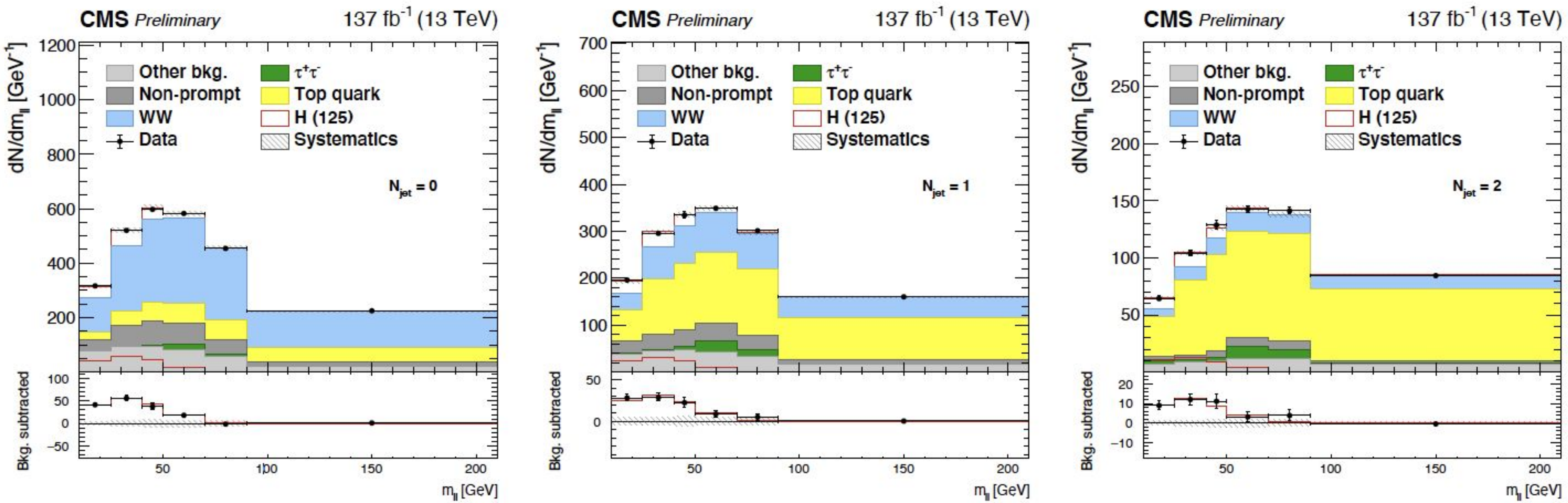
$$m_T = \sqrt{2 p_T^{\ell\ell} p_T^{miss} [1 - \cos \Delta\phi(\ell\ell, \vec{p}_T^{miss})]}$$



H→ WW full Run2 differential cross section

CMS-PAS-HIG-19-002

- New result based on 137/fb Run2 dataset
- Main challenges: control top and fake lepton backgrounds

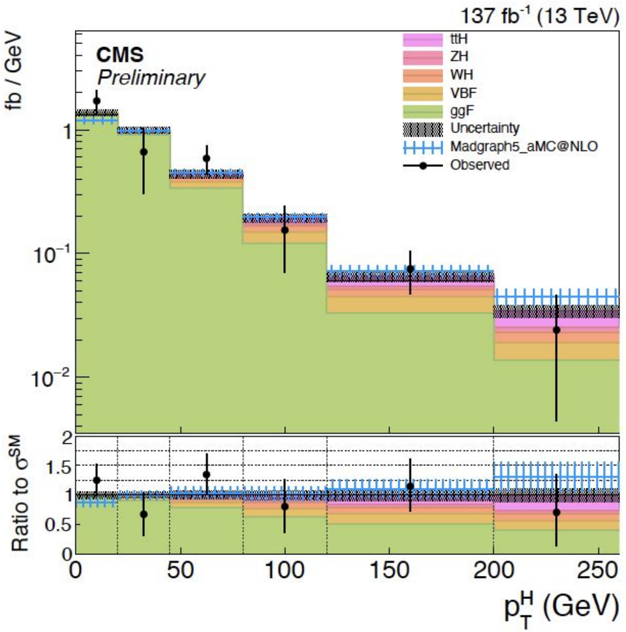


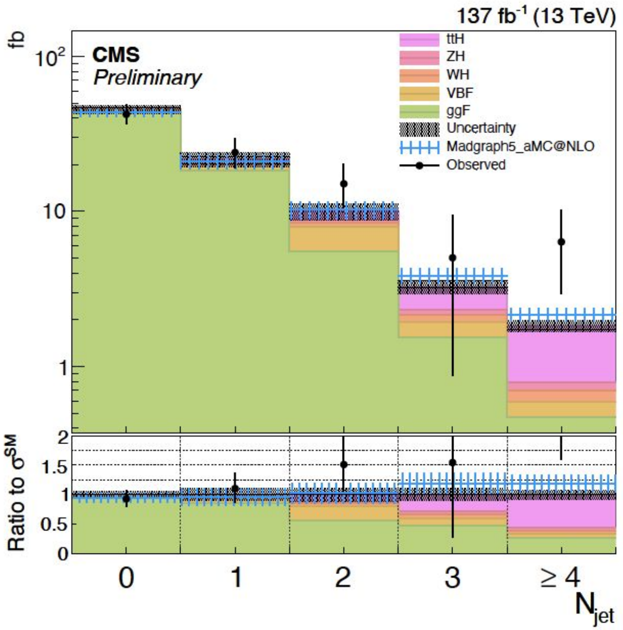
ll→ (eμ,μe)

$H\rightarrow WW$ full Run2 differential cross section

CMS-PAS-HIG-19-002

Overall fiducial measurement competitive with di-photon, larger theoretical uncertainties





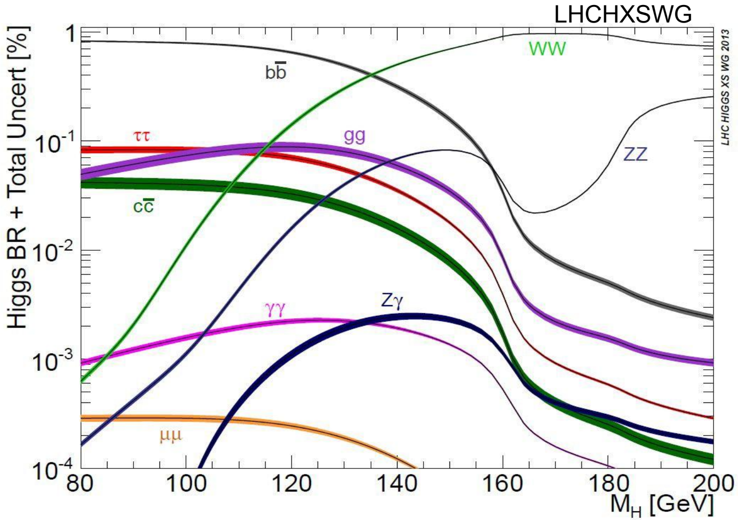
$$\mu^{\text{fid}} = 1.03^{+0.12}_{-0.11} \; \left(^{+0.05}_{-0.05}\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{theo.})\,^{+0.03}_{-0.03}\,(\text{lumi.})\,^{+0.07}_{-0.07}\,(\text{exp.})\right)$$

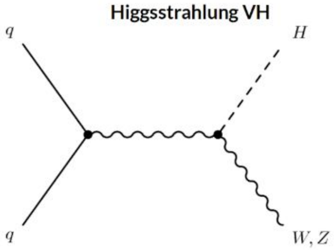
$$\sigma^{\text{fid}} = \mu^{\text{fid}}\sigma^{\text{SM}} = 85.0^{+9.9}_{-9.3}\,\text{fb}$$

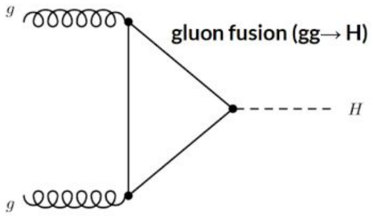
Higgs decays to third generation fermions (bb, $\tau\tau$)

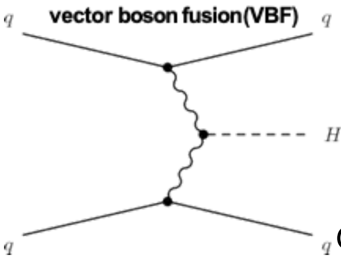
Higgs decays to fermions

- Direct probe of the Yukawa coupling
  - Main property: BR H→ fermions proportional to mass
- H→ bb and H→ $\tau\tau$ are the most sensitive channels
- Higgs decays into b quarks and into tau leptons are now well established
  - No evidence for BSM physics so far
- Beginning precision measurements on the Higgs couplings to fermions









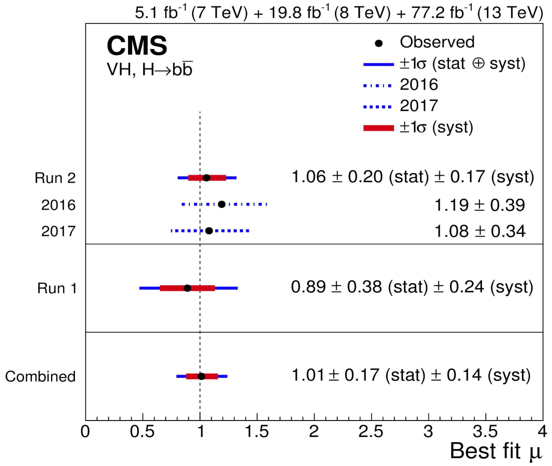
Relevant production mechanisms

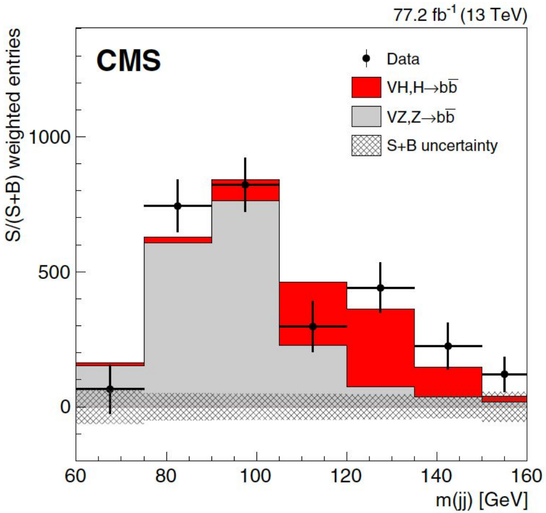
H→ bb ⇒ Phys. Rev. Lett. 121 (2018) 121801
H→ $\tau\tau$ ⇒ Phys. Lett. B 779 (2018) 283–316

H→ bb

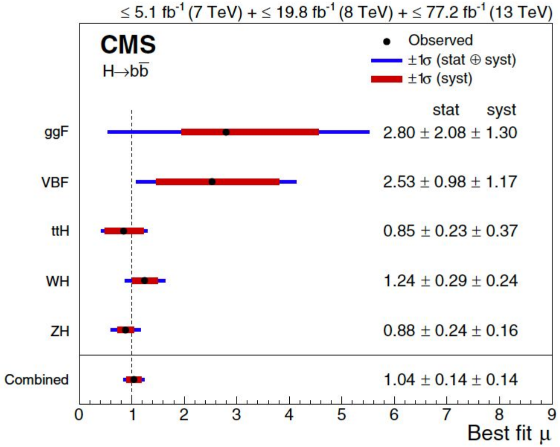
- Large BR (58%), but difficult channel
  - VH→ bb most sensitive channel, also ggH(bb), VBF, and ttH have some sensitivity
  - Established with significance > 5σ

PRL 121 (2018) 121801





Background subtracted distribution



H→ $\tau\tau$

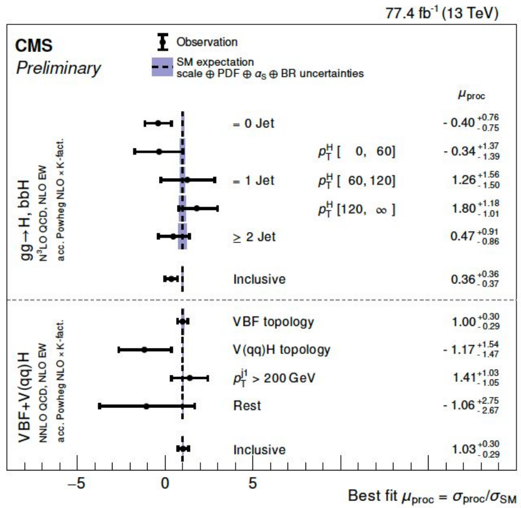
CMS-PAS-HIG-18-032

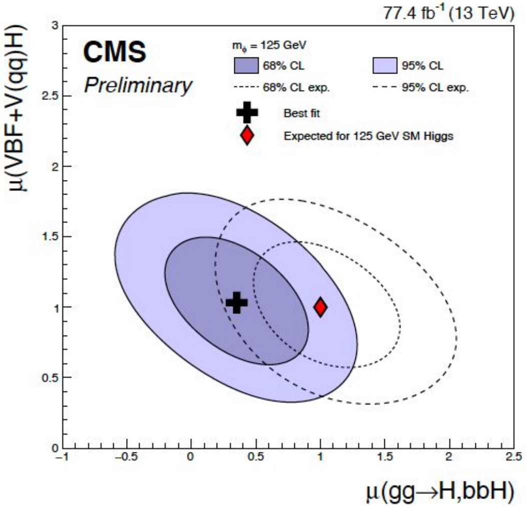
- Higgs to tau decay is the second largest BR of fermionic decays
- VBF H→ $\tau\tau$ is the most sensitive, also ggH relevant
- **New results** (77.4/fb at 13 TeV) are given in STXS bins, and split by production mode
- Machine learning widely used for categorization, 90% of background evaluated with data-driven methods
- Inclusive H→ $\tau\tau$ signal strength

$$\langle\mu\rangle = 0.75\,^{+0.18}_{-0.17}$$

- VH→ $\tau\tau$ analysis has a lower event yield, but greatly suppressed background due to additional leptons from W,Z decays
  - Latest results from JHEP06(2019)093

$$\langle\mu_{VH}\rangle = 2.5\,^{+1.4}_{-1.3}$$



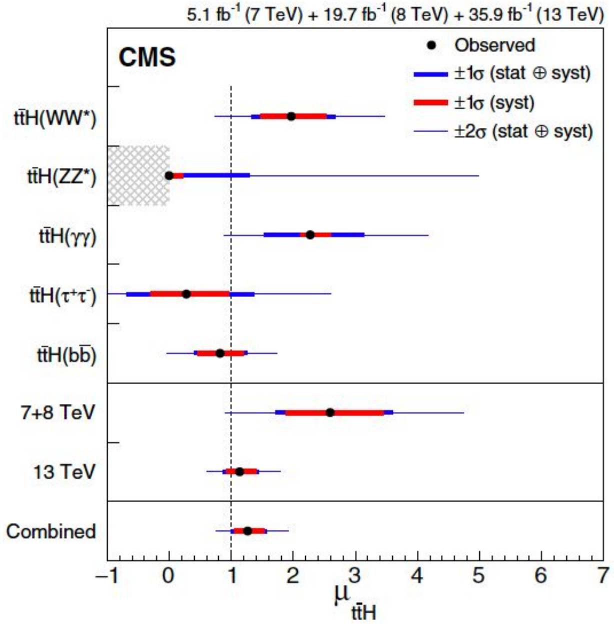


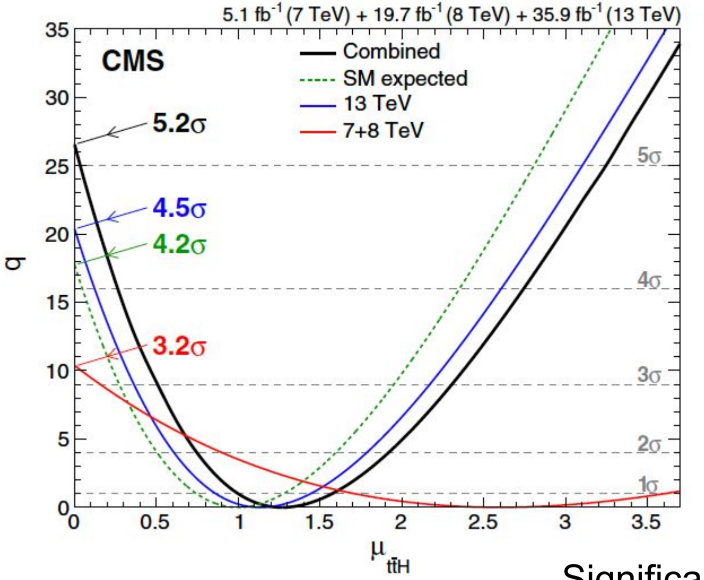
ttH and tH production measurements

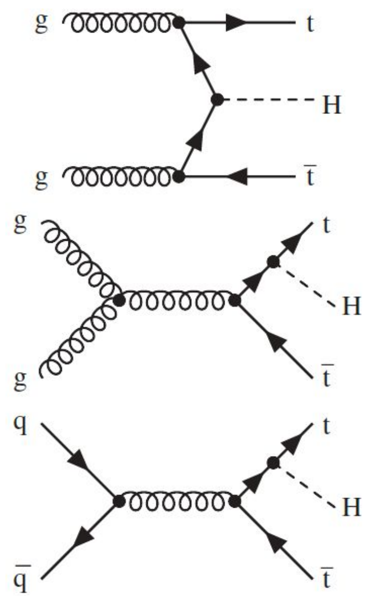
ttH

PRL 120(2018)231801

- M_{top} is too heavy for a direct H→ tt decay
- Several channels used H→ bb, WW, ZZ, $\gamma\gamma$, $\tau\tau$
  - 5.2σ observation in CMS







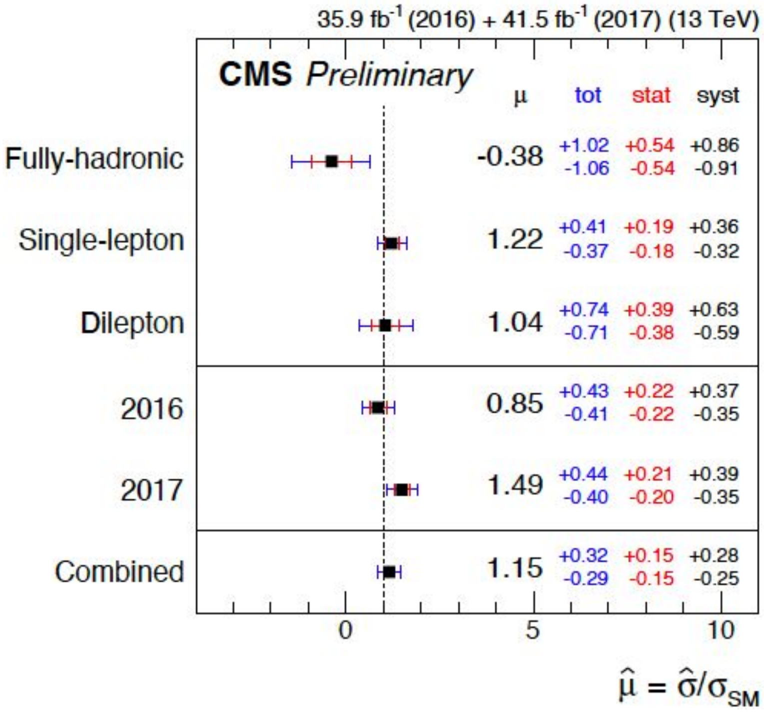
ttH production diagrams

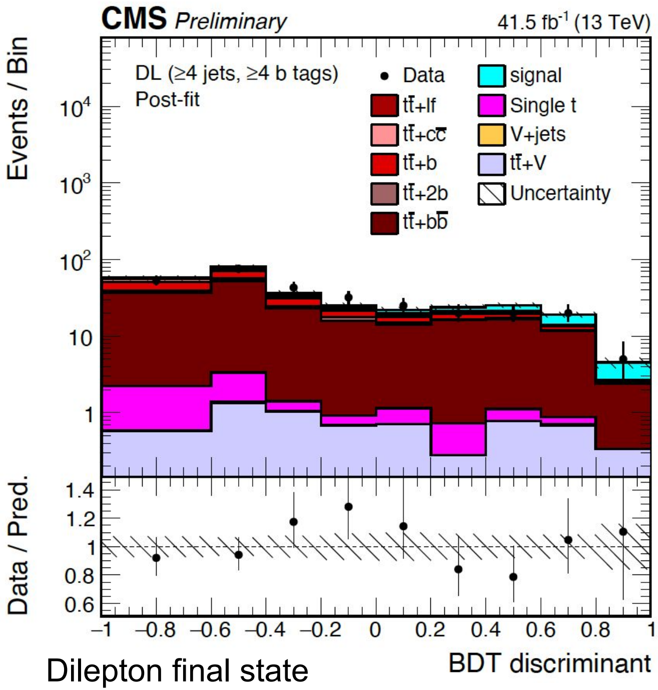
Significance 5.2 σ (4.2 σ exp)

ttH sig. strength (Run1 + 36/fb Run2) = $1.26^{+0.31}_{-0.26}$

ttH→ tt(H→bb)

- More data (2016+2017) and improved signal identification
  - ttH (H→ bb) observed significance is 3.7σ (evidence)



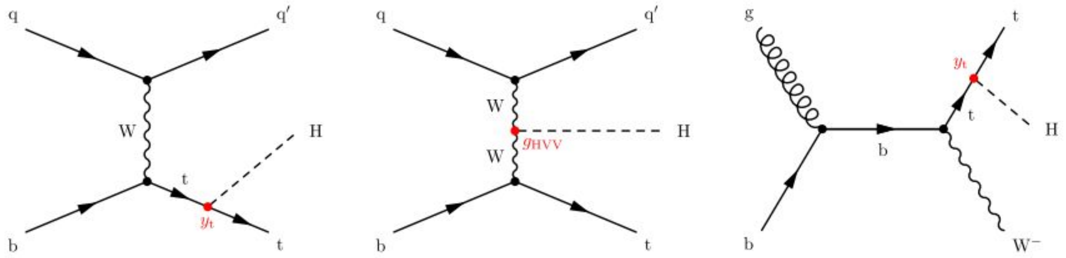


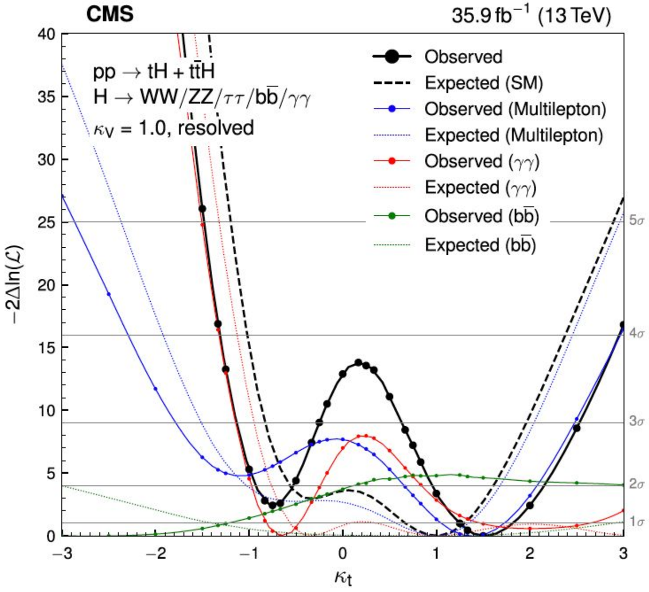
Dilepton final state

tH, Yukawa coupling sign extraction

PRD 99 (2019) 092005

- tH production cross section in SM is suppressed (~90 fb) but is sensitive to Yukawa coupling sign due to diagrams interference
- High values of tH cross section can indicate new physics





- Several channels used: H→ bb, $\gamma\gamma$, multi-lepton
- tH searches similar to ttH except lower multiplicity events
- Data favor a positive value of y_t SM by 1.5 σ

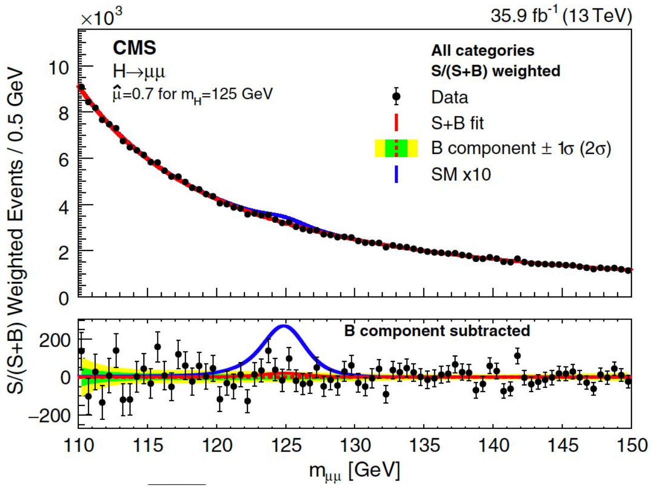
Higgs decays to light fermions (cc,$\mu\mu$)

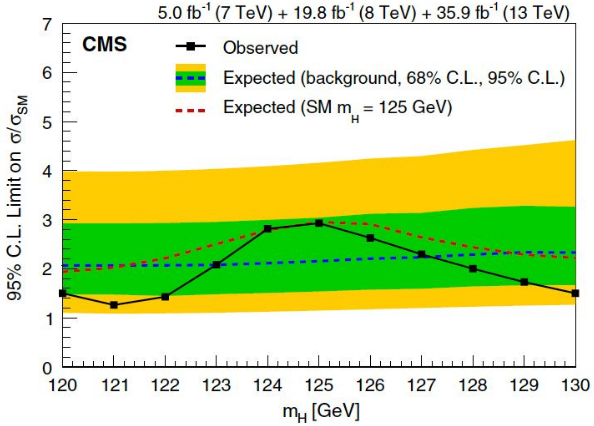
$H \rightarrow \mu\mu$

PRL 122 (2019) 021801

- $H \rightarrow \mu\mu$ very challenging at LHC
  - Very small BR: 2.2x10^{-4} + large Drell-Yan and tt+jets backgrounds
  - Search for a narrow peak over a falling background in $m_{\mu\mu}$ distribution
  - Excellent muon momentum resolution in CMS → O(1%) m_Z resolution
- Upper limit is set on signal strength modifier:

$$\mu_{\sigma(H)\times\mathcal{B}(H\rightarrow\mu\mu)} < 2.9 \text{ obs. } (2.2 \text{ exp.}) \text{ @ } 95\% \text{ CL}$$



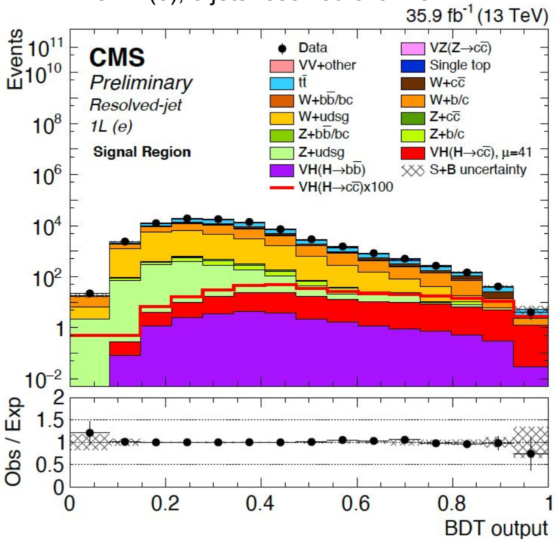


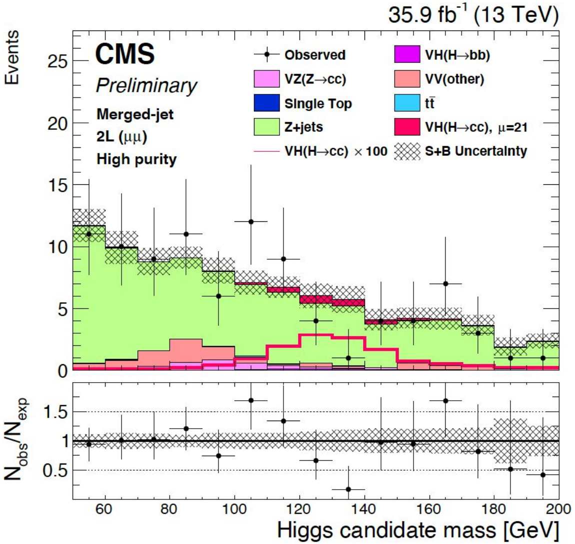
More results will come soon...

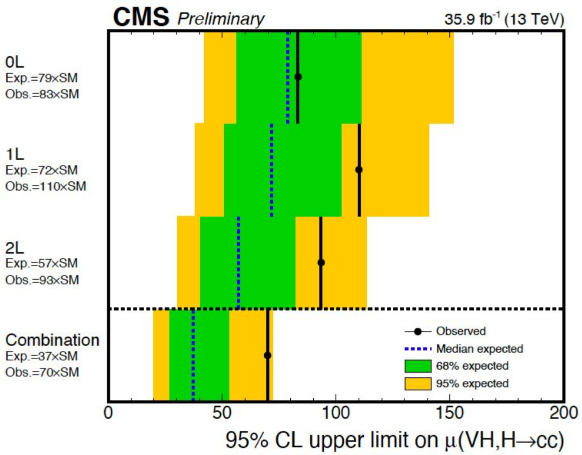
H→ cc

- BR(H→ cc) is 2.9%, similar to $\tau\tau$, but with a background much higher
- New CMS analysis optimized with categorization on leptons, and use of ML
- Using VH channel with W and Z decaying leptonically W→ lν, Z→ ll, $\nu\nu$
- Used both c-jets resolved on unresolved (merged) separated with specific algorithm
- Limit on μ <70 (μ<36 expected)
- Most sensitive result to date, but still far from SM prediction

BDT for 1l (e), c-jets resolved channel







Combinations for Higgs production and decays

EPJ C (2019) 79:421

5 production modes

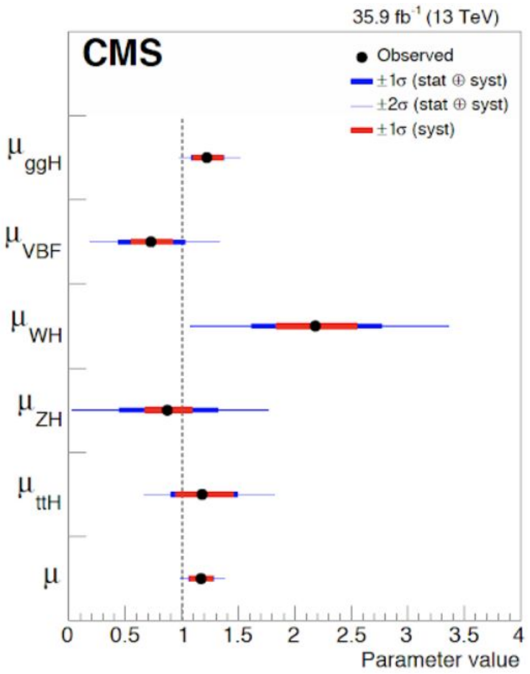
ggH, VBF, WH, ZH, ttH

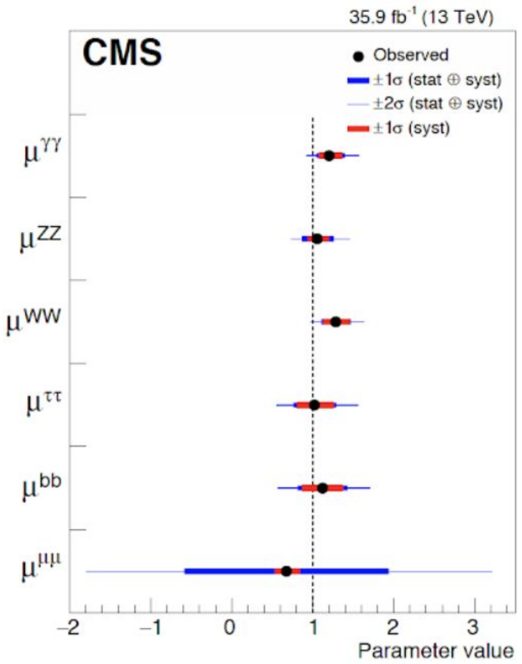
6 final states

H→ $\gamma\gamma$, ZZ, WW, $\boldsymbol{\tau\tau}$, bb, $\boldsymbol{\mu\mu}$

Overall uncertainty ~10% on current combinations

Improved results expected soon with full Run2 analyses





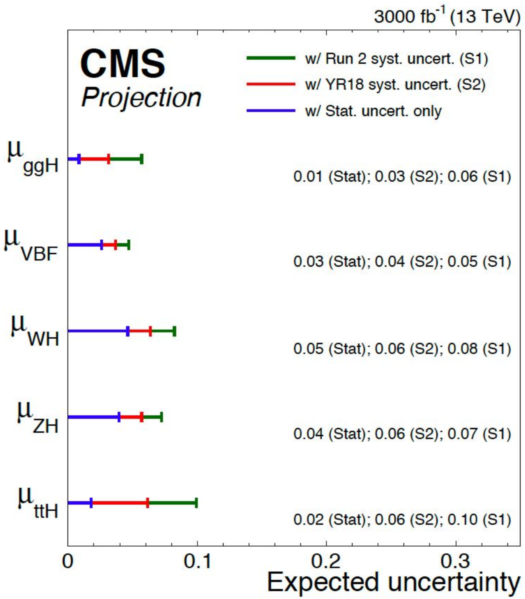
$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}}$$

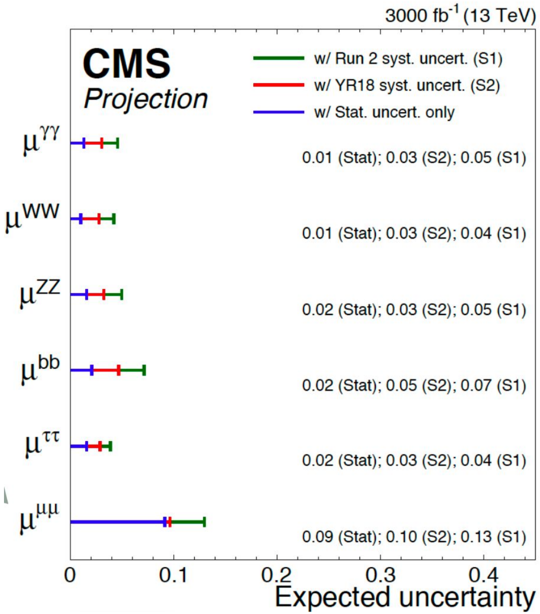
$$\mu^f = \frac{\mathcal{B}^f}{(\mathcal{B}^f)_{\mathrm{SM}}}$$

Prospects for HL-LHC

arXiv:1902.00134
CMS-FTR-18-011

- 3000/fb expected at HL-LHC
- many detector improvements
- achievable precision for Higgs measurements
    - Few percent on most Higgs cross-sections and couplings
    - Significance about 2.6σ for Higgs self-coupling measurements
    - Higgs width is measurable within 1 MeV
    - Many measurements are limited by systematics uncertainties
        - More work needed (theoretical and experimental)





- Scenario 1: all systematic uncertainties are kept unchanged with respect to those in current data analyses
- Scenario 2: the theoretical uncertainties are scaled by a factor of 1/2, while other systematic uncertainties are scaled by 1/√L

Conclusions

- LHC experiments are producing a large number of measurements on the Higgs boson
- Mass and width are being precisely measured
- Five Higgs decay modes observed: ZZ, WW, $\gamma\gamma$, bb, $\tau\tau$
- Four production modes exploited: ggH, VBF, VH, ttH
- So far SM is completely confirmed
  - But very precise measurements are around the corner to probe the details...
- Many analyses are ongoing with the full Run2 dataset
- New precision results will come with HL-LHC (3000/fb)
  - Including the observation of the higgs self-coupling

Backup

H→ 4l - STXS measurements

CMS-PAS-HIG-19-001

Simplified template cross sections (STXS 1.1) are defined phase space regions agreed between theorist and experiments to improve sensitivity to new physics and simplify the combinations of results between ATLAS and CMS