北京大學
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Search HH with bbμμ

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Higgs Potential 2022

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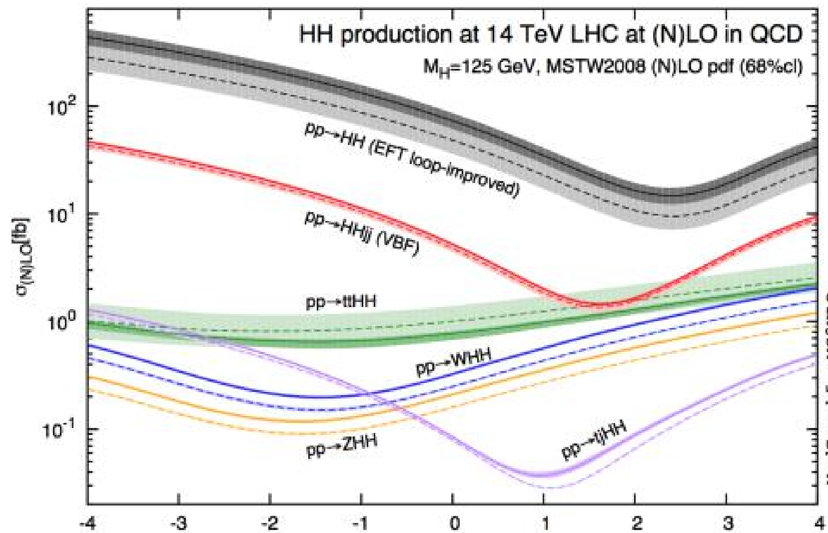
Physics Motivation

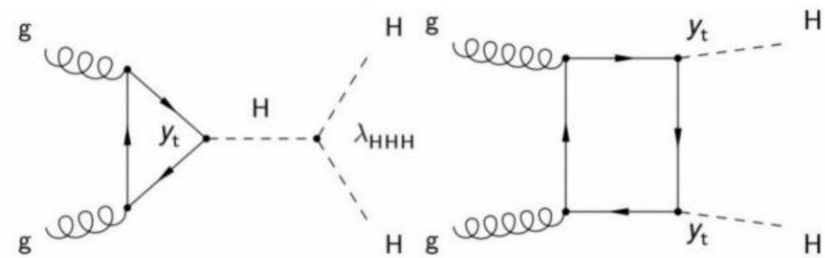
- The trilinear self-coupling of the Higgs boson λ_{HHH} is only directly accessible via HH production
- Contains information about the shape of the Higgs potential
- bbμμ is a brand new di-Higgs decay channel currently

$H \rightarrow bb$: The largest BR
$H \rightarrow \mu\mu$: The excellent resolution of $m_{\mu\mu}$

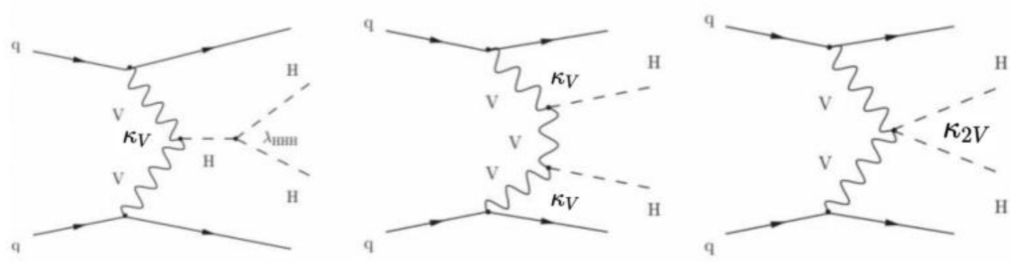
The dominant bkg of this process is DY + jets.

Other bkg, such as tt, single Higgs, which contains ggH, VBFH, ttH, ZH and bbH are also considered.



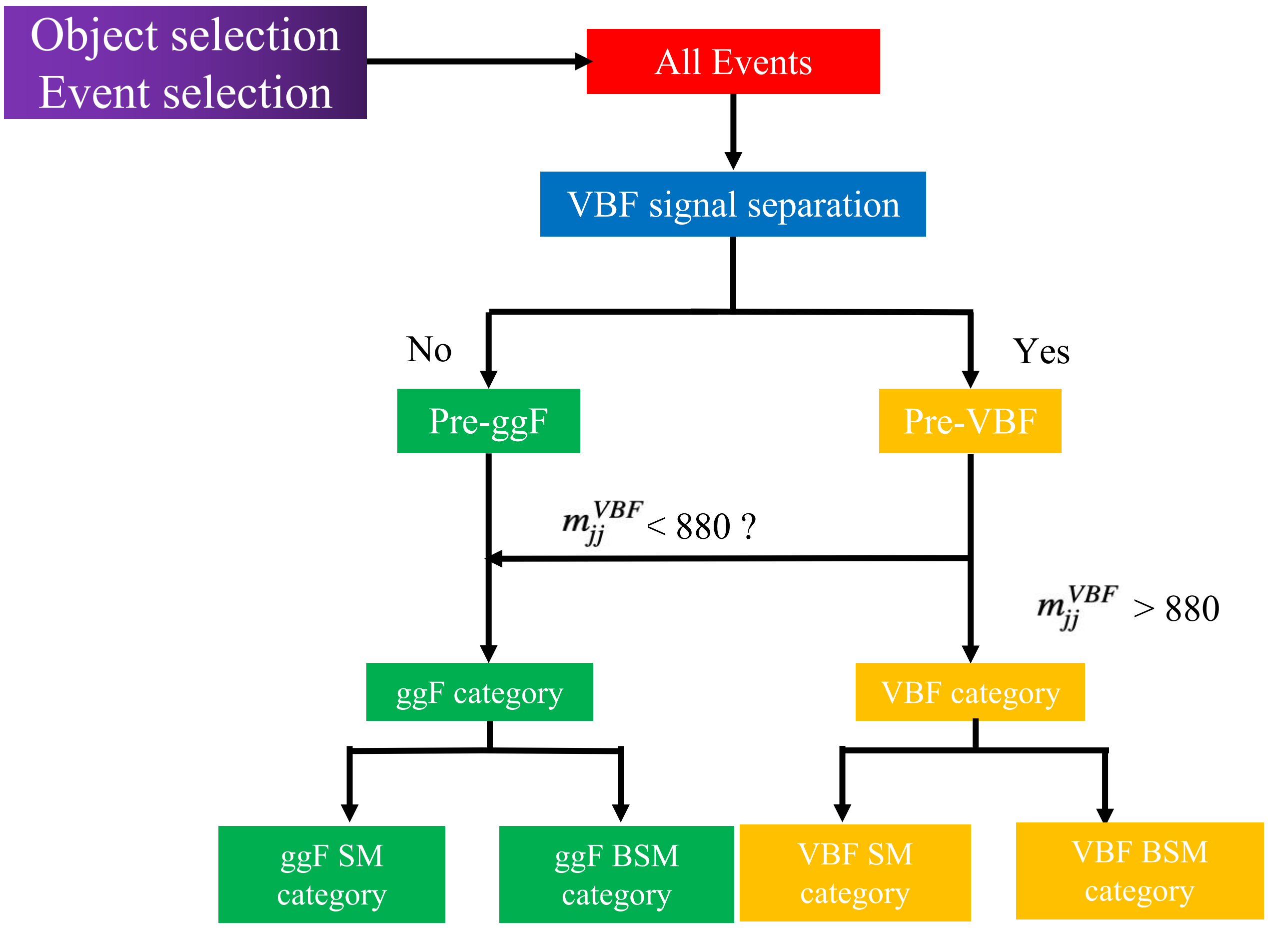


(a)



(b)

Analysis Strategy



In addition, in the two ggF categories, also used BDT approach (XGBoost) to suppress the bkg

In each signal category, do the bkg rejection to optimize the signal sensitivity vs bkg

Object selction and event selction

Object selction

For muon candidates:

- $p_T > 20$ GeV
- $|\eta| < 2.4$

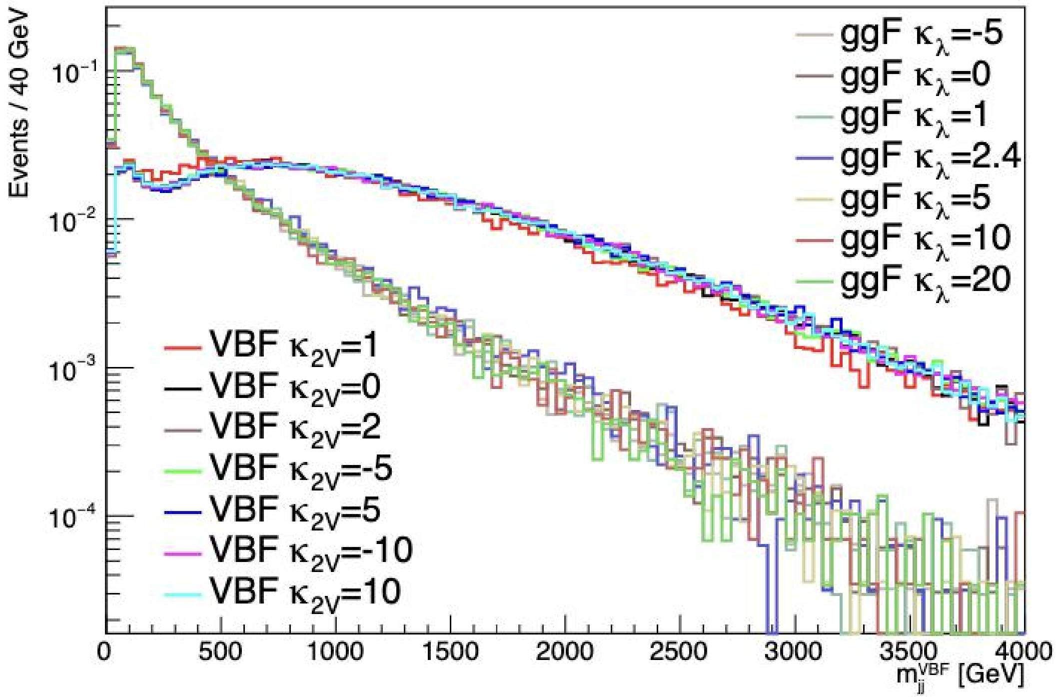
For jet candidates:

- $p_T > 20$ GeV
- $|\eta| < 4.7$ (2.4) for jet (b-tagged jet)

Event selction

- at least two oppositely charged muons
- 100 GeV < $m_{\mu\mu}$ < 180 GeV
- at least two bjets
- 70 GeV < m_{bb} < 190 GeV

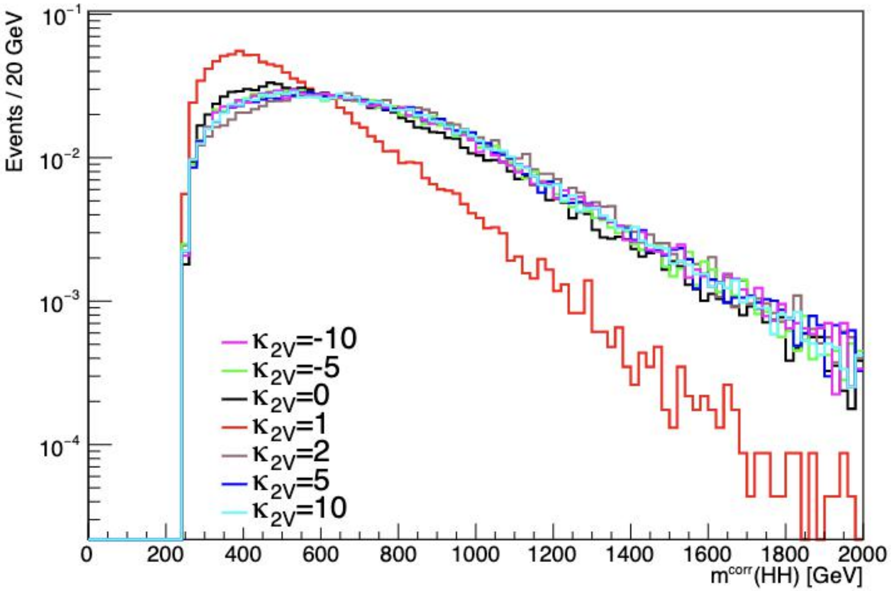
VBF and ggF categorization

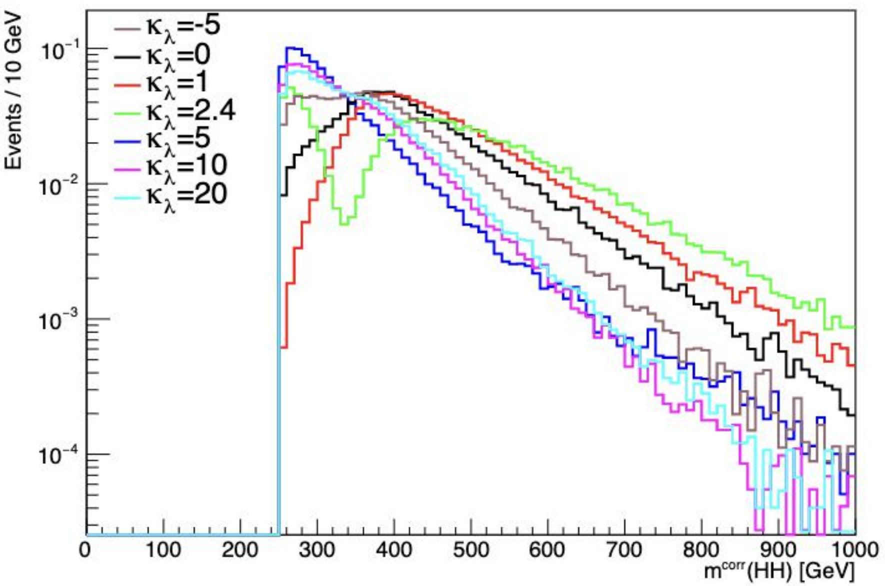


VBF as signal, ggF as bkg, use m_{jj}^{VBF} var to do optimization in order to maximize the separation of VBF and ggF signal
(SM VBF and SM ggF as benckmark)

$m_{jj}^{VBF} > 880$ GeV as VBF category

Categorization in each VBF and ggF category





In VBF category

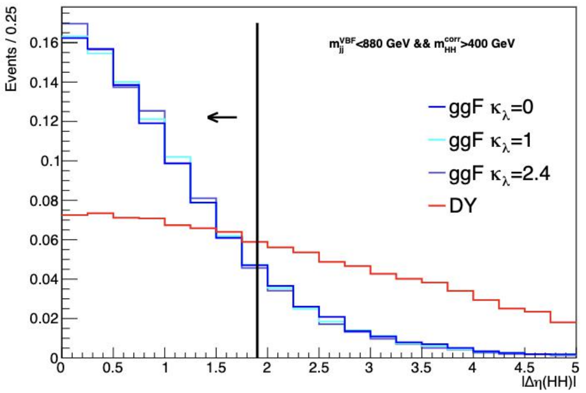
split the signal into 2 catrgories:
< 680 GeV : VBF SM category
> 680 GeV : VBF BSM category

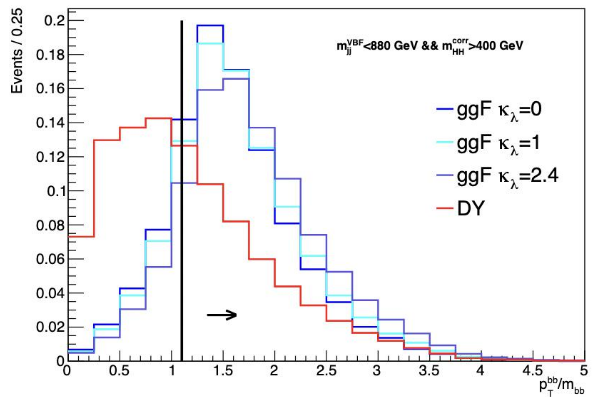
In ggF category

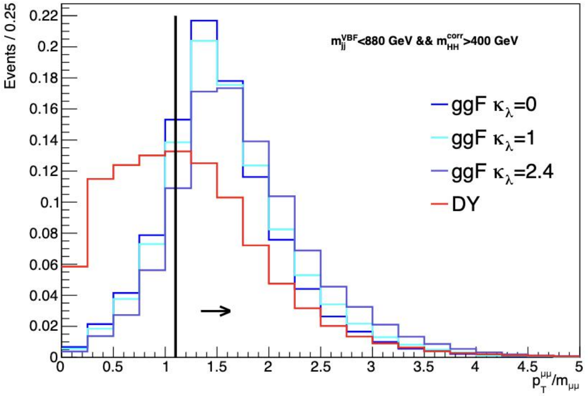
split the signal into 2 categories:
< 400 GeV : ggF BSM category
> 400 GeV : ggF SM category

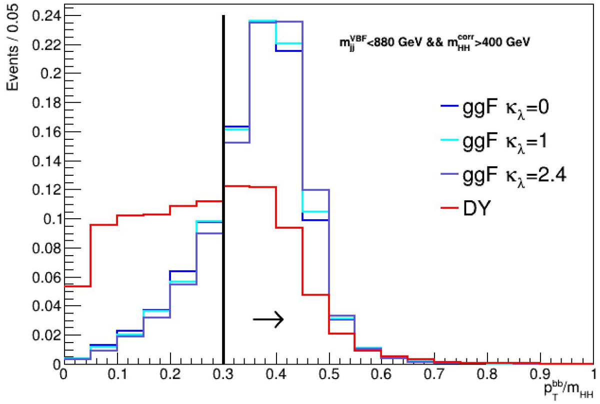
$$m_{\mathrm{HH}}^{\mathrm{corr}} = m_{\mathrm{HH}} - (m_{\mu\mu} - 125) - (m_{bb} - 125)$$

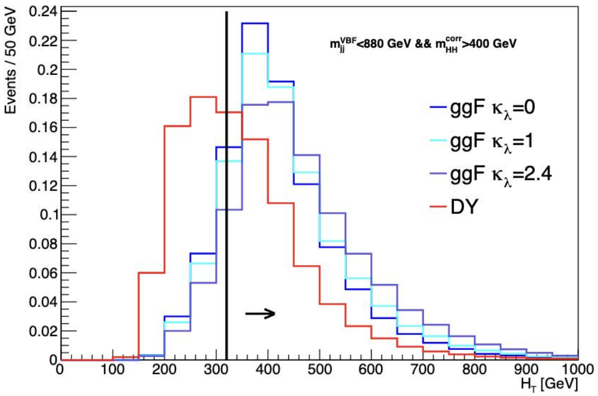
Bkg rejection in ggF SM category (cutbased analysis)





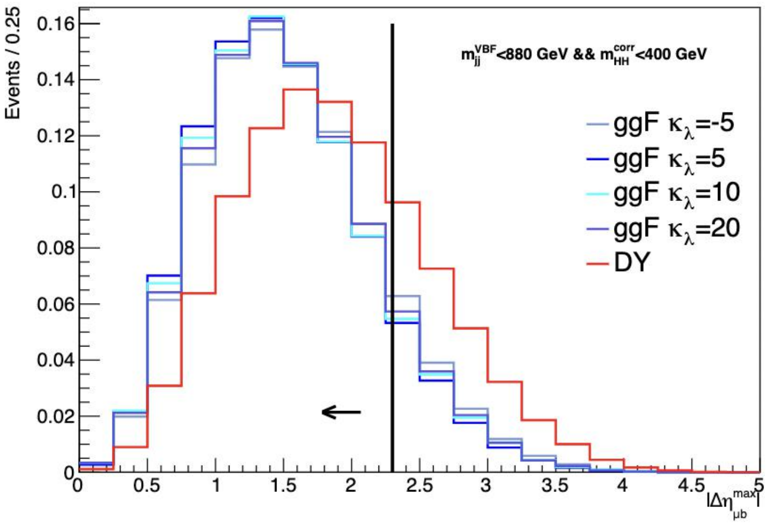


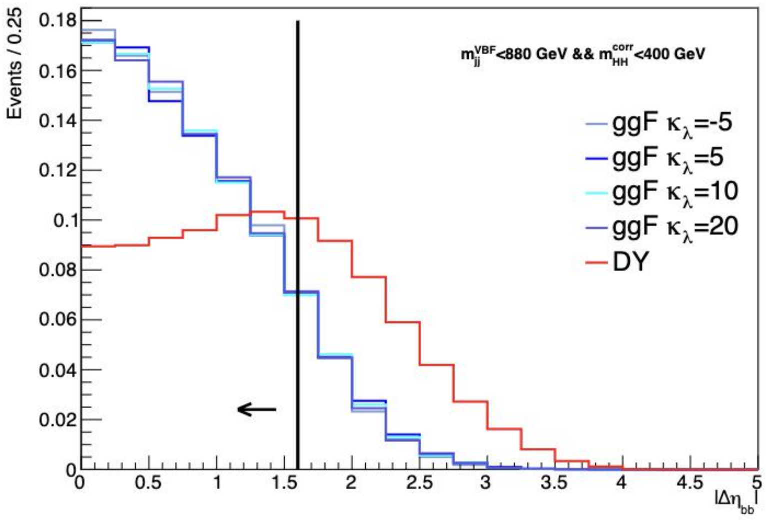


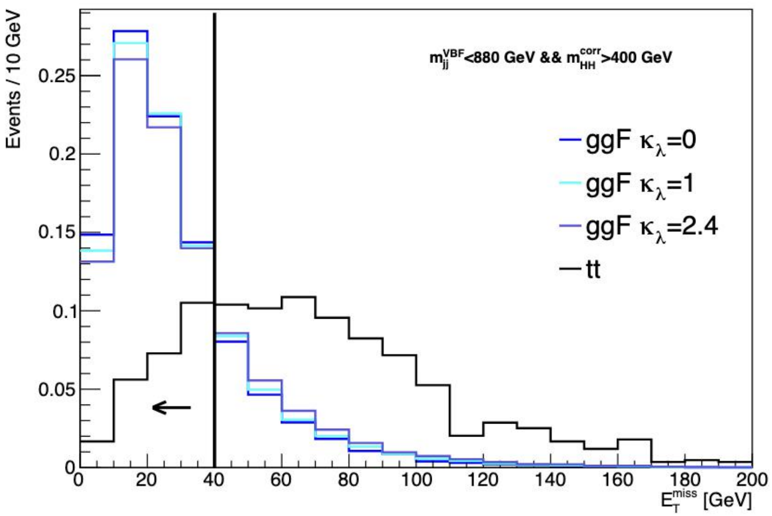


$$|\Delta\eta_{HH}| < 1.9$$
$$p_{\mathrm{T}}^{bb}/m_{bb} > 1.1$$
$$p_{\mathrm{T}}^{\mu\mu}/m_{\mu\mu} > 1.1$$
$$p_{\mathrm{T}}^{bb}/m_{\mathrm{HH}} > 0.3$$
$$H_{\mathrm{T}} > 320\ \mathrm{GeV}$$

Bkg rejection in ggF BSM category (cutbased analysis)





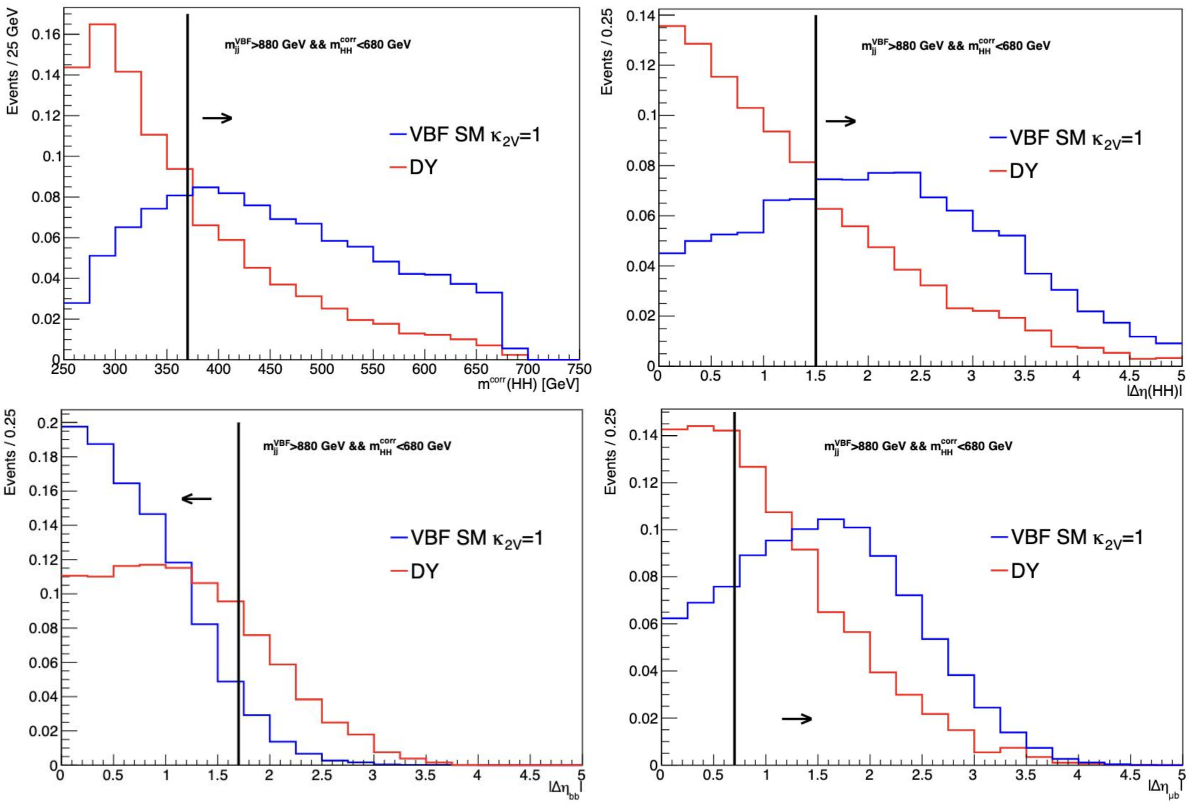


$$|\Delta\eta_{\mu b}^{max}| < 2.3$$

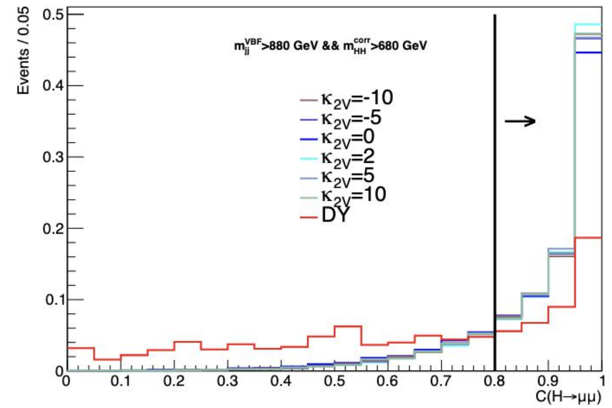
$$|\Delta\eta_{bb}| < 1.6$$

$$E_{\mathrm{T}}^{miss} < 40 \text{ GeV}$$

Bkg rejection in VBF SM, BSM category (cutbased analysis)



VBF SM category



VBF BSM category

$$m_{HH}^{\text{corr}} > 370 \text{ GeV}$$
$$|\Delta\eta_{HH}| > 1.5$$
$$|\Delta\eta_{bb}| < 1.7$$
$$|\Delta\eta_{\mu b}| > 0.7$$

$$C_{(H\rightarrow\mu\mu)} > 0.8$$

$$C_{(H\rightarrow\mu\mu)} = e^{-\frac{4}{(\eta_1^{VBF}-\eta_2^{VBF})^2}\left(\eta^{\mu\mu}-\frac{\eta_1^{VBF}+\eta_2^{VBF}}{2}\right)^2}$$

Bkg rejection(cutbased analysis)

Category	Variable Cut	Signal ϵ	DY ϵ
ggF SM	$\lvert\Delta\eta_{HH}\rvert < 1.9$ $p_T^{bb}/m_{bb} > 1.1$ $p_T^{\mu\mu}/m_{\mu\mu} > 1.1$ $p_T^{bb}/m_{HH} > 0.3$ $H_T > 320$ GeV	53% ($\kappa_\lambda = 1$)	11%
ggF BSM	$\lvert\Delta\eta_{\mu b}^{max}\rvert < 2.3$ $\lvert\Delta\eta_{bb}\rvert < 1.6$ $E_T^{miss} < 40$ GeV	55% ($\kappa_\lambda = 5$)	21%
VBF SM	$m_{HH}^{corr} > 370$ GeV $\lvert\Delta\eta_{HH}\rvert > 1.5$ $\lvert\Delta\eta_{bb}\rvert < 1.7$ $\lvert\Delta\eta_{\mu b}\rvert > 0.7$	39% ($\kappa_{2V} = 1$)	6%
VBF BSM	$C_{(H\to\mu\mu)} > 0.8$	69% ($\kappa_{2V} = 10$)	16%

Category	m_{jj}^{VBF}(GeV)	m_{HH}^{corr}(GeV)
ggF SM	< 880	> 400
ggF BSM	< 880	< 400
VBF SM	> 880	< 680
VBF BSM	> 880	> 680

Summary of the event categorization

Summary of the optimized cuts for background suppression and the corresponding efficiencies in all the four categories.

Bkg rejection(BDT analysis)

Input Variable	ggF SM	ggF BSM
$p_{\mathrm{T}}^{\mu1}$,$p_{\mathrm{T}}^{\mu2}$,p_{T}^{b1},p_{T}^{b2}	✓	✓
$E_{\mu1}$,$E_{\mu2}$,E_{b1},E_{b2}	✓	
$\eta^{\mu1}$,$\eta^{\mu2}$	✓	
η^{b1},η^{b2}	✓	✓
η_{j1}^{VBF}		✓
$E_{\mu\mu}$,E_{bb},$\eta_{\mu\mu}$,η_{bb},$\cos\theta_{\mu\mu}$,$\cos\theta_{bb}$	✓	
$p_{\mathrm{T}}^{\mu\mu}$,p_{T}^{bb},$m_{\mu\mu}$,m_{bb}	✓	✓
m_{HH},m_{HH}^{corr}	✓	
$p_{\mathrm{T}}^{b1}/m_{bb}$,$p_{\mathrm{T}}^{b2}/m_{bb}$,$p_{\mathrm{T}}^{bb}/m_{bb}$,$p_{\mathrm{T}}^{\mu1}/m_{\mu\mu}$,$p_{\mathrm{T}}^{\mu2}/m_{\mu\mu}$	✓	
$p_{\mathrm{T}}^{bb}/m_{bb}$,$p_{\mathrm{T}}^{bb}/m_{\mathrm{HH}}$,$p_{\mathrm{T}}^{\mu\mu}/m_{\mu\mu}$,$p_{\mathrm{T}}^{\mu\mu}/m_{\mathrm{HH}}$	✓	✓
H_{T},$p_{\mathrm{T}}^{\mathrm{HH}}$,$p_{\mathrm{T}}^{\mu\mu}/p_{\mathrm{T}}^{bb}$	✓	✓
E_{T}^{miss},η^{miss}	✓	✓
$\lvert\Delta\eta_{HH}\rvert$,$\lvert\Delta\eta_{\mu b}\rvert$,$\lvert\Delta\eta_{\mu b}^{max}\rvert$,$\lvert\Delta\eta_{\mu b}^{other}\rvert$	✓	✓
$\lvert\Delta\eta_{bb}\rvert$,$\lvert\Delta\eta_{\mu\mu}\rvert$	✓	✓
$\lvert\Delta R_{HH}\rvert$,$\lvert\Delta R_{\mu b}\rvert$,$\lvert\Delta R_{bb}\rvert$,$\lvert\Delta R_{\mu\mu}\rvert$	✓	✓
$\lvert\Delta R_{\mu b}^{min}\rvert$,$\lvert\Delta R_{\mu b}^{other}\rvert$,$\lvert\Delta R_{jj}^{\mathrm{VBF}}\rvert$	✓	
$\lvert\Delta\phi_{HH}\rvert$,$\lvert\Delta\phi_{\mu b}\rvert$,$\lvert\Delta\phi_{bb}\rvert$,$\lvert\Delta\phi_{jj}^{\mathrm{VBF}}\rvert$	✓	✓
$\lvert\Delta\phi_{\mu\mu}\rvert$	✓	

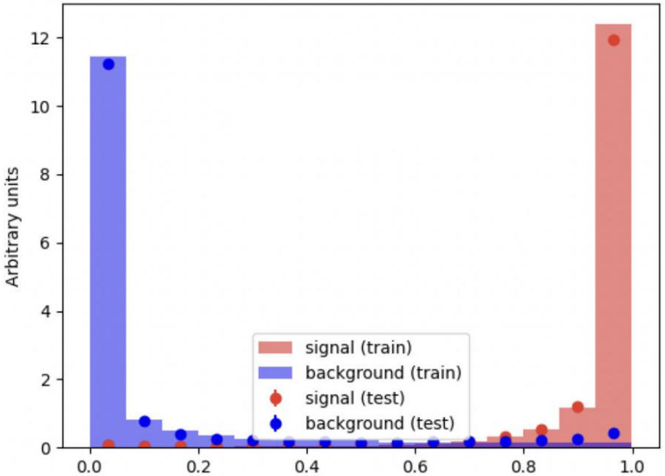
The training setup includes 2500 trees, the tree depth of 3 and a learning rate of 0.08 (0.1) for ggF SM category (ggF BSM category). The MC samples are splitted into 64%, 16% and 20% for training, testing and application.

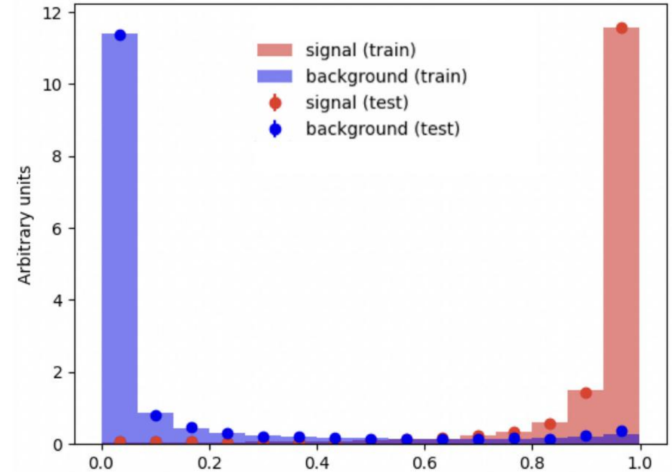
Summary of input variables for the BDT training in the two ggF categories.

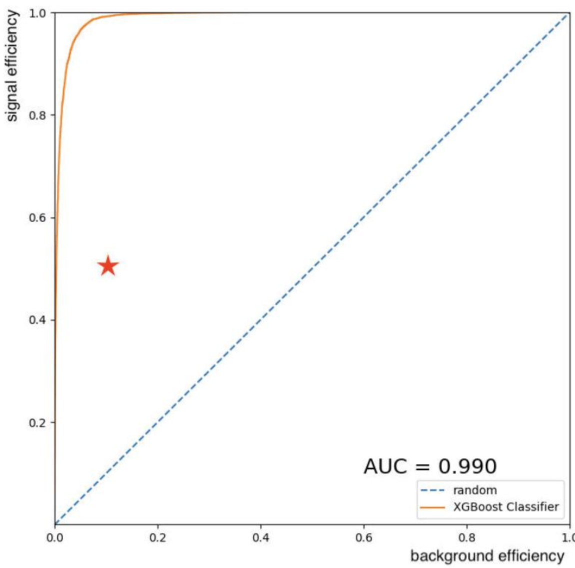
$|\Delta\eta_{\mu b}^{max}|$ is the maximal $|\Delta\eta|$ between muons and bjets, while $|\Delta\eta_{\mu b}^{other}|$ is for the left muon and bjet.

$|\Delta R_{\mu b}^{min}|$ and $|\Delta R_{\mu b}^{other}|$ are defined accordingly.

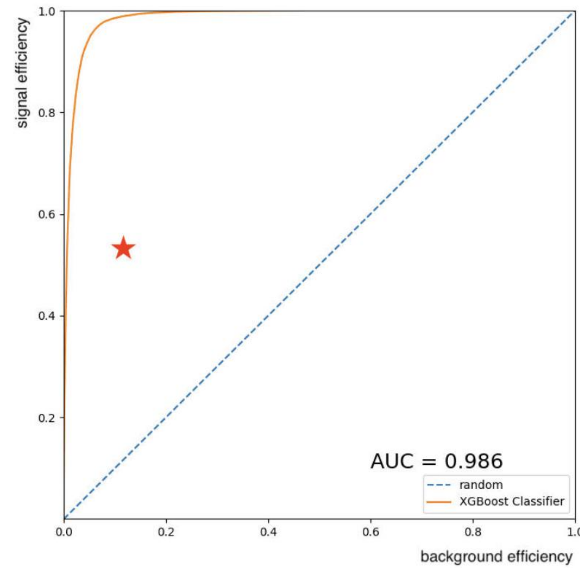
Bkg rejection(BDT analysis)





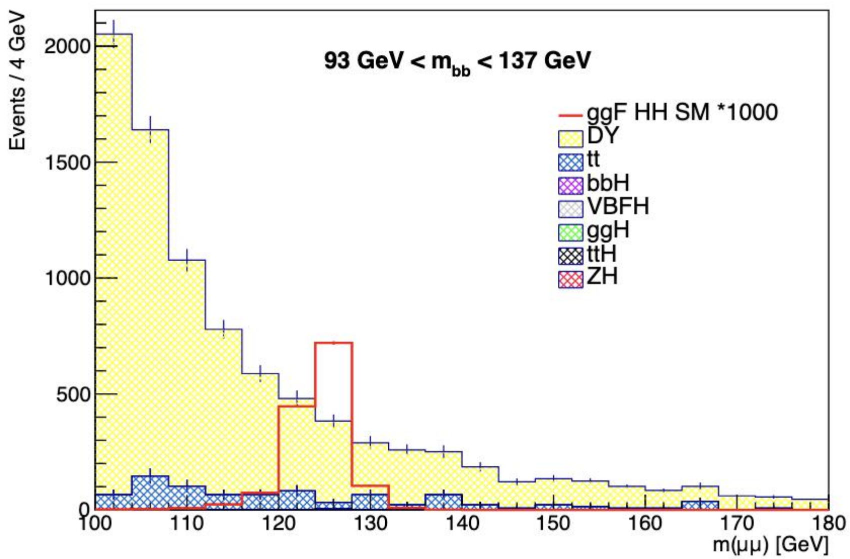


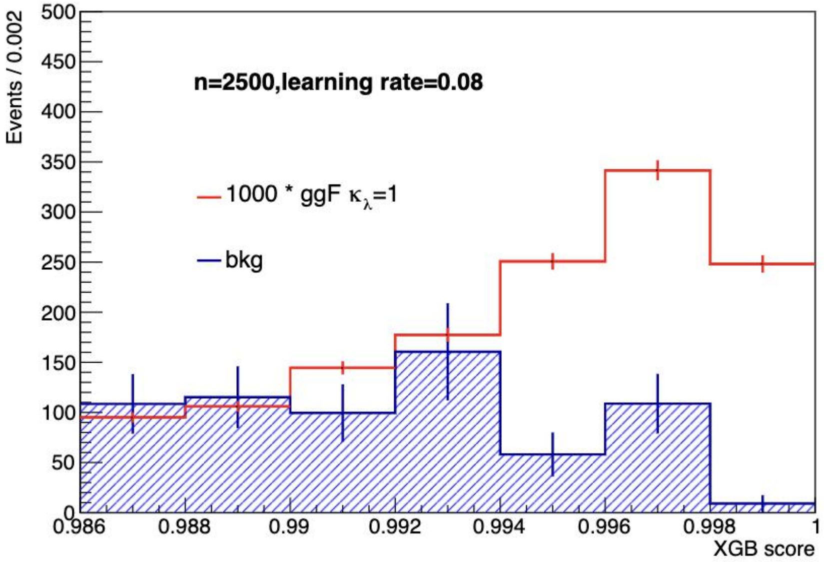
ggF SM category

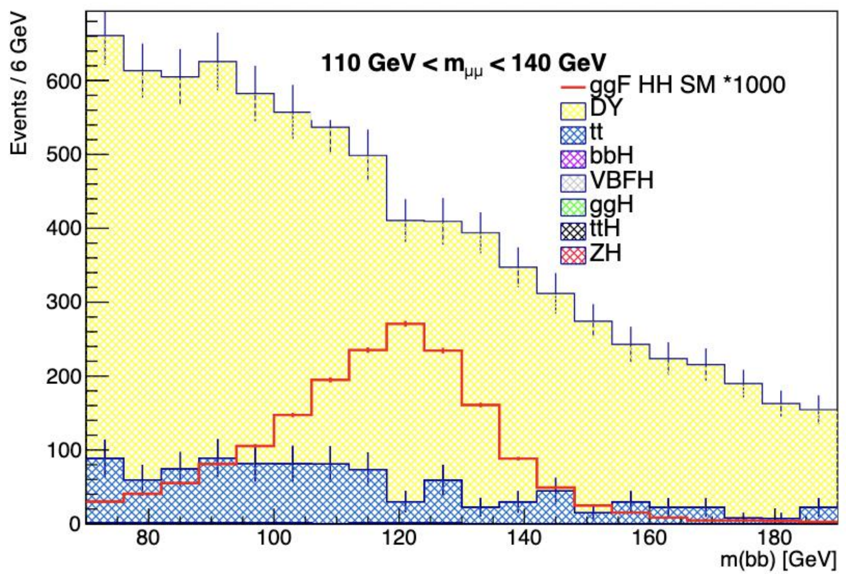


ggF BSM category

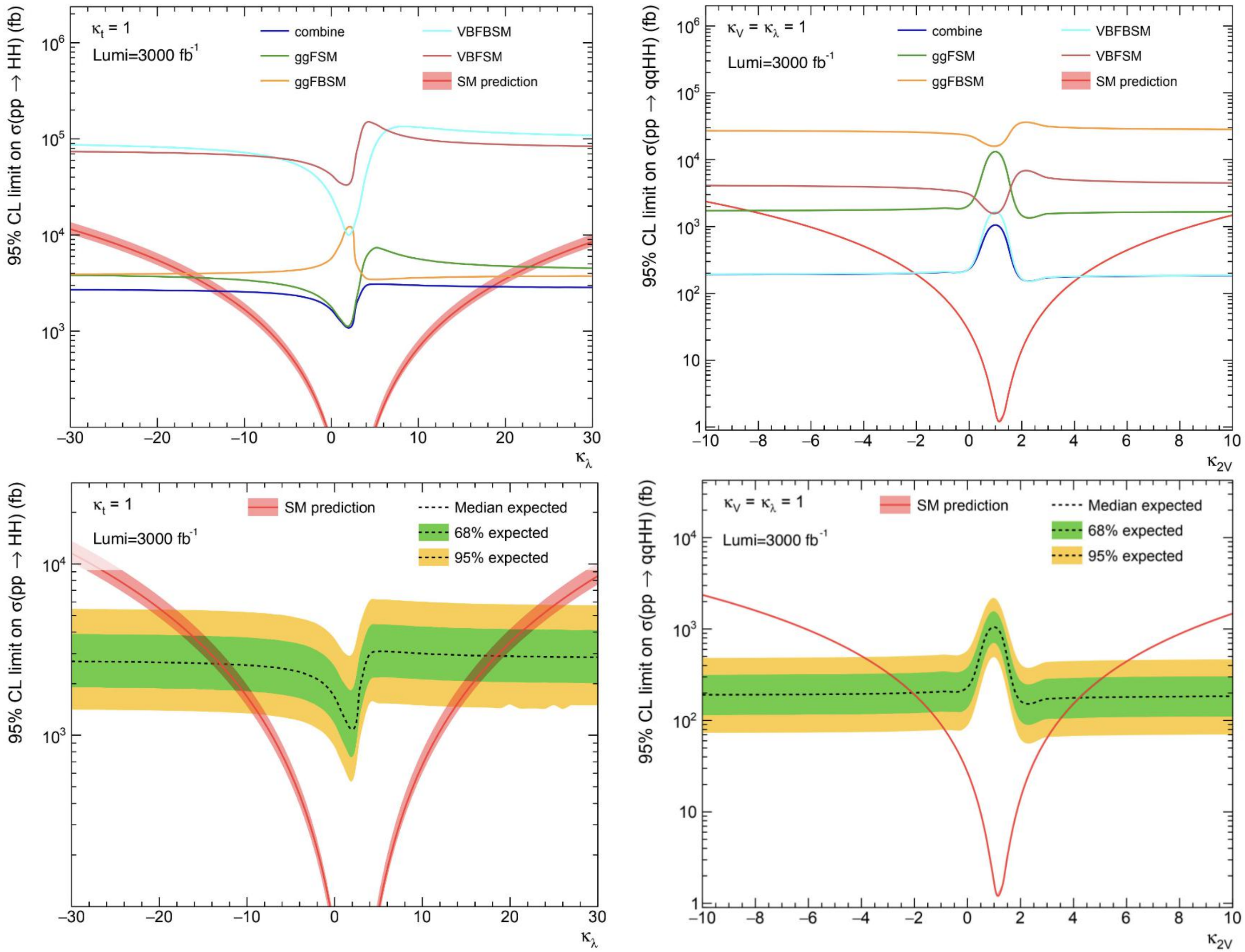
Fitting template







Result (cutbased analysis)

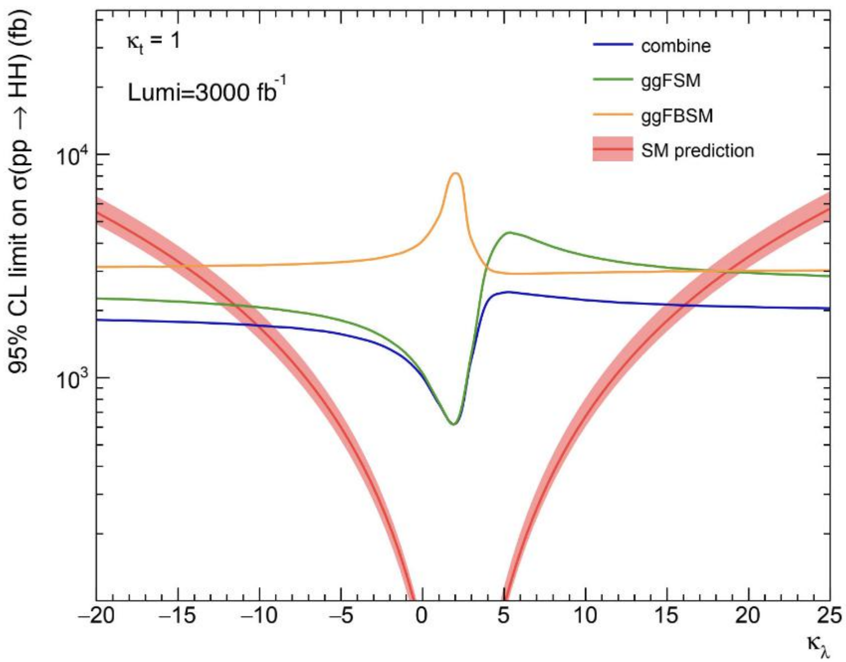


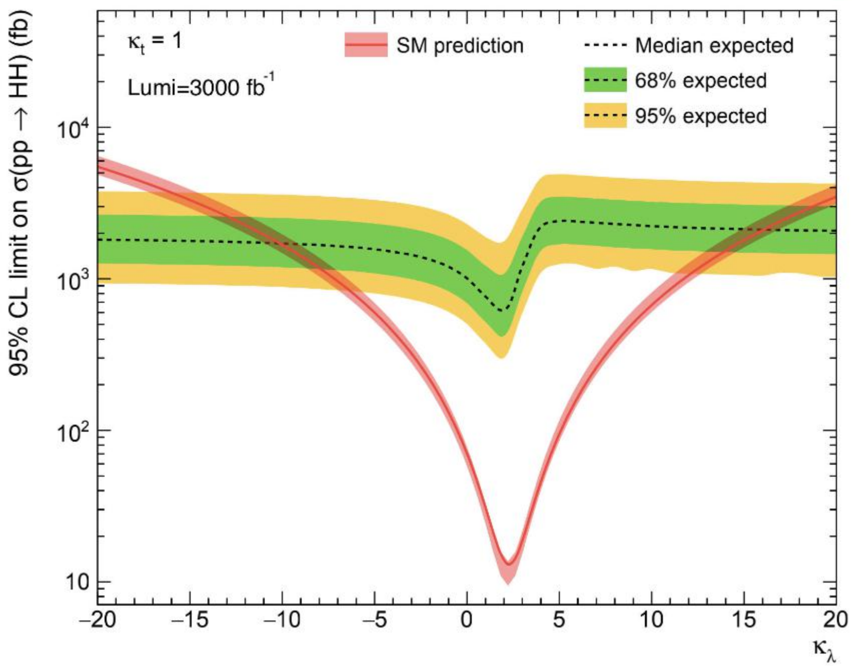
The expected exclusion is $\kappa_\lambda < -13.1$ and $\kappa_\lambda > 18.4$

The expected exclusion is $\kappa_{2V} < -2.1$ and $\kappa_{2V} > 4.2$

The expected upper limit is corresponds to 42 times the standard model prediction(Lumi=3000 fb^{-1}).

Result (BDT analysis)





The expected exclusion is
$\kappa_\lambda < -10.1$ and $\kappa_\lambda > 16.1$

The expected upper limit is corresponds to 25 times the standard model prediction(Lumi=3000 fb^{-1}).

Conclusion

- We presents a comprehensive study of the Higgs boson pair production in the rare decay of $HH \to b\bar{b}\mu^+\mu^-$ with both the ggF and VBF production modes included for the first time.
- With a luminosity up to 3000 fb^{-1}, the channel $HH \to b\bar{b}\mu^+\mu^-$ can not lead to the observation of HH with the cut-based or the BDT approach.
- It is still able to contribute in a sizeable way to the HH search combination and can be sensitive to BSM enhancement given its small rate and excellent di-muon peak.

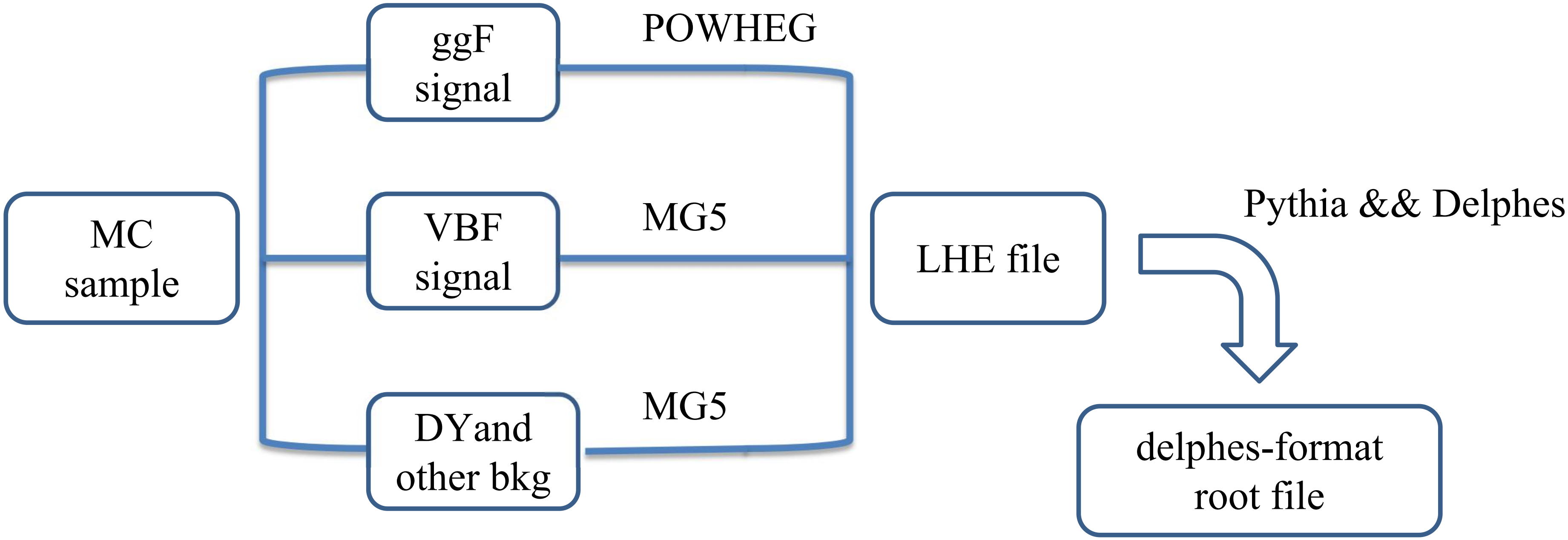
Analysis Type	300 fb^{-1}	450 fb^{-1}	3000 fb^{-1}
ggF HH (σ/σ_{SM})			
Cut-based	138	111	42
BDT	92	73	25
VBF HH (σ/σ_{SM})			
Cut-based	2440	1915	618

Analysis Type	300 fb^{-1}	450 fb^{-1}	3000 fb^{-1}
κ_λ scan			
Cut-based	(-25.7,31.1)	(-22.9,28.3)	(-13.1,18.4)
BDT	(-21.6,27.2)	(-19.0,24.7)	(-10.1,16.1)
κ_{2V} scan			
Cut-based	(-6.4,8.6)	(-5.4,7.5)	(-2.1,4.2)

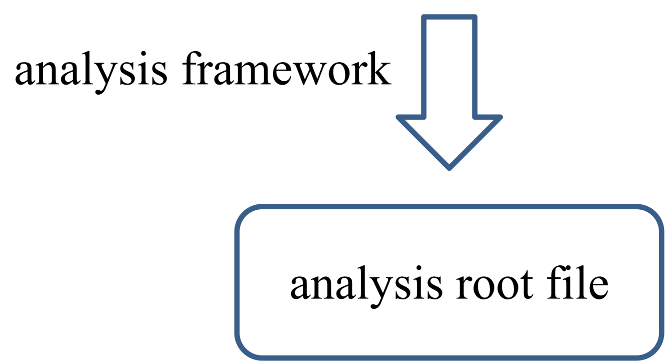
Thank you !

Back Up

MC sample



Other HH process with HH to bbWW and bbττ where WW or ττ decay to μμ in their final state are also tested, but are found to have negligible contribution due to their soft di-muon mass.



Process	$m_{l^+l^-}$ [GeV]	σ[fb]	$N^{\rm gen}_{\rm events}(\times 10^6)$
Drell-Yan	[100, 150]	5481	9.98
Drell-Yan	[150, 200]	384	10.0
Drell-Yan	[200, +∞]	201	1.0
$t\bar{t}$	—	4864	2.0
ggH	—	82836	1.0
VBFH	—	4058	1.0
ZH	—	1775	1.0
ttH	—	836	1.0
bbH	—	638	1.0
ggF signal			
$\kappa_\lambda = -5$	—	599	0.55
$\kappa_\lambda = 0$	—	70	0.55
$\kappa_\lambda = 1$	—	31	0.55
$\kappa_\lambda = 2.4$	—	13	0.55
$\kappa_\lambda = 5$	—	95	0.55
$\kappa_\lambda = 10$	—	672	0.55
$\kappa_\lambda = 20$	—	3486	0.55
VBF signal			
$\kappa_{2V} = -10$	—	2365	0.50
$\kappa_{2V} = -5$	—	722	0.50
$\kappa_{2V} = 0$	—	27	0.50
$\kappa_{2V} = 1$	—	1.73	0.50
$\kappa_{2V} = 2$	—	14.2	0.50
$\kappa_{2V} = 5$	—	279	0.50
$\kappa_{2V} = 10$	—	1479	0.50

TABLE I. Summary of Monte Carlo samples.

HL-LHC is expected to have 23 events that HH to bbμμ.