Search for Higgs boson pair production in $b\bar{b}b\bar{b}$ final state in association with a vector boson with the CMS detector

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Motivation

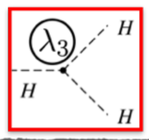
Study Higgs self coupling κ_λ and Higgs boson-Vector boson coupling C_{2V}

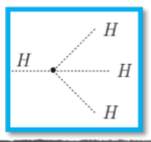
$$V(\Phi) = \sum_{n\geq 0} \frac{\tilde{\lambda}_n}{\Lambda^{2n}} \left(\Phi^\dagger\Phi - v^2\right)^{2+n} = \tilde{\lambda}_0 \left(\Phi^\dagger\Phi - v^2\right)^2 + \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

Di-Higgs study can contribute to Higgs potential study. [1]

Lagrangian can be written as the following form:
λ_3 and λ_4 corralated to 3H and 4H vertices respectively.

$$\mathcal{L} = \frac{1}{2} m_h^2 h^2 + \lambda_3 \frac{m_h^2}{2v} h^3 + \lambda_4 \frac{m_h^2}{8v^2} h^4$$



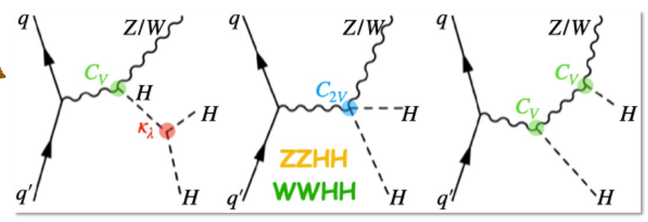


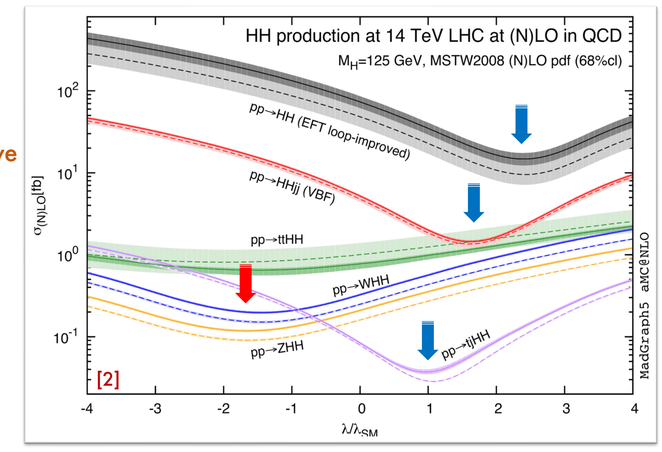
Unique features of VHH production

As 3rd largest Higgs pair production modes. VHH is demonstrated to provide competitive upper bounds. [3][4]
— VHH channel is sensitive to positive κ_λ [2]

The charged lepton and invisible neutrino from W- or Z-boson decays in the VHH production provide a good trigger of signal events.

VHH can directly distinguish ZZHH and WWHH by numbers of final states leptons.





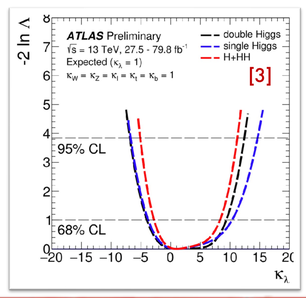
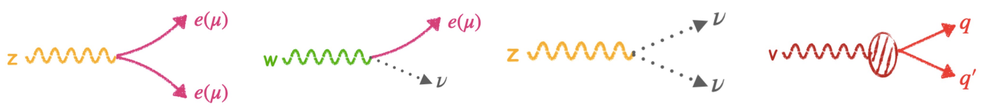


TABLE III: The sensitivity to $\lambda_{HHH} = \kappa\lambda_{HHH}^{SM}$ in several production channels of Higgs boson pairs at the HL-LHC.

[4]	SM ($\kappa = 1$)	5σ discovery potential	2σ exclusion bound
WHH	1.29σ	$\kappa \leq -7.7,\ \kappa \geq 4.8$	$-5.1 \leq \kappa \leq 2.2$
ZHH	1.32σ	$\kappa \leq -8.1,\ \kappa \geq 4.8$	$-5.4 \leq \kappa \leq 2.2$
GF($b\bar{b}\gamma\gamma$) [66]	1.19σ	$\kappa \leq -4.5,\ \kappa \geq 8.1$	$-0.2 \leq \kappa \leq 4.9$
GF($b\bar{b}\gamma\gamma$) [67]	1.65σ	$\kappa \leq -2.6,\ \kappa \geq 6.3$	$0.5 \leq \kappa \leq 4.1$
VBF [43]	0.59σ	$\kappa \leq -1.7,\ \kappa \geq 5.0$	$-0.4 \leq \kappa \leq 3.5$
$t\bar{t}HH$ [44, 45]	1.38σ	$\kappa \leq -11.4, \kappa \geq 6.9$	$-7.2 \leq \kappa \leq 2.5$

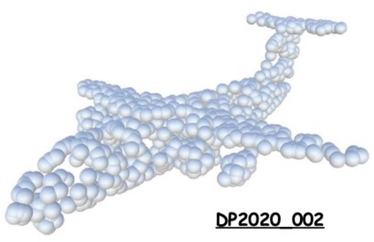
Events Selection

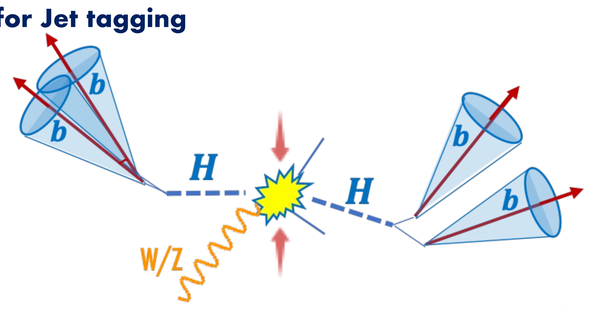
4 analysis channels: **based on the decay of vector bosons**



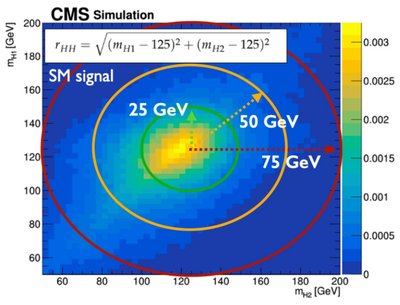
Double Leptons; **Single Lepton;** **MET;** **Full Hadronic**

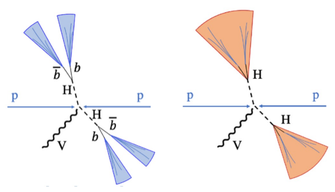
DeepJet and ParticleNet are used for Jet tagging

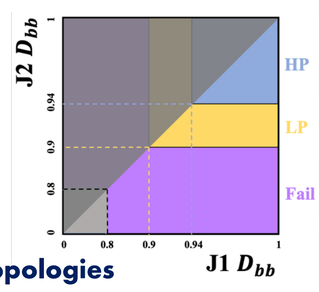




Higgs decay to (largest BR) final state: $b\bar{b}$







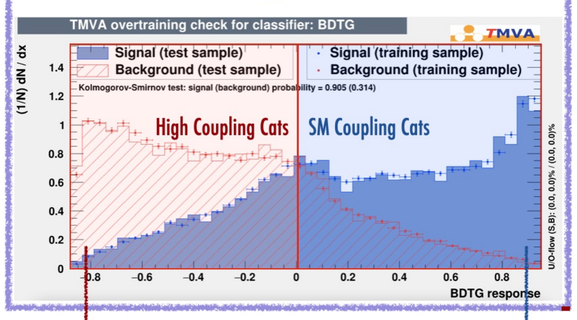
Resolved and Boosted topologies

- Signal Region(**SR**) : rHH < 25GeV
- Control Region(**CR**) : 25GeV<rHH<50GeV
- SideBand(**SB**) : 50GeV < rHH
- High Purity (**HP**) : Dbb > 0.94
- Low Purity(**LP**) : 0.90<Dbb<0.94
- Failed Region(**FR**) : 0.80<Dbb<0.90

Analysis Strategy

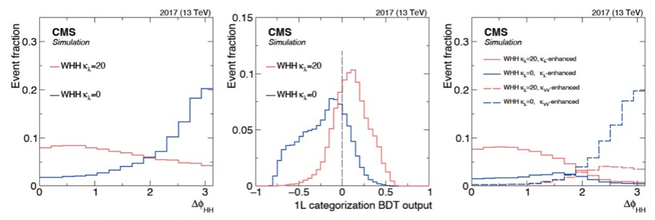
HLT/Object/Event Selections

Kl Categorization



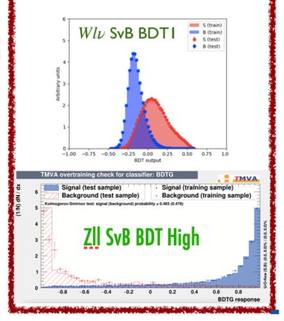
Kl Categorization

Bring extra sensitivity over Kl

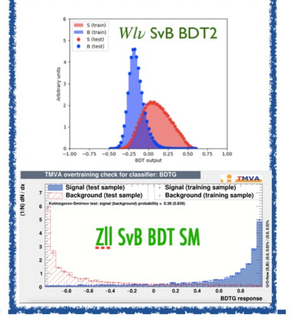


- Samples used for training is Kl = 20 vs Kl = 0
- 3 year MC are combined for training
- Variables and BDT models are optimized in all channels

SvB Classifiers



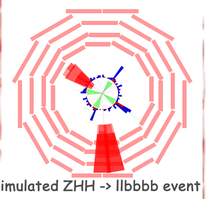
SvB Classifiers



SvB Classifiers Trained separately in High Kl/SM Kl regions

- In V-Leptonic channel
  - 3 channels X 2 Kl Cats = 6 SvB BDTs
- In V-Hadronic channel
  - An ResNet based SvB Classifier is trained
- Optimized (inputs, models) in each channel.

SvB Classifier scores will be used as the observables for template fit



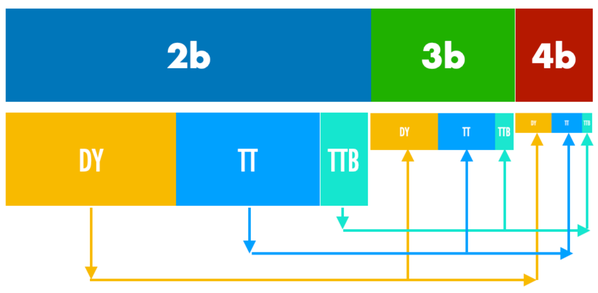
Simulated ZHH -> llbbbb event

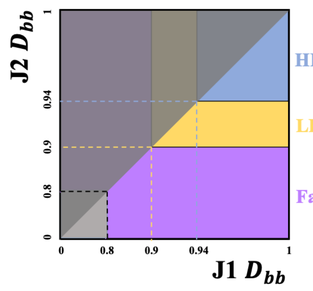
Background Modelling

Novel Machine Learning based background modelling technology is adapted

- In 2L channel (and Boosted topology), we use 2b-tagged MC events(failed selection events) to mimic the background events in reseaching regions.

$$Weight_{bin} = \frac{w_{bin,\ Pass}}{w_{bin,\ Inverted}}$$



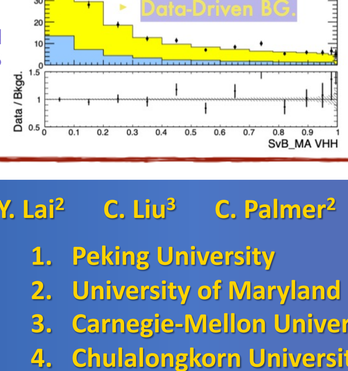


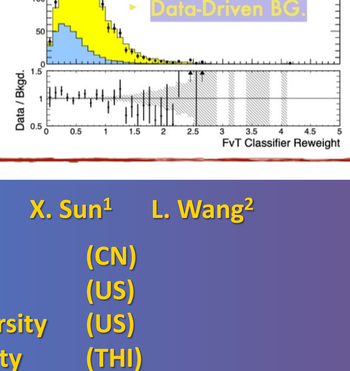
BDTs are used in the 2L channel and Boosted topology

- In Hadronic channel, ResNet based NN is used to realize the data-driven BGs modelling for QCD process from 3b-tagged data.

1.Jet Combinatoric Model(JCM): A weight only based on jet multiplicity (pseudo-tag rate fitted in the data minus TT)

2.FvT Classifier: A weight mostly based on kinematic, derived by a ResNet which has the same architecture as the SvB Classifier.

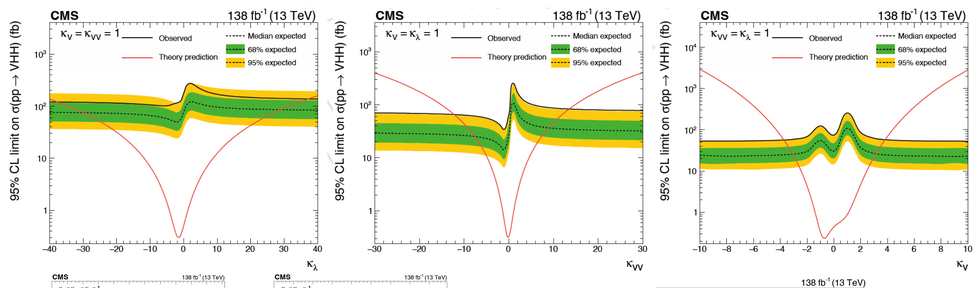


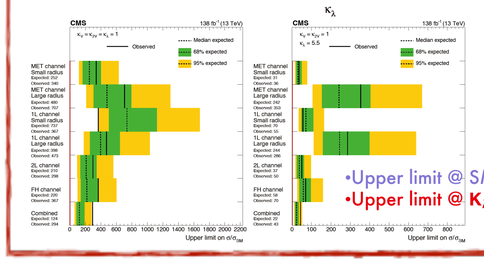


Result

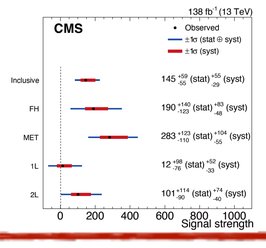
- First search for VHH production in CMS, published on Moriond 2023
  - Complementary to previous analyses, strong sensitivity at κ_λ around 5: 43(22)
- Report observed **2.6σ** excess @ SM, the observed (expected) upper limit at 95% CL is **294(124)** times the cross section from SM prediction
- The observed (expected) allowed intervals from the search at 95% CL are:

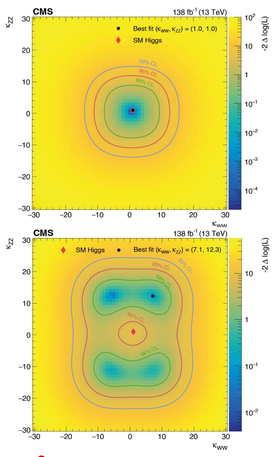
	κ_λ	κ_{VV}	κ_V	κ_{ZZ}	κ_{WW}
Observed	$(-37.7, 37.2)$	$(-12.2, 13.5)$	$(-3.7, 3.8)$	$(-17.4, 18.5)$	$(-14.0, 15.4)$
Expected	$(-30.1, 28.9)$	$(-7.2, 8.9)$	$(-3.1, 3.1)$	$(-10.5, 11.6)$	$(-10.2, 11.6)$





- Upper limit @ SM is 294(124)
- Upper limit @ κ_λ=5.5 is 43(22)





- Separate measurements on K_{zz} and K_{ww}
- Upper is expected
- Bottom is observed

- The best fit signal strength is
- Observed excess is 2.6σ with SM signal

[1] Phys. Rev. D 72, 053008 (2005)
[2] Phys. Lett. B 732 (2014) 142-149
[3] ATLAS-CONF-2019-049
[4] Phys. Rev. D 95, 073006 (2017)

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