Higgs boson self-coupling and Di-Higgs production CMS

Higgs Hunting

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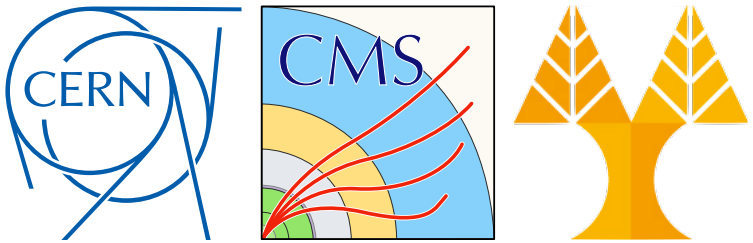
Tuesday 15th July, 2025

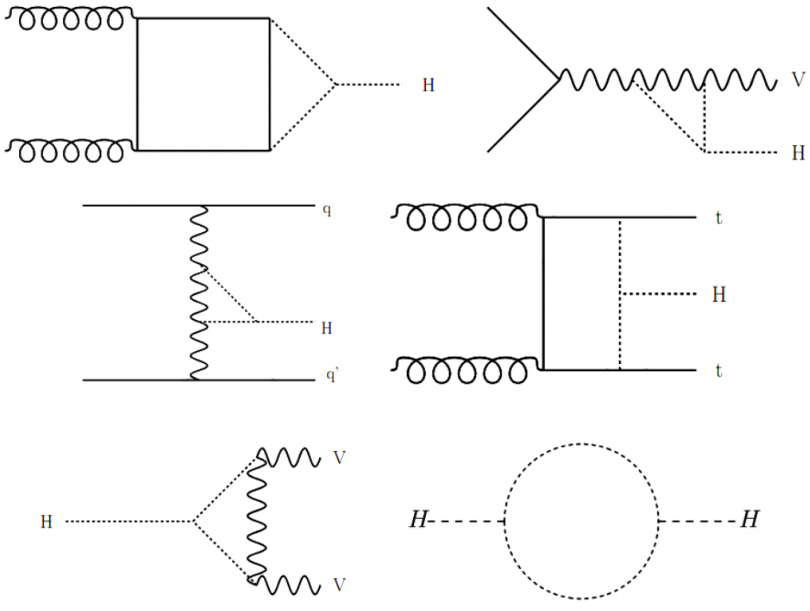


Motivation

- Important to measure the Higgs properties and compare with SM predictions
- Higgs HHH (k_λ), VVH (k_V) and VVHH (k_{2V}) couplings are potential portals to new physics, where $k_X = \frac{X}{X_{SM}}$

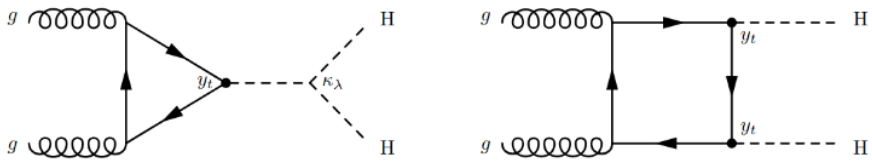
1. Single Higgs with EWK loop (NLO) corrections depends on $k\lambda$
2. Higgs pair production offers experimental access to all couplings

Single-Higgs

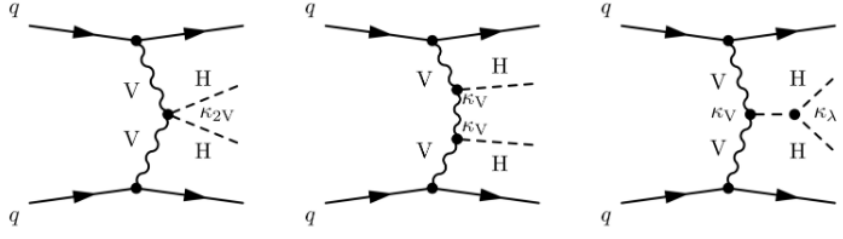


Di-Higgs

gluon-gluon fusion $\sigma(ggH)_{HH} = 31.1^{+2.1}_{-7.2} fb$



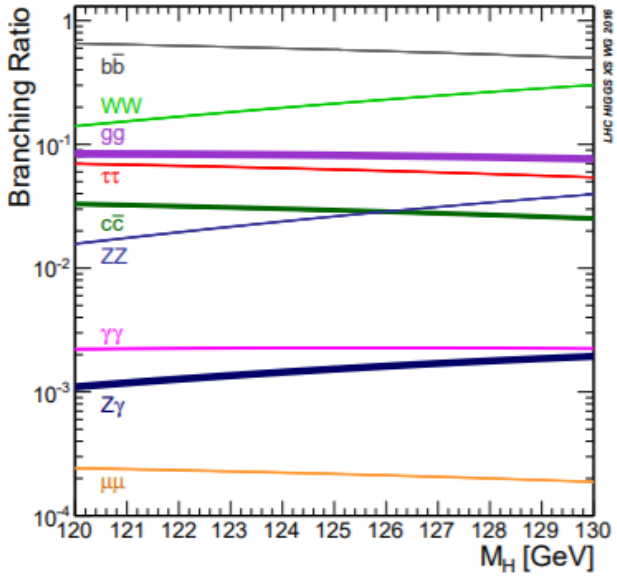
vector boson fusion $\sigma(VBF)_{HH} = 1.726^{+0.036}_{-0.036} fb$



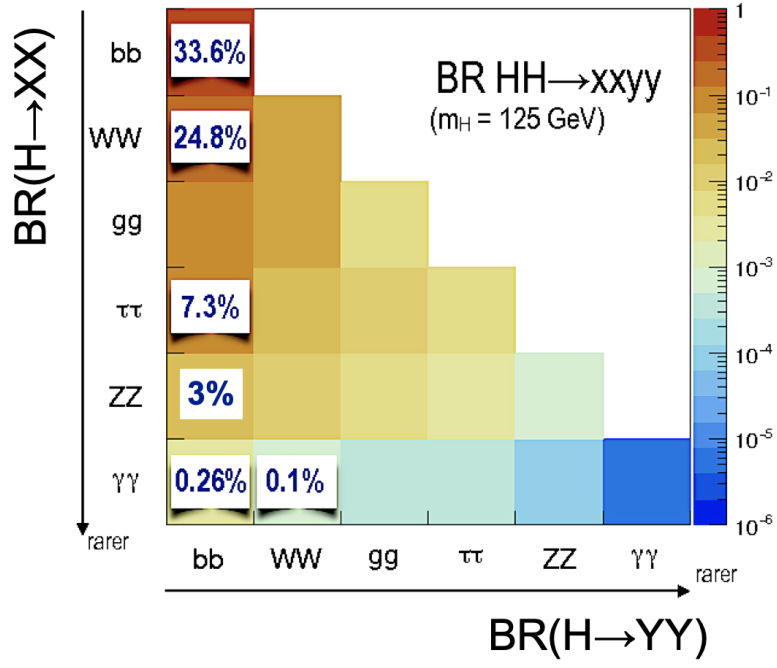
- Modifications to the Higgs couplings $\Rightarrow$ changes in the production cross-section

H and HH Decay Modes

Single-Higgs



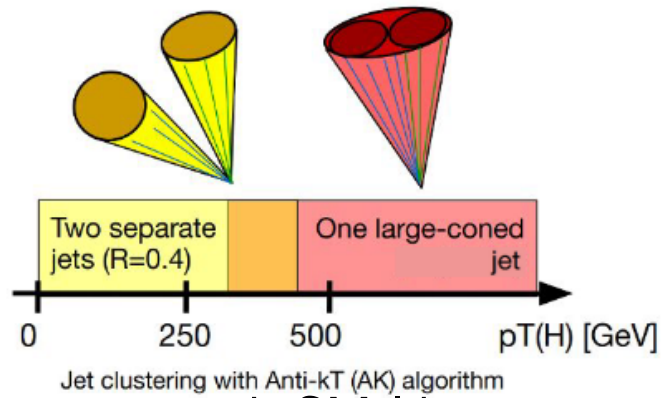
Di-Higgs



H		HH	
Analysis	Reference	Analysis	Reference
$H \to bb$	HIG-19-003,HIG-18-016,HIG-17-026	$HH \to \gamma\gamma bb$	HIG-19-018
$H \to \tau\tau$	HIG-19-010	$HH \to \gamma\gamma\tau\tau$	HIG-22-012
$H \to ZZ$	HIG-19-001	$HH \to \tau\tau bb$	HIG-20-010
$H \to \gamma\gamma$	HIG-19-015	$HH \to bbbb$	HIG-20-005,B2G-22-001,HIG-22-006
$H \to \mu\mu$	HIG-19-006	$HH \to WWbb$	HIG-21-005
$H \to WW$	HIG-20-013	$HH \to ZZbb$	HIG-20-004
$H \to ZZ, WW, \tau\tau$ (tH or $t\bar{t}H$)	HIG-19-008	$HH \to WW\gamma\gamma$	HIG-21-014

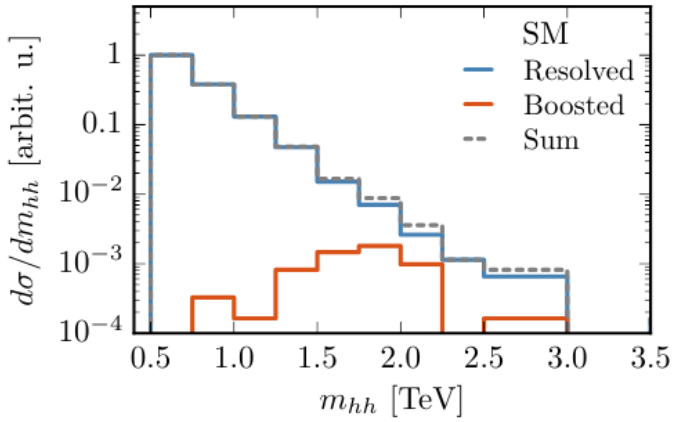
Resolved and Boosted Topologies

- Two strategies based on H P_T
  1. Resolved: H products are reconstructed as individual AK4 jets
  2. Boosted: Collinear H products forming a large-cone AK8 jet



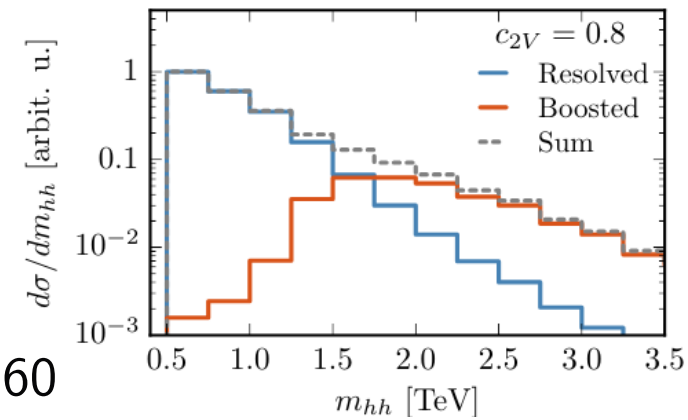
- Resolved topologies are effective in constraining scenarios with SM-like couplings, while boosted ones are sensitive to larger deviations
- Deviations in k_{2V} significantly affect the boosted regime
- Jet tagging algorithms are now developed for both scenarios (coverage of the full phase space)

$k_{2V} = 1$ (Resolved)



arxiv:1611.03860

$k_{2V} = 0.8$ (Boosted)



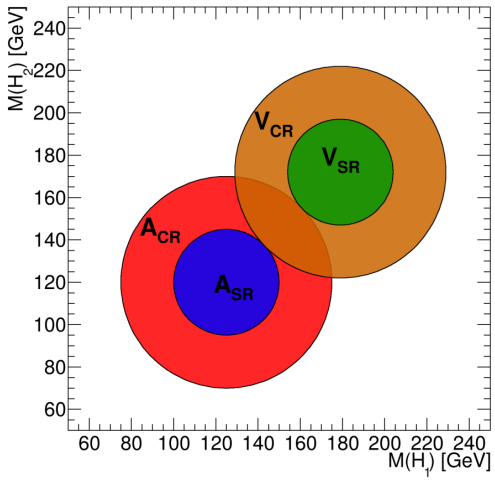
$HH \to b\bar{b}b\bar{b}$ Resolved

HIG-20-005

- Phase space: $\geq$ 4 jets, with $\geq$ 3 b-tagged
- Event categorization based on the 2D mass phase space

Background Estimation

- Using the 3b and 4b CRs
- Data driven method

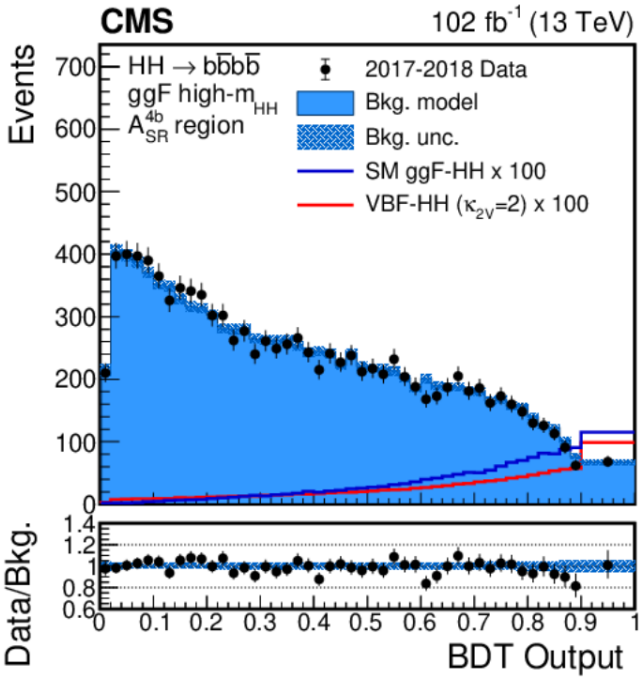


ggF/VBF Categorization:

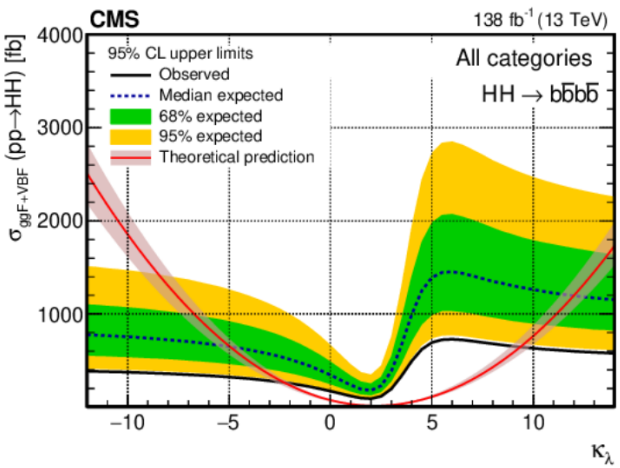
1. Presence of 2 forward jets with negative η product
2. BDT to separate ggF and VBF

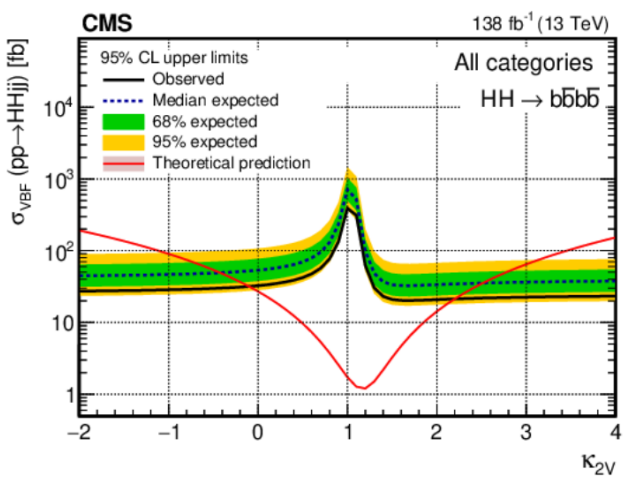
- Additional BDT for ggF Vs Bkg separation

Prefit Distribution (ggF)



-2.3 < k_λ < 9.4 (-5.0 < k_λ < 12.0) **-0.1 < k_{2V} < 2.2 (-0.4 < k_{2V} < 2.5)**





UL on σ_{HH}: 3.9 (7.8) $\times$ σ_{HH}^{SM}

$HH \to b\bar{b}b\bar{b}$ Boosted

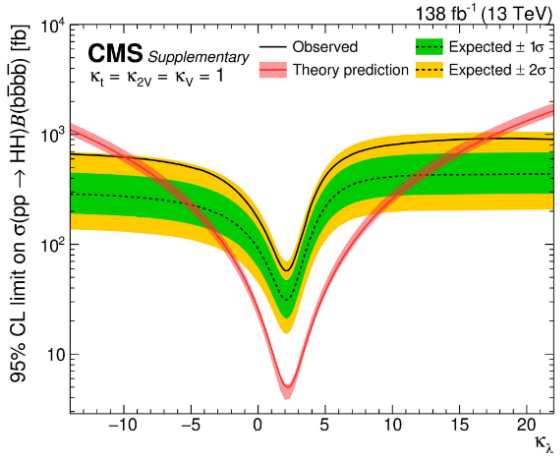
- Phase space: At least 2 AK8 jets with $P_T \geq 300$ GeV
- ggF & VBF Orthogonality: Presence of 2 forward AK4 jets with large m_{jj} and $\Delta\eta_{jj}$
- ParticleNet algorithm for boosted $H \to bb$ Vs QCD discrimination (Xbb score)

ggF

- HH: Jets with the highest Xbb score
- Event categorization based on the 2nd jet's Xbb and BDT output:

T			Cat1
M	Cat3		Cat2
L	QCD CR		
Jet2 Xbb/ggF Vs Bkg BDT	L	M	T

-9.9 $< k_\lambda <$ 16.9 (-5.1 $< k_\lambda <$ 12.2)

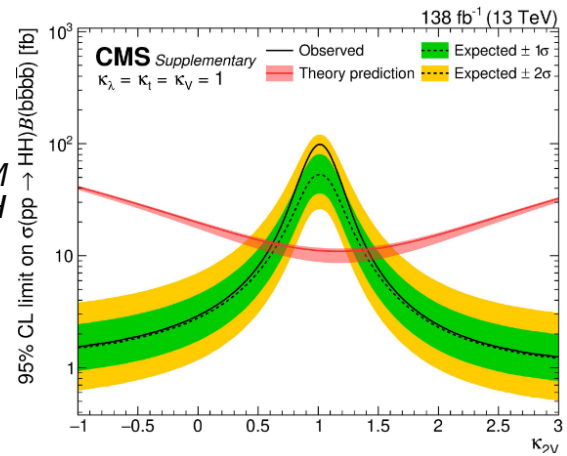


VBF

- HH: Jets with the highest P_T
- Event categorization based on the Xbb score of the 2 H candidates:

T				HP
M			MP	
L		LP		
B	QCD CR			
Jet1/Jet2	B	L	M	T

0.62 $< k_{2V} <$ 1.41 (0.66 $< k_{2V} <$ 1.37)

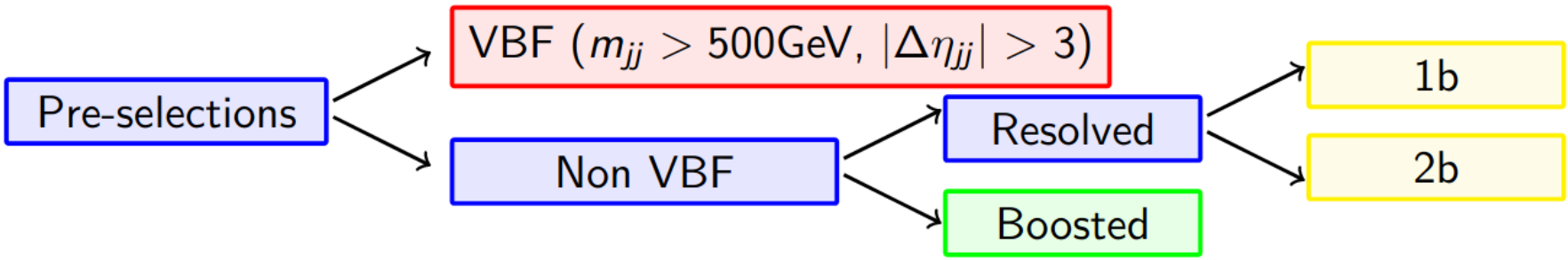


σ_{HH}: 9.9 (5.1) $\times$ σ_{HH}^{SM}

$HH \to b\bar{b}\tau\tau$

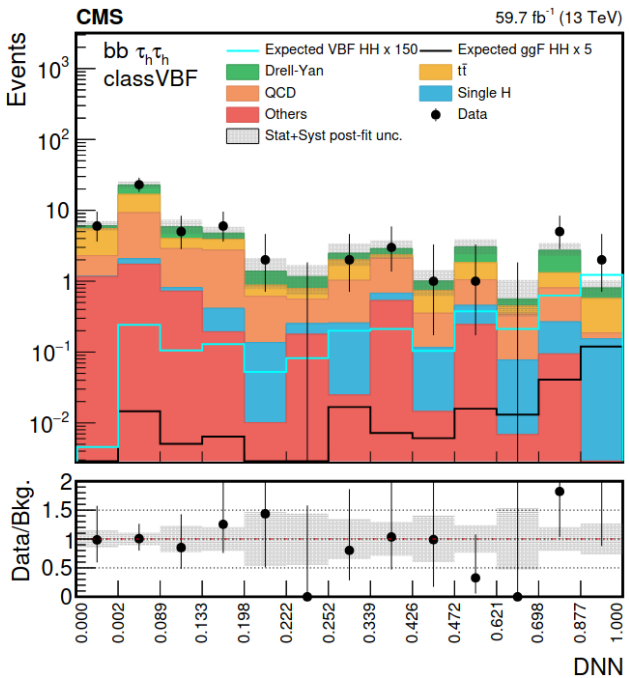
- Phase Space: 1 τ_h + 1 τ_h/μ/e and $\geq$ 2 ak4 jets

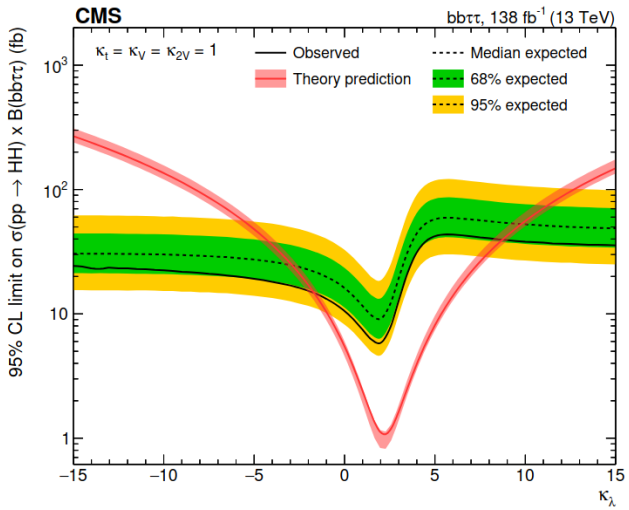
Event Categorization:

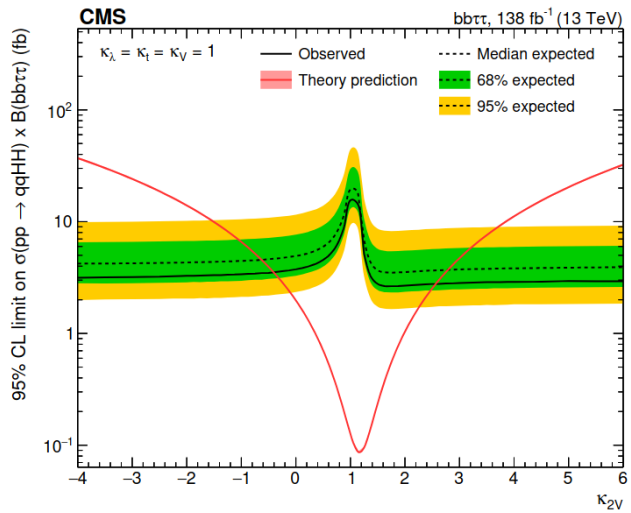


For all categories a DNN is trained to maximize the signal Vs bkg discrimination

Prefit Distribution (VBF) **-1.8 < k_λ < 8.8 (-3.0 < k_λ < 9.9)** **-0.4 < k_{2V} < 2.6 (-0.6 < k_{2V} < 2.8)**





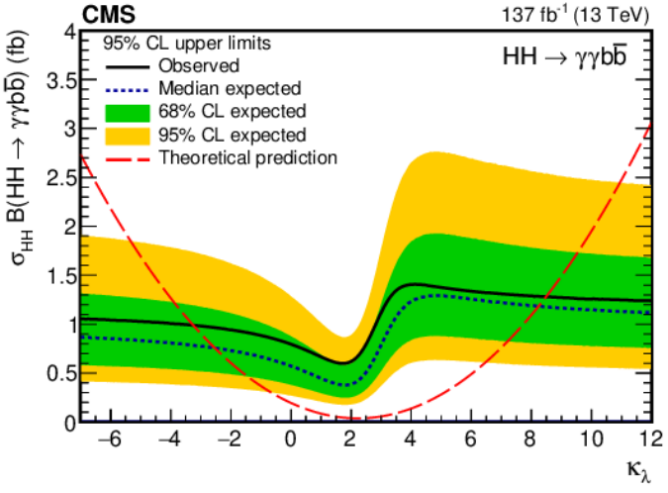


UL on σ_{HH}: 3.3 (5.2) $\times$ σ_{HH}^{SM}

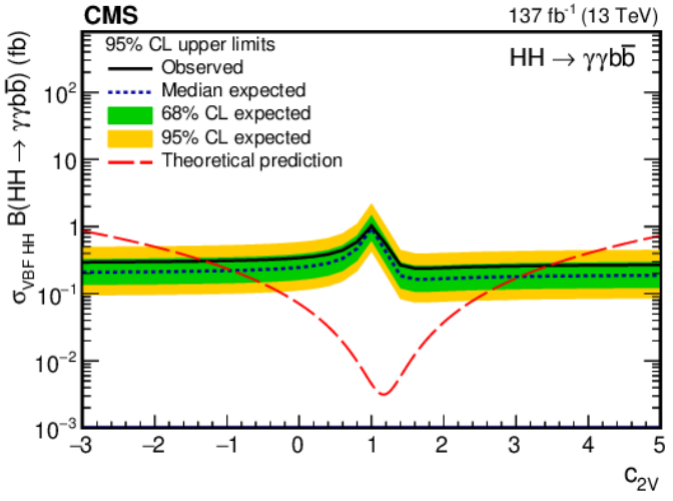
$HH \to b\bar{b}\gamma\gamma$

- ggF and VBF categorization based on the presence of 2 forward AK4 jets
- BDT training to reduce $\gamma\gamma$ +jets and γ + jets bkg
- Dedicated NN to remove $t\bar{t}H$ bkg
- 2D m_{bb} and $m_{\gamma\gamma}$ fit, for signal extraction
- Background modeling
  1. Single Higgs: Parametrize $m_{\gamma\gamma}$ and m_{bb} with analytical models
  2. QCD: Data-driven, 2D envelope method ($m_{\gamma\gamma}$ and m_{bb})
- Results:

-3.3 < $k\lambda$ < 8.5 (-2.5 < $k\lambda$ < 8.2)



-1.3 < k2V < 3.5 (-0.9 < k2V < 3.1)

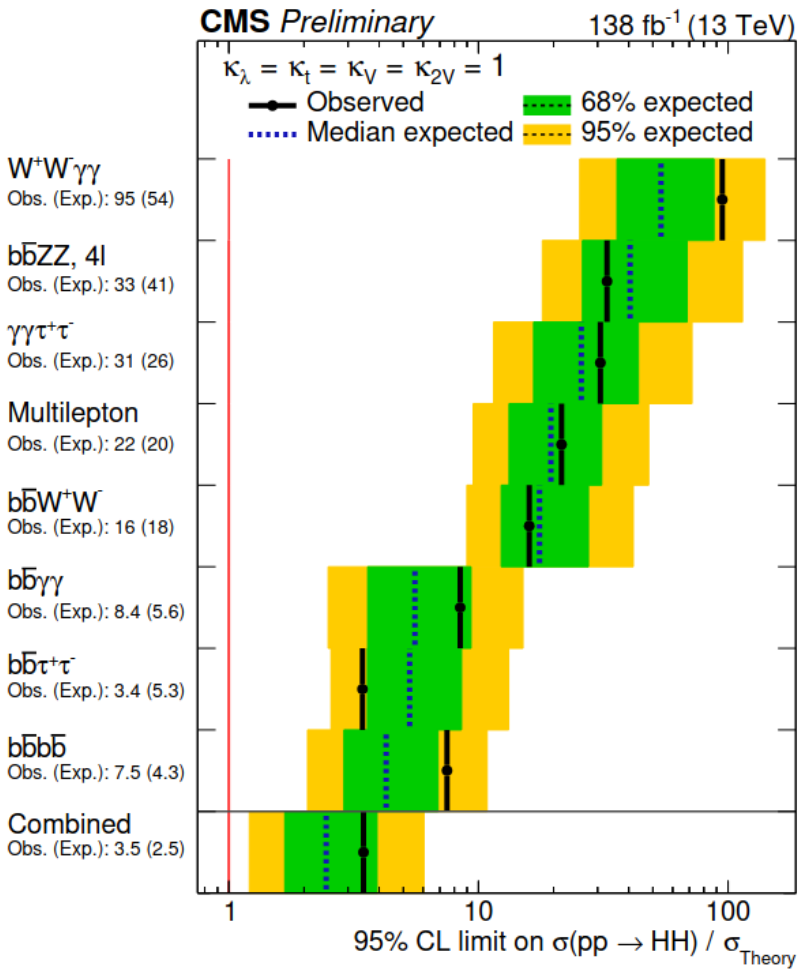


UL on σ_{HH}: 7.7 (5.2) $\times$ σ_{HH}^{SM}

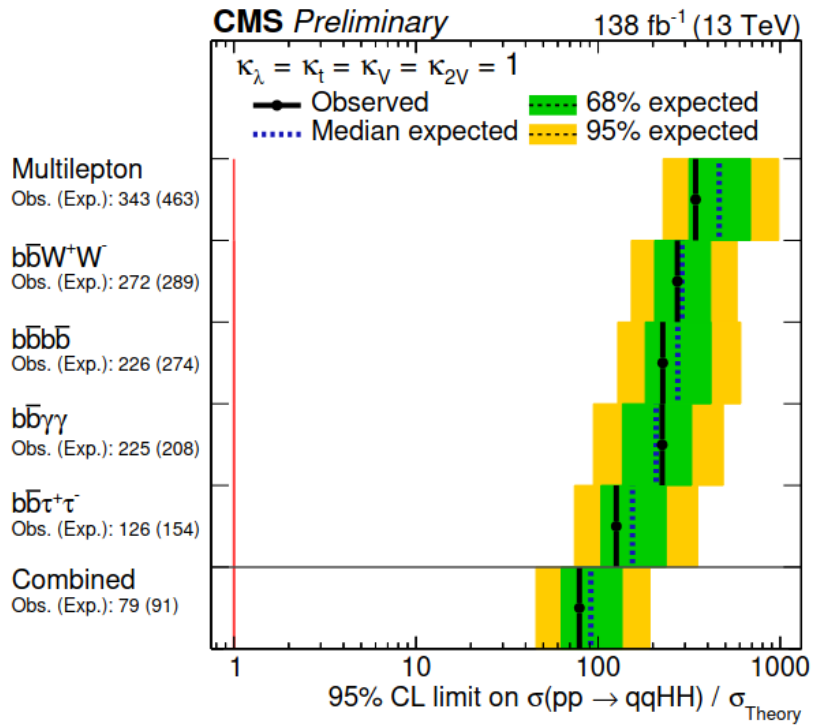
Combined Results

Higgs Pair Production Cross-Section

Inclusive Cross-Section



VBF Cross-Section

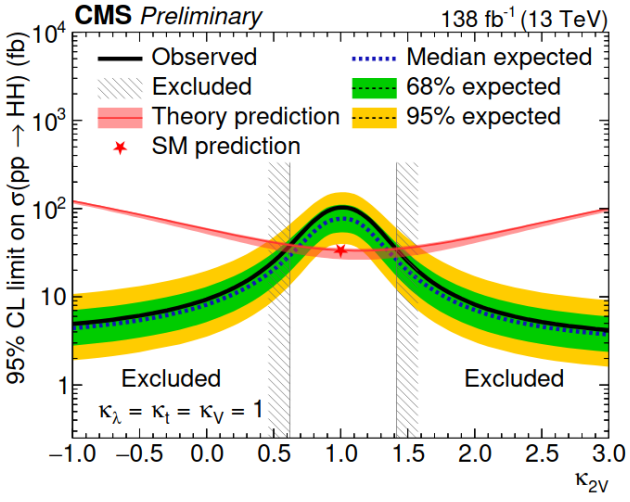


CMS-PAS-HIG-20-011

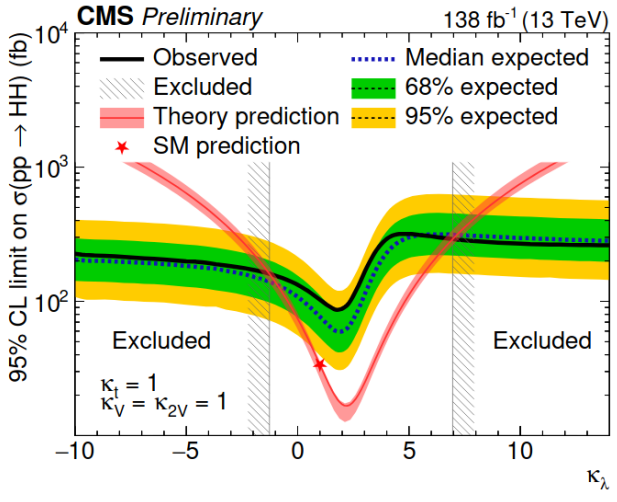
- Observed (Expected) Results
  - Inclusive: $3.5(2.5) \times \sigma_{HH}^{SM}$
  - VBF: $79(91) \times \sigma_{VBF}^{SM}$
- $HH \to bbbb$, $bb\tau\tau$ and $bb\gamma\gamma$ analyses play a significant role in the HH combination

Higgs Couplings

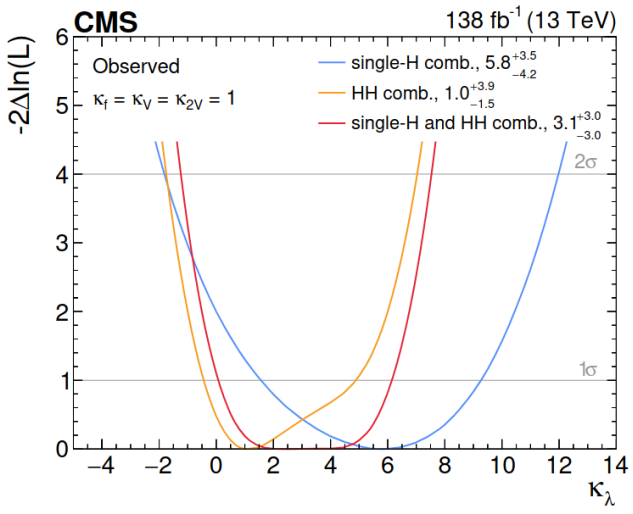
k2V [0.62, 1.42]



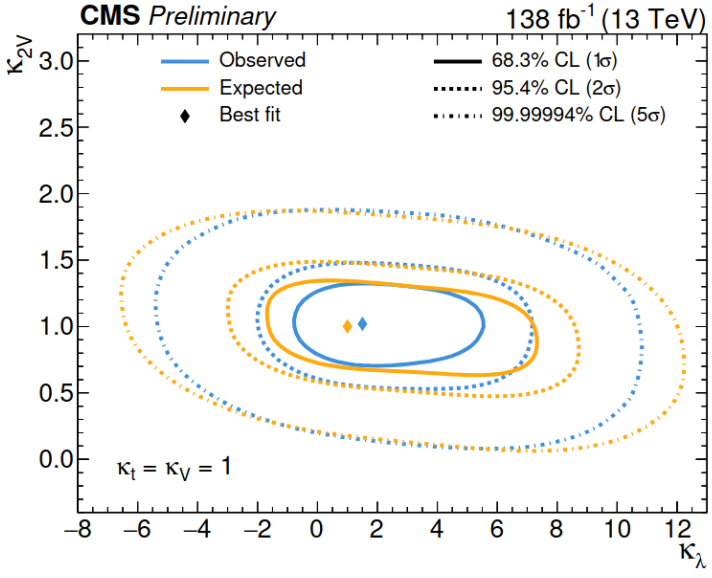
kλ [-1.39, 7.02] (HH Analyses)



kλ [-1.2, 7.5] (H + HH)



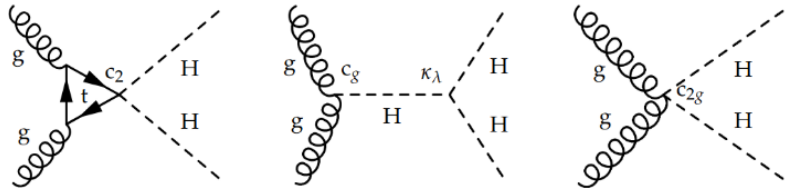
kλ Vs k2V



CMS-PAS-HIG-20-011 , HIG-23-006

- $k\lambda$ extracted from single Higgs analyses favors positive values
- k2V = 0 scenario is excluded for all $k\lambda$

BSM Interpretation



- Study the ggF production cross section as a function of 2 HEFT benchmark sets of coupling modifier combinations $(k_\lambda, k_t, c_2, c_g, c_{2g})$ and c_2 coupling modifier alone

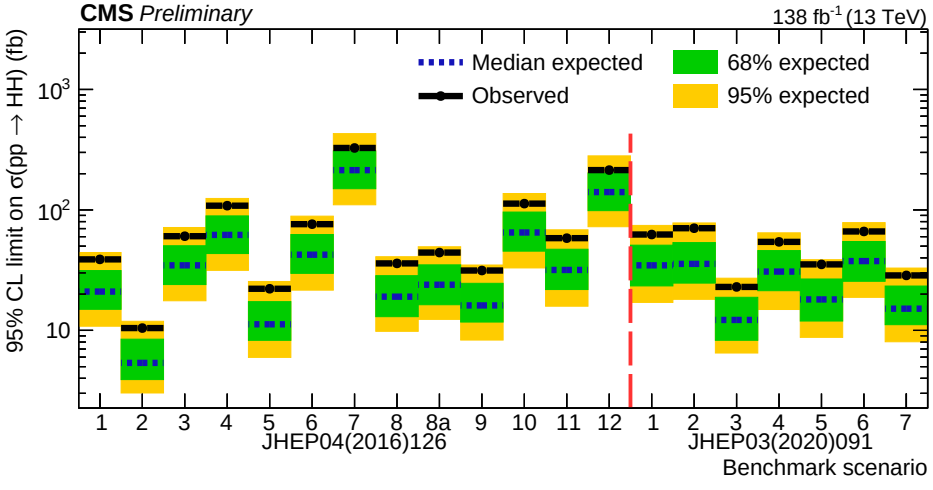
JHEP04(2016)126

	1	2	3	4	5	6	7	8	9	10	11	12	8a
κ_λ	7.5	1.0	1.0	−3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
κ_t	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c_2	−1.0	0.5	−1.5	−3.0	0.0	0.0	0.0	0.0	1.0	−1.0	0.0	1.0	0.5
c_g	0.0	−0.8	0.0	0.0	0.8	0.2	0.2	−1.0	−0.6	0.0	1.0	0.0	$\frac{0.8}{3}$
c_{2g}	0.0	0.6	−0.8	0.0	−1.0	−0.2	−0.2	1.0	0.6	0.0	−1.0	0.0	0.0

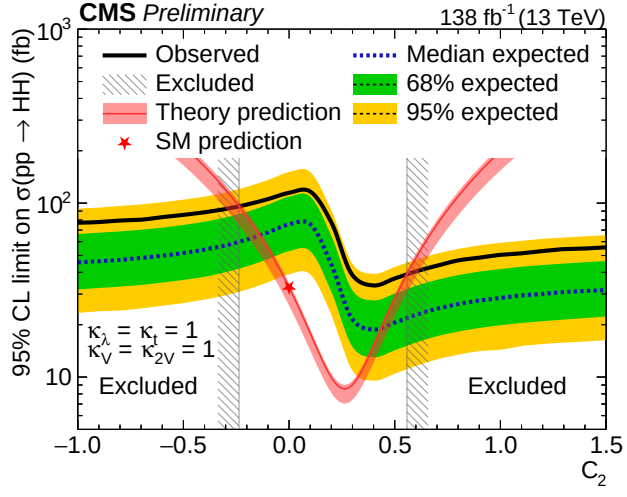
JHEP03(2020)091

	1	2	3	4	5	6	7
κ_λ	3.94	6.84	2.21	2.79	3.95	5.68	−0.10
κ_t	0.94	0.61	1.05	0.61	1.17	0.83	0.94
c_2	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	1.0
c_g	0.5×1.5	0.0	0.5×1.5	-0.5×1.5	$\frac{1}{6} \times 1.5$	-0.5×1.5	$\frac{1}{6} \times 1.5$
c_{2g}	$\frac{1}{3} \times -3$	$-\frac{1}{3} \times -3$	0.5×-3	$\frac{1}{6} \times -3$	-0.5×-3	$\frac{1}{3} \times -3$	$-\frac{1}{3} \times -3$

σ_{ggF} for HEFT Benchmarks



c_2 [-0.28,0.59]



- No significant deviations from expectations are observed
- Excess in all benchmarks, between 1 and 2 σ

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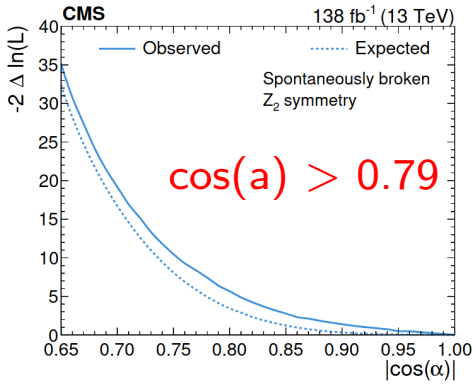
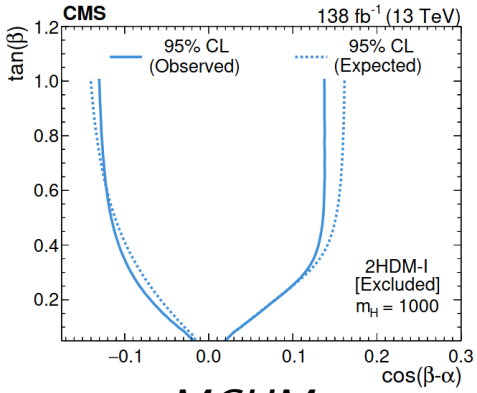
UV Models

- Mapping between k_λ, k_t and c_2 and the parameters of each model, to extract experimental constraints on those parameters
- BSM Models:
  1. Additional scalar ϕ (singlet). [1], [2]
  2. Additional Higgs doublet (2HDM). [3], [4], [5]
  3. Higgs composite models ($MCHM_{4/5}$). [6], [7], [8], [9]

Singlet with Z_2 SSB

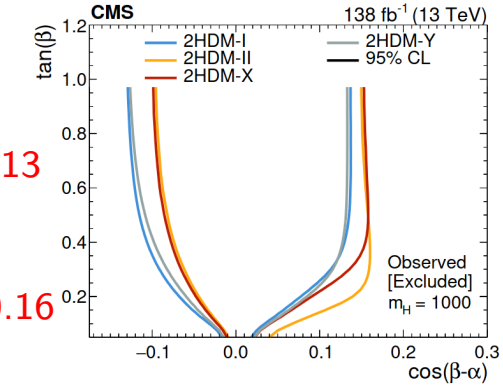


2HDM

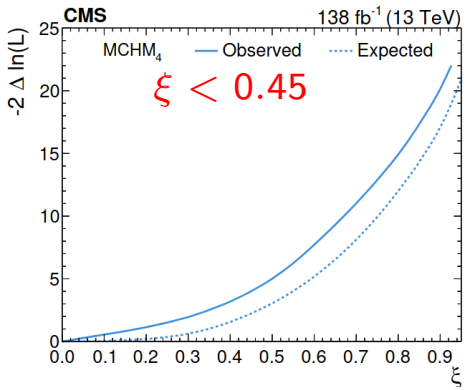


$\tan(\beta) = 0.5$ excluded for $\cos(\beta\text{-a}) < -0.13$ and $\cos(\beta - a) > 0.16$

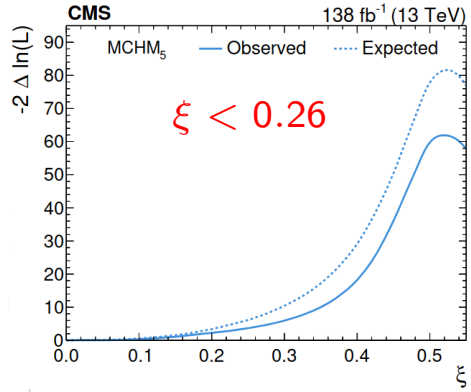
2HDM



$MCHM_4$



$MCHM_5$



- a = Mixing angle of the scalar with the doublet
- $\beta = \frac{v2}{v1}$
- $\xi = (\frac{v}{f})^2$, f is the strong dynamics scale

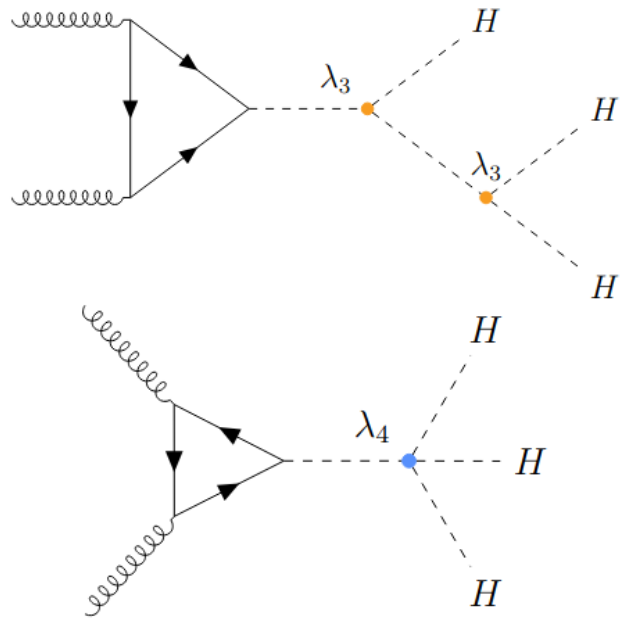
$HHH \rightarrow 4b2\gamma$

CMS-PAS-HIG-24-015

Motivation

- $V(h) = \frac{1}{2}m_h^2h^2 + \lambda_3 vh^3 + \frac{1}{4}\lambda_4 h^4$
- HHH involves both λ_3 and λ_4
- λ_3 and λ_4 measurements may reveal sensitivity to BSM effects

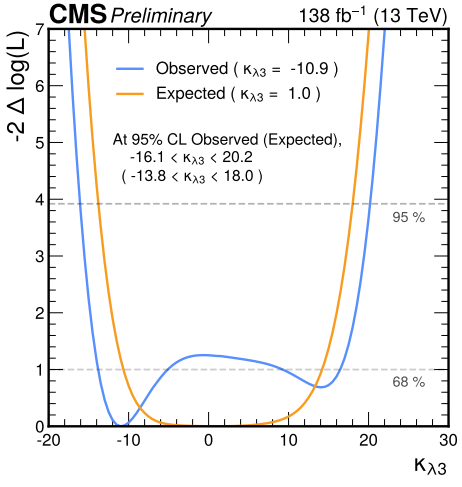
ggF (HHH)



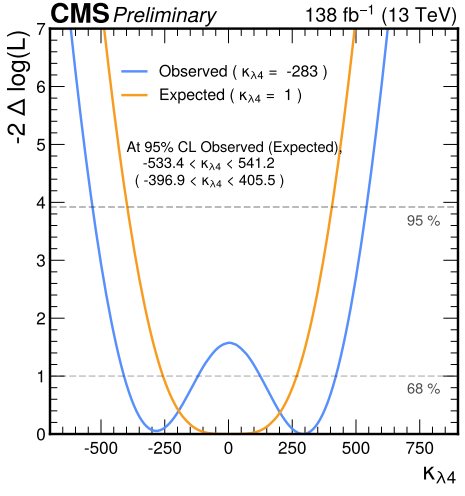
Analysis Strategy

- Phase Space: 2γ and 4 AK4 jets
- Non-Resonant and Resonant Bkg reduction via 2 separate BDTs
- Fake Photon Background Estimation: Data driven method in a photon LSR

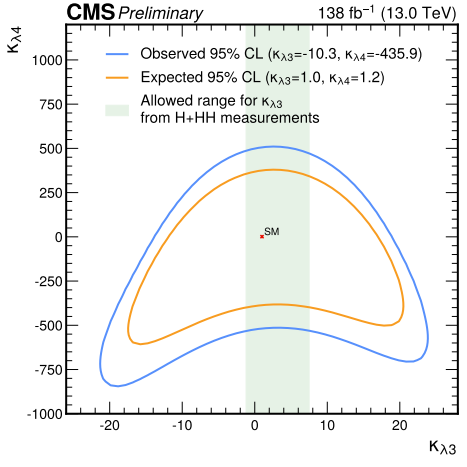
-16.1(-13.8) $< k_{\lambda 3} <$ 20.2(18)



-533(-397) $< k_{\lambda 4} <$ 541(406)



$k_{\lambda 3}$ Vs $k_{\lambda 4}$



Summary

- ML techniques have expanded the phase space and
  improved the sensitivity in determining the Higgs couplings
  The final results of the entire Run2 reach high sensitivity
  and offer very promising projections for the HL-LHC
- Strong constraints achieved on the HH cross section and k_{2V}
- Many results on BSM interpretations based on HEFT parametrization
  benchmarks, constraints on c2 and UV model interpretations
- The Run2 results pave the way for measurements of the Higgs couplings
  with the Run3 data, which benefit from improved tools and triggers

BACKUP

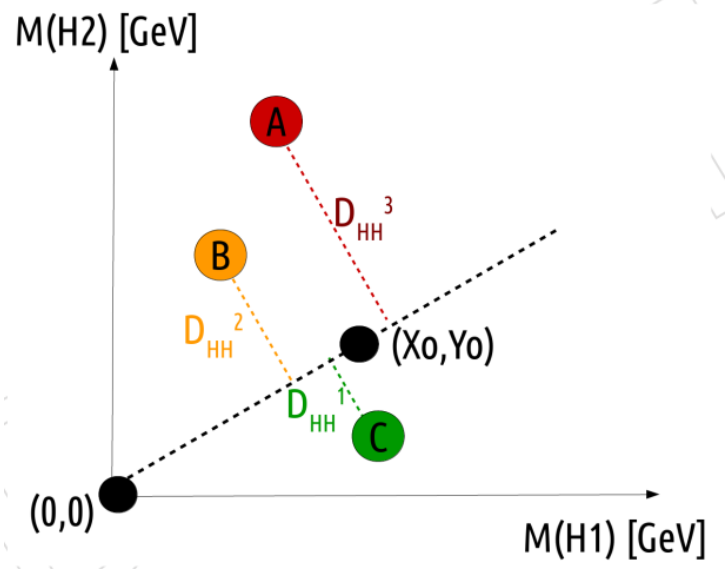
$HH \to b\bar{b}b\bar{b}$ **Resolved** (HIG-20-005)

Strategy

- Phase space: $\geq$ 4 jets, with $\geq$ 3 b-tagged (DeepJet Medium WP)
- A DNN algorithm is used for b-jet energy regression

HH Reconstruction:

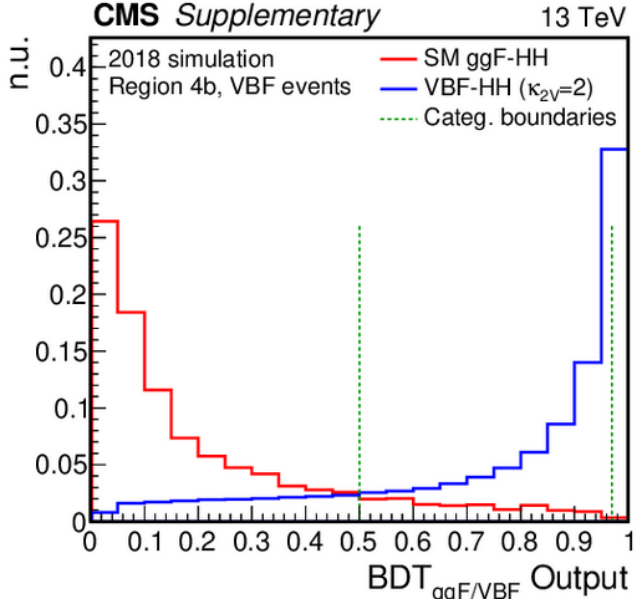
1. Create the 3 possible HH pairs from the 4 jets with the highest b-tag scores
2. Calculate their distance to the diagonal in the mass plane (D_{HH})
3. Choose the smallest D_{HH} or the leading in P_T if $|D^1_{HH} - D^2_{HH}| < 30$GeV



ggF and VBF Categorization:

1. Presence of 2 forward jets with $\eta_1\eta_2 < 0$
2. BDT trained to separate ggF and VBF, exploiting the VBF topology

- 2 ggF categories (low and high m_{HH})
- 2 VBF categories using the BDT score

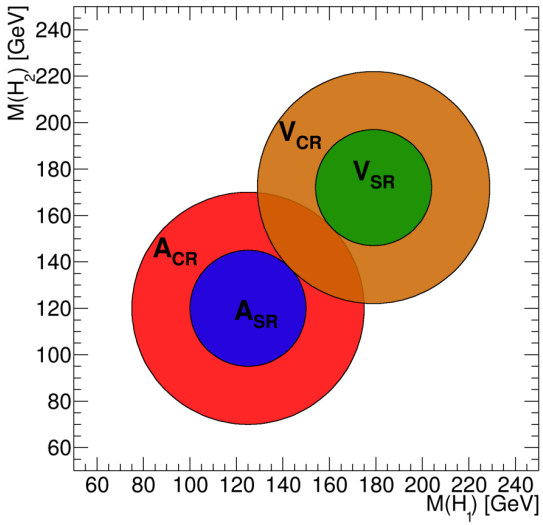


Event Categorization

- Based on the 2D mass phase space $R1 \leq \sqrt{(M(H1) - C1)^2 + (M(H2) - C2)^2} < R2$
- Both 3b and 4b regions are included
- SR : 4b with (C1,C2) = (125,120)GeV and (R1,R2) = (0,25)GeV

Control Region

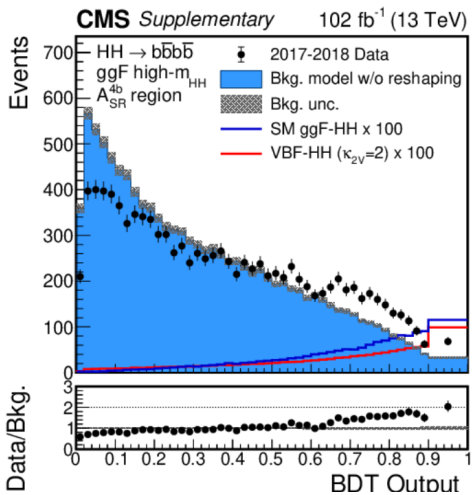
- Data driven method
- BDT-reweighting model
- Extract weights from 3b $\rightarrow$ 4b CRs
- Applied on 3b SR to model Bkg in 4b SR



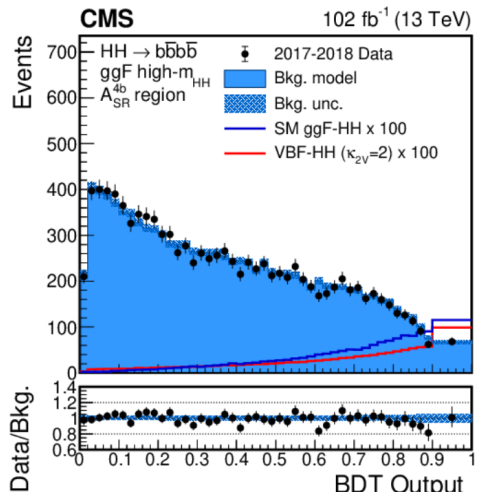
Validation Region

- Phase space orthogonal to SR (C1,C2) = (179,172)GeV
- Same BDT-reweighting model and procedure

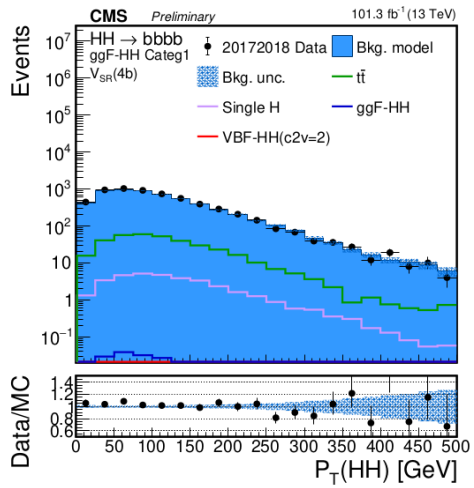
SR Before ReWeighting



SR Afte-ReWeighting



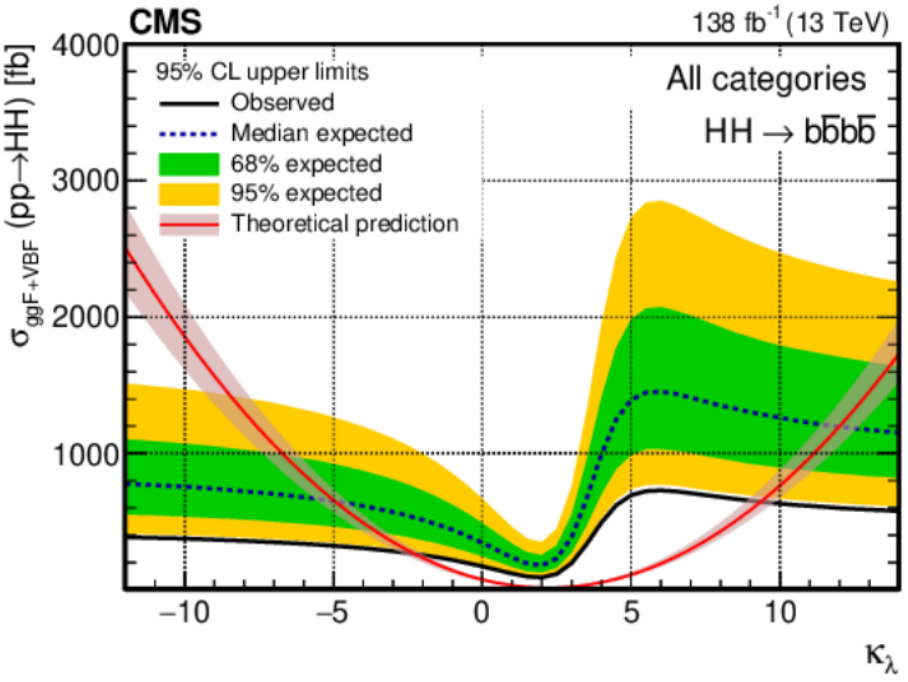
VR After-ReWeighting



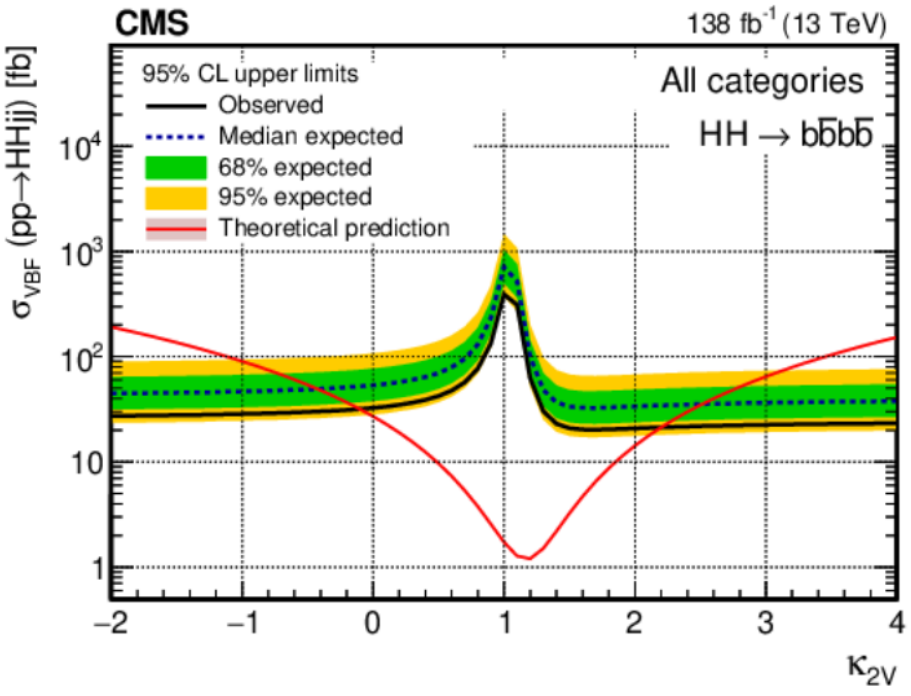
Results

- Discriminant Variables: BDT output for ggF, m_{HH} for VBF
- $k\lambda$ and k2V scans:

$k\lambda$



k2V



- Observed (Expected) Results
  - UL on $\sigma_{ggF+VBF}$: 3.9 (7.8) $\times$ $\sigma_{ggF+VBF}$
  - -2.3 $< k\lambda <$ 9.4 (-5.0 $< k\lambda <$ 12.0)
  - -0.1 $<$ k2V $<$ 2.2 (-0.4 $<$ k2V $<$ 2.5)

$HH \to b\bar{b}b\bar{b}$ Boosted (B2G-22-001)

Strategy

- Phase space: At least 2 ak8 jets with $P_T \geq 300$ GeV
- ggF & VBF Orthogonality: Presence of 2 forward AK4 jets with large m_{jj} and $\Delta\eta_{jj}$
- ParticleNet algorithm for boosted $H \to bb$ Vs QCD discrimination (Xbb score)
- Jet mass regression is performed using the PNet architecture (m_{reg})

ggF

- HH: Jets with the highest Xbb score
- Jet1:$m_{SD} \geq 50$GeV, Jet2:$m_{reg} \geq 50$GeV
- Jet1: Xbb > 0.8
- ggF Vs Bkg BDT

- Event categorization based on jet2 Xbb and BDT output:

<table>
<tr><td>T</td><td></td><td></td><td>Cat1</td></tr>
<tr><td>M</td><td colspan="2">Cat3</td><td>Cat2</td></tr>
<tr><td>L</td><td colspan="3">QCD CR</td></tr>
<tr><td>Jet2 Xbb/BDT</td><td>L</td><td>M</td><td>T</td></tr>
</table>

VBF

- HH: Leading in P_T jets
- Well separated candidates ($\Delta\Phi$,$\Delta\eta$)
- $m_{reg} \in (50, 250)$GeV
- $P_T1 \geq 500$GeV, $P_T2 \geq 400$GeV

- Event categorization based on the 2 jets Xbb score:

<table>
<tr><td>T</td><td></td><td></td><td></td><td>HP</td></tr>
<tr><td>M</td><td></td><td></td><td colspan="2">MP</td></tr>
<tr><td>L</td><td></td><td colspan="3">LP</td></tr>
<tr><td>B</td><td>QCD CR</td><td></td><td></td><td></td></tr>
<tr><td>Jet1/Jet2</td><td>B</td><td>L</td><td>M</td><td>T</td></tr>
</table>

Background Estimation and Discriminant

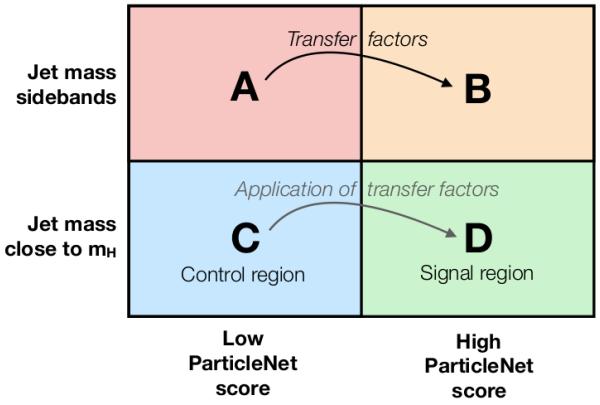
- PNet Xbb score is calibrated in a QCD region (Data driven method)

ggF

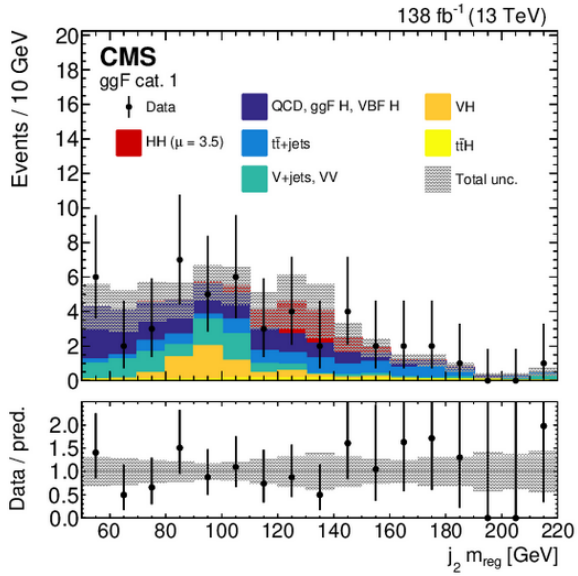
- $t\bar{t}$ recoil correction (fully hadronic final state)
- QCD is estimated from the low score region

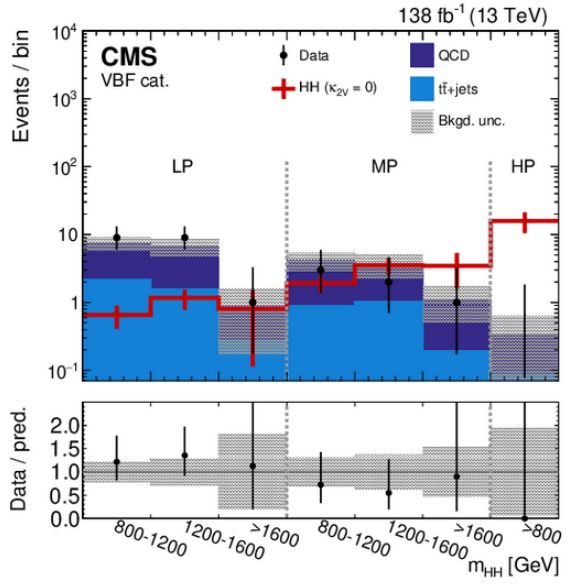
VBF

- $t\bar{t}$ normalization from a semileptonic region
- QCD MC:



- Discriminant Variables: Jet2 m_{reg} for ggF, m_{HH} for VBF

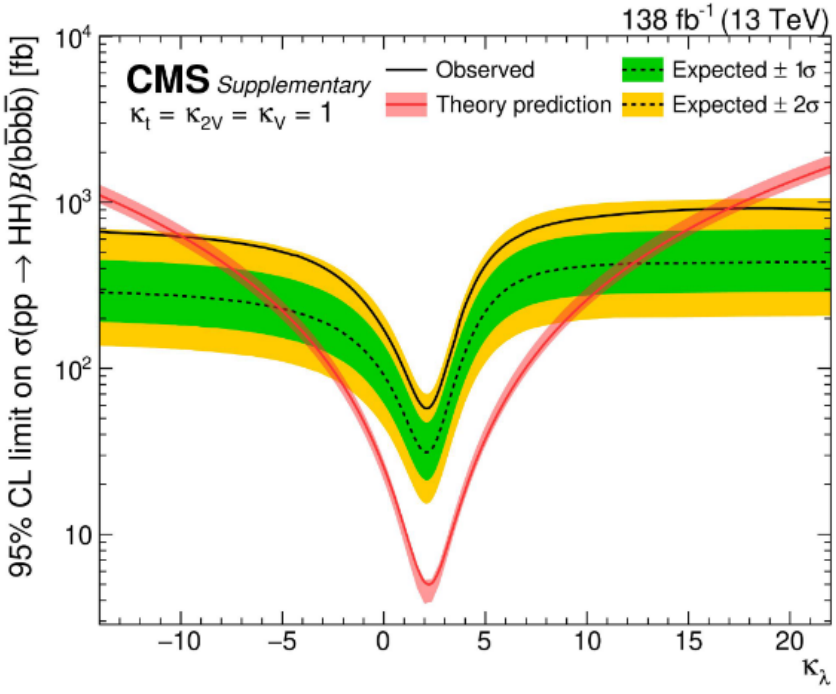




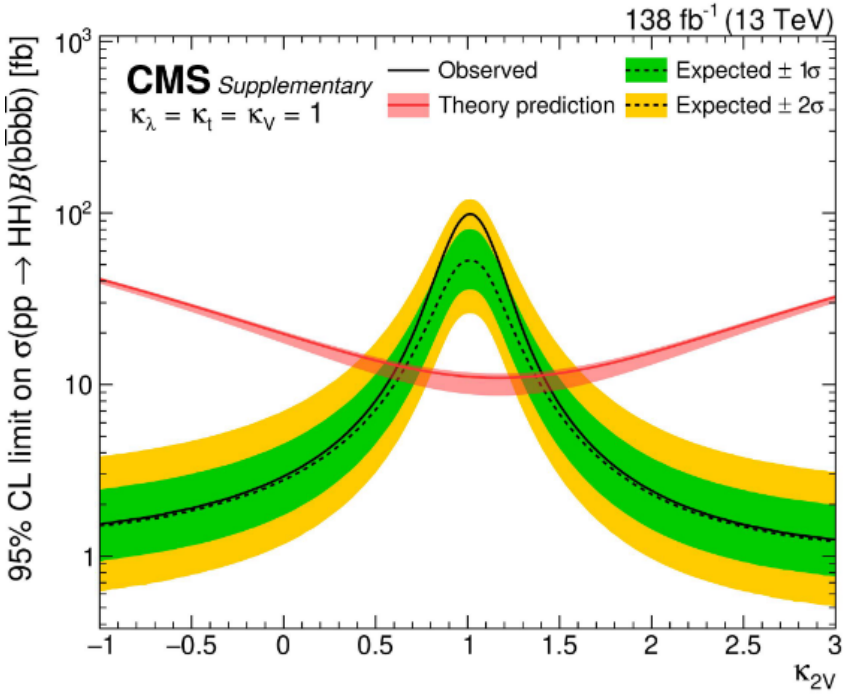
Results

- ggF and VBF combined results
- $k\lambda$ and k2V scans:

$k\lambda$



k2V



- Observed (Expected) Results
  - UL on $\sigma_{ggF+VBF}$: 9.9 (5.1) $\times$ $\sigma_{ggF+VBF}$
  - -9.9 $< k\lambda <$ 16.9
  - 0.62 $<$ k2V $<$ 1.41

$HH \to b\bar{b}\tau_h\tau_X$, $\mathbf{X} = h, \mu, e$ **(HIG-20-010)**

Strategy

- Phase Space: 1 τ_h + 1 τ_h/μ/e and $\geq$ 2 ak4 jets
- τ_h and b-jet identification using the DeepTau and DeepFlavour algorithms

$H \to \tau\tau$ Reconstruction:

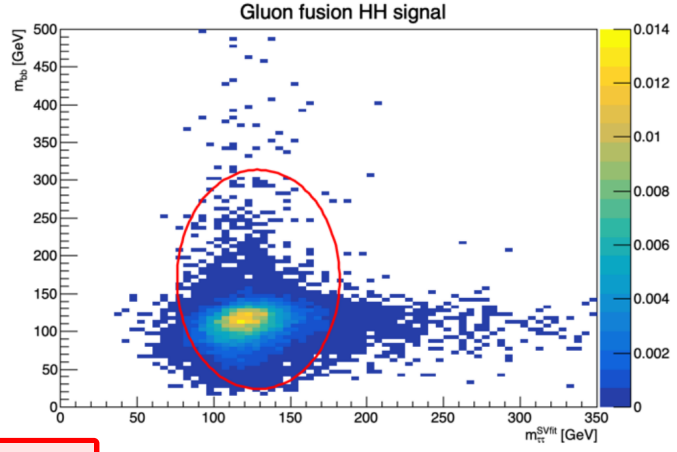
- 2 opposite sign τ leptons
- $\Delta R(\tau, \tau) > 0.5$
- SVfit algorithm for $m_{\tau\tau}$ reconstruction

H $\to$ bb Reconstruction:

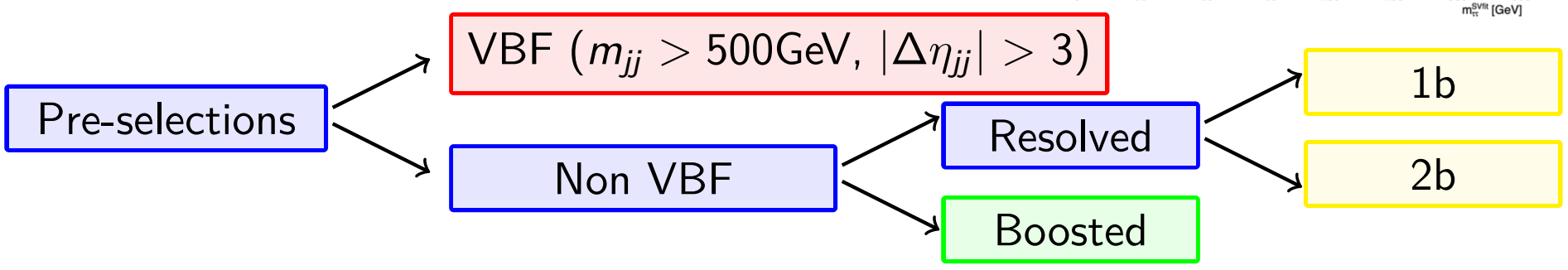
- HH-Btag NN for H $\to$ bb identification
- 2 jets with the highest HH-Btag score
- m_{bb} is the invariant mass of the 2b

HH Mass Selection:

- Elliptical cuts around m_{bb} and $m_{\tau\tau}$ expected values
- $(\frac{m_{\tau\tau}-X}{\sigma_X})^2 + (\frac{m_{bb}-Y}{\sigma_Y})^2 < 1$
- Parameters defined by minimizing bkg acceptance



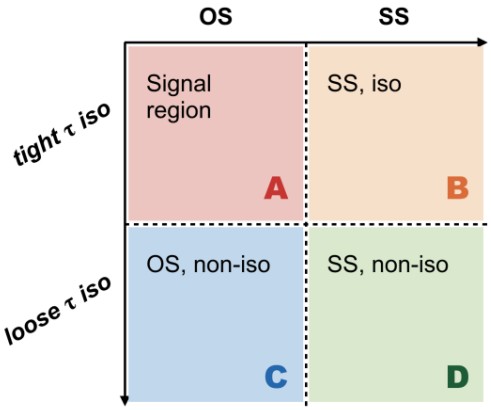
Event Categorization:



For all categories a DNN is trained to maximize the signal Vs bkg discrimination

Background Estimation

QCD (ABCD Method)



- Model is validate in the mass sideband and in different DeepTau WPs

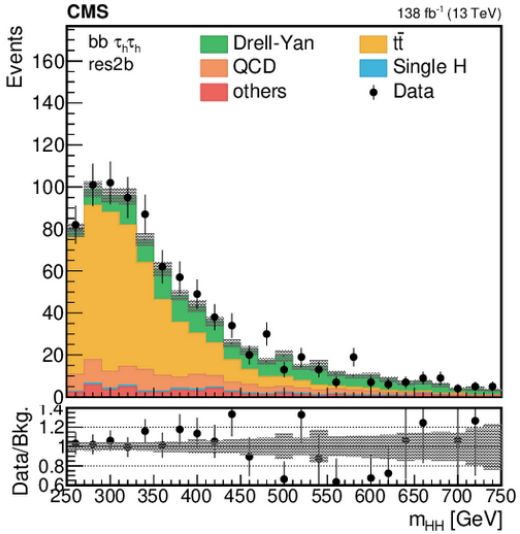
DYLL

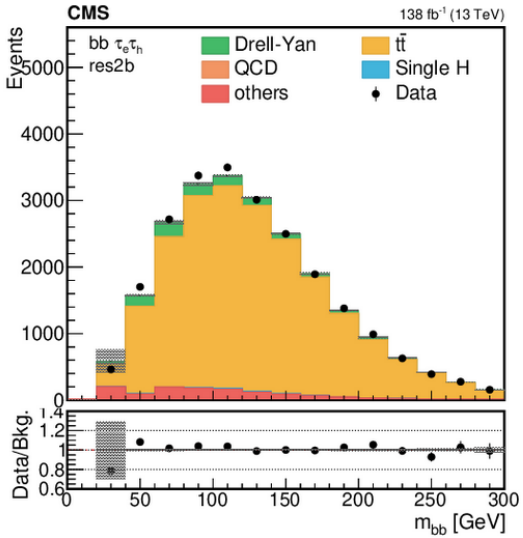
- Data-driven corrections
- From a $Z \to \mu\mu$ enriched region

$t\bar{t}$

- Data-driven corrections
- In the mass sideband of the 2b category
- Method is validated in the low DNN score region of 1b and 2b categories

▶ 2b region for $\tau_h\tau_h$ and $\tau_h\tau_e$ channels after the MC corrections

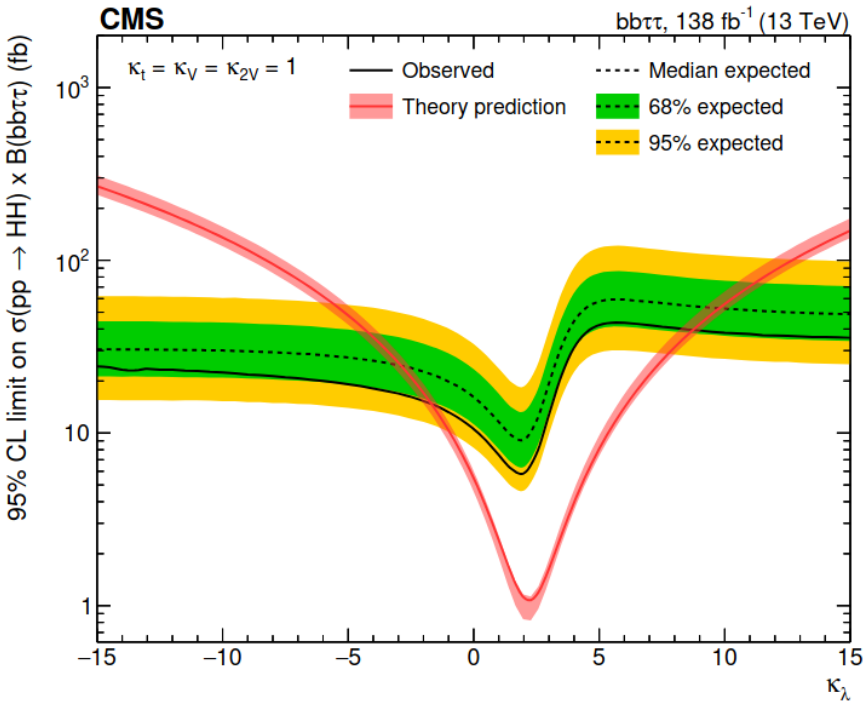




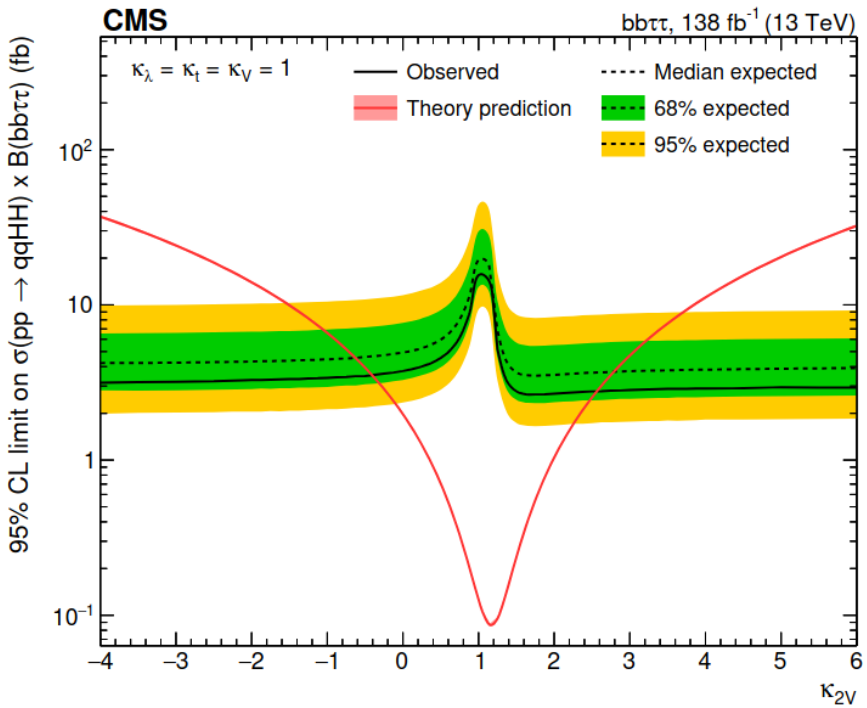
Results

- Discriminant Variable: DNN score
- $k\lambda$ and k2V scans:

$k\lambda$



k2V



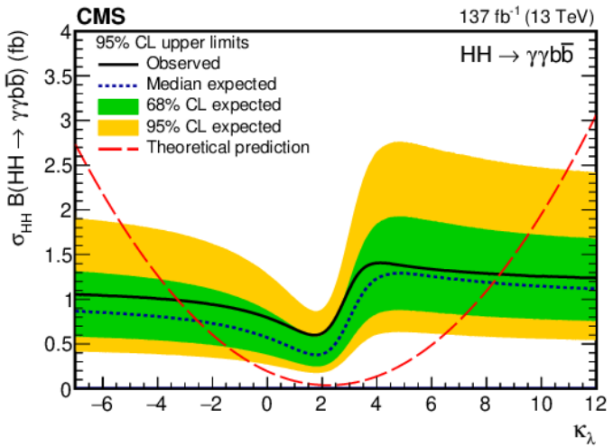
- Observed (Expected) Results
  - UL on $\sigma_{ggF+VBF}$: 3.3 (5.2) $\times$ $\sigma_{ggF+VBF}$
  - -1.8 $< k\lambda <$ 8.8 (-3.0 $< k\lambda <$ 9.9)
  - -0.4 $<$ k2V $<$ 2.6 (-0.6 $<$ k2V $<$ 2.8)

$HH \to b\bar{b}\gamma\gamma$ **(HIG-19-018)**

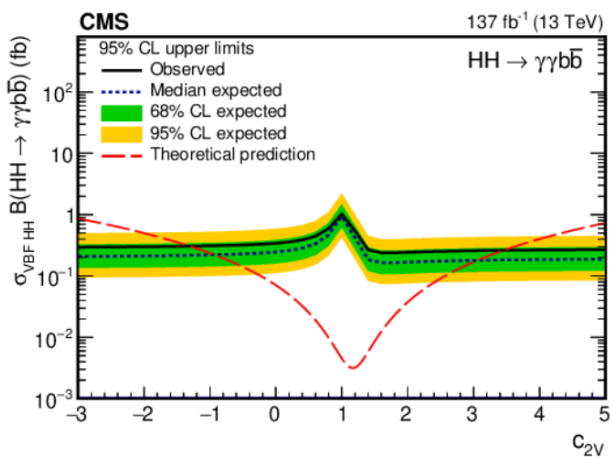
Analysis Strategy

- DNN b-jet energy regression and m_{bb} regression to improve resolution
- ggF and VBF categorization based on the presence of 2 forward AK4 jets
- Separate BDT training for ggF and VBF to reduce $\gamma\gamma$ +jets and γ + jets bkg
- Dedicated NN to remove $t\bar{t}H$ bkg
- Event categorization based on $m_{HH} = m_{\gamma\gamma bb} - m_{bb} - m_{\gamma\gamma} + 2m_H$ and BDT
- 2D m_{bb} and $m_{\gamma\gamma}$ fit, for signal extraction
- Background modeling
  1. Single Higgs: Parametrize $m_{\gamma\gamma}$ and m_{bb} with analytical models
  2. QCD: Data-driven, 2D envelope method ($m_{\gamma\gamma}$ and m_{bb})
- Results:

-3.3 < $k\lambda$ < 8.5 (-2.5 < $k\lambda$ < 8.2)



-1.3 < k2V < 3.5 (-0.9 < k2V < 3.1)



UL on $\sigma_{ggF+VBF}$: 7.7 (5.2) $\times$ $\sigma_{ggF+VBF}$

H + HH Combination

Analysis	CADI	Int. luminosity (fb^{-1})	Phase-space granularity
$H \to ZZ \to 4l$	HIG-19-001	138	STXS 1.2
$H \to b\bar{b}$ boosted	HIG-19-003	138	Inclusive
$VH(b\bar{b})$	HIG-18-016	77	Inclusive
$t\bar{t}H(b\bar{b})$	HIG-17-026	36	Inclusive
$t\bar{t}H$ multilepton	HIG-19-008	138	Inclusive
$H \to \mu\mu$	HIG-19-006	138	Inclusive
$H \to \gamma\gamma$	HIG-19-015	138	STXS 1.2
$H \to \tau\tau$	HIG-19-010	138	STXS 1.2
$H \to WW$	HIG-20-013	138	STXS 1.2

Analysis	CADI	Targeted production modes
$HH \to \gamma\gamma b\bar{b}$	HIG-19-018	ggHH and qqHH
$HH \to \tau\tau b\bar{b}$	HIG-20-010	ggHH and qqHH
$HH \to 4b$ resolved	HIG-20-005	ggHH and qqHH
$HH \to 4b$ merged jets	B2G-22-001	ggHH and qqHH
$VHH(4b)$	HIG-22-006	VHH
HH multilepton	HIG-21-002	ggHH
$HH \to WWb\bar{b}$	HIG-21-005	ggHH and qqHH

HEFT Benchmarks