Higgs couplings measurements from ATLAS and CMS

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Introduction

Nature 607, 52–59 (2022)

The Higgs boson is responsible for electroweak spontaneous symmetry breaking

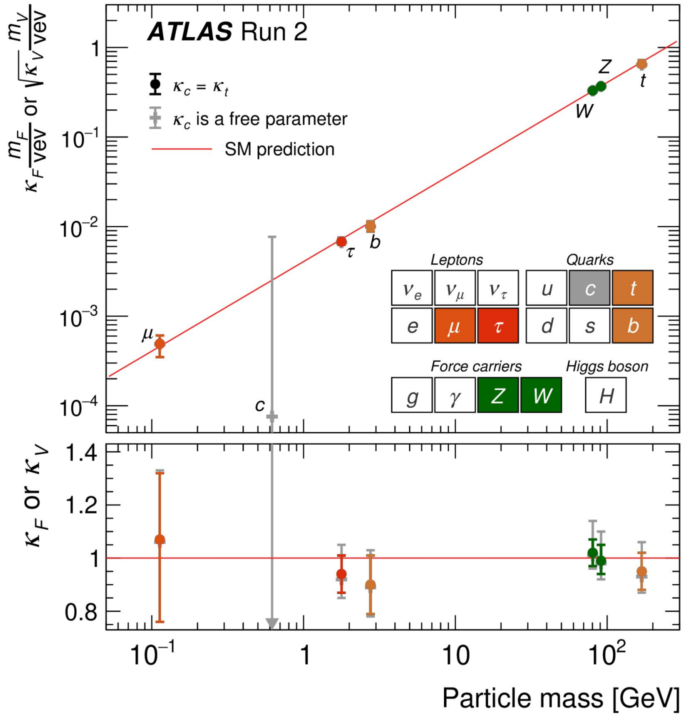
$$\mathcal{L}_\phi = (D^\mu \phi)^\dagger (D_\mu \phi) - \sum_f g_f (\bar{\psi}_L \phi \psi_R + h.c.) - V(\phi)$$

- Gives mass to vector bosons through gauge couplings and vacuum expectation value:

$$m_W = \frac{vg}{2}$$

- Fermion masses determined by Yukawa couplings:

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



H → cc

Relies on VH associate production to trigger interesting events and suppress backgrounds:

- 0, 1, and 2 leptons final states:
  - ZH → ννcc, WH → lνcc, and ZH → llcc
- Analysis strategy validated in VZ (Z→cc) channel
- ATLAS:
  - Different ΔR between c tagged jets depending on $p^T(V)$
- CMS:
  - Resolved- and merged-jets categories
  - Graph neural network used in merged topology

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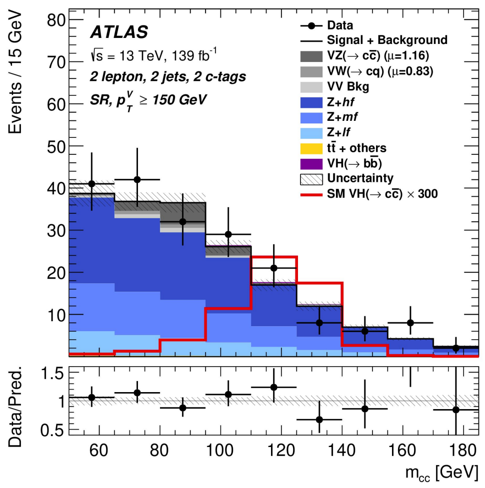
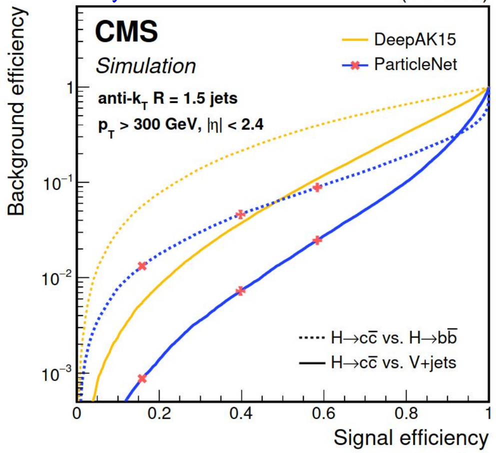
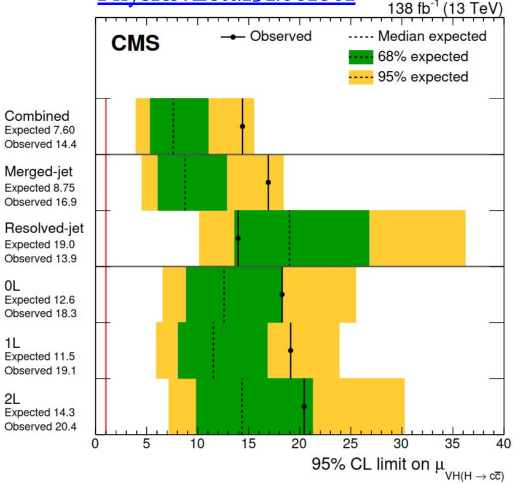


PhysRevLett.131.061801



$H \rightarrow cc$ - Results

PhysRevLett.131.061801



CMS

- $\mu(VZ, Z\rightarrow cc) = 1.01^{+0.23}_{-0.21}$
  - First observation of $Z \rightarrow cc$ at a hadron collider
  - Observed (expected) significance of 5.7 (5.9) σ
- $\sigma(VH) \times BR(H\rightarrow cc) < 14\ (7.6^{+3.4}_{-2.3})$ SM at 95% CL
- $1.1 < |\kappa_c| < 5.5$ (expected: $|\kappa_c| < 3.4$) at 95% CL

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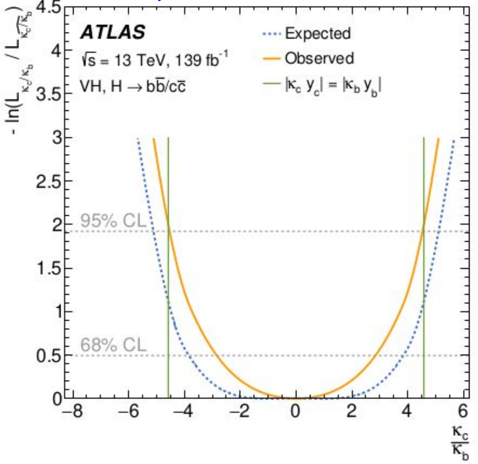


ATLAS

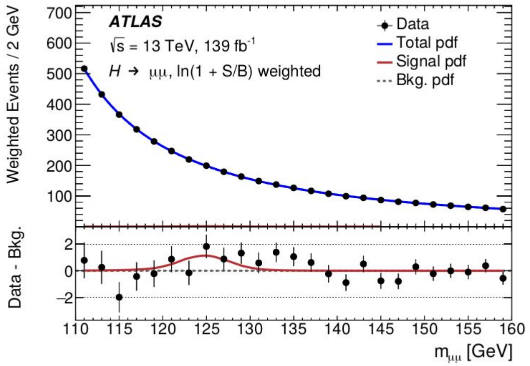
- $\mu(VH\rightarrow cc) = -9 \pm 10$ (stat.) ± 12 (syst.)
  - $\mu(VZ\rightarrow cc) = 1.16 \pm 0.32$ (stat.) ± 0.36 (syst.).
- Observed (expected) constraint of $|\kappa_c| < 8.5\ (12.4)$ at 95% CL
- Ratio κ_c/κ_b constrained to less than 4.5 at the 95% CL

H → μμ

Targeting decay channel with low branching fraction:

- Including ggF, VBF, WH, ZH, and ttH production modes
- Categorisation based on BDTs for each production mode
- Dominant DY background described by product of:
  - Core function: common to all categories
  - Empirical function: independent in each category
- Fit to data to distinguish signal peak from dominant smoothly-falling distribution from Z → μμ
  - CMS: MC template-based approach for the VBF category extracting signal strength from DNN distributions

Phys. Lett. B 812 (2021) 135980



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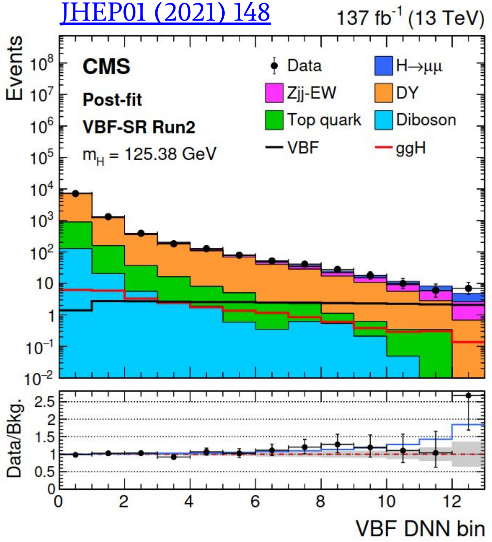

$H \to \mu\mu$ - Results

CMS:

- $\mu = 1.19\,^{+0.40}_{-0.39}\,(\text{stat})\,^{+0.15}_{-0.14}\,(\text{syst})$
  - First evidence of H→μμ process (3.0 σ significance)
- Branching fraction: $0.8 \times 10^{-4} < BR(H\to\mu\mu) < 4.5 \times 10^{-4}$ at 95% C.L.
  - SM value: $B(H \to \mu\mu) = 2.18 \times 10^{-4}$
- Coupling modifier: $\kappa_\mu = 1.07 \pm 0.22$ at 68% CL

ATLAS:

- $\mu = 1.2 \pm 0.6$ (dominated by statistical uncertainty)
- Corresponding upper limit of 2.2 at 95% CL is set on the signal strength

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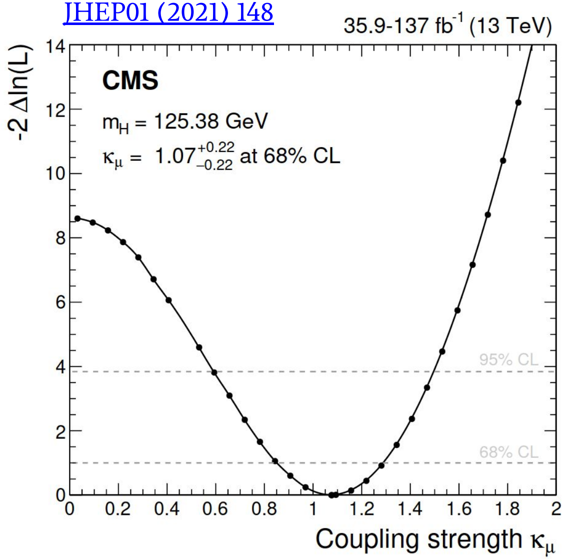

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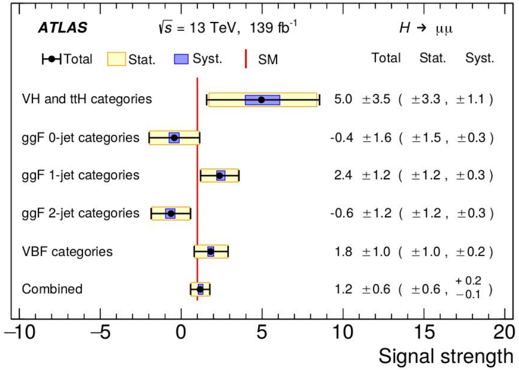


Targeting the Production Mode: ttH→bb

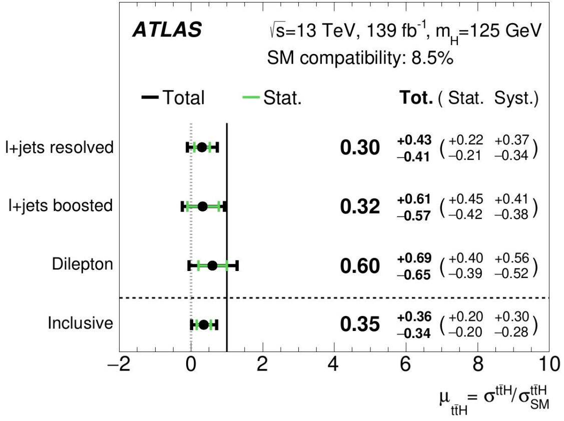
The ttH→bb process allows to measure both the κ_t and κ_b coupling values. Main challenges:

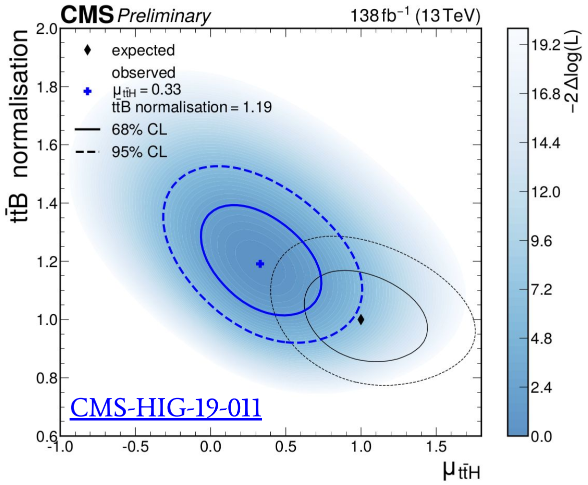
- Low signal production cross-section
- Irreducible tt+jets background especially difficult to model

Signal strength consistently below expectation both in ATLAS and CMS results:

- ATLAS:
  - $\mu = 0.35^{+0.36}_{-0.34} = 0.33 \pm 0.20\ (\text{stat})\ ^{+0.30}_{-0.28}\ (\text{syst})$
- CMS:
  - $\mu = 0.33 \pm 0.26 = 0.33 \pm 0.17\ (\text{stat}) \pm 0.21\ (\text{syst})$

JHEP06(2022)097





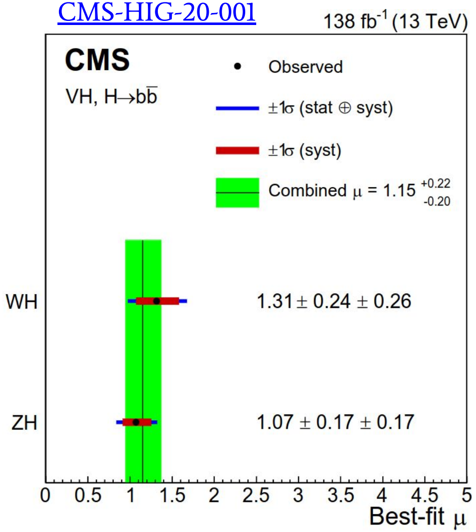
VH→bb

Targeting Higgs boson production in association with a W or Z boson

- Vector bosons decaying leptonically
  - 0, 1, and 2 leptons categories
- Observation of VH process

- ATLAS:
  - $\mu(VH) = 1.02^{+0.18}_{-0.17}$
  - Corresponding to an observed (expected) significance of 6.7 (6.7) σ
- CMS:
  - $\mu(VH) = 1.15^{+0.22}_{-0.20}$
  - Corresponding to an observed (expected) significance of 6.3 (5.6) σ

CMS-HIG-20-001



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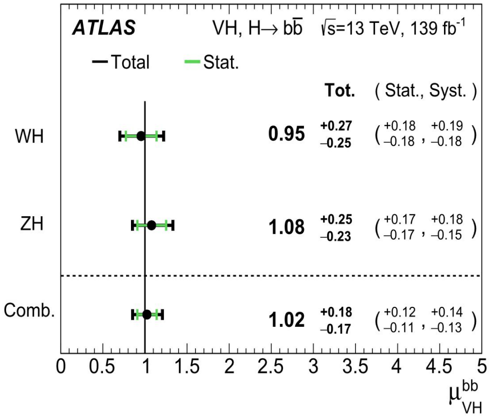
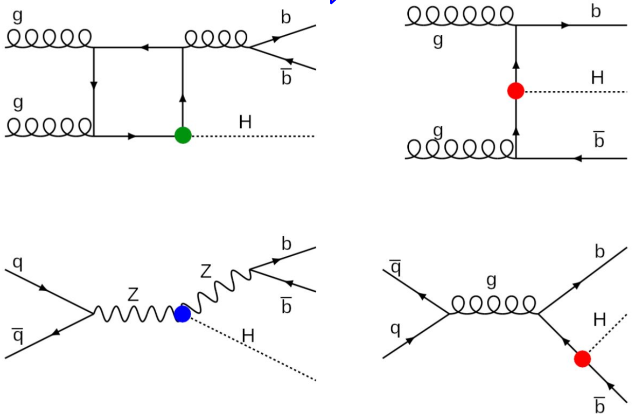


Targeting the Production Mode: bbH

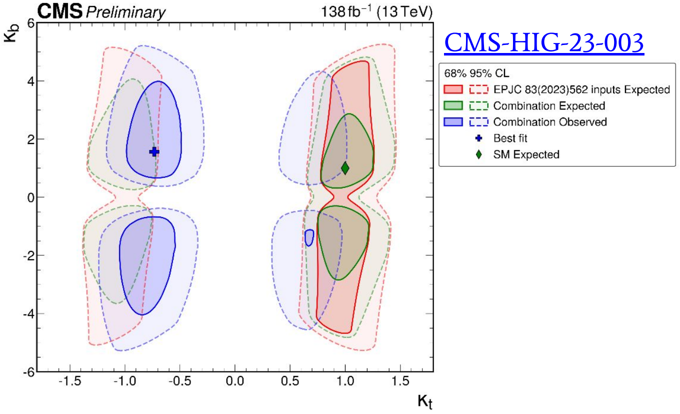
NEW!

[CMS-HIG-23-003]



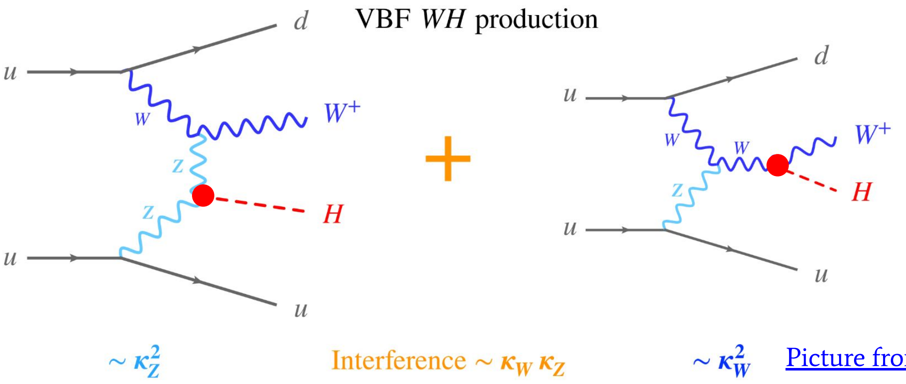
Rare Higgs production mode, sensitive to the coupling to **top** and **bottom** quarks

- Similar production cross section as ttH
  - But no top quarks in the final state
  - More challenging signature than ttH
- WW and ττ final states
- Observed (expected) upper limit 3.7 (6.1) times the SM prediction at 95% CL
- Results also interpreted in terms of couplings to top and bottom quarks
  - Best fit values: $(\kappa_t, \kappa_b) = (-0.73, 1.58)$
  - Compatible with SM within 2 σ



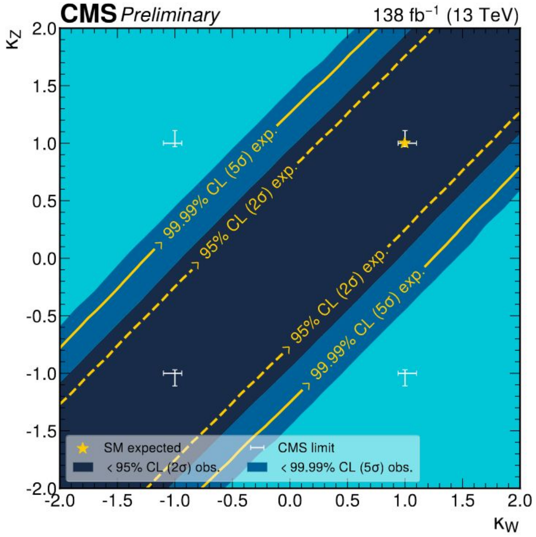
[CMS-HIG-23-003]

VBF WH→bb



Picture from Karsten Köneke

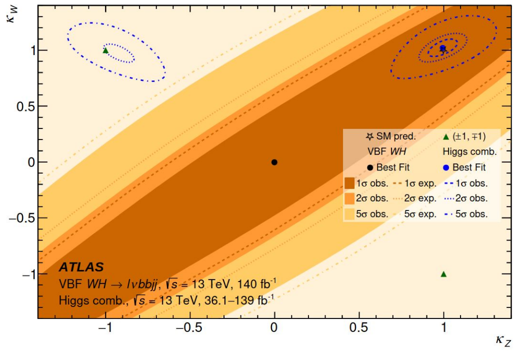
[CMS-HIG-23-007]



κ_W and κ_Z are usually measured using H→WW and H→ZZ

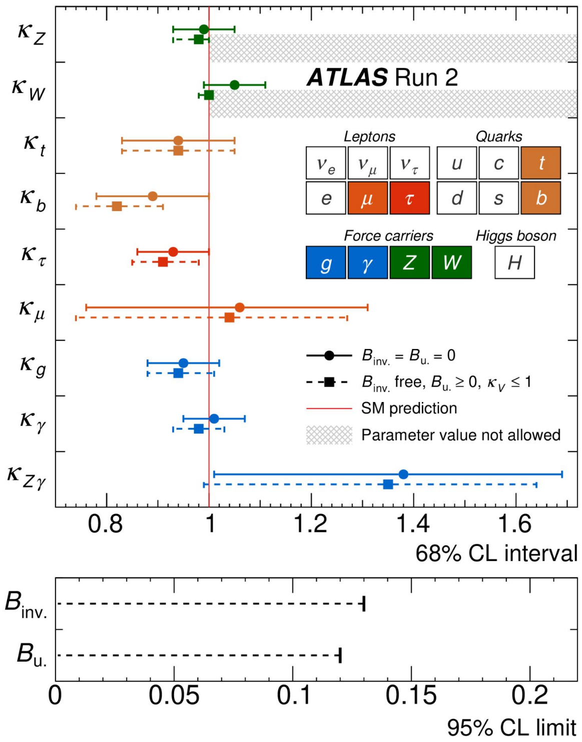
- The square of κ_W or κ_Z is involved
  - Sign is left unconstrained
- In the SM, $\lambda_{WZ} = \kappa_W/\kappa_Z = 1$
  - Negative values of λ_{WZ} would enhance the VBF WH production and are predicted by BSM models
- ATLAS and CMS results exclude negative λ_{WZ} with significance greater than 5σ

[arXiv:2402.00426]

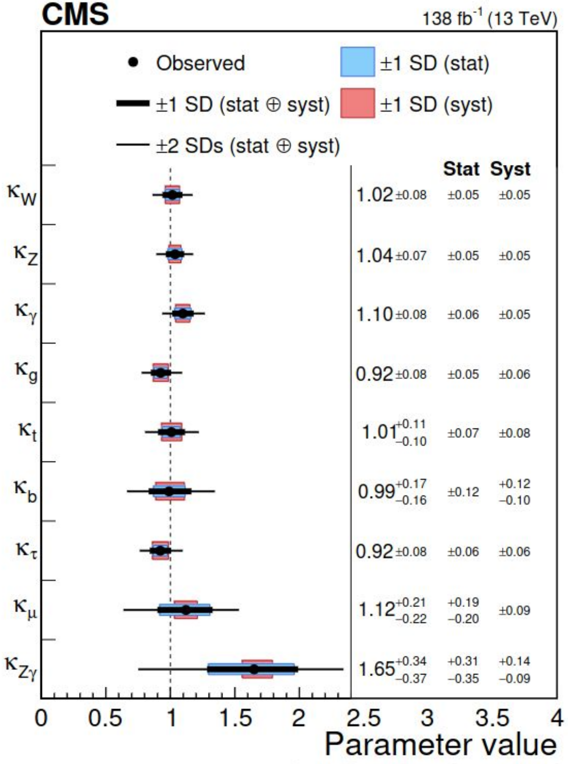


Combined Results

Nature 607 (2022) 52

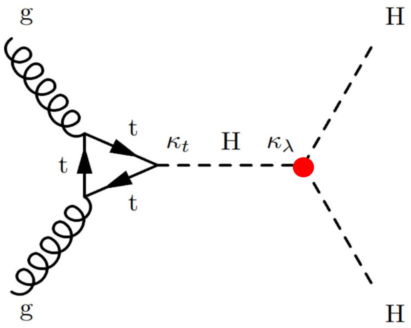


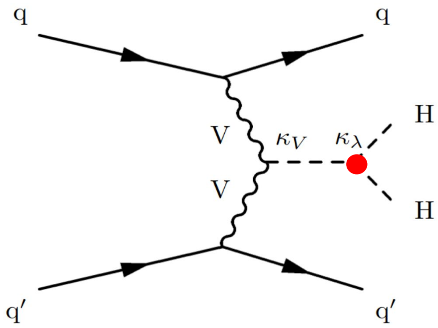
Nature 607 (2022) 60



Higgs Self-Coupling Results

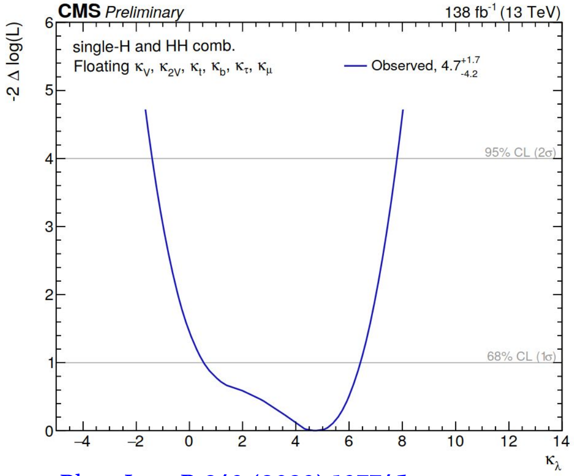
Several single- and double-Higgs measurements combined to measure the Higgs self-coupling κ_λ:



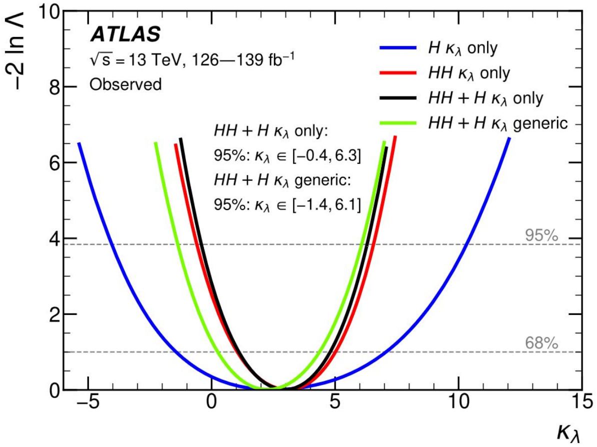


- ATLAS:
  - $-1.4 < \kappa_\lambda < 6.1$ at 95% CL
- CMS:
  - $-1.2 < \kappa_\lambda < 7.5$ at 95% CL

CMS-HIG-23-006



Phys. Lett. B 843 (2023) 137745



Conclusions

We are in the era of precision measurements of the Higgs boson properties:

- Couplings to the most massive particles are well established
  - Relative κ_W/κ_Z sign
  - ttH and bbH measurements to constraint κ_t and κ_b
- Challenging second-generation fermions:
  - Already 3-sigma evidence for $H \to \mu\mu$
  - Competitive limits on the κ_c coupling modifier
- Combination of H and HH measurements put stringent limits on Higgs self-coupling

BACK-UP

Targeting the CP Structure: ttH

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

$$\mathcal{L}_{\mathrm{t\bar{t}H}} = \frac{m_\mathrm{t}}{v}\bar{\psi}_\mathrm{t}(\underline{\kappa_\mathrm{t}} + \underline{i\gamma_5\tilde{\kappa}_\mathrm{t}})\psi_\mathrm{t}\mathrm{H}$$

$$|f_{CP}^{\mathrm{Htt}}| = \frac{|\widetilde{\kappa}_\mathrm{t}^2|}{(|\widetilde{\kappa}_\mathrm{t}|^2 + |\kappa_\mathrm{t}|^2)}$$

Targeting the CP Structure: ttH

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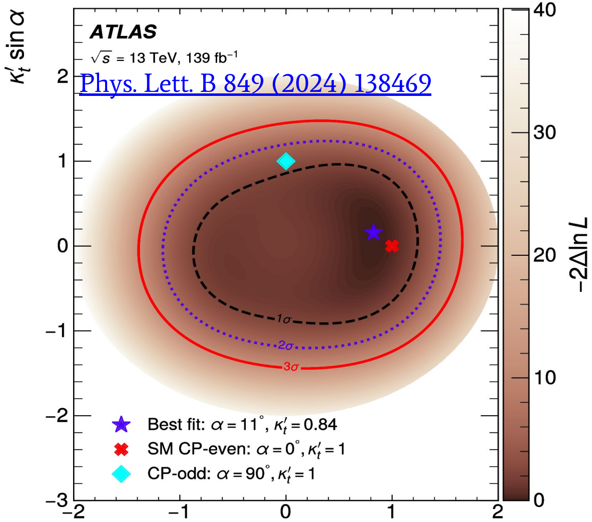
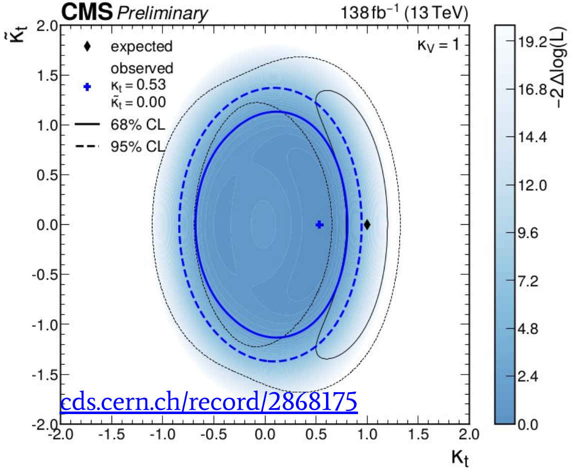
ttH→bb final state:

- ATLAS:
  - Coupling modifier $\kappa_t = 0.84^{+0.30}_{-0.46}$
  - CP-mixing angle $\alpha = 11° {}^{+52°}_{-73°}$
- CMS:
  - Best-fit values of (κ_t, κ_V) of (+0.59, +1.40)
  - Assuming $\kappa_V = 1$, a best-fit value of $\kappa_t = 0.54^{+0.19}_{-0.34}$ is obtained





Targeting the CP Structure: ttH

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

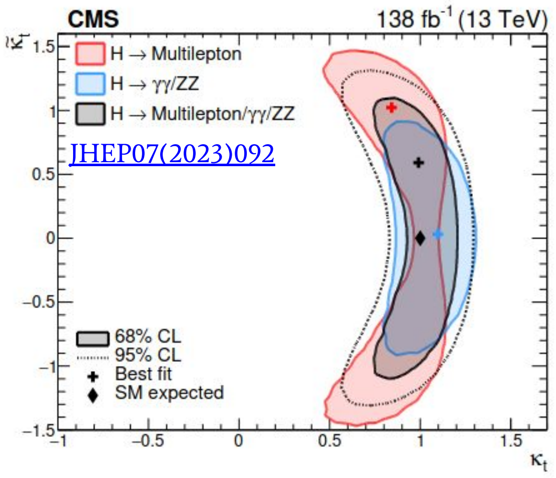
$$\mathcal{L}_{\mathrm{t\bar{t}H}} = \frac{m_{\mathrm{t}}}{v}\bar{\psi}_{\mathrm{t}}(\kappa_{\mathrm{t}} + i\gamma_5\widetilde{\kappa}_{\mathrm{t}})\psi_{\mathrm{t}}\mathrm{H} \qquad |f_{CP}^{\mathrm{Htt}}| = \frac{|\widetilde{\kappa}_{\mathrm{t}}^2|}{(|\widetilde{\kappa}_{\mathrm{t}}|^2 + |\kappa_{\mathrm{t}}|^2)}$$

CMS: Combination of multilepton, γγ, and ZZ final states:

- $|f_{CP}^{\mathrm{Htt}}| = 0.28$ with $|f_{CP}^{\mathrm{Htt}}| < 0.55$ at 68% CL
- Pure CP-odd coupling excluded at 3.7 σ

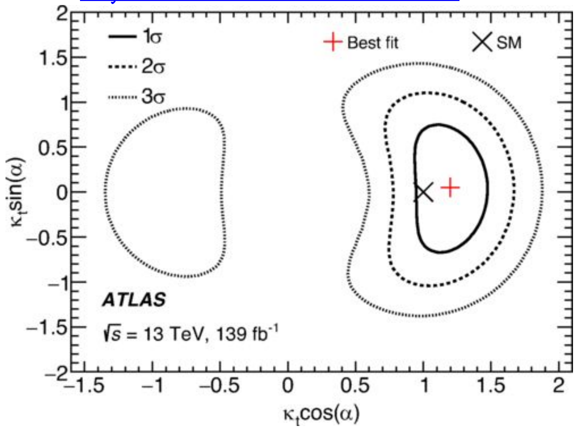
ATLAS: γγ final state

- CP-mixing angle -43° < α < 43° at 95% confidence level.

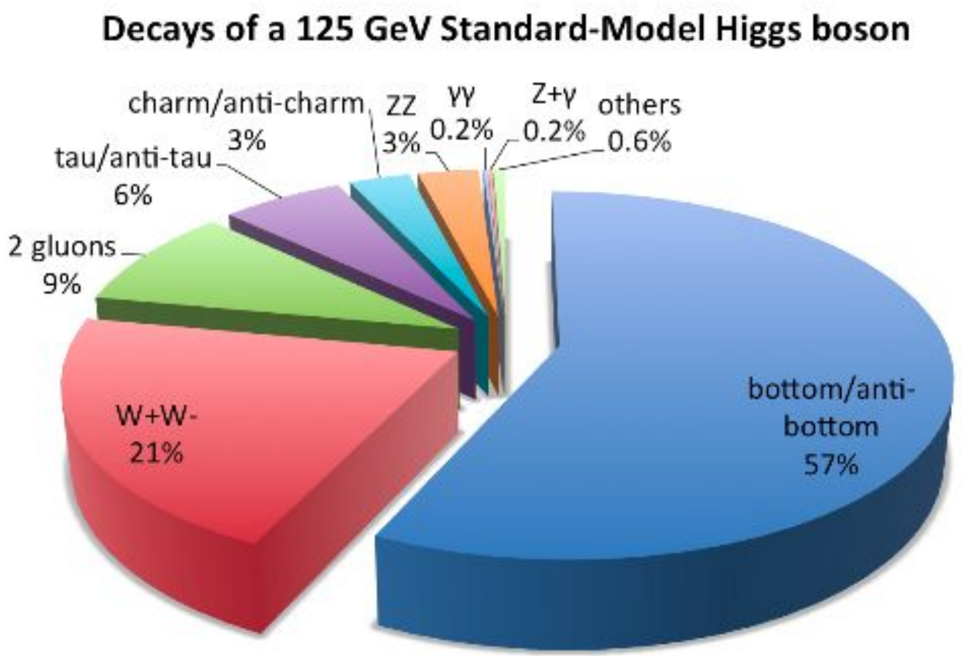


JHEP07(2023)092

Phys. Rev. Lett. 125 (2020) 061802



Higgs Branching Fractions



https://atlas.physicsmasterclasses.org/en/zpath_hboson.htm

CP Properties: ttH

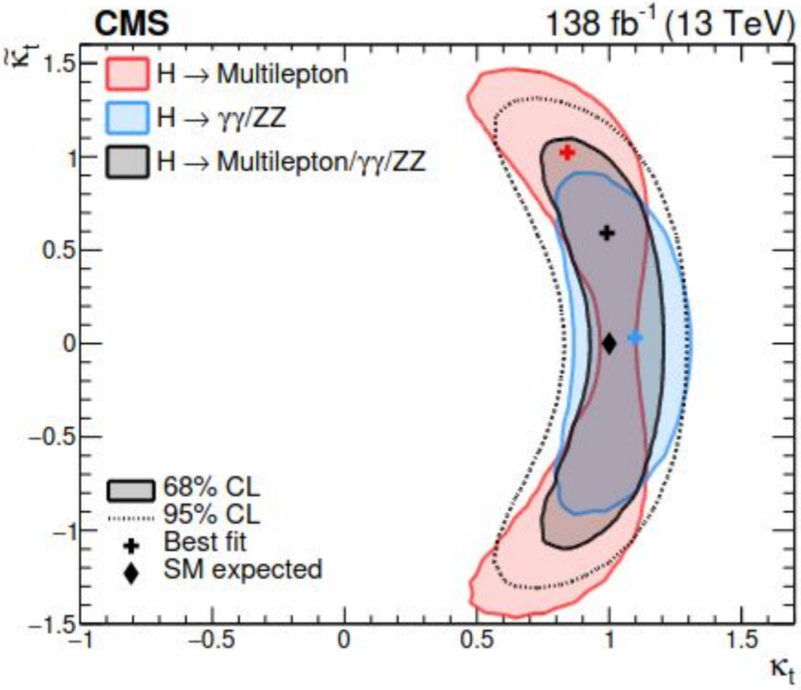
arXiv:2208.02686

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

$$\mathcal{L}_{\mathrm{t\bar{t}H}} = \frac{m_{\mathrm{t}}}{v}\bar{\psi}_{\mathrm{t}}\left(\underline{\kappa_{\mathrm{t}}} + \underline{i\gamma_5\tilde{\kappa}_{\mathrm{t}}}\right)\psi_{\mathrm{t}}\mathrm{H}$$

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

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



CP Properties: H $\rightarrow$ ττ

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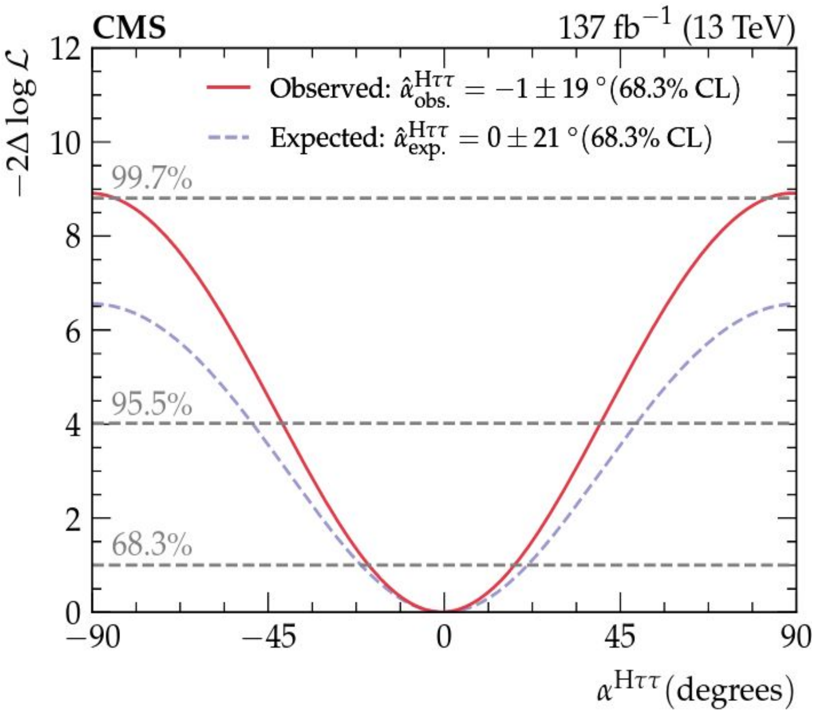
Effective Lagrangian for Yukawa coupling to tau lepton parameterized by **CP-even** and **CP-odd** components:

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

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

- α = -1° ± 19° (0° ± 21° expected)
- Pure CP-odd coupling excluded at 3 σ



H → ττ - Results

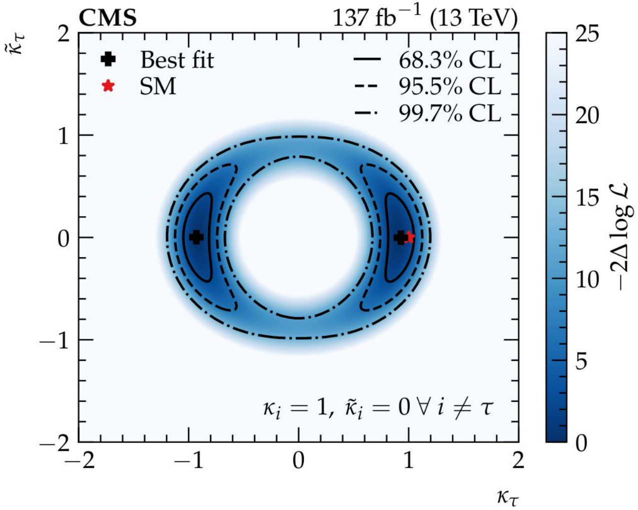
Several methods to reconstruct CP-sensitive observable ϕ_{CP}

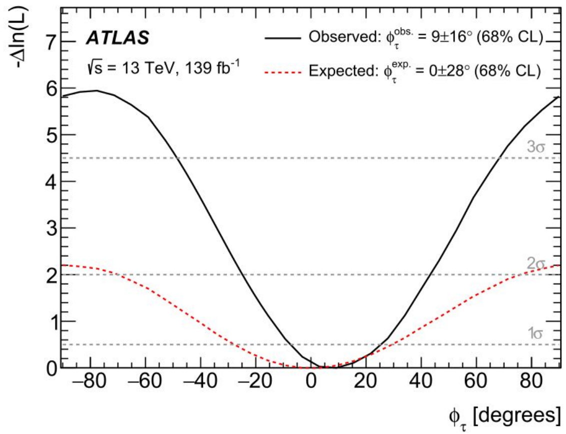
ATLAS:

- Observed (expected) $\alpha^{H\tau\tau}$ = 9° ± 16° (0° ± 28°) at 68% confidence level.
- Pure CP-odd hypothesis disfavoured at 3.4 σ

CMS:

- Observed (expected) $\alpha^{H\tau\tau}$ = -1° ± 19° (0° ± 21°) at 68% confidence level.
- Pure CP-odd coupling excluded at 3 σ



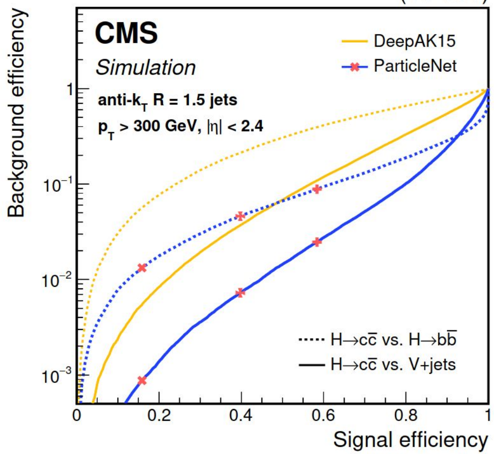


H → cc

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

- ZH → ννcc, WH → lνcc, and ZH → llcc
- Analysis strategy validated in VZ (Z→cc) channel
- ATLAS:
  - Different ΔR between c tagged jets depending on $p^T(V)$
- CMS:
  - Resolved- and merged-jets categories
  - State of the art graph neural network for merged topology

10.1103/PhysRevLett.131.041801



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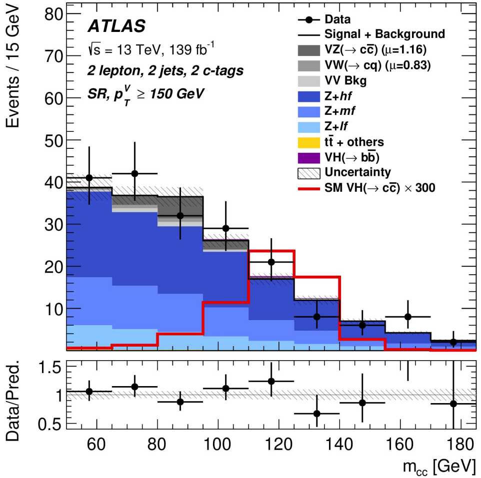

H→ee

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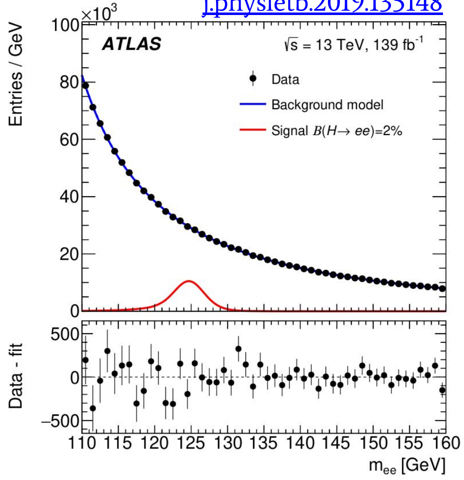

H→ee branching fraction measurement is currently out of reach at LHC:

- $BR(H\to ee) = G_F m_H m_e^2/(4\sqrt{2}\pi\ \Gamma_H) \sim 5 \times 10^{-9}$
- BSM physics may manifest in enhanced Higgs coupling to electrons
- Both ATLAS and CMS follow strategies from similar searches:
  - ATLAS: H→μμ
    - with additional interpretation in terms of BR(H→eμ)
  - CMS: H → γγ
- Upper limits on BR(H→ee) in line with expectations:
  - ATLAS: 3.6×10^{-4} (3.5×10^{-4}) at 95% C.L.
    - For B(H → eμ): 6.2×10^{-5} (5.9×10^{-5})
  - CMS: 3.0×10^{-4} (3.0×10^{-4}) at 95% C.L.

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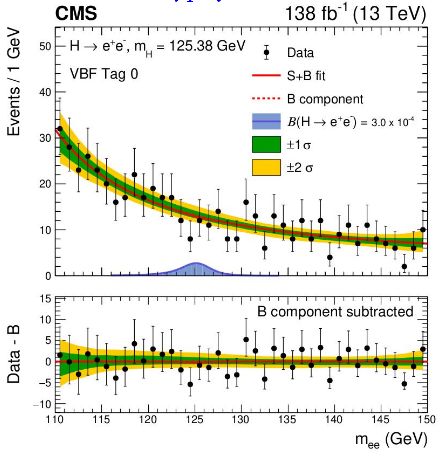

H→ee

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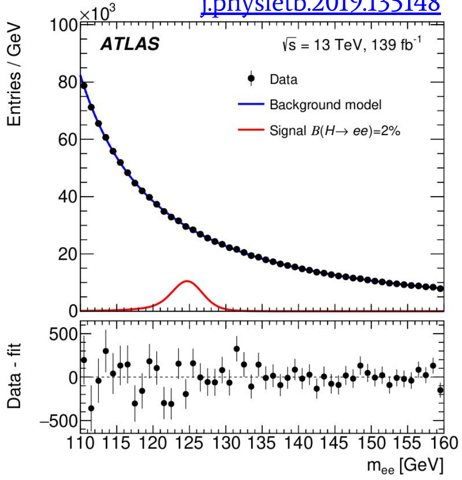

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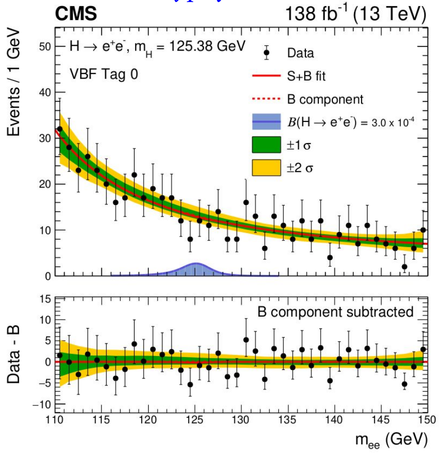

$H \rightarrow \mu\mu$

First evidence for Higgs coupling to second-generation fermions

- Dominant DY background described by product of:
  - Core function (common to all categories)
  - Empirical function (independent in each category)
- Targeting ggF, VBF, WH, ZH, ttH
- Categorisation based on BDTs exploiting the topological and kinematic differences between the different signal production modes and the background processes
- Fit to data to distinguish signal peak from dominant smoothly-falling distribution from $Z \rightarrow \mu\mu$
  - CMS: MC template-based approach for the VBF category extracting signal strength from DNN distributions

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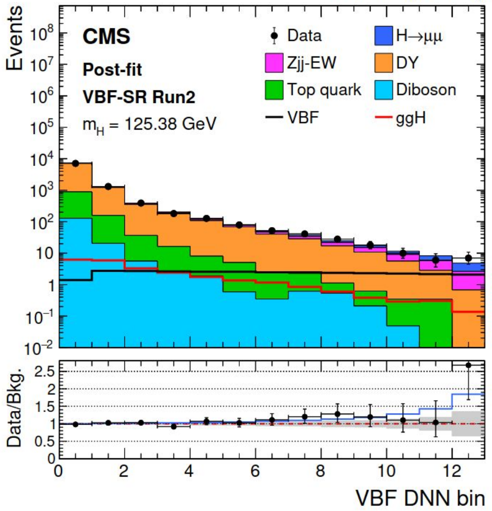
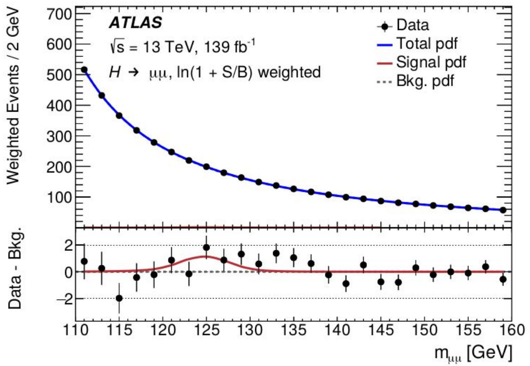
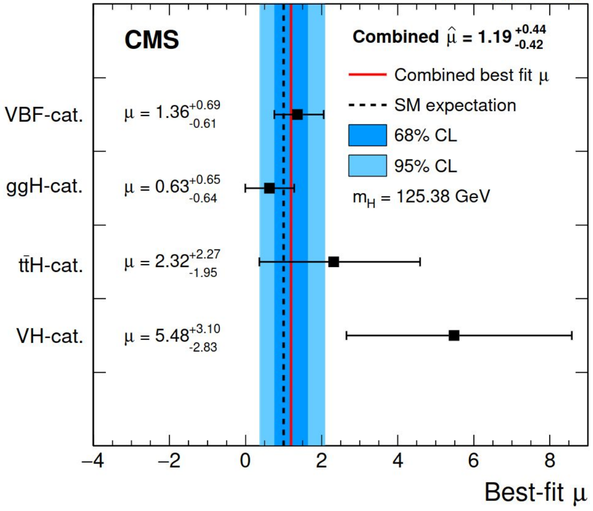


Phys. Lett. B 812 (2021) 135980



$H \to \mu\mu$ - Results

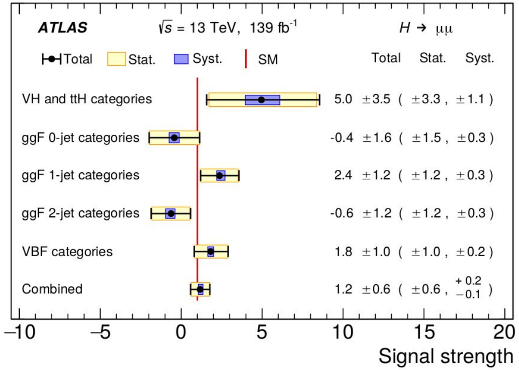
JHEP01 (2021) 148



CMS:

- $\mu = 1.19\ ^{+0.40}_{-0.39}$ (stat) $^{+0.15}_{-0.14}$ (syst)
  - First evidence of H→μμ process (3.0 σ significance)
- Branching fraction: $0.8 \times 10^{-4} < BR(H\to\mu\mu) < 4.5 \times 10^{-4}$ at 95% C.L.
  - SM value: $B(H \to \mu\mu) = 2.18 \times 10^{-4}$
- Coupling modifier: $\kappa_\mu = 1.07 \pm 0.22$ at 68% CL

Phys. Lett. B 812 (2021) 135980

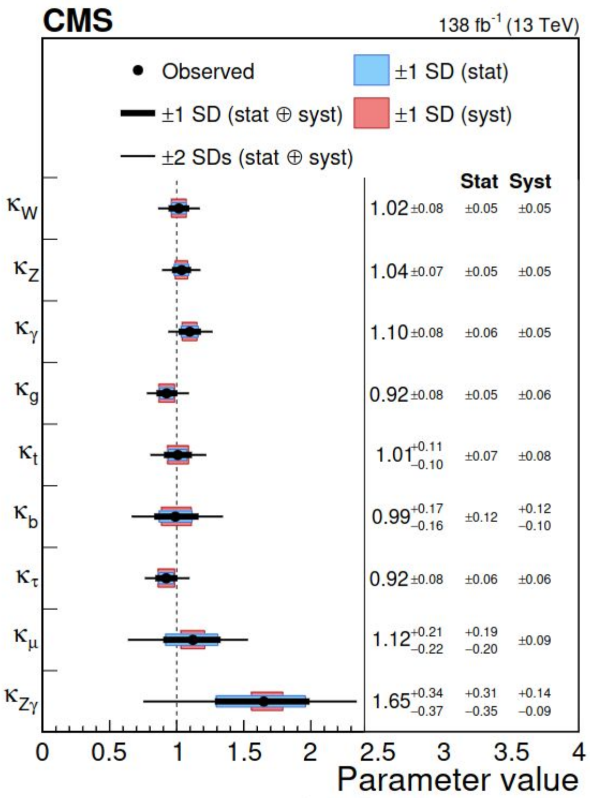


ATLAS:

- $\mu = 1.2 \pm 0.6$ (dominated by statistical uncertainty)
- Corresponding upper limit of 2.2 at 95% CL is set on the signal strength

Conclusions

Nature 607 (2022) 60



We are in the era of precision measurements of the Higgs boson properties:

- Couplings to the most massive fermions are well established
  - Sensitive to the coupling structure
  - We can test CP hypotheses
- For second-generation fermions, the Run 3 of LHC data taking may bring us to the observation of their interaction with the Higgs boson
  - Already 3-sigma evidence for H→μμ
  - Competitive limits on the κ_c coupling modifier
- Results are also interpreted in the EFT framework

Conclusions

[Nature 607, 52–59 (2022)]

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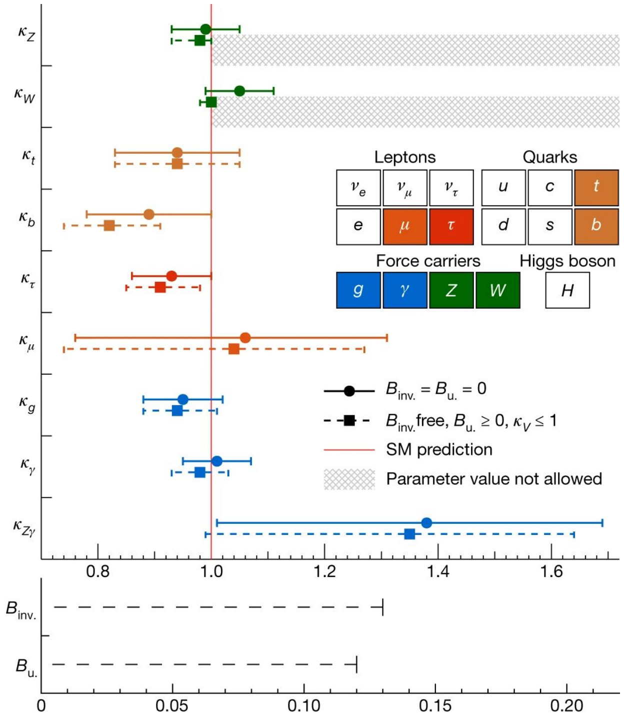
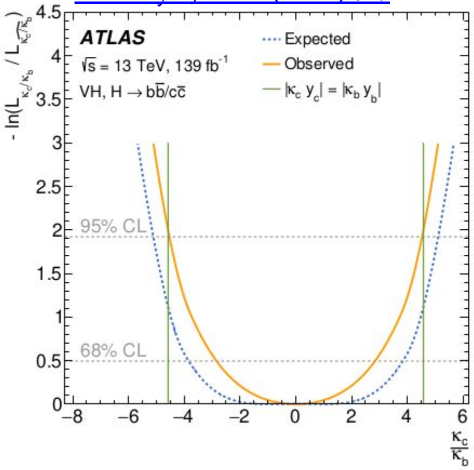


H → cc - Results

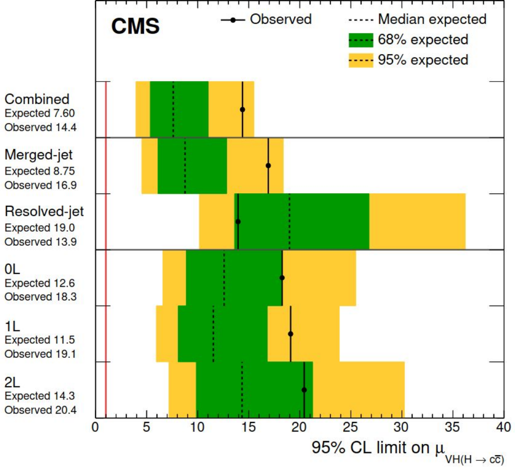
Eur. Phys. J. C 82 (2022) 717



ATLAS

- $\mu(VH\to cc) = -9 \pm 10$ (stat.) ± 12 (syst.)
  - $\mu(VW\to cq) = 0.83 \pm 0.11$ (stat.) ± 0.21 (syst.)
  - $\mu(VZ\to cc) = 1.16 \pm 0.32$ (stat.) ± 0.36 (syst.).
- Observed (expected) constraint of $|\kappa_c| < 8.5$ (12.4) at 95% CL
- Ratio κ_c/κ_b constrained to less than 4.5 at the 95% confidence level

10.1103/PhysRevLett.131.041801



CMS

- $\mu(VZ,Z\to cc) = 1.01^{+0.23}_{-0.21}$
  - First observation of Z → cc at a hadron collider
  - Observed (expected) significance of 5.7 (5.9) σ
- $\sigma(VH)$ x $BR(H\to cc) < 14$ ($7.6_{-2.3}$) SM at 95% CL
- $1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$) at 95% CL

Conclusions

We are in the era of precision measurements of the Higgs boson properties:

- Couplings to the most massive fermions are well established
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  - We can test CP hypotheses
- For second-generation fermions, the Run 3 of LHC data taking may bring us to the observation of their interaction with the Higgs boson
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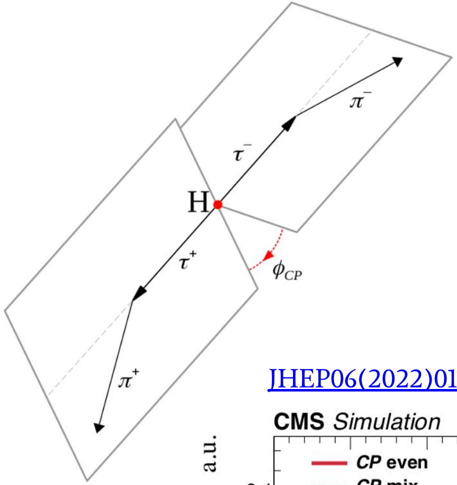
- Results are also interpreted in the EFT framework

$H \to \tau\tau$



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

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

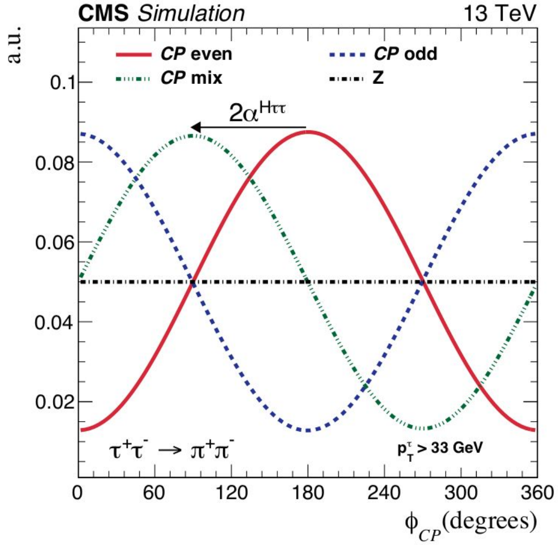
$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

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

Related to observable quantity:

$$\frac{d\Gamma}{d\phi_{CP}}(H \to \tau^+\tau^-) \sim 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

JHEP06(2022)012



$H \to \tau\tau$ - Results

Several methods to reconstruct CP-sensitive observable ϕ_{CP}

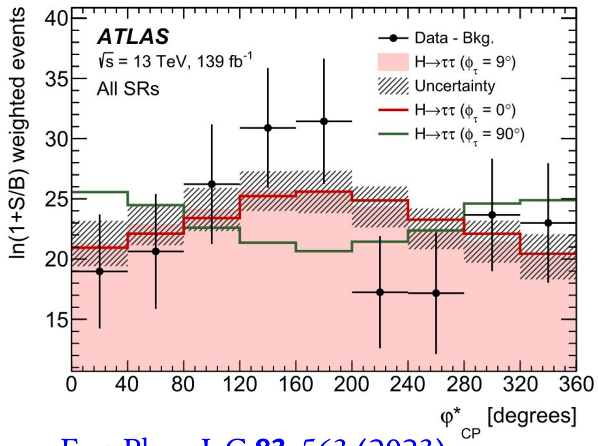
ATLAS:

- Observed (expected) $\alpha^{H\tau\tau} = 9° \pm 16°$ ($0° \pm 28°$) at 68% confidence level.
- Pure CP-odd hypothesis disfavoured at 3.4 σ

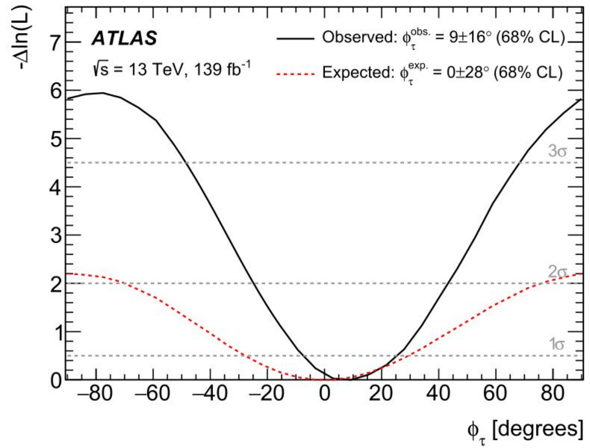
CMS:

- Observed (expected) $\alpha^{H\tau\tau} = -1° \pm 19°$ ($0° \pm 21°$) at 68% confidence level.
- Pure CP-odd coupling excluded at 3 σ

Eur. Phys. J. C **83**, 563 (2023)



Eur. Phys. J. C **83**, 563 (2023)



Targeting the Production Mode: ttH

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

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

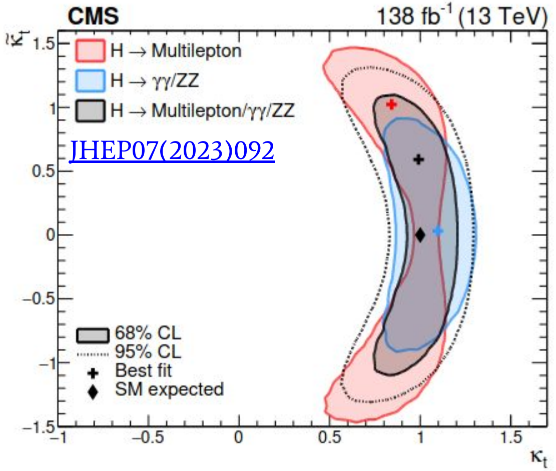
Scenario	α
Purely CP-even	0° or 180°
Purely CP-odd	90°
Mixed	$\neq 0°, \neq 90°, \neq 180°$

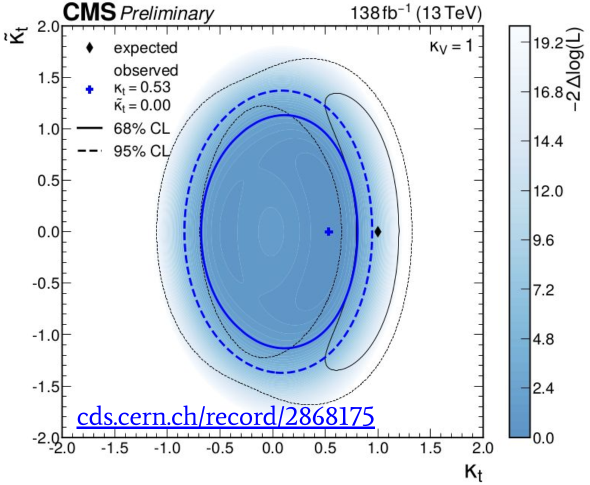
Combination of multilepton, γγ, and ZZ final states:

- $|f_{CP}^{Htt}| = \frac{|\tilde{\kappa}_t^2|}{(|\tilde{\kappa}_t|^2+|\kappa_t|^2)}$ = 0.28 with $|f_{CP}^{Htt}|$ < 0.55 at 68% CL
- Pure CP-odd coupling excluded at 3.7 σ

bb final state:

- Best-fit values of (κ_t, κ_V) of (+0.59, +1.40)
- Assuming $\kappa_V = 1$, a best-fit value of $\kappa_t = 0.54^{+0.19}_{-0.34}$ is obtained





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

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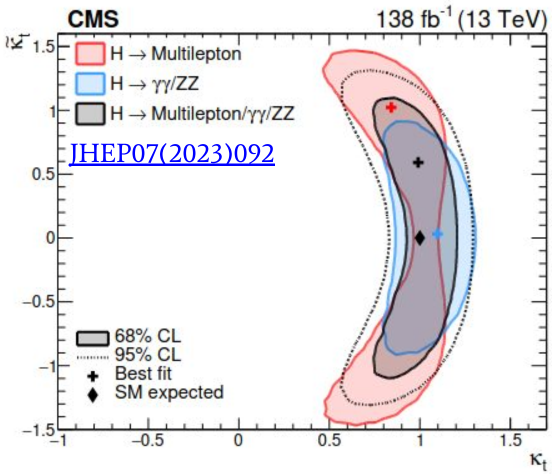
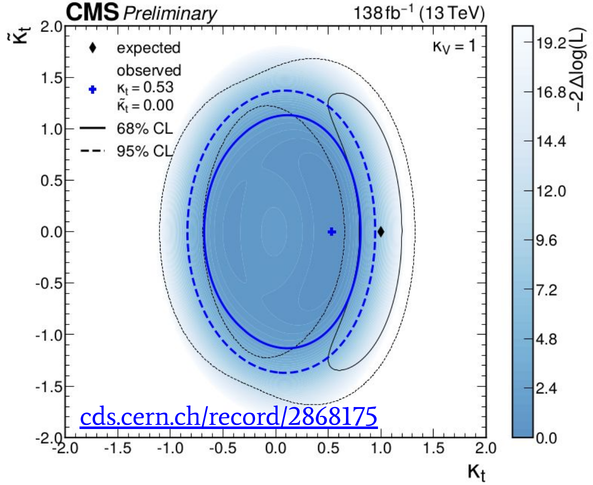


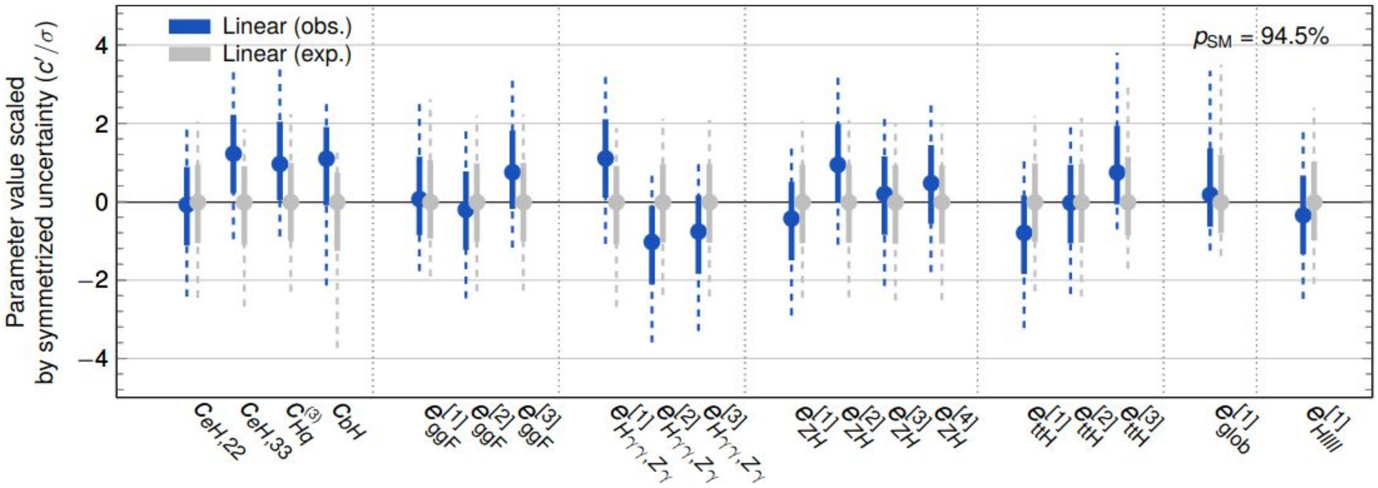


Effective Field Theory Interpretation

Combination of several Higgs ATLAS results in terms of EFT:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{j}^{N_{d=8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots$$

Introducing new operators O_i and the corresponding coefficients c_i



arXiv:2402.05742

ATLAS and CMS Public Results

- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome#Recent_Results
- CMS: https://cms-results-search.web.cern.ch/

Analyses List

- H→bb
  - ATLAS: VH bb boosted, ttH bb, WH/ZH bb
  - CMS: VH bb, WH bb AC, ttH bb
- H→ττ
  - ATLAS: H tautau, H tautau CP, VH tautau
  - CMS: H tautau AC, H tautau CP
- H→μμ
  - ATLAS: H mumu
  - CMS: H mumu
- H→cc
  - ATLAS: H cc
  - CMS: H cc
- H→ee
  - ATLAS: H ee
  - CMS: H ee
- Couplings to u,d,s?
  - ATLAS:
  - CMS:

- H→WW
  - ATLAS: H WW
  - CMS: H WW, H WW AC
- H→Zγ: LHC HZγ
- Higgs self couplings
  - ATLAS: double Higgs
  - CMS: single-double Higgs combination
- Higgs Nature papers
  - ATLAS: 10 years paper
  - CMS: 10 years paper
- ttH:
  - CMS: ttH multilepton CP
- BSM/EFT interpretation:
  - ATLAS: EFT/BSM