Recent Highlights of Higgs Boson Measurements at the LHC

A mini review

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DAE-BRNS Symposium, IISER Mohali, 13 December, 2022

Abeyance

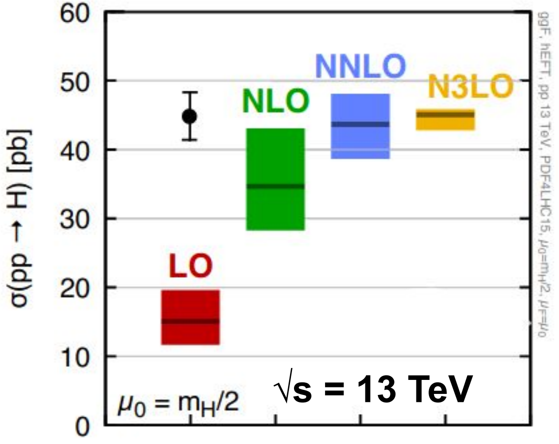
- excellent performance of the accelerator
- enormous progress in computing capabilities
- precision theoretical description of the production and decay processes of the Higgs boson as well as the relevant backgrounds.

⇒ Higgs physics has entered precision era

⇒ increases the sensitivity to search for beyond standard model (SM) physics

- Within uncertainties, no deviations, so far, from the predictions of the SM.

Accuracy in theoretical predictions for Higgs boson production cross section at the LHC



Nature 607 (2022) 7917

- A theoretical perspective
- A detailed map of H: ATLAS
- A portrait of H: CMS

This talk: glimpse on a limited selection from a plethora of very interesting analyses carried out in recent years.

Also look at plenary session talk by A.Nayak

Data

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

Run1 at √s = 7, 8 TeV (2010 - 2012) : ~20 fb^{-1}

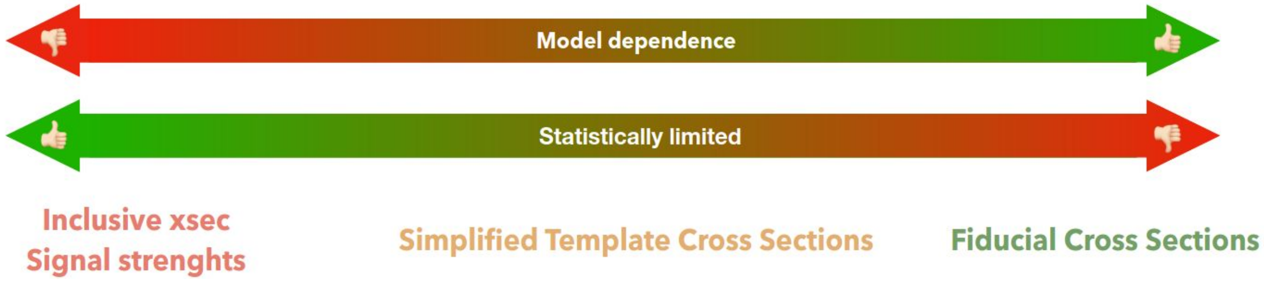
Run2 at √s = 13 TeV (2015 - 2018): ~140 fb^{-1}

Run3 at √s = 13.6 TeV (2022 onwards): collected ~ 40 fb^{-1}

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

Evolution in interpretation of data (study variables of complementary sensitivities)

a) Single H

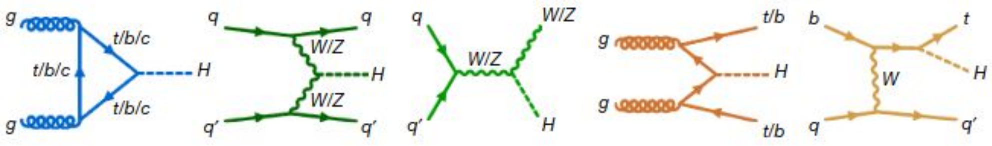


b) H pair

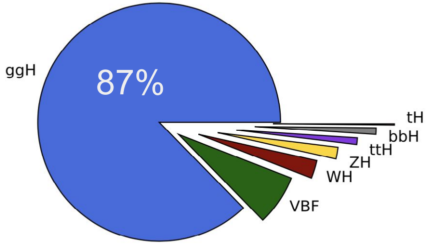
c) EFT interpretation to constrain new physics.

Only the product of Higgs boson production and decay couplings can be studied

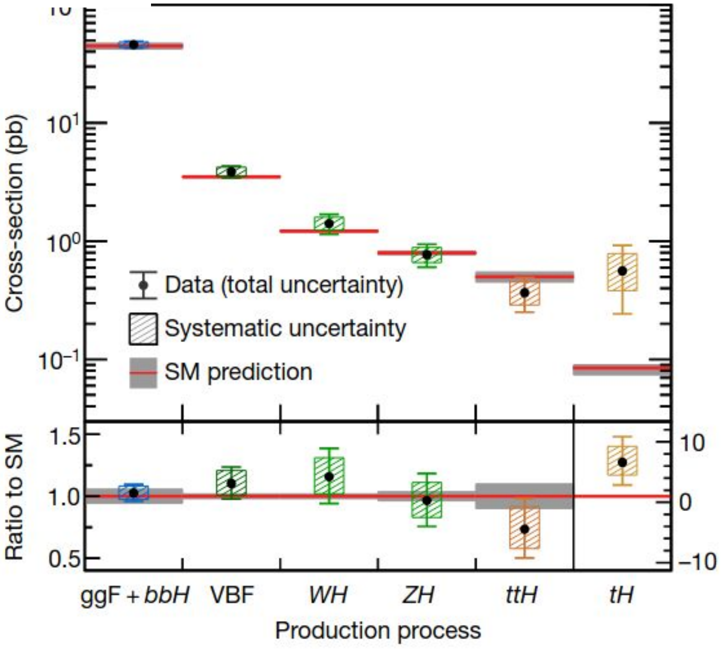
Higgs production



ggF VBF VH ttH tH



ATLAS



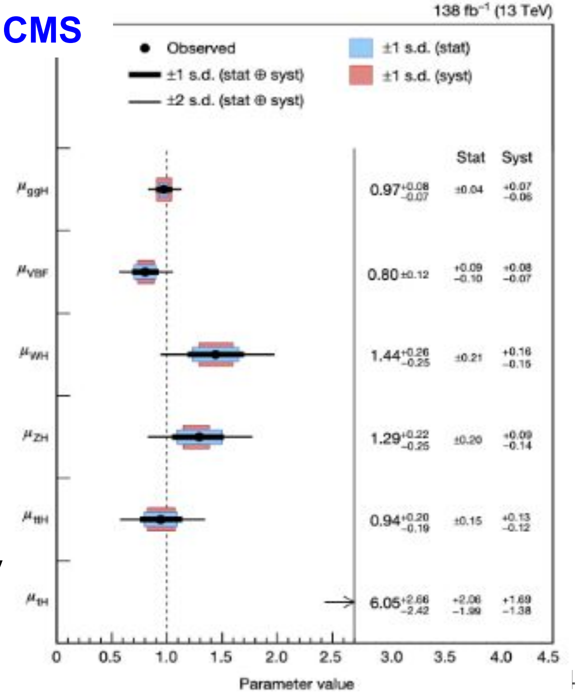
- Main 4 production modes have been observed with significance ≥ 5 sigma.
  Talk by [R.Dewanjee] on tHX production

- Signal strength =

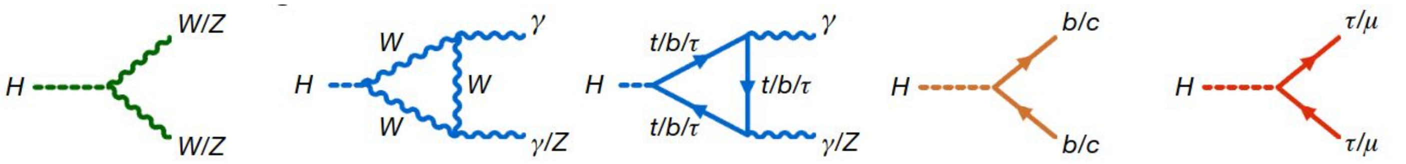
$$\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}$$

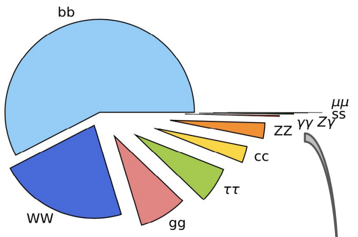
- Higgs signal strength measured with ~ 6% precision, uncertainty still dominated by statistics.

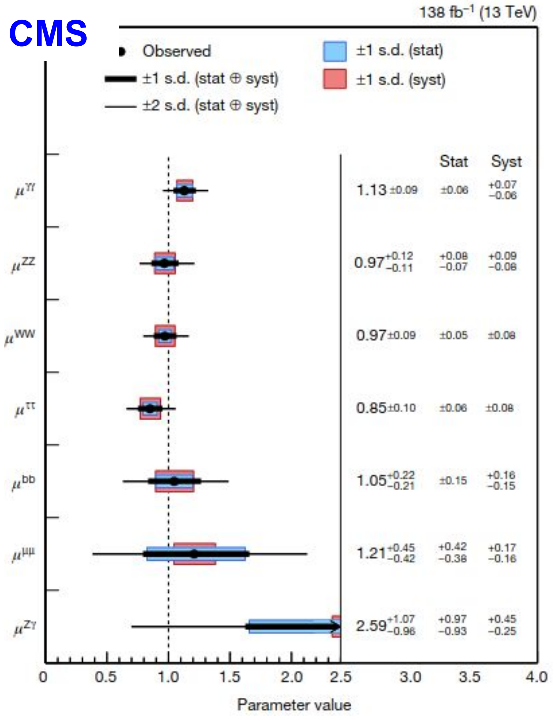
CMS



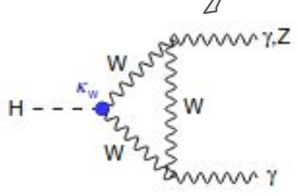
Higgs boson decays







- 3rd generation Yukawa couplings (Hff) established with Run1 data → ***a new interaction of Nature***
- Run2: first evidence of H decay to 2nd generation fermions (c quark, μ)
- Decay of H→Z γ : beyond SM physics in loop may increase the rate.



arXiv:[2204.12905](https://arxiv.org/abs/2204.12905)

Methods to measure the couplings and look for deviations from the SM:

- Signal strengths
- Coupling modifiers
- Simplified template cross sections
- Differential, fiducial cross sections
- ..

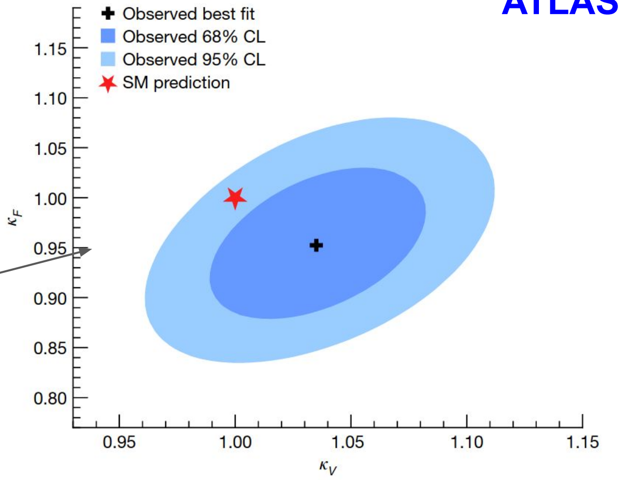
Anomalous couplings

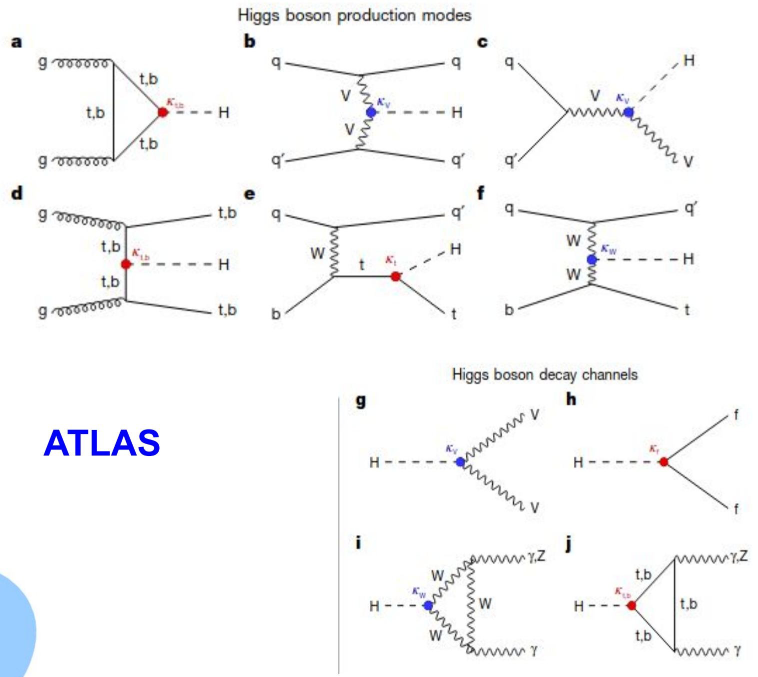
- Current precision allows for anomalous couplings.
- Describe possible deviations from SM with scale factors, $\boldsymbol{\kappa}_i$, defined s.t. the cross section or the partial decay width scales with $\boldsymbol{\kappa}_i^2$ when compared to the SM prediction.
- *Assume kinematics to be unaltered.*
- $\boldsymbol{\kappa}$- framework 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

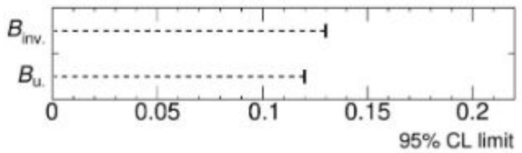
Assuming no invisible or decays to BSM particles contributing to total width.



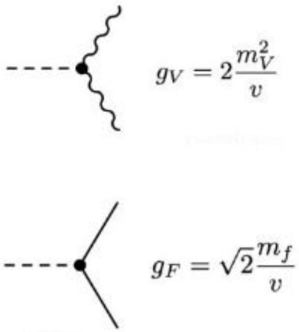


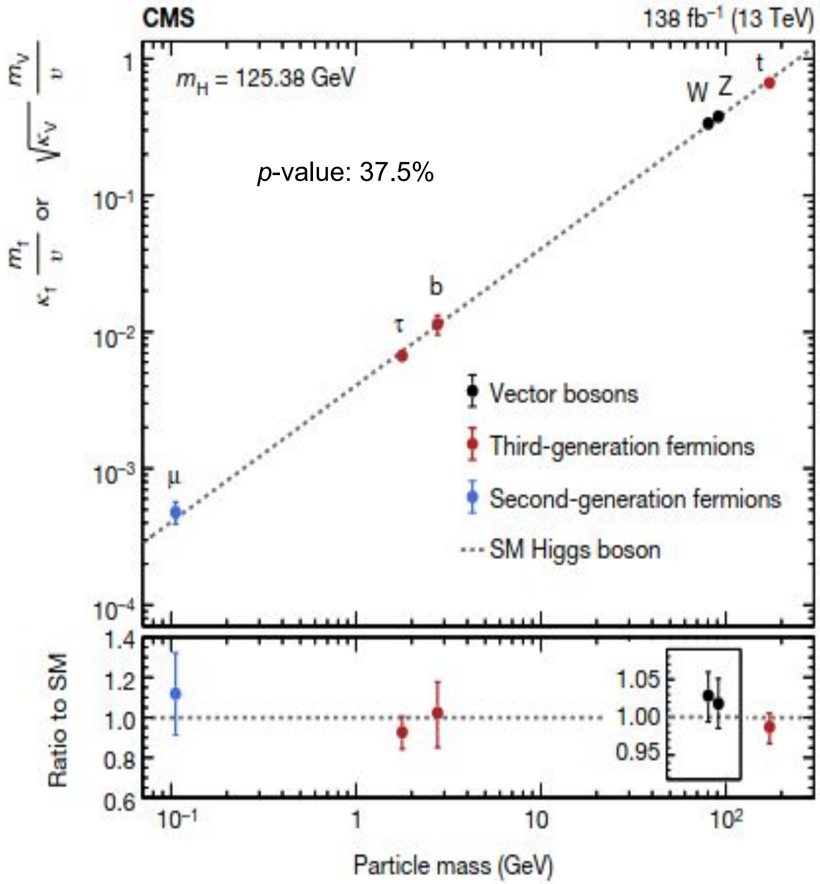
ATLAS

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



Couplings to bosons and fermions





- **Footprint of SM:** behaviour of couplings with the masses of the particles.
- So far, Higgs boson is SM like.
- However there is large room for BSM effects for the 2nd and first generation fermions.
- There are many ways to constrain BSM effects in Higgs physics using effective field theory (EFT), including non-Higgs measurements.

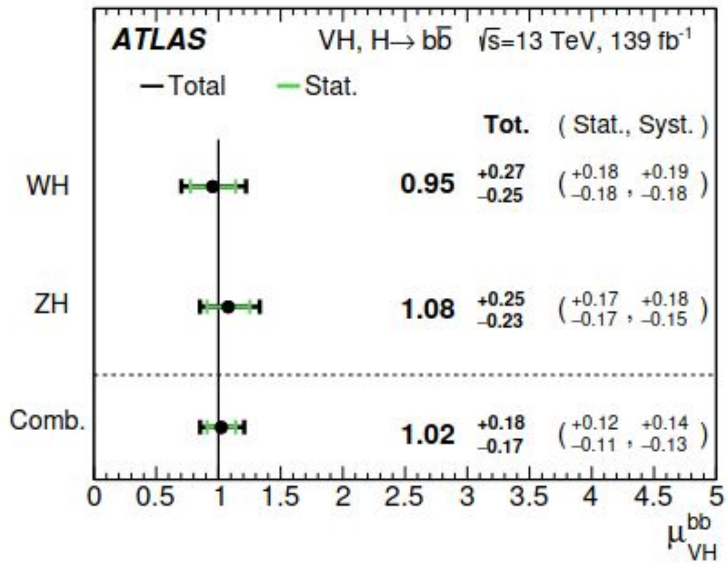
Nature 607 (2022) 7917

Coupling to bottom quark

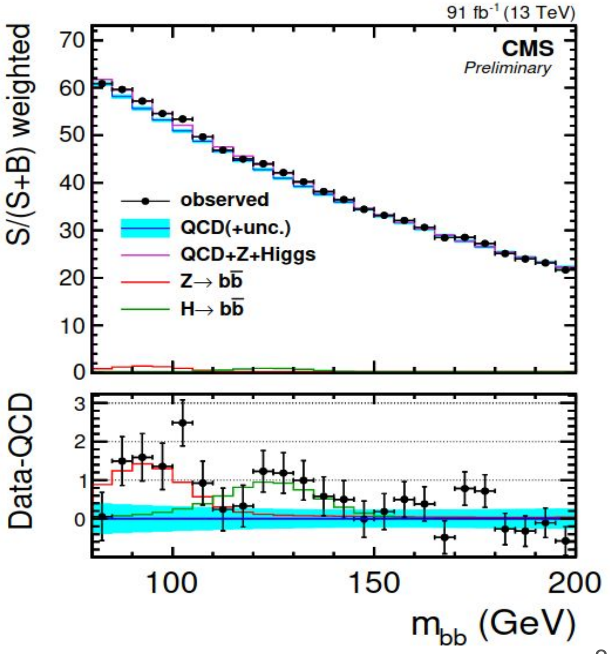
EPJC 81 (2021) 178
PAS-HIG-20-001

- Br (H→bb) = 60%
- Challenge: huge QCD multijet background
- VH production process: best sensitivity

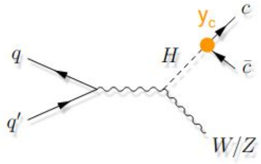
ATLAS: μ = 1.02$^{+0.18}_{-0.17}$
Obsd. (exp.) significance: 6.7 s.d.



VBF H → bb : recent CMS analysis HIG-22-009: *Parallel session talk by Soumya Mukherjee*



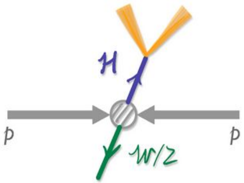
Coupling to charm quark

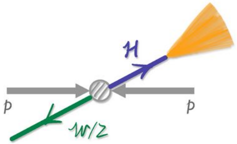


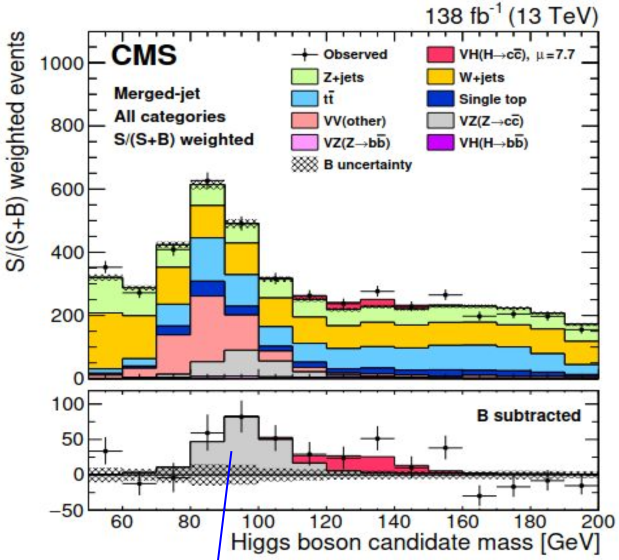
[Eur.Phys.JC 82 (2022) 717](#)
[arXiv: 2205.05550](#)

- Br (H→cc) = 3%
- Large QCD background, poor mass resolution

- Novel jet reconstruction and identification tools, and analysis techniques
- CMS uses associated production (VH) with both resolved and merged c-jet pair topologies







First observation of VZ with > 7 s.d.

CMS: Observed (expected) :
σ(VH) $\mathcal{B}$(H→cc) < 0.94 ($0.50^{+0.22}_{-0.15}$) pb

Upper limit (UL) on signal strength
at 95% CL: μ < 14 ($7.6^{+3.4}_{-2.3}$)

⇒ Strongest limits on VH(H→cc) process to date!

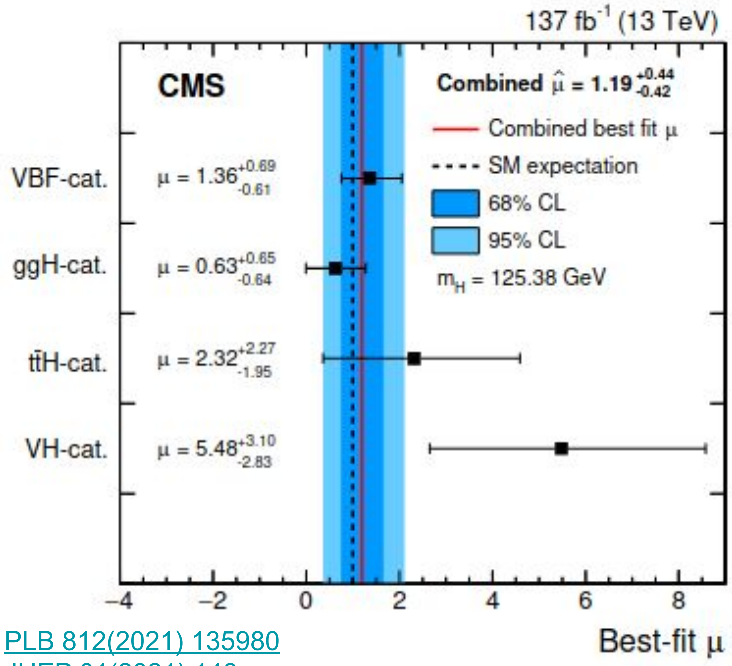
CMS: 1.1 < $|\kappa_c|$ < 5.5 obs.
$|\kappa_c|$ <3.4 exp.)
assuming all other κ_i =1 → most stringent

Crucial role of precise theoretical predictions for various processes.

Couplings to leptons

- Br ($H\to\mu\mu$) = 0.02%
- Excellent mass resolution → helps to tackle the background of $Z\to\mu\mu$

CMS: 3σ evidence → expect observation in Run3.



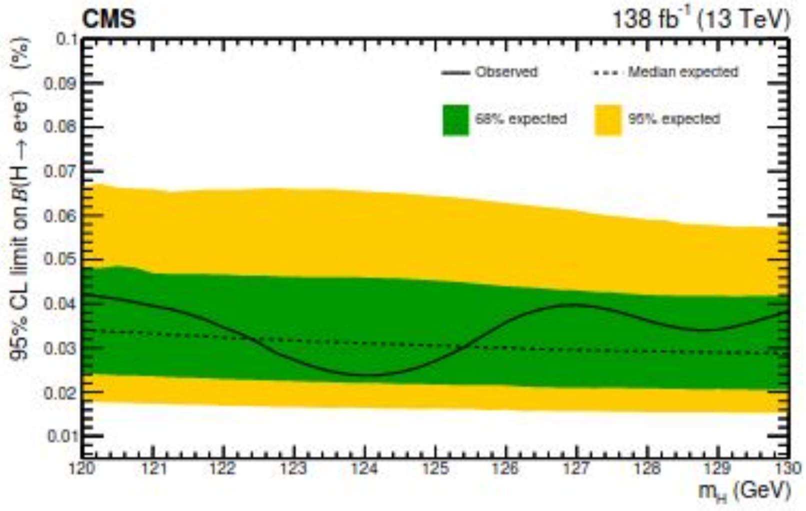
PLB 812(2021) 135980
JHEP 01(2021) 148

- Br ($H\to ee$) = $3.5*10^{-4}$ %
- Important background of $Z\to ee$ can be tackled using VBF topology.

95% CL upper limit on branching ratio:

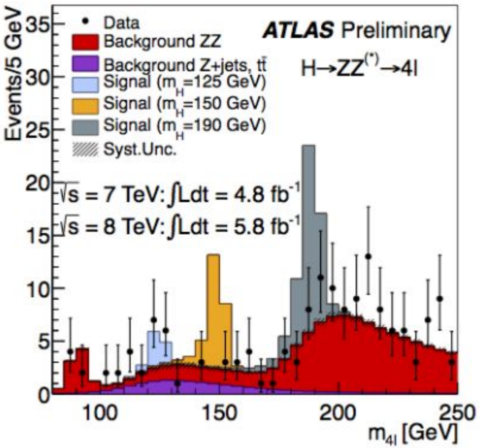
ATLAS: < $3.6*10^{-4}$ ($3.5*10^{-4}$)

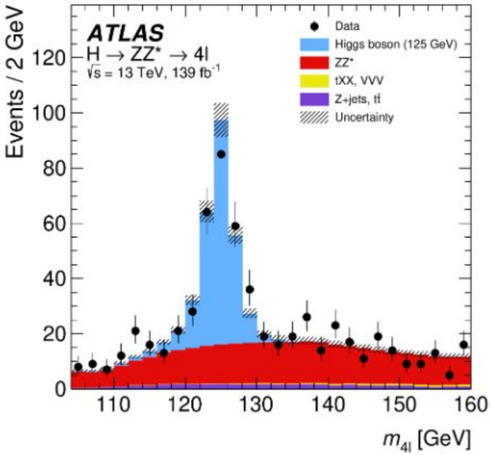
CMS: < $3*10^{-4}$ ($3*10^{-4}$)

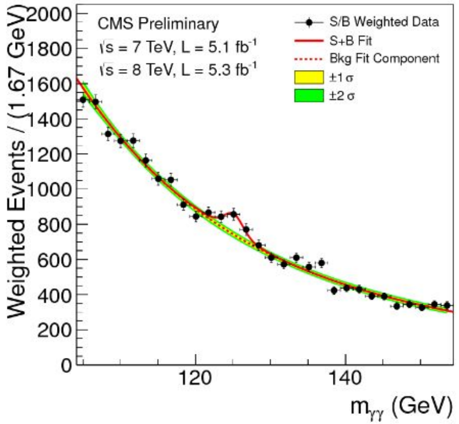


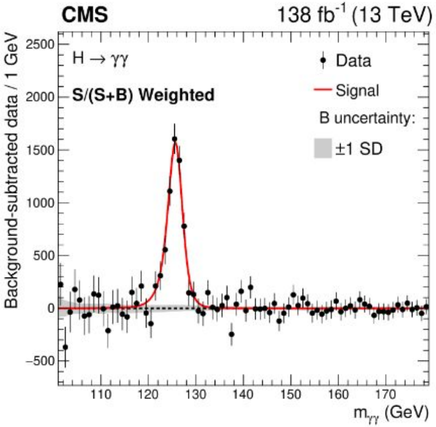
Phys.Lett.B 801(2020) 135148
arXiv:2208.00265

Higgs boson mass







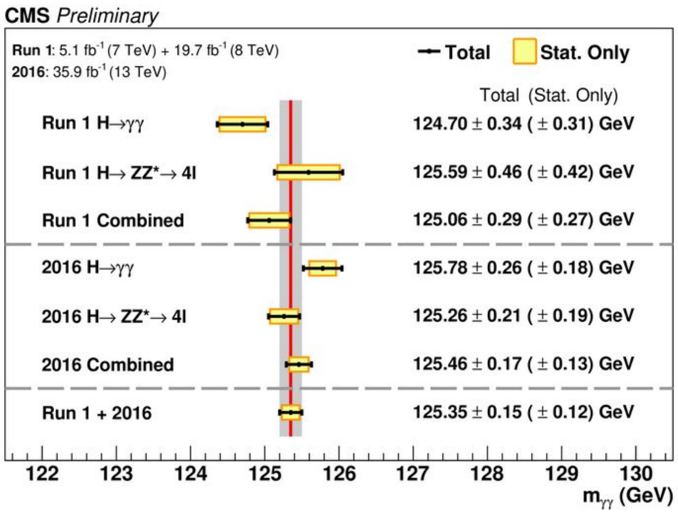


[Run 1](#)

ATLAS +CMS [4l+$\gamma\gamma$] m_H = 125.09 ± 0.21 ± 0.11 GeV

Run 2 : 30 times more Higgs bosons

N[ow](#)
Run1 + Run2 Combined m_H = 125.38 ± 0.14 GeV
Δm_H measured with ~ 0.1% precision in CMS.
→ best so far

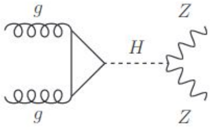


Decay Width of the Higgs boson

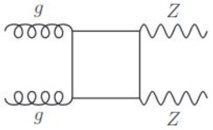
[Nat. Phys.18 (2022) 1329]

- $\tau_H \approx 1.6 \times 10^{-22}$ sec ⇒ the natural width, $\Gamma_H = 4.14 \pm 0.02$ MeV in SM. *experimental resolution: ~ 1 GeV*
- 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 .

$gg \to H \to ZZ$:



$gg \to ZZ$:

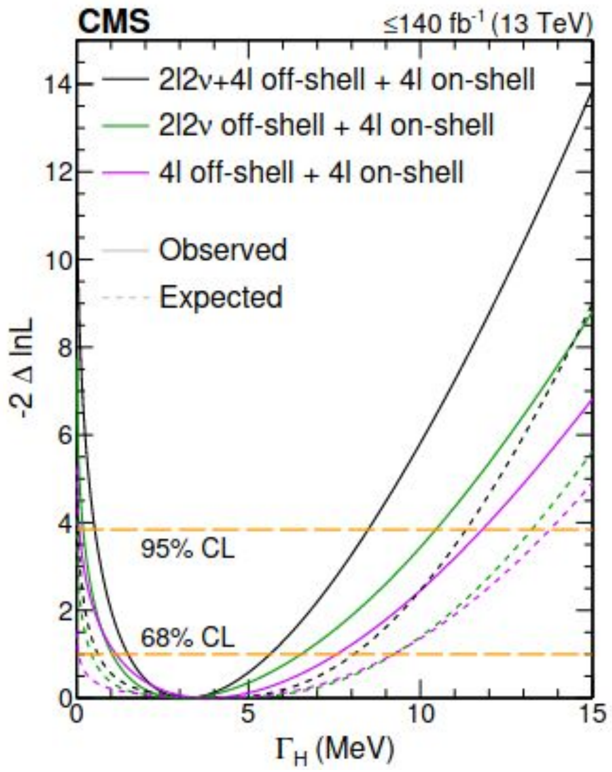


$$\sigma^{pp\to H\to ZZ}_{onshell} \sim \frac{g^2_{Hgg}\, g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{pp\to H\to ZZ}_{offshell} \sim \frac{g^2_{Hgg}\, g^2_{HZZ}}{M_{ZZ} - m_H}$$

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

- Negative interference of diagrams
- *Assuming constant coupling in the range*



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

ATLAS: $\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV

Off-shell production of Higgs established with a confidence of 3.6 s.d.

Invisible decay of the Higgs boson

ATLAS-CONF-2020-052
CMS_PAS-HIG-21-007

BR(H→invisible) = 0.1% in SM (H→ZZ→4ν)

● Too small for detection, poor E_T^{miss} resolution, background from Z→$\nu\nu$

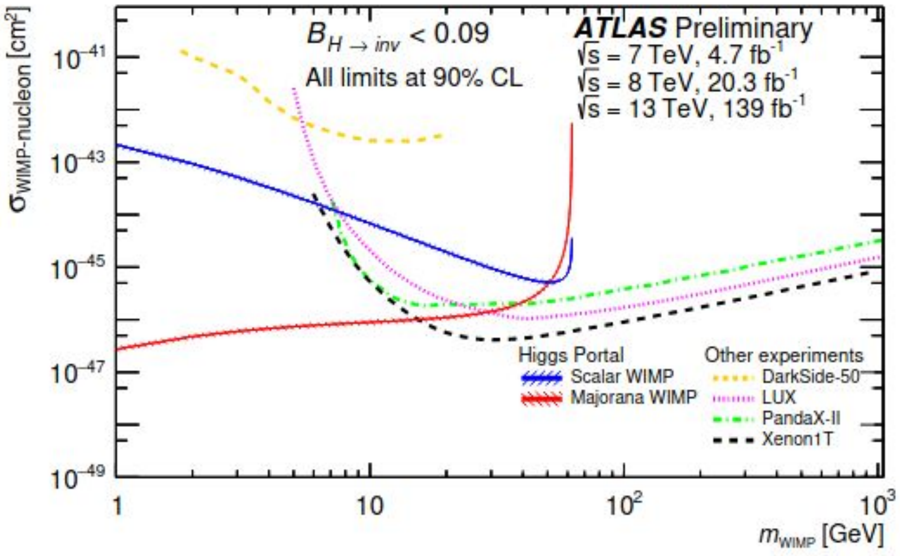
● But if H decays to WIMPs (DM candidates), BR(H→invisible) could be enhanced.

VBF + ttH, Run2+Run1 combination:

Upper limits at 95% CL

ATLAS: BR(H→inv) < 11%

CMS: BR(H→inv) < 15%

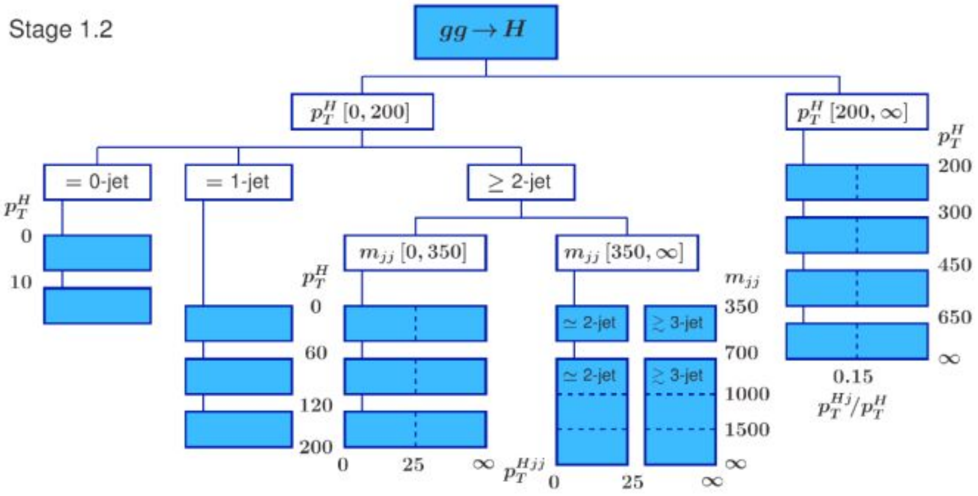


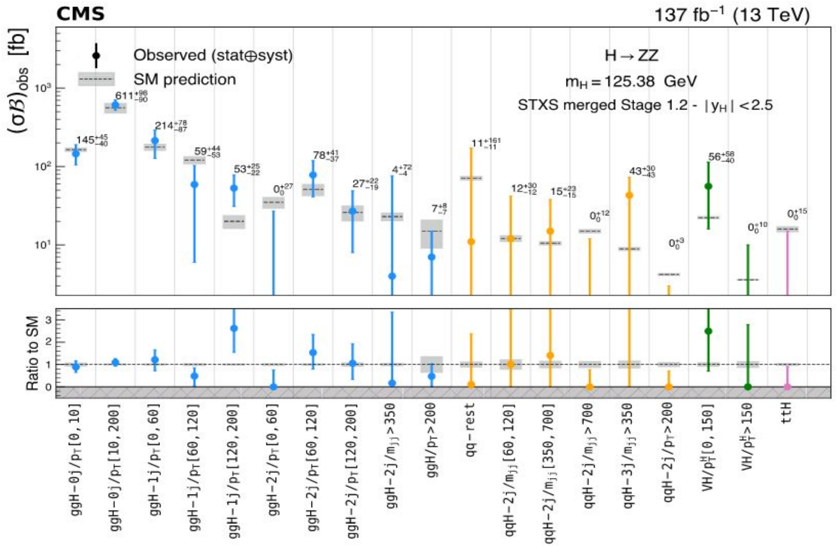
Limit on WIMP-nucleon scattering cross section in Higgs portal model → complementary to direct searches for DM.

Simplified Template Cross section: STXS

Eur.Phys.J.C81(2021) 488

- Cross sections measured, for each production mode, in bins of truth quantities, like, p_T^H , N_{jets} , m_{jj} and p_T^V (in VH mode).
- Granular measurement of the cross section for each production mode → presently most sensitive to ggH.
- Increased sensitivity to BSM effects.
- Provide a common set of definitions for the combination of the measurements in different channels.
- Allow kinematics-dependent interpretations.





Measuring the fiducial cross section

- Fiducial cross section: align the phase space of interest with detector configuration and kinematic selections on reconstruction level objects and analysis acceptance.

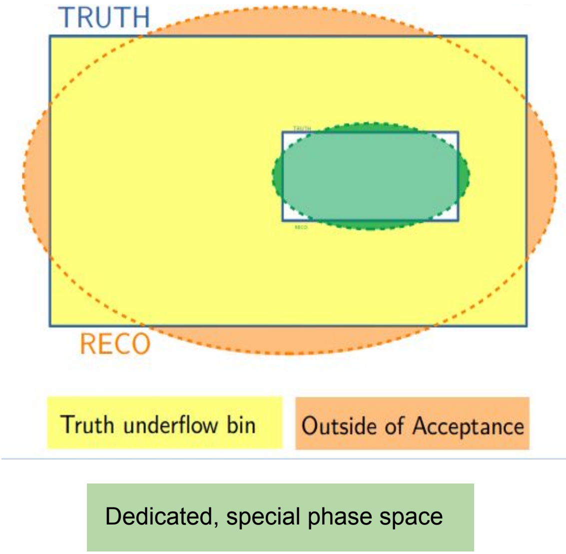
⇒ not corrected for acceptance

- Fiducial phase space 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.

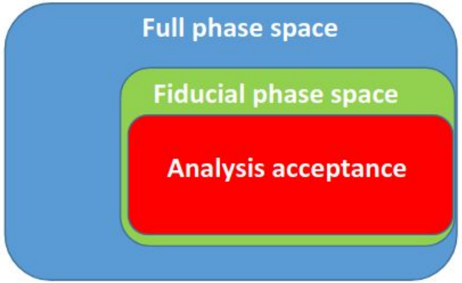
- Special phase space defined as a subset
  eg. require additional 2 jets in the event. → target VBF process requiring special topology of the 2 jets.

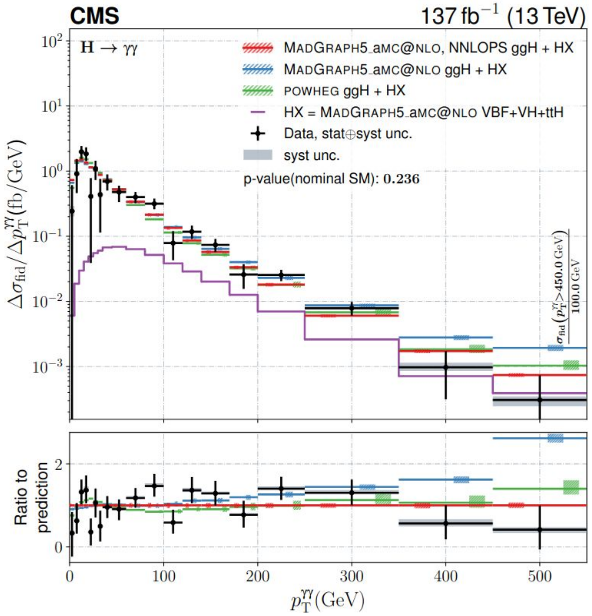


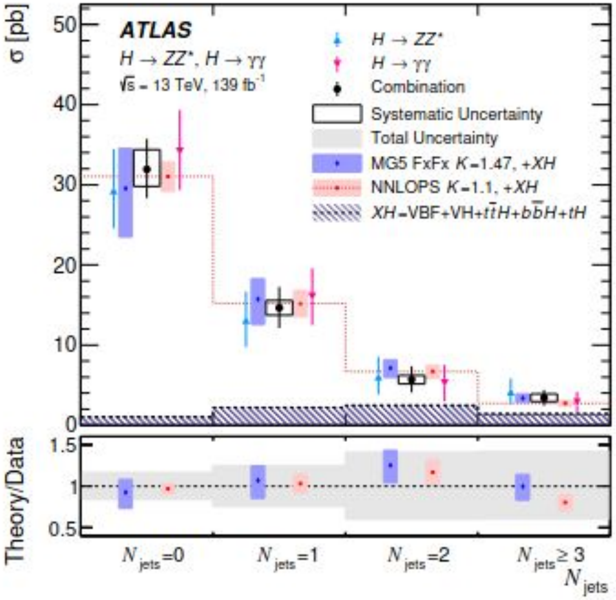
Differential cross section:

→ 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.

arXiv: 2207.08615 2208.12279

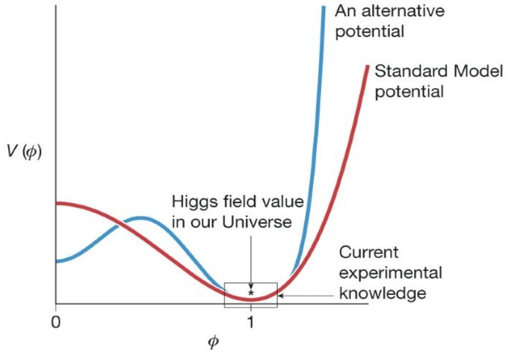
CMS (H →γγ) $\sigma_{fid} = 73.4^{+5.4}_{-5.3}\,(stat)^{+2.4}_{-2.2}\,(syst)\,fb = 73.4^{+6.1}_{-5.9}\,fb$ | 75.4 ± 4.1 fb (SM)

CMS inclusive and differential distribution for H→ WW: talk by G. Das

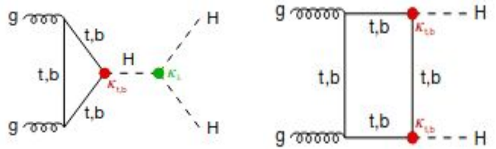
Self-coupling of the Higgs boson

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

After EWSB: $V_{\text{SM}} = \frac{m_h}{2} h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$

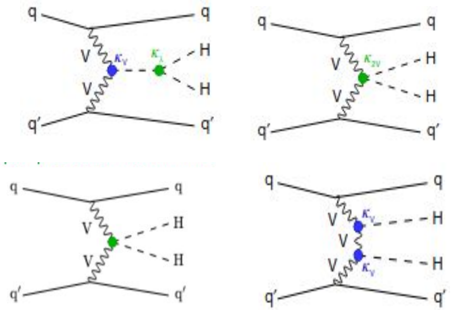


- Determination of Higgs self-coupling $\boldsymbol{\lambda}$: THE important mandate to understand the nature or shape of the Higgs potential near the minimum → related to the evolution of the universe at EW scale.



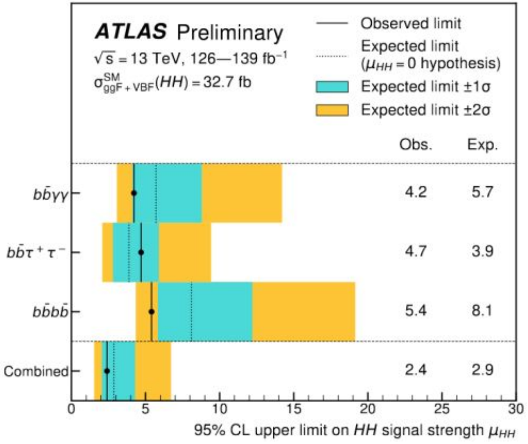
- Inclusive Higgs pair production at the LHC → direct access to HHH and VVHH vertices → $\boldsymbol{\kappa_\lambda}$, $\boldsymbol{\kappa_{2V}}$

  σ(pp→HH+X) ~ 31 fb → 10^{-3}* σ(pp→H+X)



- Target both ggF and VBF processes:

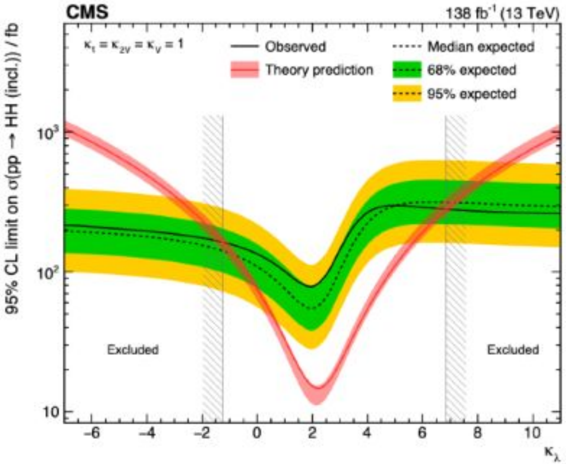
> Observed (expected) limits on HH signal strength:
>
> **ATLAS: μ_{HH} < 2.4 (2.9)**
>
> **CMS: μ_{HH} < 3.4 (2.5)**

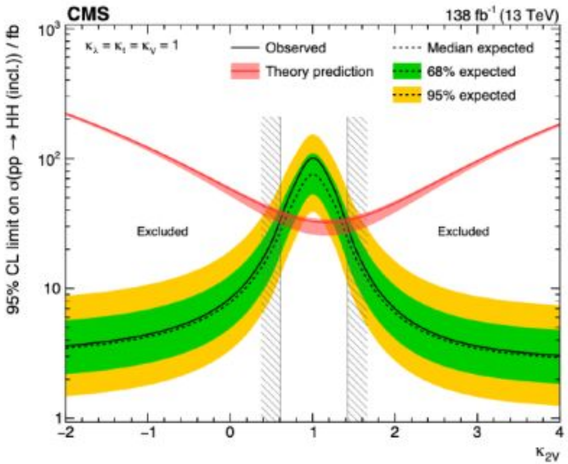


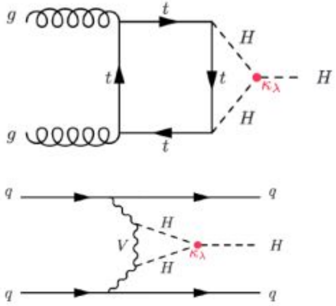
ATLAS-CONF-2022-050
Nature 607 (2022) 60-68

Limits on trilinear self-coupling and quartic couplings

- Interference among relevant diagrams→cross section dependency on the coupling modifiers







One-loop single Higgs production also involves κ_λ at higher orders, included in the ATLAS combination, of HH and H measurements.

Allowed range of κ_λ
ATLAS: [-0.6, 6.6]
CMS: [-1.2, 6.5]

Allowed range of κ_{2V}
ATLAS: [0.2, 2.0]
CMS: [0.67, 1.38]

κ_{2V} =0 excluded by CMS with a 6.6σ significance

⇒ better constraints on κ_λ and other couplings.

See parallel session talks by
S.Bhowmik , S.Mukherjee

CP properties of the Higgs boson & effective field theory

- Higgs boson in SM: $J^{CP} = 0^{++}$
- CP violation in the Higgs sector could complement other known sources → indication of BSM physics.
- Pure CP-odd Higgs excluded at the LHC at 3 s.d.
- Search for CPV in the shapes of various optimal observables (rate measurement is not sensitive to CPV)

- Fermionic couplings (Hff) modelled as : $\mathscr{L}_{ffH} = \kappa_f' y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$
→ 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 : $\mathscr{L}_{VVH} = \mathscr{L}_{SM} + \frac{c_i}{\Lambda^2}\phi \tilde{V}_{\mu\nu} V^{\mu\nu} + \dots$
→ pure CPV effects in interference term

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

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

(CP) Anomalous contributions (CP) ~~(CP)~~

If VV= WW, ZZ, Zγ → Tree-level SM

If VV= gg → 1-loop SM

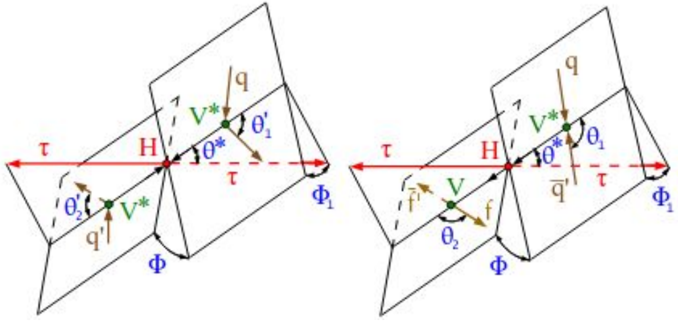
CP Violation in HVV coupling using H →$\tau\tau$

arXiv: 2205.05120

- Use jet kinematics in ggF and VBF production processes combined with decay kinematics.

- CPV effect on effective cross sections measured in terms of ratios like

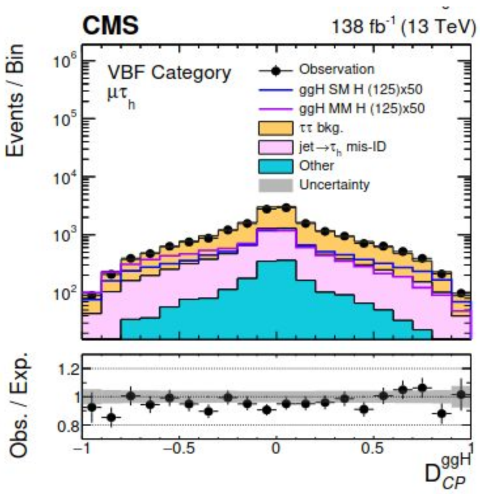
$$f_{ai} = \frac{|a_i|^2\sigma_i}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2\sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn}\left(\frac{a_i}{a_1}\right)$$

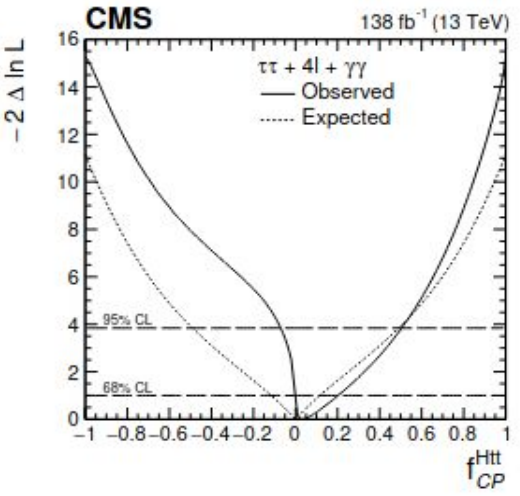


Matrix element calculations (MELA) → discriminating variables

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

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





Combined results of H → $\tau\tau$, H→ ZZ* →4l, H→$\gamma\gamma$ to achieve much higher sensitivity.

For a general discussion on EFT analysis of top and Higgs measurements: talk by S.Chatterjee

Conclusion

- Ten years back the discovery of Higgs boson marked a milestone in particle physics.
- Analyses of Run2 data have led to a significant improvement on our understanding of the resonance.

  I could present a small sample to underline the expanse of the efforts towards deciphering the Higgs sector.

- All current results are compatible with the SM expectations.
- Run3 has just started: expect to collect ~300 fb^{-1} at 13.6 TeV with Phase-1 upgraded detectors.
- 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.
- The enthusiasm to search for beyond standard model physics should not overshadow the Higgs physics programme.

Thank you!

Backup

10 years back: discovery of the Higgs boson

- Experimental confirmation by ATLAS and CMS collaborations at the LHC about the existence of the unique scalar boson described in the Standard Model. *India: partner in the CMS collaboration.*

- *Triumph of human intellect:* the simplest and elegant idea postulated in 1960s

  → 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 particles in a consistent way.

  → Higgs boson plays crucial role in vector boson scattering, provides unitarity.

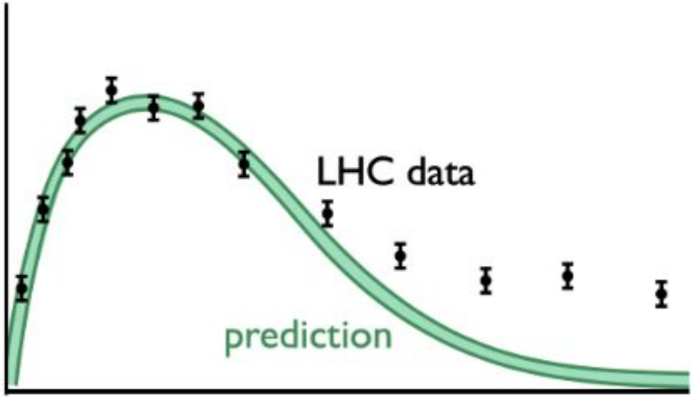
- 2013 Nobel Prize in Physics to Francois Englert and Peter Higgs.

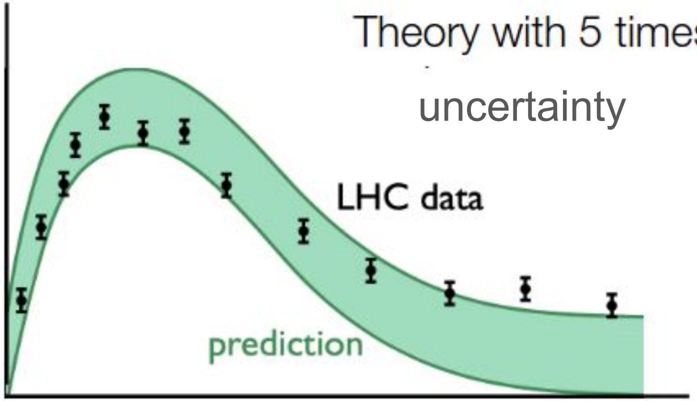
- Value of the Higgs boson mass chosen by Nature
  → quick discovery at the LHC.
  → numerous experimental measurements with multiple decay modes.

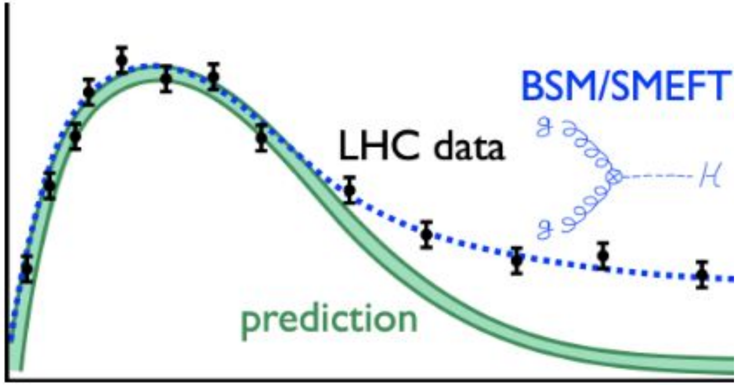
This talk is *only a glimpse* of the recent state-of-affairs

Role of precision

Gedanken experiment







We cannot afford to miss a discovery!