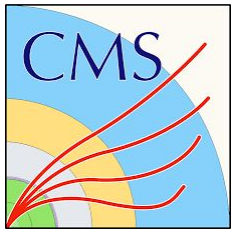


Higgs measurements from CMS

Nicolò Trevisani
KIT - Karlsruhe Institute of Technology

Discrete2022: 8th Symposium on Prospects in the Physics of Discrete Symmetries
7-11 Nov 2022, Baden-Baden (Germany)

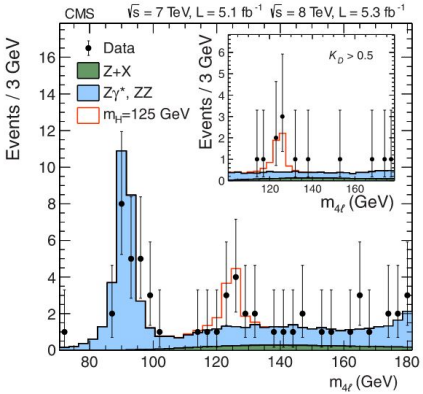
The Higgs Boson Turns 10

About 7.7 millions Higgs bosons produced during Run 2

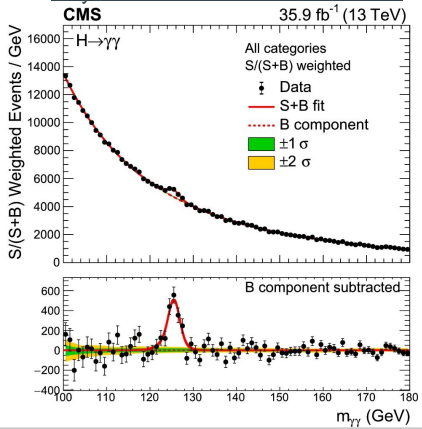
Enough data for precision measurements and search for rare decays:

- Main production modes and decay channels studied in detail
  - Decays to bosons and third-generation fermions
  - Fiducial, differential measurements, and STXS
- Rare final states now accessible (e.g., $H \rightarrow Z\gamma$)
- Going beyond mass and cross-section measurements
  - Couplings to muons and charm quarks
  - CP properties
- Double Higgs production
  - Key to study self-coupling and the structure of the scalar Higgs field potential

Phys. Lett. B 716 (2012) 30



Phys. Lett. B 805 (2020) 135425

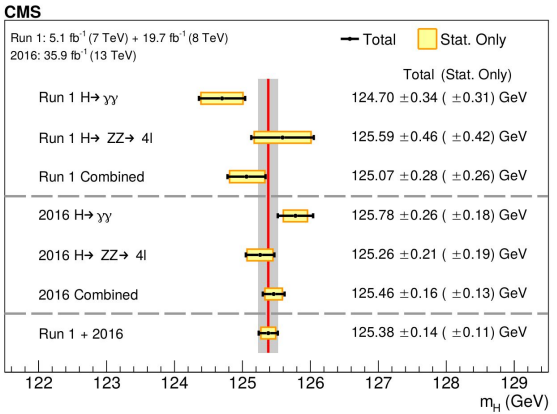


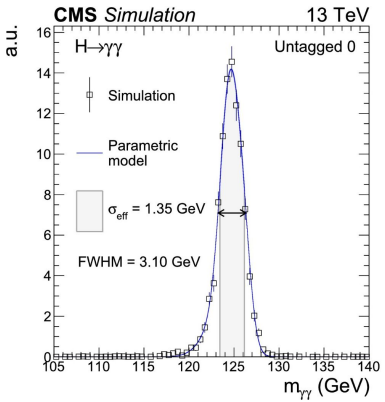
Higgs Mass

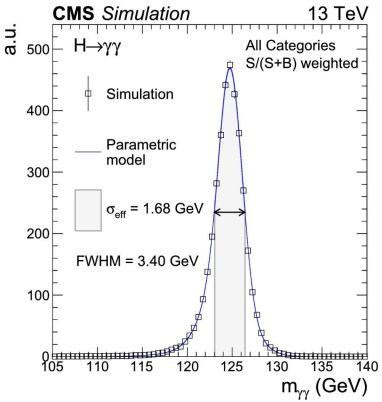
10.1016/j.physletb.2020.135425

Only Higgs free parameter, fixes all other properties

- Measured using the golden channels
  - They provide the best resolution
  - Good signal to background ratio
- Energy and momentum calibrations are key
  - Detector calibration and alignment
  - Constraints to Z mass
- Combination of H → ZZ and H → γγ results using Run 1 and 2016 data
  - 125.38 ± 0.14 GeV
  - Most precise result so far (0.11% uncertainty)



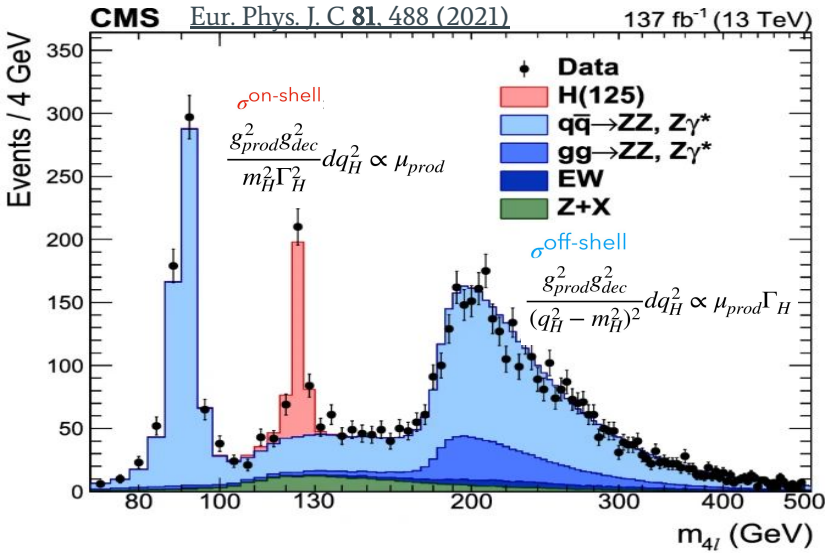




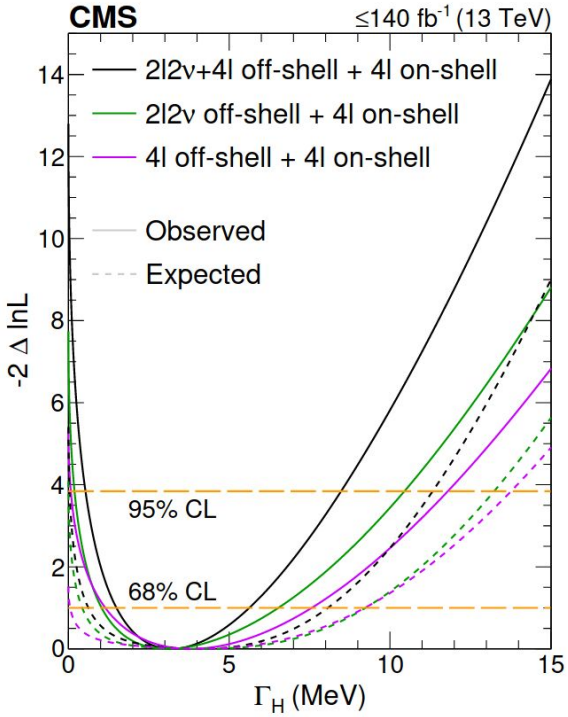
Higgs Width

Full Run 2 results:

- Evidence for off-shell production (3.6 σ)
- Ratio of off-shell and on-shell events sensitive to $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV



arXiv:2202.06923

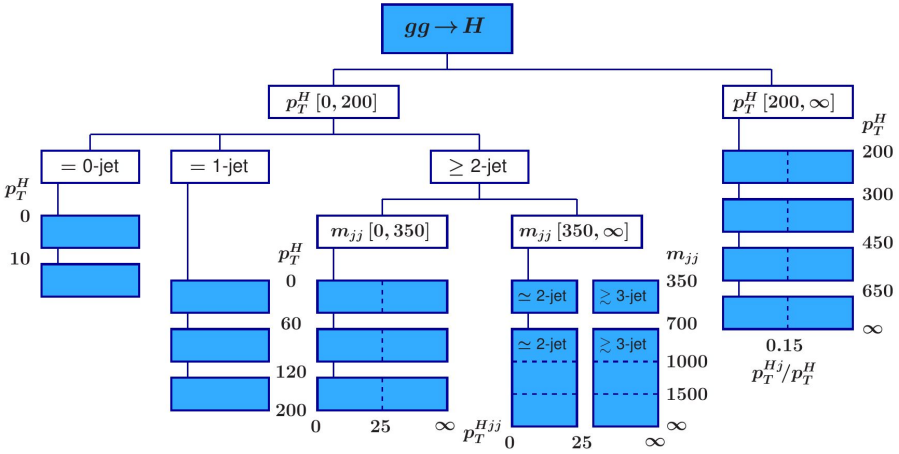


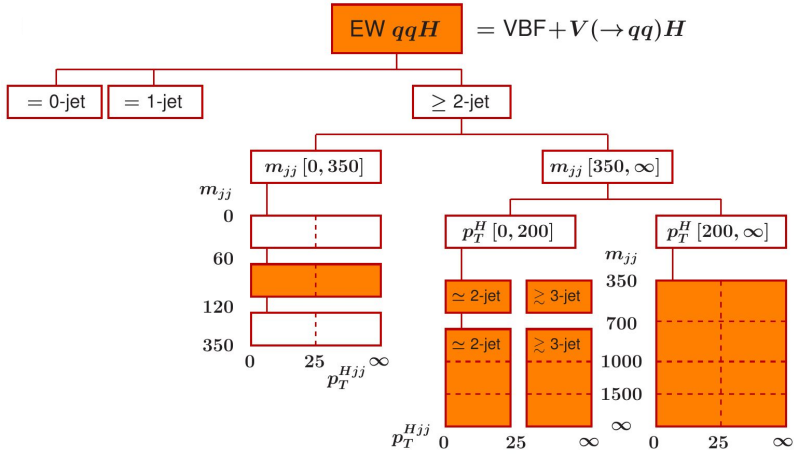
Simplified Template Cross-Section (STXS)

Main goals of the STXS framework:

- Increase the re-interpretability of the precision H boson measurements
- Minimize the theory dependence

This is achieved by defining exclusive kinematic regions in the H boson production phase space



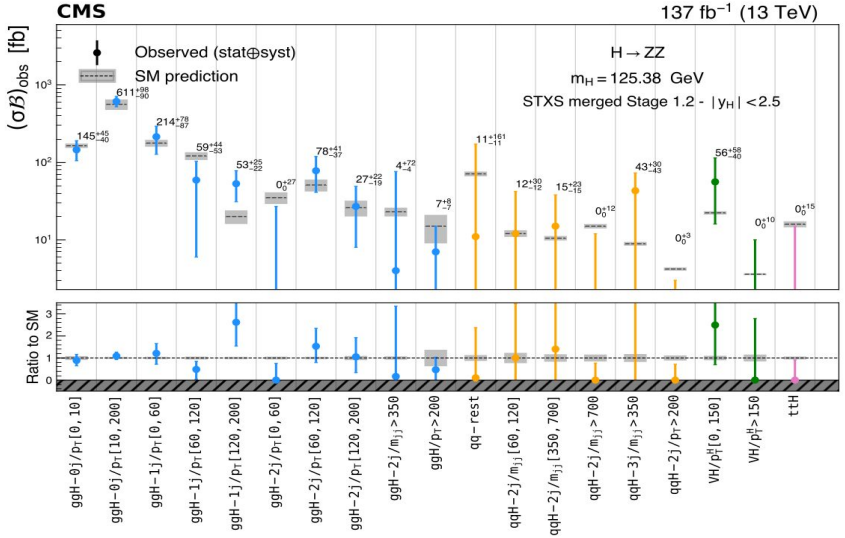


Simplified Template Cross-Section (STXS)

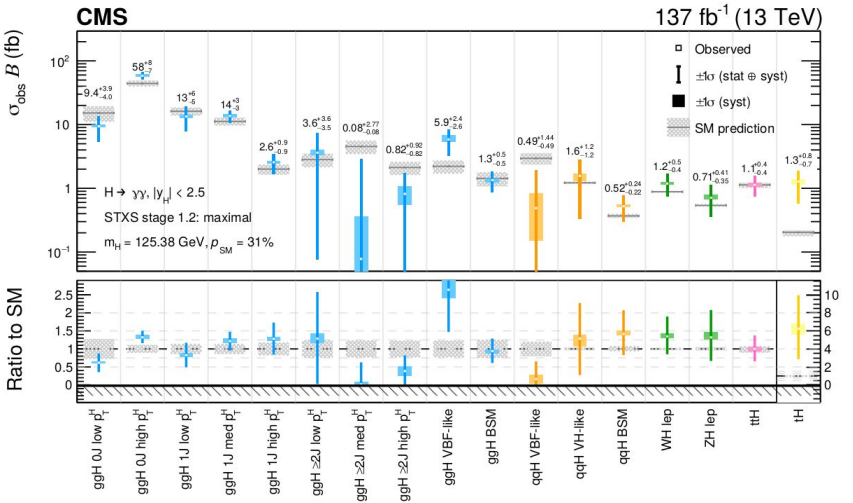
Fine binning, allowing measurement of many production modes:

- ggH, VBF, VH, ttH, tH

Eur. Phys. J. C 81 (2021) 488



JHEP07 (2021) 027



Higgs Rare Decays: H → Zγ

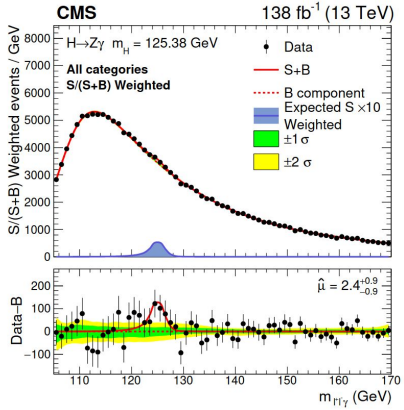
Sensitive to new physics:

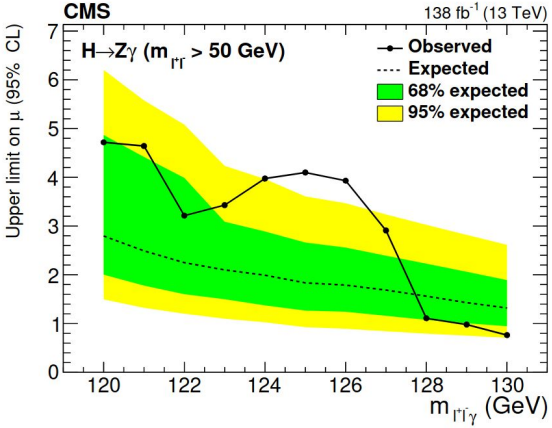
- B(H→Zγ) / B(H→γγ)
- Leading-order diagrams contain loops
- Anomalous trilinear Higgs self-coupling

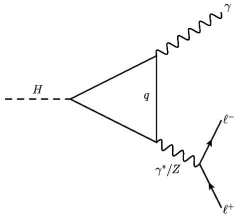
Full Run 2 results for H → Zγ →ℓℓγ:

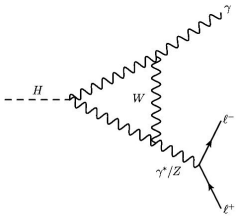
- 2.7 σ obs (2.1 σ exp)

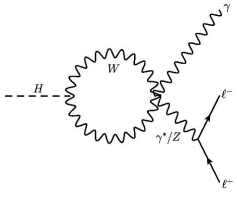
arXiv:2204.12945

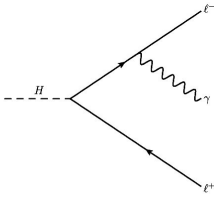




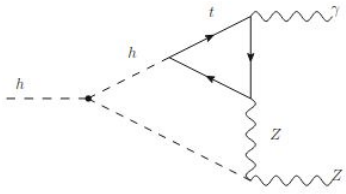


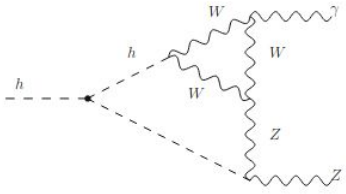






arXiv:2204.12945



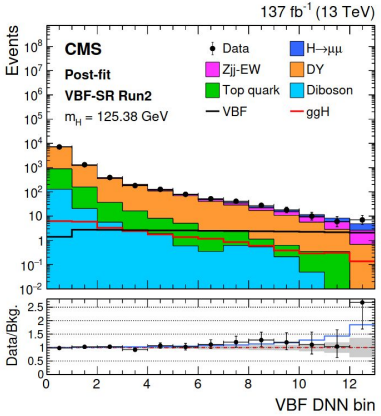


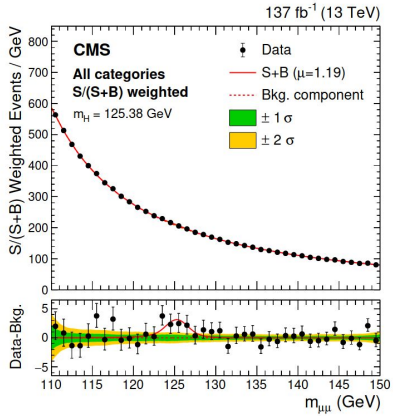
Eur. Phys. J. C **80**, 307 (2020)

Higgs Rare Decays: H → μμ

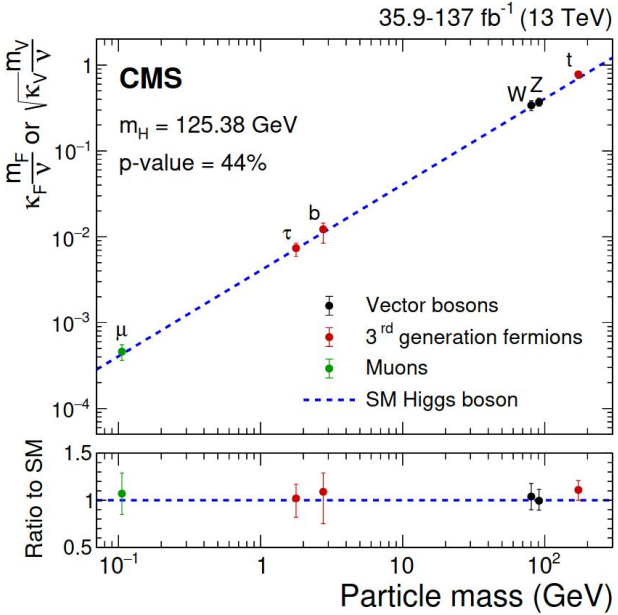
Evidence for Higgs coupling to second-generation fermions

- Fit to data to distinguish the signal peak above the dominant Z → μμ smoothly-falling distribution
- Plus MC template-based approach for the VBF category extracting signal strength from DNN distributions
- Significance: 3.0 σ obs. (2.5 σ exp.)





JHEP01 (2021) 148



Higgs Rare Decays: H → cc

arXiv:2205.05550

Targeting VH associate production to trigger interesting events and suppress backgrounds:

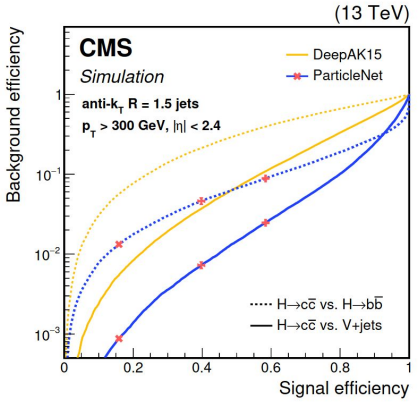
- ZH → ννcc, WH → lνcc, and ZH → llcc
- Resolved and merged categories
- State of the art graph neural network for boosted H→cc topology

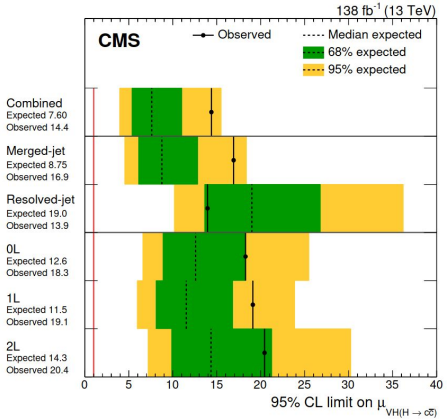
Same approach used in VZ(→ cc) channel:

- Simultaneous fit to VZ and VH processes
- First observation of Z → cc at a hadron collider

Upper limits:

- $\sigma(VH) \times BR(H \to cc) < 14\ (7.6^{+3.4}_{-2.3})$ SM at 95% CL
- $1.1 < |k_c| < 5.5\ (|k_c| < 3.4)$ at 95% CL





CP Properties: ttH

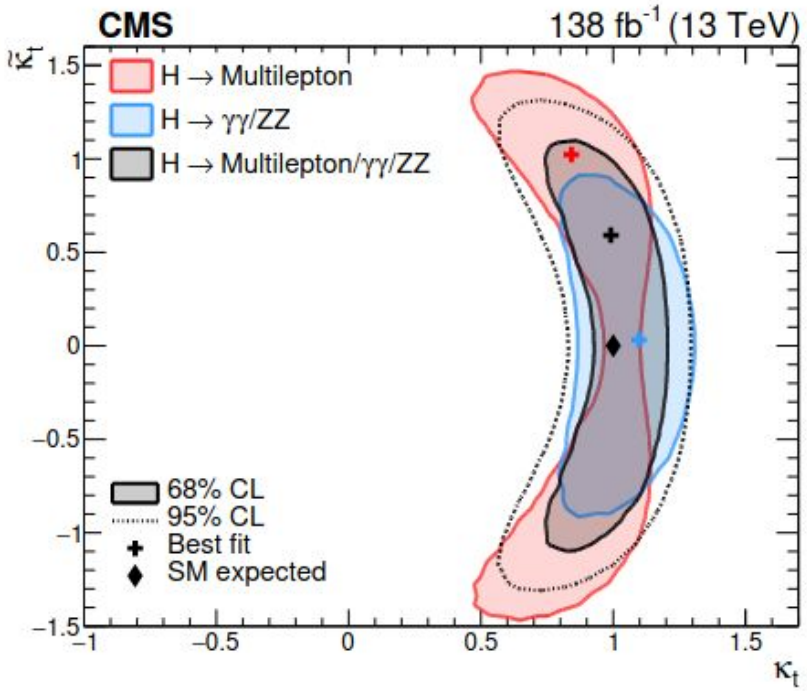
arXiv:2208.02686

Effective Lagrangian for Yukawa coupling to top quarks parameterized by CP-even and CP-odd components:

$$\mathcal{L}_{t\bar{t}H} = \frac{m_t}{v}\bar{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$$

Scenario	α
Purely *CP*-even	$0°$ or $180°$
Purely *CP*-odd	$90°$
Mixed	$\neq 0°, \neq 90°, \neq 180°$

- $|\sin^2\alpha| = 0.28$ with $|\sin^2\alpha| < 0.55$ at 68% CL
- Pure CP-odd coupling excluded at 3.7 σ



CP Properties: H → ττ

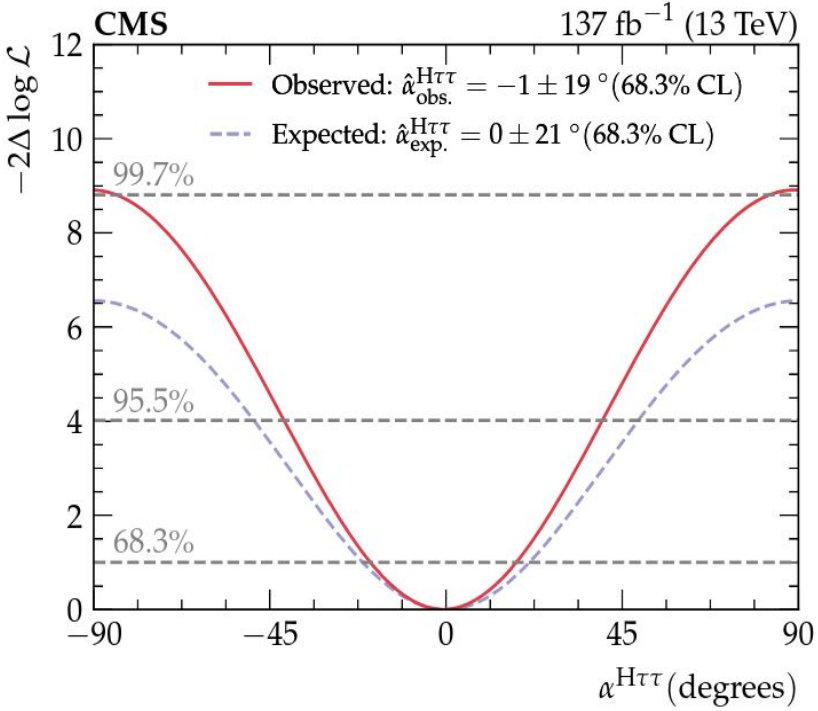
JHEP 06 (2022) 012

Effective Lagrangian for Yukawa coupling to tau lepton parameterized by **CP-even** and **CP-odd** components:

$$\mathcal{L}_{\mathrm{Y}} = -\frac{m_\tau}{v}\mathrm{H}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$

Scenario	α
Purely *CP*-even	0° or 180°
Purely *CP*-odd	90°
Mixed	$\neq 0°, \neq 90°, \neq 180°$

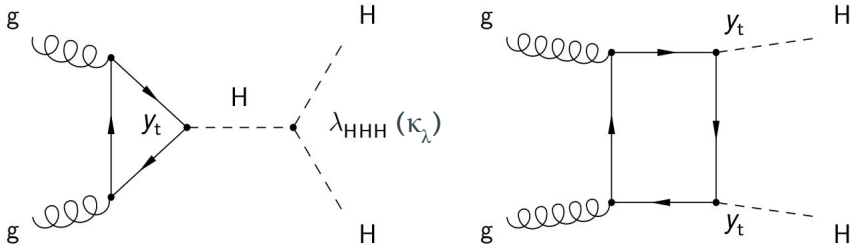
- $\alpha = -1° \pm 19°$ ($0° \pm 21°$ expected)
- Pure CP-odd coupling excluded at 3 σ



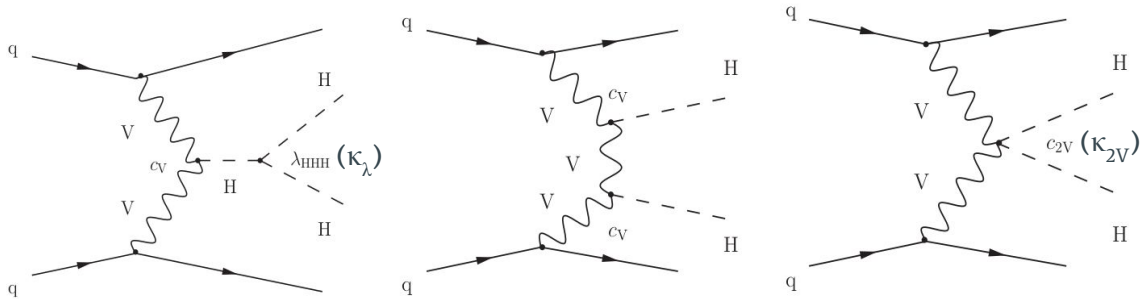
Double Higgs

Possibility to directly inspect the Higgs self coupling and HHVV coupling

- cross-section values at 13 TeV from LHC HH WG



gluon-gluon fusion
31.1 fb



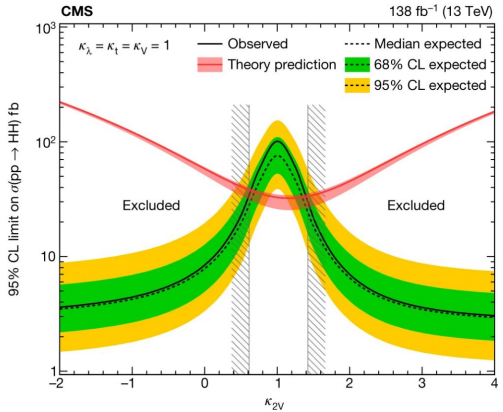
vector-boson fusion
1.726 fb

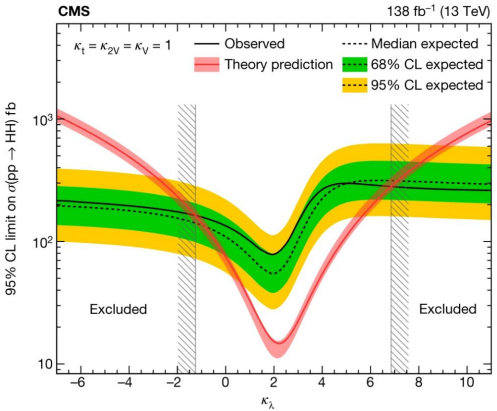
Double Higgs Results

Nature 607 (2022) 60

Combination of many final states:

- One Higgs decaying to bb to exploit high branching ratio
- Second Higgs can decay to bb, γγ, or ττ
- Combined results:
  - κ_λ in range (−1.24, 6.49)
  - κ_{2V} in range (0.67, 1.38)
  - $\kappa_{2V} = 0$ is excluded, with a significance of 6.6 σ



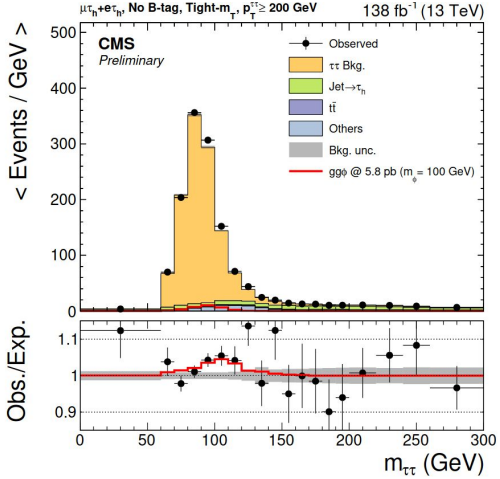


Is It Really Everything as Expected?

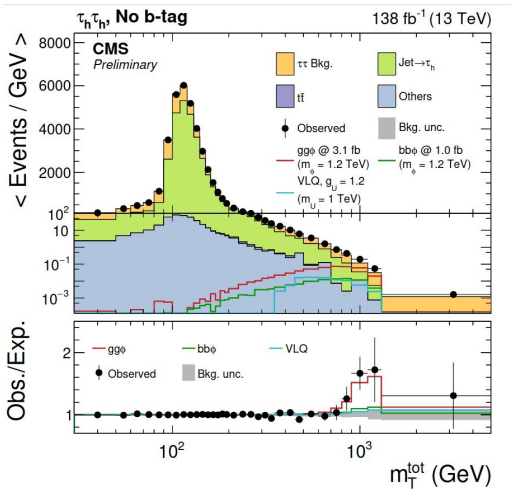
Many results agree with the hypothesis that the Higgs boson is the one predicted by the SM

- Taking a wider look, few discrepancies start to appear

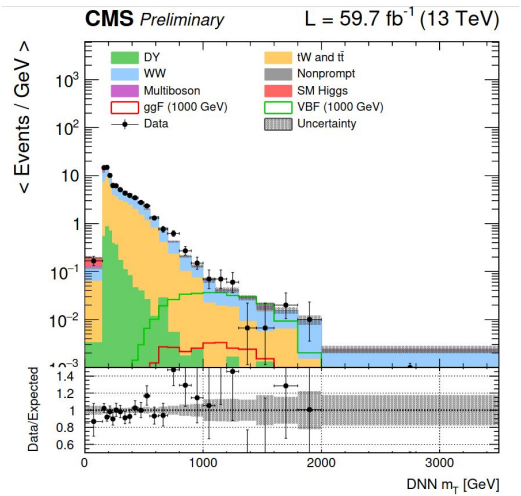
CMS-PAS-HIG-21-001



CMS-PAS-HIG-21-001



CMS-PAS-HIG-20-016

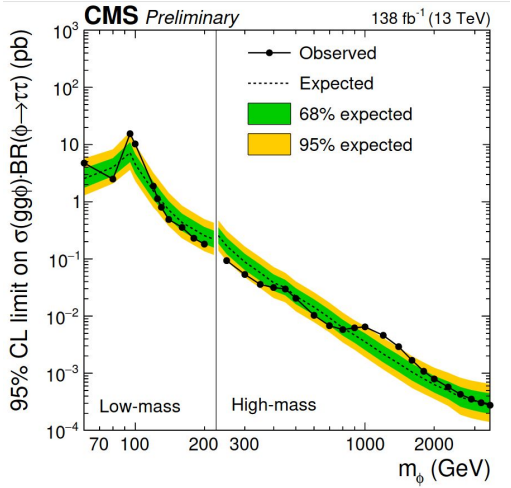


Is It Really Everything as Expected?

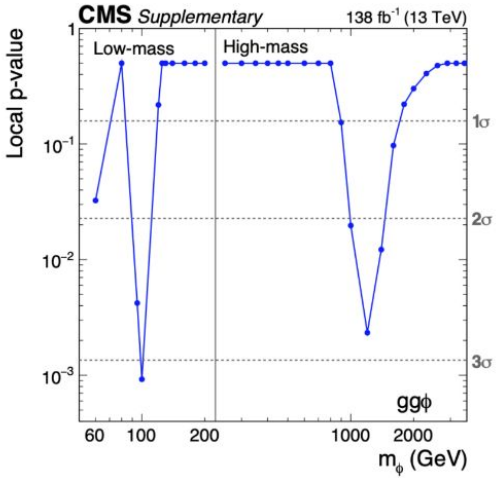
Many results agree with the hypothesis that the Higgs boson is the one predicted by the SM

- Taking a wider look, few discrepancies start to appear

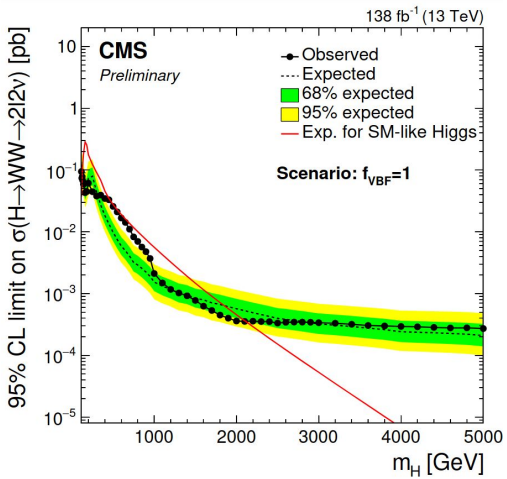
CMS-PAS-HIG-21-001



CMS-PAS-HIG-20-016



CMS-PAS-HIG-20-016



Conclusions

Ten years after the discovery of the Higgs boson, we are in the precision measurement era:

- Mass and width known with uncertainty of ~MeV
- Enough statistics to perform differential measurements
  - Easily re-interpretable thanks to the STXS framework
- Close to measure coupling to second-generation fermions
- Access to CP properties of the Yukawa coupling
- Great progress also in the di-Higgs measurement
- Many results agree with the SM, but still some discrepancies have been observed using Run 2 data

BACK-UP

Index/Summary

- The Higgs turns 10 → precision measurements
  - mass, width, STXS
- Couplings → to c quark ;)
- CP properties: ttH and tautau

ICHEP Higgs talk

Higgs Rare Decays: H → cc

Use of multivariate analysis techniques to identify jets produced by c quarks

Targeting VH associate production to trigger interesting events and suppress backgrounds:

- ZH → ννcc, WH → lνcc, and ZH → llcc
- at least one c tagged jet

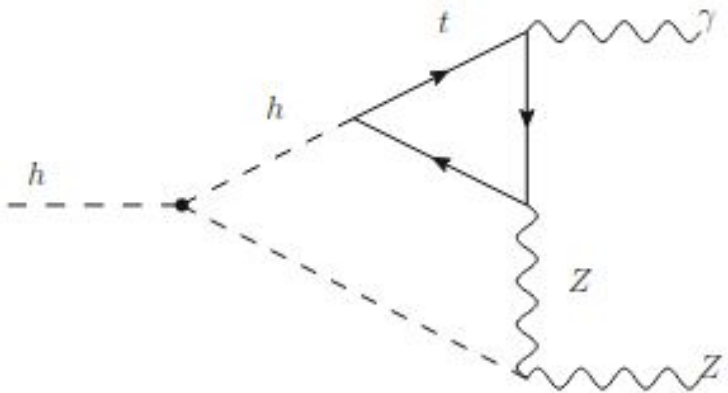
Analysis strategy validated in VZ(→ $c\bar{c}$) channel:

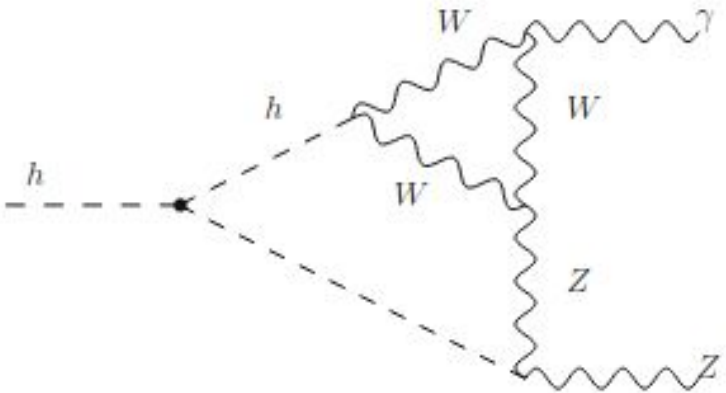
- First observation of Z → $c\bar{c}$ at a hadron collider

Upper limits:

- $\sigma(VH) \times BR(H \to cc) < 26\ (31^{}_{-8})$ SM at 95% CL
- $|k_c| < 8.5\ (12.4)$ at 95% CL

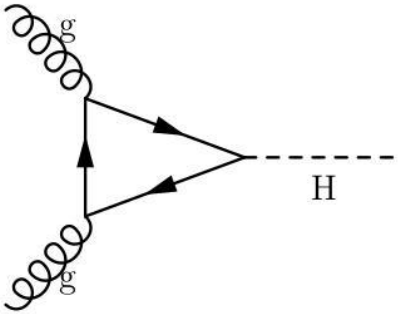
Higgs Rare Decays: $\rightarrow \ell\ell\gamma$



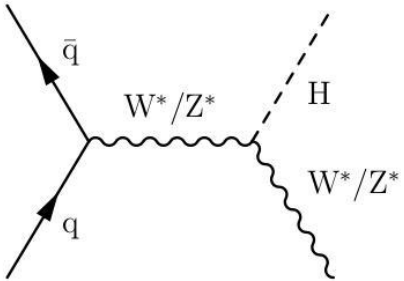


Higgs Production Mechanisms at the LHC

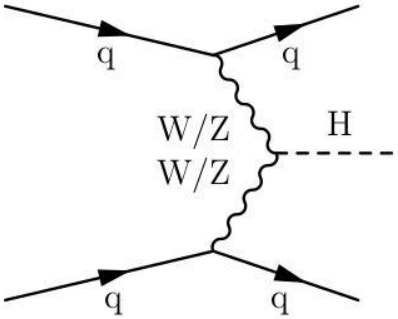
Cross-section values at 13 TeV from LHC Higgs WG



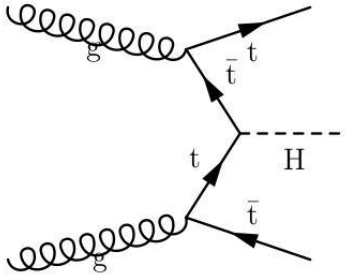
gluon-gluon fusion
48.6 pb



production in association with a vector boson
2.3 pb



vector boson fusion
3.8 pb



production in association with a top quark pair
0.5 pb

Higgs Rare Decays: H → Zγ

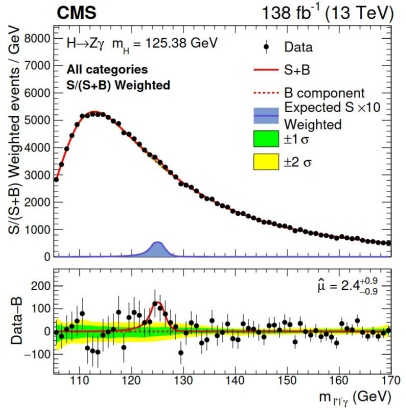
arXiv:2204.12945

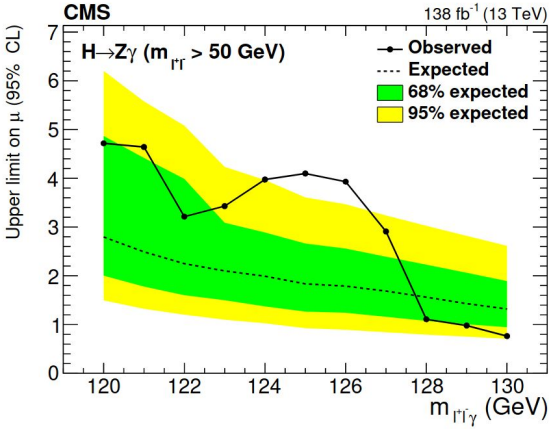
Sensitive to new physics:

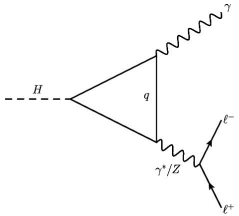
- B(H→Zγ) / B(H→γγ)
- Anomalous trilinear Higgs self-coupling

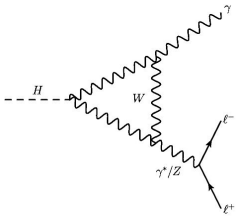
Full Run 2 results for H → Zγ →ℓℓγ:

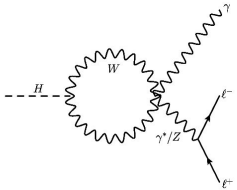
- 2.7 σ obs (2.1 σ exp)

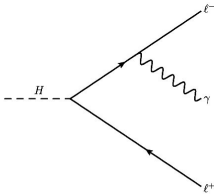




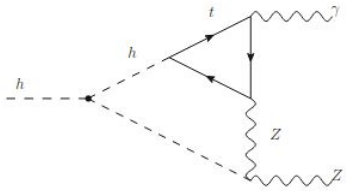


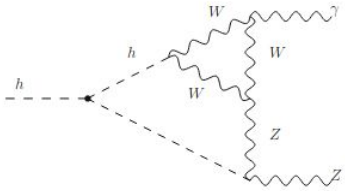






arXiv:2204.12945





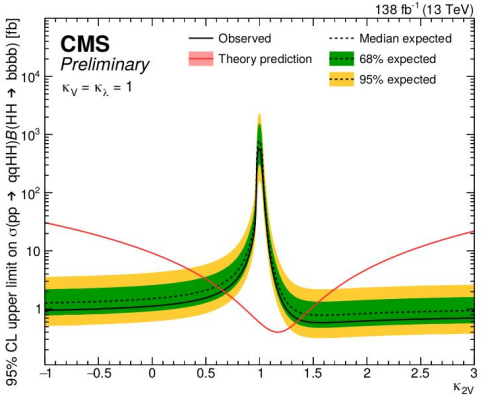
Eur. Phys. J. C **80**, 307 (2020)

HH → bb bb

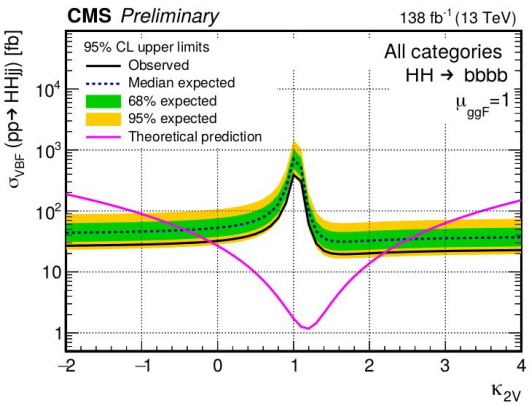
Largest branching fraction (34%)

- Boosted and resolved categories
- Multivariate classifier based on graph convolutional networks to identify signal events
- $-2.3 < \kappa_\lambda < 9.4$ ($-5.0 < \kappa_\lambda < 12.0$) - resolved analysis
- $0.6 < \kappa_{2V} < 1.4$ (obs and exp) at 95% CL - boosted analysis

CMS PAS B2G-21-001



Phys. Rev. Lett. 129 (2022) 081802



Phys. Rev. Lett. 129 (2022) 081802