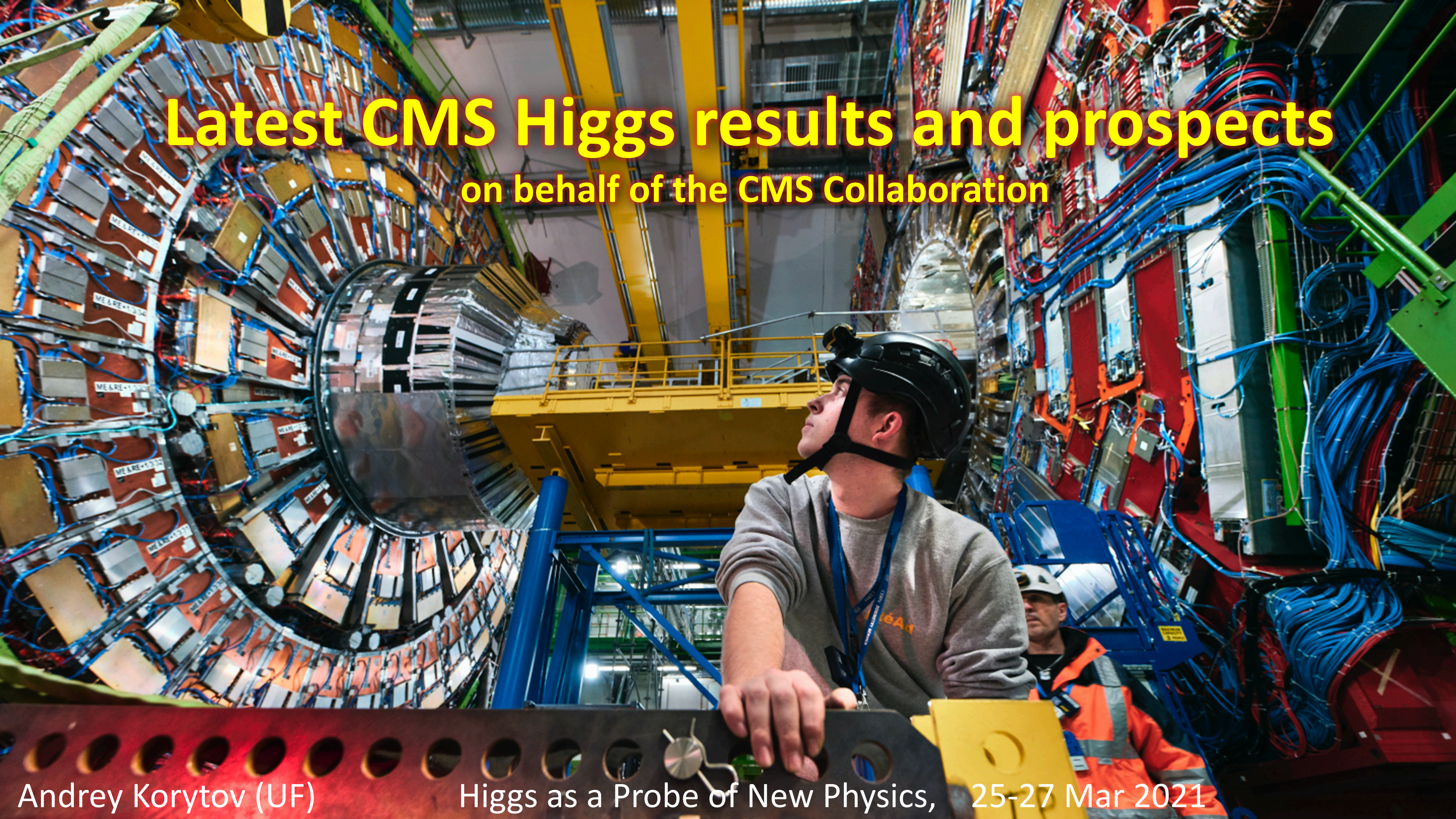
Latest CMS Higgs results and prospects

on behalf of the CMS Collaboration



Andrey Korytov (UF)

Higgs as a Probe of New Physics, 25-27 Mar 2021

Outline

Higgs boson mass – the only free parameter (assuming SM): measure it

Look for deviations in H125 boson properties from the SM predictions

- Non-SM like structures in production and decay amplitudes: spin-parity, mixed states, compositeness
- 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 explicitly abnormal production and decay modes of H125 boson

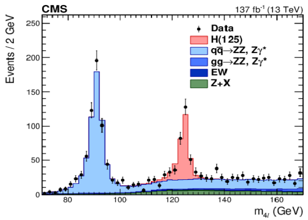
- Decays: H → $\ell\ell'$ (CLFV), H → XX, H→invisible
- Production: t → cH (FCNC), HH (at abnormal rate, resonant or not)

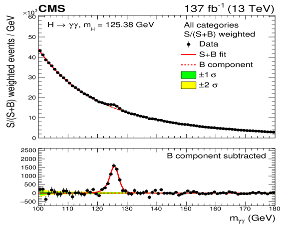
Look for other scalars (inspired by various models with extended scalar sectors)

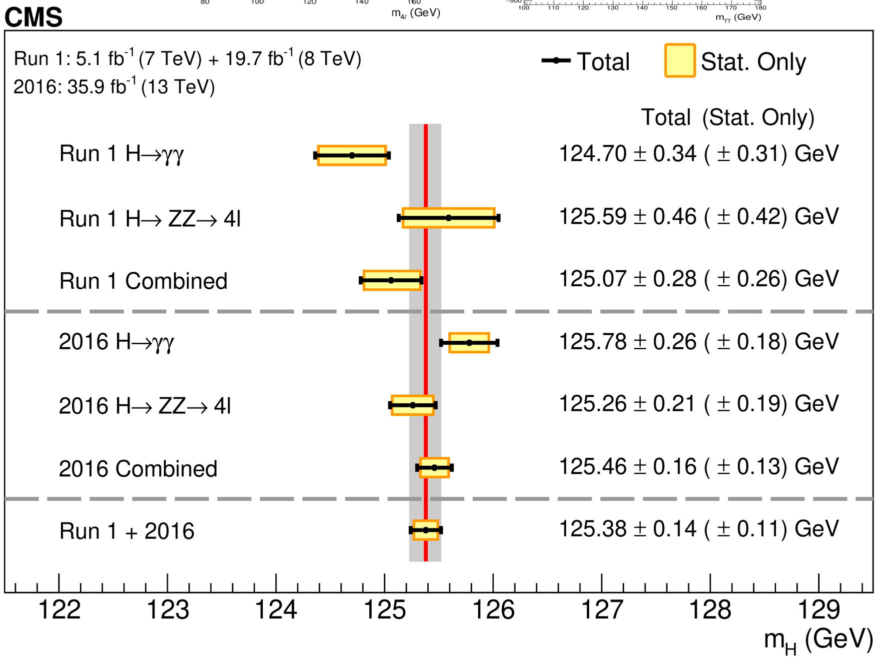
- SM + Real Singlet: H125, H
- SM + HD (2HDM, including MSSM): H125, H, A, $H^{\pm}$
- SM + HD + Complex Singlet (nMSSM): H125, H, A, $H^{\pm}$, h, $\boldsymbol{a}$
- SM + Triplet: H125, H, A, $H^{\pm}$, $H^{\pm\pm}$

In a 20-min talk, I have no choice but show only a few hand-picked 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

Workhorse channels are:

H → ZZ → 4ℓ and H→ $\gamma\gamma$

Statistical power is very similar

Emerging challenge in H→ $\gamma\gamma$: systematics ~ stat error

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

125.38 ± 0.14 GeV ($\sim$0.1% !)

Run 1 + Run 2:

expect precision better than 100 MeV

HL-LHC:

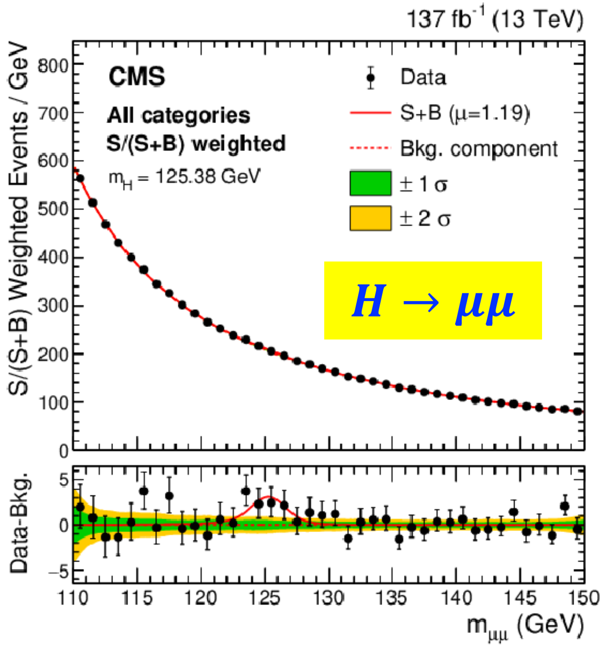
Statistical uncertainty ~10 MeV

The game will be all about controlling syst. uncertainties

Looking for deviations in SM-like properties

Established decay modes

	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):

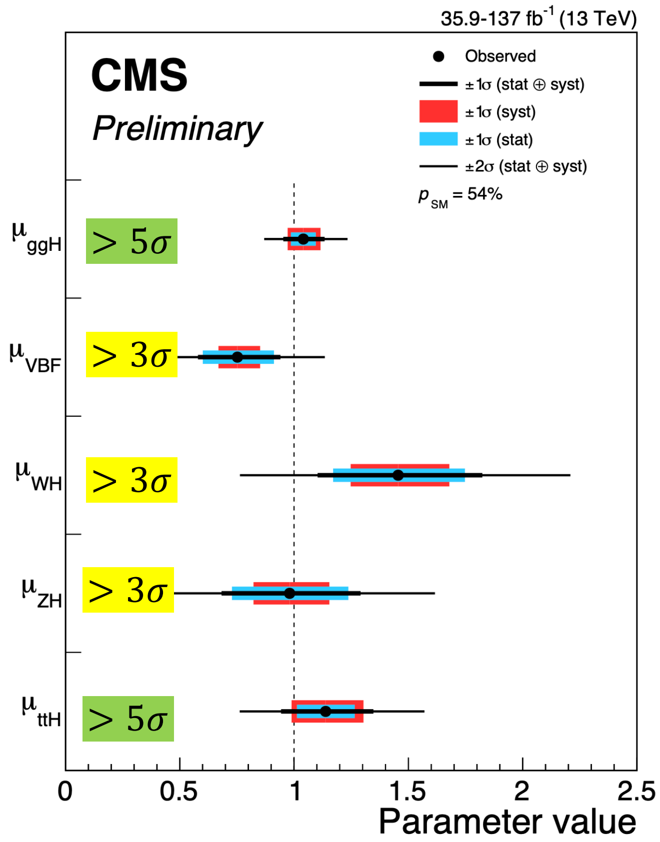
- $H \to \gamma\gamma$: $\mu = 1.12 \pm 0.09$ — 12 Mar 2021, arXiv:2103.06956 [Run 2]
- $H \to ZZ$: $\mu = 0.94 \pm 0.11$ — 8 Mar 2021, arXiv:2103.04956 [Run 2]
- $H \to WW$: $\mu_{\text{fid}} = 1.05 \pm 0.12$ — 4 July 2020, JHEP 03 (2021) 003 [Run 2]
- $H \to \tau\tau$: $\mu = 0.85 \pm 0.12$ — 31 July 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



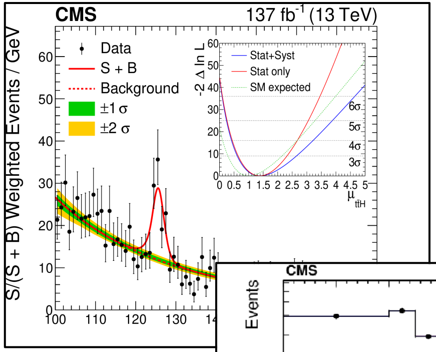
Intermediate Run 2 combination 9 Jan 2020, HIG-19-005 [mix]

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

$ttH, H \to \gamma\gamma$

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

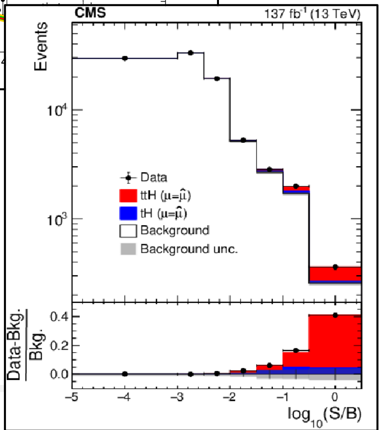
- Significance 6.6
- $\mu = 1.13 \pm 0.10$



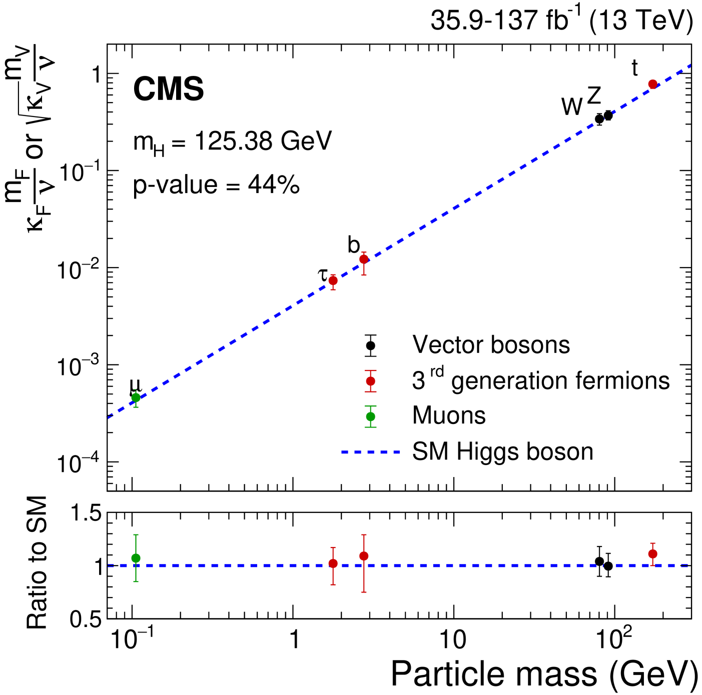
$ttH, ttH\ (H \to WW/ZZ/\tau\tau) \to leptons$

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

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



Fit for couplings modifiers



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

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's 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:

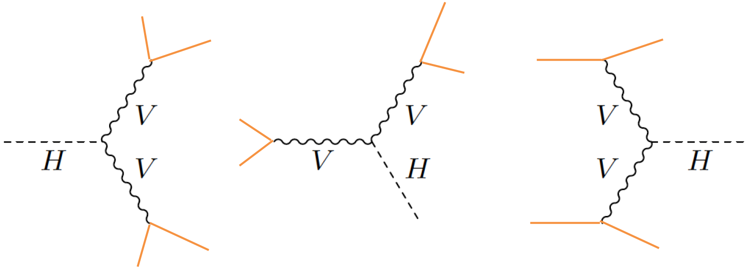
$$L = -\frac{a_1}{2v} m_V^2 H V_\mu V^\mu - \frac{a_2}{2v} H F_{\mu\nu} F^{\mu\nu} - \frac{a_3}{2v} H F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{a_4}{2v} H V_\mu \Box V^\mu + \frac{a_5}{2v} \Box H \, V_\mu V^\mu$$

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 $1/\Lambda_i$

The $\boldsymbol{a_2}$ term is CP-even. In SM, $\boldsymbol{a_2} \sim O(10^{-2})$ [it is actually the lowest-order term for $H \to \gamma\gamma$]
The $\boldsymbol{a_3}$ term is **the CP-odd term**. In SM, $\boldsymbol{a_3} \sim O(10^{-11})$ [arises due to CP-violation in the quark sector]
The $\boldsymbol{a_4}$ term is is yet another CP-even distinct operator. In SM, $\sim O(10^{-2})$
The $\boldsymbol{a_5}$ 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: $\pi^0 \to \gamma^*\gamma^* \to (ee)(ee)$

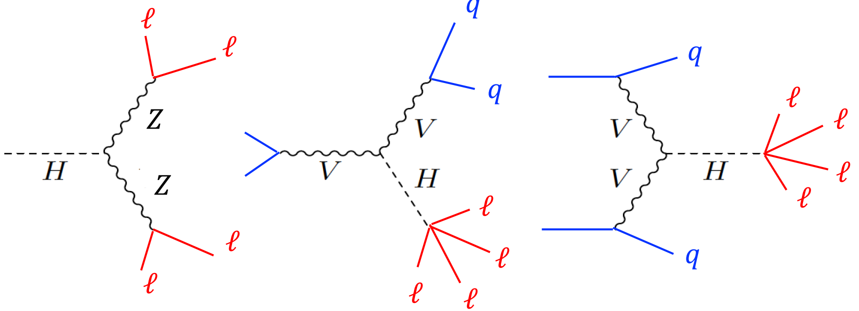
When combining, HZZ and HWW processes,
one has to assume how a_i^{ZZ} and a_i^{WW} are related to each other

Higgs bosonic (V) coupling structure

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

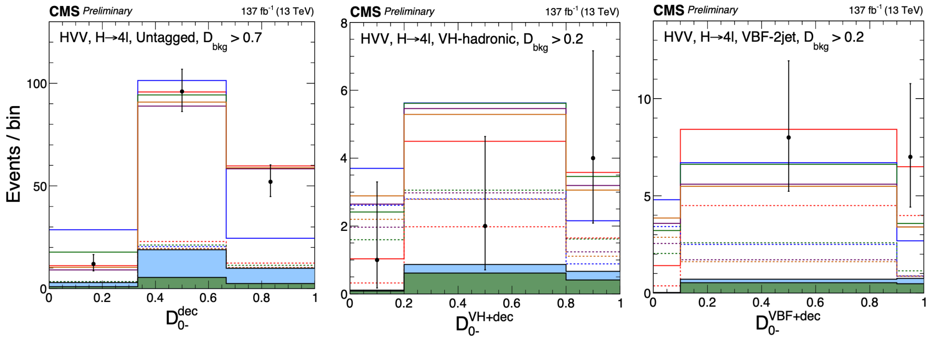
H→ZZ→4l

- 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:

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

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)

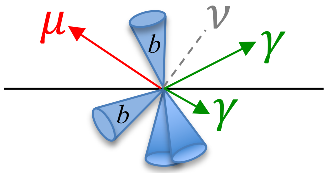
Higgs fermionic coupling structure: ttH

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

Final states used:

$pp \to tt\boldsymbol{H} \to (jjb)(jjb)(\gamma\gamma)$ [all-hadronic]

$pp \to tt\boldsymbol{H} \to (l\nu b)(jjb)(\gamma\gamma)$ [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…

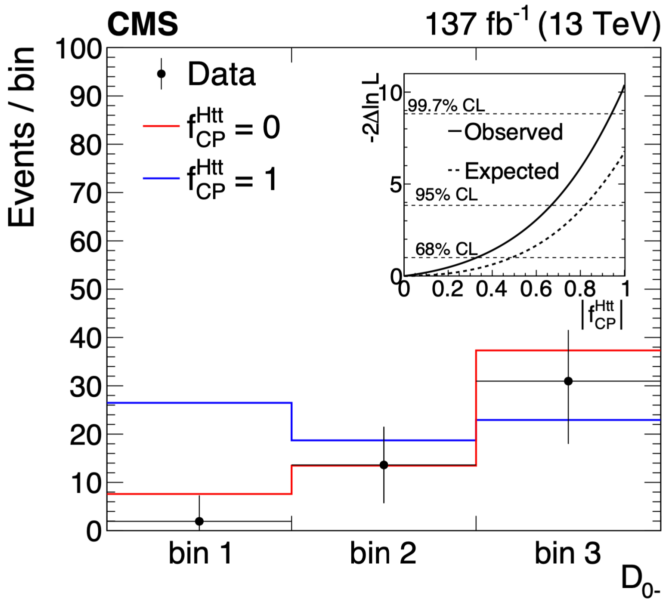
Instead, a BDT-based discriminant (D_{0-}) is built using CP-even and CP-odd MC models, with the following inputs:

- 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

Pure CP-odd ttH coupling is disfavored at 3.2σ

68% CL: $|\phi| < 35°$

95% CL: $|\phi| < 55°$



events are S/(S+B) weighted

background is subtracted

$|f_{CP}| = \sin^2\phi$

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

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

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

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

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

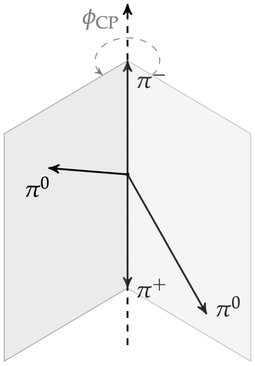
$\to \rho^\pm \nu \to \pi^\pm \pi^0 \nu\ (26\%)$

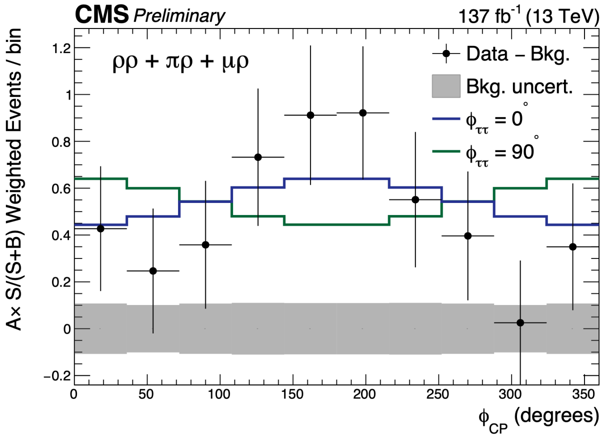
$\to a_1^\pm \nu \to \pi^\pm \pi^0 \pi^0 \nu\ (10\%)$

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

ϕ_{CP} angle for

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





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

Pure CP-odd ttH coupling is disfavored at 3.2σ

68% CL: $\phi = 4 \pm 17°$

95% CL: $|\phi| < 36°$

What about width?

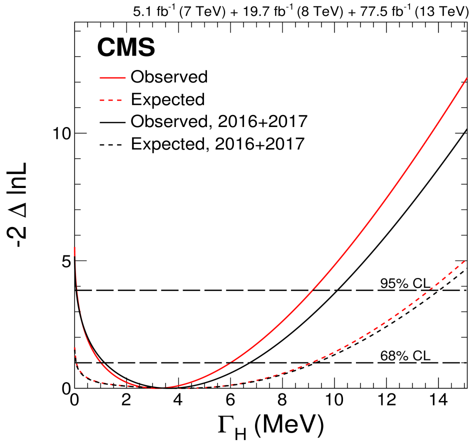
Natural width

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

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

And assuming:

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



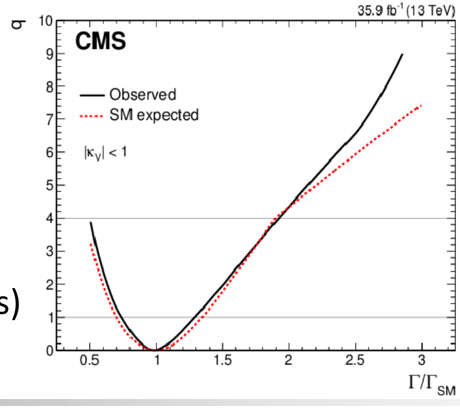
$$\Gamma_H = 3.2^{+2.8}_{-2.2}\ \text{MeV}$$

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)



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

Looking for explicitly abnormal decay/production modes of the H125 boson

Search for CLFV decays: $\mathrm{H} \to \mu\tau, \mathrm{H} \to e\tau$

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

Channels used:

- $\mu\tau_{\mathrm{h}}, \mu\tau_{e}$
- $e\tau_{\mathrm{h}}, e\tau_{\mu}$

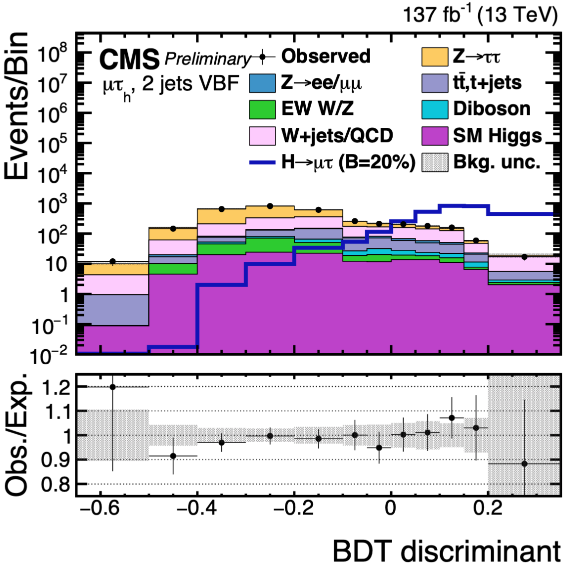
Very similar to the “nominal” $\mathrm{H} \to \tau\tau$ analysis, except that μ and **e**

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

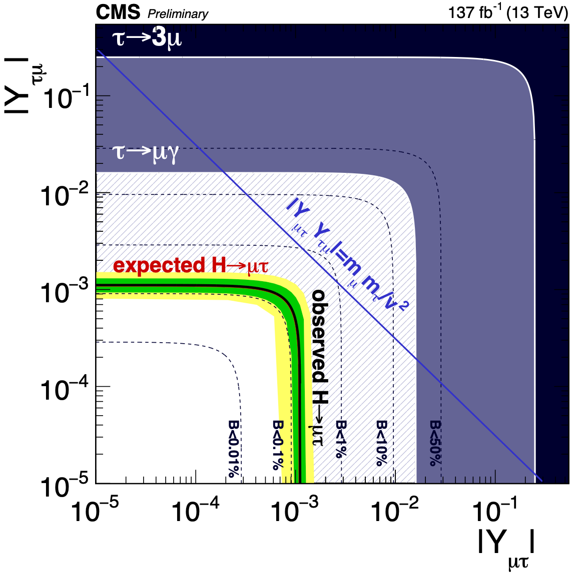
BDT is used to separate signal from non-Higgs bkg and $\mathrm{H} \to \tau\tau$

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

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



most sensitive final state in $\mathrm{H} \to \mu\tau$ search: $\mu\tau_{\mathrm{h}}$ + 2-jet VBF tag



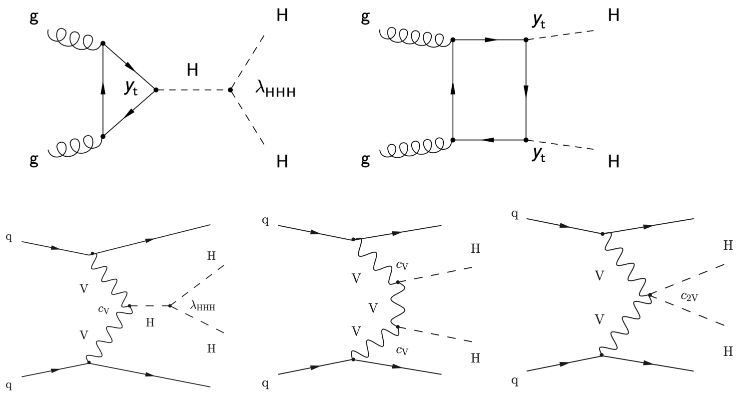
Limits on off-diagonal Yukawa couplings $Y_{\mu\tau}$

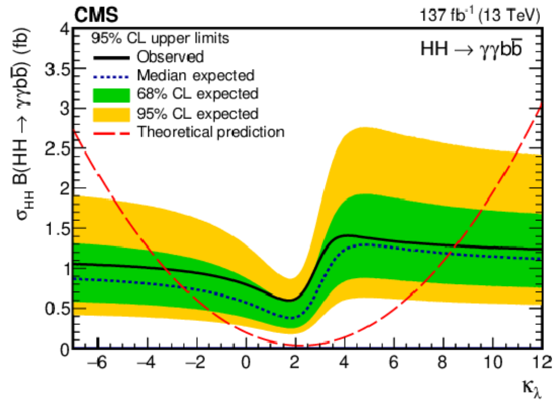
Search for HH production (non-resonant)

24 Nov 2020, HIG-19-018 [Run 2]

Search strategy:

- "choose" Higgs decays:
  - H→ $\gamma\gamma$: two photons
  - H→ bb: two jets (with b-tags)
- Categories: untagged and VBF-tagged
- Fit for a 2D-bump in $(m_{\gamma\gamma}, m_{bb})$ at (m_H, m_H)
  - non-Higgs bkg is constrained from sidebands
  - single-Higgs bkg (1D ridges) is derived from simulation





At 95% CL,

HH signal strength:	$\mu < 7.7$ (expected 5.2)
HHH coupling:	$\kappa_\lambda \subset$ **[−3.3, 8.5]**
HHVV coupling:	$c_{2V} \subset$ **[−1.3, 3.5]**

Looking for other scalars

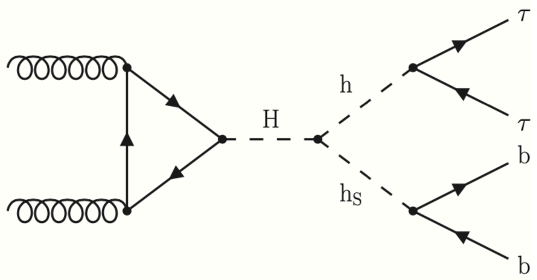
Search for H → H(125) h

20 Mar 2021, HIG-20-014 [Run 2]

Motivated by nMSSM,
in which there are 3 CP-even higgs bosons

If h is predominantly associated with the singlet filed, its coupling to SM particles are strongly suppressed; and so is its direct production. Then, H→ H(125) h becomes the dominant mechanism for h production.

No signal observed
- Limits on $\sigma\times\mathcal{B}$ as a function of m_H and m_h
- Limits on (m_H; m_h) with all other nMSSM parameters set to maximize $\sigma\times\mathcal{B}$

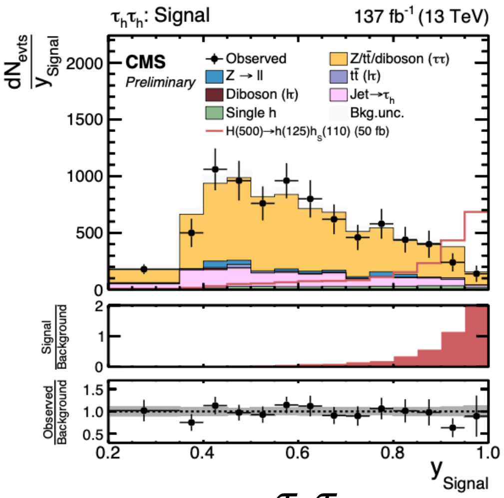


Search strategy:

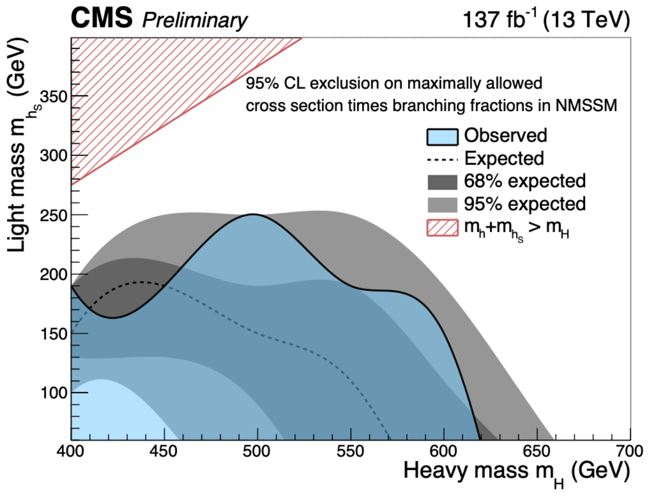
$H(125) \rightarrow \tau\tau$ $(e\tau_h,\ \mu\tau_h, \tau_h\tau_h)$

$h \rightarrow bb$

NN classifiers for different m_H and m_h



$\tau_h\tau_h$

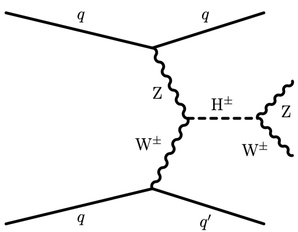


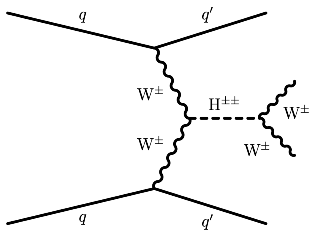
Search for $H^{\pm}$ and $H^{\pm\pm}$ in VBF production

20 Mar 2021, HIG-20-017 [Run 2]

SM Higgs Doublet + Higgs Triplet:

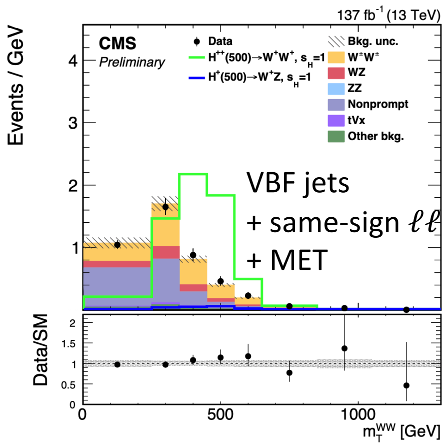
– additional H, A, $H^{\pm}$, $H^{\pm\pm}$
– W and Z masses are generated by both HD and HT vevs (s_H=1 implies W mass is fully associated with HT)
– couplings of $H^{\pm}WZ$, $H^{\pm\pm}WW$ are defined by s_H

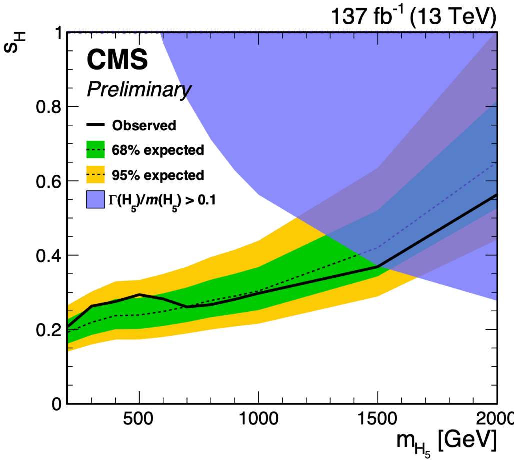




Analysis:

- Two-jet VBF tag
- Leptonic decays of W and Z
- MET
- Transvers mass m_T^{VV} – main discriminant (also m_{jj})





No signal is observed

- Set limits on $\sigma\times\mathcal{B}$ as a function of M
- Constrain (M; s_H) parameter phase space

Summary

Full Run 2 results continue to come

- the H125 Higgs looks more and more SM-like
  - keep looking for small deviations (discovery of CP-violation in the K system is a lesson!)
  - many measurements already challenge the accuracy of theoretical predictions)
- search for explicitly abnormal decays and production modes – null results so far
- search additional scalars – null results so far

Many more full-Run2 analyses are still to come (including ATLAS+CMS combinations) – stay tuned

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

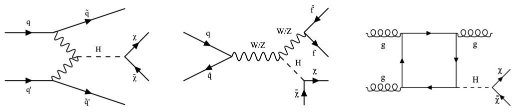
Backup

Search for H125 → invisible

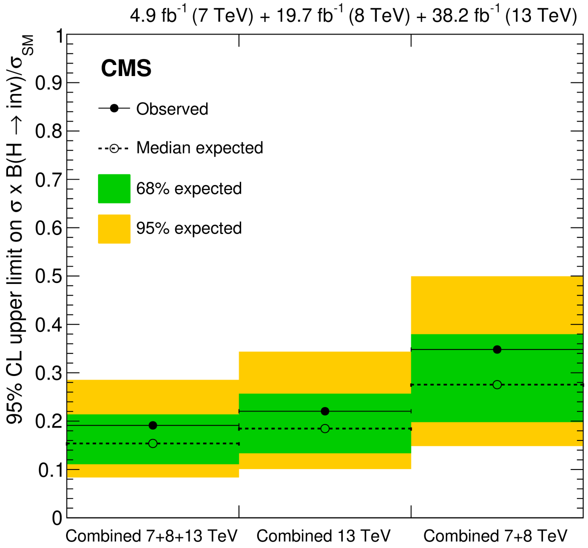
16 Sep 2018, PLB 793 (2019) 520 [Run 1 + 2016]

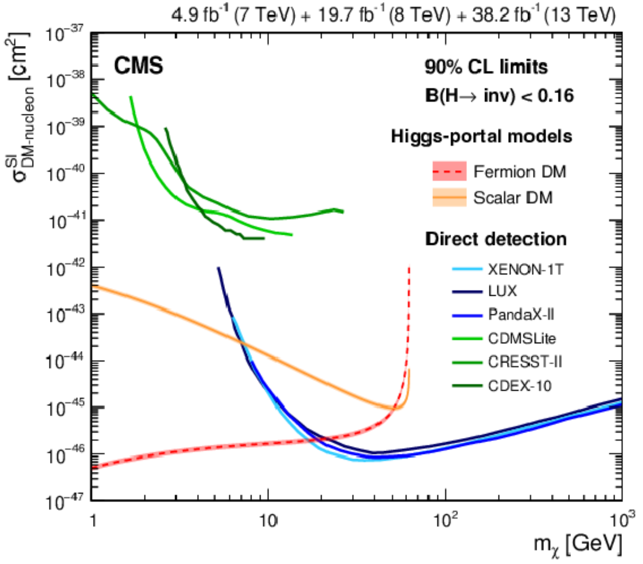
Production tag modes:

- VBF
- VH (both leptonic/hadronic)
- monojet



B(H→inv) < 0.19 at 95% CL





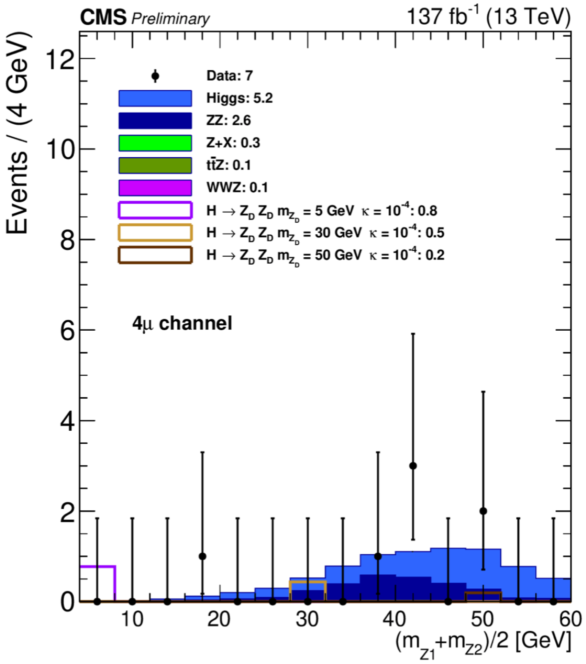
reinterpretation:

$B(H \to \chi\chi) \Rightarrow \chi$-nucleon σ

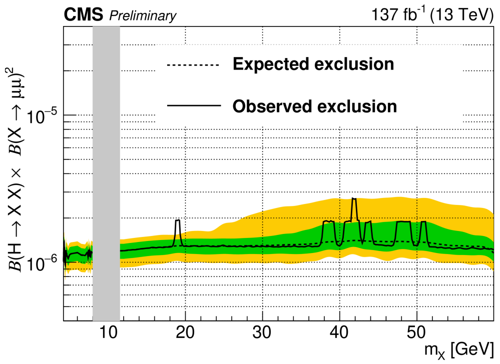
Search for H125 → ZX or $XX \to (\ell\ell)(\ell\ell)$

May 2020, HIG-19-007 [Run 2]

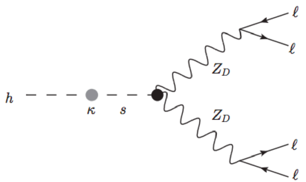
- **Search for low-mass dilepton resonances in H125 decays**

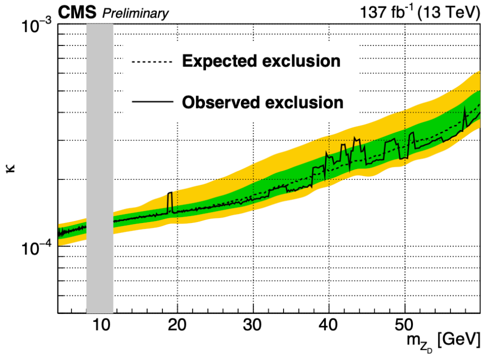


model independent limits on $\sigma \times \mathcal{B}$



Limits on model parameters

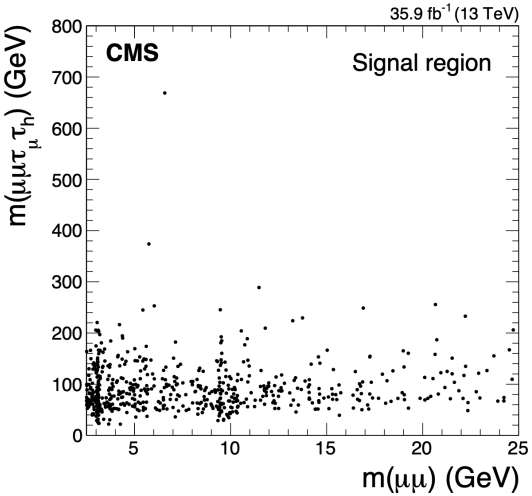


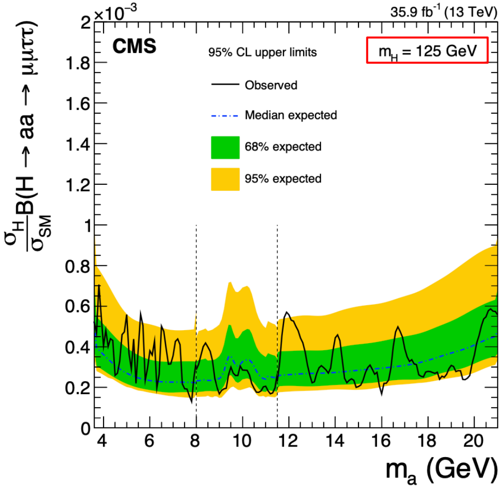


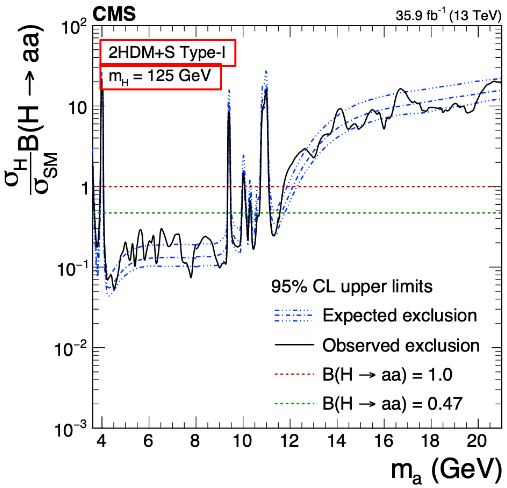
Search for $H \rightarrow aa \rightarrow (\mu\mu)(\tau\tau)$

18 May 2020, JHEP 08 (2020) 139 [Run 1 + 2016]

H does not have to be H125







B($a \rightarrow \mu\mu$) and B($a \rightarrow \tau\tau$) are model driven