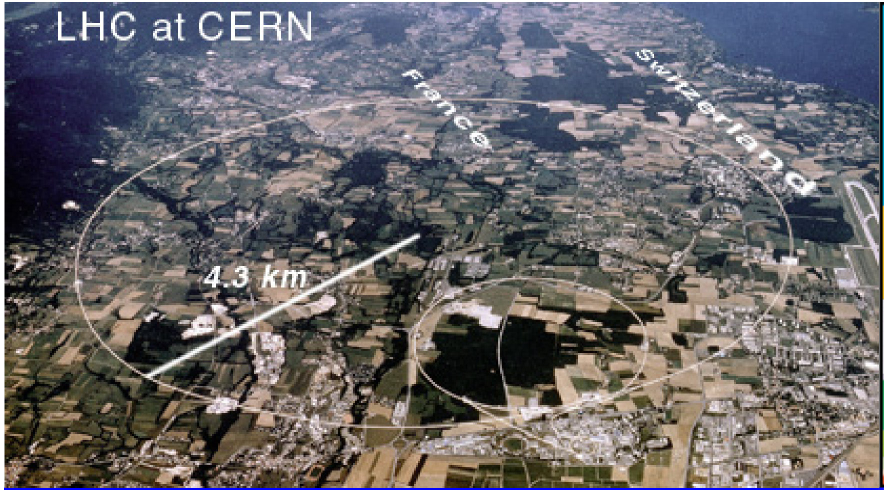

CMS
Compact Muon Solenoid

Latest CMS Higgs (125) results

on behalf of the CMS Collaboration

Guenakh Mitselmakher
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on behalf of the CMS Collaboration

20th Lomonosov Conference on Elementary Particle Physics 2021

Outline

Higgs boson mass is the only free parameter (assuming SM): I will show the CMS results of mass measurements

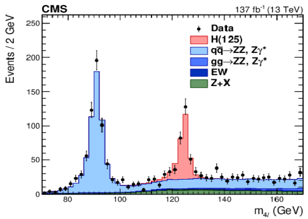
Look for deviations in H(125) boson properties from the SM predictions

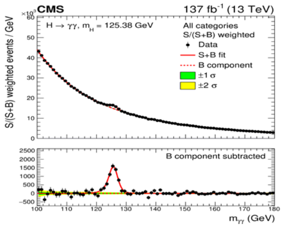
- Non-SM like structures in production and decay amplitudes: spin-parity, mixed states…
- Rates in different production and decay modes: test of couplings to SM particles
- Natural width: can provide an indirect sign for presence of abnormal decay modes

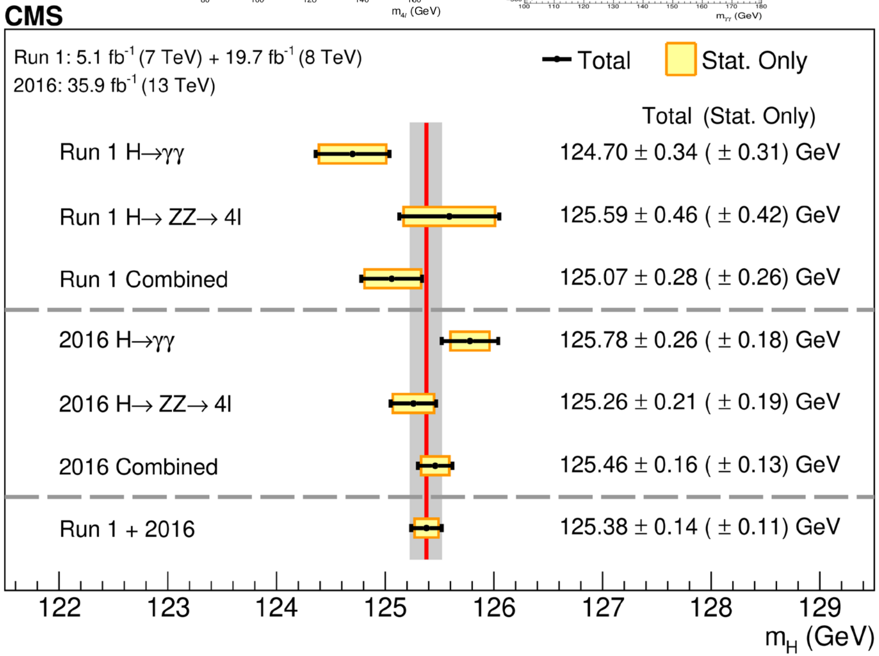
Look for abnormal wrt SM production and decay modes of H(125) boson

In a short talk, I will show only some selected (by me) results

Higgs boson mass







Higgs mass – the only free parameter in the Higgs sector (assuming SM)

all other parameters are set by the known masses of W and Z bosons, and fermions

Most precise mass measurements channels are:

$H \to ZZ \to 4\ell$ and $H \to \gamma\gamma$

statistical power is very similar

challenge in $H \to \gamma\gamma$: systematics ~ stat error

Run 1 + 2016 results: 15 Feb 2020, PLB 805 (2020) 135425

125.38 ± 0.14 GeV (~0.1% !)

Run 1 + Run 2:

expect precision better than 100 MeV

HL-LHC:

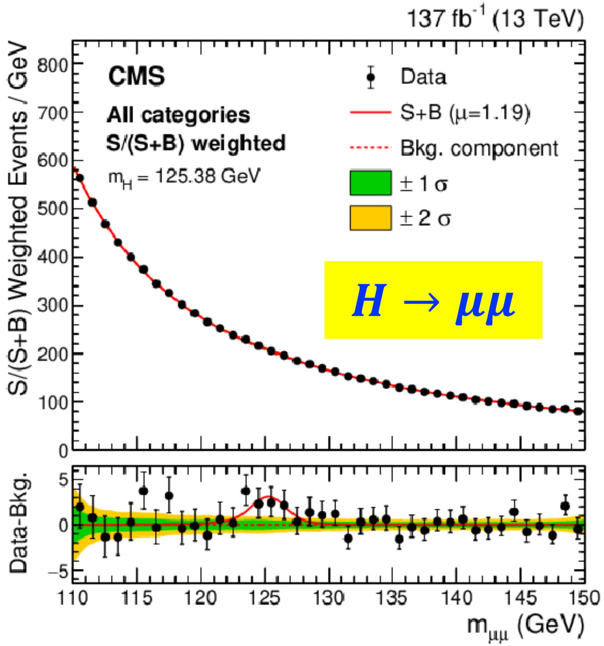
statistical uncertainty ~10 MeV

the challenge will be controlling syst. uncertainties

Looking for deviations in SM-like properties

Higgs decay modes in SM (green - established)

	bb	WW	ττ	cc	ZZ	γγ	Zγ	μμ	Remainder: gg, qq, ee
SM Higgs	58%	21%	6.3%	2.9%	2.6%	0.23%	0.15%	0.022%	9%



Latest updates for the well-established decays (>5σ):

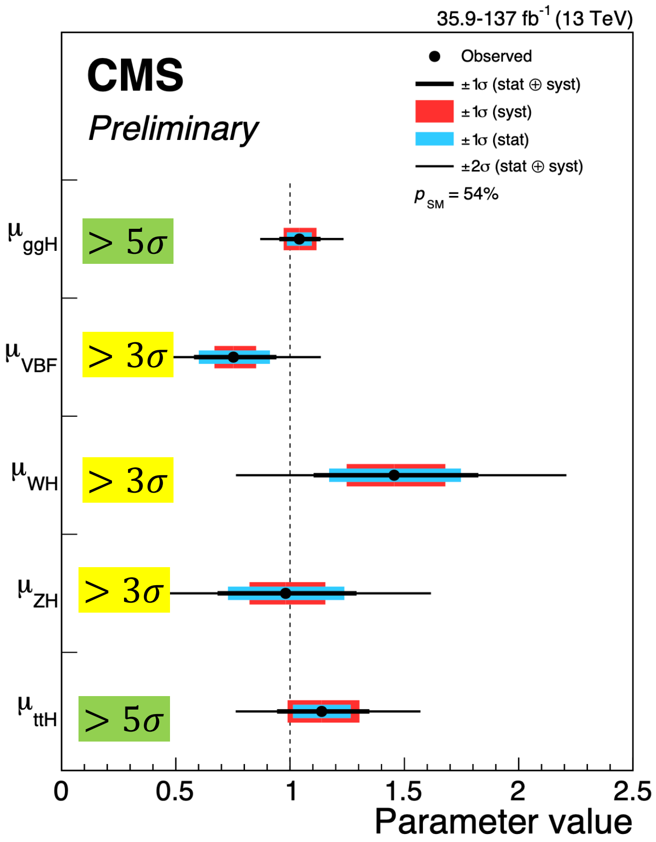
- $H \to \gamma\gamma$: $\mu = 1.12 \pm 0.09$ — 12 Mar 2021, arXiv:2103.06956 [Run 2]
- $H \to ZZ$: $\mu = 0.94 \pm 0.11$ — 8 Mar 2021, arXiv:2103.04956 [Run 2]
- $H \to WW$: $\mu_{\mathrm{fid}} = 1.05 \pm 0.12$ — 4 July 2020, JHEP 03 (2021) 003 [Run 2]
- $H \to \tau\tau$: $\mu = 0.85 \pm 0.12$ — 31 July 2020, HIG-19-010 [Run 2]
- $H \to bb$: $\mu = 1.04 \pm 0.20$ — PRL 121 (2018) 121801 [2016+2017 data]

Evidence for $H \to \mu\mu$ — 9 Sep 2020, JHEP 01 (2021) 148 [Run 2]

- Significance 3.0
- Signal strength $\mu = 1.19 \pm 0.42$

The observed decays comprise ~90% of the total Higgs width

Established production modes



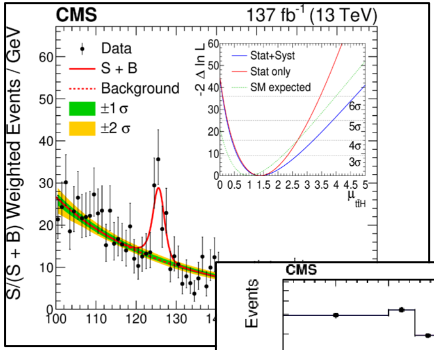
Intermediate Run 2 combination 9 Jan 2020, HIG-19-005 [mix]

- $H \to \gamma\gamma,\ H \to ZZ,\ H \to WW,\ H \to \tau\tau,\ H \to bb,\ H \to \mu\mu$
- $ttH\ (H \to WW/ZZ/\tau\tau) \to leptons$

$\boldsymbol{ttH, H \to \gamma\gamma}$

25 Mar 2020, PRL 125 (2020) 061801 [Run 2]

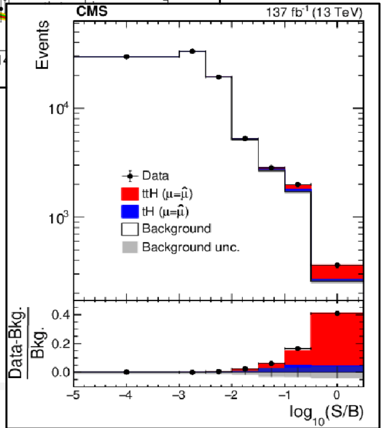
- Significance 6.6
- $\mu = 1.13 \pm 0.10$



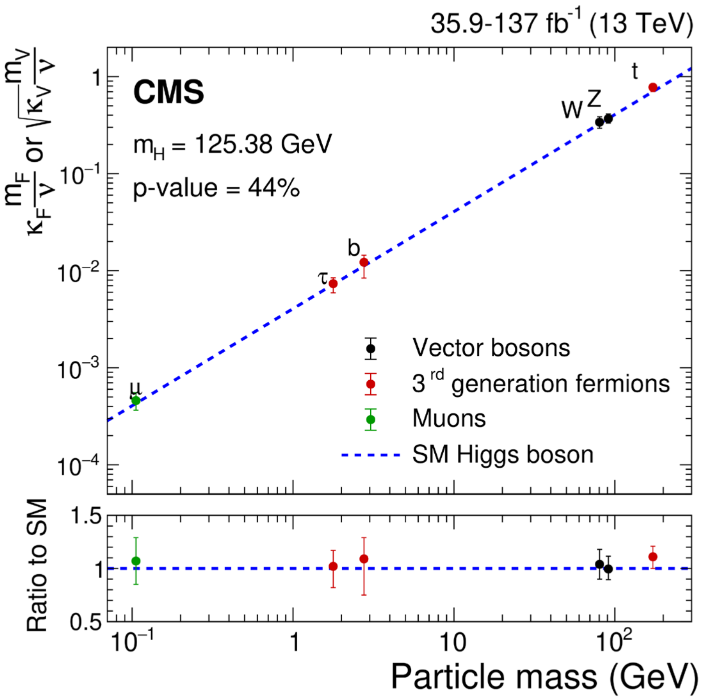
$\boldsymbol{ttH}, ttH\ (H \to WW/ZZ/\tau\tau) \to leptons$

7 Nov 2020, HIG-19-008 [Run 2]

- Significance 4.7
- $\mu = 0.92 \pm 0.24$



Fit for couplings modifiers



Event rate for $ii \to H \to ff$: $\sigma_i \mathcal{B}^f = \dfrac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$

Fit for six Higgs coupling modifiers: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$

Assuming:

- no "new physics" in loop-driven couplings ($H \to \gamma\gamma$, gg$\to H$)
- no BSM decays (invisible, not observed)
- couplings to the 1st/2nd–gen. quarks and electrons are SM-like (i.e., small and hence having a negligible effect on the fit)

Impressive agreement with SM over three orders of magnitude of couplings ! (note: ±5% for ttH coupling)

Are H125 quantum J^{CP} numbers 0^{++}, as predicted by the SM ?

INTRO: Higgs bosonic (V) coupling structure

General Lagrangian for HVV interactions up to dim-5 operators:

$$L = \boxed{-\frac{a_1}{2v} m_V^2 H V_\mu V^\mu} \boxed{-\frac{a_2}{2v} H F_{\mu\nu} F^{\mu\nu} - \frac{a_3}{2v} H F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{a_4}{2v} H V_\mu \Box V^\mu + \frac{a_5}{2v} \Box H\, V_\mu V^\mu}$$

SM dim-3 operator

In SM: $a_1 = 2$ for ZZ, WW

The term vanishes for $\gamma\gamma$

dim-5 operators: loop-induced (very small in SM) or, otherwise, non-renormalizable

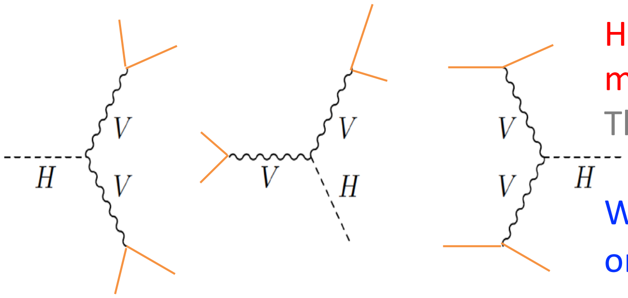
magenta factors with a_i/v are one of a conventions; they could've been written just as $1/\Lambda_i$

$\boldsymbol{a_2}$ term is CP-even. In SM, $\boldsymbol{a_2} \sim O(10^{-2})$ [it is actually the lowest-order term for $H \to \gamma\gamma$]

$\boldsymbol{a_3}$ term is **the CP-odd term**. In SM, $\boldsymbol{a_3} \sim O(10^{-11})$ [due to CP-violation in the quark sector]

$\boldsymbol{a_4}$ term is is yet another CP-even distinct operator. In SM, $\sim O(10^{-2})$

$\boldsymbol{a_5}$ term is experimentally indistinguishable from SM in on-shell studies (important for off-shell)



HVV couplings can be probed in **H→VV** decays and **VH** and **VBF** production modes: four-fermion kinematics is sensitive to the HVV coupling structure.

This technique was used to establish π^0 parity in 1962: $\pi^0 \to \gamma^*\gamma^* \to (ee)(ee)$

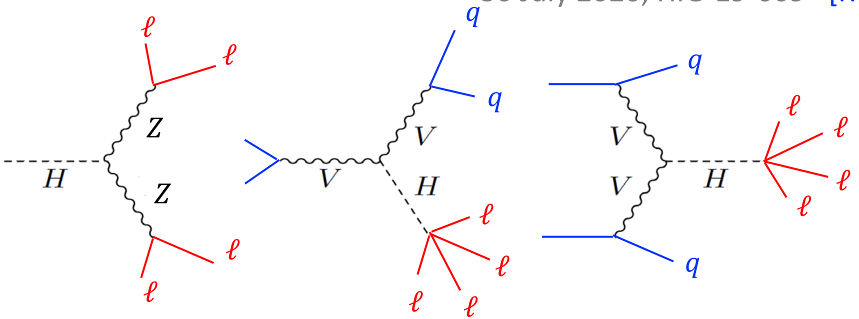
When combining, HZZ and HWW processes, one has to assume how a_i^{ZZ} and a_i^{WW} are related to each other

Higgs bosonic (V) coupling structure

30 July 2020, HIG-19-009 [Run 2]

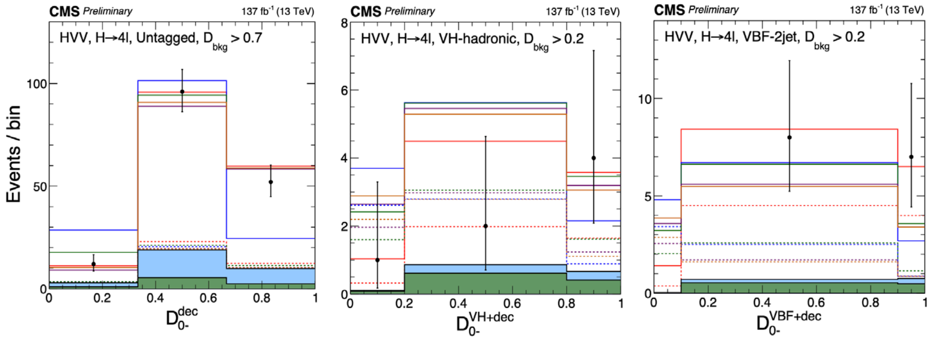
H→ZZ→4l

- On-shell analysis only
- WW and ZZ couplings a_i^{WW} and a_i^{ZZ} are related via custodial and SU(2)xSU(1) symmetries:
  - $a_1^{WW} = a_1^{ZZ}$
  - $a_2^{WW} = \cos^2\theta_W\, a_2^{ZZ} + \cdots\ (negligible)$
  - $a_3^{WW} = \cos^2\theta_W\, a_3^{ZZ} + \cdots\ (negligible)$
  - …
- Production modes: VBF tag, VH tag, untagged
- ME-based discriminants



– red line: SM 0^+

– blued line: 0^-



68% CL: $a_3^{ZZ}/a_1^{ZZ} = 0.018^{+0.066}_{-0.034}$

$a_2^{ZZ}/a_1^{ZZ} = -0.004^{+0.045}_{-0.058}$

Coupling ratios are extracted from ratios f_{a3} and f_{a2} (Approach 2), given in the paper

INTRO: Higgs fermionic (f) coupling structure

General lowest-dim Lagrangian for Higgs-fermion interactions:

$$L = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\tilde{k}_f\gamma_5\right)\psi_f H$$

κ_f term is CP-even

$\tilde{k}_f$ term is CP-odd

both are tree-level (**unlike HVV**)

Define mixing angle ϕ, where $\tan\phi = \frac{\tilde{k}_f}{\kappa_f}$

- pure CP-even state: $\phi = 0°$
- pure CP-odd state: $\phi = 90°$

SM: $\boldsymbol{\kappa_f = 1,\ \tilde{k}_f = 0;}$ **hence,** $\boldsymbol{\phi = 0}$

MSSM: $\phi \approx 0$

nMSSM: ϕ can be large, but $< 27°$ (due to existing experimental constraints)

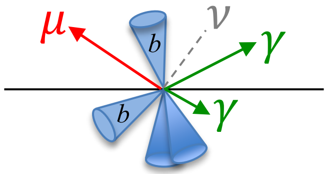
Higgs fermionic coupling structure: ttH

25 Mar 2020, PRL 125 (2020) 061801 [Run 2]

Final states used:

$pp \to ttH \to (jjb)(jjb)(\gamma\gamma)$ [all-hadronic]

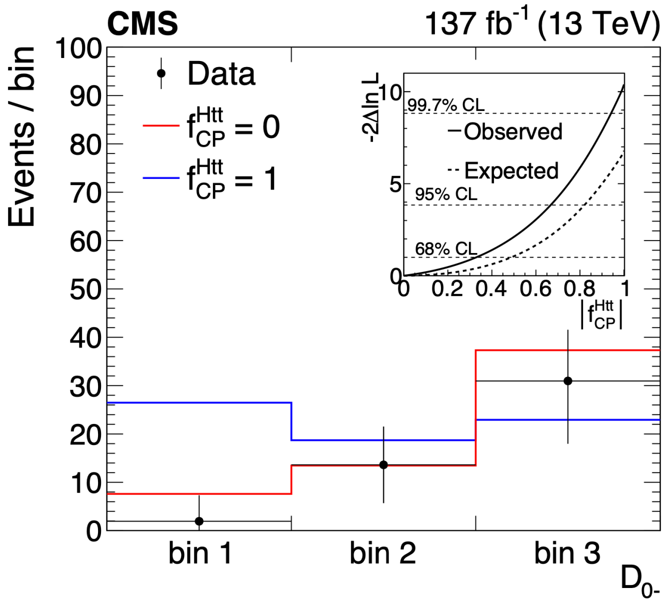
$pp \to ttH \to (l\nu b)(jjb)(\gamma\gamma)$ [semi-leptonic]



Building a ME-based discriminant that would account for a whole slew of jet mis-measurements (plus missing neutrino in semi-leptonic channel) is challenging…

Instead, a BDT-based discriminant (D_{0-}) is built using CP-even and CP-odd MC models, with the following inputs:

- kinematics of the first six jets (in pT) and their b-tag scores
- (φ, η)-direction of the diphoton system
- for semi-leptonic channel: lepton multiplicity, leading lepton kinematics



events are S/(S+B) weighted
background is subtracted
$|f_{CP}| = \sin^2\phi$

Pure CP-odd ttH coupling is disfavored at 3.2σ

68% CL: $|\phi| < 35°$

95% CL: $|\phi| < 55°$

Higgs fermionic coupling structure: $H\tau\tau$

30 July 2020, HIG-20-006 [Run 2]

Final states used: $\tau_\mu\tau_h$ and $\tau_h\tau_h$

$\tau_\mu \to \mu^\pm\nu\nu(17\%)$

$\tau_h \to \pi^\pm\nu\ (12\%)$

$\to \rho^\pm\nu \to \pi^\pm\pi^0\nu\ (26\%)$

$\to a_1^\pm\nu \to \pi^\pm\pi^0\pi^0\nu\ (10\%)$

$\to a_1^\pm\nu \to \pi^\pm\pi^\pm\pi^\mp\nu\ (10\%)$

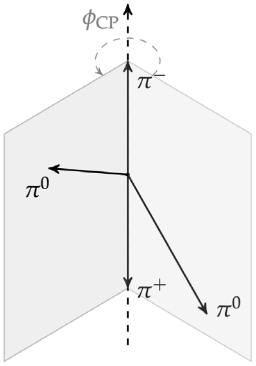
Signal (H) vs Bkg BDT enhances the signal VBF contribution with two forward-backward jets

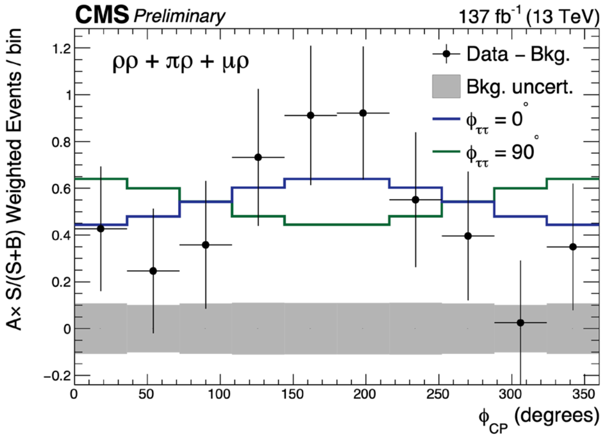
Building a ME-based discriminants that would account for jet mis-measurements and missing neutrinos is possible, but challenging…

Distributions of angles between planes set by observable particles from decaying tau leptons (ϕ_{CP}) are sensitive to CP-admixture phase ϕ

ϕ_{CP} angle for

$H \to \tau_h\tau_h \to (\rho^+\nu)(\rho^-\nu) \to \pi^+\pi^0\pi^-\pi^0\nu\ \nu$





Pure CP-odd ttH coupling is disfavored at 3.2σ

68% CL: $\phi = 4 \pm 17^\circ$

95% CL: $|\phi| < 36^\circ$

Higgs(125) width

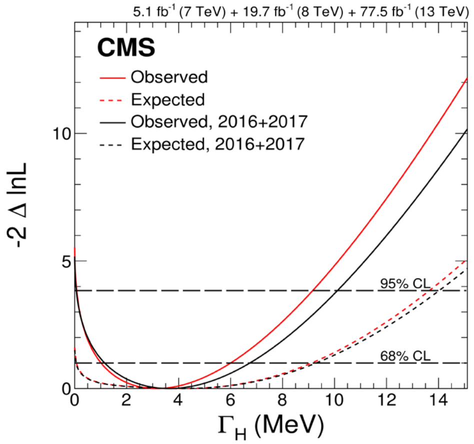
Most precise Higgs (125) width measurements (indirect)

1 Jan 2019, PRD 99 (2019) 112003 **[Run 1 + 2016 + 2017]**

From the ratio of off-shell to on-shell rates using $H \to ZZ \to 4\ell$

And assuming:

- SM-like amplitude structure for $H \to ZZ$
- No significant BSM physics in $gg \to H$ up to $m_{H*} \sim 1$ TeV



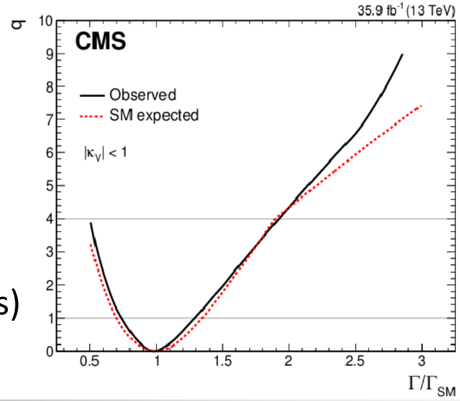
$$\Gamma_H = 3.2^{+2.8}_{-2.2} \text{ MeV}$$

25 Mar 2020, PRL 125 (2020) 061801 **[2016 dataset]**

From the combination of all on-shell decays

And assuming:

- SM-like amplitude structure for Higgs couplings
- $|\kappa_W|, |\kappa_Z| \leq 1$ (hard to build a theory violating these conditions)



$$\Gamma_H = 4.0\,^{+1.3}_{-1.0} \text{ MeV}$$

Non- SM decay/production modes of the H125 boson

Search for Charged Lepton Flavor Violation in decays: $H \to \mu\tau$, $H \to e\tau$

17 Mar 2021, HIG-20-009 [Run 2]

Channels used:

- $\mu\tau_h$, $\mu\tau_e$
- $e\tau_h$, $e\tau_\mu$

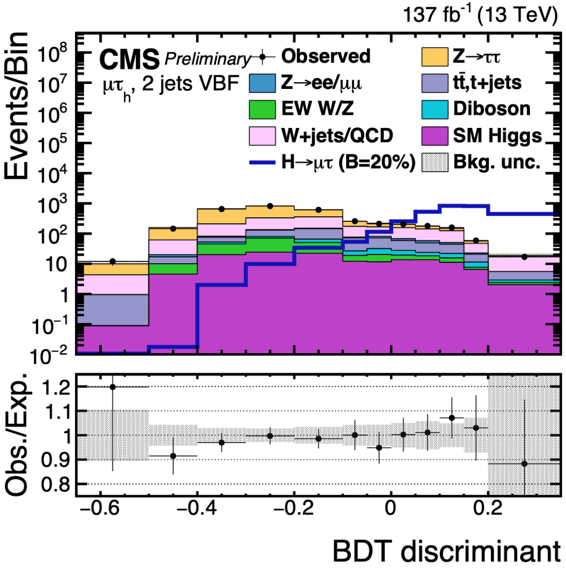
Very similar to the "nominal" $H \to \tau\tau$ analysis, except that $\boldsymbol{\mu}$ and **e**

- *are prompt*
- *tend to have larger momenta*

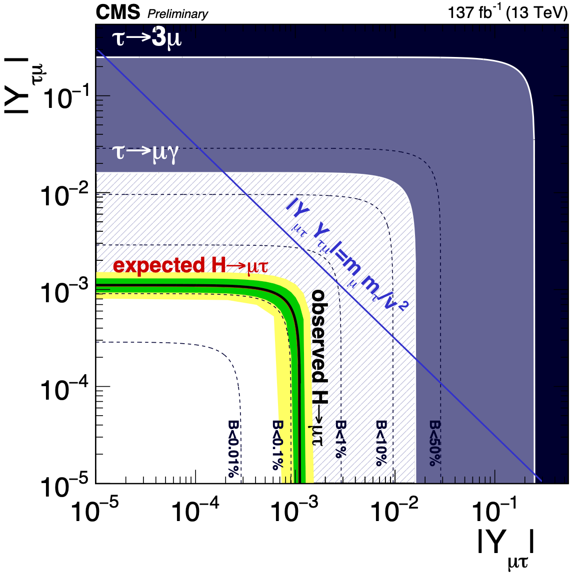
BDT is used to separate signal from non-Higgs bkg and $H \to \tau\tau$

$B(H \to \mu\tau) < 0.15\%$

$B(H \to e\tau) < 0.22\%$



most sensitive final state in $H \to \mu\tau$ search: $\mu\tau_h$ + 2-jet VBF tag

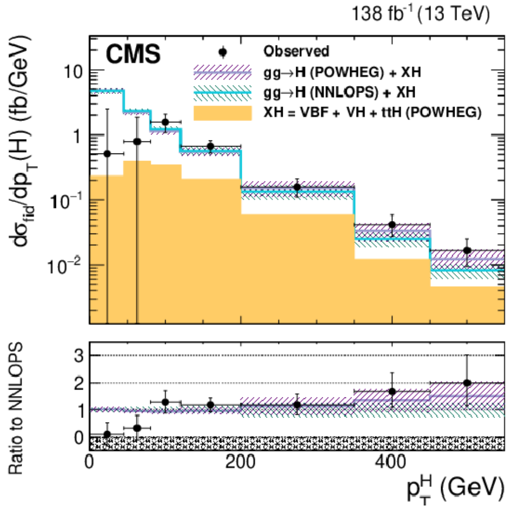


Limits on off-diagonal Yukawa couplings $Y_{\mu\tau}$

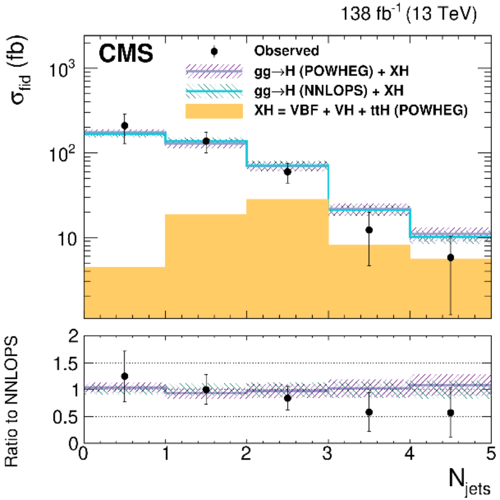
Higgs production cross-section with decays $H \rightarrow \tau\tau$

23 Jul 2021 arXiv:2107.11486 Sub to PRL

Cross sections of the Higgs boson production have been measured in the Higgs decay channel of two τ leptons. Fiducial inclusive cross section is 426 ± 102 fb, in agreement with the standard-model. Differential cross sections as functions of the Higgs boson transverse momentum, the jet multiplicity, and transverse momentum of the leading jet, are in agreement with the SM expectations, with a competitive precision with other final states.



Observed and expected differential fiducial cross section in bins of p_T^H



Observed and expected differential fiducial cross section in bins of N_{jets}

Summary

- the H125 Higgs looks more and more SM-like
  - keep looking for small deviations
  - some measurements already challenge the accuracy of theoretical predictions

Full-Run2 analyses are still to come – stay tuned

Run 3 (2022-2024) – expect to triplicate the integrated luminosity
and CMS is being made an even more capable detector!

More Higgs analyses will be at presently constructed HL LHC (High Luminosity LHC) - new accelerator at CERN.

BACKUP SLIDES