Properties of the Standard Model Higgs Boson

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on behalf of
ATLAS and CMS Collaborations, CERN-LHC

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Apologies for remote participation

More than a decade after the discovery

- The Higgs field, with a non-zero vacuum expectation value, permeates the whole universe and is responsible for the generation of masses of the standard model (SM) particles in a consistent way after the electroweak symmetry breaking.

  → the simplest and elegant idea about the origin of mass: postulated in 1960s, confirmed experimentally in 2012!
  → all the mass values are to be determined experimentally, though the nature of the interaction is specified in the theory.

- Discovery of a fundamental scalar resonance for the first time by ATLAS and CMS experiments at the CERN-LHC.

- Though the discovery completed the SM description of the particle content, there are many questions in high energy physics that are still unanswered.
  → we need a theory beyond standard model (BSM).

- Mandate after the discovery: we must check if this new particle belongs to SM or BSM.

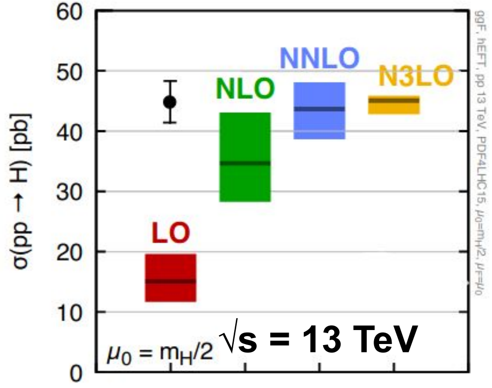
- Essentially, we study the dynamics of production and decay to understand the properties of the Higgs boson (H) in detail

  - determine the quantum numbers: charge, spin, parity, mass and width
  - check if all the predicted decay channels exist or not
  - look for indications for anomalous couplings
  - estimate the shape of the Higgs potential: constrain the trilinear and quartic couplings
  - study if the Higgs sector is minimal or if there is an extended one (in SM it is a complex doublet leading to a single scalar)
  - investigate if the Yukawa interaction conserves lepton flavor or not

Higgs physics continues to be exciting and remains a very active field of research.

Dividend of collective efforts: achieve more than anticipated!

- excellent performance of the LHC machine during its first decade of operation.
- enormous progress in computing capabilities.
- precision theoretical description of the production and decay processes of the Higgs boson as well as the relevant backgrounds.
- extensive understanding of the performance of the experiments.
- judicious application of sophisticated machine learning techniques!
  eg. b-jet identification: Deep Jet in CMS: JINST 15 (2020) P12012 , CMS-DP-2021-014

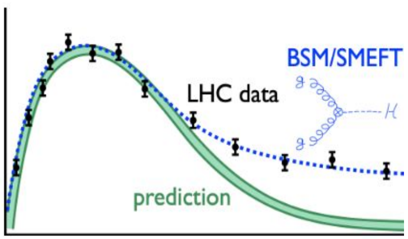


⇒ Higgs physics entered precision era quickly
⇒ increased sensitivity to search for BSM physics **by looking for deviations from SM**

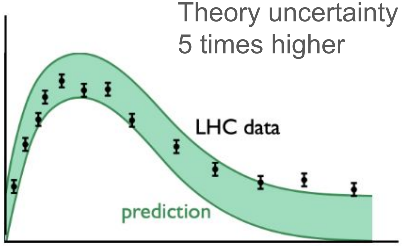
Prediction for Higgs boson production cross section

σ_{ggF} (theory) = 48.68 ± 3.9 (scales) ± 1.9 (PDF) ± 2.6(α_S) pb

We cannot afford to miss a discovery!



Theory uncertainty
5 times higher



- higher order quantum corrections in perturbative calc.
  i) upto next-to-next-to-next-to leading order (N3LO) of QCD coupling (α_S)
  ii) Electroweak corrections
  + finite quark mass effects
- PDF uncertainty: ~ 2-3%
- Uncertainty due to α_S : ~2%

This talk: *glimpses on a limited selection from a plethora of very interesting analyses carried out in recent times.*

Complementary results on rare decays and BSM searches: **Talk by Bernd Stelzer.**

Data

pp collision data collected by each of ATLAS and CMS experiments:

Run-1 at $\sqrt{s}$ = 7, 8 TeV (2010 - 2012) : ~20 fb^{-1}

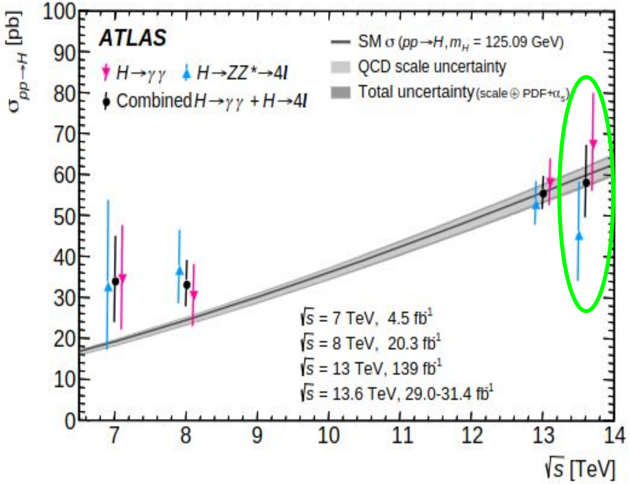
Run-2 at $\sqrt{s}$ = 13 TeV (2015 - 2018): ~140 fb^{-1}

Run-3 at $\sqrt{s}$ = 13.6 TeV (2022): ~ 31.3 fb^{-1}

⇒ Total no. of Higgs bosons produced at each interaction point ~10^7

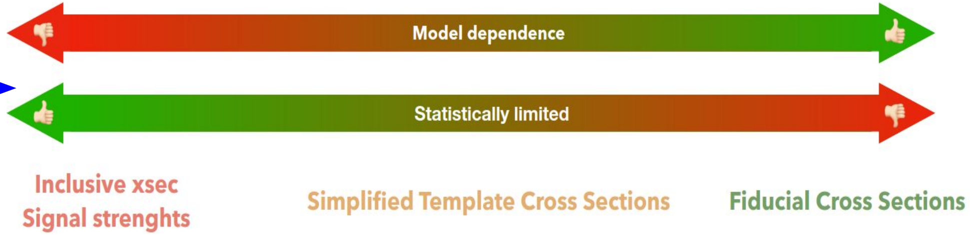
- Value of the Higgs boson mass chosen by Nature
  → quick discovery at the LHC.
  → numerous experimental measurements using the main production processes with multiple decay modes can be scrutinised.

First round of Run 3 results are out! ATLAS HIGG-2022-012



Evolution in interpretation of data

a) Single H



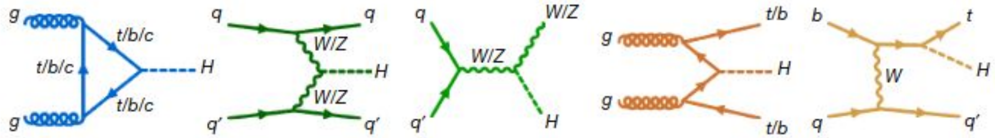
b) H pair

c) Constrain new physics via precise measurements.

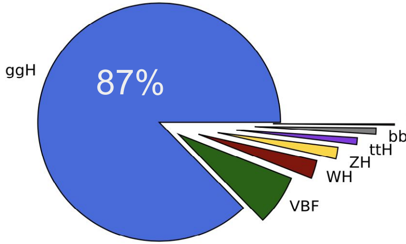
d) Effective Field Theory (EFT) interpretation via global fits.

Essential to establish a channel.
But only the Higgs boson production times decay branching fraction can be studied.

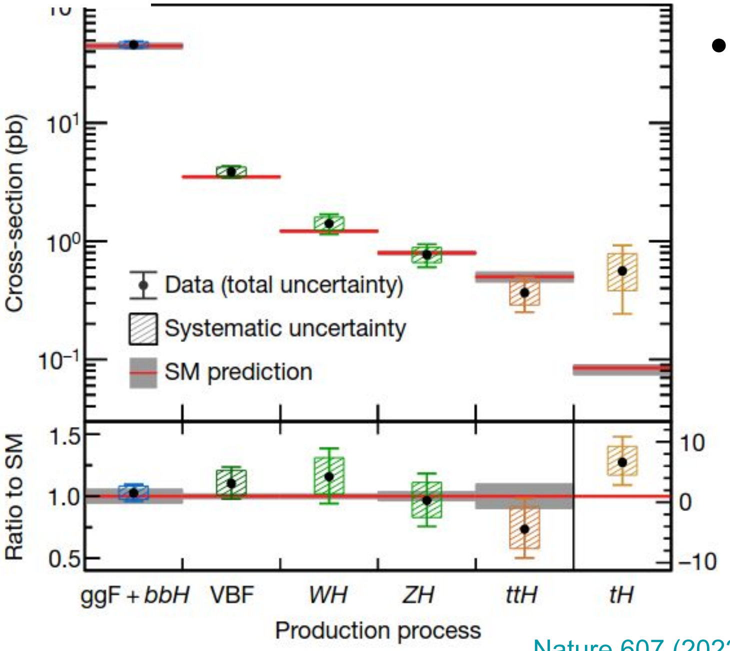
Higgs production at the LHC



ggF VBF VH ttH tH



ATLAS



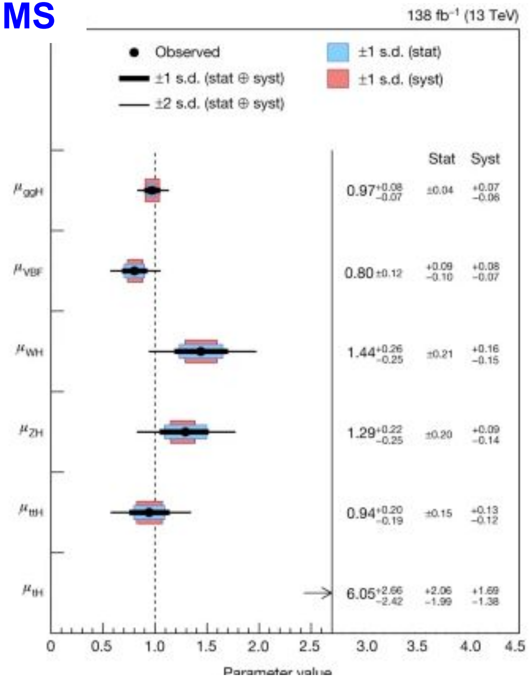
- Main 4 production modes have been observed with significance $\geq 5\sigma$

- Signal strength =

$$\boxed{\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}}$$

- Higgs signal strength measured with ~ 6% precision, uncertainty still dominated by statistics.

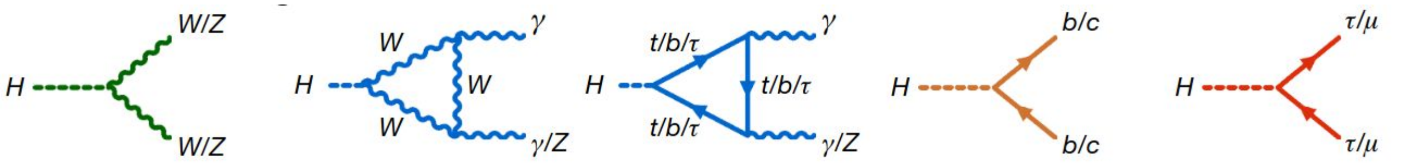
CMS

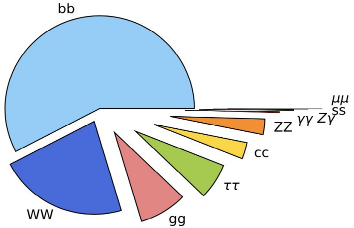


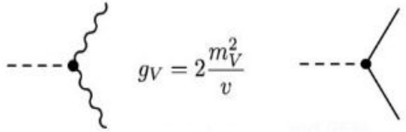
[Nature 607 (2022) 52]

[Nature 607 (2022) 7917]

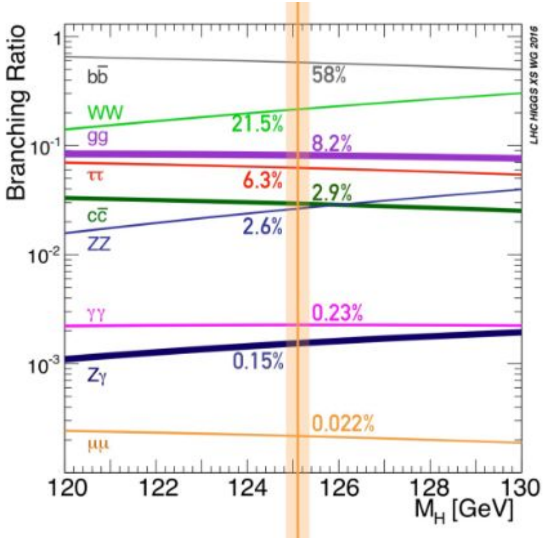
Higgs boson decays

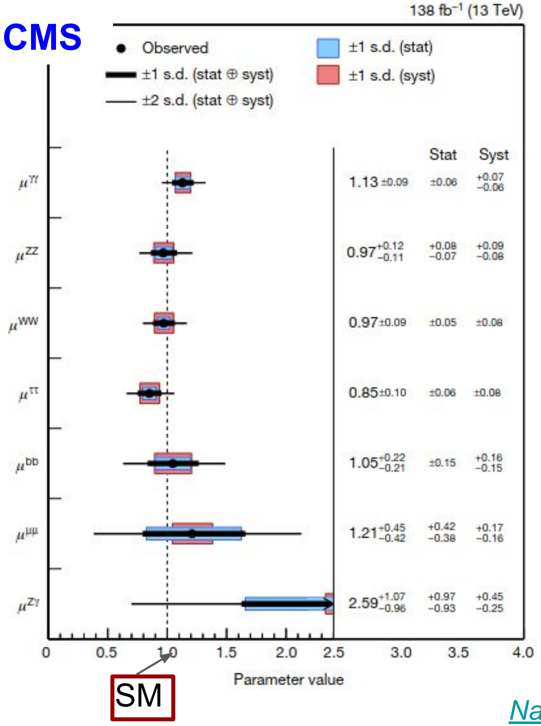






$g_V = 2\frac{m_V^2}{v}$ $g_F = \sqrt{2}\frac{m_f}{v}$



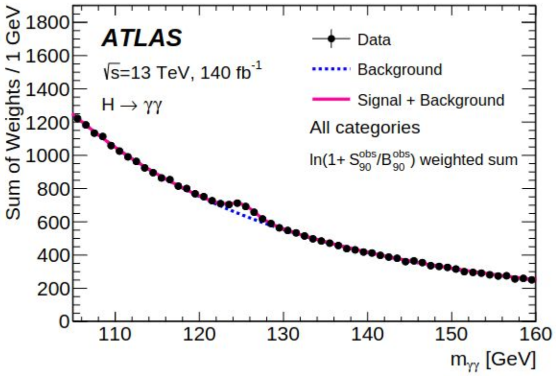


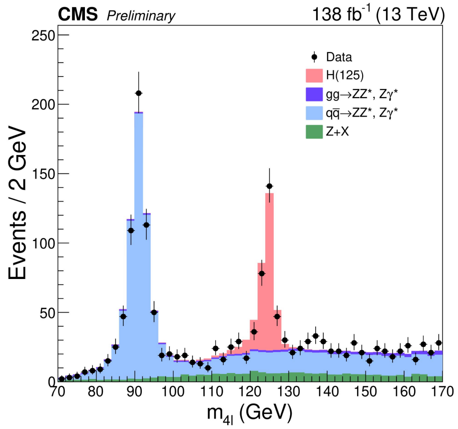
- Couplings to weak gauge bosons (V=W/Z) studied well from the early phase of LHC using H production and decays.
- Mass dependent Yukawa couplings of fermions with H
→ ***a new interaction of Nature***
- Couplings to 3rd generation fermions established well.
- First evidence of H decays to 2nd generation fermions (c quark, μ) + decay to $Z\gamma$ and other rare modes
→ **Talk by B.Seltzer**

Nature 607 (2022) 7917

Higgs boson mass

- A free parameter in SM.
- Important ingredient for predictions of SM eg.,couplings → production and decay rates of Higgs.
- Mass is best measured in high resolution (~1%) channels: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$.
- Br.($H \rightarrow \gamma\gamma$) ~ 0.23% , narrow mass peak over smooth background.
- Br.($H \rightarrow ZZ^* \rightarrow 4\ell$) ~ $1.2 * 10^{-4}$
  high S/B ratio, clean & narrow mass peak.
- Recently multiple improvements in both channels by each experiment due to better understanding of detector performances, improved calibrations, reconstruction methods & analysis strategies.
  Eg., syst. uncert. for ATLAS measurement of $H \rightarrow \gamma\gamma$ channel has improved by X3.
  .
- **Combination of Run1 + Run2 results still statistically limited.**





CMS

Run 2: $H \rightarrow 4\ell$: 125.04 ± 0.12 (stat.) ± 0.05 (syst.) GeV

Best single channel measurement

Combined Run 1 + Run 2 ($4\ell + \gamma\gamma$):

125.11 ± 0.11 GeV (stat.: ± 0.09)

CMS PAS-HIG-21-019

ATLAS

Run 2: $H \rightarrow \gamma\gamma$: 125.17 V 0.11 (stat.) ± 0.09 (syst.) GeV

Combined Run 1 + Run 2 ($4\ell + \gamma\gamma$):

125.11 ± 0.11 (stat.: ± 0.09) GeV

Best to-date precision of m_H: 0.09%

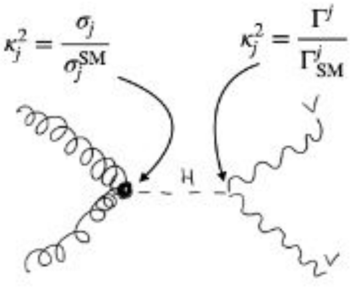
arXiv 2308.07216, 2308.04775

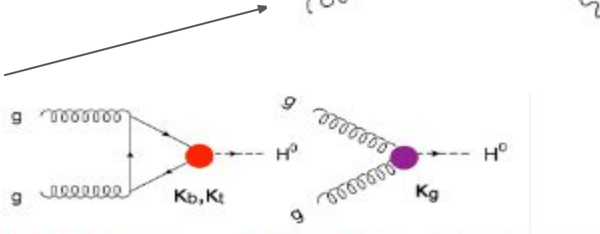
Anomalous couplings

- *Current precision in measurements allows for anomalous couplings.*
- Describe possible deviations from SM with the scale factors $\boldsymbol{\kappa}_i$ → the cross section or the partial decay width scales with $\boldsymbol{\kappa}_i^2$ when compared to the SM prediction.
- *Assume event kinematics to be unaltered.*
- **$\boldsymbol{\kappa}$- f**ramework can accommodate any non-SM invisible or undetected component.

$$(\sigma_i \times B_f) = k_i^2 \sigma_i^{SM} \frac{k_f^2 \Gamma_f^{SM}}{k_H^2 \Gamma_H^{SM}}$$

- κ_i =1 → SM
- κ_i ≠1 → BSM

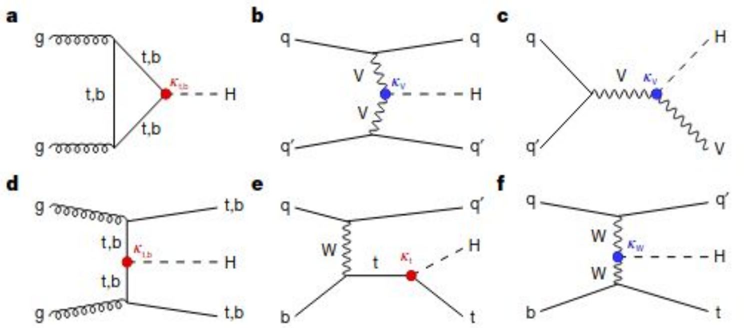




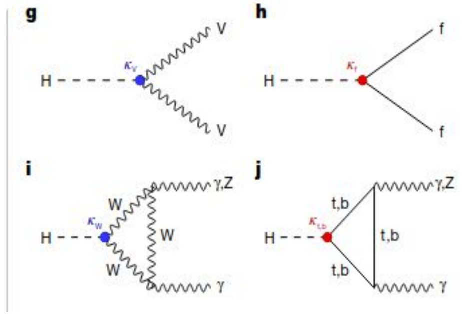
resolve loops effective couplings κ

More in talk by Stelzer

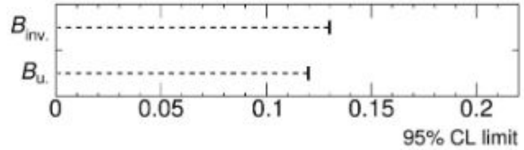
Higgs boson production modes



Higgs boson decay channels



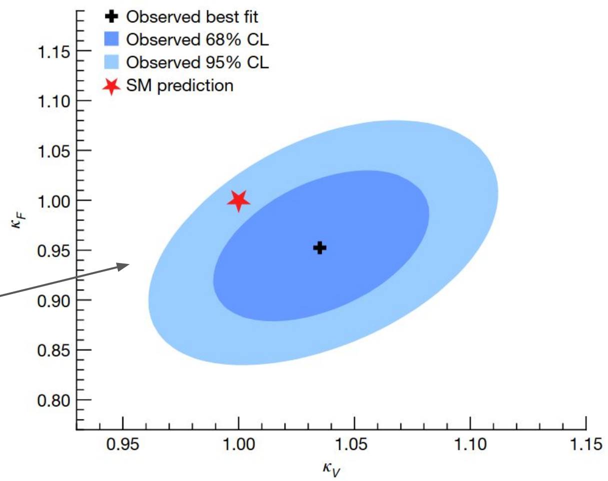
When upper limits on B_{inv} considered as free, B_u ≥ 0 with $\boldsymbol{\kappa}_{W,Z}$≤ 1



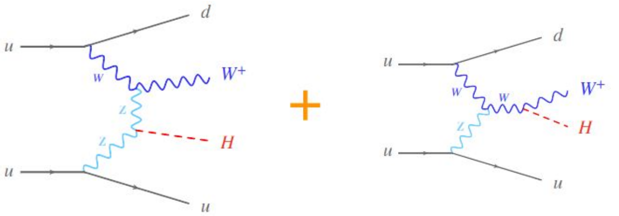
Reduced coupling modifiers to bosons and fermions

The coupling modifier framework parametrizes the production and decay modes inclusively.

Assuming no invisible or decays to BSM particles contributing to total width.



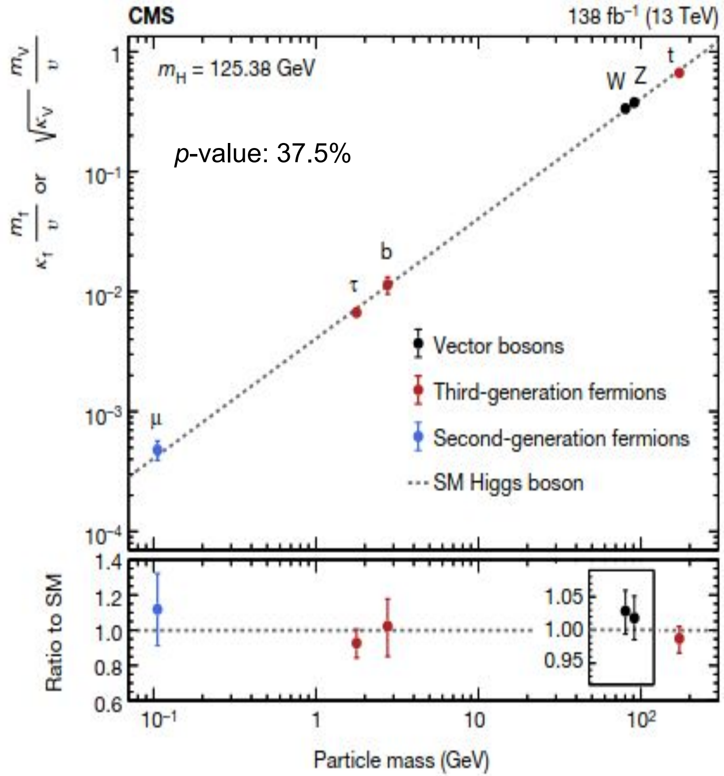
[Nature 607 (2022) 52]



Same sign coupling of H with W and Z ($\boldsymbol{\kappa}_W$ and $\boldsymbol{\kappa}_Z$) established with significance > 8$\boldsymbol{\sigma}$

[ATLAS-CONF-2023-057]

[Nature 607 (2022) 7917]



Data follows the pattern expected in SM.

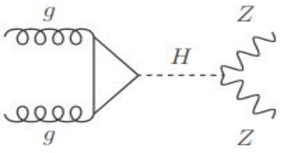
[Similar plot by ATLAS Collaboration]

Decay width of the Higgs boson

- $\tau_H \approx 1.6 \times 10^{-22}$ sec ⇒ the natural width, $\Gamma_H = 4.14 \pm 0.02$ MeV in SM.
- Γ_H can be estimated by comparing on-shell and off-shell productions of H assuming SM couplings and no new signal, other than possible enhancement of off-shell H contribution .

Higgs width can be measured directly using the on-shell width or lifetime.
But experimental resolution: ~ 1 GeV

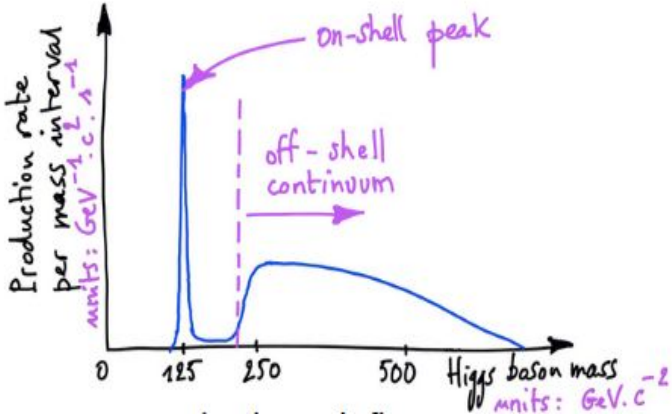
$gg \rightarrow H \rightarrow ZZ$:



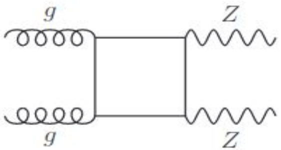
$$\sigma_{onshell}^{pp\rightarrow H\rightarrow ZZ} \sim \frac{g_{Hgg}^2 \, g_{HZZ}^2}{m_H \Gamma_H}$$

$$\sigma_{offshell}^{pp\rightarrow H\rightarrow ZZ} \sim \frac{g_{Hgg}^2 \, g_{HZZ}^2}{M_{ZZ} - m_H}$$

$$\rightarrow \quad \frac{\sigma_{offshell}}{\sigma_{onshell}} \propto \Gamma_H$$



$gg \rightarrow ZZ$:



- Negative interference of diagrams involving H and the gg → ZZ continuum.
- 15% of Higgs production x-sec. in HZZ is for large off-shell masses.

Off-shell production of Higgs established with a confidence of 3.6σ

Assume constant coupling in the range

CMS: $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV

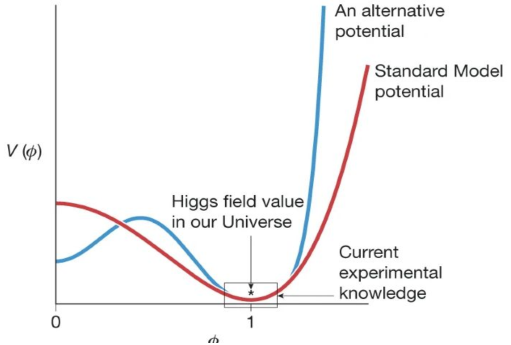
ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

[CMS PAS-HIG-21-019](#)

[arXiv:2304.01532](#)

Extracted value of H width consistent with SM.

Self-coupling of the Higgs boson

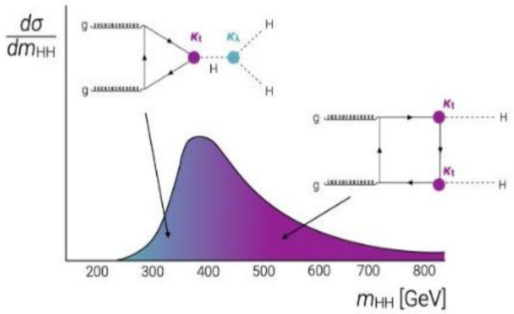


Before the electroweak symmetry breaking, Higgs potential: $V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$

$\Phi = v + h$

After EWSB: $V(h) \simeq \frac{1}{2}m_H^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \ldots$

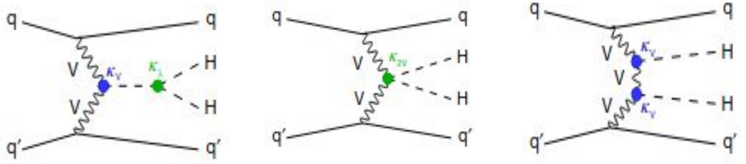
- Determination of Higgs self-coupling $\boldsymbol{\lambda}$:
  → Currently THE most important mandate to understand the nature or shape of the Higgs potential near the minimum
  → related to the evolution of the universe at the EW scale.



- Inclusive Higgs pair production at the LHC → direct access to HHH and VVHH vertices → $\boldsymbol{\kappa_\lambda}$, $\boldsymbol{\kappa_{2V}}$

  σ(pp→HH+X) ~ 31 fb almost 10^3 times smaller than σ(pp→H+X)

- Target both ggF and VBF processes:



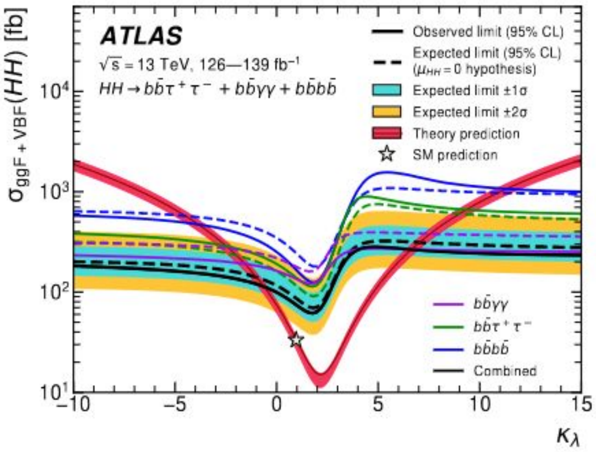
- Interference among relevant diagrams

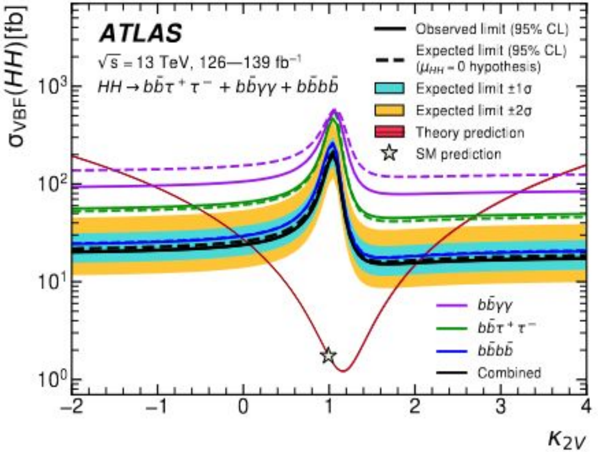
  →cross section dependency on the coupling modifiers

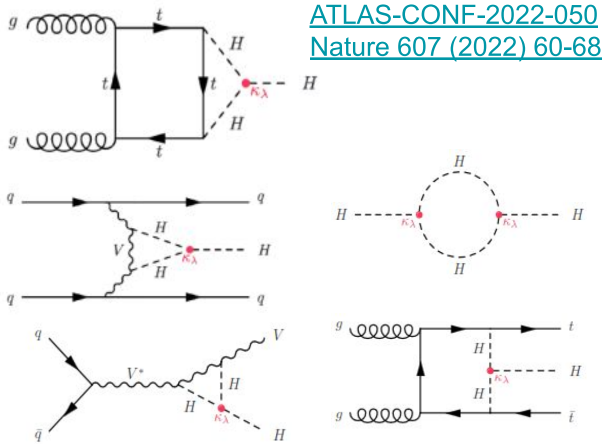
ATLAS-CONF-2022-050
Nature 607 (2022) 60-68

Limits on trilinear self-coupling and quartic couplings

PLB 843 (2023) 137745
ATLAS-CONF-2022-050
Nature 607 (2022) 60-68







Observed (expected) best limit on HH cross section by ATLAS: μ_{HH} < 2.4 (2.9) * SM

One-loop single Higgs production also involves κ_λ at higher orders,
⇒ better constraints on κ_λ and other couplings.

Combine single H and H-pair measurements for the most constrained allowed range of κ_λ (profiling κ_λ only) by ATLAS:
$-0.4 < \kappa_\lambda < 6.3$ @95% CL

$\kappa_{2V} = 0$ excluded by CMS with a 6.6σ significance.

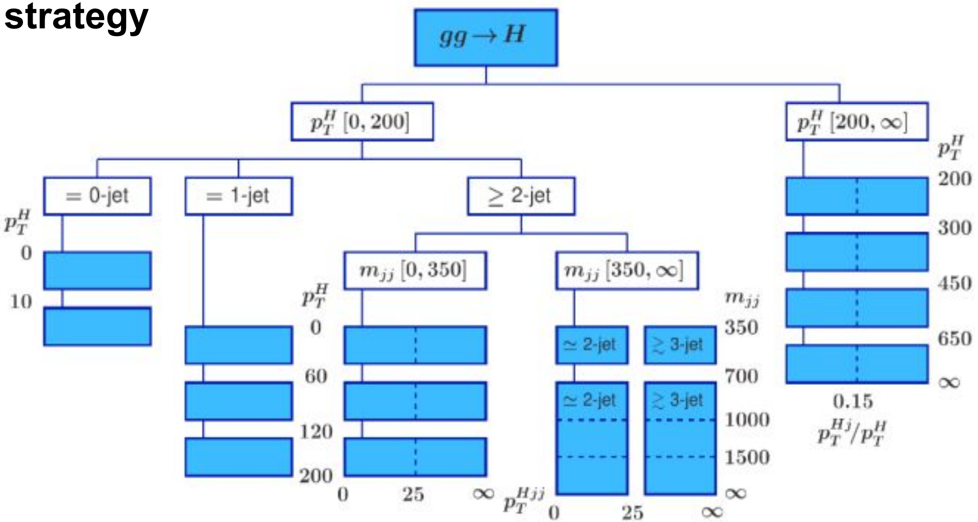
Allowed range of κ_{2V} ATLAS: [0.1, 2.0]

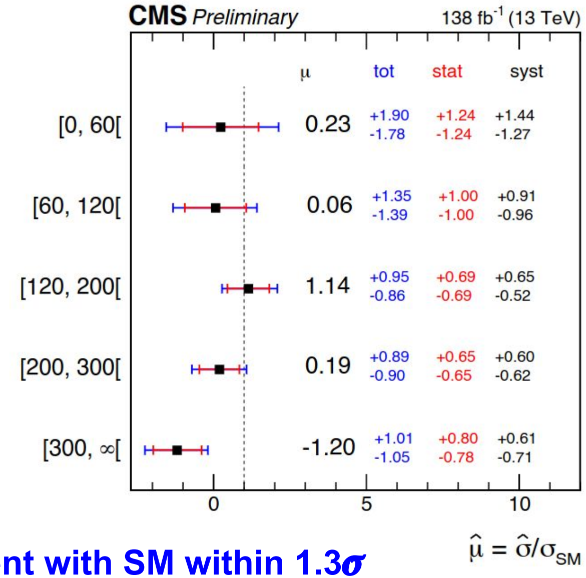
HL-LHC (Snowmass 2022) projections for SM HH:
- ATLAS γγbb+bbττ combination: 3.2σ
- CMS simple-minded combination of $\gamma\gamma$bb, $\gamma\gamma$WW, $\gamma\gamma$ττ and ttHH(bbbb) assures 5σ significance.

Simplified template cross section: STXS

- Cross sections for each production mode with specific final states, in bins of kinematic variables (eg. p_T^H, N_{jets}, m_{jj}) in exclusive regions of phase space. Specific bins have increased sensitivity to BSM.
- Granular measurement of the cross section for each production mode → allows kinematics-dependent interpretations.
- Provide a common set of definitions for the combination of the measurements → inclusive over the Higgs decays
- Analyses presently most sensitive to ggH.

strategy



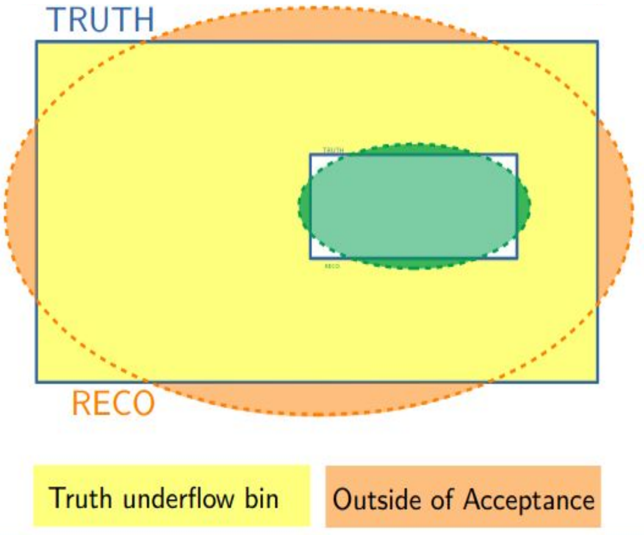


Consistent with SM within 1.3σ

CMS-PAS-HIG-19-011
JHEP 07 (2023) 088

The fiducial cross section

- Fiducial cross section: the phase space of interest aligned with detector configuration ⇒ no need for correction for kinematic selections on reconstruction level objects and analysis acceptance.



Dedicated, special phase space

- Fiducial phase space of the decay defined at the generator level is not exactly the same as that in the reconstruction level.

→ detector effects unfolded for the fiducial phase space defined at the generator level.

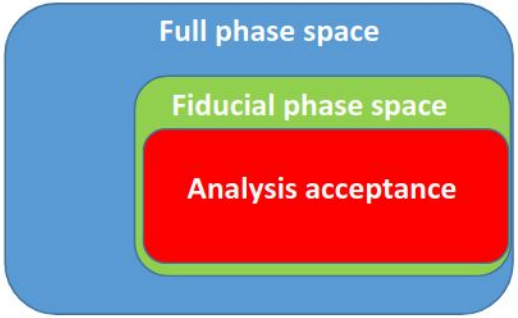
- Outside of acceptance (OOA) component part subtracted from signal before detector unfolding.

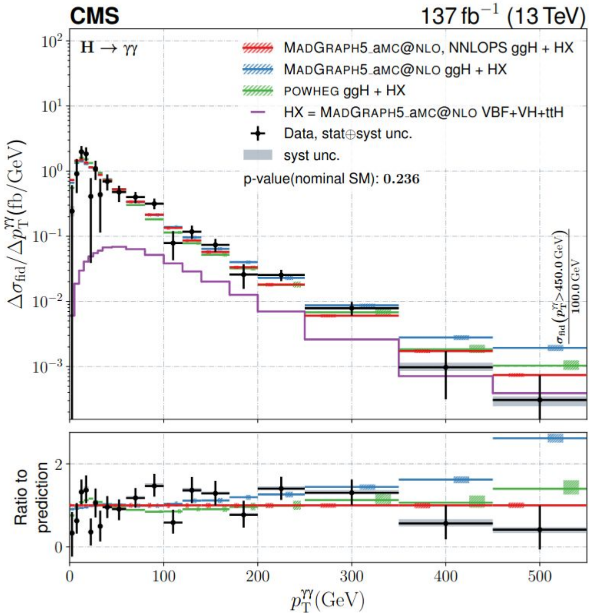
- Special phase space defined as a subset
  eg. require additional 2 jets in the event. → target VBF process requiring special topology of the 2 jets.

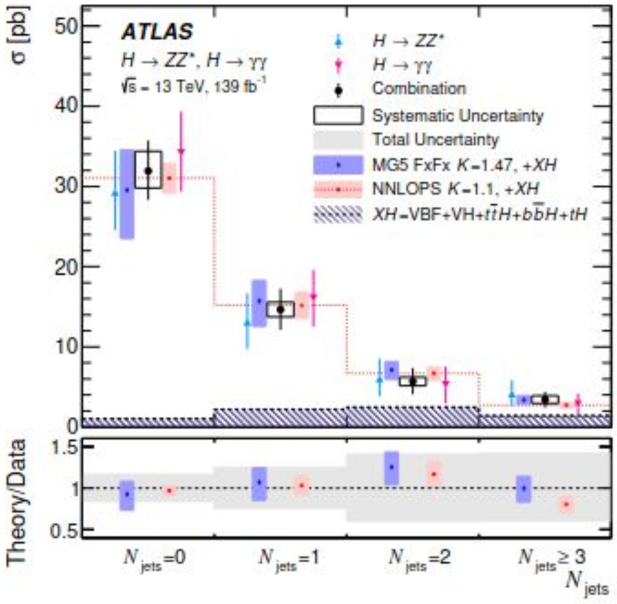
Differential cross section:

→ more information than inclusive cross sections
→ more powerful to validate or falsify models

Fiducial cross section in dedicated regions of phase space







Shape of $p_T^{\gamma\gamma}$ spectrum:

i) low p_T region sensitive to light quark Yukawa couplings.

ii) high p_T region sensitive to effective coupling to gluon.

No sensitivity of p_T to HVV couplings in SM.

CMS ($H \rightarrow \gamma\gamma$) $\sigma_{fid} = 73.4^{+5.4}_{-5.3}\,(\text{stat})^{+2.4}_{-2.2}\,(\text{syst})\,\text{fb} = 73.4^{+6.1}_{-5.9}\,\text{fb}$

SM prediction: 75.4 ± 4.1 fb

JHEP 05 (2023) 058
JHEP 03 (2023) 091

CP properties of the Higgs boson & effective field theory

- Higgs boson in SM is CP even: $J^{CP} = 0^{++}$
- CP-odd H complements other known sources → indication of BSM physics.
- Pure CP-odd Higgs excluded at > 99% CL by Run 1 data
- However, strong theoretical motivation to search for CP-violating effects in the couplings of Higgs with fermions
- Search for CPV in the shapes of various optimal observables (rate measurement is not sensitive to CPV)

- Fermionic couplings (Hff) modelled as : $\boxed{\mathscr{L}_{ffH} = \kappa_f' y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f}$
  → tree-level effect prominent in 3rd generation → ttH production, H→ $\tau\tau$ decay processes.

- Bosonic couplings (HVV): higher order operators suppressed by BSM scale Λ : $\boxed{\mathscr{L}_{VVH} = \mathscr{L}_{SM} + \frac{c_i}{\Lambda^2}\phi \tilde{V}_{\mu\nu} V^{\mu\nu} + \dots}$
  → pure CPV effects in interference term

- Effective Field Theory allows us to look for “low energy” deviations of “high energy” BSM physics.

(CP)

Anomalous contributions

(CP)

$$A(HVV) \sim \left[\boxed{a_1^{VV}} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \boxed{a_2^{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + \boxed{a_3^{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

~~(CP)~~

→ If VV= WW, ZZ, Zγ → Tree-level SM

→ If VV= gg → 1-loop SM

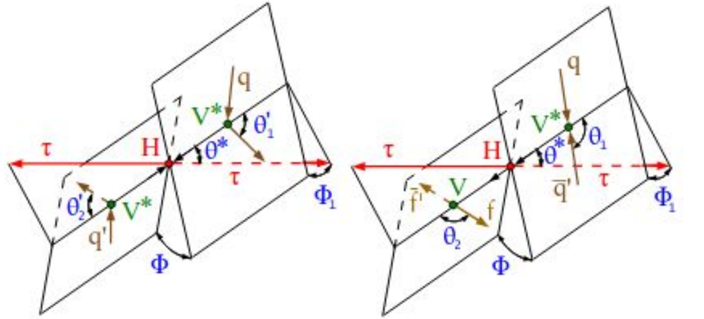
CP violation in HVV coupling using H →$\tau\tau$

PRD 28 (2023) 032013
JHEP 06 (2022) 012

- Effectively, estimate constraints on the fractional contribution of the anomalous couplings to the Higgs boson cross sections

- Effective cross sections measured in terms of ratios like

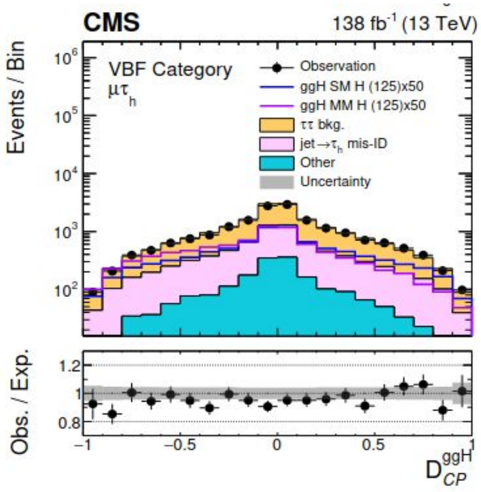
$$f_{ai} = \frac{|a_i|^2\sigma_i}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2\sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn}\left(\frac{a_i}{a_1}\right)$$

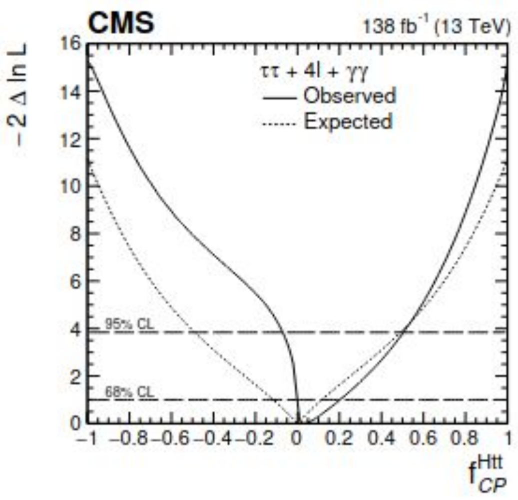


Matrix element calculations → discriminating variables

$$\mathcal{D}_{\mathrm{BSM}} = \frac{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})}$$

$$\Omega^{\mathrm{assoc}} = \{\theta_1^{\mathrm{VBF}}, \theta_2^{\mathrm{VBF}}, \theta^{*\mathrm{VBF}}, \Phi^{\mathrm{VBF}}, \Phi_1^{\mathrm{VBF}}, q_1^{2,\mathrm{VBF}}, q_2^{2,\mathrm{VBF}}\}$$





Combination of H → $\tau\tau$, H→ ZZ* →4l, H→$\gamma\gamma$ ⇒ higher sensitivity.

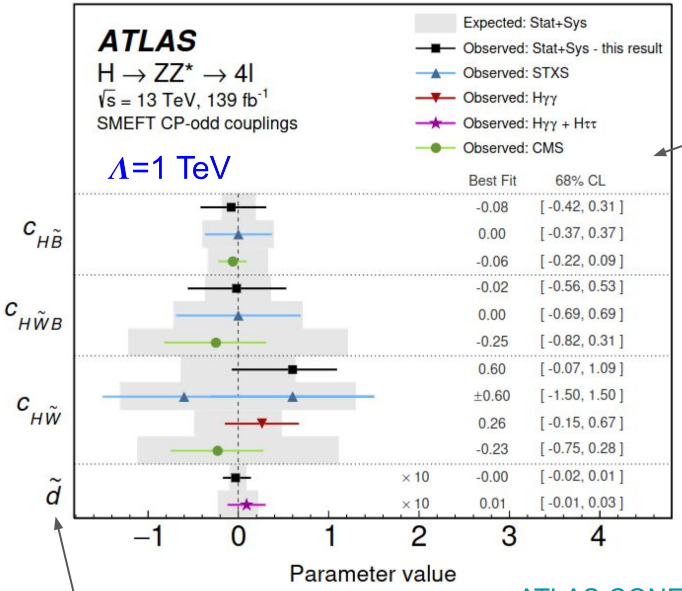
CP invariance in $H \to ZZ^* \to 4l$

SMEFT Lagrangian: $$\boxed{\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}}$$

$O_i^{(6)}$: CP-odd dimension-6 operators, invariant under SM

c_i : Wilson coeff.s, dimensionless, real → constrain these couplings using data assuming a single Higgs CP-odd BSM coupling under different assumptions.

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\tilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$



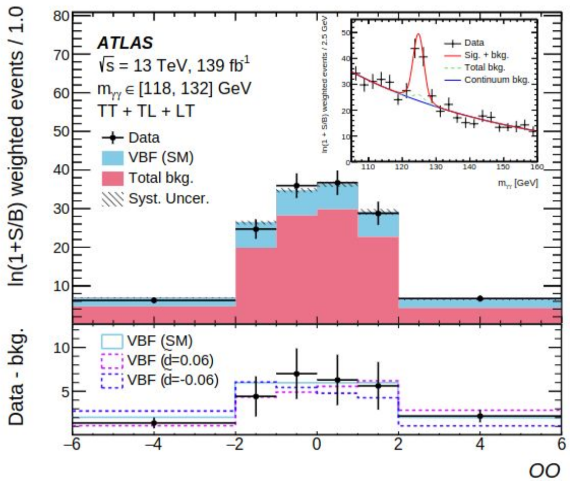
CP-odd HVV coupling

ATLAS CONF-023-057

- Couplings scale as $1/\Lambda^2$
- Some couplings relevant for production, some at decay, some for both.

Using $H \to \gamma\gamma$

- Optimum Observable depends on CP-odd interference term of SM and BSM amplitudes.

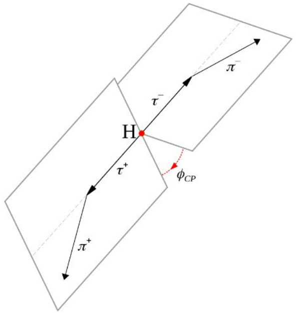


PRL 131 (2023) 061802

CP violation in $H\tau\tau$, ttH, tH

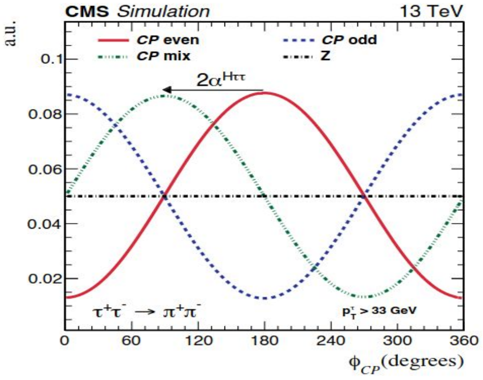
CP even CP odd

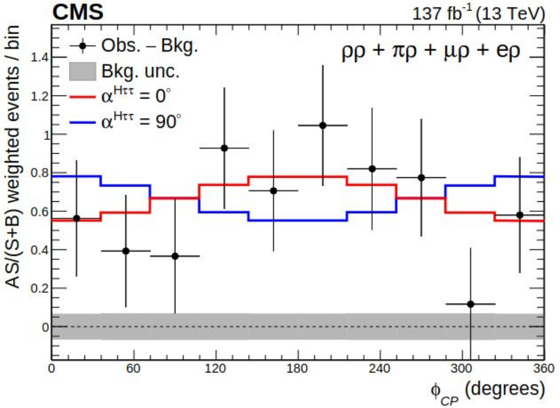
Parametrized Lagrangian for $H\tau\tau$ Yukawa coupling: $$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$



Effective mixing angle $\alpha^{H\tau\tau}$ probed via ϕ_{CP}

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





CMS: Observed $\alpha^{H\tau\tau}$: -1° ± 19°
Expected: 0° ± 20°

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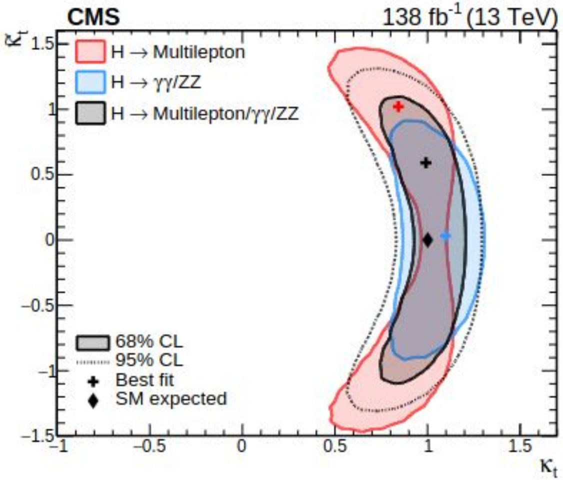
ATLAS: Observed $\alpha^{H\tau\tau}$: -1° ± 19°
Expected: 0° ± 28°

EPJC 83 (2023) 563

CMS (ATLAS) Pure CP-odd disfavoured at 3.2 (4) σ level

For ttH and tH processes, define an observable sensitive to the relative sign of the CP even and odd couplings

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \operatorname{sign}(\tilde{\kappa}_t/\kappa_t)$$



ATLAS study using ttH, Ht production and H→ bb decays: $\boldsymbol{\alpha}^{\mathbf{Hbb}}$ **: $11°^{+52°}_{-73°}$**

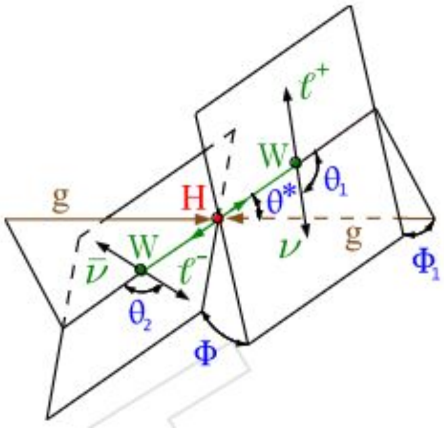
arXiv: 2303.05974

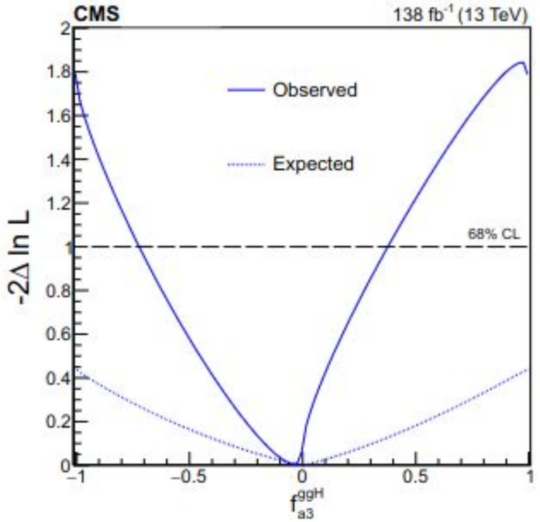
Search for anomalous Higgs-gluon coupling

CMS-PAS-HIG-22-008

- *Distinct kinematics in the off-shell region* lead to increased sensitivity (10-50%) to anomalous effects at the production vertex.
- Gluon fusion production with 2 jets ⇒ CP-odd a3 Hgg effective coupling due to a BSM pseudoscalar.

$$f_{a3}^{ggH} = \frac{|a_3^{gg}|^2\sigma_3^{gg}}{|a_2^{gg}|^2\sigma_2^{gg} + |a_3^{gg}|^2\sigma_3^{gg}} \operatorname{sign}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$





- A general test of the Higgs boson tensor structure and a search for CP violation in HVV interactions possible.
- Use gg → H+2 jets, H → WW, ZZ → leptonic decays.
- Simultaneous measurement of Higgs boson anomalous couplings to electroweak vector bosons performed in the framework of a SMEFT (Higgs or Warsaw basis).

Higgs basis

$$\delta c_z = \frac{1}{2} a_1^{ZZ} - 1,$$

$$c_{zz} = -\frac{2s_w^2 c_w^2}{e^2} a_2^{ZZ},$$

$$\tilde{c}_{zz} = -\frac{2s_w^2 c_w^2}{e^2} a_3^{ZZ},$$

$$c_{z\Box} = \frac{m_Z^2 s_w^2}{e^2} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}$$

Coupling	Observed	Expected
δc_z	$-0.06^{+0.09}_{-0.16}$	$0.00^{+0.08}_{-0.10}$
$c_{z\Box}$	$0.01^{+0.02}_{-0.06}$	$0.00^{+0.02}_{-0.02}$
c_{zz}	$0.03^{+0.30}_{-0.52}$	$0.00^{+0.23}_{-0.29}$
$\tilde{c}_{zz}$	$-0.17^{+0.42}_{-0.30}$	$0.00^{+0.29}_{-0.32}$

Conclusion

- 11 years back the discovery of Higgs boson marked a milestone in particle physics.
- Analyses of Run 1 and Run 2 data of the LHC have led to a significant improvement on our understanding of its properties.
- Only a small sample results presented today to underline the expanse of the efforts towards deciphering the Higgs sector.
- Within uncertainties results are compatible with the SM expectations.
- Waiting for good amount of data volume to be collected during Run 3.
- Interesting results continue to pour in → Stay tuned!
- High-Luminosity LHC, with Phase 2 upgraded detectors and further improved theoretical calculations, will make Higgs measurements even more interesting in the era of precision physics.

Thank you!

Back up

Statistical treatment

The combined results are obtained from a likelihood function defined as the product of the likelihoods of each input measurement.

The observed yield in each category of reconstructed events follows a Poisson distribution the parameter of which is the sum of the expected signal and background contributions.

The number of signal events in any category *k* is split into the different production and decay modes:

$$n_k^{\text{signal}} = \mathcal{L}_k \sum_i \sum_f (\sigma_i B_f)(A\epsilon)_{if}^k$$

the sum indexed by *i* runs either over the production processes (ggF, VBF, *WH*, *ZH*, tt*H*, *tH*) or over the set of the measured production kinematic regions, and the sum indexed by *f* runs over the decay final states (*ZZ*, *WW*, *γγ*, *Zγ*, bb, cc, $\tau^+\tau^-$, $\mu^+\mu^-$).
$\mathcal{L}_k$ *:* integrated luminosity of the dataset used in category *k.*
$(A\epsilon)^k{}_i$ *:* acceptance times selection efficiency factor for production process *i* and decay mode *f* in category *k*.