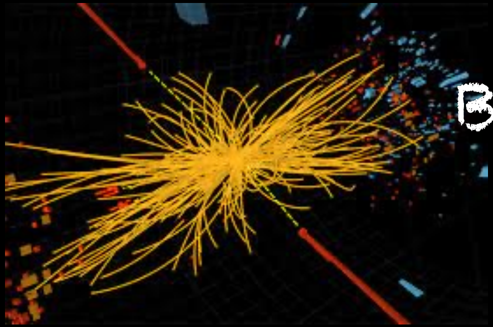
Summary of CMS Higgs Physics

Walaa Elmetenawee[1,2]

on behalf of The CMS collaboration

1- postdoctoral researcher, INFN Bari, Italy

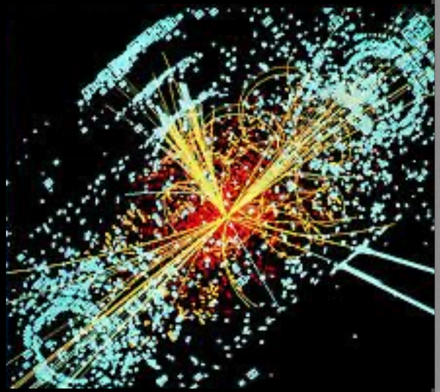
2. Lecturer, Helwan university, Cairo, Egypt



Beyond Standard Model conference

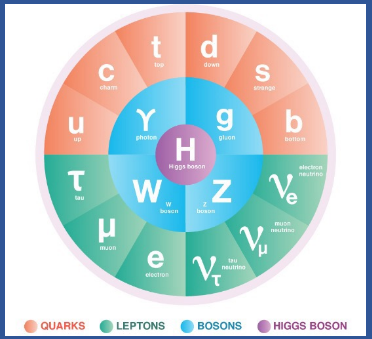
Hurghada - Egypt

6-9 Nov 2023

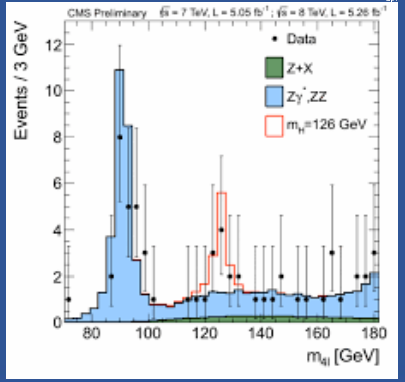


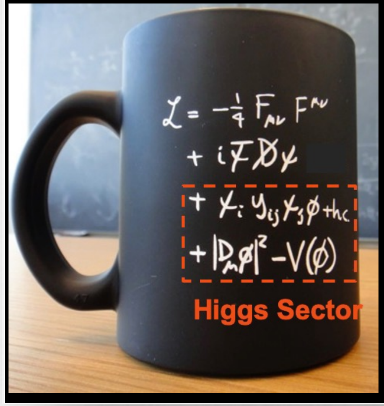
Introduction: Higgs Physics

- The Higgs boson is at the center of the Standard Model and can also serve as a bridge to Beyond-the- Standard-Model physics.
- Stability of the universe, “portal” to dark matter, CP violation etc.
- In 2012, both ATLAS and CMS have announced significant excesses at invariant masses of around 125 GeV.
- Results of further studies were consistent with the SM Higgs boson.
- Mandate after the discovery: we must check if this new particle belongs to SM or BSM.



Higgs boson discovery @ 2012





This talk will cover the latest Higgs measurements by CMS on this non-exhaustive list:

- ✓ Cross-section and couplings
- ✓ Mass and width
- ✓ Rare and exotic decays

The evolution of the Higgs boson

Mass: Phys. Rev. Lett. 114, 191803 (2015)
CP: Eur. Phys. J. C75 (2015) 476, Phys. Rev. D92, 012004 (2015)
Width: Eur. Phys. J. C(2015) 75:335, Phys. Lett. B736 (2014) 64 Coup
JHEP08(2016)045

Run 1

First Higgs boson property measurements

Mass ATLAS+CMS
125.09 ± 0.24
(± 0.21 ± 0.11) GeV

Spin/CP
Results consistent with a SM Higgs $J^{CP} = 0^{++}$

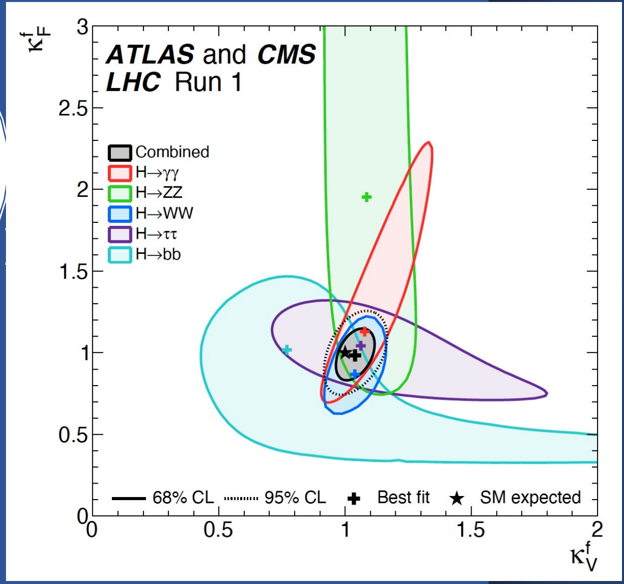
Width
$\Gamma_H < 22$ MeV @ 95% CL

Couplings
Results interpreted in terms of

Signal Strength $\mu = \frac{(\sigma.BR)_{obs}}{(\sigma.BR)_{SM}}$

Coupling modifiers (κ-framework

$\kappa_j^2 = \frac{\sigma_j}{(\sigma_j)_{SM}} \quad \kappa_j^2 = \frac{\Gamma^j}{(\Gamma^j)_{SM}}$



Run 2

Beginning of Precision Era...

More precise measurements
of the Higgs mass, width, couplings and differential cross section

More stringent constraints on anomalous Higgs boson couplings with other SM particles
Interpretation of the results in different theoretical framework (EFT, ...etc.)

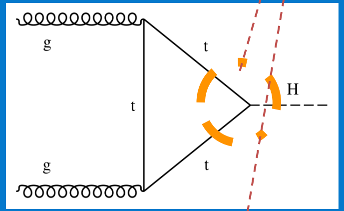
Run 3

towards higher energy and higher luminosity

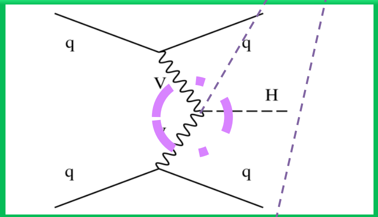
SM Higgs Boson production @ LHC

Can probe **fermionic** couplings of the Higgs e.g., Htt, Hbb

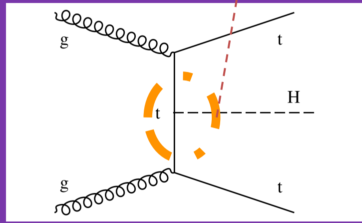
Can probe **bosonic** couplings of the Higgs e.g., HZZ, HWW



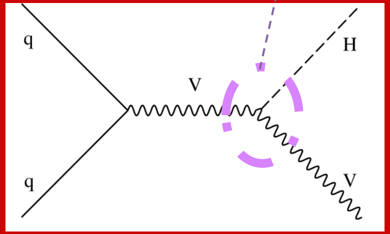
Gluon-gluon fusion ggH (87%)



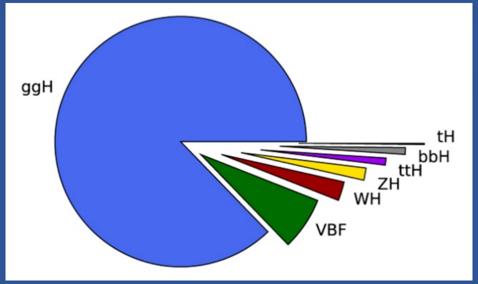
Vector boson fusion (VBF) qqH (7%)



Top quark pair associated production $t\bar{t}H$ (1%)



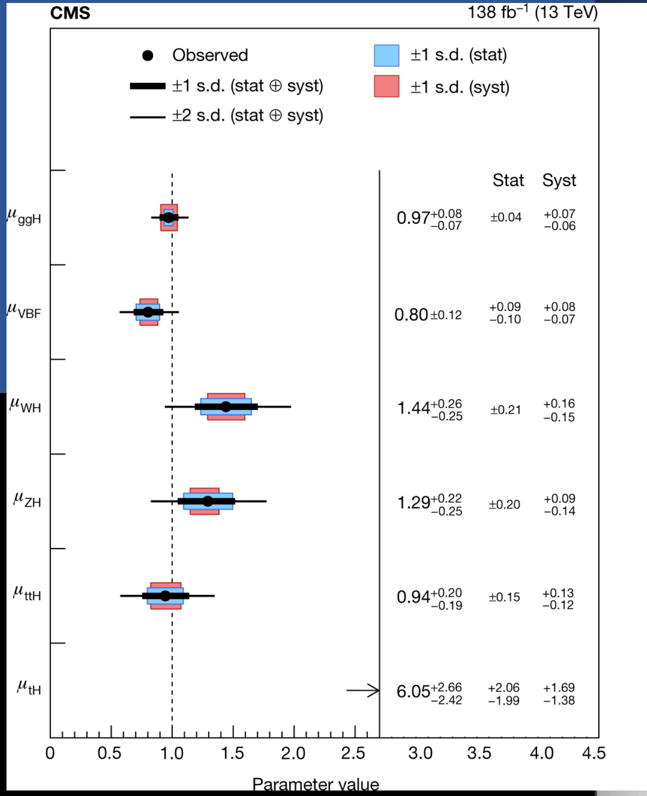
Vector boson associated production WH and ZH (4%)



- ✓ Main 4 production modes have been observed with significance ≥ 5 $\boldsymbol{\sigma}$
- ✓ Signal strength =

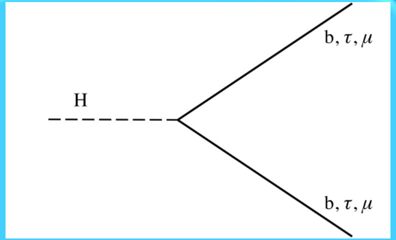
$$\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}$$

- ✓ Higgs signal strength parameters extracted for various production modes μ_i, assuming $B_f = (B_f)_{SM}$

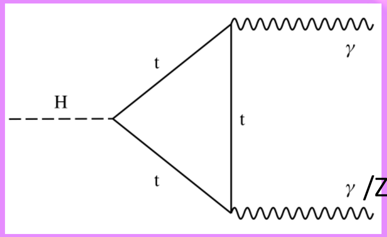


Nature 607 (2022) 60-68

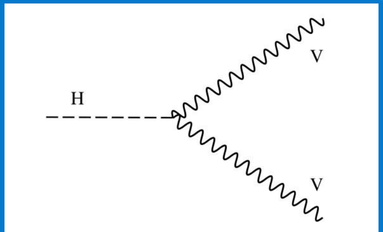
SM Higgs Boson decays @ LHC



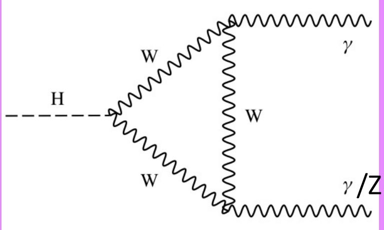
Higgs decay to two fermions



Higgs decay to two photons $H \to \gamma\gamma (Z\gamma)$

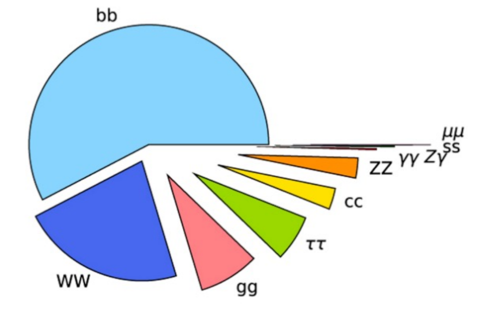


Higgs decay to two bosons $H \to ZZ$or WW

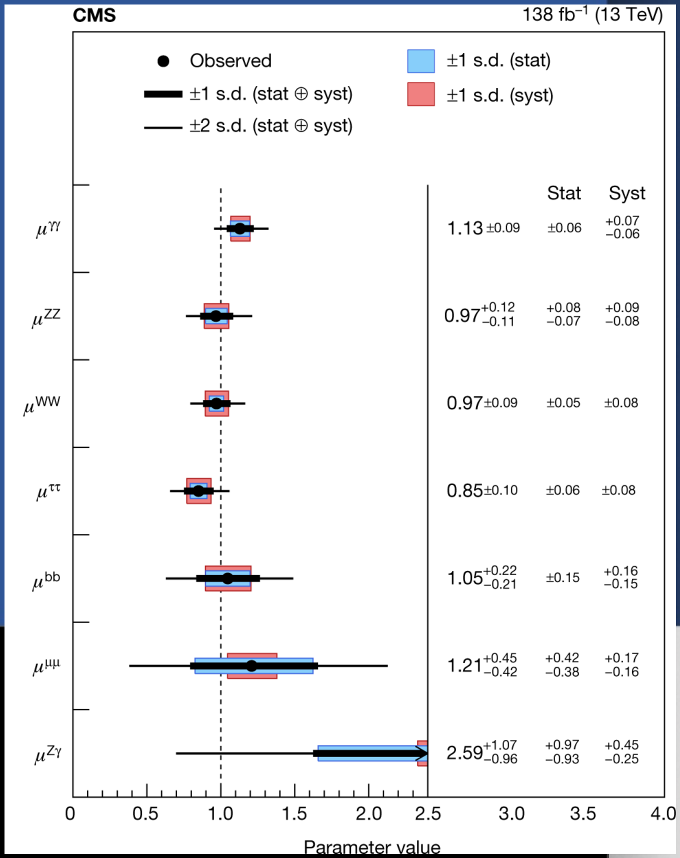


Higgs decay to two photons $H \to \gamma\gamma$ $(Z\gamma)$

Nature 607 (2022) 60-68



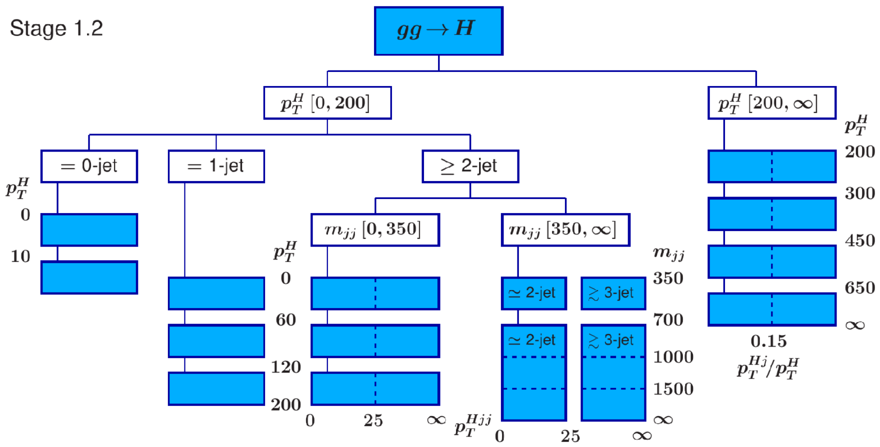
- Couplings to weak gauge bosons (V=W/Z) and to 3rd generation fermions established well.
- First evidence of H decays to 2nd generation fermions. ($H \to \mu\mu$) and Higgs rare decay ($H \to Z\gamma$).

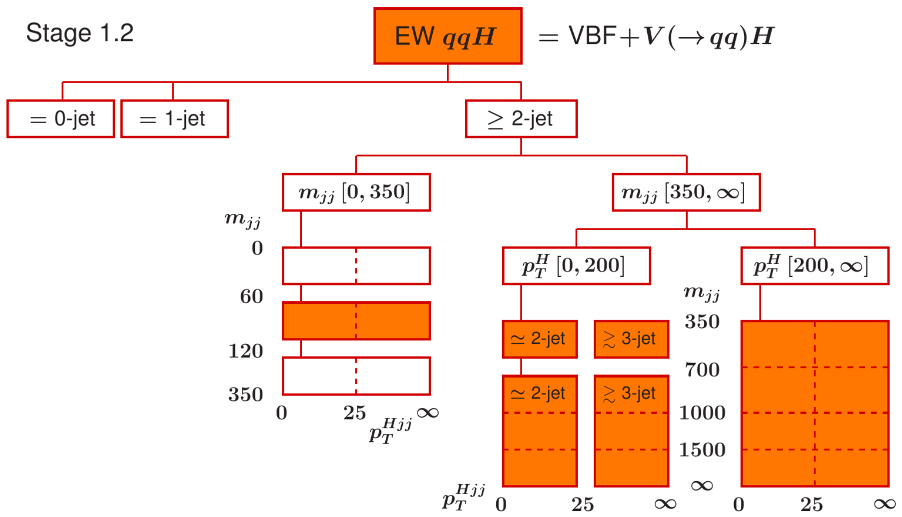


- By far most dominant decay mode is $H \to b\bar{b}$(58.2%)
  - Other $H \to$fermions scale $\propto m_f^2$
  - Can also measure decay to $\tau\tau$(6.3%) and $\mu\mu$(0.02%)
- Cleanest decay modes and best mass resolution are ZZ(2.6%), $\gamma\gamma$(0.23%).

Higgs STXS Measurements

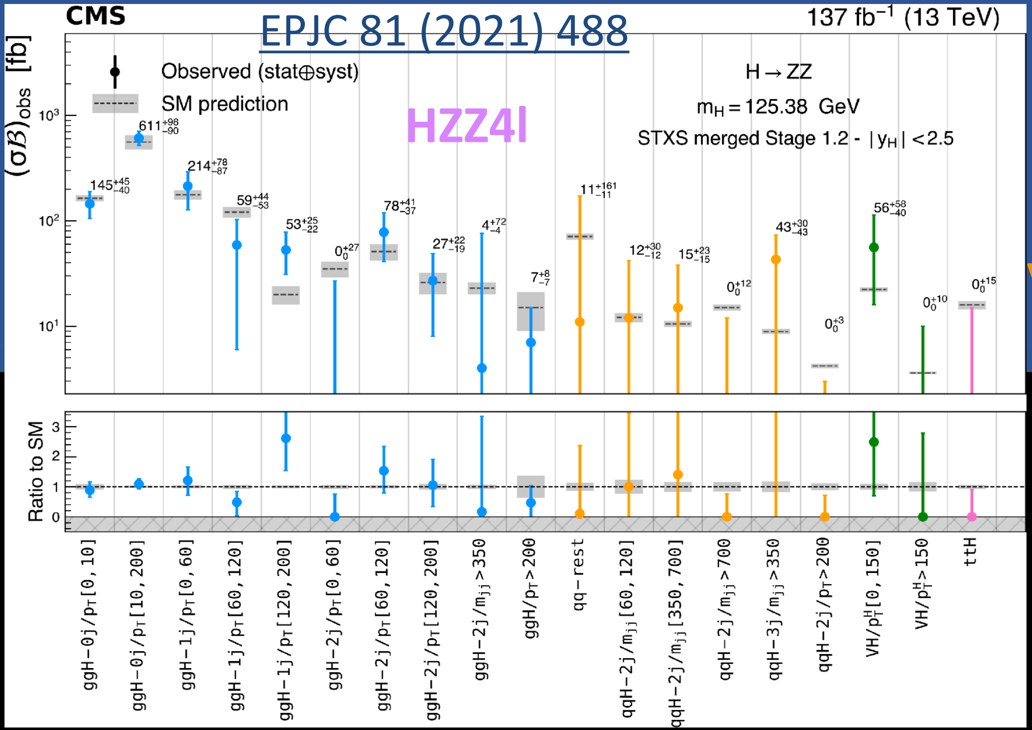
- The Simplified Template Cross Section (STXS) target maximum sensitivity, while keeping theoretical dependence as small as possible.
- Cross section split by production mode and divided in exclusive regions of phase space (bins).
- Inclusive in Higgs decay.
- The experiments are reaching the precision for measuring STXS in Stage 1.2
- Explicitly designed for combination.
- Input for EFT interpretation.



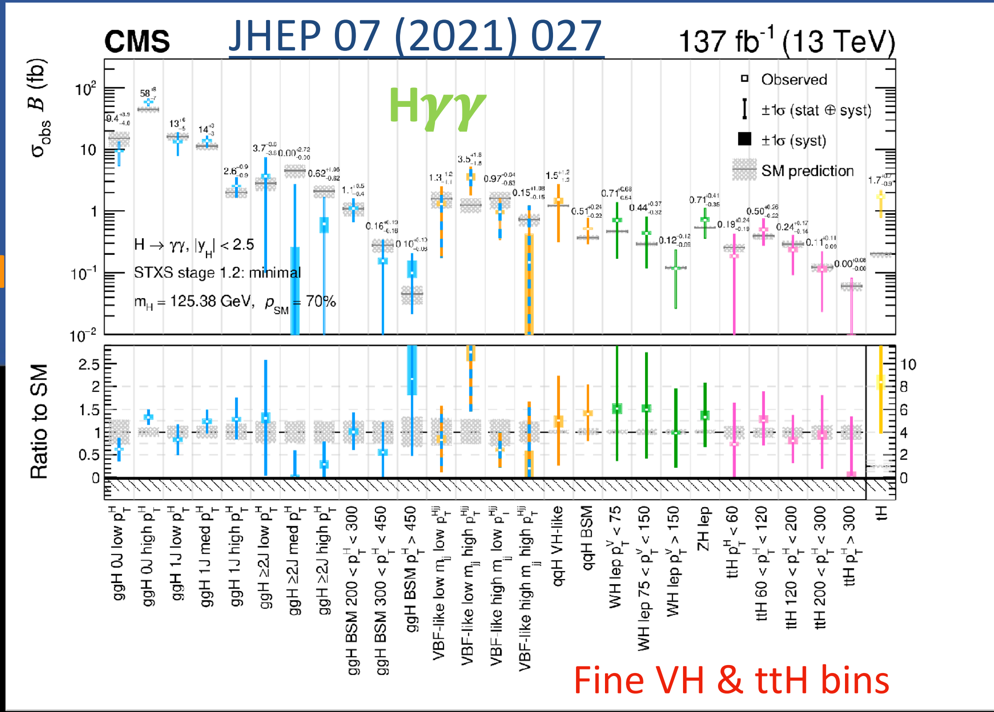


STXS in the "golden" channels

- HZZ4l: small BR, but high S/B, full m_H reconstruction with high resolution: matrix element information for categorization and m_{4l} for fits, providing merged STXS Stage 1.2 measurements .
- $H\gamma\gamma$: small BR, excellent mass resolution: BDT and cuts for categorization and $m_{\gamma\gamma}$ for fits, providing slightly merged STXS Stage 1.2 measurements.



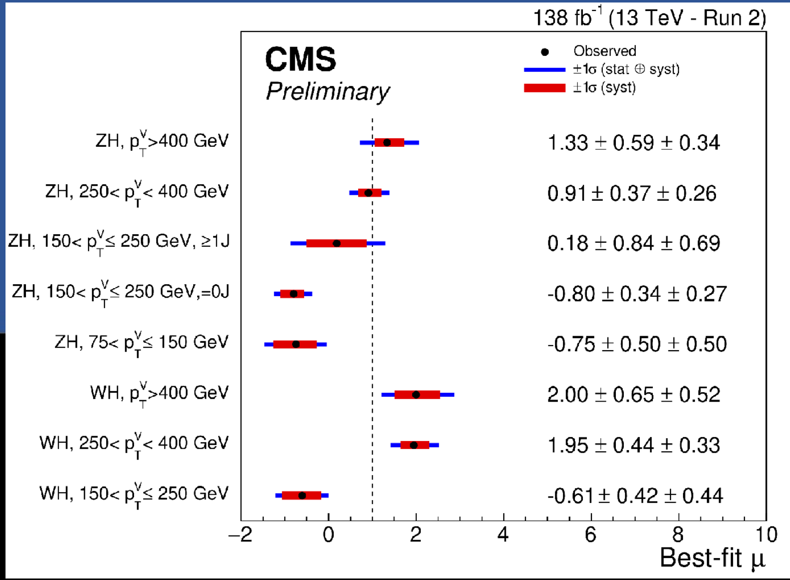
ggH
VBF+
VH Had
VH lep
ttH



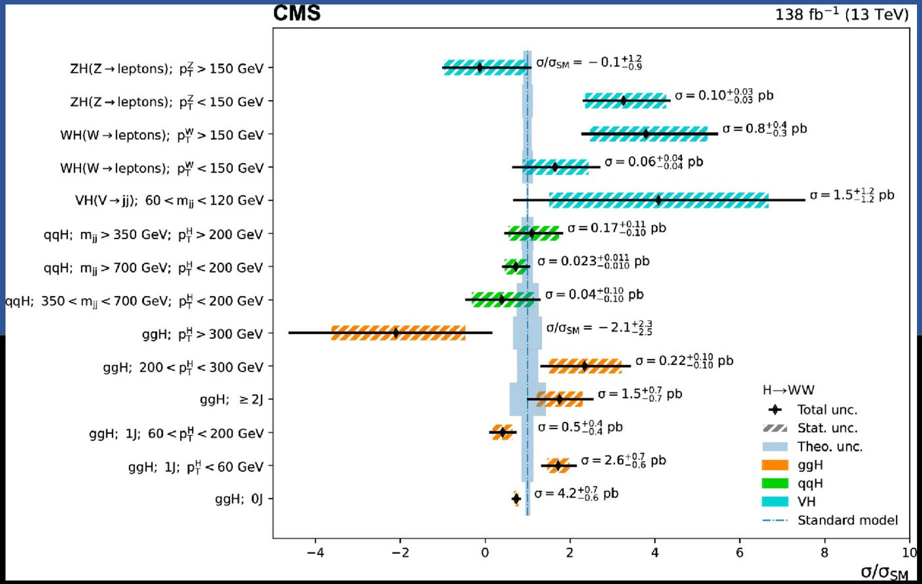
Good agreement with SM

STXS in high-stats channels

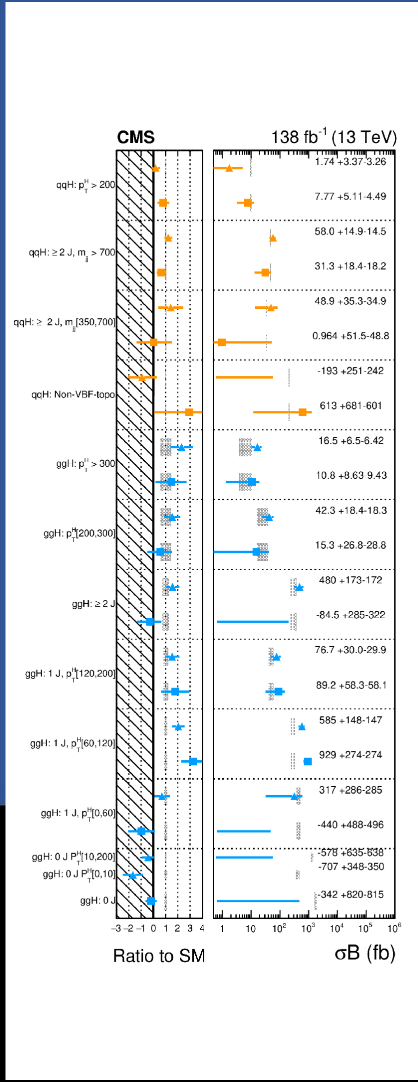
- High-stats channels including Hbb, HWW, and $H\tau\tau$ provide additional sensitivities in STXS.
- The focuses are mainly on ggH, qqH and V(lep)H.



Hbb focuses on V(lep)H
CMS-PAS-HIG-20-001



HWW focuses on ggH, qqH and V(lep)H
Eur. Phys. J. C 83 (2023) 667



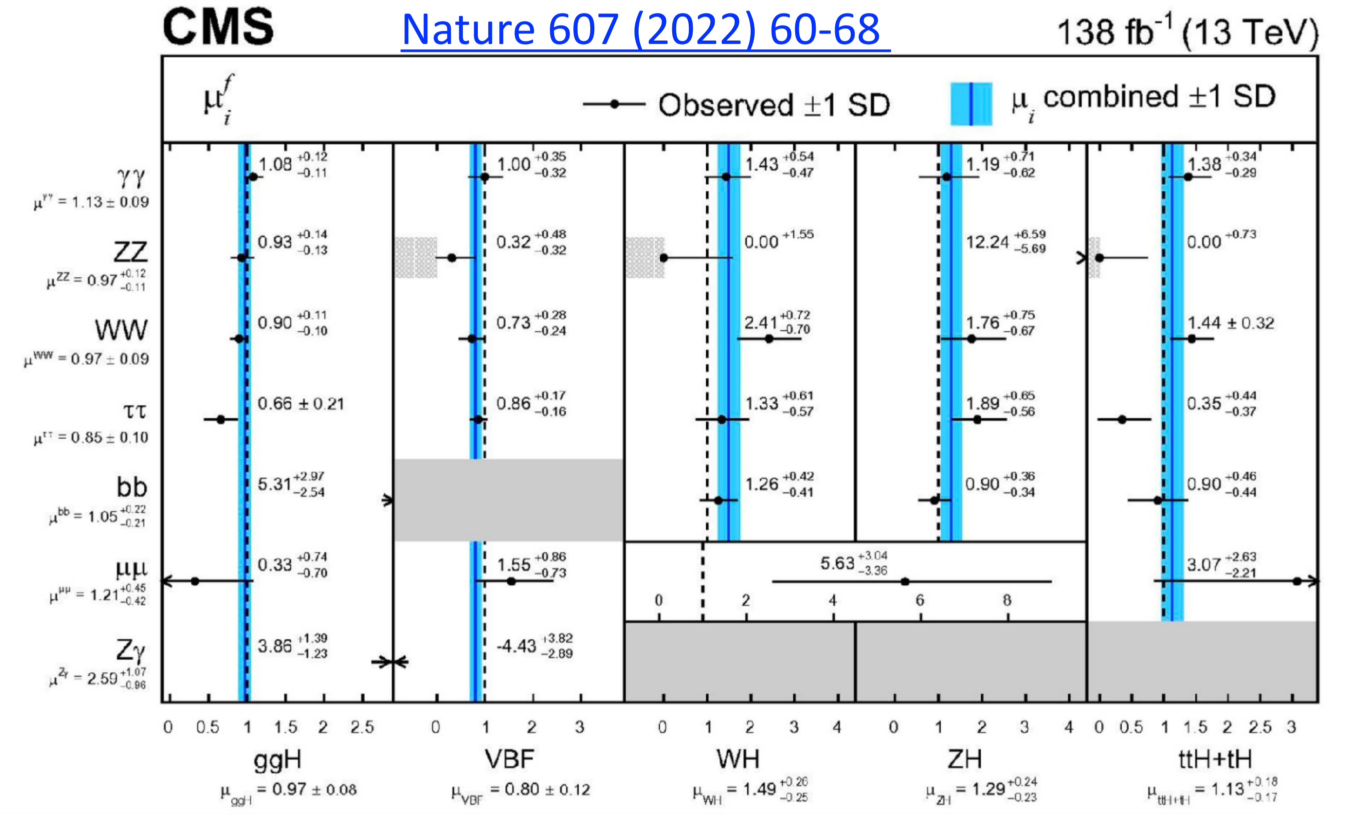
$H\tau\tau$ focuses on ggH and qqH
Eur. Phys. J. C 83 (2023) 562

The combination: signal strengths

- A deep examination of the Higgs mechanism done with full combination of available experimental observables.
- A good agreement with SM is observed at the current precision
- Few discrepancies in channels with limited statistical precision.

$\mu = 1.002 \pm 0.057$

Decay



Production

HZZ4l : JHEP 08 (2023) 040

Differential XS

- Fiducial phase space definition based on detector acceptance to minimize the model dependency: different phase space definition to target different production modes.

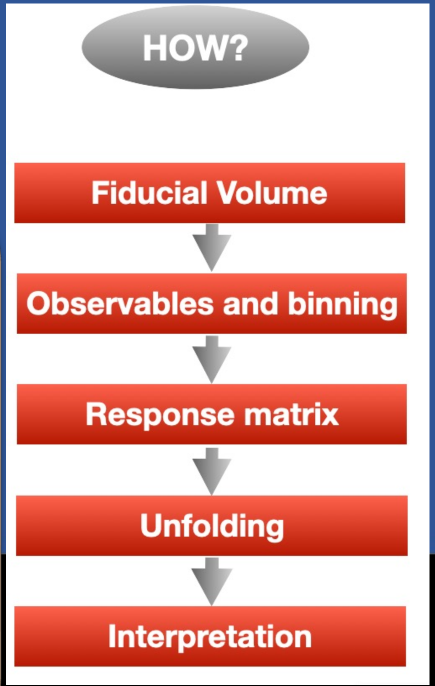
WHY?

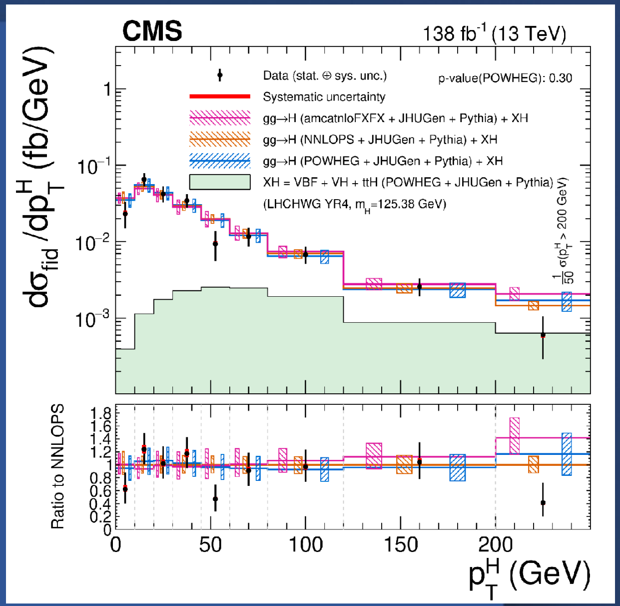
New physics might affect the shape of Higgs distribution, without affecting its overall production "**Differential measurements**" are needed to identify such effects.

✓ **Transverse momentum: $p_T(H)$**
  - Sensitive to modifications of effective Higgs Yukawa couplings.
  - Sensitivity to finite top mass effects.

✓ **Jet multiplicity and p_T**
  - New physics in the quark loop (especially at high jet p_T)

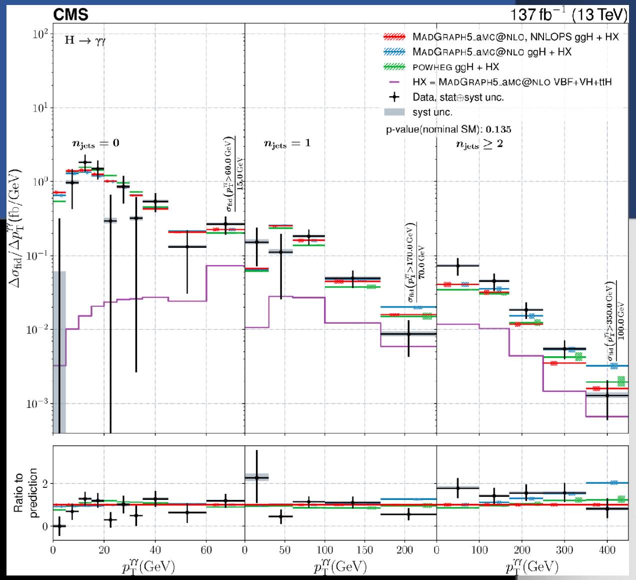
✓ **Higgs rapidity:**
  - Effects on gluon PDF.





H→ZZ: $\sigma_{\text{fid}} = 2.84^{+0.34}_{-0.31} = 2.84^{+0.23}_{-0.22}\,(\text{stat})^{+0.26}_{-0.21}\,(\text{syst})\,\text{fb}$

$$\sigma^{\text{SM}}_{\text{fid}} = 2.84 \pm 0.15\,\text{fb}.$$

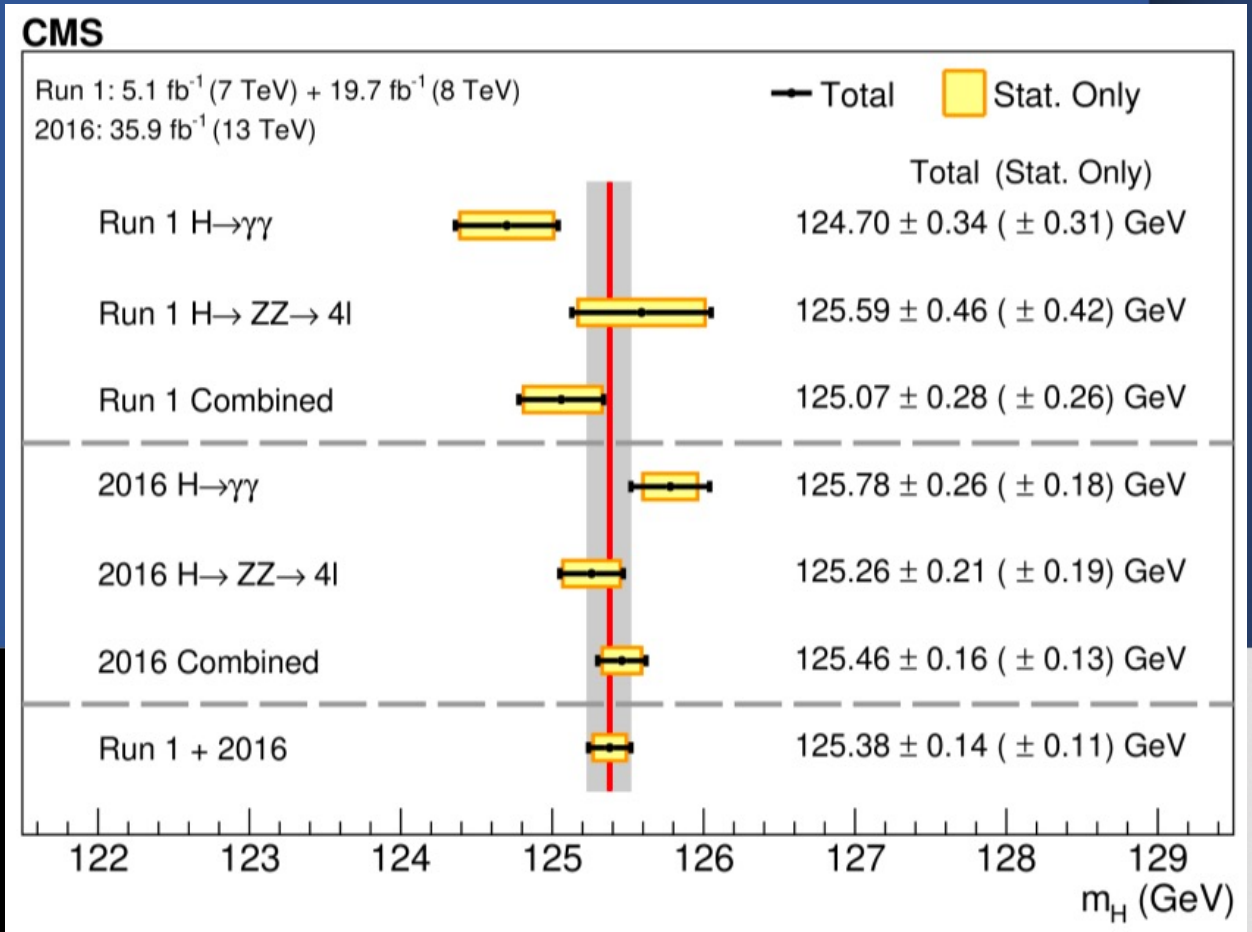


Hγγ: JHEP 07 (2023) 091

Higgs boson mass

Phys. Lett. B 805 (2020) 135425

- Fundamental parameter in the SM, it determines production and decay rates of the Higgs ➔ need to measure experimentally.
- Measured with *H→γγ* and *H→ZZ→4l*, thanks to their complete reconstruction of the final state and their excellent mass resolution (1-2%)

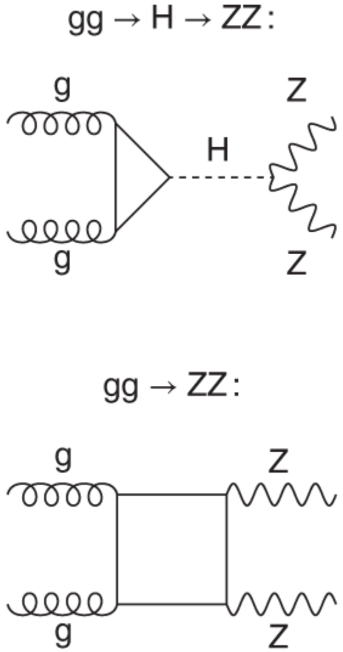


Run1 ATLAS+CMS:
m_H = 125.09 ± 0.24 GeV
Phys. Rev. Lett. 114 (2015) 191803

CMS most precise up to now:
m_H = 125.38 ± 0.14 ± 0.11 GeV
H$\gamma\gamma$ & HZZ4l with Run1+2016
Phys. Lett. B 805 (2020) 135425

The Higgs width

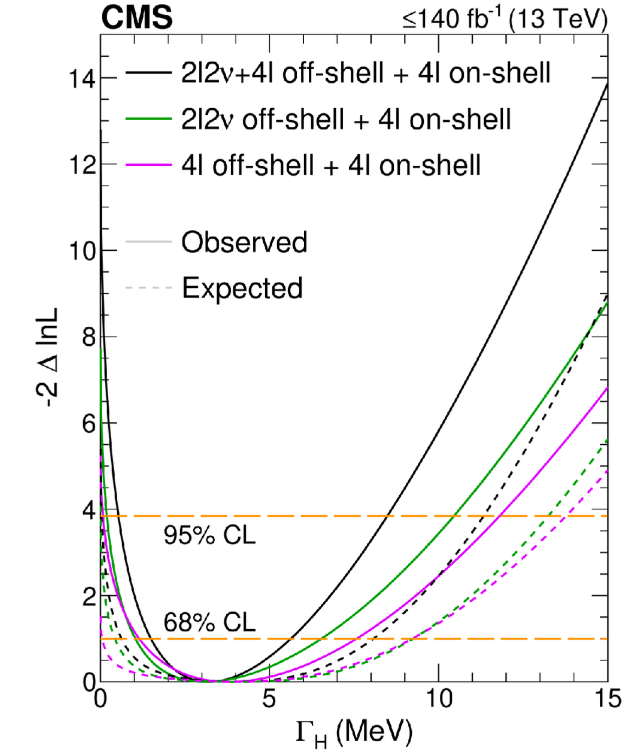
- SM Higgs width Γ_H= 4.1 MeV → experimental resolution O(1-2 GeV) are too small to allow direct measurements.
- Indirect measurement from the ratio of the on-shell/off-shell Higgs boson production.
- First evidence of off-shell Higgs boson production with 3.6 σ ($\mu_{off\text{-}shell} = 0.74^{+0.56}_{-0.38}$)



$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{(2m_Z)^2}}$$

$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

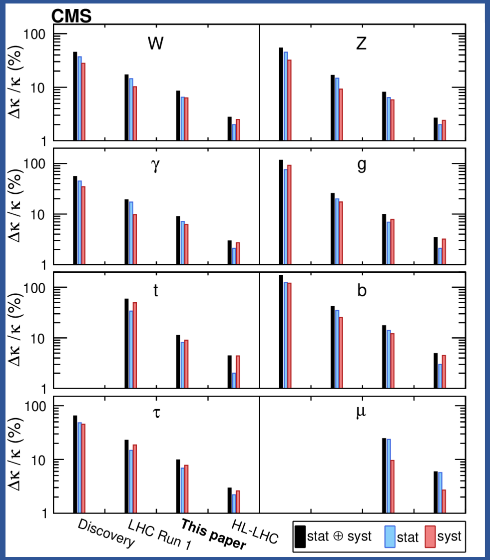
Nat. Phys. 18 (2022) 1329

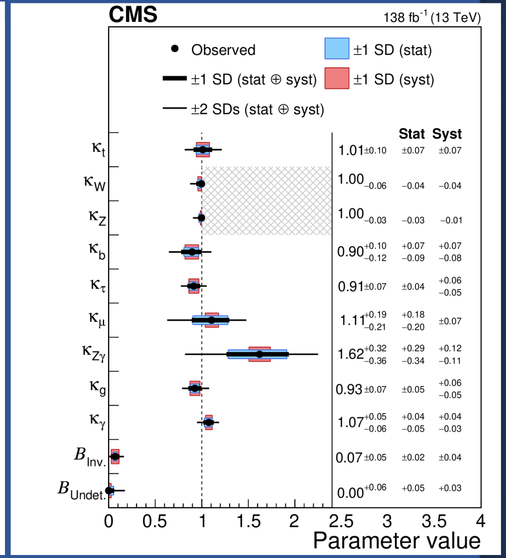


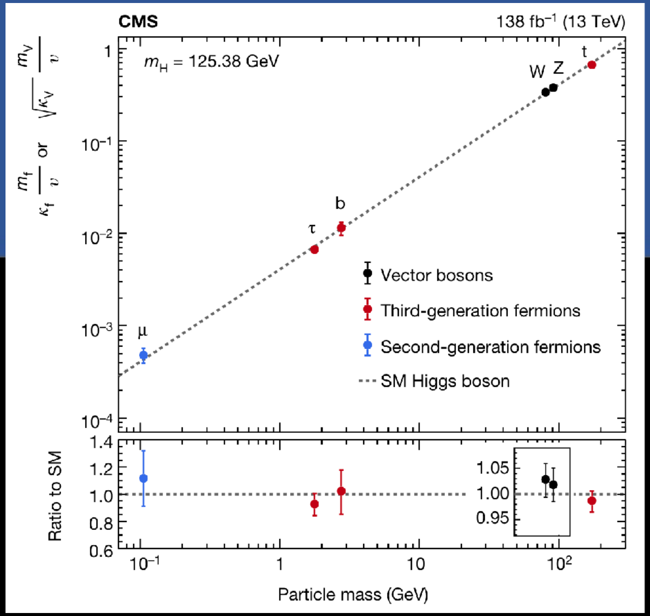
The couplings

Nature 607 (2022) 60-68

- Impressive improvement on Higgs couplings determination over the years
- couplings to boson and 3rd generation particles are now known at ~10% level, with no significant deviations from the SM predictions.







Nature 607 (2022) 60-68

- The Higgs sector of the standard model, tested across 3 orders of magnitude in particles masses shows an amazing agreement with the theoretical predictions for the scaling of the couplings.
- We are starting to probe the 2nd generation!

Higgs self-coupling

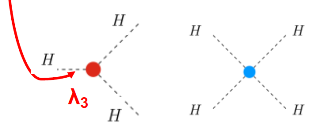
- The double Higgs processes (HH) provides a direct probe to the Higgs self-coupling but very challenging as its XS is 3 orders of magnitude smaller than the single Higgs (direct measurement).
- The Higgs self-coupling affects the Higgs propagator and enters single Higgs production via loops . Combining several channels together, it is possible to extract limits on the Higgs trilinear coupling kλ (indirect measurement).

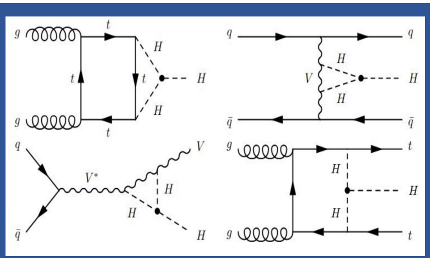
$$V(h) = \lambda v^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4 + \cdots$$

Higgs mass term — Higgs self-coupling

In SM

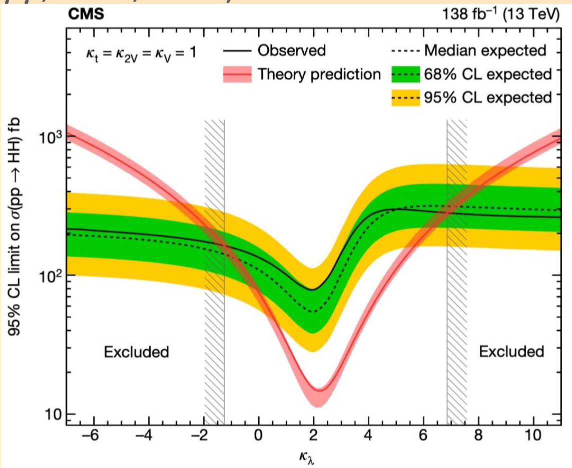
$$\lambda(=\lambda_3 = \lambda_4) = \frac{m_h^2}{2v^2} \sim 0.13$$





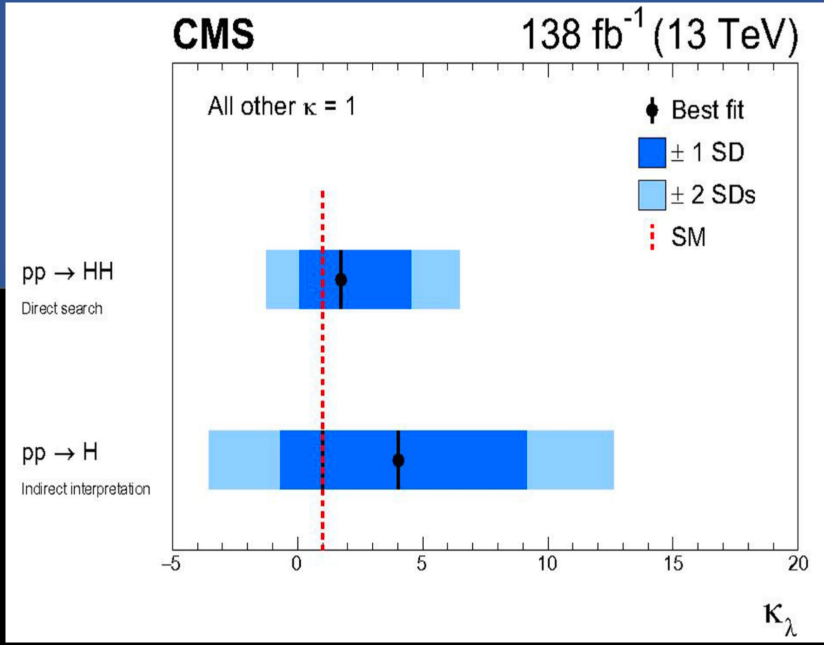
Direct measurement

Combined results from di-Higgs searches (4b, bb$\gamma\gamma$, bb$\tau\tau$, bbZZ)



$-1.24 < \kappa\lambda < 6.49$@ 95% CL

Nature 607 (2022) 60-68



Nature 607 (2022) 60-68

The HH sensitivity already surpassed the single Higgs in terms of Higgs self-coupling

Anomalous couplings

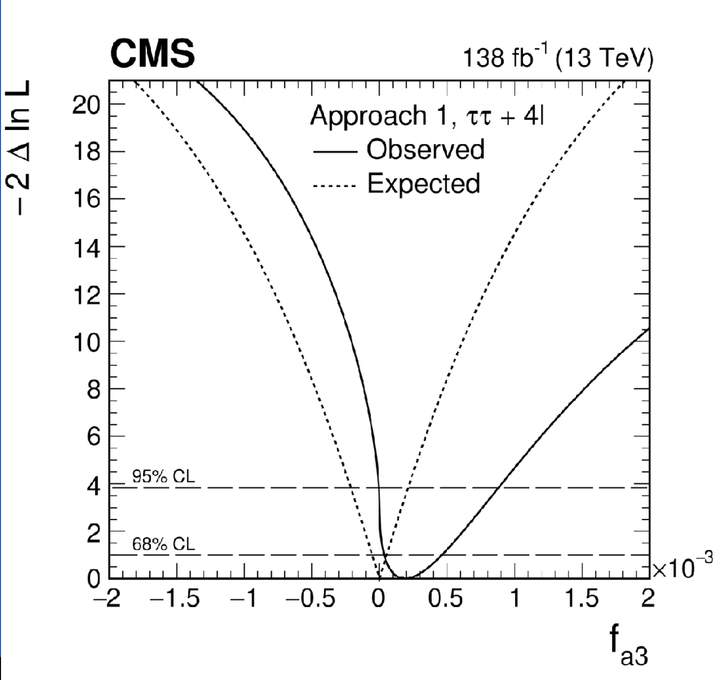
- Looking for signs of CP-violation in the Higgs sector
  - study the coupling with vector bosons (HVV) and fermions (Hff).
  - use of observables optimized to discriminate different CP hypothesis.
  - interpret the results in terms of anomalous Higgs boson couplings.

$$A(H \to ff) = -\frac{m_f}{v}\bar{\psi}_f(\kappa_f + i\tilde{\kappa}_f\gamma_5)\psi_f$$

$$A(H \to VV) \sim (A_1 + A_1^{BSM})m_V^2 + A_2 + A_3$$

0+ | 0- | Tree-level | loop

$$f_{a3} \sim \frac{|A_{0^-}|^2}{|A_{0^+}|^2 + |A_{0^-}|^2}$$



Phys. Rev. D 108 (2023) 032013

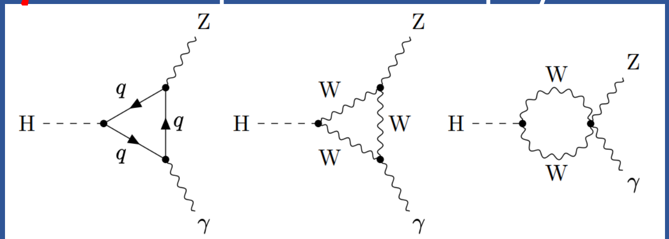
- CP structure of Higgs couplings probed for t, τ, g, Z, W, with a variety of production and decay modes
- Measurement globally agrees with SM 0^+

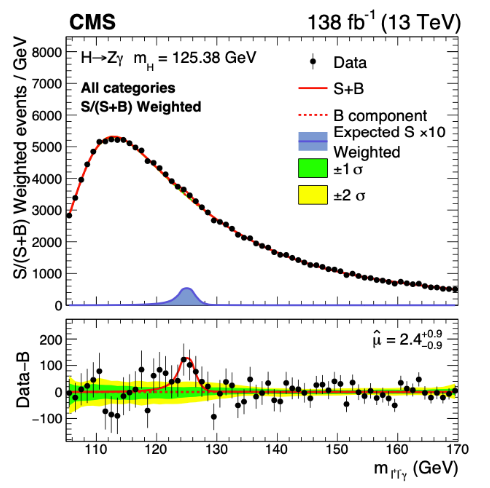
The Higgs boson rare decays: $H \to Z\gamma$

CMS: $\mu = 2.4 \pm 0.9$, local significance $2.7\ \sigma$

Very rare decay! Important for probing the Higgs properties and for validating SM/BSM theories *(BR ~1.5 ×10^{-3})*

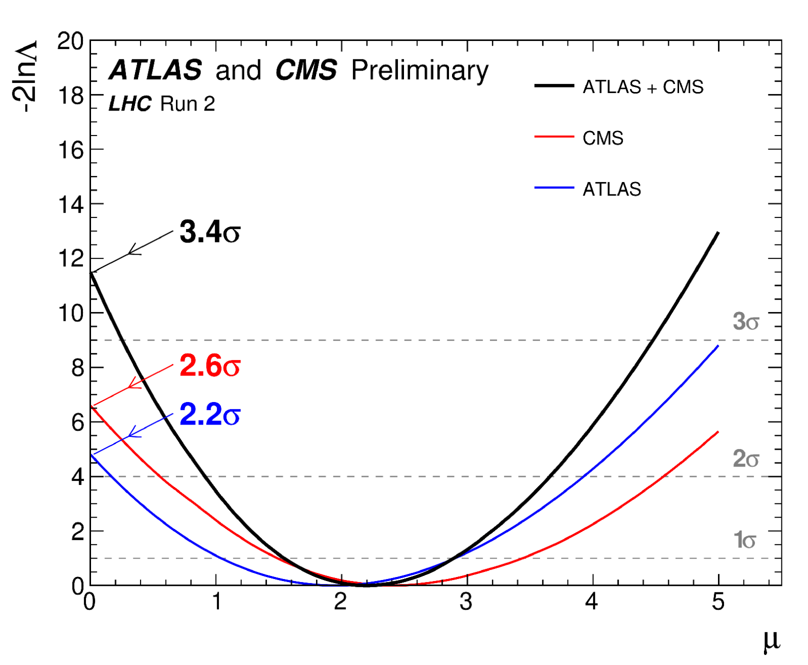
$H \to Z\gamma$ with loop where new physics can hide

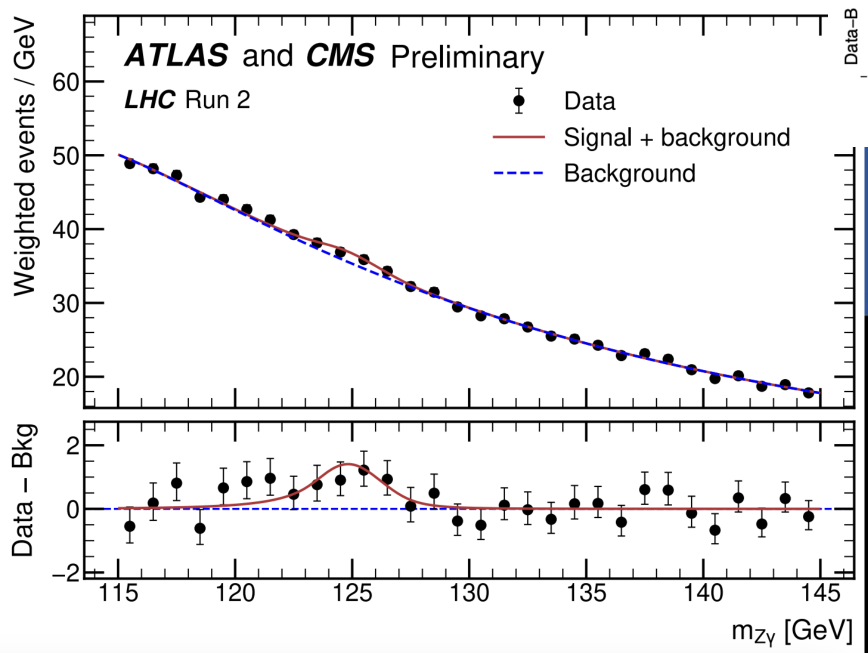




JHEP05(2023)233

First Evidence of $H \to Z\gamma$





ATLAS and CMS results are combined for

$3.4\ \sigma$

$\mu = 2.2 \pm 0.7$

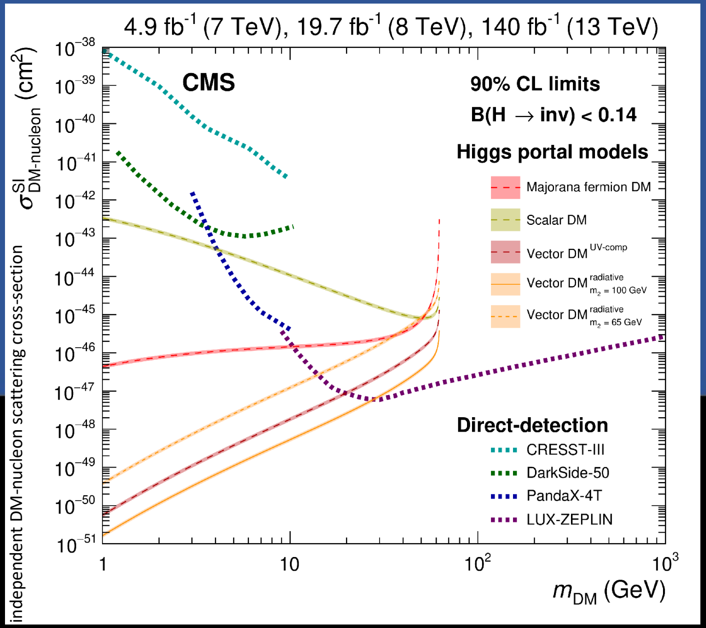
CMS-PAS-HIG-23-002

The Higgs boson invisible decays

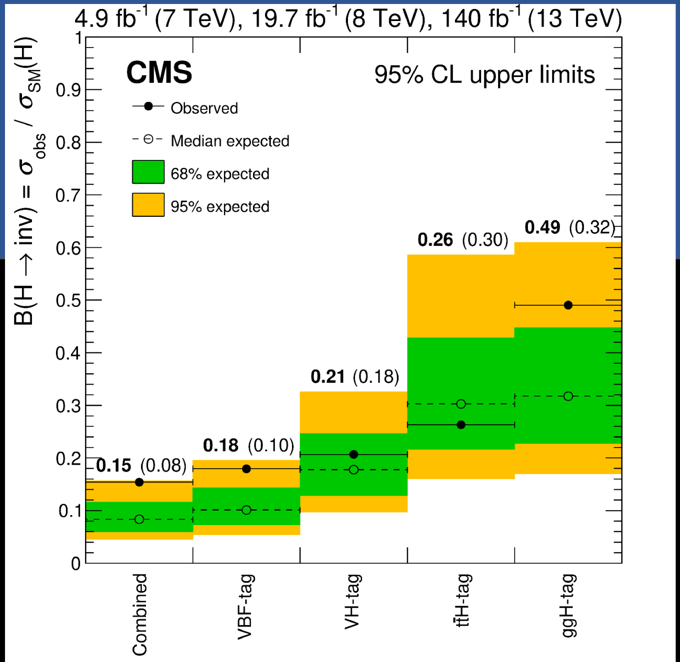
- Probe possible Higgs decay in WIMPs (Dark Matter candidates)
  - Presence of missing transverse momentum (E_T miss) in the interaction.
- SM expectation BR(H→inv) = 0.1% (given by ZZ*→4ν)
- Combination between all the signature investigated in Run 2 (+Run 1)

Constraints on WIMPs/DM nucleon scattering cross section as function of the WIMP/DM candidate mass

Eur. Phys. J. C 83 (2023) 933



Most stringent CMS limit from Run 2 VBF analysis: $\mathcal{B}_{inv}$<0.18@ 95% CL
Combination with other analyses: $\mathcal{B}_{inv}$<0.15@ 95% CL



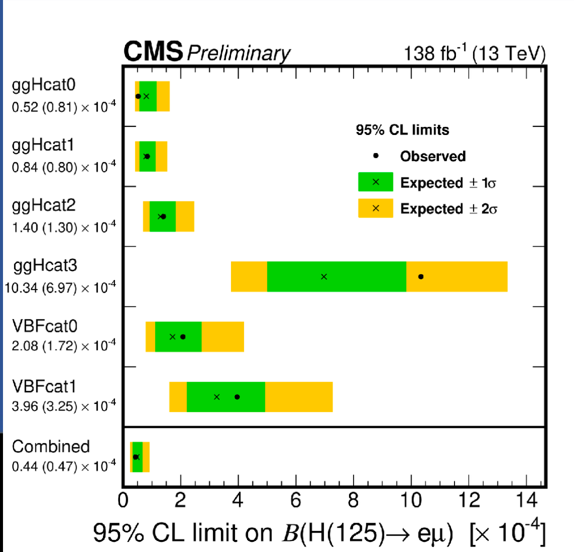
Higgs decays with lepton-flavor violation

Phys. Rev. D 108 (2023) 072004

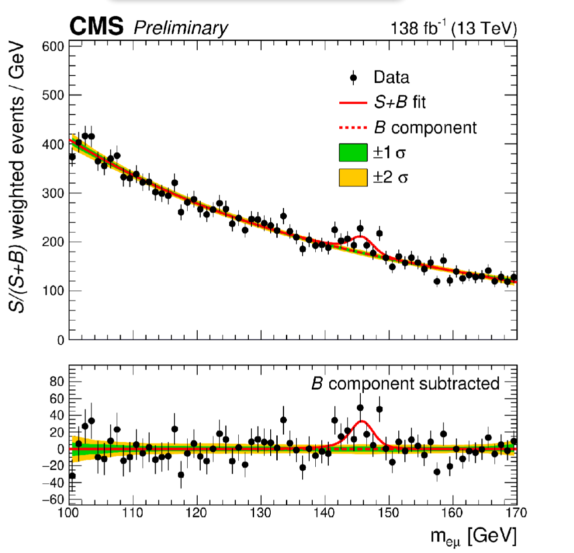
- A search for the lepton-flavor violating decay of the Higgs boson and potential additional Higgs bosons with a mass in the range 110-160 GeV to an $e^{\pm}\mu^{\mp}$ pair.

LFV observation → evidence of BSM Physics

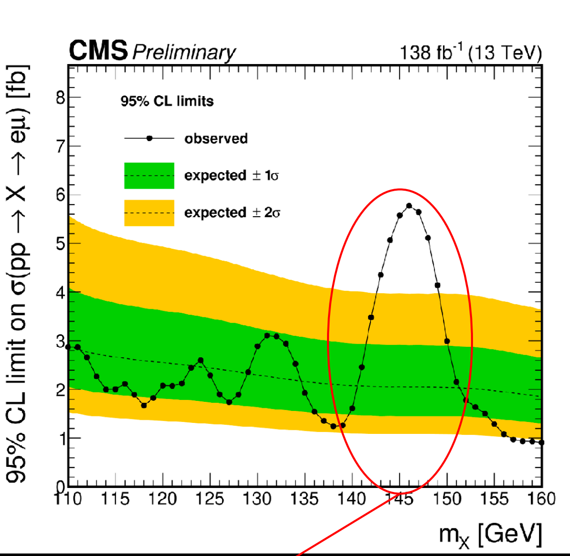
H(125)→eμ



H(X)→eμ



H(X)→eμ



- No excess is observed for the Higgs boson.
- The observed (expected) upper limit on the $BR(H \rightarrow e\mu)$ it is determined to 4.4 (4.7) $\times 10^{-5}$ @ 95% CL

- **Background:** Bernstein polynomials
- **Signal:** sum of Gaussian distributions for each production mode, category, and Higgs boson mass.

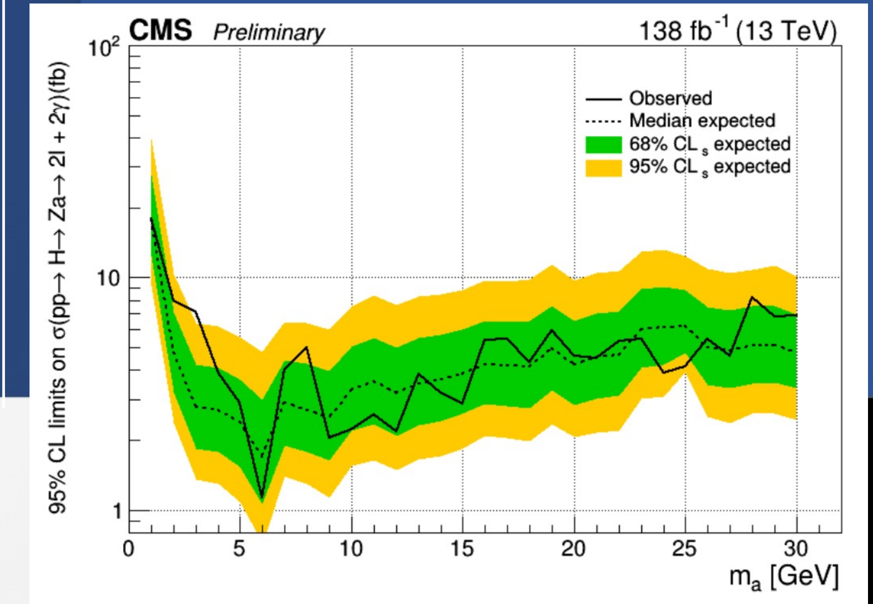
- ✓ ~146 GeV observed (expected) excess of events.
- ✓ **2.8 (3.8) σ global (local) significance.**

Exotic Higgs boson decays (H →aa && H →Za)

- Various BSM scenarios (2HDM, 2HDM+S, singlet, NMSSM, axion etc.) expect Higgs to decay to a pair of pseudoscalars and are extensively searched at CMS.
- Instead of pairs, Higgs to Z+pseudoscalar is searched as well.

H → Za → 2l+2γ

CMS-PAS-HIG-22-003



observed (expected) limits ranging from 17.8 (17.9) fb for m_a= 1 GeV to 4.7 (6.9) fb for m_a = 30 GeV.

H → aa → 4γ

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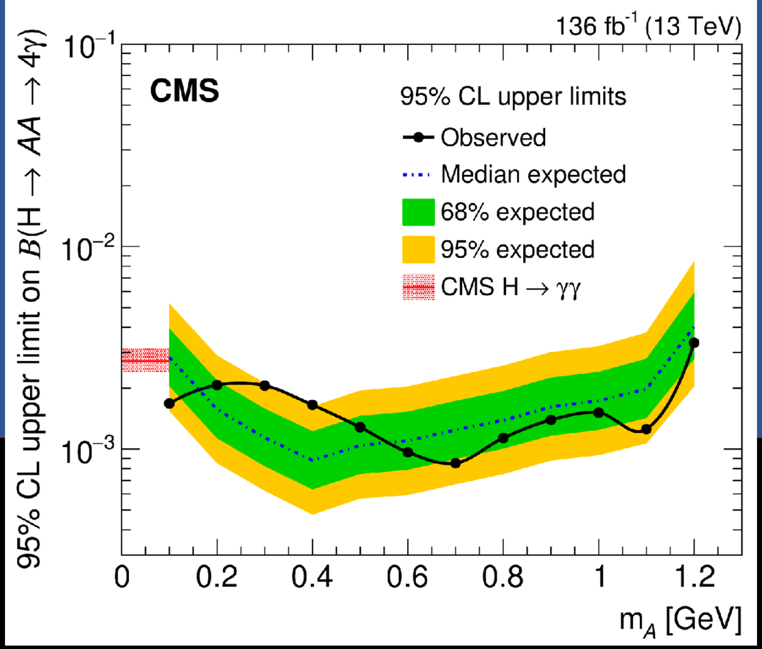
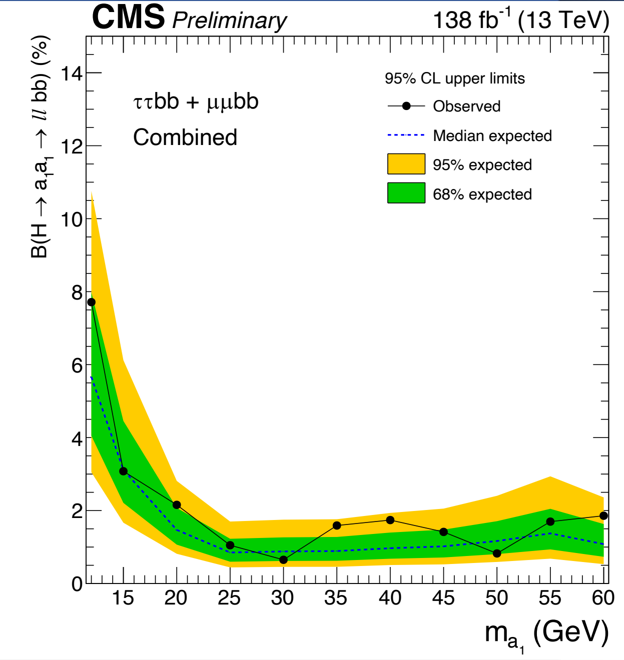


Upper limits on the branching fraction *B*(H→aa→4γ) of (0.9-3.3)×10^{-3} are set @ 95% for masses of m_a in the range 0.1-1.2 GeV

H → aa → 2l2b, l=τ,μ

CMS-PAS-HIG-22-007



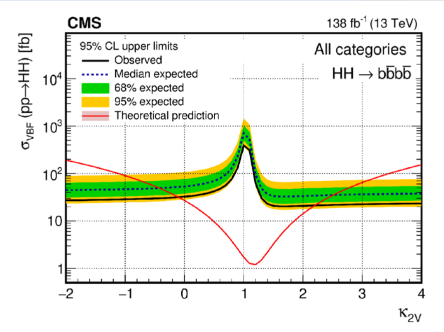
Upper limits on the B(H→a_1a_1) values of 0.23 are extracted @95% CL for most Type-II 2HDM+S models for m_{a1} values between 15 and 60 GeV.

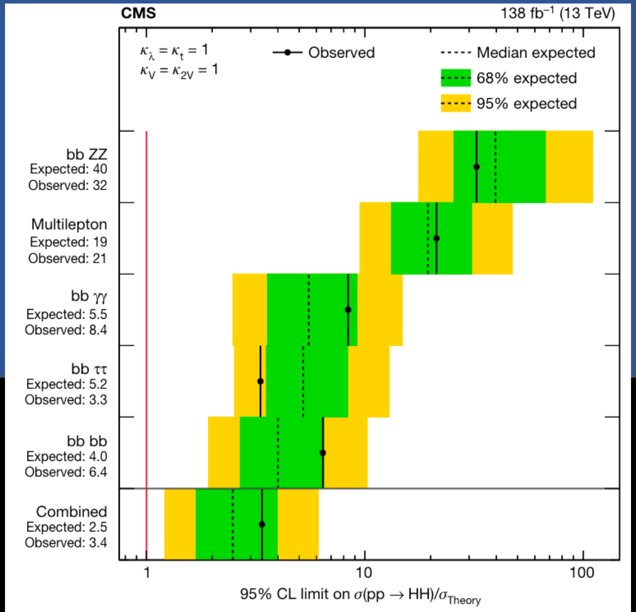
Combined HH Measurement

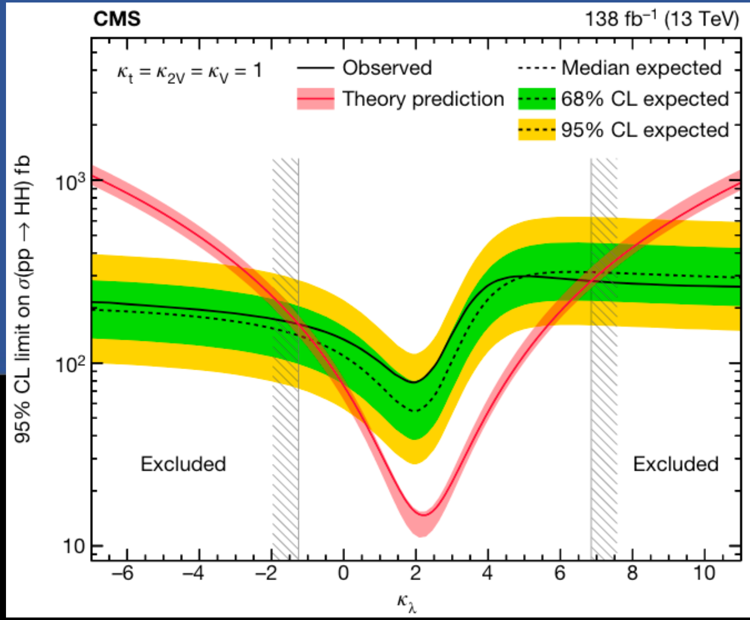
Nature 607 (2022) 60-68

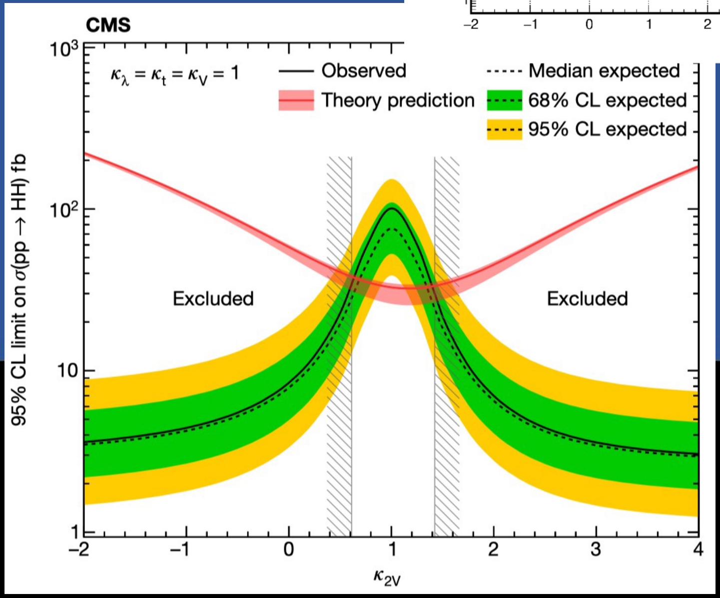
- Combined various channels (HH→4b, bbγγ, bbττ, bbZZ, multi-lepton) to maximize search sensitivity.
- Still in the era of search, upper limits get more stringent .
- The combined XS upper limit reaches 2-3 times of the SM prediction .
- The constraint on k_{2V} is impressive largely due to 4b boosted.

The boosted 4b excludes k_{2V} =0 for more than 5σ









μ_{HH}: 3.4 × SM(exp. 2.5 × SM)

$-1.2 < \kappa_\lambda < 6.5$

$0.67 < \kappa_{2V} < 1.38$

(k_{2V} = 0 excluded by 6.6σ)

Summary

LHC Run2 dataset and new analysis techniques opened the door of new Higgs measurements:

- ✓ Higgs mass precision reached to < 0.1%.
- ✓ Higgs couplings are in general at 10% and reaching out to the 1st/2nd generation fermions .
- ✓ Accessing rare production/decay processes.
- ✓ First evidence of off-shell Higgs boson production.
- ✓ STXS stage 1.2 precision can be as good as ~10% .
- ✓ Possible to measure differential cross section even very high p_T H region.
- ✓ HH keeps exploring and its upper limit is reaching ~2xSM .

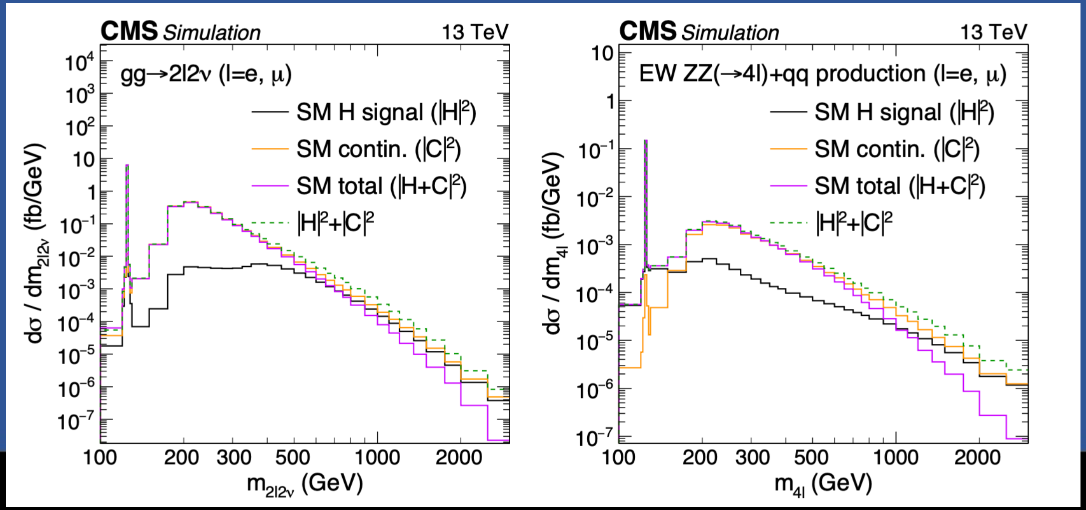
No significant deviation from SM prediction (yet!)

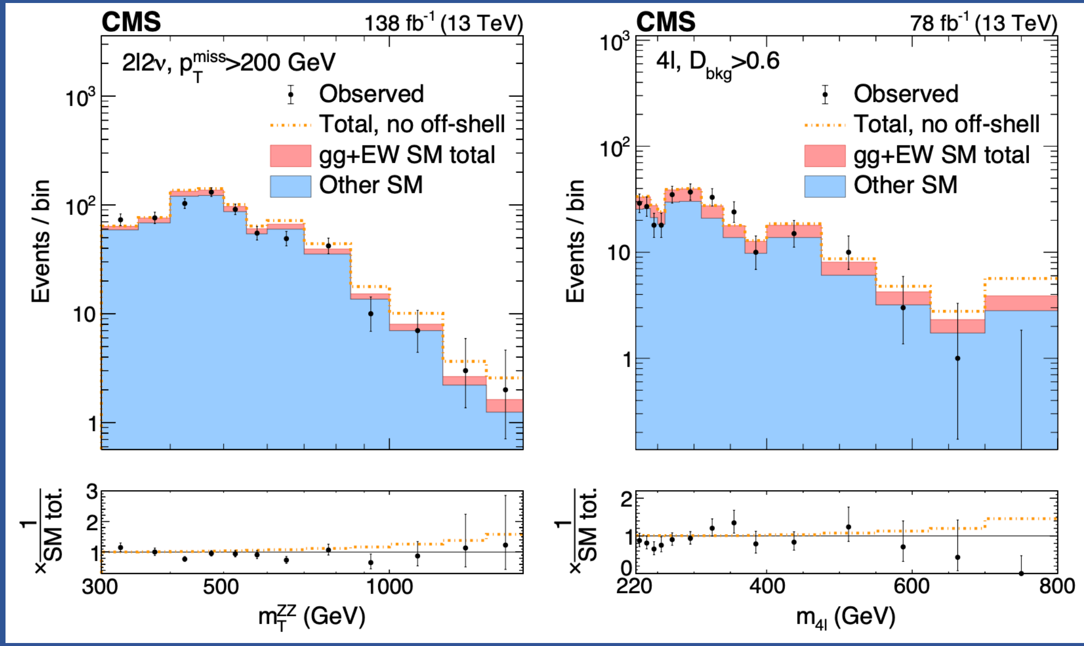
- ✓ Run3 Higgs physics just started
  - Much larger dataset than Run2 is expected
    ⇨ New physics may appear in coming years

Stay tuned for Run 3 results!!

Backup

The Higgs width



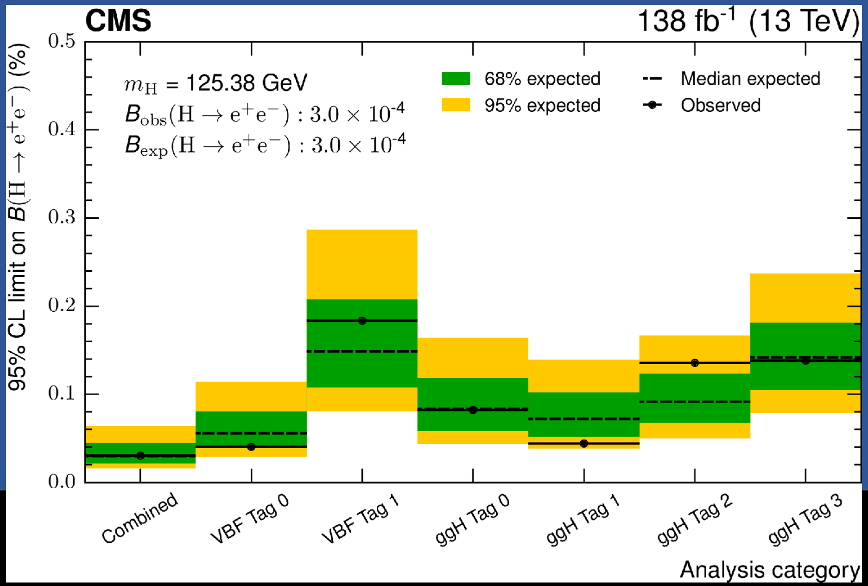


4l takes its advantage in on-shell $ll\nu\nu$ plays an important role in off-shell

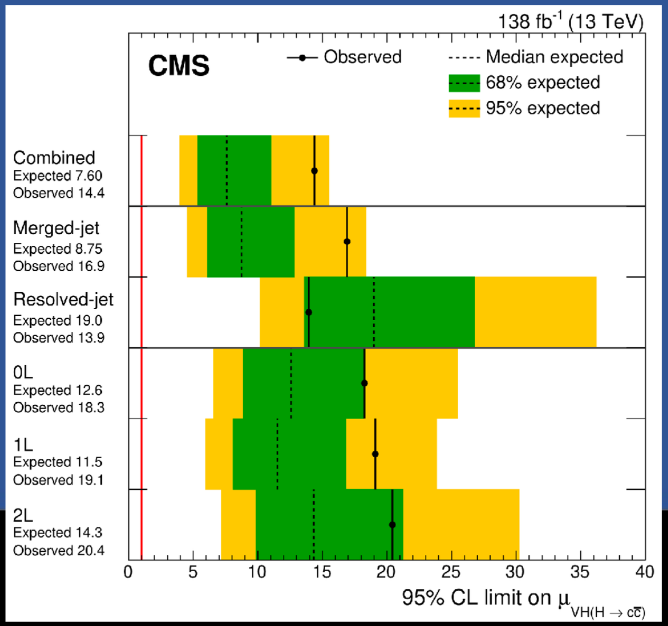
The stacked histogram displays the distribution after a fit to the data with SM couplings, with the blue filled area corresponding to the SM processes that do not include H boson interactions, and the pink filled area adding processes that include H boson and interference contributions.

Couplings to lighter fermions

- Reaching out to the first- and second-generation fermions.



$BR(H \to ee) < 3.0 \times 10^{-4} (3.0 \times 10^{-4})$ at 95% CL. Accepted by PLB



$1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$) at 95% CL. Accepted by PRL

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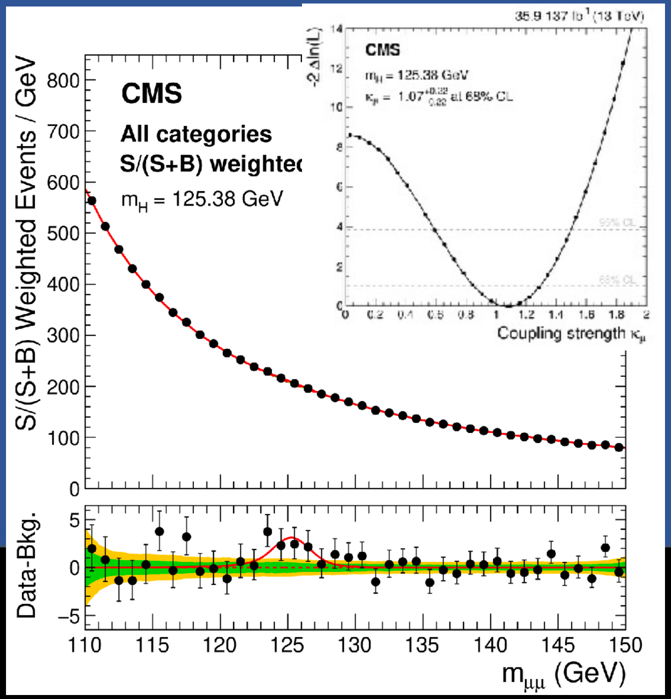
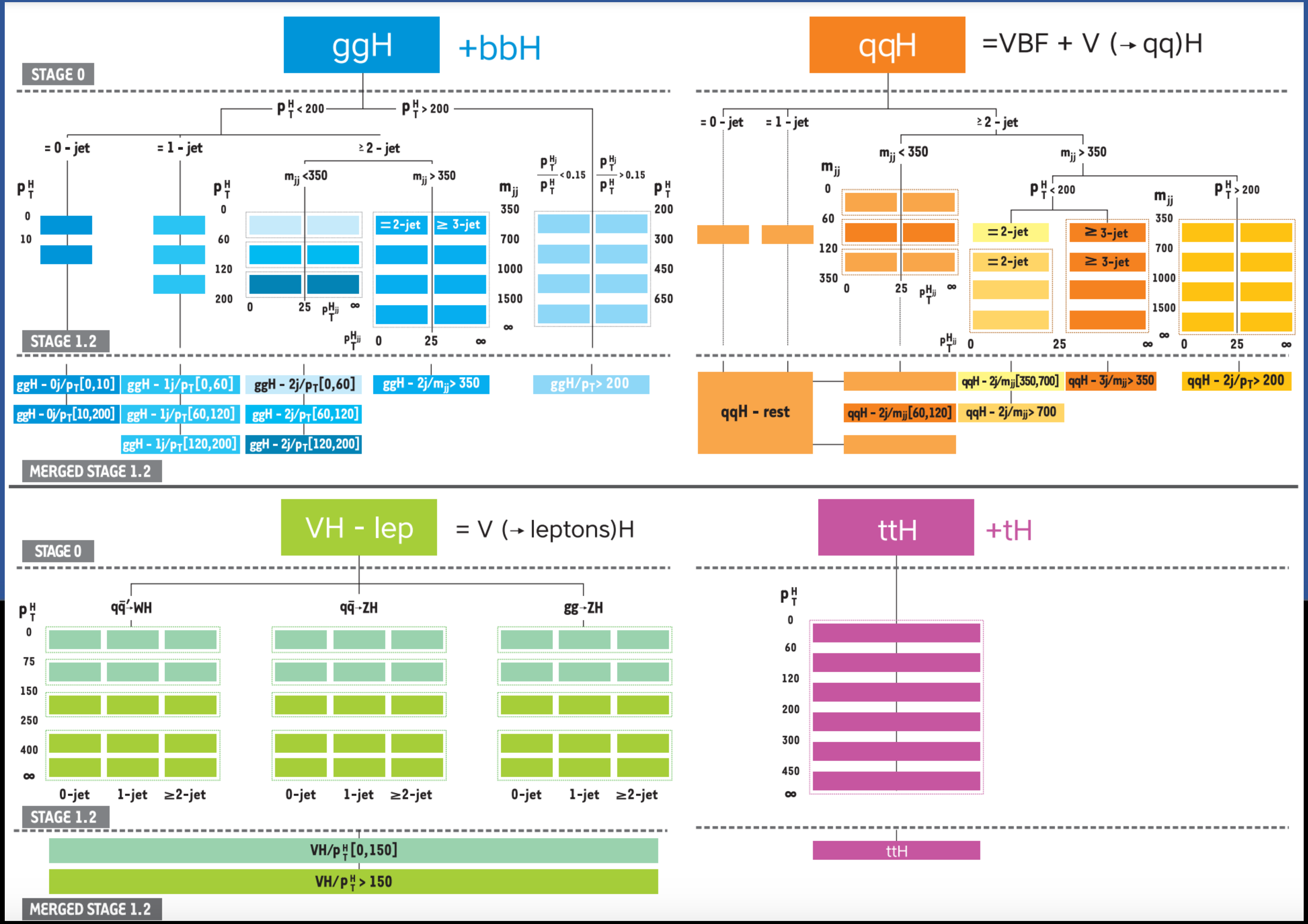


3 σ evidence so far

$\kappa_\mu = 1.07^{+0.22}_{-0.22}$

HZZ4l merged STXS Stage 1.2



Hγγ merged STXS