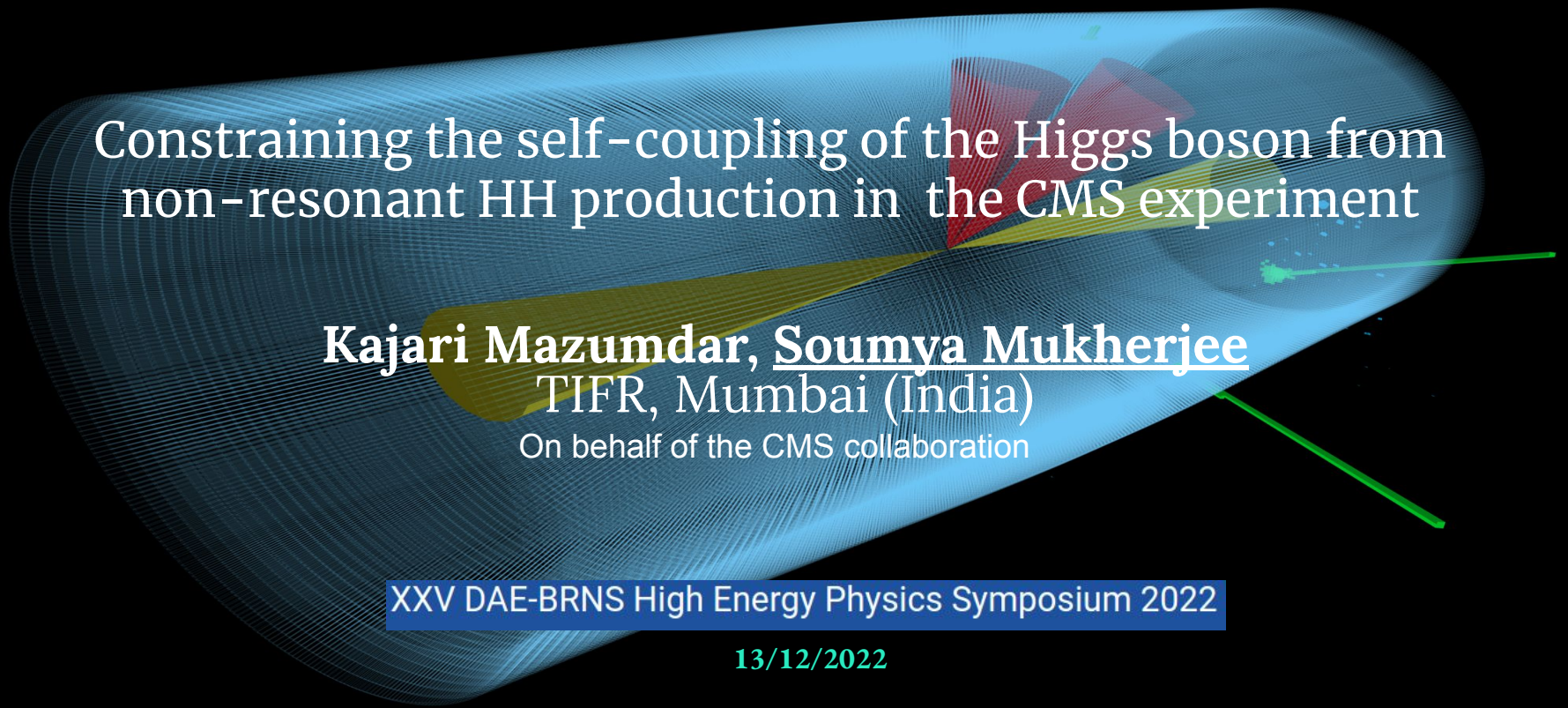

Constraining the self-coupling of the Higgs boson from non-resonant HH production in the CMS experiment

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On behalf of the CMS collaboration

XXV DAE-BRNS High Energy Physics Symposium 2022

13/12/2022

Higgs pair production in Standard Model

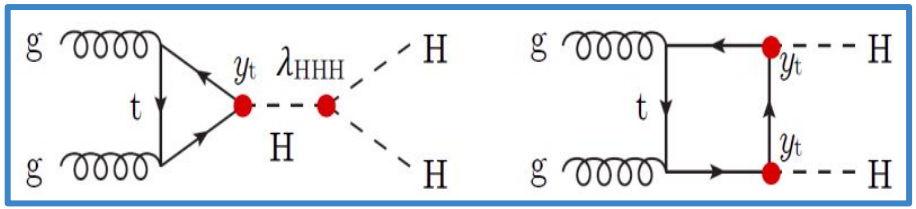
→ The shape of the Higgs potential directly related to the λ (self coupling of Higgs boson)

→ Non-resonant HH process can give the direct access of trilinear self Higgs coupling (λ_{HHH}) at the LHC

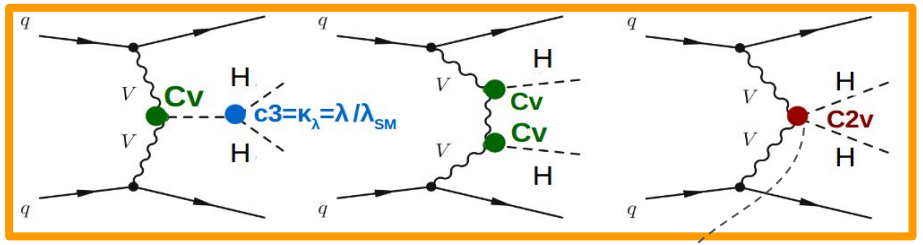
In SM :

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

ggHH



VBFHH



C_i / κ_i: modifier of SM coupling

Unique C_{2V} ~ HHVV coupling

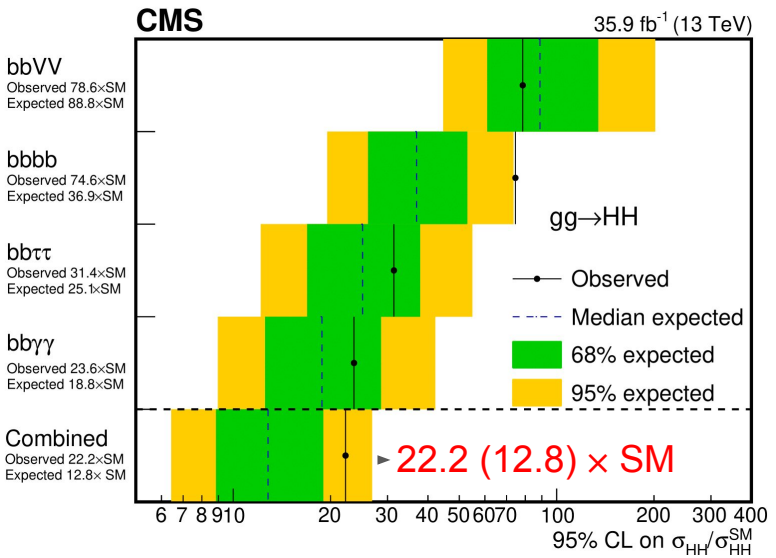
❖ **Gluon-gluon fusion (ggHH)** :
the largest production mode of HH at the LHC,
cross section with N^{2}LO QCD accuracy, σ_{ggHH} = 31.05 fb @13 TeV [1].

❖ **Vector Boson fusion (VBFHH)** : the sub-lead mode,
at N^{3}LO, σ_{VBFHH} = 1.73 fb [2].

HH search in CMS

- Using **2016 (36 fb^{-1})** data other published results from CMS (at least one H decays to bb)
  - HH→ 4b
  - HH→ bb$\tau\tau$
  - HH→ bbVV (V = W/Z)
  - HH→ bb$\gamma\gamma$

  } **& combined**



- Full Run-2 data analysis from CMS luminosity 139 fb^{-1} (4 times larger than 2016)

→ Targets **VBF HH production** mode along with major **ggHH prod.** mode
→ Able to probe the **C_{2V} [HHVV] coupling.**
→ Final state consisting one **H → WW/$\tau\tau$** also includes, **4W, WW$\gamma\gamma$, $\tau\tau\gamma\gamma$**
→ Analysis topology also covers **boosted regime** as well as resolved.

This talk will emphasis mostly the analysis techniques for HH → bb$\gamma\gamma$, HH→ 4b, HH→WW$\gamma\gamma$ and the results with combination in Run-2

New

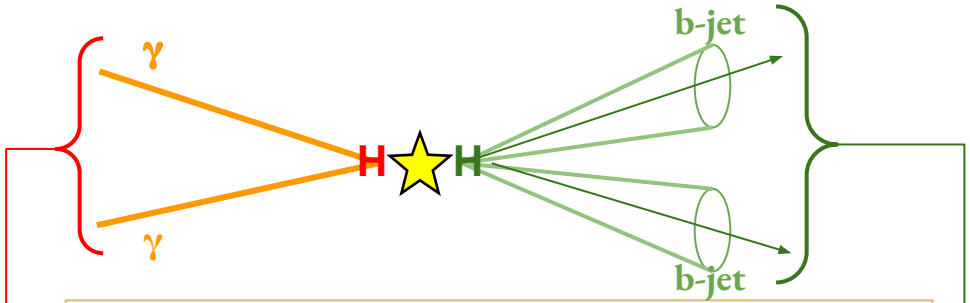
Mostly in early Run-2 + Full Run-2

	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%

Full Run-2

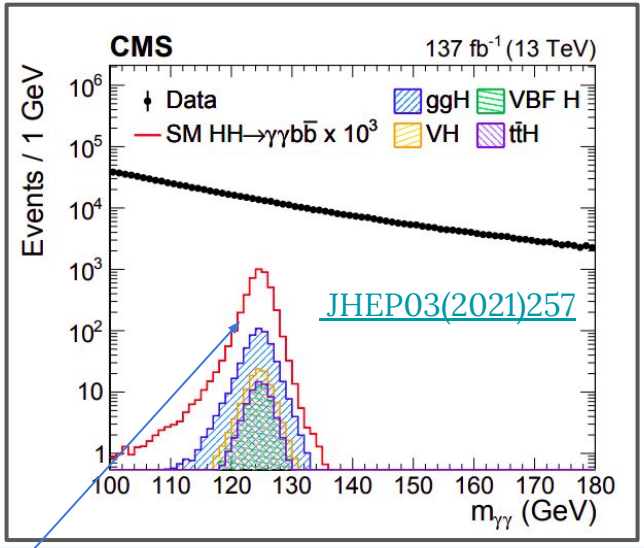
HH → multilepton talk by Sandeep

General strategy for bbγγ analysis



→ Events are triggered by a **diphoton trigger** of **30 and 18/22 GeV**
→ At least 2 photons, with $\mathbf{p_T / m(\gamma\gamma) > 0.33\ (0.25)}$
→ Finally diphoton Invariant mass of $\mathbf{100 < m_{\gamma\gamma} < 180}$ GeV

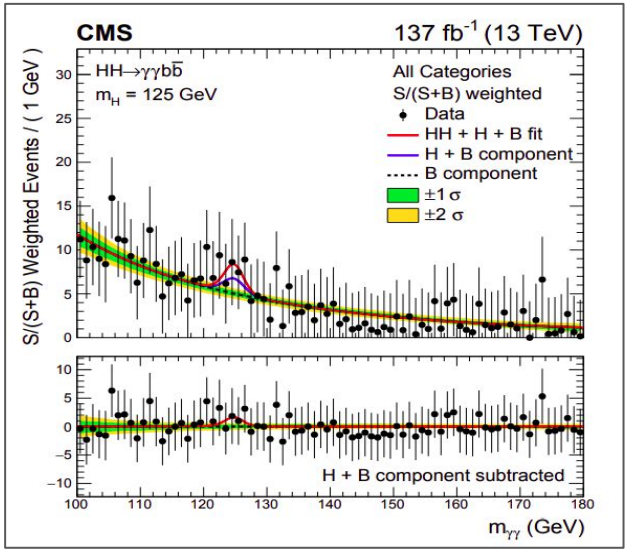
→ **Deep Neural Network (DNN) training** used to identify the b-jets from light quark or gluon jets
→ Two highest b-tagged **Anti-K_T , cone radius 0.4 (AK4)** jets selected within $|\eta| < 2.4\ /2.5$
→ Invariant mass of the b-tag jet pair, $\mathbf{70 < m_{bb} < 190}$ GeV
→ Additionally **b-jet energy regression** applied to improve the **b-jet energy resolution** and $\mathbf{m_{bb}}$ **spectrum.**

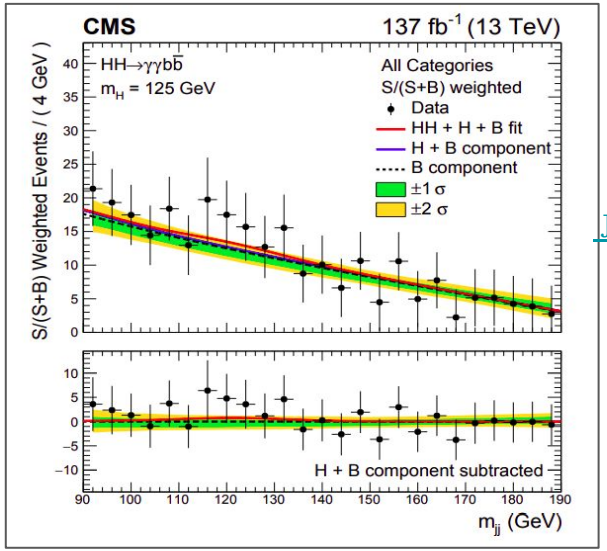


→ Signal contribution submerged in continuum background, (γγ+jets/γ+jets), due to very small x-sec.
→ **Boosted Decision Trees (BDT)**used to separate signal from backgrounds depends on kinematic features
→ Events categorized in $\mathbf{M_{HH}}$ to probe SM and BSM
→ Further categorization based on **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 $\mathbf{m_{\gamma\gamma}}$ **and** $\mathbf{m_{bb}}$ 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 estimated directly from data side-band region





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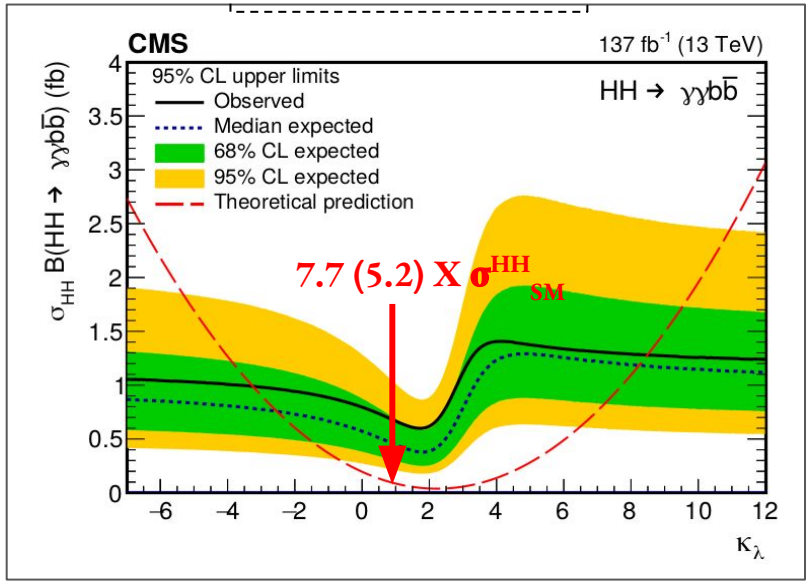
→ **No significant excess observed**

HH→ bbγγ results

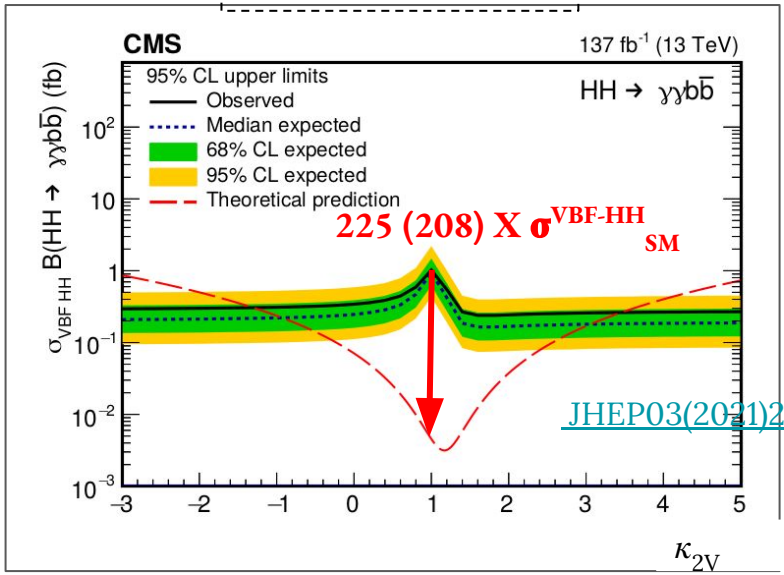
κ- framework

$\kappa_\lambda = \lambda_{HHH}^{obs}/\lambda_{HHH}^{SM}$



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

$\kappa_{2V} = C_{2V}^{obs}/C_{2V}^{SM}$



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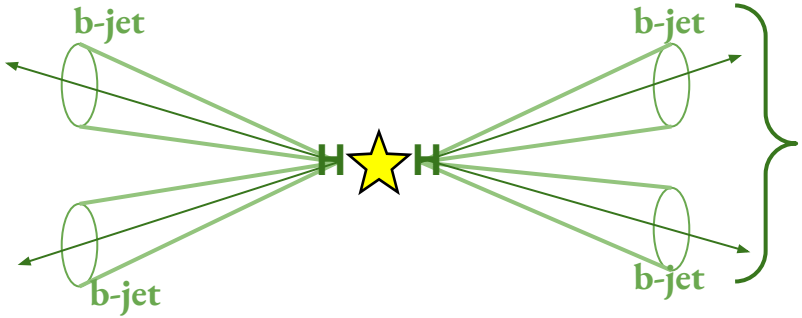
→ κ_{2V} values allowed at 95% CL
[-1.3, 3.5] (expected [-0.9, 3.1])

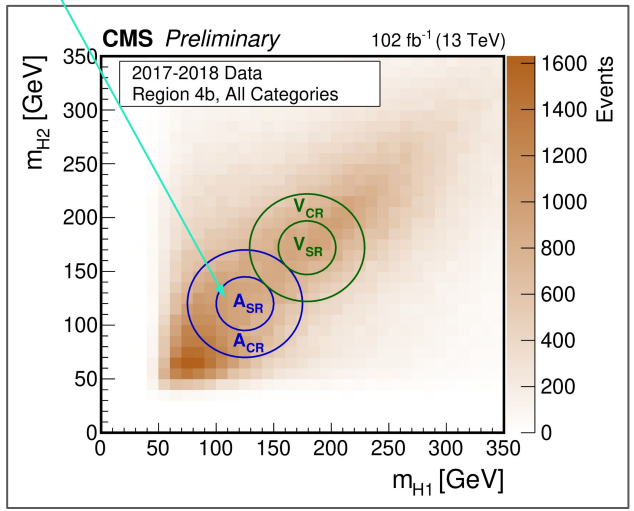
Strategy resolved 4b analysis

PRL-129 (2022) 081802



→ Overwhelming background due to the **QCD induced multijet production** and **tt hadronic decay.**
→ Hard to rely on the simulation due to mismodelling of QCD.
→ **Data driven technique** used, estimated from the **control region (CR)**.
→ **Signal region (SR)** and CR defined from **2D mass distribution of the two Higgs bosons**.

→ **Events are triggered** with at **least 4 jets criteria**
→ Jets should satisfy $\mathbf{p_T > 30(40)\ GeV}$ and $\mathbf{|\eta| < 2.4/2.5}$ 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**

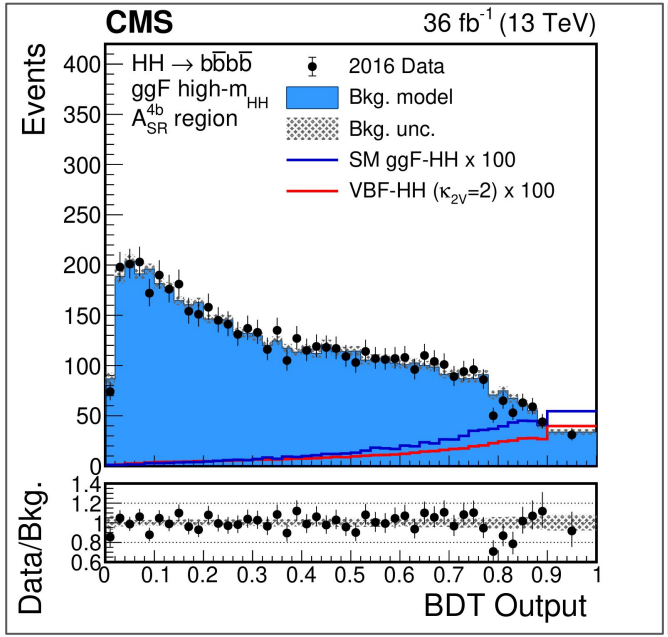


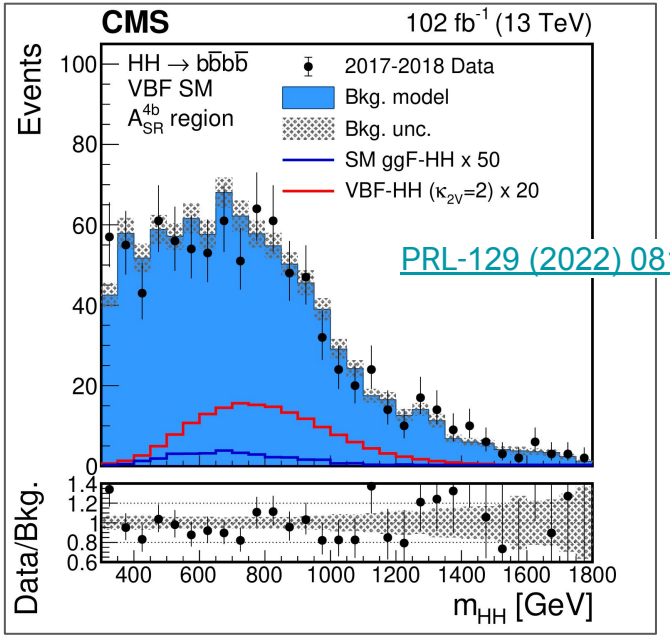
Extraction of results Resolved HH→ 4b

→ **Boosted Decision Trees (BDT)** has been performed to discriminate signal from background.

→ Signal extracted from the **BDT score in low and high m_{HH}** region separately for ggHH process, for VBFHH it is cut based analysis, m_{HH} is used to extract the results

→ No excess observed over the background only expectation





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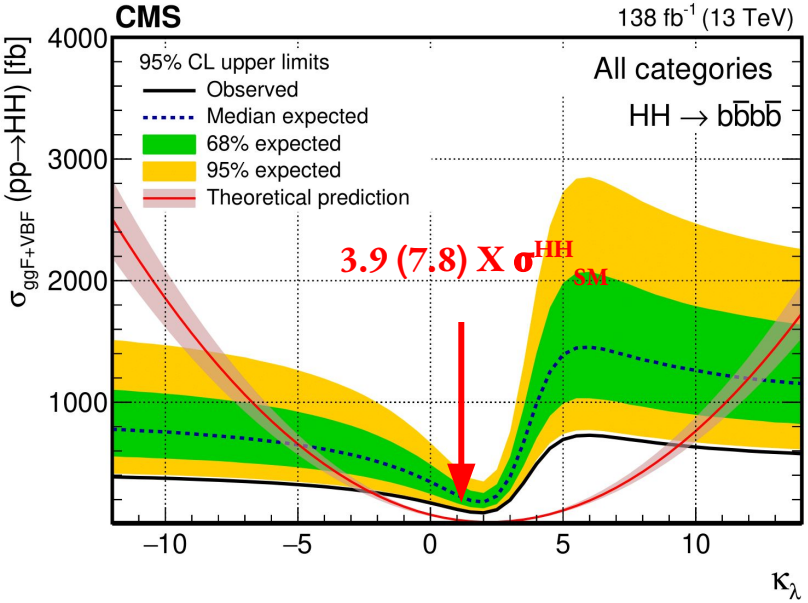
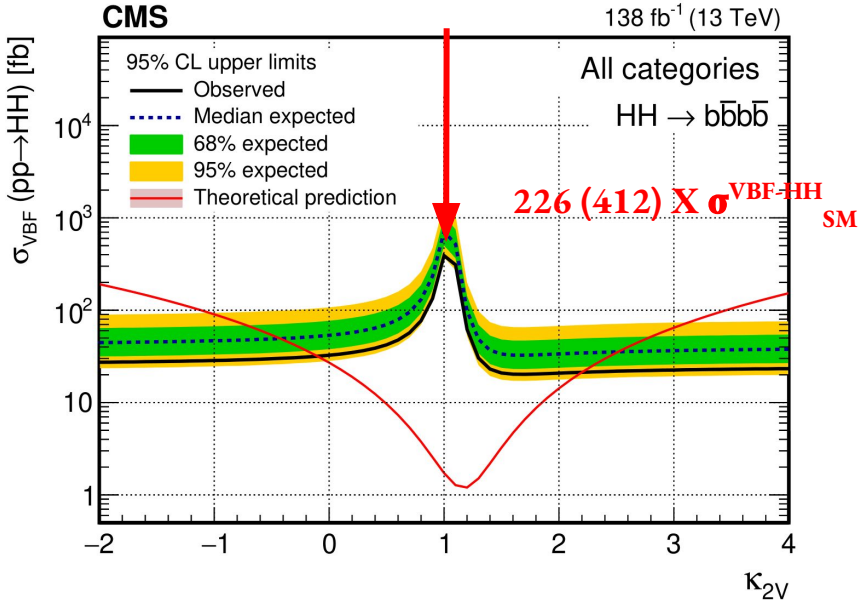
Resolved HH→ 4b results

PRL-129 (2022) 081802



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



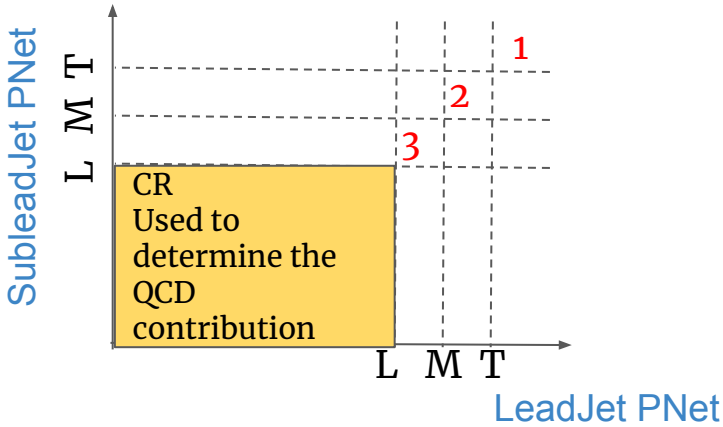
→ κ_{2V} values allowed at 95% CL
[-0.1, 2.2] (expected [-0.4, 2.5])

Boosted HH→ 4b results

arXiv:2205.06667

→ Final state with two AK8 jets with p_T > 500 (400) GeV inside |η| < 2.5
→ For VBF two extra jets with p_T > 25 GeV within |η| < 4.7

→ Higgs candidate are chosen using Graph Neural Network based ParticleNet Tagger
→ Main contributing backgrounds from QCD and tt



Results

→ Very good constraints on HH UL ~ 9.9 (5.1) × SM
→ κ_λ values allowed at 95% CL
$-9.9(-5.1) < \kappa_\lambda < 16.9\ (12.2)$
→ Only single channel to exclude $\kappa_{2V} = 0$ at 95% CL
$0.62\ (0.66) < \kappa_{2V} < 1.41\ (1.37)$

→ Analysis categorization based on the ParticleNet score
→ Finally m_{HH} used to extract the results

HH → WWγγ

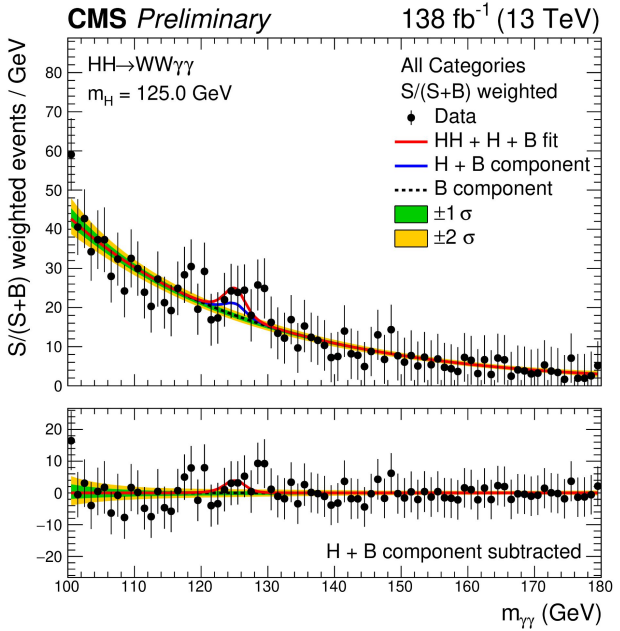
New results from CMS

CMS-PAS-HIG-21-014

→ Analysis only targets ggHH production mode in Run-2 data
→ Three orthogonal categories depending on W bosons decay
Different analysis strategy deployed.

- **Semi-Leptonic (1 L):** Multi-Class DNN
  to separate HH signal from single H and continuum background
- **Fully-Leptonic (2 L):**
  Cut-based -Because of the clean final state and low stats,
- **Fully-Hadronic (0 L):**
  2 Binary DNN to separate signal from (i) contributing backgrounds and (ii) bbγγ signal

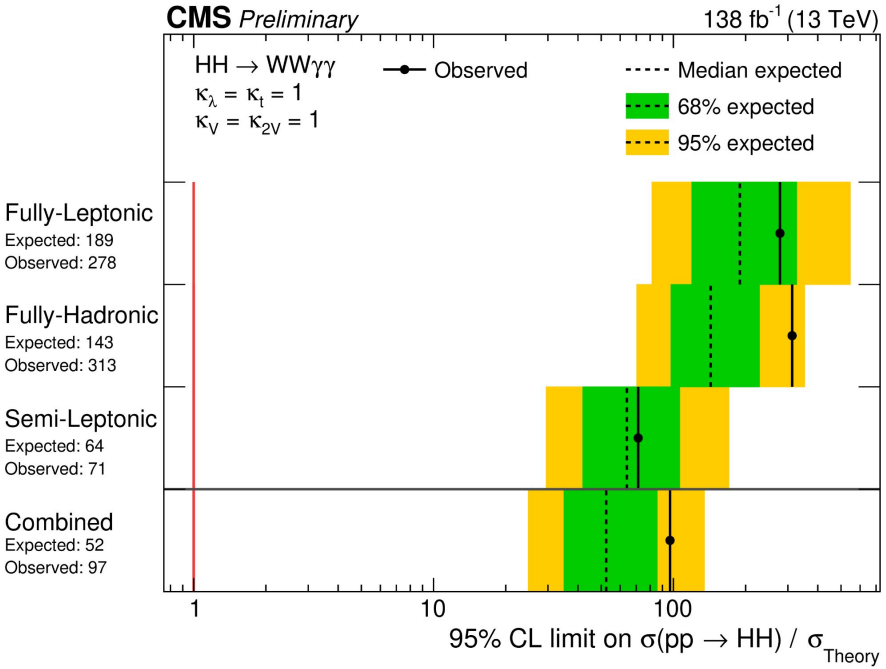
→ 1D Fitting method performed on $m_{\gamma\gamma}$ to extract the results

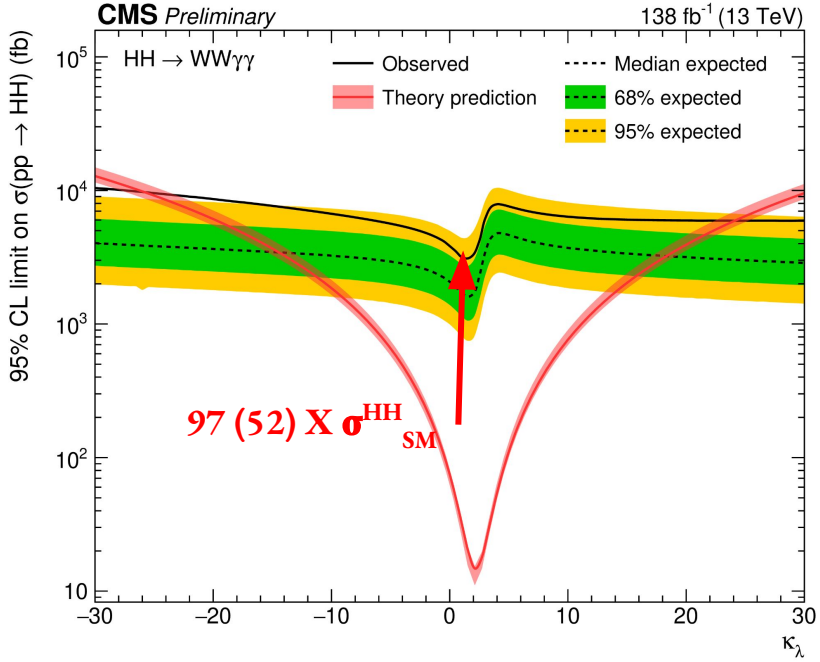


Results HH → WWγγ

New results from CMS

CMS-PAS-HIG-21-014

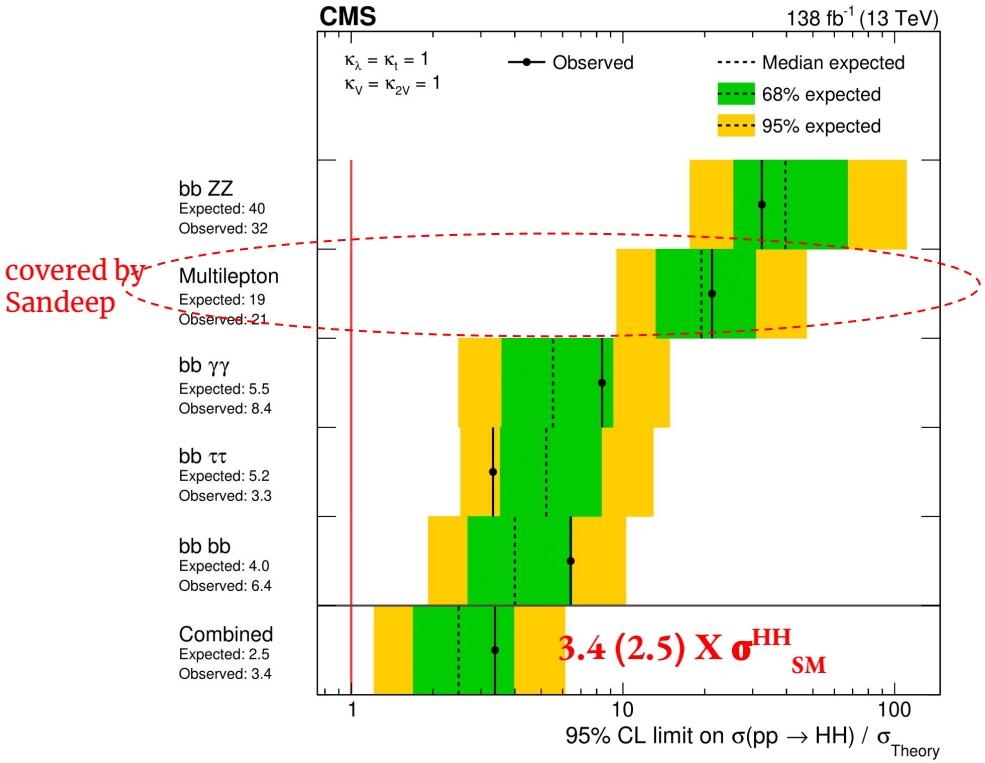




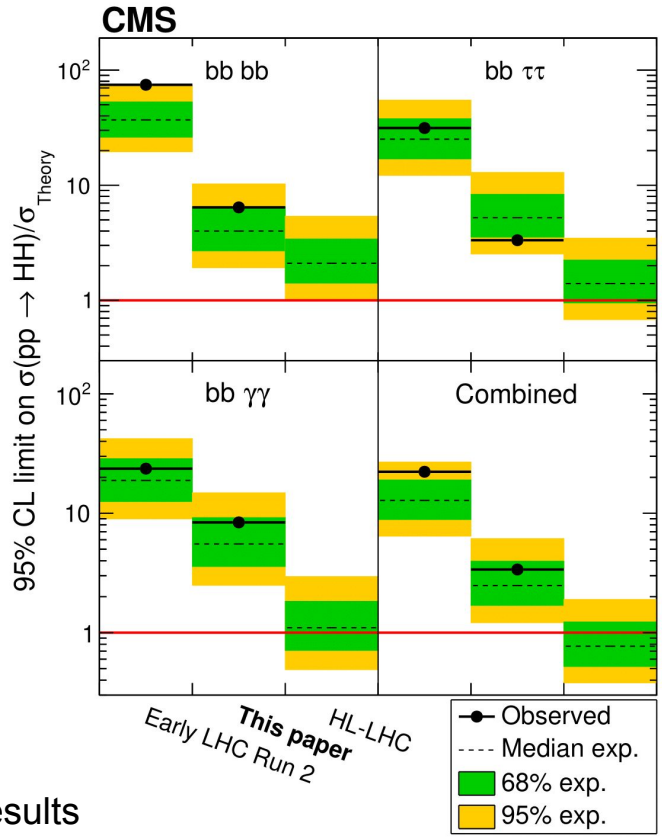
→ κ_λ values allowed at 95% CL
[-25.8, 24.1] (expected [-14.4, 18.3])

Run-2 combination

Nature 607 (2022) 60



covered by Sandeep

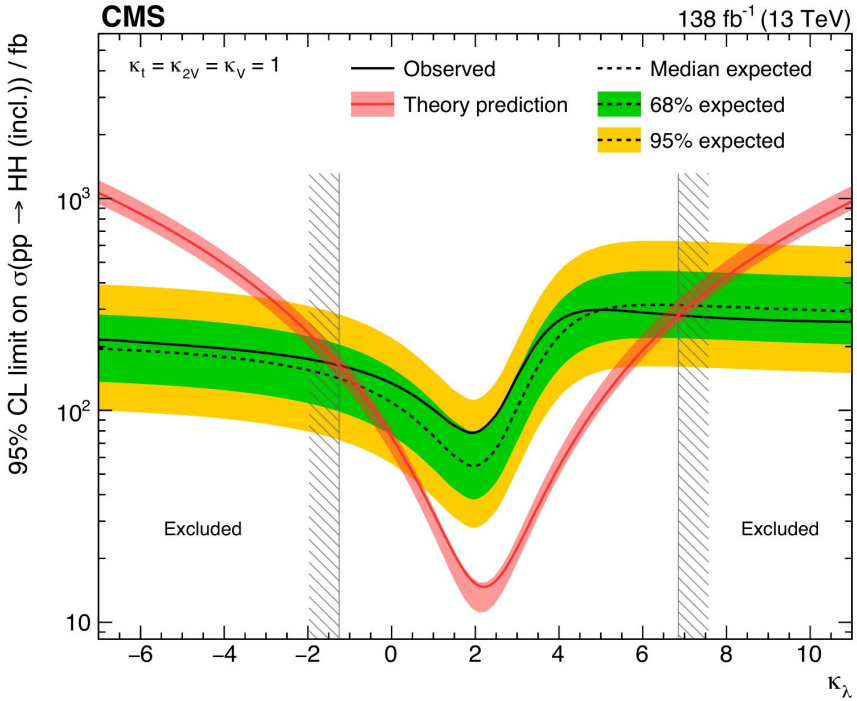


→ Significant improvement comparing to early Run 2 results

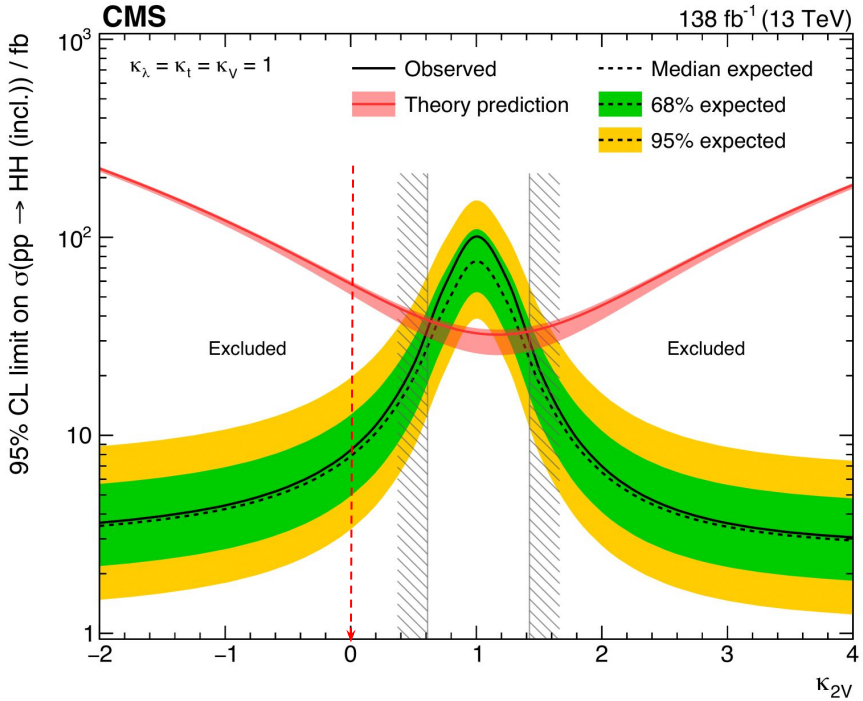
→ Sensitivity in HL-LHC sufficient to establish the existence of the SM HH production

Run-2 combination

Nature 607 (2022) 60

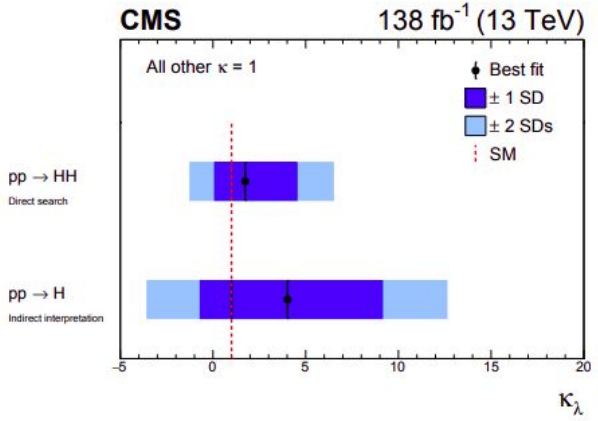


→ κ_λ values allowed at 95% CL
[−1.24, 6.49]



→ κ_{2V} values allowed at 95% CL
[0.67, 1.38]
→ κ_{2V} = 0 excluded with 6.6σ

Summary



→ Non-resonant HH combination results in CMS with 138 fb-1 data

→ Contributing channels :
bbbb (resolved+boosted), bb$\tau\tau$, bb$\gamma\gamma$, bbZZ(4l), multilepton

→ All results agree with SM prediction

→ Best sensitivity on HH production limits with the combination:
Observed (expected) UL ~ 3.4 (2.5) × SM @ 95% CL
From ATLAS 2.4 (2.9) x SM arXiv

→ Constraints on κ_λ with 95% CL : [−1.24, 6.49]
From ATLAS → [-0.6, 6.6]

→ Constraints on κ_{2V} with 95% CL : [0.67, 1.38] with Exclusion of the κ_{2V} = 0 with 6.8σ (6.5σ)
From ATLAS → [0.1, 2.0]

→ CMS also targets several other final states and also other production mode **VHH, ttHH**
Analyses are ongoing
final HH combination will be with all final states

→ Extension of HH search will be continued to explore more in Run-3 data, **Please stay tuned**