Measurement of Higgs self coupling from non-resonant Higgs pair production in CMS experiment

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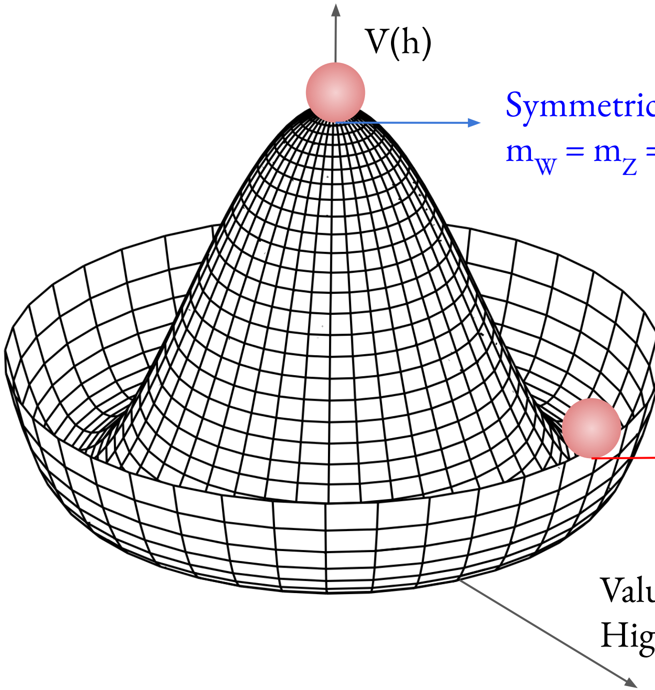
Higgs potential



Symmetric,
$m_W = m_Z = m_\gamma = 0$

Broken symmetry,
$m_\gamma = 0$,
$m_W, m_Z \neq 0$

Values of
Higgs field, h

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

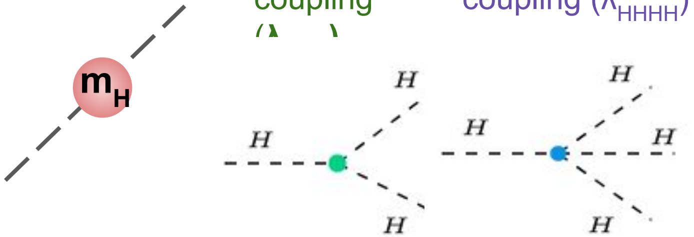
Expanding around one of it's minima : $V(\phi) = -V(v+h)$

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

Higgs mass term

Tri-linear Higgs self coupling

Quarti-linear Higgs self coupling (λ_{HHHH})

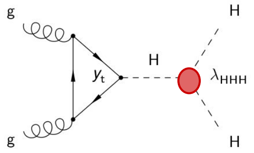


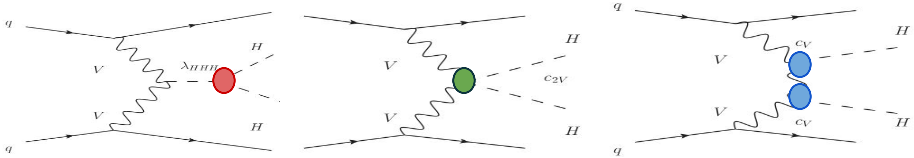
- Shape of potential gives relationship between **λ, m_H and v**
- **λ is yet to be measured experimentally**
- Measuring λ important because it probes the shape of the Higgs potential
- **Non-resonant HH production** at the LHC provides access to **λ (tri-linear Higgs coupling)**

In SM :

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

HH production at LHC





Gluon-Gluon Fusion (ggHH)
x-sec at N2LO QCD accuracy:
@ 13 TeV 31.05 +2.2% / -5.1% fb
@ 14 TeV 36.69 +2.1% / -4.9% fb

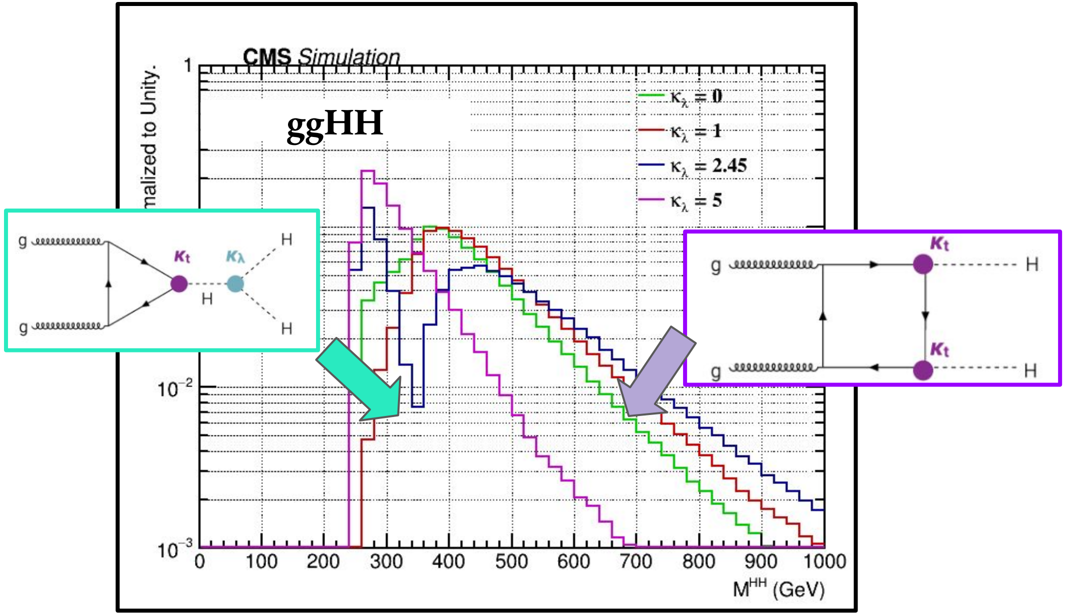
Vector Boson Fusion (VBFHH)
x-sec at N3LO QCD :
@ 13 TeV 1.726 ± 2.1% fb
@ 14 TeV 2.055 ± 2.1% fb

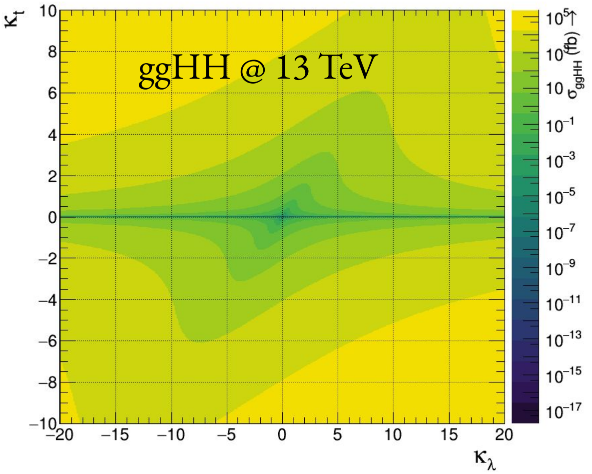
→ ggHH is the leading HH production mode
→ Cross section ~ 1000 x smaller than single Higgs
→ Two diagrams contributes with destructive interference in SM
→ Cross section depends on λ and y_t

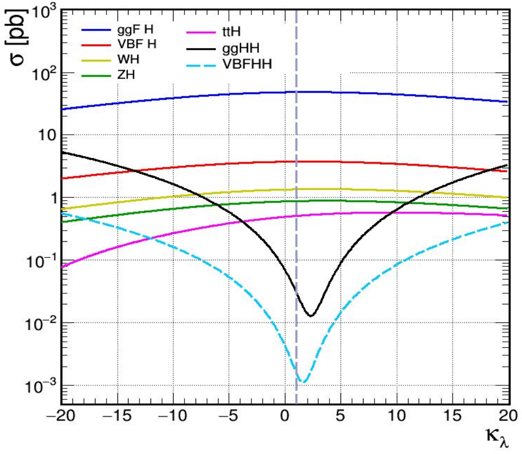
→ VBF-HH is the sub-leading HH production mode
→ **unique** process for accessing the coupling of **Higgs pair with a pair of weak gauge bosons (HHVV, V = W/Z)**
→ Cross section depends on λ and C_{2V}
→ C_V already constraints from H → VV measurements

HH production at LHC

→ Cross section and shape of m_{HH} distribution changes with the couplings.
⇒ Experimentally determine the coupling modifiers.
eg., $\kappa_{\lambda} = \lambda/\lambda_{SM}$, $\kappa_t = y_t / y_t^{SM}$

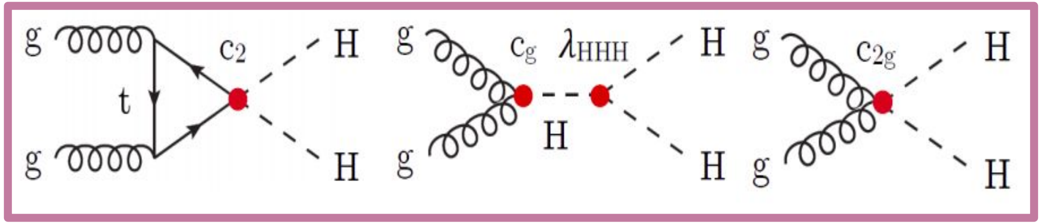






→ Utilize dependence of event kinematics on κ_{λ} and κ_{2V}

HH production in BSM



➢ C2 , Cg, C2g = 0 in SM

- Typically probed via anomalous coupling parameters in terms of modifiers of SM values ($\boldsymbol{\kappa_i}$). Anomalous values of the coupling modifiers enhance the cross section typically.

- EFT approach includes three new additional couplings for ggHH compared to SM.
Parameters of interest: κ_λ, κ_t from SM + c_2, c_g, c_{2g} from BSM

Lagrangian ~

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}\left(v + \kappa_t h + \frac{c_2}{v} h h\right)(\bar{t}_L t_R + h.c.) + \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(c_g h - \frac{c_{2g}}{2v} h h\right) G^{\mu\nu} G_{\mu\nu} .$$

Cross section dependency :

$$\frac{\sigma_{hh}}{\sigma_{hh}^{SM}} = \begin{pmatrix} A_1 \kappa_t^4 + A_2 c_2^2 + (A_3 \kappa_t^2 + A_4 c_g^2)\kappa_\lambda^2 + A_5 c_{2g}^2 + (A_6 c_2 + A_7 \kappa_t \kappa_\lambda)\kappa_t^2 \\ +(A_8 \kappa_t \kappa_\lambda + A_9 c_g \kappa_\lambda) c_2 + A_{10} c_2 c_{2g} + (A_{11} c_g \kappa_\lambda + A_{12} c_{2g})\kappa_t^2 \\ +(A_{13} \kappa_\lambda c_g + A_{14} c_{2g})\kappa_t \kappa_\lambda + A_{15} c_g c_{2g} \kappa_\lambda \end{pmatrix}$$

HH Decay Modes

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

→ The choice of final state depends on the large branching ratio and clear final state.

→ HH decay modes being explored using **full Run2 (137 fb^{-1})** data both by CMS and ATLAS collaborations:

- ❖ Modes with large branching ratios (BR) utilized for at least one of the H decays to
  - ➢ bb (58%) and WW*(21%)

→ Today's presentation emphasis on the two most sensitive channel in the context of HH from CMS experiment.

HH → bbbb (abundant decay mode with largest BR)
CMS-PAS-HIG-20-005

HH → bbγγ (tiny BR with very clean final state)
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HH→ bb$\gamma\gamma$

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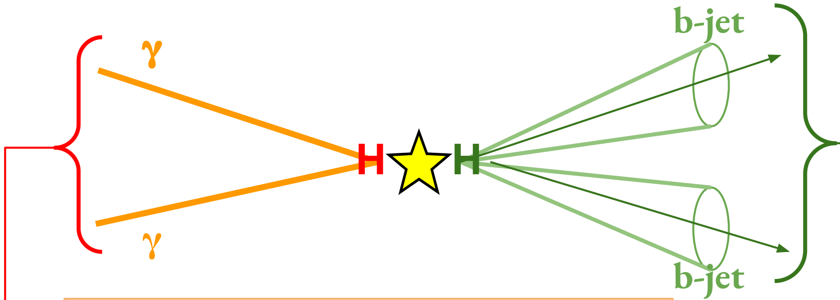
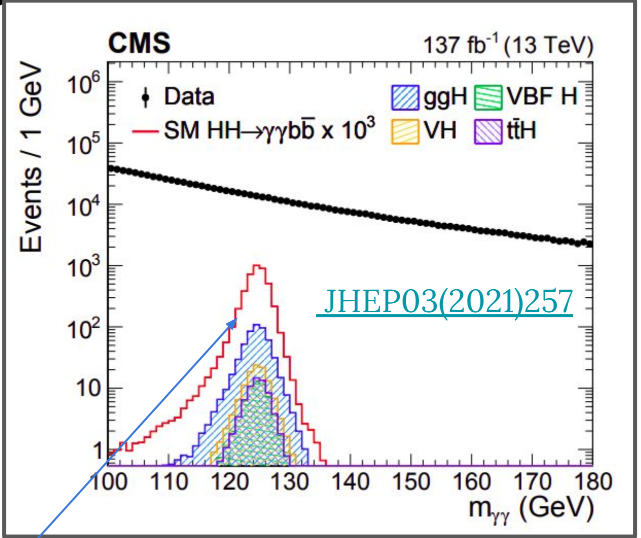
General strategy for bbγγ analysis



→ **Diphoton trigger**: p_T > 30, 18 GeV
→ p_T / $m_{\gamma\gamma}$ > 0.33 (0.25)
→ 100 < $m_{\gamma\gamma}$ < 180 GeV

→ **Deep Neural Network (DNN)** to identify the b-jets from light quark or gluon jets
→ Two highest b-tagged **anti-K_T** jets
cone radius 0.4 (AK4), $|\eta| < 2.4$
→ **70 < m_{bb} < 190** GeV
→ Additionally **b-jet energy regression** improves the **b-jet energy resolution** and **m_{bb} spectrum.**



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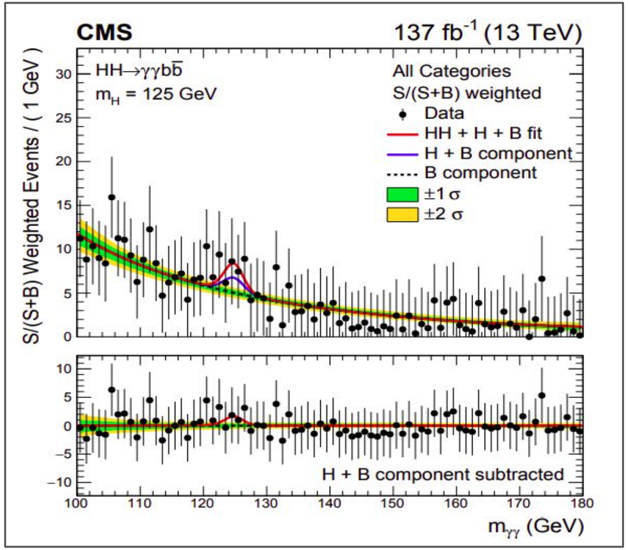
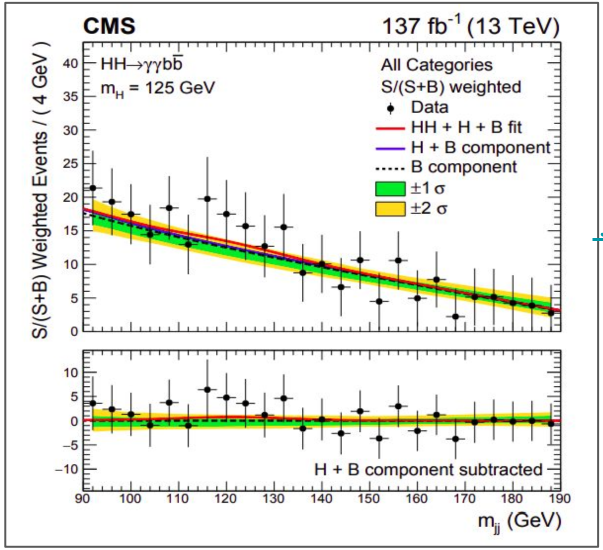
→ Signal contribution submerged in continuum background, (γγ+jets/γ+jets), due to very small x-sec.

→ 2-fold event categorization:
i) in $\mathbf{M_{HH}}$ to probe SM and BSM
ii) based on **BDT score** in each M_{HH} region to increase the signal purity and analysis sensitivity

Fitting strategy

→ Signal extracted using a parametric 2D fit of **$m_{\gamma\gamma}$ and m_{bb}** from each analysis category simultaneously.
→ HH signal and single Higgs background contribution taken from monte carlo simulation by fitting $m_{\gamma\gamma}$ by **multi-gaussian** and m_{bb} by **Double Sided Crystal Ball (DSCB)** function.
→ Continuum background from data side-band region





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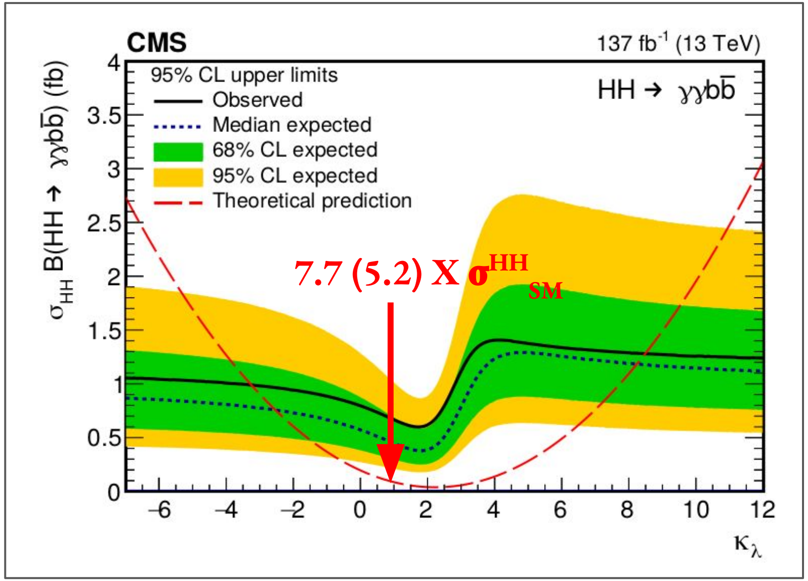
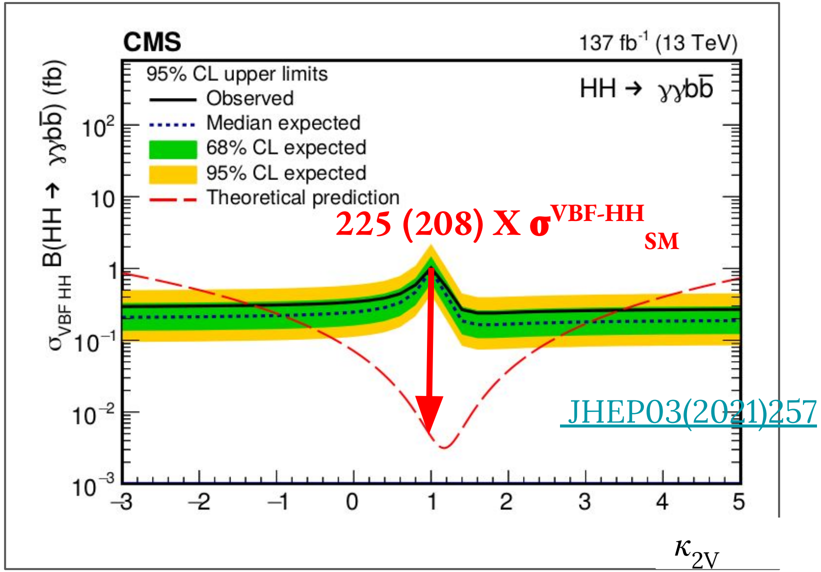
→ **No significant excess observed in data**

HH→ bbγγ results





→ κ_λ values allowed at 95% CL [-3.3, 8.5] (expected [-2.5, 8.2])

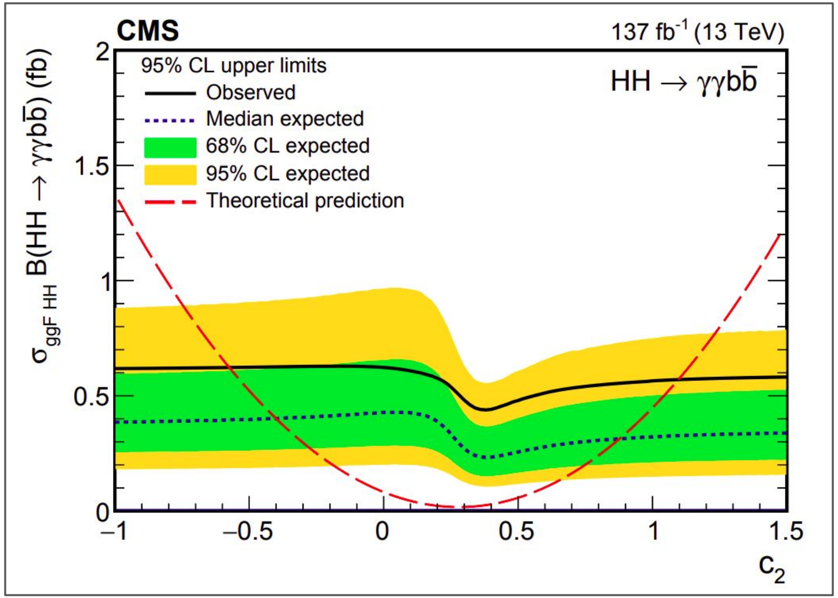
→ κ_{2V} values allowed at 95% CL [-1.3, 3.5] (expected [-0.9, 3.1])

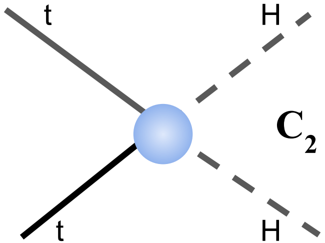
Likelihood scans are in backup

BSM C_2 coupling

- C_2 : modifier of the coupling between two top quarks and two Higgs (ttHH vertex)
- But in some scenarios of BSM ttHH may be possible → in EFT approach this coupling can be accommodated.

Allowed range of C_2 @ 95% CL





$C_2 = y_{ttHH} / y^{SM}_{ttHH}$

Observed: $-0.6 < C_2 < 1.0$
Expected: $-0.4 < C_2 < 0.9$

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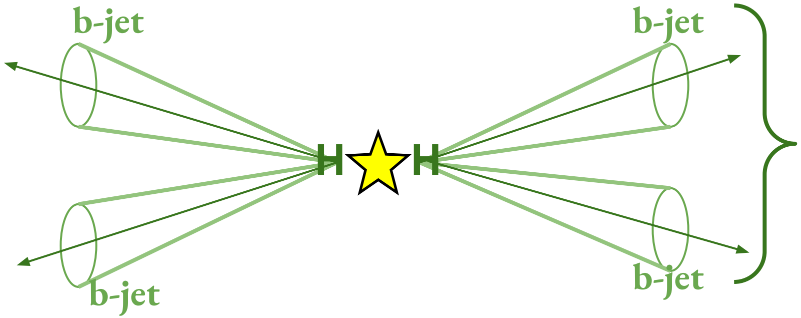
HH$\rightarrow$ bbbb resolved analysis

CMS-PAS-HIG-20-005

General strategy for 4b analysis



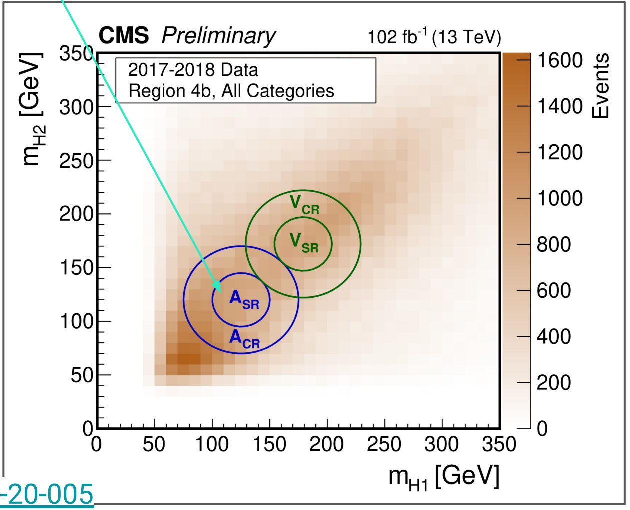
→ Overwhelming background due to the **QCD induced multijet production** and **tt hadronic decay.**
→ Hard to rely on the simulation , sued **data driven technique**
→ **Signal region (A SR)** and **control region (A CR)**.
defined from **2D mass distribution of the two Higgs bosons** (mH1, mH2)
→ Technique validated in another part of 2D space (VSR, VCR)

→ **Events are triggered** with at **least 4 jets criteria**
→ $\mathbf{p_T}$ > **30 (40) GeV** and **|η|** < **2.4** for **2016 (2017, 2018)**

→ b-tagging performed using dedicated **DNN training**

→ Additional leptons vetoed from the events

→ Combine the each pair of jets from all combination into two H candidates.
→ **96% accuracy for SM ggHH signal**

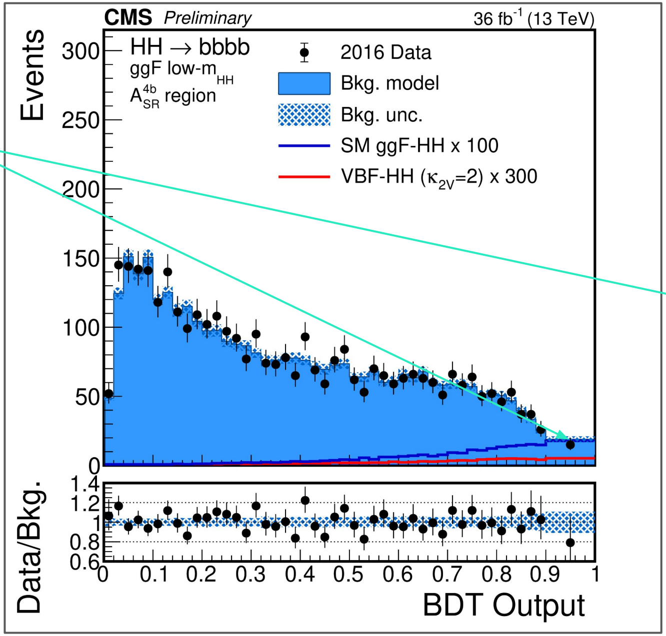


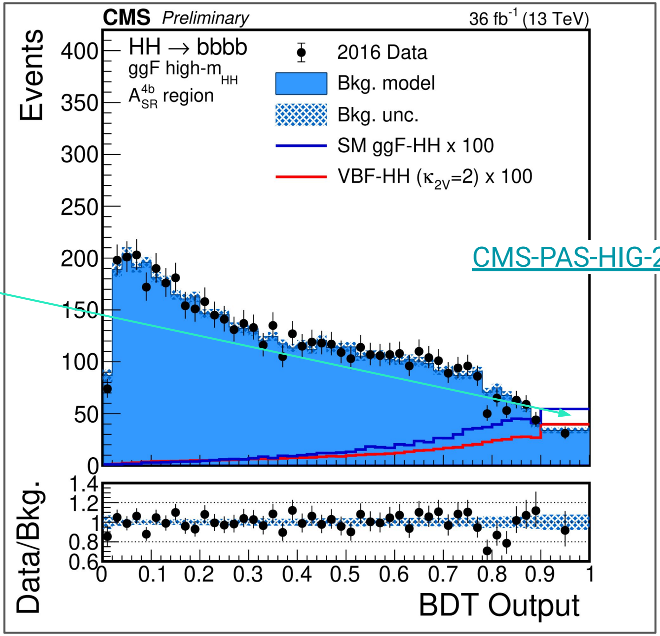
CMS-PAS-HIG-20-005

Extraction of results

→ **Boosted Decision Trees (BDT)** to discriminate signal from background.
→ Signal extracted from the **BDT score in low and high M_{HH}** region separately.
→ No excess observed over the background only expectation

Signal pure region





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HH→ 4b results

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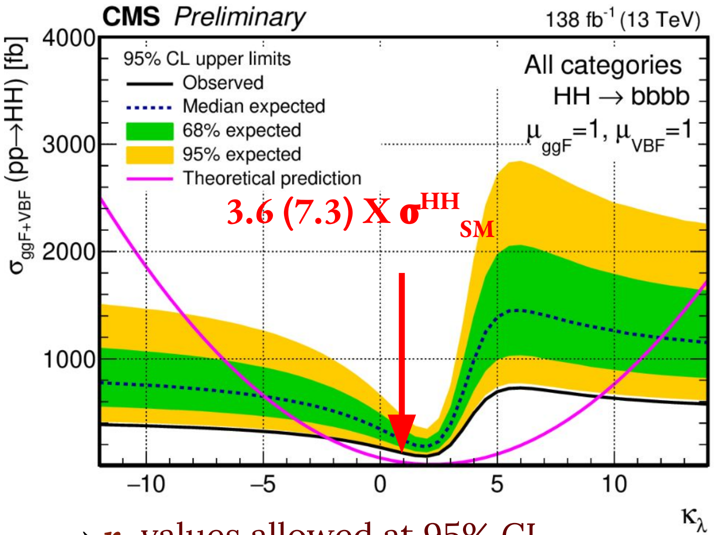
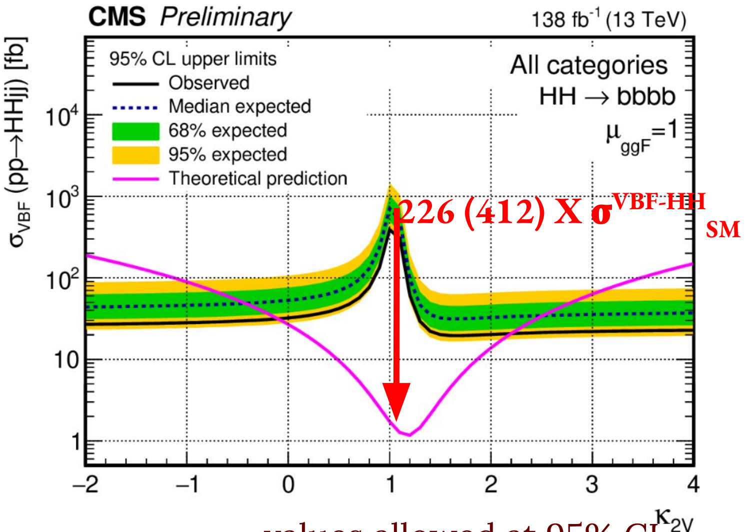




→ κ_λ values allowed at 95% CL [-2.3, 9.4] (expected [-5.0, 12.0])

→ κ_{2V} values allowed at 95% CL [-0.1, 2.2] (expected [-0.4, 2.5])

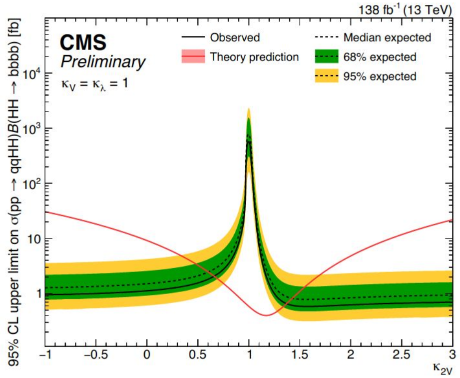
Best to date:

Summary

→ Recent CMS results from two sensitive channels presented today.

→ The most stringent upper limit on SM like HH production has been found from HH→ 4b resolved analysis.

→ Where as HH→ 4b boosted topology gives the better constraints on the κ_{2V} couplings.
Longitudinal VV amplitude in VBF-HH process.
In some BSM scenario $\kappa_V \neq \kappa_{2V}$, cross section enhanced dramatically and signal is boosted.
Search for this boosted VBF HH signature for the first time by CMS collaboration.
Values outside **0.6 <** κ_{2V} **< 1.4** excluded
strongest constraint so far, κ_{2V} **=0 excluded for the first time** [Link]



→ The final combination of all channels from full Run-2 data are on going in CMS
Please stay tuned

Thank you!

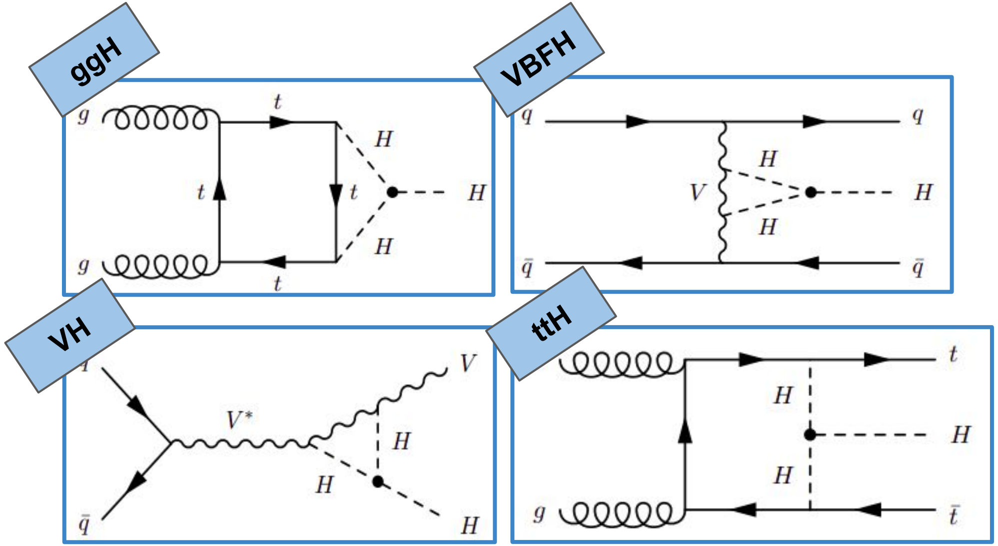
Additional Material

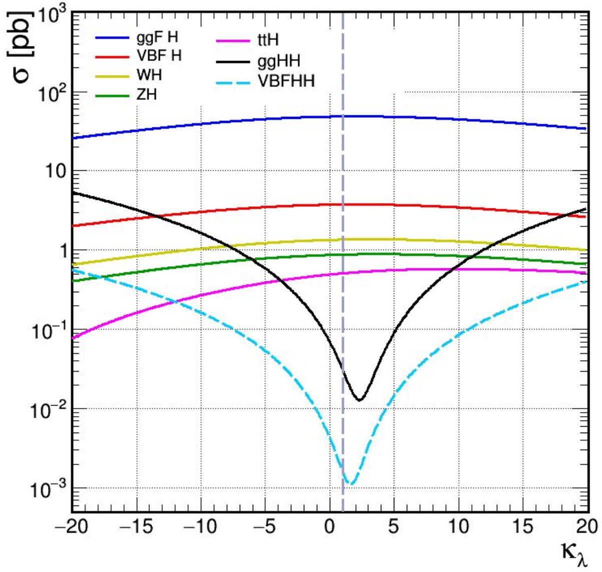
Importance of single Higgs processes

- 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.

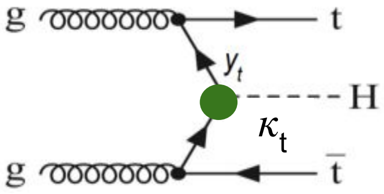
Typical NLO EW processes involve λ

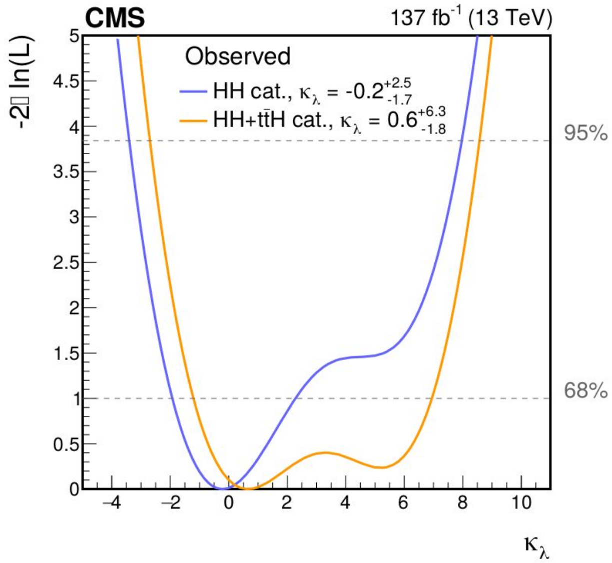


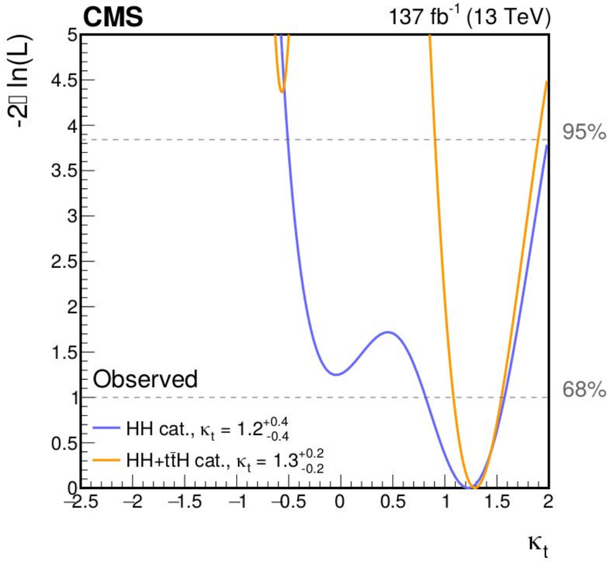


1D Likelihood scans from bbγγ

→ ttH process considered for better constraint on κ_λ and κ_t
→ ttH categories are mutually exclusive to the all (ggHH & VBFHH) HH categories [4]







→ Inclusion of ttH makes positive κ_λ preferable
rules out negative κ_t at 95% CL