Search for non-resonant production of the Higgs pair in experiments at the CERN-LHC.

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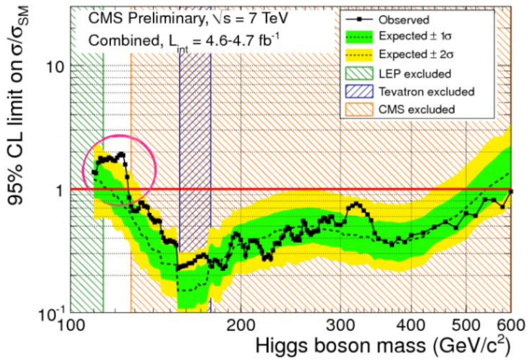
Anomalies 2021, IIT Hyderabad, 12 November, 2021.

One decade of Higgs!



Press release after CERN Seminar, 13 December, 2011:

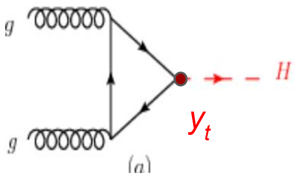
"...the Standard Model Higgs boson, if it exists, is most likely to have a mass constrained to the range 116-130 GeV by the ATLAS experiment, and 115-127 GeV by CMS. … evidences are not yet strong enough to claim a discovery."

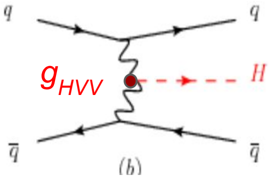
4th July, 2012 :

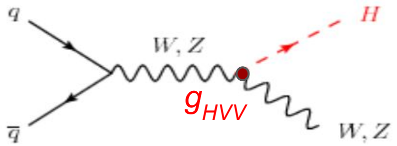
ATLAS and CMS collaborations announce discovery of the Higgs particle with mass m_H = 125 GeV!

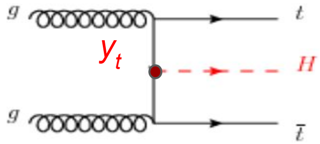
Inclusive single Higgs production at the LHC (not all are illustrated here)

Gluon-gluon fusion vector boson fusion associated production of Higgs with a vector boson (V) or top pair









- Higgs physics has taken the centre stage and likely to dominate the collider physics for the next decade too.
  Fabiola Gianotti @ LHCP2021: "*Every problem in SM originates from the Higgs interaction*"!

- **Higgs physics is now the tool for probing anomalies in data wrt Standard Model predictions or models beyond SM.**

A long way since the discovery, but still miles to go

- Mass
- Spin-parity
- Width
- Couplings
- $\mathcal{CP}$ properties

→

- New mysteries concerning the scalar sector of Standard Model
- Experimental data indicates the discovered resonance to be SM-like

- **Self-interaction** → Scalar potential of the Higgs field depends on the self-coupling λ of the Higgs

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

Expanding about the minimum:

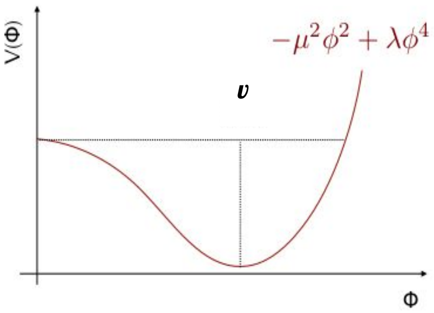
$$V(\phi) = -V(v+h)$$

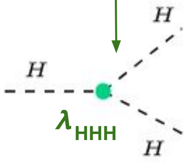
$$V = V_0 + \frac{1}{2}m_h^2h^2 + \frac{m_h^2}{2v^2}vh^3 + \frac{1}{4}\frac{m_h^2}{2v^2}h^4$$

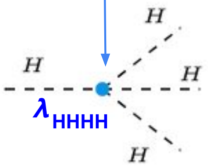
Higgs mass term

Tri-linear Higgs self-coupling

Quarti-linear Higgs self-coupling







- Leads to ElectroWeak symmetry breaking and introduction of masses of other standard model particles.

In SM :

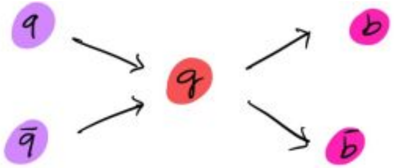
$$\lambda_{\mathrm{HHH}} = \lambda_{\mathrm{HHHH}} = \frac{\mathrm{m_H^2}}{2\mathrm{v^2}} = 0.13$$

for m_H=125 GeV, v = 246 GeV

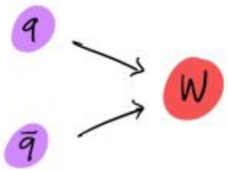
- Measuring λ extremely important because it is a fundamental test of SM. ⇒ direct probe for the shape of the Higgs potential.

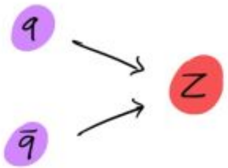
Higgs pair (HH) production at the LHC provides access to λ

Higgs @ the LHC ($\sqrt{s}$ = 13 TeV)



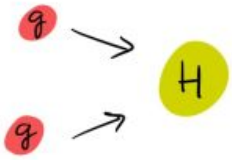
bottom 1 in a hundred ***pp collisions***



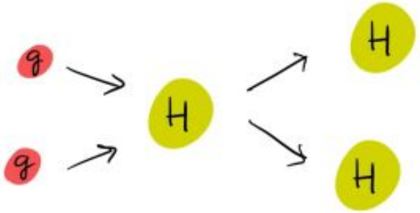


W 1 in a half a million

Z 1 in a million



H **1 in a billion**



HH **1 in a trillion**

~ 0.007 Higgs pairs/sec during LHC Run2 (pp collision at $\sqrt{s}$ = 13 TeV)

Interpretation of experimental results

- Measurements in Higgs sector still dominated by statistical uncertainties.
- Look for deviations from SM predictions.
- No hint for non-SM property as yet.
- HH production process being explored using **LHC Run2 data.**
- At present:

  i)Upper limit on inclusive production cross section of Higgs pair.

  ii)Constraints on the allowed range for anomalous couplings.

Estimate from data:

1. signal strength: $\mu = (\sigma * BR)_{obs} / (\sigma * BR)_{SM}$
2. coupling modifiers: $\kappa_i = g/g^{SM}$ $\kappa_i = 1 \Rightarrow$ SM

$\kappa_i \neq 1 \rightarrow$ anomalous couplings

$\Rightarrow$ larger/smaller production rate than SM

$\Rightarrow$ if increased rate, possibility to observe with limited data!

- The EFT formalism summarizes deviations that might appear in a very wide class of models beyond the SM.

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{M^2} \sum_k \mathcal{O}_k$$

assuming new physics scale $M >> v$

- Sub-percent level measurements can test TeV-scale new physics effect
- If E ~ m_H and M ~ 1 TeV, the effects of dim-6 (8) operators are of the order of $(v/M)^2$ = few % (10^{-4})
- With lower precision in measurements, using processes with large momentum transfer ($\mathcal{Q}$), physics at large M can be probed. $\rightarrow$ effect is $(\mathcal{Q}/M)^2$ ~ 15% for M ~ 2.5 TeV

Non-resonant Higgs pair production at the LHC

- Inclusive HH production is a rare process
  $\sigma(HH) \sim 10^{-3} * \sigma(H)$

- *Has unique sensitivity for certain Higgs couplings*

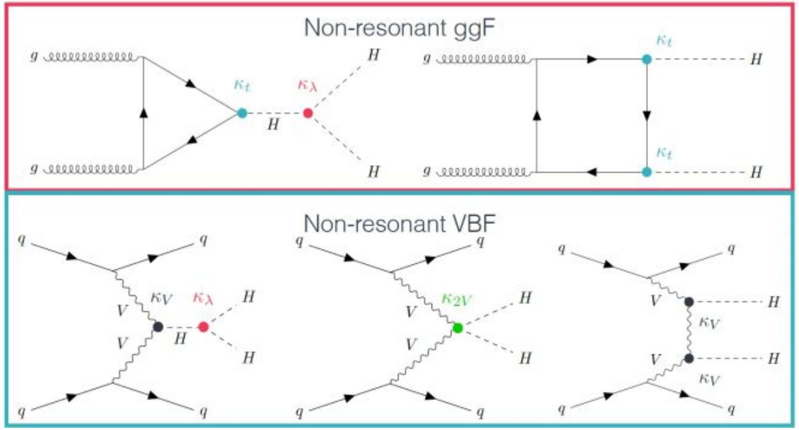
i) Higgs trilinear coupling (HHH)

$$\lambda = m_H^2 / 2v^2$$

ii) Higgs pair coupling with pair of weak bosons (HHVV)

$$g_{HHVV} = 2m_V^2 / v^2$$

iii) Also involves ttH and HVV couplings which already appear in single H productions ⇒ κ_t, κ_V *etc.* have been estimated.



$\kappa_\lambda = \lambda/\lambda^{SM}$ $\kappa_{2V} = g_{HHVV} / g_{HHVV}^{SM}$

- **Dominant Gluon-gluon fusion (*ggF*) production: σ_{ggF} = 31.05 (+ 0.5% -0.7%) fb @13 TeV**

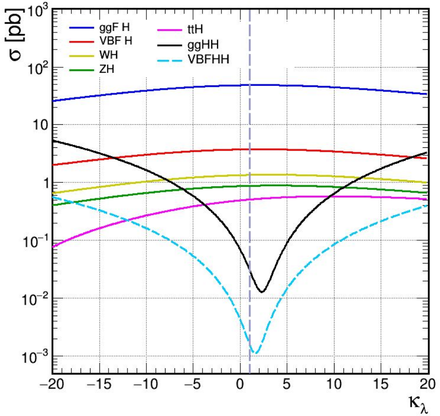
➔ accurate upto next-to-next-to leading order (N2LO) in QCD

 ➔ uncertainties due to PDF, scale, α_s, m_t

➔ *destructive interference between the two diagrams*

- **Sub-dominant vector boson fusion (VBF) production (accurate to N3LO): σ_{VBF}= 1.73 fb @13 TeV**

➔ ***unique sensitivity of the process to g_{HHVV} coupling***



Note: NLO EW corrections for single H productions also involve λ

Higgs pair production and decays

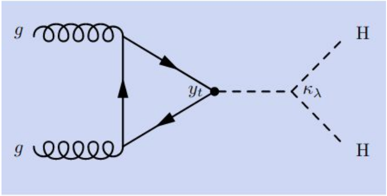
At the LHC, 3 possibilities for inclusive production of Higgs pair in SM or BSM

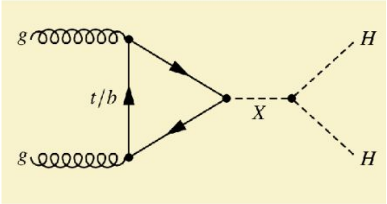
i) **Nonresonant production with SM or BSM couplings**

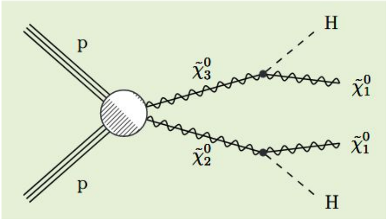
ii) Resonant production: a heavy BSM parent X decaying into HH

iii) Cascade production: two BSM parents, each producing a H

Production process dominated by gluon-gluon fusion (ggF)



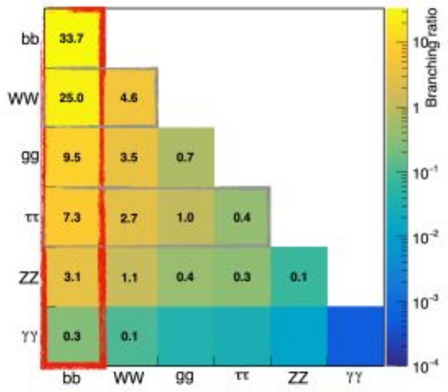




At least a precision of 20% on $\boldsymbol{\lambda}$ is needed to probe BSM modifications

Decays: Modes with large branching ratios (BR) utilized for at least one of the H decays : viz., bb (58%) and WW* (21%)

→ Comprise between event sample size and sensitivity of final state.



Present searches in a nutshell

bbbb: largest rate, but huge background of QCD production of multijets.

$bbWW$: second leading BR, large background due to top pair production.
→ searches in both semi-leptonic and di-leptonic final states.

$\boldsymbol{bbZZ, bb\tau\tau}$ **:** smaller BRs, leptons (e/μ) or hadronic-τ used for triggering depending on the final state.

$\boldsymbol{bb\gamma\gamma}$: smallest BR but very sensitive analysis thanks to the excellent acceptance ($\gamma\gamma$ trigger) and reconstruction resolution

HH → 4b final state

CMS PAS-HIG-20-005
CMS PAS-B2G-21-001

- Resolved b jets → nonresonant HH
- ggF and VBF events classified using a BDT

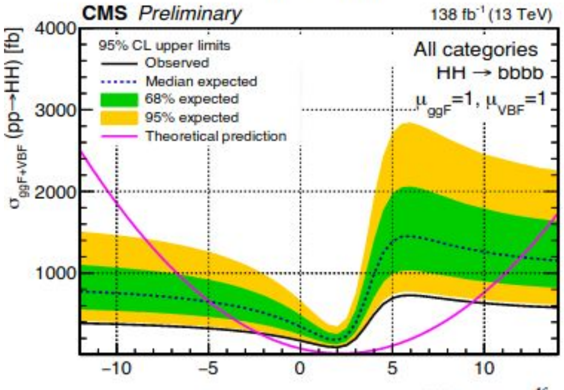
- A distance parameter between 2 Higgs candidates used to define the signal and control regions.

$$\chi = \sqrt{(m_{H_1} - c_1)^2 + (m_{H_2} - c_2)^2}$$

- The large multijet background is estimated from data.
- A maximum likelihood binned fit performed simultaneously in all signal regions.

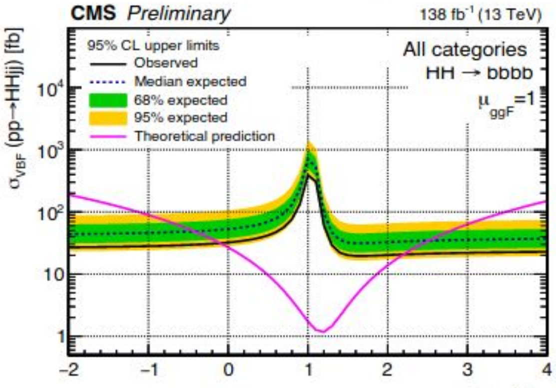
- Number of categories decided by minimum improvement on upper limit on cross-section of 10%. And there is interplay of event statistics.

κ_λ [-2.3, 9.4] (*exp:* [-5.0, 12.0])



3.6 (*exp:* 7.3) x σ_{SM}^{ggHH}

κ_{2V} [-0.1, 2.2] (*exp:* [-0.4, 2.5])



226 (*exp:* 412) x σ_{SM}^{VBF}

- Results dominated by background modelling uncertainties.

Aside:

- κ_{2V} is best constrained from resonant HH search with boosted topologies.
- Highly boosted Higgs bosons → heavy resonant particle decaying to Higgs pair ⇒ merged b jets → identified with a DNN tagger

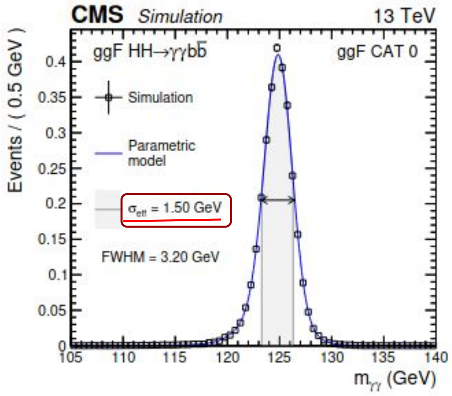
- Main challenge is the efficient reconstruction of $H \rightarrow b\ b$

→ ParticleNet multiclass classifier to discriminate between large-radius jets from $H \rightarrow bb$ decays and those from QCD multijet processes

HH studies with bb $\gamma\gamma$ final states

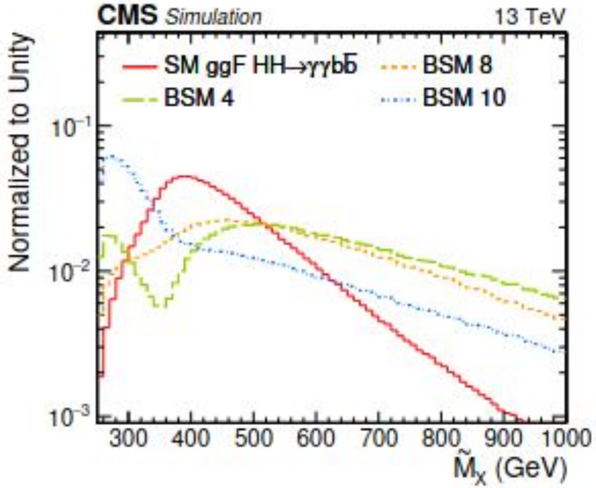
$H \to bb$: key element in the exploration with the highest branching ratio
good b-jets identification performance: 70% efficiency at 0.3 - 1% q/g mistag probability

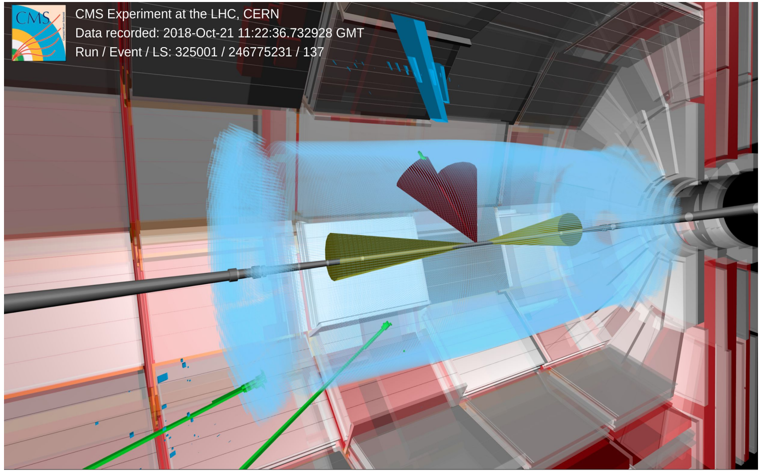
$H \to \gamma\gamma$: clean final state with excellent mass resolution, ~1%



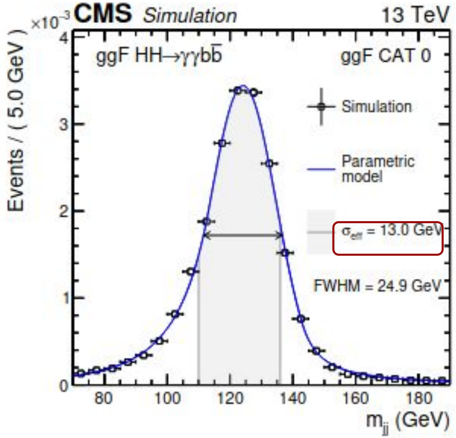
HH → 4b : CMS, 138 /fb
HH → bb $\gamma\gamma$: CMS, 137 /fb
: ATLAS, 139 /fb

BSM sensitive variable for HH → bb $\gamma\gamma$ analysis
$\tilde{M}_X = m(bb\gamma\gamma) - m(bb) - m(\gamma\gamma) + 250$ GeV





A candidate event for VBF production of HH in CMS experiment and decaying to **bb $\gamma\gamma$** final state



Overview of HH → bb $\gamma\gamma$ analysis from CMS

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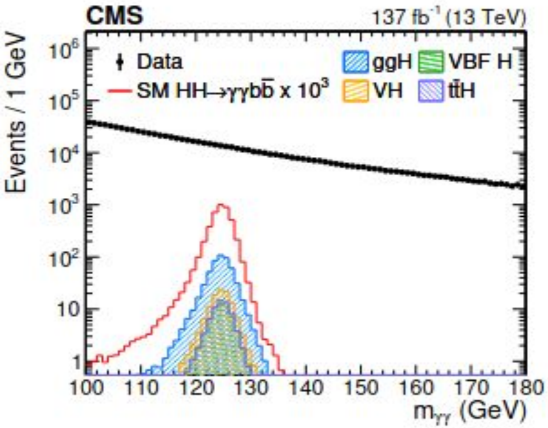
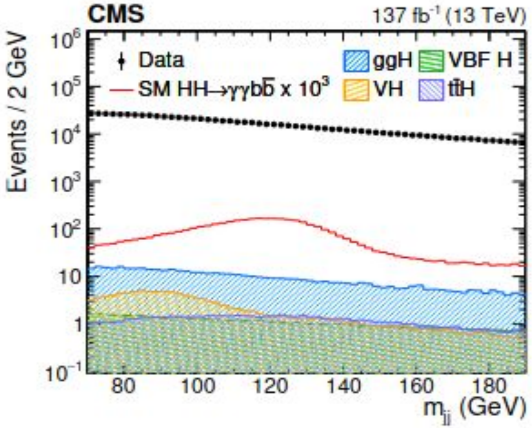
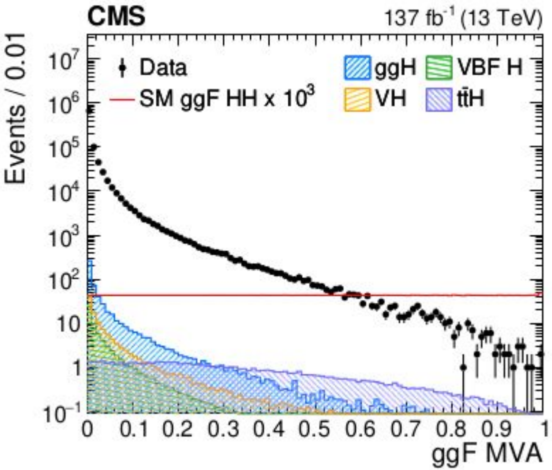
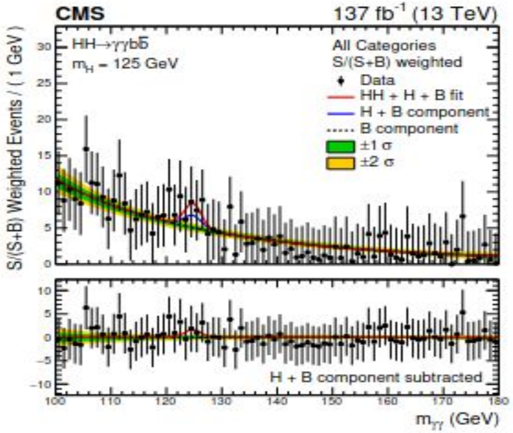


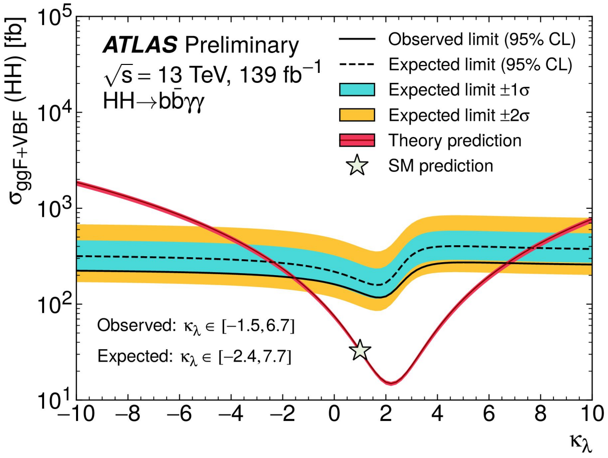


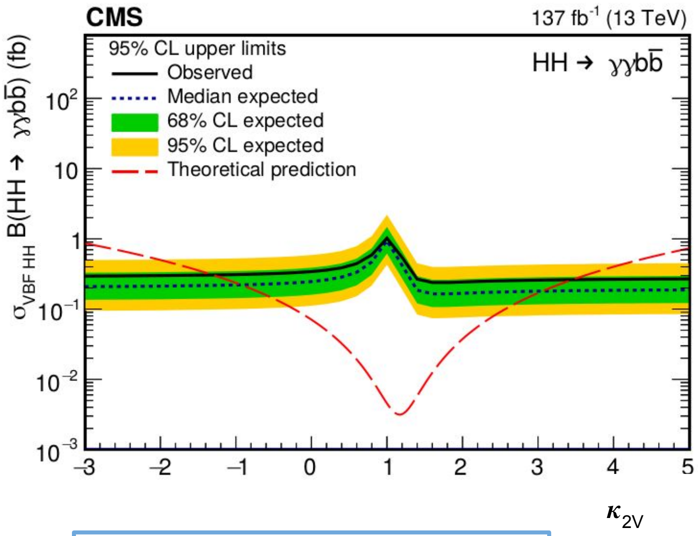


- Clean but rare final state.
- Overwhelming background from QCD production of jets + $\gamma\gamma$ or jets + γ (2nd γ is faked by a jet).
- Single Higgs production is a background here, specially from ttH (with H → $\gamma\gamma$) .
- Two different BDTs to discriminate ggF or VBF HH production processes against background · DNN against ttH.
- Multiple regions optimised for ggF or VBF processes using MVA scores and $\tilde{M}$ X = $m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma}$ + 250 GeV.
- 2D fit to $m_{\gamma\gamma}$ and m_{jj} side bands in all regions to estimate the non-resonant backgrounds with data.



Best results for HH→bbγγ analysis: from ATLAS & CMS





Observed (expected) limits:

- $\sigma^{HH}_{ggF+VBF} < 4.1\ (5.5)\ \times \sigma^{HH\ SM}_{ggF+VBF}$
- $-1.5\ (-2.4) < \kappa_\lambda < 6.7\ (7.7)$

Observed: $-1.3 < \kappa_{2V} < 3.5$
Expected: $-0.9 < \kappa_{2V} < 3.0$

95% CL Upper Limit on (VBFHH cross section*BR)

VBF HH (* SM)	
Observed	225
Expected	208

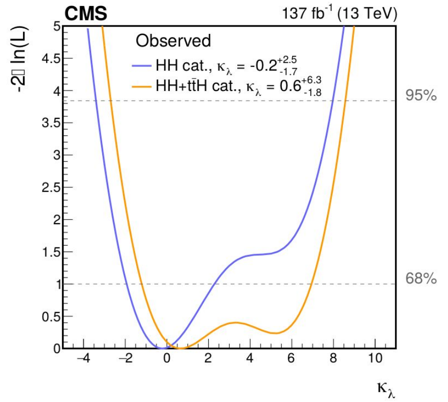
Best to date results

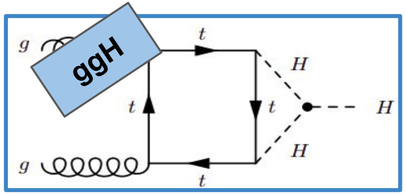
Accounting for single Higgs processes

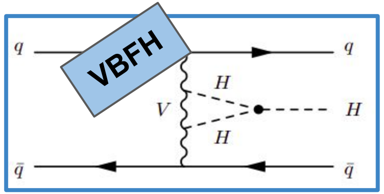
- κ_λ and κ_t couplings are present in HH as well as in single Higgs production due to NLO EW effects.
  → Cross sections depend on κ_λ and κ_t

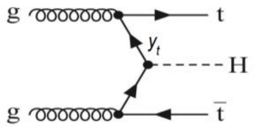
- So inclusion of the single Higgs processes gives additional improvement to search these couplings in data.
- Selection of single H events is completely exclusive to the HH ones.

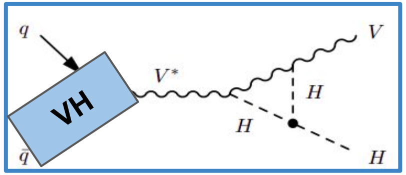
- ttH process considered for better constraint on κ_λ and κ_t
- → ttH categories are mutually exclusive to the all HH categories (ggHH & VBFHH)

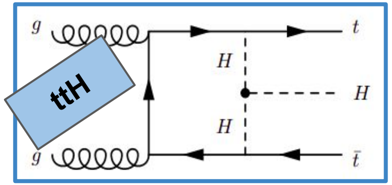


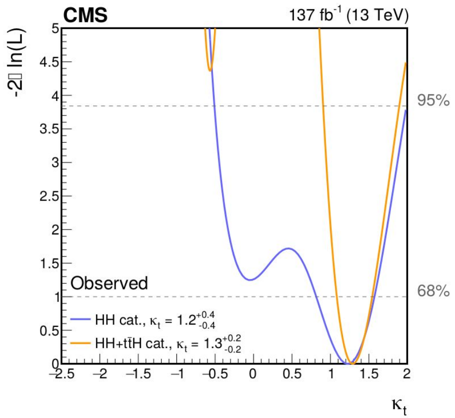










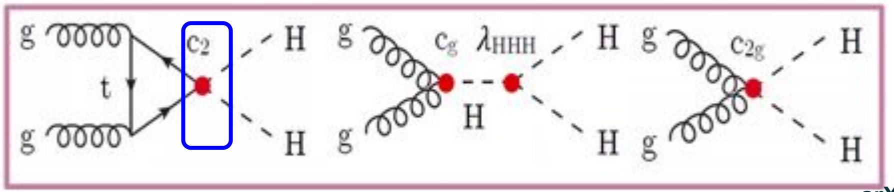


Inclusion of ttH in 1D scan makes

i) positive value of κ_λ preferable

ii) rules out negative κ_t at 95% CL

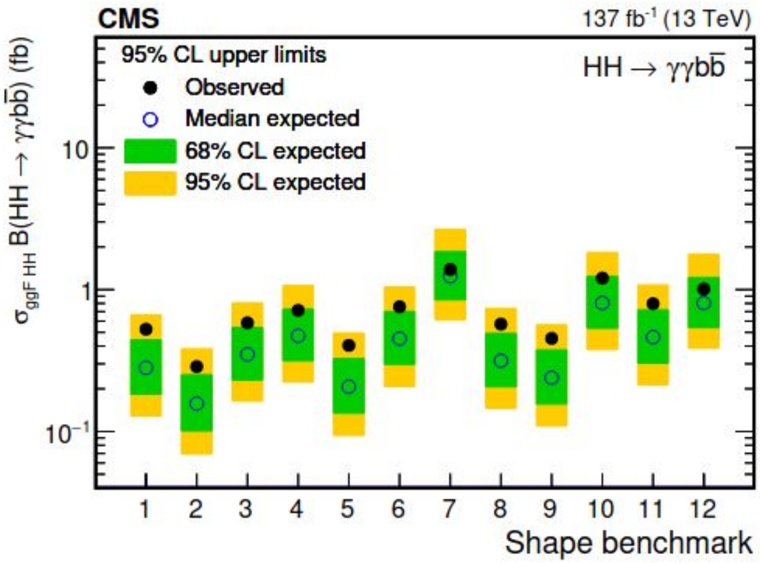
Search for anomalous couplings: CMS results

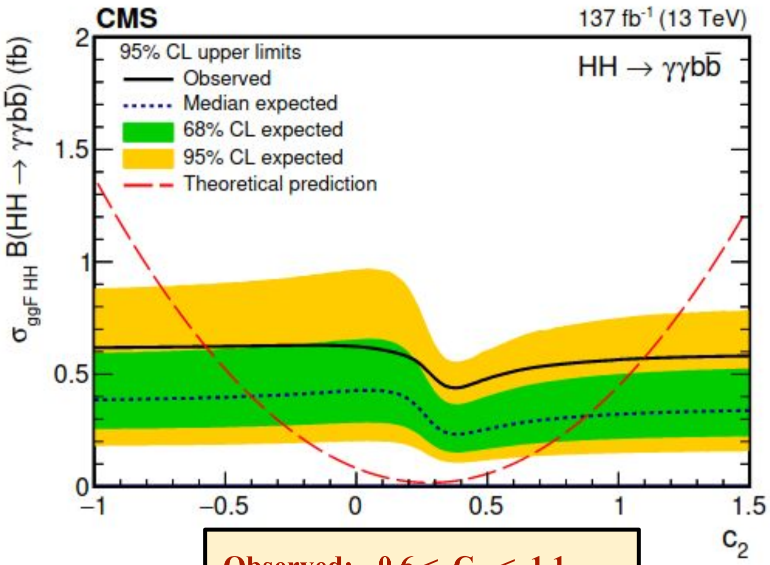


- EFT approach for gg→ HH process includes **three** types of contact interactions described by dim-6 operators.
→ **additional couplings for gg→ HH compared to SM.**

arXiv: 1610.07922
arXiv: 1410.3471

Compatibility of data with different representative BSM scenarios

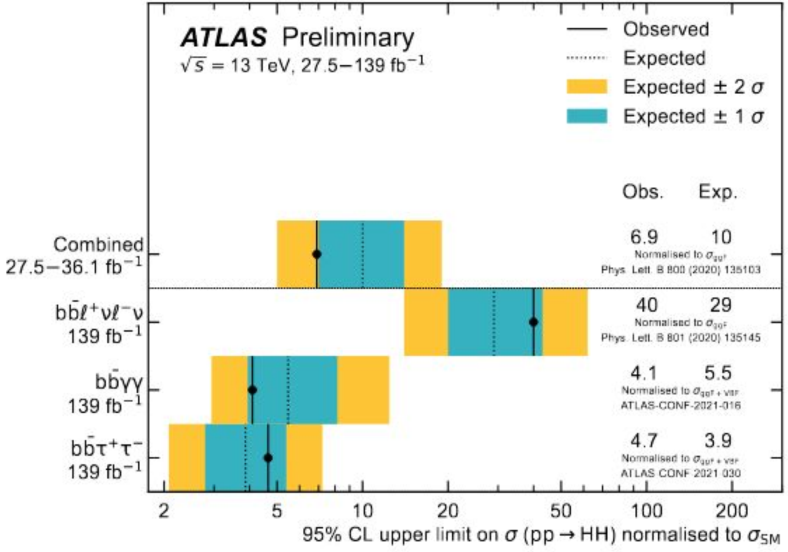


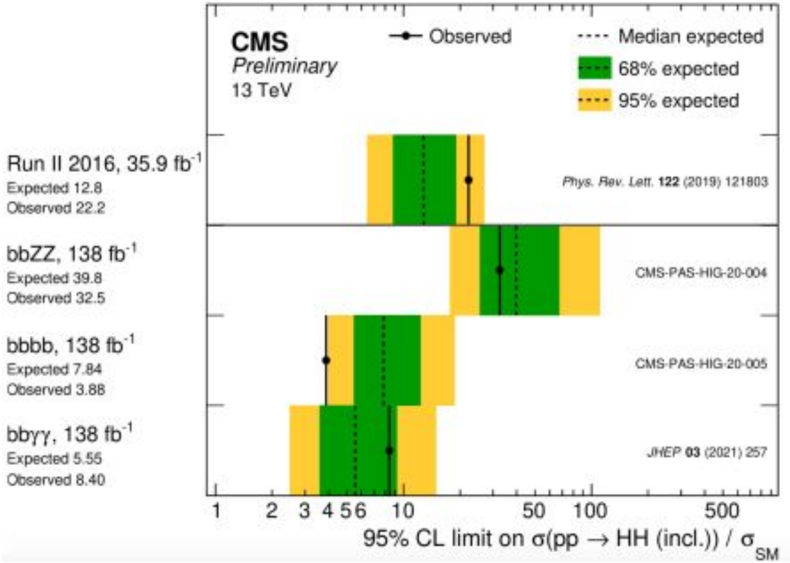


Observed: $-0.6 < C_2 < 1.1$
Expected: $-0.4 < C_2 < 0.9$

Combination of channels

ATL-PHYS-PUB-2021-031



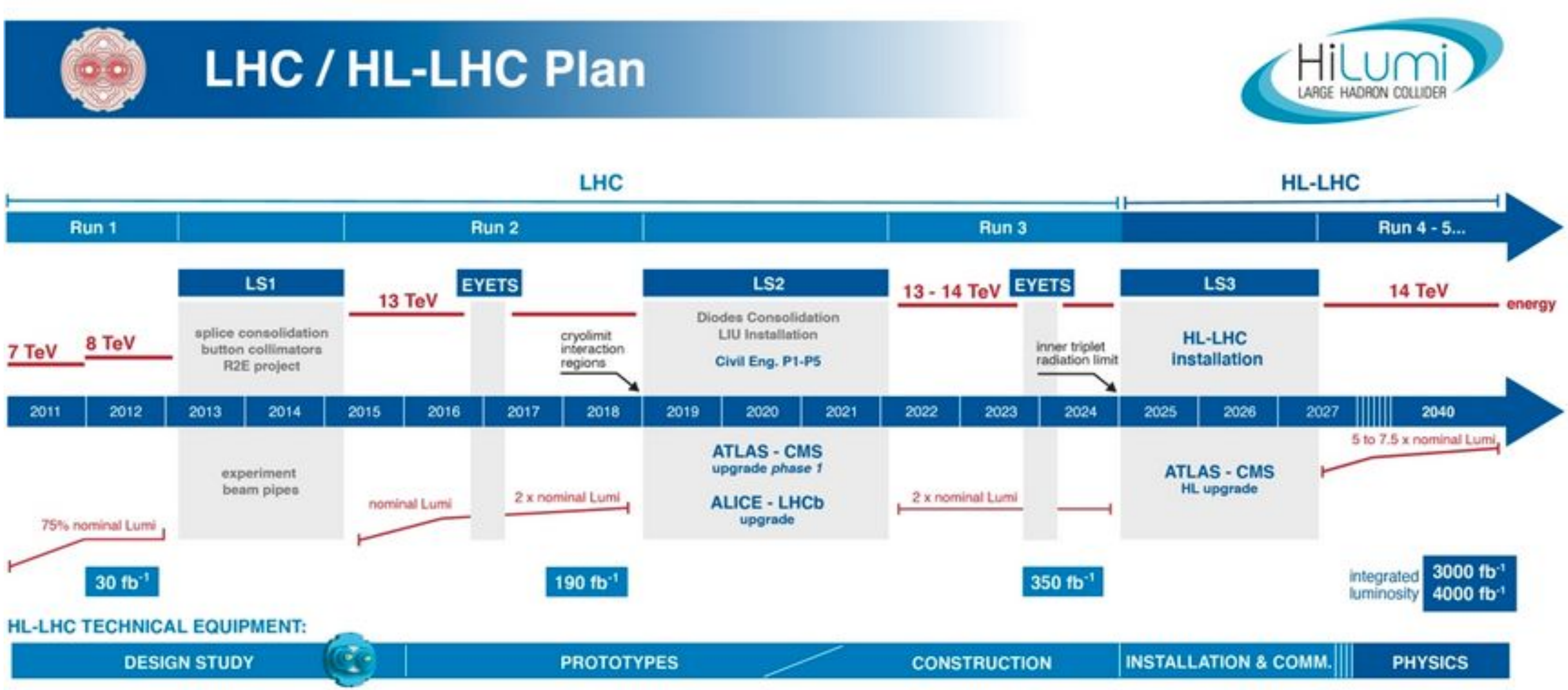


- The expected limits assume no HH production.
- The theory prediction curve represents the scenario where all parameters and couplings are set to their SM values except for κ_λ.

EFT interpretation:

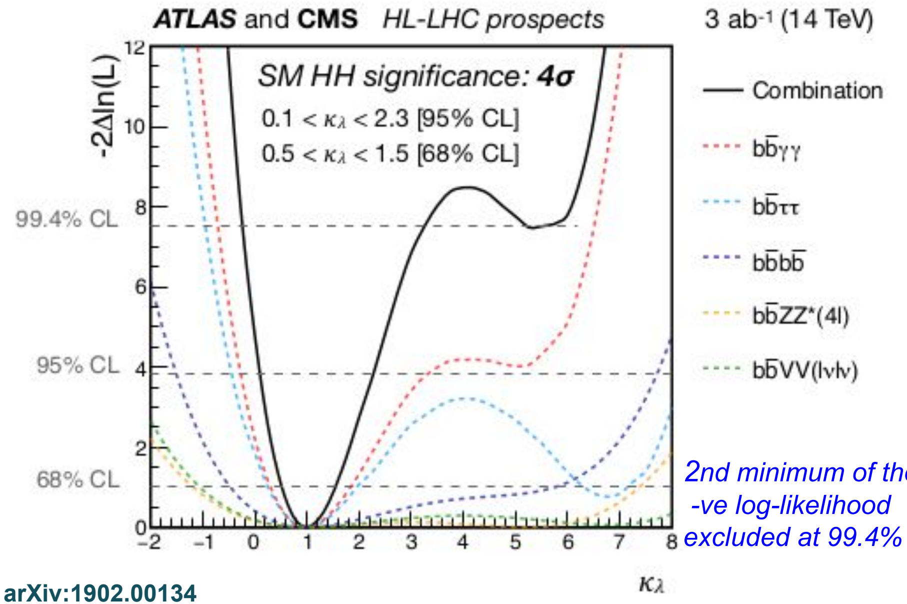
- Different approaches to reinterpret Higgs measurements searching for BSM effects using the EFT framework.
- In general, sensitivity to different types of operators from different kinematic distributions.
- Combination of several decay channels allow to constrain simultaneously large set of operators.

Near future: High Luminosity LHC



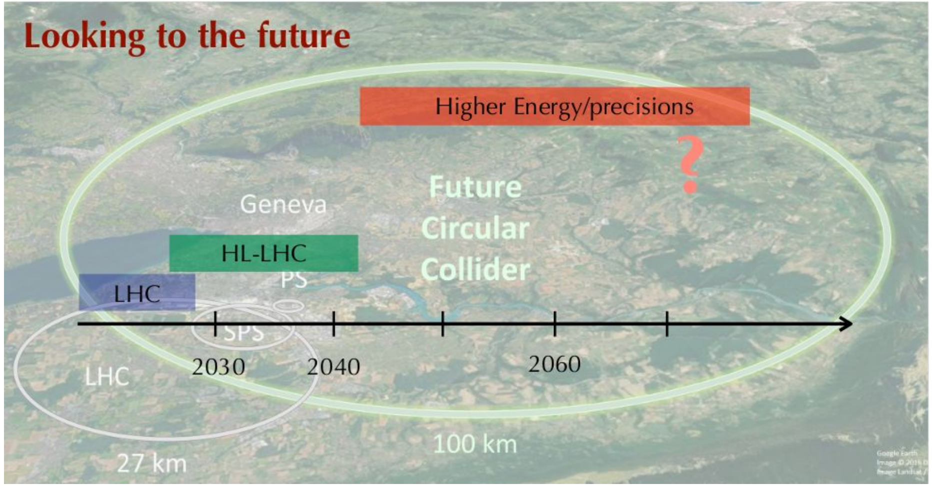
Using data corresponding to an integrated luminosity of 3000 /fb, κ_λ can be measured with an accuracy of 50% at the high luminosity LHC, after ATLAS and CMS combinations→ unless BSM contributions arise.

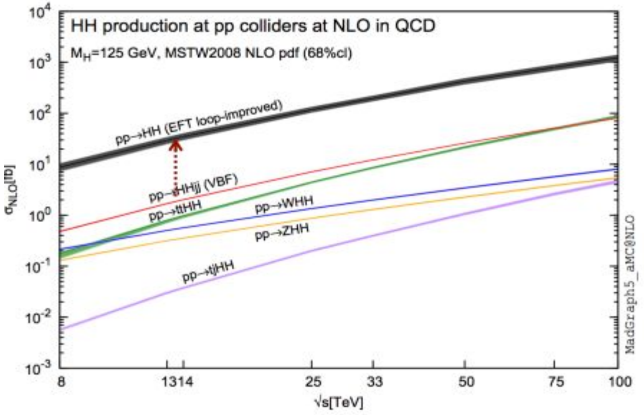
Future prospects: near and far



2nd minimum of the -ve log-likelihood excluded at 99.4% CL

arXiv:1902.00134





Going by the state-of affairs in Higgs physics surely HL-LHC will do far better actually, with real data.

Improvements in detector performance, analysis techniques and reduction of systematic uncertainties will have to match the improvements of statistical accuracy.

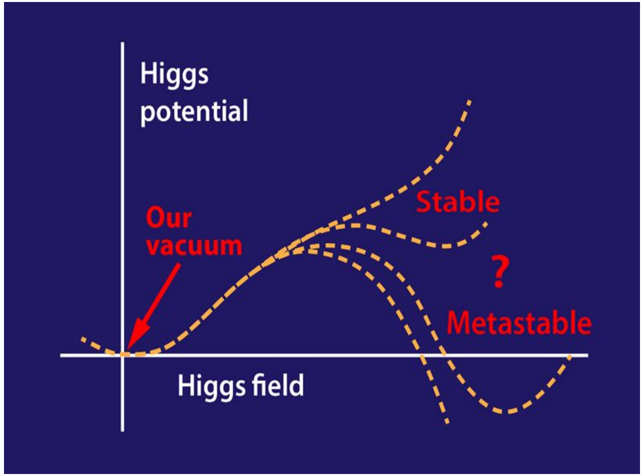
Summary

- Understanding the nature of the Higgs boson is one of the main tasks of particle physics today.
- So far no significant anomaly is observed in the Higgs sector.

- The search for Higgs boson pair production and measurement of Higgs self-coupling is highly important to understand the details of EWSB.

- This search allows us to test SM and BSM hypotheses, by looking for deviations in the κ-framework as well as via searching for new resonances.

- Given the current available integrated luminosity both the gluon-gluon fusion and the vector boson fusion production modes are being investigated using many different final states by ATLAS and CMS experiments.



In general,

- We are starting to reach the sensitivity where we expect deviations!
- We have only probed only few % of the total data volume expected at the LHC.
- Pattern of deviation can pinpoint the type of new physics.

The future prospect for Higgs physics looks bright → stay tuned!

Backup

$\boldsymbol{HH \rightarrow bbWW/ZZ}$ searches

ATLAS $\boldsymbol{bb\ell\ell}$ **Phys.Lett. B 801(2020)135145**

Fit on combined NN output → σ < 40 (29) × σ_{SM} at 95% CL

CMS $\boldsymbol{HH \rightarrow bbZZ \rightarrow bb4\ell}$ with 137 /fb **PAS HIG-20-004**

- 9 BDTs trained (for each data taking year and lepton flavour $4e/4\mu/2e2\mu$)
- Fit on BDT outputs: σ < 30 (37) × σ_{SM} at 95% CL